Development of the B-Stark motional Stark effect diagnostic for measurements of the internal magnetic field in the DIII-D tokamak

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Development of the B-Stark motional Stark effect diagnostic for measurements of the internal magnetic field in the DIII-D tokamak

A dissertation submitted in partial satisfaction of the requirements for the degree
Doctor of Philosophy

in

Physics

by

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2010
The dissertation of Novimir Antoniuk Pablant is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego

2010
DEDICATION

To

Viera I. Pablant, Ph.D.

Peace and friendship be with you.
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VITA

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ABSTRACT OF THE DISSERTATION

Development of the B-Stark motional Stark effect diagnostic for measurements of the internal magnetic field in the DIII-D tokamak

by

Novimir Antoniuk Pablant

Doctor of Philosophy in Physics

University of California, San Diego, 2010

Patrick Diamond, Chair

A new diagnostic, \( \vec{B} \)-Stark, has been developed at the DIII-D tokamak for measurements of the magnitude and direction of the internal magnetic field. The \( \vec{B} \)-Stark system is a version of a motional Stark effect (MSE) diagnostic based on the Stark split \( D_\alpha \) emission from injected neutral beams. This diagnostic uses the spacing of the Stark lines to measure the magnitude of the magnetic field, and the intensities of the \( \pi_3 \) and \( \sigma_1 \) lines to measure the magnetic pitch angle. These lines originate from the same upper level, and are therefore not dependent on the \( n = 3 \) level populations. The measurement of the magnetic pitch angle requires a specific viewing geometry with respect to the neutral beams, which is provided by the \( \vec{B} \)-Stark diagnostic installation.
The $\vec{B}$-Stark technique may have advantages over motional Stark effect polarimetry (MSE polarimetry) diagnostics in future devices with high densities and temperatures, such as ITER. Under these conditions coatings on the plasma facing mirrors are expected, which can cause changes in the polarization state of the reflected light. The $\vec{B}$-Stark technique is insensitive to the polarization direction, and can calibrate for polarization dependent transmission by using an \textit{in-situ} beam-into-gas calibration.

This dissertation describes the development and characterization of the $\vec{B}$-Stark diagnostic. The hardware design and spectral fitting techniques are discussed in detail. Calibration procedures are described including the \textit{in-situ} determination of the beam emission line profiles, viewing geometry and properties of the collection optics.

The performance of the system is evaluated over the range of plasma conditions accessible at DIII-D. Measurements of the magnetic field have been made with toroidal fields in the range 1.2 - 2.1T, plasma currents in the range 0.5 - 2.0MA, densities between $1.7 - 9.0 \times 10^{19} \text{m}^{-3}$, and neutral beam voltages between 50 - 81keV. These results are compared to values found from plasma equilibrium reconstructions (\texttt{EFIT}) and the MSE polarimetry system on DIII-D. The $\vec{B}$-Stark system has been shown to provide measurements with a random errors as low as 0.2-0.3° in the magnetic pitch angle and 0.001-0.002T in $|\vec{B}|$.

Finally, proposed future improvements for the $\vec{B}$-Stark diagnostic are presented.
Chapter 1

Introduction

This dissertation describes the development and characterization of a new diagnostic, $\vec{B}$-Stark, installed on the DIII-D tokamak at General Atomics. The $\vec{B}$-Stark diagnostic is able to measure local values of the magnitude and direction of the internal magnetic field. This system is a version of a motional Stark effect (MSE) diagnostic based on the relative line intensities and spacing of the Stark split $D_\alpha$ emission from injected neutral beams.

In the following chapters the theory, design, calibration and final performance of the $\vec{B}$-Stark diagnostic are discussed in detail. Measurements of the magnetic field are compared against values found from plasma equilibrium reconstructions (EFIT)\textsuperscript{3} and the existing motional Stark effect polarimetry (MSE polarimetry)\textsuperscript{4} diagnostic. Finally possible improvements to the $\vec{B}$-Stark diagnostic technique are discussed.

1.1 Magnetic confinement fusion

The goal of current fusion energy research is to produce power through the fusing of hydrogen isotopes.

$$D + T \rightarrow ^4\text{He}(3.5\text{MeV}) + n(14.1\text{MeV})$$

In order for the two nuclei to fuse, the Coulomb repulsion between them must be overcome. This is done by heating a deuterium-tritium plasma to very high
temperatures, \( \sim 20 \text{keV} \) (200 million \( ^\circ \text{C} \)). In addition, high densities, \( \gtrsim 10^{20} \text{m}^{-3} \), must be maintained to produce a sustainable reaction from which power can be extracted.

One of the most promising ways to attain the conditions needed for fusion is to use a magnetically confined plasma. There are several magnetic confinement configurations currently under investigation at various institutions around the world. The configuration that has shown the most success is the tokamak device. In this type of device the plasma is confined through the use of a toroidal magnetic field. The charged particles are nominally confined to the magnetic field lines, however they experience drifts due to gradients in the magnetic field. To counteract these drifts a poloidal magnetic field is introduced by producing a current in the plasma.

There are a number tokamak devices currently in operation around the world. One of the high performance devices is the DIII-D tokamak at General Atomics in San Diego where the \( \vec{B} \)-Stark diagnostic is installed. A new tokamak device, ITER, is currently under construction as part of an international collaboration in Cadarache France. The ITER experiment is expected to show the feasibility of magnetic confinement fusion for power production.\(^5\) This device will produce plasmas with higher sustained densities and temperatures than are accessible in current devices, presenting a new set of challenges for the design and operation of diagnostic systems.

### 1.2 Measurement of the internal magnetic field

The ability to accurately reconstruct the plasma equilibrium is important for assessing the stability and for controlling magnetically confined plasmas in tokamaks and stellarators. These measurements are especially important for the understanding of magnetic shear and its effects on turbulence and confinement.\(^6\) Knowledge of the plasma current and pressure profile are also important for suppression of plasma instabilities and the optimization of current drive.\(^7,8\)

Measurements of the internal magnetic field are important for the accurate
reconstruction of the plasma equilibrium and are considered essential in present
day devices. The standard diagnostic used for internal field measurements is MSE
polarimetry, which measures the magnetic pitch angle. Measurements of the direc-
tion of the magnetic field provide a strong constraint on the plasma current profile.
In addition, while not routinely used, measurements of $|\vec{B}|$ can provide a strong
constraint on the pressure profile. While it is advantageous to be able to measure
both $B_\theta/B_T$ and $|\vec{B}|$, reconstructions can be made with reasonable accuracy using
either measurement.\textsuperscript{9,10}

Another diagnostic able to measure the internal magnetic field is plasma
polarimetry. By passing a far infrared (FIR) laser though the plasma this diagnos-
tic is able to make line integrated measurements of the poloidal magnetic field.\textsuperscript{11}
Because of the line integrated nature of this measurement, it provides a weaker
constraint on the equilibrium reconstruction.

1.3 Motivation for the $\vec{B}$-Stark diagnostic

The $\vec{B}$-Stark diagnostic is able to make two primary measurements, which
are described below along with a summary of their importance.

- **Direction of the magnetic field, $B_\theta/B_T$.** Measurements of the magnetic
  pitch angle provide a strong constraint on the plasma current profile during
  plasma equilibrium reconstruction. The $\vec{B}$-Stark diagnostic provides an alternat-
  ive to MSE polarimetry, which may be important in future devices (see
  Section 1.3.1).

- **Magnitude of the magnetic field, $|\vec{B}|$.** Measurements of $|\vec{B}|$ provide a
  strong constraint on the plasma pressure profile during plasma equilibrium
  reconstruction. These measurements can also be used to study poloidal cur-
  rents within the plasma.

In addition to the measurements of the magnetic field that are the focus of
this thesis, there are a number of other measurements that can also be made using
the $\vec{B}$-Stark diagnostic. These measurements will be discussed briefly in Chapter
9.
• **n = 3 level populations.** Measurements of the sub-level populations of the \( n = 3 \) state of the deuterium atoms in the injected beam can be used to validate atomic physics calculations. This in turn can be used to improve the accuracy of both the \( \vec{B} \)-Stark and MSE polarimetry techniques. The use of an atomic code to calculate the line locations and intensities can also be used to extend the \( \vec{B} \)-Stark technique to lower magnetic fields.

• **Radial electric field.** Certain high performance plasmas can generate a significant radial electric field (\( \vec{E}_r \)).\(^{12}\) This radial electric field is important for the understanding of \( \vec{E} \times \vec{B} \) rotation and shear, which are important for plasma stability and confinement.\(^6\) By measuring the spacing of the Stark lines for multiple beam energy components, it is in principal possible to determine the radial electric field using the \( \vec{B} \)-Stark diagnostic. Measurements of \( \vec{E}_r \) are discussed in Section 3.2.3 and Section 9.2.

• **Neutral beam penetration.** The beam penetration can be measured by using the intensity of the total \( \text{D}_\alpha \) beam emission from each of the three beam components. This is especially important for validation of codes designed to simulate the beam energy deposition. An accurate model of the beam penetration is also important for the interpretation of a number of diagnostics at DIII-D. Two examples are the determination of the impurity density and \( Z_{\text{eff}} \) measurements from the charge exchange recombination spectroscopy (CER) diagnostic\(^{13}\) and the examination of the fast-ion distribution from the fast-ion deuterium-alpha (FIDA) diagnostic.\(^{14,15}\).

• **Neutral beam geometry.** The geometry of the neutral beam can be found from measurements of |\( \vec{B} \)| during a beam-into-gas calibration with a known magnetic field. Knowing the beam location can improve the calibration of many diagnostics, including the CER and MSE polarimetry systems. The results of this type of calibration are discussed in appendix E.

• **Neutral beam parameters.** There are a number of beam parameters that can be examined using the \( \text{D}_\alpha \) beam emission spectrum. These include the
beam divergence, the beam energy evolution and the evolution of the beam energy fractions.

The ability to accurately fit the Stark split neutral beam emission is also important as a part of making measurements from other features in the D$_\alpha$ spectrum.

- **Main-ion temperature and rotation.** By fitting the D$_\alpha$ emission from the thermal deuterium emission it is possible to measure the main-ion temperature, rotation and density.$^{16}$ Direct measurements of the main-ion properties are not currently available on any tokamak devices. Instead these parameters are measured for an impurity species, then related to the main-ion distribution. The current theories for relating the main-ion and impurity parameters, particularly the rotation, remain largely unverified.$^{17}$

- **Fast-ion distribution.** Ionization of the neutral beams in DIII-D produces a population of fast-ions with energies well above the thermal main-ion distribution. The fast-ion distribution is important to the understanding of the plasma equilibrium.

Both of these measurements require accurate fits of the entire D$_\alpha$ spectrum including the Stark split beam emission. More details on these spectral emission sources are given in Chapter 2. These are topics currently under investigation at DIII-D$^{16}$ and will be discussed briefly in Chapter 9.

### 1.3.1 Advantages over MSE polarimetry

The $\vec{B}$-Stark diagnostic may have advantages over MSE polarimetry in future devices with high densities and temperatures. Under these conditions, coatings can develop on the plasma facing mirrors that interfere with MSE polarimetry by changing the polarization state of the incident light.$^{18}$ In addition, the need for collection optics whose polarization properties are well known, and which do not change during plasma operations, presents a challenge for the design and calibration of an MSE polarimetry system.$^{19}$
Unlike MSE polarimetry, the $\vec{B}$-Stark diagnostic does not rely on the polarization direction, and is therefore less sensitive to any mirror coatings. Measurements of $|\vec{B}|$ are not sensitive to the mirror properties at all, while measurements of $B_\theta/B_T$ are only sensitive to polarization dependent transmission. There is a simple in-situ calibration procedure that can be used to correct for any changes to the polarization dependent transmission. This calibration is done through the use of a beam-into-gas shot and is described in Section 6.4.

1.4 Previous work

Measurements of the internal magnetic field from the spacing and intensities of the Stark split D$_\alpha$ beam emission were first proposed as a diagnostic for fusion plasmas by Mandl et al. in Ref. 20;21. Many of the other measurements described in Section 1.3 were also proposed and explored in that work. A number of other groups have also performed experiments that make use of these techniques. This prior work will be briefly summarized in this section. Results from the current diagnostic installation at DIII-D have been reported previously in Ref. 1;2.

**Measurements of $B_\theta/B_T$**

Diagnostics to measure the magnetic field line pitch, $B_\theta/B_T$, using the Stark intensities have been developed previously on JET$^{20;21}$ and TEXTOR$^{22}$. Both of these diagnostics had non-optimal midplane viewing geometries which limited the accuracy possible with the line ratio technique.

The measurements on JET suggested broad feasibility of the method but could not provide information on the achievable accuracy of the technique. In addition calibration issues were only briefly discussed and a full calibration was not attempted.

The system at TEXTOR introduced a linear polarizer into the collection optics in order to add sensitivity to the measurement of $B_\theta/B_T$. With the addition of the polarizer, the diagnostic could take advantage of both the intensities and the polarization of the lines in the Stark manifold. Preliminary results were reported
showing sensitivity to $B_\theta/B_T$. A diagnostic utilizing a similar technique is currently in development at MST.\textsuperscript{23}

More recent preliminary results from TEXTOR, using an installation with favorable viewing geometry, have shown promising results.\textsuperscript{24} The published results showed sensitivity to the measurement of $B_\theta/B_T$ and highlighted the need for a calibration of the polarization dependent transmission properties of the collection optics.

All of the diagnostics described above, both at TEXTOR and at JET, have relied on measuring the total $\pi$ and $\sigma$ intensities. In doing so they have required assumptions about the upper state ($n = 3$) level populations (see Chapter 3).

**Measurements of $|\vec{B}|$**

Measurements of $|\vec{B}|$ from the Stark spacing have also been made previously at JET.\textsuperscript{20,25} High precision measurements of the magnetic field magnitude from the Stark spacing were made in these experiments. Discrepancies were seen between the measurements and calculated values from a plasma equilibrium reconstruction. Several sources of systematic error were addressed in the discussion of these results, though an absolute calibration of $|\vec{B}|$ was not achieved.

Measurements of $|\vec{B}|$ are also routinely made in the MST reversed field pinch\textsuperscript{26}. The magnetic fields and neutral beam energies at MST are much lower than at DIII-D ($B_T \lesssim 0.5T$, $U_b \approx 30\text{keV}$), producing spectra where the individual Stark lines cannot be resolved. This reduced Stark spacing, in addition to the need for fast data acquisition, reduces the achievable accuracy in measuring $|\vec{B}|$.

**$n = 3$ level populations**

Diagnostic installations at JET have also produced measurements of the $n = 3$ level populations of the injected neutral beams.\textsuperscript{20,27,28} These measurements have shown that statistical level populations within the $n = 3$ state cannot be assumed for the typical conditions in many current tokamak devices. Several collisional radiative models have been developed in an attempt to calculate the level populations.\textsuperscript{29–32} Comparisons of the predictions from these models with experi-
mental measurements from JET are shown in Ref. 27;33. The model described in Ref. 33 matches the experimental measurements, however the parameter ranges over which these comparisons were done are fairly limited due to experimental constraints on JET. The neutral beam penetration into the plasma is also discussed in these references.

1.4.1 Advantages over previous installations

The $\vec{B}$-Stark installation on DIII-D has a number of advantages over the systems discussed above.

- **Optimized viewing direction.** The sensitivity of the $\vec{B}$-Stark diagnostic to changes in the direction of the magnetic field is highly dependent on the viewing direction (see Section 3.3). An installation with vertical or midplane views have no sensitivity to $B_\theta/B_T$.

- **Good spectral resolution.** The spectral resolution of the $\vec{B}$-Stark diagnostic is sufficient for the individual Stark lines to be fit, removing the need for assumptions about the level populations. The ability to fit the level population is required in order to perform an *in-situ* beam-into-gas calibration of the viewing geometry and polarization dependent transmission properties of the collection optics (see Section 6.4).

- **Existing MSE polarimetry system.** DIII-D has an existing MSE polarimetry system with which measurements can be compared, allowing for a validation of the $\vec{B}$-Stark diagnostic technique.

- **Wide range of available plasma conditions.** A wide variety of plasma conditions can be produced at DIII-D, particularly in terms of magnetic field and density, which are important for exploring the performance of the $\vec{B}$-Stark diagnostic.

- **Beam-into-gas calibration.** On DIII-D it is possible to use a beam-into-gas calibration (see Section 1.5.2) to find the beam emission line profiles, viewing geometry and properties of collection optics.
The $\vec{B}$-Stark diagnostic technique uses a careful treatment of the beam emission line profiles (see Section 5.1). This is an improvement on the previous work on fitting the $D_\alpha$ spectrum which has approximated the line shape to be Gaussian, see Ref. 20;24–27;34.

1.5 The DIII-D tokamak

The $\vec{B}$-Stark diagnostic is installed on the DIII-D tokamak at General Atomics in San Diego. A rendering of the device is shown in Fig.1.1 and a table with the device parameters and typical operating parameters is shown in Table 1.1. A wide range of plasma conditions are accessible, allowing the parameter scans described in Chapter 8. Both the magnetic field and the plasma current can be reversed, producing a wide range of magnetic pitch angles. An extensive set of diagnostics are available including an MSE polarimetry diagnostic with which the $\vec{B}$-Stark diagnostic can be compared.

Table 1.1: Parameters of the DIII-D tokamak. Typical plasma parameters are shown.

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<tr>
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</tr>
<tr>
<td>$I_P$</td>
<td>2MA</td>
</tr>
<tr>
<td>Pulse length</td>
<td>10s</td>
</tr>
<tr>
<td>Density</td>
<td>$\lessapprox 2 \times 10^{20}$ m$^{-3}$</td>
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</tbody>
</table>

1.5.1 Neutral beams

The $\vec{B}$-Stark diagnostic relies on viewing the emission from the neutral beams. The neutral beams inject high energy neutral deuterium into the DIII-D tokamak ($U_b \lessapprox 81$ keV) and are used for both for plasma heating rotation control. Of the eight neutral beams installed on DIII-D, three are used for $\vec{B}$-Stark measurements. The beams are labeled by their angle around the tokamak as shown in Fig.4.1.
Figure 1.1: Cutaway view of the DIII-D tokamak. A typical magnetic equilibrium reconstruction is shown within the vacuum vessel.
The neutral beams at DIII-D use a positive ion source which works by producing ionized deuterium atoms and molecules and accelerating them across a voltage potential. These high energy ions are neutralized in a cell filled with a low density deuterium gas and injected into the plasma. There are three molecular deuterium ions present in the acceleration chamber, \(D^+\), \(D_2^+\) and \(D_3^+\), giving rise to three energies within the neutral beam. These three beam energy components have corresponding energies of \(U_b\), \(U_b/2\) and \(U_b/3\).

In addition to these three distinct beam component there is also a distribution of energies between the half and third energies. This range of energies is created by the breakup of the triatomic deuterium atoms during acceleration, \(D_3^+ \rightarrow D_2^+ + D\). From the spectrum of this emission it can be seen that this collisional process is dependent of the energy of the \(D_3^+\) and preferentially occurs near the end of acceleration.

The neutral beams can inject particles with energies of 50-81keV and can be modulated with periods as short as 2ms on, 10ms off.

1.5.2 Beam-into-gas

A number of the calibrations used for the \(\vec{B}\)-Stark diagnostic are done using beam-into-gas shots. For these types of calibrations the vacuum vessel is filled with a low density neutral gas, the neutral beams are fired, and the emission spectra are recorded. These types of shots can be done with or without an applied magnetic field.

There are a variety of gasses available at DIII-D for this calibration including D\(_2\), He, Xe and Ne. Typically helium is used as it does not contain any spectral lines within the D\(_\alpha\) spectral range used by the \(\vec{B}\)-Stark diagnostic. Unless otherwise noted, beam-into-gas will refer to a beam into helium gas shot. The gas pressures used are typically in the range 0.05 - 1.0mTorr.

With the low densities used for these shots the injected neutral beams are not attenuated significantly, especially when done without the presence of a magnetic field. For this reason the length of the beam pulses during these shots must be limited to avoid damage to the vessel walls. This ultimately limits the
1.6 MSE polarimetry

MSE polarimetry is the standard diagnostic for measurements of the internal magnetic field in tokamaks and stellarators.\textsuperscript{35,36} The MSE polarimetry diagnostic also relies on the Stark split D\textsubscript{α} emission from the neutral beams, however, unlike the $\vec{B}$-Stark system, the magnetic pitch angle is measured by using the polarization direction of the Stark lines. The polarization direction of these lines is dependent on the direction of the magnetic field as described in Section 3.1. This measurement is typically made by isolating the light from the $\pi$ or $\sigma$ lines and then converting the polarization information into an amplitude modulated intensity through the use of photoelastic modulators (PEMs) and a linear polarizer. The amplitude of the this modulated signal is then recorded and analyzed, allowing the original polarization direction to be determined. Details on the MSE polarimetry diagnostic, including a discussion on the calibration and performance, can be found in Ref. 37.

The MSE polarimetry system at DIII-D can measure the magnetic pitch angle with an accuracy of 0.1° in the best cases.\textsuperscript{38} Calibration of the diagnostic is typically done using a combination of an in-vessel calibration and comparisons to magnetic reconstructions of L-mode plasmas. The in-vessel calibration is done by using a precisely timed polarization wheel and must be done in the presence of a magnetic field in order to accurately take into account any Faraday rotation from the collection optics. Calibration accuracy for a single view is typically better than 0.3°.\textsuperscript{4}

1.7 Plasma equilibrium reconstruction using EFIT

A reconstruction of the plasma equilibrium is important for the determination of many plasma parameters within the DIII-D tokamak, including the mag-
netic fields. This is typically done by using the equilibrium reconstruction code EFIT. This code is able to use measurements from a variety of diagnostics to find a solution to the Grad-Shafranov equation describing the plasma equilibrium. The Grad-Shafranov equation can be written as

$$\Delta^* \psi = -\mu_0 R^2 P'(\psi) + \frac{\mu_0^2 F F'(\psi)}{4\pi^2} \tag{1.1}$$

Where $\psi$ is the poloidal magnetic flux enclosed by a magnetic surface, $P$ is the plasma pressure, $F = 2\pi R B_T / \mu_0$ is the poloidal current function and $\Delta^* = R^2 \nabla \cdot (\nabla / R^2)$. The influence of a diagnostic on the final reconstruction relates to its ability to constrain $P'$ and $FF'$. A basic EFIT reconstruction uses external measurements of the magnetic field along with the magnetic field coil currents. An improvement to this reconstruction can be made by adding internal measurements of the magnetic field. In DIII-D the only available measurements of the internal magnetic field come from the MSE polarimetry diagnostic. This diagnostic provides only the pitch angle of the magnetic field, so while this adds a strong constraint on the plasma current profile, it does not fully constrain the plasma pressure profile. Another way to look at this is that MSE polarimetry constrains the sum of the two terms on the right hand side of Eq.1.1, not the individual terms.

To add a constraint to the pressure profile it is possible to use a kinetic EFIT. A kinetic EFIT uses measured profiles for a number of plasma parameters: ion and electron temperature and density, impurity density, and plasma rotation profiles. In addition, a calculated fast-ion pressure must be included. These additional parameters serve to constrain the kinetic pressure profile. Determining the plasma parameter profiles is a time consuming process and requires many different diagnostics to provide accurately calibrated measurements.
Chapter 2

Stark split $D\alpha$ spectrum

The $\vec{B}$-Stark diagnostic relies on fitting the $D\alpha$ emission from the neutral beams. The spectrum around $D\alpha$ is complex and must be fit as a whole in order to accurately extract measurements from the beam emission. In this chapter the various sources of emission contributing to the $D\alpha$ spectral region will be introduced along with a discussion of their importance.

2.1 Sources of emission

The spectrum used for the $\vec{B}$-Stark diagnostic is primarily made up of light from the $D\alpha$ transition in neutral deuterium atoms. This transition is from the $n = 3 \rightarrow n = 2$ states and produces light with a wavelength of 6561 Å. In addition, there are several other processes that produce light within the spectral range of the $\vec{B}$-Stark diagnostic. A few of these various emission sources are shown in Fig.2.1 and Fig.2.2 and will be summarized in this section.

It is important when discussing the $\vec{B}$-Stark spectrum to consider the emission that is beam dependent separately from the other emission sources. Emission that is not beam dependent can, in many cases, be removed from the spectrum by using beam modulation and timeslice subtraction. Timeslice subtraction involves subtracting spectra taken when the beam is off from those when the beam is on.

Any emission other than the Stark split beam emission will be referred to as the “background emission” in later chapters.
Figure 2.1: Plasma spectra from the midplane $\vec{B}$-Stark system (see Chapter 4). A spectrum taken with the neutral beams off is shown in red. With the neutral beam on, shown in blue, emission from the beam dependent sources can been seen. The difference of the two spectra is shown in black. The Stark split beam emission from the three beam energy components is seen on the left hand side of the plot. For typical plasma shots the cold $D_\alpha$ emission is much brighter than shown here and does not subtract out perfectly. No significant fast-ion or impurity emission can be seen for this particular plasma.
Figure 2.2: Spectrum from the off-midplane $\vec{B}$-Stark system. In this spectrum the individual Stark lines cannot be resolved as well as in Fig. 2.1 due to the greater Doppler broadening of the beam emission from the angular beam divergence (see Section 6.2). In this plasma, which has a higher temperature, the main-ion emission extends under the Stark components. There is fast-ion emission in the spectrum, which is under the beam emission and extends to the unshifted $D_\alpha$ line. On the right side of the spectrum a carbon impurity line (C-II) can be seen.
2.1.1 Beam dependent emission

There are a number of emission sources that are only active when the neutral beam is present.

- **Stark split beam emission.** The neutral beams on DIII-D inject particles at three distinct energies (see Section 1.5.1). Each of these beam energy components produces emission with a different Doppler shift and Stark splitting. The $\vec{B}$-Stark diagnostic relies on accurately fitting this Stark split neutral beam emission (see Fig.2.1).

- **Main-ion charge exchange.** One of the possible outcomes when a beam neutral interacts with a deuterium ion from the plasma is a charge exchange event; the electron from the beam neutral is transferred to the plasma ion. The newly formed neutral can then produce $D_\alpha$ emission. This emission is thermally broadened due to the plasma temperature and is Doppler shifted due to the plasma rotation. This broad emission typically extends under the beam emission.

- **Fast-ion charge exchange.** This is the same process as for the main-ion charge exchange, except with deuterium ions from the fast-ion distribution. In DIII-D the fast-ion distribution is created primarily by ionization of the injected beams. This process produces a very broad emission with a complicated spectral shape.

2.1.2 Beam independent emission

The spectral range of interest also contains emission from several other sources that are not dependent on the beams.

- **Cold edge emission.** Outside of the plasma there exists cold, 1–10eV, neutral deuterium gas. This gas is excited by interactions with the plasma electrons and produces bright $D_\alpha$ emission. This emission has no Doppler shift and only a small amount of thermal broadening. For many plasmas this cold edge emission is so bright as to locally saturate the detector.
- **Plasma impurity emission.** There are a number of impurity species within the plasma at DIII-D in addition to the main deuterium ions. These impurities can emit a variety of lines around the $D_\alpha$ wavelength. One of the primary impurities in DIII-D is carbon, due to the carbon tiles on the walls of the DIII-D tokamak. There are two bright carbon II lines at 6578 Å and 6583 Å, one of which can be seen in the spectrum shown in Fig. 2.2. The viewing geometry has been chosen so that the beam emission is Doppler shifted away from these particular lines. The intensity of these impurity lines increases with higher densities. For certain high density shots many small impurity lines can be seen within the $\vec{B}$-Stark spectrum, making beam modulation and timeslice subtraction necessary for accurate fitting of the beam emission.

- **Bremsstrahlung emission.** The Bremsstrahlung emission is caused by collisions of the thermal plasma particles. Over the small spectral ranges that are used for the $\vec{B}$-Stark diagnostic this emission can be considered to have a constant intensity independent of wavelength.

### 2.2 Emission from the neutral beams

The $\vec{B}$-Stark diagnostic is based on analyzing the $D_\alpha$ emission from the neutral beams. Light emitted from the neutral beams is Doppler shifted and Stark split. Each of the Stark lines is broadened when recorded from a from a particular viewing direction. The broadening of the beam emission lines is due to a number of effects including Doppler broadening from the beam divergence and the instrumental response of the spectrometer. These effects are discussed in detail in Section 6.2. The final recorded spectrum from a single beam emission line is called the beam emission line profile. The determination of this profile shape is important for fitting of the beam emission, as discussed in Section 5.1.
2.3 Emission from the plasma

There are two sources of beam dependent D\(_\alpha\) emission from the plasma that warrant additional discussion. These are the emission from main-ion and fast-ion charge exchange processes. Both of these processes produce emission in the same spectral range as the neutral beam emission and need to be accounted for in the fitting process. Additional plasma measurements can be made from these emission sources if they can be accurately fit. While these additional measurements will not be investigated as part of the present work, a discussion of a proposed combined D\(_\alpha\) diagnostic is given in Section 9.6.

2.3.1 Main-ion charge exchange

As mentioned previously, a charge exchange reaction takes place when an election is exchanged between a beam neutral and a thermal plasma ion. This charge exchange event can place the electron into an excited state which quickly emits light as it transitions to the ground state. This emission can be used to determine the local temperature, rotation and density of the deuterium plasma. This measurement however is significantly complicated by the emission from multiple charge exchange events. The newly formed deuterium neutral can change exchange again with the background plasma, and several of these interactions are possible before an ionization event occurs. This process creates a “halo” around the neutral beam from which main-ion emission is produced. The emission intensity from these secondary events can be comparable to the primary emission and must be taken into account to make accurate measurements of the main-ion properties.\(^{14,16}\)

2.3.2 Fast-ion charge exchange

In addition to interaction with the thermal plasma ions, the neutral particles can charge exchange with deuterons in the fast-ion distribution. In DIII-D this fast-ion distribution is primarily produced by ionization of the injected neutral beam. The intensity of the fast-ion emission is related both to the beam injection and the plasma density. The fast-ions are slowed down and scattered though collisions with
the background plasma creating a broad emission feature. Measurements of the fast-ion spectra can be used to determine the fast-ion density as well as validate fast-ion models.\textsuperscript{15}

### 2.4 Beam-into-gas spectra

Beam-into-gas shots, with and without the presence of a magnetic field, are used for several of the calibrations for the $\vec{B}$-Stark diagnostic. The $D_\alpha$ spectra from a beam-into-gas shot is significantly simpler than the plasma spectra described in the previous sections. When no magnetic field is present the emission from the neutral beams is not Stark split and a single Doppler shifted peak is seen for each beam energy component (see Fig.6.3). Even when using a background gas other than $D_2$, there is still some residual deuterium in the vessel from the deuterium beams that produces unshifted $D_\alpha$ emission. This background $D_\alpha$ emission is thermally broadened due to heating by the neutral beam. When a magnetic field is present the beam emission is Stark split. In addition a fast-ion distribution is created from ionization of the neutral beams, producing a broad spectral feature under the beam emission (see Fig.6.5).

Chapter 2 contains material that has been published in Review of Scientific Instruments, 2008\textsuperscript{1}, and accepted for publication in Review of Scientific Instruments, 2010\textsuperscript{2}. N. A. Pablant; K. H. Burrell; R. J. Groebner; C. T. Holcomb; D. H. Kaplan, American Institute of Physics, 2008 and 2010. The dissertation author was the primary investigator and author of these papers.
Chapter 3

\(\vec{B}\)-Stark theory

The Stark split D_{\alpha} spectrum from the neutral beam emission contains information about the local magnetic field. To interpret this spectrum it is important to understand the underlying atomic processes. In this chapter a short description will be given of the atomic processes that give rise to the Stark spectrum. The derivation for extracting the direction and magnitude of the magnetic field from the Stark spectrum will then be presented along with a discussion of the approximations used. Finally the sensitivity of the diagnostic with viewing angle and few possible improvements to the current approximations will be discussed.

3.1 Atomic theory

The D_{\alpha} line, used by the \(\vec{B}\)-Stark diagnostic, originates from the \(n = 3 \rightarrow n = 2\) transition. When no magnetic or electric fields are present the energies of the angular momentum states are degenerate and a single emission line is observed. When the atom is exposed to an electromagnetic field this degeneracy is removed and multiple lines are observed from the transition. In addition to removing the energy degeneracy in the transition, these effects introduce a directional dependence to the system and cause the emission of the lines to become polarized and to vary spatially in intensity.

