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Investigation of Coronal Plasma Dynamics in Tungsten and Carbon X-pinches

A Thesis submitted in partial satisfaction of the requirements for the degree Master of Science

in

Engineering Sciences (Engineering Physics)

by

Robert Edward Madden

Committee in charge:

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Mark Tillack
George Tynan

2008
The Thesis of Robert Edward Madden is approved and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego

2008
DEDICATION

I would like to recognize my family for their support and encouragement. To my parents and grandmother Joye, for everything they have done for me. To Barbara who helped keep me focused and achieve my goals.

I would like to recognize all the friends that have been with me on my journey. Each challenge has faded with ease given their care and stimulation.
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Chapter 2, in part, is a reprint of the material as it appears in Physics of Plasma 2008. Bott, Simon C.; Haas, David; Eshaq, Yossof; Ueda, Utako; Collins, Gilbert; Beg, Farhat N., American Institute of Physics, 2008. Some content, in part, has been submitted for publication of the material as it may appear in IEEE Transactions on Plasma Science, 2009. Bott, Simon C.; Haas, David; Collins, Gilbert; Beg, Farhat N., IEEE 2009. The thesis author led these experiments and was the primary author of both these papers.

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ABSTRACT OF THE THESIS

Investigation of Coronal Plasma Dynamics in Tungsten and Carbon X-pinches

by

Robert Edward Madden

Master of Science in Engineering Sciences (Engineering Physics)

University of California, San Diego, 2008

Professor Farhat Beg, Chair

Experiments are reported on that examine sources for investigating low density plasma (around $10^{17}$ electrons/cm$^3$). Quantitative measurements of the coronal plasma density are recovered using interferometry simultaneously with laser shadowography of the late time diode gap formation in 2- and 4-wire tungsten x-pinches using an 80 kA, 50ns current pulse are presented. Axial expansion of the gap occurs at $\sim 10^6$ cm/s for both 2- and 4-wires systems and is likely to be driven by an axial $\mathbf{J} \times \mathbf{B}$ force resulting from radial current flow in the plasma mini-diode ‘electrodes’. Radial density profiles suggest re-pinching of the low density plasma occurs after the main pinch resulting in secondary x-ray emission peak $>10$ns after the first, which is recorded with a pair of pin diodes. We also report on the first investigations of the use
of carbon fibers in an x-pinch load using a 250 kA linear transformer driver (LTD). Multi-frame laser shadowography is used to examine the evolution of the pinch, and shows that carbon loads demonstrate wire expansion, cross-point pinch and gap formation as observed in x-pinches constructed from high Z materials. Radiographs using the carbon x-pinch as the source and time-resolved x-ray emission measurements show that the carbon x-pinch has sufficient emission at distances >10 cm from a small hotspot in the 500 eV < $h\nu$ < 3 keV range to show that the carbon x-pinch has potential as a radiographic source for diagnosing low density plasmas.
1 Introduction

For more than a decade the X-pinch has been used as a source for point projection radiography. Its continued study and characterization allows for clearer understanding of how to design x-pinch loads for the needs of researchers. It also has a unique structure that has advantages for the study of wire ablation physics. Coronal plasma that ablates from the wire surface is below the densities for high contrast imaging by soft x-ray sources. For close examination of the X-pinch’s low density coronal plasma evolution other sources are needed to extract quantitative information. Initial interest and ground work for X-pinches were well established in exploding wire experiments initiated in the 1960’s [1]. Studies of exploding wires revealed a large flux of electromagnetic radiation [2] that included soft x-rays for some materials [3]. X-pinches became of interest as a radiographic source when the region of high energy emission could be restricted to and reproduced within a 100 μm region[4].

An exploding wire experiment begins by connecting the two electrodes of a pulsed power device with a fine wire, typically tens of microns in diameter (Fig 1.1). Currents driven through the wire ohmically heat the material. With ample heating, mass begins to ablate from the wire surface creating a system of low density coronal plasma surrounding a dense wire core [5-7]. Ampere's law dictates that the current density in the plasma will have associated with it an azimuthal magnetic field, the z-axis being the center of the wire. The current density in the plasma in combination with the magnetic field leads to a $\mathbf{J} \times \mathbf{B}$ force that is directed radially to the axis. So as
wire material expands radially outward at the local sound speed, magnetic forces compress plasma back on axis until a pressure balance is achieved. This pressure balance is often referred to as the Bennett relation, which can be described by

$$\frac{\mu_0}{8\pi} I^2 = N k_B (T_e + T_i)$$  \hspace{1cm} (1.1)$$

where $I$ is the current through the plasma, $N$ is the number of electrons per unit length, $k_B$ is Boltzmann’s constant and $T_e$ and $T_i$ are the electron and ion temperatures respectively. With small perturbations in the radial position of the plasma there will be localized increases in the magnetic field, which scales as $B \sim 1/r$. This quickly drives the system unstable as increasing magnetic fields lead to further radial pinching of the plasma, creating a narrow neck of plasma. This $m = 0$ magneto-hydrodynamic (MHD) instability (Fig. 1.2), as it is called, in combination with others makes for a rapidly evolving system of unpredictable structure at multiple locations along the wire [8]. The arrangement of the wire along the z-axis and the pinching gives to this type of system being called a z-pinch.

![Figure 1.1: Illustration of setup for an exploding wire Z-pincho](image)

