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Contents

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 (Alfven) waves in a highly ionized laboratory plasma. In the mid-1960s the concept of inertial-confinement fusion was brough forth, so our group's name was changed from "CTR" to "MFE."

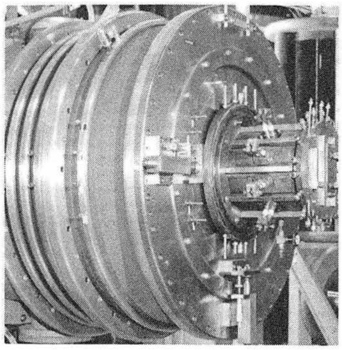
In 1971, the MFE Group accepted the challenge of developing sources, accelerators, and injectors of powerful, energetic neutral beams of hydrogen and deuterium atoms for heating and fueling magnetically confined thermonuclear plasmas. These devices were initially applied to the latest mirror-fusion machine 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 a thermal energy of particles in the plasma of 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 General Atomics 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 1988 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, 1989



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MAGNETIC FUSION ENERGY

. . . larger plasmas will require higher injection energies . . .

HEATING A PLASMA TO THERMONUCLEAR TEMPERATURES is one of the many significant challenges in fusion-energy research. In all the major magnetic-confinement fusion experiments, the plasma is heated largely by neutral beams of hydrogen isotopes injected in the energy range of 100 keV at multi-megawatt power levels. The primary focus of the MFE Group at LBL is the development of the neutral-beam injector systems. The group's 15 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).

The CLPS is now being used in the two major U.S. magnetic fusion facilities: the Tokamak Fusion Test Reactor (TFTR) at Princeton's Plasma Physics Laboratory and the Doublet D-IIID tokamak at General Atomics in La Jolla, California. In the CLPS, positive ions of either hydrogen or heavy hydrogen (deuterium) are accelerated to the desired energy, then neutralized by electron capture. The energetic neutral particles pass through the tokamak's magnetic field and into the interior, where they are reionized and trapped, transferring their energy to the plasma. The CLPS has been a highly successful device. However, research on neutral-beam sources must continue; the positive-ion approach used by the CLPS, although effective for today's experiments, appears to be at or near a fundamental limit of its performance.

When ion energy is increased beyond 100 keV or so, the probability of electron capture in the neutralizer becomes lower than the probability of re-stripping, which makes the particles positively charged again. This loss of efficiency would be a severe limiting factor in the next generation of

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tokamaks, where the larger plasmas will require higher injection energies—several hundred keV to 1 MeV—to ensure adequate penetration.

One can start with negative ions instead, accelerating them to high energies and subsequently neutralizing them by the simple process of detaching the extra electron. The yield of the neutral fraction does not decrease with increasing energy; as a result, negative-ion beams are generally the preferred starting points for the production of high-energy neutral beams. 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. Progress is being made, but a truly satisfactory solution has yet to be found.

Design, construction, and testing of prototype accelerator systems must go hand in hand with development of a negative-ion source. A substantial effort is devoted to accelerator development; during 1988 it became increasingly influenced by the goals of the ITER Project, the International Thermonuclear Experimental Reactor, which, in all probability, will use high-energy neutral beams to drive the toroidal current noninductively during steady-state operation.

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 are of interest for the Strategic Defense Initiative, for example. Sources and accelerators for various ion species are used in industrial applications such as ion implantation for semiconductor processing. And, we have maintained an academic component of our program, centering on advanced plasma theory.

Ion Sources

The next generation of tokamaks will need higher-energy neutral beams. Therefore we have investigated high-current negative-ion sources and the corresponding acceleration and neutralization systems. An early effort, 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. Since then, our research has focused on "volume sources" that produce ions throughout a volume of gas rather than on the surface of an electrode. (Surface conversion using coatings of barium or other materials less volatile than cesium remains under consideration.) The main goal of the ion-source program is to increase the steady-state current capability of negative-hydrogen-ion sources.

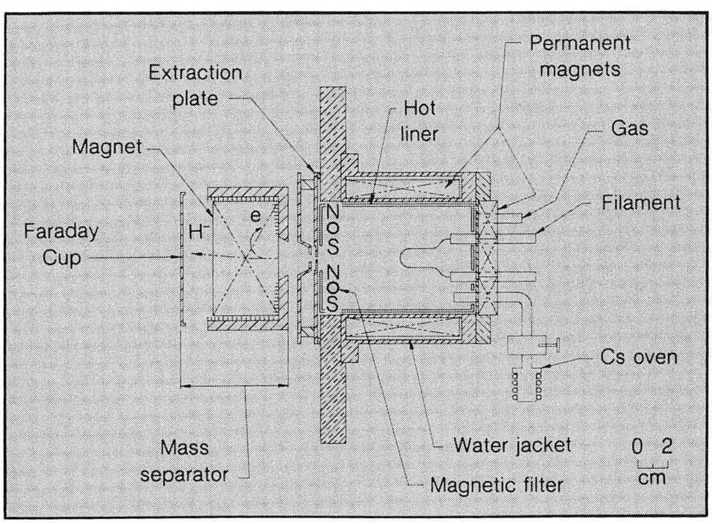
Relative Merits of Surface and Volume Sources

In earlier years we had designed and built a 1-A negative-ion source that used a cesiated "converter" electrode. Despite its groundbreaking performance, it was abandoned for two reasons. First, cesium evaporates readily, so some of it escapes from the ion source and contaminates downstream acceleration columns, reducing their voltage-holding capability. Preventing this contamination would require complicated and expensive protective measures, particularly for the long-term, steady-state operation that would characterize a fusion power plant. Second, the beam quality was not high enough for some proposed applications, and the prospects for improving it were not clear.