The splitting of the line due to the presence of an electric field is called the Stark effect; the splitting due to a magnetic field is called the Zeeman effect. In
DIII-D a Lorentz electric field is created by the movement of the neutral beam particle across the magnetic field (see Section 3.2). For the field strengths encountered at DIII-D the splitting of the beam emission can be approximated as being due to a pure Stark effect.

The atomic theory relating to the Stark-Zeeman spectrum can be found in many atomic physics texts and has been thoroughly discussed in previous work, see Refs. 21;37;39–41. A short summary of the results relating to the $\vec{B}$-Stark diagnostic will be introduced in this section, including a discussion on when the pure Stark approximation becomes invalid. The reader is encouraged to look at the references given above for a more thorough treatment.

### 3.1.1 Stark effect

When dealing with a purely electric field, and neglecting fine structure effects, the Hamiltonian for a hydrogen atom in the presence of an electric field can be written as:

$$\mathcal{H} = -\frac{\hbar^2}{2m} \nabla^2 - \frac{Ze^2}{2\pi\epsilon_0 r} + e\vec{E} \cdot \vec{r}$$

(3.1)

The calculation of the Stark energy levels is most easily done by separating the Schrödinger equation in parabolic coordinates. When using parabolic coordinates, instead of the familiar $n, l, m_\ell$ quantum numbers we have a set of parabolic quantum numbers, $|k_1, k_2, m_\ell\rangle$. The principal quantum number in spherical coordinates can be related to the parabolic quantum numbers though the relation $n = k_1 + k_2 + |m_\ell| + 1$.

**Linear Stark effect**

Using degenerate perturbation theory in first order, one finds the energy of a given state of hydrogen to be:

$$U = -R_\infty n^2 + \frac{3}{2} n(k_1 - k_2)a_0 eE$$

(3.2)

where $R_\infty$ is the Rydberg constant and $a_0$ is the Bohr radius. From this equation one can see that the energy degeneracy has only been partially removed as the
± m_\ell states produce the same energies. With this expression for the energy states we find 5 distinct upper level (n = 3) energies and 3 lower level (n = 2) energies giving rise to the 15 Stark lines. Of these 15 lines only 9 have a significant intensity.

For the D_\alpha transition (n = 3 \rightarrow n = 2) we can find the energy splitting between the individual Stark lines from Eq.3.2.

\[ \Delta U = \frac{3}{2} a_0 e E \] (3.3)

Figure 3.1: The 15 individual lines making up the Stark spectrum are displayed along with their labels. Expected intensities are shown for a view perpendicular to the electric field. Line shape has been arbitrarily chosen for clarity. The transitions leading to each line are shown in Table 3.1.

**Quadratic Stark effect**

If the Stark perturbation to the hydrogen atom is done to second order we find that energy levels can be described by

\[ U = -\frac{R_\infty}{n^2} + \frac{3}{2} n(k_1 - k_2)a_0 e E \]

\[-\frac{1}{16}(4\pi\epsilon_0 a_0^3 E^2 n^4(17n^2 - 3(k_1 - k_2)^2 - 9m_\ell^2 + 19) \] (3.4)

The effect of the quadratic correction is to redshift all of the Stark lines. For the typical Lorentz electric fields experienced by the neutral beam atoms on DIII-D, \(~\sim 5\text{MV/m}\), the quadratic correction is small compared to the accuracy in which we expect to determine the line locations. The correction at this field strength...
Table 3.1: Transitions for each of the Stark lines. The states are given in parabolic coordinates.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Transition</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi_{-7})</td>
<td>(</td>
</tr>
<tr>
<td>(\sigma_{-6})</td>
<td>(</td>
</tr>
<tr>
<td>(\sigma_{-5})</td>
<td>(</td>
</tr>
<tr>
<td>(\pi_{-4})</td>
<td>(</td>
</tr>
<tr>
<td>(\pi_{-3})</td>
<td>(</td>
</tr>
<tr>
<td>(\pi_{-2})</td>
<td>(</td>
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<td>(\sigma_{-1})</td>
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<td>(\sigma_{0})</td>
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<td>(\sigma_{5})</td>
<td>(</td>
</tr>
<tr>
<td>(\sigma_{6})</td>
<td>(</td>
</tr>
<tr>
<td>(\pi_{7})</td>
<td>(</td>
</tr>
</tbody>
</table>

is \(\sim 0.006 \text{Å}\), which translates to a shift of \(\sim 0.1\) channels on the \(\vec{B}\)-Stark system. Because all of the lines are shifted in the same direction and by a fairly similar amount, the dominant effect of the quadratic correction is to affect the measurement of the beam velocity rather than the Stark spacing.

At higher fields the quadratic Stark effect becomes more important and must be included in the calculation of the line locations.

**Line intensities and polarizations**

In addition to removing the energy degeneracy in the \(D_\alpha\) transitions, the presence of an electric field also causes the lines to become polarized and have a spatially dependent emission intensity. It is possible to calculate these effects through the use of a dipole approximation as shown in Ref. 21;37;40.

These effects are dependent on the change of the magnetic quantum number, \(m_\ell\), for the given line. The lines coming from a transition with a \(\Delta m_\ell = \pm 0\),
labeled the $\pi$ lines, produce emission that is linearly polarized parallel to the electric field. Transitions with a $\Delta m_\ell = \pm 1$, called the $\sigma$ lines, produce emission linearly polarized perpendicular to $\mathbf{E}$ when viewed transverse to the electric field. It is this polarization direction that is taken advantage of for the MSE polarimetry diagnostic.

The spatial distribution of the $\pi$ and $\sigma$ emission intensity can be expressed as geometrical factors

$$
\Phi_\pi(\Theta) = \sin^2(\Theta)
$$

$$
\Phi_\sigma(\Theta) = \frac{1}{2}(1 + \cos^2(\Theta))
$$

(3.5)

where $\Theta$ is the angle between viewing direction and the electric field.

Using the dipole approximation, the transition probabilities between the various states, $A_{if}$, can also be found. These transition probabilities have a weak dependence on the electric field and can be treated as constant for the purposes of the $\vec{B}$-Stark diagnostic.

The total emission of a given Stark line in a particular direction will depend on the geometrical factor (Eq.3.5), the transition probability and the number of atoms in the particular upper state (the level population). This can be represented as

$$
I_{if} = \Phi_{if}(\Theta)A_{if}P_i
$$

(3.6)

**Level populations**

In order to calculate the relative intensities of the Stark lines it is necessary to know the level populations. For $\vec{B}$-Stark and MSE polarimetry applications which view a neutral beam injected into a plasma the level populations can be found using a collisional-radiative model. Modeling of this process is complicated, requiring many atomic processes to be accurately understood. There have been several such models developed as discussed in Section 1.4 and Chapter 9.3.

In certain conditions, particularly high plasma densities, collisions with the plasma will overwhelm the radiative processes and equally populate the $n = 3$ levels. In this condition the atoms are said to be in statistical equilibrium (or to
be statistically populated). This is a commonly used assumption used for MSE based diagnostics.

For the $\vec{B}$-Stark diagnostic the level populations of the atoms in the neutral beam are directly measured. This provides a way to examine the accuracy of the atomic models or the assumption of statistically populated levels. These types of comparisons are discussed in more detail in Chapter 9.3.

### 3.1.2 Zeeman and fine structure effects

Along with the Lorentz electric field the neutral beam atoms are also subject to a magnetic field. For the magnetic field strengths and beam voltages used at DIII-D the Zeeman effect only has a small effect on the final line locations. At lower magnetic fields or beam energies these additional effects become increasingly important and the pure Stark approximation can no longer be used. A detailed treatment of the combined Stark-Zeeman spectrum, including a discussion on the relative strength of these effects, can be found in Ref. 21;37.

There are several atomic physics codes available for making detailed calculations of the line structure of the hydrogen atom, including the Stark, Zeeman and any fine structure effects. One of these codes, adas305 (part of the Atomic Data and Analysis Structure (ADAS))\textsuperscript{29}, has been used to investigate the validity of assuming a pure Stark effect over the range of fields seen at DIII-D. A comparisons of simulated spectra generated using ADAS and the linear Stark approximation are shown in Fig.3.2

While the Zeeman effect only has a small effect on the calculation of the line locations and spatial distribution of the emission intensity, it still has a significant effect on the polarization and is important to include in the analysis the for MSE polarimetry diagnostic.\textsuperscript{37}

### 3.2 $\vec{B}$-Stark Derivation

The B-Stark diagnostic is able to measure both the direction and the magnitude of the magnetic field by fitting the Stark split D$\alpha$ beam emission. The
Figure 3.2: Spectra have been generated using the adas305 atomic physics model and are compared against the linear Stark approximation. To generate the spectrum the geometry for the midplane $\vec{B}$-Stark chord m01 was used and the beam energy was set to 80keV. Arbitrary line widths are used for illustrative purposes. To do this comparison the ADAS spectrum was fit using the basic $\vec{B}$-Stark spectral model (see Chapter 5). The Lorentz electric field ($\vec{E}_L$) for these three plots is 1.1, 2.1 and 4.2MV/m.
magnitude of the magnetic field, $|\vec{B}|$, can be found from the spacing of the Stark lines, while the direction of the magnetic field, $B_\theta/B_T$, can be found from the relative intensities of the lines. The calculations necessary to extract $|\vec{B}|$ and $B_\theta/B_T$ from the Stark spectra are presented in this section.

As discussed in Section 3.1, the line locations and intensities can be approximated by only considering the electric field and assuming a linear Stark effect. There are two sources of electric fields that must be considered. The first is the Lorentz electric field, $\vec{E}_L = \vec{V}_b \times \vec{B}$, produced by the neutral beam particles moving across a magnetic field. The second is the radial electric field, $\vec{E}_r$, produced by the plasma. For the $\vec{B}$-Stark installation at DIII-D, typical $\vec{V}_b \times \vec{B}$ fields will have a magnitude of $\sim 5\text{MV/m}$, while typical $\vec{E}_r$ fields are around $\sim 0.05\text{MV/m}$ and can be ignored. For certain high performance plasmas however, the radial electric field can be significant and must be included in the $\vec{B}$-Stark calculations.\(^{12}\)

For the work shown in this thesis, the radial electric field is not included in any of the calculations. This is a valid approximation for the plasma shots chosen for analysis. In principle the radial electric field can be measured using the $\vec{B}$-Stark diagnostic by looking at the line spacing of the different beam energy components. This approach will be discussed briefly in Section 3.2.3 and Section 9.2.

In this section, the $\vec{B}$-Stark derivation is first presented while neglecting any radial electric field. The derivation with $\vec{E}_r$ is then briefly discussed. In these derivations we assume that the beam velocity is either known from the beam operating parameters or can be found from the Doppler shift of the central Stark line and is therefore treated as a known quantity.

### 3.2.1 Direction of the magnetic field, no $E_r$

To find the ratio of the poloidal to toroidal magnetic fields, $B_\theta/B_T$, we need to know the intensity ratio of the $\pi$ to $\sigma$ Stark emission. In general this requires the populations of the atomic upper state ($n = 3$) levels to be known. There are however two pairs of lines in the Stark manifold that originate from the same upper level, $\pi_{+3}/\sigma_{+1}$ and $\pi_{-3}/\sigma_{-1}$ (see Table 3.1). By using the ratio of the intensity of these individual lines, the direction of the magnetic field can be found without
needing to know the upper state level populations.

Using Eq.3.5 and Eq.3.6 the intensity ratio of these lines can be written as

\[ R = \frac{I_{\pi}}{I_{\sigma}} = \frac{2 \sin^2 \Theta}{1 + \cos^2 \Theta} A T_f \]  \hspace{1cm} (3.7)

where \( \Theta \) is the angle between the viewing direction and the electric field, \( A \) is the ratio of the transition probabilities, and \( T_f \) the the ratio of the transmission efficiency of \( \pi \) to \( \sigma \) light through the \( \vec{B} \)-Stark system. \( A \) can be readily calculated from basic atomic theory.

In general the transmission factor \( T_f \) is dependent on the polarization direction of the \( \pi \) and \( \sigma \) light and therefore depends on the direction of the electric field. For simplicity \( T_f \) is approximated to be a constant value for the work described in this thesis. Given the small pitch angles at DIII-D and the relatively even transmission of \( \pi \) and \( \sigma \) light through the transmission optics, this is a reasonable approximation. Further discussion on the transmission factor and the applicability of this approximation is given in Section 3.3.

Eq.3.7 can be rewritten to solve for \( \cos \Theta \)

\[ \cos^2 \Theta = \frac{2 A T_f - R}{2 A T_f + R} \] \hspace{1cm} (3.8)

With a known viewing direction \( \cos \Theta \) can be related to the magnetic field vector. To do this we start by projecting the electric field vector along our viewing vector. For this calculation it is simplest to set the \( x \)-axis along the neutral beam. In these coordinates the Lorentz electric field is given by

\[ \vec{E}_L = \vec{V}_b \times \vec{B} = V_b(B_z \hat{y} + B_y \hat{z}) \] \hspace{1cm} (3.9)

where \( \vec{V}_b \) is the beam particle velocity, and \( \vec{B} \) is the magnetic field. Let the viewing direction be given by the unit vector \( \hat{V}_w \)

\[ \hat{V}_w = \ell_x \hat{x} + \ell_y \hat{y} + \ell_z \hat{z} \] \hspace{1cm} (3.10)

Taking the dot product of Eq.3.9 and Eq.3.10, and neglecting any radial electric field from the plasma, we find

\[ \vec{E}_L \cdot \hat{V}_w = |\vec{E}_L| \cos \Theta = V_b(B_z \ell_y + B_y \ell_z) \] \hspace{1cm} (3.11)
This can be rewritten as

$$\frac{|\vec{E}_L|}{V_b B_y} \cos \Theta = (\ell_z + \ell_y \frac{B_z}{B_y})$$  \hspace{1cm} (3.12)

Now an expression for the magnitude of the Lorentz field is needed. Starting again from the Lorentz field vector, Eq.3.9, we can take the magnitude

$$|\vec{E}_L|^2 = V_b^2 (B_y^2 + B_z^2)$$ \hspace{1cm} (3.13)

Rewriting in terms of $\frac{B_z}{B_y}$

$$\frac{|\vec{E}_L|^2}{V_b^2 B_y^2} = (1 + (\frac{B_z}{B_y})^2)$$ \hspace{1cm} (3.14)

By combining Eq.3.12 and Eq.3.14 we have an expression relating $\frac{B_z}{B_y}$ and $\cos \Theta$

$$(1 + (\frac{B_z}{B_y})^2) \cos^2 \Theta = (\ell_z + \ell_y \frac{B_z}{B_y})^2$$ \hspace{1cm} (3.15)

By substituting $\cos \Theta$ from Eq.3.8 we arrive at the desired expression relating $R$ and $\frac{B_z}{B_y}$

$$\frac{2 AT_f - R}{2 AT_f + R} = \frac{(\ell_z + \ell_y \frac{B_z}{B_y})^2}{(1 + (\frac{B_z}{B_y})^2)}$$ \hspace{1cm} (3.16)

In solving for $\frac{B_z}{B_y}$ we chose the sign so that the magnitude of $\frac{B_z}{B_y}$ will be less than one as expected for our geometry.

$$\frac{B_z}{B_y} = \frac{\ell_y \ell_z \pm \sqrt{2AT_f - R}{2AT_f + R} (\ell_z^2 + \ell_y^2) - \left(\frac{2 AT_f - R}{2 AT_f + R}\right)^2}{2 AT_f - R}$$ \hspace{1cm} (3.17)

If the neutral beam is on the midplane, then we can set the $\hat{z}$ direction to be vertical. In this geometry the poloidal magnetic field $B_\theta$ is equal to $B_z$, and the toroidal magnetic field $B_T$ can be related to $B_y$ through the beam geometry

$$B_y = B_T \sin \theta_{bT}$$ \hspace{1cm} (3.18)

where $\theta_{bT}$ is the angle between neutral beam and the toroidal direction.
3.2.2 Magnitude of the magnetic field, no $E_r$

For the fields and beam energies at DIII-D, the Zeeman effect has a negligible effect on the line splitting can be ignored. In addition only the linear Stark effect needs to be considered (see Section 3.1). For the linear Stark effect the spacing between the lines can be found from Eq.3.3 and written as

$$\Delta \lambda = \lambda_0^2 \frac{3 e a_0}{2 \hbar c} |\vec{E}_L|$$  \hspace{1cm} (3.19)

The magnitude of the Lorentz electric field vector (Eq.3.9) can be written as

$$|\vec{E}_L| = |\vec{V}_b \times \vec{B}| = |V_b B \sin \theta_{bB}|$$  \hspace{1cm} (3.20)

where $\theta_{bB}$ is the angle between the neutral beam and the magnetic field. Combining Eq.3.19 and Eq.3.20 we find

$$|\vec{B}| = \Delta \lambda \frac{2 \hbar c}{\lambda_0^2 \frac{3 e a_0}{V_b} \sin \theta_{bB}}$$  \hspace{1cm} (3.21)

To find $\theta_{bB}$ we use the direction of the magnetic field from Eq.3.17. Again starting from the Lorentz electric field vector Eq.3.9

$$|\vec{E}_L| = |\vec{V}_b \times \vec{B}| = |V_b B \sin \theta_{bB}| = |V_b \sqrt{B_y^2 + B_z^2}|$$  \hspace{1cm} (3.22)

Solving for $|\sin \theta_{bB}|$ we find

$$|\sin \theta_{bB}| = \sqrt{\frac{1 + \left(\frac{B_x}{B_y}\right)^2}{1 + \left(\frac{B_x}{B_y}\right)^2 + \left(\frac{B_x}{B_y}\right)^2}}$$  \hspace{1cm} (3.23)

$B_x$ and $B_y$ can be related through $\theta_{bT}$, the angle between the beam and the toroidal direction. The angle $\theta_{bT}$ is a known value for a given beam geometry and viewing location.

$$\frac{B_y}{B_x} = \tan \theta_{bT}$$  \hspace{1cm} (3.24)

Finally we arrive at an expression for $\theta_{bB}$ in terms of the measured $\frac{B_x}{B_y}$.

$$|\sin \theta_{bB}| = \sqrt{\frac{1 + \left(\frac{B_x}{B_y}\right)^2}{1 + \tan^2 \theta_{bT} + \left(\frac{B_x}{B_y}\right)^2}}$$  \hspace{1cm} (3.25)
3.2.3 Measurement of the magnetic field, with $E_r$

For plasmas with a radial electric field comparable to the Lorentz electric field the derivation given above is not valid, and $\mathbf{E}_r$ must be included. The electric field vector is now given as the sum of the Lorentz electric field and the radial electric field.

$$\mathbf{E} = \mathbf{V}_b \times \mathbf{B} + \mathbf{E}_r$$  \hspace{1cm} (3.26)

With this electric field it is not possible to cleanly separate the calculation of the magnitude and direction of the magnetic field as done previously. Again setting $\hat{x}$ along the beam and $\hat{z}$ to be vertical we can write the radial electric field in terms of $\theta_{bT}$

$$E_x = -E_r \sin \theta_{bT}$$

$$E_y = E_r \cos \theta_{bT}$$  \hspace{1cm} (3.27)

The the electric field from Eq.3.26 can be expanded to

$$\mathbf{E} = -E_r \sin \theta_{bT} \hat{x} + (V_b B_z + E_r \cos \theta_{bT}) \hat{y} + V_b B_y \hat{z}$$  \hspace{1cm} (3.28)

From this expression we can find the magnitude of the electric field, which is measured from the separation of the Stark lines.

$$|\mathbf{E}|^2 = E_r^2 \sin^2 \theta_{bT} + (V_b B_z + E_r \cos \theta_{bT})^2 + V_b^2 B_y^2$$  \hspace{1cm} (3.29)

Using a similar derivation as in the previous section we can relate $\cos \Theta$, which is measured from the Stark intensities, to the magnetic and radial electric fields.

$$\cos^2 \Theta = \frac{(-E_r \sin \theta_{bT} \ell_x + (V_b B_z + E_r \cos \theta_{bT}) \ell_y + V_b B_y \ell_z)^2}{E_r^2 \sin^2 \theta_{bT} + (V_b B_z + E_r \cos \theta_{bT})^2 + V_b^2 B_y^2}$$  \hspace{1cm} (3.30)

If $\mathbf{E}_r$ is known, then $B_z$ and $B_y$ can be simply found by simultaneously solving Eq.3.29 and Eq.3.30. It is in principle possible to also measure $\mathbf{E}_r$ along with the magnetic field if there are more than one beam energy components, as is the case at DIII-D. The Lorentz electric field will be different for each of the beam components, allowing it to be separated from the plasma radial electric field which is not dependent on the beam velocity. Using Eq.3.30 and these multiple
measurements of $|\vec{E}|$ (Eq.3.29), it is possible to solve for the three unknowns, $E_r$, $B_z$ and $B_y$. The practical considerations for making this measurement are described in Section 9.2.

### 3.3 Diagnostic sensitivity for measurements of $B_\theta/B_T$

The sensitivity of the B-Stark diagnostic in making measurements of $B_\theta/B_T$ is highly dependent on the viewing direction. From Eq.3.7 it can be shown that the diagnostic is most sensitive when the viewing angle is $62.1^\circ$ from the electric field. When the view is either parallel or perpendicular to the electric field there is no sensitivity to the magnetic pitch angle.

The optimal viewing direction is found where $dR/d\Theta$ is maximized. This is the viewing angle at which changes in the direction of the magnetic field produce the largest changes in the ratio $I_\pi/I_\sigma$. An expression for $dR/d\Theta$ can be found from Eq.3.7.

$$
\frac{dR}{d\Theta} = \frac{8AT_f \sin \Theta \cos \Theta}{(1 + \cos^2 \Theta)^2}
$$

(3.31)

![Figure 3.3](image)

**Figure 3.3:** A plot of $dR/d\Theta$ versus $\Theta$. The maximum sensitivity is found at a viewing angle of $62.1^\circ$ away from the electric field. There is no sensitivity when the view is parallel or perpendicular to the electric field.
A plot of the $\vec{B}$-Stark diagnostic sensitivity versus viewing angle is shown in Fig. 3.3. During a plasma discharge the direction of the electric field will vary, making the asymmetry in this sensitivity curve important when choosing the viewing direction; the sensitivity falls off faster from the maximum as the view approaches perpendicular to $\vec{E}$.

The sensitivity in making measurements of $|\vec{B}|$ (Eq. 3.21) does not depend on the viewing direction.

3.4 Polarization dependent transmission through the collection optics

The relative transmission of $\pi$ to $\sigma$ light though the collection optics is dependent on polarization state of the emission, and therefore on the direction of the electric field. For the work described in this thesis the transmission factor has been approximated by the simplest model: a constant value. This approximation works acceptably in DIII-D where the transmission factor is near one, $T_f \approx 0.7$, and the pitch angle is small, $\lesssim 15^\circ$. A better approximation would be to treat the collection optics as a partial linear polarizer and use a Stokes vector treatment. This type of treatment has been described in Ref. 37 and Ref. 23. Coatings on the plasma facing mirrors would be expected to change both the direction and the degree of polarization in this approximation.

Chapter 3 contains material that has been published in Review of Scientific Instruments, 2008$^1$, and accepted for publication in Review of Scientific Instruments, 2010$^2$. N. A. Pablant; K. H. Burrell; R. J. Groebner; C. T. Holcomb; D. H. Kaplan, American Institute of Physics, 2008 and 2010. The dissertation author was the primary investigator and author of these papers.
Chapter 4

Experimental setup

In order to make measurements of the direction of the magnetic field from the relative intensities of the Stark lines, a specific viewing geometry is needed (see Chapter 3.3). To accurately fit the locations and intensities of the Stark lines, the $D_\alpha$ spectra must be recorded using a system with high spectral resolution and high throughput. To satisfy this set of requirements, a new diagnostic installation on DIII-D was necessary, including new collection optics on the machine and a new spectrometer and camera installation.

Measurements of the magnitude of the magnetic field can be made with fewer restrictions on the viewing geometry, allowing a portion of the midplane CER system to be used in addition to the dedicated $\vec{B}$-Stark views. To provide midplane viewing geometry with the high resolution $\vec{B}$-Stark spectrometer, midplane fibers were connected to the $\vec{B}$-Stark spectrometer for a portion of the operating period. To distinguish the two fiber configurations the off-midplane $\vec{B}$-Stark system will refer to the chords with sensitivity to $B_\theta/B_T$ while the midplane $\vec{B}$-Stark system will refer to the configuration with the midplane fibers. If not otherwise specified, $\vec{B}$-Stark will refer to the off-midplane system.

The hardware choices and final diagnostic configuration will be described in this chapter. A brief description of the hardware alignment procedures will be also be presented. Additional details of the hardware design and alignment are discussed in appendix A.
### 4.1 Viewing requirements

There are a number of considerations that must be kept in mind when choosing the viewing geometry for the $\vec{B}$-Stark diagnostic. These considerations are listed below along with a description of their importance.

- **Sensitivity to measurements of $B_\theta/B_T$.** The sensitivity of the $\vec{B}$-Stark diagnostic to changes in the direction of the magnetic field is highly dependent on the viewing direction. As described in Section 3.3 the optimal viewing angle is $62.1\degree$ from the electric field. In DIII-D, where $B_\theta/B_T$ is small, the motional Stark electric field is near vertical.

The DIII-D tokamak has the ability to operate with the plasma current or the toroidal magnetic field directed in either direction around the torus. Reversing the direction of either of these parameters will flip the direction of the magnetic pitch angle. A view that maintains high sensitivity with both directions of the magnetic pitch angle is desired.

- **Doppler separation of the beam components.** The neutral beams at DIII-D inject deuterium at three energies. Each of beam these energy components produces Stark emission with a different line spacing and Doppler shift. In order to accurately fit the Stark spectrum, a view is needed that shifts the beam emission away from the cold D$_\alpha$ line and separates the full energy emission from the half and third emission.

While complete separation of the full component is not necessary, it greatly simplifies the fitting process. As this separation decreases, and the lines from the full and half components overlap, a more constrained model is necessary to provide accurate spectral fits. If the radial electric field, $\vec{E}_r$ is to be measured, then separation of the half and third components is also highly desired.

- **Good radial resolution.** The measured spectra contain light from the viewing volume defined by the intersection of the viewing chord with the
neutral beam. Reducing the radial range of this viewing volume is advantageous for the $\vec{B}$-Stark diagnostic. It minimizes the broadening of the Stark lines due to variations in the magnetic field within the viewing volume. A small radial resolution also provides a simple interpretation of chord to chord measurements. The radial resolution can be minimized by viewing a small volume in the plasma and choosing a viewing direction that is tangent to the toroidal direction.

- **Bright beam emission.** The precision of the $\vec{B}$-Stark measurements is highly dependent on the intensity of the light collected. Because the beams are attenuated as they are injected into the plasma, the best beam emission intensity is found outboard of the magnetic axis.

- **A view of two neutral beams.** In order to do an *in-situ* calibration of the complete viewing geometry, which is necessary for measurements of $B_0/B_T$, a view of more than one neutral beam is necessary. If only measurements of $|\vec{B}|$ are desired, then only a view of a single beam is needed. This requirement is described in more detail in Section 6.4.

- **Modulated neutral beam.** Of the eight neutral beams installed on DIII-D some are used more commonly and with different preferred beam modulation patterns. These preferences are due both to the beam geometry as well as the requirements of other neutral beam based diagnostic systems. Ideally the $\vec{B}$-Stark diagnostic will view a commonly used neutral beam that is typically modulated during DIII-D operations. A view of a beam that is also used by the CER system is ideal as CER measurements are considered essential and have similar modulation requirements to the $\vec{B}$-Stark system.

### 4.1.1 Choice of viewing port

On DIII-D there are a limited number of ports that are available for the installation of a new diagnostic. The available ports are limited further when a specific viewing geometry is required. In order to find the best port for the $\vec{B}$-Stark diagnostic installation a survey was done on all available ports. For each available
port the considerations described in Section 4.1 were examined. Simulated spectra were constructed for each possible combination of viewing port and neutral beam. Estimates were then made for the diagnostic sensitivity over the typical ranges of the magnetic pitch angle at DIII-D, as well as for spectral separation of the beam components and the radial resolution. This process led to the selection of four available ports with adequate parameters, the best option being the $285^\circ$ R+1 port viewing the $330^\circ$ neutral beams. With this port selection the diagnostic installation provides a view of two neutral beams with favorable viewing geometry over a wide range of radii. The location of the $285^\circ$ R+1 port and the resulting views are shown in Fig.4.1 and Fig.4.2. Detailed drawing of the port installation are shown in appendix A.

4.2 Light collection and spectrometer requirements

The accuracy of the $\vec{B}$-Stark measurements will depend on both the ability to resolve the Stark lines as well as on the amount of light that can be recorded. For magnetic fields around 2T, and beam energies around 80keV, typical for DIII-D, the separation of the Stark lines is around 1 Å.

Because the primary goal of this installation is to quantify the diagnostic performance, we designed our installation to provide excellent spectral resolution at the cost of reduced light throughput. For purposes of investigating the performance of the diagnostic, longer time integration can be used as a substitute for higher light throughput. A discussion on the optimal hardware choices for future systems is given in Section 9.8.

Spectrometer

The spectrometer chosen for the $\vec{B}$-Stark system is a SPEX 3/4-m Czerny-Turner spectrometer with an $f$-number of $f/6.8$. This spectrometer was chosen for its excellent spectral resolution and instrumental response. With a 1200g/mm grating in second order it provides a dispersion of $\sim 3.75\,\text{Å/mm}$. Rather than use
an entrance slit, a linear array of 200 µm core fibers at the spectrometer entrance is used to maximize throughput.

The high $f$-number of the SPEX spectrometer is the main limiting factor to the light throughput in the $\vec{B}$-Stark system. This is made worse though the use of an old grating that is not optimized for transmission for the D$_\alpha$ spectrum in second order. An upgrade of the system to a faster 2/3-m McPherson Czerny-Turner spectrometer with an $f$-number of $f/4.7$ was attempted, however this system was ultimately rejected because of the wide instrumental response resulting from optical aberrations within the spectrometer.

**Camera**

The camera used is a Sarnoff CAM1M100 charge coupled device (CCD) camera. The camera uses a $1024 \times 1024$ pixel back-illuminated CCD detector with a 16 µm pixel pitch. To reduce the dark noise, a customized camera is used with a thermoelectric cooler (TEC), along with a water cooling system, added to the design.

For the $\vec{B}$-Stark system, the top and bottom halves of the chip are binned vertically and correspond to the two viewing chords (512 pixel vertical binning). This configuration allows all of the light from the linear fiber array to be recorded as part of the spectrum. In addition this binning configuration allows the camera to be run with a minimum integration time of 0.57 ms. The two halves of the CCD chip are read out separately, allowing the system to be run without a shutter.

**Fiber optics**

At DIII-D high neutron fluxes in the machine pit during plasma discharges, as well as limited diagnostic space, require that the spectrometer and camera are housed outside of the machine pit. The collection optics are coupled to the to the spectrometer using a set of optical fibers.

In order to maximize light throughput while maintaining narrow slit widths, custom fiber bundles were designed that are packed into two square ends at the plasma viewing end and packed into a line on the spectrometer end (see Fig.A.5).
There are a total of 38 200µm core diameter fibers in the bundle. The two square ends of the fiber bundle correspond to the top and bottom halves of the linear array and can be arranged to act as a single chord to maximize light gathering, or as separate chords. When arranged as a single chord the linear array has a height that corresponds to one half of CCD chip. Four fiber bundles have been installed allowing for a maximum of eight chords.

The fibers are mounted in a clamp that aims all of the fibers towards the lens center. The two square ends of each fiber can be stacked upon each other and the fiber clamp can be rotated to align the fibers with the neutral beam. When both ends are used as a single chord, as in the current $\vec{B}$-Stark configuration, the two spots are separated vertically in the plasma by ~3.5cm and sit just above and below the midplane at the beam centerline. With this configuration radial resolution is maintained while doubling the amount of light gathered. In the current configuration two of the fiber bundles are used to provide the two $\vec{B}$-Stark viewing chords.

