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Magnetic Fusion Energy

1989

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Foreword

Research on controlled thermonuclear reactions (CTR) at the Lawrence Berkeley Laboratory began in the early 1950s. At the time, the effort was classified and operated under the code name of Project Sherwood; the work sites, Buildings 16 and 52, were protected by a separate fence with a guard at the gate. The work concentrated on pinch discharges and other aspects of heating and confinement of plasmas in magnetic fields.

Late in 1958, in time for the Second International Conference on Peaceful Uses of Atomic Energy, held in Geneva, declassification was completed and the fence came down. Soon thereafter, the scope of the program was expanded to include more-basic studies of plasma physics, and graduate students from the University of California at Berkeley were admitted to do their thesis research in this field. Significant early achievements included the discovery of the resistive tearing instability (magnetic-field-line reconnection) in magnetized plasmas and the first demonstration of magnetohydrodynamic (Alfvén) waves in a highly ionized laboratory plasma. In the mid-1960s the concept of inertial-confinement fusion was advanced, so our group’s name was changed from “CTR” to “MFE.”

In 1971, the MFE Group took on the challenge of developing sources, accelerators, and injectors of powerful, energetic neutral beams of hydrogen and deuterium atoms for heating and fueling magnetically confined thermonuclear plasmas. These devices were initially applied to the latest mirror-fusion machine at the Lawrence Livermore National Laboratory. The effort required innovations in ion sources and beam-forming systems, and it depended heavily on computer-aided optimization, which was then something of a novelty. The highly successful program enabled the mirror facility to set a new plasma temperature record of about 150,000,000 K, corresponding to thermal motion of particles in the plasma at 13 keV.

Thereafter, many fusion experiments in the U.S. and abroad adopted neutral-beam injection for supplemental heating. The LBL work culminated in the development and transfer to industry of the Common Long-Pulse Source. The CLPS, which can supply particles at energies as high as 120 keV in pulses of up to 30 s, is now in use at both major U.S. magnetic-fusion experiments: the Tokamak Fusion Test Reactor (TFTR) in Princeton, NJ and the Doublet D-IIID at GA Technologies in La Jolla, CA.

At the TFTR, researchers from the Princeton Plasma Physics Laboratory have demonstrated that injected neutral beams can maintain the toroidal current in the presence of resistive dissipation, enabling steady-state operation of tokamaks. This has led many to think of neutral beams primarily as a means of driving the confining toroidal current noninductively, but neutral beams will also be important for heating in the next generation of tokamaks. Furthermore, those future tokamaks will need higher injection energies to ensure adequate penetration of their larger plasmas. Accordingly, we have turned to negative-ion-based injection systems, focusing our efforts on the development of H+ and D+ ion sources and the design, construction, and testing of higher-energy accelerators.

This report is an excerpt from the Accelerator and Fusion Research Division’s 1989 Summary of Activities. It contains brief descriptions of the year’s major research and development activities in the Magnetic Fusion Energy Group. Until 1982, the funding for the MFE Group came in its entirety from the Office of Fusion Energy, Office of Energy Research, U.S.
Department of Energy; since that time, an increasing fraction of the support has been coming from other sources, most notably the Department of Defense. However, the material presented here is organized according to subject matter, not according to the source of funding.

Wulf Kunkel
Magnetic Fusion Energy group leader
May 1, 1990
MAGNETIC FUSION ENERGY

HEATING A PLASMA TO THERMONUCLEAR TEMPERATURES is one of the many significant challenges in fusion-energy research. In all of today's major magnetic-confinement fusion experiments, the plasma is heated largely by neutral beams of hydrogen isotopes; the primary focus of the MFE Group at LBL is development of the neutral-beam injector systems. The group's 19 years of work began with the invention of novel multiampere positive-ion sources and of improved, computer-optimized acceleration systems. The most prominent achievement thus far has been the design, development, and transfer to industry of the Common Long-Pulse Source (CLPS), which is used in the Tokamak Fusion Test Reactor at the Princeton Plasma Physics Laboratory and the DIII-D tokamak at General Atomics, the principal magnetic fusion experiments now running in the U.S.

The CLPS has been highly successful, but its positive-ion approach has a fundamental energy limit around a few hundred keV. In the next generation of tokamaks, larger plasmas will require higher injection energies—around 1 MeV, as opposed to the 120-keV performance of the CLPS—to ensure adequate penetration. One can start instead with negative ions, accelerating them to the necessary energies and subsequently neutralizing them by the simple process of detaching the extra electron. In contrast to systems based on positive ions, the neutral-particle yield does not decrease with increasing energy. However, it is difficult to produce large quantities of negative ions. Efforts to develop suitable sources of negative hydrogen ions at the ampere or multiampere level are now underway at several laboratories.
Design, construction, and testing of prototype accelerator systems must go hand in hand with development of a negative-ion source, so a substantial effort has been devoted to accelerator development as well. Since 1988 the major portion of our Department of Energy-funded work has been directed toward the ITER Project, the International Thermonuclear Experimental Reactor. As a major initiative in this effort, we propose to design a test facility capable of accommodating a 2-MV negative-ion system at currents of 1 A or better. (After our design and testing efforts, production of the full complement of neutral-beam systems would presumably be handled by industry on behalf of the user, as with the CLPS.)

Our expertise in ion-source and accelerator development is not limited to fusion research; activities have been diversified considerably during the past few years. Energetic negative hydrogen ions and neutral-beam systems are of interest for the Strategic Defense Initiative, for example. Sources and accelerators for various ion species have industrial uses such as ion implantation for semiconductor processing and metal surface hardening. And, we have maintained an academic component of our program, centering on advanced plasma theory.