Figure 1.1: Illustration of setup for an exploding wire Z-pinch.
While some plasma is ejected axially from the pinching region, the remaining plasma is compressed to near solid densities and high temperature conditions that can result in a short pulse, or “burst”, of electromagnetic radiation [9,10]. This radiation, depending on the material of the wire and the current pulse, can be in excess of 3 keV. Short pulses of radiation in this energy range from small sources [3,11] have great potential as a source from point projection radiography. The problem with using single wire z-pinches is that the source location is unpredictable and non-stationary [12], being able to appear at any point along the length of the wire, and the occurrence of more than one pinch point will create multiple images. This issue of multiple images and unpredictable source location led directly to the development of the x-pinch. It was observed by Zakharov et al. [4,13], that the most intense emitting region was from where the wires crossed, in a region of about 100 μm.
X-pinch plasmas are produced by driving a large current (typically on the kA-MA scale) through two or more fine wires (usually tens of microns in diameter) mounted in between the electrodes of a pulsed power generator. The wires are placed in parallel and then one electrode is rotated approximately 180° so that the wires cross and touch at a single point, forming the shape of an “X” (Fig. 1.3a). As in single wire experiments the wire begins to expand and ablate, creating dense wire cores surrounded by a low density coronal plasma (Fig. 1.3b) [13-16]. In x-pinches, the current is divided between two or more wires. This makes the local magnetic field along the legs near the electrodes 1/n, n being the numbers of wires, of its magnitude at the cross point, reducing the pinching effect. Near the cross point the current in the legs combine to create a strong global field. The point at which the global field begins to dominate the $\mathbf{J} \times \mathbf{B}$ forces will accelerate plasma to the systems z-axis. In the region near the cross point this creates a column of plasma that resembles a z-pinch in form and evolution. The column reaches near solid densities and is a few hundred microns in length, because of it’s small size compared to an exploding wire z-pinch it is often...
referred to as a micro z-pinch (Fig. 1.3c) [17]. The micro z-pinch has been seen to reach diameters <100 μm [17], making for magnetic fields greater than 1000 T and pressures in excess of 390 GPa for a 80 kA current. The compression of the micro z-pinch ejects plasma out axially. This plasma combined with plasma flowing to the axis from the wire legs creates a jet like structure that has possible application to astrophysical laboratory work [13,18,19]. Magneto-hydrodynamic instabilities lead to pinching of the plasma at multiple points along the micro z-pinch. Some of these pinching points develop into “hot spots” of high density and temperature plasma that emit intense bursts of soft x-ray radiation, in the 1-10 keV range, that can have sub-nanosecond duration (Fig. 1.3d) [20,21]. Following the x-ray burst, plasma is rapidly evacuated from the central region, leaving a gap in the axial density profile, which continually expands late in time (Fig. 1.3e) [17,22,23].

The hot spots and subsequent soft x-ray emission are of great interest for their high energy density conditions and use as a source for high-energy radiography [17,22,24-28]. Because of the small source size and short soft x-ray pulse, x-pinches have been developed as a backlighting source for diagnosing dense dynamic plasma bodies [17,22,29,30]. Used as a diagnostic, x-pinches have been excellent for probing densities in the >10^{19} cm^{-3} region [22], and give temporal resolution equal to the burst duration [31,32]. However, the lower resistivity of the coronal plasma as compared to the dense cores and micro z-pinch suggest that the majority of the current would flow in this region [33]. This makes the evolution of the coronal plasma vital to the understanding of the structure and dynamics of the entire system. It is difficult to use current x-ray backlighting techniques for examination of the behavior of the coronal
plasma surrounding the dense wire cores because the corona is optically thin in the energy range being used. A suitable way to adjust for this is probing the coronal plasma with lower energy photons. The two methods explored in this work are optical probing and developing an x-pinch that will emit in a lower energy range.

Optical laser imaging methods are ideal for the electron number densities \((10^{17}-10^{19} \text{ cm}^{-3})\) of the coronal plasma. From this one can gather information on the driving mechanics of the x-pinch. While there has been optical imaging of the x-pinch [34-37], this is relatively limited and detailed quantitative studies have yet to be carried out. Mitchell et al. [23] used laser interferometry to study the developments of the jets structure emanating from the cross point and briefly noted the size of the gap and electron density of the plasma inside the gap, but does not examine their temporal evolution.

The photon energy emitted from the hot spots will determine the plasma structures that can be imaged, absorption being determined by both the material atomic number and the integral of the density over the path length. Previous studies using high Z materials such as W, Mo and Nichrome have used Ti radiation filters to image plasma object in the 3-5 keV range, and this technique has been highly successful in providing both qualitative and quantitative measurements for densities \(>10^4 \text{ kg/m}^3\) [17,22,29,30]. However, for lower density plasmas, such as those accelerated to the system axis for both x-pinches and wire array z-pinches, transmission of 3-5 keV x-ray can be very high. For example, in this range the transmission of a W plasmas with an areal density of \(3 \times 10^4 \text{ kg m}^{-2}\) (similar to ablated plasma) is \(>90\%\). At 1keV this is \(<70\%\) and at 0.5 keV this is \(<50\%\). Use of either of
these energy windows would greatly increase the contrast of images of these plasmas expanding the range of tools available to researchers investigating systems with large density ranges.

A possible candidate for a lower energy radiography source is carbon. Studies of pulsed power driven carbon fibers have so far been restricted to z-pinches, where a single fiber was the load of a pulsed power machine due to similarities with the cryogenic deuterium fibers [5,38]. The z-pinch experiments focused on optical emission and low density coronal dynamics, but did confirm that x-rays originated from the pinch regions of greatest radial compression, suggesting even a low z material may undergo a sufficiently high-quality radiatively driven collapse process to provide a useful point projection source when used in an x-pinch configuration.

The focus of this thesis is to show that optical probing methods can provide valuable information on the evolution dynamics of an x-pinch and to share the preliminary results of the investigation into carbon x-pinches as a radiographic source. Chapter 2 provides a background of the experimental setup, details of the pulsed power drivers and an overview of the diagnostics. Chapter 3 details the results of an investigation of x-pinch dynamics using optical probing methods in combination with other diagnostics to determine driving mechanisms of gap formation and differences between two and four wire x-pinches. Chapter 4 presents the first investigations of carbon fiber x-pinches, where the gross system dynamics are investigated to assess possible application as a radiography source. A summary of results are presented in Chapter 5.
Chapter 1, in part, is a reprint of the material as it appears in Physics of Plasma 2008. Bott, Simon C.; Haas, David; Eshaq, Yossof; Ueda, Utako; Collins, Gilbert; Beg, Farhat N., American Institute of Physics, 2008. Some content, in part, has been submitted for publication of the material as it may appear in IEEE Transactions on Plasma Science, 2009. Bott, Simon C.; Haas, David; Collins, Gilbert; Beg, Farhat N., IEEE, 2009. The thesis author led these experiments and was the primary author of both these papers.
2 Experimental Setup

2.1 Pulsed Power Devices

The basic principle of pulsed power machines is to charge and store electrical energy and then release that energy in a short amount of time compared to the charge time. The use of such machines in plasma physics has allowed laboratory studies to reach plasma regimes previously inaccessible. The experiments reported on here were carried out on two different pulse power machines. The 2 and 4 wire experiments with optical probing were carried on a pulser with a conventional water pulse forming line driver. The studies on carbon x-pinches were carried out on a state-of-the-art pulsed power device known as a linear transformer driver (LTD). The LTD used was the recently completed GenASIS machine at UCSD.

2.1.1 X-pinch pulser

In the compact pulser, electrical energy is stored in a Marx bank (4x50 kV, 0.22 \(\mu\)F capacitors). A circuit diagram of the Marx bank with a photo of the actual device can be seen in Figure 2.1 and Figure 2.2, respectively. Each capacitor in the Marx bank is charged in parallel to 46 kV with a charge time on the order of a minute. When triggered by a thyratron the 930 J of stored energy is then discharged from the capacitors via the closing of spark gaps in a series connection. The pulse then traverses a shielded cable to a coaxial pulse forming line (PFL) that uses de-ionized water as the dielectric (see Figure 2.3). The pulse forming line is capped by a SF\(_6\)
Figure 2.1: Circuit diagram of Marx bank.

