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March 1992

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Magnetic Fusion Energy

1991

Accelerator and Fusion Research Division
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

March 1992

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LBL-31520, December 1991.

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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."

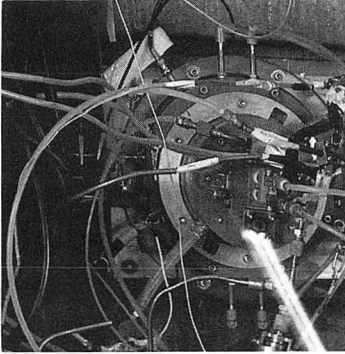
In 1971, the MFE Group took on the challenge of developing sources, accelerators, and injectors of powerful, energetic neutral beams of hydrogen and deuterium atoms for heating and fueling magnetically confined thermonuclear plasmas. These devices were initially applied to the latest mirror-fusion machine 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 DIII-D 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 1991 *Summary of Activities*. It contains brief descriptions of the major research and development activities in the Magnetic Fusion Energy Group during fiscal years 1990 and 1991.

Wulf B. Kunkel
Magnetic Fusion Energy group leader (through 1991)
William S. Cooper III
Magnetic Fusion Energy group leader



2.

MAGNETIC FUSION ENERGY

THE PROPOSED INTERNATIONAL THERMONUCLEAR EXPERIMENTAL REACTOR, or ITER, is the next logical step in the worldwide magnetic-confinement fusion program. Its goals include “ignition” of the plasma and self-sustaining “burn” for as long as two weeks at a time. Since 1988, the major portion of our Department of Energy-funded work has been directed toward this ambitious project. In 1990 and 1991, we continued refining our design for a prototype neutral-beam injection system for ITER and our proposal to build a test facility capable of accommodating a 1.3-MV negative-ion system at currents of 1 A or better. We have also continued development of ion sources and accelerators.

Our expertise in these areas is not limited to fusion research; activities have been diversified considerably during the past few years. Ion sources and accelerators have industrial uses such as ion implantation for semiconductor processing and metal surface hardening. Our program also has an academic component centering on advanced plasma theory.

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Heating a plasma to thermonuclear temperatures is one of the many significant challenges in fusion-energy research. The primary focus of the MFE Group at LBL is development of neutral-beam injector systems for this purpose. The group's 20 years of work in this field 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). It is used in the Tokamak Fusion Test Reactor (TFTR) at Princeton and the D-IIID tokamak at General Atomics, two of the principal MFE experiments now running in the U.S.

The CLPS has been highly successful, but its positive-ion approach to neutral-beam production 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. Accordingly, we 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 here and at several other 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.

After our design and testing efforts, production of ITER's complement of full-scale neutral-beam modules would be handled by private industry, as with the CLPS.

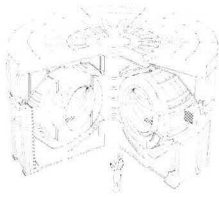
Neutral-Beam Injection for ITER

In ITER, neutral deuterium beams with a total power of about 75 MW will be injected to heat the plasma and to drive the toroidal current in the center of the plasma during steady-state operation, as shown in Figures 2-1 and 2-2 and explained in the sidebar. The energy needed to ensure the required plasma penetration, 1.3 MeV, is an order of magnitude greater than that of the CLPS. Beam steering is another necessary feature, as is steady-state operation for as long as two weeks. This combination of energy, current, and pulse length has never been achieved; further, the plasma generator and accelerator must be compatible. To meet these needs, we are proposing a neutral-beam injection system based on negative-ion sources and our constant-current, variable-voltage (CCVV) electrostatic accelerator design. A basic design is in place and is being refined in the course of extensive, ongoing interaction with our fellow participants in the ITER Engineering Design Activity.**

Neutral-Beam Test Facility Initiative

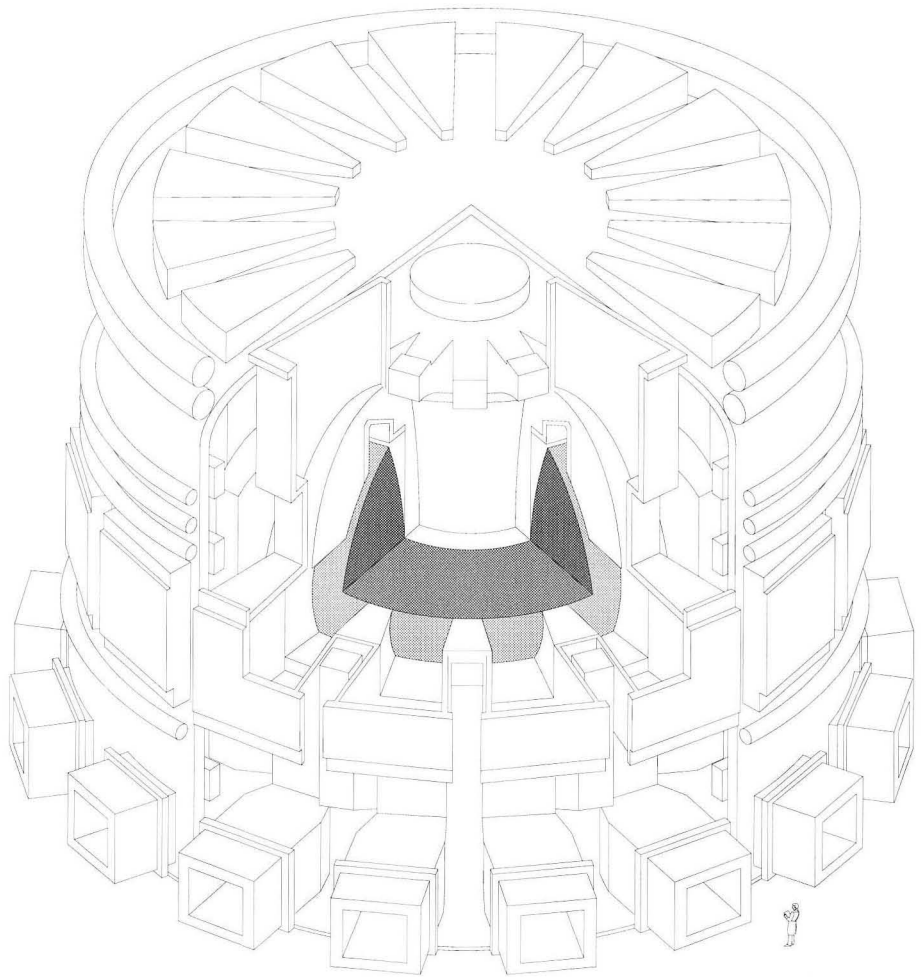
* Positive ions could be accelerated just as well at higher energies. The problem is in the neutralizer, where the desired effect, electron capture, is outweighed by the increasing probability of restripping.

** The other three ITER partners (the European Communities, the USSR, and Japan) are examining variations of a different electrostatic accelerator technology that uses electrostatic weak focusing for space-charge control and magnetic fields for secondary-particle control. Because of the risk and the tight deadline, the ITER R&D plan calls for concurrent development of both approaches.

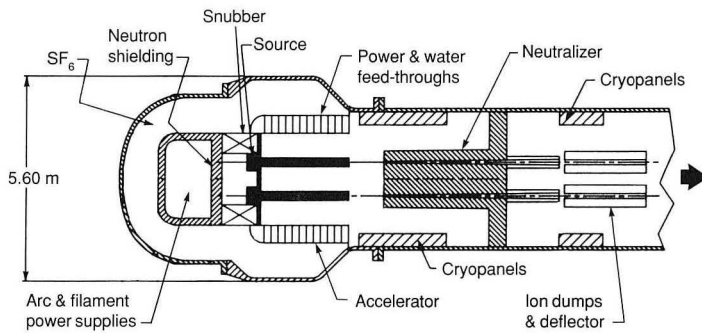


XBL 908-5557

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" (right) compares in size to that of the Tokamak Fusion Test Reactor now running at the Princeton Plasma Physics Laboratory. (above) (After PPPL and LLNL artwork.)