In ITER (Figure 2-1), a total of about 75 MW of neutral deuterium beams will be injected to heat the plasma and to drive the toroidal current during steady-state operation (see sidebar). The energy required, 1.3 MeV at maximum, is an order of magnitude greater than that of the CLPS. Beam steering is another necessary feature. One of the most challenging requirements is pulse length; one of the key features of the ITER experimental program is eventual steady-state operation for as long as two weeks. To meet these needs, we are proposing a neutral-beam injection system based on negative-ion sources and our constant-current, variable-voltage (CCVV) accelerator. A basic design is in place and will be refined in the course of extensive, ongoing interaction with our fellow participants in the ITER Conceptual Design Activity.

The proposed ITER neutral-beam injection (NBI) system is shown in Figure 2-2. The $D^+$ beam is extracted from a negative-ion source and its energy is boosted by a CCVV accelerator. This energetic beam of negative ions is converted into a beam of neutral atoms by detaching the extra electron from most of the ions; the detached electrons and remaining ions are swept away electrostatically, leaving a 1.3-MeV $D^0$ beam that, if it were charged, would have a current of 7.7 A. As implied by the name of the CCVV accelerator, the voltage, and thus the beam energy, can be varied without loss of current or beam quality. (The energy must be kept low at startup to prevent "shine-through," then ramped up as the plasma density increases.) The beam can also be steered to tailor the spatial profile of the plasma current and to control power deposition in the center of a burning plasma. The floor space required is always an issue in designing a tokamak, as complete NBI systems, including the arrays of cryopanels that maintain the vacuum, tend to be quite large. To minimize the "footprint" of the ITER systems, the NBI modules are stacked three high.

* Nineteen-ninety is the third and final year of the Conceptual Design Activity. The next step, given continued support by the four ITER parties (the US, the European Communities, the USSR, and Japan), would be an Engineering Design Activity that would advance to a reasonable starting point for fabrication and construction.
Figure 2-1. The proposed International Thermonuclear Experimental Reactor is an ambitious scientific and technological step toward a demonstration power reactor. LBL's role within the U.S. effort involves the design and development of neutral-beam systems to heat the plasma and drive the toroidal current. The artists' renderings show approximately how ITER's "core" compares in size to that of the Tokamak Fusion Test Reactor at the Princeton Plasma Physics Laboratory, typical of today's larger experiments. (After PPPL and LLNL artwork.)

Figure 2-2. The ITER conceptual design calls for three stacks of three 1.3-MeV neutral-beam injectors providing a total of 75 MW. Each injector can provide 10 MW, so ITER can continue to operate if one of them is down for repair or modification. The performance specifications are ambitious, especially in terms of pulse length—two weeks, as opposed to a few tens of seconds for today's NBI systems. (Overall layout diagram courtesy of LBL and Grumman.)
Development of an NBI system for ITER will require a new test stand considerably larger than the Neutral Beam Engineering Test Facility where we developed the CLPS. The requirements include shielding from neutrons generated in the beam dump and from x-rays generated by high-energy electrons. There must also be adequate clearance around the high-voltage supply. We propose to build a Test Facility for Accelerators (TFA) at LBL and demonstrate a 1.3-MV, 1-A negative-ion accelerator system as a proof of principle. The facility's preliminary design is shown in Figure 2-3. This facility could be readily expanded for testing of a complete beamline, scaled down to about 2 A (about one-fourth of the delivered neutral-beam current of an ITER beamline) but at the full 1.3-MeV energy.

The proposed location for the TFA is adjacent to existing MFE Group facilities in Building 5 at LBL. An LBL location offers advantages for the multinational ITER collaboration, including accessibility to international airports and absence of classification and citizenship restrictions.

Test Facility Initiative

Figure 2-3. An ITER NBI test facility at LBL could be located adjacent to the current MFE Group buildings. The conceptual design, still being refined, could be upgraded for 2-MV, multiampere operation for ongoing usefulness. Intended initially for accelerator testing, it could be readily expanded to accommodate testing of a scaled-down ITER NBI beamline (2.5 MW of D⁹ at 1.3 MeV).
Neutral Beams and Current Drive

In addition to their primary role of heating the plasma, injected neutral beams help confine and control it. In a tokamak, the plasma is confined by the combination of two principal magnetic fields, as shown in simplified form by Figure 2-4: a toroidal field in the plane of the torus and a poloidal field wrapped around it.

A plasma is very hot, i.e., the particles move at high speeds. In the absence of a magnetic field, they move randomly; the toroidal field guides them circumferentially through the torus, spiraling along the lines of force. This field is generated by external coils. Under the influence of the toroidal field alone, the plasma would move toward the outer wall, so a poloidal field is added. The poloidal field is the result of a very large electrical current—about 20 MA in ITER—coursing through the highly conductive plasma.

This current in the plasma is initiated inductively by the poloidal-field coils; they may be thought of as the primary of a transformer in which the plasma is the secondary. During the initial physics phase of operation, when ITER will be used for “shots” less than 200 seconds long, the plasma current can be driven by the coils alone. However, the subsequent technology-experiment phase will involve sustained burns of up to two weeks; this is far beyond the ability of a transformer system to store and deliver power, so supplemental noninductive drive will be required. In these longer experiments, the bulk of the current will be driven by the neutral beams, which primarily affect the center of the plasma. Additionally, up to 45 MW of rf power will drive the current around the edge of the plasma.

Figure 2-4. This highly simplified and generalized sketch of the tokamak concept shows the two principal magnetic fields—toroidal and poloidal—that work together to confine and stabilize the plasma.

