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Particle Beam Fusion Progress Report for 1989

M. A. Sweeney

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Particle Beam Fusion Progress Report for 1989

M. A. Sweeney, Scientific Editor

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Abstract

This report summarizes our progress on the pulsed power approach to inertial confinement fusion. In 1989, we achieved a proton focal intensity of 5 TW/cm^2 on PBFA II in a 15-cm-radius applied magnetic-field (applied-B) ion diode. This is an improvement by a factor of 4 compared to previous PBFA-II experiments. We completed development of the three-dimensional (3-D), electromagnetic, particle-in-cell code QUICKSILVER and obtained the first 3-D simulations of an applied-B ion diode. The simulations, together with analytic theory, suggest that control of electromagnetic instabilities could reduce ion divergence. In experiments using a lithium fluoride source, we delivered 26 kJ of lithium energy to the diode axis. Rutherford-scattered ion diagnostics have been developed and tested using a conical foil located inside the diode. We can now obtain energy density profiles by using range filters and recording ion images on nuclear track recording film. Timing uncertainties in power flow experiments on PBFA II have been reduced by a factor of 5. We are investigating three plasma opening switches that use magnetic fields to control and confine the injected plasma. These new switches provide better power flow than the standard plasma erosion switch. Advanced pulsed-power fusion drivers will require extraction-geometry applied-B ion diodes. During this reporting period, progress was made in evaluating the generation, transport, and focus of multiple ion beams in an extraction geometry and in assessing the probable damage to a target chamber first wall.

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Acronyms, Abbreviations, and Definitions

2-D	two-dimensional geometry or simulation code
2 1/2-D	a simulation code that uses two dimensions in coordinate space and three dimensions in velocity space to calculate particle positions
3-D	three-dimensional geometry or simulation code
4-D woven graphite	four-directional woven graphite
achromatic lens system	a ballistic ion beam transport scheme that employs solenoidal focusing
A-K gap	the physical gap between the cathode tip and the opposing anode surface; also, the gap between the virtual cathode formed by an electron sheath emanating from the cathode tip and the anode surface (this reduced gap is also known as the effective gap)
applied-B diode	a diode with an applied (i.e., external) magnetic field
ATHETA	a computer code developed at Sandia for solving magnetostatics problems in two dimensions using cylindrical coordinates; used to design magnetic field coils and anode and gas cell shapes in pulsed power diodes
AVS	Stardent software that allows 3-D objects to be viewed, animated, and manipulated on a computer terminal screen
barrel diode	an ion diode configuration in which an axisymmetric ion source is focused radially inward toward the center of a cylindrically symmetric device (a barrel diode is the same as a radial diode)
Bdot probe	dB/dt loop probe used to measure ion current in the MITL and in the POS region near the diode load
Blackjack 5	accelerator at Maxwell Laboratories on which POS experiments, using PBFA-II hardware, were done
BOLVAPS	Boil Off Lithium VAPor Source: an active source that produces lithium vapor by rapid ohmic heating of a thin film laminate containing lithium

BUILDPPF	a post-processor routine that allows new PFF files to be constructed from one or more existing PFF files
channel transport	transport scheme using magnetic field of Z-discharge current to confine the ion beam; also known as wall-confined channel transport
charge exchange	process whereby a beam ion in the A-K gap exchanges its charge with a background neutral
CONRAD	a one-dimensional, Lagrangian hydrodynamic code, developed at the University of Wisconsin, that includes the effects of vaporization and condensation of wall materials and the deposition of x-rays and ions in the reactor chamber gas and in the walls
CR-39 film	a nuclear track recording diagnostic on which ion images are recorded during PBFA-II experiments; can be used with filters to determine energy distribution of the ion beam
CT	Current-Toggled plasma opening switch; switch that uses a rapidly rising external magnetic field at the cathode to open the gap further
divergence	the spreading (increase in spot size) of a beam because of scattering, instabilities, etc.
D-T	deuterium-tritium fuel or neutrons
DYNAID	DYNamic Anode Ion Diode: an implicit, one-dimensional, multi-species, collisional fluid code that can handle large applied electric and magnetic fields; being developed at SNL to model charge-exchange neutrals, ionization, and other particle interactions in an ion diode
EHD	electrohydrodynamic: a lithium ion source that relies on intense electric fields to release ions from a surface
extraction diode	an ion diode configuration in which an ion source is transported longitudinally down the axis of a cylindrically symmetric device
FFT	fast Fourier transform
FGF	full-gap flow
FLASH	a post-processor for QUICKSILVER that produces 3-D graphics
FODS	fiber optic distribution system

FPA	Fusion Power Associates
FWHM	full width at half maximum
Gamble II	a terawatt-level pulsed power accelerator at Naval Research Laboratory that operates in negative or positive polarity
HELIA	a four-stage linear inductive adder electron-beam accelerator that uses an extraction ion diode geometry and has been operated in positive polarity; originally designed as proof-of-principle experiment for Hermes III
Hermes III	a 20-stage inductive-voltage-adder electron-beam accelerator, with a demonstrated positive-polarity capability, that is used primarily as a gamma-ray simulator
HIBALL	Heavy Ion Beams and Lithium Lead reactor conceptual design developed by the University of Wisconsin that uses lead-lithium waterfall for protection of the chamber walls
IC	induction cavity
hybrid code	an electromagnetic simulation code that uses a mixed fluid and particle description for the plasma
ICF	inertial confinement fusion
IDF	ion distribution function
IDR	a computer code developed at SNL to analyze waveform data from pulsed power accelerators
IIF	insulated indigenous flow
IONMIX	University of Wisconsin code for computing equation of state and radiative properties of plasmas in local thermodynamic equilibrium (LTE) and not in LTE
IPC	ion pinhole camera
ITF	Integrated Test Facility: a facility used for testing hardware before installation on PBFA II
JASON	computer code that solves the two-dimensional Poisson equation
JPL	Jet Propulsion Laboratory

KfK	Kernforschungszentrum Karlsruhe
L/R	inductance/resistance
LANL	Los Alamos National Laboratory
LC	inductance-capacitance
LEF	locally emitted flow
LEVIS	Laser EVaporation Ion Source: an active ion source that relies on a laser to evaporate neutrals from a surface
LIBORS	Laser Ionization Based On Resonance Saturation: method for ionizing a neutral lithium vapor by using a dye laser tuned to the 670.8-nm line
LIBRA	Light Ion Beam Reactor Assessment: reactor design developed by the University of Wisconsin and by KfK in Karlsruhe, Germany, using laser-generated transport channels
LIBRA-LiTE	modified version of LIBRA using ballistic focus with an achromatic lens system
LIF	light ion fusion
LiF	lithium fluoride: a passive ion source used to produce the first high-energy Li ⁺ beam on PBFA II
LMF	Laboratory Microfusion Facility
MACH2	two-dimensional MHD fluid code, developed by MRC and used in simulating plasma opening switch performance
MAGIC	two-dimensional, electromagnetic, particle-in-cell code developed at MRC and used to simulate MITL, POS, and ion diode operation
MHD	magnetohydrodynamics
MIP	Magnetically Injected Plasma: a source of plasma in an opening switch in which the injection process is controlled by an externally applied magnetic field at the anode; also, name of an opening switch that uses such a magnetic field to control plasma injection

MITE	Magnetically Insulated Transmission Experiment: an accelerator at SNL originally designed as one module of PBFA I, the precursor to PBFA II; used for power flow studies and extraction ion diode experiments
MITL	magnetically insulated transmission line: a transmission line in which most electrons are retrapped at the cathode
MRC	Mission Research Corporation
NDF	neutral distribution function
NEUTRAL	one-dimensional PIC code developed at SNL to model the ion-neutral charge exchange process in an ion diode
NRL	Naval Research Laboratory
OMA	optical multichannel analyzer
ONEDANT	one-dimensional diffusion transport code, developed at Los Alamos National Laboratory and used to calculate neutron propagation from the target to the LMF chamber walls
PBFA II	Particle Beam Fusion Accelerator II, at SNL; uses applied-B, barrel-geometry ion diode
PET	pentaerythritol
PFF	Portable File Format: a machine-independent file format for simulation code data
PFL	pulse forming line
PIC	particle-in-cell, a technique for simulating motion of particles and generation of electromagnetic fields on a fixed grid
PICDIAG	a computer code, developed at SNL, to model ion transport in the diode and the response of various ion and x-ray diagnostics on PBFA II and SABRE
PI-110A	accelerator used for early ion production experiments using passive sources
PIN	p-type, intrinsic n-type diode used to record time-resolved data

PLOTPFF	a post-processor plotting routine for particle-in-cell simulation codes that employs portable file formats
PMT	photomultiplier tube
POS	plasma opening switch
PROTO I	an early applied-B, barrel-geometry ion diode machine at SNL on which proton focusing experiments were performed in the mid 1980s
PSI	Pulsed Sciences, Inc.
PTRAN	Monte Carlo code developed at SNL to model ion scattering diagnostics
QUICKSILVER	a multitasked, finite-difference, three-dimensional, fully relativistic, electromagnetic, particle-in-cell simulation code developed at SNL and used for ion diode design
radial diode	ion diode configuration in which an axisymmetric ion source is focused radially inward toward the center of a cylindrically symmetric device (a radial diode is the same as a barrel diode)
RFS	range-filtered scintillator
RH	relative humidity
SABRE	Sandia Accelerator for Beam Research Experiments with a self-magnetically insulated extraction ion diode
Saturn	SNL accelerator used primarily for weapons effects experiments and imploding liner experiments; so named because of multi-ring geometry of the diodes when operated in a bremsstrahlung mode
separatrix	magnetic flux surface on which the stream function $r \times A \times \theta$ is zero
SNL	Sandia National Laboratories
SuperMITE	SNL accelerator originating as a demonstration module for PBFA II; used for power flow studies
TEM	transverse electromagnetic
TOF	time of flight

TRIDIF	A magnetic diffusion code using a triangular mesh that was developed at SNL in the 1970s to calculate time-dependent magnetic fields in two dimensions; uses either rectangular or cylindrical coordinates and can accurately treat slanted surfaces
UCLA	University of California, Los Angeles
UFO	SNL UnFold Operator code used to correct the time response of PINs and associated cables
UNM	University of New Mexico
V_{crit}	voltage parameter that defines the degree of magnetic insulation of electrons in an applied-B ion diode: $V_{\text{crit}} = cB_0d$, where B_0 is the field in the gap before the power pulse arrives and d is the initial A-K gap; voltage below which effective gap will go to zero
V-I	voltage-current
VERA	fully automatic nuclear track counting system based on an image processor
wall-confined	see <i>channel transport</i>
wire-guided	transport scheme using the magnetic field of a current-carrying wire to confine an ion beam
XRD	x-ray diode
zinger	location in the transmission line at which electron loss occurs because of the presence of a magnetic null; location is characterized by spalling of the metal

Technical Overview 1989

J. P. Quintenz

The Light Ion Beam Inertial Confinement Fusion (ICF) Program at Sandia National Laboratories (SNL) is funded by Defense Programs within the Department of Energy. The goal of our research for Defense Programs is to produce ignition and propagating burn in the laboratory, ultimately with the fusion yield in the neighborhood of 500 megajoules (MJ). This fusion yield is required for applications in weapons effects simulations and weapons physics studies. A longer-term goal of our program is to produce comparable yields in a repetitive (rep)-rated facility for energy production. Yields of several hundred MJ will require ion beam intensities of 50 to 100 TW/cm² and several MJ deposited in the target itself. To achieve these extreme beam conditions, we must improve our understanding of the physics involved in ion beam generation and focusing, as well as in beam-target interaction. In this report, we document our progress in each of these areas.

Experiments with ion beams on the Particle Beam Fusion Accelerator II (PBFA II) have demonstrated improved focusability during this reporting period. Using a flashover proton source in a 15-cm-radius applied-magnetic-field (applied-B) ion diode, we have achieved a 5 TW/cm² proton focal intensity averaged over a 6-mm-diameter sphere. This represents a significant improvement, by a factor of 4, in proton beam intensity compared to our previous PBFA-II experiments. Low-level plasma opening switches enhanced the ion flow, and the protons were ballistically transported from a curved anode surface through a current-neutralizing gas cell to the diode axis.

Eventually, we will require a higher mass ion to achieve higher power intensities. The ion of choice is singly charged lithium accelerated to 30-MeV kinetic energy. Presently, there are four potential lithium ion sources: a lithium fluoride passive source, an electrohydrodynamic or EHD source using liquid lithium, a Boil Off Lithium VAPor Source (BOLVAPS), and a Laser EVaporation Ion Source (LEVIS). We have made progress in developing these lithium ion beam sources. In particular, the lithium fluoride source has delivered 26 kJ of lithium beam energy to the PBFA-II diode axis.

The beam intensity incident on a target is limited by the available ion power as well as by the divergence (spread) of the ion beam. In fact, intensity is proportional to the ion power and inversely proportional to the square of the beam divergence. Therefore, improving beam divergence is a high-leverage approach to increasing the beam intensity. In 1989 we completed the QUICKSILVER three-dimensional (3-D), relativistic, electromagnetic, particle-in-cell (PIC) computer code and performed the first fully 3-D simulations of an applied-B ion diode. From these simulations, coupled with analytic theory, we have determined that electromagnetic instabilities play a major role in ion beam divergence. These first 3-D simulations represent a major milestone in the QUICKSILVER development project. The project

continued through the reporting period with further development targeted toward adding physics algorithms, increasing user friendliness, and implementing the code on a massively parallel processor.

Three-dimensional PIC simulations represent the newest addition to our suite of computational tools. However, two-dimensional (2-D) PIC simulations with the MAGIC code are still the workhorses in our computational effort. These simulations have provided insight into (1) the operation of magnetically insulated transmission lines (MITLs), both in positive polarity (ion-beam mode) and negative polarity (electron-beam mode), (2) the coupling of feed electrons from the MITL into the applied-B ion diode, and (3) the effect of these electrons on diode impedance behavior. The simulations have also provided insight into operation of a plasma-filled diode. The latter effort is an attempt to improve power coupling from the accelerator into useful ion beam by adjusting the variation of diode impedance with time. Another process that limits the available ion power is thought to be charge exchange of beam ions with background neutrals in the diode anode/cathode gap. A theory for this charge exchange process has been developed, and a computer model is being designed to simulate this process.

Target experiments in 1989 emphasized the development of an experimental diagnostic capability for beam characterization. Ion beam target experiments will require the routine measurement of beam characteristics such as composition, intensity, energy uniformity, and synchrony near the target location. For this purpose, we are developing Rutherford-scattered ion diagnostics. These diagnostics have been tested in target experiments on PBFA II by employing a conical scattering foil located on axis inside the ion diode. Several other diagnostics have been developed to measure scattered ions, nuclear reaction products, x-rays from beam-induced inner shell fluorescence, and x-rays produced by target heating. We have designed an ion pinhole camera that allows us to determine energy density profiles as a function of energy by using range filters and recording ion images with nuclear track recording detectors, such as CR-39 film.

The data analysis computer code PTRAN has been written to assist in interpreting the output from beam and target diagnostics. This ion-transport Monte Carlo code can model the response of intense ion beam diagnostics based on Rutherford scattering. PTRAN has modeled ion pinhole cameras, magnetic spectrographs, and Thomson parabolas. PTRAN can remove the degradation of the PIN detector signals caused by their response functions as well as that of associated cabling. This computational tool has greatly sped up the analysis of beam performance data.

A critical element in advancing the pulsed power approach to ICF is the power flow between the energy storage section of a high-power accelerator and the load region where the ion diode is positioned. During this reporting period, power flow research has enabled improvement in the power available to the ion diode, as well as improvement (by more than a factor of four) in the synchrony and

symmetry of power flow near the diode. Problems have been identified with coupling the standard plasma erosion opening switch to a high impedance load. Such a switch relies on ion acceleration toward the cathode produced by electric fields and by the self-magnetic field of the power pulse. Consequently, three new plasma opening switch configurations have been invented: the segmented erosion switch, the magnetically injected plasma switch, and the current toggled switch. These new switches limit and localize the total mass of plasma ions within the switch region by employing magnetic fields, thereby increasing the rate at which plasma can be removed and reducing the downstream electron flow that results from the switch itself. Initial PBFA-II experiments and code simulations with these novel switch concepts look very promising. Nevertheless, experimental data show clear evidence of power loss with these new switches, caused by electron flow to the anode. This "launched" electron flow can carry a significant amount of the current near the load and constitutes a significant loss. We are investigating methods to characterize and limit this launched flow.

A long-range goal for ICF is the construction of a Laboratory Microfusion Facility (LMF) for Defense Programs applications and for demonstration of fusion energy generation in the laboratory. Designs for both an LMF for light ions and the Light Ion Beam Reactor Assessment (LIBRA) concept were advanced in 1989. Strong teaming with partners from the Naval Research Laboratory (NRL), Cornell University, and the University of Wisconsin have provided comprehensive reports for both the LIBRA and LMF concepts. These future applications require extraction diode technology, as well as inductive-voltage-adder generators similar to those found in the Hermes-III facility. We are building on our experience with Hermes III to lend credibility to these designs.

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Particle Beam Fusion Progress Report for 1989

Chapter 1. Beam Theory

Overview

J. P. Quintenz

During this reporting period, we made progress in several areas that are critical to the development of a theoretical understanding of the physics of ion diodes and multiple-cathode, magnetically insulated transmission lines.

QUICKSILVER, a three-dimensional, relativistic, electromagnetic, particle-in-cell computer code, became fully operational with the completion of its particle handling package. This allowed the first truly three-dimensional simulation of an applied-B ion diode. The first simulations with QUICKSILVER confirmed the existence of instabilities in the anode-cathode (A-K) gap and a consequent divergence induced in the ion beam. We now have a tool available for in-depth study of the linear and nonlinear evolution of the diode equilibria and the growth and saturation of various instabilities in the diode. We used many early simulations to validate the QUICKSILVER code and to determine the time and space resolution that is required to capture the essential physics of this device. Every simulation of applied-B ion diodes with QUICKSILVER has shown a strong instability with waves traveling in the electron drift direction and saturating in a few nanoseconds. The general features of this instability agree with analytic theory during the linear growth phase.

In addition to implementing the particle handling package, QUICKSILVER functionality was enhanced in several areas. We now have the ability to treat multiple dielectric regions in a fields-only simulation. We developed a new portable, efficient, and machine-independent file format to transfer large output files from one computer to another; this is an essential feature, given the distributed nature of the QUICKSILVER suite of codes. We added new postprocessing capabilities to simplify the interpretation of output data by the physicist. Data in one, two, and three dimensions can now be rendered in graphical form, including three-dimensional animation capabilities. Parallel processing will become more and more important as we move to the new computer architectures. We tested QUICKSILVER in a multitasking environment, efficiently utilizing all four processors of a CRAY X-MP. We have also funded research at the University of California, Los

Angeles (UCLA) and the Jet Propulsion Laboratory (JPL) on the implementation of PIC algorithms on massively parallel processors.

Applied-B ion diode behavior is critically dependent upon the characteristics of the anode plasma. We are developing a new computer code called DYNAmic Anode Ion Diode (DYNAID) to study the particle collisions and interactions with neutrals that become significant at the high plasma densities found in and near the anode plasma. DYNAID will be our first attempt at adding ionization and other particle interactions to a model of an ion diode that includes details of the anode plasma. Another one-dimensional code, NEUTRAL, has been used successfully in the past to treat just the ion-neutral charge exchange process. Although the two codes have significantly different algorithms, they agree well when only charge exchange is included in DYNAID.

One possible result of charge exchange between neutrals and ions in the A-K gap is diode voltage decay. Charge exchange events between energetic ions and neutrals can produce fast neutrals that can then easily cross the magnetic field in the diode. If enough fast neutrals are subsequently ionized out in the A-K gap, the effect is as if the anode emission surface were rapidly crossing magnetic flux surfaces. Since the total magnetic flux between the cathode and the anode emission surface determines the diode voltage, a loss of total flux leads to voltage decay. As the ion emission surface moves across the gap, it is also being eroded as ions are removed. These two competing mechanisms, combined with the increase in the ion erosion rate (current density) with diode voltage, can lead to an unstable situation and the identification of a maximal voltage decay rate. This insight can help determine the optimal ion source area in applied-B ion diodes and emphasizes the need to reduce the neutral population in and near our anode plasmas.

One indicator of the total energy available in the ion beam in an applied-B ion diode is the coupling efficiency of the diode to the accelerator. On PBFA II, our ion diodes are attached to an MITL feed. The character of the electron flow in MITLs depends upon the transmission line impedance and, after a transient phase, upon the load impedance at the end of the line; the higher the load impedance, the greater the proportion of the total line current that is carried in electrons and the farther the electron flow extends away from the MITL cathode. If the load impedance is higher than the self-limiting impedance of the MITL, significant electron loss can occur in the feed to the diode and a reduced coupling efficiency results. Since applied-B ion diodes typically have an initial high impedance phase, we need to develop a detailed understanding of the power flow region near the diode.

We have completed many two-dimensional PIC simulations of applied-B ion diodes that include detailed modeling of the feed and diode regions. These simulations have provided insight and shown us that we must carefully design the

feed transition and diode together as a unit. In addition to the MITL feeding the diode, we often employ a plasma opening switch (POS) in the feed region near the diode to sharpen the power pulse at the diode, and we will eventually rely on the POS to provide voltage and power gain. The POS acts as a constriction in the MITL and can launch electrons that contribute to coupling inefficiency. We have also investigated the effects of these MITL constrictions in an attempt to determine the minimum acceptable constriction, given coupling constraints. These studies are helping us set requirements on POS opening characteristics.

One possible way to enhance the coupling efficiency of a POS or MITL (or both) to an ion diode is to lower the initial impedance phase of the diode. We have proposed the use of a plasma prefill in the diode to accomplish this purpose. Simulations of a plasma-prefilled applied-B ion diode have been very encouraging, and we plan experiments to test this concept.

One promising approach to a Laboratory Microfusion Facility (LMF) and eventual energy production using light ion beams involves linear induction accelerator technology. Hermes III and SABRE are two examples of this accelerator type at Sandia. To use an inductive accelerator to drive an ion diode, we may need to operate these accelerators in a positive-polarity mode. It is important to understand the implications of this polarity reversal on the total current carried by electrons in the transmission line and on the distribution of these electrons across the MITL that is feeding the diode. Of particular interest is the electron flow into the diode itself, because these electrons are likely to affect diode performance. We have developed a theory for describing these electron flows and have performed several two-dimensional PIC simulations to confirm this theory.

The usual configuration for these accelerators includes a solid cathode, and voltage addition occurs at the positive conductor. In this configuration, all electrons are emitted with the same total energy because they come from the same conductor at the same potential. In positive polarity, however, the anode is the single solid conductor, and the voltage addition occurs at the negative electrode side of the accelerator. Electrons emitted in this configuration can all have different total energies because they are emitted from separate cathodes at different relative potentials. Our simulations indicate that electron flow in the MITL for a positive-polarity Hermes-III experiment can be significant. Careful current measurements on upcoming SABRE experiments will assist in verifying these results and assessing the impact on extraction diode design for inductively added accelerators.

In summary, we have made rapid progress in the areas of code development, ion diode theory, and the theory of electron flow in positive-polarity inductive adders. We are providing theoretical guidance to researchers by helping explain experimental results and suggesting new measurements.

Code Development

QUICKSILVER Three-Dimensional Electromagnetic PIC Code Development Project

D. B. Seidel, M. L. Kiefer, T. D. Pointon, R. S. Coats, W. A. Johnson, and J. P. Quintenz

The three-dimensional electromagnetic PIC code QUICKSILVER, as well as associated pre- and post-processors and libraries, became operational with full functionality during this reporting period. We completed and tested the particle handling portions of the code, including the multitasking of the particle algorithms. With this functionality, QUICKSILVER has rapidly become a valuable tool in the inertial confinement fusion (ICF) program for the understanding of a variety of devices. Using QUICKSILVER, we have investigated the stability of applied-B ion diodes. (These simulations are described elsewhere in this report.) We have also used QUICKSILVER to simulate the zinger experiment that was fielded on the SuperMITE accelerator by Savage and Mendel and to simulate a new voltage probe designed by Mendel.

Features of QUICKSILVER's particle handler include three-dimensional relativistic particle dynamics in three coordinate systems, models for particle emission via beam injection and space-charge-limited emission, and a locally charge-conserving algorithm for current and charge allocation. In addition, the code supports a large number of diagnostics to allow the QUICKSILVER user to visualize particles and particle-related physics efficiently. The entire particle handler was written to utilize the simultaneous multiprocessing capabilities of state-of-the-art supercomputers. Tests of this feature on a four-processor CRAY X-MP/416 supercomputer have demonstrated speedups in excess of three when compared to runs using only a single processor.

To move QUICKSILVER output data easily from one machine to another, we developed the Portable File Format (PFF). We designed this format to be portable, efficient, and machine independent so a user could move large data files from the CRAY X-MP to a VAX or UNIX workstation for postprocessing. The capabilities of PFF include directories of the datasets contained in the files, allowing users a simple means to randomly access and manipulate data. We have written FORTRAN and C versions of the PFF library for the CRAY X-MP, VMS VAXes, and UNIX workstations.

Also during this reporting period, we wrote an interactive program called PLOTPFF to postprocess QUICKSILVER snapshot and time history PFF files. PLOTPFF allows a user to open several PFF files and load selected datasets into memory. The user can request contour plots of scalar data over an arbitrary plane, or x-y plots of scalar data along a line. For history datasets, PLOTPFF makes simple x-y

plots. Although the FLASH postprocessor produces three-dimensional graphics that give qualitative insight into the processes being simulated, PLOTPFF greatly enhances our ability to extract quantitative information from simulation data.

We wrote another tool called BUILDPFF to allow a user to build new PFF files by selectively copying datasets from one or more PFF files. Copied datasets can be selected by position or by matching a user-supplied string to a substring of the dataset title. QUICKSILVER writes data into output files sequentially as it computes the data, which is not necessarily the order in which the user wishes it. BUILDPFF allows the user to reorder the datasets as desired and to add directories to PFF files that do not have them.

New features added to QUICKSILVER include a uniform, applied magnetic field and a new diagnostic capability that allows the time averaging of field snapshot data. This averaging can be done internal to QUICKSILVER (by specifying the number of timesteps to average and the timesteps over which to center the averages) and external to QUICKSILVER in PLOTPFF. This method provides great flexibility in filtering unwanted high-frequency numerical noise.

We added the capability to model multiple arbitrary dielectric volumes to QUICKSILVER's fields-only mode. If the dielectric material is the same in all cells, QUICKSILVER uses the same field-solving algorithms that it used before this enhancement. If there are multiple dielectrics, the code uses two different algorithms. The first algorithm conserves memory use at the expense of additional computation; the second minimizes computation at the expense of increased memory usage. The first algorithm uses only one three-dimensional array to store dielectric information for the field solver. This results in a 40% increase in computation time over the uniform dielectric case. The second algorithm uses three three-dimensional arrays and results in a 10% increase in computation time.

We have written a prototype program, called QSAVS, for visualizing and animating QUICKSILVER output. QSAVS converts raw QUICKSILVER output into three-dimensional geometric objects that can then be viewed, manipulated, and animated with Stardent Computer's AVS software on a Stardent graphics workstation. We can represent particle positions with spheres at each position and animate a time sequence of particle positions in real time on the workstation (3 frames/s with 10,000 spheres in each frame). We can represent field magnitudes with spheres at each data location, with each sphere colored according to its magnitude. We can also represent field vectors as small, equal-length line segments at each data location. Each line segment is oriented in the vector direction and is colored according to the value of the vector magnitude. We also have the capability to produce videotapes of time-sequenced data using various video equipment.

In related work, we have funded researchers at UCLA and JPL during this period to investigate the implementation of PIC algorithms on computers with hundreds or thousands of processors (massively parallel computers) such as Sandia's nCUBE hypercube with 1024 processors. Because of the disparate data structures storing the particle and grid data and the time-dependent nonuniformity of the particle distribution, efficiently implementing QUICKSILVER on massively parallel computers is very difficult. The UCLA/JPL researchers have investigated parallel implementations of one-dimensional and two-dimensional electrostatic PIC techniques on a hypercube computer. They have shown that a 64-processor hypercube can perform the particle handling efficiently and can execute at twice the speed of one CRAY X-MP processor. They have also begun to investigate dynamically repartitioning the simulation among the hypercube processors to efficiently utilize the processors (that is, by maintaining an equal amount of work for each processor) as the particle distribution changes in time. Their results are encouraging and indicate that it will be possible to utilize a 1024-processor hypercube efficiently.

DYNAID: An Ion Diode Code with a Dynamic Anode Plasma

T. D. Pointon

PIC codes are used extensively in the Sandia ICF program to simulate ion diodes. We designed these codes to model the self-consistent electrodynamics of collisionless plasmas. Except near the anode, the ions and electrons in an ion diode are effectively collisionless, and thus these codes successfully reproduce most macroscopic behavior of ion diodes. However, experiments¹⁻¹ strongly suggest very high plasma densities ($>10^{15}$ atoms/cm³) within a few millimeters of the anode and even higher neutral densities. At such densities, charged particle collisions and interactions with neutrals (such as charge exchange and ionization) become significant. None of this physics is addressed with the current versions of our PIC codes. Because we strongly suspect that expansion of the anode plasma or flux penetration into the anode plasma (or both) play a major role in the impedance collapse seen in experiments, we need to develop simulation tools to model the effect of anode plasma processes on overall diode performance.

Two major features of simulating the entire diode with a detailed anode plasma model seem to dictate that the treatment of particles needs to be kinetic; therefore, a fluid treatment is inadequate. First, there is a vast range of collisionality over the entire diode, ranging from very collisional deep in the anode plasma (where a fluid treatment should be valid) to essentially collisionless out in the middle of the dynamic gap. Second, cross sections are often sensitive functions of energy over the range of particle energies encountered near the anode, where collisional effects need to be included.

The first attempt to develop such a simulation tool was NEUTRAL,¹⁻² a one-dimensional PIC code that includes only charge exchange between beam ions and a neutral layer above the anode. Unfortunately, adding ionization and other particle interactions to NEUTRAL is very difficult, if not impossible. To include both charge exchange and ionization, we are developing a new one-dimensional code called DYNAID. It models a slab geometry diode with an anode at $x = 0$ and cathode at $x = d$, space-charge-limited emission of ions and injection of neutrals at $x = 0$, and a Poisson solver for the self-consistent electrostatic field for the charge distribution in the diode that is subject to boundary conditions $\phi(x = 0) = V(t)$ and $\phi(x = d) = 0$. The key feature of DYNAID is its treatment of the ions in the anode plasma directly with an ion distribution function (IDF) $f_i(x, v, t)$, advanced in time with the Boltzmann equation,

$$\frac{\partial f_i}{\partial t} + v \frac{\partial f_i}{\partial x} + \frac{qE}{m} \frac{\partial f_i}{\partial u} = \left[\frac{\delta f_i}{\delta t} \right]_{\text{coll}}, \quad (1-1)$$

where v is the ion velocity, $u = \gamma v$ (formulating the problem relativistically from the start eases the inclusion of electrons later), and the collision operator on the right-hand side represents all interaction terms. The neutrals are handled in the same way as in the NEUTRAL code, using a neutral distribution function (NDF) $f_n(x, v, t)$ advanced with the simpler equation (neutrals drift force free),

$$\frac{\partial f_n}{\partial t} + v \frac{\partial f_n}{\partial x} = \left[\frac{\delta f_n}{\delta t} \right]_{\text{coll}}. \quad (1-2)$$

To advance these equations in time, we define a two-dimensional grid (x_j, u_k) in phase space and define the IDF and NDF at these points, $f_{i,jk} \equiv f_i(x_j, u_k)$ and $f_{n,jk} \equiv f_n(x_j, u_k)$. At each timestep the code handles the left-hand side of each equation using standard fluid algorithms, then the IDF and NDF are adjusted to model collisions. This technique has two potential advantages over PIC methods for our problem:

- Large variations in density are handled efficiently. The trouble with using a PIC code is that if it uses ten particles/cell to represent the ion beam where the density is 10^{12} atoms/cm³, we will need thousands of particles per cell in the anode plasma where the density is orders of magnitude higher. In DYNAID, the number of IDF grid points is fixed, and only the magnitude at each point varies.
- Particle interactions are handled efficiently. NEUTRAL performs charge exchanges particle by particle, and the complexity of the operations inhibit vectorization. Since the number of particles in the anode plasma is large because of the problem outlined previously, this increases the simulation cost further. In DYNAID, the change in the distribution functions for ions at momentum u_k

interacting with neutrals at momentum u_l ($l < k$) at location x_j in time Δt (on a uniform grid) is

$$\Delta f = f_{ijk} f_{njl} \Delta u \sigma(|u_k - u_l|) (u_k - u_l) \Delta t , \quad (1-3)$$

where $\sigma(u)$ is the cross section for the process at relative momentum u . For charge exchange, we simply transfer Δf from f_{ijk} to f_{ijl} , and Δf from f_{njl} to f_{njlk} . This simple transfer of material between IDF and NDF grid points can be vectorized. Although not yet implemented, treatment of additional interactions should also be very efficient.

