SAND80-0974
Unlimited Release
UC-21

Particle-Beam-Fusion Progress Report July 1979 Through December 1979

**Directorate of Pulsed Energy Programs 4200
Sandia National Laboratories
Albuquerque, New Mexico 87185**

Prepared by Sandia National Laboratories, Albuquerque, New Mexico 87185
and Livermore, California 94550 for the United States Department
of Energy under Contract DE-ACO4-76DPO0789

Printed January 1981

Sandia National Laboratories

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

NOTICE: This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government, any agency thereof or any of their contractors or subcontractors. The views and opinions expressed herein do not necessarily state or reflect those of the United States Government, any agency thereof or any of their contractors or subcontractors.

Printed in the United States of America

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

NTIS price codes

Printed copy: \$11.00

Microfiche copy: A01

Dr. 2594

Sandia Laboratories

Albuquerque, New Mexico
Livermore, California

date: March 25, 1981

to: Distribution

K. J. Willis

from: K. J. Willis - 3152

MASTER

subject: SAND80-0974, Particle-Beam-Fusion Progress Report July 1979
Through December 1979, Sandia National Laboratories, Albuquerque,
New Mexico

Attached is a replacement copy of the referenced document.

Please destroy the copy of this report which you received in mid-February.

KJW:jb

Attach.

*No record of having
received SAND-80-0974 previously
Reg.*

THIS PAGE
WAS INTENTIONALLY
LEFT BLANK

SAND80-0974
Unlimited Release
Printed January 1981

Distribution
Category UC-21

Particle-Beam-Fusion Progress Report July 1979 Through December 1979

Directorate of Pulsed Energy Programs 4200
Sandia National Laboratories
Albuquerque, New Mexico 87185

Contents

Introduction	9
Chapter 1. Fusion Target Studies.....	13
Continuing Studies of Ion Energy Deposition in Partially Ionized Material	13
Initial Study of the Ramifications of Ion Range Variation on the Efficiency of Hydrodynamic Implosions.....	14
Revised Calculations of Central Igniter Magnetic Targets.....	15
References.....	16
Chapter 2. Target Experiments.....	17
Overview	17
Investigation of Shell Stability in Cylindrical Targets.....	17
Experiment Investigation	17
Analysis of Data From the Experiments	20
Numerical Investigation.....	21
Two-Frame Radiography System	22
Five-Frame Proximity Focus Camera.....	24
Neutron Detector Development.....	24
Target Fabrication.....	26
References.....	30
Chapter 3. Particle-Beam Source Development.....	31
Overview	31
Diode Physics and Focusing.....	32
Proto I Ion Beam Extraction Diode Simulations.....	32
Numerical Simulation of the SMAUG Ion Diode	35
Diode Code Development.....	37
TRIDIF, A Triangular Mesh Magnetic Diffusion Code	38
Beam Propagation.....	40
Multichannel Proton Beam Overlap Studies.....	40
Ion-Charge Exchange and Energy Loss in Plasma Channels	41
Calculated Electron Deposition Levels Sufficient to Drive ICF Targets.....	42
Pulsed Power Development	44
Equivalent Circuit Modeling of Asymmetry Effects in Magnetically Insulated Transmission Lines.....	44
Effects of Nonsimultaneity on the Central Convolute for PBFA-I	45
Modeling of Nonsimultaneity Effects on Imploding Liners Driven by Proto II.....	47
Simulation of Radiation Losses in the MITE High-Voltage Experiment.....	47
The Motion of Single Electrons in Inductive Fields.....	49
Linear Accelerators and Laser Drivers.....	51
Particle Simulations of Pulselac B Gap	51
Numerical Simulation of Charge Neutralization in Charged Particle Beams Propagating in Vacuum	52
Generation and Propagation of Large Area E-Beams	56
References.....	60

Contents (Cont)

Chapter 4. Particle Beam Experiments.....	61
Overview	61
Radial Ion Diode.....	61
Extraction Diode	63
Ampfion Diode (Automagnetic Plasma-Filled Ion Diode)	64
Propagation of Light Ions in a Plasma Channel	65
Laser Heating of a Molecular Gas Channel	67
Plasma Source Development	70
Spherical Electron-to-Ion Converter	72
Pulselac Program.....	72
Overlap of Charged Particle Beams.....	74
Review Paper on Intense Ion Beam Physics and Technology	79
References.....	79
Chapter 5. Pulsed Power.....	81
Overview	81
PBFA I	82
PBFA I Assembly and Test.....	82
Effect of Module Jitter on Output Power.....	83
Sensitivity of Output Power to Gas-Switch Timing	83
Positive-Polarity Power Transport in the HydraMITE Power- Flow Lines	84
Magnetically Self-Insulated Output Convolute.....	85
Magnetically Self-Insulated Coaxial to Triaxial Convolute (CTC)	87
PBFA II.....	89
SuperMITE.....	89
Gas Switch Program	90
Preliminary X-Ray Triggering Studies of SF ₆ Insulated Gaps.....	90
Voltage Addition With Parallel-Plate Lines.....	92
Superfast, High-Energy Density Pinches	92
Foil-Initiation Studies	93
Diagnostics.....	94
Results	94
Proto II Optimization at 11 TW.....	96
Magnetically Self-Insulated Ion Diode	96
Quasi-Planar, Magnetically Self-Insulated Ion Diode Experiment.....	96
Theory for Magnetically Self-Insulated Focusing Diode	97
Application to Current Particle Beam Fusion Accelerators	97
Advanced Pulsed-Power Studies	100
INTREPID--Fast Opening, High-Current Switch	100
Nanosecond Surface Flashover Studies in Vacuum.....	101
References.....	102

Contents (Cont)

Chapter 6. Pulsed Power Applications	103
Overview	103
Reactor System Studies	104
Pellet Injection, Tracking, and Targeting	104
Beam-Aiming Method	104
Beam Incidence and Timing	105
Pulse Repetition Rate and Reactor Power Level	106
Pellet Lifetime in Reactor Cavity	106
Effects of Hydrodynamic Motion on the Pellet Trajectory	106
Example of Pellet-Injection Parameter Values and Velocity Limits	107
Summary of Pellet-Injection, Tracking, and Targeting Investigation	107
Thermal Transport in a Reactor Chamber Filled With an Inert Gas	108
Impulse and Overpressure on PBFA Pellet Chamber	109
First Wall-Design Study	109
ETF Scoping Study	111
Laser-Channel Study	113
Target-Development Facility Design Study	113
Repetitive Pulse-Power Development	113
Pulse-Power Development Plan for Inertial Confinement Fusion	113
1.5-MV Resonant Transformer System	114
Oil Breakdown Tests	115
Spark Gap for Plus/Minus Capacitor Banks	116
Repetitively Pulsed Marx Generator Development	117
Repetitively Pulsed Electron-Beam Diode	117
Electron Beam Sources for Gas Lasers	122
Plasma-Injected Microsecond Diode Studies	122
RAYITO	124
Pulse-Power Consideration for High-Energy KrF Lasers	125
References	128
Chapter 7. Electron-Beam Fusion-Accelerator Project	129
PBFA I Project	129
Overview	129
Tank Structure	133
Energy Storage Section (Installation)	133
Energy Storage and Dummy Load System	133
Marx Charging System	134
Marx Firing System	135
Energy-Storage Section (Pulsed-Power Tests)	135
Charging System	136
Firing System	137
Energy Storage System Tests	137

Contents (Cont)

Pulse Forming Section.....	137
Intermediate-Storage Capacitors.....	137
Gas Switches.....	137
Pulse-Forming Lines.....	137
Pulse-Transforming Line.....	137
Gas Switch Trigger System.....	137
Power Flow/Front End Section.....	138
Accelerator Support Systems.....	138
Vacuum System.....	138
Insulating Gas Systems.....	138
Deionized Water System.....	138
PBFA Data Acquisition System.....	138
Cable Plant.....	138
Data-Recording Equipment.....	140
Software.....	140
Control/Monitor System.....	141
PBFA II Project.....	142
Overview.....	142
SuperMITE.....	142
Presentations.....	145
Invention Disclosure.....	146
Publications.....	147

Particle Beam Fusion Progress Report

July 1979 Through December 1979

Introduction

Sandia's Particle Beam Research Program is oriented toward providing proof of principle for inertial confinement fusion using technology that is useful for both military and civilian objectives. The following technical and management abstracts represent highlights from this reporting period. More detailed overviews of topics precede each chapter.

The major current activity is focused on completing the 30-TW Particle Beam Fusion Accelerator (PBFA-I) and defining the design for the upgrade of this machine (PBFA-II); this upgrade will provide 1 MJ of light ions believed necessary to establish proof that inertial confinement fusion yield can equal energy stored in the accelerator (net energy gain).

As detailed in the previous semiannual report, great advantages can be obtained by using light ion beams in place of electrons. The technical basis for employing light ions has rapidly developed. To use these developments fully, a beam voltage twice that of the 2-MV PBFA-I is necessary as well as polarity reversal of the output pulse. In addition, refinements in calculations suggest that 1 MJ and 100-TW beams will be needed to approach net energy gain. Consequently, the program for designing PBFA-II was changed to provide the optimal power source for light ions (100 TW, 4 MV) and emphasis on the electron approach was reduced. It is possible to nearly double the energy stored in the same space occupied by each of the 36 PBFA-I Marx-energy stores; such a unit is currently being tested. The PBFA-I tank has been constructed to accept 72 modules when upgrading takes place; PBFA-II will store 15 MJ, nearly four times the energy stored in PBFA-I. The schedule calls for ceasing experiments and upgrading PBFA-I between mid-1983 and mid-1984. The total cost estimate is currently being recalculated and it is expected to be about 30% higher than preliminary estimates made about two years ago. This increase reflects the change in baseline to ions, nearly quadrupling (rather than only doubling) the energy available, and the inflation factors.

Technical Overview

During this reporting period, solutions for several problems on the critical path to net-energy-gain were obtained and several aspects of operating the thirty-six module PBFA-I were verified as the machine neared completion and pulsed-power testing began. Important advances were made in the most critical area—that of supplying power to an ion diode and converting that power to beams focused on a target. We have devised and proof-tested a polarity-reversing section that can be inserted in the pulse-forming lines of PBFA. With this device, PBFA will operate in the positive polarity mode with less than 5% energy degradation; reversing polarity in the Marx generator would have caused 40% reduction in machine performance. Recent success in operation of vacuum magnetically insulated transmission lines (MITLs) with topologically complex magnetic surfaces increases markedly our ability to use several types of ion-diode modules with PBFA. Specifically, power flow in a coaxial MITL has been converted with nearly 100% efficiency into flow in a triaxial line (a configuration required for the "extraction" version of the magnetically insulated ion diode). In addition, this result, together with numerical modeling, indicates that the multiple lines of PBFA can also be configured into a single, low-impedance feed to drive imploding foils.

Another pulsed power accomplishment is the successful test of a compact, water-pulse line that combines tapered lines with a configuration electrically resembling an autotransformer. The same advances that resulted in the ability to create efficient polarity reversal are essential elements for close-coupling the "primary" and "secondary" turns of this transformer-like device. This highly efficient technology will double the terminal voltage of PBFA-II to 4 MV without extensive alterations of the accelerator tank; tests have been made in the MITE facility which was the original test bed for PBFA-I. More exhaustive tests are in progress with the SuperMITE accelerator.

This work is being pursued with FY79-80 Plant Engineering and Design (PE&D) funds to accurately determine performance and cost specifications for PBFA-II.

The Proto II accelerator, originally specified as an 8-TW machine, has been operated at 11 TW to drive superfast high current density pinches using thin, cylindrical-foil loads. (Currently only one-half of the machine is coupled to foil loads; a future modification will reconfigure the design to supply all of the power to a foil.) Power flow and diagnostic problems have been solved, resulting in 4-MA current flow to the foil over a low loss radial disc transmission line employing self-magnetic insulation. The initiation phase of current flow in wires and foils has been measured with holographic techniques. The observations prove that foils produced more uniform plasmas and are, therefore, superior for obtaining power compression in cylindrical implosions. Together with the advances in power flow, significant improvements in foil fabrication techniques have paved the way for scaling this technology to produce high-power densities with efficiencies up to 50%.

Ion-diode research has resulted in continued progress; during this period we have approximately doubled the previously reported power density to $\sim 1 \text{ TW/cm}^2$ using a "radial" diode on Proto I. Using this device to implode cylindrical targets, x-ray signals have been observed from hot, dense material stagnating on axis. Implosion velocities measured at $\sim 20 \text{ cm}/\mu\text{s}$ are in agreement with hydrocode calculations. A scale-up radial-diode design for the Proto II accelerator, which has an electric power 10 times greater than Proto I, is nearly completed. This diode is planned for use in target experiments until PBFA-I comes on line with intense ion beams.

One option for PBFA diodes is an "extraction" diode similar in principle to the highly successful Proto I "radial" design. The extraction version produces a conical beam of ions that may be injected into a plasma channel for transport to a target or focused directly upon one side of a target. The radial design places an aximuthally uniform "sheet" beam upon spherical or cylindrical targets. The radial diode is well-suited to near term applications, but its scalability must be determined at higher power levels; it is not well-suited for applications requiring isolation between diode and target. Experimental tests with the extraction version have resulted in improved understanding of electron leakage; work is in progress to reduce such leakage and improve ion focusability.

A new and very attractive ion-diode concept (AMPFION, or automagnetic field-insulated ion diode) that produces bunched beams has been initially tested. This diode incorporates self-energized magnetic coils rather than employing external capacitor banks to provide insulating fields. Bunching is accomplished by varying the diode impedance from a lower to higher value during the pulse by means of an eroding plasma sheath. Hence, the voltage rises during the pulse without need for special pulse-power lines. Initial tests accelerated ions from carbon plasmas and confirmed theoretical predictions for bunching; work is in progress to improve the focusing behavior.

Work at NRL in support of the Sandia program has concentrated upon another diode approach that uses a combination of electron reflexing and a self-generated magnetic field to attenuate electron leakage. This approach is well suited for single shot applications requiring extracted beams and is most efficient with low impedance drivers such as would be provided by several PBFA lines connected in parallel. Another effort at NRL has centered on the use of wall-guided discharges to transport ion beams; this effort has shown efficient transport of ion beams accelerated with the NRL diode. Further details are not included in this report, but are available in various NRL publications.

Ion transport over distances of 0.5 to 3 m in channels will be important for both PBFA-II and for future applications. Proof-of-principle for beam transport and subsequent combination using wire-initiated, current-carrying channels was established during the past one to two years using electron beams. Recently, this technology reached a state of maturity with the completion of theoretical modeling and experiments confirming efficient multiple-electron-beam transport to a target. With this six-beam configuration, $\sim 50 \text{ kJ}$ of electron energy was transported to a target over a 0.5 m path with only a few percent energy loss. However, in agreement with theory, as the target diameter was reduced below about 1.5 cm, the efficiency was observed to decrease. The same theory predicts that for ions transport, efficiency will remain high for target diameters $\lesssim 1 \text{ cm}$, a size compatible with existing target designs.

During this period, similar technology which is complimentary to the NRL effort was used for the first time to demonstrate efficient transport of ion beams at Sandia. The Sandia experiment employed wire-guided discharges without the presence of walls

to stabilize the discharge. In preliminary results, 5-kA/cm² ion beams were transported 50 cm with 80 to 90% efficiency. For future applications, the guide wires would be replaced by weak, preionizing laser beams. Several aspects of beam transport in channels have been theoretically analyzed. For instance, charge exchange of ions in channels will not significantly reduce transport efficiency; a search for combinations of easily handled transport gases suitable for ionization with readily available lasers has identified ammonia as the gas, and CO₂ as the appropriate laser.

Target experiments focused upon studies of stability in the fuel-pusher interface region of high-aspect ratio pellets. Well characterized targets with known perturbations were employed and holographic techniques were used to measure the instability growth. Classical Rayleigh-Taylor theory is able to explain measured evolution of stability during the early part of the implosion; decreases in the predicted amplitudes late in time are under study. These experiments are continuing as part of a plan to understand and circumvent instability growth in fusion targets.

The diagnostics of spherical implosions will be greatly facilitated with a new two-frame radiographic system designed to take x-ray backlighted "snapshots." The new system improves upon a previously developed single frame radiographic system in terms of resolution, maneuverability, and precision, and is expected to play an important role in future target experiments. The initial experiments have been designed to examine directly with x-ray backlighting the dynamics of the pusher fuel interface. Targets with thin, gold overlays to make the interface readily visible are on order.

We have continued to improve models for ion-energy deposition in hot material. The model includes effects of electrons and background ions in varying stages of ionization, as well as the equilibrium charge state of the incident ion. Although range

changes are typically less than a factor of two, differences in the hydrodynamic response between corrected and uncorrected stopping powers can be considerable, and they must be included in target design. The installation of the ion energy deposition package in several often used hydrocodes has been important for target design and interpreting results of ion-beam diagnostics that rely on materials response.

We have continued to refine models that will guide light ion technology for applications in a high-yield survivable test chamber. Particular emphasis has been placed upon studies of test chamber walls in gas-protected systems; straightforward engineering solutions have been proposed. In addition, further quantification has been obtained for pellet injection and beam channel formation requirements. Development of the technology for repetitive operation of pulsed-power accelerators continued with the 10-Hz operation of a 1.2-MV transformer for 10⁵ consecutive shots at full voltage. Measured efficiency was 91%. Development of repetitively operable electron diodes for laser excitation or for creating electron-cloud virtual cathodes in ion diodes requires cathode operation in the kA/cm² range. A cathode suitable for such application has been operated reliably at 1 kA/cm² for 3 x 10⁵ consecutive shots.

Management Overview

The program continued to grow during this period as evidenced by the data in Table 1. SNLA's particle-beam experiment, target design, and diagnostics development activities have intensified as the July 1980 operational data for PBFA-I draws near.

Table 1. SNLA Particle-Beam Fusion Program Resources

	PBFA-I				PBFA-II	
	75	76	77	78	79	80
Operating (M\$)	3.7	4.8	6.5	8.7	9.3	13.3
Personnel	44	46	63	68	72	85
Construction (M\$)	0.3 [†]	0.4 [†]	9.1	4.4	1.0 [*]	1.5 [*]

^{*}PE&D

[†]CP&D

During this reporting period, preliminary design criteria were developed for the 4100-ft² addition to the PBFF laboratory building. The annex will house a machine shop and be used to fabricate, modify, and store pulsed-power components and systems for pulsed-power research. In addition, the Title I architect for PBFF-II was selected, and facility engineering was initiated. Finally, the assembly and installation of SuperMITE (PBFA-II prototype) were completed and SuperMITE's initial, pulsed-power tests were successful.

Summary of Major Accomplishments

1. Assembly of PBFA-I Marx generator completed and partially tested.
2. Positive polarity in self-magnetically insulated lines achieved.
3. Coaxial to triaxial convolute using self-magnetic insulation completed.
4. SuperMITE Marx generator completed.
5. Polarity-reversing powerflow demonstrated.
6. Transformer to convert PBFA to 4-MV operation initially tested.
7. Foil-wire comparison shows superior properties of foils in initiation phase.
8. Proto II operated at 11 TW.
9. Rayleigh-Taylor theory experimentally confirmed in initial growth of instability.
10. Two-frame backlighting radiographic system completed.
11. Five-frame proximity focus camera completed.
12. Thin parylene foils for plasma-implosion work were fabricated to high tolerances.
13. Radial ion diode achieved ~ 1 MA/cm² current density on target.
14. Extraction diode initially tested and shown to have low-electron loss.
15. Ampfion diode shown to have proper impedance behavior for efficient bunching.
16. Efficient transport of multiple electron beams to target demonstrated.
17. Ion beams efficiently transported in a wire-guided discharge.
18. Triangular-mesh magnetic-field diffusion code developed and placed on-line.
19. Substantial improvements in computation efficiency of diode code completed.
20. Charge exchange in beam transport shown theoretically to be unimportant.
21. Improved package for ion energy deposition completed and installed in hydrocodes.
22. Scoping of studies for applications identified the required parameter ranges.
23. High-voltage transformer system operated at 10-Hz repetition rate at high efficiency.

Chapter 1. Fusion Target Studies

Most of the target design activity for the past 6 mo is described in classified semiannual reports. An area of considerable activity is the theoretical examination of instability properties that is discussed in this progress report as Chapter 2. In Chapter 1, we describe the development of ion-deposition physics as well as some changes in computational methods for targets employing magnetic thermoinsulation. Although this target approach is currently inactive, it may hold promise in future applications.

Continuing Studies of Ion Energy Deposition In Partially Ionized Material (T. A. Mehlhorn)

In recent months the change in emphasis of the particle beam fusion program from electrons to light ions came largely as a result of the expectation of superior energy deposition characteristics for ions. With electrons one needs to strive for an "enhanced" level of deposition employing some reflex mechanism in order to achieve a suitable final stage of energy compression in the target. Moreover, the bremsstrahlung generated by relativistic electron beams results in a significant problem in target performance due to preheat. With ions one expects shorter ranges with more definite cutoffs (perhaps even a Bragg peak) leading to a more favorable specific energy deposition level (MJ/g) with less low-level preheat from profiles with low-energy tails. Furthermore, bremsstrahlung preheat is no longer a problem with nonrelativistic ion beams and target performance should correspondingly improve for the same incident powers in ions as compared to electrons. We have been continuing our studies into the physics of ion energy deposition in ICF target materials (especially under partially ionized-plasma conditions) in order to verify the validity of these expectations.

For 6 mo we have continued the development of our ion energy deposition model. During this time we have attempted further verification of the physical model and have begun to investigate the ramifications of our results. It has been found that the qualitative aspects of ion energy deposition in matter are indeed favorable for driving ICF targets: there is a much shorter range for ions than for electrons; the deeply penetrating straggling tail of the distribution is absent; and no significant preheat mechanisms have been identified to date. However, quantitatively it has been found that the ion "range" is not a simple scalar quantity, but rather is a function of the target density, temperature, and degree of material ionization. Figure 1 serves to demonstrate this phenomena. Figure 1a depicts the degree of material ionization in gold and aluminum targets at 0.01 solid density as a function of the material temperature as given by a Saha model. Using this information to determine the number of free and bound electrons in the material, one can integrate the calculated ion stopping power of the target to obtain the ion ranges displayed in Figure 1a. As can be seen, the aforementioned range changing is initially realized as an effective range shortening in heated matter as compared to the range of normal cold matter. This occurs because the free electrons created by ionization have a larger stopping power than the bound electrons since the latter are indeed "bound" and can only accept energy to some minimum quantum cutoff. We find that the minimum range in heated material is roughly one-half that of cold matter. With increasing plasma electron temperature, a gradual relengthening of the ion range due to a decoupling between the ion and the plasma electron velocities occurs. Figure 2 shows the strength of the coulomb interaction between the ion and the plasma electron as a function of the relative velocity of the two particles. As this ratio becomes less than unity, the coupling decreases and the range increases.

Initial Study of the Ramifications of Ion Range Variation on the Efficiency of Hydrodynamic Implosions (T. A. Melhorn)

We have performed some initial calculations to study the effect of the previously described changing ion range on the efficiency of hydrodynamic implosions. In this work we chose to begin in a simple 1-D planar geometry since the ρR of a uniformly irradiated planar foil is a constant in such a system. Thus, the effects of a changing range on the hydrodynamic response of a planar target will be most dramatic since ion-energy deposition into a constant ρR will also result in deposition into a fixed spatial interval. We have compared the response of a target with deposition into a constant ρR (static cold matter deposition case) with the response from calculations that use a dynamic deposition model (ion range determined as a function of the local density temperature, degree of ionization in the target). Figures 3a and 3b display the acceleration and velocity time histories of the front and rear surfaces of a CH foil that is uniformly and normally irradiated by a 750-kV proton beam with a pulse duration of 25 ns and an incident power density of 10 TW/cm². Note that while the front surface dynamics are fairly similar in both instances, the rear surface velocity in the case of depositing into a constant ρR is much higher than for the self-consistent case. This can be explained by noting that the range of a 750-kV proton is $\sim 13.5 \mu\text{m}$ and, in the constant ρR deposition case, the proton Bragg peak causes a very high deposition near the end of the range; this leads to an efficient coupling into a high velocity rear surface blowoff. In the self-consistent deposition case, the dynamics of the changing range makes the time integrated ion energy deposition profile appear to be broad and diffuse. Also, for this case, the rear surface is not preferentially accelerated. A third curve on these plots shows that the conditions of the static deposition case can be reproduced more closely. This is accomplished by increasing the proton energy to 1 MeV so that the shortened range in the heated target corresponds to the original position of the cold material Bragg peak.