Ions in plasma spiral along lines of force

Neutral beams help drive the toroidal current

Toroidal current sets up a poloidal magnetic field

Field coils encircling torus set up a toroidal magnetic field

Figure 2-4. This highly simplified and generalized sketch of the tokamak concept shows the two principal magnetic fields—toroidal and poloidal—that work together to confine and stabilize the plasma.
It is not yet clear which of several negative-ion source technologies will be best suited to the high-current, long-pulse needs of future NBI systems. One of our earliest efforts, a “surface-conversion” source in which hydrogen ions were produced on the surface of a cesium-coated molybdenum electrode in a hydrogen plasma, achieved the first steady-state yield of more than an ampere of H⁺. However, the partial cesium coating—required in order to optimize the ion yield—had the undesirable side effect of contaminating the accelerator downstream.

Work continues on surface-conversion sources, using cesium and less-volatile coating materials such as barium and magnesium. Another strong component of our ion-source program focuses on “volume-production” sources that produce ions throughout a volume of gas rather than on the surface of an electrode. The main goal is to increase the steady-state current capability of these sources. In the meantime, we have resumed development of a promising rf-driven surface-conversion scheme; it could eventually supplant both the volume-production and the thermionic surface-conversion sources for very-long-pulse operation.

In volume-production sources, gas-phase reactions, as opposed to electron capture on a metal surface, are thought to play a major role in forming H⁺ ions. (There is evidence that surface processes at the discharge-chamber walls are also significant.) However, there is serious concern, that obtaining the needed production rate from a volume source would require unacceptable extremes of background gas density or power density in the discharge. Further parameter studies, aided by our recently developed vacuum-ultraviolet diagnostic technique, are in progress, as described in the Plasma Diagnostics section below. This year, while experimenting with the positions and shapes of the filaments, we achieved an output of 1 A/cm² using a fairly high gas flow with a cesium additive (Figure 2-5).

**Figure 2-5.** This small multicusp plasma source is being used to study the effects of various technologies and parameters on volume production of H⁺ ions. This small device can produce current densities in excess of 1 A/cm² with the introduction of cesium vapor or 250 mA/cm² without it. The multicusp source was developed at LBL in 1983; it was the first successful H⁺ volume-production source. Its name comes from the topology of the magnetic field that confines the plasma.
Figure 2-6. Several approaches have been shown to reduce the ratio of electrons to ions in the small multicusp volume-production source. A positively charged collar can draw off the electrons; its position and voltage can be chosen for the desired tradeoff between effectiveness at electron removal and perturbation of the ion beam. Adding gaseous Cs⁺ or Ba⁺ also improves the electron-to-ion ratio, and so does lowering the plasma potential (at the cost of some reduction in current).

An actual NBI system would use deuterium instead of hydrogen, so we have begun testing D⁻ yields as well. Generally speaking, our deuterium runs have yielded about 70% as much current density as the hydrogen runs, with an electron-to-ion ratio three to four times greater.

The basic technology used for the small multicusp source has a variety of possible applications, including many that involve positive ions. Previously we had developed a source of atomic N⁺ of exceptional purity (better than 98%). It could prove useful in ion implantation for surface hardening of steel, where ionized molecular nitrogen (N₂⁺) would result in an undesirably shallow implant layer. In 1989 we built on this work by demonstrating production of a variety of other positive ions, including B⁺ and C⁺ and, with sputtering targets, various metals such as Cu⁺. Operating at a low arc voltage with CO gas, we also produced a C⁻ beam.
The availability of a noncesiated source of copious C\(^-\) opens up a variety of possibilities. Cyclotron-based techniques for radiocarbon dating and for medical “tracer" sample analysis could be reinvigorated, for instance. There are also possibilities in materials science, including the deposition of thin films of diamond, as well as attempts to synthesize a class of carbon nitrides that, according to some theoretical calculations, might turn out to be even harder than diamond.

Our 1989 research on surface-conversion sources centered around a 15-cm-diameter multicusp “bucket" that can be equipped either with tungsten filaments and a separate conversion electrode or with barium-oxide cathodes.\(^*\) The goal of the experiments was to examine the yield and the energy distribution as a function of the bias voltage on the converter, which has implications for the basic processes involved in H\(^+\) formation at surfaces (\textit{sidebar}). In one series of experiments we used an “all-in-one" bariated cathode, as opposed to separate tungsten heating filaments and bariated converter, to determine whether tungsten contamination compromises the effectiveness of the converter. The before-and-after data indicated that this is not a significant concern, at least at the low power levels we used.

In working with tungsten filaments and a separate converter, we found that the results were very sensitive to the preparation of the converter surface and to the effectiveness of \textit{in situ} cleaning techniques. Suspecting that material coming from the filament might be contaminating the converter surface, we switched to a barium-oxide cathode—a coaxial, resistively heated, porous tungsten cylinder impregnated with barium oxide. Although the shapes of the energy spectra are different, the yields are comparable, indicating that contamination of the converter surface by cathode material is not a serious problem at these low power levels.

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\textit{Production of Negative Ions}

Volume production and surface conversion are two fundamentally different ways of producing negative ions. Both types begin with a gas of the desired species (hydrogen or deuterium in our work) that is partially ionized by any of several means, but thereafter they diverge at the level of basic chemical physics.

In surface conversion, a negatively charged element (either a coated cathode or a separate, coated converter element) draws positively charged ions from the plasma. Some of them are backscattered, a process in which they sometimes become transformed into negative ions by capturing two electrons from the metal surface. Meanwhile, the surface has been adsorbing the species that makes up the plasma. Of the incoming positive ions that are captured rather than backscattered, some sputter these adsorbed atoms out of the surface; these can likewise emerge as negative ions. In either case, the sheath separating the plasma from the converter—a sheath a few tenths of a millimeter thick in an intense discharge—accelerates the negative ions. Those that leave the source by this means are said to have been “self-extracted.”