Currently, charge exchange is the only interaction included in DYNAID. Figure 1-1 shows a comparison between DYNAID and NEUTRAL simulations for $V = 500$ kV, $d = 2$ mm, an initial neutral layer 0.5 mm thick, and a density of 2×10^{17} atoms/cm³. The agreement provides confidence in the basic operation of DYNAID. Work is now under way to add ionization. The main problem is not modeling the interaction but developing a workable model for the electrons in this simple slab geometry.

Ion Diodes

Three-Dimensional Particle Simulations of Ion Diodes with QUICKSILVER

T. D. Pointon, D. B. Seidel, M. P. Desjarlais, R. S. Coats, M. L. Kiefer, and J. P. Quintenz

The completion of the first version of the three-dimensional PIC code QUICKSILVER with a fully self-consistent particle handler has enabled us to begin three-dimensional simulations of ion diodes. Almost all two-dimensional ion diode simulations have been in the r - z plane, which automatically enforces azimuthal symmetry. The goal of the QUICKSILVER simulations is to examine the stability of ion diodes when the assumption of azimuthal symmetry is relaxed, because analytic work has indicated that azimuthal fluctuations can be unstable.¹⁻³ Because the diode gap is small compared to the anode radius in PBFA II, the simulations are done in Cartesian geometry, as shown in Figure 1-2, and use a uniform applied field. These simplifications allow us to compare more easily the simulation results to analytic theory.

Figure 1-1. Comparison of (a) ion flux and (b) neutral flux at the cathode, normalized to the Child-Langmuir flux, for DYNAID (solid) and NEUTRAL (dashed) simulations of the test problem described in the text.

Figure 1-2. QUICKSILVER geometry used for ion diode simulations. The input wave is applied as shown. Electrons and ions are emitted using the space-charge-limited emission model from the regions highlighted on the cathode and anode, respectively.

Every simulation has shown a strong instability with waves that travel in the y direction and saturate in a few nanoseconds. The general features of this instability in the linear growth phase are consistent with analytic theory. The large amplitude fluctuations in the nonlinear regime lead to electron loss and growth of ion beam divergence and energy spread. We performed all simulations with protons using the same basic parameters: applied magnetic-field $B = 2$ T and gap $d = 1$ cm ($V_{\text{crit}} = 5.5$ MV), gas cell recession $x_0 = 0.5$ cm, periodic length $L_y = 10$ cm, and emission area 44 cm^2 . The feed geometry and inlet boundary condition give a feed impedance of 113Ω (per side and 10 cm width). The system is driven with an input transverse electromagnetic (TEM) wave that is linearly ramped from zero to the open circuit voltage $V_{\text{oc}} = 20$ MV in rise time τ_r .

Our first series of simulations examined the dependence of the results on rise time, zoning in y , and the number of particles. During this series, we continually improved our diagnostics: we modified the code as needed to get information on ion beam divergence, energy spread, and electron loss current. The results of this first series showed that a rise time of 5 ns was sufficient to eliminate spurious behavior and that systems with 50 cells and 250,000 particles with waves traveling in the y direction had adequate resolution.

The second series of simulations had more detailed diagnostics. The development of the PLOTFFF and BUILDFFF postprocessors gave us the ability to extract quantitative information quickly from field snapshots for the first time (in the form of contour plots of selected planes) and from line plots along pencils of the three-dimensional simulation volume. We also introduced Fourier analysis diagnostics by using 64 cells in the y direction to Fourier transform efficiently the E_y field component in y . Linear theory analyzes the stability of modes proportional to $\exp[i(k_y y - \omega t)]$. To analyze the spectral evolution of the instability, we chose selected pencils of cells in the y direction at selected points in the (x, z) plane, did a fast Fourier transform (FFT) of each pencil in y , and saved time histories of the real and imaginary parts of the lowest ten modes: $E_{yr}(x, k_{ym}, z, t)$ and $E_{yi}(x, k_{ym}, z, t)$, where $k_{ym} = mk_0$ ($m = 0, 1, \dots, 10$) and $k_0 = 2\pi/L_y$. We could then Fourier analyze these time histories in time with the IDR¹⁻⁴ signal processor to give full ω - k_y decomposition of the instability. Other special diagnostics included snapshots of energy and p_y distributions for ions passing through the gas cell and the energy distribution of electrons hitting the anode.

The more detailed diagnostics on the first two runs in this series indicated that we had problems with electron emission and that the timestep was too large. We corrected these problems, and the third run in this series represents our best simulation to date. Figure 1-3 shows a plot of the diode V_D voltage and current time histories. The Desjarlais theory¹⁻⁵ with a saturated electron sheath predicts operation at 3.0 MV, and MAGIC simulations of the x - z plane are in good agreement with this. The unexpectedly low impedance in the QUICKSILVER simulation is still unexplained. The electron loss current gives a diode efficiency of 95%. Figure 1-4 shows a plot of the time history of the ion beam divergence θ_H ; this divergence is considerably larger than in experiments on PBFA II.

The ion diode simulations show the existence of a violent instability that strongly affects the ion beam. Although we have refined key input parameters, we see significant discrepancies between the impedance behavior in the simulations and analytic theory, and the divergence is larger than seen in experiment. Many of these problems came to light only after we developed new diagnostics, and we are actively developing further diagnostics to help us understand these differences.

Maximal Decay and the Decay Instability in Applied-B Ion Diodes

M. P. Desjarlais

The basic V_* theory¹⁻⁵ predicts a divergent ion current at a critical, limiting voltage $V_* = 0.6cB_0d$. This connection between the limiting diode voltage and the gap flux can lead to rapid voltage decay if the diode is being operated in the high enhancement regime $V \approx V_*$. Motion of the anode emission surface across flux

Figure 1-3. Voltage and current time histories for our best proton simulation.

Figure 1-4. Time history of the ion beam divergence at the gas cell for our best proton simulation.

surfaces reduces the acceleration gap flux and, therefore, V_* . Because the anode magnetic field is greatly enhanced relative to the applied field as a result of diamagnetic effects, a thin layer can absorb a significant fraction of the original diode flux.

For an anode layer of thickness δ , the voltage is limited by $V_* = 0.6c(B_{0d} - B_a\delta)$, where B_a is the self-consistent anode magnetic field, often several times the value of the applied field. We can construct a variety of models that appear feasible for describing the flux penetration. Perhaps the simplest is to assume a perfectly ionized plasma layer on the anode surface and to invoke finite resistivity to explain the flux penetration. This assumes that the initial equilibrium is a balance of the plasma pressure against the diode magnetic field. However, very high plasma pressures are needed to support the anode surface against the extreme magnetic fields present (on the order of 6 T). One-dimensional simulations by T. W. Hussey¹⁻⁶ have shown that, for a wide range of reasonable parameters, the magnetic field simply compresses the anode plasma and its internal field until the internal field pressure rises to balance the external magnetic pressure. One can argue at this point that the plasma simply diffuses across the magnetic field. The difficulty here is that order of magnitude departures from classical diffusion $v_d = -\nabla P / \sigma B^2$ are required to explain the inferred penetration rates.

One reasonable explanation is to assume that the significant neutral population, which is unaffected by the magnetic field, is expanding and ionizing at the active anode surface, thereby advancing the emission surface across flux surfaces. The layer width δ may be described dynamically by $\dot{\delta} = v_o - v_e$, where v_o is the velocity of the anode material across flux surfaces, v_e is the erosion velocity of the beam given by $v_e = J_i / qn_o$, J_i is the ion current density, and n_o is the density of the ionized flux. This model contains two parameters, v_o and n_o , that (for now) must be determined either experimentally or empirically. Note that if $J_i = qn_o v_o$, $\dot{\delta} = 0$. This is simply a balance between erosion and the influx of new material. It is a stable fixed point for the voltage in that, for fixed anode area and a steady accelerator load line, a decrease in voltage increases the erosion velocity, driving $\dot{\delta}$ negative, which raises the voltage.

The rate at which the diode voltage decays is given by

$$-\dot{V}_* = 0.6c(\dot{B}_a \delta + B_a \dot{\delta}) \quad (1-4)$$

The first term is usually much smaller and can be neglected. Using pressure balance and the expression for $\dot{\delta}$, this can be rewritten as

$$-\dot{V}_* = 0.6c \left[B_c^2 + 2\mu_o J_i \left(\frac{2MV}{q} \right)^{\frac{1}{2}} \right]^{\frac{1}{2}} \left(V_o - \frac{J_i}{qn_o} \right). \quad (1-5)$$

The right-hand side is positive for $J_i < qn_o V_o$, as expected. More interestingly, Equation (1-5) achieves a maximum value for

$$J_i = \frac{1}{3} qn_o V_o - \frac{2}{3} \frac{B_c^2}{2\mu_o} \left(\frac{q}{2MV} \right)^{\frac{1}{2}}. \quad (1-6)$$

The second term is typically much smaller than the first. The function $-\dot{V}_*$ is shown schematically in Figure 1-5.

The limiting voltage V_* is a local quantity in the diode. Variations of V_* from place to place on the anode surface will lead to variations of the ion current density. Similarly, $-\dot{V}_*$ is a local quantity and we should consider the stability properties of a small variation in V_* . If the system starts out to the left of the maximum in Figure 1-5, the increased current densities associated with lower values of V_* lead to a greater $-\dot{V}_*$ and, hence, the perturbation is enhanced. Conversely, if the system starts out to the right of the maximum, the increased current density associated with the local decrease in V_* leads to a lower $-\dot{V}_*$ and the perturbation is reduced. The primary consequence of this behavior is that, for initial current densities to the left of the maximum, the current density will increase locally to approach the maximal decay. When this point is reached, the emission area associated with maximal decay will broaden in response to increases in total current in order to maintain the maximal decay rate.

For initial current densities to the right of the maximum, the system is stable with uniform emission over the whole anode being favored. This state could be conducive to good focus and would have a slower decay rate. Only when the anode is uniformly active can the diode approach the steady-state balance of erosion with influx. Otherwise, the area, rather than the current density, will increase in response to decreasing voltage and increasing current. It is possible that going to smaller anodes on PBFA II will allow us to operate the diode in a stable regime. The critical parameters that affect the success of this approach are the uniformity and magnitude of the neutral flux. If the ionized flux at the emission surface $n_o V_o$ increases in time, the stable regime may be elusive and the impedance decay rate will increase. A source that provides a very low background of neutral particles could deliver very dramatic improvements in both impedance history and beam divergence.

Figure 1-5. Schematic of function $-\dot{V}_*$.

Understanding Applied-B Ion Diode Coupling to PBFA II

S. E. Rosenthal

We have explored two aspects of applied-B ion diode coupling to the power feeds of PBFA II. The first concerns modification of the voltage-current (V-I) characteristic of the MITL that feeds into the diode. The second involves a modification of the ion diode V-I characteristic itself.

The MITL characteristic is the diode voltage V plotted against the self-limited feed current $I_{SL}(V)$. We assume a simple pressure balance description for $I_{SL}(V)$. The mechanism that we consider for the MITL characteristic modification is a constriction of the MITL A-K gap. A partially opened POS produces such an effect.

The ion diode characteristic is the diode voltage plotted against the ion current calculated by the equilibrium diode theory.¹⁻⁵ The mechanism under consideration for diode characteristic modification is a preloading of diode electrons by use of a plasma prefill of appropriate density. The resultant diode characteristic is determined by numerical simulation.

Figure 1-6 shows the general interrelationships of the typical ion diode, magnetically insulated feed characteristics, and the accelerator load line. The open-circuit voltage at the y intercept of the load line is an increasing function of time until its peak value is reached (at t_3 in Figure 1-6). The operating point is roughly determined by the intersection of the load line and whichever characteristic gives the larger current. The feed is essentially the load for the accelerator if the load line intersects the feed characteristic at a larger current than that given by the intersection with the diode characteristic. The difference between the two intersection current values is the current lost in the feed. The diode current is sufficient to insulate magnetically the feed after time t_2 in Figure 1-6. The insulating voltage for the diode A-K gap, V_C , can be large enough that the diode would never leave its constant enhancement mode, thus leaving the feed as the main load for the accelerator throughout the pulse. In such a case, the load line at peak open-circuit voltage, relative to the characteristics, would look like Figure 1-6 at t_1 .

The slope of the feed characteristic is a function that increases with the minimum A-K gap of the feed. The diverging-current voltage (V_*) for the diode characteristic is proportional to V_C . So, for a given open-circuit voltage, the diode can run well enhanced only for V_C below the value for which the load line at peak open-circuit voltage intersects the feed characteristic above the diode characteristic. This maximum V_C decreases as the feed A-K gap decreases.

Figure 1-6. Generic ion diode and magnetically insulated feed characteristics shown with accelerator load lines at several times in the pulse.

Constricted Gap in MITL

The POS in the MITL feed can become magnetically insulated before it opens completely; it thus presents the MITL with a constricted gap. As a consequence of the additional current required to insulate the smaller gap at the POS location, the loss front downstream of the POS occurs over a significantly greater distance than it would have in the absence of the gap constriction. The downstream saturated flow initiated by the loss front can persist throughout the pulse when the gap constriction is significant, such as one-third of the vacuum gap. This effect is not lessened by narrowing the gap constriction in the power flow direction unless the length becomes less than the vacuum gap.

The current and voltage measurements imply that some POS configurations on PBFA II open only to one-third to one-half the vacuum gap. We have investigated the effect of the ion diode applied magnetic field on the behavior of the augmented electron flow downstream of such a constricted gap with MAGIC simulations. In these simulations, we represented the POS simply by a permanent deformation of the MITL anode to form a gap of one-third the normal value. We did not add a special POS magnetic field to the normal diode applied field. Figure 1-7 illustrates the geometry.

Normally, only those magnetic flux surfaces that are close to the feed cathode are accessible to the feed electrons; the feed electrons enter the diode along these surfaces. Because the constricted feed gap can launch electrons well above the cathode, even flux surfaces that are near the feed anode are accessible to the feed electrons downstream from the gap constriction. The effect of populating flux surfaces well above the feed cathode with feed electrons could be beneficial or disastrous, depending on the particular applied field geometry.

In a number of the field geometries used on PBFA II, some of the accessible flux surfaces intersect the anode above the ion emission area, and their electrons do not contribute to the enhancement of the ion current. These flux surfaces constitute a loss channel for many feed electrons. The primary effect of the constricted gap is that more current is required to insulate the feed, whose self-limited current is defined by the minimum gap. This increased current loads down the accelerator; this effect is also exaggerated in the simulations because of the large source impedance (18.5Ω compared to 4Ω for PBFA II).

The constricted feed gap can cause one of three outcomes, depending on the applied-B geometry and on the ratio of V_C to the peak open-circuit accelerator voltage V_{OC} . How much of the large self-limited feed current the ion current provides varies from nearly all to almost nothing, with the remainder always provided by the electron loss. The three possibilities are

Figure 1-7. Geometry of diode simulations with partially opened POS modeled as a permanent feed gap constriction.

- The ion current eventually becomes well enhanced, exceeding I_{SL} for the constricted feed gap.
- The ion current increases beyond the constant enhancement value, but remains less than I_{SL} .
- The ion current never increases beyond constant enhancement, remaining much less than I_{SL} throughout the pulse.

As an example of Case 1, the ion current in the typical proton-focusing geometry (but with a Li ion source) with a V_* of 4.4 MV was delayed 10 to 15 ns more than normal, but the diode eventually ran well enhanced, exceeding the self-limited current of the gap constriction, as Figure 1-8 shows. The eventual shift of the accelerator load from the feed gap constriction to the ion diode was possible because the peak open-circuit voltage load line intersected the reduced-impedance self-limited feed characteristic at a voltage above V_* . Because of the different set of flux surfaces that channeled the electrons to the diode (compared to the full-gap feed case), the equipotential surfaces near the edge of the emitting anode are correspondingly different and cause a defocusing of the ion beam edge. Figure 1-9 shows a plot for a PBFA-II shot for which the POS remained partially opened.¹⁻⁷

Figure 1-8. Characteristics for simulated low- V_* diode with reduced-impedance feed. $Z_0 = 6.4 \, \Omega$ compared to fully opened gap impedance of $18.5 \, \Omega$.

Figure 1-9. Characteristics for PBFA-II Shot 2650.

A vacuum impedance of 6.4Ω at the POS matches the feed current data well. On this shot, the insulating gap voltage V_C was low enough that the load line eventually intersected the reduced-impedance feed characteristic above the diode characteristic. A diode with $V_C > 11$ MV could not have operated enhanced with this POS.

A Li-focusing geometry, where V_* is too large for the small feed impedance, provides an example of Case 3 in Figure 1-10. The diode remained in the constant enhancement regime, with ion current that was much less than the self-limited feed current. The load line, even at peak open-circuit voltage, intersects the self-limited feed characteristic well below the diode characteristic. Consequently, the feed gap constriction essentially remains the load for the accelerator throughout the pulse. The ion current supplies only 7% of I_{SL} ; the rest is supplied by the feed loss. Appropriate changes in the applied field would allow increased enhancement of the ion current in this case; however, the ion current would always fall below I_{SL} .

These results highlight a crucial problem with high- V_C operation when we rely on the POS for pulse compression and possibly voltage gain. The POS is most likely to remain only partially open during the pulse when configured for the high-voltage output required for high- V_C diode operation. Unfortunately, high- V_C operation is the condition that can least tolerate a partially opened POS.

Figure 1-10. Characteristics for simulated high- V_* diode with reduced-impedance feed.

Plasma Prefill of Ion Diode

A diode that produced ion current that was near, or that even exceeded, the I_{SL} early in the pulse as the voltage increased toward its peak value would improve the previously discussed high- V_C condition. We also expect that the POS would be less likely to remain partially open while feeding a low-impedance diode, which would avoid the problem. In the nonequilibrium rising-voltage portion of the pulse, the actual ion diode characteristic when $V_C > 10$ MV can depart significantly from the corresponding theoretical equilibrium ion diode characteristic (see Figure 1-11). The ion current is well below the saturated characteristic value until near peak voltage. Hence, even without a POS, there is much to gain from the ability to change the diode characteristic in a desirable way. This is partly our motivation for attempting to modify the ion diode characteristic to favor lower-impedance operation early in the pulse. Also, if we bring the ion current more in phase with the diode voltage, we would achieve greater beam power. Plasma prefill is a technique that has been discussed previously^{1-8,1-9} for starting out an applied-B ion diode with low impedance.

Using MAGIC¹⁻¹⁰ simulations, we began investigating how to use plasma prefill to modify precisely the ion diode characteristic. We needed to determine whether it was possible to pull the diode characteristic down relative to the feed characteristic without sacrificing the desired peak power operating point or without degrading the ion beam by defocusing or inducing inhomogeneities.

Our initial simulations considered the prefill density as the main variable, assuming a uniform spatial distribution of prefill plasma. The goal was to determine the possible changes to the diode characteristic within the previously mentioned constraints. We modeled a 15-MV- V_C Li ion diode and assumed a C^{+3} plasma for the prefill. We simulated diodes with prefill electron number densities of 0.4, 2.0, 4.0, 10.0, and 40.0 $\times 10^{12}$ atoms/cm³, which corresponded to total electron charges of 0.063, 0.314, 0.628, 1.571, and 6.285 mC, respectively.

The results demonstrate a prefill (uniform) density regime for which the diode can operate nearly instantaneously on the theoretical saturated characteristic (such as for $V_C = 15$ MV Li: $1 \times 10^{12} < n_e < 1 \times 10^{13}$ atoms/cm³, C^{+3} plasma). The plasma provides the electron space charge required for the saturated equilibrium. With the proper plasma prefill density, the saturated electron density profile can (in a sense) be the initial condition.

The total diode electron charge needed to operate on the saturated characteristic at peak power can be calculated^{1-5,1-11} and is 1.62 mC (10.3×10^{12} atoms/cm³) for our configuration (half-diode). The simulations allow us to examine the dynamics that result from initializing the charge to the peak-voltage value. The charge actually required early in the pulse at lower voltage is substantially less. We

Figure 1-11. Comparison of actual high- V_C ion diode characteristics, from both simulation and PBFA-II data, with corresponding theoretical characteristics. Inset is PBFA-II Shot 3652 comparison.

found that an initial value of about 25% of the theoretical peak-voltage value keeps the diode characteristic close to the theoretical characteristic throughout the pulse. Figure 1-12 shows the characteristics for four different prefill charges. Note that initializing close to the theoretical peak-voltage charge of 1.6 mC puts the ion diode characteristic below the feed characteristic while reaching close to the full peak voltage.

An informative figure of merit is the beam impedance; this is the ratio of the diode voltage to the ion beam current. For the $V_C = 15$ -MV Li example without plasma fill, the beam impedance drops steadily from a very large value down to about $10\ \Omega$ when the diode voltage reaches 8 MV; with plasma fill, the beam impedance is nearly constant (about $10\ \Omega$) when diode voltage is above 1 MV. On PBFA II, this translates to enhanced ion beam current 24 ns earlier with plasma than without. The relatively low plasma densities required do not produce a POS in the diode, do not lower the peak power operating voltage, and do not cause noticeable momentum spread in the ion beam. Figure 1-12 shows that too high a plasma density loads down the accelerator; it also disrupts the beam. Figure 1-13 shows a summary of beam impedance results. These plots show a range of plasma density that gives impedance control without sacrificing voltage. Subsequent simulations will explore the sensitivity of these results to plasma inhomogeneity.

Figure 1-12. Characteristics from simulations of four different levels of uniform plasma prefill. Prefill electron number density ($\times 10^{12}$ atoms/cm³) = (a) 2.0, (b) 4.0, (c) 10.0, and (d) 40.0.

Figure 1-13. Beam impedance as a function of diode voltage for four different uniform prefill densities.

Power Flow

Electron Flows in Multiple-Cathode Magnetically Insulated Systems

S. E. Rosenthal

Hermes III¹⁻¹² is a 730-kA, 22-MV, 40-ns-wide pulsed power accelerator designed to operate in negative polarity to power electron beam diodes. The significant feature of this accelerator is the series voltage addition that occurs along the power flow direction in the coaxial MITL. Properly timed pulses are supplied by radial disk power feeds. We have recently become interested in evaluating the feasibility of applying this technology in positive polarity to power ion diodes for ICF.

The essential, dominating difference between negative and positive polarities in this accelerator is that the cathode is one continuous conductor (the inner line of the coaxial MITL) in negative polarity; in positive polarity, the cathode is split into 20 separate conductors, the sections of the outer line of the MITL that are between the radial disk feeds.

The idealized schematic of the geometry of Figure 1-14 shows the vacuum equipotential surfaces at a time when all the pulses have arrived at the final MITL at full amplitude; this illustrates how the voltage addition occurs. Note that the voltage across the final MITL gap is the sum of the voltages of each of the feed gaps. In negative polarity, the cathode is a single, continuous conductor, and it is related to the same set of equipotentials all the way along the adder to the final MITL. The highlighted area of Figure 1-14 shows the likely flow pattern in negative polarity. Such a flow remains continuous throughout the adder to the final MITL.

In positive polarity, the cathode is split into separate sections, each related to a different set of equipotentials. The alternate light and dark areas of Figure 1-15 show the likely flow regions from each cathode. At the final MITL, the flow will extend across the entire gap based on this simple view. The self-consistent interaction between the fields and the electrons does not change these conclusions substantially.

The equilibrium magnetic insulation theory for one dimension has proved to be useful and quite successful in the negative-polarity Hermes-III design and data analysis. As an important first step in understanding how Hermes III works in positive polarity, we need to learn to what extent (if any) the simple theory (that is so successful in negative polarity) applies. A theory is needed to allow us to characterize the electron flows in positive polarity. We use numerical simulation with the MAGIC code to guide us in this effort.

Figure 1-14. Idealized negative-polarity voltage adder geometry illustrating band of parapotential flow near the single, continuous cathode.

Figure 1-15. Idealized positive-polarity voltage adder geometry illustrating bands of parapotential flow from multiple cathodes.

Figure 1-16 shows the constant anode current of 750 kA and the anode currents from a MAGIC simulation of negative-polarity Hermes III. The points are given during the maximum-voltage time (20 MV) of the pulse at each diagnostic location along the accelerator (the first one is after the fourth feed, the second after the eighth feed, and so on) to the final MITL position. The difference between the two curves is the electron flow current. This increases slightly with voltage or position along the adder according to the one-dimensional theory; measurements also agree.

Figure 1-16. Electron flow increases slightly with voltage in simulations of negative-polarity Hermes III. The numbers on the abscissa are spool numbers or number of upstream gaps in the simulation; the numbers in parentheses are the corresponding number of Hermes-III gaps. The second 5(20) position is downstream of the first 5(20) position in the final MITL.

MAGIC simulations of Hermes III, including many of the original simulations of Poukey,¹⁻¹³ show the different features of positive polarity. The calculations include the self-consistent coupling between the electrons and the fields; yet, the results are not qualitatively different from what we concluded from the vacuum equipotentials.

Compared to negative-polarity operation,

- The electron flow increases more dramatically with voltage or, in this case, with the number of cathodes.
- The final MITL impedance is substantially less for the same voltage.
- There is more turbulence in the adder; regions where the electron density increases away from the cathode occur more often.
- Just as expected from the vacuum equipotentials, the flow extends across the entire gap of the final MITL. We refer to this as full-gap flow (FGF).

The locally emitted flow (LEF) of the final MITL is about one-half of the FGF. The locally emitted electrons would lose the full accelerator energy if lost to the anode, and the other half of the FGF injected into the final MITL from the adder includes many electrons that are close to the anode potential. Note that the term “saturated” is not used here because it strictly relates to a single-cathode electron flow; also, it would cause confusion if the LEF itself were saturated.

As in the negative-polarity case, Figure 1-17 shows that the anode current from the positive-polarity simulation is roughly constant throughout the system, but in going from negative to positive polarity, the anode current has increased from 750 kA to 1.05 MA; the voltage is 17 MV. The cathode current decreases more rapidly with the number of upstream gaps, with the corresponding electron flow (difference between anode and cathode currents) in the first sections less than in negative polarity and rapidly increasing to about double the negative-polarity value in the final MITL. Half of this electron flow is injected from the adder; the other half is the LEF, which is about the same as the electron flow in the negative-polarity final MITL.

The importance of learning the consequences of this additional electron flow on the operation of an ion diode motivates us to establish a theoretical model that can help us characterize the electron flow from current measurements.

Preliminary measurements on positive-polarity Hermes III¹⁻¹⁴ agree with this qualitatively, but there are some discrepancies. The experiment shows greater electron flow in the first sections, the flow increases less rapidly through the adder, and then it increases more rapidly after the final feed, reaching about the same value as shown in the final MITL. These results need to be repeated in additional, well-controlled experiments. If confirmed, we will need to understand the meaning of these discrepancies.

Figure 1-17. Positive-polarity simulation particle plot in z-r plane at 22 ns.

The snapshot of Figure 1-18 from a positive-polarity Hermes-III MAGIC simulation near the time of peak voltage shows some features of the electron flow. A portion of the electron diode load that we used is included in the right-hand side of the picture. Note the turbulence in the adder section and the regions of increasing electron density away from the cathode. Also, as the vacuum equipotentials suggested, the flow does indeed fill the whole gap of the final MITL.

Knowing that the flow extends all the way to the anode in the final MITL, we can consider a pressure balance derivation and, with fewer assumptions than previously needed,¹⁻¹⁵ derive a simple relationship between the anode and cathode currents and the voltage. The resultant constant-voltage equilibria are consistent with the increased electron flow observed above 14 MV in the positive-polarity simulation. They also indicate just the current increase necessary to account for the impedance decrease observed in the final MITL when the polarity is changed from negative to positive in both the simulations and the Hermes-III experiments.

In the MAGIC simulation, we have labeled the electrons according to their cathode of origin. Returning to the particle snapshot, we can peel away the injected flow to see its spatial relationship to the LEF in Figure 1-19. As suggested by the vacuum equipotentials, the injected flow remains radially separate from the LEF. There are only occasional departures from this stratified equilibrium, as indicated by

Figure 1-18. Electron flow increases with number of upstream gaps in simulation of positive-polarity Hermes III. The numbers on the abscissa are spool numbers or number of upstream gaps in the simulation; the numbers in parentheses tell the corresponding number of Hermes-III gaps. The second 5(20) position is downstream of the first 5(20) position. Triangles represent experimentally measured currents at peak voltage: anode (open) and cathode (solid).

the two spikes in the LEF shown at this time. Subsequent peeling back of each component of the injected flow shows that these components are not themselves radially layered due to the turbulence in the adder MITL.

Because there is no mixing of the locally emitted and injected flows, we could also use the original one-dimensional theory that was so successful in negative polarity. In this case, rather than using the anode and cathode currents (whose difference is the total flow), we use two cathode currents whose difference is just the LEF. The voltage calculated from the LEF approach should agree with the FGF result to the extent that there is FGF and the injected and locally emitted flows do not radially mix. The voltage waveforms calculated from the simulation currents by the two methods match the simulation voltage waveform well.

Both the FGF and LEF models applied to positive-polarity Hermes-III data give voltage waveforms that agree closely. Figure 1-20 provides two examples of voltage versus time plots computed from current measurements on positive-polarity Hermes III. The agreement between the two methods shown in each example indicates that FGF and radial separation between the injected and locally

emitted flows occur in the actual experiment. Now that we can diagnose two important features of the electron flow in the final MITL of Hermes III, we can begin to examine how the injected electron flow in positive polarity might impact the operation of an ion diode.

Figure 1-19. Positive-polarity simulation z-r particle plots showing (a) the injected flow from the adder cathodes and (b) the LEF of the final MITL.

Figure 1-20. Comparison of FGF and LEF voltages calculated from current waveforms measured on two different Hermes-III shots.

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Chapter 2. Ion Beam and Ion Source Experiments

Overview

R. W. Stinnett

During the past year we have made significant progress both in demonstrating focusability of ions on PBFA II and in developing Li ion sources. Experiments on PBFA II using a 15-cm-radius applied-B ion diode with a flashover proton ion source achieved an approximately 5 TW/cm^2 proton focal intensity (averaged over a 6-mm-diameter sphere). Additional experiments that we conducted using a LiF ion source produced the first high-energy Li^+ beam seen on PBFA II, which delivered 26 kJ of Li beam energy to the axis of the diode.

Research on the electrohydrodynamic (EHD) ion source demonstrated that a vertical liquid Li surface can be produced and maintained in the laboratory by "rapid wicking" through porous Inconel frits. Implementation of this technology on PBFA II allowed us to conduct two full-scale EHD experiments in which some Li beam was produced.

Laboratory tests of the Boil Off Lithium VAPor Source (BOLVAPS) demonstrated the production of a 1- to 2-mm-thick layer of Li vapor with a density approaching $1 \times 10^{17} \text{ atoms/cm}^3$ by rapid ohmic heating of a thin-film laminate. These tests provide the basis for full-scale experiments on PBFA II.

We conducted other laboratory experiments using a dye laser that operates at the 670.8-nm resonant transition of Li to ionize Li vapor produced by BOLVAPS or other techniques. Laser power and energy densities of $3 \times 10^4 \text{ W/cm}^2$ and 14 mJ/cm^2 are sufficient to ionize the Li vapor, producing electron densities of $>10^{16} \text{ atoms/cm}^2$; these results agree with theory. We also investigated using this laser for direct evaporation and ionization in the laboratory and on PBFA II. This Laser EVaporation Ion Source (LEVIS) successfully produced ions but showed problems with contamination and low diode impedance in initial tests.

We performed magnetohydrodynamic (MHD) calculations of the response of an anode plasma layer to the rising magnetic field in an applied-B ion diode to investigate joule heating of the plasma layer and the leakage of flux behind the ion-emitting surface. These effects, which could contribute to divergence and diode impedance collapse, are acceptably small for thin ($\sim 1\text{-mm}$) plasma layers at moderate (10^{16} to $10^{17} \text{ atoms/cm}^3$) densities.