From the limited studies done to date, it would seem that the dynamics of the ion range changing with temperature, density, and ionization can have a significant effect on the hydrodynamic response of a target. However, it appears that as long as the deposition model includes the dynamics of these processes,

a. Degree of material ionization as a function of material temperature for both aluminum and gold as determined by the Saha equation. Both curves are for .01 ρ_0

b. Range of a 2-MeV proton as a function of material temperature in both aluminum and gold at .01 ρ_0

Figure 1. Ion "Range" Is a Function of the Target Density, Temperature, and the Degree of Material Ionization

Figure 2. Coupling Function $G(y)/y^2$ vs the Dimensionless Velocity Ratio y where $y = v_{\text{ion}}/v_{\text{field}}$.

it is possible to adjust various beam and target parameters to obtain the same results that might be expected from naive static deposition calculations.

a. Rear Surface

b. Front Surface of a 15- μ m CH Foil. The beam intensity is 10 TW/cm² with a pulse length of 25 ns.

Figure 3. Acceleration and Velocity vs Time of the Front and Rear Surface.

We attempted to apply the rocket equation formalism¹ used for laser driven ablative acceleration to help quantify the hydrodynamic conversion efficiency of ion driven foil ablations; however, this proved impossible. The ion driven ablation process is substantially different from that of laser driven ablation since there is no formation of a steady state ablation profile with a well-defined ablation velocity. Since the rocket equation assumes such a well-defined ablation process, this appears to be the cause of the inappropriateness of the model. While a more penetrating interpretation of the physical mechanism causing this difference is still forthcoming, this fact has significant repercussions in the area of target

stability calculations. Many simple models for ablation front stability²⁻⁵ assume that the mean flow is "self similar" (that is, unchanging in the frame co-moving with the front). These results, suggest that such models may be too simplistic and that time-dependent mean states will have to be considered for ion driven ablations.

We have continued to study the physics associated with the energy deposition of ion beams in ICF target materials and have attempted to improve the accuracy and reliability of our deposition model.

The physical mechanisms leading to range shortening and subsequent range relengthening with increasing plasma electron temperature have been delineated. We have initiated studies of the effects of range changing on the hydrodynamic response of a target and have found that the ion energy, ionic specie, and target materials can probably be tailored to achieve a certain level of target performance. However, the physics of ion energy deposition at these power levels is not as simplistic as first thought because of the dependence of the range on target density, temperature, and degree of ionization. Ion-driven ablations seem to differ markedly from laser-driven ablations. The more simplistic ablation-front stability models developed for laser fusion are not directly applicable to ion-driven problems.

Revised Calculations of Central Igniter Magnetic Targets (M. A. Sweeney)

In previous semiannual reports⁶ we have evaluated a class of high-gain targets for use in a commercial fusion power reactor driven by electrons or light ions. The targets are larger than conventional ablatively-driven targets and have a lower beam-intensity requirement.⁷ A magnetic field provides thermal insulation of preheated, low density fuel. The addition of a cryogenic fuel layer increases gain without requiring significantly increased beam power and intensity.

In previous numerical modeling of these targets we had assumed that the reaction-produced alpha particles are transported nonlocally and noninstantaneously in both fuel regions (moderate field case) or locally in the preheated, low density fuel region and nonlocally and noninstantaneously in the high density fuel region (high field case). It has been pointed out⁸ that the hydrocode being used does not

conserve energy correctly if alpha particles are transported noninstantaneously. We have therefore repeated some of the target calculations, assuming non-local but instantaneous transport in order to determine the effect on target performance. (The instantaneous assumption had always been made in calculating the performance of conventional ablative targets.)

With the instantaneous assumption, gains for both electron and ion beam targets are higher, and power and intensity requirements are lower. For example, without voltage shaping, gains of 20 to 30 at about 50 TW/cm² can be obtained with electrons if the initial magnetic field in the low-density fuel is >30 to 60 kG (moderate field case), the initial fuel radius is 0.3 to 0.4 cm, and the fuel preheat temperature is 10 to 15 eV. For the same field and preheat temperature, gains of 30 to 40 at about 80 TW/cm² can be obtained with light ions if the initial fuel radius is 0.2 cm. (A larger ion target would require lower intensities, but aspect ratios and fuel convergence ratios, which are here about the same as for conventional ablative designs, would be larger than for the same size electron target.) With the previous noninstantaneous assumption, the intensity requirement was about 100 TW/cm² for both electrons and light

ions; gains were 10 to 20 for the electrons and 20 to 30 for the ions at these intensities. An electron thermal conduction reduction factor of at least 10 is required in the low-density fuel region for both electron and ion targets to produce significant gain. In the earlier calculations, the factor required was 20 for the electron targets and 13 for the ion targets.

A. V. Farnsworth, Jr. and M. A. Sweeney have submitted for publication a paper discussing the behavior of these targets. It is expected that no further calculations will be done for these target configurations.

References

1. NRL Report 3890, Dec. 1978
2. J. P. Boris, "NRL Inertial Confinement Fusion Theory," June-July 1979.
3. S. E. Bodner, *Phys. Rev. Lett.* 33:761, 1978
4. L. Baker, *Phys. Fluids* 21:295, 1978
5. P. J. Catto, *Phys Fluids* 21:30, 1978
6. A. V. Farnsworth, Jr., *Breakeven and High Gain Magnetic Targets*, SAND79-0002 (Albuquerque: Sandia Laboratories, 1979) p 47; M. A. Sweeney and A. V. Farnsworth, Jr., *Central Igniter Magnetic Targets with Voltage Shaping*, SAND79-0002 (Albuquerque: Sandia Laboratories, 1979) p 48; M. A. Sweeney and A. V. Farnsworth, Jr., *Low Power, High Gain Targets Employing Magnetic Thermoinsulation*, SAND79-1011 (Albuquerque: Sandia Laboratories, 1979), p 21.
7. M. J. Clauser, *Phys. Rev. Lett.* 34:570, 1975.
8. G. O. Allshouse, private communication.

Chapter 2. Target Experiments

Overview

The role of the Target Experiments Division is to provide an experimental basis for the construction and ignition of thermonuclear targets. Recent interest areas of investigation include studies of deposition, stability of the fuel pusher interface, particle ejection from shocked surfaces, and the fuel physics for targets with an embedded magnetic field. Support for these efforts has required the development of various diagnostics as well as a limited target fabrication capability.

During the reporting period, additional measurements of the stability of the fuel pusher interface in multishell, high aspect ratio targets have been performed with well characterized precision targets. The growth rates are consistent with classical Richtmyer theory; however, the amplitude of the stability appears to decrease (as observed optically) late in time. This apparent decrease could be attributed to stabilization of instabilities due to mode interaction, or could be a difficulty with the observation because of material ejection into the central volume. Further experiments and theoretical analysis are currently underway to investigate these phenomena.

The diagnostic capabilities in the area of target implosions have been greatly enhanced by the development of a multiframe flash radiography system. This system should permit direct measurements of average pusher velocity and of pusher stability in spherical particle beam driven ICF capsules. Initial experiments with this diagnostic are currently in progress.

A five-frame proximity focus camera has been designed to measure the time-dependent spatial distribution of deposition and other implosion phenomena in targets. This high resolution device may also provide a significant increase in the resolution of the multiframe radiography system. Future work in both areas is planned.

A neutron hodoscope array has been assembled to provide for improved time of flight statistics on low-yield thermonuclear targets. The procedures for assembling such an array are described and data demonstrating its usefulness is presented in this report.

In addition to these areas, the target experiments group has provided diagnostic support for the channel-propagation experiments (described in Chapter 4) and for the foil initiation experiments and foil-implosion experiments to be presented in a later report.

Most of our target fabrication is being performed by the Los Alamos Scientific Laboratory. These tasks include the fabrication of precision flat and cylindrical targets for stability experiments, special targets for the flash radiography experiments, and the development of techniques for far term targets. To supplement these efforts, we have developed the capability to perform thin film deposition, parylene deposition, and plasma polymerization. These limited capabilities are in direct support of near term target requirements and should provide a rapid response to experimental and theoretical target requirements.

Investigation of Shell Stability in Cylindrical Targets (F. C. Perry and M. A. Sweeney)

The major goal of the physics of implosion stability study at Sandia National Laboratories is to optimize target design for the particle-beam accelerator (PBFA I) which is nearing completion, and for its upgrade (PBFA II), which is scheduled for operation in 1984. In the present experiments, attention is focused on the stability of the pusher fuel interface and on the shock wave that converges in a surrogate fuel.

Experiment Investigation

These stability phenomena are being studied by using a single beam of the hydra electron beam accelerator (1.1 MeV, 0.5 TW, 100-ns pulse) to implode an ablatively driven multishell cylindrical target.¹ These targets consist of a nickel or copper ablator, a polyethylene buffer, and a high aspect ratio

($r/\Delta r \approx 15$) gold pusher. A four-pulse holographic interferometer system is used to obtain spatially and temporally resolved images of the implosion. Pressures in the target shells are 0.1 to 1.0 TPa. The thickness of the ablator exceeds twice the csda range for 1.1-MeV electrons; the temperature from beam deposition at the inner edge of the pusher is sufficiently low (~ 0.03 eV) to preclude melt until just before maximum compression.² Thus, we can be certain that the view field of the optical diagnostic is not occluded by beam-generated plasma and that the implosions studied are "ablatively" driven.

Data has been obtained for both initially unperturbed and perturbed targets (cf Figure 4-7). Well-defined initial perturbations at the buffer pusher interface are provided by a regular scoring of the outer edge of the pusher using tungsten carbide or diamond milling.³ Figure 5 shows the initial and imploded states of one such target. These are 36 scorings with an amplitude $\eta_0 = 25 \mu\text{m}$ and a wavelength $\lambda_0 = 368 \mu\text{m}$. Figure 6 shows the imploded states of a cylindrical target in which six equally spaced holes were drilled completely through the pusher.

Figure 4. Holographic Interferograms of an Unperturbed Cu/CH₂/Au Cylinder

Figure 5. Holographic Interferograms of a Perturbed Cu/CH₂/Au Cylinder

Figure 6. Holographic Interferograms of the Imploded Configurations of a Cu/CH₂/Au Cylinder Fabricated With Six Equally Spaced Holes Drilled Completely Through the Gold Pusher

Figure 7. Holographic Interferograms of the Implosion of an Unperturbed Cu/CH₂/Au Cylinder Containing 1 Atmosphere of Air

Analysis of Data From the Experiments

Holographic interferometry of the inner surface of an initially perturbed Cu/CH₂/Au cylinder reveals that perturbations develop on this surface after the shock breaks through (Figures 5 and 6). Perturbation growth occurs and, later in time, saturation can occur. The early growth rate of these perturbations is in agreement with the linear growth predicted by Richtmyer⁴ for shock passage through a material interface (cf Figure 8). Later, the growth rate is slower and is accompanied by the distortion and necking characteristic of nonlinear Rayleigh-Taylor development previously observed at much lower accelerations than those encountered in these experiments (10^{14} cm/s^2).⁵

There is evidence that smoothing of the implosion boundary occurs later, as shown in Figures 8 and 9. For example, measurement of the crest-to-trough amplitude (η) and the wavelength (λ) of the perturbations at the inner surface of the pusher for the experimental configuration of Figure 5 indicates that the

dominant wavelength decreases linearly for about 80 ns until a time corresponding to a pusher displacement of 10 initial pusher thickness. This linear decrease by a factor of 1.5 is consistent with the geometric decrease in radius. Figure 9 shows that the decrease in the amplitude (η) during the same time period is much larger, about an order of magnitude.

This significant reduction (as observed optically) in the initial growth of the perturbation of the pusher void interface is encouraging. A less encouraging aspect of the results is the extremely "spiky" character of the interface. These spikes appear to damp out or stabilize over a period of time, but they also reappear later at random positions along the pusher boundary, indicating that jetting into the convergence volume may be occurring.

This problem of instability growth and saturation in high aspect ratio target implosions will be addressed further in forthcoming experiments using the powder gun and two stage light gas-gun facilities. In addition, by designing an experiment with a smaller number of perturbations we plan to determine the location of the observed perturbations on

the inner surface of the gold pusher relative to the initial scoring on the outer surface of the pusher.

Figure 8. Wavelength λ and amplitude η of Perturbations at the Inner Surface of the Gold Pusher for the Experimental Configuration in Figure 2 vs Time.

Figure 9. Ratio of η/λ for the Cylindrical Target of Figure 2 vs Time.

Numerical Investigation

We are currently simulating the experimental configuration illustrated in Figure 5 using the two-dimension Eulerian code CSQ.⁶ The code contains a complete material equation of state (including material phases, mixed phases, and an elastic plastic model) and can simulate the extreme distortions of jetting.⁷ Modeling of the experimental configuration with 36 perturbations is intractable because of zoning and time constraints. We are therefore modeling the target dynamics in Cartesian geometry (Figure 10) since the gold pusher thickness is small compared to the central void radius, and perturbation growth also occurs in planar targets with defined perturbations. Furthermore, growth occurs in the cylindrical targets before the onset of significant convergence. One perturbation is modeled with a reflecting mass boundary at the left and right of the Eulerian mesh (Figure 8). It should then be possible to determine the location of the observed perturbations relative to the initial scoring of the outer gold surface.

Figure 10. Initial Material Configuration for Numerical Modeling of the Experimental Configuration in Figure 5.

On the scale of the perturbations, which have a width of about $70\text{ }\mu\text{m}$, the beam intensity is uniform. A peak deposition of 1.5 TW/g at the surface is assumed. This value agrees with an experimentally measured free surface velocity of $0.9\text{ cm}/\mu\text{s}$ in previous one-dimensional simulations² of very similar unperturbed $\text{Ni}/\text{CH}_2/\text{Au}$ cylinders. The indepth deposition of the electron beam energy is assumed classical. The deposition profile is determined from a separate two-dimensional transport code⁸ assuming a cosinusoidal angular distribution for the incident electrons and a beam radius equal to the 0.311-cm cylinder radius. A planar source is used in the CSQ calculation with the areal density computed along paths normal to the target surface. Typically, about 100 such paths are used per deposition calculation. Computational accuracy is checked by comparing results for a planar test problem with those obtained using a finer-zoned one-dimensional Lagrangian code⁹ with the same equation-of-state.

The numerical problem has been formulated and the deposition routine has been modified and confirmed. The two-dimensional calculation is currently being performed. In the next semiannual, the calculational results and comparison with the experiment

will be presented. Efforts are also underway at the University of Rochester to simulate these experiments using DAISY.

Two-Frame Radiography System (J. Chang and D. L. Fehl)

Previous work on the Rehyd accelerator, as recorded in the January-June 1979 Progress Report, demonstrated that the prototype dual channel-plate x-ray DCXC camera--together with an $80\text{-}\mu\text{m}$ dia, 3-ns duration, flash x-ray source--could yield single-shot radiographs of rapidly imploding, electron-beam driven targets (Figure 11). The images were of improved quality compared to previously published results, and the resolution of the system was at least four line pairs/mm with the target penetration of ~ 0.5 to 1.0 g/cm^2 of gold. The means of radiographically measuring the average implosion velocity of a particle beam driven target were then in hand, and a two-frame radiographic system for making such measurements has been under construction for the past 6 months.

Figure 11. Flash Radiographs of a Gold Electron-Beam Target Taken Just Before (Figure 11a) the Rehyd Accelerator Was Fired and 400 ns After (Figure 11b) the Electron Beam Pulse Peak. The target was a sphere of 3 mm OD and $200\text{-}\mu\text{m}$ -thick walls. A gold stepwedge with 0.1-g/cm^2 -thick steps and a blemish on the phosphor screen are visible in the pictures.

The new two-frame system is illustrated in Figure 12. A thin walled, spherical target will be imploded within the diode chamber of the Hydra accelerator. At specified times t_1 and t_2 during the process, two independently gated and vertically hung flash x-ray sources will cast high resolution shadows of the target on two independently gated DCXC cameras. The imploding targets have been designed specifically to provide good definition of the moving pusher fuel boundary and to yield a reliable averaged-implosion-velocity measurement. The space frame, onto which the x-ray sources and cameras are affixed, rigidly defines the geometry for the measurement but also allows for XYZ adjustment of the radiographic system relative to the target.

The flash x-ray source output for this new system has been optimized through improvements in the diode design. These modifications permit more efficient coupling of the pulse line energy to the diode resulting in a 4 to 5 fold increase in the point x-ray source intensity.

Figure 12. Artist's Conception of the Two-Frame Radiographic System. At the top two high-voltage pulsers independently gate the flash x-ray sources at the end of "gooseneck" coaxial lines. Two curved DCXC cameras are visible at the bottom. The whole space-frame is designed to fit the Hydra accelerator with XYZ spatial adjustment.

The DCXC camera has been redesigned for the two-frame system, as sketched in Figure 13 and pictured in Figure 14. An incident x-ray image is still

converted into an electron image in a front micro-channel plate (MCP); a pulsed, 0.2-T magnetic field then transfers this electron image to a back MCP, where it is amplified. A P-11 phosphor converts the electron image into a visible image (directly exposes Polaroid film via a fiber optics array). In the new system the drift tube has been reduced from 14 to 7 cm ID; the vacuum pumping port has been transferred to the front of the camera, and the front and rear flanges have been redesigned to permit either 40- or 25-mm-dia MCPs and phosphor to be used.

The electronic pulse systems have also been redesigned and constructed. All voltage pulses are divided and terminated within the vacuum of the camera in order to shorten electrical leads. New electronics packages include a capacitor discharge bank (for the guiding magnetic field), fast, high voltage triggers, and dependable MCP pulser. The relative timing of the two flash x-ray sources and the four pulsed electro-optical components on the camera will be set by a CORDIN six-channel delay generator with a 1-ns time resolution.

The camera has been tested to date with steady-state voltages. Asymmetric distortion of a square object has been reduced to 6% over a 25-mm field of view in one camera.

Figure 13. Sketch of the Redesigned DCXC Camera for the Two-Frame Radiographic System. An x-ray shadow of the object is cast on the front MCP where it is converted to an electron image and preamplified. This image is then accelerated through an aperture, guided to the back of the camera (which can be protected from direct exposure to x-rays), and amplified in a second MCP. This amplified electron image then strikes a phosphor and is converted to a visible image that directly exposes Polaroid film via fiber optics array.

Figure 14. Photograph of the Redesigned DCXC Camera. The entire assembly is mounted at the right, vacuum pumping is accomplished at that interface. The guiding magnetic field is supplied by a pulsed coil wrapped about the length of the tube. The film mounting stage is visible at the top left.

Five-Frame Proximity Focus-Camera (D. L. Fehl)

Recent work with ion beam driven targets has motivated the development of a prototype framing camera designed to sample soft x-ray (≤ 3 keV) images. Microchannel plates (MCPs) are more sensitive to photons in this energy regime than to hard x-rays (> 10 keV). The prototype framing camera is sketched in Figure 15. An array of five pinholes in vacuum casts five time varying x-ray images of a soft x-ray luminous object onto five independently gated microchannel plates. Corresponding electron images emerge from the plates and strike a P-11 phosphor held at 5-kV potential. These images are guided by the electrostatic potential between the MCP array and the phosphor; the image is sharp because the gap is ~ 3 mm. In the phosphor the electron image is converted into a visible image that is conducted out of the vacuum region with a fiber optics array and directly exposes Polaroid film.

Preliminary measurements have been made with the camera under steady state conditions; the system will be tried on Proto I. It should prove useful in examining the temporal and spatial variations of an ion beam focus and the implosion of ion-beam driven targets.

Figure 15. Sketch of Prototype, Five-Frame, Proximity Focused X-ray Camera. Five time-varying soft x-ray images are sequentially sampled by five gated MCPs. The resulting electron images strike a phosphor and the resulting visible light exposes film.

Neutron Detector Development (R. J. Leeper, W. M. McMurtry, and J. Chang)

Both for better interpretation of low yield neutron experiments with detectors close to the target and for improving the accuracy of neutron time of flight systems, a detector system of greater sensitivity was required.

Two neutron detector hodoscope arrays (first described in the January to June 1979 Semiannual Report) have been assembled and tested. A schematic drawing of one hodoscope array is shown in Figure 16. Each NPM-74 detector consists of a fast plastic scintillator coupled to an Amperex XP2041 photomultiplier tube. The major advantage of such a detector arrangement is that by adding the outputs of each detector together, neutron data of good temporal and statistical precision can be obtained at low total neutron yield ($10^5/4\pi$ Sr at 2 m). This is accomplished simply by intercepting more neutrons due to the larger solid angle of the array. However, as discussed in the January to June 1979 Semiannual Report, it is necessary in such an array to have the gains of each detector matched to insure that one or more high-gain detectors do not dominate the system and result in poor statistics. Also it is important that the transit times of each detector be synchronized by adding and subtracting delay to properly overlap each detector in time. During this reporting period, we have

successfully carried out both tasks and in addition have tested the response of each hodoscope detector to a low-yield 3-ns neutron pulse.

Neutron Hodoscope Schematic

Figure 16. Neutron Hodoscope Schematic

The gains of the individual detectors comprising the hodoscope were balanced, using the Compton edge technique. In this technique, the Co^{60} Compton edge half-heights of each detector are aligned by detector high voltage adjustment. The alignment of the half-heights insures that the gains of each detector are equal since the half-height of the Co^{60} Compton edge represents the deposition of 1.25 MeV of energy.¹⁰

The electronics used to observe and align the Compton edges are shown in Figure 17. The linear gate and stretcher module is required to condition the signal from the fast plastic scintillator for pulse-height analysis with the ORTEC 6240 multichannel analyzer. Figure 18 shows the set of aligned Compton edges for one of the hodoscope arrays.

Figure 19 shows the neutron hodoscope passive-sum electronics used to synchronize the timing of each hodoscope element and to test the response of the hodoscope detector to a 3-ns neutron burst.

In order to synchronize the timing, the EGG/ORTEC 4 port delay box was adjusted so that the neutron pulse of each detector was brought into coincidence when exposed to a 3-ns neutron source through 10.2 cm of lead at a distance of 2 m. The largest adjustment needed was 8 ns. The Bishop 5 port adder then passively added the signals from each hodoscope element. The sum pulse was then displayed on a Tektronix 7904 oscilloscope.

Figures 20 and 21 contrast individual hodoscope element response to hodoscope sum response. In Figure 20, where only individual detector responses to a low level 3-ns burst are displayed, there is ample evidence of poor neutron statistics. In three of the four traces, evidence of individual neutron contributions is clearly evident. The fourth shows a reasonably nice trace. The sum responses to the same low level source shown in Figure 21 exhibit much better statistical precision. No individual neutron contributions are evident and each pulse is well-defined so that, for an example, a neutron arrival time could be extracted from the leading edge of any of the pulses.

In summary, two neutron hodoscope detector arrays have been built and tested. The gains of each detector element comprising each hodoscope array have been easily and precisely balanced using the Co^{60} Compton edge technique. The timing of individual hodoscope elements has been synchronized using a 3-ns neutron burst. Finally, in tests with a low yield 3-ns neutron source, it has been shown that the hodoscope detector array does certainly improve neutron sensitivity and statistics.

Target Fabrication (K. W. Bieg and T. D. Hund)

Current and future target experiments need precise, well characterized targets fabricated to extreme tolerances of sphericity, concentricity, surface-finish, etc. Furthermore, the development of new materials or technologies is frequently necessary in order to meet the unique requirements of inertial confinement fusion target designs. Target fabrication activities address these demands on a timely basis. During this reporting period, we moved into a new target-fabrication laboratory within the PBFF accelerator

building and concurrently expanded our capabilities. In-house functions are generally directed toward support of near-term experimental activities, including magnetic thermoinsulation (MTI) targets, imploding foils, and various physics experiments. In addition, the Los Alamos Scientific Laboratory CMB-6 group has been responsible for fabrication of flash-radiography targets, cylindrical multishell targets for stability studies, and the development of fabrication techniques required for certain far-term, multishell target designs. These techniques include methods for lapping and polishing small spheres, plugging fill holes in thin-walled gold fuel capsules, and creating low density, low pore size foams.