Any finite fiber size, and corresponding finite spot size in the plasma, will cause some Doppler broadening of the neutral beam emission lines. This is a particular concern for the $\vec{B}$-Stark system because of the separation of the viewing volumes from the two ends of the fiber bundle. To examine this effect the camera can be run in imaging mode during a plasma discharge, allowing the spectrum recorded from each individual fiber in the bundle to be examined. This type of image is shown in Fig.A.6 in appendix A. While differences in the Doppler shift of the beam emission are seen from fiber to fiber, corresponding to each fiber having a slightly different viewing location, no obvious differences are seen between the two ends of the fiber bundle. This result verifies that the fibers are properly aligned with the neutral beam. The fiber to fiber variations are analogous to the broadening that would be seen if a single large fiber were used.

**Collection optics**

The limit on the light throughput of the collection optics is given by the size and collection angle of the fibers and the need for a small viewing volume.
Given these constraints a 2″ achromatic lens was chosen to fill the fibers with an $f$-number of $f/2.3$. This configuration provides a spot size of $\sim 2\text{cm}$ at the beam centerline.

In order to reduce the Doppler broadening of the beam emission due to the finite lens size, a lens mask has been installed. This broadening arises due to different parts of the lens viewing the beam at slightly different angles (see Section 6.2). The lens mask reduces the lens aperture in one direction and is aligned with the fiber clamp. Were it not for the lens mask the acceptance angle of the spectrometer, which is far less than the design of the collection optics, would be the limiting factor for this broadening effect.

A re-entrant port design and two mirrors are required to provide a view of the $330^\circ$ neutral beams from the $285^\circ$ R+1 port. This design is described in more detail in appendix A.

### 4.3 System alignment

A careful alignment must be done of both the collection optics as well as the spectrometer and camera. A brief description of these alignment procedures will be presented in this section.

**Alignment of the collection optics**

Alignment of the collection optics is done in conjunction with the spatial calibration described in Section 6.1. During a vent of DIII-D, a target is setup within the vacuum vessel and the fibers are back-lit from the spectrometer end. The two mirrors and the fiber clamp are adjusted to align the spots to the desired locations along the neutral beam. A perfect focus is not needed and the distance of the fibers from the lens is fixed at the designed value. Once an initial alignment is complete, the mirrors can be replaced without any adjustment of the fiber and lens mask positions. A disassembly of the adjustable mirror mounts is required for mirror replacement, and must be readjusted each time.
Alignment of the spectrometer and camera

A careful alignment of the spectrometer and camera are necessary for accurate spectral fitting. The main goals in this alignment are to minimize the instrumental response and ensure that the instrumental profile is constant across the recorded spectrum.

The spectrometer mirrors and grating must be aligned to ensure that the wavelength reading is accurate and that the image of the entrance slit remains centered as the wavelength is changed. Alignment of the spectrometer mirrors is done using a laser and a set of targets placed over the mirrors and at the entrance and exit ports. Alignment of the grating is done by using a calibration lamp (typically a cold cathode neon lamp) and iteratively adjusting the grating until the spectrometer is correctly calibrated in both 0th order and 2nd order by using a known emission line.

In a Czerny-Turner spectrometer configuration (see Fig.C.1) the horizontal and vertical focal planes are separated. The horizontal focal plane, where the best horizontal (wavelength) focus can be obtained, is tilted with respect to the spectrometer and is dependent on the spectrometer wavelength setting. To obtain the best instrumental response the camera must be aligned to this horizontal focal plane at the D$_\alpha$ wavelength.\textsuperscript{42}

Once the camera has been centered at the spectrometer exit the following procedure is used to align the chip to the horizontal focal plane. A neon calibration lamp is setup to illuminate the fibers. The spectrometer is set to a wavelength near D$_\alpha$ where more than one neon emission line can be recorded with reasonable separation across the spectrum. A series of spectra are recorded with the camera adjusted to various distances away from the spectrometer. The distance providing the best focus is found for each of the neon lines by fitting the emission spectra and determining the camera location at which the width of the instrumental profile is minimized. If the camera is properly aligned with the horizontal focal plane all of the emission lines will be focused at the same camera distance, otherwise camera must be tilted and the process repeated.

At best horizontal focus with the current configuration, using the SPEX
3/4-m spectrometer and the linear fiber array, the instrumental response is primarily due to the size of the fibers and the curvature of the image at the exit plane. The instrumental response is nearly identical across the entire spectrum. For systems where the instrumental response is comparable to the other broadening mechanisms special care is required to ensure that the response does not change across the recorded spectral range.

4.4 Data acquisition

Before every shot a dark spectrum is recorded that is later subtracted from the actual data to remove any dark current or ambient light from the final spectrum. The intensity response and dark noise of the CCD is dependent on the temperature of the chip. Data acquisition will typically raise the temperature of the chip and interfere with the accurate subtraction of the dark current. In order to maintain the CCD at a constant temperature during data acquisition the camera is continually triggered between shots.

4.5 System maintenance

Once installed, little maintenance of the diagnostic is required except the periodic replacement of the in-vessel mirrors, particularly the plasma facing mirror. The mirrors have been protected as much as possible by recessing them within the diagnostic port and encasing them within a protective shroud with a shutter (see Fig.A.2). Nonetheless noticeable coatings can be seen to build up on the mirrors during a run period.

4.6 Final system parameters

\vec{B}\text{-Stark views}

The final \vec{B}\text{-Stark} installation on DIII-D provides two viewing chords with optimized viewing directions and a view of two neutral heating beams as shown
in Fig.4.1 and Fig.4.2. The two $\vec{B}$-Stark chords will be referred to as $b01$ and $b02$ and have viewing locations with major radii of 191.5cm and 205.3cm respectively. The radial resolution of these views and is 1-3cm as found from the change in radius of the viewing volume across the full width at half maximum (FWHM) of the neutral beam.

The present configuration has a dispersion of $0.06\text{Å}/\text{channel}$, a spectral range of $\sim60\text{Å}$, and an instrumental response with a FWHM of $0.5\text{Å}$.

**Midplane $\vec{B}$-Stark views**

For a portion of the 2009/2010 DIII-D run campaign fibers with a midplane viewing geometry were attached to the $\vec{B}$-Stark spectrometer. This configuration provided views of the $30^\circ$ neutral beams from the $315^\circ$ t-0 port.

These midplane views are not sensitive to the magnetic pitch angle, but provide excellent data for measurements of $|\vec{B}|$. Because of the smaller divergence of the neutral beams in the horizontal direction, views on the midplane produce a narrower beam emission profile than the off-midplane $\vec{B}$-Stark views (see Section 6.2). This allows the individual Stark lines to be much more easily resolved. Only one of the installed midplane $\vec{B}$-Stark views has a favorable viewing geometry for spectral analysis, and will be referred to as $m01$. This chord has a viewing location with a major radius of 170.5cm.

Since only the viewing location in the vessel was changed and not the acquisition hardware, the instrumental response and dispersion of this midplane system are identical to the off-midplane configuration.

**Midplane CER views**

In addition to the $\vec{B}$-Stark views described above, four chords from the midplane CER system were tuned to $D_\alpha$ for the dedicated experiment described in Chapter 8. This system also views the $30^\circ$ left beam from the $315^\circ$ t-0 port as shown in Fig.4.1. The light from the plasma is coupled to the spectrometer using 1500µm core diameter fibers. To record the spectra from the plasma an Acton 2/3-m Czerny-Turner spectrometer is used coupled to an older Sarnoff CCD camera.
Figure 4.1: Top down view of the DIII-D vessel geometry. The $330^\circ$ left, $330^\circ$ right and $30^\circ$ left neutral beams are shown by solid black lines. The off-midplane $\vec{B}$-Stark and midplane $\vec{B}$-Stark views are shown in red. The midplane CER views are shown in blue.
Figure 4.2: B-Stark diagnostic geometry. Outlines of the DIII-D vessel are shown at the midplane and at a toroidal angle of 285°. The B-Stark viewing chords cross the 330° \textbf{LEFT} and 330° \textbf{RIGHT} neutral beams. The angle between the 330° \textbf{LEFT} neutral beam and the B-Stark chord is 57.8°. The angle between the vertical direction and the B-Stark chord is 59.9°. The FWHM of the neutral beams is \( \sim 14 \text{cm} \) in the horizontal direction and \( \sim 26 \text{cm} \) in the vertical direction\textsuperscript{43}. (adapted from Ref. 1)
This camera uses a $512 \times 512$ CCD detector with a $18 \mu m$ pixel pitch and is used with 256 pixel vertical binning. A more detailed description of the system configuration is described in Ref. 44.

In order to use the system for measurements of $|\vec{B}|$, the entrance slits on the spectrometer were reduced to $70 \mu m$. In this configuration the system has an instrumental response with a FWHM of $\sim 1\AA$ and a dispersion of $0.10 \AA$/channel. The instrumental response of this system is primarily due to aberrations within the spectrometer and is highly asymmetric (more discussion on the instrumental profile is given in Section 6.2). The chord names from the CER system will be retained, and they will be referred to as $t_{17} - t_{20}$.

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Chapter 5

Fitting methods

The $\vec{B}$-Stark diagnostic ultimately relies on fitting a spectral model to the recorded Stark split $D_\alpha$ spectrum. This model attempts to reproduce the spectrum from the Stark split beam emission as well as the other sources of $D_\alpha$ emission introduced in Chapter 2.

Two spectral fitting software packages have been developed for the $\vec{B}$-Stark diagnostic: CERFIT_STARK and BST_SPECTRAL_FIT. Both are based on using a non-linear least squares fitting technique to fit a spectral model to the recorded plasma spectrum. The first package, CERFIT_STARK, is a modified version of the CERFIT code used for CER analysis at DIII-D. It uses a basic fitting model and is optimized for fast fitting of the Stark spectrum for multiple timeslices. The second fitting package, BST_SPECTRAL_FIT, is a flexible general purpose spectral fitting application with support for complex spectral models. This package provides all of the features of CERFIT_STARK while simplifying the creation and integration of complex spectral models. The BST_SPECTRAL_FIT package was developed for two purposes. First, it can be used to fit the beam emission profile shape, which is needed for fits of the Stark split $D_\alpha$ spectrum (see Section 6.3). This package allows the basic spectral model in CERFIT_STARK to be extended, providing more accurate fits of the $\vec{B}$-Stark spectra.

In this chapter line profiles will be discussed along with their importance in the $\vec{B}$-Stark fitting schemes. Next the basic Stark spectral model will be described, which is common to both software packages. Finally, some of the advanced fitting
techniques made possible with \texttt{bst\_spectral\_fit} will be presented. Additional details on the fitting software are given in appendix B including a discussion of the core fitting algorithms.

The results presented in this thesis are from spectral analysis using the basic spectral model unless otherwise specified. When using the basic spectral model both spectral fitting packages produce identical results.

5.1 Line profiles

When creating a model to use for spectral fitting, it is necessary to consider the profile that is recorded for a line emission source. The instrumental response of the spectroscopic system causes light gathered at a single wavelength to produce a spectral profile in the recorded spectrum. When viewing the plasma, the final recorded spectrum is a convolution of the true emission spectrum with this instrumental response.

A convenient way to handle line profiles is to model them as a sum of Gaussians. With a small number of Gaussians, line profiles can be accurately represented, even those with complicated shapes. Using this representation greatly simplifies the convolution process described in Section 5.1.1; the result of a convolution of two Gaussians is another Gaussian. This allows the convolved spectrum to be simply and efficiently calculated when both the model and the line profiles use a Gaussian representation. This representation also allows for the profile scaling technique described in Section 5.1.2.

The process of finding the instrumental line profile is described in Section 6.2.4.

Beam emission line profile

When viewing emission from an injected neutral beam it useful to extend the concept of line profiles to the effects of line broadening caused by the Doppler effect. By considering the beam emission to have an effective line profile, the beam emission spectrum can be modeled simply though the central wavelengths and
intensities of the Stark lines.

Both $\vec{B}$-Stark fitting packages rely on the use of effective beam emission profiles. Because the beam profile is caused, in part, by Doppler broadening effects, it will be different for each of the beam energy components (see Section 6.2). For the $\vec{B}$-Stark spectral models, the line profiles for each beam component are found though the calibration process described in Section 6.3.

In addition to differences in the profiles from three beam energy components, there are several effects that will cause each line within the Stark manifold to have a different line profile (see Section 6.2.3). This effect is fairly small for the off-midplane $\vec{B}$-Stark and midplane CER views and is ignored in the basic fitting model.

### 5.1.1 Profile convolution

As introduced in the beginning of this section the recorded spectrum is a convolution of the true spectrum with the instrumental response. One way to separate the true spectrum from the broadening effects of the line profiles is by fitting a spectral model to the recorded spectrum. This is done by convolving the instrumental response with a model of the true emission, and varying the parameters of the model to produce a fit to the recorded spectrum. In many cases the model for the true emission can be very simple. In particular the emission from atoms with a thermal (Maxwellian) distribution can be accurately modeled by a single Gaussian.

While not typically needed for the $\vec{B}$-Stark system, this convolution process can be used to handle impurity lines in the recorded spectrum than cannot be removed though the use of background subtraction. Convolution is especially important for accurate modeling of these lines in cases where the instrumental response is very non-Gaussian. This process is also important for the related measurement of the main-ion temperature and rotation that can be made by fitting the main-ion charge exchange emission.
5.1.2 Profile scaling

When dealing with Doppler broadening effects on the beam emission line profiles it is useful to consider a scaling technique. This technique is especially important when dealing with the line profiles from the multiple beam energy components. The scaling process retains the shape of a profile while adjusting its width. This makes it possible to maintain a consistent definition of the line center (see section iv: calibration: line center).

The scaling technique requires that the profile is modeled using a sum of Gaussians. For every Gaussian in a profile, the width and the distance of from the profile center are multiplied by a scale factor. The amplitude is also scaled so as to retain the total profile intensity.

\[ A_S = A/s \]
\[ W_S = W \times s \]
\[ L_S = C + (L - C) \times s \]

(5.1)

Here \( s \) is the scale factor, \( C \) is the center of the profile, \( A \), \( W \) and \( L \) are the amplitude width and location of a particular Gaussian in the original profile, and \( A_S \), \( W_S \) and \( L_S \) represent these values in the scaled profiles. For the purposes of the \( \vec{B} \)-Stark diagnostic the profile center, \( C \), is generally chosen to be the centroid.

With this definition scaling a profile leaves the location of the centroid unchanged.

This scaling technique is one of the important features provided by the \texttt{BST_SPECTRAL_FIT} application.

5.2 Basic spectral model

Rather than attempt to fit the individual line in the spectrum, the basic spectral model uses a simple physics based model to calculate the expected line wavelengths and intensities from the Stark split neutral beam emission. This process greatly reduces the number of free parameters as compared to treating each emission line separately. Once emission lines have been calculated, they are
converted from wavelength to channel location and given the appropriate beam emission line profile.

This basic spectral models assumes that the emission from the neutral beams can be described by the linear Stark effect. Any effects of the plasma radial electric field, $\vec{E}_r$, are neglected. Of the 15 Stark lines only the central nine have significant emission intensity, the remainder are ignored in the fitting model.

**Free parameters in the Stark model**

The free parameters in the model are chosen so that they do not depend on the viewing geometry or the properties of the collection optics. For this reason the electric field and the ratio of $\pi$ to $\sigma$ emission are fit rather than directly fitting for the magnetic field. This choice of parameters also allows the same spectral model to be used for both the calibrations and the data analysis. An additional advantage to this parametrization is that it allows the calibration to be adjusted after the shot spectra have been analyzed. Finally, this parametrization allows measurements of $|\vec{B}|$ to be made using a different source for measurements of $B_\theta/B_T$, which is important when analyzing spectra from the midplane views (see Section 8.2.2).

The free parameters in the basic Stark model are given below. A typical fit using this basic model, and including a single Gaussian and a linear term for the background, has a total of 27 free parameters.

- **The $n = 3$ upper level populations.** The level populations are allowed to be different for each of the three beam energy components. This produces six free parameters for each of the beam components corresponding to the six upper level states.

- **Ratio of the $\pi$ to $\sigma$ emission.** This is the value of the expression shown in Eq.3.7. The effect of the transmission factor, $T_f$, is included in this value.

- **Magnitude of the electric field.** This is the Lorentz electric field described by Eq.3.9.
• **Projected beam velocity.** The full energy beam velocity, projected along the viewing direction, is left as a free parameter. The relative velocities between the three energy components is assumed to be known. This parameter must be fit as an accurate measurement of the beam velocity is not currently available at DIII-D. In addition by fitting the projected beam velocity the spectral model does not require the viewing geometry.

• **Central wavelength.** The wavelength at the center of the spectrum (spectrometer setting) is also left free. This is currently required because of the way that the central wavelength of the beam emission is determined within the beam emission line profile. This requirement is discussed further in Section 6.3.1 and Section 9.1.2.

**Assumptions**

There are a number of assumptions and approximations that go into the basic fitting model, many of which have already been discussed. For clarity these assumptions are summarized here.

• **The spacing of the Stark lines can be described by the linear Stark effect.** This is a good approximation at the beam energies and magnetic field strengths typically used at DIII-D. At lower fields or beam energies this approximation becomes invalid and a more complex treatment of the spectra would be come necessary (see Section 3.1).

• **The plasma radial electric field is negligible.** For many plasmas at DIII-D the radial electric field can be neglected, greatly simplifying the spectral model. This approximation becomes invalid however for certain high performance plasmas. The validity of this assumption is discussed in detail in Section 3.2.

• **The neutral beams inject particles at only three distinct energies:** $U_b$, $U_b/2$ and $U_b/3$. Here here $U_b$ is the energy of the full energy beam component. It is seen however that the neutral beams also inject particles at
a range of energies between the half and third components (see Section 1.5.1). The current model approximates this additional emission by attaching it to the third component profile as described in Section 6.3.2. There is also some energy spreading and slowing down of the beam particles due to collisions with the neutralizing gas within the neutral beam line. The amount of energy lost by the beam particles can be different for the three energy components, changing the energy ratios from their expected values.

- **All of the beam emission profiles have similar shape.** While the line profile for each beam component is given a different width, they are all constrained to have the same shape. This is necessary in order to maintain a consistent definition of the line center between the three beam components (see Section 6.3.1). Without this constraint it is not possible to accurately fit the projected beam velocity.

- **The profile for all of the lines within a Stark manifold is the same.** Each of these lines actually has a slightly different profile. This approximation is discussed in detail in Section 6.2.3.

For the work described in this thesis we make an additional approximation by determining the beam emission line profiles from beam-into-gas without magnetic field spectrum. This choice of beam profiles is discussed in detail in Section 6.2.

**Background emission**

Emission that is not dependent on the beam can typically be removed by using beam modulation and timeslice subtraction (see Section 2.1). In general, timeslice subtraction is not needed unless impurity emission lines are present in the spectrum. For many plasma shots at DIII-D a lack of background subtraction has only a minor effect on the $\vec{B}$-Stark results.

In the basic spectral model any remaining spectral features, apart from the direct beam emission, must be modeled though the use of Gaussians and up to a quadratic polynomial. This remaining beam dependent background emission,
including the main-ion and fast-ion features, is typically modeled using a single Gaussian plus a linear term. The actual emission, particularly from the fast ion emission, is not well described by this model. This leads to a number of systematic errors as described in Section 7.0.4 and Chapter 8. A model for the fast-ion emission is under development and is discussed in Section 9.1.3.

Initialization

Initialization of the $\vec{B}$-Stark spectral model must be done before a fit can be performed. This initialization process is done automatically and allows fitting of the $D\alpha$ spectrum without significant setup by the user. Additional information is required for the initialization procedure that is not required by the spectral model during the fitting process.

Using a known viewing direction, the projected beam velocity is initialized from the expected neutral beam voltage. The Lorentz electric field is initialized by using the toroidal field coil current and calculating the vacuum toroidal field at the viewing location.

To initialize the ratio of the $\pi$ to $\sigma$ emission, a linear fitting process is used. The populations levels are constrained to be equal (statistical equilibrium values), and only the total beam emission intensity of each beam component and the $\pi/\sigma$ ratio are allowed to vary. This same procedure is used to initialize the intensity of the background emission.

Typically this initialization is done for every fit, even when fitting multiple timeslices. The option is also available to use parameter values from the fit to the previous timeslice. The initialization procedure is discussed in more detail in appendix B.

5.3 Extended spectral model

While the basic spectral model, described above, can be used for precise measurements of the magnetic field in many cases, there is significant room for improvement. Typical fits using the basic model are shown in Chapter 7. In these
fits, a clear pattern in the residuals can be seen, indicating a mismatch between the spectral model and the actual spectrum. As described in Section 7.0.4 and Section 8.3, this mismatch is the largest source of systematic error in the system.

In order to construct more complicated spectral models and improve the quality of the spectral fit, a new spectral fitting package, `bst_spectral_fit`, was developed. An extended model for the Stark split $D_\alpha$ spectrum was developed along with this fitting package.

The other main motivation for the development of the `bst_spectral_fit` spectral fitting package was for the fitting of the beam emission profiles. This process requires a complex set of constraints and will be discussed in detail in Section 6.3. This process relies on the ability to scale profiles as described in Section 5.1.2.

A few of the features and capabilities of the `bst_spectral_fit` and the extended model are described below.

- **Different line widths within a Stark manifold.** By using the profile scaling technique described in Section 5.1.2 the profiles of the individual lines within the Stark manifold can be allowed to have different widths while retaining the complex shape of the beam emission profile. This is particularly important for midplane $\bar{B}$-Stark views where the variation of the line widths across the manifold are very significant (see Section 6.2.3).

- **Inclusion of an analytical fast-ion model.** The lack of an accurate fast-ion model is a significant issue for the quality of the spectral fits using the basic model. This model is described in more detail in Section 9.6.

- **Fitting of the beam emission line profile from beam-into-plasma spectra.** Determination of the beam emission line profile is a significant issue for the $\bar{B}$-Stark system. It is impractical to model all of the effects that contribute to the profile, and the profiles seen in from beam-into-gas without magnetic field spectra do not perfectly represent the true beam-into-plasma beam profiles (see Section 6.3). With `bst_spectral_fit`, and the use of profile scaling, it is possible to allow the profile shape to be a free parameter.
as part of the spectral fit. With high quality spectra this can be used as a method of determining the true beam emission profile shape. This procedure is discussed in more detail in Section 9.1.1.

- **Inclusion of beam emission calculation from atomic physics codes.** As part of the eventual goal of validating complex atomic physics codes for the $D_{\alpha}$ beam emission, it is useful to be able to integrate them into the spectral fitting process. This type of integration can be simply done using `BST_SPECTRAL_FIT`. These codes and the fitting process are described in more detail in Section 9.4.

- **Development of complex models and constraints.** `BST_SPECTRAL_FIT` has been designed to facilitate the development of complex spectral models. Complex constraints, including those involving the interaction of several fitting models, can be straightforwardly added as part of the fitting process. These capabilities have been successfully used for several other projects not related to the $\vec{B}$-Stark diagnostic.$^{16;46;47}$

- **Alternate spectral sources.** Spectral sources other than the $\vec{B}$-Stark acquisition system can be easily integrated into `BST_SPECTRAL_FIT`. This is useful during calibration procedures, and will facilitate future work characterizing the $\vec{B}$-Stark performance through the use of simulated spectra (see Section 9.5).

Finally `BST_SPECTRAL_FIT` has an easy to use graphical user interface and contains routines to plot the spectrum and the contributions of each of the models. The `BST_SPECTRAL_FIT` has been written in an interpreted language (IDL); this facilitates model development, however it makes the software slower than `CERFIT_STARK` (which is written in FORTRAN).

Chapter 5 contains material that has been published in Review of Scientific Instruments, 2008$^1$, and accepted for publication in Review of Scientific Instruments, 2010$^2$. N. A. Pablant; K. H. Burrell; R. J. Groebner; C. T. Holcomb; D.
H. Kaplan, American Institute of Physics, 2008 and 2010. The dissertation author was the primary investigator and author of these papers.
There are a number of parameters that must be calibrated in order to make accurate measurements with the $\vec{B}$-Stark diagnostic. In this chapter these calibration requirements will be discussed in detail along with the specific calibration techniques used for the $\vec{B}$-Stark system. The parameters for which calibrations are necessary are summarized below.

- **Beam emission line profiles.** In order to accurately fit the Stark spectrum it is necessary to know the shape of the beam emission line profiles. The beam emission line profiles and their importance were introduced in Section 5.1.

- **Viewing geometry.** In order to measure $B_\theta/B_T$, the full three dimensional viewing direction with respect to the neutral beams is required. For measurements of $|\vec{B}|$ only the angle between the neutral beams and the viewing direction is required. In order to relate the measurements from the $\vec{B}$-Stark diagnostic to the plasma, it is necessary to know the viewing radius.

- **Transmission properties of the collection optics.** Measurements of $B_\theta/B_T$ also require the relative transmission of $\pi$ versus $\sigma$ light through the collection optics to be known. Once the light travels though the fiber optics, the polarization will be scrambled making the relative transmission though the spectrometer unimportant.

- **Dispersion and intensity properties.** To interpret the recorded spectra
the dispersion and intensity response of the spectroscopic acquisition system must be accurately characterized.

To find this set of parameters we have used empirical *in-situ* calibration approaches whenever possible. The specific steps used to calibrate the $\vec{B}$-Stark system are summarized below. Each of these calibrations will be described in more detail later in this chapter.

- **Dispersion calibration.** The $\vec{B}$-Stark diagnostic relies on the ability to precisely measure the wavelength spacing between emission lines. This requires the conversion from channel number to wavelength to be accurately calibrated across the entire spectrum. See Section 6.6.1 for more details.

- **Whitelight (flat field) intensity calibration.** This calibration corrects for channel to channel variations of the detector, wavelength dependent transmission though the system and any vignetting effects in the camera or spectrometer. This calibration is needed in order to correctly determine the relative amplitudes of the Stark peaks. See Section 6.6.2 for more details.

- **In-vessel absolute intensity calibration.** While an absolute intensity calibration is not needed for measurements of the magnetic field, this calibration is important for some of the other measurements than can be made using the D$_\alpha$ spectrum (see Section 1.3). Some of the possible measurements that require this calibration are the beam penetration and the main-ion and fast-ion densities. See Section 6.6.2 for more details.

- **In-vessel spatial calibration.** This calibration provides the viewing radii of the $\vec{B}$-Stark chords. See Section 6.1 for more details.

- **Beam-into-gas without magnetic field calibration.** This type of calibration provides an approximate shape for the beam emission line profiles. See Section 6.2 and Section 6.3 for more details.

- **Beam-into-gas with magnetic field calibration.** Using this calibration it is possible to determine the viewing direction as well as the relative trans-
mission of $\pi$ versus $\sigma$ light through the collection optics. See Section 6.4 for more details.

While in principal the beam-into-gas with magnetic field calibration can provide the actual geometry and properties of the collection optics, in practice it should be thought of as providing three calibration coefficients. This is discussed in more detail in Section 6.4 and Section 8.2.1.

6.1 In-vessel spatial calibration

For a measurement of the magnetic field made with the $\vec{B}$-Stark diagnostic to be related to the plasma equilibrium, it is necessary to accurately know the viewing radius. The viewing radius also is required for the in-situ geometry calibration described in Section 6.4.

An in-vessel spatial calibration is used to find the radius at which the $\vec{B}$-Stark views cross the neutral beams. This process is also used to find the effective location of the diagnostic viewing lens. The in-vessel calibration described in this section assumes that the locations of the neutral beams are known. With enough viewing chords it is also possible to determine the beam locations by combining this in-vessel calibration with information from a beam-into-gas calibration. This procedure is discussed in appendix E.

If the beam locations are accurately known, the in-vessel calibration can in principle provide the full viewing geometry. There are limitations to the accuracy of these in-vessel measurements however, as discussed in Section 6.1.1, and a beam-into-gas with magnetic field calibration of the geometry is generally preferable (see Section 6.4). In addition the beam-into-gas procedure effectively treats the geometry as a set of calibration coefficients, and can provide a more general calibration of the system.

In-vessel calibrations are done before (forward calibration) and after (backward calibration) each run campaign at DIII-D. A comparison of the forward and backward calibrations allow us to determine if any of the viewing optics or fibers have moved during the run period.
Target setup

The in-vessel spatial calibration is done by going into tokamak vacuum vessel and aligning a 1/4" thick aluminum target with the expected beam location. Scribe lines on the target are aligned with the expected beam center locations by using fiducial marks on the vacuum vessel and graphite wall tiles. Once the target has been aligned, the optical fibers are back illuminated from the spectrometer end, producing spots on the targets. The spot locations are traced onto the target for later measurement.

The $\vec{B}$-Stark viewing chords cross both the $330^\circ$ LEFT and $330^\circ$ RIGHT beams. Measurements of the viewing location are made using a horizontal target aligned to the expected position of the $330^\circ$ LEFT beam. The locations at the $330^\circ$ RIGHT beam can then be found by a projection of the viewing vector. For the midplane CER and midplane $\vec{B}$-Stark chords, which view the $30^\circ$ LEFT beam, an identical procedure is used except that a target is placed vertically at the expected beam center location.

To find the location of the viewing lens, several vertical targets are setup between the neutral beam and the lens. The targets are aligned to the radial direction using the graphite wall tiles. Again the fibers are backlit and the spot locations at each target are recorded. For this calibration all four $\vec{B}$-Stark fibers are used, including the two that are not currently used for spectral acquisition. The effective lens location, after reflections from the mirrors, can be found by fitting a geometry model to the measurements of the spot locations. This process is similar to the geometry fit described in appendix E.

Spot centers

For the $\vec{B}$-Stark system, the fiber bundles are arraigned in a square pattern on the machine end. Each of the $\vec{B}$-Stark chords consists of two spots corresponding to the two legs of the fiber bundle as described in Section 4.2 and Section A.2 and shown in Fig.A.5. To find the viewing location, the centroid of both spots at the target location are found and the average location used.

Since the viewing direction is at an angle to the target, the projection of
the square fiber array is roughly a convex quadrilateral. The focus is sufficiently good that all of the individual fibers can be seen. During the in-vessel calibration procedure the outline of the spot is carefully traced retaining the shape of the outermost individual fibers. The approximate centroid is then found by drawing a quadrilateral that best matches the spot outline and measuring the location of the corners. The reproducibility of this procedure is very high, \( \pm 0.5 \text{mm} \).

**Viewing location at beam center**

In cases where the viewing chord does not pass directly through the centerline of the neutral beam, it is important to consider how to best define the viewing location. For the midplane views, the obvious choice is where the view crosses a vertical plane that passes through the beam center. Given the viewing geometry of the off-midplane \( \vec{B} \)-Stark system and the shape of the neutral beams, which are extended vertically, this is a reasonable definition for these chords as well. This is especially important for the off-midplane \( \vec{B} \)-Stark system when viewing the \( 330^\circ \) **right** beam, where the viewing location is 8–10cm below the midplane.

### 6.1.1 Accuracy

The error in the measurement of the spot locations with respect to the vacuum vessel is estimated to be better than 3mm. This estimate includes errors in the alignment of the target as well in the measurement of the spot centers. The locations of the beam center-lines however are not accurately known, and this affects the determination of the viewing locations. A fit of the \( 30^\circ \) **left** beam location, described in appendix E, indicates that the beam is \( \sim 5 \text{cm} \) from the expected location. Similar errors are expected for the locations of the \( 330^\circ \) beams.

Another source of uncertainty in these measurements is that each view gathers light from the volume where the view and beam cross. The actual weighted viewing location may not be exactly at the beam center, particularly if the beam is not symmetric or the view does not pass through the center of the beam. Using the beam center should however give a good approximation to the weighted viewing
While the error in the determination of the viewing location may be as much as several centimeters, the use of a beam-into-gas calibration to find the viewing geometry will in large part correct for these errors (see Section 6.4).

The error in the effective lens location determined from this procedure can only be considered accurate to within a few centimeters. The target alignment procedure used for this portion of the calibration, based on the location of the wall tiles, is much less accurate than the one used to determine the viewing locations. In addition, anytime the mirrors are moved, such as when the mirrors are replaced, the effective lens location can be shifted. Given the inaccuracies in this calibration, the limited time available for in-vessel calibration activities, and the preferred use of a beam-into-gas geometry calibration, this in-vessel lens location calibration was only done once after the initial installation of the diagnostic.