Figure 2.2: Photo of Marx bank. Capacitors and switches are submersed in oil.
filled self breaking spark gap. This allows charge to build in the line until there is an ionization breakdown in the SF$_6$, acting as a switch before the load.

The impedance for coaxial water filled PFL is given by

$$Z = \frac{377}{2\pi e_r^{1/2}} \ln\left(\frac{b}{a}\right)$$

(2.1)

where $e_r$ is the relative dielectric constant of the insulator ($e_r = 78.38$ for water), a and b are the inner and outer radius of the conductors, respectively. For $a = 7.5$ cm and $b = 9.5$ cm the PFL has a given impedance of 1.6 $\Omega$. If the transit time of the PFL is given by $\tau = d/c_w$, $d$ being the length of the PFL and $c_w$ the speed of light in water ($c/9$), then for $d = 90$ cm the transit time will be 27 ns. The capacitance of the PFL is $C_{PFL} = \tau/Z$, giving a capacitance of approximately 17 nF. The PFL acts as a fast discharging capacitor in series with the Marx bank.

Current is delivered to an x-pinch load between two brass electrodes separated by 10 mm. The electrode structure is contained inside a small vacuum chamber held below $6 \times 10^{-4}$ mbar for each shot. The relatively large machine impedance compared to the load makes the current response fairly stable for a variety of loads. Current traces

Figure 2.3: Illustration of pulsed power machine with Marx Bank.
of a short circuit and x-pinch load are shown in Figure 2.4. The traces were obtained by use of a Rogowski current probe placed around one of the four return current posts, and the signal was then numerically integrated to obtain the current. The Rogowski probe uses the principle of magnetic inductance to create a current through a conductive loop placed in toroidal geometry around a post (Figure 2.5). The voltage in the conductive loop as seen by the oscilloscope is then a function of the current through the post and the geometry of the probe.

\[
V = \frac{z\mu_0}{2\pi} \ln \left( \frac{b}{a} \right) \frac{dI}{dt} 
\]  

(2.2)

The maximum load current is approximately 80 kA with a rise time of 50 ns.

Figure 2.4: Example of current through a load and short circuit in the X-pinch pulser.
2.1.2 Linear Transformer Driver

In GenASIS, the LTD [39] recently completed at UCSD, the electrical energy is stored in twelve 20 nF capacitors. Figure 2.6 shows the LTD circuit diagram. The capacitors were charged to 70 kV, giving a stored energy of 588 J. The low capacitance naturally gives the discharge a small pulse width, making it so that no pulse compression is required. The current trace shown in Figure 2.7, has a rise time of 150 ns, while the charge time was on the order of 10 seconds. The LTD, also triggered by a thyatron, delivers the current to the load via a conical magnetically insulated transmission line (MITL) which both raises the load to provide excellent diagnostics access, and reduces the electrode diameter to ensure efficient coupling of the generator to the load. The x-pinch is loaded between two brass electrodes separated by 10 mm. The electrode and MITL structure is contained inside a small

![Circuit diagram of LTD](image_url)
Figure 2.7: Example of current through a carbon load and short circuit in GenASIS.

vacuum chamber held below $6 \times 10^{-4}$ mbar for each shot. Measurements of $\text{d}I/\text{d}t$ were taken by Bdot probes [39] mounted in the generator return path, and by use of a Rogowski coil placed around one of four return current posts. The signals from both were then numerically integrated to obtain the current from the machine and the current seen by the load.

The generator has a relatively low impedance (~0.3 Ω). This becomes important when there is a change in the load inductance because it can result in a measurable change in the drive current. For each x-pinch load, a dip in the current trace is observed shortly after peak current, and this is likely to be due to the rapid change in inductance as the x-pinch cross point is compressed to small radius.
2.2 Laser Imaging

The primary method for investigating plasma dynamics was by optically probing the plasma with a frequency doubled Nd-YAG laser (532 nm) with a pulse length of 5 ns. A spatial filter was placed in the beam path soon after the laser to reduce diffraction patterns in the beam profile resulting from imperfections in the optics inside the laser and frequency doubling casings. The spatial filter used lenses in a telescope configuration with a small aperture tens of microns in diameter at the focal point, blocking most of the imperfections of a different focal point. The beam was then expanded to approximately 20 mm in diameter. For some experiments the laser beam was split into two beams before the chamber containing the x-pinch. One of the beams would then be optically delayed by 6 ns relative to the other beam prior to entering the chamber. The cases in which this was done provided two images from the same shot. After the chamber, the image was collected by focusing optics and projected onto a ST-402ME CCD camera manufactured by the Santa Barbara Instrument Group (SBIG) or a PULNiX developed TM-250. The cameras captured for the duration of the experiment, making the shutter time equal to the laser pulse width. The images were then downloaded to the computer using proprietary and LabVIEW software for the SBIG and PULNiX cameras respectively. ND filters were placed in the beam path after the chamber and each camera was fitted with narrow band filters centered on the laser wavelength to reduce the self emission seen from the x-pinch.

To determine the resolution of the system an image was taken of two wires that begin touching and slowly diverge from one another along the length of the image. Line outs were taken perpendicular to the path of divergence. The line out to first
exhibit two discernible peaks by the Rayleigh criterion was taken to be the point at which the wires were resolved. By this method the estimated resolution is <30 μm.

2.2.1 Shadowgraphy

A simple technique used to image plasma objects is shadowgraphy. This method of imaging plasmas provides useful information if there is a variation in the density of the plasma object that spans both above and below the critical density for the wavelength being used. For a body of plasma, the density at which electromagnetic radiation of a specific wavelength is refracted in a direction with a component opposed to the original direction of propagation is called the critical density, denoted

\[
n_c = \frac{\varepsilon_0 m_e e^2}{\omega^2} \quad (2.3)
\]

where \(\varepsilon_0\) is the permittivity of free space, \(m_e\) the mass of an electron, \(e\) the charge of an electron and \(\omega\) the angular frequency of the electromagnetic wave. For the 532 nm laser used in these experiments the critical density is \(4 \times 10^{21}\) electrons/cm\(^3\). In the image, the dark areas are where the plasma was equal to or greater than the critical density. Light passing through the plasma will be refracted by gradients in the index of refraction perpendicular to the direction of propagation of light. The curvature of the light ray can be described by

\[
\frac{\partial^2 x}{\partial z^2} = \frac{1}{n} \frac{\partial n}{\partial x} \quad (2.4)
\]

where \(z\) is the direction of propagation, and \(n\) is the index of refraction, which can be written as a function of electron density. The curvature of light from the \(z\) to the \(x\) direction is a function of the inverse of the index of refraction and the gradient of the
index of refraction in the direction of curvature. An analogous equation can be written for gradients in the $y$ direction. In this set of experiments light refracted outside the collecting optics will set an upper limit on the density seen in the image less than that of the critical density. For these experiments the upper limit is $\sim 10^{20}$ electrons·cm$^{-3}$.