PBFA-II Applied-B-Field Ion Diode Proton Beam Characteristics

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An applied-B-field ion diode on PBFA II²⁻¹ has produced a 17-TW proton beam, which allows us to investigate beam generation and transport physics that are pertinent to ICF experiments. We fed power to the diode via two conical self-MITLs that incorporated POSs. The diode utilized a pair of magnetic field coils in disc-shaped cathodes to produce a 3-T axial magnetic field that insulated the 16-mm A-K gap from electron loss. We configured the 15-cm-radius anode with a 5.5-cm-high curved ion-emitting region. A 2.6-MA ion beam originated from this region, accelerated to 6 MV in the A-K gap, and ballistically moved toward the axis in a current-neutralizing gas cell. The best transport (75%) occurred with narrow 5.5-cm-high anode sources in which we observed a 180-kJ proton beam within 1.2 cm of the diode centerline. The full width at half maximum (FWHM) of the beam focused at the centerline of the diode was 5 to 7 mm. This beam gave a peak proton power density of approximately 5 TW/cm².

A cross-sectional view of the diode is shown in Figure 2-1. This diode is a scale-up of a smaller diode²⁻² used previously on the Proto-I accelerator. Two cathode coils supply the primary insulating magnetic field in the A-K gap, but work with four anode coils to produce uniform magnetic insulation along the anode surface to give a proton beam with zero canonical angular momentum. The ion source operates by surface flashover and is produced from a series of concentric grooves machined in stainless steel that are 0.9 mm wide, 1.5 mm deep, separated by a 0.3-mm-wide land, and filled with carnauba wax. Electron loss early in the diode power pulse creates an anode plasma on the wax. This plasma is a mix of ions and neutrals that produces beam energy spread and yields a beam with comparable currents of proton and C ions. The thickness of this plasma required placing the zero stream function (separatrix) of the applied-B field about 3 mm from the anode surface to achieve a zero canonical angular momentum beam.

When we apply the PBFA-II power pulse to the 18.5- Ω self-MITLs, a spiral-gun-array POS shunts the leading edge of the current pulse. The POS consists of two arrays of four guns, each with a 25 cm² aperture, located 20 cm above and below the diode. When the POS opens, the rising voltage pulse allows electrons to flow into the diode to fill the A-K gap and form a virtual cathode of azimuthally drifting electrons. This enhances the ion flow about a factor of 10 over the normal space-charge-limited value at peak power but results in a beam turn-on delay with respect to the voltage of about 5 ns. The beam is then accelerated by the applied electric field in a distance of about one-third the A-K gap because of the compression of the

Figure 2-1. Cross-sectional view of the diode showing the diagnostics layout.

equipotentials toward the anode surface. During ballistic transport to the diode centerline, the beam undergoes self- and applied-B-field bending. At 12.5 cm radius, it enters a gas cell outfitted with a 2- μm -thick Mylar window and 5-torr Ar fill that allows current neutralization and reduces the self-field bending by a factor of about 10. The applied field bending varies as B^2 , roughly as the square of the distance from the midplane, and is not affected by the gas cell. For this reason, the anodes had a complex shape to allow a good focus at the centerline. Figure 2-2 shows typical proton trajectories for a 6-MV, 2.6-MA proton beam that were obtained with the simulation program PICDIAG²⁻³ as well as the applied-B-field lines calculated with the magnetic diffusion program TRIDIF.²⁻⁴ The protons were emitted normal to

Figure 2-2. Trajectories calculated with PICDIAG for a 6-MeV, 2.6-MA proton beam.
 (Upper) Trajectories in the horizontal plane where $x = r\cos\theta$ and $y = r\sin\theta$.
 (Lower) Trajectories in the vertical plane and applied-B-field lines calculated with TRIDIF are displayed on a schematic of the diode.

anode shape Q1 described in Figure 2-2, and we assumed the beam was 90% current neutralized in the gas cell.

Diagnostics

We measured the current with dB/dt loops on the negative transmission line feeds before and after the POS and near the edges (for ion current) of the cathodes at 13 cm radius. We determined the diode voltage in two ways. First, using an array of six range-filtered scintillator fiber optic channels (the RFS voltage monitor in Figure 2-1), we observed protons from a 6-cm² flashover source in the bottom transmission line. In this case, we made an LdI/dt correction for the 20-nH inductance between the monitor and diode positions. Second, we specified the diode voltage by an LdI/dt correction to the voltage measured across the vacuum insulator stack. This measurement was only accurate after peak power when full self-magnetic insulation was established in the vacuum transmission lines.

We measured the beam with full beam and shadowbox witness plates, $K\alpha$ and Rutherford-scattering pinhole cameras, and a magnetic spectrometer. The shadowbox consisted of an aperture plate at the gas cell window with an array of 35 holes (1.5 mm in diameter), which we used with a witness plate at a 7 cm radius. We observed three additional 90° sectors of the beam at 3.8 cm radius with time-integrated $K\alpha$ pinhole cameras.²⁻⁵ One camera recorded the total incoming beam, a second recorded the beam transmitted through a slotted mask at the gas cell window, and a third recorded the beam after it passed through a Au foil at the centerline.

We measured the proton beam energy spectrum and focused power density with a time-resolved magnetic spectrometer²⁻⁶ that observed protons Rutherford scattered from a 1- μ m-thick Au foil. The foil was located at the center of the diode as shown in Figure 2-1. The spectrometer utilized 250- μ m-thick PIN (p-type, intrinsic n-type) diodes and CR-39 film to observe the beam. We used a 1-mm-diameter aperture at the entrance to the spectrometer with a 3-mm-wide slit mounted 3.8 cm above the target to give an energy-resolved ($\delta E/E \sim 1.5\%$), one-dimensional image of the beam in the horizontal plane. We also observed the spatially resolved energy density of the focused beam at the on-axis Au foil with an array of six range-filtered Rutherford-scattering ion pinhole cameras.²⁻⁷ Because the Rutherford-scattering cross section varied as $\sin^4 \theta$ with scattering angle θ and the effective target thickness varied with incident beam angle, the scattering probability was most uniform with angle for the transmission geometry target. This therefore required that we perform separate shots to obtain accurate data with both the spectrometer and the pinhole camera. The filters provided energy discrimination and, because the diode voltage dropped throughout the pulse, this implicitly yielded a time-resolved focus.

Experimental

Beam Generation

Figure 2-3 shows the electrical characteristics of PBFA-II Shot 2679. This shot utilized an applied-B field that varied across the anode surface from 2.2 T at the midplane to 3.2 T at the A-K gap and gave a TRIDIF-calculated V_{crit} of 12.8 ± 0.5 MV across the 5.5-cm-tall anode-emitting region. We obtained the first 35 ns of the voltage pulse with the RFS monitor and the remainder with the inductively corrected monitor. The diode current rises before the ion current because of electrons flowing into the diode along the applied-B-field lines prior to the formation of the virtual cathode. After the virtual cathode is established, experiment²⁻⁸ and theory^{2-9,2-10} demonstrate the existence of a limiting voltage at which the ion current diverges. This limiting voltage, $V_* \sim 0.6cB_0d$, is proportional to the flux (B_0d) in the A-K gap. The heavy dashed line in Figure 2-3 shows the result of a time-dependent calculation of the voltage decay caused by a flux loss behind the active anode surface.²⁻¹⁰ The initial starting voltage is the theoretical operating-point voltage determined from the steady-state theory. The time-dependent part of the calculation contains one free parameter that characterizes the anode plasma motion.

The currents obtained upstream (I_{feed}) and downstream (I_{diode}) from the POS indicate that the POS carried about 1.0 MA of current. When open, the POS operated like a 10- Ω MITL and absorbed power until the diode impedance dropped below about 5 Ω . The diode power pulse showed a factor of 2 increase in rise rate and was 10% higher at peak with use of this POS. We fired three shots with a dual flashboard plasma source POS that utilized six 75-cm² apertures above and below the diode. This arrangement gave a much later opening time, and the POS acted like a 5- Ω MITL. In this case, the POS intercepted energy until the diode impedance dropped to 2 Ω .

We obtained data first with flat anodes of various heights. The narrow anodes gave a longer beam turn-on delay, more voltage overshoot, more rapid impedance collapse, and less energy coupled to the diode. In this case, we attributed these effects to the requirement for a smaller dynamic gap, which accentuates the effects of anode plasma motion. For a 5.5-cm-tall anode, about 650 kJ of electrical energy was coupled to the diode with 450 kJ in ions. This increased to 750 and 600 kJ, respectively, for an 8-cm-tall anode. However, tall anodes produced proton beams that were very susceptible to applied-B-field bending near the coils. For a 5.5-cm-tall anode, we observed 180 kJ of proton beam energy within 1.2 cm of the diode center. This dropped to 85 kJ when the anode height was increased to 8.5 cm. A PICDIAG simulation that modeled the beam transported to the target region (assuming half of the beam current was protonic and the remainder was C) agreed with these experimental values to within 20%.

Figure 2-3. Electrical characteristics of the diode.

Other criteria for successful diode operation were magnetic insulation uniformity (conformity of the B field lines to the anode surface), B field strength, size of the A-K gap, and position of the gas cell. Decreasing the magnetic insulation in a region of the anode resulted in higher current density. For this reason, it was necessary to use less insulation at the midplane of the anode to compensate for the tendency for lower current density there, if uniform current density was desired. Larger B fields and A-K gaps gave longer beam turn-on delays and a larger-focus FWHM. The reason for this is not fully understood. However, a nonuniform anode plasma could occur during the longer turn-on associated with the large gaps, thereby giving a poorer focus. Another possibility is that the shorter cathode tips used with large gaps result in the electrons forming a virtual cathode from the feed region near the diode or gas cell.

Proton Focus

Figure 2-4 shows the rear surface spall on a 1.6-mm-thick stainless steel shadowbox aperture plate that was exposed to the beam from a 6.5-cm-tall flat anode. The spall shows well-defined top and bottom edges that are azimuthally symmetric in an axial position to ± 1 mm and located where predicted with PICDIAG for the peak power beam. Figure 2-5 shows a representation of the proton beam that we produced from shadowbox damage patterns obtained for anode Q1 (Shot 2646) with a plot of the anode slope. The patterns represent front surface blowoff on a brass witness plate and were typically 2 mm wide. These patterns imply an intrinsic divergence of 13 mr and would give a 3.8-mm-FWHM focus. The data also show that the beamlets were randomly scattered within 1 mm of their desired positions. This indicates a global divergence of 20 mr, which is sufficient to produce the

Figure 2-4. Rear surface spall pattern for a 9.5-cm-tall shadowbox aperture plate.

Figure 2-5. Representation of proton beam produced from shadowbox damage patterns. (Upper left) Shadowbox beamlet damage patterns. (Upper right) Slope of anode Q1 versus axial position. (Bottom) Ion trajectories projected on a schematic of the diode.

5.5-mm-FWHM focus observed on this shot. Figure 2-6 also shows the projections of the beamlets that allow for self- and applied-B-field bending of the beam. The 6-cm-tall anode used in this shot resulted in a 10% lower diode impedance than observed for PBFA-II Shot 2679; therefore, the applied-B-field bending was greater.

Figure 2-6 shows that the open quadrant Ti cone target $K\alpha$ pinhole camera image for Shot 2646 is represented by the projection of the image on a 3.8-cm-radius cylinder. This figure also shows a similar projection based upon a time-integrated PICDIAG simulation for the beam. The simulation used the beam energy that was determined from the magnetic spectrometer and beam current of the ion dB/dt loops. The simulation included small-angle scattering in the gas cell window and gas and assumed that the current neutralization inside the gas cell was 90%. It assumed normal emission from the anode surface Q1 and a histogram current density function that increased by a factor of 2 above the nominal value at axial distances between 33% and 66% of the anode half-height. This gave a better PICDIAG fit to masked $K\alpha$ camera images than uniform current density. This current density enhancement at anode half-height was difficult to discern from the shadowbox witness plate damage patterns because the beamlets swept above and below the midplane.

Figure 2-6. $K\alpha$ images observed from the open quadrant on Shot 2646 and calculated for this geometry with the PICDIAG computer code. (Left) The $K\alpha$ camera image observed from the open quadrant on Shot 2646. The peak intensity is divided into 15 contour levels. (Right) The $K\alpha$ image calculated for this geometry with the PICDIAG computer code. The peak intensity is divided into nine contour levels. The nonuniformities represent 25 fiducial holes located in the Ti target that identify possible target motion caused by the applied-B field.

A comparison of the experimental and theoretical data in Figure 2-7 shows that azimuthal nonuniformities of the beam at 3.8 cm radius are $\pm 40\%$. Similar analysis of the images of the beam projected through a 6-mm-wide slit at the gas cell window show a $\pm 25\%$ variation. Nonuniformities in current density at the anode result in local applied electric and magnetic self-focusing²⁻¹¹ of the beam during transport and contribute to the nonuniformities at the $K\alpha$ target. A current density variation of $\pm 20\%$ in this diode would give magnetic steering errors of 1° and increase current density variations on the $K\alpha$ target by at least 10%, in agreement with these measurements. The most intense region of the beam appears to oscillate up and down in a serpentine pattern in Figure 2-7. This indicates that the virtual cathode sheath is not symmetric in the azimuthal direction, implying asymmetric power flow or unstable virtual cathode development.

We obtained the images in Figure 2-7 with the Rutherford-scattering pinhole camera array on Shot 2646. Figure 2-7 shows the focus of a 67° sector of the proton beam on the Au foil at the center of the diode. The horizontal FWHM of the focus increased from 5.5 mm at beam energies above 6.5 MeV to 7 mm at beam energies between 4.0 and 3.6 MeV. The vertical profile of the beam shows the effects of magnetic sweeping. The best vertical focus of 4.9 mm FWHM occurred in the

Figure 2-7. Rutherford-scattering pinhole camera images for Shot 2646 displayed as a function of beam energy. The peak current density for the 6.5 to 5.7 MeV image is 21 kJ/cm^2 . The contour levels show equal beam charge density on target and energy densities of $0.65 \times \text{Energy (MeV) kJ/(cm}^2\text{MeV)}$.

5.7 to 5.1 MeV energy interval. We obtained similar results for Shot 2679, except that we mounted the target in the reflection geometry for the pinhole camera; as we expected, this gave an asymmetric profile because of the variation in scattering sensitivity with beam angle. The horizontal FWHM for Shot 2679 was 5 mm for the high-energy portion of the beam.

Figure 2-8 shows the PIN diode signals and CR-39 image from the magnetic spectrometer with beam power unfoldment for a 67° sector, which was based upon computer-generated response curves for the spectrometer. We observed that the beam had an energy spread of $\pm 5\%$ throughout the power pulse. The beam energy is also plotted in Figure 2-3, where it appears to be 20% and 10% below the diode voltage early and late in the pulse, respectively. This may be caused by a charge exchange mechanism²⁻¹² in a weakly ionized anode plasma that was penetrated by the applied electric field. In the charge exchange process, an accelerated ion captures an electron from a slow neutral atom, resulting in a fast neutral and a new ion at somewhat less than the total gap potential. In this case, the final ion energy is less than that for full gap acceleration.

We determined the focused proton beam power in Figure 2-8 from the PIN signals for the 67° beam sector that struck the Au foil target and converted into power on a vertical planar target. Energy and temporal integration of the CR-39 tracks and PIN signals gave energy densities of 73 and 67 kJ/cm² on the target, respectively, above 5 MeV. These energy densities are consistent with data obtained with the Rutherford-scattering pinhole camera array that showed a target energy density of 63 kJ/cm² above 5.1 MeV. The peak power density of 4.8 TW/cm² determined from the PIN signals is also consistent with a forward PICDIAG simulation of the beam focus that gives 5.3 TW/cm². The measured value (projected to equivalent power density deliverable to a 6-mm-diameter spherical target and the baseline for PBFA II) is 5.4 ± 0.9 TW/cm².

Figure 2-8. PIN diode signals and CR-39 image from magnetic spectrometer. (Upper left) Proton focus power for Shot 2679. (Upper right) Raw PIN diode data from the magnetic spectrometer. The largest signal corresponds to ions at 5.9 MeV. (Lower) The image of the beam as recorded by the CR-39 in the magnetic spectrometer. The image is blocked at several locations by 2-mm-diameter holes in the CR-39 to allow ions into the PINs.

LiF Ion Source Experiments on PBFA II

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We are performing LiF field-enhanced ion source experiments on PBFA II. The source consists of a thin coating of LiF on a microscopically rough substrate. Diagnostics to measure ion beam energy, purity, and transport include electrical monitors, Faraday cups, nuclear activation, ion pinhole camera (IPC), Rutherford magnetic spectrograph, and shadowbox aperture array. With PBFA II operating at three-quarters energy, the source has produced 16 TW of ion power and 550 kJ of ion energy with 70% diode efficiency. We have focused over 26 kJ of Li beam energy to the diode center axis with a peak energy density of about 1.3 kJ/cm². PICDIAG simulations of the Li focus indicate the intrinsic source divergence is about 45 mr with a 20- μ m-grade porous stainless steel substrate.

PBFA II was designed to provide a 30-MV, 150-TW power pulse to an applied-B ion diode to allow us to investigate the suitability of light ions for ICF.²⁻¹³ Singly ionized Li is the desired ion for acceleration because it has the proper range in ICF target materials at 30 MeV, is magnetically stiff (compared to protons), and should be obtainable in a single charge state (because of the large second ionization potential for Li). For PBFA II, the Li ion source should provide less than a few nanoseconds turn-on delay with respect to the arrival of the accelerating pulse and an ion current density of greater than 5 kA/cm² over an active anode area of up to 800 cm². A Li⁺ beam purity of greater than 90% is required, and the source must operate in the PBFA-II vacuum (10⁻⁵ torr). To obtain a good focus, the intrinsic source divergence must be less than 10 mr and the ions must originate from a thin (<1 mm) layer that is conformal to the anode surface. A LiF field-enhanced ion source on PBFA II has satisfied several of these requirements.

Experimental

The field-enhanced source consists of a thin (1- to 3- μ m) coating of LiF vacuum deposited on a microscopically rough anode substrate. For most of these experiments, the substrate was a porous "20- μ m-grade" stainless steel frit (Mott Metallurgical Corp.). Two-dimensional JASON calculations of the LiF-coated frit protrusions indicate that the anode electric field should be locally enhanced by about a factor of 3.5, which is sufficient to initiate a number of ion-producing processes.²⁻¹⁴ These include dielectric breakdown, valence-to-conduction-band electron tunneling, surface flashover, and explosive fragmentation of the LiF surface.

We used a flat, nonfocusing cylindrical anode for these experiments. The anode had an inside radius of 15 cm and an ion-emitting height that we varied from

6 to 9 cm. We operated PBFA II at three-quarters energy without a POS. Figure 2-9 shows the ion diode configuration with a 2- μm -thick Mylar gas cell window separating the diode vacuum gap from the 1-torr Ar-filled transport region. We monitored diode electrical behavior using conventional methods.²⁻¹⁵ In addition to the nuclear activation diagnostics described previously,²⁻¹⁶ the diagnostics at large radius included a shadowbox aperture array²⁻¹⁵ to observe Li beam divergence and steering as well as filtered Faraday cups to measure beam current density and composition. We measured the on-axis Li beam energy spectrum and focused power density with a time-resolved magnetic spectrometer.²⁻¹⁷ This device observed ions Rutherford scattered from a 0.25- μm -thick Au foil located at the center of the diode. We used a dE/dx multiframe ion pinhole camera²⁻¹⁸ to measure the spatially resolved energy density of the focused beam. The camera also recorded ions scattered from the on-axis Au foil. We modified the camera for Li experiments to allow a large 12-cm² field of view. Both these latter instruments have a low energy cutoff of about 4 MeV for Li, primarily caused by energy loss in the gas cell and scattering foils.

Results and Discussion

Previous experiments with the LiF ion source on PBFA II at one-half energy produced over 9.2 TW of ion power and over 300 kJ of ion energy, with 80% ion current efficiency.²⁻¹⁶ Electrical monitors and nuclear activation measurements at large radius suggested that the accelerated ion beam was primarily Li (two-thirds, by energy), with a small (<15%) proton fraction. We performed these experiments with the diode magnetic field separatrix conformal to the anode surface. This configuration prevented the Li^+ from reaching the diode centerline because of stripping Li^+ to Li^{+3} in the gas cell foil and the accompanying change in canonical angular momentum.²⁻¹⁹ Our attempts to bring the horizontal position of the focus on axis for Li^+ by moving the separatrix toward the cathode resulted in poor diode efficiency and large electron loss in the power feeds.

We resolved this difficulty by pushing more applied magnetic field flux toward the cathodes above the active anode region using anode feed coils.²⁻²⁰ This improvement, shown in Figure 2-10, gave efficient diode operation with the separatrix in a position to focus Li^+ , thus permitting the use of on-axis particle diagnostics. Figure 2-11 shows electrical characteristics of Shot 2621, with the accelerator at three-fourths energy and the diode magnetic field shown in Figure 2-10. With an A-K gap of 1.6 cm and an insulating applied field of 2 T, the diode was critically insulated for 10.3-MeV electrons. In this experiment, peak ion power was 16 TW, ion energy was 550 kJ, and the ion current efficiency (ion current/diode current) was 70% at peak power. The time delay between the diode current and the onset of the ion current was 5 ns. The voltage pulse decays rapidly about 15 ns after the onset of ion current. In proton diodes utilizing a surface

Figure 2-9. PBFA-II applied-B ion diode and diagnostic layout for LiF ion source experiments.

Figure 2-10. Diode magnetic field topology configured to focus Li^+ , including anode feed coils.

Figure 2-11. Diode electrical behavior for PBFA-II Shot 2621, with magnetic field topology shown in Figure 2-10.

flashover ion source, we attributed this voltage decay to magnetic flux penetration of the anode plasma surface that was caused by ionization via charge exchange processes of fast neutrals, which freely expand across the A-K gap.^{2-21,2-22} A similar mechanism is likely to pertain to the LiF source, with comparatively faster voltage decay due to the relatively smaller dynamic gap. The time-resolved measurement of the peak Li beam energy, as determined by the on-axis magnetic spectrometer diagnostic, has agreed well with the electrical diode voltage monitors; this indicates that the beam is accelerated primarily as Li^+ and not in higher charge states.

Figure 2-12 shows the multiframe ion pinhole camera images of the on-axis Li focus with the improved diode magnetic field design. The beam is well centered horizontally but vertically elongated as a result of the flat, nonfocusing anode surface. The peak energy density on this experiment was 1.3 kJ/cm^2 for Li ions above 5 MeV, with a total on-axis Li beam energy of 26 kJ. Nuclear activation measurements confirm this beam energy measurement with an ErD_2 target positioned immediately behind the Rutherford-scattering foil. PICDIAG simulations²⁻²³ of the ion beam transport have predicted that the on-axis Li beam energy should be about a factor of 3 higher than the measured value. We performed these simulations assuming the experimental applied-B field and electrical parameters, uniform ion emission from the active anode surface, 100% Li^+ purity, and complete current neutralization inside the gas cell. The simulations suggest that about 15% of the Li ion beam energy is lost in the gas cell foil, and approximately half the beam strikes the cathodes with a flat, 7.5-cm-high anode surface. There are several possible explanations for the factor of 3 discrepancy between the experiments and the PICDIAG simulations, such as nonuniform anode emission, incomplete transport physics in the code (i.e., different or incomplete current neutralization inside the gas cell), or a lower beam purity than had been indicated on previous experiments, where the separatrix was on the anode.^{2-16,2-24}

The horizontal FWHM of the Li beam focal intensity, as measured by the ion pinhole camera, was typically about 1.5 cm for the LiF-coated, 20- μm -grade frit source, which implies a total beam half-angle divergence of about 50 mr. Of this, 25 mr is caused by a variable magnetic field stream function with respect to the gas cell foil, flux penetration of the anode plasma, and multiple final charge states that result from the low diode voltage and the consequent incomplete stripping of Li^+ in the gas cell foil. Subtracting the beam-transport-derived divergence in quadrature, the indicated intrinsic source divergence is 45 mr.

Depending on the details of the ion production mechanism, the beam divergence may be related to the source substrate topology. A simple analysis of an

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Figure 2-12. Ion pinhole camera images of Li⁺ focus with diode magnetic field topology shown in Figure 2-10.

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array of individual emitters of tip radius r_o and spacing λ predicts a microdivergence given by

$$\theta \sim \left\{ 2 \frac{E_s r_o}{V_o} \left[1 - \sqrt{\frac{2r_o}{\lambda}} \right] \right\}^{1/2}, \quad (2-1)$$

where V_o is the gap applied voltage and E_s is the electric field stress necessary for ion emission. Analysis of the surface topology by profilometry as well as by optical and electron microscopy suggested that $\lambda \sim 150 \mu\text{m}$ and $r_o \sim 25 \mu\text{m}$ for the 20- μm -grade frit. To obtain the indicated source divergence requires that $E_s = 5 \text{ MV/cm}$ for a 5-MV diode voltage. An experiment with a finer-pore, 2- μm -grade frit ($\lambda \sim 70 \mu\text{m}$, $r_o \sim 12 \mu\text{m}$) gave an IPC image FWHM of about 1.0 cm and an inferred intrinsic divergence of about 25 mr, in reasonable agreement with the prediction given previously.

Conclusions

The field-enhanced LiF ion source being tested in PBFA II satisfies several required Li ion source criteria. The source has proved to be a valuable tool for investigating Li ion diode characteristics, beam transport, and Li diagnostic development; meanwhile, researchers are developing more advanced sources. With PBFA II in the three-quarters energy configuration and the diode magnetic field configured to focus Li^+ , the source has produced 16 TW of ion power and 550 kJ of ion energy with 70% efficiency. Also, we have focused 26 kJ of Li beam energy to the diode centerline. This energy is a factor of 3 below that predicted by PICDIAG beam transport simulations. The discrepancy may be due to incomplete modeling of Li beam transport physics, nonuniform ion emission, or lower ion beam purity. We plan to conduct further experiments to resolve this issue. With 20- μm -grade frit as the ion source substrate, the inferred intrinsic source divergence is about 45 mr. Experiments and modeling suggest that this may be reduced to the required 10 mr microdivergence with a finer substrate topology. Additional improvements in the beam focus will result when we increase the diode voltage and properly shape the gas cell foil and anode surfaces.

EHD Source Research

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One of the requirements for an electrohydrodynamic (EHD)-driven Li ion source for PBFA II is that a vertical liquid surface must be established on the anode surface. In the past, the candidates for this liquid surface were LiNO_3 (a low melting temperature salt) and Li. The majority of the effort until this period was with LiNO_3

because a vertical surface could be produced by the wicking process described in previous reports. The major problem with LiNO_3 is that it dissociates at high temperatures. Also, small-scale dc experiments indicated that the dominant ion was a cluster and not Li^+ . We decided that more effort should be put into achieving a vertical liquid Li surface. The original experiments, which involved porous metal frit material saturated with liquid Li and covered with carnauba wax, were not successful because a solid crust formed on the surface after the wax evaporated, and the temperature rose above the melting point. Subsequently, we pursued five strategies:

1. *In-situ deposition of Li into a warm anode in PBFA II.* An advantage of this method is that we could deposit up to several micrometers (at about $1\text{ }\mu\text{m}/\text{min}$). Because the Li layer would be thin, it would not couple to the applied magnetic field. Disadvantages to this method are that the layer would be nonuniform (50% nonuniformity over the height of the anode) and the gas cell would be partially covered with Li.
2. *Liquid Li in the frit.* This is the method that we already use. There are ways to prevent the liquid from being expelled by the applied magnetic field. However, we have found that the Li will certainly be oxidized, even with the wax coating.
3. *In-situ deposition of Li, then use BOLVAPS slow pulse to melt.* This is similar to Strategy 1. The major problems would probably be contamination and nonuniformity of the Li layer.
4. *Use BOLVAPS anode with slow pulse to melt LiAg alloy.* This could eliminate some of the corrosion problems because LiAg is less reactive than Li. However, the LiAg liquid would not provide as pure a source as Li metal.
5. *In-situ wicking of frits from a reservoir.* This would be the best way if we can find a way to wick Li, as in previous work using LiNO_3 . The other major problem is that the magnetic pressure could expel the Li (because of its thickness).

Although we considered all five of these options, the real breakthrough came with wicking Li in Inconel frit from a reservoir. Once wicked, the Li would wet the vertical surface. Although this technique worked well for a Li salt (LiNO_3), the results for Li were initially disappointing because wetting of the surface did not occur, presumably because of corrosion of the Li during the slow wicking process and the low solubility of oxygen in Li at 350°C . To overcome these problems, we designed and tested a rapid heating reservoir fixture. This fixture can heat the reservoir and porous material to 600°C in less than 5 min. We performed experiments with both stainless-steel and Inconel frits. For Inconel, complete

wetting occurred on 2-cm x 4-cm samples in less than 1 min after reaching 450°C. This was the first time that a vertical liquid Li surface had been achieved. This is now the baseline technique for producing a vertical liquid Li surface.

We performed a series of wicking experiments to determine minimum wicking and wetting temperatures. We also determined the temperatures at which we observed Li vapor in the chamber. This is important, because we want to wick and wet the anode at low temperatures so that Li vapor will not deposit on diode parts, including the diagnostics and the gas cell. For these tests, we had two thermocouples, one on the reservoir and one near the fritted material. The temperatures discussed here will be the average of the two. The minimum temperature at which wicking begins is 390°C. We detected no vapor for temperatures up to 440°C. At temperatures above 455°C, Li evaporated at a high enough rate to cover windows and other surfaces, so PBFA-II anodes should operate at less than 450°C.

One of the major problems with solid Li is that it reacts with water vapor to produce LiOH continuously. Even if wicking and wetting could be done on an anode in PBFA II, we would still have to worry about the Li reacting in the reservoir when exposed to the atmosphere. In using our small wicking fixture in the laboratory, we coated the Li in the reservoir with a thin layer of diffusion pump oil and set the fixture out in the laboratory for two days. We then placed the device in the vacuum chamber and performed a wicking and wetting experiment. The experiment was a success in that wicking and wetting occurred at about the same temperatures as in previous experiments. This, of course, is another breakthrough in the EHD program, because now reservoir-type anodes can be filled with frit and Li and be exposed to atmosphere for several days before the shot. During this period, we modified PBFA-II EHD anodes and, as described in the next paper by Woodworth et al., initial tests with frits were done in the Integrated Test Facility (ITF) and in PBFA II.

The other problem that we worked on since the last report involves Li ejected by the applied magnetic field. J. R. Woodworth et al. are investigating one method to time the cathode and anode B fields to reduce the magnetic pressure across the frit material. Another approach to prevent Li from coming out of the fritted material is to use smaller-pore-sized frit. This approach will also give a smoother surface, which should make a more uniform EHD source. The pressure required to expel a liquid from a capillary is $P = 2\gamma/r$, where γ is the surface tension and r is the radius of the capillary. The frit manufacturer (Mott) uses a bubble point method to determine the pore size of the frit. The makers immerse (and wet) the porous material in alcohol and then apply pressure to determine when bubbles first appear. As a first approximation, we can use their data to predict the pressure at which liquid Li

would be driven from the pores. The Mott data and the estimate for liquid Li are listed in Table 2-1 for various frits available from the manufacturer. All these numbers are for 0.16-cm-thick material.

The approximation for the 20- μm -grade frit that is normally used agrees with our original estimate of about 155 torr (3 psi). By using the 0.2- μm -grade frit, we can gain a factor of ≈ 20 over the present frit, because a difference in magnetic field across the frit of 1 T results in a pressure of 3000 torr (58 psi) ($B^2/2\mu$, where μ is the magnetic permeability); however, we must still be careful to prevent the Li from being ejected. Timing the magnetic field in addition to using finer frit may solve the ejection problem.

We designed and partially set up another long-range experiment to provide a thin, clean, vertical liquid surface during this period. The object of the experiment is to determine if a thin, falling liquid Li film could be made. If successful, a continuously flowing "Li waterfall" over a surface would provide a clean Li film that could be used for short-term PBFA-II experiments as well as for future repetitive (rep)-rate experiments. These first small-scale experiments would be a cooperative effort with Division 2542, which includes experts who use liquid metal electromagnetic pumps. The apparatus for the small-scale experiments is now on hand. We will perform the experiment in our Dri-lab glove box; however, the experiment is now on hold because of the relocation of the laboratory to Area IV.

Table 2-1. Manufacturer data for frit pore size.