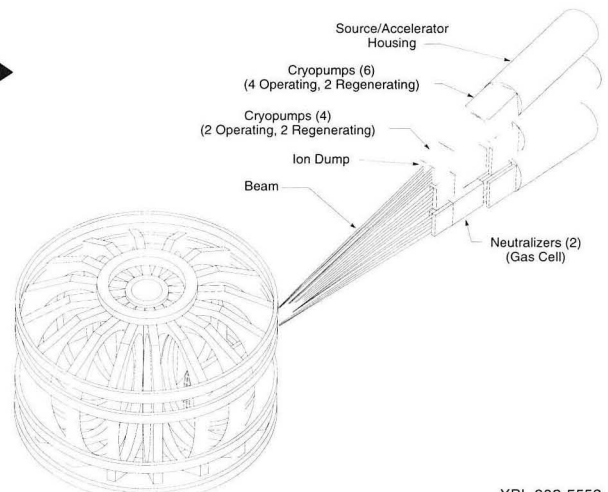


XBL 908-5560



XBL 905-1822A

Figure 2-2. The ITER conceptual design calls for three stacks of three 1.3-MeV neutral-beam injector modules 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.)

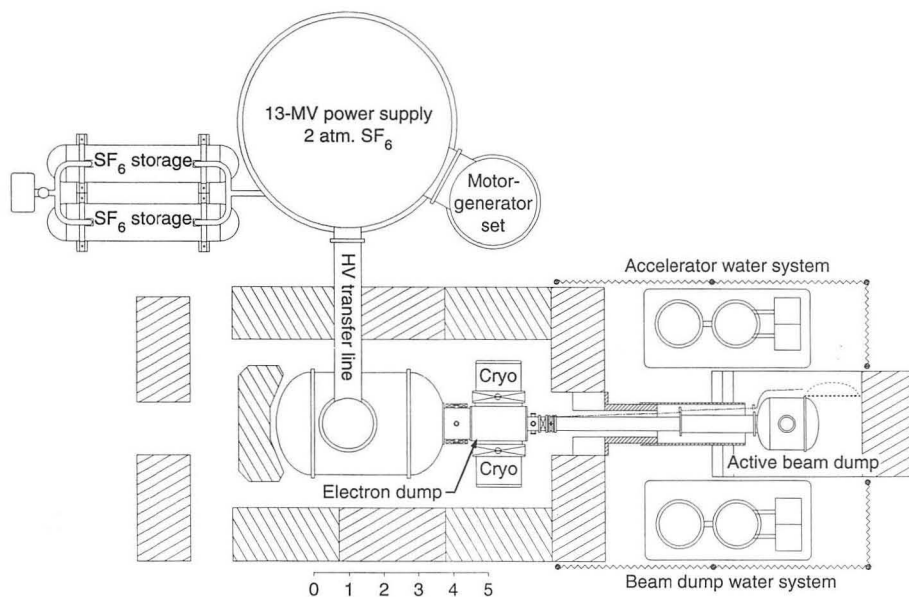


XBL 908-5558

After several years, development of the experimental CCVV accelerator has turned increasingly toward the ITER initiative. After pre-acceleration of the beam to 250 kV, a short matching stage focuses the beam and accelerates it to 300 kV; then each acceleration stage increases the beam energy by as much as 250 keV. The acceleration stages use electrostatic quadrupoles for focusing. The proposed LBL proof-of-principle test for the ITER accelerator design is shown in Figure 2-3. The hardware will be built at an existing site, suitably modified, within the Bevatron accelerator complex. This is already a controlled-access radiation area, and features such as enclosed floor space, a large overhead crane, adequate utilities, and concrete shielding blocks are available.

The goal of the test is to accelerate 1.4 A of H^- to 1.3 MeV for two seconds. This test will represent a single channel of the accelerator portion of the actual multichannel accelerator module for ITER neutral-beam injection. Each of the 16-channel ITER beam modules will also include a beam neutralizer and ion-beam dumps. The system must provide a 1.3-MeV D^0 beam that would have a current of 7.7 A if charged.

An important objective of this effort is the transfer of technology to U.S. industry. According to the ITER R&D Plan, the two accelerator designs—ours and that of the other ITER partners—will undergo proof-of-principle tests. The design that is selected will be incorporated in a Scalable Model Beamline Demonstration, which will deliver two-week-long D^0 pulses at the full energy and about one-fourth the power of an ITER neutral-beam module. Our proof-of-principle test is expected to include industrial involvement so that potential bidders in the private sector can ramp up toward the Scalable Model Beamline test and the actual ITER systems.



XBL 917-6769

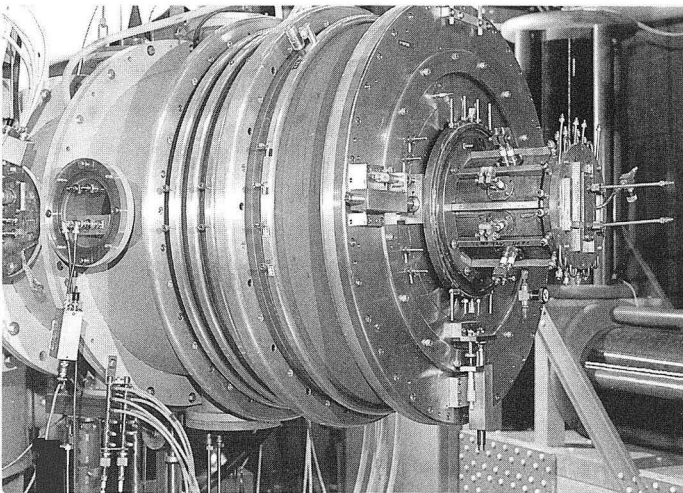
Figure 2-3. The goal of the LBL proof-of-principle test is to accelerate 1.4 A of H^- to 1.3 MeV for two seconds in this proposed facility, which could be built in the Bevalac complex. This test will represent a single channel of the accelerator portion of the actual multi-channel accelerator module for ITER neutral-beam injection. Each ITER neutral-beam module will also include a beam neutralizer. It must provide a 1.3-MeV D^0 beam that would have a current of 7.7 A if charged.

CCVV Accelerator with ESQ Focusing

The CCVV accelerator concept is at the heart of our ITER neutral-beam initiative. Thus far we have successfully tested the two-module prototype at energies as high as the design maximum of 200 keV and a current of 100 mA of He^+ in pulses of 1 s. This is equivalent in space-charge effects to the design's operating point, 140 mA of D^- . (This performance significantly exceeds the best 1989 measurement: 42 mA of H^- accelerated to an energy of 200 keV for 200 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.

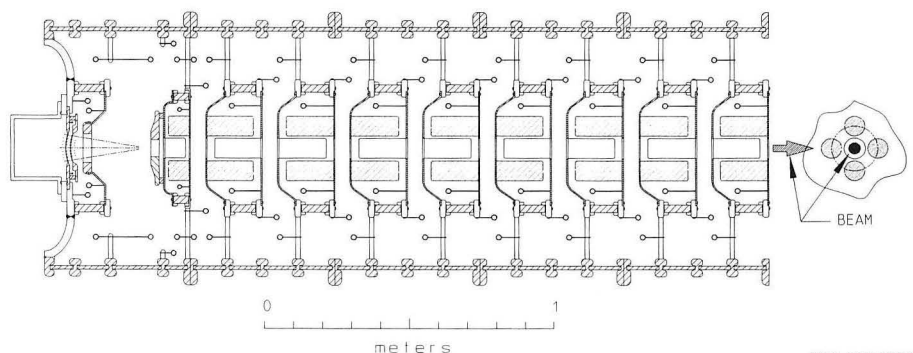
For ITER neutral-beam-injection applications, a CCVV accelerator needs to have an energy range of 2:1. The output beam energy may be varied by tuning the acceleration voltages and the ESQ focusing voltages; this may be performed rapidly without altering the accelerator's mechanical configuration. Because the electrostatic quadrupoles provide strong focusing (as contrasted with designs that depend on the accelerating electrodes for weak focusing), the energy can be varied without requiring a change in the current. The average accelerating gradient can be kept as low as 3–5 kV/cm to reduce the chance of high-voltage insulation breakdown. Another advantage is that the transverse electric fields sweep away electrons at a mean energy of 64 keV (in the ITER design), minimizing x-ray hazards. Secondary positive ions are similarly swept away.

Figure 2-4 shows the proposed accelerator in schematic form. This new accelerator will have quadrupole units approximately 2.5 times larger in length and diameter than the unit described in the 1989 *AFRD Summary of Activities*, but will use approximately the same field strength. Thus it will achieve an acceleration of 250 keV per module, reaching the final beam energy of 1.3 MeV with only four stages, given a 300-keV pre-accelerated input beam.