While the viewing radii found from this in-vessel spatial calibration are used in the $\vec{B}$-Stark analysis, the viewing direction is only used as a rough check against the beam-into-gas calibration. Accordingly, the possible systematic errors in the lens location do not influence the final measurements of $B_\theta/B_T$ and $|\vec{B}|$.

## 6.2 Line profiles

To fit the Stark split $D_\alpha$ spectrum, it is necessary to know the shape of each of the beam emission lines (see Section 5.1). In this section the sources of the beam emission line profile broadening will be examined along with some estimates of the expected profile widths.

### 6.2.1 Line profile broadening effects

There are a number of effects that contribute to the line shape of the neutral beam emission. The primary broadening effects for the neutral beam emission without the presence of a magnetic field are given below. These broadening mechanisms will be covered in more detail in Section 6.2.2.
• **Spectrometer instrumental response** The primary causes of instrumental spreading (see Section 5.1) in the $\vec{B}$-Stark system are the width of the entrance slit (or fiber width in the case of the linear fiber array used without slits), curvature of the image at the exit plane, and aberrations from the spectrometer optics.

• **Geometrical beam divergence** The neutral particles from the beams are injected at a range of angles. This angular distribution, or beam divergence, is produced by a number of processes including the focusing of the beam. When the beam emission is viewed from a particular direction, a range of Doppler shifts is seen corresponding to the angular distribution.

• **Finite lens size** The light gathered from different portions of the lens have slightly different viewing angles with respect to the neutral beam and see different Doppler shifts.

• **Finite viewing volume** The angle between the view and the beam, and therefore the Doppler shift of the beam emission, will be slightly different over the viewing volume.

• **Beam energy distribution** While the beams nominally inject particles at three distinct energies, the output will actually contain a distribution of energies leading to a Doppler broadening of the emission line. One source of this energy spreading is collisions of the particles within the neutralizer cell.

• **Beam energy variations** The $\vec{B}$-Stark system uses a time integrated measurement of the spectrum. Beam energy variations during this integration period cause changes in the Doppler shift of the emission, and lead to a broadening of the recorded line.

All of these processes, except for the spectrometer response, are dependent on the beam energy, and produce a different profile shape for each beam energy component. The beam emission profiles shapes for the $\vec{B}$-Stark system are shown in Fig.6.3, which shows a spectrum from a beam-into-gas without magnetic field shot.
When looking at the Stark split beam emission, it can be seen that each of the lines within the Stark manifold has a slightly different profile shape. This change in the line profiles arises when there is a distribution in the amount of Stark splitting of the beam emission. The effects that contribute to the change in the line profiles across the Stark manifold are given below. The central line of the Stark manifold, which is unshifted by the Stark effect, has the same profile as the emission when no fields are present. These effects are examined in more detail in Section 6.2.3.

- **Beam divergence** The Lorentz electric field will be different for beam particles at different angles, producing a different amount of Stark splitting. How this affect the individual line shapes depends on the viewing geometry.

- **Beam energy distribution.** Similar to the effect of the beam divergence, particles with different energies will experience a different Lorentz electric field and therefore a different amount of Stark splitting. Beam energy variations during the integration time produce the same type of effect.

- **Finite viewing volume** A range of radii, and therefore a range of magnetic fields, will be contained within the finite viewing volume. This will produce a range of Stark splitting for a given view.

### 6.2.2 Estimates of broadening contributions

Estimates of the various broadening effects allow us to determine which mechanisms ultimately limit the ability to resolve the Stark lines. These estimates are useful for guiding the hardware design for $\vec{B}$-Stark diagnostic installations. In addition the contribution of the various broadening effect can guide the development of spectral models for the Stark split beam emission spectrum.

Any of the broadening mechanisms that are due to Doppler broadening will be dependent on the beam velocity and will therefore be different for the three beam components. The estimates given in this section will be for the full energy beam component at 80keV.
Instrumental response

For the $\vec{B}$-Stark and midplane $\vec{B}$-Stark systems, linear fiber arrays are used at the spectrometer and effectively act as the entrance slit. The instrumental response for this system is due to the image of these fibers at the exit slit, along with the curvature of this image. The instrumental response for these chords has a FWHM of 8 channels ($0.5\text{Å}$).

For the midplane CER system, the main source of instrumental broadening is aberrations within the spectrometer. This aberration gives the instrumental response a FWHM of $\sim1\text{Å}$. The instrumental profile for this system is highly asymmetric as seen in Fig. 6.1c.

Beam divergence

The neutral beams at DIII-D have an angular divergence with a FWHM of $\sim1.1^\circ$ in the horizontal direction and $\sim2.5^\circ$ in the vertical direction. If the angular divergence of the beam is small and is assumed to have a Gaussian distribution, then the FWHM of the final line profile can be simply related to the FWHM of the beam divergence angle distribution (see Ref. 34).

$$\Delta_{\text{FWHM}}^\lambda \approx \lambda_0 \frac{v_b}{C} \Delta_{\text{FWHM}}^\alpha \sin \theta_{vb}$$  \hspace{1cm} (6.1)

Where $v_b$ is the beam velocity, $\theta_{vb}$ is the angle between the viewing direction and the beam and $\lambda_0$ is the unshifted wavelength of the line.

For the $\vec{B}$-Stark chords, which have a vertical viewing component, this broadening comes out to $1.5\text{Å}$. This width is larger than the typical Stark separation on DIII-D, which is around $1\text{Å}$, and will blend the lines together in the recorded spectrum. For the midplane chords the broadening is significantly less, $0.7-0.8\text{Å}$ depending on the angle of the particular viewing chord.

Finite collection optics

Light gathered from different portions of the lens records the beam emission with a range of Doppler shifts. For the $\vec{B}$-Stark system, a lens mask is used to reduce the aperture of the lens in the direction along the beams, limiting this
broadening effect (see Section 4.2). For the midplane \( \vec{B} \)-Stark systems the limiting factor on the broadening is the spectrometer acceptance angle (or \( f \)-number). The fibers that connect the spectrometer to the collection optics preserve the collection of angle of the light passed though them. The portion of the lens that illuminates the fibers within the collection angle represents an effective lens size.

By calculating the difference in the Doppler shift of the beam emission from the two extremes of this effective lens size, it is possible to estimate the maximum broadening from this effect. For the all three \( \vec{B} \)-Stark systems this broadening is \( \lesssim 0.4 \text{\AA} \).

**Finite viewing volume**

This broadening mechanism is similar to the finite collection optics effect but with the geometry reversed; light from various locations within the viewing volume have different Doppler shifts in the final spectrum. This effect can be minimized by reducing the spot size within the plasma, which is also important for achieving good radial resolution. For the \( \vec{B} \)-Stark system the spot sizes in the vessel are comparable to the effective lens sizes, \( \sim 1-2 \text{cm} \), and produce a similar amount of line broadening, \( \lesssim 0.4 \text{\AA} \).

**Final estimate**

To estimate the final width of the beam emission line profiles the individual broadening effects can be added in quadrature. If all of the effects were Gaussian this calculation would provide an exact result. Since these effects are not Gaussian, this type of calculation must be taken only as a rough estimate. The broadening effects described previously are summarized in Table 6.1. The final calculated profile width roughly matches with the observed profile widths found using a beam-into-gas shot.

For the \( \vec{B} \)-Stark and \( \vec{B} \)-Stark midplane chords, which have a very narrow instrumental response, the beam divergence is the primary cause of the profile broadening and limits the amount that the Stark lines can be resolved. For the midplane CER system the instrumental response, due to aberrations from the
Table 6.1: A summary of the main broadening contributions to the beam emission line profiles. Estimates of these effects are shown for the three $\vec{B}$-Stark systems. A final estimate of the beam profile width is arrived at by adding the individual effects in quadrature.

<table>
<thead>
<tr>
<th></th>
<th>off-midplane</th>
<th>midplane $\vec{B}$-Stark (Å)</th>
<th>midplane CER (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Instrumental</td>
<td>0.5</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Divergence</td>
<td>1.6</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Lens size</td>
<td>0.4</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Viewing volume</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td></td>
<td>1.7Å</td>
<td>1.1Å</td>
<td>1.4Å</td>
</tr>
<tr>
<td></td>
<td>(27 channels)</td>
<td>(17 channels)</td>
<td>(14 channels)</td>
</tr>
</tbody>
</table>

spectrometer optics, is comparable to the broadening from the beam divergence. The beam emission profiles found from a beam-into-gas calibration (see Section 6.3) are compared to the instrumental profiles for the three $\vec{B}$-Stark systems in Fig.6.1.

Figure 6.1: Comparison of the instrumental profile with the total beam emission profile taken from a beam-into-gas shot with 80keV beams. In all cases the instrumental profile has been moved for comparison with the beam profile.

6.2.3 Different line widths within Stark manifold

When fitting the Stark split neutral beam emission is important to consider the profiles of the individual lines within the Stark manifold. Differences in the profiles of the individual Stark lines can arise when there is a distribution in the
amount of Stark splitting of the beam emission. A few of the mechanisms that can cause this distribution in the Stark splitting were summarized previously.

The most important of these effects for the $\vec{B}$-Stark diagnostic at DIII-D is the angular beam divergence. The Lorentz electric field ($\vec{E}_L = \vec{V}_b \times \vec{B}$) will have a range of values corresponding to the angular distribution in the beam. The angular distribution also affects the Doppler shift of the lines, so the two effects are closely coupled. Because of this coupling between the Doppler shift and the Stark splitting, the change in the profile shape across the Stark manifold is dependent on both the beam and the viewing geometry.

For a midplane viewing geometry this effect is easy to estimate, as shown in Ref. 34. For the $\vec{B}$-Stark system, which has a vertical viewing component, a three dimensional derivation is needed.

**Simulations of profile shape due to beam divergence**

In order to examine the variation of the profile shape across the Stark manifold, a simple Monte-Carlo simulation of the beam divergence has been developed. While an analytical expression for the profile shape given a horizontal and vertical beam divergence is straightforward, this simulation procedure allows for more flexibility in terms of adding additional effects for future studies.

As in Section 6.2.2, the beams are assumed to be mono-energetic and to have a Gaussian angular distribution. The actual geometry for the beams and the $\vec{B}$-Stark views are used, and a purely toroidal magnetic field is assumed. I assume a beam energy of 80keV and use the spectrometer wavelength setting. The widths of the lines profiles are shown in Fig.6.2 for the $\vec{B}$-Stark and midplane $\vec{B}$-Stark systems.

Because of the coupling between the Doppler and Stark effects, the change in the profile widths across the Stark manifold is larger for the midplane views than for the $\vec{B}$-Stark views. For the $\vec{B}$-Stark views this effect is fairly small, causing a $\sim4\%$ change in the beam divergence contribution to line profile widths across the Stark manifold. For the midplane views this effect causes a change of $\sim17\%$ across the Stark manifold. The effect of this 17% variation on the final line
Figure 6.2: Shown is the FWHM of simulated line profiles from the beam divergence. For the $\vec{B}$-Stark system the change in width across the Stark manifold is 4%, for the midplane systems this change is 17%.
shape is significantly lessened for the midplane CER system because of the wide instrumental response from the spectrometer. Using the estimates of the other profile broadening effects given in Table 6.1 it is found that the final change in the profile widths across the Stark manifold for the midplane CER system should be around 5%.

**Approximations for fitting**

In the basic model the profile of each line within the Stark manifold for a given beam component is assumed to be identical. This assumption leads to a small mismatch between the model spectra and the actual plasma spectra and ultimately affects the accuracy of the diagnostic. In the extended model the change in the shape of line profiles can be approximated by scaling the beam emission line profile (see Section 5.1.2 and Section 5.3). This is a good approximation for the $\vec{B}$-Stark system, where the line width is primarily due to beam divergence, but less so for the midplane CER system, which has a wide and asymmetric instrumental response. An improvement to this approximation is discussed in Section 9.1.1.

### 6.2.4 Determination of the instrumental profile

To determine the instrumental profile, the spectrum from a calibration line source is fit using a sum of Gaussians. Typically a neon pencil style discharge calibration lamp is used to illuminate the fibers from within the port. When illuminating the fibers it is important to fill them with an $f$-number at least equal to that of the spectrometer. To do this a reflective surface with a flat response is placed over the lens and the neon lamp placed so as to illuminate this surface. Another way to do this calibration, which illuminates the fibers more similarly to the plasma, is to fill the vessel with neon gas and use a beam-into-gas shot. For the $\vec{B}$-Stark system these two methods of illumination produce identical spectra.
6.3 Beam into gas without $B_T$

To accurately fit the beam emission spectrum the shape of the beam emission profiles must be accurately known. There are a large number of effects that produce the final line profile shape for the beam emission as described in Section 6.2. Many of these broadening sources, such as the angular beam divergence, are not well characterized and cannot be easily modeled.

Given the complexity of these numerous broadening effects, an empirical method is needed to determine the beam emission line profile shape. One possible method is to use a beam-into-gas without magnetic field calibration. Without a magnetic field present there is no splitting of the $D_\alpha$ spectrum and the beam emission produces three lines corresponding to the full, half and third energy component emission, see Fig.6.3. The shape of these lines encompass all of the broadening effects and provides a reasonable approximation to the profile of the Stark split lines recorded during a plasma discharge.

The beam emission line profile can be found from a beam-into-gas without magnetic field shot by fitting the spectrum with a sum of Gaussians. Because of the Doppler broadening effects, this calibration must be done at every beam voltage that will be used during plasma operations.

6.3.1 Determination of the line center

In the $\vec{B}$-Stark spectral model, the Stark lines are modeled as producing light at a single wavelength which is then given a spectral profile. In order to properly add the profile to the overall spectrum, a definition is needed of the profile center. If the profile is symmetric the central wavelength has an obvious definition. For an asymmetric profile, such as the beam emission profile, there is no well defined choice. Two seemingly reasonable choices are the centroid or the wavelength of maximum intensity, however these will not in general be at the same wavelength. Regardless of the definition chosen, the wavelength separation between profiles of different shapes is not well defined.

If the beam energies and the viewing geometry were known exactly, then
Figure 6.3: Spectrum from a deuterium beam into helium gas shot with no magnetic field. The gas pressure used was 0.37 mTorr. The unshifted D$_\alpha$ peak is from residual D$_2$ gas in the vessel. The profile for the full energy beam emission has been fit using four Gaussians, outlined in purple. This profile was then scaled to fit the half (orange) and third (green) emission. A single Gaussian was used for the emission between the half and third components and attributed to the third component profile. Shot 136467, 30ms integration time.
the Doppler shifted wavelength of each beam component could be determined independently and the profile center unambiguously determined. In practice however, neither the beam energy or the viewing geometry is known with enough precision for this to be done with reasonable accuracy. Instead we need to measure the spacing of the three peaks to infer the beam energy.

To make the relative measurements between the beam profiles meaningful we force the shape of all of the profiles to be same, while allowing their widths to vary. This process retains a consistent definition of the line center between the three beam energy profiles. The details on the scaling procedure are given in Section 5.1.2. Improvements to this approximation are discussed in Section 9.1.1.

There still remains the choice of how to define the profile center. For the work described in this thesis the profile center is chosen to be the centroid. This works fine for any relative measurements between the beam emission lines, however it does not necessarily match any absolute calibration of the spectrometer. For this reason the spectrometer wavelength is currently left as a free variable in the \( \vec{B} \)-Stark spectral model. A procedure to determine the beam center while retaining an absolute wavelength calibration is discussed in Section 9.1.2.

### 6.3.2 Emission between the half and third components

Another complication in determining the beam emission line profiles is that, in addition to the beam energy components, the neutral beams also inject particles with a wide range of energies between the half and third components (see Section 1.5.1). The emission from the particles with these energies can be clearly seen in Fig.6.3. To handle this broad emission in the \( \vec{B} \)-Stark spectral model an approximation is made by fitting the emission with a single Gaussian and attributing it to the third component profile. We expect this approximation to have a minimal effect on the overall \( \vec{B} \)-Stark fit since the spectral separation of the third component emission line is so poor. This extra Gaussian is excluded when calculating the centroid of the third component line profile.
6.3.3 Fitting procedure

The bst\_spectral\_fit spectral fitting package is used to extract the beam profiles from the beam-into-gas without magnetic field spectrum. First the emission from the full energy component is fit as a sum of Gaussians. The profile found from this fit is fixed and is then used as the profile to be scaled for the half and third component profiles. The locations of the three beam emission peaks are constrained to have a spacing consistent with having energies of $U_b$, $U_b/2$ and $U_b/3$. In the fitting process the projected beam velocity for the full component and the central wavelength are allowed to be free parameters. An extra Gaussian is added to the third component to approximate the emission between the half and third components as described in Section 6.3.2. A fit to a beam-into-gas spectrum using this process is shown in Fig.6.3.

Measurements made from fits of the beam-into-plasma Stark spectrum are most heavily affected by the emission from the full component. For this reason the beam emission profile shape is found using only the full component emission. It is also possible however to leave the profile shape free while fitting the emission from all three energy components in the beam-into-gas spectrum simultaneously.

6.3.4 Dependence on gas species and pressure

While using a beam-into-gas without magnetic field calibration gives a reasonable approximation to the true beam-into-plasma line profiles, these profiles are found to be slightly too wide when attempting to fit spectra from a beam-into-plasma or a beam-into-gas with magnetic field shot. Our hypothesis is that this broadening of the emission in a beam-into-gas without magnetic field shot is due to collisions of the neutral beam particles with the background gas. This effectively increases the beam divergence and produces more Doppler broadening of the line profiles. Given that this broadening is not seen when a magnetic field is present, even in beam-into-gas shots, it can be inferred that this process involves multiple ionization and recombination events of the beam neutrals. When a magnetic field is present, the beam particle gets trapped after the first ionization event and no longer contribute to the beam emission spectrum except as part of the fast-ion fea-
ture. This process is further supported by the presence of a large fast-ion feature in the beam-into-gas with magnetic field spectrum.

An assessment of the magnitude of this effect has been made by using a number of beam-into-gas shots with different gas species and pressures. For these shots the vessel was filled with He, Xe or D$_2$ gas at various pressures ranging from 0.07 to 0.70mTorr. Spectra taken with each gas species and pressure were fit using the procedure outlined previously. The results from this study are shown in Fig.6.4.

Changes in the line width of $\sim$5% are observed over the range of gas species and pressures that were studied. For a given gas species, a reduction of the gas pressure produces a narrower profile. The effect of the gas species on the profile width depends on the beam energy, suggesting that scattering cross sections involved depend strongly on both the gas species and the particle velocity.

These results are consistent with the apparent reduction in the profile width needed to fit beam-into-gas with magnetic field or plasma spectra, as discussed in Section 9.1.1.

### 6.3.5 Beam-into-plasma best fit

Another way to find the beam emission profile shape is by treating it as a free parameter as part of an overall fit of the Stark split D$_{\alpha}$ spectrum from a beam-into-plasma shot. This procedure is discussed in Section 9.1.1, along with some preliminary fits. A fit with a free profile shape and free widths for the individual Stark lines is shown in Fig.9.1. The FWHM of the profile from the central Stark line of the full energy beam component is 12.7 channels (0.8 Å), which is 7.5% narrower than the beam into xenon gas calibration shown in Fig.6.4.

### 6.4 Beam into gas with $B_T$

One of the advantages of the $\vec{B}$-Stark technique over MSE polarimetry is that the necessary viewing geometry and transmission properties of the collection optics can be straightforwardly determined \textit{in-situ} by using a beam into gas with
Figure 6.4: Shown are the profile widths using the full component best fit. For the third component values, the extra Gaussian is not included in the width. These measurements were taken using the midplane \( \vec{B} \)-Stark system.
toroidal field calibration. This type of calibration can be repeated whenever the properties of the collection optics are expected to have changed. This is especially important for future devices with high temperatures and densities, such as ITER, where coatings on the plasma facing mirrors are expected to cause changes to the reflectivity and polarization properties of the mirror.

The ability to use this calibration technique is unique to the $\vec{B}$-Stark diagnostic. For a beam into gas shot, the $n = 3$ level populations are not expected to be in statistical equilibrium. This can readily be seen from the difference in the shape of the Stark spectrum between the beam-into-gas and the beam-into-plasma cases in Fig.6.5 and Fig.7.1 respectively. Atomic physics models able to accurately predict the level populations in a beam-into-gas shot have not yet been developed. This does not present a problem for the $\vec{B}$-Stark diagnostic because the level populations are free parameters in the fitting model.

As mentioned in the chapter introduction, this calibration only provides the actual geometry and properties of the collection optics if the viewing location is exactly known and the spectral model is an exact match for the recorded spectrum. In general this calibration must instead be thought of as providing a set of three calibration coefficients (see Section 8.2.1).

### 6.4.1 Requirements and assumptions

With the simple approximation of a constant transmission factor, $T_f$, the in-situ beam-into-gas calibration can be done using a purely toroidal field with a known magnitude at the viewing location. The magnitude of a toroidal magnetic field has a $1/R$ decay on the midplane. This allows the local magnetic field to be found from the radial location of the viewing volume and the magnetic field on axis. The magnetic field on axis can be simply found from the toroidal field coil current.

In order to determine both the full viewing geometry and the ratio of $\pi$ to $\sigma$ transmission, a view of two neutral beams is required. If only $|\vec{B}|$ is to be measured, then the relevant geometry can be found using only a single beam. If the geometry of the view is well known, then only a single beam is needed in order
to find the transmission ratio.

The beam-into-gas calibration procedure used for the $\vec{B}$-Stark diagnostic has a number of requirements:

- The major radius of the viewing locations are known.
- A view of two neutral beams is available.
- The location of both beams is known.
- The magnetic field at the viewing locations is known.

With enough viewing chords it is possible to combine measurements of $|\vec{B}|$ from this type of beam-into-gas calibration with measurements from the in-vessel calibration to fit the neutral beam locations, see appendix E.

A number of approximations are made to simplify the calibration for the $\vec{B}$-Stark system. These approximations are summarized below.

- The transmission factor, $T_f$, is a constant.
- The viewing locations and neutral beams are on the midplane.
- The weighted center of the viewing volumes are on the neutral beam center-line.

If the collection optics are treated as partial linear polarizer, a modified version of this calibration can be used as discussed in Section 6.4.4.

### 6.4.2 Derivation for beam into gas with $B_T$ calibration

The derivation for extracting the geometry and the transmission factor from a beam-into-gas with magnetic field spectrum will be discussed in this section. For simplicity, the viewing locations and neutral beams are assumed to be on the midplane. For the geometry of the $\vec{B}$-Stark diagnostic at DIII-D this is reasonable approximation.

The first step is to find the magnitude of the Lorentz electric field (Eq.3.9).

$$|\vec{E}_L| = |\vec{V}_b \times \vec{B}| = |V_b B \sin \theta_{BB}| \quad (6.2)$$
Where $\theta_{bb}$ is the angle between the beam and the magnetic field. For this calibration the field is purely toroidal, making $\theta_{bb}$ equivalent to the angle between the beam and the toroidal direction. Again we define the $\mathbf{x}$ direction to be along the neutral beam (beam coordinates). Using the unit viewing vector (Eq. 3.10) we can write an expression for the projected beam velocity. The projected beam velocity can be directly measured from the spectral fit.

$$V_{b,\text{proj}} = \mathbf{\hat{v}}_b \cdot \mathbf{\hat{v}}_w = V_b \ell_x$$

Combining this expression with the Lorentz electric field (Eq. 3.9) the $\ell_x$ component of the viewing direction, $\ell_x$, can be found.

$$\ell_x = \frac{V_{b,\text{proj}} |\mathbf{B}| |\sin(\theta_{bb})|}{|\mathbf{E}_L|}$$

With the value $\ell_x$ found from two different neutral beams it is possible to calculate the complete viewing vector. First we write the unit viewing vector in beam coordinates for the two beams.

$$\mathbf{\hat{v}}_{w1} = \ell_{x1} \mathbf{\hat{x}}_1 + \ell_{y1} \mathbf{\hat{y}}_1 + \ell_{z1} \mathbf{\hat{z}}_1$$

$$\mathbf{\hat{v}}_{w2} = \ell_{x2} \mathbf{\hat{x}}_2 + \ell_{y2} \mathbf{\hat{y}}_2 + \ell_{z2} \mathbf{\hat{z}}_2$$

Here $\mathbf{\hat{x}}$ is in the beam direction as before. We can relate the viewing direction in each coordinate system by doing a rotation. For simplicity I will choose the $\mathbf{\hat{y}}$ direction so that the two beams lie in the $\mathbf{\hat{x}}$-$\mathbf{\hat{y}}$ plane. If both beams are on the midplane, as they are in DIII-D, then this is the obvious choice. With this choice of coordinate systems, we can relate the viewing directions.

$$\ell_{x2} = \ell_{x1} \cos \alpha + \ell_{y1} \sin \alpha$$

$$\ell_{y2} = -\ell_{x1} \sin \alpha + \ell_{y1} \cos \alpha$$

$$\ell_{z2} = \ell_{z1}$$

where $\alpha$ is the angle between the two beams and can be found from the known beam geometry. Since $\ell_{x1}$ and $\ell_{x2}$ are known from Eq. 6.4 we can use Eq. 6.6 to solve for the complete viewing vector. In beam 1 coordinates

$$\ell_{y1} = \frac{\ell_{x2} - \ell_{x1} \cos \alpha}{\sin \alpha}$$

$$\ell_{z1} = \sqrt{1 - \ell_{x1}^2 - \ell_{y1}^2}$$

(6.7)
The viewing vector in beam 2 coordinates can now be found from Eq.6.6.

To find the transmission ratio we start with Eq.3.16.

\[
\frac{2AT_f - R}{2AT_f + R} = \frac{(\ell_z - \ell_y \frac{B_z}{B_y})^2}{1 + (\frac{B_z}{B_y})^2}
\]

(6.8)

Since \(\ell_z\) and \(\ell_y\), are known from Eq.6.6 and Eq.6.7, \(T_f\) can be found for each beam. In general determining \(\frac{B_z}{B_y}\), requires the poloidal field structure to be known. If the beams are on the midplane, and the field is purely toroidal, then \((\frac{B_z}{B_y})\) is zero in our usual beam coordinates and Eq.6.8 reduces to

\[
\frac{2AT_f - R}{2AT_f + R} = \ell_z^2
\]

(6.9)

and \(T_f\) is simply

\[
T_f = \frac{R}{2AT_f} \frac{1 + \ell_z^2}{2AT_f - \ell_z^2}
\]

(6.10)

If a poloidal field is present or the beams are not on the midplane, a coordinate transformation can be used to obtain the same expression.

6.4.3 Spectral fitting

It is important for this calibration to use a background gas that does not produce significant line emission in the same spectral range as the Stark split neutral beam emission. The background gas is excited by the neutral beam, and its emission cannot be removed using timeslice subtraction. The gas emission lines can be broadened through a number of processes, including Stark, Zeeman and thermal broadening. Given these broadening effects, along with the complexity of the Stark split neutral beam emission, it can be difficult to include these lines as part of the overall spectral fit.

Several gasses have been examined for this calibration, D\( _2\), He, Xe and Ne. Both xenon and neon have strong emission lines in the spectral range of the beam emission for the geometry and beam voltages at DIII-D. D\( _2\) gas has many weak emission lines which affect both fitting of the background and the Stark components.. Helium however has minimal emission in the spectral range of interest.
A spectral fit from a beam into helium gas shot is shown in Fig. 6.5. The effectiveness of the technique to calibrate the $\vec{B}$-Stark system is discussed in detail in Section 8.2.1.

As mentioned previously, the geometry and transmission factor found from this calibration should in general be thought of as a set of calibration factors. To get an idea of how much the calibrated transmission factor deviates from the actual value, one can compare the calibrated values found for the two beams, $330^\circ$ \textbf{LEFT} and $330^\circ$ \textbf{RIGHT}. With a purely toroidal field the Lorentz electric field is in the vertical direction for both beams, and the true value of $T_f$ will be identical. The calibrated values for $T_f$ differ however by 15\% for chord \textbf{B01} and 5\% for chord \textbf{B02}.

The viewing geometry found from this beam-into-gas calibration can be compared to the values from the in-vessel calibration. For \textbf{B01} the viewing direction differs by 0.7\°, while for chord \textbf{B02} the direction differs by 4\°. This must be taken only as a rough comparison as the viewing direction found from the in-vessel calibration can only be considered accurate to within a few degrees (see Section 6.1.1).
6.4.4 Collection optics as a partial linear polarizer

With the simple approximation of a constant transmission factor, the in-situ beam-into-gas calibration can be done using a purely toroidal field; if the partial linear polarizer approximation is used (see Section 3.3), it becomes necessary to use multiple beam-into-gas spectra taken with different poloidal magnetic fields (for a midplane view a vertical magnetic field can also be used). Such a calibration could be done by adding a poloidal field ramp during a beam-into-gas shot with multiple beam blips.

6.5 Alternate calibration techniques

The calibration using a beam-into-gas with magnetic field technique described in Section 6.4 is very attractive as it provides a way to do an in-situ calibration with a known magnetic field. The beam-into-gas with magnetic field calibration however does have a few drawbacks. Most importantly it cannot be used unless the level populations can either be fit or an atomic physics model is developed that can accurately calculate the level populations for beam-into-gas shots. Fitting of the level populations is not possible at low fields where the line separation is not sufficient to resolve the individual lines or the linear Stark approximation becomes invalid. A second drawback to the beam-into-gas with magnetic field technique is that because the spectrum has such a different shape from the plasma case, any mismatch between the fitting model and the spectra can produce errors in the calibrated values of the geometry and transmission factor. The effect of these fitting errors are discussed more in Section 7.0.4 and Section 8.2.1.

There are however other possible methods that can be used to calibrate the \( \vec{B} \)-Stark system. One possible method is to use a plasma with a simple shape where an accurate EFIT reconstruction can be done using only external magnetic measurements. This is often possible using an L-mode plasma. If the reconstruction can be trusted to be accurate, then this calibration still provides an in-situ calibration but it does so using a beam-into-plasma shot rather than a beam-into-gas shot. This calibration method will be less sensitive to mismatches between the
fitting model and the actual spectra. The adjusted calibrations shown in Section 8.2 effectively use this technique.

6.6 Spectrometer and detector calibration

In order to accurately extract the wavelength and intensity of the lines from the recorded spectrum, an accurate calibration of the dispersion and intensity response of the system is necessary. These calibrations will be summarized this section. For a more detailed description see appendix C and appendix D.

6.6.1 Dispersion calibration

In order to make accurate measurements with the \(\vec{B}\)-Stark system, accurate conversions are needed between wavelength and detector channel. The spectral fitting techniques employed for the \(\vec{B}\)-Stark diagnostic can generally resolve the line locations to better than 0.1 channels. The conversion between wavelength and location must also be at least this accurate over the entire \(\vec{B}\)-Stark spectral range.

A common approximation used for spectroscopic analysis is to assume a constant dispersion across the spectrum. While this can work in applications where only the central portion of the spectrum is used, or the required spectral accuracy is low, this approximation cannot be used effectively for the \(\vec{B}\)-Stark diagnostic. A full calculation is necessary that takes into account the change in the dispersion across the recorded spectrum.

For an ideal spectrometer the dispersion, \(\Delta \tilde{A}/\Delta \text{channel}\), can be found from the grating equation and the spectrometer geometry. The dispersion varies across the spectrum and depends on the wavelength setting of the spectrometer (central wavelength). At the level of accuracy that is required for the \(\vec{B}\)-Stark system it is important to also take into account deviations from the ideal dispersion due to misalignment of the system and aberrations from the spectrometer optics.