Grade (pore size in μm)	(Mott) Alcohol ΔP (in. of H_2O)	Liquid Li ΔP (psi)
0.2	68 to 95	45 to 63
0.5	45 to 54	30 to 36
2	18 to 22	12 to 14.6
5	14 to 16	9.3 to 10.6
10	8 to 11	5.3 to 7.3
20	5 to 7	3.3 to 4.7
40	3 to 4	2.0 to 2.7
100	0.5 to 1.5	0.3 to 1.0

EHD Li Ion Source Development

J. R. Woodworth, R. G. Adams, K. W. Bieg, A. L. Pregenzer, W. H. Jaramillo, and M. M. Dillon

The goal of this ion source project is to provide a Li ion source that utilizes the EHD instability on a molten Li surface. To test this source, we must field anodes in PBFA II with pure molten Li surfaces. When these anodes are subjected to intense electric (E) fields (~ 10 MV/cm for 10 ns), the liquid surface should become EHD unstable, deforming into a dense array of liquid cusps. We predict that field desorption of Li ions from the peaks of these cusp structures will form a pure, low-divergence Li ion beam.²⁻²⁵

In this reporting period, we implemented solutions to the problems that had been preventing us from testing this source on PBFA II, took several shots on PBFA II, and developed new techniques that dramatically improved the purity of the Li surface on the anode. The E fields on the anode in the accelerator shots taken to date were not high enough to turn on the EHD-ion source, but these tests have validated our solutions to a number of problems and have given us direction for later, higher-voltage shots.

Magnetic field mapping experiments performed early in the year indicated that we could provide the proper B-field topology in the applied-B diode without causing magnetic forces in the diode to eject molten Li from the anode before the accelerator shot. On the basis of our B-field tests, we fielded a molten Li anode on PBFA II for Shot 2867. This shot did not produce a Li ion beam but held off ~ 2.5 MV across the diode A-K gap, indicating that we had solved the Li ejection problem for this shot with the separatrix on the anode and a critical insulating voltage of 7.5 MV.

Shot 2867 provided a molten Li anode surface by bolting porous stainless-steel frits to the anode (the frits had been dunked in molten Li in an Ar atmosphere, then coated with wax to protect them from moisture in the air). After the diode was under vacuum, the wax was melted off the anode as the anode temperature was slowly raised past the melting point of Li. This produced a Li surface that had a visible corrosion layer on it. Small-scale experiments by R. A. Gerber and C. C. Cianciabella demonstrated that molten Li would rapidly "wick up" porous Inconel 600 frits if the frits were heated in vacuum from room temperature to 400°C in ≤ 10 min. These "rapid wicking" tests produced a much cleaner molten Li surface.

On the basis of Gerber and Cianciabella's tests, we modified our anodes, frits, and heater system to allow us to use this "rapid wicking" technology on full PBFA-II anodes, then took two accelerator shots with this new type of anode. Shot 3000, with a 9.3-MV critical insulating voltage, operated at a diode voltage of ~ 5 MV. This shot produced only a small amount of ion beam, which appeared to be relatively pure Li.

Shot 3022, with a 13-MV V_{crit} , operated between 3 and 4 MV instead of the ~7 MV that had been expected. We are still analyzing the reasons for this anomalously low voltage.

We saw evidence that Li was not wicking up the Inconel anode frits in PBFA-II shots as quickly or as uniformly as it had in tests in the PBFA-II ITF, presumably because of the extra time the anodes were exposed to room air in the PBFA-II shots. Therefore, we designed and fielded a system to purge dry air over the Li in the PBFA-II anodes until the anodes were actually under vacuum to improve the uniformity and purity of the Li anode surface on future accelerator shots.

In a parallel effort to reduce Li susceptibility to air corrosion while positioned in the anode, we performed laboratory tests to expose Li metal samples in a F gas atmosphere to produce a surface passivation film. These experiments resulted in a significantly increased period of time that Li samples could tolerate air exposure without moisture contamination.

Initial PBFA-II operation with the dry air purge assembly provided satisfactory wicking behavior. Consequently, this simple air purge procedure has become the baseline contamination prevention method for future accelerator EHD shots.

Ion Sources Using the 670.8-nm Resonant Transition of Li

G. C. Tisone, K.W. Bieg, and P. L. Dreike

The BOLVAPS process²⁻²⁶ (previously described) makes a 1-mm-thick Li vapor layer by rapid ohmic heating of a thin-film laminate that contains Li. The vapor is ionized using an efficient process called Laser Ionization Based On Resonance Saturation (LIBORS).²⁻²⁷ Requirements for a PBFA-II ion source and the BOLVAPS/LIBORS technique have been discussed previously.²⁻²⁶ J. K. Rice et al.²⁻²⁸ describe BOLVAPS/LIBORS experiments in which thin foils coated with LiAg alloy are heated to produce a Li vapor layer. Modeling of LIBORS²⁻²⁸ predicts that a laser power of 3×10^4 W/cm² for 1 μ s will ionize a 1- to 2-mm-thick, 1×10^{17} atoms/cm³ layer of Li gas. The area of the ion diode to be illuminated is 500 to 800 cm².

In other experiments, we investigated the use of a laser to produce an ion source by directly vaporizing and ionizing a thin film of Li or Li alloy. This technique has been previously discussed.^{2-29,2-30} Our experiments investigated thin-layer substrate combinations to minimize the laser energy requirements. The objective was to identify parameters for which the existing 100-J, 1- μ s, 670.8-nm tuned dye laser could be used to produce an ion source for a PBFA-II diode by direct laser evaporation and ionization. We used other wavelengths and laser pulse

lengths to compare with a model of evaporation that we developed, and we have implemented the LEVIS concept on PBFA II.

Small-Scale BOLVAPS/LIBORS Experiments

P. L. Dreike and G. C. Tisone²⁻²⁶ discuss measurements of Li vapor produced by the slow-bank heating of LiAg films to temperatures of 600 to 1200°C. Here we describe experiments with the full BOLVAPS/LIBORS process.

We preheated the BOLVAPS films to about 700°C for 18 ms. At this time, we measured densities of about 1×10^{14} atoms/cm³ using laser-induced fluorescence. After another 0.7 μ s, we applied a 0.4- μ s fast heating pulse to raise the temperature from 1150° to 1250°C, at which point Li densities of 0.5 to 5×10^{16} atoms/cm³ are expected.²⁻²⁶ We then ionized the Li vapor by the LIBORS laser 2 μ s after the fast heating pulse ended. We recorded the line shape of the Li 460.3-nm transition using an optical multichannel analyzer (OMA) that was gated on for 3 μ s at the beginning of the laser pulse. We inferred the electron density of the resulting plasma from Stark broadening of this line.²⁻³¹ We assumed the singly ionized Li density to be equal to the electron density. We observed laser energy densities from 14 to 240 mJ/cm², which correspond to intensities from 2.8×10^4 to 4.8×10^5 W/cm². We expect to be able to deliver 3×10^4 W/cm² over 800 cm² to a PBFA-II diode. The heating pulses also represent the heating that can be delivered to the anode of a PBFA-II diode. Table 2-2 summarizes the results of several measurements on coupons from the same coating run for which the final coupon temperatures were nearly equal. Figure 2-13 shows broadening of the 460.3-nm Li transition for three plasma densities.

T_{slow} is the temperature reached using the preheat pulse, and n_0 is the initial density produced at this temperature. T_{pk} is the temperature after heating by the fast bank pulse, and n_e is the electron density inferred from the measurements of the broadening of the 460.3-nm Li line. Because the final electron density is independent of the incident laser energy, we conclude that the Li layer can be totally ionized at the lowest energy density from the tuned laser (within the uncertainties of the measurements). This energy density generally agrees with modeling of the LIBORS process.²⁻²⁸

To determine what impurities might be present, we took several shots for which the emission spectra were recorded with low resolution over about an 80.0-nm range as shown in Figure 2-14. Many of the lines can be attributed to Li ns²S or nd²D to 2p²P transitions. We identified two Ag lines and one Li⁺ line. The intensities of the Ag lines do not yield quantitative densities for Ag. The Li⁺ excitation is most likely produced by the arc associated with breakdown of the fast

Table 2-2. Measured Li and electron densities.

E_{laser} (mJ/cm ²)	T_{slow} (°C)	n_o ($\times 10^{14}$ atoms/cm ³)	T_{pk} (°C)	n_e ($\times 10^{16}$ atoms/cm ³)
14	690	1.3	1220	1.8 to 2.4
14	690	1.1	1220	1.1 to 1.5
14	670	0.8	1220	1.5 to 2.0
31	670	0.9	1200	1.3 to 1.7
31	700	1.3	1210	1.4 to 1.8
149	730	0.9	1210	1.5 to 1.9
158	690	2.0	1220	1.0 to 1.3

BOLVAPS heating pulse. Radiation from the high states of Li^+ could indicate presence of Li^{+2} , but LIBORS modeling predicts temperatures of 1 eV, for which the density of Li^{+2} should not be significant.

The results presented here have demonstrated the feasibility of using the BOLVAPS/LIBORS technique for producing anode plasmas in a PBFA-II ion diode. Implementation of this technique is now under way.

Figure 2-13. The broadening of the 460.3-nm Li transition is shown for three plasma densities. The absorption at the highest density by the neutral excited Li is shown in (a).

Figure 2-14. Spectra of the ionized Li for three wavelength regions.

Direct Evaporation and Ionization

The second approach to producing an anode plasma is to directly evaporate and ionize a thin Li film with a laser. Earlier investigations^{2-29,2-30} of laser-produced plasma formation from Li thin films on glass and steel substrates suggested that the laser energy required for evaporation and ionization could be reduced significantly by proper thermal design of the thin film-substrate combination. Table 2-3 shows the thermal diffusivity (α), conductivity (κ), and diffusion depth (D) for Li and candidate substrate materials. The diffusion depth is given by

$$D = \sqrt{4\alpha t} \quad , \quad (2-2)$$

where t is the laser pulse heating duration.

Table 2-3 shows that, for most substrates, the 1- μ s dye-laser pulse length is too long to utilize the laser efficiently because most of the absorbed energy will diffuse away from the surface. If the energy requirements can be lowered enough by careful design of the Li substrate, the existing tuned dye laser can be used to produce an ion source. Once Li vapor is formed at densities greater than 1×10^{15} atoms/cm³, the vapor can be ionized by using LIBORS.²⁻²⁶ We studied the evaporation and ionization using a simple model for laser heating and melting of thin Li films on low-conductivity substrates.²⁻³² We compared the results using this model with experimental measurements of laser energies to vaporize thin films from insulating substrates. The model assumes constant optical and thermal properties through the melt. It neglects the latent heat of melting (0.42 kJ/g) because it is much less than the enthalpy change during heating ($\rho\Delta T = 4.8$ kJ/g). It also neglects the heat of vaporization for the 0.2-nm thickness of Li that is required to be evaporated for the ion source.

Table 2-3. Thermal properties of materials.

Material	α (cm ² /s)	k (W/cm K)	Laser pulse length	
			1 μ s D (μ m)	10 ns D (μ m)
Stainless steel	0.0400	0.1300	4.0	0.40
Li	0.4200	0.8200	13.0	1.30
Plastic	0.0012	0.0021	0.7	0.07
Quartz	0.0070	0.0140	1.7	0.17
Aerogel ²⁻³³ (0.1g/cm ³)	0.0005	0.0001	0.4	0.04

The model calculates the laser energy (flux times laser pulse length) required to bring the temperature to the boiling point of Li ($T_v = 1317^\circ\text{C}$) from an initial temperature of T_o . The absorbed laser flux is given by

$$F = F_o (1 - R) \left\{ 1 - \exp\left(-\frac{d}{\delta}\right) \right\} \quad (2-3)$$

where d is the film thickness, δ is the optical skin depth (14.7 nm for Li), R is the reflectance, and F_o is the incident flux. Following the model of Ghez and Laff²⁻³², the absorbed flux necessary to bring the thin film on an insulating substrate to its vaporization temperature is

$$F = \frac{\alpha_f \kappa^2 (T_v - T_o)}{\alpha \kappa_f d g(\tau)} \quad , \quad (2-4)$$

where

$$g(\tau) = 2\sqrt{\frac{\tau}{\pi}} - 1 + \exp(\tau) \operatorname{erfc}\sqrt{\tau}$$

and

$$\tau = \frac{\alpha_f^2 \kappa^2 t}{\alpha \kappa_f d^2} \quad .$$

The subscript f refers to the Li film properties. We used the model to predict the curves in Figure 2-15, which show the energy required for vaporization as a function of laser pulse width for several thin-film/substrate combinations. Figure 2-15 also shows measurements of the minimum energy to vaporize a thin film from the insulating substrate using a dye laser tuned to 670.8 nm and a 1.06- μm , 10-ns Nd:YAG laser. At the minimum dye laser energy, we still observed plasmas of the order of 5×10^{15} atoms/ cm^3 . For comparison with the thermal model, we treated R as an adjustable parameter and obtained the best agreement when $R = 50\%$. The fact that this value is lower than the literature value²⁻³⁴ (96%) reflects the assumptions in the model and the actual surface of the films. Also, significant vapor is evolved at temperatures lower than the boiling point. Recent studies²⁻³⁵ suggest that removal of thin films from insulating substrates may correlate better with melting temperatures. Using the melting temperature, this model would require $R = 94\%$. We obtained similar results with thin LiAg films on insulating substrates (0.3 J/ cm^2 for 0.2- μm -thick films on plastic and 0.15 J/ cm^2 on silica aerogel). Time-integrated spectra near the 460.3-nm Li transition are similar for plasmas generated

Figure 2-15. The minimum laser energy required to evaporate thin Li films from an insulating substrate, assuming $R = 50\%$ and $T_V = 1317^\circ\text{C}$. The data at 10 ns and 1000 ns were taken with 1- μm and 670.8-nm lasers, respectively.

from a thin film of Li and a thin film of LiAg. The spectra from LiAg plasmas show a Ag I line at 468.8 nm. The results in Figure 2-15 show the advantages of using a laser with a short pulse length for evaporation. The conduction of the substrate is not as important at these pulse lengths. This opens up the possibility of using a short-pulse laser for evaporation and using the dye laser for the ionization.

This study of thin films has demonstrated that laser energy densities $\geq 0.15 \text{ J/cm}^2$ can be used to produce Li^+ plasmas from thin films on insulating substrates. Further improvement is possible if the optical reflectivity of the films can be reduced. With these energy densities, it is feasible to use the existing 100-J laser to generate anode plasmas in a PBFA-II ion diode.

We took several shots on PBFA II to test the concept of direct laser evaporation ion sources. These shots used LiAg or LiMo films (250 nm) on an insulating substrate with an anode illumination height of 2 cm. Figure 2-16 shows the diode configuration with the laser, the distribution cone, and the diagnostics. This configuration used existing laser beam paths that were designed for LIBORS/BOLVAPS ion source use.

PBFA-II DIODE FOR LEVIS LASER-PRODUCED LITHIUM ANODE PLASMA EXPERIMENT

Figure 2-16. PBFA-II diode for a dye-laser-produced Li ion source that uses a neodymium laser system (NLS) to vaporize the Li surface.

We obtained the best results of this first series of LEVIS ion source shots on PBFA II using anodes with thin LiAg films over an epoxy substrate. Figure 2-17 shows the voltage, impedance, and current traces for one of the LiAg shots. The diode voltage with current flowing on these shots was not as high as that previously attained with LiF sources. The power pulse of the machine arrived about 1 fs after the start of the dye laser pulse. The LEVIS shots were characterized by a spotty, nonuniform turn on and impedance collapse. We speculated that early-time contamination filling the A-K gap in the diode kept the diode from reaching higher voltages.

Figure 2-17. Diode electrical behavior on a PBFA-II shot with a laser-produced Li ion source. For this shot: A-K gap = 1.3 cm, $V_{crit} = 10.9$ MV, and tuned laser pulse length = 1.5 ms.

Development of the BOLVAPS Li Vapor Source for PBFA II

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We are developing PBFA II to produce a ~4-MA, 30-MeV Li^+ beam. PBFA II is a 36-module pulsed power generator that drives an applied B ion diode.²⁻¹³ The ion emission area of the diode is 500 to 1000 cm^2 . A 1- to 2-mm-thick, 10^{16} to 10^{17} atoms/cm^3 Li^+ plasma on the anode would be a suitable ion source. We are pursuing the BOLVAPS/LIBORS technique to make this plasma. BOLVAPS makes a thin layer of Li vapor by rapid ohmic heating of a thin-film laminate, one layer of

which contains Li. LIBORS²⁻³⁶ is a laser ionization technique. Earlier work²⁻²⁶ describes the formation of a 4-mm-thick, 5×10^{15} atoms/cm³ Li gas by ohmic heating ($>1000^{\circ}\text{C}$) of an LiAg film on a Ta foil as well as its ionization by LIBORS. To avoid foil expansion and deformation problems upon heating as well as to minimize the required heating current, thin films are now deposited on rigid substrates of alumina ceramic or porcelain enameled steel. BOLVAPS films consist of a 3- to 5- μm -thick Mo layer, a 1- μm -thick LiAg layer, and a 0.3- μm -thick Ag overcoat. The films are preheated to 700°C for ~ 10 ms to melt the LiAg and outgas volatile contaminants, then heated to 1100° to 1200°C in ~ 400 ns to evaporate high-density Li. Small-scale tests of films on polished alumina produced Li plasmas with electron densities of 5×10^{16} atoms/cm³ and an estimated thickness of 2 mm.

This article describes the BOLVAPS anodes currently being built for PBFA II and the pulsed power system for heating them. We address major design issues as part of the component descriptions and summarize important results from small-scale experiments.

BOLVAPS Components

Figure 2-18 shows the BOLVAPS components and subsystems schematically. One design constraint was to fit BOLVAPS/LIBORS into an applied-B ion diode with a 15-cm anode radius and a 2- to 7-cm half-height. Figure 2-19 is a simplified drawing of the BOLVAPS/LIBORS diode. Note that the anode is split into symmetric top and bottom halves to accommodate the disk transmission lines that deliver heating current to the BOLVAPS films. BOLVAPS is built up on a stainless-steel anode shell. The shell is a structural member supporting atmospheric pressure in the anode magnet coils, which must be resistive enough for the pulsed magnetic fields to diffuse through it. The shell is also part of the heating current return path.

Figure 2-19 shows that the BOLVAPS films are insulated from the shell by a refractory material. The insulator may be either an alumina ceramic "insert" attached to the shell or porcelain enamel fused to the shell. These two design options are shown on the left and right sides, respectively, of Figure 2-19. The insert option provides a robust insulator that need not be thermal-expansion matched to the steel. We chose alumina because, in earlier experiments, BOLVAPS films adhered well to it when heated. The enamel option offers cost and performance advantages, but requires further development.

Figure 2-18. Major components of BOLVAPS. The Li reservoir is a layer of LiAg covered with a layer of Ag.

Figure 2-19. Major components of an applied-B diode with a BOLVAPS/LIBORS ion source. The anode is 30 cm in diameter. The figure shows the fiber optic distribution system (FODS).

It would be difficult to attach transmission lines directly to the BOLVAPS thin films. As shown in Figure 2-19, a 5- to 10- μm -thick Au film is fused to the insulator to make solderable contacts. Au is used because the leads must survive oxidative cleaning steps in preparation for thin-film deposition. The approximate location of the leads on the anodes is indicated in Figure 2-19. The high-voltage lead goes around the corner from the equatorial flange to the active region of the anode. A second lead makes the ground connection at the top (or bottom) of each half-anode. The edge of the thick film is tapered to connect to the thin film by using a shadow-masking technique while spraying the thick-film ink.

The thin-film laminate has three layers that are sputter deposited using a post-cathode magnetron sputtering system.²⁻³⁶ Although it might be possible to use a single-layer metallic film containing Li in principle, we chose to use the three separate layers to serve the three functions of a heater layer, a Li reservoir, and a corrosion barrier. The heater layer is 3- to 5- μm -thick Mo. The Li reservoir is a 1- μm -thick layer of LiAg alloy. The corrosion barrier is 0.3 μm of Ag. We chose to use thin films because of the large pulsed current needed to heat from 700° to 1200°C in <1 μs ; this will be discussed later.

The films are fixed rigidly to the substrate to define the anode surface accurately. The 10-ms preheat to 700°C would cause a freestanding film to deflect by many millimeters because of thermal expansion. The thermal expansion of the film is constrained so long as the film is bonded to the substrate. Thermal stress calculations show that the Mo film yields in compression at 230° to 250°C. These thermal stresses can buckle the film from its substrate because the film-substrate bond is mechanical. The strength of this bond is affected by the cleanliness and roughness of the substrate surface. Roughness also affects film resistivity, so a uniform substrate is crucial.

Our original reasons for choosing a Mo heater were that it has a low thermal expansion coefficient, is refractory, is inert to Li, and has low resistivity compared with LiAg. The purpose of using a low resistivity material was to decouple the two layers so that the LiAg resistivity jump upon melting would not adversely affect the thermoresistive stability of the ohmic heating. We found that, at 25°C, the sputtered Mo films have a resistivity about ten times the bulk value, but they have a resistivity change of <10% from 25° to 1000°C. This is very important for uniform and reproducible heating, because heating is nearly thermoresistively stable.

We chose the 50-atomic percent LiAg alloy as a Li reservoir because it is relatively corrosion resistant compared with Li and has a high vapor pressure compared with other alloys. Free or alloyed Li combines with atmospheric water to form refractory LiOH. LiAg films retain sufficient vapor pressure for about 2 hr in 50% relative humidity (RH) air, compared with about 2 min for Li.

The top layer of 0.3- μm -thick Ag slows LiAg corrosion, extending its useful life in 50% RH air to 4 hr. This extra 2 hr is very important for the experimental setup on PBFA II, which takes most of a day. The LiAg-Ag combination melting temperature of 600°C defines the minimum preheat temperature for outgassing volatile contaminants.

The pulsed power system that provides the heating pulses consists of a "slow" (or "preheat") pulser, a fast pulser, and a transmission line system for each anode half. The pulsers are located on top of the accelerator, about 12 m from the anode. The preheat pulsers were designed based on ohmic heating calculations and include the effect of thermal conduction into the alumina. The pulsers are 38-mF, 2.25-kV capacitor banks that charge 200- μH inductors in series with the anode films. They are crowbarred with freewheeling diodes to give an inductance-capacitance (LC) rise time of 4 ms to a peak current of 22 kA and an inductance/resistance (L/R) fall time of 30 ms. To minimize stray resistance, a bundle of four size-0000 welding cables carries current to the anode. This wave shape will heat the films to 700°C in 8 ms and roughly maintain this temperature for about 10 ms. We chose this pulse length because it allows outgassing volatiles to dilute by diffusing through the entire PBFA-II vacuum system.

The fast-heating pulse length is limited by two factors. First, Li gas at 100°C has a thermal velocity of 1 mm/ μs . Calculations of collisionless expansion of the gas show that the density gradient scale length increases for heating pulses $>1 \mu\text{s}$. Second, the voltage due to the heating current causes the evolving Li gas to break down, shorting out the heating pulse. Small-scale tests showed that heating is maximized by arranging for the breakdown to occur in 400 ns. Conduction of heat from the film into the substrate is negligible on a submicrosecond time scale. A simple calculation shows that an action ($\int I^2 dt$) of $1.25 \times 10^2 \text{ A}^2\text{s}$ will heat a 5- μm -thick, 100-cm-circumference Mo film from 700° to 1200°C, assuming bulk Mo properties for the film.

The fast pulsers are composed of four parallel 15- μF capacitors with individual gas switches. The rise time is set by an inductance originally chosen to give a 1- μs rise to a peak current of 500 kA. The pulsers can be reconfigured to deliver 400-ns-rise-time, 700-kA pulses. To avoid preionizing the Li and preheating the plasma, the pulse is ended by a fuse-driven shorting switch that decouples the capacitors and transmission line. Transmission lines consisting of two parallel 120-m-long, 100-m Ω triplates connect each fast pulser to the anode. The triplates are hot-press-laminated Cu sheet and Kapton. We are currently testing prototype alumina insert anodes and have installed the heating system in PBFA II.

Small-Scale Experiments

Figure 2-20 shows the apparatus that we used to perform experiments to study ohmic heating, film heating uniformity, Li evaporation, and combined Li evaporation and ionization. Our standard sample, of either alumina or enameled stainless steel, is a "coupon" that is 3.5 cm wide x 7.6 cm long. Thick-film Au contact pads that are 1.8 cm wide with a 3.8-cm separation are screen printed and fused to the insulator. A 1.5-cm-wide thin-film laminate is sputter deposited over and between the contact pads, in the same system used for anodes. The films are heated using small preheat and fast banks. We inferred the temperature during the preheat pulse from near-infrared radiance in a 5-mm-diameter focal spot that we measured using an Iacon Model 1100 pyrometer, and assumed an emissivity of 0.4. We qualitatively examined uniformity by open shutter photography of self-luminous films at 800° to 900°C using two or three pyrometers. Results indicate that we have achieved heating uniformity of 1% to 2% on 0.2- to 20-mm-scale lengths on alumina coupons.

We measured Li vapor density in the range of 1×10^{13} to 1×10^{16} atoms/cm³ during the preheat pulse using a laser-pumped fluorescence technique as shown in Figure 2-20. A dye laser beam was split into a reference beam and a probe beam.

Figure 2-20. Schematic of the experimental setup for testing coupons, and a level diagram showing the laser fluorescence density diagnostic.

The reference beam passed through a heat pipe that maintained Li vapor at a known density. The probe beam passed through BOLVAPS vapor. The 319.6-nm light pumped a forbidden transition in Li and we detected decay light at 610.4 nm with photomultiplier tubes (PMTs). We obtained the BOLVAPS vapor density by comparing the two PMT signals, taking into account known geometrical factors.

Figure 2-21 shows Li density versus temperature for two different experiments. Both experiments used freestanding 25- μm -thick Ta foil heaters. In the first experiment, 1- or 2- μm -thick Li films were vapor deposited in situ; in the second experiment, we used 1- or 2- μm -thick LiAg films. We heated the foils with 3-ms pulses and made the measurements 0.1 ms after the pulses ended. The density that we measured using pure Li is in reasonable agreement with a literature value,²⁻³⁴ with departures that we attribute to depletion of Li during the heating pulse. The Li density from LiAg is reduced from pure Li by two orders of magnitude. Li density from the Mo-LiAg-Ag laminate on alumina coupons falls between the dashed lines on the graph.

Figure 2-21. Li vapor density from Li- and LiAg-coated Ta foils heated with 3-ms pulses.

We inferred film temperature in experiments using both slow and fast banks by combining the pyrometer measurement with the measured electrical energy input to the films. We were unable to measure Li neutral density in this situation because of Li light from the fast pulse breakdown. Earlier work²⁻²⁶ describes BOLVAPS/LIBORS experiments with temperatures in the 1150° to 1250°C range; we measured plasma electron densities from 0.5 to 5.5×10^{16} atoms/cm³, which is consistent with the neutral densities in Figure 2-21.

MHD Calculations of Anode Plasmas

T. W. Hussey, S. A. Slutz, and M. P. Desjarlais

We have performed a series of idealized MHD calculations of the response of an anode plasma layer to the rising magnetic field in an applied-B ion diode. The purposes of this study were to consider joule heating of the plasma layer (which could pose potential problems for Li ion diodes) and the leakage of flux behind the ion-emitting surface (which is related to impedance collapse). We find that, as induced $\mathbf{J} \times \mathbf{B}$ forces move the plasma toward the wall, the entrained initial field is compressed until it just equals the rising external field. Achieving such equilibrium decreases both joule heating and flux leakage into the plasma. For relatively thin (~1 mm) plasma layers at moderate densities (10^{16} to 10^{17} atoms/cm³), we calculate that this equilibrium is achieved quite rapidly, leading to acceptably low levels of both flux penetration and joule heating.

In a recent paper, Slutz²⁻³⁷ concluded that joule heating resulting from a rising diamagnetic current in an applied-B ion diode would be sufficient to bring the anode plasma quickly to a multi-keV temperature. This would, for densities above $\sim 10^{16}$, lead to a considerable fraction of collisional ionization of Li⁺ to Li²⁺ and Li³⁺. Thus, we concluded that ideal initial conditions for such an anode plasma would be a relatively thick (to allow a sufficient supply of ions) layer of low-density ($< 10^{16}$ atoms/cm³) plasma. We have found, however (from a series of idealized MHD calculations), that if the anode surface has a conducting substrate, then much of the diamagnetic current can flow there, and this flattens the magnetic field distribution in the anode plasma. This shunting of diamagnetic current to the wall, shown to be more effective for thinner plasma layers, considerably reduces joule heating. Furthermore, Desjarlais^{2-9, 2-38} has shown that impedance collapse may be related to the rate of flux loss across the ion-emitting surface, which would also be altered by reduced field gradients in the plasma.

One-Dimensional MHD Calculations

We performed a series of idealized calculations with the one-dimensional MHD code, TITAN; we assumed the following:

1. A plasma of uniform density, n_0 , temperature, T_0 , extending a distance r_0 from the anode; ablation of new material from the substrate was ignored, as was the ionization of any neutrals that might be present in the gap.
2. An ideal-gas equation of state for singly ionized Li.
3. An initially uniform, $B_0 = 5$ T external magnetic field that rose exponentially (time constant = 40 ns) to ~ 10 T in 30 ns. Note that the rising component of field is assumed here to be in the same direction as the applied field, whereas experimentally it may have a perpendicular component.
4. A highly conductive substrate, but with heating and blowoff from this layer ignored.
5. Erosion of ions from the plasma surface ignored.

The worst of these approximations is probably the first, because a nonuniform density and temperature distribution, a flux of material ablated off the anode surface, or the ionization of a significant number of pre-existing neutrals would be required to give the observed late-time expansion of plasma away from the anode.²⁻⁴¹ Nevertheless, results of calculations employing these approximations are instructive in that they point to the existence of an effect that must be considered in more detailed models.

Figures 2-22 and 2-23 qualitatively illustrate the effect of anode plasma layer thickness on field penetration. Figure 2-22 shows density profiles at four different times as well as magnetic field profiles at those times for a 1-mm-thick, 10^{17} atoms/cm³ plasma. Figure 2-23 shows the same quantities for the same density plasma with a thickness of 4 mm. A key observation is that magnetic field profiles are nearly perfectly flat for the 1-mm-thick case and, for the 4-mm-thick case, the field rises at the outer edge first and does not penetrate to the wall until later. We note that these plasmas are very low beta ($\beta \approx 0.01$), so that variations in the field to account for pressure equilibrium would be nearly indistinguishable in the field plots. Because current density is proportional to the derivative of the magnetic field, we find that the thicker layer is heated to ~ 100 eV, while the thinner one is heated to only ~ 20 eV.

It is tempting (based on simply comparing the field profiles of Figure 2-22) to conclude that rapid diffusion of field through the thinner layer causes it to be uniform in that case. If that were so, however, there would be little in the way of $\mathbf{J} \times \mathbf{B}$ force to push the plasma toward the wall, and the density distribution would appear to change little in time. In fact, we observe a shelf in density that increases approximately linearly with field, suggesting that a frozen-field approximation is

Figure 2-22. Calculated density and magnetic field contours at four different times from a one-dimensional MHD calculation of a 1-mm-thick, $10^{17} \text{ atoms/cm}^3$ Li^+ plasma compressed by a magnetic field that rises from 5 to 10 T in 30 ns.

Figure 2-23. Calculated density and magnetic field contours at four different times for a 4-mm-thick, 10^{17} atoms/cm³ Li⁺ plasma layer.

more appropriate. Figure 2-23, which shows the 4-mm-thick case, best illustrates this effect. As the field rises initially, a current gradient is set up, which begins to accelerate the plasma toward the wall. As the plasma compresses, so does the applied B-field entrained within it (initially 5 T in these calculations). When the compressed field equals the field outside the plasma, all the current flows in the wall, and the plasma density rises linearly with field, implying little further acceleration. A comparison of Figures 2-22 and 2-23 indicates that this transition from acceleration phase to compression phase occurs nearly instantaneously in the thin case and in about 30 ns in the thick case. This is because, for a thicker plasma, bulk compression requires a much higher velocity. Also, we note that for a given thickness, this transition occurs more rapidly for lower density than for higher density. Because significant joule heating will occur only when there are significant field gradients in the plasma, a rapid transition to the compression phase produces little heating.