XBC 880-10009

Figure 2-4. The accelerator that would be used for the ITER proof-of-principle test is a CCVV accelerator with ESQ focusing, shown here in schematic form. It is a scaled-up version of one we have been working with since 1987 (*photo*) with quadrupole units approximately 2.5 times larger in length and diameter.



XBL 917-6770

An electrostatic low-energy beam transport system, or LEBT—a spinoff from our CCVV accelerator research—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) showed that the system is noise-free and stable and that it 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 could be reduced to one or two simple electrostatic ring lenses.

Since the demonstration of the electrostatic LEBT, we have pursued various lines of inquiry to make the design of such devices easier. We have derived simple analytic formulas to replace the complicated Courant-Snyder matrix system in determining various aspects of beam behavior. We have also derived improved envelope equations and incorporated them into a new modeling code, a beam envelope code called *ESQACL*. This code provides the option of using actual field maps along the beam axis and is designed to interact with a three-dimensional Poisson solver and particle code such as *ARGUS*.

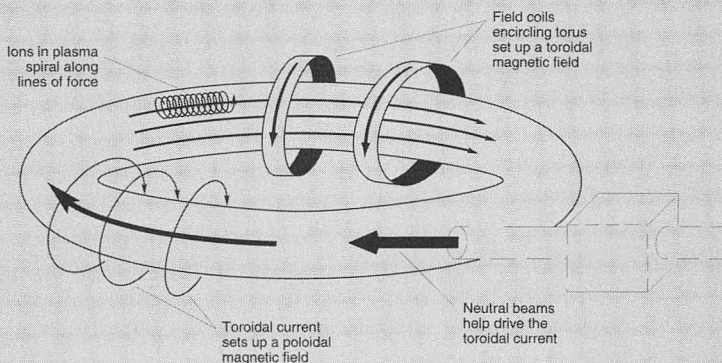
Electrostatic LEBT for High-Energy Accelerators

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: a toroidal field in the plane of the torus and a poloidal field wrapped around it, as shown below.

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-phase experiments 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 50 MW of rf power will drive the current around the edge of the plasma.



XBL 906-5559

Ion Sources

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 neutral-beam injection 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. A second 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 surface-conversion sources for very-long-pulse operation.

Volume and Surface-Conversion Sources

In volume-production sources, gas-phase reactions, as opposed to electron capture on a metal surface, play a major role in forming H^- ions. However, there is evidence that surface processes at the discharge-chamber walls are also significant (*sidebar*). In 1990 we demonstrated that H^- formation in our small multicusp source could be substantially enhanced by seeding the plasma with barium or by placing a barium washer at the extraction aperture

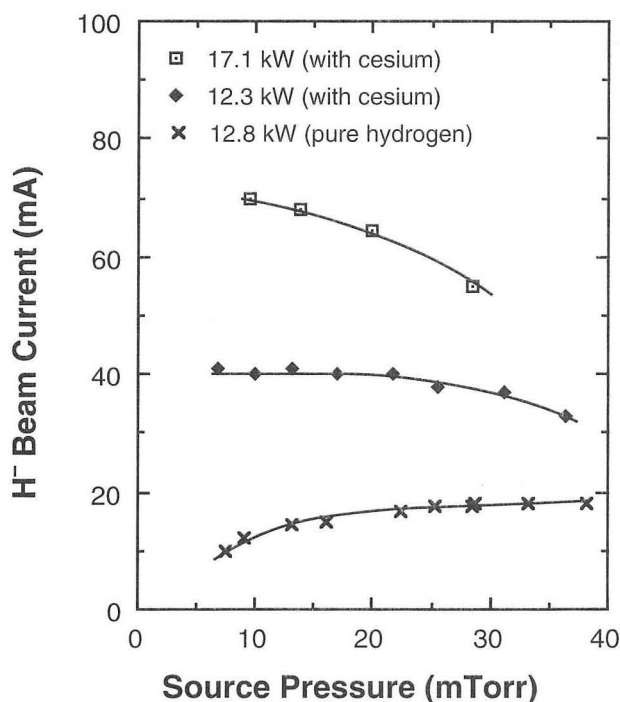


Figure 2-5. One of our volume-production sources, operated with cesium, has achieved a current of 75 mA, at a current density of 48.7 mA/cm², at the extraction aperture in a 270-ms pulse. (The plot does not show the 75-mA datum.)

XBL 908-2934A

ture.* The washer and plasma electrode were electrically isolated from the source chamber so that we could bias them at various voltages. The results clearly indicate an enhancement of the H^- signal; the enhancement process is production of H^- on the surface of the barium washer.

As shown in Figure 2-5, one of our volume-production sources, operated with cesium, achieved a current of 75 mA (current density of 48.7 mA/cm²) at the extraction aperture in a 270-ms pulse. This was a considerable achievement for long-pulse operation of large-aperture sources. Future investigations will include reducing warmup time, reducing cesium consumption (or substitution of a more benign yet equally effective material), and increasing the current density in a way that is relatively uniform across the extraction aperture.

In our ongoing work with surface-conversion sources, we have found that the production of ions at a barium converter depends heavily upon the geometry of the plasma generator. We are now testing a new source that has an annular plasma generator with the intent of optimizing the uniformity and quality of the plasma delivered to the converter. This source is designed to produce 200 mA of D^- in the steady state.

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 porcelain-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 designs. The antenna's long-term survivability in the plasma has been demonstrated; the porcelain-coated antenna can maintain a clean plasma in continuous operation for a week or more. This is an attractive feature in high-power, steady-state applications. The rf energy sets up an oscillating magnetic field, which, in turn, produces an electric field.

Since our work with it began in 1989, we have made continuing improvements in our rf-driven H^- source. A unit has been developed, under contract to AccSys Technologies, for calibration of detectors at the Superconducting Super Collider. Another is being developed for use in the SSC's

Production of Negative Ions

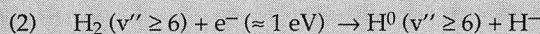
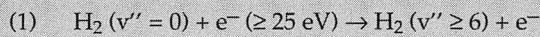
Volume production and surface conversion are two fundamentally different ways of producing negative ions. Both types begin with a gas of the desired species (hydrogen or deuterium in our work) that is partially ionized by any of several means, but thereafter the two methods diverge at the level of basic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

In surface conversion, a negatively charged element (either a coated converter/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 the adsorbed atoms out of the surface; the atoms that are sputtered out can emerge as negative ions.

The sheath of positive ions that surrounds 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:

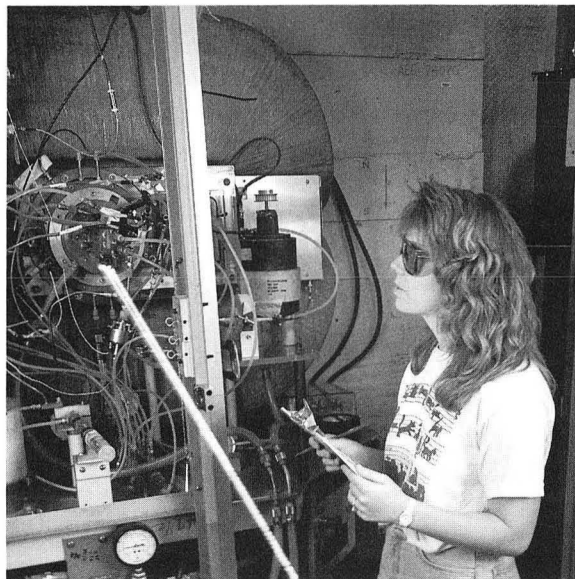


Reaction (2) can also work in reverse, which is thought to be an important mechanism for H^- loss in the discharge.

RF-Driven H^- Source

* These are two fundamentally different approaches. The "seed" pellets of barium are placed in the bottom of the source; they are consumed in the discharge and the barium becomes a component of the plasma. The washer, on the other hand, acts as a conversion surface.

Figure 2-6. We recently succeeded in using a nitrogen-laser photocathode system to start the rf-driven H^- source. This scheme will enable us to eliminate the tungsten filament, which has a limited lifetime and contributes impurities to the plasma.



injection system, either as a backup for a more-conventional H^- source or, possibly, as the primary injection source.