Figure 17. Block Diagram of Co^{60} Compton Edge Electronics

Figure 18. EGG NPM-74 Compton Edges

Figure 19. Neutron Hodoscope Passive-Sum Electronics

1 V/div 10.2 cm Pb
20 ns/div 4.7×10^4 Neutrons

1 V/div 10.2 cm Pb
20 ns/div 2.4×10^5 Neutrons

1 V/div 10.2 cm Pb
20 ns/div 9.3×10^4 Neutrons

1 V/div 10.2 cm Pb
20 ns/div 1.8×10^5 Neutrons

Figure 20. Typical Individual Detector Responses to a 3-ns Neutron Pulse

2 V/div 10.2 cm Pb
20 ns/div 1.6×10^5 Neutrons

2 V/div 10.2 cm Pb
20 ns/div 1.9×10^5 Neutrons

2 V/div 10.2 cm Pb
20 ns/div 1.7×10^5 Neutrons

2 V/div 10.2 cm Pb
20 ns/div 1.8×10^5 Neutrons

Figure 21. Typical Neutron Hodoscope Sum Responses to a 3-ns Neutron Pulse

Our target fabrication laboratory currently has capabilities to perform evaporative thin-film depositions, parylene deposition, and plasma polymerizations. We are also installing a magnetron-sputtering apparatus for the deposition of a variety of inorganic materials. This laboratory also contains a clean room/clean bench area to minimize particulate contamination during target fabrication and assembly, and a microassembly/inspection station. In addition, we have constructed an in-house microradiography apparatus similar to those described in the literature for contact x-radiography of laser-fusion targets.¹¹ This unit contains an exposure chamber which may be evacuated to minimize soft x-ray attenuation and a Picker multifocus x-ray source; the system has a geometric resolution of less than $0.3\text{ }\mu\text{m}$ for a 3-mm target. Additional excellent characterization and analysis facilities are available elsewhere within Sandia.

Approximately 30, high-quality MTI electron-beam exploding pusher targets have been fabricated as a cooperative effort between the LASL CMB-6 group and ourselves. Initial mandrel/fill tube preparation and assembly and pyrolytic vapor deposition of the seamless, insulating parylene coating was accomplished at Sandia. Aluminum deposition, final assembly, and radiographic characterization was performed at LASL. Figure 22 shows a contact x-radiograph of a completed target. These targets are spherical to $5\text{ }\mu\text{m}$ and have a wall uniformity of approximately 5%. We are presently exploring methods to fabricate ion-beam exploding pusher targets with thin ($\sim 10\text{ }\mu\text{m}$), parylene shells. These spheres have a calculated bursting pressure of 5-7 atm, an elastic buckling pressure of about 1 atm, and a DT leak rate of less than a few percent per minute (sufficiently slow to be useful with our present fill-in-place apparatus). Also being examined are sputtered and evaporated low-density, high-strength coatings and blown or molded glass (at KMS Fusion) for these high-aspect ratio shells.

We have made substantial improvements on the foil-fabrication process and have been supplying foils for the Proto II imploding foil experiments and various bench tests. Typical Proto II foils have an overall areal density of $\sim 100\text{ }\mu\text{g}/\text{cm}^2$; half of the areal density is aluminum vapor deposited on a supporting polymer film. Currently, the fabrication process involves vapor depositing thin parylene films on a water-leachable cylindrical mandrel. Previous KTFR polymer cast films were not adequately reproducible (and therefore difficult to characterize) and contained longitudinal thickness variations as a result of inherent difficulties with the casting process

and the polymer itself. Conversely, parylene has excellent mechanical properties and yields free-standing films of uniform thickness. Unfortunately, the water soluble Rigidax mandrel we had been using proved unacceptable with this new process; it had a rough surface with numerous pits several microns in depth. Since parylene is conformal to the substrate texture, this roughness added significantly to the effective areal density of the foils and caused significant undissolved mandrel residue. As an alternative, we have used a novel water soluble phosphate glass mandrel that may be polished to an arbitrarily smooth surface and dissolves in less than an hour at 70° to 80°C . This process leaves insignificant mandrel residue, as verified by scanning electron microscopy, Auger spectroscopy, and electron microprobe analysis. Typical surface roughness of current glass mandrels is better than 3000Å. Future efforts will concentrate on mandrel development, synthesis of parylene derivatives containing deuterium or metal additions, and fabrication of all metal foils.

In summary, target fabrication activities are directed toward supporting near-term target experiments, and the development of material and processes to meet these and far term target requirements in a timely manner. Current emphasis is on electron- and ion beam exploding pusher targets, foil development, and targets designed to answer physics questions pertinent in inertial confinement fusion.

Figure 22. A Contact X-Radiograph of a Completed Target

References

1. F. C. Perry, L. P. Mix, and A. J. Toepfer, *Appl. Phys. Lett.* 34:151 (1979)
2. F. C. Perry, L. Baker, D. Ghiglia, L. P. Mix, M. A. Sweeney, and A. J. Toepfer, *Bull. Amer. Phys. Soc.* 24:721 (1979).
3. These cylindrical targets were fabricated by Los Alamos National Scientific Laboratory, CMB6.
4. R. D. Richtmyer, *Communications on Pure and Applied Mathematics*, 13:297-319 (1960).
5. F. C. Perry, *Bull. Amer. Phys. Soc.* 24:1003 (1979)
6. S. L. Thompson, *CSQ II-An Eulerian Finite Difference Program for Two-Dimensional Material Response - Part 1. Material Sections*, SAND77-1339 (Albuquerque: Sandia Laboratories, Jan. 1979).
7. M. M. Widner, F. C. Berry, L. P. Mix, J. Chang, and A. J. Toepfer, *J. Appl. Phys.* 48:1047 (1977); J. R. Asay and L. D. Bertholf, *Mass Ejection From Material Surfaces Subjected to Impulse Loading* SAND78-0549 (Albuquerque: Sandia Laboratories 1978).
8. J. A. Halbleib, Sr and W. H. VanDevender, *CYLTRAN: A Cylindrical Geometry Multimaterial Electron/Photon Monte Carlo Transport Code*, SAND74-0030 (Albuquerque: Sandia Laboratories, March 1975).
9. S. L. Thompson and H. S. Lauson, *Improvements in the CHARTD Radiation-Hydrodynamic Code II: A Revised Program*, SC-RR-71-0713 (Albuquerque: Sandia Laboratories, Feb. 1972).
10. J. B. Birks, *The Theory and Practice of Scintillation Counting*, Pergamon Press, 1964, p 377.
11. T. M. Henderson, D. E. Cielaszyk, and R. J. Simms, *Rev. Sci. Instrum.*, 48(7):835 (1977).

Chapter 3. Particle-Beam Source Development

Overview

Ion diodes using applied magnetic fields to control electron flow have recently produced current densities of about 0.5 MA/cm^2 on the Proto I accelerator. This was obtained using a cylindrically symmetric configuration that produced a radially converging ion beam for near term studies. Our present far term reactor scenario is based on using plasma channels to transport beams from many modules to a central target region. For this application, the ion diodes must have an "extraction" capability; i.e., it must be possible to aim and focus the beam at a spot some tens of centimeters from the diode where the entrance to the plasma channel would be located. A series of computer simulations of the Proto I extraction diode (a configuration which employs applied external magnetic fields) has been carried out to study how the electron losses can be controlled by shaping the magnetic field contour. This work is presently being extended to a more recent experiment which produced an ion current $I_i = 350 \text{ kA}$ at an efficiency of $I_i/I_e \approx 1$. These simulations are using our new optimized particle-in-cell diode code that is about a factor of 2 to 3 faster than last year's version.

One of the limits on the focusability of ion diodes that rely on external magnetic fields for electron insulation is magnetic flux diffusion into the anode. These fields impart a net canonical angular momentum to the ions that limits their final radius at the focus. A new code based on a triangular finite difference mesh has been constructed to study flux diffusion in curved or irregularly shaped surfaces. The results provide an estimate of the initial canonical angular momentum and provide fields that can be incorporated in simplified models of the emission surfaces which are being used to study sources of beam divergence.

The recent shift in emphasis towards light ion beams was motivated by many factors, including their superior energy deposition characteristics and their greater power enhancement capabilities. The overlap gain and deposition symmetry for a three-disk ion-beam configuration has been studied theoretically using a Monte Carlo trajectory model. For a

channel injection angle of 8° , the computed power gain obtained by overlapping the beams was 7.7, with an energy deposition efficiency of 85%. This is much higher than the gain of 2 to 3 previously computed for electrons. An additional gain of a factor of ~ 5 has been predicted for ion beams by using a voltage ramp and channel transport to allow the ion beam to bunch before reaching the target region. A novel method for achieving bunching with electrons has been studied in collaboration with NRL. Deposition levels as high as 100 TW/g/MA in thin copper foils are predicted.

The question of charge exchange was studied for an ion beam propagation in a plasma channel; at channel parameters of 10^{-6} g/cm^3 and 10 eV the effect was found to be minor for C^{+4} beams at 16 and 26 MeV.

In the pulsed power area, an equivalent circuit model has been developed for studying wave asymmetry effects in magnetically insulated transmission lines. The combination of several transmission lines into one and the transmission of power with minimal loss to loads in large radial lines depends critically on wave symmetry. The method has been used to study the effects of switch jitter in both Proto II and PBFA I. The results for Proto II indicate that the leakage losses predicted by this model are only 10% of the available energy for reasonable switch jitters. For PBFA I, results were obtained for both conventional and plasma-filled diode loads. The latter diodes appear as short circuits early in time and thus are less sensitive to switch jitter. An analytic model was used to study particle trajectories in radial-line configurations such as Proto II. The field conditions required for emitted electrons to either return to the cathode or drift to the anode were defined.

Additional numeral simulations for the Pulselac-B linear-ion accelerator were completed during this reporting period. These computations studied the ion dynamics and space-charge neutralization process. The neutralization was found to be very effective at magnetic fields of $\sim 13 \text{ kG}$, but decreased at lower fields.

The importance of space-charge neutralization of ion beams led to a more general study of the neutralization process. This work was divided between the transverse mode (electrons are emitted perpendicular to the ion velocity from boundaries surrounding the beam) and the longitudinal mode (the neutralizing electrons move in the same direction as the ions). In the latter case, a variation of the Pierce instability was studied by analytic theory and 2-D particle simulation techniques. The early work of Pierce showed that a 1-D neutralized electron beam bounded by conducting planes was unstable if $L\omega_p/V_0 > \pi$, where ω_p is the plasma frequency, V_0 is the electron velocity, and L is the system length. The simulations show that similar behavior results for an ion beam injected through a conducting plane into a vacuum with either injected or emitted electrons, although the details are complicated by 2-D effects. Heavy or medium mass ion reactors that do not incorporate a gas fill might have to contend with this instability.

Diode Physics and Focusing

Proto I Ion Beam Extraction Diode Simulations

(J. P. Quintenz and D. J. Johnson)

Initial numerical simulations of the Proto I ion beam extraction diode have been completed. The diode has a rather complex configuration and in order to model its behavior many of the diode code's features were employed. The various aspect ratios in the diode required the use of nonuniform zoning. The importance of applied and self-magnetic field effects required the inclusion of an A_θ solve to compute the B_r and B_z components of the field, subject to the imposed boundary conditions. The difficulties of the numerical simulation coupled with some experimental uncertainties demand that the results presented here be considered preliminary. Plans for future simulations will be discussed later.

The diode configuration as modeled by the code is shown in Figure 23. The diode consists of two annular cathodes opposite a hollow anode. Two sets of coils provide the applied magnetic field used to insulate the electron flow from the anode and provide the mechanism for the formation of a virtual cathode opposite the anode surface. The model is only approximate in that the actual diode has curved surfaces designed to produce a radially convergent ion beam. The dimensions in the model were chosen because they maintain the important parameters, such as A-K

gaps and coil positions relative to the anode surface within the constraints of the code.

Figure 23. Extraction Diode Configuration.

The three simulations discussed in this report investigate the effects of varying the coil currents I_1 and I_0 with all other diode parameters being constant. Of most interest are the variations of the electron and ion currents and the electron current density on the anode when the coil currents are varied.

For all of these simulations, the diode voltage was maintained at 1 MV. The inner gap (g_i) was 2.5 mm and the outer gap (g_o) was 3 mm. The coil radii were $r_i = 2$ cm and $r_o = 6$ cm. Both coils were located 1.6 cm from the anode surface. The region of immediate concern in this diode is in the gap region and near the anode surface. If a particle exceeds a distance of 2.3 cm from the anode surface, it is removed to economize on the number of simulation particles in the system. This approximates the condition that would prevail if the space charge was completely neutralized there. The distance is far enough from the region of interest that the results of the simulation will hopefully not be affected by this assumption.

Table 2 presents the important results from these three simulations. The vacuum equipotential plot is shown in Figure 24. Figure 25 shows the vacuum magnetic flux contours for Case 1083 in Table 2. Note the boundary conditions on the magnetic field. The field fully penetrates the outer cathode, partially penetrates the inner cathode ($A_\theta = 0$ at $r = 1$ cm instead of the inner cathode surface) and is fully

excluded from the anode. Figure 26 shows the magnetic flux contours after a steady state has been reached. These contours include the effects of the electron-produced self B_r and B_z . The consequence of including self B_r and B_z effects is that the total B_r component of the magnetic field can be reduced by as much as 20% near the cathode surface and increased by as much as 75% near the anode surface when compared with the applied field strength alone. This result underscores the importance of including these effects in analyzing a diode of this type. Figure 27 is an electron-particle map for this case. Figure 28 is an equipotential contour plot after a steady state has been reached. These simulations are provided to show expected trends when coil currents are varied. As the ratio of the inner to outer coil currents is increased, the electron loss region on the anode moves outward radially. The total electron-loss current is sensitive to the magnetic fields in both gaps. The best ion production efficiency (I_i/I_e) in these three simulations was about 0.4 with a total ion current of 65 kA. This should be contrasted with the most recent experimental results which indicate an ion production efficiency of $\frac{I_i}{I_e} \approx 1$ with a total ion current of 350 kA.

The reason for the significant difference between these simulations and the experimental results can be explained by comparing the latest experimental diode configuration with the diode model assumed in the simulations. These simulations were done before information on division of the feed conduction current was available from the experiment. The division assumed in the simulations was that electron current that is emitted from the inner cathode flows in as conduction current along the inner conductor of the magnetically insulated transmission line; current emitted from the outer cathode flows in as conduction current along the outer cathode. Under this assumption, the conduction current supplying the

inner cathode contributes to the B field in the A-K gap, but the conduction current supplying the outer cathode does not. (The beam currents from each gap contribute to the gap field). It has been shown experimentally that the appropriate current split is crucial to proper diode performance. This current split can be adjusted by varying the feed inductance and has been optimized to reduce electron current loss. The next series of simulations of the extraction diode will include the appropriate current division, together with other configuration changes, to model the latest experimental results. These simulations are under way. Once the remaining differences between the simulation model and the physical diode are resolved, the simulation code should prove to be a valuable tool in the process of optimizing this diode configuration.

Figure 24. Vacuum Equipotentials for the Extraction Diode.

Table 2. Summary of Simulations

Case No.	Coil Currents (kA)		Electron Current (kA)	Ion Current (kA)	Ratio of Ion Current to Electron Current	Applied Field and Gaps (kG)	
	Inner	Outer				Inner	Outer
1082	91	65	320	60	0.19	14	14
1083	182	65	160	65	0.41	24	14
1084	182	32.5	475	140	0.29	24	8

Figure 25. Vacuum Magnetic Flux Contours for the Extraction Diode.

Figure 27. Electron Particle Map for the Extraction Diode.

Figure 26. Self Plus Applied Magnetic Flux Contours.

Figure 28. Steady-State Equipotential Contours.

Numerical Simulation of the SMAUG Ion Diode

(J. P. Quintenz and
J. P. VanDevender)

Magnetically insulated ion diodes use magnetic fields (either self or applied) to inhibit electron motion from cathode to anode and thereby increase the fraction of the total diode current which flows in the form of ion current. The extraction diode described in the preceding section is an example of a diode that uses an applied magnetic field to achieve electron insulation. In this section, we describe the SMAUG diode that uses the self-magnetic field produced by the diode current itself to accomplish insulation.

The SMAUG diode is fed from a self-magnetically insulated coaxial line near axis. The plasma covered anode and the thin foil cathode flare out, as shown in Figure 29. The gap d between the anode the cathode increases with radius so that the net current at any radial position self-magnetically insulates the electron flow.

In order to understand more fully the experimental results obtained with the SMAUG ion diode and to attempt to predict how this diode configuration might scale with changes in voltage, impedance, and other parameters, a computer code has been developed to simulate this experiment. This diode, as modeled by the code, is shown in Figure 29. The computer code used to model this experiment is the particle-in-cell code described in this report with the added complication of including ion emission from the slanted anode surface.

Since the diode consists of a tapered anode opposite a planar cathode, a model for accurately representing the space charge limited emission of ions from a slanted surface is needed. The model obtained is similar to that described for electrons¹ with the modified Childs-Langmuir law replaced by a Gauss' law scheme.² This scheme uses the computed electric field near the emission surface together with the space charge limited emission conditions (the electric field on the emitting surface is zero) to determine, via Gauss' law, the required charge enclosed in the specified volume. Enough charge is added to the volume to satisfy this condition. This model has been compared with analytic monopolar 1-D results with excellent agreement.

The first simulations using this model are for the experimental configuration described elsewhere in this report. Figure 29 is an electron particle map for this geometry with a few sample electron trajectories shown. Each dot in this figure describes a simulation

particle location (each simulation particle representing typically $\sim 10^9$ - 10^{11} electrons in the physical system) at one point in time after a steady state has been reached. In this figure, the r and z axes are drawn to a different scale and hence the actual 82° taper angle appears to be about 45° . This figure displays an important feature of the electron flow in this configuration. The electron orbits are tightly trapped at small radius where the insulating magnetic field is strongest. As the radius increases, the orbit excursion into the anode cathode gap increases. This is due to the decrease in magnetic field strength caused both by the $1/r$ field fall off and the decrease in total enclosed current due to ion flow. For an assumed diode voltage of 1 MV (near the peak experimental diode voltage), the simulation predicts an electron current of 360 kA and an ion current of 45 kA. These values are plotted on the experimental current and impedance traces of Figure 30; the agreement is quite good. To compare the simulation with experimental carbon activation results, the ion trajectories in the code were projected ballistically in the force free region between the cathode foil and the collector, using the ion exit angle at the foil. The ion charge was accumulated in bins corresponding to the experimental carbon block size. The results of this comparison are shown in Figure 31. The agreement is again quite good with differences most probably due to some small radius gap closure, ion impurities, and incomplete space-charge or current neutralization in the drift region present in the experiment but ignored in the simulation.

Figure 29. Electron Particle Map of SMAUG Simulation with Sample Electron Trajectories (note different r and z scales).

Figure 30. Current and Impedance Traces. Simulation results shown as broken line.

Figure 31. Carbon Activation Results. Simulation results shown as solid blocks.

To investigate the effects of ions on magnetic insulation in this configuration, a simulation has been performed without ions. In this case, the simulation predicts an electron current of 230 kA drawn by the diode which is in good agreement with the experimental result of 200 kA obtained when the anode did not "turn on" and emit ions. Figure 32 is a plot of the computed ion current density vs radius for simulations in this configuration with and without electrons. The ion current density is enhanced by as much as a factor of 2 over the single species result when electrons are present. The enhancement varies with radius as expected. Near the inner radius of the anode (where the electrons are overtrapped), there is little ion current enhancement. At the large radius where the electron flow is saturated, the enhancement is very near the expected bipolar-flow value.

Figure 32. Comparison of Ion Current Density in SMAUG Simulations With and Without Electrons.

In the SMAUG diode configuration, the impedance varies with the radius from a value of about 18 Ω at the inner radius to near 9 Ω at the outer radius. The simulation results demonstrate that, in a variable impedance geometry, the magnetically insulated line tends to run at the minimum impedance value. The simulation results for the SMAUG diode are plotted on the Z/Z_0 vs voltage curve of Figure 33 as triangles. (The case with both electrons and ions is represented as an open triangle; the case with electrons only, as a solid triangle.) For these points, Z_0 was chosen to be the minimum impedance of the tapered A-K gap of 9 Ω . The simulations confirm the experimental results which indicate that $V/I_T Z_0$ is 40% less with ions than it is without ions.

Figure 33. Summary of Various Simulation and Experimental Results.

The model has been used to investigate diode scaling with voltage. A new constant impedance configuration was chosen for these simulations. The

diode considered has a constant impedance ($Z_0 = \frac{60d}{R}$) of 9Ω . Simulation results for two different voltages are plotted in Figure 33 as circles. These results indicate that over this range the value of Z/Z_0 is insensitive to voltage changes. If, in this configuration, ion emission is suppressed in the 2-MV case, the value of Z/Z_0 increases again by about 40%. This result is plotted in Figure 33 as a square. As a final simulation, a diode with characteristic impedance of 18Ω at 2 MV has been considered. The resulting value of Z/Z_0 , plotted in Figure 33 as an asterisk, indicates insensitivity to changes in characteristic impedance.

These simulations have proven useful in the interpretation of the experimental SMAUG diode results. The scaling information provided by the code has been used in the analysis of a 4π version of this concept.

Diode Code Development (M. M. Theimer, J. P. Quintenz)

The original particle-in-cell (PIC) diode simulation code developed at Sandia in the early 70's has undergone a continual evolution since its inception.^{1,3-6} Both electron and ion diodes have been investigated with the code providing information on particle currents and flow patterns. A wide variety of diode configurations have been tested successfully. During the code's development, an effort was made to make the code general enough to treat the wide variety of applications that have arisen in the past and to anticipate some of the needs of the future. The increase in code generality has been coupled with improvements in the code structure which make code use much easier.

Recently, as simulations became more involved and time consuming, a need to improve the code efficiency (especially as measured in run time) was realized. Since most of the code's execution time is involved with particle pushing (advancing particles through their self-consistent electric and magnetic fields), this was the logical part of the code in which to begin an optimization process. Changes have been made to the code with two goals in mind: to improve the overall run time and to make a smooth transition in the eventual transfer of the code to a CRAY-1 computing system. A detailed description of these changes can be found elsewhere.⁷ A summary of these changes and their results is presented here.

The first change made in the code was that of the particle pushing algorithm. Several pushing schemes were considered for accuracy and execution time; the

ease of vectorization was evaluated in each. A self-starting predictor corrector integration scheme was chosen as the best method to incorporate in the diode code to advance the particles. This scheme was vectorizable with the least amount of required extra storage. The accuracy and speed of the algorithm are comparable with other second order schemes. The new integration scheme and the field interpolation code have been vectorized. The remaining sections of the particle pushing code are conditional in nature and cannot be vectorized.

Vectorization was performed primarily in anticipation of eventually transferring the code to a CRAY-1 computing system. A second consideration was a possible increase in the addressing efficiency of variables in memory. This improvement results because vectorization usually produces longer code sequences* that allow an optimizing compiler to overlap more efficiently computational and memory access instructions. However, this type of improvement is highly machine- and code-dependent and the amount of reduction in run time achieved through the increased code sequence length in this code has not been investigated in detail.

The cost of vectorization has been an increase in storage requirements of about 5%. This additional storage requirement was minimized by revising temporary storage arrays as much as possible. The resulting particle pushing code which can be expected to run between 5 and 10 times faster on a CRAY-1 than original scalar version did, and which has a program structure that is more easily optimized by the optimizing compilers available on the Sandia CDC computers is well worth the additional storage expense.

The subroutine and decision-making structures of the diode code's particle pusher have been revised in order to streamline the algorithm and to facilitate vectorization. Two changes yielded the greatest improvement in efficiency: minimizing the number of subroutine calls made and a revising the method of checking for particle surface encounters. Minimizing the number of subroutine calls is also necessary for purposes of vectorization.