For low densities, in which the transition to the compression phase occurs early for a wide range of thicknesses, we would expect joule heating to be small and to vary little with thickness. Calculations show, however, that in this regime, shock heating associated with the rapid acceleration of plasma to compression velocity as well as the subsequent adiabatic compression can dominate. This component of heating is found to increase with thickness until the time required to transition from the shock phase to the compression phase just equals the pulse length. For thicknesses greater than this, the final temperature depends only on density.²⁻³⁷

Analytic Model

Within the context of the above approximations, we will consider the two-dimensional parameter space in which the initial plasma thickness, r_0 , and the initial plasma density, n_0 , are varied. In principal, the initial plasma temperature, T_0 , is also a variable, but we find that this affects the final temperature only modestly, so we have taken $T_0 = 5$ eV in all cases. Figure 2-24 shows the parameter range considered by the calculations, with the Li ion density extending from 10^{15} to 10^{18} atoms/cm³ and the plasma thickness extending to 1 cm. At low density and small radius, we see the region of parameter space that corresponds to insufficient mass to supply a constant 3 kA/cm² beam of ions for 20 ns. For higher densities and greater thicknesses, neither the shock wave nor the diffusion wave reaches the wall, and thickness plays no role.²⁻³⁷ We can apply the present analysis to the intermediate region.

Figure 2-24. A map of the regions in the initial density plasma layer thickness parameter space for which various models apply.

We have found that the following mechanisms dominate the heating of the plasma in the calculations:

- Joule heating prior to the transition to the compression phase
- Shock heating associated with acceleration of plasma to the compression velocity
- Adiabatic compression after the compression phase.

We can analytically estimate each of these contributions to the final plasma electron temperature separately; we find their sum agrees well with calculations.

We first note that each of these three heating mechanisms requires that we know the time of transition from the shock phase to the compression phase. Consider the simplified equation of motion for a layer of density, ρ , accelerated by $\mathbf{J} \times \mathbf{B}$ forces (in CGS units):

$$\frac{d}{dt}(\rho v) = \frac{1}{c} J \times B, \quad (2-5)$$

where $B_0 = 5$ T is the initially applied field, $B = B_0 e^{\alpha t}$ is the rising anode field, and $\alpha^{-1} = 40$ ns (in this case) is the time constant. One may approximate the expression for current by

$$J = \frac{c(B - B_0)}{4\pi \delta} \quad (2-6)$$

where $\delta = (\eta c^2 t / \pi)^{1/2}$ cm is the approximate diffusion length and η is resistivity. We assume the plasma is anomalously resistive²⁻³⁷ and set the anomalous collision frequency to ω_{pi} , the ion plasma frequency, giving

$$\delta \approx 1.68 \times 10^7 t^{1/2} n_i^{-1/4} = 31 t^{1/2} \rho^{-1/4} \text{ cm}, \quad (2-7)$$

where we assume singly ionized Li ($A = 7$). By combining the above equations, integrating, and setting $d\rho/dt = 0$, we obtain for small αt (at an early time, before the plasma has moved much)

$$v \approx 2.73 \times 10^{14} B_0^2 n_i^{-3/4} \alpha t^{3/2} \text{ cm/s}. \quad (2-8)$$

Then, we note that during the uniform-field bulk compression phase (assuming an exponentially rising field), the thickness must decrease as $r = r_0 e^{-\alpha t}$, corresponding to a velocity of

$$v = \alpha r_0 e^{-\alpha t}. \quad (2-9)$$

The time at which Equation 2-8 exceeds Equation 2-9 corresponds to the time of transition from the shock phase to the compression phase.

We may now estimate the shock heating that must occur as the velocity increases to that given by Equation 2-9. The kinetic energy per unit area is just $\rho \alpha^2 r_0^3 e^{-2\alpha t} / 6$. If we estimate that approximately this amount of energy goes into internal energy and use $\Delta E_i = \rho c_v \Delta T$, $c_v \approx 2.0 \times 10^{11}$ and $\alpha = 4 \times 10^{-8}$, we have (temperature in eV)

$$\Delta T_{\text{shock}} \approx 500 r_0^2 e^{-2\alpha t_t}, \quad (2-10)$$

where t_t is the transition time obtained from Equations 2-8 and 2-9.

Next we consider the joule heating that occurs prior to t_t , when field gradients still persist in the plasma. The temperature change rate associated with this process is

$$dT_j/dt \approx 1.24 \times 10^{10} B_0^2 (e^{\alpha t} - 1)^2 / n_0 t \text{ eV/s.} \quad (2-11)$$

To integrate this from 0 to t , we note that only a layer of thickness $\delta(t)$ is heated. Because we would like to calculate the mean heating of the entire anode layer, we reduce this instantaneous heating rate by the factor $\delta(t)/r(t)$ if $\delta(t) < r(t)$, giving

$$\Delta T_j \approx 1.24 \times 10^{10} B_0^2 / n_0 \int_0^{t_t} dt \frac{(e^{\alpha t} - 1)^2}{t} \chi, \quad (2-12)$$

where χ is the minimum of $\delta(t)/r(t)$ and one.

Heating due to adiabatic compression after the transition time is obtained by noting that $PV^{5/3}$ is constant, giving

$$\Delta T_c = e^{0.67 \alpha (t_{\text{final}} - t_t)}. \quad (2-13)$$

Figure 2-25 plots the sum of Equations 2-10, 2-12, and 2-13 over the same parameter space as Figure 2-24. Note that the knees in the temperature curves are associated with the transition from being shock dominated to being joule-heating dominated.

Figure 2-26 gives contour plots over the $n_0 - r_0$ parameter space of the fraction of Li^+ that is collisionally ionized to Li^{+2} , obtained by integrating the cross section from Lotz²⁻³⁹ over a Maxwellian velocity distribution and time. From this figure, we note that this ionization fraction depends primarily on density for large r_0 and on thickness for small r_0 . In addition, we note that for thicknesses less than about 1 mm, this fraction is less than ~1%, a level that should be acceptable for diode operation.

Conclusions

Figures 2-25 and 2-26 show results that differ from those of Slutz²⁻³⁷ in that here we find that the key parameter is layer thickness, not density. Slutz's²⁻³⁷ analysis concluded that the anode plasma density should be less than 10^{16} atoms/cm³, and the role of plasma layer thickness was not considered. Here, Figure 2-26 suggests that densities of 10^{17} atoms/cm³ or greater are acceptable when the layer is ≤ 1 mm thick.

Finally, it is important to note that this model would predict little in the way of flux loss across the ion-emitting surface for a thin plasma layer on account of the very small field gradients. Desjarlais²⁻³⁸ has shown, however, that the impedance collapse observed in ion diode experiments may be related to such a flux loss. Because we have shown here that this is inconsistent with a thin, relatively uniform plasma layer of constant total mass, we find²⁻⁴⁰ that we must invoke the infusion of new material. This would result either from the ionization of neutrals already present in the gap or from a significant flux of thermal-conduction-driven ablated material from the anode surface. Because diode performance without this infusion of new material seems promising, an attempt to understand and decrease the amount of material infused should be advantageous.

Figure 2-25. Contours of the base 10 logarithm (contour spacing = $10^{1/2}$) of the fraction of the final plasma electron temperature in the initial density plasma layer thickness for the parameter space of Figure 2-24.

Figure 2-26. Contours of the base 10 logarithm (contour spacing = $10^{1/2}$) of the fraction of the Li^+ plasma that is collisionally ionized to Li^{+2} in 30 ns.

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Chapter 3. Target Experiments and Diagnostics

Overview

M. K. Matzen

The goal of the light ion beam ICF program is to produce ignition and propagating burn in the laboratory, ultimately with fusion yield in the neighborhood of 500 MJ. The experimental path to reach this objective is well defined and involves many physics issues that must be addressed at each step. The path starts with beam characterization and proceeds through understanding the ion deposition profiles, producing x-rays with an ion beam, characterizing a beam-produced hohlraum environment, coupling the radiation to a fusion capsule, characterizing the capsule implosion dynamics, and producing fusion yield. During this calendar year we emphasized development of the experimental capability for the first step, beam characterization.

A necessary requirement for unambiguous ion beam target experiments is a routine measurement of the beam characteristics (composition, intensity, energy, uniformity, and synchrony) near the target location. In an analogy to a laser beam splitter, a thin foil can be placed near the target region. Through judicious selection of the foil material, a small fraction of the beam that passes through this foil will be Rutherford scattered, induce inner-shell fluorescence transitions, or produce nuclear reaction products. Accurate measurements of these scattering processes give a direct measure of the beam characteristics. Our first set of target experiments on PBFA II was devoted to developing these experimental techniques.

In most of the beam characterization experiments performed this year, an azimuthally symmetric proton beam impinged on a conical scattering foil. One shot used a planar Au scattering foil. Most conical scattering foils were Ti; Teflon, Al, and Ta cones were also used. These on-axis cones provide a scattering source for measurement of the beam very near a target, which would be placed inside the cone, whereas the foils at larger radius provide an off-axis scattering source. We used several different diagnostics to measure scattered ions, nuclear reaction products, x-rays produced by beam-induced, inner-shell fluorescence, and x-rays produced by target heating.

Scattered ions were detected with a magnetic spectrometer or an ion pinhole camera. Nuclear reaction products were measured by neutron time-of-flight or by nuclear activation techniques.

The inner-shell fluorescence was measured with x-ray diodes (XRDs), PINs, x-ray pinhole cameras, and spectrometers (crystal and grazing incidence). The time-dependent PIN traces first show the production of $K\alpha$ radiation from the proton interaction with the target; they later record a signal from protons that are Rutherford scattered into the detector. The XRD signals from the Ti cone experiments also show two major peaks. The first peak results from direct heating of the Ti by the proton beam, whereas the second occurs when the heated, expanding Ti cone stagnates on the cylindrical axis of symmetry. The elliptical crystal spectrum produced when an Al cone is heated by a proton beam shows the existence of the $K\alpha$ satellites for Al charge states up to Al IX. This result demonstrates both direct heating of the Al foil by the beam and the interaction of the beam with the inner-shell Al electrons. Calculations with a collisional radiative equilibrium code indicate that, in order to reach the Al IX charge state, the target has been heated to temperatures of 20 to 60 eV, depending on the density of material that is emitting these x-rays.

Future experiments will be designed to correlate the beam energy measured on a conical foil to the beam energy delivered to a central target. These experiments are precursors to measuring the ion beam x-ray production efficiency and the resulting hohlraum temperature.

Chapter 4. Diagnostics

Overview

R. J. Leeper

In this reporting period, we continued developing Li beam activation diagnostics. A new Li activation diagnostic uses fast neutron activation of praseodymium (Pr) in conjunction with the $D(^7\text{Li}, n)^8\text{Be}$ nuclear reaction. This nuclear activation scheme has major advantages in experiments with large thermal neutron backgrounds compared to our previous Li beam activation diagnostic, which employed fast neutron activation of Cu. These advantages occur because thermal neutron capture in Cu can lead to a long-lived 12.71-hr activity that can compete with the desired 9.74-min activity. In Pr, this does not happen. In addition, the Pr scheme is 1.5 times more sensitive than the Li-Cu diagnostic.

During a Li activation diagnostic calibration experiment at the Los Alamos National Laboratory (LANL) Van de Graaff facility, we discovered that fast neutrons could be produced via the reaction $^{12}\text{C}(^7\text{Li}, n)^{18}\text{F}$. We realized that the neutrons produced by this reaction could cause undesirable interference in our proton and Li beam activation diagnostics if precautions were not taken. We have now studied this reaction and know its effect on our diagnostics.

We have developed an ion pinhole camera to obtain energy density profiles for a multiterawatt ion beam as a function of ion energy. The camera is designed for ion beam transport and focusing experiments on PBFA II. Because the camera resolves energies with range filters and records ion images with CR-39 film, it is passive and essentially insensitive to a hard x-ray dose of up to 10^5 rad.

Using a recently developed elliptical crystal x-ray spectrograph diagnostic, we made the first observation of $K\alpha$ x-ray satellites from a target heated by an intense ion beam. The satellites are produced when thermal ionization is accompanied by inner-shell ionization from beam ion impact. In these experiments, we used PBFA II to irradiate a conical Al target with a proton beam. To make these measurements, the elliptical crystal spectrograph was contained inside a 1000-kg W shield. The peak ionization stage reached by the Al target was +8. Collisional radiative calculations indicate a peak electron temperature of 20 to 60 eV.

We developed a new Monte Carlo code called PTRAN to model diagnostics based on Rutherford scattering. An important part of the ICF diagnostics program is the determination of the intensity and spatial distribution of intense ion beams when they are focused onto a target. Many of the present diagnostics utilize Rutherford scattering from thin high-Z foils to reduce the beam intensity at the

detectors to acceptable levels. We developed PTRAN as a powerful and user-friendly code to model the response of these diagnostics, thus providing assistance to experimenters in the design of new diagnostics and in the interpretation of experimental results. The code has already modeled ion pinhole cameras, magnetic spectrographs, and Thomson parabolas. The three-dimensional code handles particle detection by both CR-39 nuclear track material and PIN diode detectors. It provides, for the first time, accurate estimates of the total average energy and power that can be delivered to a spherical target using the whole diode.

We have also developed a full data analysis procedure for the PBFA-II Rutherford magnetic spectrograph, which simultaneously records time-integrated data on CR-39 nuclear track recording film and time-resolved data on an array of PIN diode detectors. We wrote a detailed Monte Carlo code to calculate the response of the spectrograph and developed a deconvolution routine that removes the degradation of the PIN detector signals caused by the time response of the PIN detectors themselves and their associated cables. A final part of the analysis involves unfolding the PIN signals with the instrument response functions to determine the time-resolved energy spectrum of the beam. Various moments of this distribution provide the time-resolved power density, current density, and mean ion energy distribution for each resolved ion species in the beam.

A Multiframe Ion Pinhole Camera for Intense Ion Beam Transport and Focusing Experiments

W. A. Stygar, L. P. Mix, T. A. Mehlhorn, D. F. Wenger, W. E. Nelson, R. J. Leeper, J. E. Maenchen, P. Reyes, A. Schmidlapp, D. E. Hebron, T. R. Lockner, and D. J. Johnson

We have developed an ion pinhole camera to obtain energy density profiles for a multiterawatt ion beam as a function of ion energy. The camera was designed for ion beam transport and focusing experiments on PBFA II.⁴⁻¹ Because the camera resolves energies with range filters and records ion images with CR-39, it is passive and essentially insensitive to a hard x-ray dose of up to 10^5 rad. The dose delivered to the camera on a PBFA-II shot is less than 10^4 rad, enabling the camera to be fielded with no x-ray shielding.

Description of the Apparatus

Figure 4-1 is a schematic of the camera. The ion beam from the PBFA-II applied-B ion diode⁴⁻² is focused onto a thin ($0.5\text{ }\mu\text{m}$) Au diagnostic target. The Au is deposited on a $2\text{-}\mu\text{m}$ -thick Mylar substrate, which is stretched across a brass ring as shown in Figure 4-2. The edges of the rectangular Au area provide an in-situ measurement of the edge response and geometric distortion of the camera. Because the edge response that we measure can be explained by pinhole blurring and

scattering in the gas cell window, we have concluded that the images are not significantly distorted by target expansion or electromagnetic fields. Figure 4-2 also shows the two small Au disks that serve as spatial fiducials; these locate the position of the beam with respect to the center of the target.

Figure 4-1. Schematic of the multiframe ion pinhole camera. The electromagnetic shield is not shown.

Figure 4-2. Detail of the Au scattering target.

Beam ions that scatter elastically from the Au are imaged through six W pinholes, each of which is 0.2 mm in diameter and 0.1 mm thick. Baffles limit the field of view (as shown in Figure 4-1) to an area slightly smaller than that of the target ring, and reduce the signal from ions that scatter off the ring and other nearby hardware. The object-to-pinhole distance is 25.6 cm, the pinhole-to-image distance is 15.0 cm, and the diameter of the field of view is 2.0 cm.

The images are recorded on CR-39 nuclear track recording film. The film is covered with six range filters and records six images of the beam, each with a different lower bound on the ion energy. Subtracting images with adjacent cutoff energies results in beam images with upper and lower energy bounds.

The images are read from the CR-39 film with VERA,⁴⁻³ a fully automatic nuclear track counting system that is based on an image processor. Figure 4-3 shows VERA; it consists of a Vicom Model 1800 digital image processor (with an imbedded 68010 microprocessor) interfaced to an automated Zeiss Universal optical microscope. Scanning at a rate of 2 to 3 cm²/hr, VERA measures the nuclear track density $n = n(x,y,d)$ as a function of the CR-39 coordinates (x,y) with 300- μm resolution and the track diameter d with 0.6- μm resolution. Because VERA maintains the microscope focus automatically, it conducts a complete two-dimensional scan of a CR-39 film without operator intervention. A complete scan requires processing over 10,000 images, with each image having an area of 300 μm x 300 μm .

Figure 4-3. Schematic of VERA, a fully automatic nuclear track counting system that is based on an image processor.

Calculating Sensitivity

Figure 4-4 shows the response function (the track density that is recorded on the CR-39 per unit beam energy density at the target) for the difference of two filtered images. E_1 and E_2 are the energies that correspond to the mean ion ranges of the two filtered images; these calculated energies include the effects of the gas cell windows, gas in the cell, Au and Mylar of the scattering foil, and Al range filters. The actual response function more closely resembles the dashed line in Figure 4-4 because of straggling and the reduced sensitivity of the film to obliquely incident low-energy ions. We are presently fabricating a scattering chamber to measure filtered CR-39 response functions at the LANL Van de Graaff facility.

We assume that the shape of the response function is given by the solid line in Figure 4-4, that each point of the Au target receives equal contributions from each point of the diode sector, and that the target is in a transmission geometry.⁴⁻⁴ We used a Monte Carlo code to calculate the sensitivity of the camera, which is

$$S(E) = 8.36 \times 10^{-4} \phi E^3 \text{ J/cm}^2, \quad (4-1)$$

where J is the energy density of the beam at the Au foil, ϕ is the difference in track density (in cm^{-2}) at the CR-39 film between two filtered images, and

$$E = \left(\frac{2E_1^2 E_2^2}{E_1 + E_2} \right)^{1/3}, \quad (4-2)$$

where E_1 and E_2 are the cutoff energies (in MeV) of the filters. For a uniformly emitting anode, the largest source of error is from the width of an energy bin; the error is approximately $(E_2 - E_1)/E$ if $(E_2 - E_1) \ll E$.

Figure 4-4. The solid line is an idealized model of the response function of the difference of two filtered images; the dashed line is a more accurate representation of the actual response. $R(E)$ is in units of track density recorded by the CR-39 per unit beam energy density at the target.

Results

Figure 4-5 shows the result of a scan for a PBFA-II proton shot. The Au disks and the edges of the rectangular Au target can be clearly seen. When images with adjacent cutoff energies are subtracted and the differences are corrected according to their response functions, we obtain the images of the beam as a function of proton energy as shown in Figure 4-6. These images show that the horizontal FWHM of the beam was 5.7 mm on Shot 1734 for protons with energies above 3.2 MeV. The peak energy density at the target was 9 kJ/cm² for protons above 2.3 MeV, and the total beam energy delivered to the target (for protons with energies above 2.3 MeV) was 6 kJ for a 67° sector of the applied B ion diode.

Figure 4-5. The result of a VERA scan of a CR-39 film fielded in the camera. The linear scale in the upper right corner ranges from 0 to 1.6×10^6 tracks/cm². The cutoff energies for images 1 through 6 are 3.2, 2.7, 2.3, 1.8, 1.3, and 1.1 MeV, respectively.

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PTRAN: A Monte Carlo Code to Model Ion-Scattering Diagnostics

L. P. Mix and R. J. Leeper

An important part of the Sandia ICF program is to determine the intensity and spatial distribution of the intense particle beams when they are focused onto a target. Many of the present diagnostics utilize scattering from thin, high-Z foils to reduce the intensity at the detectors to acceptable levels. We developed PTRAN, a powerful and user-friendly, three-dimensional Monte Carlo code, to model the response of these intense ion beam diagnostics, thereby providing assistance to experimenters in the design of new diagnostics and in the interpretation of experimental results. To date, the code has modeled ion pinhole cameras, magnetic spectrometers, and Thomson parabolas. The code handles particle detection by both CR-39 nuclear track material and PIN diodes. The code provides accurate estimates of the total average energy and power that can be delivered to a spherical target using the whole diode (based on measurements from an angular sector of the diode). This section presents a brief overview of the code and discusses some of the important scaling relations for ion pinhole cameras.

Code Details

Simplicity and speed were major considerations in the design of the code. Figure 4-7 shows the three-dimensional geometry assumed in cross section: a barrel-shaped ion diode, scattering from a planar foil at the diode center, and transport from the scatterer to a detector region. Both electric and magnetic fields may be present; hence, the code can model ion pinhole cameras as well as magnetic spectrometers and Thomson parabolas. Extensive plotting capabilities are included.

The code calculates the response of various scattering diagnostics using Monte Carlo techniques and provides statistical estimates for the precision of each of the calculated parameters. Particles are emitted from a spherical anode surface toward a target. The anode emission height, azimuthal extent, and vertical extent can be specified as well as the distribution of the emitted ions (macroscopic and microscopic divergence.) A scattering foil at the origin scatters the particles, either up along the z axis if in transmission, or down if in reflection. Pinholes, slits, and detectors (CR-39 film and PIN diodes) located at specified axial positions collimate and record data from the individual particles. The beam transport portion of the code models beam attenuation by the various foils and apertures used in the experiment. Contour plots of particle intensity at the center of the diode as well as at the detector plane provide a direct comparison with experiment. This code introduced the concept of an average current density on a spherical target. When coupled with realistic beam profiles, this feature allows theorists to use realistic current densities in designing both diagnostic and thermonuclear targets.

We designed PTRAN as a multipurpose code to study a number of diagnostic configurations. Simplification of the input was a major consideration. Although there are 78 possible input parameters for a simulation, we selected default parameters for all but eight of these. We selected a free-format data input scheme using keywords for the data; this technique is similar to a number of other codes written for the ICF program.

Figure 4-7. Schematic of the scattering geometry modeled by PTRAN. The diode axis is vertical through the center of the planar scattering foil, and the anode is cylindrically symmetric to this axis. Foil holders and other geometric details that are included in the code are not shown.

Ion Pinhole Camera Results

We have used PTRAN extensively to study the sensitivity of various diagnostics to changes in experimental conditions. Here we present calculations for the ion pinhole camera diagnostic to illustrate the types of calculations that can be performed. In particular, we discuss the effects of ion energy, nonuniform ion emission from the anode, and focusing errors on the observed signals.

Ion pinhole cameras are typically fielded to measure not only the shape of the focused ion beam, but also its total energy, by measuring the distribution of ion tracks on CR-39 film. When the ions are allowed to strike PIN diodes, the power on target can be inferred. A unique feature of the PTRAN code is that the response is presented in terms of the average power or energy that would be expected to hit a

spherical target from the full diode, based on a measurement from an angular sector of the diode. The absolute response from both power and energy measurements depends on the energy of the ions. In Figure 4-8a and 4-8b, we plot the response for CR-39 film in units of J/cm^2 on target/(particles/ cm^2 on CR-39) and PIN diodes in units of $\text{V}/(\text{TW}/\text{cm}^2$ on target) as a function of the ion beam energy for typical PBFA-II parameters. The solid lines are calculations for ions emitted symmetrically from the top and bottom halves of the anode; the broken lines are for ions emitted either entirely from the top half of the anode or entirely from the bottom half of the anode. Although large errors can occur in estimates of power and energy if most of the beam comes from either the top or bottom half of the diode, the average of simultaneous measurements taken above and below the scattering foil is within 10% of the value expected if the emission were symmetric. The track density scales inversely as energy cubed, and the PIN signal scales inversely with energy squared when all the ion energy is absorbed in the PIN; if a PIN whose thickness is much less than an ion range is used to measure the ion power, the scaling is inversely to the fourth power of the energy.

Beam steering errors can cause the beam to focus at spots other than the center of the diode. The effect of this off-axis focusing is demonstrated by the contour plots in Figure 4-9. The almost horizontal contour lines indicate that little effect on the response is expected if the beam focus is to the right or the left of the diode axis. Nevertheless, the response can change significantly if the beam focus is not on the exact diode midplane; the vertical sensitivity is caused by the angular dependence of the Rutherford scattering.

PTRAN can readily adapt to changing PBFA-II experimental geometries for the analysis of existing data as well as aid in the design of new diagnostics. Although the focused beam parameters inferred from the scattering diagnostic can have large errors if the emission from the anode is nonuniform, the average of simultaneous measurements in transmission and reflection is insensitive to the emission uniformity.

Figure 4-8. Response of (a) CR-39 nuclear track material and (b) PIN diodes to proton beams as a function of ion energy for typical PBFA-II geometry. The solid lines represent emission symmetric about the diode equator; the broken lines represent emission from only the top half of the diode or the bottom half of the diode.

Figure 4-9. Response of CR-39 nuclear track material for typical PBFA-II parameters for different beam steering errors. (The response for the beam focal spot is centered above, below, or to the side of the diode center.)

Data Analysis for the Rutherford Magnetic Spectrograph on PBFA II

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To overcome the unique difficulties in directly measuring the time-resolved energy spectrum of intense ion beams,⁴⁻⁵ we constructed a magnetic spectrograph that uses a Rutherford-scattering foil and fielded it on PBFA II.⁴⁻⁶ The instrument simultaneously records time-integrated data on CR-39 film and time-resolved data on a set of PIN diodes. This section discusses the details of the data analysis that provides time-resolved power density, ion current density, ion energy spectra (including mean ion energy), and ion species identification.

A typical experimental configuration has already been described,⁴⁻⁶ although the particular dimensions have evolved as the device was improved (to optimize resolution and to increase shielding, for example). Figure 4-10 shows the spectrograph schematically. The ion beam is focused on axis through a gas cell; a thin Au foil scatters a portion of the beam out of the gas cell, and the beam travels through a collimator where it is deflected by a magnetic field. The signal is recorded simultaneously on an array of PIN diodes (time-resolved data) and on CR-39 film (time-integrated data).

Calculation of the Response Functions

To calculate the response of the spectrograph, we wrote a Monte Carlo computer code that simulates ion trajectories in the device geometry shown in Figure 4-10. Ions with a specified energy, E , are generated uniformly along the cylindrical anode and are ballistically directed toward the on-axis beam spot. The trajectory is rejected if it fails to pass through the aperture in the target holder.

Quantities such as power density will depend on the type of beam spot (area of focus) assumed in the calculation. In the present calculations, the beam spot is a uniformly loaded disk in a plane perpendicular to the midplane. For the proton results discussed here, independent calculations have shown an 11% difference between this choice and a Gaussian radial distribution (with a width based on an imaging diagnostic of the actual focus) striking a 6-mm-diameter sphere. Therefore, we include the factor 1.11 to express our results as power density on a 6-mm-diameter sphere instead of on a flat disk.

Along the ion trajectory, collisional energy loss (through the two Mylar gas cell windows, in the Ar gas, and in the Au scattering foil) is calculated using the continuous-slowing-down approximation and appropriate stopping power tables.^{4-7,4-8} Energy loss straggling is taken into account by the simple Bohr theory⁴⁻⁹ Gaussian distribution of width

$$\sigma_{\text{Bohr}}^2 = 4\pi N e^4 Z_{\text{ion}}^2 \Delta x , \quad (4-3)$$

where N is the volume density of target electrons and Δx is the distance over which energy losses occur in the target.

The penetration depth into the Au scattering foil is uniformly sampled, and the particles are forced to scatter toward the collimator. We use the Rutherford-scattering cross section (expressed in laboratory frame coordinates⁴⁻¹⁰) to

Figure 4-10. Schematic of the geometry of the magnetic spectrograph used in Monte Carlo calculations.

appropriately weight the particles to account for the change in direction and energy. Multiple scattering is taken into account by the Gaussian distribution⁴⁻¹¹ of width

$$\sigma = \frac{14.1}{p\beta} Z_{\text{ion}} L^{\frac{1}{2}} \left[1 + \frac{1}{9} \log_{10}(L) \right], \quad (4-4)$$

where p is the ion momentum (in MeV/c), β is its velocity divided by c , and L is the target penetration in radiation lengths.⁴⁻¹¹

We chose the new path to pass through the back collimator aperture. The trajectory is rejected if this path fails to pass through the front aperture. This trajectory determines the direction of the particle entering the constant magnetic field region (the "magnet"). Within the magnet, motion follows the standard Larmor orbits. As the ion exits the magnet, it strikes the CR-39 film that is placed along the circumference. A tally is made to calculate the sensitivity as a function of the circumferential x coordinate and of the y coordinate, which is perpendicular to the magnetic deflection.

For measurements from the system using two small, round collimator apertures, the reflection in the y direction is governed by the geometry of the device. Figure 4-11 shows a comparison of several proton shots on PBFA II that used

identical geometries. Each shot is scaled in amplitude to the Monte Carlo result. The excellent agreement in shape between calculation and experiment indicates that the geometry and physics of the spectrograph are well understood. Later experiments incorporated a narrow slit to allow one-dimensional imaging of the beam.

Figure 4-11. Comparison of the shape of the y distribution for several PBFA-II proton shots with Monte Carlo calculations.

If the exiting (x,y) location corresponds to an active area of one of the PIN detectors, the program continues to deposit the ion energy as the ion passes through the detector. One electron-hole pair is formed for every 3.6 eV of energy deposited in the detector. The current is proportional to the voltage measured for the PIN response function.

The PIN response functions were calculated by varying the incident ion energy in many code runs. Figure 4-12 shows one set of proton responses as a function of incident energy. Separate sets of response functions must be calculated for each possible ion and ion charge state in the magnet. The computer program also calculates the average time of flight for each ion specie to each PIN.

Figure 4-12. Sixteen PIN diode response functions for protons on PBFA-II Shot 2679. The numbers refer to PIN diode numbers.

Data Reduction

Figure 4-13 shows an uncorrected PIN waveform from PBFA-II Shot 2621. This example illustrates how the signals from different ion species are separated by their time of flight from the deep-penetrating bremsstrahlung radiation. The charge states of Li refer to the post-scattering charge in the magnet. Once the species of the signal are identified, their calculated time of flights are used to shift the signals to a common time base at the anode.

The degradation of the signal caused by the response of the PIN detector and associated cables is removed by solving

$$S_i(t) = \int h(t-\tau) S_i^{CC}(\tau) d\tau \quad (4-5)$$

for the cable-compensated signal $S_i^{CC}(t)$, where $h(t)$ is the unit impulse response. This is accomplished by using the Sandia unfold operator code UFO⁴⁻¹² with a normalized, measured response to a picosecond burst of bremsstrahlung for $h(t)$.

Figure 4-13. Uncorrected waveform of PIN 12 for PBFA-II Shot 2621, illustrating the presence of bremsstrahlung, protons, and Li ions in different charge states in the magnet.

For the narrow (7-ns) signals of the proton results discussed here, cable compensation plays a significant role. Corrected PIN signal amplitudes are increased by as much as a factor of 2, resulting in a 20% to 25% larger peak power density. We must specify a time grid for the solution histogram $S_i^{CC}(t)$. The UFO code compares coarse grids with fine ones to check for unstable oscillations.

UFO also determines the time-resolved energy spectrum $\Phi(E,t)$ by solving the set of equations

$$S_i^{CC}(t) = \int R_i(E) \Phi(E,t) dE \quad i = 1, N_p, \quad (4-6)$$

where $R_i(E)$ is the calculated PIN response function for the i^{th} PIN and N_p is the number of PINs used. For a multiple-species beam, there are separate signals, response functions, and energy spectra for each ion specie.

Figure 4-14 shows the time-resolved energy spectrum $\Phi(E,t)$ for PBFA-II Shot 2679, which used a proton ion source. The proton power density and mean energy are given by

$$p(t) = \int E \Phi(E,t) dE \quad (4-7)$$

$$\langle E \rangle = \int E \Phi(E,t) dE / \int \Phi(E,t) dE \quad (4-8)$$

and are shown in Figure 4-15. The various symbols on the power density curve are results of different solutions (coarse versus fine time grids) of Equation 4-5. We calculated the height of the flat top of the power density curve to maintain the energy integral that was obtained from analyzing the time-integrated CR-39 data. The reasonable shape of the curve suggests agreement between the analyzed PIN and CR-39 data. A more direct comparison of analyzed CR-39 and PIN data, which have been time integrated, is an important crosscheck of the analysis.⁴⁻⁵

Uncertainties in the data (such as baseline correction of the PIN signals) are bounded by comparing the time integrals of these signals to the counts on the CR-39. Uncertainties in the beam profile or angular distribution on the scattering foil are reduced by comparing the profile or distribution to independent diagnostics fielded simultaneously on each shot. For the peak power density on Shot 2679, we estimated the overall error to be 20%.