It appears that for fusion purposes, negative ions will have to be produced in cesium-free sources. One possibility is the volume-production source, in which gas-phase reactions are thought to play a major role in forming H^- ions (as opposed to surface-conversion sources, in which the H^- ions are formed by electron capture on a metal surface). There is serious concern, however, 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. Evidence is beginning to indicate that the discharge-chamber walls play a significant role even in so-called volume-production sources. Perhaps the solution lies in modification of the walls, or even in a return to the converter-electrode concept without cesium (barium appears to be a possible substitute).

To examine this phenomenon in cesiated and bariated volume sources, we have used the small (7.5-cm-diameter) multicusp plasma source shown in Figure 2-1. Although most investigations of cesiated sources had focused on surface conversion, some recent work has been done on cesiated volume sources, particularly in the USSR. Large increases in H^- output implied that cesium might enhance H^- production with other source geometries. These results were confirmed in our experiments, which showed great improvement in the electron-to-ion ratio as well. Figure 2-2 shows the H^- current density as a function of discharge current with and without cesium.

It has been demonstrated at LBL and elsewhere that a similar enhancement can be obtained by adding barium to the hydrogen discharge. Barium evaporates less readily than cesium and should therefore pose less of a contamination problem. Figure 2-3 shows the dependence of H^- output on the source liner temperature and therefore the amount of barium in the source plasma. This result, along with other observations, demonstrated that H^- ions generated on the anode walls are responsible for the large increase in output current when barium or cesium is added to a multicusp source. Techniques are now being developed to provide a clean barium surface on the walls of the source.



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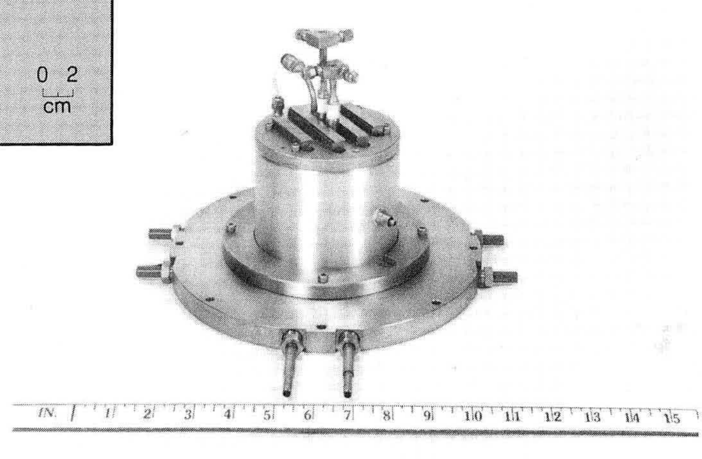

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Figure 2-1. This multicusp plasma source is being used in studies of the effects of cesium and barium on volume production of H^- ions. Current densities higher than 250 mA/cm^2 have been extracted from this small device. The multicusp source was developed at LBL in 1983; it was the first volume source to successfully produce H^- ions. Its name comes from the topology of the magnetic field that confines the plasma.

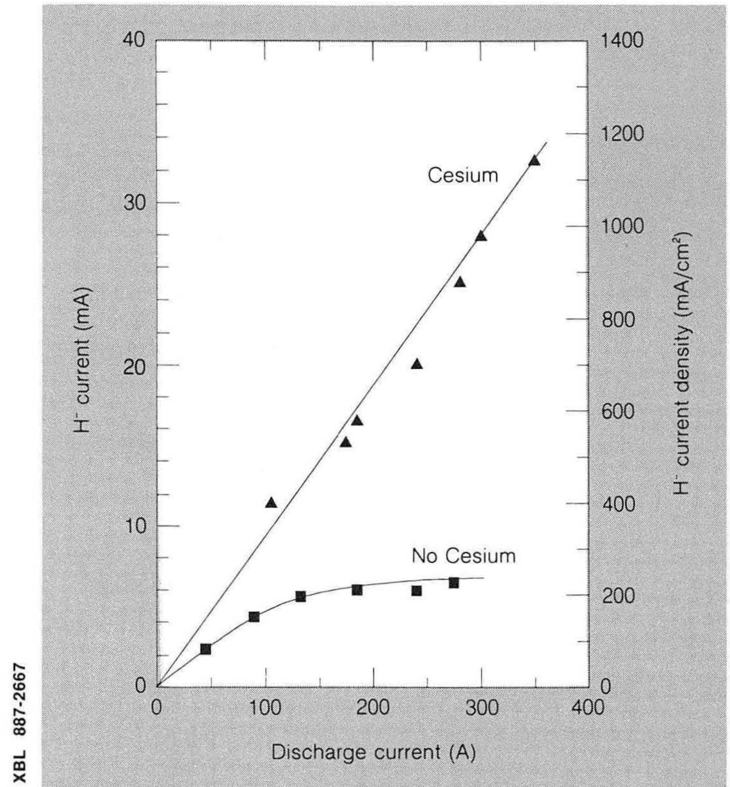

Figure 2-2. When cesium was introduced into the small multicusp source, H^- output increased by about a factor of two relative to a pure hydrogen discharge. Further addition of cesium resulted in an overall improvement of H^- output by a factor of five, and H^- current densities exceeding 1 A/cm^2 were obtained. Cesium confers another benefit as well. Operation with pure hydrogen causes a high electron-to-H^- ratio that increases with discharge current; addition of cesium to the discharge reduced the ratio by an order of magnitude at high discharge powers.