### 2.2.2 Interferometry

An interferometer uses the principle of the interference of light from a coherent source, light and dark fringes are created by differences in path length. These experiments used a Mach-Zender interferometer [40]. This type of interferometer splits the light source, in this case a laser, into a reference and object beam. The object beam passes through the chamber where the plasma will be and the reference passes around the outside of the chamber. The reference and object beams are then recombined by optics on the other side of the chamber. A set of fringes will then be seen on the imaging plane. A diagram of this can be seen in Figure 2.8. When the object beam is passed through a medium, such as a body of electrons present in plasma, it will travel a different optical path than the reference beam. Changes in the

![Figure 2.8: Illustration of optical setup for simultaneous shawography and interferometry.](image)
optical path of one of the beams will change the fringe pattern at the imaging plane. The distance a fringe moves by is related to the path integral of the refractive index along the beam path. Since the refractive index for plasma is proportional to the electron number density, the fringe shift a function of the path integral of the electron density. For a 532 nm laser, the integral for electron density is

\[ \int n_e (cm^{-3}) dl = 4.2 \times 10^{17} f \]  \hspace{1cm} (2.5)

where \( dl \) is the path length and \( f \) is the fringe shift. So by comparing interferograms before and during a shot the fringe shift can converted into an electron areal density.

The range of densities that can been detected by the interferometer for a given wavelength of light used are the ability to resolve a shift in the fringe position, usually about ~1/4 of the fringe spacing, and the refraction of light outside the optical system as in shadowgraphy. For this system the minimum detectable areal density in the interferograms was \( \int n_e dl = 1 \times 10^{17} \text{ cm}^2 \). The upper limit is the same as that for shadowgraphy.

### 2.3 X-ray Detection

Time resolved x-ray emission was observed using filtered silicon PIN diodes. The diodes used were AXUV high speed photodiodes from International Radiation Detectors, each one 1 mm x 1 mm and used a 40 V bias voltage across the terminals. Only relative yields were gathered for comparison of 2 and 4 wire x-pinches. For carbon x-pinches, an initial qualitative investigation of emission was examined.

The energy collected by the diodes can be calculated by converting the voltage \( V \) seen by the oscilloscope to a current using the impedance \( R \) of the cable (50 \( \Omega \)) and
then to a power by the diode responsivity $\varepsilon$ (A/W). Integrating the power over a given time period then gives the energy collected.

$$E = \int \frac{V}{R} dt$$  \hspace{1cm} (2.6)

By placing different filters over the diodes it was possible to collect qualitative data about the difference in the energies ranges emitted from the x-pinch. In the experiments on 2 and 4 wire x-pinches the diodes were filtered with 7.5 $\mu$m nickel plus 300 $\mu$m polypropylene (diode A) and 15 $\mu$m tin (diode B) filters to facilitate a qualitative comparison of high and low energies in the 3.5 – 10 keV range. The transmission curves for the filters used are shown in Figure 2.9a. The filters used on the diodes in the carbon x-pinch experiments were 25 $\mu$m Be, 3 $\mu$m Cu and 3 $\mu$m Al. This gave preliminary information about the spectral range emitted by carbon. The transmission curves for these filters are in Figure 2.9b.

![Figure 2.9](image.png)

Figure 2.9: (a) Transmission curves of 7.5 $\mu$m nickel plus 300 $\mu$m polypropylene and 15 $\mu$m tin filters. (b) X-ray Transmission curves for 25 $\mu$m Be, 3 $\mu$m Cu, 2 and 3 $\mu$m Al.
2.4 Time Integrated Pinhole Cameras

The pinhole camera is a simple idea and one of the earliest methods of capturing an image on film. In a pinhole camera, light from an object travels through a pinhole and an inverted image of the object is projected onto a film. A diagram of this idea can be seen in Figure 2.10. The film used in this diagnostic was Kodak BioMax MS [41].

![Figure 2.10: Diagram of a pinhole camera.](image)

By changing the ratio of the distances from the object to the pinhole and pinhole to the film the magnification of the image is changed. In the experiments done here the pinholes used were tens of microns in diameter. For pinhole imaging there are both geometric and diffraction resolution limitations given by

\[ L_{geo} = d(1 + \frac{P}{q}) \]  \hspace{1cm} (2.7)

\[ L_{diff} = 1.22 \frac{\lambda}{d} \]  \hspace{1cm} (2.8)
where $d$ is the diameter of the pinhole, $p$ is the distance from the object to the pinhole, $q$ is the distance from the pinhole to the imaging plane and $\lambda_p$ is the photon wavelength. In the images presented the diffraction and geometric resolutions become comparable for photons $>100$ eV. For a pinhole diameter of 50 $\mu$m and a magnification of 3, the spatial resolution would be 70 $\mu$m.

Chapter 2, in part, is a reprint of the material as it appears in Physics of Plasma 2008. Bott, Simon C.; Haas, David; Eshaq, Yossof; Ueda, Utako; Collins, Gilbert; Beg, Farhat N., American Institute of Physics, 2008. Some content, in part, has been submitted for publication of the material as it may appear in IEEE Transactions on Plasma Science, 2009. Bott, Simon C.; Haas, David; Collins, Gilbert; Beg, Farhat N., IEEE 2009. The thesis author led these experiments and was the primary author of both these papers.
3 Low Density Coronal Plasma Evolution

3.1 Background

Much of the research on x-pinches has been carried out to characterize the implosion dynamics at the cross-point, in order to more fully understand the x-ray generation mechanics [17,22]. A substantial amount of work on the examination of x-pinch dynamics has been carried out with the use of x-ray backlighters, using x-pinches in parallel load configurations (using the x-ray burst of one to image the other) [17,25,42-44]. Radiography has also been used in conjunction with self-emission soft x-ray imaging to examine differences in the dynamics and output of two and four wire x-pinch configurations [45]. In addition several studies examined the effect of wire number on the emission yield from an x-pinch. Results showed that x-ray power in energies >3.5 keV were several times greater for four wire x-pinches [45-48], however, it is unclear in these studies whether differences in linear mass density or symmetry are responsible for the differences in x-ray output.