Although the average energy equation is precise, the power density equation should use response functions based on energy and time of flights at the target, not the anode. While protons lose very little energy before reaching the target (and hence it makes little difference), this is not true for higher-mass ions because of their larger stopping powers. Demonstrated agreement between calculation and experiment gives us confidence in applying PTRAN to generate response curves.

Figure 4-14. Time-resolved proton energy spectrum for PBFA-II Shot 2679.

Figure 4-15. Mean energy and power density on a 6-mm-diameter sphere for PBFA-II Shot 2679. "Coarse" and "fine" refer to the time grid chosen for solutions to Equation 4-5.

Li-Pr Activation Calibration

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We have developed an improved nuclear activation method to measure Li ion beam intensity. We had been measuring Li beams with the Cu activation method. This method requires that Cu samples be activated by fast neutrons produced by the $d(^7\text{Li},n)$ reaction. The fast neutrons induce activity in the Cu samples by the $^{63}\text{Cu}(n,2n)^{62}\text{Cu}$ reaction, which leads to β^+ decay of ^{62}Cu with a half-life of 9.74 min. Unfortunately, naturally occurring Cu is also composed (31%) of ^{65}Cu isotope. The reaction $^{65}\text{Cu}(n,2n)^{64}\text{Cu}$ leads to the production of ^{64}Cu with β^+ decay and a half-life of 12.71 hr. Additionally, ^{63}Cu may readily capture thermalized neutrons and lead to ^{64}Cu as well. Using POS techniques at high Li beam energies, we anticipate the production of low-energy neutrons, with the long-lived component of Cu activation overwhelming the short-lived component. Cu activation results could become ambiguous and therefore useless. So, we looked for an activation technique that has only a single significant fast decay mode.

This new activation method of Pr has been calibrated at the LANL tandem accelerator for Li energies between 4 and 30 MeV. We performed activation of Pr at 90° relative to the beam at 7.6 cm from the Pr samples to the neutron source. Thus, we reproduced the Cu activation geometry exactly.

Figure 4-16 shows the results of this new calibration in terms of the calibration factor F (counts/Li ion/g Pr) as a function of Li ion kinetic energy (MeV). The graph reveals that Li-Pr activation(x) is, on the average, 1.5 times more sensitive than Li-Cu activation($\bullet$). More importantly, we do not anticipate a long-lived activity component from the activation of Pr.

This new technique needs more accurate calibrations. As the energy of PBFA II continues to approach energies greater than 10.0 MV, the Li-Pr technique must be used to measure Li ion beam intensities.

Figure 4-16. Calibration F factor versus Li ion energy ("x" corresponds to Li-Pr data; "•" corresponds to Li-Cu data).

Observation of $K\alpha$ X-Ray Satellites from a Target Heated by an Intense Ion Beam

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We have made the first observation of $K\alpha$ x-ray satellites from a target heated by an intense ion beam. The satellites are produced when thermal ionization from beam heating is accompanied by inner-shell ionization from beam ion impact. We used PBFA II to irradiate a conical Al target with a proton beam. The nominal beam parameters were 50 to 75 kJ in a 1-cm spot, 15- to 20-ns pulse length, and 4- to 5-MeV protons at a peak power of 1-2 TW/cm². We used an elliptical crystal x-ray spectrograph inside a 1000-kg W shield to record the spectra. The peak ionization state reached by the Al target was +8. We performed collisional radiative calculations that indicate a peak electron temperature of 20 to 60 eV.

$K\alpha$ x-ray satellite transitions appear when inner-shell ionization from the K shell of an atom is accompanied by simultaneous vacancies in the $n = 2$ or $n = 3$ shells. The satellites appear as lines that are blue-shifted with respect to the normal $K\alpha$ 1s-2p transition because of the reduced screening of the nucleus, which results when there are fewer "spectator" electrons. (These are excited electrons that do not participate in the actual transitions.) Researchers have studied these satellites extensively⁴⁻¹³ using beam foil spectroscopy, in which heavy energetic projectiles are used to create multiple ionization in the target atoms. Multiple L- and M-shell vacancies are also produced when target atoms are thermally ionized. These vacancies have been used as the basis for studies of hot electron transport in laser-heated targets, where the inner-shell ionization was produced by the hot electrons^{4-14,4-15}. $K\alpha$ spectroscopy has proved useful as a temperature diagnostic in absorption spectroscopy of laser-produced plasmas.⁴⁻¹⁶⁻⁴⁻¹⁸ Nardi and Zinamon⁴⁻¹⁹ have also suggested that $K\alpha$ satellites can be used as a temperature diagnostic for targets heated by light ion beams in inertial fusion experiments. Our research demonstrates this use. The satellite spectra determine the ionization distribution, and the temperature can be derived from this distribution using collisional radiative calculations. This method is applicable for relatively low temperatures (10 to 100 eV) where K-shell line ratio techniques are difficult to apply. It has the advantage that it does not depend on an absolute detector calibration, as do filtered broadband continuum measurements. Another motivation for $K\alpha$ spectroscopy is that the ionization distribution is one of the most important factors in determining the stopping of ions in hot plasmas. However, as pointed out by Nardi and Zinamon,⁴⁻¹⁹ the interpretation of satellite spectra is quantitatively complicated by opacity and the density dependence of the ionization distribution.

Experiment

We performed these experiments on PBFA II using an applied-B ion diode. Details of the accelerator and the diode are given elsewhere.⁴⁻²⁰⁻⁴⁻²² Figure 4-17 shows a schematic diagram of the diode, target, and diagnostics. Power from the accelerator flows into the top and bottom of the barrel-shaped diode through conically shaped MITLs. Ions accelerated from the inner surface of the barrel are focused to a spot at the center. We presently use a hydrocarbon flashover ion source to provide a proton beam for studies of the diode physics and for experiments aimed at understanding beam-target interaction physics. We are developing Li ion sources for future experiments.

It was not possible to directly measure the incident beam power for this target. We can estimate nominal beam parameters from other shots, where the target was designed to optimize measurement of the incident beam energy. The nominal parameters are 50 to 75 kJ of protons delivered to a 1-cm-diameter spot. The pulse width measured with a magnetic spectrograph is typically 15 to 20 ns⁴⁻²² with a voltage of 4 to 5 MV at peak ion power. The proton power density incident on the conical target was approximately 1 to 2 TW/cm².

The proton beam available on PBFA II provides a unique capability for experiments on beam-heated plasmas. However, this accelerator's environment is harsh. Electron losses in the power feeds leading to the diode result in high-energy x-rays (5- to 10-MeV endpoint bremsstrahlung) with a typical dose of 1000 rad (Si) in the region where diagnostics are located. We therefore encase the diagnostics within a 1000-kg W canister, which provides about 10 cm of shielding. In addition, the large amount of energy delivered to the diode creates significant debris, which can destroy delicate diagnostic elements such as x-ray crystals.

The primary diagnostic in these experiments, an elliptical crystal x-ray spectrograph,⁴⁻²³ has many advantages in the PBFA-II environment. The x-rays from the source, located at one of the elliptical foci, are focused to pass through a slit located at the other focal point. This slit eliminates scattered x-rays from the line of sight and minimizes the amount of crystal substrate fluorescence that can reach the film. The detector plane is curved to the locus of the Johann crossover points so the line broadening induced by the source size is greatly reduced.^{4-23,4-24} This last feature is crucial because the plasmas created in these experiments are 1 to 2 cm in spatial extent.

The spectrograph we used is similar to those designed by Henke⁴⁻²³ and Hammel.⁴⁻²⁴ The focal length is 49.2 cm, and the instrument is equipped with a 1-mm-wide space-resolving slit, which provides a magnification of 1- and 2-mm resolution at the source. We mounted a pentaerythritol (PET) crystal to an Al

Figure 4-17. Schematic cross-sectional diagram of the PBFA-II diode region. The diagnostics are packaged inside a W shield to protect them from the hard x-ray background. A similar package on the bottom is not shown.

substrate (X-Ray Optics, Inc., Jacksonville, Florida) with eccentricity 0.9188 and height parameter of 4.17 cm. The range covered with this crystal was $6.40 \text{ \AA}$ to $8.66 \text{ \AA}$, with a resolution of better than 1200. The spectra were recorded on Kodak DEF film.

Results

Figure 4-18 shows the spectrum obtained from an Al cone target, with the data corrected for film response.^{4-25, 4-26} The target was $75 \text{ }\mu\text{m}$ thick with a half-angle of 15° and a diameter at the midplane of 14 mm. This target thickness corresponds to one-half the range of 5-MeV protons in the cold material. The satellites corresponding to one to five holes in the L shell are clearly visible (Al V-IX). The transitions corresponding to Al I-IV are blended into one line because the

wavelength shift from removal of the $n = 3$ electrons is only a few milli-angstroms.⁴⁻²⁷ We can immediately observe from this spectrum that the peak ionization state reached in the target was +8 (B-like).

Figure 4-18. $K\alpha$ satellite spectrum obtained from an Al target irradiated by the PBFA-II proton beam. The top spectrum is the same data with amplitude scaled by a factor of 15.

Flashover hydrocarbon ion sources are known⁴⁻²⁸ to produce comparable numbers of protons and C ions. Although the diode is configured to focus protons and not C ions, we have considered whether the satellites in this spectrum could arise from multiple ionization events produced by accelerated C ions instead of from thermal ionization produced by proton beam heating. A proton spectrum would not include satellites with more than one L-shell vacancy;⁴⁻²⁹ therefore, we are not concerned with multiple ionization produced by the proton component of the beam. We compared the PBFA-II data with data obtained by Watson et al.⁴⁻²⁹ in which a Van de Graaff accelerator bombarded an Al foil with 22-MeV C IV ions. Table 4-1 shows this comparison. The satellites from the PBFA-II spectrum are blue-shifted with respect to the beam-foil-produced spectrum of Watson et al., with the shift becoming more pronounced as the number of L-shell holes increases. The wavelengths in both spectra are measured relative to the neutral $K\alpha$ line. Watson⁴⁻²⁹ quotes a wavelength accuracy of ± 2.5 mÅ, and we estimate an accuracy of better than ± 4 mÅ for the PBFA-II spectrum. The observed blue shift of 14 to 34 mÅ is consistent with an empty M shell in the PBFA-II Al target. The C projectiles in the

Table 4-1. Comparison between Al spectra obtained on PBFA II and a beam-foil spectrum using C projectiles.

Observation of $K\alpha$ x-ray satellites					
Number of L-shell holes	Wavelength ($\text{\AA}$)			Intensities ^a	
	PBFA II	Watson et al. ⁴⁻²⁹	$\Delta\lambda$ (m $\text{\AA}$) ^b	PBFA II	Watson et al. ⁴⁻²⁹
0	8.340	8.341	1	21.00	0.190
1	8.270	8.284	14	1.60	0.590
2	8.202	8.223	21	1.00	1.000
3	8.126	8.151	25	0.66	0.650
4	8.044	8.078	34	0.74	0.250
5	7.969	8.001	32	0.28	0.063

^a Intensities have been normalized so that the intensity of the satellite with two L-shell holes equals one in both sets of spectra.

^b Wavelength difference between the two sets of spectra.

beam-foil experiment preferentially produce simultaneous ionization in the K and L shells, leaving the M shell intact. The remaining M-shell electrons contribute to the screening of the nucleus, which results in a longer wavelength for any given transition compared to a configuration with an empty M shell. The screening provided by the M-shell electrons becomes more important as the number of L-shell holes increases. Thus, the wavelength difference between full and empty M shells is larger for satellites with more L-shell holes.

In addition, it is clear from Table 4-1 that the intensity distribution among the satellites is different in the two cases. C projectiles produce a distinct intensity pattern that reflects the ionization probabilities from the various levels and the fluorescence yields for the radiative decay. Because this distinct pattern is not reproduced in the PBFA-II data, we conclude that the satellites in the PBFA-II Al spectrum do not arise from C-induced multiple ionization. This conclusion extrapolates to C ions with lower energies because the M shell would remain filled and the intensity pattern would exhibit a weak shift toward fewer L-shell holes, which creates an even larger difference between the PBFA-II spectrum and the C-beam-foil spectrum.

Based on the dominance of the line due to neutral through Ne-like charge states, the target is relatively cold during most of the pulse. Because of this, if C ions

strike the target in sufficient numbers to induce target heating, then the time-averaged satellite wavelengths should resemble the beam-foil data. Because this is not the case, C ions did not contribute to the target heating, and the Al satellites observed on PBFA II are from thermal ionization induced by the proton beam.

The shape of the $K\alpha$ lines depends on the number of spectator electrons. The broad line that corresponds to neutral through Ne-like ions is asymmetric toward the short-wavelength side (Figure 4-19a) because of the relative strengths of the lines corresponding to the various ionization states. The F-like line is resolved into three features (Figure 4-19b). The O-like line also exhibits some internal structure, and the lines from N-, C-, and B-like Al are symmetric.

We have difficulty calculating the wavelengths of the individual term-dependent lines because this demands that the energy levels be calculated to better than one part in 3000. We have performed Herman-Skillman calculations^{4-30,4-31} to obtain a first-order approximation to the wavelengths. These calculations did not include a relativistic correction or detailed configuration interaction. However, these corrections are expected to cancel approximately, so the net adjustment to the wavelengths is small. The agreement with the experimental values is within 0.065 Å for the F-like through B-like satellites, but is not sufficient to allow reliable term-dependent identifications. The discrepancy is worse for the neutral through Ne-like ions because the final state for these transitions is not the ground state. Figure 4-19b shows the calculated wavelengths for the F-like satellite compared to experiment. The calculated lines shown are for the $1s2s^22p^5$ initial configuration only. Two of the three features in the F-like satellite can be attributed to the $2s^22p^5$ configuration, and the third feature may arise from the $2s2p^6$ configuration. A more accurate calculation is needed to provide a reliable identification. If this identification can be achieved, an investigation of the mechanisms that determine the relative strengths of the three features would be a logical next step.

In principle, the relative satellite line intensities contain the information needed to infer the time-integrated ionization distribution. However, these intensities also depend on time-dependent beam intensity, hydrodynamic motion of the target, and opacity. The unfoldment of these interrelated factors is beyond the scope of the present work. It is reasonable, however, to determine qualitatively the peak temperature required in the target to produce Al IX. We performed collisional radiative calculations that included the extra ionization produced by the incident beam. The details of the code can be found in Lee⁴⁻³² and Dukart.⁴⁻³³ Figure 4-20 shows the ionization distribution obtained by the code for an electron density of 10^{21} atoms/cm³. At this density, the minimum temperature required to produce Al IX is 40 eV. From calculations at different electron densities, we find that the peak

Figure 4-19. Detail from the Al $K\alpha$ satellite spectrum showing (a) the transitions from the neutral through Ne-like ions and (b) the F-like satellite. The wavelengths of the lines from different ionization states are from House.⁴⁻²⁷ "F-like" refers to the ionization state before the beam-induced inner-shell ionization. We calculated the theoretical wavelengths for the $1s2s^22p^5$ initial configuration only. The final configuration is $1s^22s^22p^4$; the two configurations have not received any net shift to bring them into agreement.

Figure 4-20. Ionization distribution from the collisional radiative equilibrium code for an electron density of 10^{21} atoms/cm³ and an incident beam power of 5 TW/cm².

temperature reached in this target was 20 to 60 eV. The wide range results because we do not know the density of the plasma at which the bulk of the emission occurs.

These experiments prove, in principle, the temperature diagnostic suggested by Nardi and Zinamon.⁴⁻¹⁹ Actual temperature measurements will require development of time-resolved diagnostics and analysis that considers opacity and target hydrodynamics. Recent results⁴⁻¹⁷ from absorption spectroscopy of laser-produced plasmas suggest that it should be possible to measure plasma electron temperatures to within a few electron volts if the ionization distribution is characteristic of the local instantaneous plasma conditions. However, it is necessary to know the plasma electron density. The method used by Davidson⁴⁻¹⁷ was to tamp the target with a low-Z element so that the probed element did not expand and remained at high density. Then, the probed element is expected to be in local thermodynamic equilibrium, and the density dependence of the ionization distribution would be negligible. A second method is to include two different elements in the plasma. By measuring the ionization distribution of both elements, it should be possible to determine the electron density and temperature uniquely.

The range of applicability for this diagnostic is restricted to plasma conditions that produce ions with vacancies in the $n = 2$ shell and to ions that have a reasonable cross section for inner-shell ionization by the beam ions. The lowest

atomic number ion that has a $K\alpha$ transition that can be recorded with a crystal spectrograph is F, and the highest atomic number ion whose $K\alpha$ transition has been excited by the PBFA-II beam is Ti. (Higher-Z elements may work, depending on the voltage used in future experiments.) This defines a temperature range accessible to this technique of approximately 10 to 200 eV.

Li-C Activation Relevant to PBFA II

C. L. Ruiz, A. Schmidlapp, and G. Cooper (UNM)

During recent Li-Pr activation experiments⁴⁻³⁴ at the LANL tandem accelerator, we discovered an unexpected reaction $^{12}\text{C}(^7\text{Li},n)$ that produced very energetic neutrons. These neutrons activate Cu or Pr samples. Li ion intensity measurements on PBFA II make use of the Li-Cu activation technique. This technique relies on the production of fast neutrons in the $d(^7\text{Li},n)$ reaction, from the Li beam striking a deuteron (D_2)-loaded target (ErD_2).

Neutrons from carbonated targets can cause unwanted activation in either Cu or Pr and therefore cause an overestimate of Li beam intensity if we assume that all activity is due to Li. But there is C in the gas cell region of the diode (in the form of Mylar or Lexan skirts), and any Li striking these materials could add activation counts to Cu or Pr samples. Our discovery of activation by neutrons produced by $^{12}\text{C}(^7\text{Li},n)$ initiated a measurement of the calibration factor on Cu. Figure 4-21 shows the F-factor plotted against the Li ion kinetic energy (MeV). Fortunately, for energies below 14 MeV, the unwanted activation from C materials is not significant compared to the F-factor for Li-Cu activation. Nevertheless, this activation has considerable impact on the measurement of proton beam intensities. In such beam measurements, Pr samples are activated by gamma rays from the $^7\text{Li}(p,\gamma)$ reaction. Additional activation of Pr is due to the naturally abundant D_2 in the proton beams and the $^7\text{Li}(d,n)$ reaction. Calibrations for the activation contributions from both these ion species have been done.⁴⁻³⁵ However, any C in the proton beam (estimated to be 50%) will also strike the Li target. The inverse reaction $^7\text{Li}(^{12}\text{C},n)$ will occur in the Li target and will produce energetic neutrons, which contribute additional activation to the Pr sample. This C beam may have three times the energy of the proton beam and could reach 20 to 30 MeV in charge state +3.

The Li on C calibration suggests that C on Li could lead to erroneous proton beam ion intensity measurements. As a result of this study, we propose to filter out all energetic C ions so they do not impinge on Li targets. Only protons and D_2 will be allowed to contribute to Pr activation in order to assure a correct intensity measurement.

Figure 4-21. F-factor plotted against the Li ion kinetic energy (MeV). "x" is the Li-C calibration and "•" is the Li-Cu activation.

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Chapter 5. Power Flow Research

Overview

M. A. Sweeney, D. H. McDaniel, G. E. Rochau, and C. W. Mendel

The goal of SNL POS research is to store energy inductively in an MITL until peak current is reached, and then to open the switch rapidly (in <5 ns) to transfer energy to an ion diode load that is connected in parallel to the switch. If this is done successfully into a high impedance ($>10 \Omega$) load, we will obtain voltage multiplication and power gain on PBFA II. During 1989, we made progress toward meeting this ultimate goal.

Data obtained from PBFA-II experiments are now more accurate and reproducible: timing uncertainties are 1 to 2 ns and the opening current level can be set to within 4%; two years ago, these uncertainties were 5 to 10 ns and 15%.⁵⁻¹ In addition, more extensive diagnostics are being used than in previous switch experiments on PBFA II or on the Blackjack 5 accelerator at Maxwell Laboratories. Much better plasma uniformity has been obtained with the erosion switch,⁵⁻² which uses acceleration of ions toward the cathode by electric fields and the self-magnetic field of the power pulse to enhance "erosion" of the ions. However, even with improvement by a factor of five in uniformity, the erosion switch does not couple well to high-impedance loads. Analysis of the data indicates that plasma mass is entering the load region. This mass and the associated launching of electrons toward the anode make magnetic insulation during the opening phase and efficient coupling to the load impossible.^{5-3,5-4} Therefore, we have abandoned further development of this switch for voltage and power gain and we have begun studies on PBFA II and other accelerators of three switch designs that use magnetic fields to provide more control and confinement of injected plasma in the vacuum power feed.

The first design is a modification of the standard erosion switch with plasma injected through six equally spaced, azimuthal segments, as shown in Figure 5-1. This segmented switch⁵⁻³ had a slower current risetime into short circuit loads compared to switches using a magnetically injected plasma (MIP) source. Nevertheless, power flow was better than for the standard erosion switch. Two-dimensional PIC and three-fluid simulations with finite loads in the PBFA-II geometry, by E. L. Lindman⁵⁻⁵ of Mission Research Corporation (MRC) and R. J. Mason⁵⁻⁶ of LANL, respectively, showed that the magnetic field from current conduction through the "plasma spokes" produces less ion ejection downstream and better power flow than with an unsegmented switch. In experiments on PBFA II, all three of these switch designs coupled current efficiently into 5- Ω electron beam loads⁵⁻³; coupling to 10- Ω loads is less efficient.

Figure 5-1. Schematic of the segmented erosion switch on PBFA II.

The other two designs use a MIP source to set the opening current.^{5-7,5-8} A preimposed magnetic field at the anode injects the plasma and holds it in place. The switch opens after the magnetic pressure of the conduction current overcomes the pressure produced by the injecting magnetic field and by the plasma inertia and pushes a gap open at the cathode. Once the switch opens, the machine current forces the plasma back into the anode. This switch has been termed the MIP switch. A schematic of the geometry and location of the switch is shown in Figure 5-2. The downstream current risetime into short circuit loads was faster (7 ns versus 12 ns) than for the segmented switch. When a rapidly rising external field is added at the cathode⁵⁻⁸ in addition to the field at the anode, plasma can be pushed back into the anode more rapidly; with this design, termed a current-toggled (CT) POS, switch operation is less dependent on plasma density. A schematic of the geometry and location of the switch is shown in Figure 5-3. This CT POS performs as well as the MIP POS when coupled to short-circuit and high-impedance loads. Moreover, data on SuperMITE and PBFA II indicate that, with the addition of the rapidly rising field, we can couple current more efficiently when opening near peak generator current.

Figure 5-2. Schematic of the configuration of the MIP POS on PBFA II.

Figure 5-3. Schematic of the configuration of the CT POS on PBFA II.

Nevertheless, the difference between the anode and cathode currents at the load in the experiments indicated a problem with power loss caused by electron flow to the anode, particularly for the designs utilizing the MIP sources. (In most experiments done at other laboratories, only the downstream anode current is measured; however, it is the cathode current that is more important, because it is this current that couples to the load.) If we can learn to control this "launched" electron flow⁵⁻⁹ (called "launched" because the voltage is high and the electrons are close to the anode), more energy will be available to the ion diode. The importance of electron flow is not a new concept; it has been investigated theoretically and simulated with PIC codes in the past. What is new, however, is data obtained during the latter part of 1988 and in 1989 that show clear evidence of electron flow in switch experiments; in experiments with electron beam loads, one-half of the current is in electron flow. We will be looking at how and where these electrons are lost in the anode feed and determining their effect on the ion diode. It is not likely that we can retrap these launched electrons; however, it may be possible to utilize some of them in the ion diode itself to reduce the diode impedance faster for better compatibility with the POS.

Analysis of the coupling of the segmented switch to an ion diode indicated that the switch sharpened the risetime of the ion diode current by a factor of two and gave a smaller beam divergence as seen from witness plate data. Experiments to couple a MIP switch to an ion diode done at the end of 1989 reinforced our conviction that methods to reduce the ion diode impedance more quickly need to be investigated and that an increase in the flow impedance, defined as $V/(I_{in}^2 - I_{load}^2)^{1/2}$, will decrease electron flow to the anode. Recently PBFA-II experiments with magnetically controlled switches have been done at one-half (30 kJ/module), three-fourths, and full charge energy at a rate of one shot/day. Coupling of these switches to higher impedance loads is being investigated experimentally. Experiments in which the plasma generators on the load side of the switch are eliminated suggest that the opening point of the switch is further away from the load compared to the case for which plasma injection occurs in both directions from the MIP flashboard source. Such experiments represent an intermediate step that uses lower magnetic fields and higher plasma densities. We have not yet developed a magnetic field coil that can generate sufficient field to demonstrate the magnetic pressure principle on PBFA II without the use of some plasma inertia to also control the plasma.

Dynamics of Plasma Injection Along Magnetic Field Lines in the PBFA-II Plasma Opening Switch

M. A. Sweeney and M. H. Frese

The object of this study was to predict the plasma density distribution as a function of time in the POS region that results from the interaction of the preimposed magnetic field of the MIP source with the plasma injection pulse. Simulations were done with MACH2,⁵⁻¹⁰ a two-dimensional MHD code that uses boundary-fitted, arbitrary quadrilateral grids to fit the actual experimental geometry of the conic switch region and the adjacent semi-toroidal plasma source region of PBFA II, as shown in Figure 5-4. Neither the accelerator power pulse nor the load behavior was included. Because the Alfvén velocity is very high relative to the plasma injection velocity, an explicit calculation would require unacceptable computer expense for these preliminary calculations. An implicit computation without a very high convergence rate scheme would be little better. For ideal operation of the MIP source, the field lines are effectively stiff and not subject to displacement by the plasma. We therefore computed plasma motion by ignoring any traverse movement and restricting the velocity to lie along the field.

Simulations using this approach agree qualitatively with microwave interferometry measurements of the electron density in the laboratory test stand⁵⁻¹¹ as shown in Figure 5-5. The simulations were done before the measurements were

Figure 5-4. Computation grid fitting the experimental configuration for magnetically controlled plasma injection. The dots mark the locations of the simulation density probes.

Figure 5-5. Electron density versus time at simulation density probe locations and at one microwave interferometer location. The injection velocity peaked at $10 \text{ cm}/\mu\text{s}$ and the inflow electron density was set to $5 \times 10^{13} \text{ particles}/\text{cm}^3$ in the simulation. The experimental measurement by B. V. Weber of NRL was 2 cm downstream of the cathode simulation density probe location shown in Figure 5-4.

made. Better agreement could be obtained by adjusting the unknown plasma source mass flux rate. The simulations, supported by the experimental measurements, show that the MIP switch plasma is larger and more diffuse than the erosion switch plasma.⁵⁻¹² Hence, the region over which significant motion occurs is also larger. A simulation in which plasma is injected only from the upstream side of the flashboard shows that this may be an easy way to lower the mass of the switch plasma.

The main implication of the study is that cathode density measurements may not provide an adequate measure of the mass in the switch. The total switch mass rises faster than the cathode density and falls before the cathode density peaks. If switch mass is an important determinant of switch opening time, use of cathode density diagnostics to determine plasma formation time will therefore be misleading. This study was performed by M. H. Frese of NumerEx under contract to SNL.⁵⁻¹³ In 1990, MHD simulations of the plasma during the accelerator pulse for the MIP and CT switch configurations will be studied.

Analytic and Computational Investigations of POS Phenomena

M. A. Sweeney and E. L. Lindman

The object of this study was to develop an understanding of the interaction between POSs and pulsed power phenomena. Several codes were utilized in the analysis. The PIC code MAGIC⁵⁻¹⁴ was used to study magnetic insulation, plasma instabilities, switch operation, and blade load performance. ATHETA⁵⁻¹⁵ was used to generate stationary magnetic fields to study the effects of additional magnetic field components on magnetic insulation and electron trajectories in the switch region. IDR, the SNL code to manipulate experimental data, was used in evaluating data from Blackjack 5 and PBFA II. In addition, a complete description of the magnetic transition at the vacuum-plasma interface, including nonlinear effects such as the relativistic mass increase and violation of quasineutrality, was obtained analytically. The conclusions of the study follow. More details are available in the contractor report by E. L. Lindman.⁵⁻⁵

Electron transport along magnetic field lines in the complex geometry of the PBFA-II switch region is a serious obstacle to the use of the rapidly rising external field at the cathode for the CT switch. Studies on MAGIC to assess the problem are an extension of previous research on MITLs done at SNL and reported in earlier progress reports and elsewhere. A schematic of the computational region in the cylindrical geometry calculations is shown in Figure 5-6. Electrons are emitted on field lines that intersect the cathode, and large current loss is expected when these field lines also intersect the anode. The breakdown of magnetic insulation can occur more easily in the smaller gap that exists between the virtual cathode, which is produced by electron flow along the field lines, and the anode. Substantial current loss is seen in simulations in which such a virtual cathode forms close to the anode.

The simulations show that a double-blade load will produce a broader and therefore less destructive damage pattern than a single-blade load under conditions of near-perfect top-to-bottom symmetry in the accelerator. A schematic of the computational region for these studies is shown in Figure 5-7. The improvement obtained with double-blade loads may be difficult to observe in PBFA-II experiments, however, because a delay in the arrival of the power pulse from one-half of the accelerator compared to the other would produce a similar effect. In addition, a 5-ns delay from one-half of PBFA II in a pulse with a 13-ns risetime has a striking effect on the load impedance histories because of the differences in current flow; in contrast, the effect on the load voltage is quite weak.

MAGIC simulations of one segment of a six-segment POS show that such a switch suppresses the ejection of low-density plasma toward the load (as seen in a conventional erosion switch) because the magnetic field can pass through the open segments and apply a force that retards downstream plasma motion.

Figure 5-6. Schematic of the computational region for PBFA-II MITL studies of electron trajectories and magnetic insulation. The load impedance was assumed to be 10Ω ; the gap impedance was assumed to be 5, 10, or 15Ω . Calculations were done with and without the preimposed MIP field, with and without the rapidly rising CT field, and with and without ion emission.

Figure 5-7. Schematic of the computational region for double-blade load studies with and without a delay in the arrival of the power pulse from one-half of PBFA II.

We also studied analytic theory for the transverse electric and magnetic modes in a cylindrical transmission line. Comparison of this theory with Blackjack 5 and PBFA-II data suggests that large azimuthal asymmetries are present in electrode surface currents between neighboring Bdot probe data on the same electrode and between probes facing each other on the anode and cathode after corrections for radial dependence. If these asymmetries play a central role in switch operation, conclusions based on two-dimensional cylindrically symmetric codes may be incorrect. Moreover, to achieve optimum switch performance and coupling to an ion diode load, effects of asymmetric power flow will have to be minimized. MAGIC was used to search for evidence of filamentation instabilities that would cause electron current to flow in filaments instead of in a uniform sheet. However, at least for the short wavelength region investigated ($\lambda < 10c/\omega_{pe}$), no evidence for such instabilities was seen.

Analysis of 1989 In-Plasma Bdot Probe Measurements on PBFA II

M. A. Sweeney and S. S. Payne

The object of this research was to analyze in-plasma Bdot probe experiments done on PBFA II in April 1989 with a conventional erosion switch.⁵⁻² The SNL code IDR was used to manipulate the experimental data. Six of the in-plasma diagnostic shots were into short-circuit loads on the top half of the accelerator; four were for varying plasma fill times, and the remainder were calibration shots. Locations of all the Bdot probes are shown in Figure 5-8. Probes were located on the anode and cathode upstream, downstream, and at the load as well as farther out in the plasma-filled A-K gap. In the experiments, which were done by G. E. Rochau, the Bdot loops were oriented to give negative signals for magnetic flux so that, if electrons struck the probes, the signals would become more negative. The in-plasma probes near the cathode compared well in time with a standard calibration curve based on probes located upstream of the switch region. Nevertheless, in-plasma probes near the cathode were very susceptible to electron strikes and were therefore more difficult to match in amplitude to the standard curve. In contrast, probes near the anode compared well in both time and amplitude with the standard curve. A two-loop coaxial probe configuration that might reduce the effects of electron strikes to the probes near the cathode was proposed by B. V. Weber⁵⁻¹⁶ of NRL during the sixth POS workshop at SNL, which was held in August 1989.