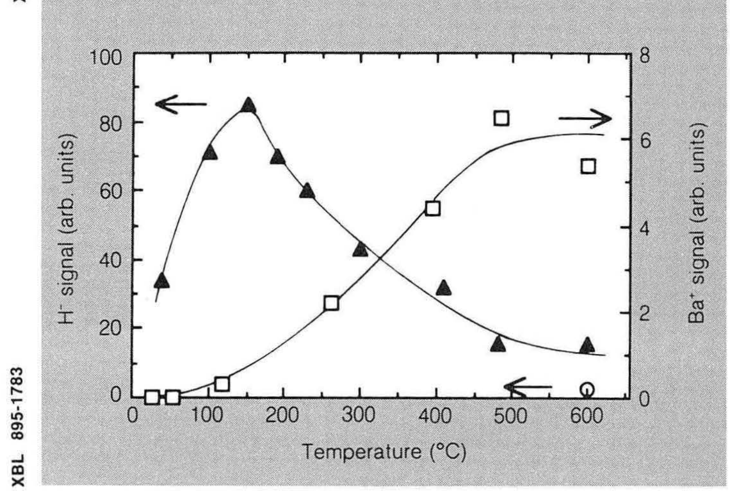

Figure 2-3. When the small-aperture source was seeded with barium, the H^- output was dramatically enhanced. (The single open circle at lower right indicates a baseline figure for unseeded, pure-hydrogen operation.) However, as liner temperature increased, H^- production diminished. The reduction may have been due to the increasing amount of Ba^+ in the plasma at higher temperatures.

Large-Aperture Source and Preaccelerator

In optimizing the performance of the Large-Aperture H^- Volume Production Source (Figure 2-4) we have delivered H^- beams of up to 100 mA from the preaccelerator at a beam energy of 100 keV. The extracted beam current increases with arc power in the source; at present we are limited by the maximum continuous arc power we can use without overheating the cathode. The gas pressure in the source is 10 mTorr. Our goal is to cut both the electron-to-ion ratio and the gas pressure by more than a factor of 2 while simultaneously doubling the current density (the current produced per square centimeter of source extraction area).

This source has an extraction area of 6.7 cm^2. In studying the effect of the extraction area, we found that the current density J is inversely proportional to $a^{0.75}$, where a is the aperture radius; in other words, the larger we make the radius, the lower the current density becomes. Further, the apparent ion "temperature" (deduced

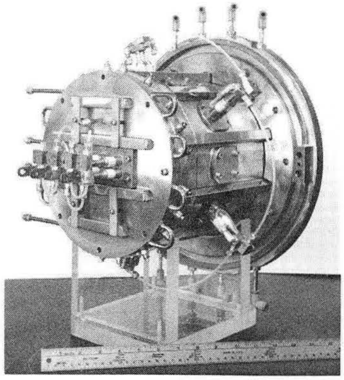

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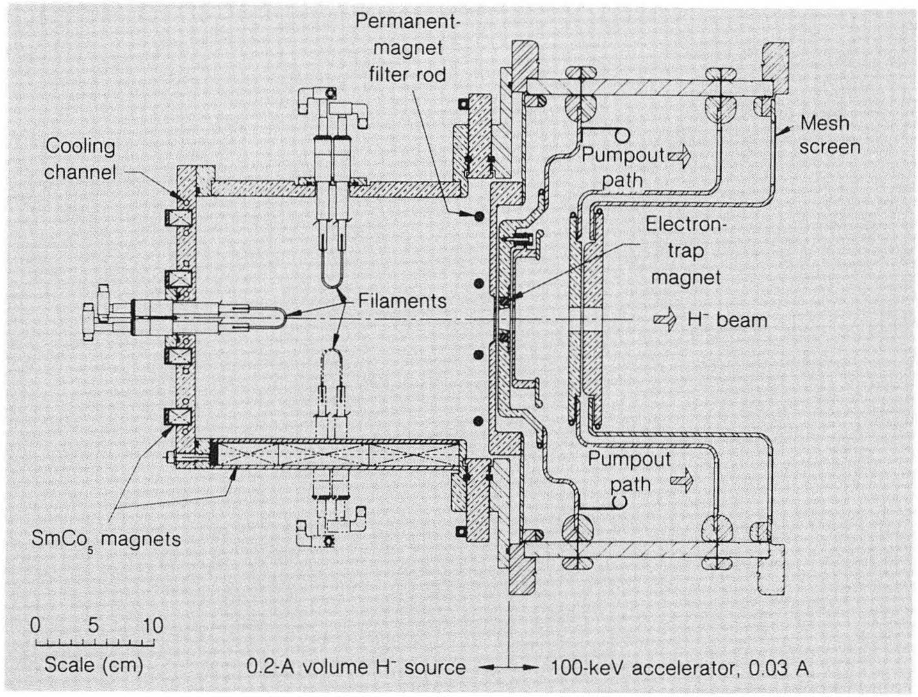
Figure 2-4. This Large-Aperture H⁻ Volume Production Source might be the precursor of the sources for the next generation of fusion experiments. The ratio of extracted electrons to H⁻ ions from this source is about 10:1. Improving the ratio to 5:1 or better is a major goal for further research.



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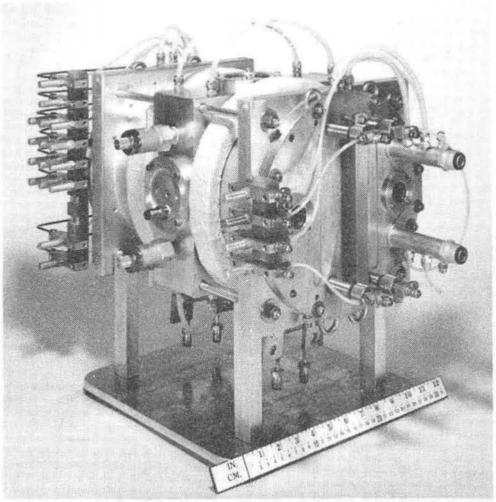
from the beam emittance) is unexpectedly high, and it begins increasing with radius only after the radius is made larger than a certain critical size. The subject of sheath formation, which appears to be the limiting mechanism, is not well understood for negative-ion and electron extraction.