The original code called several subroutines for each particle during each time step. By rewriting these subroutines so that they performed their function on all simulation particles in the system at once rather than just on one particle per call, the overhead of performing numerous subroutine calls with their associated parameter setup and transmissions was nearly eliminated.

* A code sequence is a section of code containing no branching instructions or statement labels.

Revision of the particle surface encounter check yielded similar benefits. By creating a two-dimensional array which contains all surface information (encoded in integer form) pertinent to each mesh zone of the simulation region, it was possible to reduce the check down to a single memory access and comparison instruction. This one statement check was then placed outside the surface encounter subroutine so that the subroutine was called only if a surface had actually been encountered. (Less than 1% of all particles in the system encounter a surface during any given time step in most simulation runs.) The cost for this revision was an additional storage requirement of about 5%. All other changes in the code that resulted in vectorization or enhanced efficiency accounted for an additional 5% increase in storage requirements.

As a check of the new code version, a diode test case (consisting of a hollow cathode opposite a planar anode) was run with three progressively smaller time steps and correspondingly larger number of simulation particles. The same test cases were also run with the original diode code as a comparison. In all cases, the steady state convergence rates were essentially the same and all important simulation quantities varied by $\leq 1\%$. Table 3 lists the time steps, steady-state particle numbers, average currents, and execution times of each of these test cases. As can be seen, the new version of the diode code runs between two and three times faster than the original version does. At even larger particle numbers, this factor may be even better.

In conclusion, the revision of the particle pusher in Sandia's diode code has reduced the program's execution time for a typical simulation case by a

factor of 2 to 3 from that of the original version while still retaining comparable accuracy. The cost of this optimization has been an increase in storage requirements of about 15%. The new version has also been structured to run efficiently on a CRAY-1 computing system in anticipation of a possible additional decrease factor of 5 to 10 in execution time over that attainable on nonvector machine such as a CDC-7600.

TRIDIF, A Triangular Mesh Magnetic Diffusion Code (J. R. Freeman)

The design of conventional dc magnets for plasma physics or high-energy accelerator experiments has been greatly aided by the development of numerical codes that compute the magnetic fields produced by specified current and magnetic-material distributions. The more advanced of these codes have included the capability for treating curved or irregular boundaries,⁸ variable permeability, and three dimensional field distributions.⁹ Recent designs^{10,11} for ion beam inertial confinement fusion diodes employ pulsed solenoidal fields in which the current risetime is shorter than the flux diffusion time in the electrodes of the diode. This provides a means for giving the fields proper shaping for good beam focusing. The problems facing the designers here require not only much of the sophistication of the conventional magnet-design code, but also the capability for including a calculation of the time dependent diffusion of the magnetic flux and the eddy currents in the surrounding media.

**Table 3. Run Statistics for Hollow-Cathode Diode Test Case
(Total simulation time was 0.3 ns)**

Version	Time Step (10^{-13} s)	Steady-State Particle Number	Av. Electron Current (10^6 amp)	Av. Ion Current (10^6 amp)	Execution Time (s)	Ratio of Old-to-New Version Execution Times
Old	3.00	4540	.10836	.011713	2450	2.15
New	3.00	4755	.10885	.012080	1142	
Old	1.50	9280	.10920	.013509	8170	2.49
New	1.50	9160	.11030	.013531	3284	
Old	0.75	18470	.10712	.013960	35966	3.08
New	0.75	18920	.10883	.014330	11691	

TRIDIF is a code that solves the finite difference representation of the diffusion equation,

$$\frac{\partial A}{\partial t} = - \frac{1}{\mu_0 \sigma} \nabla \times \nabla A$$

using a two-dimensional triangular spatial mesh. Each mesh point is surrounded by six nearest neighbors. The time integration uses fully implicit centered differencing. At each time step, the difference equation is ordered to resemble that usually used for triangular mesh solvers⁸ of Poisson's equation. The alterations required for the time derivative term include modifying the source term in Poisson's equation and changing the coefficient that multiplies the central point of the basic seven-point mesh module. A fast, direct matrix inversion method¹² is used at each time step to satisfy the difference equation exactly at each mesh point. This method was included to overcome convergence difficulties that occurred when a standard successive overrelaxation method was attempted initially. These problems were most severe for large meshes that contained very fine zoning in one portion and coarse zoning elsewhere. The speed and reliability of the matrix method is essential for time dependent problems which can include thousands of time steps.

TRIDIF is basically a modest extension of the existing code SUPERFISH, published by Halbach and Holsinger.¹² SUPERFISH provides an attractive foundation for many reasons. A triangular mesh provides an excellent description of curved and irregular surfaces. An optimizing automatic mesh generator that is part of the code reduces the time required to zone a problem. The code can treat problems with regions of vacuum, sources, or metal conductors; the boundary conditions can be Neumann or Dirichlet. Cartesian or cylindrical geometry are options.

Magnetic flux that diffuses into the anodes of cylindrical ion diodes reduces their focusability. The ions are emitted with a nonzero canonical angular momentum that prevents them from reaching the axis of the cylinder.

Figure 34 shows sample results from the code for the Proto I ion diode experiment. The lower boundary is the axis of symmetry and the left-hand boundary is a plane of symmetry. The field coils are driven

by two capacitor banks that drive currents in opposing directions. The first produces a negative field of 2 to 4 kG at the anode with a 1-ms risetime. The second bank is triggered near the time of peak negative current; it generates about a 15 to 20 kG positive field with a 0.07-ms risetime. The combination provides a way for reducing the total flux at the ion emission surface and increasing the focusability. Figure 35 shows an expanded view of the computational mesh; the good resolution of curved surfaces which the triangular mesh provides is evident. The streamlines produced by the initial slow risetime bank are shown in Figure 36. The absence of numerical ripple is apparent. Work is underway to study the effects of azimuthal anode grooves (required for anode plasma uniformity).

Figure 34. Magnetic Field Lines for the Proto I Ion Diode at the Risetime of the First (Slow) Capacitor Bank.

Figure 35. Triangular Grid Used for the Case Shown in Figures 34 and 36.

Figure 36. Expanded View of the Streamlines in the Metal Anode for the Case of Figure 34.

Beam Propagation

Multichannel Proton Beam Overlap Studies

(T. P. Wright)

Overlap and symmetry calculations are being performed for 2.0-MeV protons in the 36-beam, 3-disk arrangement of current-carrying plasma channels shown in Figure 37. Results of two cases studied to date are reported. The channel currents, radii, and maximum ion injection angles for the two cases were 65 kA, 0.6 cm, 8° and 100 kA, 1.0 cm, 16° , respectively.

Figure 37. Geometrical Configuration for a 36 Beam, 3-Disk Channel Arrangement.

Profiles of overlap current density gain and fraction of protons reaching a given target radius are shown in Figure 38. The poor efficiency in the 16° case is due to the larger ion divergence angle inside the overlap radius and the larger overlap radius due to the larger channel size. The geometrical limit¹³ on the gain for cold beams with 100% efficiency is $N/4 = 9$; these results show that proton beam overlap works quite well. Higher overlap gains can be obtained at the expense of efficiency. However, since high power and high efficiency are both desirable, and since channel transport is easier for lower beam-injection angles, efforts to produce beams with injection angles below 10° are underway.

Figure 39 shows the symmetry in the incident ion flux at the surface of targets of various sizes for the 8° case. The incident flux in 10° latitude bands was normalized to the flux in the first 10° band at the equator. The large flux variations and lower polar

flux seen in the larger targets is due to the relatively high degree of separation of the beams from the three disks. The symmetry improves for the smaller targets where there is more overlap of the individual disk sources.

Figure 38. Overlap Current Density Gain and Transport Efficiency for Two Cases: (a) Channel Radius = 6 mm, Maximum Ion Injection Angle = 8°; (b) Channel Radius = 10 mm, Maximum Ion Injection Angle = 16°.

Figure 39. Equator-to-Pole Flux symmetry (normalized to equatorial value), as a Function of Target Radius.

Figure 40 shows the average angle of incidence of the protons on the target surface in 10° latitude bins. The average angle increases toward the pole (as expected) and the spread narrows. This information is useful for detailed ion deposition studies in target design.

Figure 40. Average Angle of Incidence With Respect to Surface Normal as a Function of Latitude for Several Target Radii.

For a spherical target of 0.6-cm radius, the results can be summarized as

Beam Injection Angle	8°	16°
Overlap Gain	7.7	9.1
Efficiency	85%	37%
Asymmetry (equator to pole)	32%	33%

These results for ion overlap are encouraging and further studies are underway.

Ion-Charge Exchange and Energy Loss in Plasma and Channels (T. P. Wright, T. A. Green, and T. A. Mehlhorn)

In reactor scenarios of light ion beam transport along plasma channels, there is the possibility that charge exchange can cause ion-beam diffusion out of the channel. A Monte-Carlo transport code was written to study this question; it appears that, at ion energies above 2 MeV/nucleon, charge exchange spreading of the beam is a second order effect which will not seriously affect beam transport.

The Monte-Carlo code transports ions in an applied uniform current density plasma channel. The maximum ion-injection angle is determined from the total channel current, ion energy, and ratio of initial beam area to channel area. The exact trajectories are computed with charge exchange cross sections calculated from semiempirical formulas developed from

results found in the literature. Energy loss along the trajectory is calculated using the continuous slowing down approximation (CSDA).¹⁴ Carbon ions in air plasma channels have been studied using carbon-nitrogen charge exchange cross sections. The plasma channel radius was taken to be 1.0 cm and the plasma current was 100 kA. The plasma parameters were selected based on MHD code simulations of air plasma channel formation.¹⁵ The mass density in the expanded channel was taken to be 10^{-6} g/cm³ and the temperature was 10 eV which gave an average ionization state of 3 for the nitrogen. The injected beam radius was fixed at 5 mm and the channel length was 3 m.

Two cases were studied, 16 MeV C⁺⁴ and 26 MeV C⁺⁴, in order to obtain some scaling with ion energy. The former case was chosen because 16 MeV C⁺⁴ ions could be produced by PBFA I and experimental comparisons could be made with the calculations. The latter case is more relevant to ICF scenarios since ion energies ≥ 2 MeV/nucleon are needed according to target calculations. Figure 41 shows a sample ion trajectory for the 26-MeV case with electron-capture events indicated with a downward-pointing triangle and stripping events indicated with an upward-pointing triangle. Results of the two cases are

E_0	$\theta_{\max}$	$\bar{N}$	$\bar{\Delta E}$	ϵ_p	$\bar{Z}_f$	ϵ_E
16 MeV	10°	77	2.9 MeV	.81	4.9	.66
26 MeV	9°	32	2.2 MeV	.94	5.4	.86

where

- $\theta_{\max}$ is the maximum ion injection angle,
- $\bar{N}$ is the average number of charge exchanges,
- $\bar{\Delta E}$ is the energy lost,
- ϵ_p is the particle transport efficiency
- $\bar{Z}_f$ is the average carbon charge at the end of the channel, and
- ϵ_E is the net energy transport efficiency.

For the 16 MeV case, the fractional energy loss per particle (CSDA) and fractional particle loss due to charge exchange are about the same, whereas in the 26 MeV case, the fractional energy loss per particle is larger than the fractional particle loss.

We infer from these results that light ion beams with energies in excess of 2 MeV/nucleon will strip to an average ionization state close to fully stripped; the net effect will be to assist beam confinement in the channel and increase beam energy loss. The

efficiency of beam energy transport depends primarily on collisional energy loss and charge exchange appears as a secondary loss.

Figure 41. Sample Carbon Ion Trajectory in 3-m Channel. Injected energy and charge state were 26 MeV and +4. Stripping events are indicated by an upward-pointing triangle and capture events are shown by a downward-pointing triangle.

Calculated Electron Deposition Levels Sufficient to Drive ICF Targets

One of the factors that led to the shift to ions as the primary driver for ICF targets was that deposition levels were too low (~ 1 TW/g/MA). Although other factors may still make ions look more favorable deposition no longer seems to be a stumbling block. We have recently calculated electron deposition in excess of 100 TW/g/MA in thin, Cu foils and in thick paralyne targets using the Grad-B drift transport, bunching, and focusing mechanisms as reported by Halbleib, Wright, Ottinger, and Goldstein.^{16 17}

The Grad-B transport involves a hollow current-neutralized electron beam propagating by axial Grad-B drift in an azimuthal magnetic field generated by a wire or rod on axis. Since the axial drift depends linearly on the accelerating voltage of the diode, beam bunching by voltage ramping can be accomplished perhaps more easily than for ions. Ottinger

and Goldstein¹⁷ have reported that bunching factors of 5 are reasonable. Also, by rapidly changing the magnetic field at some axial location, the drifting electrons can be made to reflex and focus as reported by Halbleib, Wright, and Goldstein.¹⁶ Figures 42a and 43a show two possible realizations of foil and plasma-gradient transitions. Figures 42b and 43b show representative electron trajectories from a Monte Carlo transport code. For the thin foil cases, the beam strikes the foil over an area determined by the beam radius ($r_b = 3$ mm in this case), and subsequently reflexes and focuses to a smaller radius. In the plasma gradient transition, the beam focuses down to the Alfvén radius ($r_A = 0.9$ mm in this case) before it strikes the thick target.

Mean specific power depositions (MSPD) without any bunching obtained in the calculations were:

Thin foils (5/25 μ m Cu)

MSPD inside $r_b = 3$ mm 100 TW/g/MA

Peak MSPD at $r = 0.5$ mm 140 TW/g/MA

Thick Target (paralyne)

MSPD inside $r_A = 1$ mm and

depth = 0.5 mm 50 TW/g/MA

MSPD inside $r = 0.5$ mm,

same depth 100 TW/g/MA

Figure 42. (a) Schematic of Grad-B Drift Transport Region with Thin Foil Transition. (b) Sample Electron Trajectories Showing Reflexing and Focusing at the Foil Target.

Figure 43. (a) Schematic of Axial Plasma Gradient Transition. (b) Sample Electron Trajectories Showing Collisional Focusing in Front of the Thick Target.

Without bunching, these deposition levels are 2 orders of magnitude higher than obtained in previous studies by Halbleib and Wright.¹⁸ With a factor of 5 from bunching and a beam current of 0.5 MA/beam, the power deposition corresponding to 100 TW/g/MA is 250 TW/g/beam without any overlap enhancement. The deposition in a carbon ablative target should be at least as good as in the paralyne because it is more dense. With an overlap factor of 2 on a 1-cm-dia 700-mg carbon target, this amounts to a deposition level of 110 TW/cm² which is in the range needed for ablative magnetic target designs according to earlier calculations by Sweeney and Farnsworth.¹⁹

Questions of channel overheating due to high bunched beam-current density and a realistic spherical beam transport configuration still need to be addressed.

Pulsed Power Development

Equivalent Circuit Modeling of Asymmetry Effects in Magnetically Insulated Transmission Lines (D. B. Seidel)

A method of modeling asymmetries in magnetically insulated transmission systems has been developed using equivalent circuit techniques. In particular, this method has been used to consider lack of symmetry due to nonsimultaneous switching and its subsequent effects on magnetic insulation. The rationale for adopting an equivalent circuit approach is that it is tractable, whereas the alternative of a fully self-consistent, three-dimensional, time-dependent particle code clearly is not.

The method is simply a generalization of earlier work by Bergeron²⁰, whose technique for a uniform, symmetrically driven transmission line has been extended to allow for variations in both line geometry and sources in two dimensions. As a result of this allowed variation, when Maxwell's equations are integrated over a small section of line (Figure 44), a more general form of the telegrapher's equation is obtained that describes the equivalent circuit in Figure 45. Since higher order (non-TEM) modes are neglected in this approach, it is required that the geometry vary slowly, relative to the conductor separation. For each section of line, the circuit parameters

L , C , and G must be determined by the appropriate integration of the static field over the line section. In addition, the conductance G varies nonlinearly with voltage and current as described in Ref. 20. However, here a slightly different model (boundary current model²¹) for the critical insulating current has been used that exhibits better agreement with experimental results.²¹ Solution of the network that results from the connection of the equivalent circuits modeling each section can be accomplished numerically using the computer code SCEPTRE.²² Two examples of this technique follow.

Figure 44. Sample Transmission Line Section on Radial Disc Line.

Figure 45. Equivalent Circuit for Transmission Line Section.

Effects of Nonsimultaneity on the Central Convolute for PBFA-I (D. B. Seidel and J. P. VanDevender)

For several diode concepts currently envisaged for PBFA-I, a central convolute structure will be required that combines the 36 magnetically insulated transmission lines (MITLs) into a common radial disc feed. However, lack of simultaneity between the pulses in the 36 MITLs could conceivably have a disastrous effect upon magnetic insulation in the central feed. Simulations of this phenomenon have been performed using equivalent circuit techniques²³ for a conventional ion-diode type load and for a plasma-filled ion diode²⁴ load.

Figure 46 shows the geometry under consideration. Six radially converging MITLs, each of which represent 6 of the 36 PBFA lines in parallel, feed a radial-disc triplate feed with inner and outer radii of 20 cm and 50 cm, respectively, and a 3.5-mm plate spacing. The last 95 cm of each MITL is modeled using two equivalent circuit sections and the disc is divided into three radial and six azimuthal sections. Each MITL is driven with a matched voltage source with a 1-ns risetime, 10-ns fall time, 40-ns pulse-width, and 4.8-MV open circuit voltage. Each line's pulse can be arbitrarily delayed in time. The innermost sections of the disc feed are then connected to the central load whose impedance is given by an appropriate circuit model for the particular diode.

Figure 46. Equivalent Six-Line PBFA-I Geometry.

For the case of a conventional Child-Langmuir diode, we let the load resistance be proportional to $V_L^{-1/2}$ (V_L is the load voltage). The proportionality constant is chosen to match the diode to the line at the desired operating voltage. For the case of a plasma-filled ion diode, we assume the electrons are magnetically insulated and the ions are limited by Child-Langmuir flow across an A-K gap, which is time varying due to plasma erosion,²⁴ i.e.,

$$R_L = \frac{9x^2}{4A} \sqrt{\frac{m_i}{2eV_L}}$$

$$x = (n_0 e A)^{-1} I_L$$

$$x(0) = 0$$

where x is the A-K gap, A is the anode surface area, m_i is the ion mass, e is the ion charge, and n_0 is the plasma-fill density. The differential equation for x is solved simultaneously with the circuit solution.

The effects of nonsimultaneity on the performance of the conventional space charge limited ion diode is examined by delaying the pulse inputs as shown in Figure 47. These delays were obtained by randomly arranging the expected values of six events with a standard deviation of 3 ns, which is predicted for the PBFA accelerator.²⁵ Figure 48 shows a comparison of energy delivered to the load and energy lost to leakage due to loss of magnetic insulation for symmetric and asymmetric incident pulses. We see that the asymmetry severely degrades performance. Figure 49 shows a comparison of load currents for both cases as well as the leakage current over one of the central disc feed sections. We see that the asymmetry causes the major part of the current to be delivered to a point off-center in the feed where the nonsimultaneous pulses converge.

Figure 50 shows a similar comparison of energies for the plasma-filled ion diode. For this example, we assume protons with a fill density of $2.5 \times 10^{15} \text{ cm}^{-3}$ and an anode surface area of 0.25 m^2 . Again, we see that the asymmetry degrades performance, but not to the extent of the previous example. In addition, the diode voltage waveform (Figure 51) is ideal for bunching, and this is not affected by lack of simultaneity.

Figure 47. Pulse Arrival Time Asymmetry.

Figure 50. Energy Delivered to Load and Energy Lost to Leakage for Both Symmetric and Asymmetric Excitations With a Plasma-Filled Ion Diode Load.

Figure 48. Energy Delivered to Load and Energy Lost to Leakage Due to Loss of Magnetic Insulation for Both Symmetric and Asymmetric Excitations. The load is a magnetically insulated, space charge limited ion diode.

Figure 49. Comparison of Currents Between the Symmetric and Asymmetric Excitations With a Magnetically Insulated, Space-Charge-Limited Ion Diode Load.

Figure 51. Comparison of Voltages Between the Symmetric and Asymmetric Excitation With a Plasma-Filled Ion Diode Load.

Results so far have indicated that the effects of nonsimultaneity are strongly dependent upon the diode load. Not surprisingly, diodes with low early-time impedance (e.g., plasma-filled diodes) perform best with nonsimultaneous MITL pulses. Future efforts will involve using this technique to help design convolutes that minimize these unwanted asymmetric effects for various diodes.

Modeling of Nonsimultaneity Effects on Imploding Liners Driven by Proto II

(D. B. Seidel and D. H. McDaniel)

Recent experiments²⁶ on the Proto II accelerator indicate an important dependence of performance upon switching simultaneity. This dependence has been numerically simulated using equivalent circuit techniques²⁷ with the SCEPTRE code.²⁸

For modeling purposes, the magnetically-insulated, tapered radial disc feed is divided into eight equal pie sections, each of which is subdivided into three sections radially. Each of the outermost sections is driven with a matched voltage source using the Proto II voltage profile. Each source can be arbitrarily delayed in time. The innermost sections feed a central load, which in this case is an imploding liner.

Modeling of the liner's impedance is complicated because the liner is moving, and thus its inductance is time-dependent. If we assume the impedance is purely inductive, then the voltage across the load is

$$V_L = \frac{\partial}{\partial t} (L_L I_L) = L_L \dot{I}_L + \dot{L}_L I_L \quad (1)$$

Although the SCEPTRE code does not allow for time-varying inductances or capacitances, a series resistance equal to $\dot{L}_L$ will effectively produce the voltage drop prescribed in Eq (1). As long as $\dot{L}_L$ is greater than zero, L_L and $\dot{L}_L$ can be obtained dynamically by using SCEPTRE's capability of solving first-order ordinary differential equations (with time as the independent variable) simultaneously with the circuit solution. We thus additionally solve

$$\dot{L}_L = - \frac{\mu_0 \ell_0}{2} \frac{v}{r} \quad (2)$$

$$\dot{r} = v \quad (3)$$

$$\dot{v} = - \frac{\mu_0 \ell_0}{4\pi m} \frac{I_L^2}{2} \quad (4)$$

where μ_0 is the permeability of free space, ℓ_0 is the axial length of the liner, m is the liner mass, and r and v are the liner's radial position and velocity, respectively. Equation (2) is obtained by noting that $\dot{L}_L = [\partial L_L / \partial r] \dot{r}$ and (3) and (4) are simply the equation of

motion of the liner due to the $\frac{B^2}{2\mu_0}$ pressure.

As an example, consider a liner with a mass of 9.6×10^{-4} g, a length of 2.0 cm, and initial radius of 0.635 cm. The arrival times of the input pulse (2.5-MV peak open-circuit voltage) are delayed corresponding to measured delays from a typical experimental shot (see Figure 52) on Proto II. Figure 53 shows a comparison of the energy lost to leakage current due to loss of magnetic insulation for this case compared to a similar run with no delay between the eight pie sections. The total available energy to a matched load is 216 kJ. Figure 54 shows a similar comparison for liner kinetic energy. As one would expect, loss of symmetry increases losses due to magnetic insulation breakdown at the expense of the liner's velocity. However, even for the asymmetry shown in Figure 52, leakage losses represent less than 10% of the total available energy. This tends to indicate that delays comparable to those shown in Figure 52 will not lead to catastrophic breakdown.

Simulation of Radiation Losses in the MITE High Voltage Experiment

(D. B. Seidel)

Recently, the water convolute has been tested on the MITE accelerator. One area of concern was energy loss through radiation at the line's termination. This termination (Figure 55) consisted of abruptly ending a parallel plate line 60 cm wide with a plate separation of 30 cm. At this point, three 5-cm-diameter copper sulfate resistors spaced 20 cm apart were placed across the line. In addition to radiation losses from the open-ended waveguide, there are dispersive effects due to the capacitance of the abruptly-ending parallel plates and the resistive grating's inductance.

Figure 52. Pulse Arrival Time Asymmetry.

Figure 53. Energy Lost to Leakage Currents Due to Loss of Magnetic Insulation for Both Symmetric and Asymmetric Excitation.