The dispersion calibration process used for the \(\vec{B}\)-Stark diagnostic will be briefly summarized in this section. A detailed discussion on this calibration, including a presentation of the achieved accuracy is given in appendix C.
Wavelength to detector channel calculations

For a particular wavelength, the recorded location on the detector can be found from the angle at which the light exits the spectrometer, $\theta_f$.

$$x = f \tan \theta_f \tag{6.11}$$

Here $f$ is the effective focal length, which is the focal length multiplied by the magnification of the system. For a Czerny-Turner spectrometer with ideal optics it is possible calculate the expression for $\theta_f$ (see appendix C). Using this calculation the conversion from wavelength to detector channel can be written as

$$x = f \tan \left( \alpha - \phi + \arcsin \left( \frac{m\lambda}{d} + \sin(\phi + \alpha) \right) \right) \tag{6.12}$$

where $\alpha$ is the tilt angle of the grating and is defined by

$$\alpha = \arcsin \left( \frac{-m\lambda_0}{2d \cos(\phi)} \right) \tag{6.13}$$

Here $\phi$ is the angle between the first mirror and the grating (see Fig.C.1), $m$ is the spectrometer order, $d$ is the grating spacing and $\lambda_0$ is the central wavelength (spectrometer setting).

The accuracy of this calculation depends on the details of the spectrometer and camera configuration. In cases where accurate alignment is not possible, or significant aberrations are present in the system, a correction to this expression is needed. For the \(\vec{B}\)-Stark system a third order correction to the expression in Eq.6.12 is used.

$$x = a_0 + a_1 \tan \theta_f + a_2 \tan^2 \theta_f + a_3 \tan^3 \theta_f \tag{6.14}$$

For ideal optics $a_1 = f$ and $a_0 = a_2 = a_3 = 0$.

By calibrating the coefficients in this expression, the conversion between wavelength and channel can be done to within the accuracy of the peak fitting over the entire spectral range of the \(\vec{B}\)-Stark system.

Calibration procedure

A calibration lamp with known emission lines is used to calibrate for the coefficients in Eq.6.14. This calibration lamp, a cold cathode neon lamp, is reflected
into the fibers from the machine end. With the current spectrometer configuration, the central wavelength setting is not reproducible to the accuracy needed, and instead must be found as part of the calibration. Ideally this calibration would be done by fitting a large number of lines within a single spectrum. Given the spectral range of the spectrometer however, this is not feasible and instead a calibration technique has been developed that requires only two spectral lines.

A pair (or more) of calibration lines is chosen near the wavelength at which the spectrometer will ultimately be operated. These lines are scanned across the detector by adjusting the spectrometer setting. At each spectrometer setting a spectrum is recorded and the locations of the calibration lines are found. For a given wavelength and location it is possible to determine central wavelength of the spectrum from Eq.6.14. If the coefficients are properly calibrated then for a particular spectrometer setting the central wavelength found from each calibration line will be the same. A fitting procedure is employed to find the set of coefficients that minimizes the differences between the calculations of $\lambda_0$ at each spectrometer setting.

The coefficient $a_0$ represents an offset of the optical axis from the center of the detector. This parameter has little effect on the final calibration over the wavelength ranges we are interested in and is always set to zero.

The accuracy of this calibration technique can be checked by using the same coefficients to calculate the wavelength of other known calibration lines. This technique has also been checked against results from a ray tracing code with a model of the $\vec{B}$-Stark spectrometer (see appendix C).

### 6.6.2 Intensity calibration

There are two types of intensity calibrations that are employed for the $\vec{B}$-Stark diagnostic; a whitelight (flat field) correction, and an absolute intensity calibration. These calibrations will be briefly discussed in this section. Additional details on the whitelight correction can be found in appendix D.
Whitelight (flat field) calibration

In any spectroscopic system the intensity response varies with wavelength and with location on the detector. There are number of effect that contribute to this intensity response including:

- Wavelength dependent transmission of the collection optics, fibers and spectrometer.
- Wavelength dependent efficiency of the CCD detector.
- Vignetting from the spectrometer and camera.
- Efficiency variations across the detector channels.

For the $\vec{B}$-Stark system the change in the intensity response across the spectrum is $\sim 5$-10%.

The camera used for the $\vec{B}$-Stark system also has a significant fringing (etaloning) effect when viewing $D_\alpha$ light. This fringing effect is caused by the incident light undergoing multiple reflections within the silicon layer of the chip and creating an interference pattern. When viewing a whitelight source this effect shows up as a complicated semi-periodic variation in the recorded intensity. This pattern is very sensitive to the wavelength of the incident light, and small changes in the spectrometer setting can produce large changes in the fringing pattern. In the $\vec{B}$-Stark system this fringing effect produces a $\sim 5\%$ effect in the intensity response. This fringing effect is discussed in detail in appendix D.

A uncorrected whitelight spectrum from the $\vec{B}$-Stark diagnostic is shown in Fig.6.6. To calibrate for this wavelength and channel dependent intensity response, a whitelight calibration is done. The procedure is to illuminate the system using a light source with a constant (or known) spectral output. A spectrum is taken and each channel is calibrated to produce a flat response over the recorded spectrum. This calibration must be repeated anytime that the system configuration changes.

Ideally this type of calibration would be combined with the absolute intensity calibration and be done from within the vacuum vessel. Since the DIII-D vessel is not accessible during a run period, this calibration must instead be done
**Figure 6.6:** An uncalibrated spectrum from the \( \vec{B} \)-Stark diagnostic illuminated by a whitelight source. Data is shown for chord \textbf{b01}. The whitelight calibration corrects for the channel to channel and wavelength dependent variations seen in this spectrum.

without including the collection optics. This provides an acceptable approximation as most of the effects that contribute to the whitelight response are due to the spectrometer and camera systems.

Because there is no automated whitelight calibration system installed for the \( \vec{B} \)-Stark diagnostic, an empirical model of the whitelight response, including the fringing effects, has been developed. With the use of this model the appropriate whitelight correction can be calculated for any wavelength setting. This procedure is outlined in detail in appendix D. In general a direct measurement of the whitelight response is preferred to this modeled response and is used whenever possible.

With the use of this whitelight calibration the error in the relative intensity response is less than 1%.

**Absolute intensity calibration**

With an absolute intensity calibration it is possible to determine the actual luminance of the various contributions to the D\( \alpha \) spectrum. The primary measurements made by the \( \vec{B} \)-Stark system, magnetic field and level populations, do not require this absolute calibration as they rely on the relative intensities of the emission lines. There are however several additional measurements that become
possible with an absolute calibration, including the neutral beam penetration and the main-ion and fast-ion densities.

The absolute intensity calibration is similar to the whitelight calibration except that it must be done from within the machine vacuum vessel to take into account the transmission properties of the collection optics. A calibrated light source with a uniform illumination and a known luminescence is brought into the vacuum vessel and placed at the approximate viewing location. Spectra are recorded at every wavelength that is to be used during plasma operations.

Any changes in the reflectiveness of the plasma facing mirrors due to coatings or erosion by the plasma will affect the absolute intensity calibration. These effects can be tracked and compensated for by using in-situ beam-into-gas calibration shots. This requires the gas density and beam parameters to be reproducible between calibration shots.

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Chapter 7

Results: \( \vec{B} \)-Stark spectral fitting

High quality fits of the Stark split beam emission can be made using the basic Stark model described in Chapter 5. Fits to typical beam-into-plasma spectra from the three \( \vec{B} \)-Stark systems are shown in Figs.7.1–7.4. For these fits the beam emission line profiles were taken from a beam into helium gas calibration as described in Section 6.3. In each of these figures the top figure shows a spectrum taken with a 10ms integration time. Timeslice subtraction was used to remove the beam-independent emission sources. In the bottom figure 20 timeslice subtracted spectra have been averaged together to provide an effective 200ms integration time. This timeslice averaging was done over a time period where the plasma parameters were kept constant. The background in these fits, shown by the dashed line, is made up of a single Gaussian summed with a linear term.

Overall the shape of the recorded spectrum is well reproduced by the basic \( \vec{B} \)-Stark spectral model. The different beam emission line profiles between the three \( \vec{B} \)-Stark systems can be clearly seen in these spectra. These profiles have been described in Section 6.2 and are shown in Fig.6.1. While the recorded Stark spectra are asymmetric, this is almost entirely due to the profile shape and the varying widths of the lines within the Stark manifold rather than any asymmetry in the line intensities.

In all of the fits it was possible to extract the individual population levels, even for the overlapping half and third beam energy component emission. In general the ability to accurately fit individual population levels from overlapping
beam component emission depends on how closely the Stark lines line up.

(a) Off-midplane $\vec{B}$-Stark chord b01, 330° left, 10ms integration time.

(b) Off-midplane $\vec{B}$-Stark chord b01, 330° left, 200ms integration time.

**Figure 7.1**: Fitted D$_\alpha$ spectra from the $\vec{B}$-Stark B01 chord viewing the 330° left neutral beam. In Fig.(a) a 10ms integration time is used. In Fig.(b) timeslice averaging has been used for an effective 200ms integration time.
Figure 7.2: This figure is similar to Fig. 7.1 except viewing the 330° \text{right} neutral beam.
Figure 7.3: This figure is similar to Fig.7.1 except for the midplane CER chord τ17 viewing the 30° \textbf{LEFT} neutral beam.
Figure 7.4: This figure is similar to Fig.7.1 except for the midplane $\vec{B}$-Stark chord m01 viewing the 30° left neutral beam.
7.0.3 Fitting quality

The ability to make accurate measurements of the magnetic field using the D$_\alpha$ spectrum is highly dependent on the quality of the fits that can be made. To examine the quality of the match between the $\vec{B}$-Stark model and the recorded spectrum, one can look at the weighted residual. The weighted residual is defined by

$$R_{\text{weighted}} = \frac{y_{\text{data}} - y_{\text{model}}}{\sigma_{\text{data}}}$$

(7.1)

For a perfect fit, where the model matches the spectrum to within the error in the data, the weighted residual will be within ±2 for 95% of the data points. For such a case the residual will be randomly distributed with no pattern across the channels.

It is important to keep in mind that the weighted residual is both a measure of the accuracy of the model as well as the uncertainty in the data. For this reason fits to low intensity spectra will produce lower residuals for the same spectral models. The fitting quality is also not always related to the measurement accuracy. In cases where the fitting model is not well constrained by the data, such as when the separation of the Stark lines is small, a better fit can be found in the sense of smaller residuals. There is, however, more variability in the range of model parameters that produce a good fit, and the end result is a less accurate measurement.

An obvious pattern is seen in the residuals from Figs.7.1–7.4, indicating a mismatch between the model and the data. This is especially noticeable in the time averaged spectra which have less uncertainty in the spectral data. Similar errors are seen for beam-into-gas with magnetic field spectra as shown in Fig.6.5. These residuals show that while the basic model, using profiles taken from a beam-into-gas without magnetic field calibration, provides a reasonable spectral fit for all of the $\vec{B}$-Stark systems, there is still room for improvement in the spectral model.

There are several interesting conclusions that can be gathered from these fits. First the beam emission profiles that are being used are too wide to properly fit the spectrum. This can be most easily seen in Fig.7.4b where the model is unable to match the peaks and troughs in the recorded spectra. This mismatch
in the line profile width has been discussed in detail in Section 6.3. Furthermore
the change in the width of the lines within the Stark manifold can also be seen
in Fig.7.4b where the lines are significantly more narrow on the blue side of the
spectrum. These effects are discussed further in Section 9.1.1.

In these spectral fits, it is also possible to see that there is emission under the
Stark lines that is not properly handled by the current spectral model. Emission
can be seen just to the blue side (lower wavelength) of the full component Stark
emission as well as between the full and half component emission. This emission
is due to charge exchange emission from the fast-ion distribution and is expected
to have a complicated emission shape under the Stark components. A discussion
of future work to add a fast-ion model into the spectrum is discussed in Section
9.1.3.

7.0.4 Effect of fitting quality on system calibration

The main effect of any mismatch between the spectral model and the actual
data is to affect the calibration of the system. When examining multiple times from
a single shot, or shots with similar plasma conditions, the fitting errors will be the
same in every case, producing a systematic offset in the measurements from the
true values.

Because the spectra from beam into gas shots are much different than those
from plasma shots (see Fig.6.5), fitting errors become a significant issue for an accu-
rate in-situ beam into gas calibration of the viewing direction and the transmission
factor. Errors in the determination of the profiles or the background can lead to
noticeable calibration errors. Calibration errors are discussed in more detail in
Section 8.2.1.

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Instruments, 2008\textsuperscript{1}, and accepted for publication in Review of Scientific Instru-
ments, 2010\textsuperscript{2}. N. A. Pablant; K. H. Burrell; R. J. Groebner; C. T. Holcomb; D.
H. Kaplan, American Institute of Physics, 2008 and 2010. The dissertation author
was the primary investigator and author of these papers.
Chapter 8

Results: $\vec{B}$-Stark performance

In this chapter the performance of the $\vec{B}$-Stark diagnostic will be examined in detail. The achievable accuracy in measuring the magnetic field will be examined over a range of plasma conditions. Measurements of the magnetic field made from the $\vec{B}$-Stark system will be compared against values from plasma equilibrium reconstructions using \textsc{efit} and MSE polarimetry system. For measurements of $|\vec{B}|$, comparisons will additionally be shown between the $\vec{B}$-Stark and midplane CER views. The effectiveness of the \textit{in-situ} calibration techniques will be discussed and analysis of the error, both random and systematic, will be presented.

8.1 Experimental conditions

In order to make the best possible comparisons with the MSE polarimetry system over a wide range of conditions, a dedicated experiment was conducted at DIII-D. For this experiment inner wall limited L-mode plasmas were used. This type of discharge was chosen as it allowed for the widest possible range of densities and currents while using a single plasma shape, shown in Fig.8.1. In addition it provided a discharge free of edge localized modes (ELMs), simplifying the spectral analysis. Beam timing was optimized to provide good background subtraction for both beams viewable by the $\vec{B}$-Stark system, and to provide optimal data for the MSE polarimetry system. A portion of the midplane CER system was tuned to the $D_\alpha$ spectrum to be used for measurements of $|\vec{B}|$ (see Section 4.6).
Over the course of the experiment measurements were made with parameters in the following ranges:

- **toroidal field**: 1.2 - 2.1T
- **plasma current**: 0.5 - 2.0MA
- **density**: $1.7 - 9.0 \times 10^{19} \text{m}^{-3}$
- **neutral beam voltage**: 50 - 81keV

In addition to this dedicated run day, the $\vec{B}$-Stark system has been routinely taking data in its current configuration since March 2009. Data from a wide range of plasma shapes and plasma parameters have been recorded including shots with $I_P$ and $B_T$ reversed from their usual directions.

Beam into gas shots, both with and without magnetic fields were taken for the calibrations described in Section 6.3 and Section 6.4. These calibrations were done using beam into helium gas, with gas pressures of 0.37mTorr. These calibrations, including the full geometry calibration, were used for all of the results presented in this section unless otherwise noted.

Typical spectral fits of the Stark spectrum at full field, $\sim 2T$, are described in Chapter 7 shown in Figs.7.1–7.3.

### 8.2 Comparison of magnetic measurements with EFIT and MSE polarimetry

Precise measurements of both $|\vec{B}|$ and $B_\theta/B_T$ are possible over all the plasma conditions for which data is available. Both measurements are possible even at fields as low as 1.1T with 80keV beams, or with beam voltages as low as 50keV with 2T magnetic fields. This demonstrates that the $\vec{B}$-Stark diagnostic is effective even with poor separation of the Stark lines and without constraints on the level populations. A spectral fit at low field is shown in Fig.8.2.

Comparisons of $B_\theta/B_T$ and $|\vec{B}|$ between $\vec{B}$-Stark measurements and values from an EFIT reconstruction with MSE polarimetry are shown for the two $\vec{B}$-Stark
Figure 8.1: An *efit* reconstruction of the plasma shape used for the dedicated experimental day. The dotted lines represent the magnetic surfaces. The red dots represent the viewing radii of the two off-midplane $\vec{B}$-Stark chords.
Even with poor line separation it is possible to determine the pitch angle without assumptions about the level populations. An equivalent Stark separation would be seen for 40keV beams with 2T magnetic fields.

chords and the two neutral beam views in Figs.8.3–8.6. In all cases the spectra were recorded and analyzed using a 10ms integration time.

The shot shown in these plots (shot 136725) was chosen because it contains a ramp of the applied toroidal field. During this shot the line separation changes dramatically, going from the spectrum shown in Fig.7.1 to the one shown in Fig.8.2.

### 8.2.1 Calibration

In Figs.8.3–8.6, measurements made using the full in-situ calibration, described in Section 6.4, are shown in red. For measurements of $B_θ/B_T$, this in-situ calibration produces an offset in the measurements from the EFIT values for all of the views. If however the calibration of the transmission factor is manually adjusted by $\sim 5\%$ (excluding measurements from $330^\circ$ RIGHT, see below), an excellent match with EFIT can be obtained. This improvement is illustrated by the cyan points in the figures. Once the appropriate transmission factor has been found for a given chord and beam combination, it can be effectively used for the analysis.
**Figure 8.3:** Comparison of $B_\theta/B_T$ and $|\vec{B}|$ between $\vec{B}$-Stark and reconstructions from EFIT with MSE polarimetry. Data is shown for the $\vec{B}$-Stark b01 chord viewing the 330° LEFT neutral beam. B-Stark measurements, calibrated using an *in-situ* beam into gas calibration (red crosses), are made using a 10ms integration time. EFIT with MSE polarimetry results (solid line) are calculated every 20ms with a 10ms averaging used for the MSE polarimetry measurements. An adjustment in the value of the transmission factor by $\sim 5\%$ produces a good match with the EFIT values, as shown in blue crosses. From *in-situ* calibration: $T_f = 0.67$. Adjusted calibration: $T_f = 0.70$ (4% difference).
**Figure 8.4**: Comparison of $B_\theta/B_T$ and $|\vec{B}|$ between $\vec{B}$-Stark and reconstructions from **EFIT** with MSE polarimetry. Data is shown for the $\vec{B}$-Stark b02 chord viewing the 330° **LEFT** and 330° **RIGHT** neutral beams. The data presented is similar figure to Fig.8.3 except from the other $\vec{B}$-Stark viewing chord viewing chord. The scatter of the measurements at the end of the shot is due to the low magnetic field. From *in-situ* calibration: $T_f = 0.58$. Adjusted calibration: $T_f = 0.61$ (5% difference).
Figure 8.5: Comparison of $B_\theta/B_T$ between $\vec{B}$-Stark and reconstructions from EFIT with MSE polarimetry. Data is shown for the $\vec{B}$-Stark b01 chord viewing the 330° RIGHT neutral beams. The calibration of $|\vec{B}|$ for this chord and beam combination is imperfect, and will be discussed further in Section 8.2.1. From in-situ calibration: $T_f = 0.780$. Adjusted calibration: $T_f = 0.67$ (14% difference).
Figure 8.6: Comparison of $B_\theta/B_T$ between $\vec{B}$-Stark and reconstructions from EFIT with MSE polarimetry. Data is shown for the $\vec{B}$-Stark b02 chord viewing the 330° RIGHT neutral beams. As the magnetic field is ramped down the lines from the full and half components overlap and the fit of the level populations producing those lines becomes poorly constrained. This produces the systematic deviations from EFIT seen in $B_\theta/B_T$. In this case no adjustment to the in-situ calibration of $T_f$ is needed. From in-situ calibration: $T_f = 0.62$. 
of all other shots to produce a match to the \texttt{EFIT} value. There is however a small density dependence in the required calibration, as described in Section 8.3.2.

For the measurements of $|\vec{B}|$, the \textit{in-situ} calibration provides a very good match to the values from \texttt{EFIT}, except for chord \texttt{B01} viewing $330^\circ$ \textbf{RIGHT} (see Fig.8.5). For for the two $\vec{B}$-Stark chords viewing $330^\circ$ \textbf{LEFT} (Fig.8.3 and Fig.8.4), and for all of the midplane CER chords (Fig.8.7) the \textit{in-situ} calibration provides a nearly perfect match to the values from \texttt{EFIT}. More details on the accuracy of the $|\vec{B}|$ calibration are given in Section 8.2.2.

While the reason for the inaccuracy of the calibration for chord \texttt{B01} viewing $330^\circ$ \textbf{RIGHT} is currently unknown, there are several possibilities. One possibility is that the overlap of the full and half components of the spectrum (see Fig.7.2) affects the accuracy of the calibration process. Another possible reason for the calibration offset is an incorrect determination of the viewing location, which will be discussed later in this section. Because of this overlap of the components, and because the views do not pass though the center of this beam, the inaccuracy in the calibration for this chord and beam combination is not considered to be indicative of the accuracy of the \textit{in-situ} calibration in general.

The amount that the transmission factor must be adjustment from the \textit{in-situ} calibration depends on the choice of beam profile and beam-into-gas with magnetic field shots. It also depends on the type of background model used for fitting of the calibration and plasma spectra. This points to the error in the calibration being due to the fitting errors rather than a problem with the \textit{in-situ} technique. These fitting errors are discussed in more detail in Section 7.0.4. The needed calibration values are generally within 5% of the \textit{in-situ} values for any of the calibrations available.

As mentioned in Chapter 6, the transmission factor and the viewing geometry should be thought of as set of three calibration factors in the final measurement. The most useful way to think about these is as $a_1 = \ell_x$, $a_2 = \ell_y/\ell_z$ and $a_3 = T_f$. The value of $a_1 (\ell_x)$ calibrates the measurement of $|\vec{B}|$. The other two calibration factors, $a_2 (\ell_y/\ell_z)$ and $a_3 (T_f)$, allow the calibration of $B_\theta/B_T$ to be adjusted. In Figs.8.3–8.6 only $a_3 (T_f)$ was adjusted. This worked very well for Fig.8.3, provid-
ing a perfect match to \textbf{EPIT}. In Fig. 8.4 however, there remains a mismatch that is dependent on $B_\theta/B_T$. By adjusting both $a_2 (\ell_y/\ell_z)$ and $a_3 (T_f)$ this remaining mismatch can be resolved.

Mismatches between the spectral model and the recorded data are the most significant source of errors in the calibration. The sources of the spectral mismatch and their effect on the calibration were discussed in Chapter 7.

Another possible source of these calibration errors is that the beam-into-gas calibration relies on the viewing locations and the angle between the two neutral beams to be accurately known. There may however be errors in the expected location of the neutral beam. Results from the calibration of the $30^\circ$ \textbf{LEFT} beam shown in appendix E indicate that the viewing locations may be several centimeters from their expected locations. There may be additional errors introduced for the views of the $330^\circ$ \textbf{RIGHT} beam, where the viewing volumes are 8-10cm below the midplane at the beam center line. For the view of this beam the weighted center of the viewing volume is not obvious, in addition the average beam direction in the viewing volume may not be along the beam center. The asymmetry in the beam emission profile for this beam (see Fig. 7.2) indicates an asymmetric angular distribution of the beam particles in this viewing volume.

Using an \textit{in-situ} beam into gas calibration, the current calibration error in determining $B_\theta/B_T$, as compared to \textbf{EPIT} with MSE polarimetry, can be as large as 0.05 (3.0$^\circ$) depending on the choice of profile shape and background model. For $|\vec{B}|$ the calibration error is estimated to be less than $\sim 0.005T$ (0.25$\%$) (see Section 8.3.1).

### 8.2.2 Measurements of $|\vec{B}|$

For measurements of $B_\theta/B_T$ it is straightforward to compare the $\vec{B}$-Stark measurements to \textbf{EPIT} with MSE polarimetry. Unlike $B_\theta/B_T$, the value of $|\vec{B}|$ found from an \textbf{EPIT} reconstruction with MSE polarimetry is not a well constrained quantity. For a more accurate reconstruction of $|\vec{B}|$, a kinetic \textbf{EPIT}, described in Section 1.6, must be used. In Figs. 8.3–8.6 the adjustable parameters of the MSE \textbf{EPITs} were chosen to match the results from kinetic \textbf{EPITs} run for a few timeslices.
A direct comparison of $|\vec{B}|$ between the $\vec{B}$-Stark system, including the midplane CER views, and a kinetic \textsc{efit} is shown in Fig.8.7.

Another way to examine the accuracy of the $|\vec{B}|$ measurement is to compare measurements between the $\vec{B}$-Stark and midplane CER views. These two systems view different beams and have different viewing geometry and instrumental responses, producing a large difference in the beam emission profiles (see Fig.6.1). In addition the systems have entirely different light collection optics, spectrometers and camera systems. The viewing radii of two of the CER views coincides with two of the $\vec{B}$-Stark views, providing a simple comparison between the two systems. These matching views produce a measurement of $|\vec{B}|$ that matches to better than 0.005T for all shots that have been analyzed. The match between these two systems is shown in Fig.8.7.

Effect of magnetic pitch angle on $|\vec{B}|$

It is important to keep in mind that in order to find $|\vec{B}|$, a measurement of $B_\theta/B_T$ is needed, as shown in Eq.3.21 and Eq.3.25. This dependence is weak, so only a rough estimate of $B_\theta/B_T$ is needed. For the $\vec{B}$-Stark system, at typical values of $B_\theta/B_T$, a $1^\circ$ error in the pitch angle produces an error of 0.005T (0.2%) in the calculation of $|\vec{B}|$. The this effect can be seen in Figs.8.3–8.6 by looking at the difference between in the measurement of $|\vec{B}|$ with the \textit{in-situ} and adjusted calibration of the transmission factor. The change in the value of $B_\theta/B_T$ between the calibrations produces only very small changes in $|\vec{B}|$.

If a measurement of $B_\theta/B_T$ is not available, it is possible to use a reconstruction using only magnetics as a reasonable estimate in many cases.

Because no $\vec{B}$-Stark measurements of $B_\theta/B_T$ are available for the CER midplane views due to the geometry, the values of $|\vec{B}|$ shown in Fig.8.7 are calculated using $B_\theta/B_T$ found from \textsc{efit} with MSE polarimetry.

8.2.3 Measurements in reverse plasma current

Measurements taken with the plasma current or toroidal field in the reverse direction provide an important test for the $\vec{B}$-Stark system. These cases provide
Figure 8.7: Comparison between $\vec{B}$-Stark and kinetic EFIT values for $|\vec{B}|$. Measurements from the $\vec{B}$-Stark chords (B01, B02) viewing the 330° LEFT beam are shown as red crosses. The midplane CER views (T17–T20) viewing the 30° LEFT beam are included and shown as blue diamonds. EFIT values are shown with solid black lines. For the $\vec{B}$-Stark measurements of $|\vec{B}|$, values of $B_\theta/B_T$ found from EFIT are used in determining the angle between the beam and the magnetic field. The values for chords B01 and T18 view the plasma at the same radii and the measurements overlap, the same is true for B02 and T20.
a significant change in the direction of the Lorentz electric field compared to the normal case, forward $I_P$ and $B_T$. This in turn produces a significantly different spectral shape as shown in Fig.8.8. A comparison of the $\vec{B}$-Stark measurements with values found from EFIT with MSE polarimetry is shown in Fig.8.9. The red points indicate $\vec{B}$-Stark analysis with the in-situ calibration as before, the cyan points however come from the manual calibration needed for a match in Fig.8.3. The difference in the adjusted values from the EFIT values is consistent with the density dependent errors discussed in Section 8.3.2. There is also a noticeable discrepancy in the value of $|\vec{B}|$, which may be due to inaccuracies in the values from the between shot EFIT with MSE polarimetry reconstruction used for this plot.

**Figure 8.8:** A fit of a spectrum in reverse plasma current. The signal in this spectrum is quite low causing a large amount photon noise in the spectrum. The lack of a residual pattern as compared to Fig.7.1 is due to the larger error in the spectrum rather than to a better match to the spectral model.
Figure 8.9: Comparison of $\vec{B}$-Stark and EFIT for a reverse plasma current discharge. Chord $b_{01}$ viewing $330^\circ$ left, 10ms integration time. Here a control room EFIT (EFIT01) is shown in the solid black line. The the same adjusted calibration for the transmission factor found in Fig.8.3 is used, $T_f = 0.70$. The scatter in the measurement of $B_\theta/B_T$ is due to the low signal in this shot (see Fig.8.8). The recorded intensity for a timeslice in shot is less than half of the signal in the shot shown in Fig.8.3.
8.2.4 Measurements of $B_T$ compared to vacuum magnetic field

A comparison between the $\vec{B}$-Stark measurements of $B_T$ with the vacuum magnetic field provide a useful gauge of the effect of the plasma on the toroidal magnetic field. This type of comparison is shown in Fig. 8.10. The vacuum field differs from the true plasma toroidal magnetic field by more than 0.1T (5%) for many shots at DIII-D. A discussion on the effect of the plasma on $B_T$ is given in Ref. 25.

![Graph](image_url)

**Figure 8.10:** A comparison of $B_T$ found from $\vec{B}$-Stark measurements, a kinetic EFIT reconstruction and the vacuum field. The vacuum magnetic field is found from the toroidal coil current by assuming a $1/R$ fall off of the field magnitude.

8.3 Measurement errors

To examine the performance of the B-Stark system it is important to look at both the random and systematic errors. Random errors are due to photon noise;
the amount that this affects the measured parameters depends on the uniqueness of
the fitting solution (see Section 7.0.3). The highest accuracies are found when the
beam emission intensity and Stark line spacing are maximized. This is achieved at
lower plasma densities with full magnetic field and maximum neutral beam voltage.
Systematic errors in the current system are primarily due to mismatches between
the spectral model and the recorded spectrum, as discussed in Section 7.0.4 and
Section 8.2.1.

**Measurements of the random error**

To measure the random error in a way that encompasses all possible contribu-
tions, the standard deviation in the final results is used. To remove any linear
trends in the data, the standard deviation is calculated from the difference between
successive measurements.

\[
\Delta y_i = y_i - y_{i+1}
\]

\[
\sigma_{y_i} = \frac{\sigma_{\Delta y}}{\sqrt{2}} \tag{8.1}
\]

Here we assume that the data is sampled at a constant frequency. If the error in the
measurements is larger than the trend, then this technique will also compensate for
quadratic or higher order trends to some extent. The standard deviation is found
by using a subset of the data points in the time series, typically 20 data points
or equivalently 800ms. This provides adequate statistics to make a reasonable
measurement of the standard deviation in the data.

This technique has the disadvantage that any actual variations in the mag-
netic field will cause the calculated error to be higher than the actual measurement
error. Also even a single poorly fit timeslice within the window used for the cal-
culation can have a significant effect on the measured error. For this reason the
errors measured using this technique must be thought of as the upper bound of
the measurement error within the calculation window.

The random errors reported in the next sections are the minimum errors
seen using this technique. These minimum errors are achieved for some period in
nearly all of the shots in the dedicated experiment with full field and full beam

energy. The largest errors seen using this technique, which includes variations in the plasma, are generally not more than a factor of two above the reported minimum error.

8.3.1 Errors in the measurement of $|\vec{B}|$

Random error

Measurements of $|\vec{B}|$ were made with high accuracy over the entire range of plasma conditions, including at low fields. With 10ms integration time, the random errors in the measurement of $|\vec{B}|$ are $0.001-0.002$T ($\lesssim 0.1\%$) for the $\vec{B}$-Stark and midplane CER views. This error increases as the recorded intensity or the line separation decreases. This increase of the error with decreasing intensity is especially noticeable for the midplane CER views which have low throughput compared to the $\vec{B}$-Stark views. At the lowest intensities seen during the dedicated experiment the measured error in $|\vec{B}|$ from the midplane CER views is $\sim 0.006$T.

Systematic error

The systematic error in measurements of $|\vec{B}|$ is estimated to be less than $\sim 0.005$T. This value is arrived at by looking at comparisons between the $\vec{B}$-Stark and the midplane CER system and by comparing with EFIT values. The measurements of $|\vec{B}|$ from the $\vec{B}$-Stark chord b01 and the midplane CER chord t17, which have matching radii, match to within the measurement error in most cases.

8.3.2 Errors in the measurement of $B_\theta/B_T$

Random error

At full field the random error in measuring the ratio of the $\pi_{\pm 3}$ to $\sigma_{\pm 1}$ lines is $\sim 0.006$ ($\sim 0.5\%$) for the $\vec{B}$-Stark chords and $0.012$ ($\sim 1.5\%$) for the CER midplane chords. How this error translates into the error in $B_\theta/B_T$ depends on the exact viewing geometry. For the two $\vec{B}$-Stark viewing chords the errors in $B_\theta/B_T$
are $\sim 0.004 \ (0.2^\circ)$ and $\sim 0.006 \ (0.3^\circ)$. This error in the pitch angle is comparable to the error in the measurements from MSE polarimetry system\textsuperscript{38}. The error in the pitch angle becomes larger with lower emission intensity or reduced Stark line separation.