In volume-production sources, gas-phase reactions are dominant (though surface conversion can take place at the chamber walls) and vibrational excitation of diatomic hydrogen atoms is thought to play a key role. Our model involves a two-step reaction:

\begin{align*}
(1) & \quad \text{H}_2 (v'' = 0) + e^- (\geq 25 \text{ eV}) \rightarrow \text{H}_2 (v'' \geq 6) + e^- \\
(2) & \quad \text{H}_2 (v'' \geq 6) + e^- (\approx 1 \text{ eV}) \rightarrow \text{H}^0 + \text{H}^-
\end{align*}

Reaction (2) can also work in reverse, which is thought to be an important mechanism for H\(^+\) loss in the discharge.

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* The conversion electrode is cooled, and is biased negatively at a few hundred volts to draw positive ions from the plasma and propel the negative ions toward the extraction aperture. It does not play a significant role as a secondary cathode.
A different way to circumvent converter-surface pollution from cathode material is to position the cathode far from the converter and create a magnetically confined plasma column (Figure 2-7). The apparatus is a variation of the Uramoto-type sheet-plasma source we had experimented with in earlier years; we have modified that volume-production source in order to place a surface-conversion electrode near the plasma. One of the main drawbacks of the sheet-plasma source was inefficiency at converting positive ions to negative ions. Using the new source, we continued to study conversion efficiency. Figure 2-8 compares our early results to those obtained at the FOM Institute in Amsterdam using a different sheet-plasma surface-conversion source; barium converter electrodes were used throughout. FOM observed a dramatic increase in conversion efficiency with increasing positive-ion density, whereas we have consistently observed a slight drop in efficiency. (Note that these curves are for "self-extracted" negative ions, i.e., no extraction voltage is applied.)

We attribute the difference to the higher electron temperature and primary-electron density in our source. Both of these factors increase the barium-ion density in the discharge and thus the barium-ion bombardment of the converter surface. The higher density of Ba⁺ (and electrons) near the converter tends to destroy negative ions, and the increased bombardment is thought to sputter off the hydrogen accumulated in the surface layers of the target.

Figure 2-7. After disappointing volume-production results with our Uramoto-type sheet-plasma ion source, we recently modified it to accept a surface-conversion electrode. In this program, we are studying and trying to improve the conversion of positive ions to negative ions.
High-frequency rf (around 1.7 MHz in our present work) offers a different and potentially more robust approach to generating the plasma in both volume-production and surface-conversion sources. Our rf-driven source is based on the same “bucket” with a multicusp magnetic field as the thermionic-cathode ion source. However, it has a glass-coated antenna instead of a filament or cathode. The antenna is immersed in the plasma instead of external to the discharge chamber as in some older designs. The rf energy sets up an oscillating magnetic field, which, in turn, produces an electric field. Voltage is applied to the antenna intermittently with a pulse length of 1 ms and a repetition rate of about 100 Hz.

The maximum H\(^+\) output current for both rf induction and dc filament discharges is presented in Figure 2-9. When compared with the same input power and at the same source pressure, rf discharges generally produced at least 40% more current than dc filament discharges. The extracted electron to H\(^+\) ratios are about the same throughout the range of discharge power tested. Unlike dc filament discharge, the shape of the H\(^+\) pulse was very uniform even though the source pressure was maintained at 15 mTorr. When the rf plasma was operated at a pressure higher or lower than 15 mTorr, the H\(^+\) current level would decrease but the pulse shape always remained uniform.

The rf source, with no filaments or cathode to burn out, seems to be a very attractive candidate for long-pulse fusion applications and for a great many other uses as well. A development program is already underway to develop rf sources for the Superconducting Super Collider: one for calibration of detectors, which will be an essential step in the experiments there, and another as a backup for a more conventional ion source in the injector system.
Figure 2-9. The hot tungsten cathode in a multicusp-filtered "bucket" source has been replaced with a water-cooled rf antenna consisting of a few turns of glass-coated copper tubing. When energized by a few kW of rf power in the 1–2 MHz range, electrodeless (induction) discharges occur. These discharges are suitable for ion production without the tungsten contamination and cathode-life limitations of the hot-cathode version.

Charge Neutralization for Semiconductor Processing

Among the more recent technology spinoffs from our fusion-energy research is an improved electron-beam charge neutralization system for ion implanters, which we developed under the sponsorship of Extrion Division, Varian Associates. The neutralizer, shown in Figure 2-10, is an improved means of delivering electrons to silicon or other semiconductor wafers to neutralize the positive charge that builds up during ion implantation. It incorporates a large, directly-heated lanthanum hexaboride (LaB$_6$) cathode like those developed for our MFE research, along with a magnetic beam-guiding system. This beam-based system has several advantages over the comparatively haphazard electron flooding techniques that are used today, in which primary electrons at about 350 eV strike a production target, giving off secondary electrons at various energies that bounce off the chamber walls and make their way to the wafer. In particular, the output is free of damaging, higher-energy electrons, and its flow is even and predictable.

In our system, the accelerated electrons begin their course perpendicular to the ion beam and then merge with it after going through a 90° bend induced by the magnetic field of a curved solenoid. The bend keeps the cathode out of the line of sight of the wafer so that it does not interfere with the ion beam. An opening in the solenoid allows the ion beam to enter and merge with the electron beam; this mingling also provides space-charge

* The magnetic fields used are too weak to have a significant effect on the ion beam, which is far more "rigid" than an electron beam of comparable energy because ions are so much more massive than electrons.
compensation for better ion-beam propagation. In order to steer the low-energy electron beam around the corner, a vertical or perpendicular component of the magnetic field is employed; this component is generated by a pair of Helmholtz coils.

The 100-mA beam arriving at the wafer is very uniform in its density. The energy distribution also has good uniformity: within a circle of 5 cm diameter, Langmuir-probe traces show electron energies of 30 eV and below, with the majority under 10 eV.