Analysis of the data taken during the four shots with varying plasma fill times indicates that switch performance is not affected by the presence of the in-plasma probes. The data suggests that measurable azimuthal asymmetries are present in the plasma, especially for the longer fill times. Current is observed to

Figure 5-8. Schematic showing the location of upstream, downstream, and in-plasma Bdot probes during the April 1989 in-plasma probe experiments on PBFA II.

arrive at the in-plasma probes at different times for different azimuthal locations. Moreover, plasma appears to be shielding the probes at the cathode and at the downstream side of the region where plasma is injected into the gap from flashboards at the anode (at locations 32, 42, and 52 in Figure 5-8) because current rise is delayed compared to probes further downstream. The analysis suggests that plasma density is either being pushed or dragged along by the magnetic field toward the load and that the magnetic field penetrates the plasma at a velocity near the Alfvén speed simultaneously along the anode and cathode. The main conclusion of the analysis is that either a plasma flow switch configuration or a magnetically controlled switch configuration is necessary to reduce the amount of switch plasma pushed downstream toward the load. In addition, the placement of probes within the plasma injection region, instead of just at the edge of this region, should increase our ability to analyze early time switch behavior. This study was performed by S. S. Payne of MRC, under contract to SNL.⁵⁻¹⁷

Plasma Opening Switch Workshops

M. A. Sweeney

Two day-long workshops on POSs were held at SNL in January and August of 1989. Data from the experiments were reviewed and critiqued, and new theoretical analysis of switch physics were presented. The workshops included participants from 11 outside institutions, including Cornell University, LANL, Maxwell Laboratories, MRC, S-Cubed, the University of New Mexico (UNM), and NRL.

Major priorities identified by attendees at the first workshop were

- Measure voltage at the POS and load for MIP switches on PBFA II.
- Measure electron densities for the MIP source and the PBFA-II flashboards on a laboratory test stand with a microwave interferometer.
- Understand and control electron flow in switches.
- Add extra field components to simulation codes to model the MIP⁵⁻⁷ and CT⁵⁻⁸ switches.
- Demonstrate voltage gain on PBFA II.

Because of funding limitations, we decided that the two designs that use a MIP source would be emphasized in future experiments on PBFA II.

At the second workshop during 1989, progress was reported in meeting research priorities that were identified at the first workshop. The switch plasma is being characterized: Bruce Weber of NRL, with the assistance of Gary Mowrer of SNL, has measured the electron density of the MIP source on a laboratory test stand

using a 140 GHz microwave interferometer, spectroscopic analysis is being done on the test stand and on PBFA II by J. Bailey of SNL, and in-plasma Bdot probe data from several erosion switch shots are being analyzed by S. S. Payne of MRC. The measured electron density for the MIP source, which peaks at about $1 \times 10^{13}/\text{cm}^3$, is in rough agreement with a lower limit of $3 \times 10^{12}/\text{cm}^3$ measured earlier on the SuperMITE hardware by M. E. Savage of UNM and C. W. Mendel. An electron launcher probe has been developed by M. E. Savage and C. W. Mendel that can measure the time-resolved voltage at the switch location. Testing the modifications to improve performance of the MIP and CT switches is underway. These modifications include one-sided (upstream) injection of plasma from the MIP flashboards and a redesign of the central vacuum inductor stalk used with the CT switch. Additional theoretical modeling of these switches has been done by M. H. Frese of NumerEx and E. L. Lindman of MRC, and a study of MIP/ion diode coupling by M. Desjarlais of SNL has begun. An expanding inductor model is being developed by J. P. Quintenz and C. W. Mendel of SNL as a predictive tool to analyze PBFA-II data in circuit codes and is being tested against data from PBFA II and SuperMITE experiments. In addition, studies of the performance of these switches at long conduction times (300 ns) are under way on the MITE accelerator by H. N. Woodall.

At the second workshop, attendees identified two new major priorities:

- To investigate ways to couple accelerator energy to an ion diode while ensuring compatibility among the POS, the diode, and the MITL
- To investigate modifications to the MIP and CT switches to open the plasma gap more and reduce electron flow so that more current can be delivered to the ion diode.

A number of suggestions were made that may improve the switches and enhance our ability to analyze switch behavior. These ideas include

- Using an improved vacuum, perhaps by glow discharge cleaning of the surfaces
- Using a smaller cathode radius to better insulate the electron flow
- Decreasing the MIP source density while increasing the slow-field magnitude
- Interchanging the first and second cathode to reduce electron flow in the CT switch
- Using microwave interferometry and fluid simulations to assess proposed changes to the MIP source
- Taking visual framing photographs of the POS region during long conduction time experiments on SNL's MITE accelerator (as is being done by a Cornell graduate student, L. Adler⁵⁻¹⁸)

- Using in-plasma probes on PBFA-II experiments with the MIP and CT switches.

Some of these ideas were tried on PBFA II during the experimental series that began in mid-September and included testing of magnetically controlled switches at higher energy levels on PBFA II.

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Chapter 6. Advanced Driver Development

Overview

J. J. Ramirez

During this reporting period, our work on advanced drivers concentrated on issues relevant to the Laboratory Microfusion Facility (LMF) and to LIBRA, an inertial fusion reactor design developed by the University of Wisconsin and by KfK in Karlsruhe, Germany. The design concepts developed for both these applications require the generation, transport, and focusing of multiple ion beams delivered to the target. The LMF design concept uses 36 independent accelerator modules that deliver ~20 MJ of ion beam energy to a 2-cm-diameter pellet in ~15 ns. The individual beams are transported ~4 m to the pellet, located at the center of the target chamber. The individual ion beams are generated by extraction-geometry applied-B ion diodes. Power is fed to the ion diode by a high-voltage pulsed power generator based on the Hermes-III accelerator technology. The results reported here include experiments and analysis of various ion beam transport options being pursued for the LMF; this work was performed at NRL and at SNL. The LMF target chamber design has been pursued at the University of Wisconsin. These activities include computational and experimental research into damage to the first wall of the target chamber and analysis of the mechanical response of the chamber structure to the energy released by the fusion target. The University of Wisconsin has also been developing a design concept for an inertial fusion reactor that is driven by a light ion beam. A comprehensive report of the LIBRA project was prepared, and a summary of the results are presented here. Both LMF and LIBRA require the development of efficient extraction-geometry applied-B ion diodes that are powered by inductive voltage adder generators. We performed the initial experiments on the HELIA accelerator and results are discussed here. Hermes III, an electron beam accelerator, uses a 20-stage inductive voltage adder and operates with a negative-polarity inner conductor. The LMF and LIBRA drivers make use of the same inductive voltage adder design but operate in the opposite polarity. We performed experiments to investigate the performance of HELIA and Hermes III in positive polarity, and we discuss these results here.

Light Ion Beam Transport for LMF

C. L. Olson

For LMF, transport and focusing of high-current ion beams (~26 to 32 MeV Li, ~1 MA) over distances of several meters is required. During this time period, we made considerable progress on analysis of transport systems for LMF. The transport system must provide a length of about 4 m for axial bunching of the beam, a

standoff distance between the diode and the target, line-of-sight shadowing of the diode from the target to provide diode survivability, and focusing from a beam radius of 10 to 20 cm down to a target radius ≈ 1 cm. Three schemes that meet all four goals are being studied for LMF:

- Achromatic lens system
- Low-mass, wall-confined z-discharge channels
- Wire-guided transport

The baseline approach is the achromatic lens system, which we are studying at SNL. The backup approaches are low-mass channels and wire-guided transport; these are being studied in theory and experiments at NRL. The following section summarizes the work on the achromatic lens system. The next section discusses the work that was performed at NRL on low-mass channels and wire-guided transport.

The baseline achromatic system uses ballistic transport at a large radius from the diode (outer radius r_0) to a solenoidal lens, and then ballistic drift down to a target of radius r_p . The system consists of two lenses: an ion diode that acts as a self-field lens and a B_z solenoid lens.⁶⁻¹ In the diode, the self-magnetic field B_θ of the beam bends the ion trajectories. The region from the diode to the target is filled with a gas to provide charge and current neutralization. The beam drifts ballistically from the diode to the solenoidal lens with all trajectories about parallel to the z axis. In the B_z solenoid, the ions are focused toward the target. The ions then drift ballistically from the solenoid to the target.

The system is achromatic to first order in α for a diode with

$$V / V_0 = 1 + \alpha \quad (\alpha \ll 1) \tag{6-1}$$

$$I / I_0 = (V / V_0)^k \quad (k = \text{constant}) , \tag{6-2}$$

where V_0 and I_0 are the diode voltage and current at the start of the usable pulse, and typically $k \simeq 2.2$. As the voltage increases, the current increases, and the beam focuses more in the "diode lens." At the same time, the beam is magnetically stiffer, so it focuses less in the solenoid. The two effects can be tuned against each other so that the radial miss distance at the target is

$$\Delta r = -\alpha^2 (L / F) r_0 \tag{6-3}$$

where L is the distance from diode to lens, and F is the distance from lens to target. Because Δr has no term linear in α , the system is achromatic to lowest order in α .

We studied several aspects of this two-lens system with emphasis on analysis of the filamentation instability. We also compared the phase space acceptance areas of the lens system to the two backup systems.⁶⁻² Figures 6-1 to Figure 6-3 show the geometries for the three systems for these comparisons. In all cases, the coordinate θ_0 is in the plane of the figure, and ϕ_0 (representing angular momentum) is out of the plane. The radius r_1 is the actual trajectory exit radius at the target, r_c is the equivalent channel radius, and r_w is the wire radius.

Figure 6-1. Achromatic lens system.

Figure 6-2. Wire-guided transport.

Figure 6-3. Channel transport.

Complicated analytic expressions for the acceptance phase space boundaries on ϕ_0 were derived in terms of θ_0 , r_0 , and other parameters. As an example, the results are plotted in Figures 6-4 to 6-6 for the three cases. For the achromatic lens case (Figure 6-4), the acceptance in ϕ_0 , r_1 space is large. For the wire case (Figure 6-5a, b), the acceptance is restricted; a finite minimum value of ϕ_0 is required to give the particles enough angular momentum to miss the wire. The two cases correspond to trajectories starting at the outer edge of the diode (Figure 6-5a) and the inner edge of the diode (Figure 6-5b). For the channel case (Figures 6-6a, b) the acceptance area is again restricted, but does continue on down to $\phi_0 = 0$. (We used typical LMF parameters: 30-MeV Li^{+3} , $r_w = 0.05$ cm, $r_c = 0.7$ cm, $I_w = 50$ kA, and $I_c = 50$ kA.)

In real diode-transport configurations, there will be some angular momentum ($\phi_0 \neq 0$) created, such as by combinations of diode microdivergence, beam-steering errors, foil scattering, and gas scattering. Both the ballistic transport lens and the channel cases can accept $\phi_0 = 0$ beams (if they can be made) and can tolerate certain amounts of $\phi_0 \neq 0$. On the other hand, the wire case requires $\phi_0 \neq 0$ in a carefully prepared manner.

These results show that in regard to angular momentum, the baseline ballistic case is the most accepting transport scheme; the channel transport scheme is less accepting. The wire transport scheme is the least accepting because it requires a tailored nonzero ϕ_0 distribution to be fully accepted.

Figure 6-4. Achromatic lens acceptance region.

(a) For $\theta_0 = 0.1$ and $r_0 = 10$ cm.

Figure 6-5. Wire acceptance regions.

(b) For $\theta_0 = 0.05$ and $r_0 = 5 \text{ cm}$.

Figure 6-5. (continued)

(a) For $\theta_0 = 0.1$ and $r_0 = 10$ cm.

Figure 6-6. Channel acceptance regions.

(b) For $\theta_0 = 0.05$ and $r_0 = 5 \text{ cm}$.

Figure 6-6. (continued)

Low-Mass Channel and Wire-Guided Transport for LMF

P. F. Ottinger, D. D. Hinshelwood, J. M. Neri, S. J. Stephanakis, J. J. Watrous, and F. C. Young (NRL)

This year, we investigated in detail two techniques for transporting intense ion beams. Previous work^{6-3,6-4} on z-discharge transport was extended with particular emphasis on developing a low-mass channel appropriate for LMF. Earlier work demonstrated that wire-guided transport⁶⁻² is a viable scheme for transporting intense ion beams over few-meter distances. Both techniques are considered alternatives to the baseline approach of ballistic transport with solenoidal focusing.⁶⁻¹

We performed a detailed analysis of prompt- γ data from the $^{19}\text{F}_{(p,\gamma)}$ reaction from z-discharge ion beam transport experiments. Results show that energy losses observed during transport are attributable to classical stopping in the background fill gas of the channel. A new nuclear diagnostic⁶⁻⁵ using the $^7\text{Li}_{(p,\gamma)}^8\text{Be}$ reaction was also fielded to provide a more accurate measure of ion beam intensity. This reaction is much less sensitive to proton energy than the $^{19}\text{F}_{(p,\gamma)}$ reaction in the energy range provided by Gamble II. We have demonstrated the feasibility of this diagnostic, and it will be used in future experiments that measure transport efficiency.

We also devoted a great deal of effort to the problem of theoretically calculating the injection efficiency of a focused ion beam into either a z-discharge or wire-guided transport channel. We developed a general method for determining the injection efficiency and are now applying it to specific problems. For the case of z-discharge transport with a simple ion source and an arbitrary aperture radius, the injection efficiency can be calculated exactly. For the case of wire-guided transport, the efficiency cannot be calculated exactly and requires a numerical treatment. The outcome of this effort will be to provide a direct side-by-side comparison of injection efficiency for both transport schemes as well as a method for optimizing the ion source with respect to injection efficiency.

We have begun bench testing the low-mass z-discharge channels. The preliminary results are very promising. Meter-long discharges have been successfully fired using ~5-mil-thick Kapton tubes without punching through the Kapton. The thin Kapton tube was covered with copper tape and filled with 1 to 2 torr of air. Discharges were established and magnetic field measurements showed fairly uniform radial current distribution until near the peak current of 40 kA. We took two successful Gamble-II shots with channel lengths of 1 and 2 m.

In an actual LMF reactor, the z-discharge transport channel must be powered from the generator side instead of from the load side, as in previous experiments.

Higher-current discharges in higher-pressure gases may also be required. This means that high voltages (on the order of tens of kV) will be present at the channel input, which may result in breakdown to nearby grounded areas. The outer wall can be insulated and the 1-m separation (for focusing in an LMF system) between the diode and channel input may prevent breakdown between them. We carried out experiments that successfully demonstrated that this type of breakdown can be avoided. We also constructed improved hardware that allows easy variation of the channel length and clean measurement of the channel voltage and current. Future experiments using this hardware will be used to establish the channel breakdown electrical characteristics as a function of length and fill pressure.

We successfully completed a series of wire-guided ion beam transport experiments on Gamble II. We used both 1-m-long and 1.5-m-long, 1-mm-diameter wires in a 15-cm-radius chamber. Wire currents ranged between 15 and 30 kA. We used prompt- γ and shadowbox diagnostics to evaluate beam transport, and the results agreed well with theoretical predictions. We observed transport efficiency of about 70% or better.

We completed a comprehensive theoretical evaluation of wire-guided transport for LMF. We showed that ion beam injection efficiencies greater than 70% can be achieved with reasonable LMF values of wire current (20 to 80 kA), ion source current density (10 to 20 kA/cm²), and microdivergence (5 to 10 mrad). Theoretical results also indicate that time-of-flight bunching of the ion beam during transport will not be limited by velocity dispersion during transport. However, chaotic orbit behavior and ion losses due to the perturbing effects of a small number of return current wires must be avoided. Chaotic losses are greatest for three return-current wires. Figure 6-7 indicates that placing four return-current wires on a circle of radius greater than about 1.4 times the beam envelope radius will minimize this effect. In Figure 6-7, r_w is the radial location of the return-current wires, R_0 is the beam envelope radius, and R_r is the ratio of transport efficiency with the perturbing return-current wires at r_w to the efficiency with the wires moved to very large radius. Next year, we will perform experiments to confirm these theoretical results.

Positive-polarity insulator performance on Gamble II was improved significantly when Westinghouse coated a G5-type polyurethane insulator with Limitrak (a coating made by Westinghouse). Results show that the flashover limit in positive polarity has been increased to about 1.8 MV across the insulator. Operation is reliable, and we routinely obtain greater than 30-kJ ion beams. This insulator considerably outperforms the previous positive-polarity insulator without Limitrak, for which performance was not reliable, the flashover limit across the insulator was 1.5 MV, and the ion beam energy was only 10 to 15 kJ. This is particularly important for ion beam diagnostics that have strong voltage sensitivity, such as the prompt- γ diagnostic.

Figure 6-7. Variation of η_0/η_i with r_w/R_0 for four return-current wires with data shown for six different sets of LMF system parameters.

LMF Target Chamber Design

R. R. Peterson, R. L. Engelstad, J. W. Powers, H. Y. Khater, M. E. Sawan, E. G. Lovell, G. A. Moses, and J. S. Lipschultz (University of Wisconsin)

As part of the SNL light ion fusion program, the Fusion Technology Institute of the University of Wisconsin conducted research into issues related to a light-ion-beam-driven LMF. This work consisted of two major components and some minor efforts. The major components were

- Computational and experimental research into the damage to the first wall of the target chamber caused by the intense target-generated x-rays
- Computational study of the mechanical response of the target chamber structure to the microexplosion of the fusion target.

Other important parts of this work were calculations of neutron-induced radioactivity in the target chamber structure and the resulting biological dose rates and fragmentation of structures inside the target chamber caused by the target x-rays. All these are part of a long-term effort to design a target chamber that can

simultaneously meet the requirements imposed by light ion beam propagation and survive the effects of repeated microexplosions of fusion targets.

Figure 6-8 shows a picture of the current LMF target chamber design, and Table 6-1 lists the general parameters. The base case target chamber design is a 4.5-m-high, 1.5-m-radius, circular cylindrical shell that is capped with 1.5-m-radius hemispherical shells on both ends. The containment vessel is made of Al 5083 or 6061-T6 (which is 12.5 cm thick) to withstand the pressure loading from the target explosion. We selected this particular alloy to minimize the radiological dose rate near the target chamber a few days after the LMF has ceased operating. The inner surface of the Al is lined with 2 cm of woven graphite. This graphite provides protection for the Al from vaporization by the target x-rays and from the damaging shocks that result. For the purposes of this study, we assume that the target chamber is filled with 10 torr of He gas, although there are indications that the gas density should be reduced to 1 torr for proper beam propagation.

Figure 6-8. Overhead view of the light ion fusion LMF target chamber.

Table 6-1. LMF target chamber parameters.

Geometry	Hemispherically capped cylinder
Radius	1.5 m
Height of cylindrical walls	4.5 m
Total height	7.5 m
Wall material	Al 5083 or 6061-T6, 2 1/4 Cr-1 Mo Steel
Wall thickness	12.5 cm
Thermal liner material	4-D woven graphite
Thermal liner thickness	2 cm
Number of beam ports	36
Port diameters	36 cm
Fill gas	10-torr He

Propagation of the ion beam to the target is in a ballistic mode, with free electrons from the target chamber gas providing the current and charge neutralization necessary for ballistic transport. We prefer the ballistic transport mode over ion transport in plasma channels because of its relative simplicity and because it does not require additional structures inside the target chamber. The beam transport system carries the ion beams from ion diodes to the target. As seen in Figure 6-8, the diodes are placed 4 m from the target and the ion beams come off the diodes as unfocused annular beams that are focused on target by lens magnets. The lens magnets are placed 1.5 m from the target in order to focus a 6-mrad-divergence beam over an area of 1.5 m onto a 0.9-cm-radius spot (roughly the size of the target). The 1 to 10 torr of He target chamber gas provides the current and charge neutralization. The wall of the target chamber is placed in front of the lens magnets and, therefore, is (at most) 1.5 m from the target.

The pressure loading on the target chamber first wall consists of at least two components that are in effect over different periods of time. Initially, the wall experiences a very-high-pressure pulse, perhaps in the megabar range, that has a width of only tens of nanoseconds. This pulse is produced by the creation and blowoff of a vapor layer by the intense x-ray pulse from the target. A second pressure pulse is produced by the energy content of the vapor and the target chamber gas in the target chamber pressure vessel. This pressure pulse will typically reach a peak of several bars and lasts tens to hundreds of milliseconds. The two components have impulses that are comparable.

Preliminary calculations of the pressure impulse were performed with the CONRAD computer code. In these calculations, we assume that the x-rays from the target deposit instantaneously into the graphite liner. In these one-dimensional simulations, we assumed that the wall was a spherical surface of radius 1.5 m. We

used the x-ray spectrum that we expect to be radiated by a HIBALL-type target. We assumed that the target chamber gas was 10 torr of He, although there is very little absorption of the target x-rays by the chamber gas. These simulations used equation-of-state tables calculated by the IONMIX computer code. The unvaporized portion of the wall was treated as an immovable barrier. The peak pressure, the amount of mass vaporized, and the time-integrated impulse are plotted against total target yield in Figure 6-9. The peak pressure from the vaporization for a target yield of 1000 MJ was 0.75 Mbar; hence, launching of shocks into the material is definitely possible.

Figure 6-9. Peak pressure, vaporized mass, and impulse versus target yield for a 1.5-m-radius sphere.

In addition to the very short pressure spikes from vaporization, the target chamber gas imposes a lower-peak but very-long-duration residual pressure on the first wall. The residual pressure can have a very large effect on the mechanical response of the target chamber. Based on CONRAD simulations, 0.77 MPa is the best estimate for the residual pressure. We expect that the residual pressure on the wall will rise over a period of tens to hundreds of microseconds and remain significant until most of the vapor has recondensed, which may take hundreds of milliseconds. Because the history of the residual pressure is important to the structural response, this will be studied further with two-dimensional computer simulations that can account for the nonspherical target chamber. We will also investigate how changes in the chamber geometry and gas venting schemes might change the nature of the residual pressure and result in an improved target chamber design.

As previously noted, the proposed LMF target chamber consists of a capped cylindrical shell that is 1.5 m in radius and 4.5 m in height. For the actual surface area of this chamber, there are a relatively large number of beam ports of substantial size; see Figure 6-10. We performed an extensive analysis of the structural response of this chamber. The results of fatigue calculations were governed by the loadings of the 1000-MJ shots for both steel and Al, and the primary failure mode was yielding. The results of the fatigue calculations with steel show that the chamber can be built with a thickness of 2.4 cm or less. However, this is not recommended at this time because a thorough buckling analysis has not been completed. Therefore, we assume that the thickness of the chamber should be at least 3 cm.

Radius: 1.5 m
Length: 4.5 m
No. of Beam Ports: 36
Beam Port Radius: 18.0 cm

Figure 6-10. Proposed LMF chamber design.

We also studied neutron-induced radioactivity in the chamber walls. We performed one-dimensional analyses of the neutron transport, activation, and gamma ray transport in the LMF target chamber. We used the ONEDANT neutron transport code to calculate the propagation of neutrons from the target to the LMF target chamber structures. We have used the neutron spectrum that is predicted for the HIBALL target. Radioactivity induced in the structure is calculated with the DKR-ICF code; the dose rate is then calculated at a given position. Using ONEDANT to transport the gamma rays from the activated material to a given position, we then calculate the dose rate at that position. We have assumed that the average target yield is 200 MJ and that 500 targets are shot in a year. The pulsing scheme is two shots a day, separated by 6 hr, with 18 hr between the last shot of the day and the first shot of the next day. Operations continue in this manner five days/week for 50

weeks and then the facility is shut down for maintenance. We have gathered the results versus time for a 150-cm-radius target chamber made of three materials: Al 5083, Al 6061, and 2.25 Cr-1 Mo steel. For these calculations, we assume the Al walls to be 6 cm thick and the steel walls 3 cm thick. In all cases, the walls are lined with 1 cm of Boral and are surrounded by a 241-cm-thick borated water shield. One day after shutdown, the two Al alloys are the same and are much higher strength than the steel. After one week, all walls have the same dose rate. From one week to ten years, Al 5083 is much better than the other two materials.

Reentry into the target chamber area by maintenance personnel can only be performed after a cool-down period to reduce the dose rate to acceptable levels. If we operate for a year and use the dose rate at the outside surface of the chamber as a measure, the cool-down period is determined by the calculations presented in the previous section. The choice of an acceptable dose rate is very important in determining the cool-down period. If we use 2.5 mrem/hr as an acceptable dose rate and the wall is made of Al 5083, the cool-down period would be about two weeks. If instead we allow each worker to receive 1.25 rem in a 40-hr work week, then the cool-down period is reduced to slightly more than a week. There are also the questions of tritium and target debris; we assume that all such materials can be removed before reentry.

Saturn Experiments for LIF First Wall Materials

R. R. Peterson (University of Wisconsin)

The first surfaces in a light ion fusion (LIF) ICF target chamber are those that are in direct line-of-sight of the target and are most susceptible to the damaging effects of x-rays, debris ions, and shocks in the target chamber fill gas. The nature of the response depends upon the choice of fill gas and its pressure. If the pressure is less than about 0.01 torr, the x-rays and ions reach the first surface with little attenuation. The x-ray pulse is typically only 1 ns in duration, so the first surface material moves little during energy deposition. The x-rays generate a shock wave that moves through the ablated material toward the solid surface. This shock wave is very strong and has peak pressures on the vapor-solid interface of 100 GPa or more. This is clearly enough to launch a shock wave into the solid material.

Table 6-2 contains results of CONRAD radiation hydrodynamics simulations of this shock phenomena in some representative ICF target chamber designs. We have considered the same phenomenon in an experimental arrangement using the Saturn pulsed power x-ray source. Using a Ne gas puff, Saturn generates 100 kJ of x-rays in roughly 1-keV emission lines with a pulse width of 20 ns and 400 kJ of softer x-rays in a pulse of 100 ns. Table 6-2 shows the results of CONRAD simulations for samples of Al and graphite using the actual x-ray source data from Saturn.

Table 6-2. Computer simulations of ablatively driven shocks.

	LMF-LIF	LMF-LF	LIBRA-LITE	Saturn	Saturn
X-ray energy (MJ)	279	220	100	0.1	0.1
X-ray propagation distance (cm)	150	400	150	3.8	3.8
X-ray fluence (J/cm ²)	987	110	354	550	550
X-ray pulse width (ns)	1	1	1	20	20
X-ray power intensity (GW/cm ²)	987	110	354	28	28
Material	Graphite	Frost	Li	Al	Graphite
Peak pressure @ vapor-solid interface (GPa)	175	1.2	8.4	24	18
Impulse (Pa-s)	277	90	378	401	253

In Table 6-2, LMF-LIF⁶⁻⁶ is a target chamber design that uses light ion beams to drive the target to ignition. The first surface is a 1-cm-thick heat shield made of a four-directional, rigidized graphite weave. LMF-LF⁶⁻⁷ is a design using short-wavelength lasers to drive the target. A water frost layer is formed on the metal first surface to protect it from the target x-rays and ions. LIBRA-LITE, a light ion reactor design, fires at a rate of several times per second, so the solid surface cannot be allowed to ablate and cannot be manually reconditioned between shots. The first surface in the LIBRA-LITE target chamber is a film of liquid Li that is replenished between shots through a porous backing material.

The results presented in Table 6-2 show that impulses equal in magnitude to these ICF target chamber values can be obtained on Saturn. CONRAD simulations have shown that the peak pressure is a function of x-ray intensity, while the impulse is a function of the x-ray fluence.⁶⁻⁸ The spectral and temporal conditions in Saturn are not a perfect match to those predicted for ICF target chambers, but they are close enough for meaningful comparisons and validation of CONRAD simulations and to establish the existence of materials that are suitable for first wall protection.

A series of experiments like those suggested by the above computer simulations have been performed on Saturn for Al 6061 and for different types of graphite. These were uninstrumented experiments, so the only results are the pre- and post-exposure condition of the samples. Results of samples irradiated with Ne pinch x-rays are shown in Table 6-3. These indicate that all samples except 2 and 5 were destroyed. Sample 5, a two-directional woven graphite in a C matrix, K-Karb, was not damaged in the plane of the graphite fibers; but, these planes became delaminated. Sample 2, Al 6061 with a layer of alumina blasted on its surface, survived well except that the alumina was ablated. All the other samples were fine-grained graphites or graphites with short fibers. Sample 3, Graphnol, was a fine-grained graphite that fractured into six pieces; the others were turned into powder.

In a second series of experiments, several materials were exposed to Ar pinch x-rays. The three- and four-directional graphite weaves were an attempt to stop the delamination that we observed in the K-Karb. The Al samples were an extension of the previous experiments with alumina coatings. However, the C coating on the surface was felt to be easier to apply in situ between shots as a sacrificial layer in an LMF. The C carpet is a new idea for LMF target chamber wall protection.⁶⁻⁹ The results of these experiments are given in Table 6-4. The Al survived both with and without C coatings. The four-directional weave was successful in combating delamination and the same sample has been exposed to a total of four shots with no apparent damage. The three-directional weave suffered delamination. The graphite carpet was almost totally undamaged by the x-rays. The unfiltered two-directional weave was destroyed, but the filtered sample survived.

Table 6-3. Samples of LMF first wall materials irradiated on Saturn (neon gas puff source).

Sample no.	Shot no.	Material	Total x-ray energy fluence (J/cm ²)	<900 eV energy fluence (J/cm ²)	Pulse width (ns)	Result
1	658	Graphite H-451 fine grained	1900	440	21	destroyed powder
2	658	alumina-coated Al6061	1900	440	21	survived
3	664	Graphnol fine-grained graphite	1600	370	18	destroyed six pieces
4	665	Graphite A05 short random fibers in a C matrix	2200	510	13	destroyed nothing left
5	669	K-Karb two-dimensional woven graphite in a C matrix	3400	730	16	survived delaminated
6	669	Graphite CGW fine grained	3400	730	16	destroyed powder
7	669	Graphite AJT fine grained	3400	730	16	destroyed powder
8	669	Dunlop breakpad graphite fibers in a C matrix	3400	730	16	destroyed shredded

Table 6-4. Samples of LMF first wall materials irradiated on Saturn (argon gas puff source).

Sample no.	Shot no.	Material	Total x-ray energy fluence (J/cm ²)	<900 eV energy fluence (J/cm ²)	Pulse width (ns)	Result
1	736	Bare Al 6061	2204	242	16	survived
2	736	C-coated Al 6061	2204	242	16	survived
3	736	Stapleknit graphite	2204	242	16	survived delaminated
4	737	Four-directional woven graphite (FMI)	2039	209	16	survived
5	739	Three-dimensional random fiber graphite	2673	237	11	destroyed
6	737	A05 graphite fine grained	2039	209	16	survived
7	739	Two-dimensional woven graphite (unfiltered)	2673	237	11	destroyed
8	739	Two-dimensional woven graphite (filtered)	2673	237	11	survived
9	737	Graphite carpet	2039	209	16	survived

LIBRA—A Light Ion Beam Fusion Conceptual Design

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The light ion beam reactor (LIBRA) study is a self-consistent conceptual design of a 330-MWe power plant with an accompanying economic analysis. A comprehensive report summarizing all aspects of this study was completed during this time period.⁶⁻¹⁰

The LIBRA project began as a small study project in 1982. It was intermittently funded by the Kernforschungszentrum Karlsruhe (KfK) over the time period 1982 to 1988 to study critical issues. During that time, the technical work was performed by scientists at Fusion Power Associates (FPA), Pulsed Sciences, Inc. (PSI), and KfK. In 1989, the scoping studies were elevated to a preconceptual design phase by a combination project for SNL and KfK. The main effort was then directed through the University of Wisconsin with the participation of FPA, PSI, and SNL scientists.

The idea of this project is to develop a preconceptual deuterium-tritium (D-T) fusion reactor study to the point that one could make a technical, environmental, and economic comparison of LIBRA to previous magnetic fusion as well as inertial confinement fusion commercial reactor designs. This has been accomplished with reference to the current state of the art in physics and technology.

In the LIBRA reactor, fusion targets are imploded by 4-MJ shaped pulses of 30-MeV Li ions at a rate of 3 Hz. The target gain is 80, leading to a yield of 320 MJ. The high-intensity part of the ion pulse is delivered by 16 diodes through 16 separate z-pinch plasma channels formed in 100 torr of He with trace amounts of Li. The blanket is an array of porous, flexible SiC tubes that have $\text{Li}_{17}\text{Pb}_{83}$ flowing downward through them. These tubes (INPORT units) shield the target chamber wall from both neutron damage and the shock overpressure of the target explosion. The target chamber is "self-pumped" by the target-explosion-generated overpressure into a surge tank that is partially filled with $\text{Li}_{17}\text{Pb}_{83}$, which surrounds the target chamber. This scheme refreshes the chamber at the desired 3-Hz frequency without excessive pumping demands. The blanket multiplication is 1.2 and the tritium breeding ratio is 1.4. The direct capital cost of a 330-MWe LIBRA design is estimated to be \$2843/kWe, while a 1200-MWe LIBRA design will cost approximately \$1300/kWe. Table 6-5 shows specific design parameters. Figure 6-11 shows a schematic of the overall reactor design and Figure 6-12 shows a cross section of the reactor chamber.