Sheet-Plasma Source

While making progress with the development of multicusp volume-production sources and continuing to keep surface-conversion sources in mind, we have been exploring another type of volume-production source: the sheet-plasma source, in which a plasma is confined in a sheetlike geometry less than 1 cm thick. The seminal event in this investigation was a 1986 paper by J. Uramoto of the Institute of Plasma Physics in Nagoya, Japan, which indicated that high current densities could be obtained over large areas from such a sheet. In 1987 we built a source designed to produce ions from an 8-mm-thick plasma sheet (as shown in Figure 2-5) and began experimenting with it.

In the initial experiments, we obtained a very high H^+ current density inside the source (about 1 A/cm^2) over a large plasma area (10 × 30 cm) while operating at low pressure (approximately 5 mTorr). However, the H^- yield was relatively low (7 mA/cm^2). In an attempt to improve the yield, we developed a lanthanum hexaboride (LaB_6) plasma cathode to replace the tungsten-filament cathodes we had previously used.

The new cathode has provided greater plasma uniformity in the vertical direction of the sheet, and contamination from cathode material has been greatly reduced. Unfortunately, neither the H^- yield nor the plasma density far from the sheet has been sufficiently improved. (Arc operation at 40 A and 80 V, with a 5-mm-thick, 20- × 30-cm sheet at 2 mTorr H_2 pressure, has produced 50 mA/cm^2 of H^+.) We must conclude that the sheet-plasma source is not a promising candidate volume H^-/D^- production for fusion purposes. It may, however, prove quite useful for other plasma research. A large, uniform plasma sheet, used in conjunction with an appropriate plasma cathode, has attractive advantages where long cathode lifetime and freedom from cathode-material contamination are more critical than extracted-ion density. Due to its lack of cathode contamination, this plasma source is being evaluated for use as an H^+ source for surface conversion of H^+ to H^- in applications where a clean barium surface is required.



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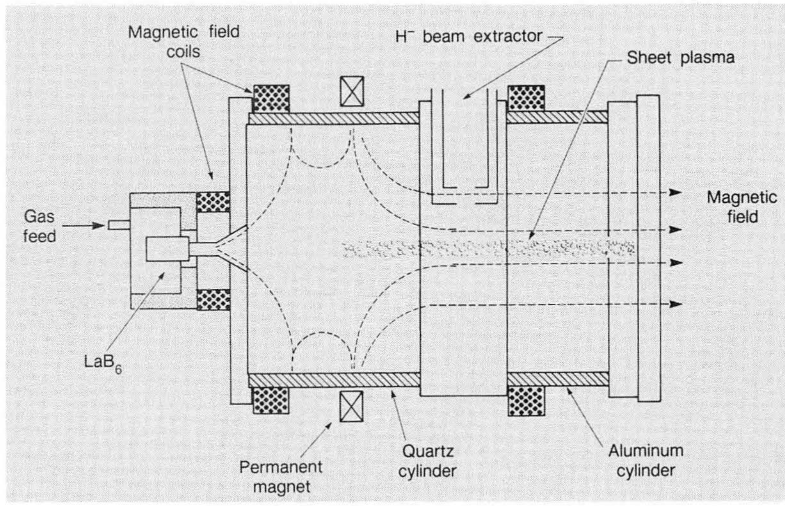

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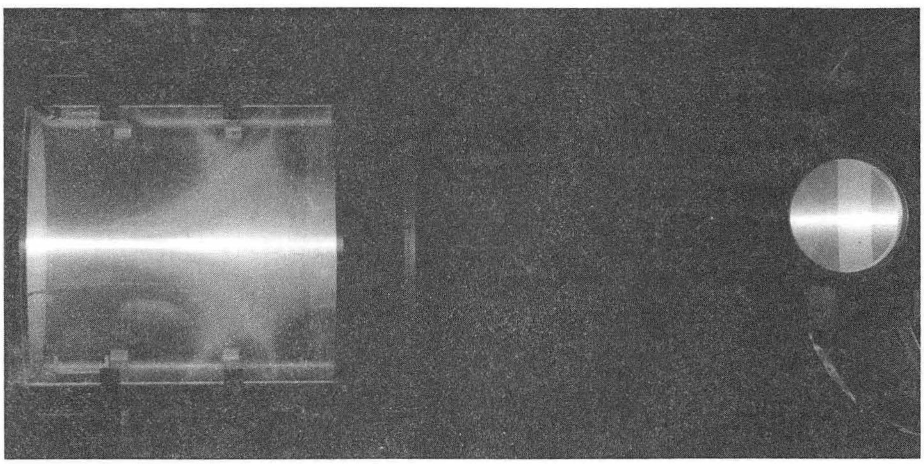

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Figure 2-5. In the experimental sheet-plasma ion source, replacement of the tungsten-wire filament by a cylindrical plasma cathode using a lanthanum hexaboride emitter enabled extraction of ions at low pressure with almost no contamination from cathode material. The flat shape of the plasma is created by a pair of linear permanent-magnet bars.

Ion-Source Chemical Physics

The development of more-efficient, higher-current negative-ion sources requires a thorough understanding of the chemical and physical processes within these devices. We have developed a technique—vacuum-ultraviolet laser absorption spectroscopy—to measure the concentrations of the neutral hydrogen species within the plasma discharge volume. The experimental details and preliminary measurements of atomic hydrogen have been discussed previously. The technique has recently been extended to measure the concentration of molecular hydrogen, the other major neutral species present.