The development of more-efficient, higher-current negative ion sources requires a thorough understanding of the physical and chemical processes within these devices. We had earlier developed a vacuum-ultraviolet laser absorption spectroscopy technique to measure the concentrations of neutral hydrogen (H₀) within the plasma discharge volume. The experimental apparatus is shown schematically in Figure 2-11. The technique has recently been extended to measure the concentration of molecular hydrogen (H₂), the other major neutral species present.

Ion-Source Chemical Physics
In a variation on the general theme of Raman spectroscopy, we can also determine the energy content of each species, i.e., the translational energy distribution for the atoms and the translational, rotational, and vibrational energy distributions for the molecules. Such measurements are critically important because the reactions governing H⁻ formation and destruction in volume plasma sources are sensitive to these parameters. Studies of the hydrogen molecules in the volume source indicate that a large fraction of them are vibrationally and rotationally excited. Quantized rotational levels as high as \( J'' = 8 \) are well-represented. Vibrational levels as high as \( v'' = 8 \) have been observed (though the lower quantum vibrational levels are much more abundant, as shown in Figure 2-12).

The vibrational results are especially intriguing, as the distributions do not agree at all with what existing models would lead us to expect. Figure 2-13 gives an example of the data: the logarithmic dependence of high-\( v'' \) populations on vibrational energy has a straight negative slope, whereas we expected a “plateau” of positive deviation from this monotonic slope from \( v'' = 5 \) to \( v'' = 11 \). We believe, however, that the H⁻ production mechanism that has been proposed is qualitatively accurate and that the disagreement results from inaccurate cross sections in the model of the \( H_2 \) vibrational distribution. Research continues as we seek a better understanding of the phenomena involved in this important process.

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* The atoms, ions, and molecules undergo translational motion through space. The molecules also rotate, or tumble, about various axes, and, on a much faster time scale, they exhibit vibration, which may be interpreted as expansion and contraction of the bonds between their atoms. Translation occurs in the classical continuum, whereas the rotational and vibrational states are quantized (though described well by semiclassical treatments).
Figure 2-12. Quantized rotational levels as high as \( J'' = 8 \) are well-represented in the volume-production ion source. Vibrational levels as high as \( v'' = 8 \) have been observed, though the lower quantum vibrational levels are much more abundant. Note that the rotational distributions of all vibrational levels are similar.

Figure 2-13. The dependence of high-\( v'' \) populations on vibrational energy is logarithmic, with a straight negative slope, whereas we had expected a positive deviation from this, or a "plateau," from \( v'' = 5 \) to \( v'' = 11 \).
Materials Modification and Synthesis

The performance, durability, and economic attractiveness of today’s “high-tech” products are often predicated on advanced metals and other materials and on effective, affordable techniques for manufacturing them. Closely allied with our ion-source R&D is an ongoing investigation of suitable technologies and applications for ion beams and plasmas in this field. These programs involve close interdisciplinary collaboration with colleagues from LBL and elsewhere.

In 1989 we continued development of the Metal Vapor Vacuum Arc (MEVVA) ion source, which works on different principles than the ion sources described in the previous section, and demonstrated its usefulness for large-scale, high-dose ion implantation in metal surfaces. Another program relates to the quest to deposit industrially useful diamond coatings on surfaces. In our work, which yielded its first results in 1989, we deposited diamond on a surface by a Plasma Assisted Chemical Vapor Deposition (PACVD) process.

MEVVA Development and Characterization

The MEVVA ion source has enjoyed widespread use since it was invented at LBL; universities and government laboratories in Australia, China, West Germany, Japan and the Soviet Union established MEVVA R&D and application programs. We are in communication with these workers and have set up some collaborative research programs.

In 1989 we built a new MEVVA source designed specifically for implanting ions in the surfaces of metals. (Generally speaking, industry would do this to smooth and harden the surfaces of metal parts.) The effectiveness of the MEVVA technology for high-dose metal-ion implantation was successfully and thoroughly demonstrated. The MEVVA program comprises three parallel components: ion-source development, ion-beam characterization, and ion-implantation research.

In the new source, MEVVA V (Figure 2-14), a vacuum-arc discharge creates an intense plume of highly ionized metal from the cathode. The ion beam is formed using a 10-cm-diameter set of extractor grids. MEVVA V incorporates the multi-cathode “Gatling-gun” feature that was developed for MEVVA IV. This feature allows rapid switching among 18 separate cathodes, so it is easy to change metallic species or substitute for a spent cathode without breaking vacuum.

Figure 2-14. The MEVVA V ion source was designed specifically for ion implantation. It incorporates a broad-beam extractor (10 cm in diameter) and a multiple cathode assembly (18 separate cathodes). The “Gatling gun” cathode array, like the MEVVA concept itself, is a fairly direct spinoff from injector research and development for the SuperHILAC heavy-ion linear accelerator.
The maximum beam extraction voltage is 100 kV, and since the ion charge states vary typically from 1 to 5 (depending on the metal), the ion energy in the extracted beam can be up to several hundred keV. The record beam current extracted is 3.5 A; the beam is delivered in 250-μs pulses at a repetition rate of up to several tens of Hz. We have carried out an extensive study of ion beam characteristics as a function of various source parameters for both the MEVVA IV source, which is now being commissioned in the injector beamline at the SuperHILAC heavy-ion linear accelerator, and MEVVA V.

In this work, we examined the charge state distribution of the ion beam produced from 48 different elements—nearly all of the solid metallic elements. Besides being a unique and important contribution to vacuum-arc physics, these data are important for ion implantation. We also investigated the spectra of ions produced from a number of different alloy and compound cathodes. The beam current was measured as a function of source parameters such as arc current, extraction voltage, cathode species, and extractor grid spacing; beam divergence and cathode erosion rates were also measured. Finally, a parametric study of the beam “noise” (fractional current fluctuation level) was completed in collaboration with GSI in Darmstadt, West Germany. The beam noise was found to reach its minimum at an arc current corresponding to the perveance match condition. In other words, there is an ideal plasma density for any given geometry of the beam-formation electrodes; at this density, the beam current is maximized and the beam divergence and noise are minimized. These results provide a guide to optimal source operation; they are especially important when MEVVA sources are used as injectors for accelerators.