**Systematic error**

Calibration errors in $B_\theta/B_T$ can be as large as 0.05 (3.0$^\circ$) as discussed in Section 8.2.1. In addition to these calibration errors, the systematic difference between $\vec{B}$-Stark and \texttt{EFIT} varies with density as can be seen in Fig.8.11. For the density range achieved in the dedicated experiment a change in the comparison of $B_\theta/B_T$ of 0.02 (1$^\circ$) is seen. This systematic change with density is likely caused by fast ion emission, which is not accurately handled in the current model. Work is continuing to include a fast-ion model to the fit, as described in Section 9.1.3.

![Figure 8.11: Scatter plot of the difference in $B_\theta/B_T$ between $\vec{B}$-Stark and \texttt{EFIT} over the achieved density range. All of discharges from the dedicated L-mode experiment with full beam energy are shown. The color of the points represents the current at the given time. In general the shots with the highest currents had higher densities, however there are number of shots where this is not the case. The adjusted calibration from Fig.8.3 is used, $T_f = 0.70$. This calibration was done at low density. The $\vec{B}$-Stark measurements of $B_\theta/B_T$ systematically deviate from the \texttt{EFIT} values at higher density. This trend is attributed to the need for a fast-ion emission model.](image-url)
Chapter 8 contains material that has been published in Review of Scientific Instruments, 2008\textsuperscript{1}, and accepted for publication in Review of Scientific Instruments, 2010\textsuperscript{2}. N. A. Pablant; K. H. Burrell; R. J. Groebner; C. T. Holcomb; D. H. Kaplan, American Institute of Physics, 2008 and 2010. The dissertation author was the primary investigator and author of these papers.
Chapter 9

Future work

This chapter focuses on several topics relating to future applications of the \( \vec{B} \)-Stark diagnostic technique. We discuss possible improvements to the \( \vec{B} \)-Stark analysis techniques that have been identified during the development process. Preliminary results from these techniques are presented when available. As discussed in Section 1.3, the \( \vec{B} \)-Stark diagnostic can be used for a number measurements in addition to the magnetic field. A few of these measurements are discussed along with some preliminary results. Finally some thoughts on hardware design and diagnostic performance for future diagnostic installations are discussed.

9.1 Improvements to the spectral fitting model

In Chapter 7 and Chapter 8 several outstanding issues with the calibration of the \( \vec{B} \)-Stark diagnostic were discussed which appear to be due to a mismatch between the basic spectral model and the recorded plasma spectrum. A number of possible improvements to the \( \vec{B} \)-Stark spectral model and analysis techniques have been identified that may be able to resolve these calibration issues and improve the accuracy of the \( \vec{B} \)-Stark measurements. Some of these improvements have been implemented in the extended spectral model (see Section 5.3), however further work is needed to fully investigate their effect on the \( \vec{B} \)-Stark analysis.

In addition to the techniques discussed in this section, there are a number of other improvements to the \( \vec{B} \)-Stark spectral model that will extend the technique
to a wider range of plasma conditions. These model improvements will be discussed in Section 9.2 and Section 9.4.

### 9.1.1 Determination of the beam emission line profiles

One of the most important remaining issues with the $\vec{B}$-Stark diagnostic technique is the determination of the line profiles for the Stark split beam emission, as discussed in Chapter 6.2.

**Profile shape**

As discussed in Section 6.3, the use of a beam-into-gas calibration to find the beam emission line shape can only provide an approximation for the actual beam profile shape needed for fitting of plasma data. The most promising approach to improve upon this procedure is to fit the profile shape as part of an overall fit of a high quality beam-into-plasma spectrum.

This type of complex fitting is possible using the **bst** spectral fitting package (see Section 5.3 and appendix B). In order do to this type of calibration it is necessary to use very high quality spectral data. This can be obtained by using plasma shots with constant parameters and averaging $\vec{B}$-Stark spectra over multiple timeslices.

To accurately fit the beam emission profiles, it is necessary to take into account the variation in the line profile widths within the Stark manifold. A preliminary fit with the profile shape allowed to vary is shown in Fig.9.1. The line profile in this case was modeled using three Gaussians.

In this fit the line profiles for all of the beam emission lines are constrained to have the same shape. All of the individual Stark lines from the full and half components are allowed to have different widths. There is not enough separation between third component Stark lines to achieve a well constrained fit if they are allowed free widths; accordingly the width of Stark lines from the third component emission are constrained to have the same width. An extra Gaussian has been added to the third component beam profile and is allowed to vary as part of the
fit. The background is modeled using a linear term. In total there are 54 free parameters in this fit.

A very significant improvement in the quality of the fit can be seen. The \( \chi^2 \) value of the fit with a free profile shape is reduced by a factor of three from the fit using the basic model. In this fit it can be seen that the \( \pi_{+2} \) and \( \sigma_{-1} \) lines are shifted with respect to the spectral model. This is the expected shift from the Zeeman effect (see Fig.3.2), and shows that at this level of fitting accuracy the linear Stark approximation is not sufficiently accurate.

In the fit in Fig.(b) it is also possible to see the effects of the fast-ion emission. This emission is the main cause of the non-zero background, and is not perfectly handled by the linear background term. Improved modeling of this emission will also improve the quality of the spectral fit. Progress on the development of a fast-ion emission model is discussed in Section 9.1.3.

Finally, in this fitting procedure the profile width for all of the lines within the Stark manifold was allowed to vary. Given the results shown in Section 6.2.3, it would be better to constrain the line widths to vary linearly across the manifold. This would reduce the number of free parameters and allow the third component to be more accurately fit. The variation of the line widths across the Stark manifold in this fit is \( \sim 10\%-20\% \).

**Profile center**

As discussed in Section 6.3.1, it is important to retain a consistent definition of the line profile center so the wavelength separation between the lines can be meaningfully measured. The current approach is to use a single line profile *shape* for all of beam emission line profiles while allowing the *width* of the profiles to vary (see Section 5.1 and Section 5.3).

This scaling technique for the line profiles works reasonably well when the line broadening is primarily due to the Doppler broadening effects. However in cases where there is a large non-Gaussian instrumental response, this technique is not as effective. In these cases an improved procedure can be used that treats the instrumental response separately from the rest of the beam emission broadening
Figure 9.1: Fit of a midplane $\vec{B}$-Stark spectrum using the basic and extended models. In Fig.(a) the basic spectral model is used with the beam emission line profiles taken from a beam into helium gas calibration. In Fig.(b) the same spectrum is fit with a free profile shape and free line widths for the Stark lines from the half and full component emission. Spectra from this shot were timeslice averaged for a total integration time of 100ms.
effects. The final line shape is then found by convolving the instrumental profile with this separated beam profile. To handle lines with different widths within the Stark spectrum, the beam emission profile is scaled before the convolution.

Another possible improvement to the handling of the line profiles shapes is an absolute calibration of the line profile center. In the current work the beam emission line profile center is simply defined as the centroid of the profile. With this definition it is not possible to relate the line location to any absolute wavelength calibration. It is possible however to calibrate the beam profile center though the use of a beam-into-gas without magnetic field shot. The procedure described in Section 6.3 can be used except that instead of leaving the central wavelength as a free parameter, the profile center is allowed to vary. Once this profile center has been determined, it can be used during regular $\vec{B}$-Stark analysis. This type of calibration can be done straightforwardly using the bst_spectral_fit spectral fitting package.

9.1.2 Wavelength calibration

With the improvements to the determination of the beam emission line profile center suggested in the previous section, it becomes possible to use an absolute wavelength calibration, rather than fitting the central wavelength as is currently done in the basic spectral model (see Section 5.2 and Section 6.3.1).

An absolute wavelength calibration can be done either using an impurity line from the plasma emission or though an external calibration lamp. If a calibration lamp is to be used, it is best to illuminate the fibers from within the diagnostic port, ensuring that the instrumental response is the same as in the actual plasma data. The use of impurity lines from the plasma emission requires the development of a spectral model for their emission. Any plasma emission lines will have Zeeman splitting due to the presence of an magnetic field, and broadening due to the finite temperature of the impurity. Convenient lines to use for this type of calibration are the C – II emission lines near D$_\alpha$. It is also possible to use the cold edge D$_\alpha$ emission at the beginning of a plasma shot.

If an absolute calibration of the central wavelength is to be used, it is
important to do the wavelength calibration for every plasma shot. At the accuracies involved for the $\vec{B}$-Stark system, where peaks are fit to better than 0.1 channels, very slight changes in the hardware configuration can be significant. As an example of this sensitivity to movement of the hardware, on the CER systems at DIII-D noticeable changes in the central wavelength can be seen with temperature changes in the diagnostic room and can be correlated with the air conditioning cycle.

### 9.1.3 Addition of an accurate fast-ion model

In order to accurately fit the relative line intensities from the Stark split beam emission, models are needed for any other beam dependent emission in the same spectral range. As discussed in Chapter 2, the two most significant sources of beam-dependent $\text{D}_\alpha$ emission are the main-ion and fast-ion charge exchange emission. Over the spectral ranges of interest for the $\vec{B}$-Stark diagnostic, the thermal main-ion emission can be reasonably fit using a single Gaussian. The fast-ion distribution however is more complicated and produces a broad spectrum with a complex shape that depends on the properties of the injected beams and the plasma parameters.

In DIII-D the fast-ion distribution is created primarily by ionization of the neutral beams. These fast-ions, initially injected at three energies corresponding to the beam components, are slowed down through collisions with the background plasma. In addition these collisions cause pitch angle scattering, increasing the range of Doppler shifts that are recorded.

The fast-ion $\text{D}_\alpha$ spectrum can be calculated analytically as shown in Ref. 48. When projected onto the $\vec{B}$-Stark diagnostic geometry this provides a spectral model that can be used as part of the overall fit of the $\text{D}_\alpha$ spectrum. This analytical model for the fast-ion spectrum has been adapted for DIII-D as part of the development of a main-ion temperature and rotation diagnostic described in Ref. 16. The fast-ion model has been integrated into the extended $\vec{B}$-Stark spectral model using the $\text{bst\_spectral\_fit}$ fitting package.

A preliminary spectral fit including the contribution from the fast-ion emission is shown in Fig.9.2. This shot has a very low plasma density, $1.6 \times 10^{19} \text{m}^{-3}$,
(a) Constant background, $\chi^2 = 3529$, $B_\theta/B_T = 0.12$, $|\vec{B}| = 1.944$

(b) With FIDA emission model. $\chi^2 = 2608$, $B_\theta/B_T = 0.11$, $|\vec{B}| = 1.933$

**Figure 9.2**: Fitted D$_\alpha$ spectra from the $\vec{B}$-Stark B01 chord viewing the 330° LEFT neutral beam. In Fig.9.2a a fit using the basic spectral model is shown with a single Gaussian for the main-ion emission and a constant background. In Fig.9.2b a model for the fast-ion emission has been added to the fit. These spectra were recorded with a 10ms integration time.
providing a large fast-ion population. A marked improvement can be seen in the quality of the fit, especially on either side of the Stark split beam emission. The difference in the measured values of $B_\theta/B_T$ and $|\vec{B}|$ between the two spectral fits is significant as shown in the figure. This difference in magnetic pitch angle, on the order of $\sim 1^\circ$, may explain the density dependent differences between $\vec{B}$-Stark and EPIT discussed in Section 8.3.2.

9.1.4 Emission between the half and third beam energy components

In the basic spectral model it is assumed that the neutral beams inject particles at three distinct energies corresponding to the full, half and third energy beam components. As discussed in Section 1.5.1 and Section 9.1.4 the beams also inject particles with intermediate energies. These are currently handled by attaching an extra Gaussian to third energy beam emission profile. The fits of the beam emission spectrum can be improved by using a better spectral model for this emission. To develop this type of model a better understanding of neutral beam energy distribution is needed.

9.1.5 Polarization dependent transmission

In the work described in this thesis the ratio of the transmission of $\pi$ versus $\sigma$ light through the collection optics has been approximated to be constant with changes in $B_\theta/B_T$. A better approximation would be to treat the collection optics as a partial linear polarizer. These approximations were discussed in Section 3.3.

9.2 Measurements of $E_r$

In the basic spectral model the radial electric field generated by the plasma has been ignored. For many high performance plasmas this radial electric field can become important and must be taken into account during the spectral fitting process (see Section 3.2). In principal the radial electric field, $\vec{E}_r$, can be found as
part of the fit of the Stark spilt beam emission spectrum so long as there is more than one beam energy component. This procedure has been discussed in Section 3.2.3.

With the inclusion of the radial electric field, the value of $I_{\sigma_3}/I_{\pi_1}$ is no longer the same for all three beam energy components. Likewise the spacing of the Stark lines for three components can no longer be simply related though the relative beam velocities. Instead the spectral model needs to be re-parametrized to directly fit $B_T$, $B_\theta$ and $\vec{E}_r$. In order to measure the radial electric field, the fitting process will need to be able to accurately measure the spacing of the Stark lines not only for the full component but also for the half and third components.

If mono-energetic beams are being used, such as negative-ion based neutral beams, measurements of $\vec{E}_r$ will require the use of multiple views at a single radius.

### 9.3 Measurements of the level populations

In addition to measuring the magnetic field the $\vec{B}$-Stark diagnostic can also make measurements of the $n = 3$ level populations of the injected deuterium atoms from the neutral beams. These measurements can be used to validate predictions from atomic theory and atomic physics codes. Once validated, these atomic physics codes can be used for improvements in the $\vec{B}$-Stark diagnostic technique as discussed in Section 9.4. Calculations of the level populations can also be used to improve the analysis from the MSE polarimetry diagnostic.$^{37}$

The level populations are most sensitive to the plasma electron density and the beam injection energy. At high enough plasma densities, $\gtrsim 10^{20}\text{m}^{-3}$, the level populations are expected to reach statistical equilibrium.$^{29-31}$ Below these densities, models of the atomic processes involved in neutral beam injection into a plasma are needed in order to predict these populations. Several models using a collisional radiative technique have been developed as described in Section 1.4. The data collected during the dedicated experiment described in Chapter 8 provides scans of the plasma density and beam energy, which can be used to further investigate the accuracy of the atomic physics calculations over a wide range of
parameters.

Before these types of studies can be conducted however, improvements are needed in the $\vec{B}$-Stark spectral model. The current mismatches between the basic spectral model and the recorded spectrum, shown in Chapter 7, produce systematic errors in the measured population levels on the order of the expected deviations from statistical equilibrium. The fast-ion emission is of particular concern as it is density dependent and will skew any studies on the dependence of the level populations on the plasma density.

Work is continuing to use the $\vec{B}$-Stark diagnostic data to validate one of these atomic models, the \texttt{adas305} code.\textsuperscript{29} This model is a part of ADAS and this work is being done as a collaboration between the ADAS group, DIII-D and UW Madison. This validation is being approached in two ways. The first is though the direct measurement of the level populations with the $\vec{B}$-Stark diagnostic. The second is by integrating the results from the \texttt{adas305} code into the $\vec{B}$-Stark fitting procedure and evaluating the match to the recorded spectrum.

\section*{9.4 Integration of ADAS atomic physics calculations}

The integration of an atomic physics code able to accurately calculate the $n = 3$ level populations of the injected neutral beams can be used to significantly improve the $\vec{B}$-Stark diagnostic technique. The integration of such an atomic code will both improve the precision of the $\vec{B}$-Stark measurement and allow the technique to be extended to devices where the Stark lines cannot be well resolved.

With the use of a validated atomic code the level populations can be calculated instead of being treated as free parameters in the fit. This can greatly improve the fitting precision as the total $\pi$ and $\sigma$ intensities can then be used in determining the magnetic pitch angle rather than using only the $\pi_{\pm3}$ and $\sigma_{\pm1}$ lines. This will reduce the effect of photon noise on the final measurement as more of the spectrum is being used.

The use of this atomic code is also important for extending the $\vec{B}$-Stark
technique to machines with low magnetic fields or beam energies, particularly at low densities. At low densities the level populations are not expected to statistical and need to either be calculated or directly fit. At lower fields however the separation between the individual Stark lines becomes too small to fit the individual level populations. In addition at low enough fields the linear Stark approximation becomes invalid and a more complicated model of the Stark emission becomes necessary.

Work is in progress to integrate the adas305 atomic physics code into the bst_spectral_fit spectral fitter. Integration is complete, however further work on the atomic code is still needed in order to produce an output that changes smoothly enough to be used as part of a fitting procedure.

9.5 Fitting of simulated data

The fitting of simulated spectral data can be used to explore the performance of the $\vec{B}$-Stark diagnostic technique over larger parameter ranges that were achievable through experiments at DIII-D. Using the results from the $\vec{B}$-Stark system for real plasma data, the accuracy of these simulations can now be validated.

There are two related goals that can be addressed through doing these types of simulations. The first is to guide the design of future diagnostics; the second is to estimate the performance of a $\vec{B}$-Stark installation on future devices.

The accuracy of measurements made using the $\vec{B}$-Stark diagnostic are dependent on both the light throughput of the system as well as on how well the Stark lines can be resolved. In addition, the accuracy for measurements of $B_\theta/B_T$ are also dependent on the viewing direction. When designing a hardware installation it is often necessary to make trade-offs between the throughput, spectral response and viewing geometry. A thorough investigation on the importance of these effects would be very useful in guiding these design choices.

These types of simulations, once validated against actual $\vec{B}$-Stark results, can also provide extrapolations of the $\vec{B}$-Stark diagnostic performance to future machines. A specific goal is to estimate the performance of a $\vec{B}$-Stark diagnostic in-
stalled on ITER. The magnetic field and beam energies will be significantly higher than they are on DIII-D, both of which will produce a higher Lorentz electric field and therefore greater splitting of the Stark lines. This greater spectral line separation is expected to result in improved accuracy for the $\vec{B}$-Stark measurements. A challenge for simulating plasma performance in ITER will be determining the neutral beam properties sufficiently to determine the expected beam emission profile shape and emission intensity. These beam profile issues and some simulation efforts are discussed in Ref. 49.

9.6 Combined $D_\alpha$ diagnostics

The $D_\alpha$ spectrum contains a wealth of information that can be extracted from a spectral fit. With the proper viewing geometry and spectroscopic system, a single diagnostic can provide all measurements listed in Section 1.3. This is especially attractive as many of these measurements are complementary. For example the neutral beam energy fractions and the beam penetration are important for the modeling of the main-ion or fast-ion emission. Work is currently in progress at DIII-D to implement many of these additional measurements.\textsuperscript{16} The development of $\text{BST\_SPECTRAL\_FIT}$ has proven important in developing the spectral models needed for these measurements.

The views needed for this type of combined $D_\alpha$ diagnostic are also the same as those needed for a CER diagnostic. Since these two diagnostics use different spectral ranges it is possible for them to share fibers and collection optics by using dichroic filters to split the light into different spectrometers. This type of configuration has been installed at JET\textsuperscript{50} and TEXTOR\textsuperscript{24} and is being considered for installation on ITER.\textsuperscript{49}

9.7 Integration of $|\vec{B}|$ measurements into $\text{EFIT}$

A future project planned at DIII-D is to integrate measurements of $|\vec{B}|$ from the $\vec{B}$-Stark diagnostic directly into the plasma equilibrium code $\text{EFIT}$. These
measurements will be made as part of the main-ion temperature and rotation diagnostic currently in development at DIII-D.\textsuperscript{16}

9.8 **Hardware choices for a production system**

For the current installation we have chosen to sacrifice light throughput for improved spectral resolution. In this section a short discussion will be given on optimizing the hardware choices for future installations to provide the best magnetic field measurements.

9.8.1 **Spectrometer**

The primary limitation to the light throughput of the current $\vec{B}$-Stark installation is the use of a spectrometer with a high $f$-number. Any future installations should consider a spectrometer with a wider acceptance angle. It is important however to choose a spectrometer that produces a narrow instrumental response that is constant across the recorded spectral region. The issue of accurately measuring the wavelength difference between lines in the spectrum becomes much more complicated if the spectral response is not constant. Simulations of the kind described in Section 9.5 can be used to explore the trade-off between throughput and spectral resolution when choosing a spectroscopic installation.

Another consideration when choosing the spectroscopic installation is the spectral range to cover. If a combined D$\alpha$ diagnostic is to be implemented (see Section 9.6) a spectral range encompassing all of the D$\alpha$ emission sources is required. The spectral range of the $\vec{B}$-Stark system, as configured for the work described in this thesis, is too small for accurate fitting of the main-ion and fast-ion emission.

A final consideration in the design of a spectroscopic system is the inclusion of a spectral filter for the cold D$\alpha$ emission. This emission is often so bright as to saturate the detector, preventing removal by timeslice subtraction. This saturation can also cause distortion in the response of the surrounding pixels in some detectors. A partial notch filter or a blocking bar at the spectrometer exit can be used to prevent this saturation.
9.8.2 Whitelight and wavelength calibration

Routine whitelight and wavelength calibrations can improve the accuracy of the \( \vec{B} \)-Stark measurements as well as simplify the design and maintenance of the collection and acquisition components of the system. A system to automatically perform these calibrations for every shot is in place for the midplane \( \vec{B} \)-Stark and midplane CER systems and is recommend in future diagnostic designs.

Whitelight calibration

As described in Section 6.6.2 and appendix D, a whitelight (flat field) calibration is important for accurate measurements of the Stark line intensities. The whitelight response of the system is dependent on the spectrometer setting and can also be sensitive to small movements in the alignment of the fibers and the camera. This has proven to be a significant issue for the \( \vec{B} \)-Stark system due to a fringing (etaloning) effect of the CCD detector.

Ideally the whitelight calibration would be done using a light source within the vacuum vessel. While this is impractical, it is generally straightforward to include a whitelight illumination system within the diagnostic port, which can still provide an accurate calibration in most cases. This is routinely done for the midplane \( \vec{B} \)-Stark and midplane CER systems at DIII-D and greatly simplifies the maintenance of the system.\(^{51}\)

In the design of future systems it is important to consider the effect of the fiber arrangement on the accuracy of the whitelight calibration. With the fiber bundle configuration used for the off-midplane \( \vec{B} \)-Stark system, it is not possible to illuminate each of the individual fibers in the bundle from within the port in the same manner as the plasma. This reduces the accuracy of the final whitelight calibration. A system consisting of a single large diameter fiber coupled to fiber bundle, such as is used for the midplane \( \vec{B} \)-Stark system, is easier to illuminate evenly, but results in a loss of throughput due to packing fraction losses.
Wavelength calibration

As discussed in Section 9.1.2 it is useful to be able to make routine calibra-
tions of the central wavelength of the $\vec{B}$-Stark system. A calibration lamp and a
whitelight source can easily be integrated into a single system as is done for the
midplane $\vec{B}$-Stark and midplane CER systems.$^{51}$
Chapter 10

Conclusions

A new diagnostic for measurements of the internal magnetic field based on the relative intensities and spacing of the Stark split D$_\alpha$ beam emission has been successfully installed on the DIII-D tokamak.

The $\vec{B}$-Stark diagnostic technique has been shown to be effective for making measurements of both the magnitude and direction of the internal magnetic field in the DIII-D tokamak. Both measurements have been shown to be possible with high precision over the range of plasma parameters accessible in this device. These measurements are possible even at low fields or beam energies where the individual Stark lines are not well resolved. With the current installation, measurements of $B_\theta/B_T$ can be made with a time resolution and measurement precision comparable to MSE polarimetry. Measurements of $|\vec{B}|$ are highly accurate and would provide a strong constraint for magnetic equilibrium reconstruction, particularly for the pressure profile.

The geometry of the views as well as the necessary transmission properties of the first mirror and collection optics can be found using a beam into gas shot. The calibration of the geometry needed for measurements of $|\vec{B}|$ has been shown to be highly accurate, however improvements in this calibration are still needed to achieve the desired accuracy in the measurements of $B_\theta/B_T$. This calibration relies on the ability to measure the $\pi$ to $\sigma$ intensity ratio without assumptions about the level populations. The use of this calibration is promising for the possibility of a $\vec{B}$-Stark system to be used in future devices where coatings on the plasma facing
mirrors may change the reflection properties.

The ability to accurately fit the recorded Stark split beam emission spectrum requires that the beam emission line profiles are accurately known. The beam emission line profiles can be approximated through the use of a beam into gas shot without magnetic field. Scattering of the neutral beam particles on the background gas however broadens the emission profile. This scattering effect is minimized though the use of a low gas pressure. To improve the accuracy of the \( \vec{B} \)-Stark measurements, and particularly the calibration procedures, improvements to the determination beam emission profiles are needed.

Better modeling of the fast-ion and main-ion charge exchange emission would also help to improve the accuracy of the \( \vec{B} \)-Stark diagnostic. The fast-ion emission has been shown to have a noticeable impact on the quality of the current spectral fits. This emission is thought to be responsible for a density dependent systematic error in the measurements of the magnetic pitch angle.

Overall the \( \vec{B} \)-Stark diagnostic has been shown to be an effective alternative to MSE polarimetry in current and future fusion devices. In devices with stronger magnetic fields and higher energy beams, such as ITER, the spacing between the Stark lines will be larger, and improved measurement accuracy is expected.

Chapter 10 contains material that has been published in Review of Scientific Instruments, 2008\(^1\), and accepted for publication in Review of Scientific Instruments, 2010\(^2\). N. A. Pablant; K. H. Burrell; R. J. Groebner; C. T. Holcomb; D. H. Kaplan, American Institute of Physics, 2008 and 2010. The dissertation author was the primary investigator and author of these papers.
Appendix A

Hardware

A new port installation and spectroscopic acquisition system were required for the $\vec{B}$-Stark diagnostic as described in Chapter 4. This appendix contains some of the details of the hardware configuration for the $\vec{B}$-Stark system.

A.1 Collection optics and port design

The $258^\circ$ $r+1$ diagnostic port was chosen to provide optimal sensitivity for measurements of the magnetic field as described in Chapter 4. This port does not directly view the $330^\circ$ neutral beams, requiring a design with two internal mirrors to achieve the desired view. A re-entrant port design was used in order to bring the vacuum window and viewing lens closer to the plasma. A protective shroud with a remotely actuated shutter is placed around the mirrors and vacuum window to protect them from interactions with the plasma. In addition, a sapphire protective shield is placed directly in front of the vacuum window.

As part of the design of the collection optics and port arrangement, detailed ray tracing simulations were done using the OpTaliX ray tracing software. Ray tracing was used both in determination of the expected spot size in the plasma and to ensure that no loss of throughput was introduced by the mirror and shroud design.
Figure A.1: A view of the 258° $\mathbf{r+1} \vec{B}$-Stark port installation. Simplified versions of the diagnostic views are shown in Fig.4.1 and Fig.4.2
A.2 Fiber bundles

In order to maximize throughput through the spectrometer while maintaining narrow slits on the spectrometer, custom fiber bundles were designed for the $\vec{B}$-Stark diagnostic. A diagram of the fiber design is shown in Fig. A.5. The fibers in these bundles are arraigned in a vertical line on the spectrometer end, and in a square pattern on the machine end. The square arraignment on the machine ends minimizes the spot size within the plasma. The fiber bundle is additionally split into two ends on the machine size to allow for more flexibility in the viewing configuration. The two ends correspond to the upper and lower halves of the linear array on the spectrometer end.

The two legs of the fiber bundle can be arraigned to be used as a single view, or as separate views. The fiber clamp (Fig. A.4) supports either of these configurations. Four of these fiber bundles have been installed for a maximum of eight viewing locations. In the current configuration however two bundles are used in the combined configuration for two viewing location with maximum throughput.

As discussed in Section 4.2 with the fiber bundle configuration it is possible to directly examine the effect of Doppler broadening due the finite viewing volume in the plasma. For one of the run days on DIII-D the $\vec{B}$-Stark camera was operated in imaging mode, rather than in the spectroscopic binning mode normally used. One of the images from this run day is shown in Fig. A.6. In this image the spectra from the individual fibers can be seen. The Doppler shift of the beam components, shown on the right hand side of the image, is slightly different for each of individual fibers.

The fibers were built by Fiberguide Industries using 38 200$\mu$m core fibers. These fibers have numerical aperture of 0.22 ($f$-number $f = 2.3$).

For the midplane $\vec{B}$-Stark system 1500$\mu$m fibers are used at the machine end. These large diameter fibers are coupled to short fiber bundles with identical linear arrays as those shown in Fig. A.5.
A.3 Spectrometer and camera

For spectral acquisition a SPEX 3/4-m Czerny-Turner spectrometer is used, coupled to a Sarnoff CAM1M100 CCD camera. The arrangement of the spectrometer and camera are shown in Fig.A.7. To protect the camera from neutron damage, as well as to reduce neutron noise in the final spectra, the spectrometer and camera are placed outside of the DIII-D machine pit. In addition, six inches of borated-polyethylene neutron shielding and two inches of lead gamma shielding are placed around the camera installation.

The specifications and alignment of the spectrometer and camera were described in Section 4.2 and Section 4.3. To facilitate these alignments, the camera is mounted with a number of translation and rotation stages as shown in Fig.A.8. There are three translation stages and two rotation stages in this mount. In addition, the spectrometer can be tilted by adjusting the length of the legs, providing the last rotation direction. The camera mount has a locking mechanism which is used to prevent movement of the camera after alignment as well as to reduce the effect of any vibrations in the system. The mounting system for the camera is shown in Fig.A.8.

While in normal operation the linear fiber array serves as the entrance silt, a slit assembly is retained for fiber and spectrometer alignment and characterization. To achieve the minimum spectrometer response for a given slit width, the fiber array and the slit must both be aligned to the spectrometer. To achieve this the fiber arrays are mounted on a translation and rotation stages so that they can be adjusted with respect to the slit assembly. In addition, the slit assembly can be rotated with respect to the spectrometer. The fiber array mount is shown in Fig.A.9.
Figure A.2: Shown is the re-entrant port design for the $\bar{B}$-Stark diagnostic.
**Figure A.3**: The lens and lens mask assembly. This assembly is attached to the external alignment tube and placed up to the vacuum window. Alignment of the lens mask with respect to the fiber clamp is ensured through a tab and slot design. The $f$-number of the lens was chosen to be $f = 2.3$ for possible future upgrades to a faster spectrometer.
Figure A.4: Fiber clamp assembly. This assembly is attached to the external alignment tube. Alignment pins ensure that the fiber clamp is aligned to the lens mask. The distance of the fiber ends to the lens is fixed in this design.
Figure A.5: Fiber bundle design for the off-midplane $\vec{B}$-Stark system. The linear array is used on the spectrometer end and corresponds to one half of the detector. The two square ends of the bundle are placed one on top of the other at the machine end. Fiber bundles were manufactured by Fiberguide Industries using 200$\mu$m core SFS200/210/233RFT fibers.
Figure A.6: This image was taken with the $\vec{B}$-Stark camera in imaging mode during plasma shot 136779. The top half of the image corresponds to chord $b_{01}$ and the bottom half to $b_{02}$. In normal operation these two halves are binned vertically into the two spectra for those chords. The horizontal stripes across the image correspond to the illumination from the individual fibers in the liner fiber array. The dark line on the top half of the image is from a broken fiber in the fiber bundle. This image can be compared to Fig.2.2 which shows a similar spectrum.
Figure A.7: Layout of the spectrometer and camera in the diagnostic room. In this rendering, part of the neutron shielding igloo has been removed. The spectrometer has been pulled back from the camera in this rendering for clarity.
Figure A.8: Mounting of the camera is shown. Using the translation stages, the camera can be moved in all three directions. A second goniometer (not shown) is included in the final installation allowing the camera to be tilted in two directions. The third tilt direction is achieved by adjusting the length of the legs on the spectrometer. A locking mechanism is used to prevent movement and avoid vibration effects after the camera location has been calibrated.
Figure A.9: Mount for the fiber bundles on the spectrometer entrance slit. The fibers are placed against the slit jaws and can be moved and rotated for alignment to the slit. The slit assembly can be rotated for alignment of the slit to the spectrometer.
Appendix B

Spectral fitting software

As introduced in Chapter 5, two spectral fitting packages have been developed for fitting of the $\vec{B}$-Stark spectra. In this appendix some the details of these fitting packages will be discussed. Both of these packages are designed to do a non-linear least squares fit of a spectral model to a recorded spectrum. While different core fitting algorithms are used, the final fits found from the two software packages are exactly equal in all cases, so long as the same spectral model is used.