Figure 54. Kinetic Energy of Imploding Liner for Both Symmetric and Asymmetric Excitations.

Figure 55. Termination Geometry

A rudimentary low frequency analysis can be applied to this problem using variational solutions for the circuit parameters of the open-ended parallel plate waveguide²⁹ and the inductive grating.³⁰ These solutions are valid for $b/\lambda < 1$ and $a/\lambda < 1$, respectively, where λ is the wavelength of propagation in the medium. Figure 56 shows the combined circuit representation of the termination, where G and B are the radiation conductance and the susceptance, respectively, of the open-ended guide; X_a and X_b are the reactive parameters of the grating. R_L is the parallel resistance of the copper-sulfate resistors.

Figure 56. Equivalent Circuit Representation of Termination.

If a time-harmonic source $V_0 e^{i\omega t}$ is assumed, the circuit can be solved for $I_L(f)$, the total current through the load resistors at frequency $f = \omega/2\pi$. We can then define a transfer function

$$E(f) = \frac{I_L(f)}{I_L(0)}$$

and a phase shift

$$\phi(f) = \arg[I_L(f)/I_L(0)]$$

$E(f)$ can be interpreted as attenuation of the current due to high frequency radiation and reactive effects. Similarly, ϕ is a measure of dispersion; i.e., linear phase shift representing no dispersion.

Figure 57(a) and (b) shows E and ϕ as a function of f for R_L equal to both 16Ω and 40Ω . Also plotted is the function

$$A(f) = \left| \frac{V_s(f)}{V_s(0)} \right|$$

where $V_s(f)$ is the frequency spectrum of the source voltage pulse from the MITE experiment. We see that $E(f) > 0.9$ over the 3-dB bandwidth of the source pulse even with R_L as high as 40Ω (characteristic line impedance Z_0 is 20.9Ω). Also, over this bandwidth, $\phi(f)$ is essentially linear. As a result, these high-frequency effects upon the load current are slight and their omission will not cause significant error; the power lost to radiation and dispersion will be relatively small.

Figure 57. High Frequency Attenuation Effects Upon Load Current

The Motion of Single Electrons in Inductive Fields (J. W. Poukey)

The problem of magnetic insulation in radial lines that feed imploding liner loads continues to evade a comprehensive theoretical treatment. The problem is time dependent and the feed geometry is complex, so simulating the device for the entire pulse time with an electromagnetic particle code has not been attempted. Rather, we have looked for simpler problems that can be solved more easily and will hopefully shed light on the system behavior. One such problem is the question of "When will an electron return to the cathode?" Some answers to this question were reported in the previous Semiannual. In uniform constant $\vec{E}$ and $\vec{B}$ fields, where $\vec{E}$ is perpendicular to $\vec{B}$, the orbits of electrons which start at the cathode with zero energy are perfect cycloids, with the electron just "touching" the cathode surface at each bounce. If $\vec{E}$ and/or $\vec{B}$ are allowed to vary spatially, the resulting orbits depend on the form of the variations, but energy conservation precludes the possibility of an electron ever reaching the cathode with finite energy. Several examples, with $\vec{B}$ varying along the cathode and $\vec{E}$ varying perpendicularly to it, were discussed previously; the main result of the previous study was that for typical Proto II parameters, the electrons $\vec{E} \times \vec{B}$ drift parallel to the cathode, while ∇B drifting away from it towards the anode.³¹

A logical next step is to consider electron behavior near a cathode when a spatially uniform, but temporally varying, $B_z(t)$ is applied. As shown in Figure 58, we work in a Cartesian system bounded on three sides by conductors but open at the top. We compute the motion of an electron emitted from the cathode with initial conditions $x = 0, y = y_0, \vec{v} = 0$. The fields (from Maxwell's equations) are

$$B_z = B_z(t), E_x = \dot{B}_z y \quad (5)$$

where "dot" denotes $\partial/\partial t$. As an interesting side comment, note that the drift of an electron, if it gets away from the cathode, will be

$$\vec{V}_D = - \frac{\dot{B}_z}{B_z} y \hat{y} - \frac{m}{e} \frac{\ddot{B}_z}{B_z^2} y \hat{x} \quad (6)$$

so that (for typical parameters) the main drift will be parallel to the cathode, and the "inertial" drift will be towards or away from the cathode, depending on the sign of $\dot{B}_z$. The radius of the orbit curvature as it drifts may be deduced using magnetic moment invariance.^{32,33} The trajectory equations when $B_z(t)$ is linear (that is, $B_z(t) = B_0(1 + \alpha\omega_c t)$) are (scaling lengths to y_0)

$$\alpha^2 y'' + T y = T, y(1) = 1, y'(1) = 0 \quad (7)$$

$$x(T) = \int_1^T \frac{1 - Ty(T)}{\alpha} dT \quad (8)$$

where $T \equiv B_z(t)/B_0$, $\omega_c \equiv eB_z/m$, and ω_c^0 is ω_c at the time the electron leaves the cathode. Note the problem depends only on the parameter α , the fractional change in B_z in a time ω_c^{-1} . Equations (7) and (8) were solved for various α using a 3rd order Runge-Kutta scheme. The main result is shown below:

Case	Result
1. $B_z < 0, B_z $ increases	Electron always returns to K with finite energy
2. $B_z > 0, B_z $ decreases	Electron never returns to K
3. $B_z < 0, B_z $ decreases	Electron never leaves K
4. $B_z > 0, B_z $ increases	Electron never leaves K

In Case 1, the time to return to the cathode T_{ret} was computed for various α :

$2\pi\alpha$	T_{ret}	$\omega_c^0 t_{ret}/2\pi$
0.01	1.0097	0.97
0.05	1.046	0.92
0.10	1.088	0.88
0.50	1.362	0.72

Note that as $\alpha \rightarrow 0$, the result approaches the usual cycloid, with $\omega_c^0 t_{ret} = 2\pi$. For larger α , the B_z increases faster so the electron is brought back sooner. Trajectories for $2\pi\alpha = 0.01$ and 0.50 are shown in Figure 59. (The orbits have been continued after the electron hits the cathode in recognition of the possibility that the emitting surface is a plasma.)

In Case 2, for small α the orbit is again nearly a cycloid, but now the minimum X reached is always slightly greater than zero. For large α , the electron always moves away from the cathode, because E_x is larger at larger y . This is illustrated in Figure 60, for $2\pi\alpha = 0.5$. In Cases 3 and 4, $E_x > 0$ so electrons cannot be emitted at all.

Figure 58. Schematic of Trajectory Calculation in Applied $B_z(t)$, Inductive E .

Figure 59. Electron Trajectories for $B_z < 0, |B_z|$ Increasing.

To be directly relevant to a diode or the Proto II line, these calculations would have to be extended to include both spatial and temporal variations in B_z and E ; even then one must ignore some self-field effects. No general conclusion concerning the "return to the cathode" problem seems possible, as we have found that an electron may return or not, with the constant-field cycloid as the borderline case. The calculation may give insight into future time dependent diode-code calculations and, for Proto II, at least suggests (Case 1) that failure of magnetic insulation for small

radii (where $B_\theta > B_c$) is less likely at early times when B_θ is increasing.

Figure 60. Electron Trajectory for $B_z > 0$, $|B_z|$ Decreasing.

Linear Accelerators and Laser Drivers

Particle Simulations of Pulselac B Gap (J. W. Poukey and S. Humphries)

During this period, we continued to use the 2-D (r, z) steady state particle simulation code to study space-charge neutralization and ion dynamics in the Pulselac ion-accelerator device. The gap geometry and applied $\vec{B}$ field are shown in Figure 61. This $\vec{B}$ is produced by eight coils located at $r = 6$ and 10.5 cm, with $z = \pm 2, \pm 3$ cm. The four coils at $r = 6$ cm carry 60 kA, those at $r = 10.5$ carry 30 kA. This gives a B_r near $z = 0$ of about 13 kG, well above the critical field

B_c . Thus, ions can be accelerated by the applied $V = 200$ kV without electrons leaking across to the $z = 0$ boundary. The ion map is shown in Figure 62, the electron map in Figure 63, and the equipotentials in Figure 64. These figures show the state of the system at $t = 27$ ns ($t = 0$ being the time when ions are first injected into the gap from the left (1-MeV, 10-kA protons)). The electrons have neutralized the ions (between the upper and lower walls) and excluded the applied ϕ to less than 10 kV in most of the region; ϕ will go somewhat lower but not to zero if the run is continued (ran to 40 ns). Note in Figure 63 that the electrons have formed what might be termed a "virtual cathode" near the entrance to the smaller annulus; its shape is nearly that of the $\vec{B}$ lines. The ions (Figure 62) acquire very little divergence.

Figure 61. Geometry of Simulated Pulselac Gap and Applied $\vec{B}$. Total z -length of system is 1.4 cm; radial coordinate r runs from 5 to 11.5 cm.

Changing the applied $\vec{B}$ to be only slightly larger than B_c (coil currents 6 and 12 kA), the ion beam is nearly as well neutralized, but now the situation is not as well defined. Some electrons get into the acceleration gap and try to escape out the top ($r = 11.5$ cm boundary); in the code runs these were reflected to simulate the mirroring that occurs in the experiment. Orbits for some typical electrons are shown in Figure 65; the electron map is given in Figure 66. The more diffuse map in Figure 66 (compared with Figure 63) is caused by the weaker $\vec{B}$

(applied) that leads to a larger gyroradius and more diffusion. Because the neutralization is not as complete, the ion beam in this case does acquire a slight but noticeable divergence. It should be noted that the ion beam in these cases is always underneutralized, because the gap between ion-beam edge and wall is filled with electrons. So, for overall neutralization ($E = 0$ boundary conditions) the ion-beam interior must contain fewer electrons.

This work led us to reexamine our models for space charge neutralization processes because the obvious question is, "How much of the calculated deviation from perfect neutrality is due to purely numerical effects?" This problem received considerable attention, and the preliminary results are discussed elsewhere in this report. However, as mentioned above, at least a part of the effect seems to be physical, although the conclusion of our work so far vis-a-vis Pulselac is that the deviation from neutrality can be made very small.

Figure 62. Ion Map for Strong-Applied $\vec{B}$ Case. The 10-kA, 1-MeV ion beam is accelerated from left to right through 200 kV.

Numerical Simulation of Charge Neutralization in Charged Particle Beams Propagating in Vacuum (J. W. Poukey and J. P. Quintenz)

The problem of computing the time dependent neutralization of an ion beam propagating in a vacuum or tenuous background is important and sometimes crucial in a number of applications, such as the drift region of an ion diode,³⁴ the Pulselac device,³⁵ or

the reactor chamber envisioned in various particle ICF schemes. As suggested by Figure 67, the problem can be divided into two parts: the transverse problem where electrons are emitted from walls that parallel the ion-beam direction; and the longitudinal problem where electrons are either injected through a boundary with the ions or are emitted from this boundary self-consistently. The situation may be complicated by an applied magnetic field.

Figure 63. Electron Map Corresponding to Figure 62 at $t = 27$ ns

Figure 64. Equipotentials Corresponding to Figures 62 and 63.

0.1150

0.0 0.0140

Figure 65. Trajectories of Sample Electrons for the Weak-Applied $\vec{B}$ Case.

0.1150

0.0 5.10000X10⁻⁰⁸ 0.0140

Figure 66. Electron Map Corresponding to Figure 65.

SIMULATION OF SPACE CHARGE NEUTRALIZATION OF BEAMS

A. TRANSVERSE

B. LONGITUDINAL

Figure 67. Classification of Space Charge Neutralization Problems. Examples of the transverse problem are the drift region of Pulselac or ion diodes. An example of the longitudinal problem is a vacuum reactor chamber for a particle ICF scheme.

Although there are a number of possible computational approaches, our work in the past has mainly involved particle electrons and either particle or simple fluid ions, in both 1-D and 2-D codes. The basic problem with all particle (brute force) approaches is the one that plagues all particle simulations: a relatively modest number of particles on a grid of finite spacing, and this inevitably results in nonphysical fluctuations in densities and fields. Many techniques are known to reduce the fluctuations; the problem however, remains unsolved and in the neutralization question can become especially troublesome. In that question one is often dealing with small deviations from neutrality that are difficult to calculate accurately, but which nonetheless can produce large and physically significant fields. The degree of difficulty here is very problem-dependent; it depends on the number of particles and cells one can afford, on the system size, and on the length scales (Debye) that must be resolved.

Often in the past, it has been tacitly assumed that ion beams are easy to neutralize; that it can be taken for granted that electrons from somewhere will rush in and cancel the ion charge exactly. That this is not always the case may be shown easily from a simple 1-D textbook³⁶ counterexample (Figure 68). Here we have plotted the steady state potential across a uniform ion beam between infinite conducting plates emitting space charge limited electrons. The reduction in $\phi_{\max}$ (as compared to the case of no electrons) is only about 60%—not nearly enough for most applications. As shown in Reference 35, this $\phi_{\max}$ may be reduced to nearly zero if a mechanism is present that gives the electrons a velocity parallel to the walls. An ion beam with such poor neutralization as in Figure 68 will typically expand to the wall a distance of a few centimeters.

Figure 68. Sketch of a 1-D Equilibrium in Which Neutralization Does Not Occur.

Transverse Problem

Figure 69 demonstrates that perfect neutralization is impossible in the 2-D transverse problem. A conducting cylindrical box has ions streaming through it, with electrons emitted from the wall. If perfect neutralization could be achieved, then $\rho = e(n_i - n_e) = 0$, which implies $\vec{E} = 0$ everywhere in the box. Since any real system will have electrons with non-zero energy, these will freestream to the walls, leaving $n_i > n_e$, and unless $\vec{E}$ becomes nonzero, no further electrons will be pulled into the ion beam. Further, since no real system will have an n_i which is exactly uniform everywhere, to have $n_e = n_i$ requires an $\vec{E}$ to maintain the nonuniform n_e . This simple result is a mathematical one; it may or may not have important physical consequences, depending on the problem parameters. In many applications, one may neutralize the ions to such a high degree that the beam will not acquire an important divergence (from $\vec{E}$, at least). This is apparently the case, for example, in the "drift space" of D. J. Johnson's "barrel" diode.³⁴

Figure 69. Simple Argument to Prove That Perfect Neutralization is Impossible in 2-D. If it were possible, then $\vec{E} = 0$, which implies the electrons would freestream to the walls.

Therefore, since one is always dealing with the case of partial neutralization, it behooves us to consider the possible equilibria, as illustrated in Figure 70. Equilibrium A involves space charge limited electrons flowing into the ion beam from the wall. To the extent that the ends at $z = 0$ and $z = L$ can be ignored (or have vanishing $\vec{E}$ themselves), one has the condition that the total charge must vanish; unless the ion beam extends exactly to the wall (in which case one still has incomplete neutralization as shown in Figure 68); the ion beam itself will always be underneutralized. This is precisely the result found in all the simulations of the Pulselac B gap, as discussed elsewhere in this report.

Figure 70. Two possible Steady States With Partial Space Charge Neutralization. In A, space charge limited electrons flow in from the walls and E (on the boundary) vanishes. Thus, the total charge must be zero and the ion beam (unless it extends to the wall) must be underneutralized. In B, there are no electrons from the walls, but an electron Debye sheath exists at the ion beam edge; i.e., one has a quasineutral plasma state.

However, there is a second possible equilibrium (B in Figure 70)--the walls have stopped emitting electrons, all of which are trapped in the ion beam. These electrons have finite temperature and thus there is a nonneutral plasma sheath of size $\lambda_D = (\epsilon_0 kT_e / ne^2)^{1/2}$ at the beam edge; the beam interior is only quasineutral, $n_e = n_i \exp(e\phi/kT)$. However, the typical potentials in the beam are then of order kT/e ; if kT is "small" the ion beam may be said to be neutralized (except in the sheath) for all practical purposes. This State B is the one apparently reached in the Pulselac experiments, where the ion-beam divergence is so small that neutralization must have been achieved to within 0.2%.³⁷ However, our "brute force" simulation techniques thus far have been unable to reach such a state. The basic reason is that the oscillations and plasma waves in the simulation drive at least a few electrons to the walls; to maintain $\vec{E}$ (boundary) = 0, more flow in, and the system remains in state A. On the other hand, the simulations

are still of value and still possess at least some degree of reality; in a typical Pulselac case, for example, they predict neutralization to within about 5% (much better than the 40% from the analytic example in Figure 68). However, in simulations of the D. J. Johnson "barrel" diode, the problem of length scales and fluctuations is more severe. By trying various assumed fractional neutralizations in the code, we have concluded that, to explain the experimental observations, the neutralization must be nearly perfect. Hence, we have in this case simply set $\rho = 0$ (in the drift region, not the gap) and used the simulations to study the gap itself and the ion dynamics in the magnetic fields.³⁴ The simulation then only describes reality to the extent that electric fields in the drift region can be ignored.

Longitudinal Problem

A considerable effort has been initiated on the longitudinal neutralization problem (Figure 67). This would be important, for example, in a possible vacuum reactor chamber with high energy ions injected and with the intent of ballistically focusing them on a target. The research efforts are concentrating on two approaches: 1-D analytic stability work and particle simulations, and 2-D particle simulations of an idealized system (see Figure 71). Here ions (5 kA) are injected with high energy through a conducting boundary in a cylindrical system. We have simplified the system by ignoring magnetic effects and concentrated on the electrostatic problem where an equal density of electrons is injected with the same velocity as the ion beam. One might expect that the result would be trivial: the electrons would accompany the ions across the system with $n_e = n_i$ everywhere. However, what occurs is quite different. As shown by the trajectories in Figure 72, the electrons undergo an "electrostatic pinch," a deep positive potential well is formed (~ 200 kV) as in Figure 73. The number of ions in the system substantially exceeds the number of electrons. We emphasize that this is a steady-state result, not a transient. This nonneutral state comes about as follows: the initial T_e (transverse to the propagation) causes some electron spreading (a temporary state B in Figure 70), which leads to $n_i > n_e$ in the beam interior, causing a positive potential so that electrons are accelerated in the $+z$ direction, further causing a decrease of n_e , until the electrons are accelerated both axially and radially to the point where their own space-charge limits further decrease in n_e .

Figure 71. Ion Map From the 2-D Particle Simulation of an Idealized Vacuum Reactor Chamber, the Longitudinal Neutralization Problem.

Figure 72. Electron Orbits Corresponding to Figure 71, Showing the Electrostatic Pinch.

Figure 73. Equipotentials Corresponding to Figure 71 and 72.

This general result has been found insensitive to:

- Electron initial temperature,
- Input radial distribution of electrons and ions,
- Time step,
- Particle number,
- System length (doubling the system length results in a second electrostatic pinch with approximately the expected Langmuir wavelength),
- Outer wall radius,
- Whether the right-hand system boundary is conducting or symmetry,
- Whether the ions are introduced gradually or abruptly at $t = 0$,
- Whether the ions are represented by particles or a simple fluid,
- Input current.

Further, we obtained the same qualitative result when instead of injecting electrons, we allowed them to be emitted from the wall in the space-charge-limited mode, although then the details differ. Simple dimensional arguments show that for fixed geometry and high energy ions (typically greater than or equal to a few megavolts), the latter problem has a "universal" solution in which densities scale like the injected ion density n_i , and potentials scale like $n_i L^2$ (L = system length).

For the parameters studied, the space charge limited emission case neutralized better (~ 90 kV)

than the injected e-beam case (~ 230 kV). Space-charge-limited emission from both sides does better still (~ 50 kV). However, the nonneutralization phenomenon persists, unless the injected ion density is reduced by a factor of (roughly) 3 or more; in that case one finds a nicely neutralized state with small stable oscillations. Obviously, there is a limiting ion current that can be stably neutralized.

To understand this, we must look at the 1-D work. Pierce³⁸ in 1944 showed that electrons streaming over ions of equal density in a system with conducting boundaries will be unstable if $L\omega_p/V_0 > \pi$, where ω_p = plasma frequency and V_0 is electron velocity. Preliminary 1-D particle simulations show the same result. If the ion density exceeds the "Pierce limit," one finds violent instability with a relatively short growth time ($\sim L/V_0$). The same basic physics apparently applies in 2-D, although an exact analytic criterion is not known. We interpret the "electrostatic pinch" in Figure 72 as the saturation state of the Pierce instability. This work is not considered finished or the results completely understood; the work will be continued. The results so far (if they are confirmed experimentally) are important to most proposed ion-fusion schemes, but means to circumvent difficulties are available: (1) the potentials will give only a slight divergence to a high-energy (10's of MeV) ion beam, (2) one can envision providing other sources for the neutralizing electrons than the annulus on the wall where the ion beam is injected, and (3) we have not considered the possibility of a background gas or preformed plasma. This work points out the need for increasing attention to space-charge-neutralization questions. In vacuum propagation of ion beams, it cannot be taken for granted.

Generation and Propagation of Large Area E-Beams (J. W. Poukey)

In order to investigate the use of an applied longitudinal magnetic field (B_0) to produce a uniform, large cross-section beam suitable for deposition in a large volume of gas (e.g., KrF or some other gas suitable for a laser system) analytic and code work was done on the problem of producing and propagating e-beams with a large cross-section area.

Since the current levels of interest are in megampere range, self-fields are crucial, and since the problems are 2-D (at least), fully self-consistent solutions must be obtained numerically. The code used for the work described herein is a variant of the Sandia diode code.^{39,40} This is a 2-D particle simulation code that follows up to $\sim 10^4$ charged particles self consistently in their own (or applied) fields. The fields are computed in the quasistatic approximation (i.e., $\nabla \times \vec{E} = 0$) and the displacement current is neglected. For the

diode part of the problem, this should be a good approximation. For the gas-propagation phase, it means that the background plasma is included only via the assumption of charge neutrality; current neutralization effects are not included since these are inductive.

A possible diode module for the laser system is shown in Figure 74. The calculations were done in cylindrical coordinates r, z (assuming θ -symmetry). An actual system might be rectangular, but this would only alter the details of the trajectories near the beam edge. Specific parameters used were $d = 4.6$ cm, $R = 49$ cm, and $R_w = 59$ cm; B_0 varied from 0 to 15 kG, with a voltage, $V = 1.5$ MV, applied between cathode K and anode A.

Figure 74. Diode Schematic.

The steady-state solution found by the code for $B_0 = 6$ kG (using a 61×41 mesh, 4600 simulation electrons) is shown in Figure 75. The electrons are emitted in the space charge limited mode with zero energy at the K, so their density is higher there. Figure 75 shows particular trajectories, even near the outer edge these are virtually straight lines (note that these lines are projections of the actual 3-D orbit onto the r - z plane.) The same answer is obtained for larger B_0 values, and we conclude that 6 kG is sufficient to produce a uniform, unpinched electron beam. The diode current from the code is 1.1 MA. This is lower than the Child's law value of 1.5 MA because of relativistic effects. In fact, from Reference 39, it is

easy to estimate what the relativistic correction should be: $1-(3/28)$ (eV/mc²) which gives a theoretical current of 1.03 MA. This is in reasonable agreement with the code; note that the code should give slightly more current since a small length of shank was allowed to emit. The self B_0 at the beam edge is about 4.5 kG, so the applied B_0 is only slightly more than the maximum self field.

Figure 75. Trajectories For $B_0 = 6$ kG.

If B_0 is reduced to zero, trajectories such as those in Figure 76 are obtained, together with substantial current reduction (pinching $\rightarrow$ higher electron density at smaller $r \rightarrow$ some K shutoff). Since this is certainly unacceptable, an intermediate value, $B_0 = 2$ kG, was tried. The results were intermediate between Figures 75 and 76; electrons near the edge pinched inward by about 5% in crossing the gap. This is perhaps marginal, but the current was reduced to about 0.9 MA. We conclude that the B_0 values of 2 kG to 6 kG bracket the minimum acceptable B_0 ; i.e., one wants $B_0^{\min} \approx B_{\text{self}}^{\max}$.

When the beam emerges from the diode, it enters a gas at a pressure of ~ 1 atm. Space-charge-neutralization should occur almost instantly,⁴¹ and require little of the beam energy. We will simply assume that there are no electric fields, and that collisions can be neglected in calculating the behavior of all but the leading edge of the beam.⁴² Thus, this problem might be entitled, "The Alfvén Problem With Applied B_z ."⁴³

We will discuss in turn scaling, envelope theory, and results from the particle code.