The rf-driven H^- source needs a supply of electrons to ensure reliable plasma breakdown when the rf is applied. Traditionally, the electrons have been provided by a small filament. We recently succeeded in using a photocathode system to trigger the rf-driven source. In this set-up, shown in Figure 2-6, a beam of light from a nitrogen laser illuminated the cathode surface through a small window in the back flange of the ion source. When using magnesium as the photocathode, we found that the photoemission current was large enough to start a discharge in either hydrogen or argon. This photocathode scheme will enable us to eliminate the tungsten filament, which has a limited lifetime and contributes impurities to the plasma.

As part of a study of the H^- production mechanism in rf plasmas, we measured the electron energy distribution. Langmuir-probe samplings taken at different phases of the rf cycle indicate that the electron density does not vary significantly during the cycle.

Cyclotron Mass Spectrometer

In collaboration with LBL's Physics Division, we recently began development of a compact axial-injection research cyclotron based on permanent magnets rather than the usual electromagnets. The new instrument will be used for ultrasensitive accelerator mass spectrometry, replacing the bulky, cumbersome, and much more expensive van de Graaff generators usually employed for this purpose. With its combination of sensitivity and small size—it will be portable, though not in the sense of being carried by hand—the system will have the potential for great practical benefit. For example, exhausts and effluents could be checked for minute quantities of hazardous materials. Moreover, the instrument's predicted sensitivity will allow detection of tiny tracer concentrations of ^{14}C , opening the door to many potential applications in environmental science, biomedical research, and archeology. To facilitate ^{14}C tracer work, the effort also encompasses optimization of an ion source that uses gaseous CO or CO_2 rather than sputtering of solid graphite.

The performance, durability, and economic attractiveness of today's high-technology products are often predicated upon specialized materials and upon effective, affordable techniques for manufacturing them. A branch of the MFE Group, in close interdisciplinary collaboration with colleagues from LBL and elsewhere, investigates plasma and ion-beam techniques for modifying and synthesizing materials. The program has three parts: development of the Metal Vapor Vacuum Arc (Mevva) ion source, research on techniques for depositing metallic thin films and multilayers using metal-plasma guns, and attempts to deposit industrially useful diamond coatings on surfaces.

In 1990 and 1991 we continued development of the fifth version of the Metal Vapor Vacuum Arc ion source (Mevva V, shown in Figure 2-7), characterizing its output and integrating it fully into our activities. The Mevva program comprises three parallel components: ion-source development, ion-beam characterization, and ion-implantation research. Mevva V, built in 1989, is designed specifically for implanting ions in the surfaces of metals. The features of this pulsed source include high current (more than 1 A at peak), broad extracted beam area (10 cm diameter), and, with the 18-cathode "Gatling gun," easy switching from one ion species to another.

The major challenge ahead is development of a direct-current (continuous-beam) Mevva ion source. This requires not only a dc version of the plasma arc itself, but also an extraction area of unusually large cross section to accommodate the high-power beam. Thus far, we have demonstrated dc production of a metal plasma with ion currents as high as 6 A at the extractor location. A 600-mA, 20-keV dc beam of Ti has been produced using an 18-cm-diameter extractor, and a 10-A, 100-keV pulsed beam of Ti has been formed with a 50-cm-diameter extractor (Figure 2-8). Our goal is to integrate these technologies, producing a dc beam with the very large extractor.

The Mevva V test stand has evolved into what may be considered a complete "Mevva ion implantation facility." Ions of 49 different elements have been used, and the effectiveness of the Mevva technology for high-dose metal-ion implantation has been successfully and thoroughly demonstrated.

Materials Modification and Synthesis

Mevva Development and "Mini-Programs"

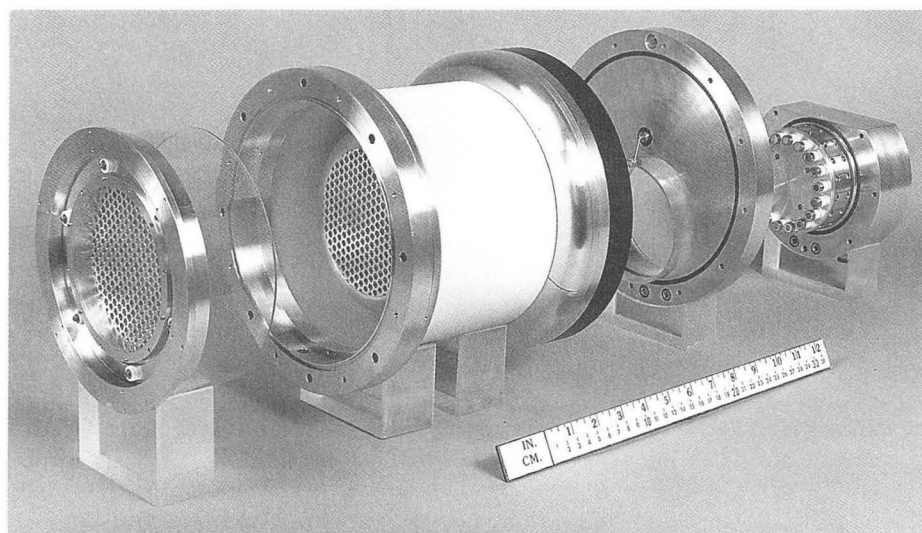
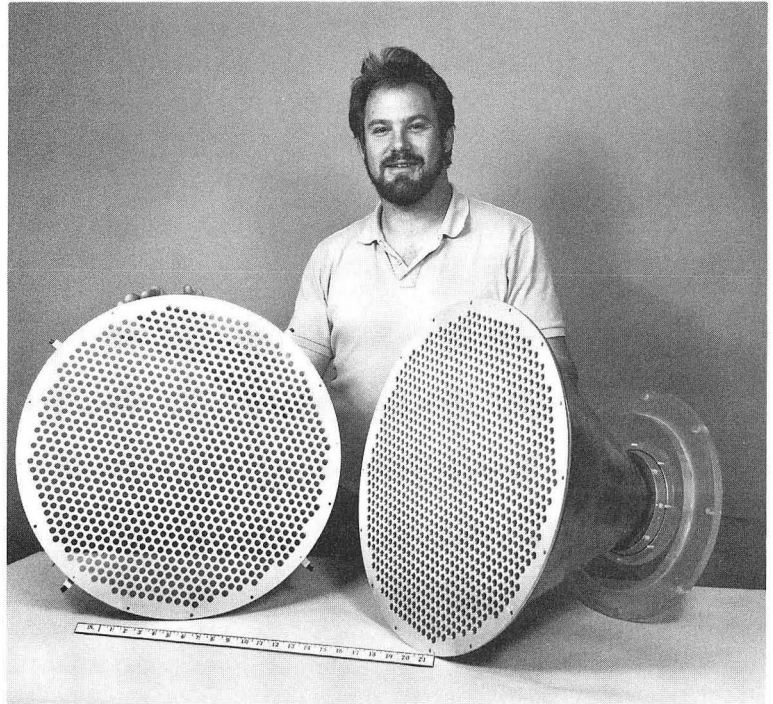


Figure 2-7. The Mevva V ion source was designed specifically for ion implantation. It incorporates a broad-beam extractor (10 cm in diameter) and a multiple cathode assembly (18 separate cathodes). The "Gatling gun" cathode array, like the Mevva concept itself, is a fairly direct spinoff from injector research and development for the SuperHILAC heavy-ion linear accelerator.

CBB 892-1124

Figure 2-8. This set of 50-cm-diameter beam-formation electrodes was used to produce a 10-A, 100-keV beam of Ti ions.



CBB 913-1344

We have carried out a wide range of ion-implantation “mini-programs” to demonstrate its applications. Recent additions to our program of collaborative investigations include tribology (the study of frictional characteristics), anomalously deep penetration into a metallic surface, corrosion resistance, and hydrogen embrittlement.

Metallic Thin Films and Multilayers

A new part of our research program, recently funded by the DOE Office of Basic Energy Sciences, will further the applications of our pulsed-metal-plasma-gun technique for fabricating metallic superlattices, multilayers, and thin films—items interesting both for fundamental science and for applications. Multilayers will be synthesized that are relevant to x-ray optics and to magnetic and magneto-optical recording media. Fabrication of thin films of high-temperature superconductors will also be investigated. Our program, in collaboration with materials scientists at LBL and elsewhere, will apply the technique in these three fields. This fabrication technique is new and has not yet been explored except in our preliminary testing.

Diamond Synthesis

Along with LBL’s Materials 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. We are now able to grow uniform films of high purity and good crystallinity on substrates of silicon and silicon nitride 1 inch in diameter. The next step is to investigate 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.