We have carried out a wide range of ion-implantation “mini-programs” to demonstrate applications of MEVVA V. Some highlights are listed below.

**Superconducting Thin Films.** We have used high-dose metal ion implantation as a means of fine-tuning the composition of high temperature superconducting thin films. In these experiments, carried out together with LBL’s Applied Science Division, thin films of Y-Ba-Cu-O that had been deposited by rf magnetron sputtering from a single target were implanted with Cu. As shown in Figure 2-15, this altered their composition and raised their critical zero-resistivity temperature or $T_c$.

**Metallic Oxidation Resistance.** The first major phase of a collaborative research program with LBL’s Materials and Chemical Sciences Division has been completed. We have been investigating how the high-temperature oxidation properties of a Fe-Cr-Al alloy of the kind used for high-temperature turbine blades might be improved by high-dose implantations of Mg, Ti, Y, Zr, Mo, Pd, Hf, W, or Th. Results are now being analyzed.

**Steel Surface Hardening.** In an experiment that is now in an exploratory phase, we are collaborating with the Naval Research Laboratory to study the implantation of Ti, and, separately, the mixed Ti/C beam obtained from a TiC cathode, into Type 440C hard steel. Such implantations could improve the wear and hardness characteristics of the steel surface. The experiments involve very high doses—in the range of $1 \times 10^{18}$ cm$^{-3}$. Several rounds of LBL implantation followed by NRL analysis have been carried out.
Figure 2-15. Implantation of Cu ions into a Y-Ba-Cu-O film greatly improved its superconductivity characteristics. The Cu:Y ratio, initially too low for good superconductivity at 2.0:1, was increased to 2.2:1 by the implantation.

**Implantation-Depth Research.** A study of the implantation depth profiles of a range of metal ion species (Ti, Cr, Y, Zr, Nb, Mo, Pd, Ba, Dy, Ta, W, Ir, Pt, and U) in a carbon substrate was carried out collaboratively with the U.K. Atomic Energy Agency in Harwell, England. This fundamental investigation will clarify the effect of the broad distribution of ion charge states (and hence the broad energy spectrum) of MEVVA-produced ion beams, thus improving the interpretation of surface-modification work.

**Field Modification of Equipment.** The Corpus Christi Army Depot has begun an ion-implantation project, part of which involves MEVVA technology. The program focuses on helicopters, which have a great many moving parts and notoriously high maintenance needs. The goal is to demonstrate the usefulness of metal-ion implantation as an overhaul procedure to improve existing machinery. One 1989 run involved the implantation of Mo into Al coupons for enhanced corrosion resistance; corrosion testing is presently in progress. We are now fabricating a target manipulator for use in the implantation of Pt into steel bushings that are used in helicopter engines.

**Diamond Synthesis**

Along with LBL’s Materials and Chemical Sciences Division, we have established a program to investigate the synthesis of polycrystalline diamond thin films on substrates that are of technological value. The metallic substrate is immersed in a microwave-produced hydrogen/methane plasma, and diamond films grow from the plasma state by chemical vapor deposition. The goal is to develop industrially applicable techniques for depositing diamond thin films onto large, three-dimensional substrates. Figure 2-16 shows the results of the initial experiments: the early growth stages of a thin film, consisting of faceted diamonds about 1–2 μm in size.
In our first experimental PACVD diamond synthesis system, microwave energy is provided by a 500-W magnetron at 2.45 GHz. The microwave power is delivered to a simple plasma chamber via standard waveguide components, and a hydrogen/methane plasma is established. During processing, the sample is situated inside a quartz vessel and immersed in the discharge; substrate temperature is monitored by a two-wavelength infrared pyrometer. Further steps in this program include optimizing process control in order to form uniform thin films, along with investigation of possible techniques for bonding the film to the substrate more strongly—an important requirement for moving such diamond films out of the laboratory and into applications.

Figure 2-16. Scanning electron microscopy reveals the first faceted diamond crystals synthesized in our microwave-plasma device. The crystals are about 1–2 μm in size. The diagonal band of heavy deposition marks the location of a scratch provided to promote nucleation. Longer processing would have resulted in more-complete coverage. The Raman scattering spectrogram by MCSD shows the distinctive signature of true, high-quality diamond: a strong peak at 1332 cm⁻¹. The large peak on the right is from the silicon substrate.
Accelerators for Negative Ions

The experimental fusion reactors now being planned or proposed—the ones in which experimenters hope to attain "ignition," or a self-sustaining fusion reaction—will have substantially larger plasmas than today's experiments. High neutral-beam energy will be crucial for penetrating these larger plasmas. Furthermore, variable beam energy is highly desirable; the energy can be kept low initially to prevent "shine-through," then raised as the plasma density increases. Our efforts have been concentrated on development of high-current, high-energy negative-ion accelerators whose energy can be varied without sacrifice in current. We have found a promising way to accomplish this with a Constant-Current, Variable-Voltage (CCVV) accelerator using electrostatic quadrupole (ESQ) focusing. A prototypical section of this accelerator was completed and tested in 1988, and experimentation with it continues.

CCVV Accelerator Testing

The CCVV accelerator is intended for dc operation in the MeV energy range but can be tuned for lower energy without reducing beam current. (The current is fixed by the ion source and preaccelerator.) ESQ focusing reduces the risk of voltage breakdown as compared to the conventional Pierce-type accelerator column because the transverse electric fields that provide focusing also sweep out secondary ions and electrons that could trigger breakdowns. These features are useful for fusion-reactor startup and, coincidentally, for industrial spinoff applications such as processing of semiconductors and surface hardening of materials.