We work in rectangular coordinates x, y, z as in Figure 77. The beam enters the gas at $z = 0$ with density n_0 , velocity V_0 , x -width $2X_0$, and y -width Δy . We shall assume Δy (typically $\gtrsim 1$ m) to be large enough that we may take all quantities as independent of y . The problem is to compute the electron behavior.

Figure 76. Trajectories, $B_0 = 0$.

Besides the applied B_0 (applied in the z -direction and assumed constant in space and time), the only field will be

$$B_y = \mu_0 \int_0^x j_z dx \quad (9)$$

where $j_z = -nev_z$ and the total current is

$$I = \Delta y \int_{-\infty}^{\infty} j_z dx \quad (10)$$

which (from continuity) is independent of z , so that $I = -2\Delta y X_0 n_0 e V_0$. The motion of the electrons is governed by

$$\frac{d\vec{v}}{dt} = -\frac{e}{m\gamma} (\vec{v} \times \vec{B}) \quad (11)$$

where $\gamma = (1 - V_0^2/c^2)^{-1/2}$ is constant because $E = 0$ and is related to the input (diode) energy eV by $\gamma = 1 + eV/mc^2$. By scaling lengths in X_0 , velocities in V_0 , densities in n_0 , and B in $B_{y0} = -\mu_0 n_0 e V_0 X_0$, one finds that the problem depends only on two parameters; $P_1 = B_{y0}/B_0$ and $P_2 = eX_0 B_{y0}/m\gamma V_0$. The parameter P_2 is just proportional to ν/γ , appropriately defined for rectangular coordinates:

$$\frac{\nu}{\gamma} = \frac{\pi}{2} \frac{X_0}{\Delta y} \frac{|I|}{I_A} = \frac{|P_2|}{4} \quad (12)$$

where $I_A = 4\pi \epsilon_0 mc^2 V_0 \gamma / e$ is the usual Alfven current. The parameter (P_2) is also proportional to the ratio of magnetic-field energy density at the beam edge to input beam-energy density. The ν/γ value for the beam from the diode in Figure 75 (if $\Delta y = 1$ m) is 13, suggesting that a substantial B_0 will be needed to prevent pinching.

Figure 77. Schematic of Beam Propagation Problem.

From Eqs (9) - (11), an envelope theory can be constructed. The result of this calculation is that the beam envelope $X(z)$ will oscillate with the total cyclotron frequency ω_t between X_0 (see Figure 77) and

$$X_m = X_o - 2|\omega_y|V_o/\omega_t^2,$$

where $\omega_y \equiv eB_{yo}/m\gamma$, $\omega_z \equiv eB_o/m\gamma$, and $\omega_t^2 \equiv \omega_y^2 + \omega_z^2$. Note that as $B_o \rightarrow \infty$, $X_m \rightarrow X_o$ as it must. For the $B_o = 6\text{ kG}$ case in Figure 75, the amplitude of the envelope "wiggles" will be only 3% of X_o .

However, the envelope theory is of limited validity. Unless $\omega_z^2 > \omega_y^2$, the envelope slope will become infinite. In fact, for small $B_o (<< |B_{yo}|)$, the model breaks down after a time given by $\omega_t t = \pi/2$. For times less than this, the beam may pinch all the way to the axis (line focus) if $|\omega_y|X_o < 2V_o$, or equivalently from Eq. (4) if $\nu/\gamma < 1/2$. In this case, the pinch z-distance is⁴⁴

$$z_p = \left[\left(\frac{V_o}{\omega_y} \right)^2 - \left(\frac{V_o}{|\omega_y|} - X_o \right)^2 \right]^{1/2}, B_o \rightarrow 0 \quad (13)$$

The particle simulation code used was written in rectangular geometry, and essentially just solves Eqs.(9) and (11) together, where j_z is obtained by summing particle velocities near each mesh point.

Several particular cases were simulated, but we illustrate the result with three runs for a 3-MA, 2-MeV electron beam with $X_o = 15\text{ cm}$, $\Delta y = 100\text{ cm}$. The runs were made for $B_o = 20, 7$, and 2 kG; since $B_{yo} = 19\text{ kG}$, $\nu/\gamma = 8$, we expect from the envelope theory that only the 20-kG case will be acceptable in terms of propagating the whole beam with slight pinching, and this is the result obtained. Figure 78 shows the 20-kG case, where 100% of the beam propagates with small oscillations near the edge. The amplitude of the oscillation is about 0.46 cm, in approximate agreement with the analytic envelope result (0.41 cm).

Figure 79 exhibits some trajectories for the $B_o = 7\text{-kG}$ case. About 85% of the beam propagates and there is considerable density variation. Note the different classes of orbits in Figure 79. Near the beam edge ($B_y > B_o$), some electrons reverse direction due to the large self- B_y field. Near the z-axis ($B_y < B_o$), the electrons move nearly straight. In between, one sees orbits containing loops (Larmor radius of order 1 cm); here the B_o and B_y are comparable.

Figure 80 shows the beam for $B_o = 2\text{ kG}$. Here only about 1/4 of the beam propagates and there is gross pinching. A B_o this weak is of little use for beam propagation.

The net result of the computer simulations is that one needs B_o to be comparable to the maximum B_y (self); in fact, a B_o slightly less than this will probably

be satisfactory (but not less than $B_{y,\text{max}}/2$). The result has been obtained only for initially cold beams (no transverse velocities); a hot beam could raise the required B_o slightly, but based on previous work⁴⁵ would not change the basic result.

Figure 78. Electron Map, $B_o = 20\text{-kG}$ Case.

Figure 79. Trajectories From $B_o = 7\text{-kG}$ Case. These are projections of the actual 3-D orbits on the x-z plane.

Figure 80. Electron Map, $B_0 = 2$ kG.

References

1. J. P. Quintenz, *J Appl Phys* 49:4377, 1978.
2. R. Lee, S. A. Goldstein, and D. J. Johnson, *Bull Am Phys Soc* 22:1062, 1977.
3. J. W. Poukey, J. R. Freeman, and G. Yonas, *J Vac Sci Technol* 10:954, 1973.
4. J. W. Poukey, *J Vac Sci Technol* 12:1214, 1975.
5. J. P. Quintenz and J. W. Poukey, *J Appl Phys* 48:2287, 1977.
6. J. P. Quintenz and M. M. Widner, *J Appl Phys* 51:4688, 1980.
7. M. M. Theimer and J. P. Quintenz, *Optimization of the Particle Pusher in a Diode Simulation Code*, SAND79-1748 (Albuquerque: Sandia Laboratories, September, 1979).
8. A. M. Winslow, *J Comp Phys* 1:149, 1966.
9. A. G. Armstrong, C. J. Collis, N. J. Diserens, M. J. Newman, J. Simkin, and C. W. Trowbridge, *GFUN3D User Guide*, Report RL-76029/A, (Oxon, OXII, OQX, England: Rutherford Laboratory, 1976).
10. D. J. Johnson, G. W. Kuswa, A. V. Farnsworth, Jr., J. P. Quintenz, R. J. Leeper, E. J. T. Burns, and S. Humphries, Jr., *Phys Rev Lett* 42:610, 1979.
11. S. Humphries, Jr., G. W. Kuswa, C. W. Mendel, and J. W. Poukey, *IEEE Trans in Nuc Sci* NS-26, 4220, 1979.
12. K. Halbach and R. F. Holsinger, *Particle Accel* 7:213, 1976.
13. T. P. Wright and J. A. Halbleib, *Phys. Fluids* 23:1603, 1980.
14. T. A. Mehlhorn, *A Finite Material Temperature Model for Ion Energy Deposition in Ion Driven ICF Targets*, SAND80-0038J (Albuquerque: Sandia Laboratories, 1980).
15. P. A. Miller, L. Baker, J. R. Freeman, L. P. Mix, J. W. Poukey, and T. P. Wright, in *Proc 2nd Int Topical Conf on High Power Electron and Ion Beam Research and Technology*, Cornell University (Vol I, pp 393-406, 1977).
16. J. A. Halbleib, T. P. Wright, and S. A. Goldstein, *Phys. Rev. Lett.* 45:344, 1980.
17. P. F. Ottinger, and S. A. Goldstein, *Phys. Rev. Lett.* 45:340, 1980.
18. J. A. Halbleib and T. P. Wright, *Phys. Fluids* 23:1612, 1980.
19. M. A. Sweeney and A. V. Farnsworth, SAND79-1045J (Albuquerque: Sandia Laboratories, 1979. Also submitted for publication).
20. K. D. Bergeron, *J Appl Phys* 48:3065, 1977.
21. S. Shope, J. W. Poukey, K. D. Bergeron, D. H. McDaniel, A. J. Toepfer, and J. P. VanDevender, *J Appl Phys* 49:3675, 1978.
22. J. C. Bowers and S. R. Sedore, *SCEPTRE: A Computer Program for Circuit and System Analysis* (Englewood Cliffs, NJ: Prentice Hall, 1971).
23. See "Equivalent Circuit Modeling of Asymmetry Effects in Magnetically Insulated Transmission Lines," in this report, p. 55.
24. C. W. Mendel, Sandia Internal Memorandum RS4244/2, December 1978.
25. See "Effect of Module Jitter on Output Power," in this report, p. 7, Chapter 5.
26. D. H. McDaniel and R. W. Stinnett, "The Effect of Simultaneity on Peak Current Delivered to an Inductive Load," *Particle Beam Fusion Progress Report*, June through Dec. 1977 (Albuquerque: Sandia Laboratories, 1979).
27. "Equivalent Circuit Modelling of Asymmetry Effects in Magnetically Insulated Transmission Lines," in this report, p. 55, Chapter 3.
28. J. C. Bowers and S. R. Sedore, *SCEPTRE: A Computer Program for Circuit and System Analysis*, (Englewood Cliffs, NJ: Prentice Hall, 1971).
29. N. Marcuvitz, *Waveguide Handbook*, MIT Radiation Laboratory Series, Vol. 10, pp 179-183 (1951).
30. *Ibid*, pp 286-289.
31. See *Particle Beam Fusion Progress Report*, SAND80-0974 (Albuquerque: Sandia Laboratories, 1979), and M. J. Clauser et al, *Bull Am Phys Soc*, 24:978, 1979.
32. G. Schmidt, *Physics of High Temperature Plasmas*, (New York: Academic Press, 1966).
33. T. G. Northrop, *The Adiabatic Motion of Charged Particles*, (New York: Interscience Press, 1963).
34. D. J. Johnson et al, *Phys Rev Lett*, 42:610, 1979.
35. See the Pulselac theory section of this report, and J. W. Poukey and S. Humphries, Jr., *Appl Phys Lett*, 33:122, 1978.
36. E. Stuhlinger, *Ion Propulsion for Space Flight*, (New York: McGraw-Hill, 1964).
37. S. Humphries, Jr., C. W. Mendel, and J. W. Poukey, *Bull Am Phys Soc*, 24:1032, 1979.
38. J. R. Pierce, *J Appl Phys*, 15:721, 1944.
39. J. W. Poukey, *J Vac Sci Technol*, 12:1214, 1975.
40. J. P. Quintenz and J. W. Poukey, *J Appl Phys*, 48:2287, 1977.
41. C. L. Olson and J. W. Poukey, *Phys Rev*, A9:2631, 1974.
42. G. Yonas et al, *Nucl Fus*, 14:731, 1974.
43. H. Alfven, *Phys Rev*, 55:425, 1939.
44. J. W. Poukey, memo to E. Patterson, Aug. 4, 1975.
45. J. W. Poukey, A. J. Toepfer, and J. G. Kelly, *Phys Rev Lett*, 26:1620, 1971.

Chapter 4. Particle Beam Experiments

Overview

Experimental research into ion-beam sources was carried out in many areas. Near term goals of the effort include the development of more intense ion sources for target irradiation experiments on present accelerators and for PBFA I. For the longer run, we are investigating sources that can drive targets at levels necessary to achieve net energy gain on PBFA II. We are also studying sources and techniques necessary for reactor operation. This chapter is divided into ten sections which report on this work.

1. Development of the radial ion diode has continued; improvements have led to attainment of ~ 1 MA/cm² fluence on 3-mm-dia cylindrical exploding-pusher diagnostic targets on Proto I. Extension of this work to Proto II is in progress.
2. A variation on the topology of the radial diode is the "extraction" geometry diode. It has been tested with the emphasis mostly on geometric and field variations that are needed to improve efficiency.
3. Tests of a plasma-filled ion diode (ampfion) have shown that bunched, neutralized, carbon-ion beams can be produced efficiently in a scalable fashion. The resulting beam has low-intrinsic divergence. Diagnostic improvements are being developed to allow characterization of the focus.
4. Ion beam transport experiments were conducted using wire-initiated plasma channels; efficient transport was achieved in agreement with expectations.
5. Work on laser initiation of plasma channels has been directed towards use of a CO₂ laser and molecular gases. Calculations and initial cross-section measurements are encouraging and a complete test system is being assembled.
6. The optimum ion species for use on PBFA I and PBFA II will probably be deuterium or helium according to recent target calculations. Development of a light-gas source has been carried out using a conical Z pinch and a fast diaphragm valve; initial results have been obtained.

7. A spherical electron-to-ion converter has been studied theoretically. The first simple experimental test of such a device has been performed.
8. Rapid development in the Pulselac program has occurred with improvements to linac operation and advances in electron neutralization sources being obtained. Support from the Heavy-Ion Fusion Program has been forthcoming and a larger accelerator is being designed. Pulselac C will be a 4-MV, 16-stage, inductive accelerator for multikilo-ampere beams of intermediate-mass ions.
9. The final beam combination experiment with the Proto II multiple electron beam system was carried out. The encouraging results were in excellent agreement with theory and will guide future work with multiple-ion beam systems.
10. An extensive review paper on intense ion-beam work has been prepared for publication. It should prove a major step in establishing conceptual unity in the field.

Radial Ion Diode

(D. J. Johnson, E. J. T. Burns,
A. V. Farnsworth, and
J. P. Quintenz)

In this section we report the improved focusing performance of a radial, magnetically insulated ion diode, which has been described previously.¹ The improvements were achieved by using better anode-plasma production techniques, by making corrections for ion-beam angular momentum and self-magnetic field defocusing, and by reducing the diode size. These improvements have resulted in ion-current densities of ~ 1 MA/cm² upon 3-mm-dia cylindrical targets.

The experimental data were obtained using the 10¹²-W Proto I accelerator. A cross-sectional view of the diode is shown in Figure 81 along with a schematic of the diagnostics used. The applied magnetic field (B_{app}) is created in 70 μ s and, therefore, conforms to the aluminum anode surface because of the ~ 2 -mm

skin depth of this field. The anode is then pulsed positive and electrons that are emitted from the cathode discs spiral axially along B_{app} -field lines to establish uniform equipotential surfaces (virtual cathode) near the anode. The imposed electric field then creates an anode plasma via surface flashover² across 1.5-mm deep, 0.35-mm wide epoxy-filled grooves in the aluminum anode. Ions are then extracted and accelerated from the 120-cm² anode plasma by the virtual cathode toward the diode center line. The resultant ion beam is composed primarily of protons and has much lower divergence and better spatial uniformity than the polyvinylchloride screens previously used¹ with this type of diode.

Figure 81. Cross-Sectional View of the Radial Diode

During transport to the target located at the center of the diode, the proton beam is space-charge-neutralized by electrons emitted from the walls of the cathode discs. Since the B_{app} field prevents current neutralization of the beam, it is focused by a combination of geometric focusing and self-magnetic field bending. In these experiments, the anode radius of curvature was progressively increased from the 6-cm geometric spherical surface to 9- to 10.5-cm radius to compensate for self-magnetic field bending. Nonzero initial canonical angular momentum was given to the ions by the B_{app} field outside the anode-emission surface because of the B_{app} -field skin depth, the epoxy-filled grooves, and the ~ 0.3 -mm-thick anode plasma. This was minimized by introducing a reversed B_{app} field before the main pulse; the reverse-bias field had a 1-ms risetime and 20% of the amplitude of the primary B_{app} field.

The diagnostic apparatus included current and voltage monitors of the diode performance and an array of four calibrated dB/dt loops to measure the ion-beam current at 1.9-cm radius as shown in Figure 81. In addition, the ion-beam focus quality was measured via observation of both thick- and thin-target response to the beam. Thin-target response was measured with x-ray photodiodes that responded to thermal radiation and a pinhole camera that recorded proton induced 1.49-keV K-line radiation in aluminum. Thick target response measurements consisted of a qualitative observation of rear-surface spall and change in interior crystalline structure of thick-wall steel cylinders.

Typical diode characteristics and ion-beam current at 1.9-cm radius are shown in Figure 82 for a diode gap of 5 mm and B_{app} field of 18 kG. Two XRD signals and an atomic excitation pinhole photograph are also shown in Figure 82 for a 4.5-mm-midplane-dia, 8- μ m-thick aluminum target with 3.5° half angle. The bare XRD (10- to 30-eV range) responds initially to the thermal radiation from the target, whereas the 2- μ m-thick Kimfol-filtered XRD (200- to 300-eV range) responds primarily to thermal radiation from the late-time stagnation of foil material on axis. The XRD data in Figure 82 show a delay of ~ 12 ns between the prompt thermal radiation from the target and the stagnating foil material on axis. Data obtained for targets of diameter (D), varying from 3 to 9 mm, show stagnation delay times which varied as D^2 . Since the implosion velocity is expected to scale as the square root of the target temperature, these data imply an increase in target-current density for smaller targets which scales as D^{-2} . (Magnetohydrodynamic effects, resulting from the ion current striking the targets and causing a magnetic field, may be influencing the results.) Here we assume a $D^{-3/2}$ current-density relationship. This is consistent with a $D^{-1/2}$ self-magnetic field compression of the beam envelope in the z direction and ideal radial convergence. That would only occur if no ions were to miss the smaller targets because of angular momentum effects.

The pinhole camera photograph presented in Figure 82 shows an image on axis due to thermal radiation from the stagnating foil material in addition to the image of the beam profile upon the target due to beam-induced atomic excitation. Because the target half-angle was 3.5°, no attempt was made to obtain the axial-beam profile from the on-axis pinhole camera photographs. Rather the photographs were used to determine the magnitude of the target current as a function of target diameter. This determination used the theoretical atomic excitation photon yield for a

given target and the absolute sensitivity of the Kodak No-Screen film. The theoretical photon yield was determined by a computer code that calculated the quantity of photons incident upon the pinhole for the target geometry and the current and voltage for a given experiment. According to this analysis, the proton current on targets with diameters from 3 to 9 mm varied from 140 to 175 kA, respectively. This demonstrated that the beam FWHM in the plane of the diode was less than 3 mm. (It should be noted that 2-D hydrodynamic calculations of target response generally necessitated assuming ~ 350 -kA incident upon these targets with 1.7-mm FWHM to obtain the experimental stagnation time. This suggests that either there may be an error in the quantitative atomic-excitation analysis or the above-mentioned MHD effects were indeed occurring.)

Figure 82. Typical Electrical Characteristics of the Radial Diode and the Ion Current (I_T) Measured at a Radius of 1.9 cm. The signals from bare and filtered XRDs are shown along with a atomic excitation photograph of the target response.

The effect of the beam upon a thick (6.4-mm-OD, 3.2-mm-ID) low carbon steel cylindrical target is shown in Figure 83. This target was sectioned, polished, and etched in a 5% nitric-acid solution. The width of the rear surface spall (~ 0.25 mm) indicated a 70- μ s-long pressure pulse exceeding the spall strength of steel (~ 16 kbar). Microscopic examination of the etched target reveals changes in the steel microstructure at midplane of the target of ~ 3 -mm width and 0.5-mm depth (the light zones in the figure). The markings observed in the transformed grains are similar to those observed in explosively

loaded iron and steel plates stressed above 130 kbar ($\alpha \leftarrow \epsilon \rightarrow \alpha$).³ These data indicate an axial-beam profile with FWHM < 2 mm.

Figure 83. Spall Pattern on a 6.25-mm-OD Steel Target Exposed to the Ion Beam

By combining all the above measurements, the peak target current density can be estimated. The target ion current is assumed to be 150 kA as measured by atomic activation (one third of that measured by the calibrated dB/dt loops at a 1.9-cm radius). For a 2-mm FWHM Gaussian profile, the peak proton-current density is ~ 375 kA/cm² for a 6-mm-dia target. This current density increases to ~ 1 MA/cm² for the 3-mm-dia targets assuming the $D^{-3/2}$ current-density dependence with target diameter specified above. Additional experimental work will soon be performed to further quantify the focus characteristics of this diode.

Extraction Diode (D. J. Johnson, G. S. Mills, and J. P. Quintenz)

An ion diode in "extraction" geometry has been studied. If successful, it would be suitable for producing an ion beam that can be combined with other

beams upon a single target using the PBFA accelerator. The performance of such a diode was investigated with the Proto I accelerator and is shown schematically in Figure 84. The experimental work consisted of optimizing ion generation efficiency that is inherently related to electron loss and anode damage. With this diode there is a strong tendency for the beam to originate symmetrically on both sides of the outer cathode rather than between the two cathodes, especially late in the power pulse. This problem arises because the B_{app} -fields radial (and therefore its strength) varies as R^{-1} when the field lines are parallel to the anode-cathode gap. This configuration produces a much smaller anode-cathode gap, and also a much smaller anode-virtual cathode gap near the outer cathode because of the larger electron Larmor radius there. We currently believe that the smaller gap results in sufficient electron loss outside of the outer cathode to heat the transmission line near the anode to $\sim 400^\circ\text{C}$ and thereby desorb gas which becomes a plasma and a source of ions by avalanche.

Figure 84. Cross Section of the Extraction Diode Used on Proto I

Experimental work with this diode involved varying the inner and outer currents, gaps, and B_{app} -field ratios. When 67% of the total diode current was

supplied by the lower transmission line, $\sim 50\%$ of the diode current was detected as ion current 5 cm from the anode throughout the 25-ns pulse. However, this configuration was not adequate to prevent anode damage; consequently, focusing data with epoxy-filled anodes were not acquired. This work is continuing, using the Hydramite accelerator and a triaxial magnetically insulated convolute. The new diode to be used has a 20-cm^2 anode area instead of the 50-cm^2 area used on the Proto I diode. The difficult problem of focusing the proton beam to a spot 25 cm from the anode with this diode will be addressed after efficient ion-beam generation and operation with no anode damage are achieved.

Ampfion Diode (Automagnetic Plasma-Filled Ion Diode) (C. W. Mendel and G. S. Mills)

The Ampfion diode was constructed and installed on the Hydramite accelerator during the second half of 1979. Testing has shown that the diode behaves as predicted.^{4,5} The diode (Figure 85) has a magnetic field coil that is in series electrically with the ion-acceleration gap. This avoids the use of a separate field pulser and precludes any diode-power pulse from occurring without an insulation field. In addition, electron leakage boosts the insulation field automatically. Because the field is pulsed on only during the fast-time scale of the accelerator pulse, the ions have no canonical angular momentum (which would increase focal size) and there are no magnetic fields in the drift region; therefore, charge and current neutrality are achieved in the drift region. The field coil and first cathode structures each consist of 120 vanes of 0.010-in. phosphor bronze. The first cathode vanes are radial, the field coil vanes are spiral and are anchored at positions roughly 90° apart on their inner and outer supports. The "spider" electrode is shown covered with mesh in Figure 85, but we have achieved satisfactory operation with no mesh over the spider, making it easier to achieve plasma fill.

Plasma fill is accomplished with six carbon-plasma guns. The initial fill electron density is about 10^{14} cm^{-3} and contains roughly equal amounts of C^+ and C^{2+} . Small amounts of C^{3+} and C^{4+} are also seen.

The impedance of the diode rises rapidly in time as the plasma is removed from the gap. To allow a good impedance match to the accelerator, a series inductance roughly equal to one-half the product of the machine impedance and the machine-pulse

length is built into the diode-feed region. Since the "impedance" of the inductor is given by

$$R_L \equiv \frac{V}{I} = \frac{L(dI/dt)}{I},$$

which decreases in time and becomes negative after peak current, the net impedance of the inductance and the ion diode in series can be made quite constant. The impedance seen by the machine, the diode impedance, and the machine and diode power pulses are shown in Figure 86.