The MFE Group at LBL maintains a plasma-theory branch operating in the borderland where physics blends into mathematics. Their 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.

The immediate purpose of this work is to understand heating and transport in plasmas—in particular, gyroresonant absorption of energy. Ion cyclotron range of frequency (ICRF) heating, one of the important 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 matches 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. We have obtained the first completely explicit, analytic formula for the conversion coefficient of a magnetosonic wave into an ion Bernstein wave, and also for collisionless absorption associated with the passage of a magnetosonic wave across a minority-ion gyroresonance layer. These results, based on a slab model, agree well with numerical approximations that came from solving the wave equations on a computer. The next step in this research is to treat realistic tokamak geometries.

Working with realistic tokamak geometries, we have come up with the first analytic solution to the reflection problem. In this work, we studied the interaction and propagation of ballistic waves as the mechanism by which magnetosonic waves are reflected by the gyroresonant layer.

The systematic treatment of guiding-center and oscillation-center plasma dynamics by Lie transform methods has been extended from the Hamiltonian Vlasov equation to irreversible kinetic equations describing collisions or other statistical effects. And the linearized Vlasov-Maxwell system, heretofore treated as non-self-adjoint, has been shown to have a Hermitian structure in a Hilbert space with indefinite metric.

A new formulation of wave propagation for multicomponent fields has led to significant corrections to the Bohr-Sommerfeld quantization condition for eigenmodes. This work has applications wherever the Bohr-Sommerfeld quantization condition applies, including not only confined plasmas but also molecular and nuclear structure. In this work, the use of Gutzwiller trace formulas in quantum chaos is interpreted in terms of the geometry of Lagrangian manifolds, leading to deeper understanding and simpler derivations. Because most real systems have some symmetry (leading to conservation laws), the Gutzwiller trace formula has also been generalized to deal with symmetry.

Plasma Theory and Nonlinear Dynamics

Wave Dynamics and Gyroresonant Energy Absorption

Publications and Presentations

Ion and Plasma Sources

I.G. Brown, "Metal vapor vacuum arc ion sources," invited paper, 1991 International Conference on Ion Sources (Bensheim, Germany, 1991).

I.G. Brown and J.C. Kelly, "Charge-to-mass separation in a current coaxial lens," *J. Appl. Physics* **68**, 6368 (1990).

I.G. Brown and H. Shiraishi, "Cathode erosion rates in vacuum arc discharges," *IEEE Trans. Plasma Sci.* **PS-18** (1990), p. 170.

Ian G. Brown and Xavier Godechot, "Vacuum arc ion charge state distributions," in *Proceedings of the Fourteenth International Symposium on Discharges and Electrical Insulation in Vacuum* (Santa Fe, NM, 1990), *IEEE Trans. Plasma Sci.* **PS-19** (in press); Lawrence Berkeley Laboratory report LBL-29244 (1990).

I.G. Brown, J.E. Galvin, R.A. MacGill, and F.J. Paoloni, "A broad-beam multi-ampere metal ion source," in *Proceedings of the International Conference on Ion Sources* (Berkeley, CA, 1989), *Rev. Sci. Instrum.* **61** (1990), p. 577.

I.G. Brown, M.R. Dickinson, J.E. Galvin, and R.A. MacGill, "Development of dc broad beam Mevva ion source," 1991 International Conference on Ion Sources (Bensheim, Germany, 1991).

I.G. Brown, M.R. Dickinson, J.E. Galvin, X. Godechot and R.A. MacGill, "Metal vapor vacuum arc ion sources," 14th International Symposium on Discharges and Electrical Insulation in Vacuum (Santa Fe, NM, 1990); Lawrence Berkeley Laboratory report LBL-28703 (1990).

I. Brown and X. Godechot (LBL) and P. Spädtke, H. Emig, D. Rück and B. Wolf (GSI), "Review of MEVVA ion source performance for accelerator injection," *IEEE Particle Accelerator Conference* (San Francisco, CA, 1991); Lawrence Berkeley Laboratory report LBL-29913 (1990).

I.G. Brown (LBL) and P. Spädtke, H. Emig, D.M. Rück, and B. Wolf (GSI), "Beam intensity fluctuation characteristics of the metal vapor vacuum arc ion source," *Nucl. Instrum. Meth. A* **295**, 12 (1990).

Publications and Presentations

W.S. Cooper and W.B. Kunkel, "High-brightness H^- ion source," NPB Technical Symposium and Scientific Interchange (Boulder, CO, 1991).

I.S. Falconer, A.J. Studer, P.D. Swift, B.W. James, D.R. McKenzie, I.G. Brown, and X. Godechot, "Time evolution of the cathode spot plasma in metal vapor vacuum arcs," 43rd Annual Gaseous Electronics Conference (Urbana, Illinois, 1990).

J.E. Galvin, I.G. Brown, and R.A. MacGill, "Charge state distribution studies of the metal vapor vacuum arc ion source," in *Proceedings of the International Conference on Ion Sources* (Berkeley, CA, 1989), *Rev. Sci. Instrum.* **61** (1990), p. 583.

Xavier Godechot and Ian Brown, "Low energy metal ion beam source," 17th IEEE International Conference on Plasma Science (Oakland, CA, 1990); Lawrence Berkeley Laboratory report LBL-28498a (1990).

X. Godechot and I. Brown, "Low energy metal ion source," accepted for publication in *J. Vac. Sci. Tech. A*; Lawrence Berkeley Laboratory report LBL-30791 (1991).

W.B. Kunkel, "Giant ion sources of neutral beam injectors for fusion," invited paper, *Rev. Sci. Instrum.* **61**, 354 (1990).

W.B. Kunkel, K.N. Leung and C.F.A. van Os, " H^- enhancement process in a multicusp ion source," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); abstract also published in Lawrence Berkeley Laboratory report LBL-29221 (1990).

J.W. Kwan, G.D. Ackerman, O.A. Anderson, C.F. Chan, W.S. Cooper, G.J. deVries, W.B. Kunkel, K.N. Leung, and R.P. Wells, "Testing of a long pulse cesiated volume-production H^- source," abstract submitted to the 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); abstract also published in Lawrence Berkeley Laboratory report LBL-29221 (1990).

J.W. Kwan, G.D. Ackerman, O.A. Anderson, C.F. Chan, W.S. Cooper, G.J. deVries, W.B. Kunkel, K.N. Leung, P. Purgalis, W.F. Steele, and R.P. Wells, "Testing of an advanced "volume" H^- source

and pre-accelerator," *Rev. Sci. Instrum.* **62** (June 1991); also published as Lawrence Berkeley Laboratory report LBL-29664 (1990).

J.W. Kwan, G.D. Ackerman, O.A. Anderson, C.F. Chan, W.S. Cooper, G.J. deVries, K.N. Leung, A.F. Lietzke, and W.F. Steele, "Operation of a dc large aperture volume-production H^- source," *Rev. Sci. Instrum.* **61**, 1 (1990) 369.

J.W. Kwan, G.D. Ackerman, O.A. Anderson, C.F. Chan, W.S. Cooper, G.J. deVries, W.B. Kunkel, W.F. Steele, and R.P. Wells, "Optimization of the LBL advanced source," abstract submitted to the NPB Technical Symposium and Scientific Interchange (Boulder, CO, 1991).

Ka-Ngo Leung, "Research and development of volume H^- source for NPB application," submitted to the Second Neutral Particle Beam Technical Symposium and Scientific Interchange (Naval Ocean Systems Center, San Diego, CA 1990).

K.N. Leung, "State of H^- source development," in *Proceedings of the 1991 IEEE Particle Accelerator Conference* (San Francisco, CA, 1991); Lawrence Berkeley Laboratory report LBL-30402 (1990).

K.N. Leung, "Review of high brightness H^- sources," in classified *Proceedings of the Second Neutral Particle Beam Technical Symposium* (Naval Ocean Systems Center, San Diego, CA, 1990).

K.N. Leung, C.F.A. van Os, and W.B. Kunkel, " H^- enhancement process in a multicusp ion source operated with a barium insert structure," *Appl. Phys. Lett.* **58**, 14 (1991).

K.N. Leung, C.F.A. van Os, and W.B. Kunkel, " H^- enhancement process in a multicusp ion source operated with a barium insert structure," submitted to *Phys. Rev. Lett.* (1990); also published as Lawrence Berkeley Laboratory report LBL-29226 (1990).