A CCVV accelerator using ESQ focusing is being developed at LBL to accelerate negative ions efficiently to the energy range that the next generation of tokamaks will require. Our existing 200-keV single-beam prototype system (Figure 2-17) is designed to accelerate up to 200 mA of H\(^-\) or an equivalent current of heavier ions, such as 140 mA of D\(^-\). The accelerator is modular. A matching-and-pumping stage focuses and transports a 100-keV beam without acceleration; then a CCVV accelerating stage increases the beam energy by up to 100 keV. (The CCVV stage can also transport a beam at constant energy or even decelerate it.) Both stages use electrostatic quadrupoles for focusing.

Using two of these two-stage modules, we have accelerated a 42-mA H\(^-\) beam to an energy of 200 keV for a period of 200 ms. At the slightly reduced energy of 180 keV, we accelerated a 40-mA beam for more than 400 ms. When the matching-and-pumping stages are tuned properly, the beam loss can be less than a few percent and emittance growth is insignificant.

Plans for 1990 include testing of the system with higher beam currents at 200 keV. Among of the limitations of the test program is the intensity of beams from the available negative-ion sources. Continued progress in the ion source development program should alleviate this problem, allowing eventual testing of the CCVV accelerator at its full capacity.

For NBI applications, a CCVV accelerator only needs to have an energy range of about 2:1. In other applications, such as semiconductor processing, surface hardening, or fusion-plasma diagnostics, much wider energy ranges may be needed. The output beam energy may be varied not only by adding or removing CCVV modules, but also by suitably tuning the acceleration voltages and the ESQ focusing voltages (which may be performed rapidly without altering the accelerator's configuration). Numerical simulations that we performed in 1988 demonstrated that the energy of a CCVV stack could be tuned from 1 MeV down to 20 keV without any change in mechanical configuration or reduction of beam current.
Figure 2-17. This constant-current, variable-voltage (CCVV) accelerator module is based on electrostatic-quadrupole (ESQ) technology. Each module consists of a matching-and-pumping stage (the part with a dark insulator band) and a 100-keV acceleration stage. CCVV modules can be cascaded to obtain the desired beam energy. The apparatus at the far left is a test stand for the accelerator; at far right is a volume-production ion source. Below: work on the matching-and-pumping stage affords a view of the internal structures.
Computer Modeling

The design of CCVV systems relies heavily on computer modeling, most of which has been done with a simple code that describes the beam envelope. A typical result is shown in Figure 2-18, which traces the beam envelope through 10 complete modules of a 1-MeV accelerator. We have also used the WOLF particle code to model the preaccelerator, and another code, faster and simpler but less accurate, to model the electron trap.

In 1989 we began a project in which the 3-d particle code ARGUS is used to model the entire 200-keV prototype of the CCVV accelerator, including the preaccelerator and electron trap, the ESQ matching stage, and the CCVV accelerator stage. ARGUS, developed by Science Applications International Corp. and adapted for our use, has already provided accurate modeling of ion and electron behavior in the preaccelerator/electron trap section. When the ESQ portion of the code is fully operational, we will be able to check the accuracy of our envelope-code models by making detailed comparisons between the models' output and experimental results.

One of the problems that can arise in an NBI system is the generation of secondary electrons in ionizing collisions between D⁻ particles and background-gas molecules. If these electrons are propagated through the accelerator long enough to reach high energies, they can produce damaging x-rays when they strike metal surfaces such as the accelerating and focusing electrodes. The findings, based on a computer model called SECONDARIES, were reassuring: of all the secondary electrons born in an early accelerating gap, only 2% make it through two more gaps, and only 0.5% survive all the way through the accelerator. Most of the secondary electrons are swept out by the transverse electric fields in the quadrupole sections before they gain much energy. The mean energy of the electrons that stop in the accelerator is only 25.4 keV, which leads us to believe that x-ray damage to insulators will not be a problem in a 1-MeV CCVV accelerator.
To construct a high-energy accelerator, we would stack the modules described above to obtain the required beam energy. Previously, we had completed a detailed design for a 1-MeV single-channel system, as well as a conceptual design for a multichannel system that would accelerate 10 A of D⁻ to 1–2 MeV. The multichannel system could be used, in conjunction with a suitable D⁺ source and a plasma neutralizer, as part of a neutral-beam injector for ITER.

A spinoff from our CCVV accelerator research—an electrostatic low-energy beam transport system, or LEBT—appears to be well suited for use in the injector systems of accelerators for high-energy physics, such as the SSC or the proposed Large Hadron Collider at the European Center for Nuclear Research. The injectors for these machines are operated with short pulses at low duty cycles. Under these conditions, stable gas neutralization of the low-energy beam, as needed in most magnetic LEBTs, is hard to achieve. Our LEBT incorporates ESQ focusing in the beam-transport stage, along with an electrostatic ring lens to match the beam into an rf-quadrupole accelerator (RFQ). Computer modeling and test-stand measurements (with a simulated RFQ entrance) indicate that the system is noise-free and stable and causes negligible emittance growth in H⁻ and He⁺ beams. In cases where pumping is of no concern and the distance between the ion source and the first accelerating structure must be kept as short as possible, the system can be reduced to one or two simple electrostatic ring lenses.