Absorption spectroscopy allows us to measure not only the concentration of each of these species, but also the energy content, i.e., the translational energy distribution for the atoms and the translational, rotational, and vibrational energy distributions for the molecules. These measurements are critically important because the reactions governing H^- formation and destruction in volume plasma sources are sensitive to these parameters.

Figure 2-6 shows typical hydrogen-atom measurements obtained with vacuum-ultraviolet spectroscopy. Circles indicate the absorption profile obtained from a multicusp volume source; triangles mark the absorption profile of a cesiated Penning surface-conversion source. The area under each curve is a measure of the concentration.

Preliminary measurements of the hydrogen molecules in the volume source indicate that a large fraction of them are vibrationally excited; vibrational levels as

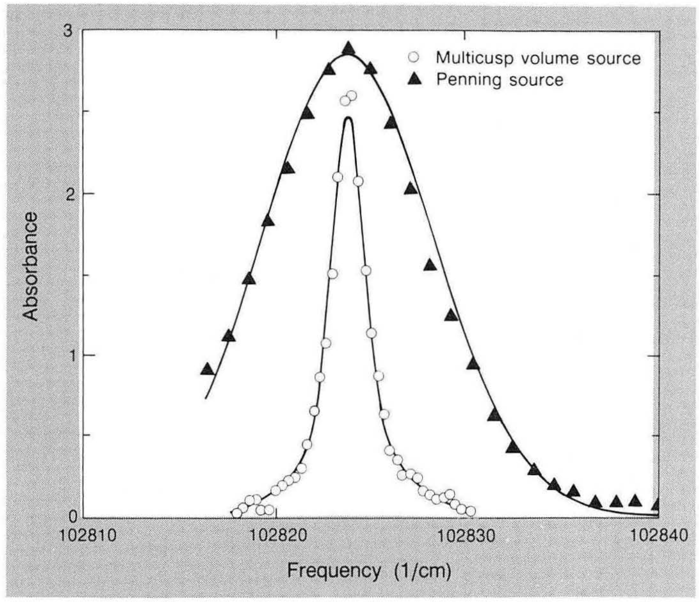

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Figure 2-6. Absorption spectra obtained through vacuum-ultraviolet (VUV) laser spectroscopy show that the Penning source (triangles) has a larger, more-energetic hydrogen-atom population than the volume source (circles). The area under each curve is a measure of the concentration. The disparity reflects a difference in the chemical physics of the two sources.

high as V = 5 have been observed. This finding agrees qualitatively with the accepted models of these sources. We are currently refining these measurements to quantitatively test the predictions of these models, especially for the higher vibrational levels, where the hydrogen-molecule population is thought to be a determining factor in H^- production.

Atomic-Nitrogen Ion Source

A spinoff from our fusion-related work on multicusp plasma sources may prove to have considerable commercial importance. In 1988 we developed a version of the small multicusp plasma source that provides an extremely pure supply of atomic-nitrogen ions (Figure 2-7).

Nitrogen-ion implantation is used industrially to increase the surface hardness and wear resistance of metals, resulting in a tremendous increase in the lifetime of tools. The implantation process also produces much smoother surfaces, resulting in less friction for contacting surfaces such as ball bearings. The quality of the hardening and smoothing is a function of the depth of implantation. For any given acceleration energy, atomic-nitrogen ions (N^+) are implanted deeper than molecular-nitrogen ions (N_2^+). The N_2^+ ions must be removed from the beam because they would result in an undesirable shallow implant layer.

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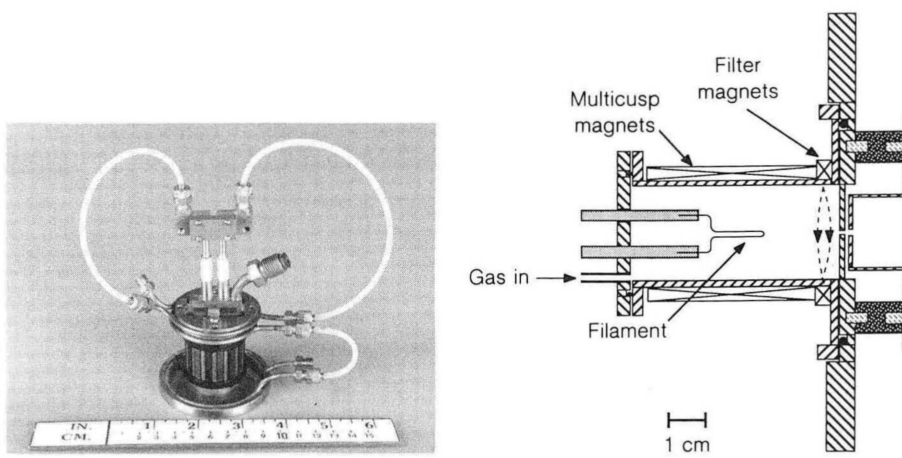

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Figure 2-7. This atomic-nitrogen ion source, a spinoff of our fusion research, could provide great technical and economic benefit to industry by serving as an ion-implantation source for hardening and smoothing metal surfaces. The desirable ions for implantation are atomic nitrogen (N^+); for effective and economical treatment, it is important to minimize the proportion of molecular-nitrogen ions (N_2^+) in the output.

Removal of N_2^+ calls for mass separation in which a large magnet is used to bend the ion beam; this imposes significant limits on implanter design by requiring relatively low-energy ion extraction and by increasing the beam path and losses. By providing nearly pure N^+, our ion source allows elimination of the mass-separation step, resulting in a simpler, more-efficient, more-compact implanter with greater throughput. In addition, this ion source can be scaled up in size; beams of very large area could provide much-faster implantation and further cost savings.