Figure 85. Cutaway View of the Ampfion Diode

Figure 86. Machine Power and Impedance

These impedances have two desirable effects: the machine sees a very good match and the rising-diode impedance causes a rapidly-rising diode voltage which generates a bunched or axially focused beam. By adjusting the plasma load and the field inductance, a good impedance match and optimum bunching can be obtained if the focal length of the diode has been chosen properly. The diode characteristics have been checked against the model used in design and the agreement is exceptional. This leads to a high level of confidence in our ability to extend this design to diodes for other accelerators.

The beam diagnostics are still underway at the time of this report. However, we have shown that the ion beam does bunch, that it does propagate with net-current neutrality, and that it has reasonable efficiency (estimated 35% to 50%). Diagnostics of the low-voltage carbon beam are difficult and the focal size has not yet been measured, but it is less than a few centimeters in diameter. This is an encouraging result for an extraction diode of 30-cm diameter and 42-cm focal length, considering the early stage of development.

Two major problems have been found:

1. At the end of the pulse, the ion-diode impedance rises to such an extent that electron conduction takes over and damages the aluminum plasma contact ring. The resultant aluminum vapor causes plasma gun, and diagnostic and cleanup problems.
2. Poor plasma-fill uniformity leads to nonuniform plasma sheath thickness that impedes focusing and centering.

Several options are being explored to remedy these difficulties.

Propagation of Light Ions in a Plasma Channel

(J. N. Olsen, D. J. Johnson, and L. Baker)

For the successful operation of an ICF reactor, it will be necessary to propagate a light ion beam over 2 to 3 m and overlap many few-TW-beams at the target.⁶ It is envisioned that the propagation will be obtained in laser-initiated current-carrying plasma channels. We report here the efficient propagation of ion beams in wire-initiated plasma-discharge channels as a prelude to future laser-initiated channel tests. The ion beam is injected by a magnetically insulated ion diode⁷ when the channel current reaches 40 kA and the diameter of the expanding

channel matches the input beam. In these experiments, stable unconfined channels have been formed and 80% to 90% propagation efficiencies have been observed over 50-cm lengths.

The magnetically insulated ion diode will be described here only briefly. The Hydra accelerator is pulsed in positive polarity and the output is transported to the anode shown in Figure 87 by two magnetically self-insulated vacuum-transmission lines. The anode-cathode gap is insulated against electron current by the magnetic field from an 80- μ s risetime current in a vane structure behind the cathode. Ions extracted from the spherical-anode surface, which is covered by a cloth ion emitter, are ballistically focused to the channel input. A gas puff, started 515 μ s before the diode pulse, partially charge and current neutralizes the focusing region. A 2- μ m thick plastic foil separates the diode vacuum from the channel-fill gas. Previous best results with this diode of 60 kA/cm² at 13-cm focal length were significantly degraded to 5 kA/cm² by our longer focal length (23 cm) and changes in the gas-puff system.

Figure 87. Schematic of the Magnetically Insulated Diode and Wire-Initiated Plasma Channel. The anode-to-channel distance and channel length are 23 cm and 50 cm, respectively. The channel return current flows in a 10-cm-dia aluminum pipe, which is lined with a 6.3-cm-ID Lucite tube to prevent transverse breakdown.

Typical operating parameters for the Hydra ion diode are shown in Figure 88. The inductively corrected diode voltage remained nearly constant at 800 kV for 60 ns; the impedance fell from 3.0 to 1.5 Ω during that time, giving a peak power of 0.28 TW. The total diode energy was 21.2 kJ; 12 kJ of the total was delivered during the 60 ns of peak voltage. A full accounting of the distribution of energy between electron and transmission line losses, ion losses, and focusable ion currents has been given by Johnson.⁷

Figure 88. Typical Ion-Diode Characteristics. The inductively corrected voltage, impedance obtained from averaged current monitors, and diode power are shown.

Design of the plasma channel involves matching the channel current to the incoming ion beam and choosing a gas density to yield an appropriately expanded channel at the time of peak current. Single-particle dynamics in a channel of uniform current density require a channel current (I_{ch})

$$I_{ch} = \frac{2^{3/2} \pi}{\mu_0} \sqrt{\frac{MV}{Ze}} \theta^2 \quad (1)$$

to provide sufficient azimuthal magnetic field so that ions will oscillate about the axis after entering at an angle θ . M , Z , and V are the ion mass, charge state, and the acceleration voltage, respectively. In the diode geometry shown in Figure 87, the maximum input angle is 15° at a 23-cm focal length. The inductively corrected diode voltage shown in Figure 88 averages 0.8 MV during the 60 ns of peak voltage and power. Thus for protons, deuterons, and carbon C⁺, $I_{ch} = 44$ kA, 62 kA, and 154 kA, respectively. As reported⁷ earlier, protons dominate during the peak-power time, with C⁺ becoming important later. Our carbon activation diagnostic⁸ is insensitive to carbon and, as discussed below, requires only a small correction for deuterons so that a 44-kA channel current will confine those ions which we measure.

Selection of the channel gas pressure and composition is dictated by matching the channel expansion at the time of peak current to the input beam diameter; i.e., using an analytic self-similar model for channel evolution,⁹ the initial fill pressure p_0 of D_2 is

$$p_0 = 1.37 \left(\frac{J_0^{2/7} t_{pk}^{3/4}}{a} \right)^{28/5} \quad (2)$$

where p_0 is in pascals and the channel radius (a) is in centimeters. In this model the channel current is fitted to a particular power law in order for a self-similar solution to hold:

$$I_{ch} = J_0 t_{pk}^{3/4}$$

In Eq (2), J_0 is in kiloamperes and t_{pk} is in microseconds. The current rise-to-peak time, $t_{pk} = 2.5 \mu s$, is determined by the inductance of the geometry and the capacitance required to achieve a given I_{ch} . Thus channel radii of 1.0 and 1.5 cm require $p_0 = 8.5 \times 10^3$ and 9.3×10^2 Pa of D_2 , respectively. In practice the fill density was varied until efficient propagation was observed ($p_0 = 5.3 \times 10^3$ Pa) indicating that the channel was matched to the input beam.

Propagation of the beam was measured by the carbon-activation technique⁸ wherein protons of energy greater than 0.46 MeV, incident upon a carbon target, drive the

$^{12}C(p,\lambda)^{13}N(\beta^+)^{13}C$ sequence. The β^+ emission of the ^{13}N nucleus is observed via coincidence counting of annihilation events. As described by F. C. Young et al of NRL,⁸ the current density calculated from the activation counting is corrected for the natural abundance of deuterons in the proton beam. Referring again to Figure 87, the carbon-disc target is held in an aluminum "salt-shaker" to contain activated debris caused by target ablation in the 5-kA/cm² beam. The salt-shaker itself is mounted in a nylon insulator with the 0.001-in. tungsten wire for initiating the discharge strung through the center of seven 1-mm-dia holes.

A series of shots with very similar voltage, current, and power resulted in the transport efficiencies of Figure 89. The input current density is 4.9 kA/cm² in a 6.2-cm² channel cross section; transport efficiencies of 80% to 90% are obtained. The current densities in these shots are low compared to earlier best results⁷ of 60 kA/cm², a difference due to changes in the diode geometry and gas-puff arrangement. The essential result, however, is that good transport efficiency is observed.

Several significant features of the experiment are worth noting. First, consistent with the electron beam-propagation experiments of P. A. Miller,¹⁰ we

used tungsten wire to initiate the discharges. The choice of wire material appears to play a dominant role in initiating the discharge, but does not affect the subsequent channel evolution. Second, the radii of the input beam and channel must be carefully matched; a 20% decrease in channel radius was found to cut the transport efficiency to 20% to 30%. Finally, the time delay and gas expansion during the initiation phase (600 to 800 ns) may require substantial (2x) deviation from the fill pressure of Eq (2) to obtain the optimal channel diameter. None of these observations suggest any obstacles for the eventual use of laser-initiated channels, or alter the fundamental results of this work--that of efficient propagation of an intense ion beam in a wire-initiated channel.

Figure 89. Transport Efficiency as Measured by Carbon Activation. Shot-to-shot variations in the diode are greater than the experimental errors ($\pm 10\%$) due to calibrations and counting statistics. These shots (Nos. 8397, 8400, 8401, 8402, and 8405) were selected as close to duplicates in Hydra performance.

Laser Heating of a Molecular Gas Channel

(J. N. Olsen and L. Baker)

Systems studies¹¹ of ion-beam-driven inertial-confinement fusion have established the requirement that ion beams be transported over distances of 2 to 3 m to the target. It has been demonstrated that a wire-initiated¹² or wall-confined¹³ discharge channel in a few hundred pascals of gas will confine and guide an intense ion beam. For a viable reactor scheme, it is necessary to replace the wire initiation with a technique, such as laser initiation, that can be repetitively pulsed.

As a technique for laser initiation of a discharge channel, we propose that an infrared laser be tuned to a molecular-vibration frequency of the channel

gas. Rapid relaxation of the vibrational excitations would lead to a gas temperature high enough to guide an electrical discharge by a weak preionization. Vibrational-absorption cross sections are large enough so that the required laser energy is reasonable and the energy dependence is not of a threshold nature. Moreover, the laser technology in the relevant wavelength region is highly developed. Approximate extrapolation of the absorption cross sections reported here to higher energy densities indicates that less than 10 J of line-tuned laser energy would be required for each particle-beam channel.

Out of a multitude of possible combinations of infrared laser and channel gas, we have chosen to consider the CO₂ laser operating on the 00⁰1 to 10⁰0 band and NH₃ gas, pumped in the $\nu_2 = 950\text{-cm}^{-1}$ mode. A search of candidate molecules¹⁴ shows that NH₃ has the lowest mass, fewest atoms, and an anomalously fast vibrational-translational relaxation time.¹⁵⁻¹⁷

In this report we present the first steps toward such laser-initiated discharge channels wherein we determine the temperature and density changes that are to be expected with reasonable laser energies. To this end, absorption cross sections were measured as a function of gas pressure, line tuning, and laser energy for NH₃ gas. Based on these values, a number of hydrodynamic simulations were performed with the CHARTB hydrocode,¹⁸ showing that an efficient conversion of initial vibrational temperature into translational temperature occurs.

The absorption measurements were performed with a Lumonics Model TEA-103-2 line-tunable CO₂ laser that provided about 5 J in a single line; the pulse shape was a characteristic 200-ns spike with a 600-ns tail. Roughly 60% of the energy was in the initial spike. The beam was weakly focused by a 10-m focal-length mirror through a 5-cm long absorption cell with a 1.6-cm² cross section. Measured transmissivities (V) are converted to an effective absorption cross section (σ) through

$$\sigma = \frac{1}{NL} \ln \left(\frac{1}{V} \right) \quad (3)$$

where N is the molecular-number density and L is the cell length.

The sensitivity of the absorption cross section to laser-line selection and NH₃ gas pressure is shown in Figure 90 at 2.7 J/cm². The ν_2 mode is an inversion doubled pair of lines,¹⁹ $\nu_2 = 932$ and 968 cm^{-1} ; the first is most closely matched by the P(32) transition. Maximum absorption is observed for the P(32) and P(34) lines with a rapid falling off of σ as the laser is tuned either to lower or higher frequencies. The σ 's for all lines show an approximately linear dependence upon pressure. The existence of a family of absorption curves, rather than a single curve, could be very

important in matching the channel-heating scheme to the hydrodynamics of the subsequent discharge.

Figure 90. Absorption Cross Sections for CO₂ Laser in NH₃ Gas as a Function of Pressure and Line Tuning

Saturation effects in NH₃ were studied and the transition from small signal to possibly saturated absorption is displayed in Figure 91. The input-energy densities varied from 0.04 to 2.8 J/cm² on the P(32) line. The triangles indicate the difficulty of fitting a simple saturation model to the data. Extrapolating from the lowest and middle energies to the highest energy, a transmissivity corresponding to an effective $\sigma = 0.98 \times 10^{-20}$, is obtained. This deviates significantly from the measured $\sigma = 2.5 \times 10^{-20}$. This is understandable considering the energetics of inter-modal-vibrational relaxation in the NH₃ molecule; i.e., at 2.7 J/cm² the number of photons absorbed per molecule rises to 3.4 and relaxation to at least the ν_1 mode (1627 cm^{-1}) will occur. This has the effect of delaying saturation and increasing the effective σ above that extrapolated from lower energy densities.

At this point, we consider the response of the gas to energy inputs that are consistent with the absorption data just presented. The first priority here is to show that for a reasonable vibrational translational relaxation time (τ), significant gas temperatures are observed as the input energy is equilibrated between the initially excited vibrational modes and the translational degrees of freedom. We assume that the absorbed energy (E_a) is immediately partitioned between rotational and vibrational degrees of freedom to give an initial vibrational (and rotational) temperature (T_v) determined by only the rotational and vibrational contributions to the specific heat.

Figure 91. Saturation Effect in NH_3 as a Function of Gas Pressure. Typical error bars for each curve are shown to the left.

In the CHARTB hydrocode¹⁸, this T_v forms an energy reservoir that is assumed to equilibrate to the translational temperature (T) such that

$$\frac{\partial T_v}{\partial t} = \frac{T - T_v}{\tau} \quad (4)$$

The energy released from this decay is the source term for the hydrodynamic motion equations by conservation of energy.

For the specific case of NH_3 , some molecular dynamics are added to CHARTB. For a given T and T_v , partition functions Z are calculated for NH_3 , NH_2 , NH , N , and H species, each of which uses separate translational and vibrational rotational temperatures. Analogous to Saha relations for ionization equilibrium, we find for dissociation

$$\frac{N_n}{N_{n-1}N_H} = \frac{Z_n}{Z_{n-1}Z_H} \quad (5)$$

where, if subscript n denotes NH_3 , then $n-1$ denotes HN_2 . Dissociation is taken as a loss term in the energy balance. The pressure is $P = N_{\text{total}}kT$ and the translational energy is $E_t = 3/2 P$.

For CHARTB, the entropy and sound speed are required for the translational temperature. These are given to sufficient accuracy by $S = C_v(\ln P - 5/3 \ln \rho)$, and $C_v = (1.14 P/\rho)^{1/2}$. Tabulated values²⁰ for NH_3 are used to obtain certain quantities such as $\gamma = 1.14$ in the sound speed where partial dissociation is not important.

The thermal conduction coefficient k_T is temperature-dependent and data is available only for the equilibrium case $T_v = T$. Such an equilibrium value was used because the channel-expansion rate and the central temperature are little affected. We feel that nonequilibrium errors in k_T do not significantly degrade our results.

For a heating simulation in a region of interesting temperature, we chose an initial $T_v = 3000$ K at fill pressure $P_0 = 6.6 \times 10^3$ Pa. From the specific heat, this requires $E_a = 0.32$ J/cm³; this involves a modest extrapolation from our data of Figure 91 to 5.5 J/cm². Calculated temperature and mass-density profiles for $\tau = 30$ ns, 1 μ s, and 20 μ s are shown in Figures 92 and 93, respectively ($\rho_0 = 5.0 \times 10^{-5}$ g/cm³), each at a time, $t = 1.5 \tau$. The initial channel radius is 3 mm. We note first that the temperature is not a strong function of τ with final temperatures of 2300 K for $\tau = 30$ ns and 1 μ s, falling to 1850 K for $\tau = 20 \mu$ s. Much more hydrodynamic motion occurs for $\tau = 20 \mu$ s simply because of the time scale; the actual radial velocity is slower, being proportional to $\tau^{3/4}$.

Figure 92. Channel Temperature at $t = 1.5 \tau$ for 30-ns, 1- μ s, and 20- μ s Relaxation Times

Figure 93. Channel Mass Density at $t = 1.5 \tau$ for the Same Cases as in Figure 92

The principal utility of the simulation for various τ is to show that the final temperature is not a rapidly varying function of τ , and to suggest that substantial rarefaction may be obtained at a slightly lower temperature. These are generic features of molecular gas heating by vibrational excitation, illustrated in this case by varying the assumed τ for NH_3 . To be specific for NH_3 , a pressure-relaxation time $p\tau = 2 \text{ ns} \cdot \text{atm}$ has been reported;¹⁷ for a $6.6 \times 10^3 \text{ Pa}$ NH_3 initial fill, $\tau = 30 \text{ ns}$ is appropriate. No appreciable hydromotion occurs and a final temperature of 2300 K (0.197 eV) is calculated by CHARTB.

The temperature which must be attained in order to guide the discharge may be estimated from the gas-breakdown literature.²¹ The preionization quoted there ($N_i \sim 10^{10}$ to 10^{11} cm^{-3}) arises from space-charge distortion of the applied field and corresponds to the avalanche-to-streamer transition. The required temperature is found from the Saha equation where $T = 2880 \text{ K}$ for $N_e = 3 \times 10^{10} \text{ cm}^{-3}$.

The absorption data presented here will have to be extended to higher energy density in order to determine whether more energy can be absorbed to overcome the onset of dissociative losses and increases in specific heat due to electronic terms as we attempt to reach a temperature where partial ionization may start ($\approx 3000 \text{ K}$).

Plasma Source Development (C. W. Mendel, G. S. Mills, and R. B. Spielman)

Among the prime candidate ion diodes for PBFA-I is the plasma-filled, magnetically self-insulated diode (Ampfion) developed by C. W. Mendel. The A-K gap of this diode requires a plasma fill of $\sim 10^{14} \text{ cm}^{-3}$ in order to function properly; an array of solid carbon-loaded guns has met this requirement to date. For target-drive experiments, ion-range restrictions indicate D^+ or He^{++} ion beams will be optimum (which means that the diode A-K gap must be filled with plasma containing either of these two species). A gas loaded plasma gun of a considerably different design must be used. We describe the adaptation of a conical z-pinch (CZP) gun²² to accommodate a fast-opening gas valve for use with these light gases.

Difficulties arise with D_2 and He systems because of the high thermal velocity of the atoms ($\sim 8 \times 10^4 \text{ cm s}^{-1}$), the requirement that there be no neutral atoms in the A-K gap during the diode power pulse, and the lengthy opening time of conventional gas-puff valves ($\geq 100 \mu\text{s}$). Initial work has been directed toward development of a fast ($< 100 \mu\text{s}$)-opening, noncontaminating, gas valve that could be used with the CZP gun.

The valve that was developed is a stretched latex diaphragm ruptured by a spark between an electrode touching one side of the latex and the gas in the plenum. A schematic of the system in a development configuration is shown in Figure 94. The stretched latex was advantageous because an opening of sufficient size results from an initial pinhole and contraction of the diaphragm; this avoids the relatively high energy and plasma contamination involved in rupturing a Mylar diaphragm with exploding wires. Figure 95 shows a series of fast-framing pictures at three different time intervals (after the rupturing spark was triggered) on three different diaphragms. The bulging of the diaphragm, especially at $50 \mu\text{s}$, is due to the 20-Pa-He fill in the plenum; the back light is supplied by a second discharge inside the plenum. Good repeatability of diaphragm opening vs time was obtained once the skill of stretching the latex over the plenum opening was developed. These results showed that in $50 \mu\text{s}$ a suitable opening for the CZP gun was obtained, limiting the travel distance of the neutral gas to $\sim 4 \text{ cm}$ before the plasma leaves the gun. This performance exceeds requirements since the present diode design calls for a gun-to-A-K gap distance of $\sim 30 \text{ cm}$.

Figure 94. Schematic Diagram of the Diaphragm-bursting Pulse Circuit and the Test Setup used to Determine Opening Times

$t=150\mu\text{sec}$

$d=5.2\text{cm}$

$t=100\mu\text{sec}$

$d=2.7\text{cm}$

$t=50\mu\text{sec}$

$d=1.2\text{cm}$

Figure 95. Fast-Framing Photographs of Successive Shots Showing the Diaphragm Aperture (d) at Various Times (t) After Firing the Rupture Pulse

The CZP gun described in Reference 22 was modified as shown in Figure 96 to allow mounting of the latex diaphragm at the gun nozzle. The gun volume is filled via a manual valve and the diaphragm burst spark is fired $50\mu\text{s}$ (or other desired interval) before the Z-pinch main power is triggered. To date, the diaphragm has worked satisfactorily and measurements of the CZP-gun plasma output are in progress. Continued work with the modified gun is necessary to demonstrate that plasmas of adequate density and the desired charge state ($2+$ for He) can be generated reliably; the gun will then be mated to the plasma-filled ion diode.

Figure 96. Schematic of the Conical Z-Pinch Gun and the Modified Inserts Used to Adapt the Latex Diaphragm to the Exit Nozzle

Spherical Electron-to-Ion Converter

(P. A. Miller)

The first experimental test of the spherical electron-to-ion converter concept was carried out. The theory of operation of this ion source was described in the last report. A single beam from Hydra was transported by a 17-cm-long plasma channel to a 10-cm-dia evacuated, thin-glass sphere ("light bulb"). In the concept (1-D spherically symmetric), the electrons reflex through the sphere walls and accelerate ions which converge on a levitated central TN target. In the present experiment, the single-beam irradiation provided grossly nonuniform illumination of the sphere and most of the crucial parts of the 1-D theory could not be addressed quantitatively. Significant results included the following:

1. X-Ray diagnostics indicated that most of the REB was indeed stopped by the glass, which was about 8% of a CSDA range, and some REB transport was seen through the light bulb. This means that reflexing was occurring and that the fields inside the light bulb were not being shorted out by some unanticipated plasma process.
2. Neutron diagnostics indicated that ions (deuterons in a doped sphere) were accelerated in the sphere and hit the levitated diagnostic target. Their spatial distribution and energies are unknown; no 2-D calculations for this asymmetric configuration are available to compare with the indicated ion quantity.
3. The timing and triggering circuitry, including the magnetic drive to propel the aluminum diagnostic target to the sphere's center, performed almost perfectly.
4. The glass-sphere fabrication and aluminum coating processes have all been successful. The 250- μ -wall spheres with tubulations have all survived pumpdown, which means that similar improved designs with walls even closer to the theoretical limits of glass strength are possible.

So far no simple failure modes for the concept have been found. A critical test of the theory awaits

either 2-D calculations or an experiment in something more closely approaching spherical geometry. It is anticipated that such an experiment on Proto II and PBFA I would be difficult and time consuming; it remains to be decided whether further, more detailed measurements in simple systems are warranted. For example, it may be possible to infer the energy of electrons reaching the levitated central target by making spatially resolved, filtered, bremsstrahlung measurements.

Pulselac Program

**(S. Humphries, Jr., J. R. Freeman,
G. W. Kuswa, C. W. Mendel,
and J. W. Poukey)**

The goals of the Pulselac Program are to investigate the general principles of neutralized ion beam transport in vacuum and the use of these principles for the development of high current, multistage, linear ion accelerators.^{23 24} Such accelerators would have numerous advantages for use as inertial fusion drivers.²⁵⁻²⁷ During the past 6 mo, experimental work has continued with the development of practical pulsed large-area electron sources and the construction and testing of a five-stage carbon-ion accelerator. Additionally, with the advent of support from the Heavy Ion Fusion Program, studies have been made for the design of the Pulselac C accelerator. This will be a sixteen-stage inductive Linac well-suited to in-depth studies of high-current ion-beam transport.

Pulse Large-Area Electron Sources

One of the major practical problems for neutralized ion-beam transport is the means for providing electrons over large areas of the accelerator. Standard thermionic emitters would consume prohibitively large amounts of power. The duty cycle of the electron sources would be only about 10^{-6} (even in a reactor) so that pulsed sources are of greatest interest. A recently developed electron source is shown in

Figure 97. It consists of a laminate of two layers of high dielectric-strength insulator (0.1-mm Kapton) surrounding a metal sheet with a grounded-front surface of commercial perforated metal stock. The assembly is mounted on a grounded metal substrate such as the inner wall of an accelerator drift tube. When the central activation plate is pulsed with an oscillating high voltage (~ 20 kV), fringing electric fields are set up at the points where the perforated metal contacts the insulator, as shown. These fields can exceed 200 kV/cm along the surface so that a vacuum surface breakdown is induced. The exposed insulator surfaces are rapidly covered by a plasma that can act as an electron source. The advantages of the geometry shown in Figure 97 are:

1. There is no exposed high voltage since the activation plate is completely enclosed.
2. The front surface of the source exposed to the ion beam is composed of relatively thick metal directly connected to the substrate.
3. The breakdowns are capacitively ballasted, permitting many areas of plasma to be initiated with a single-voltage feed.
4. The capacitive coupling of energy to the surface is maximized for the highest energy transfer to the plasma.