In this chapter the evolution of low density coronal plasma near the cross point has been studied following the radiation burst associated with pinching. All experiments in this chapter were carried out on the compact 80 kA pulser described in section 2.1.1. Two and four wire tungsten x-pinches were examined using shadowgraphy and interferometry, giving estimations of the rate of expansion of the gap and electron densities in and around the gap as it evolves. From this one may be able to determine the driving mechanics and conditions prior to and during pinching.
X-ray measurements using a silicon diode provide a comparison of relative yields.

The load configurations were two wire x-pinches made of 7.5 μm diameter tungsten wires and four wire x-pinches of 5 μm diameter tungsten wires. The different wire diameters were chosen with the purpose of keeping the mass per unit length of both load configurations similar. The two and four wire configurations had a linear mass density of 17 μg/cm and 15 μg/cm respectively. For this work an angle of 60° is maintained between the legs above and below the cross point.

3.2 Results

The post-yield gap development of a two wire x-pinch is depicted by the shadowgraphs from single shots in Figure 3.1. Note that in these figures the full numbers are relative to current start and the numbers in parentheses are relative to the first x-ray peak. Prior to pinching, the wire cores have expanded to over three times their original diameter and a micro z-pinch has begun to form at the cross point (Fig. 3.1a). In the next image (Fig. 3.1b), 5 ns after the first x-ray burst, plasma has been evacuated from the cross point region as evidenced by the transmission of light through the center. From this point on, the ends of the gap continuously move away from each other. In the same image, ablation flares can be seen feeding plasma from the legs to the center axis where a jet-like structure is formed above and below the cross-point and propagates axially outwards. Instead of plasma continuing to evacuate from the central region, figures 3.1c and 3.1d show that plasma not only remains in the gap, but that it has specific structure. A dark column, indicating higher density than the surrounding plasma, can be seen connecting the ends of the gap in figures 3.1c and 3.1d which are respectively 10 ns and 16ns after the formation of the micro- z-pinch.
Figure 3.1: (a)-(e) Shadowgraph images of 2 wire 7.5 μm W x-pinches with times relative to the start of the current given in nanoseconds. Times relative to the first x-ray peak are in parenthesis.

Figure 3.2: (a)-(e) Shadowgraph images of 4 wire 5 μm W x-pinches with times relative to the start of the current given in nanoseconds. Times relative to the first x-ray peak are in parenthesis.

A complementary shadowgraphy time series from single shots of 4-wire x-pinches is shown in Figure 3.2. The 4-wire x-pinch appears to go through the same development stages as the 2-wire case. Each stage however, is 5 – 8 ns earlier in the 4-wire case, relative to the current. In Figure 3.2b the image is co-incident with the first x-ray peak. One might expect to see remnants of the micro z-pinch here, but knowing that the plasma dynamics evolve quickly close to x-ray burst [22], the uncertainty in the timing of the x-ray pulse (±1 ns) and the laser pulse length (5 ns), it is unlikely that the micro z-pinch will be resolved. Figure 3.2c shows that plasma has re-formed in the gap 17 ns after the first x-ray burst to a density greater than the previous image, and again a column structure is observed. This stage in the gap development for 4-wires
Figure 3.3: Diagram of gap measurement. Horizontal lines indicate position of the ends of the gap. The “x” in the center of the image indicates the location where density measurements were taken in interferograms.

correlates closely to Figure 3.1d in the 2-wire case, and both systems show an apparent second plasma compression following the initial micro z-pinch disruption. Late in time the plasma appears to have freely expanded to a disordered distribution about the gap (Fig 3.2d and 3.2e).

The gap size was determined by drawing lines along the bottom and top of the gap and taking the distance between the lines as the size of the gap. The ends of the gap are defined as the points at the ends of the wire legs where the density is beyond the critical density for the laser. An example of this is shown in Figure 3.3. Plots of the variation of the gap size with time for two and four wire experiments are shown in Figure 3.4. The errors in the gap size are one standard deviation and the errors in the timing are the pulse length of the laser. A linear fit has been applied to both with the slope being an estimate of the expansion velocity of the gap, which was a previously undetermined quantity for x-pinches. Dividing this number by two gives an approximation of how fast the dense plasma structure moves away from the central region where pinching occurred.
This expansion velocity is $1.4 \pm 0.3 \times 10^6$ cm/s and $1.1 \pm 0.4 \times 10^6$ cm/s for two and four wire x-pinches, respectively, the errors in velocity being derived from the linear fit applied to the data. It should also be noted that plasma along the vertical axis, that divides the x-pinch in half, moves away from the center at a different rate than that of what is defined as the ends of the gap. This is perhaps related to the curved shocks observed on radiographic images by Shelkovenko et al [17].

A temporal evolution of the areal electron density inside the gap of a 2-wire x-pinch was extracted from a time series of interferograms from single shots, examples of which can be seen in Figure 3.5. The early stage of the micro z-pinch in Fig. 3.5a is too dense for fringes to be seen through it, denoting densities $>10^{20}$ electrons/cm$^3$. 

Figure 3.4: Dependence of the gap size on time for (a) 2 wire x-pinches made of 7.5 μm W and (b) 4 wire x-pinches made of 5 μm W.
Figure 3.5: (a)-(e) Interferograms of 2 wire 7.5 μm W x-pinches with times relative to the start of the current given in nanoseconds. Times relative to the first x-ray peak are in parenthesis.

Figure 3.6: (a)-(e) Interferograms images of 4 wire 5 μm W x-pinches with times relative to the start of the current given in nanoseconds. Times relative to the first x-ray peak are in parenthesis.

range, as would be expected. In Fig. 3.5b a small column approximately 150 μm in length is connecting the ends of the gap; this is the micro z-pinch 2 ns before the time of pinching. Though the density in this column is greater than the interferogram sensitivity, fringes can be followed through the gap because diameter of the column is below the resolution of the optical system. Images at times subsequent to the initial micro z-pinch disruption are presented in Figure 3.5c to 3.5e, and all show that at least one fringe can be seen continuously into the center of the gap. The interferograms of four wire x-pinches are shown in Figure 3.6, and were taken simultaneously with the shadowgraphs in Figure 3.2. These interferograms show the same features as described above, and the fringe spacing was decreased to reduce sensitivity to the large density gradients seen in the two wire experiments. On most shots, fringes could be followed all the way into the gap from far outside. At large radii, comparison of the
Figure 3.7: (a) Dependence of areal electron density on time for 2 wire x-pinches made of 7.5 μm W. Triangular markers at 49 and 54 ns indicate shots that had only one discernable x-ray peak. (b) Dependence of areal electron density on time for 4 wire x-pinches made of 5 μm W.