Presently, nitrogen implantation is so expensive that it is used only in items such as military hardware. By significantly reducing costs and increasing process efficiency, this source could help make nitrogen implantation cost-effective for large-scale commercial use. The resulting increase in the lifetime of tools and other items would bring economic benefits for industry and consumers.

Cathode Development

Today's fusion reactors operate only for brief periods, as exemplified by the use of the term "shots" for reactor cycles; therefore, pulsed neutral-beam sources are adequate for plasma heating. They use 20 or more tungsten filaments as electron emitters, a configuration that is not nearly durable enough for the dc or extended long-pulse operation that will be needed for upcoming tokamaks. These problems might be solved by the LaB_6 cathode, which could also prove useful as an electron emitter for high-powered free-electron lasers. We began experimenting with LaB_6 cathodes in 1986; improvements continued during 1988.

Figure 2-8 shows the latest directly heated LaB_6 cathode. This coaxial-configuration cathode was modified to reduce thermal stresses and therefore increase operating lifetime. It consists of a thin LaB_6 cylinder with a coaxial tantalum rod that carries the heater current. During startup of previous versions, uneven heating caused thermal stresses that occasionally fractured the previous LaB_6 cylinders. In the latest model, the thermal stresses are greatly reduced by a thin longitudinal slot cut through the cylindrical wall, greatly increasing the life of the cathode.

Directly heated LaB_6 cathodes are preferable for applications requiring high current output. For lower current output or situations when the available power is limited, indirectly heated cathodes are more suitable. A 2-cm-diameter, indirectly heated LaB_6 cathode was designed to replace the oxide cathode in a 2-A electron gun where only 300 W of heating power was available. This cathode (Figure 2-9) is heated by a bifilar-wound tungsten filament. Efficient heat shielding of the assembly kept the required heater power low. A temperature of 1670 K was necessary to attain the required emission current density of 78 mA/cm^2, which corresponds to a total emission current of 2.2 A. The power required to attain this temperature was 290 W (28 A at 10.25 V). The bifilar-wound filament provides an additional benefit: reducing the magnetic field perpendicular to the emitting surface to less than 4 G at operating power.

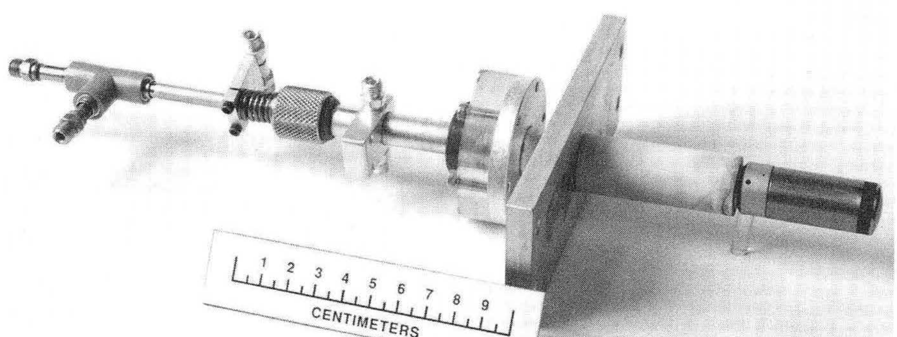

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Figure 2-8. The latest directly heated LaB_6 cathode consists of an LaB_6 cylinder (the dark disk at far right) with a tantalum rod, which carries the heater current, running through its center. Not visible in this photograph is a thin longitudinal slot cut through the cylindrical wall; the slot greatly reduces thermal stress during startup, increasing cathode life considerably.