Both packages rely on a common set of acquisition and retrieval routines for the recorded spectra. These routines handle background subtraction, whitelight correction, and any timeslice averaging or timeslice subtraction. These routines also calculate the uncertainty in the spectrum using an empirical measurement of the dark noise and photon noise calculated from the measured photoelectron efficiency of the CCD detector. Complicated timeslice averaging and subtraction schemes are supported by these retrieval routines with proper tracking of the final spectrum weighting. This set of spectral retrieval routines is written in the C language and includes FORTRAN and IDL wrappers so that it may be called by the specific spectral analysis packages.

B.1 cerfit_stark

The cerfit_stark spectral analysis software package is a modified version of cerfit\textsuperscript{45}, the spectral analysis package used for the CER system at DIII-D.
While **CERFIT-STARK** retains many portions of the original package, the greater complexity of the Stark split beam emission has required a significant rewriting of many of the core routines.

In **CERFIT-STARK**, each emission line in the spectral model is given a Gaussian shape. These Gaussians are then convolved with a line profile to create the final spectrum. The line profile is made up of a sum of Gaussians, allowing convolution with the emission lines to be done in a simple analytical manner. In addition to the instrumental response profile, **CERFIT-STARK** introduces beam emission line profiles. Each line from the spectral model can be assigned to a profile for a given beam and energy component. The locations and widths of the Gaussians are described in terms of detector channels, which is the most appropriate measure when dealing with the instrumental response.

In addition to the Gaussian description, the spectral model also contains support for a polynomial background of up to quadratic order.

The overview of the spectrum generation from the model is as follows. A physics based model is used to calculate the line wavelengths and intensities of the Stark split beam emission from each of the three beam components. This model uses a set of physical parameters, which are described in Section 5.2. An additional parameter, the line temperature, is not used for the beam emission (set to zero), but is used for the modeling of the main-ion charge exchange and any impurity emission. The line wavelengths are converted to detector channel location using the procedure described in Section 6.6.1 and appendix C. Any temperatures are also converted to line width in channels. Once converted to channel location, the lines are convolved with the appropriate line profiles and added to the total spectrum.

The **CERFIT-STARK** application is written using the **FORTRAN 95** language and makes heavy use of modularization. A non-linear least squares fitting algorithm developed by Bunch *et al.* 52 is used as the core non-linear least squares fitting routine by **CERFIT-STARK**. Specifically the subroutine DGLG is used, part of the **ALGORITHM 717** suite. Details of the minimization technique can be found in Ref. 52;53. Ultimately this routine minimizes the weighed residual, which for the
case of \texttt{CERFIT\_STARK} is defined as:

\[ R_{\text{weighted}} = \frac{y_{\text{data}} - y_{\text{model}}}{\sigma_{\text{data}}} \]  

(B.1)

where \( y \) is the channel intensity in the spectrum.

All parameters are scaled by their initial guesses so that all parameters handled by the fitter have values around 1.0. For greater flexibility, the parameter bounds are handled outside of the core fitting routine. To do this, any bounded parameters are given an arcsin representation:

\[ x_{\text{scaled}} = \sin^{-1} \left( \frac{2x - b_U - b_L}{b_U - b_L} \right) \]  

(B.2)

where \( b_U \) and \( b_L \) are the upper and lower bounds respectively. As this scaled parameter, \( x_{\text{scaled}} \) approaches \( \pm \pi \) the actual parameter value, \( x \), will approach the bounds. The fitter will not adjust the \( x_{\text{scaled}} \) past \( \pm \pi \) as this reverses the direction that the actual parameter was changing in, creating a local minimum.

It was found that to achieve the highest quality fits, and improve the stability of the fitter, analytical derivatives were required. This requires the calculation of the partial derivative of the residual between the model and the final spectra with respect to each fit parameter. These derivatives include any scaling or bounding, as well as the conversion between wavelength and channel.

\section*{Initialization}

In order to get a convergent fit, the fitting parameters must be initialized to be near the expected final values. This initialization is done though a combination of external estimates and a \textit{linear} fit of the line intensities. This initialization procedure is described in Section 5.2.

With the Gaussian representation of the model and the line profiles, the intensity of each line has a linear relation to the intensity in the final spectrum. This can be utilized as part of the model initialization process. In this procedure we initialize the total \( \sigma \) and \( \pi \) emission for each beam component, assuming statistical level populations, along with any Gaussian or polynomial background. The \( \sigma \) and \( \pi \) intensities are then used to scale the population levels and determine a starting
point for the ration of $\pi$ to $\sigma$ emission. The result of this initialization process is shown in Fig.B.1.

When fitting multiple timeslices, the user also has the option to manually set a parameter or to use the results from the previous fit. The last option is not typically used, as a single bad fit can throw off the fitting for the rest of the time series.

**Fitting performance**

The *cerfit_stark* package has been partially optimized for fast fitting of time series of spectra. Using this routine a series of $\vec{B}$-Stark spectra from a plasma shot can be analyzed in $\sim$1 minute using a single process on a 3GHz machine. This is certainly fast enough for between shot analysis, though not fast enough for any real-time processing. There is, however, significant room for improvement in this fitting performance, as a lot of unnecessary initialization is currently done between every iteration of the fitter.

**B.2 bst_spectral_fit**

The *bst_spectral_fit* spectral analysis package was developed to provide a flexible application for the development of spectral fitting model. It also provides a GUI based interface for user interaction with the fitter and improved visualization tools. This software package has support for arbitrary spectral models, and provides mechanisms for various models to interact. It also simplifies the process of developing interfaces for external interaction with the models, both from the user or from other applications. Support for line profiles, based on sums of Gaussians, is integrated into the software. These use of these line profiles, however, is not required for a spectral model.

*bst_spectral_fit* has been written in the *idl* language using an object-oriented architecture. While the use of *idl* greatly simplifies model development, it is an interpreted language and limits the speed of the fitting process.

The *mpfit* non-linear least squares fitting package is used as the core fit-
Figure B.1: The spectrum generated by the basic model after initialization is shown in Fig.(a). The final spectrum after completion of the fit is shown in Fig.(b). Here the recorded spectrum is taken from the \( \vec{B} \)-Stark chord \( \textbf{b01} \) viewing the \( 330^\circ \) left beam. Integration time is 10ms.
ting routine for \texttt{BST\_SPECTRAL\_FIT}. The \texttt{MPFIT} software is based on the \texttt{MINPACK-1} library and uses a Levenberg-Marquardt\textsuperscript{55} algorithm. \texttt{MPFIT} includes support for parameter bounds, and these are taken advantage of by \texttt{BST\_SPECTRAL\_FIT}. In addition, it has been found that analytical derivatives are not needed for accurate fits of the \( \vec{B} \)-Stark model when using \texttt{MPFIT}. The same definition of the weighted residuals (Eq.B.1) is used as in \texttt{CERFIT\_STARK}.

**Architecture**

\texttt{BST\_SPECTRAL\_FIT} was designed to be used both as a stand alone spectral fitting application, and as a component to be embedded in other software. For this reason the core fitting routines and the basic handling of the models is kept separate from the user interface and any specific implementations of model control.

The core fitting model uses the concept of a model dispatcher. This dispatcher will find any existing models when the core fitting object is created. It can then use a standard model interface to initialize the fitting models and interact with them during the fitting process. Models do not necessarily have to provide a spectral model and can be used to provide constraints to other models.

A model can be added to the fitter by creating a new object derived from a base model class. Using specifically crafted file names, as in the \texttt{IDL} convention, new models can simply be placed into a specified folder and they will be automatically picked up and used by the fitter.

The rest of the \texttt{BST\_SPECTRAL\_FIT} application is built around this core fitting object. This application uses a concept of addons to allow development of model specific control and user interaction. Addons make use of a dispatching system nearly identical to the one used for the models. A base GUI is created as part of the overall application into which addons can add interfaces. A collection of object based widget handling tools was developed to simplify the process of creating the GUI interfaces for the addons.

Addons are also used to provide the spectrum to be fit, allowing the source to be changed through the enabling of various spectral addons. For example, addons have been written that allow the spectrum to be taken from the \( \vec{B} \)-Stark retrieval
routines, an slice though an image, or a user defined function.

Applications

For fitting of the $\vec{B}$-Stark spectra, a model has been developed that follows the procedure used in cerfit_stark (see Section B.1). Convolution has not been included as it unnecessary for fitting the Stark split beam emission. This, however, could be easily added though the use of a convolution model.

One of the important features of bst_spectral_fit is the ability to fit the line profile shape along with the parameters of a spectral model. A sum of Gaussians model has been developed where each Gaussian can be assigned to a profile with a given label. Once assigned, other models, such a scaled profile model, or the $\vec{B}$-Stark model, can make use of this profile. The Gaussians in the profile can be kept fixed to reproduce the basic spectral model, or can be allowed to vary as part of the fit, allowing for procedures described in Section 6.3 and Section 9.1.1.

Another example of a possible use of bst_spectral_fit involving model interactions is the inclusion of a fast-ion model. The fast-ion model requires the neutral beam penetration to be known. This can be found from the fit of the Stark split neutral beam emission using the $\vec{B}$-Stark model and then used by the fast-ion model as part of the fitting process. Implementation of this type of combined D$\alpha$ modeling is currently in progress.

While bst_spectral_fit has been designed specifically for spectral fitting, it can also be used to fit any one dimensional weighted data set.
Appendix C

Dispersion calibration

The B-Stark diagnostic relies on knowing the Stark split and Doppler shifted wavelengths of the neutral beam emission lines. What we actually measure is the channel location of the lines on our detector. We need to be able to find the wavelength from the channel number. Since we are attempting to find the locations of the peaks to sub-pixel accuracy, the channel to wavelength conversion must be equally accurate.

For a system with ideal optics, the dispersion can be found from the grating equation and the system geometry. In a real system, there are distortions due to the optics involved. These aberrations can cause differences between the dispersion calculated from the grating equations and the actual dispersion. In principal, if the optical configuration is known, these aberrations can be calculated. However, in general the configuration is not exactly known, and in addition these calculations can be quite complicated.

In this appendix an empirical correction to the ideal dispersion calculations will be discussed along with the calibration procedures used for the $\vec{B}$-Stark system.

C.1 Grating equations

In this section the final detected location of a particular wavelength though a Czerny-Turner will be derived under the assumption of ideal optics. In this approximation any optical aberrations in the system will be ignored. The angles
used in the derivation are described in Fig.C.1.

**Figure C.1:** Diagram of a Czerny-Turner spectrometer configuration. The layout shown is for the SPEX 3/4-m spectrometer used for the $\vec{B}$-Stark diagnostic. Here $\alpha$ is the tilt angle of the grating, $\theta_i$ and $\theta_m$ are the angles of the incident and reflected light from the grating normal, $\theta_f$ is the exit angle from the spectrometer, $f$ is the focal length of the object mirror and $x$ is the final detected location. All angles are drawn assuming *ideal* optics, that is, all aberrations are ignored.

In order to calculate where a particular wavelength will end up on the detector we need to find the angle at which light from a given wavelength is reflected from the grating, $\theta_m$. We begin with the standard grating equation.

$$\sin \theta_i + \sin \theta_m = \frac{m\lambda}{d} \quad (C.1)$$

where $m$ is the grating order, $\lambda$ is the wavelength and $d$ is the grating spacing. The indent angle of light on the grating, $\theta_i$, can be related to the angle $\phi$, which is a known design parameter of the spectrometer, and to $\alpha$, the tilt angle of the grating.

$$\theta_i = -\phi - \alpha \quad (C.2)$$
Using the above expression we can solve for $\theta_m$ using the grating equation.

$$\sin \theta_m = \frac{m\lambda}{d} - \sin \theta_i$$  \hspace{1cm} (C.3)

$$\theta_m = \arcsin\left(\frac{m\lambda}{d} + \sin(\phi + \alpha)\right)$$  \hspace{1cm} (C.4)

In general the grating tilt, $\alpha$, is not a measured quantity, instead the central wavelength on the detector is measured. For the central wavelength, $\lambda_0$, the angle of reflected light from the grating, $\theta_m$ can also be simply related to $\alpha$ and $\phi$.

$$\theta_{m0} = \phi - \alpha$$  \hspace{1cm} (C.5)

Using this definition along with Eq.C.2, the grating equation can be written as

$$\sin(\phi - \alpha) - \sin(\phi + \alpha) = \frac{m\lambda_0}{d}$$  \hspace{1cm} (C.6)

From this expression it is possible to solve for the grating angle given the central wavelength.

$$\alpha = \arcsin\left(\frac{-m\lambda_0}{2d\cos(\phi)}\right)$$  \hspace{1cm} (C.7)

Now that we have an expression for the grating tilt, we can calculate $\theta_m$ for an arbitrary wavelength, so long as we know $\lambda_0$ and $\phi$. Combining Eq.C.4 and Eq.C.7 we get a solution for $\theta_m$.

$$\theta_m = \arcsin\left(\frac{m\lambda}{d} + \sin\left[\phi + \arcsin\left(\frac{-m\lambda_0}{2d\cos(\phi)}\right)\right]\right)$$  \hspace{1cm} (C.8)

### C.1.1 Location solution

From the expression for $\theta_m$ in Eq.C.8 it is possible to find the location at the image plane where light of a given wavelength will be detected, $x$. To do this the focal length of the spectrometer, $f$, must be known along with the final angle of the light from the optical axis, $\theta_f$

$$x = f \tan \theta_f$$  \hspace{1cm} (C.9)

For the Czerny-Turner configuration the exit angle can be related to $\theta_m$.

$$\theta_f = \alpha - \phi + \theta_m$$  \hspace{1cm} (C.10)
The final expression for the line location, given an arbitrary wavelength, can now be found by combining Eq.C.9, Eq.C.10 and Eq.C.8.

\[ x = f \tan \left( \alpha - \phi + \arcsin \left[ \frac{m\lambda}{d} + \sin(\phi + \alpha) \right] \right) \] (C.11)

C.1.2 Wavelength solution

While for the \( \tilde{B} \)-Stark diagnostic we typically do conversions from wavelength to detector channel, the reverse calculation can be useful as well. To solve for the wavelength given a location and the central wavelength we start from Eq.C.3 and Eq.C.10.

\[ \lambda = \frac{d}{m} \left( \sin(\phi - \alpha - \theta_f) - \sin(\phi + \alpha) \right) \] (C.12)

\( \theta_f \) can be found from Eq.C.9 and \( \alpha \) can be found from Eq.C.7.

C.1.3 Central wavelength solution

In general the central wavelength of the system is found by calibrating the system using a light source with known emission lines. In this case the wavelength and location of the line on the detector are known, and \( \lambda_0 \) is the unknown quantity. To find \( \lambda_0 \) again we start from Eq.C.3 and Eq.C.10.

\[ \frac{m\lambda}{d} + \sin(\phi + \alpha) - \sin(\phi - \alpha + \theta_f) = 0 \] (C.13)

With some algebra this expression can be rewritten as:

\[ \frac{m\lambda}{d} + \sin \alpha [\cos \phi + \cos(\theta_f + \phi)] + \cos \alpha [\sin \phi - \sin(\theta_f + \phi)] = 0 \] (C.14)

To simplify things and make the derivation more clear, it is useful to define the following.

\[ A = \cos \phi + \cos(\theta_f + \phi) \]
\[ B = \sin \phi - \sin(\theta_f + \phi) \]
\[ C = \frac{m\lambda}{d} \] (C.15)
With these definitions we can rewrite Eq.C.14.

\[ C + A \sin \alpha = B \cos \alpha \]  
\[ (C + A \sin \alpha)^2 = B^2 (1 - \sin^2 \alpha) \]  
After expanding and gathering terms we arrive at a quadratic expression for \( \sin \alpha \):

\[ (A^2 + B^2) \sin^2 \alpha + 2AC \sin \alpha + (C^2 - B^2) = 0 \]  
Using the quadratic equation and replacing \( \sin \alpha \) with the expression from Eq.C.7, we arrive at our final solution for \( \lambda_0 \).

\[ \lambda_0 = \frac{-2d \cos \phi}{m} \left( -AC \pm \sqrt{-C^2 + (A^2 + B^2)} \right) \]

C.2 Calibration

For the conversions between location and wavelength given in Eq.C.12 and Eq.C.11, three parameters are needed, \( \lambda_0 \), \( f \) and \( \phi \). The value of \( \phi \), or at least a good estimate for it, is known from the spectrometer specifications. The spectrometer focal length, \( f \), is dependent on the exact placement of the entrance slit and detector, as well as on any additional optics added to the system, and is not generally known. While \( \lambda_0 \) can be estimated from the spectrometer setting, the accuracy in this estimation is not generally sufficient, and \( \lambda_0 \) must be treated as an unknown quantity. This is especially true for the \( \vec{B} \)-Stark system where the SPEX-3/4m spectrometer has a very inaccurate wavelength control.

Using a calibration with two lines of known wavelength and location, both \( \lambda_0 \) and \( f \) can be found. An analytical expression for \( \lambda_0 \) is not apparent, instead a numerical solution us used. First the expressions for \( x \) (Eq.C.11) for the two calibration lines are divided in order to eliminate \( f \).

\[ \frac{x_1}{x_2} = \frac{\tan[\alpha - \phi + \arcsin(m\lambda_1 / d + \sin(\phi + \alpha))] \arcsin(m\lambda_1 / d + \sin(\phi + \alpha))]}{\tan[\alpha - \phi + \arcsin(m\lambda_2 / d + \sin(\phi + \alpha))]} \]

This equation can be numerically solved to find \( \lambda_0 \). Once \( \lambda_0 \) is known, Eq.C.11 can be used to find \( f \).
Calibration correction

The procedure outlined above will not be accurate if aberrations or misalignment of the system cause the dispersion to deviate from the ideal equations. In such a case, it is necessary to develop a way to correct for any aberration or misalignment effects. In general these non-ideal effects will be dependent on both the exit angle $\theta_f$ and on the central wavelength $\lambda_0$. The $\lambda_0$ dependence is due to the tilt of the grating changing the spectrometer $f$/number, and is negligible for the wavelength ranges used by the $\vec{B}$-Stark system.

For the $\vec{B}$-Stark system most conversions will be done from wavelength to location. For this reason a third order correction to the ideal equations is used of the form:

$$x = a_0 + a_1 \tan \theta_f + a_2 \tan^2 \theta_f + a_3 \tan^3 \theta_f$$  \hspace{1cm} (C.21)

For ideal optics $a_1 = f$ and $a_0 = a_2 = a_3 = 0$. If the correction is small, higher terms can be ignored and an ideal calculation can be used as an approximation.

The calibration procedure used to find the coefficients was described in Section 6.6.1. This process involves scanning calibration lines across the detector by changing the wavelength setting of the spectrometer. At each spectrometer setting $\lambda_0$ is calculated from each of the calibration lines. When the coefficients in Eq.C.21 are properly calibrated, then for each spectrometer setting the value of $\lambda_0$ found from all the calibration lines will be the same. This allows us to construct a residual that represents the quality of the calibration.

$$R_i = \lambda_{0i} - \text{mean}(\lambda_0)$$  \hspace{1cm} (C.22)

where the $\text{mean}(\lambda_0)$ is calculated for the particular spectrometer setting. With this defined residual it is possible to do non-linear least squares fit of the calibration coefficients.

In the final calibration, $a_0$ is constrained to be zero. The coefficient $a_0$ represents an offset of the optical axis from the center of the detector. Over the wavelength ranges used in this calibration, the $a_0$ and $\lambda_0$ cannot both be constrained by the fitting procedure. With $a_0$ set to zero, $\lambda_0$ takes on a different meaning than before: it is now the wavelength at the center of the detector, not the
central wavelength as determined by the grating equation. This is advantageous as this means that the spectrometer wavelength setting is the same as $\lambda_0$. This also means that $a_1$ can be used in the ideal equations directly.

In addition to being able to fit all of the coefficients in Eq.C.21 separately, the fitting routines used can also use an additive correction technique. In this procedure the $a_1$ term is first found with the higher order terms set to zero, finding the best fit in the ideal approximation. This $a_1$ term is then held fixed as the higher order terms are fit. Using this procedure, the calibration can be used with either the ideal approximation or with the corrected dispersion. Care should be taken when using this procedure as it will not produce good results if the needed correction is large.

**B-Stark results**

In order to find the locations of the lines for the spectra taken with the calibration lamps, a single Gaussian was used to fit each line. This provides a very precise measurement of the line position. In doing this, however, we assume that the line profile is the same across the chip, which is true for the $\vec{B}$-Stark system. The results from the calibration are shown in Fig.C.2, both with the full third order correction and with an assumption of ideal optics. With the full correction the accuracy in calibration is limited only by the ability to fit the line locations; the conversion from wavelength to channel can be done with an accuracy of better than 0.05 channels. For this system the full correction is only a modest improvement over the ideal approximation.

To check the accuracy of the calibration it is important to use the results to calculate the line locations for lines that were not used for the calibration. The results of this type of check are shown in Fig.C.3. Here lines were chosen that were far, 200 $\AA$, from the ones used for the calibration. Even this far from where the calibration was done, the calibration still provides reasonable accurate results.

In a previous configuration of the $\vec{B}$-Stark system, which included a set of reducing lenses between the spectrometer and the camera, the use of the third order calibration was very important. Due to aberrations introduced by the lenses,
the assumption of ideal optics would produce a calibration that was only accurate to \(\sim 3\) channels at the edges of the spectrum. The full third order calibration however resulted in a calibration accurate to better than 0.1 channels.

**Figure C.2:** The accuracy of the dispersion calibration is shown for the \(\bar{B}\)-Stark chord \(b_01\). The plot shows the difference between the calculated and actual position of neon calibration lines used for the calibration. The black line represents calculations done with the full third order correction. The red line represents calculations done assuming ideal optics. In both cases the 6506.5 Å line was used to determine \(\lambda_0\). The location of the 6532.9 Å line was then calculated and compared to the actual line location. These same two lines were used for the calibration procedure. The spectrometer wavelength setting was scanned between 6552.5−−6492.5 Å in second order.

**Ray tracing results**

In order to develop and validate the calibration procedure, a ray tracing program \texttt{OpTaliX} was used to model a symmetric Czerny-Turner spectrometer with the same parameters as the SPEX-3/4m. With the ray tracing program the detected locations were calculated for a number of wavelengths at a series of spectrometer settings. The same calibration procedure as described above was then used to calibrate the dispersion at the simulated detector location.

The use of this simulated calibration allows for a closer examination of the
Figure C.3: Check of the dispersion calibration using alternate neon lines. For this check two neon lines at 6304.789\AA{} and 6334.428\AA{} were scanned across the chip. The coefficients from the third order calibration shown in Fig.C.2 were then used to calculate the line locations. The 6304.789\AA{} line was used to calculate $\lambda_0$, then the location of the 6334.428\AA{} line was then calculated and compared to actual location. Even though the lines used for this check are separated from the lines used for the calibration by 200\AA{}, the calibration is still accurate to better than 0.2 channels.
results. Multiple lines are used across the spectrum, ensuring that the calibration
is valid across the entire chip. Also the value of the central wavelength is known,
allowing the accuracy of its determination as part of the calibration to be examined.
Finally, a wider spectral range can be examined than is possible with the actual
spectrometer.

The ray trace results are summarized in figures Fig.C.4 and Fig.C.5. These
results show that the calibration procedure described in this appendix does work
very well for finding the correction coefficients. With this correction, it is possible
to convert between location and wavelength very accurately across the entire de-
tector. The ray tracing results also verify that for the wavelength range of interest
there is negligible dependence of the correction coefficients on $\lambda_0$. In Fig.C.5 it
is very clear that the assumption of a constant dispersion across the detector is
highly inaccurate, this is also seen with the actual $\vec{B}$-Stark system.

In the ray tracing model the detector is placed at the location of best
focus in the wavelength direction with the grating in 0th order, and centered on
the optical axis. With this configuration the camera is slightly defocused, and
$\lambda_0$, from the grating equation, is slightly offset from the detector center due to
spherical aberrations.

For the results shown in the figures, 11 lines were traced through the system.
The lines used were between $6511.0 - 6611.0 \text{Å}$ with $10 \text{Å}$ separation between lines.
The grating tilt was then adjusted so that $\lambda_0$ varied from $6511.0 - 6616.0 \text{Å}$. For
each grating position the location of the lines on the detector surface was output.
The location was determined by the centroid of the lines on the imaging plane.
To find the correction coefficients, the locations of the $6541.0 \text{Å}$ and $6571.0 \text{Å}$ lines
at each spectrometer setting (grating tilt) were used in the calibration procedure
described above.
Figure C.4: Results from performing a calibration procedure with simulated data generated using a ray tracing program. Here the calibration procedure show in Fig.C.2 was reproduced with the ray tracing data. As before two lines were used for the calibration procedure, 6541.0 Å and 6571.0 Å. In this plot the 6531.0 Å was used to determine $\lambda_0$, then the location of the 6571.0 Å was then calculated. The difference between the actual and the calculated location is shown. The black line represents calculations done with the full correction. The red line represents calculations done assuming ideal optics. Note that the channel range shown is larger than in Fig.C.2.
Figure C.5: Results of various methods of calculating the line positions. Black: Calculated with correction in Eq.C.21. Blue: Additive correction. Red: Calculation using the ideal optics calculation. Yellow: Constant dispersion (Paraxial assumption). In all cases, except the paraxial case, a fit was done using lines at 6541.0 Å and 6571.0 Å and 14 spectrometer settings in the range 6511.0–6616.0 Å. A line is plotted for each spectrometer setting showing the error between the calculated and actual positions for lines between 6511.0 Å and 6611.0 Å. For these calculations the 6531.0 Å line was used to determine $\lambda_0$. For the paraxial case, the focal length was calculated using the same lines but using only a single spectrometer setting (no fitting done.)
Appendix D

Whitelight correction

D.1 Introduction

In order to obtain accurate intensity measurements from the $\vec{B}$-Stark spectra, any non-uniformities in the intensity response of the system must be taken into account. This is a process common to all spectroscopic systems and is generally called either a flat field or whitelight correction. To calibrate the intensity response the system is illuminated with a uniform whitelight source. Spectra taken with this whitelight illumination can then be used as a correction to the final data spectra.

The whitelight response will have both a wavelength dependence as well as a dependence on the spatial location of the channels on the detector. The main sources of the non-uniformity in the whitelight response of the $\vec{B}$-Stark system are summarized below.

- Fringing effect within CCD detector.
- Efficiency variations across the pixels of the CCD detector.
- Wavelength dependent efficiency of the CCD detector.
- Wavelength dependent transmission through the collection optics and spectrometer.
- Vignetting within spectrometer or camera housing.
When a whitelight spectrum can be taken with the system configured and illuminated in the same way as for the recorded plasma spectra, the whitelight correction procedure is quite simple to perform. The process is as follows:

1. Take a whitelight spectrum with the same system configuration and illumination as for the data spectra. Other than the fringing effect, all other whitelight effects have a weak dependence on wavelength. Therefore, if no fringing effect is present on the system, the whitelight spectra may be taken at any wavelength near to the one that is used when taking data. Because the fringing effect has a strong dependence on wavelength, the whitelight spectra must be taken at the same wavelength as for data.

2. Correct the whitelight spectrum for the known response of the source. For a calibrated whitelight source the intensity versus wavelength curve is generally known.

3. Use the corrected whitelight spectrum to correct the data spectrum. First the whitelight spectra is normalized by dividing it by its mean. The data spectra is then divided by this normalized whitelight spectra.

The process for whitelight correction is significantly more difficult if it is not possible to illuminate the system in the same way as when taking data. This is an even greater issue when compounded with the fringing effect which produces a two dimensional pattern on the detector which is highly sensitive to the wavelength of the light incident on the detector. The $\tilde{B}$-Stark system has both of these issues, making the whitelight correction a complicated process.

### D.2 Fringing (etaloning) in back-illuminated CCDs

The fringing, or etaloning, effect occurs in Back-Illuminated CCDs when light incident on the chip can perform multiple internal reflections within a silicon layer of the CCD chip. Since the two sides of the silicon layer are parallel, the
silicon layer acts as an etalon. Depending on the wavelength of the light, and the thickness of the silicon, the multiple reflections will cause constructive or destructive interference of the incident light. When used in a spectroscopic application, this results in a fringing pattern as the wavelength changes across the chip. In addition, the thickness of the silicon layer changes slightly across the chip, making the pattern vary spatially on the chip. The result is a complicated two-dimensional fringing pattern across the entire chip, as seen in Fig.D.1.

The etaloning effect can only be present when the silicon layer is at least partially transparent in the wavelength range of interest. While the optical transmission efficiency of silicon is very low, the thickness of the silicon layer of typical back-illuminated CCDs is very small, $< 30\mu m$. The optical transmission of silicon goes down with wavelength, so the fringing effect is generally seen only at longer wavelengths. For most CCDs detectors this effect only becomes significant in the near infrared. For the particular camera that we are using, a Sarnoff CAM1M100, the specification on the silicon layer thickness is $10\mu m$. This thickness is consistent with having a significant fringing effect at the wavelengths which the $\vec{B}$-Stark diagnostic relies on, around $6561\AA$.

### D.3 $\vec{B}$-Stark whitelight constraints

There are a number of issues that are specific to the $\vec{B}$-Stark configuration that make performing an accurate whitelight calibration particularly challenging.

- The $\vec{B}$-Stark system relies on making accurate measurements of the relative intensities of the Stark lines. An accuracy in the measurement of the line intensities of better than 1% is desired.

- The magnitude of the fringing effect in the $\vec{B}$-Stark camera around $D_\alpha$ is about 5%.

- The period of the fringing effect across a spectrum is $\sim 20-40$ pixels, which is comparable to the line width of the Stark components. This is significant since it means that there will be no averaging over the fringes when determining the line intensities.
• The system is not equipped with any system to automatically take whitelight spectra. In order to take a whitelight spectrum, a whitelight source must be manually placed in front of the fibers in the diagnostic port. The DIII-D vacuum vessel cannot be entered except during yearly vents.

• Fiber bundles are used to couple light from the plasma to the spectrometer. It is not possible to illuminate the fibers in the bundle in exactly the same way as the plasma. This discrepancy means that the two dimensional fringing pattern on the chip will not be properly weighted in the final spectrum when using a whitelight source.

• The spectrometer that we are using does not have accurate wavelength control. In general the wavelength can only be set to within $\sim 1\,\text{Å}$.

• The vertical position of the image change can change whenever the wavelength of the spectrometer is adjusted. This vertical shift can be as large as $\sim 5$ pixels. Because of the use of the fiber bundles, the vertical illumination of the chip varies with a period of $\sim 13$ pixels (see Fig.D.1).

• The position of the image drifts slightly from day to day due to small movements of the spectrometer and camera hardware.

D.4 Description of whitelight response

While the $\vec{B}$-Stark camera is generally run in spectroscopic mode, where the top and bottom halves of the detector are binned vertically, it is also possible to use the camera in imaging mode. By running the camera in imaging mode, the illumination of the detector and the two dimensional nature of the fringing pattern can be examined. An image of the whitelight response of the detector is shown in Fig.D.1, this image was taken with a whitelight source in the $\vec{B}$-Stark diagnostic port. Spectra taken using the same illumination are shown in Fig.D.2, where top and bottom halves of the image correspond to the chords $b_{01}$ and $b_{02}$ respectively.
The dark band in the middle of the image is the space between the two linear fiber arrays (see Section 4.2 and Section A.2). The horizontal stripes, which go across the entire image, correspond to the individual fibers in the linear fiber arrays. The dark line on the upper half of the image is a broken fiber in the array. The rest of the patterning is due to the fringing effect.

**Figure D.1:** Image taken with a whitelight source in the $\vec{B}$-Stark diagnostic port. $\lambda_0 = 6548.0\text{Å}$ in 2nd order. The top half of the image corresponds to chord $b01$; the bottom half to chord $b02$.

When in spectroscopic mode, the two dimensional pattern seen in the im-
Figure D.2: Spectrum taken with a whitelight source in diagnostic port. $\lambda_0 = 6548.0\text{Å}$ in 2’nd order. Spectrum taken on 2009-04-15. Dotted lines at 0.93 at 1.02 illustrate magnitude of the fringing effect.
age is summed into the oscillating pattern seen in Fig.D.2. The fringing effect introduces a oscillation to the spectrum with a peak to peak height of $\sim 5\%$.