A shot image to a pre-shot image denoted no detectable plasma density in this region. Areal electron densities are then determined by tracing unbroken fringes from large radii into the center of the gap. A small “x” has been placed in the center of Figure 3.3 to illustrate the position where the fringe shift was measured. Inputting the fringe shift into equation 2.5, an areal electron density can be determined for each interferogram.

Interferograms here and those reported on by Mitchell et al. [23] showed that up to pinching, the magnetic field is very efficient at sweeping plasma to the z axis. Because the micro z-pinch column was beyond the resolution capabilities of the
system, measurements of the areal electron were taken after the time of pinching, as determined by the time of x-ray emission. Plots of the areal electron density in the center of the gap versus time for both 2-wire and 4-wire x-pinches are shown in Figure 3.7 along with 4th order polynomial trend lines to help discern behavior. Both plots show that after pinching the areal density is initially low, and then increases to \( \sim 10^{18} \) electrons/cm\(^2\), which is still several orders of magnitude below solid densities determined for the initial z-pinch in previous work [17,22]. This change in density seems too ordered and dramatic to originate from random flux caused by thermal motion and expansion. The plot of the gap density for two wire x-pinches (Figure 3.7a) has two data points at 49 and 54 ns indicated by triangular markers that are far below the densities at similar times. With such a large difference in the magnitude of areal electron density, these are likely to be related to differences in dynamic processes, and this is discussed in the next section.

From the interferograms it was also possible to construct radial electron density profiles. With this type of measurement an idea of how the plasma expands radially in time, information previously unexplored. By following a fringe from the gap region radially outward and measuring the fringe shift every 100 µm, it was possible to plot the electron density as a function of distance from the system axis. A plot of radial position and areal electron density from a sequence of four interferograms of two wire x-pinches are shown in Figure 3.8. Taking the radial position of the half maximum density and the time of each image it is possible imply a radial expansion rate of the plasma. Order of magnitude estimates give an expansion rate of \( 10^6 \) cm/s for both two and four wire cases. The interferograms used for this
analysis were taken after maximum current when magnetic compression would be low and the plasma could freely expand. If we assume that the expansion velocity measured here is approximately the local sound speed, we can estimate a value for $ZT_e$ using the measured density. This value is ~120 eV. If we take an average ionization state for W of 8 this gives a temperature of ~15 eV. This measurement is taken after the second compression, i.e. that of the low density corona, and so may provide information regarding this event. Given this measurement was taken several nanoseconds after the second compression and that for a high z material substantial cooling is likely to have occurred, the value of ~15 eV represents a lower limit on the temperature of the re-compression pinch.

Temporally resolved x-ray information collected showed that the average timing of intense x-ray emission associated with the initial micro z-pincha was 34±1.5 ns and 40±1.0 ns after the beginning of the current for four and two wire pinches,
Figure 3.9: Time integrated pinhole images of 2 wire 7.5 μm W x-pinches with diode traces from the same shot. (a) Only one peak in the diode trace and (b) two peaks in the diode trace.

respectively. Since the change in load inductance will be very small, this difference in timing is most likely due to a small difference in the linear mass density of the two configurations. It should also be noted that both are well before peak current at 50 ns. Over the series of data, a discernible second peak in the x-ray signal occurred about 80% of the time, and on average about 16 ns after the first peak for both configurations. This is around the time when plasma was observed to re-compress into a column formation in the gap (Fig. 3.1d and 3.2c). Two time integrated pinhole images of two wire x-pinches are shown in Figure 3.9 with diode traces for the same
shot. In the traces diode A was filtered with 7.5 μm Ni and 300 μm polypropylene and diode B was filtered with 15 μm Sn. Figure 3.9 shows single peaked x-ray emission profiles resulted in the observation of a single hotspot, and that two hot spots could be resolved in cases when two x-ray peaks were observed. The two hot spots in Fig. 3.9b are approximately 100 μm apart.

The four wire x-pinches gave total yields >3 keV of about 1.5 times greater than that of two wires. When comparing individual peaks, on average the two wire x-pinches have first peaks 1.2 times the power radiated from four wires, with comparable full width half maximums (FWHM). Comparing the yield of first and second peaks, the first peak from two wire x-pinches were 1.3 times that of there second peak. The four wire x-pinch’s first peak yield was two thirds the energy of its second peak, though it should be noted that the FWHM of the four wire second peak averaged 6 ns longer than the first peak.

3.3 Discussion

In previous studies it has been shown that multiple pinches do occur in x-pinches [32], but it was also shown that these multiple pinches are typically within a nanosecond of each other, most likely being formed by bifurcation of the micro z-pinch into multiple pinch regions [33]. However, the second x-ray peaks seen in the experiments described here are 16 ns after the first, on average, which is long after the initial micro z-pinch has disassembled. If electron beams accelerated by the potential difference across the expanding mini-diode gap generated these second peaks, the peaks would be expected to have broader FWHM and stronger emission at higher energies [49]. This is not observed in these experiments. The time of this second x-ray
emission is near the peak current delivered through the machine, which means that the current has continued to rise for more than 10 ns after the first x-ray pulse. It may be possible that the rising current in the coronal plasma about the initial gap reforms the plasma on axis by means of magnetic compression. Indeed, Figures 3.1c and 3.1d, taken near peak current, show that a column of plasma has formed on axis with density exceeding that of the surroundings. The measurements of the electron areal density inside the gap in both two and four wire experiments show that the density is less than $2 \times 10^{17} \text{ cm}^{-2}$ after the initial x-ray burst occurs and then rises, reaching a peak, $>7 \times 10^{17} \text{ cm}^{-2}$, around the time of maximum current. If the plasma is dispersed after pinching to such a degree that the magnetic field cannot re-compress it, then the x-ray signal would likely only have a single peak. There were two instances where density information at the same time relative to current start was obtained for shots which demonstrated single and double x-ray peak structures. In the gap density plot of two wire pinches (Figure 3.7a) there are two data points at both 49 ns and 54 ns. In each case the lower density value belonging to an x-pinch that had only one x-ray peak. For these shots, the system may have been unable to re-compress plasma back into the gap, and therefore did not have a sufficiently high density to produce a significant second x-ray peak. If the initial linear mass density of the wires is increased slightly so that the initial x-ray burst is near in time to the maximum current it should reduce the possibility of a second pinching and hence the multiple well separated peaks observed in these experiments. Applying a linear relationship between the linear mass of the load and the timing of the x-ray burst relative to the current, based on work at Cornell
University [43,44,48], then the linear mass for the pulser used in these experiments should be increased to about 21 μg/cm.