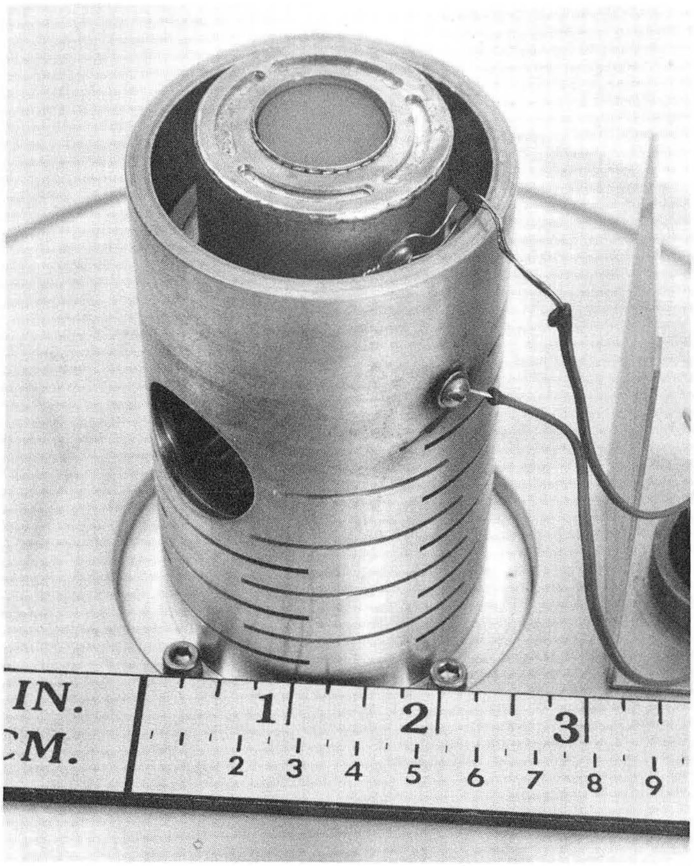

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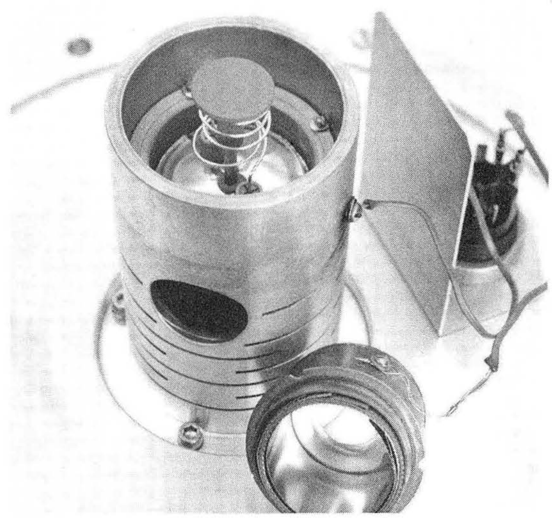
Figure 2-9. Where high current output is not important or the available power is limited, indirectly heated cathodes are preferred. This 2-cm-diameter, indirectly heated LaB_6 cathode was designed to replace the oxide cathode in a 2-A electron gun that had to operate with only 300 W of heating power. The bifilar-wound filament not only saved heater current, but also reduced the magnetic field perpendicular to the emitting surface to less than 4 G (0.4 mT) at full operating power. These photographs show the complete cathode assembly. The LaB_6 is the thin, dark disk at top center; it is violet when fresh and turns black during operation.



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Accelerators for Negative Ions

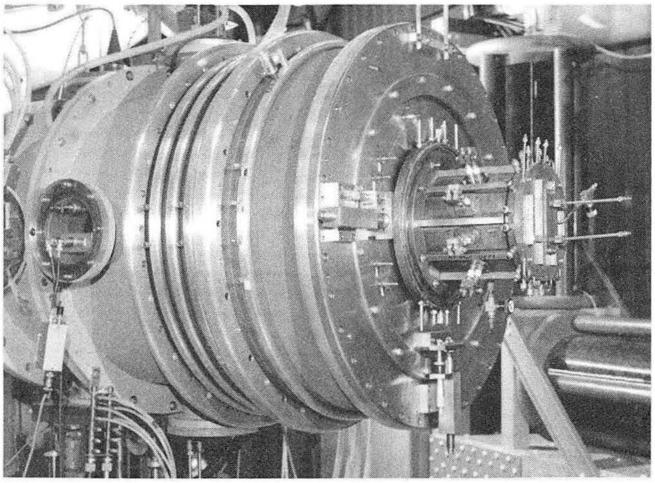
The experimental fusion reactors now being planned or proposed—the ones in which experimenters hope to attain "ignition," or a self-sustaining fusion reaction—will have substantially larger plasmas than today's reactors, so high neutral-beam energy will be crucial. In the Toroidal Ignition and Burn Experimental Reactor (TIBER) proposed in 1986, for instance, beam energies of at least 500 keV would be needed, whereas under present plans, ITER would use 1.3-MeV neutral beams. 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. (Some plasma diagnostics that examine the alpha particles produced in the fusion reaction also require that the beam energy be varied to match the velocity of the alphas.) Our efforts have been concentrated on development of high-energy negative-ion accelerators whose energy can be varied without great 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.

Constant-Current, Variable-Voltage Accelerators

Our CCVV accelerator concept 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 with the conventional technique of "ring focusing" in a Pierce-type accelerator column. And, unlike magnetic focusing, it is suitable for low-energy, high-current beams whose energy can be varied. 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 efficiently accelerate negative ions to the energy range that the next generation of tokamaks will require. Our existing 200-keV single-beam prototype system can accelerate up to 0.2 A of H^- or an equivalent current of heavier ions.

Figure 2-10 shows a modular CCVV design based on these principles. A matching-and-pumping stage, which contains the ESQ, focuses and transports a beam without acceleration; then an accelerating stage increases the beam energy by up to 100 keV. (The same type of module can also decelerate a beam if this is desired.)



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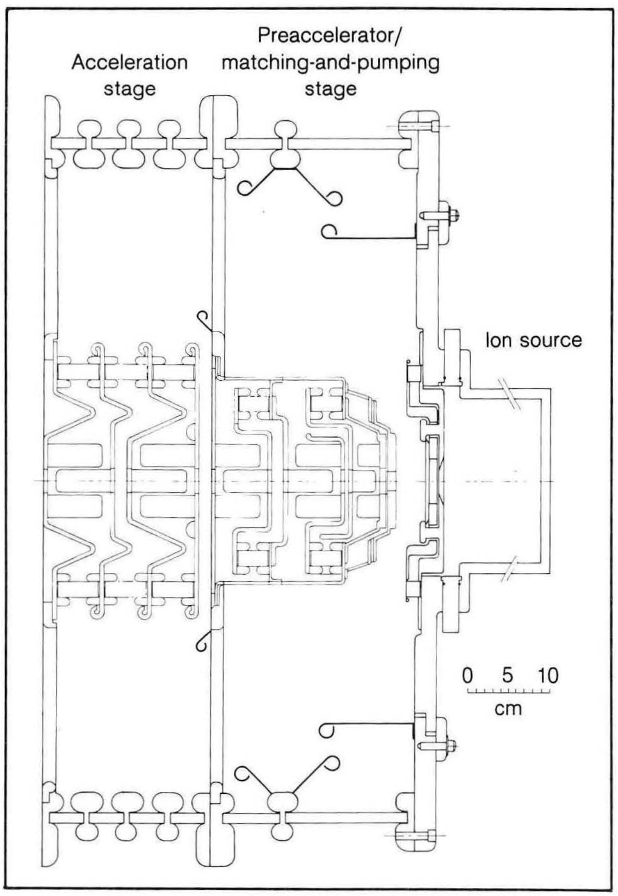
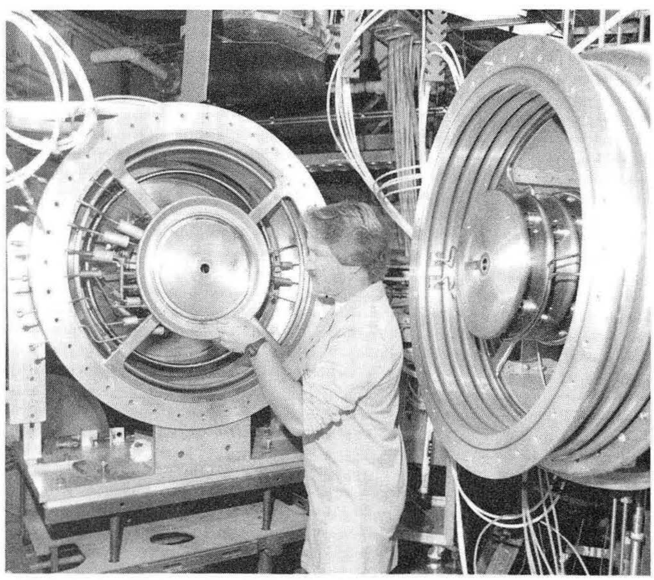