K.N. Leung, C.F.A. van Os, and W. B. Kunkel, " H^- enhancement process in a multicusp source operated with an insert structure," NPB Technical Symposium and Scientific Interchange (Boulder, CO, 1991).

K.N. Leung, G.J. DeVries, W.F. DiVergilio, R.W. Hamm, C.A. Hauck, W.B. Kunkel, D.S. McDonald and M.D. Williams, "Characteristics of an rf driven H^- ion

source," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); abstract also published in Lawrence Berkeley Laboratory report LBL-29221 (1990).

K.N. Leung, G.J. DeVries, W.F. DiVergilio, R.W. Hamm, C.A. Hauck, W.B. Kunkel, D.S. McDonald, and M.D. Williams, "RF driven multicusp H^- ion source (U)," *Rev. Sci. Instrum.* **62**, 100 (1991); also published as Lawrence Berkeley Laboratory report LBL-29315 (1991).

K.N. Leung, O.A. Anderson, C.F. Chan, W.S. Cooper, G.J. deVries, C.A. Hauck, W.B. Kunkel, J.W. Kwan, A.F. Lietzke, P. Purgalis, and R.P. Wells, "Development of an advanced "volume" H^- source for neutral beam application," *Rev. Sci. Instrum.* **61**, 9 (1990); also published as Lawrence Berkeley Laboratory report LBL-27506 (1990).

K.N. Leung, W.F. DiVergilio, R.W. Hamm, C.A. Hauck, W.B. Kunkel and M.D. Williams, "Development of an rf driven H^- ion source," Second Neutral Particle Beam Technical Symposium and Scientific Interchange (Naval Ocean Systems Center, San Diego, CA, 1990).

K.N. Leung, W.F. DiVergilio, C.A. Hauck, W.B. Kunkel and D.S. McDonald, "Optimization of an rf driven H^- source," 1991 IEEE Particle Accelerator Conference (San Francisco, CA, 1991); Lawrence Berkeley Laboratory report LBL-29961 (1991).

C. Y. Li, C.H. Dittmore, W.B. Kunkel, K.N. Leung, L.G. Wiley, and M.D. Williams, "Production of pure H^+ , N^+ , C^+ and C^- ion beams," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); abstract also published in Lawrence Berkeley Laboratory report LBL-29221 (1990).

R.A. MacGill, I.G. Brown, and J.E. Galvin, "Some novel design features of the LBL metal vapor vacuum arc ion sources," in *Proceedings of the International Conference on Ion Sources* (Berkeley, CA, 1989), *Rev. Sci. Instrum.* **61** (1990), p. 580.

J. Sasaki and I.G. Brown, "Ion spectra of metal vapor vacuum arc ion sources with compound and alloy cathodes," in *Proceedings of the International Conference on Ion Sources* (Berkeley, CA, 1989), *Rev. Sci. Instrum.* **61** (1990), p. 586.

H. Shiraishi and I.G. Brown, "Operational characteristics of a metal vapor vacuum arc ion source," in *Proceedings of the International Conference on Ion Sources* (Berkeley, CA, 1989), *Rev. Sci. Instrum.* **61** (1990), p. 589.

Hiroshi Shiraishi and Ian G. Brown, "Performance of a high-current metal vapor arc ion source," *Rev. Sci. Instrum.* **61**, 12 (1990), p. 3775.

A. Studer, I.S. Falconer, P.D. Swift, B.W. James, D.R. McKenzie, I.G. Brown, and X. Godechot, "The evolution of pulsed metal vapor vacuum arcs," *Plasma Technology Conference 1991*, Sydney University (Sydney, Australia, 1991).

C.F.A. van Os, K.N. Leung, and W.B. Kunkel, "H⁻ production from a barium converter with different discharge configurations," *Appl. Phys. Lett.* **57**, 9 (1990); also published as Lawrence Berkeley Laboratory report LBL-28835 (1990).

C.F.A. van Os, K.N. Leung, and W.B. Kunkel, "Plasma-generator-induced effects on the dynamics of a negative-ion surface conversion source," *J. Appl. Phys.* **69**, 6 (1991).

C.F.A. van Os, A.F. Lietzke, K.N. Leung, and W.B. Kunkel, "Development of a large area, low pressure surface conversion source aimed at producing 200 mA of D⁻ in steady state," 1991 IEEE Particle Accelerator Conference (San Francisco, CA, 1991); Lawrence Berkeley Laboratory report LBL-29975a (1991).

C.F.A. van Os, J.W. Stearns, A.F. Lietzke, K.N. Leung, and W.B. Kunkel, "A dc low-pressure D⁻ source for ITER neutral beam system," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); abstract also published in Lawrence Berkeley Laboratory report LBL-29221 (1990).

M. Wada, R.V. Pyle, and J.W. Stearns, "Dependence of H⁻ production upon the work function of a Mo surface in a cesiated hydrogen discharge," *J. Appl. Phys.* **67**, 10 (1990).

B.H. Wang, I.J. Amster, F.W. McLafferty, and I.G. Brown, "Metal vapor vacuum arc as a primary ion source for secondary-ion mass spectrometry," *Int. J. Mass Spectrom. Ion Processes* **100**, 51 (1990).

M.D. Williams, K.N. Leung, G.M. Brennan and D.R. Burns, "Testing of a H₂⁺-enriched ion source for deuterium simulation," *Rev. Sci. Instrum.* **61**, 1 (1990); also published as Lawrence Berkeley Laboratory report LBL-26824-R (1990).

M.D. Williams, K.N. Leung, P. Purgalis and S. Wilde, "Development and application of directly-heated planar LaB₆ cathodes," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); abstract also published in Lawrence Berkeley Laboratory report LBL-29221 (1990).

A.T. Young, G.C. Stutzin, K.N. Leung, and W.B. Kunkel, "Analysis of a H⁻ ion source discharge," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); abstract also published in Lawrence Berkeley Laboratory report LBL-29221 (1990).

A.T. Young, G.C. Stutzin, K.N. Leung, and W.B. Kunkel, "H⁻ formation in volume-production ion sources," NPB Technical Symposium and Scientific Interchange (Boulder, CO, 1991).

A.T. Young, P. Chen, W.B. Kunkel, K.N. Leung, C.Y. Li (LBL) and J.M. Watson (SSC Laboratory), "Quantum yield measurements of photocathodes illuminated by pulsed ultraviolet laser radiation," 1991 IEEE Particle Accelerator Conference (San Francisco, CA, 1991); Lawrence Berkeley Laboratory report LBL-29976a (1991).

A.T. Young, P. Chen, W.B. Kunkel, K.N. Leung, C.Y. Li, and G.C. Stutzin, "Laser diagnostics of H⁻ formation in a magnetic multicusp ion source," 1991 IEEE Particle Accelerator Conference (San Francisco, CA, 1991); Lawrence Berkeley Laboratory report LBL-29987a (1991).

Beam Physics and Technology

O.A. Anderson, "Non-matrix analysis of AG problems with space charge," in *Proceedings of the 2nd European Particle Accelerator Conference* (Nice, France, 1990); also published as Lawrence Berkeley Laboratory report LBL-29074 (1990); abstract also published as Lawrence Berkeley Laboratory report LBL-28228a (1990).

O.A. Anderson and L. Soroka, "A high-current MV dc electron accelerator," 1991 IEEE Particle Accelerator Conference (San

MAGNETIC FUSION ENERGY

Francisco, CA, 1991); abstract also published in Bull. Am. Phys. Soc. (1991).

O.A. Anderson and L. Soroka, "New design procedures for an advanced electrostatic LEBT," NPB Technical Symposium and Scientific Interchange (Boulder, CO, 1991).

O.A. Anderson, G.D. Ackerman, C.F. Chan, W.S. Cooper, G.J. deVries, W.B. Kunkel, J.W. Kwan, L. Soroka, and R.P. Wells, "Testing the CCVV accelerator with He⁺ beams," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); abstract also published in Bull. Am. Phys. Soc. (1990).

O.A. Anderson, L. Soroka, C.F. Chan, R.P. Wells, G. Koehler, W.S. Cooper and W.B. Kunkel, "1A/channel ESQ D⁻ accelerator for ITER neutral beam injection," 17th EPS Conference on Controlled Fusion and Plasma Heating (Amsterdam, The Netherlands, 1990); also published as Lawrence Berkeley Laboratory report LBL-28593 (1990).