This is not the ultimate or optimum reactor concept, but it is a very attractive low-power, low-capital cost option to large (>1000 MWe) fusion power reactor designs that have been published previously. Hopefully, LIBRA will be known as the first full-scale, self-consistent light ion beam fusion reactor design and will challenge other scientists around the world to develop even more advantageous concepts. It is possible that only in such a competitive atmosphere will we ever achieve the goal of providing a clean and inexhaustible energy source in the 21st century.

Table 6-5. LIBRA parameters.

General		Li ion beams	
Net electric power	331 MW	Energy	25 to 35 MeV
Gross electric power	441 MW	Number high power	16
Thermal power	1161 MW	low power	2
Recirculation power fraction	0.25	Peak power on target	400 TW
Driver efficiency	0.235	Pulse compression ratio	5
Target gain	80	Pulse length on target	9 ns
ηG	18.8	Current/channel	0.3 MA
Direct capital cost (1989)	\$2843/kW	Entering on target	1.1 MA
		Ion energy transport efficiency	0.63
Target performance		Laser-guided, freestanding channels	
D-T mass	3.2 mg	Length	5.4 m
Input energy	4 MJ	Radius	0.5 cm
Yield	320 MJ	Peak B-field	27 kG
X-ray yield	67 MJ	Peak current	100 kA
Neutron yield	217 MJ	Rise time	1 μ s
Charged particle yield	28.5 MJ	Voltage drop	1 MV
Endothermic loss	7 MJ		
Neutron multiplier	1.02		

(continued)

Table 6-5 (continued)

Applied-B diode		Cavity	
Anode source	Liquid Li	Gas pressure	100-torr He
Anode current density	5 kA/cm ²	Radius to first surface	3 m
Anode radius	8.4 cm	Pumping time	300 ms
Focal length	70 cm	Impulse in INPORTs	25 Pa-s
Microdivergence	5 mrad	Vaporized LiPb mass/shot	8 kg
Macrodivergence	120 mrad		
Conversion efficiency	0.80		
HELIA pulsed power		INPORT tube blanket	
Waterline energy	11.1 MJ	Tube material	SiC
No. of cells/module	26	Packing fraction	0.33
Voltage/cell	1.15 MV	Coolant/breeder	Li ₁₇ Pb ₈₃
Cell diameter	2.9 m	Li-6 enrichment	90%
Module diameter	5.15 m	Thickness	1.35 m
Module length	14.4 m	Energy multiplier	1.28
PFL output voltage	1.15 MV	Tritium breeding ratio	1.4
Impedance	3Ω		
Dielectric	water		
Switch type	metglas saturable reactor		
Tritium			
Inventory: target prep	680 g		
Reactor hall	174 g		
Effluent release	32 Ci /day

Figure 6-11. LIBRA reactor design.

Figure 6-12. Cross section of target chamber.

HELIA Applied-B Extraction Ion Diode Experiments

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To achieve pellet ignition and energy gain, the particle beam approach to ICF will require the transport and focusing of multiterawatt ion beams from multiple light ion drivers operated in extraction geometry. As a first step in a long-term program to develop high-power light-ion driver modules, we conducted a series of experiments to explore the coupling of the high-impedance ($20\text{-}\Omega$), four-stage HELIA linear induction accelerator to an applied-B ion diode in extraction geometry. This brief experimental series, consisting of 24 ion diode shots performed over a five-week period in July and August 1989, was intended to characterize the diode performance for a variety of insulating magnetic field geometries and ion source configurations in preparation for more detailed experiments to begin in February 1990.

Figure 6-13 shows a schematic of the 5-cm-mean-radius planar extraction ion diode. The diode was powered by HELIA, a four-stage linear induction accelerator^{6-11,6-12} that is operated in positive polarity at about 3.2 MV and 150 kA with a 30-ns FWHM power pulse. The output of the accelerator was close-coupled to the diode through a short, tapered MITL section. We attempted to accurately control the radial insulating magnetic field geometry using four anode and cathode field coils that were driven by individual 60-kJ capacitor banks. Magnetic field mapping was performed with a concentric array of large Bdot loops that were located at the anode surface and at the plane of the cathode tips. Magnetic field profiles were also calculated based on the measured field coil currents and experimental diode geometry using the ATHETA and TRIDIF codes. Electrical diagnostics included inductive cavity voltage monitors, Bdot loop current monitors in the cavities and the tapered MITL section, and single-loop Bdot ion current monitors ICO and ICI located at the outer and inner cathode tips, respectively. We estimated the diode voltage by inductively correcting the cavity monitor voltages to the diode position, and, on some shots, by measuring the time history of the proton beam energy with a filtered Faraday cup array. We are working on improved MITL and diode voltage diagnostics to permit more detailed studies of power coupling to the diode in the future. Ion beam diagnostics included witness plates, shadowboxes, carbon nuclear activation samples, Faraday cups, and a Thomson parabola. We measured time-integrated electron losses to the anode MITL using four-chlorostyrene radiochromic film detectors. We studied electron loss patterns to the anode emitting surface with a time-integrated x-ray pinhole camera.

Figure 6-13. HELIA positive-polarity applied-B extraction ion diode.

We performed a number of experiments to study accelerator-diode coupling. We varied both the critical insulating magnetic field (specified by the minimum insulating voltage V_{crit} across the anode emitting surface) and the insulating magnetic field geometry while maintaining a fixed A-K gap of about 8 mm for all experiments. The highest ion coupling efficiencies $I_{\text{ion}}/I_{\text{tot}}$ of 50% to 60% at peak ion power were obtained for a grooved epoxy flashover ion source with $V_{\text{crit}} < V_{\text{open circuit}}$ with the insulating magnetic field satisfying the uniform magnetic insulation condition for extraction geometry diodes⁶⁻¹³ to within better than 10% across the anode emitting surface and with the separatrix near midgap (Figure 6-14). We observed exceptionally short ion delays of 2 to 5 ns for this diode configuration. Therefore, direct losses from the extended MITL electron sheath to the anode emitting surface along applied-B-field lines may be important for this high-impedance diode. Lower ion coupling efficiencies of 30% to 50% were obtained with the separatrix very near or penetrating the anode surface. This field geometry may introduce electron losses along flux lines from a less insulated region of the cathode MITL to the anode.

Figure 6-14. Uniform insulation applied magnetic field profile with separatrix near midgap, calculated from measured field coil currents using TRIDIF.

We also performed several Li source experiments using a metal frit anode insert with a 2- to 6- μm -thick LiF coating as the ion source. A three-quarter power shot was taken with the anode highly insulated to a V_{crit} of 4.5 MV, approximately uniform magnetic insulation, and the separatrix near the anode. The LiF source turned on very slowly (42-ns ion delay), and the high diode impedance resulted in large current losses in the MITL and poor ion coupling efficiency (21%) at peak ion power. LiF shots at lower V_{crit} (2.5 and 3.6 MV), with approximately uniform magnetic insulation and the separatrix near midgap, had slightly better performance with an ion delay of 13 ns and ion coupling efficiency of 28%.

In these initial experiments, we have demonstrated that an extraction ion diode with an epoxy flashover proton source can be efficiently coupled to a high-impedance linear induction accelerator operated in positive polarity. Insulating magnetic field profiles can be accurately controlled using individual capacitor banks to drive each of the anode and cathode field coils. We can further improve ion coupling efficiency by more accurately approximating the uniform insulation condition over the full anode emitting surface. The rapid turn on of epoxy flashover anode sources suggests that electron losses from the MITL sheath current to the anode emitting surface along applied magnetic field lines may play an important role in the operation of this diode. Passive LiF ion sources have not yet exhibited diode impedance profiles that would permit efficient energy coupling to the HELIA ion diode.

Positive-Polarity Voltage Adder MITL Experiments on HELIA

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HELIA is a four-stage, 4-MV, 250-kA, 30-ns FWHM accelerator that was used as a proof-of-principle experiment for the 22-MV, 730-kA, 40-ns Hermes-III gamma ray simulator. In these electron beam accelerators, the currents from two or more pulse forming lines (PFLs) are added in high-power linear induction cavities. The cavity outputs are then added in an MITL. The MITL outer conductor is established by the cavity bores and has a constant diameter. The inner conductor is coaxial with the cavity bores and extends through the length of the cavities. It is reduced in diameter at the feed gap of each successive cavity to increase the MITL impedance. The impedance of each MITL section is set such that the current through each cavity is constant, and the voltage at any point through the system is derived from the sum of the preceding cavity voltages. Under normal operating conditions, the MITL is used with the inner conductor as the cathode stalk, and it is terminated with an electron beam diode load. The overall system, from the PFLs to the diode, has been

demonstrated to be between 87% and 100% efficient in negative polarity.⁶⁻¹⁶ Similar efficiencies have been demonstrated with the 16-TW, 20-stage Hermes-III accelerator.⁶⁻¹⁵

We are investigating the feasibility of applying this technology to an ion beam accelerator for the ICF program. We have also developed a conceptual design for an LMF that uses accelerator modules very similar to Hermes III.⁶⁻¹⁷ A key issue in these designs is the performance of the voltage adder MITL when operated in reversed polarity with the inner conductor positive.

HELIA has been reconfigured with the inner conductor as the positive electrode (anode) so that the voltage adder efficiency, component interaction, accelerator reliability, and MITL current flow in a positive-polarity system can be further investigated. The polarity reversal was accomplished by removing the inner conductor of the MITL and installing it from the opposite end of the system. This, in effect, grounds the negative end of the cavity system instead of the positive end. The energy storage, pulse-forming components, and cavities are operated in negative polarity as before. For these experiments, the accelerator was operated with two different MITL impedance configurations (with and without extension sections) that provide up to 14 ns of round-trip time isolation between the diode load and the adder section.

System Description

Figure 6-15 is a schematic drawing of the positive-polarity adder system. The diode A-K gap is adjustable from a short circuit to approximately a 7-cm spacing. Table 6-6 lists the free-space impedance at each cavity bore for the two MITL adder center conductors. These are the same conductors used in the negative-polarity configuration. The free-space impedance with conductor A was selected for "matched-impedance" MITL operation in negative polarity. This was accomplished by making the operating impedance of the n th MITL section approximately equal to nZ_o , where Z_o is the "source impedance" for each of the cavities. Conductor B was selected for "overmatched" operation.

MITL extension sections can be inserted between cavity 4 and the diode. In each case, these extension sections maintain the free-space impedance that was established at cavity 4. Also shown in Figure 6-15 are current monitor locations along the inner conductor of the MITL after each cavity gap feed. There are four monitors at each location, equally spaced on the circumference of the inner conductor. There are also current monitors located on the inner and outer conductors near the diode load. The MITL current monitors are made up of B-dot-current-loop pairs that are

Figure 6-15. Schematic of the positive-polarity adder system.

Table 6-6. Free-space impedance of the MITL adder sections.

Cavity #	Z, Conductor A (Ω)	Z, Conductor B (Ω)
1	7.2	10.1
2	12.4	17.6
3	17.2	24.8
4	22.0	31.9

contained within a common housing. The loops are rotated 180° so that one output is negative polarity and the other positive. The two loop outputs are routed to a Balun unit, where one signal input is inverted and then both inputs are added. This process cancels induced cable noise signals while preserving the current signal. This common mode rejection scheme has proven effective in measuring currents flowing within the MITL. Single-loop Bdot monitors and Vdot monitors located at each cavity vacuum insulator stack provide a measurement of the input power to the MITL adder.

System Performance

Figure 6-16 is a sample of current wave shapes that were measured at positions A1 through A4 in the adder section of HELIA when operated in positive polarity (see Figure 6-15). Current along the inner conductor is constant, and there is no current loss from the outer to inner conductor in the MITL adder section.

Figure 6-16. Current wave shapes measured along the inner conductor of the “overmatched” positive-polarity adder with a 3.8-cm A-K gap.

Figure 6-17 shows a sample of time-correlated voltage and current waveforms. The voltage waveform is the algebraic sum of the voltages measured at each of the four cavity vacuum tube insulators. The current pulse was total current measured by a Bdot monitor in the inner conductor of the adder section.

Figure 6-17. Time-correlated comparison of the summed cavity voltage and the total current flowing in the system.

Figure 6-18 is a plot of several shots showing current flow along the cathode and anode within the system. Figure 6-18a is a plot of boundary current flowing in the adder section of the MITL as measured at positions IC1 through IC4 and boundary current downstream of the adder section at position C5 (see Figure 6-15). The difference between current measured at position IC4 and the total current flowing in the system is sheath current within the adder section. Sheath current electrons are emitted from the surfaces of the cavity bores. The kinetic energy obtained by electrons in the sheath when they are accelerated to the anode depends on the potential at which they are emitted. The data plotted were obtained with diode A-K gaps ranging from 2.8 to 6.8 cm. As can be seen, the measured boundary current decreases gradually in successive cavities. This decrease of about 10% to 15% of the total current is sheath electrons that are flowing within the adder section. Because these sheath electrons are not emitted at full potential, they may be

considered a loss current to an ion diode load. Because they would have an average energy corresponding to half of the full voltage potential, these electrons would represent a power loss of less than 10%.

Figure 6-18a also shows a marked decrease in boundary current measured at position C5 downstream of cavity 4. This decrease becomes more significant with large diode A-K gaps. Boundary current is 30% of total current with a 6.8-cm A-K gap, compared to 78% of total current with a 2.8-cm A-K gap. Because of the proximity of the diode load and its configuration, this decrease is more sensitive to diode A-K variations than in the case where an MITL extension is used. Decreasing boundary current in the MITL just beyond the final cavity is more readily defined in the Hermes-III positive-polarity experiment because of the transit time isolation between the adder section and the diode load. Sheath current contributed after the last cavity is at full potential and does not necessarily represent a loss if those electrons can be retrapped or coupled to an ion diode (or both).

Figure 6-18b is a plot of anode currents measured through the system along the inner conductor. For A-K gaps ≤ 3.8 cm, the current is approximately constant. With the 6.8-cm spacing, a reduced current is seen at positions A4 and A5. For the larger gaps, this may be an increased system loss or electrons may again be bypassing these monitor locations.

In the absence of loss between the third and fourth cavity feed gaps, the difference between currents measured at IC4 and C5 is sheath current caused by the electrons emitted downstream of the fourth feed gap. Figure 6-19 shows a comparison of these measured currents. Figure 6-20 shows a voltage calculation done for a shot in which the A-K gap was set at 3.8 cm. The voltage can be calculated⁶⁻¹⁷ from these currents in the same manner that is appropriate for a single-cathode MITL. This calculated peak voltage of approximately 2.7 MV agrees with peak voltage measured with filtered CR-39 nuclear track recording film.⁶⁻¹⁸

(a)

(b)

Figure 6-18. Plot of measured currents with the "overmatched" adder in positive polarity: (a) boundary current and (b) anode current.

Figure 6-19. Current waveforms measured at positions IC4 and C5.

Figure 6-20. Calculated voltage using IC4 and C5 current waveforms with the "overmatched" MITL and a 3.8-cm A-K gap.

Figure 6-21 is a comparison of the operating impedance between positive and negative polarity with the "overmatched" MITL. The data plotted were taken without an MITL extension, but data acquired with a 1-m extension indicate little difference, except that the curve shifts approximately 0.5 cm to the left. It has been shown that, in negative polarity, the ramped portion of the plots represent the load-dominated region and the plateau sections are established by the MITL operating impedance.⁶⁻¹⁹ The data presented here were calculated using the ratio of the algebraic sum of the four cavity voltages and the total current and are plotted as a function of A-K gap. Filtered CR-39 packs were also used to record the peak voltage on several shots. Peak voltages recorded by the CR-39 agreed with summed voltages that were corrected for time coincidence with the total current pulse, when the A-K gap was ≥ 3.8 cm. When smaller gaps were used, the summed voltage and CR-39 measured voltage no longer agreed, and the CR-39 voltage was substantially lower.

Figure 6-21. Comparison of positive- and negative-polarity operation using the "overmatched" MITL adder.

These data indicate that the system appears to be matched in positive polarity by a smaller load impedance as compared to negative polarity. Thus, at a given equilibrium voltage, the system operates with a higher total current in positive polarity because of increased electron flow. In the case of the "matched-impedance"

adder, a gap of approximately 3.8 cm provides a nearly matched load to the positive MITL adder. For the negative "matched-impedance" adder, a gap of about 6 cm provides an equivalent match. The ratio of the positive to negative A-K gap is about 0.64%. This ratio agrees with the ratio of the operating MITL impedance that was calculated, assuming minimum-current, single-cathode, and self-limited MITL flow⁶⁻¹⁷ and a full-gap MITL flow, where the electron sheath extends across the entire gap.

Conclusions

The experiment has shown that HELIA can be 85% to 95% efficient in current transport through the positive-polarity adder and that overall system reliability is not adversely affected by the polarity reversal. The system behavior, as demonstrated by the data presented here, is essentially the same in positive polarity as it is in negative polarity. Because of the decrease in measured current flowing through each successive cavity and given a constant total current, the sheath current after each cavity feed gap is correspondingly increasing. The decreasing current flow in the cavities translates to an increase in voltage within those cavities. This voltage increase is more significant in larger facilities and can be seen in the reversed-polarity experiment on Hermes III.

HERMES-III Positive-Polarity Experiment

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Hermes III^{6-15,6-20} is a 22-MV, 730-kA, 40-ns electron beam linear induction accelerator with an MITL adder to produce bremsstrahlung radiation. The technology employed in Hermes III is the basis for a conceptual design of a light ion beam driver⁶⁻¹⁶ for an LMF. As an ion accelerator, the MITL must operate with the center conductor positive with respect to the outer conductor. Hermes III was operated in a positive-polarity configuration to provide information on the operation of the adder and on its interaction with the linear induction cavities. The positive configuration could also provide a test bed for ion beam generation, focusing, and transport experiments at a future date. To accomplish the polarity reversal, the MITL was removed, the 20 cavities were rotated 180°, and the MITL was reinserted through the cavities. The Marx generators and pulse-forming networks were operated in negative polarity as before. Two diode configurations were used: an inverse electron beam diode and a pinched-beam ion diode. The ion diode was used to accelerate protons and Li ions.

Experimental Description

Figure 6-22 shows a cross-sectional view of the Hermes-III cavity adder and MITL. Monitors are located at each of the cavity spools within the adder (positions 1 to 4) and along the extension MITL (positions 5 to 9). The adder portion is 12.6 m long with a 6-m MITL extension terminated by the diode. Voltage is applied to the MITL at each of the cavities. Figure 6-23 is a drawing of the electron beam diode used for most of the shots. Figure 6-24 is a drawing of the pinched-beam ion diode. Current measurements were made at each cavity and on the inner and outer conductors at each spool location and on the extension MITL. Peak voltage measurements were made at each cavity. Peak output voltages were determined from range measurements in filtered CR-39 nuclear-track-recording film detectors.⁶⁻¹⁸

Figure 6-22. Cross section of the Hermes-III cavity adder and MITL.

Figure 6-23. Electron beam diode.

Figure 6-24. Ion diode.

The total machine current is carried on the center conductor of the MITL adder, the boundary current flows on the outer conductor, and a sheath current flows between the inner and outer conductors. Electrons flowing in the sheath current have varying kinetic energies, which are determined by the potential difference between the anode and the cavity from which they are emitted. These sheath current electrons represent an energy loss if they are not recaptured at the surface from which they were emitted.

Because the sheath current increases down the length of the adder section, the boundary current decreases in a corresponding manner. Within the adder section, the cavity current is the same as the boundary current. The cavity current is inversely proportional to the load impedance for the cavities. Therefore, the load impedance for each cavity must increase down the length of the adder; the cavity output voltage would then also increase down the length of the adder. Table 6-7 shows the results of a simplified model of the Hermes-III adder section, where the sheath current was assumed to increase linearly from 0% to 30% of the total current along the length of the adder.

The sheath power is the sheath current at a cavity times the voltage at that location in the MITL (power that would be lost if these electrons were accelerated to the anode), and the available power is the power capable of being delivered to a matched-impedance load. The efficiency is the power from the cavities minus the sheath power divided by the total available power. This is a greater efficiency than would be obtained if a 30% current loss at full voltage were assumed.

Experimental Results

For the experiment, Hermes III was operated at three levels: at half-voltage for 19 shots, full voltage for 5 shots, and approximately 80% voltage for 26 shots. At each level, the total current along the inner conductor of the MITL adder remained constant within measurement accuracy; hence, negligible loss of sheath current occurs. The boundary current decreased to 60% to 70% of the total current at the end of the adder. This fraction was the same for the three operating levels. In the extension MITL, there was a marked decrease in the boundary current and the magnitude of this drop in boundary current was a function of the operating level. Figure 6-25 is a normalized plot of the measured peak currents for the full- and half-operating points with the electron beam load. Peak total current for each of the two cases is 820 kA and 390 kA, respectively. The boundary current within the adder decreases nearly linearly to ~65% of the total current and is the same for the two operating levels. However, the fraction of boundary current in the extension MITL depends on the operating voltage.

Table 6-7. Calculated voltages, current, and power for a Hermes-III cavity adder with a sheath current assumed to increase linearly from 0% to 30% of the total current.

Cavity #	Cavity V (MV)	Cavity I (MA)	Cavity P (TW)	Sum V (MV)	Sheath P (TW)
1	0.950	0.760	0.722	0.950	0.011
2	0.965	0.748	0.722	1.915	0.023
3	0.980	0.736	0.721	2.895	0.035
4	0.995	0.724	0.720	3.890	0.047
5	1.010	0.712	0.719	4.900	0.059
6	1.025	0.700	0.717	5.925	0.071
7	1.040	0.688	0.716	6.965	0.084
8	1.055	0.676	0.713	8.020	0.096
9	1.070	0.664	0.710	9.090	0.109
10	1.085	0.652	0.707	10.175	0.122
11	1.100	0.640	0.704	11.275	0.135
12	1.115	0.628	0.700	12.390	0.149
13	1.130	0.616	0.696	13.520	0.162
14	1.145	0.604	0.692	14.665	0.176
15	1.160	0.592	0.687	15.825	0.190
16	1.175	0.580	0.682	17.000	0.204
17	1.190	0.568	0.676	18.190	0.218
18	1.205	0.556	0.670	19.395	0.233
19	1.220	0.544	0.664	20.615	0.247
20	1.235	0.532	0.657	21.850	0.000
Available power		14.44 TW			
Total sheath power		2.37 TW			
Power from cavities		14.00 TW			
New power		11.63 TW			

Efficiency = 80.5%

Figure 6-25. Normalized total and boundary currents for high-voltage (squares) and low-voltage (triangles) shots. Position 5 is just beyond the adder. The cavity currents (circles) match the boundary currents in the adder section.

For two shots, a 10-cm x 10-cm nylon mesh screen was placed on the anode surface at two points on the electron beam diode. CR-39 range detectors were placed opposite these locations on the cathode surface (see Figure 6-23). The screen serves as a source of protons when it is struck by electrons. These protons are then accelerated across the A-K gap. For the 90% operating point, the CR-39 indicated 12-MeV protons at Position 1 and 18-MeV protons at Position 2 on the same shot. The CR-39 detector at Position 1 may have been located such that protons greater than 12 MeV missed the detector because of magnetic sweeping.

Six shots were taken with the pinched-beam ion diode shown in Figure 6-24, four with a nylon mesh proton source and two with a LiF-coated stainless steel Li source. Energetic Li ions were measured by activation and neutron times-of-flight (TOFs) and by nuclear threshold techniques. The activation and neutron TOFs require neutrons produced by the $d(^7\text{Li},n)$ reaction. Li ions strike a thick, deuterated C target, CD_2 . The energy of the neutrons produced is ≥ 14 MeV. In the activation method, the neutrons strike a Cu slug of known weight, such that the reaction $^{63}\text{Cu}(n,2n)$ produces ^{62}Cu that decays by β^+ ($\tau_{1/2} = 9.74$ min). By measuring the activity (counts/min, cpm) and comparing this value with a calibrated yield (cpm/gm of Cu per Li ion), the number of Li ions striking the detector can be estimated.

We estimated that a minimum of 10 kJ of Li ions were produced on the two Li shots. Confirmation that Li ions produced the neutrons is seen in the 14 MeV neutron spectra from a TOF detector placed 15 m from the source. Because of saturation problems at the detector from bremsstrahlung radiation, it was not possible to determine the peak Li voltages. An activation threshold technique also confirmed the production of Li ions. The reaction was $p(^7\text{Li},n)^7\text{Be}$, which has a threshold of 13.5 MeV. After each shot, the activated CH_2 target sample was placed near a NaI detector to allow observation of the 478-keV gamma rays emitted from the decay of Be. The measurements confirmed Li beams with energies ≥ 13.5 MeV.

Current measurements from the ion-diode Bdot monitor, shown in Figure 6-24, indicated a peak current of 90 kA for a proton shot and 73 kA for a Li shot. These measurements are a lower bound to the ion current because the Bdot monitor will measure net current. The Li ions produced in the A-K gap should be singly ionized and the current should be reduced from the proton case by a factor of 2.65, the square root of the ion mass ratio. However, when the ions pass through 13- μm -thick aluminized Mylar cathode foil, they are stripped of electrons and become triply ionized, thus increasing this current by a factor of 3. Activation of the stainless-steel witness plate was evident with the proton shots, but little activation was seen on the Li shots, indicating little proton current was present.

Theory and Numerical Simulation

Some basic issues concerning magnetically insulated flow in the positive-polarity Hermes-III accelerator have been addressed by simple physical models using the electromagnetic, relativistic PIC code MAGIC.⁶⁻²¹ These issues relate primarily to the consequences of multiple-cathode electron emission in MITLs. The noteworthy feature of positive-polarity operation (in which the outer electrode is the cathode) is that the 20 radial power feeds of Hermes III divide the cathode surface into 20 separate sections. Hence, the electron flow at the end of the MITL is populated by what can be considered as 20 distinct classes of electrons. Each class is defined by the potential difference between the anode and the cathode from which its members were emitted. In negative polarity, there is only one class of electrons because all electrons are emitted from the same cathode, the uninterrupted inner conductor of the coaxial line.

Because each successive class of electrons is emitted with a different set of canonical momenta and total energies, consideration of the allowed momentum-energy values for electrons in the flow⁶⁻²² in the final MITL shows that the electrons injected into the flow from the various adder section cathodes must necessarily travel very close to the extension MITL anode.

Figure 6-26 shows electron trajectory maps from a MAGIC simulation at 22 ns into the pulse. At this time, the flat top of the input voltage has been reached at each of the feeds and the system is still line dominated. The maps compare the spatial distribution of electrons that were emitted from all the adder section cathodes (Figure 6-26a) with that of the electrons that were emitted from the cathode of the final MITL (Figure 6-26b). We call the flow that is created by the electrons emitted from the final MITL cathode insulated indigenous flow (IIF). The electrons injected into the final MITL from the adder fill in the gap between the IIF and the MITL anode. The injected flow, together with the IIF, form what we call full-gap flow (FGF). A simple prescription exists for the calculation of line voltage from the final MITL total (anode) and boundary (cathode) current waveforms based on FGF. There is some radial mixing of electron classes in the final MITL flow, but describing the flow as radially layered is reasonably appropriate and allows us to calculate the line voltage from the IIF as well.

The variation of simulated anode and cathode currents with axial position in Figure 6-27 shows how the portion of the total current carried by the electrons, $I_{\text{total}} - I_{\text{boundary}}$, increases with an increasing number of electron classes in the flow. Figure 6-28 shows how the percentage of the total current $[100 (1 - I_c/I_A)]$ carried by the electron flow increases with position for Hermes-III Shot 619 (a full-voltage shot) and for the corresponding MAGIC simulation. The percentage of electron flow that is calculated from the simulated voltages and anode currents using the FGF model is also included for comparison. The FGF description is expected to be valid beginning axially at monitor position 4, Figure 6-28.

When the FGF model is valid, the MITL voltage can be calculated from the line currents by the expression

$$V = (Z_0/2) (I_A^2 - I_C^2)^{1/2}, \quad (6-4)$$

where I_A and I_C are the anode and cathode currents, respectively. This equation is based on pressure balance and assumes that the flow extends across the whole gap and that the electron density profile of this flow is radially uniform. The uniform density assumption is not restrictive, because the voltage is insensitive to the density profile. The FGF voltage expression underestimates the voltage when the flow does not extend across the whole gap.

(a)

(b)

Figure 6-26. Electron trajectory maps from MAGIC at 22 ns into the full-voltage Hermes-III simulation show the contrast between the injected flow and the IIF of the final MITL. Both flows are present in the simulation and together make up the FGF.

Figure 6-27. Plot of midpulse total and boundary currents versus axial position from the full-voltage Hermes-III simulation. The location numbers correspond to those of the experiment (see Figure 6-5).

Figure 6-28. Comparison of full-voltage Hermes-III electron flow currents as a percentage of the total current from computer simulation, Shot 619, and FGF model.

The single-cathode MITL voltage-current relationship based on pressure balance is 6-17, 6-23, 6-24

$$V = Z_0(I_A^2 - I_C^2)^{1/2} - (mc^2 / 2e)(I_A^2 / I_C^2 - 1) . \quad (6-5)$$

This expression can be applied to the multiple-cathode positive-polarity Hermes III if a modified I_A is used. This modified anode current includes only the IIF and therefore is given by the full anode current downstream of the last radial feed less the flow current just upstream of the last feed. Both the experiment and the simulations indicate that there is insignificant loss along the system, so the modified anode current becomes the cathode current just upstream of the last radial feed. The IIF and FGF calculated voltages for Hermes-III Shot 619 are presented in Figure 6-29. The agreement indicates that both the IIF and the FGF assumptions are correct if the current measurements are accurate. The 16-MV peak is about 20% less than what would be expected from extrapolating the range-filtered CR-39 measurements made on lower-voltage shots.

Conclusions

We measured efficient current transport in the positive-polarity MITL adder experiment. High-energy ions were detected, indicating that the high-voltage pulse was transported efficiently to the end of the extension MITL. We will further investigate the interaction between the MITL adder and the induction cavities.

Theoretical considerations pertaining to multiple-cathode MITLs and comparison of numerical simulations and Hermes-III current measurements indicate that electron flow, on the average, occupies the entire A-K gap of the final MITL of Hermes III operated in positive polarity. FGF occurs even though the transfer of anode current from beginning to end of the accelerator is nearly 100% efficient. We are presently investigating the implications of FGF for coupling energy to an applied-B ion diode.

Figure 6-29. Comparison of calculated voltages for Hermes-III Shot 619. The IIF voltage was calculated from cathode currents just upstream and downstream of the 20th feed; the FGF was calculated from the anode and cathode currents just downstream of the 20th feed.

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APPENDIX. 1989 Presentations and Publications by Topic and by Author

Topical Index, Arranged Chronologically

Reviews

J. P. VanDevender, "Light Ion Driven ICF," American Association for Advancement of Science Annual Meeting, San Francisco, CA, January 14-19, 1989 (invited talk).

J. P. Quintenz, J. E. Bailey, K. W. Bieg, D. D. Bloomquist, D. L. Cook, J. T. Crow, R. S. Coats, M. S. Derzon, M. P. Desjarlais, P. L. Dreike, R. A. Gerber, T. W. Hussey, D. J. Johnson, W. A. Johnson, R. P. Kensek, G. W. Kuswa, J. R. Lee, R. J. Leeper, T. R. Lockner, J. E. Maenchen, D. H. McDaniel, P. F. McKay, T. A. Mehlhorn, C. W. Mendel, Jr., L. P. Mix, E. L. Neau, C. L. Olson, T. D. Pointon, A. L. Pregonzer, T. J. Renk, G. E. Rochau, S. E. Rosenthal, C. L. Ruiz, L. X. Schneider, S. A. Slutz, R. W. Stinnett, W. A. Stygar, M. A. Sweeney, G. C. Tisone, B. N. Turman, J. P. VanDevender, J. R. Woodworth, "Status of the PBFA-II Light Ion Beam Fusion Program," Particle Accelerator Conference, Chicago, IL, March 20-23, 1989 (invited talk).

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