Presuming that a second compression is occurring, it may be uncertain that the evolution of the gap will be the same as that of a case where there is only one compression near the time of maximum current. Certainly the radial density profile will differ in time after the first pinch. However, the axial expansion of the gap is likely to be independent of second pinching because the magnetic pressure associated with pinching is only in the radial direction. This is reflected in the approximately linear relationship of gap size and time in Figure 3.4. Should the mechanism driving the gap open be a point explosion originating from the smallest pinching point in the neck of the micro z-pinch, a snowplow model [50] would suggest that the velocity of expansion would reduce with time, as the plasma is decelerated by collision with the plasma above and below the gap because there is no force continuing to drive it axially. Even if the second pinching provided a second point explosion, the gap size late in time (>60 ns) would show some deceleration in the expansion velocity. Figure 3.4 shows the gap expanding at a near constant rate late in time, suggesting other mechanisms are involved in the gap development. A possible driving force in the gap expansion is a \( \mathbf{J} \times \mathbf{B} \) force resulting from the current traveling radially inward from the legs to the micro z-pinch. Measurements of the current from the Rogowski probe shows that current continues to flow after pinching occurs making it feasible that this force can act for some duration after pinching. The linear expansion of the gap size in time seen in Figure 3.4 would suggest that it is the \( \mathbf{J} \times \mathbf{B} \) force driving the gap open. A more conclusive result would require building an accurate snowplow model of the
system. While the use of the snowplow model for systems such as wire arrays is possible because of the relatively simple density profile determined by ablation models [51], the complex mass distribution of plasma at the ends of the gap in x-pinches and non-linear processes make developing an accurate model difficult and will require further studies.

Chapter 3, in part, is a reprint of the material as it appears in Physics of Plasma 2008. Bott, Simon C.; Haas, David; Eshaq, Yossof; Ueda, Utako; Collins, Gilbert; Beg, Farhat N., American Institute of Physics, 2008. The thesis author led these experiments and was the primary author of this paper.
4 Development of Low Z X-pinches for Radiography

4.1 Background

When an x-pinch not previously investigated is being developed it is necessary to examine how the system compares to previously studied x-pinches. Significant characteristics are the evolution dynamics and the x-ray yield. The spatial, temporal and spectral characteristics of the x-ray source are of particular importance when assessing its application to radiography.

All of the experiments in this chapter used loads made of two wires of 30 μm carbon fiber. All fired in the LTD generator GenASIS. Laser imaging methods such as the shadowgraphy described in 2.2.1 provide excellent qualitative information on the evolution of the system. By taking images at different times relative to the current pulse an idea of how the low density coronal plasma changes in time, assuming minimal shot to shot variability.

In the carbon x-pinch experiments the radiation source was tested for flux and source size by taking radiographic images of a copper mesh (250 μm wire, 380 μm cells) and an array of wires of various diameter (30 μm, 25 μm, 15 μm, 10 μm, 7.5 μm, 5 μm). The x-pinch radiation was filtered with 2 μm aluminum and images recorded on Kodak BioMax MS film [41]. The mesh was placed 11 cm from the x-pinch and 3.2 cm from the film, providing a magnification of 1.3. The wire array was 12 cm
from the x-pinch and 17.5 cm from the film, giving a magnification of about 2.5. A schematic of the setup is given in Figure 4.1.

The time resolved x-ray characteristics observed by silicon PIN diodes can give information on the time at which the x-ray pulse begins, the duration and whether there are multiple peaks. With use of filtering on the diodes, information can be collected on the energy radiated from the pinch and how different energy ranges behave during the systems evolution.

4.2 Results and Discussion

Figure 2.7 in Chapter 2 shows the drive current for both a short circuit and a typical carbon x-pinch load on the LTD generator called GenASIS. Typical load current was 140-180 kA with a rise-time of 150 ns. Note that the load current trace has a small pulse approximately 30 ns in duration before the main pulse. This small pulse is most likely related to the voltage build up and breakdown across the wire, and is more pronounced than in metallic loads since carbon is an insulator. The generator has a relatively low impedance generator (≈0.3 Ω) and this means that a change in the load
inductance has measurable effect on the drive current. For each x-pinch load, a dip in
the current trace is observed shortly after peak current, and this is likely to be due to
the rapid change in inductance as the x-pinch cross point is compressed to small
radius.

Shadowgraphs allowed an examination of the carbon x-pinch dynamics. A
selected sequence of images that show different stages before and after maximum
current can be found in Figure 4.2, the time below each image refers to the amount of
time after the beginning of the current the image was taken. The first image in the
sequence (Fig. 4.2a) was taken at half the current rise. At this point the wires cores
have expanded to approximately double in width and small flaring structure is
developing along the legs. In the region where the two wires cross, a small vertical
column has begun to form which denotes the beginning of the high compression phase
to form the micro z-pinch. In all the images there is a high degree of top to bottom
asymmetry in the plasma structure on the central vertical axis. The plasma on the
anode side of the crossing point reaches further towards the electrode and contains
greater mass. The height to width ratio is greater than that of most jet like structures
seen in x-pinches such as those described by Mitchell et al. [23], most likely due to the
low radiative loss rate for carbon relative to typical x-pinch loads. Figure 4.2b shows

Figure 4.2: (a)-(e) Shadowgraph images of 2 wire 30 μm C x-pinches with times relative to the start of the current drive.
the continued expansion of the legs and growth of instabilities in the low density coronal plasma along their length. At cross point, a micro z-pinch has formed that is several hundreds of microns in length.

In Figure 4.2c, which is near peak current, a gap has appeared at the cross point, suggesting that the high compression phase which produces the radiative hotspot has already occurred. The coronal plasma in Figure 4.2d has become highly dominated by instabilities and plasma appears to have re-entered the cross point area. By the time of Figure 4.2e plasma cleared far from the cross point region. These dynamics consistent with those observed for metallic loads (e.g. [20,37,52]) and the expansion of the ‘legs’, compression of the plasma at the cross-point and formation and expansion of a mini-diode gap are well recognized phases of an x-pinch.

For radiographic imaging a 2 μm aluminum filter was employed to cutoff energies below 500 eV. Initial testing used a fine copper mesh at a magnification of 1.3. This was done to examine whether at typical source-to-image plane distances, often greater than a few centimeters, sufficient flux was emitted to enable good contrast imaging. An example radiograph is given in Figure 4.3. This image

![Image](image_url)

Figure 4.3: Radiographic image(hv > 500 eV) of a copper mesh (250 μm wire, 380 μm cells) at a magnification of 1.3.
indicated that good contrast radiography is possible, at least at the system distances used here. In addition the clear imaging of the 250 μm wires suggests that the image is generated either by a single source with a size less than ~200 μm, or by smaller sources which are closely separated.

In order to examine the limits of the spatial resolution, radiographs of a series of fine wires were taken to provide a simple estimate of the resolving power of the hotspot produced. The wire diameters were 5 μm, 7.5 μm and 10 μm W, 15 μm Mo, 25 μm Al and 30 μm C arranged in descending order from left to right as shown in Figure 4.4a. Figure 4.4b shows a radiograph of this set-up using a 2 μm aluminum filter.