O.A. Anderson, L. Soroka, J.W. Kwan and R.P. Wells, "Application of electrostatic LEBT to high energy accelerators," in *Proceedings of the 2nd European Particle Accelerator Conference* (Nice, France, 1990); abstract also published as Lawrence Berkeley Laboratory report LBL-28227a (1990).

O.A. Anderson, L. Soroka, J.W. Kwan, and R.P. Wells, "Electrostatic LEBT for beam transport and matching into an RFQ," abstract submitted to the Second Neutral Particle Beam Technical Symposium (Naval Ocean Systems Center, San Diego, CA, 1990).

O.A. Anderson, L. Soroka, R.P. Wells, W.S. Cooper, and W.B. Kunkel, "1 ampere/channel ESQ D⁻ accelerator for ITER neutral beam injection," synopsis for the IAEA 13th International Conference on Plasma Physics and Controlled Nuclear Fusion Research (Washington, D.C., 1990); Lawrence Berkeley Laboratory report LBL-28828 (1990).

O.A. Anderson, W.B. Kunkel, W.S. Cooper, A.F. Lietzke, K.N. Leung, C.F.A. van Os, L. Soroka, J.W. Stearns, and R.P. Wells, "1 ampere/channel D⁻ source and ESQ accelerator for fusion reactor neutral beam injection," combined extended synopsis for the IAEA 13th International Conference on Plasma Physics and Controlled Nuclear Fusion Research (Washington, D.C., 1990); Lawrence Berkeley Laboratory report LBL-28957 (1990).

O.A. Anderson, W.S. Cooper, W.B. Kunkel, K.N. Leung, A.F. Lietzke, C.F.A. van Os, L. Soroka, J.W. Stearns, and R.P. Wells (LBL) and M. Matsuoka, Y. Okumura, M. Akiba, M. Araki, M. Hanada, T. Inoue, H. Kojima, M. Kuriyama, Y. Matsuda, M. Mizuno, Y. Ohara, M. Seki, S. Tanaka, and K. Watanabe (JAERI), "Negative ion source and accelerator systems for neutral beam injection in large tokamaks Part A: 1 ampere/channel D⁻ source and ESQ accelerator for fusion reactor neutral beam injection," in *Proceedings of the 13th International Conference on Plasma Physics and Controlled Nuclear Fusion Research* (IAEA) (Washington, D.C., 1990), in press; also published as Lawrence Berkeley Laboratory report LBL-29539 (1990).

C.F. Chan, O.A. Anderson, W.S. Cooper, A.F. Lietzke, and L. Soroka, "Optic design of an 1-amp preaccelerator for surface conversion D⁻ source," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); abstract also published in Lawrence Berkeley Laboratory report LBL-29221 (1990).

W.S. Cooper, "Reliability analysis of an ITER neutral beam system," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); abstract also published in Bull. Am. Phys. Soc. (1990).

J.W. Kwan, G.D. Ackerman, O.A. Anderson, W.S. Cooper, C.F. Chan, G.J. deVries, W.B. Kunkel, L. Soroka, W.F. Steele, and R.P. Wells, "Testing of a high current dc ESQ accelerator," 1991 IEEE Particle Accelerator Conference (San Francisco, CA, 1991); Lawrence Berkeley Laboratory report LBL-29974 (1991); abstract also published as Lawrence Berkeley Laboratory report LBL-29974a (1991).

Peter Purgalis and the LBL ITER team, "ITER neutral beam system, U.S. conceptual design," ITER Neutral Beam Specialists Meeting (Garching, Germany, 1990).

P. Purgalis, O.A. Anderson, C.F. Chan, W.S. Cooper, G.J. DeVries, W.B. Kunkel, J.W. Kwan, A.F. Lietzke, L. Soroka, and R.P. Wells (LBL); W.B. Lindquist and L.L. Reginato (Lawrence Livermore National Laboratory); and D. Sedgley (Grumman Space Systems Division), "ITER neutral beam system update," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); abstract also

published in Lawrence Berkeley Laboratory report LBL-29221 (1990).

L. Reginato, "Modulator applications in high energy accelerators," 19th Power Modulator Symposium (1990), Lawrence Berkeley Laboratory report LBL-29103 (1990).

B. Abraham-Shrauner and O.A. Anderson, "Space-charge effects in warm ion sheet beams in the Vlasov-Maxwell approximation," *Phys. Fluids B* **2**, 9 (1990); also published as Lawrence Berkeley Laboratory report LBL-24339-R (1990).

Materials Modification and Synthesis

M.A. Brewer, I.G. Brown, M.R. Dickinson, J.E. Galvin, and M.C. Salvadori, "Simple, safe and economical microwave plasma assisted chemical vapor deposition facility," submitted to *Rev. Sci. Instrum.* (1991).

M.A. Brewer, I.G. Brown, M.R. Dickinson, J.E. Galvin, R.A. MacGill, and M.C. Salvadori, "Simple and inexpensive microwave plasma assisted CVD facility," 44th Annual Gaseous Electronics Conference (Albuquerque, New Mexico, 1991).

I.G. Brown, M.R. Dickinson, J.E. Galvin, X. Godechot, and R.A. MacGill, "Broad-beam, high current, metal ion implantation facility," in *Proceedings of the 8th International Conference on Ion Implantation Technology* (Guildford, UK, 1990), *Nucl. Instrum. Meth. B* **55**, 506 (1991); Lawrence Berkeley Laboratory report LBL-28685 (1990).

I.G. Brown, M.R. Dickinson, J.E. Galvin, X. Godechot, and R.A. MacGill, "Some novel surface modification applications of a new kind of high current metal ion implantation facility," *J. Mater. Eng.* **13**, 217 (1991).

I.G. Brown, M.R. Dickinson, J.E. Galvin, X. Godechot, and R.A. MacGill, "Versatile high current metal ion implantation facility," Seventh International Conference on Surface Modification of Metals by Ion Beams (Washington, D.C., 1991).

I.G. Brown, R.A. MacGill, and J.E. Galvin, "Apparatus for coating a surface with a metal utilizing a plasma source," U.S. Patent No. 5,013,578 (7 May 1991).

I.G. Brown, R.A. MacGill, J.E. Galvin, and M.R. Dickinson, "Continuous high current

metal ion source," U.S. Patent No. 07,728,566; (11 July 1991).

I.G. Brown, X. Godechot, and K.M. Yu, "Novel metal ion surface modification technique," *Appl. Phys. Lett.* **58**, 1392 (1991).

I.G. Brown, X. Godechot, and K.M. Yu, "Plasma immersion surface modification with metal ion plasma," Spring Meeting of the Materials Research Society (Anaheim, California, 1991); *Mat. Res. Soc. Symp. Proc.* **223**, 371 (1991).

P. Buckley, L.J. Lowder, R. Brown, J. G. Cowie, and I.G. Brown, "Noble metal implantation to reduce hydrogen embrittlement in steels," International Conference on Metallurgical Coatings and Thin Films (San Diego, California, 1991).

W. Cai, W. Tian, R. Wu, X. Godechot, and I.G. Brown, "Study of the corrosion rate behavior of ion implanted Fe-based alloys," Seventh International Conference on Surface Modification of Metals by Ion Beams (Washington, D.C., 1991).

G. Dearnaley, J.L. Ing, S. Sugden, I.G. Brown, and X. Godechot, "Anomalous ranges of ions implanted into carbon," Seventh International Conference on Surface Modification of Metals by Ion Beams (Washington, D.C., 1991).

X. Godechot, M.B. Salmeron, D.F. Ogletree, J.E. Galvin, R.A. MacGill, K.M. Yu, and I.G. Brown, "Thin film synthesis using miniature pulsed metal vapor vacuum arc plasma guns," Materials Research Society Spring Meeting (San Francisco, California, 1990); *Mat. Res. Soc. Symp. Proc.* **190**, 95 (1991).

P.Y. Hou, I.G. Brown, and J. Stringer, "Study of the effect of reactive element addition by implanting metal ions in a preformed oxide layer," *Nucl. Instrum. Meth. B* **59/60**, 1345 (1991); 7th International Conference on Ion Beam Modification of Materials (Knoxville, Tennessee, 1990).

P. Hou, V. Chia, and I. Brown, "Diffusion of ion-implanted yttrium in Ni-24wt%Cr," Seventh International Conference on Surface Modification of Metals by Ion Beams (Washington, D.C., 1991).