XBL 894-7101

Figure 2-10. ***Top:*** **This constant-current, variable-voltage (CCVV) accelerator module is based on electrostatic-quadrupole (ESQ) technology. The stage with the dark insulator band is the matching-and-pumping stage; to the left of it is a 100-keV acceleration stage. These modules can be cascaded to obtain the desired beam energy. The apparatus at the far left is a test stand for the accelerator; at the far right is the volume-production ion source described earlier.** ***Bottom:*** **work on the matching-and-pumping stage affords a view of the module's internal structures.**



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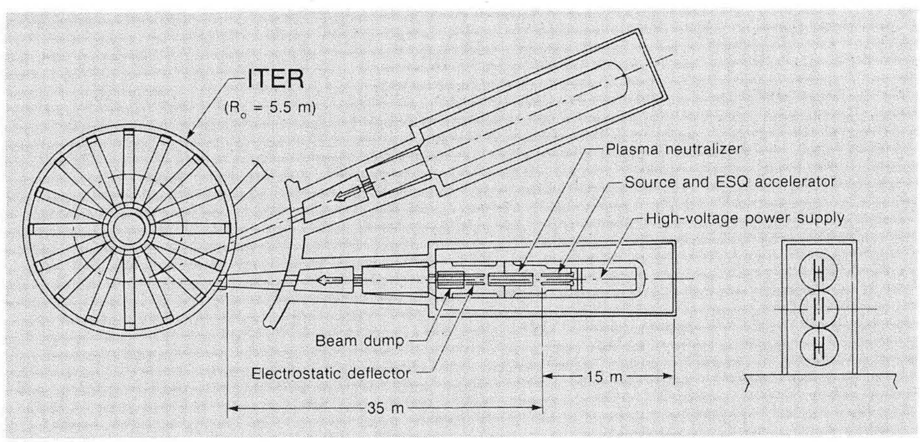
Testing is being done in two steps: first the matching-and-pumping stage is tested by itself, and then it is tested with an accelerating stage. We have transported a nearly continuous beam through the matching-and-pumping stage at up to 100 keV; when the stage is tuned properly, the beam loss can be less than a few percent. The proportion of undesirable full-energy electrons in the beam is too small to be measured—less than one or two percent. Emittance does not appear to be increased by the matching-and-pumping stage, and the characteristics of the output beams are in reasonable agreement with computer-modeled predictions. The highest beam current we transported, limited by the capabilities of the volume source we were using, was 64 mA of H^-.

Testing with the accelerator stage began early in November 1988. In an early test, we measured 32 mA of beam current entering the matching-and-pumping stage from the preaccelerator at 100 keV and 30 mA being delivered from the acceleration stage at 200 keV.

Future CCVV Systems

To construct a high-energy accelerator, we would stack the modules described above to obtain the required beam energy. In 1988 we 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 was proposed for use, in conjunction with a D^- source and a plasma neutralizer, as a neutral-beam injector for ITER. Figure 2-11 shows the proposed injection scheme.

For current-drive applications, the 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 done 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.



XBL 894-7102

Plasma Theory

Fusion research owes a great debt to complex theoretical studies. These studies are conducted on the borderline between physics and mathematics, and their practical applications (if any) are not always immediately obvious. The MFE Group at LBL maintains a plasma-theory branch whose pure and applied studies help other researchers understand the phenomena of hot plasmas in fusion reactors and the possibilities for future development.

The group's 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 geometric relationships of wave propagation in a plasma and into differences between the behavior of the incoherent waves typical of natural phenomena, as compared with coherent waves.*

Gyroresonant Energy Absorption

In 1988, most of our theoretical studies focused on gyroresonant absorption of energy by a plasma. 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 ω is either twice the local gyrofrequency $\omega_i(x)$ of a dominant ion species or the fundamental gyrofrequency $\omega_m(x)$ 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 (where x is the horizontal axis of a two-dimensional section of a tokamak) and a "pressure-anisotropy wave" that travels through wave-vector space (k-space). 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 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. The standard approach yields differential equations that must be solved numerically, i.e., through approximation using some number of sample values. Our approach uses several new techniques to replace approximate numerical solutions with explicit, exact analytical solutions. It yields values for the coefficients of absorption, reflection, conversion, and transmission, as well as for the power deposition profile.

The techniques used in our new approach 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.

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.

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