The radiograph clearly shows that both the 30 μm and the 25 μm wire can be imaged using a carbon x-pinch at a magnification of 2.5. Figure 4.4c shows a line out taken horizontally along the radiograph showing both these wires, and also the 15 μm wire is below the resolution capability of the source.

The approach of radiographing wires of various diameters does not place exact limits on the source size, and is certainly not as complete as the determination of this from diffraction profiles in [53]. However, it does demonstrate that a suitably small source does indeed occur in carbon x-pinches and provides spatial resolution of the order of a few tens of microns. It is interesting to note that this limit is in the same range observed for low z materials from vacuum spark gap investigations [54].

For some applications where high time resolution is not critical, such as the off-line characterization of Inertial Confinement Fusion capsules [55], a radiography
Figure 4.4: (a) Illustration of linear wire array with wires of varying diameter. (b) Radiographic image of a wire array at a magnification of 2.5. The film was filtered with 2 μm Al. (c) Line out taken horizontally along radiograph.

source may be considered acceptable, provided exposure is less than a few microseconds (depending on the radiation window utilized) However, much of the application of x-pinch radiography is in the analysis of exploding wire systems, including both x-pinches and wire array z-pinches, and for this temporal resolution at least of the order of a few ns is required.

To investigate this, time-resolved x-ray emission was recorded on the filtered Si diodes. The radiation recorded on the softest channel (Al, $h\nu > 500$ eV) has a peak prior to the inductive dip in the current for the shot in Figure 4.5. At the time of pinching, indicated by the dip in current, emission can last for a few hundred nanoseconds for this energy range. The signal was cut off by the measurement.
device at approximately 1.6 V. The beryllium filter (hν > 1keV), recorded two peaks in the radiation output before the dip and a large well define peak at the time of pinching, which is also cut off.

The first peaks occur on the current rise, and the large single peak coincides with the inductive dip and with the large broad emission of lower energy Al filtered diode. Peaks during the current rise are most likely due to the load being under massed for the current, or the result of hotspot formation along the x-pinch ‘legs’, similar to single wire experiments, with pinching at the cross point occurring close to current maximum. The peak at pinching had a full width half maximum (FWHM) in the range of 15-20 ns. The Al channel shows greater emission than the Be channel at all points, and no emission was observed with harder filters transmitting energies >3 keV. This indicates that emission is likely to be from a thermal plasma source, the x-pinch hot-
spot, and not as a result of other mechanisms, such as an electron beam impacting the electrodes. This is supported by the fact that the FWHM of the peaks is relatively short, whereas electron beam sources generally last for a greater period, and would be expected to be observed in harder emission channels.

Chapter 4, in part, has been submitted for publication of the material as it may appear in IEEE Transactions on Plasma Science, 2009. Bott, Simon C.; Haas, David; Collins, Gilbert; Beg, Farhat N., IEEE 2009. The thesis author led these experiments and was the primary author of this paper.
5 Summary

This work studied optical probing methods and new sources for examining the dynamics of the low density coronal plasma seen in x-pinches. The optical probing methods used were to examine the coronal plasma evolution close to the wire cross-point for two and four wire tungsten x-pinches. These methods lead to information about the dynamics previously undetermined. The early development including wire expansion and formation of a micro z-pinch were observed to be the same as in previous studies. High magnification revealed differences in complexity of the structure of the low density plasma in the gap, following the first x-ray yield, and allowed a quantitative analysis of its evolution.

Shadowgraphs gave an estimation of the velocity at which the gap opened along the vertical axis to be $1.4\pm0.3\times10^6$ cm/s and $1.1\pm0.3\times10^6$ cm/s for two and four wire x-pinches, respectively. This velocity was linear in time which implies a force drives the gap open for tens of nanoseconds, most likely due to a radial current giving rise to an axial $\mathbf{J}\times\mathbf{B}$. Measurements of gap velocity from radiographs from Cornell University [22] match closely (within errors bars) to those derived here from shadowgraphs.

Interferograms allowed recovery of both the evolution of radial density profiles of the coronal plasma after gap formation, and the change of electron density at the gap center as a function of time. Both two and four wire cases showed a rise in the density of plasma at the center of the gap late in time after pinching occurred. This
increase in density, also visible as a column at the axis on shadowgraphs, reached
maximum density near the maximum of the current drive. X-ray signals revealed that
a majority of shots showed two peaks, the first being 10-16 ns before maximum
current and the second near maximum. Even though the plasma expands after
compression of the micro z-pinch, at the time indicated by the x-ray signals there is
sufficient energy remaining in the rising current to re-compress the plasma, forming a
second plasma column and it is this which is observed by interferometry
measurements. Measurements of the plasma expansion after the second compression
event infer a lower limit of 15 eV on the temperature of this object.

Re-compression appears to result from early pinching relative to maximum
current through the load. Optimizing the mass per unit length of the load should lead
to the first pinching occurring at maximum current and yield greater x-ray power with
reduced number of peaks.

Use of laser imaging on the first reported on carbon x-pinches demonstrated
that these x-pinches evolve in a similar manner to those constructed from high Z
metallic wires typically used, such as tungsten. Radiographs of a fine Cu mesh and a
range of fine wires demonstrated that the hotspot formed in carbon x-pinches is
sufficiently small to resolve a 25 μm wire at a magnification of 2.5 with x-rays
>500eV, but that a 15μm wire images at the same time cannot be distinguished. The
diode signals for the same energy cutoff showed that emission lasts for hundreds of
nanoseconds, and this is too long for use as a radiographic source for imaging dynamic
objects. Diode signals recording energies >1 keV, however, show promise to give
some time resolution for use on plasma experiments. These typically showed 2 peaks,
one of which has a FWHM of ~20 ns. Radiographic studies will half to be done to examine if flux in this energy range will still be sufficient for imaging. Subsequent studies will examine if it is possible to improve performance by varying the mass of the x-pinch to change the pinch time relative to the peak current or by further investigating suitable filter arrangements.

Chapter 5, in part, is a reprint of the material as it appears in Physics of Plasma 2008. Bott, Simon C.; Haas, David; Eshaq, Yossof; Ueda, Utako; Collins, Gilbert; Beg, Farhat N., American Institute of Physics, 2008. Some content, in part, has been submitted for publication of the material as it may appear in IEEE Transactions on Plasma Science, 2009. Bott, Simon C.; Haas, David; Collins, Gilbert; Beg, Farhat N., IEEE 2009. The thesis author led these experiments and was the primary author of both these papers.
References