V.C. Kannan, A.J. Filo, and I.G. Brown, "Morphology of uranium precipitates in

silicon," 12th International Congress for Electron Microscopy (Seattle, Washington, 1990).

G.S. Pomrenke, M.B. Scott, R.L. Hengehold, Y.K. Yeo, and I.G. Brown, "Photoluminescence of the actinide uranium implanted into binary and ternary III-V semiconductors," March meeting of the American Physical Society (Anaheim, CA, 1990), *Bull. Am. Phys. Soc.* **35** (1990), p. 820.

G.S. Pomrenke, R.L. Hengehold, Y.K. Yeo, I.G. Brown, and J.S. Solomon, "Actinide activated luminescence in uranium implanted III-V semiconductors," *J. Appl. Phys.* **67** (1990), p. 2040.

X.Y. Qian, D. Carl, J. Benasso, N.W. Cheung, M.A. Lieberman, I.G. Brown, J.E. Galvin, R.A. MacGill, and M.I. Current, "A plasma immersion ion implantation reactor for ULSI fabrication," *Nucl. Instrum. Meth. B* **55**, 884 (1991); 8th International Conference on Ion Implantation Technology (Guildford, United Kingdom, 1990).

X.Y. Qian, M.H. Kiang, J. Huang, D. Carl, N.W. Cheung, M.A. Lieberman, I.G. Brown, K.M. Yu, and M.I. Current, "Plasma immersion Pd ion implantation seeding pattern formation for selective electroless Cu plating," *Nucl. Instrum. Meth. B* **55**, 888 (1991); 8th International Conference on Ion Implantation Technology (Guildford, United Kingdom, 1990).

X.Y. Qian, M.H. Kiang, N.W. Cheung, I.G. Brown, X. Godechot, J.E. Galvin, R.A. MacGill, and K.M. Yu, "Metal vapor vacuum arc ion implantation for seeding of electroless Cu plating," *Nucl. Instrum. Meth. B* **55**, 893 (1991); 8th International Conference on Ion Implantation Technology (Guildford, United Kingdom, 1990).

M.C. Salvadori, J.W. Ager III, and I.G. Brown, "Diamond growth on silicon nitride by microwave plasma chemical vapor deposition," submitted to *Diamond and Related Materials*.

M.C. Salvadori, J.W. Ager III, I.G. Brown, and K.M. Krishman, "Diamond synthesis by microwave plasma CVD using graphite as the carbon source," *Appl. Phys. Lett.* **59**, 2386 (1991); Lawrence Berkeley Laboratory report LBL-30558 (1991).

M.C. Salvadori, M.A. Brewer, J.W. Ager III, I.G. Brown, and K.M. Krishman, "The effect of a graphite holder on diamond synthesis by microwave plasma chemical vapor deposition," accepted for publication in *J. Electrochemical Society*; Lawrence Berkeley Laboratory report LBL-29989 (1990).

W. Tian, R. Wu, W. Cai, R. Wang, X. Godechot, and I.G. Brown, "Influence of multi-element ion beam bombardment on the corrosion behavior of iron and steel," Seventh International Conference on Surface Modification of Metals by Ion Beams (Washington, D.C., 1991).

G.J. Varentop, M. Kawasaki, R.M. Nix, I.G. Brown, M. Salmeron, and G.A. Somorjai, "The formation of hydrogenated amorphous carbon films of controlled hardness from a methane plasma," *Phys. Rev. B* **41** (1990), p. 3200.

K.M. Yu, B. Katz, I.C. Wu, and I.G. Brown, "Formation of iridium silicide layer by high dose iridium ion implantation into silicon," *Nucl. Instrum. Meth. B* **58**, 27 (1991).

Theory

Alain Brizard, "Conservation properties of a gyrokinetic Fokker-Planck collision operator," in *Proceedings of the 1990 Sherwood Fusion Theory Conference* (Williamsburg, VA, 1990); Lawrence Berkeley Laboratory report LBL-28632a (1990).

Alain Brizard, "Derivation of a reduced kinetic equation using Lie-transform techniques," in *Proceedings of the 1991 Sherwood Fusion Theory Conference* (Seattle, WA, 1991); Lawrence Berkeley Laboratory report LBL-30399 (1991).

Alain J. Brizard, "Gyrokinetic description of low-frequency nonlinear plasma dynamics," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); Lawrence Berkeley Laboratory report LBL-29221 (1990).

Alain Brizard, "Nonlinear gyrofluid equations for high-beta tokamak plasmas," *Nucl. Fusion* (February 1990); Lawrence Berkeley Laboratory report LBL-28643 (1990).

Daniel R. Cook and Allan N. Kaufman, "Multiple mode conversion," in *Proceedings of the 1990 Sherwood Fusion Theory*

Conference (Williamsburg, VA, 1990); Lawrence Berkeley Laboratory report LBL-28678a (1990).

Daniel Cook, Allan N. Kaufman and Eugene R. Tracy, "ICRF action transfer from magnetosonic to ion Bernstein wave," in *Proceedings of the 1991 Sherwood Fusion Theory Conference* (Seattle, WA, 1991); Lawrence Berkeley Laboratory report LBL-30400 (1991).

Daniel R. Cook, Eugene R. Tracy, Tor Fla, Huanchun Ye, and Allan N. Kaufman, "Analytic extraction of the Bernstein wave in gyroresonant heating," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); Lawrence Berkeley Laboratory report LBL-29221 (1990).

S.C. Creagh and R.G. Littlejohn, "Semi-classical trace formulas in the presence of continuous symmetries," accepted by *Phys. Rev. A* (1991); Lawrence Berkeley Laboratory report LBL-30700 (1990).

Stephen C. Creagh and Robert G. Littlejohn, "Semiclassical trace formulas for systems with non-Abelian symmetry," Lawrence Berkeley Laboratory report LBL-30733 (1990).

Stephen C. Creagh, Jonathan M. Robbins, and Robert G. Littlejohn, "Geometric properties of Maslov indices in the semiclassical trace formula for the density of states," submitted to *Phys. Rev. A*; Lawrence Berkeley Laboratory report LBL-29066 (1990).

Maria Ekiel-Jezewska, Tor Flå, and Allan N. Kaufman, "Modulational destabilization of an electromagnetic wave by particles resonant with its group velocity," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); Lawrence Berkeley Laboratory report LBL-29221 (1990).

Allan N. Kaufman, "Phase-Space Plasma-Action Principles, Linear Mode Conversion, and the Generalized Fourier Transform," in *Nonlinear and Chaotic Phenomena in Plasmas,*

Solids, and Fluids, edited by W. Rozmus & J. A. Tuszynski (World Scientific, Singapore, 1991, ISBN 981-02-0386-1); Lawrence Berkeley Laboratory report LBL-29662 (1990).

A.N. Kaufman, D.R. Cook, H. Ye, L. Friedland, and R.A. Cairns, "Analytic derivation of reflection coefficient in gyroresonant rf heating," synopsis for the IAEA 13th International Conference on Plasma Physics and Controlled Nuclear Fusion Research (Washington, D.C., 1990); Lawrence Berkeley Laboratory report LBL-28796 (1990).

Mitsuo Kono and Allan N. Kaufman, "Action-principle approach to self-consistent nonlinear wave-particle interaction," 32nd Annual Meeting of the American Physical Society, Division of Plasma Physics (1990); Lawrence Berkeley Laboratory report LBL-29221 (1990).

Robert G. Littlejohn, "Geometrical aspects of trace formulas," Lawrence Berkeley Laboratory report LBL-29719 (1990).

Robert G. Littlejohn, "Semiclassical structure of trace formulas," Lawrence Berkeley Laboratory report LBL-28628 (1990).

Robert G. Littlejohn and William G. Flynn, "Geometric phases and the Bohr-Sommerfeld quantization of multicomponent wave fields," Lawrence Berkeley Laboratory report LBL-30312 (1990).

Robert G. Littlejohn and William G. Flynn, "Geometric phases in the asymptotic theory of coupled wave equations," submitted to *Phys. Rev. A*; Lawrence Berkeley Laboratory report LBL-30856 (1991).

Huanchun Ye and Allan N. Kaufman, "Gyroresonance crossing, quasilinear diffusion and conservation laws in axisymmetric toroidal plasma," in *Proceedings of the 1990 Sherwood Fusion Theory Conference* (Williamsburg, VA, 1990); Lawrence Berkeley Laboratory report LBL-28660 (1990).

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