**Future CCVV Systems**

**Electrostatic LEBT for High-Energy Accelerators**

**Fusion research owes a great debt to complex theoretical studies conducted on the borderline between physics and mathematics. The MFE Group at LBL maintains a plasma-theory branch whose pure and applied studies help other researchers understand the phenomena observed in hot plasmas and the possibilities for future development. The plasma theorists have sought new ways of comprehending gyroresonant absorption; their goal is to understand the physics of the phenomenon and thereby describe it in simpler mathematical terms. Their work has yielded not only simplified mathematical approaches, but also insights into the geometry of wave propagation in a plasma, and into differences between the behavior of the incoherent waves typical of natural phenomena and the behavior of coherent waves.**

**Plasma Theory and Nonlinear Dynamics**

**Wave Dynamics and Gyroresonant Energy Absorption**

In 1989, an important focus of our theoretical studies was the investigation of the basic properties of wave systems, especially in the area of short-wavelength asymptotics, i.e., WKB theory. We have also investigated the nonlinear dynamics of classical Hamiltonian systems, along with related topics in statistical mechanics. These areas of research reinforce one another, since the short-wavelength asymptotics of wave fields incorporates not only the entire framework of classical Hamiltonian dynamics, but also additional structures relevant to wave systems. Because of this connection, WKB approximations are sometimes called “semiclassical” methods.

**Our group’s approach to these problems in nonlinear dynamics is to apply forefront ideas from theoretical physics and modern mathematics. Especially relevant are the physical concepts of invariance and covariance, in which the properties of a physical theory are, respectively, independent of or dependent upon the observer and the system of coordinates. Such ideas have long been a driving force in theoretical physics; they underlie such**
fields as the special and general theories of relativity, or the classical mechanics of Hamilton and Jacobi.

The immediate purpose of this work is to understand heating and transport of plasmas—in particular, gyroresonant absorption of energy. One of the main heating schemes for tokamaks involves irradiation of the plasma by a coherent magnetosonic wave. This radiation is partially absorbed at a resonance layer, where the wave frequency $\omega$ is either twice the local gyrofrequency of a dominant ion species or the fundamental gyrofrequency of a minority species.

In studying gyroresonant absorption, it is important to understand mode conversion (how and where the waves couple into one another) inside a tokamak. A significant advance, beginning in the early 1980s, was the introduction of the wave-phase-space viewpoint. It was shown that the waves are separated by their characteristic ray paths, and that they typically meet pairwise at the sites of mode conversion. Simplifying the physical picture to a succession of pairwise conversions allowed an analytically intractable fourth-order differential equation to be reduced to two second-order equations.

In search of better understanding and further simplification, we have looked at the problem in terms of two waves: a magnetosonic wave traveling in $x$-space and a “pressure-anisotropy wave” that travels through wave-vector or $k$-space. Figure 2-19 shows a typical gyroresonance process. Because the particles within a tokamak gyrate at different rates, depending on the local magnetic field, the wavelength of the pressure-anisotropy wave changes as the wave propagates through the plasma; in other words, the wave moves through phase space. The successive mode conversions are linked by the pressure-anisotropy waves. With this understanding, each mode conversion can be modeled in wave-vector space with a single first-order ordinary differential equation.

This approach, which incorporates several techniques that we originated, represents a significant advance over the standard treatment of gyroresonant absorption, which uses the local dielectric tensor (which is rapidly varying at the resonance) and the wave electric field in $x$-space. Our approach uses several new techniques to replace approximate numerical solutions with explicit, exact analytical solutions. These techniques include

- congruent reduction, which yields coupled equations for linear mode conversion with slowly varying dispersion functions for the various modes
- wave propagation in $k$-space for the modes involved in the resonance absorption process
- metaplectic transformations that locally convert partial differential equations into first-order ordinary differential equations, which are much easier to solve analytically
- identification of absorption as linear conversion to a continuum of Case-van Kampen modes, which are then spectrally transformed to explicitly uncover the Landau-damped collective modes.
- recognition of the energy conservation problem in terms of wave-action conservation in phase space, which can be obtained through Weyl symbol calculus
Figure 2-19. This schematic phase-space diagram depicts a typical gyroresonance process. An incident electromagnetic ray comes in on the upper dispersion surface. As it crosses the gyroresonance layer, it excites a continuum of gyroresonant ballistic waves (GBWs), which then propagate in six-dimensional phase space. They may come across the dispersion surface of the reflection branch (the lower surface), in which case each GBW mode-converts to a reflected ray.

We have produced a complete solution for the one-dimensional slab model of second-harmonic absorption, and are currently generalizing this work to include minority heating. Future plans include extension of our understanding to two- and three-dimensional models.

In treating the nonlinear interaction of extended systems (such as electromagnetic fields and distributions of charged particles) it is highly desirable to formulate a variational action principle. The primary advantage is that, in making transformations of variables appropriate for various approximation schemes such as expansions in wave amplitude or eikonal expansions, a variational approach yields self-consistent equations appropriate to the particular approximation. Further, such an approach implies continuous symmetries, such as invariance with respect to space-time translations or wave phase shifts, that yield the local conservation laws appropriate to these approximations.

The implications of these studies could reach beyond fusion. Wave phenomena are ubiquitous in nature. Semiclassical methods in wave dynamics have a vast range of applicability, from quantum mechanics at the nuclear, atomic and molecular levels to a new field of astrophysics called helioseismology in which the propagation of shock waves through stars is studied in order to infer their internal characteristics. These semiclassical methods are also commonly used in studies of optics, radio transmission, and acoustic phenomena, including the detection of cracks or other faults in metals and the propagation of sound waves through the ocean or earth.

Covariant Lagrangian Field Theories

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Publications and Presentations

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Abstracts, Talks, and Proceedings


C.F.A. van Os, K.N. Leung, A.T. Lietzke, J.W. Stearns, and W.B. Kunkel, "H⁺ production from non-cesiated converter-type negative ion sources," Fifth International Symposium on the Production and Neutralization of Negative Ions and Beams (Brookhaven National Laboratory, 1989); Lawrence Berkeley Laboratory report LBL-27951 (1989).


Laboratory Reports

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