### D.5 Whitelight correction procedure

A procedure has been developed to correct for the whitelight response of the $\vec{B}$-Stark system including the fringing effect. The goal of this calibration is to be able to generate an accurate correction for any given wavelength setting of the spectrometer without requiring a new whitelight spectrum to be taken. This procedure will first be summarized in this section, then some of the individual steps in the calibration will be discussed in more detail.

The full correction procedure is fairly involved as it takes into account both the wavelength and spatial dependence of the fringing effect. The steps in the whitelight correction procedure are given below.

1. Take images at a series of spectrometer wavelength settings. Three types of images must be taken at each wavelength setting:
   - (a) Whitelight image.
   - (b) Dark image.
   - (c) Neon image.

These images should be taken over at least two periods of the fringing effect to allow for accurate fitting of the fringing response. The neon image is used to accurately determine the central wavelength of the spectrum. This is necessary because the wavelength control of the spectrometer is not sufficiently accurate to be used. In order to minimize vertical smearing of the image due the chip being illuminated during readout, long exposure times are required. To obtain decent photon statistics given the limited dynamic range of the chip, multiple frames must be taken at each wavelength setting and averaged together.

2. Average the multiple images taken at each spectrometer setting during the scan.
3. Determine the central wavelength in each image by fitting the neon lines visible in the images with neon illumination. For the $\vec{B}$-Stark system it is sufficient to fit the neon lines with a single Gaussian.

4. Fit the wavelength dependent response of every pixel in the image. The fitting function that should be used for this fitting (assuming that the fringing is purely sinusoidal) is $\text{linear} \times (1 + \text{sinusoid})$. For simplicity an approximation to this function has been used for the results shown in this appendix, $\text{linear} + \text{sinusoid}$.

5. To find the whitelight correction needed at a given wavelength extract the fringing correction for every pixel given the fits of the response from Item 4. The correction is given by $\text{correction} = 1 + \text{sinusoid}/\text{linear}$. This correction will only remove the fringing component (sinusoidal) of the whitelight response, not the portion that changes linearly with wavelength.

This fringing correction can now be used to correct any whitelight images. To accurately determine a spectrum correction, this image correction must be weighted by the illumination of the chip, then all the rows of the correction image must be summed. When a whitelight image with the correct illumination is available, the weighting is simply given by the corrected image.

For the $\vec{B}$-Stark system, it is not possible to take a whitelight image with the same fiber illumination as plasma data. It is possible however to determine the relative illumination of the fibers for plasma data. This can be done by taking an image during a plasma shot, as shown in Fig.A.6 in appendix A. In order to use this information to properly weight the correction, it is necessary develop a way to reconstruct a whitelight image given the relative fiber illuminations. The procedure to do this reconstruction and then complete the whitelight calibration is given below.

6. Apply the pixel by pixel fringing correction found in Item 5 to a whitelight image.

7. Fit the entire whitelight image to a model based on the illuminations of the individual fibers in the linear array. The goal is to be able to reconstruct
a whitelight image given the fiber illuminations. Details on the fitting and reconstruction procedure are given in Section D.5.4.

8. Take images during a plasma shot. This image will be used to determine the relative illumination of the fibers. Care must be taken not to introduce vertical smearing due the chip readout. This can be done either by choosing a frame where the plasma terminates during the exposure, or by using long exposure times.

9. Apply the pixel by pixel fringing correction found in Item 5 to the plasma image. An corrected image taken during a plasma discharge is shown in Fig.A.6.

10. Find the fiber illumination during a plasma shot. To do this we use the model developed for the whitelight image in Item 7. Only a small portion of the plasma image should be used that includes the beam emission. Because the camera can shift slightly from day to day we introduce a vertical shift parameter into the fit.

11. Reconstruct a whitelight image with the proper illumination using the model found in Item 7 and the fiber illuminations and shift found in Item 10.

12. To find the final fringing correction for a spectrum, use this image reconstruction for weighting when summing the rows of the fringing correction image. When doing the weighting, normalize the intensity of each of the columns of the weighting image. This normalization ensures that weighting is based on the actual illumination the detector, and does not include the linear response of the system.

13. Determine the linear correction spectra by summing the rows of the linear portion of the image fit in Item 4.

14. The fringing and linear corrections can now be applied to spectra taken during plasma operations.
A possible complication for this correction is that the light that makes up the beam emission portion of the spectra comes from a different place in the plasma than the light that makes up some of the other features of the D$_\alpha$ spectrum, such as the cold edge emission. If the illumination of the fibers from these various locations in the plasma is significantly different, then a good correction will not be possible. This is not expected to be a significant effect for the $\vec{B}$-Stark diagnostic.

**D.5.1 Fit of intensity versus wavelength response**

The method chosen to separate the fringing effect from the rest of the system response, is to fit the pixel response versus wavelength to a simple model. The simplest model is to assume that the fringing is sinusoidal with wavelength while the remaining system response is linear with wavelength. This can be expressed by the following equation.

$$I = (a_0 + a_1 \lambda)(1 + a_2 \cos((\lambda + a_4)\frac{2\pi}{a_3}))$$  \hspace{1cm} (D.1)

Where $I$ is the final intensity and $\lambda$ is the wavelength at the given pixel. For simplicity, an approximation to this equation is used.

$$I = a_0 + a_1 \lambda + a_2 \cos((\lambda + a_4)\frac{2\pi}{a_3})$$  \hspace{1cm} (D.2)

With this simplified model, the amplitude of the fringing correction is found by dividing the sinusoidal portion by the linear portion.

$$
\text{correction} = 1 + \frac{a_2 \cos((\lambda + a_4)\frac{2\pi}{a_3})}{a_0 + a_1 \lambda}
$$  \hspace{1cm} (D.3)

The results shown in this appendix use the simplified model and correction.

As an additional simplification, instead of using the wavelength at a given pixel, the central wavelength of the detector is used. This is equivalent to assuming that the change in the dispersion across the detector is the same at every spectrometer setting. Over the wavelength range of interest, $\sim 100 \text{Å}$, this effect should be small compared to the other sources of error. To take into account the actual wavelength at a given pixel would require doing a dispersion calibration at every row of the detector.
For this calibration process, the fits of the fringing effect must be done separately for each detector pixel. Small changes in the thickness of the silicon layer of the CCD chip will change the parameters of the fringing effect. Rather than use the spectrometer setting to determine the central wavelength a neon calibration lamp is used. A line with a known wavelength from the calibration lamp is fit using a single Gaussian, and central wavelength calculated (see appendix C).

Fig.D.3 shows typical fits using the fringing model described in Eq.D.2. Fits are shown for two representative pixels. The mean $\chi^2$ for fits of the pixel response is 2366.0.

![Graph of pixel response versus spectrometer wavelength setting.](image)

**Figure D.3:** Typical fit of pixel response versus spectrometer wavelength setting. Here a linear + sinusoidal model is used. Fits are shown for two pixels, (row = 200, col = 200) and (row = 230, col = 200).
There are a number of issues with this fitting procedure that limit its accuracy. As the spectrometer wavelength is changed, the image is shifted vertically and potentially rotated due to grating being slightly tilted by the spectrometer wavelength control mechanism. This effect is generally 1-2 pixels, although it can be as large as 5 pixels. Because the system is illuminated by a fiber array, which produces light and dark bands across the image, this shift will cause the illumination at a given pixel to change. The model used for this calibration does not take this effect into account. This changing of the illumination means that the assumption of a linear response with wavelength is not correct. If this shift is small and roughly linear with wavelength, then the model will still be fairly accurate in determining the fringing. However, because of this shift, the linear response of a given pixel cannot be determined. When the rows are summed to create a spectrum, the effect of this shift will mostly average out. The magnitude of this potential effect has not been quantified.

D.5.2 Fit results

The results of this calibration process (Item 1–Item 5) are shown in Fig.D.4. This is the same image shown in Fig.D.1 but with the pixel by pixel fringing correction from Eq.D.3 applied. The fringing effect has been almost completely removed using this procedure.

D.5.3 Linear response

Over the spectral range of the system, and the wavelength range of the scan used for the fits, \( \sim 100\,\text{\AA} \), the slope of the linear response of each channel is expected to be constant with respect to wavelength. Instead however, the slope of the linear response is observed to change across the chip.

This effect is seen when looking at fringing corrected spectra created from the images in the wavelength scan. It is important to look at spectra instead of individual pixels so that any effects from the image shifts is averaged out. For a given channel, the response versus wavelength is linear; however the slope of the
Figure D.4: Image taken with a whitelight source in diagnostic port. Fringes have been removed by using the correction from Eq.D.3 $\lambda_0 = 6548.0\text{Å}$ in 2nd order.
response is not the same across the chip. Normalized fringing corrected spectra are shown in Fig.D.5, and the linear slope of each channel is shown in Fig.D.6.

![Normalized spectra from fringing corrected images taken during the wavelength scan described in Item 1. Each colored line represent the corrected spectrum from one spectrometer setting. A slight change in the linear response of the system is seen that is dependent on the spectrometer setting.](image)

**Figure D.5:** Normalized spectra from fringing corrected images taken during the wavelength scan described in Item 1. Each colored line represent the corrected spectrum from one spectrometer setting. A slight change in the linear response of the system is seen that is dependent on the spectrometer setting.

The cause of this effect is unknown, however it appears to be due to the CCD chip. One possibility is that it is due to the chip thickness changing across the chip in one direction. The consequence of this effect is that to achieve the best whitelight correction, the linear correction, as well as the fringing correction, will need to be found for each spectrometer setting that is used. Overall this is a small effect in comparison to the flatness of the light sources that are used for the
Figure D.6: Slope of a linear fit of the pixel response versus wavelength. In all cases, the linear fit was very good. In these plots, the wavelength of every channel is calculated for each spectrum. This wavelength is then used in making the linear fits. Using the central wavelength instead results in a very minor difference. The small ripples in this plot are likely due to imperfect removal of the fringing effect.
D.5.4 Image reconstruction

The fringing effect creates a two dimensional pattern over the CCD chip. In order to accurately find the fringing correction for a spectrum from an image, it is important to know the two dimensional pattern of the whitelight illumination of the CCD chip. If it were possible to illuminate the system with a whitelight source in the same way as the plasma, then this is an easy task. For the $\vec{B}$-Stark system, light from the plasma is coupled to the spectrometer using a fiber bundle containing many small fibers. These fibers are not evenly illuminated by the plasma viewing optics. It is not possible to set up a whitelight light source outside of the DIII-D vessel that would provide the same relative illuminations of the fibers.

It is however possible to find the relative illumination of each of the fiber by taking an image of the plasma. A procedure has been developed for constructing a two dimensional weighting image using an image taken during a plasma discharge, and whitelight image taken with illumination from within the $\vec{B}$-Stark port. The goal of this procedure is to reconstruct what a corrected whitelight image would look like if the fibers had the same relative illumination as is expected from the plasma.

To do this a model is developed that describes a corrected whitelight image given the intensities of each of the individual fibers. With the spectrometer that we are using, the horizontal focal plane is tilted from the vertical focal plane. The camera is aligned with the horizontal focal plane so that the instrumental response in the horizontal direction remains constant across the chip. This however means that the instrumental response in the vertical direction is different for each column. There is more blurring of the fiber images on the right side of the chip than the left. An assumption is made that for a given column of the image, each fiber in the array has the same vertical instrumental response. With this assumption a model is created that describes each column of the image. The parameters of the model are then fit for every column.

The model is constructed using the following considerations.
• Each fiber in the array is given an illumination

• The spacing between the fibers is assumed to be constant.

• The location of this equally spaced fiber array is left free for each column. This will take into account any rotation of the image with respect to the spectral direction.

• For a given column, all fibers are assumed to have the same vertical response. The shape of this vertical response is modeled as a sum of Gaussians and left free as part of the fit of each column.

• The background consists of constant term plus a wide Gaussian.

The actual fits are done using the `bst_spectral_fit` fitting package. To fit a whitelight image, first a number for columns, \( \sim 200 \), are averaged together; the model described above is then used to fit the response. The results of this fit are shown in Fig.D.7. The relative illumination and spacing of the fibers found from this average fit are now held constant, and a fit is done for every column individually. As part of this fit the vertical fiber response is allowed to vary.

Using the responses found for each column in the image, along with the fiber array spacing and location, it is now possible to reconstruct a whitelight image knowing only the relative illuminations of the fibers. When doing this reconstruction, it is important to keep in mind the location the fibers in the image shift from day to day due to mechanical motion of the camera or spectrometer. This is not a problem in the horizontal direction, where the image changes slowly, but is important in the vertical direction. To take this into account, a parameter was added to the model to allow an overall vertical shift of the fiber array. At this time any changes in the rotation are not taken into account.

Corrected whitelight spectra are shown in Fig.D.8, where the correction was created with or without an image reconstruction for weighting. The spectra for which the corrections are applied was taken from an image that was part of the series that was used to create the correction. This figure shows that using the
Figure D.7: Fit of a column, averaged between 200-400, from a whitelight image. All fibers are modeled using a vertical response consisting of three Gaussians.
Figure D.8: Comparison of whitelight correction methods. The spectra shown here are created from an image that was part of the series used to create the whitelight correction. Three correction types are shown. 1.) Image is fringing corrected, then summed into spectrum. 2.) Image is summed into a spectrum, fringing correction is done without weighting. 3.) Image is summed into a spectrum then fringing correction is done using weighting from an image reconstruction. \( \lambda_0 = 6548 \). In these spectra the image correction and the spectrum correction with reconstruction are almost exactly equivalent.
reconstruction to generate a spectrum correction is as effective as correcting the image first, then generating the spectrum.

There are a number of complex background features in the whitelight images due to scattering inside the spectrometer. These features complicate the fitting process and require careful constraining of the background terms. When determining the fiber illuminations and spacing, an area of the image must be chosen where the background appears flat.

For the image fits three Gaussians are used to describe the vertical response for the fibers. This number of Gaussians provides the best balance between the quality of the fits and the stability of the fitter. When doing fits for the individual columns, the surrounding 11 columns were averaged together. This improves photon statistics, and improves the stability of the fitter. The stability improvement comes from averaging out small defects in the image, guaranteeing that the fit for each column will be very similar to the previous fit. For each column fit, the results from the previous column are used for the initial model values.

This procedure ignores any effects that will cause the fiber response or spacing to change vertically across the chip, such as the curvature of the image at the exit plane. These effects are small enough to be ignored for the accuracy of the fits that are needed.

D.5.5 Difference between imaging and spectroscopic mode

One unexpected issue with the above procedure is that spectra taken with the camera in spectroscopic mode do not have the same response as spectra taken with the camera in imaging mode. In spectroscopic mode, 512 rows of the CCD chip are first binned, then readout. In imaging mode, each pixel is read out separately, then 512 rows are binned in software. The difference between the two methods can be seen in Fig.D.9. To make this plot, the image and the spectrum were taken one after the other with the same fiber illumination. In both cases a dark spectrum or image was subtracted from the whitelight image. The difference between the two normalized spectra is \( \sim 1\% \).

This difference is due to a firmware bug in the camera that affected the
Figure D.9: Comparison of normalized whitelight response in imaging mode and spectroscopic mode. Spectra shown from imaging mode are found by summing the rows over half the chip for each chord. Dotted lines are shown at 1.0+/-.005.
readout of the chip in spectroscopic mode. With this bug the photo-electron response of the CCD was different in imaging and spectroscopic mode, leading the discrepancies seen.

A similar effect would been seen if the CCD had a non-linear response given the large difference in exposure per pixel in imaging versus spectroscopic mode. In imaging mode, each pixel has $\sim 1000$ counts/pixel/frame. In spectroscopic mode, each channel has $\sim 500$ counts/channel/frame, which is equivalent to $\sim 1$ counts/pixel/frame.

D.5.6 Final whitelight correction results

To test the results of the whitelight correction procedure, I used the calibration procedure on several different whitelight spectra, taken with different illuminations and at different wavelengths. When this procedure is used on the images that were used to determine the correction, the correction is very good. This result can been seen in Fig.D.8 where the fringing pattern has been reduced from a $\sim 5\%$ effect to a $<0.5\%$ effect.

The results of applying the procedure to whitelight spectra, taken in spectroscopic mode, are shown in Fig.D.10. In this figure the results of the correction are shown with or without using an image reconstruction for weighting when creating the correction. While the an image reconstruction only provides a modest improvement in these spectra, the effect may be larger for the actual plasma correction since the fiber illumination is less uniform than for these whitelight spectra.

Overall, the fringing pattern has been reduced from a $\sim 5\%$ effect to a $\sim 1\%$ effect. At this point this represents the best correction possible using the current procedure. There are three main reasons that the fringing effect is not completely removed by this procedure.

- The response of the camera in imaging mode and spectroscopic mode is not the same. This is the largest effect and ultimately limits the current correction accuracy achievable.

- The model used to fit the pixel response versus wavelength is not perfect.
**Figure D.10**: Comparison of correction done with or without an image reconstruction. Spectra were taken on 2009-04-15. Lambda0 = 6548Å. At this point this represents the best possible correction using this correction technique. Dotted lines at 1.0+/−0.005.
The biggest issue here is probably the vertical movement of the image as the spectrometer setting is changed.

- The reconstruction of the image is imperfect. This has only a small effect on the final spectral correction.

Because of the difference in the response between imaging mode and spectroscopic mode, the final \( \vec{B} \)-Stark analysis uses a whitelight spectrum taken in spectroscopic mode rather than this full calibration procedure whenever possible.
Appendix E

Determination of the neutral beam and viewing lens

There are a number of diagnostics at DIII-D that rely on emission from or excited by the injected neutral beams. The intersection of the viewing chords with the neutral beams provides a viewing volume that localizes the measurements within the plasma. In order to know where this viewing volume is located, the position of the neutral beams within the plasma must be accurately known. In addition, many of these diagnostics, including $\vec{B}$-Stark, rely on the viewing direction with respect to the beams, making the neutral beam position even more critical.

The beam locations have been estimated using laser alignment and thermocouple measurements on the walls of the DIII-D vessel. The accuracy of these estimations is not well known, especially when considering the true beam profiles.

By using the measurements from the $\vec{B}$-Stark diagnostic during beam-into-gas shots, where the magnetic field is known, it is possible to make an in-situ determination of the actual beam geometry. This calibration will be summarized in this appendix.
E.1 Methods

The goal of this calibration is to find the location of the neutral beams with the minimum number of assumptions about the geometry of the beams or the diagnostic system. In order to find the geometry of the $\vec{B}$-Stark system we need to find the following parameters:

- Location of the neutral beam.
- Radii of the viewing locations.
- Location of the viewing lens.

Using the Stark split $D_\alpha$ spectrum from the injected neutral beams two parameter can be measured for each viewing chord: the Lorentz electric field at the viewing location and the projected beam velocity. To relate these parameters to the geometry we need to know the actual beam velocity; since this is not available, it must also be found as part of the calibration procedure. Finally measurements are available for where the viewing chords intersect the target from the in-vessel spatial calibration (see Section 6.1). This target has a known location with respect to the vacuum vessel, though it may not correspond to the exact location of the neutral beams.

In order to do this calibration multiple viewing chords of the beam are needed. All together, assuming that everything is on the midplane and allowing for an arbitrary rotation around the machine center, there are nine unknown parameters. For the $\vec{B}$-Stark viewing chords an additional unknown parameter is distance of the lens above the midplane. Since each viewing chord provides three parameters, at least three viewing chords are needed to constrain the problem. While the off-midplane $\vec{B}$-Stark system does not have enough views, the midplane CER system does (see Section 4.6) and can be used to find the location of the $30^\circ$ left beam.

The procedure for this calibration is to develop a model that uses lens and beam geometry parameters along with beam energy to predict the measured values. The parameters in the model can then be varied as part of a non-linear
least squares fit to the actual measurements. While this calibration can be done using a single beam-into-gas with magnetic field shot, the use of multiple shots, including those without field can be used to improve the accuracy of this fitting procedure. In addition when doing this calibration a beam-into-plasma shot was used where a kinetic \textbf{efit} was used to determine the internal magnetic field. The inclusion of this shot allows for the consistency between the measurements of the Lorentz electric field between beam-into-gas and beam-into-plasma shots to be examined.

The free parameters and measurements used for the fit of the geometry are summarized in Table E.1. Three shots were used in this calibration: 136576 is a beam-into-gas with magnetic field shot, 136576 is a beam-into-gas without magnetic field shot, and 136721 is an L-mode beam-into-plasma shot. In the final setup there are 12 total free parameters and 15 total measurements.

The values for the projected beam velocity and the effective electric field are found using the basic $\vec{B}$-Stark spectral model (see Chapter 5). Errors are roughly estimated as 0.1% for the Lorentz electric field ($\vec{E}_L$) measurements, 0.1% for the projected beam velocity ($\vec{V}_{b,proj}$) from 136576, and 0.5% for $\vec{V}_{b,proj}$ from 136575 and 136721 (from Stark fits). The error for the target distances are set as 3mm, the expected measurement error. The error for the angle between the targets is arbitrarily set at 0.1%.

There are a number of assumptions that then go into this calibration. The basic spectral model involves a number of assumptions described in Section 5.2. In addition the geometry model used for this calibration makes the assumptions described below.

- The magnetic field on the midplane has a $1/R$ decay.
- The viewing location for the beam is at the point where the chord crosses the centerline of the beam.
- All of the viewing chords pass through a single point at the lens.
Table E.1: Measurements and free parameters in fit of the 30° left beam geometry. In all cases measurements were made for each of the four midplane CER chords: T17-T20. Here $\vec{V}_b$ is the beam velocity, $\vec{V}_{b,\text{proj}}$ is the beam velocity projected along the viewing direction and $\vec{E}_L$ is the Lorentz electric field. The beam crossover refers to the point where the 30° left and 30° right beam cross.

(a) Free parameters: 12 total

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<td>lens radius</td>
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<td>lens toroidal angle</td>
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<td>$\vec{V}_b$</td>
<td>136721 (beam-into-plasma)</td>
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(b) Measurements: 15 total

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E.2 Results

The results of the geometry fit are shown in Fig.E.1. The final weighted residuals in this fit are below two, indicating a good fit of the geometry to the measurements. The final parameters are compared to the geometry reported by the neutral beam group and an in-vessel spatial calibration in Table E.2.

Figure E.1: Here the in-vessel spatial calibration and geometry fit are compared. The black lines are from the in-vessel calibration. The red lines are from the beam-into-gas calibration. The red dashed line represents the target location while the thick red and black solid lines represent the beam locations. The angle between the $30^\circ$ Left and $30^\circ$ Right beams is fixed.

From this fit we can see that the beam is found to be at a different location than reported by the beam group, and also not to be aligned with the target. This change in the beam location caused the viewing radii of the midplane CER chords to move sightly, $\sim 1\text{-}3\text{cm}$.

In order to get the best possible fit the magnetic field on axis for shot 136575 changed slightly from the expected value of $\mathbf{b_{\text{coil}}} \times \frac{144\mu_0}{2\pi R_0}$ where $\mathbf{b_{\text{coil}}}$ is the current in the toroidal magnetic field coil. The change in the value is fairly small and within the error of the fit. This offset from the expected value, if real, can explained in a number of ways.

- The beam-into-gas and beam-into-plasma spectral fits are affected differently
by mismatches between the basic spectral model and the recorded spectra (see Section 7.0.4).

- The EFITS are inaccurate. While kinetic EFITS are used for this analysis, there may still be some small errors.

- The actual viewing location for the chords are not at the nominal beam center.

- The target location is not correct.

If the value of the magnetic field on axis for shot 136575 is fixed, similar final parameters are found, however the quality of the fit is not as good.

Table E.2: Final parameters from the geometry fit are compared with values from an in-vessel spatial calibration assuming the beam locations reported by the neutral beam group. All angles are in degrees. Errors in the final parameters (σ) are as reported by the non-linear least squares fitter (MPFIT). These errors likely not very accurate since only rough estimations were used for the measurement errors.

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<tr>
<td>Beam crossover toroidal angle</td>
<td>61.6</td>
<td>60.2</td>
<td>0.3</td>
</tr>
<tr>
<td>θ_{br}</td>
<td>24.19</td>
<td>23.79</td>
<td>0.14</td>
</tr>
<tr>
<td>Lens radius (cm)</td>
<td>273.5</td>
<td>266.3</td>
<td>5.9</td>
</tr>
<tr>
<td>Lens toroidal angle</td>
<td>70.3</td>
<td>69.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Magnetic field on axis (T)</td>
<td>-2.159</td>
<td>-2.149</td>
<td>0.008</td>
</tr>
<tr>
<td>V_{b} 136575 (10^6 m/s (keV))</td>
<td>2.796 (81.6)</td>
<td>2.760 (79.5)</td>
<td>0.011</td>
</tr>
<tr>
<td>V_{b} 136576</td>
<td>2.796 (81.6)</td>
<td>2.755 (79.2)</td>
<td>0.009</td>
</tr>
<tr>
<td>V_{b} 136721</td>
<td>2.781 (80.7)</td>
<td>2.753 (79.1)</td>
<td>0.007</td>
</tr>
<tr>
<td>Radius τ17 (cm)</td>
<td>183.5</td>
<td>184.7</td>
<td>0.32</td>
</tr>
<tr>
<td>Radius τ18</td>
<td>189.9</td>
<td>191.5</td>
<td>0.36</td>
</tr>
<tr>
<td>Radius τ19</td>
<td>196.6</td>
<td>198.4</td>
<td>0.41</td>
</tr>
<tr>
<td>Radius τ20</td>
<td>203.7</td>
<td>206.3</td>
<td>0.46</td>
</tr>
</tbody>
</table>

E.3 Conclusions

Using the Stark split beam emission from the neutral beams along with in-vessel measurements of the chord intersections on a target it is possible to find
the geometry of the neutral beams and the viewing. Multiple viewing chords are needed for this calibration, so this calibration cannot be applied to the off-midplane \vec{B}\text{-Stark} system. These measurements rely on the location of the in-vessel target being accurately known as well as the ability to make accurate fits of the Stark spectrum. There are currently some uncertainties in the location of the target with respect to the DIII-D vacuum vessel. Improvements in the target determination are planned during the current DIII-D maintenance period.

The viewing radii found using this calibration have been used during the \vec{B}\text{-Stark} analysis of the midplane CER chords (see Fig.8.7).

This type of geometrical fit also provides an \textit{in-situ} measurement the beam energy. Assuming that the target location is correct, the actual beam velocities are \sim1\% lower (\sim2\text{keV}) than the values reported by the neutral beam system.
Glossary

**fortran 95** A modern version of the *fortran* language with support for modular programming.

**fortran** The programming language used for the development of the *cerfit_stark* spectral fitting package (see *fortran 95*).

**idl** Interactive Data Language. An interpreted programming language with advance support for mathematical processing.

**ADAS** Atomic Data and Analysis Structure. ADAS is a set of atomic data sets and analysis codes to aid in the spectral analysis and plasma modeling.

**adas305** A code within ADAS for calculations of the Stark split $D_\alpha$ emission from neutral beams injected into a plasma. *adas305* using a collisional radiative model to calculate the level populations of the low $n$ states of the injected deuterium atom.

**backward calibration** A calibration done after the completion of a run period on DIII-D.

**beam component** The neutral beams at DIII-D inject neutral deuterium at three distinct energies, the full, half and third energy components. These energies arise from different molecular configurations of deuterium in the acceleration chamber of the neutral beams and correspond to $D^+$, $D^+_2$ and $D^+_3$.

**beam-into-gas** For a beam-into-gas shot the tokamak is filled with a low density neutral gas and the neutral beams are fired. These types of shots are used for several of the $\vec{B}$-Stark calibrations. These shots can be done with or without the presence of an applied neutral beam. See Section 1.5.2.

**beam-into-plasma** Describes a normal plasma shot with neutral beam injection.

**bst_spectral_fit** A general purpose non-linear least squares spectral fitting package developed along with the $\vec{B}$-Stark diagnostic. This package includes a flexible model for fitting of the Stark split $D_\alpha$ spectrum.
burning plasma A plasma producing enough fusion energy to maintain a self-sustaining reaction.

CCD charge coupled device.

centroid The weighted center of a distribution. In spectroscopy it is the weighted center of an emission line profile. For a smooth function the centroid can be calculated be the following formula: \[ \int x f(x) \, d\!x / \int f(x) \, d\!x. \]

CER The charge exchange recombination spectroscopy diagnostic is used to measure impurity temperature, rotation and density within the DIII-D tokamak. This diagnostic relies on emission from the impurity species after charge exchange interactions with the neutral beams. Alternate acronyms for this diagnostic at other fusion devices are CXR, CXRS and CHERS.

CERFIT-STARK A non-linear least squares fitting package developed to fit Stark split D$_\alpha$ spectrum for the $\vec{B}$-Stark diagnostic. This fitting package is built around the basic fitting model described in Chapter 5. This software package is a heavily modified version of CERFIT, which is used for analysis of spectra from the CER diagnostic on DIII-D.

chord Refers to a single view of the plasma and neutral beam.

dark current The signal recorded by CCD in the absence of incident light.

dark noise The noise recorded in a dark image taken with a CCD camera. This includes any dark current as well as any readout and reset noise.

DIII-D A tokamak device located at General Atomics in San Diego. The $\vec{B}$-Stark diagnostic has been installed on this device.

EFIT A plasma equilibrium reconstruction code used at DIII-D.

ELM edge localized mode.

FAC Flexible Atomic Code. An atomic code to calculate various atomic properties and processes.

fast-ion Ions in the plasma with energies outside of the thermal distribution. The fast-ion distribution in DIII-D is created by ionization of the neutral beam and subsequent slowing down due to collisions in the plasma.

FIDA Fast-ion deuterium-alpha. A diagnostic to measure the confined fast-ion distribution.

FIR far infrared.
forward calibration  A calibration done before the start of a run period on DIII-D.

FWHM  full width at half maximum.

gpmm  Groves per millimeter. The standard unit to describe the groove density of a diffraction grating used within a spectrometer.

ideal approximation  For a spectroscopic system this assumes ideal optics and perfect alignment. With this approximation any aberrations in the system are ignored.

ITER  The next generation fusion experiment designed to demonstrate a device producing net fusion energy gain. The ITER design is a large scale tokamak similar to DIII-D. This device is currently being built as a collaboration between six nations and the European union.

JET  The Joint European torus is an experimental tokamak device located at the Culham Science Centre, Oxfordshire, UK.

main-ion  The ions in the plasma making up the bulk thermal distribution.

midplane  The plane extending horizontally though the middle of the tokamak. $z = 0$ is defined by this plane.

MSE  motional Stark effect.

MSE polarimetry  motional Stark effect polarimetry. A diagnostic able to make measurement of the internal magnetic pitch angle using the polarization of the lines from the Stark split neutral beam emission.

MST  The Madison symmetric torus (MST) is a reversed field device located at the University of Wisconsin at Madison.

paraxial approximation  Using this approximation the properties of an optical system are defined by their values on the optical axis.

PEM  photoelastic modulator.

TEC  thermoelectric cooler.

TEXTOR  An experimental tokamak device located at the Jülich Research Centre in Germany.
Symbols

\( \vec{B} \) Magnetic field.

\( B_\theta \) The magnetic field in the poloidal direction.

\( B_T \) The magnetic field in the toroidal direction.

\( D_\alpha \) The deuterium emission line from the \( n = 3 \rightarrow n = 2 \) transition.

\( \vec{E} \) Electric field.

\( \vec{E}_L \) Lorentz electric field created from a particle moving in a magnetic field.

\( \vec{E}_r \) Radial electric field created by the plasma.

\( H_\alpha \) The hydrogen emission line from the \( n = 3 \rightarrow n = 2 \) transition.

\( I_P \) Plasma current.

\(|k_1, k_2, m_\ell\rangle\) Quantum state in parabolic coordinates.

\( \lambda \) Wavelength.

\( \lambda_0 \) Wavelength at the center of the spectrum.

\(|n, l, m_\ell\rangle\) Quantum state in spherical coordinates.

\( T_f \) The ratio of the transmission of \( \pi \) versus \( \sigma \) light though the collection optics.

\( U \) Energy.

\( U_b \) Full component beam energy.

\( \vec{V}_b \) Beam velocity.

\( \vec{V}_{b,\text{proj}} \) Beam velocity projected along the viewing direction.
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