Figure 97. Capacitively Ballasted Surface Flashboard-Electron Source

Experiments have confirmed operating characteristics of the device. A high-voltage plate, suspended 2 cm in front of the plasma surface, drew source-limited electron-current density of over 10 A/cm² during a microsecond pulse. As expected, the plasma was initiated on the positive cycle of the activation-plate voltage. The 20-kV detector plate was not shorted over 10- μ s time-scales, indicating little evolution of gas or plasma. Applications for large-area electron-beam sources for laser excitation and other purposes also exist.

Five-Stage Injector, Pulselac B

A five-stage injector, shown in Figure 98 was operated to demonstrate the feasibility of multistage ion acceleration in magnetically insulated gaps. The

stages were powered electrostatically with independent floating-voltage sources. Carbon-ion beams over 3 kA were produced for 0.5- μ s pulselengths at energies up to 600 keV. Behavior was consistent with previous results from a two-stage injector.²⁸ Of greatest importance was that the divergence of the output beam was less than 0.7 degrees. A number of technological improvements were made in building the system, and experience was gained in the design of ion-beam transport systems to meet tight spatial constraints. Sections of the five-stage injector are presently being used in experiments on beam neutralization and focusing.

- A. Carbon-plasma gun array.
- B. Plasma expansion chamber.
- C. Extraction slots.
- D. Magnetically insulated injector gap.
- E. Graded lucite-insulator rings.
- F. Drift tube - magnetic coil assemblies.
- G. Gaps 2 and 3.
- H. Gaps 4 and 5.

Figure 98. Pulselac B, Five-Stage Injector

Linear-Induction Accelerator, Pulselac C

The next 2 yr of Pulselac research will center on Pulselac C, a 4-MeV linear-induction accelerator for multi-kiloampere ion beams. If successful, Pulselac C will provide a firm demonstration of high-current ion-beam accelerator technology. The unique beam-output parameters will be ideally suited for studies of

ion-beam transport in a reactor environment. A cross-sectional view of one stage is shown in Figure 99. Design goals are listed in Table 4.

Table 4. Pulselac C Parameters

	Measurements
Accelerator Length	6 m
Number of Gaps	16
Voltage per Gap	250 kV
Beam Current	5 kA
Pulseline Impedance	12.5 ohm
Pulselength	50 ns
Cross-Sectional Area	200 cm ²
Gap Magnetic Field	4 kG
Longitudinal Gradient	0.75 MV/m
Injector Voltage	100 kV
Injector Pulselength	600 ns
Ion Species	C ⁺
Bunched-Beam Pulselength	20 ns
Bunched-Output Power	50 GW
Output Divergence	LT 0.5 deg
Focused-Beam Spot	LT 1 cm ²
Beam Energy	1 kJ
Repetition Rate	1 ppm

Overlap of Charged Particle Beams

(J. Halbleib, P. A. Miller,
L. P. Mix, and T. P. Wright)

The overlap of charged particle beams transported by use of preformed, current-carrying plasma channels is an essential part of present concepts of light-ion-driven fusion. A theoretical approach that addresses this critical CPB overlap process has been tested experimentally in detail by use of electron beams; the final results are presented here.

A figure of merit for the CPB overlap process is current density gain G , which is the ratio of beam-current density at the target surface to that of the individual beams in the transport channels. The obtainable values of G are dependent on particle species, transverse energy, geometry of the channel-target interface, etc. Detailed calculations²⁹ have indicated that for the case of electron beams, $G < 3$, while for practical cases of light ions, G can be > 10 ; this is because of the differences in masses and effective temperatures of the two types of beams. At present, sources providing multiple ion beams are not available to test this overlap theory experimentally. Consequently, the first test of this critical theory has been performed using a multiple electron-beam system. In the following section we outline the goals of the

experiment and describe the apparatus. Subsequently, we summarize the theoretical treatment of beam overlap, describe diagnostic procedures, and then compare the experimental results with calculations.

1. Pulselac C acceleration gap.
2. Magnet-coil/drift-tube assembly.
3. Vacuum insulator.
4. Ferrite core.
5. Annular beam transport region.

Figure 99. One Stage of Pulselac C

Experimental Design and Apparatus

In the experiment, several electron beams were generated simultaneously and transported through plasma channels^{30 31} to a common cylindrical target. Various targets with different diameters were used, and measurements were made of the total energy

delivered to the targets. All of the available energy could be delivered to sufficiently large cylinders and, as the diameter of the target was decreased, progressively less of the energy reached the target. The goal of the experiment was to measure the dependence of delivered energy on target diameter and to compare this with theoretical predictions. Agreement would imply that the physical models are correct in the present energy-density regime. Further work would still be required, however, to investigate collective effects that may be important with higher energy-density systems.^{32, 33}

The electron-beam source was the Proto II accelerator³⁴ at Sandia National Laboratories. The front end of the accelerator was configured to drive 12 separate electron-beam diodes in parallel. These diodes were arranged in coplanar fashion in a 1-m dia circle as shown in Figure 100. On each accelerator shot, 12 pinched electron beams were generated; 6 of these were stopped by 0.64-cm-thick solid aluminum or copper anodes. The other six were extracted from the diodes through thin, compound diaphragms in the centers of the anodes. The six extracted beams were transported by preformed plasma channels that had the target as a common terminus. The channels were formed in parallel by the discharge of a 20- μ F-capacitor bank system charged to 65 kV. System inductance was 330 nH. The six plasma channels used for beam transport were formed in the ambient laboratory atmosphere and were guided by 25- μ m-dia tungsten wires. Figure 100 is for illustrative purposes only; it shows channel formation but no REBs are present. In the actual experiment this view was obscured by additional apparatus, the diode region (outer annular region with brass cathodes) was evacuated, and only six channels were formed. The central-target cylinder was pulsed to high voltage by a symmetric feed (top and bottom) of two capacitor banks, only one of which was used for the photograph.

The phenomenology and limitations of plasma-channel transport have been discussed in more detail elsewhere.³² Basically, the channels start with initial diameters less than 1 mm and expand with radial velocities of about 1.5 mm/ μ s. The central part of each channel consists of singly-ionized air at a few electron volts temperature with a mass density reduced below ambient by a factor near 4. There is evidence that the tungsten wire plays a role only in initiating the discharge, and it does not "explode" nor affect subsequent channel dynamics. The channels' features should be the same as if they had been laser-initiated. As the channels expand, the current rises to a peak in 4 μ s; at this time the accelerator is fired. The conductivity of the channels is high enough to provide space-charge and current neutralization of the

beam fields. Ideally there are no collective effects, and the beam is guided only by the channel fields from the channel current. Consequently, the peak current in each channel must be the Alfvén current, which is about 65 kA for 1.5-MeV.

For this experiment, Proto II was operated in a mode that provided a pulse with nominal parameters of 1.5 MV, 3.5 MA, 20-ns FWHM, 5 TW, and 100 kJ. The energy and power of each individual beam was about 8 kJ and 0.4 TW; a total of 50 kJ was transported 0.46 m. The aluminum targets had diameters ranging from 6 to 32 mm.

Theoretical Model

The time-independent theoretical model for channel transport is based upon an earlier technique³⁵ that combines coupled electron/photon collisional transport with electron transport in static, externally applied electric and magnetic fields of arbitrary spatial dependence. Since the relatively short-pulse REBs are not injected until the highly conducting plasma channels have been well established, the electrons of the charge- and current-neutralized beam are assumed to follow single-particle trajectories in the quasi-static externally applied field of the channel conduction current. While the material geometry in the numerical model is constrained to be two-dimensional, cylindrical, and invariant with respect to rotation about an axis of symmetry, particle-trajectory descriptions are fully three-dimensional. This three-dimensional capability is essential in the present application because of the azimuthal dependence of the multibeam source and because of the preferential orientation of the x-ray pinhole camera whose exposure environment is to be predicted by the model.

Figure 101 is an R-Z plot of a random sample of trajectories for a 1.91-cm-OD, 1.27-cm-ID cylindrical target. Only that portion of the electron trajectories outside the target is plotted. Experiments have confirmed efficient transmission along the plasma channels.³⁰ Consequently, trajectories are initiated in the model calculations at a distance of one betatron wavelength (~ 2.3 cm) beyond the geometrical beam "overlap radius" (~ 1.2 cm) to ensure spatial phase mixing.³⁶ The overlap radius is defined as the radius at which the edges of the individual beams and channels start to merge. The magnetic field is a superposition of the fields due to the six channel-conduction currents and the axial-return currents in the target cylinder. Field effects are ignored inside the solid target because of the high-collision frequency. On the other hand, collisional effects are ignored outside the target.

Figure 100. Photograph of Channel Formation for the Photo II MEB Experiment

Figure 101. R-Z Trajectory Plot for Beam-Electrons Incident on a 1.9-cm OD Target Cylinder. Target zoning for deposition analysis is indicated but trajectories inside the target are suppressed. The quantities I_B , I_C , and I_R are the magnitudes of the beam currents, channel-conduction currents, and return currents ($3I_C$), respectively; directions of the electron flows are indicated by the arrows.

Since the target radius is about three quarters of the geometrical overlap radius in this calculation, $\sim 100\%$ of the beam strikes the target.²⁹ The beam/target coupling efficiency (the percent of the beam energy deposited in the target) is about 80%. As is evident from Figure 101, most of this energy is deposited within the beam radius. A few of the reflected electrons reenter the target; however, the majority of the reflected electrons ($\sim 20\%$ of the beam energy) is lost through axial drift in the field of the return currents.

The numerical model was also employed to predict the coupling efficiencies and three-dimensional energy deposition profiles as a function of the target OD. In addition, spatially and spectrally resolved predictions of the x-radiation emitted within a small solid angle about a direction corresponding to the orientation of an experimental pinhole camera were obtained. According to the calculated results, the

total x-ray emission in the direction of the pinhole should be proportional to the coupling efficiency.

Target Diagnostics and Results

The fraction of the beam energy transported to the central-target cylinder was determined from measurements of the bremsstrahlung produced by the electron beams. An x-ray pinhole camera was positioned in the plane of the transport channels and viewed the cylinder transverse to its axis. Thermoluminescent dosimeters (TLDs) were positioned at one end of the central-target cylinder. Additional TLDs were placed behind the solid aluminum anodes of those beams which were not transported to provide a reference measurement of the dose expected when 100% of the electrons were stopped in aluminum.

Both diagnostics relied on the theoretical calculations presented in the preceding section for interpretation of the results. The absolute TLD measurements were calculated to depend strongly on the kinetic energy of the electrons striking the aluminum (roughly as the square of the energy). The uncertainties in the absolute voltage-monitor calibrations would have made this technique inaccurate if only one TLD reading had been made. However, the ratio of the TLD doses from the cylindrical targets to those from the solid anodes was calculated as independent of voltage, to within the accuracy of the Monte Carlo calculation, over the range 0.5 to 1.6 MeV. This ratio was used to determine the transport efficiency for the 3.2- and 1.9-cm-dia cylinders.

The presence of electron-drift losses near the ends of the cylinders would have complicated interpretation of TLD data for the smaller diameter cylinders. However, the x-ray pinhole camera was able to resolve this loss spatially and thus was used to infer the transport efficiencies to smaller cylinders. A typical x-ray photograph is shown in Figure 102. Previous work³⁷ has shown that the image on the developed film is proportional to the energy absorbed in the film emulsion in this regime; absolute calibrations were not required. The spatial distributions in the x-ray images were in good agreement with the theoretical predictions. The observed x-ray intensities were compared with the predicted intensities calculated using the techniques described above. By normalizing the experimental photographic intensities to the theory for the 3.2-cm dia cylinder, the absolute transport efficiencies could be inferred for smaller diameter cylinders.

Figure 102. X-ray-Pinhole Photograph of 6-Beams Incident on a 1.9-cm OD Target. The vertical axis of the cylinder is indicated.

A comparison between the transport efficiencies predicted using the numerical model and the experimental data is shown in Figure 103. Surprisingly, the agreement between theory and experiment is much better than one might have expected based on possible inaccuracies in both. The only significant disagreement occurs for the smallest cylinder for which the measurement is about 5% below the calculated transport efficiency of 19%. We interpret this result as strong support (in this regime of energy densities) for the models used to calculate plasma-channel formation, channel-overlap geometry, and electron and photon transport, and for the experimental procedures used. Also shown for reference in Figure 103 is a calculated prediction of transport efficiency for protons injected into the same channel system used here for the electron beams. The ions would reach a smaller radius with higher efficiency than do the electrons, and thus would irradiate a target with higher power fluence. This result, along with their more favorable energy-deposition properties³⁸ and the recent rapid advances in ion-diode research,^{32, 39} make light ions more attractive than electrons for ICF use.

Figure 103. Beam-Target Coupling Efficiency as a Function of Target Radius. For the 2-MeV proton-reference calculation, the maximum angle of injection of protons into the channels was taken to be 8 degrees.

Review Paper on Intense Ion Beam Physics and Technology (S. Humphries, Jr.)

A review paper has recently been completed on the subject of intense ion-beam physics and technology. It will be published in *Nuclear Fusion*. The paper presents, for the first time, a unified treatment of the

intense ion-beam field that has led to light ion fusion research at Sandia; it is divided into sections on methods of intense ion-beam generation and applications to fusion research. Subjects treated in the first section include the theory of high-current ion injectors, experiments in the field since 1973, methods for diagnosing high-ion fluxes, and the physics of beam transport in vacuum and plasma. The second section includes material on applications to magnetic fusion, the physics of ion beam driven inertial-fusion targets, light ion fusion experiments, and multistage accelerators using neutralized-transport principles. Over 250 references are catalogued.

References

1. D. J. Johnson, G. W. Kuswa, A. V. Farnsworth, Jr., J. P. Quintenz, R. J. Leeper, E. J. T. Burns, and S. Humphries, Jr., *Phys Rev Lett*, 42:610, 1979.
2. S. Humphries, Jr., *J Appl Phys* 49:501, 1978.
3. W. C. Leslie, "Microstructural Effects of High Strain Rate Deformation," *Metalurgical Effects at High Strain Rates*, eds R. W. Rohde, B. M. Butcher, J. R. Holland, and C. H. Karnes (New York: Plenum Press, 1973).
4. C. W. Mendel, Internal Report RS4244/2, December 1978.
5. C. W. Mendel, *Conference Record, IEEE Int'l Conf on Plasma Sci*, June 4-6, 1979, p 76.
6. D. Cook, *3rd ANS Topical Meeting on the Technology of Controlled Nuclear Fusion*, (Santa Fe, May 9-11, 1978).
7. D. J. Johnson, A. V. Farnsworth, D. L. Fehl, R. J. Leeper, and G. W. Kuswa, *J Appl Phys*, 50:4524, 1979.
8. F. C. Young, J. Golden, and C. A. Kapetanakis, *Rev Sci Instrum*, 48:432, 1977.
9. S. I. Braginskii, *Sov Phys JETP*, 34:1068, 1958.
10. P. A. Miller, L. Baker, J. R. Freeman, L. P. Mix, J. W. Poukey, and T. P. Wright, *Proc. of the 2nd Int'l Topical Conf. on High Power Electron and Ion Beam Research and Technology*, Vol. I (Cornell University, 1977).
11. D. Cook, *Third ANS Topical Meeting on the Technology of Controlled Nuclear Fusion*, (Santa Fe, May 9-11, 1978).
12. J. N. Olsen, D. J. Johnson, and L. Baker, *Bull Am Phys Soc*, 24:978, 1979.
13. F. L. Sandel, F. C. Young, S. J. Stephanakis, F. W. Oliphant, G. Cooperstein, A. Goldstein, and D. Mosher, *Bull Am Phys Soc*, 24:1031, 1979.
14. *Tables of Molecular Vibration Frequencies, Consolidated Volume I*, NSRDS-NBS 39, Nat Bur Standards, 1972.
15. H. E. Bass and T. G. Winter, *J Chem Phys*, 56:3619, 1972.
16. H. K. Shin, *J Phys Chem*, 77:346, 1973.
17. R. V. Ambartsumyan, V. S. Letokhov, G. N. Makarov, and A. A. Puretskii, *Sov Phys JETP*, 41:871, 1976.
18. S. L. Thompson, Sandia Labs. Report SC-RR-71 0713, 1971 (unpublished).
19. G. Herzberg, *Infrared and Raman Spectra*, (New York: D. Van Nostrand Co., 1945).
20. D. R. Stull and H. Prophet, *JANAF Thermochemical Tables 2nd Ed.*, NSRDS-NBS37, National Bureau of Standard, 1971.
21. P. Felsentahl and J. M. Proud, *Phys Rev*, 139A:1796, 1965.
22. C. W. Mendel, Jr., *J Appl Phys*, 42:5483-5491, December 1971.
23. S. Humphries, Jr., *J Appl Phys*, 49:501, 1978.
24. S. Humphries, Jr. and J. W. Poukey, *Particle Accelerators*, 10:71, 1979.
25. S. Humphries, Jr., G. W. Kuswa, C. W. Mendel, and J. W. Poukey, *IEEE Trans Nucl Sci*, NS-26:4220, 1979.
26. S. Humphries, Jr., G. Yonas, and J. W. Poukey, *Collective Methods of Acceleration*, eds N. Rostoker and M. Reiser (New York: Harwood Academic Publishers, 1979, p 595).

27. S. Humphries, Jr., *Proc. of the Heavy Ion Fusion Workshop*, ANL-79-41, ed R. C. Arnold (Argonne National Laboratory, 1978, p 93.
28. S. Humphries, Jr., J. R. Freeman, J. Greenly, G. W. Kuswa, C. W. Mendel, J. W. Poukey, and D. M. Woodall, *J Appl Phys*, to be published.
29. T. P. Wright, *J Appl Phys*, 49:3842-3850, 1978; T. P. Wright and J. A. Halbleib, Sr., SAND79-2064J (Albuquerque: Sandia Laboratories, 1979), also submitted for publication; J. A. Halbleib, Sr. and T. P. Wright, SAND79-2063J (Albuquerque: Sandia Laboratories, 1979), also to be published in *Phys. Fluids*.
30. P. A. Miller, R. I. Butler, M. Cowan, J. R. Freeman, J. W. Poukey, T. P. Wright, and G. Yonas, *Phys Rev Lett*, 39:92-95, 1977.
31. J. Benford, *J Appl Phys*, 48:2320-2323, 1977.
32. P. A. Miller, D. J. Johnson, T. P. Wright, and G. W. Kuswa, *Comments on Plas Phys and Controlled Thermonuclear Fusion*, 5:95-103, 1979.
33. P. F. Ottinger, D. Mosher, and S. A. Goldstein, *Phys Fluids*, 22:332-337, 1979; D. Mosher, D. G. Colombant, S. A. Goldstein, and R. Lee, *IEEE Conference Record-Abstracts*, 1978 IEEE Int'l Conf. Plas. Science, Monterey, CA, USA (New York: IEEE, 1978, p 113; J. R. Freeman, P. A. Miller, L. Baker, J. P. Quintenz, T. P. Wright, J. W. Poukey, L. P. Mix, and M. M. Widner, *Ibid*, p 177.
34. T. H. Martin, D. L. Johnson, and D. H. McDaniel, *Proc. Second Int'l Topical Conf. on High Power Electron and Ion Beam Research and Technology*, Vol. 2 (Ithaca, NY: Cornell University, 1977), pp 807-818.
35. J. A. Halbleib, Sr. and W. H. Van Devender, *J Appl Phys*, 48: 2312-2319, 1977.
36. T. P. Wright and J. A. Halbleib, Sr., *Bull Am Phys Soc*, 24:949, 1979.
37. C. M. Dozier, D. B. Brown, L. S. Birks, P. B. Lyons, and R. F. Benjamin, *J Appl Phys*, 47:3732-3739, 1976.
38. M. J. Clauser, *Phys Rev Lett*, 35:848-851, 1976.
39. D. J. Johnson, G. W. Kuswa, A. V. Farnsworth, Jr., J. P. Quintenz, R. J. Leeper, E. J. T. Burns, and S. Humphries, Jr., *Phys Rev Lett*, 42:610-613, 1979.

Chapter 5. Pulsed Power

Overview

The Pulsed Power Research Division worked primarily in the PBFA I, PBFA II, foil implosion, ion diode, and advanced-energy storage and switching programs. The assembly and test of the PBFA I accelerator progressed through the first firing of the 3.76-MJ energy store. For the first time, 36 high-energy Marx generators were synchronously fired with a rms jitter of less than 5 ns. This achievement is a benchmark in the development of distributed, extendable, pulsed-power sources.

Power-flow research for PBFA I continued with positive-polarity pulse-generation and power-transport experiments on HydraMITE. The power flow to the diode was examined theoretically and experimentally on HydraMITE and MITE, and a new experiment with a coaxial to triaxial, magnetically self-insulated post/hole convolute was conducted. The results indicate that the extremely large power densities that have been passed through smooth geometries can be used in applications that require more complicated power feeds. Ion-beam generation, dense-plasma production, and x-ray-simulation sources can each benefit from this technology.

The program for developing the 4-MV, short-pulse technology required for PBFA II was defined and work has begun. A 1.2- to 5.3-MV pulse conditioner was invented and tested. Radiation losses in water dielectric convolutes were explored theoretically and experimentally. A PBFA II pulse conditioner was designed and fabricated for the MITE accelerator. Tests will be conducted in February and March of 1980. The associated program for understanding high-voltage, high-current, low-jitter gas switching was also developed, and the first experiments were conducted. The switch program includes experiments on the basic streamer formation and propagation processes in high-pressure SF_6 gas. The program contains a substantial electrode-material development effort in collaboration with Sandia's material sciences department; it features advanced switch concepts like KrF-laser triggering and x-ray triggering. Additionally, switch development with commercial suppliers is being initiated. Experiments will continue through FY 80 and FY 81.

The program for dense-plasma production with imploding foils featured a detailed study of the initial phase of foil and multiwire implosions. The initial phase of foil implosions was shown to be more stable than the corresponding phase of multiwire experiments. The output power of Proto II was increased from 5 to 11 TW and the energy was increased from 100 to 320 kJ in preparation for higher energy experiments. The power flow and current-driven liner experiments were initiated during this reporting period. The results of these experiments will be reported in a separate document.

Magnetically self-insulated electron-flow technology was applied to ion-beam production and focusing. An initial quasi-planar experiment called SMAUG was conducted on the MITE experiment and analyzed with 2-D steady-state simulations. The experiment and theory were in excellent agreement and provided a basis for scaling to the more efficient, quasi-spherical geometry. The projected ion efficiencies for Proto II and PBFA I are 25% and 48%, respectively, and the expected power densities on a 3-mm diameter target are 9 and 22 TW/cm², respectively. However, the diode requires the development of a large area (2000 cm²) ion source. Because other ion diodes are more highly developed, further work in this diode is considered of low priority.

Advanced experiments in the ICF program could be performed if a few tens of megajoules were available for carefully executed, single-shot experiments. The power source for these experiments could be an explosive generator with an explosively driven, fast-opening switch. The INTREPID experiment was designed to investigate the plasma dynamics. The switch has been examined in 1-D hydro simulations and in experiments at the 1-MA level. The successful experiment, which had a characteristic opening time of 450 ns, showed that the approach is promising. A model of the switch mechanism has been formulated and will be investigated in forthcoming experiments.

The results of each of these activities is reviewed in the following sections. We are on schedule for PBFA I and PBFA II, and have made substantial progress in the research and development of long-term pulsed power sources.

PBFA I

PBFA I Assembly and Test (J. F. Seamen)

PBFA I is a 36-module, particle-beam accelerator as shown in Figure 104. Each module consists of a Marx generator, a transfer capacitor, a triggered gas switch, a double pulse-forming line, water dielectric multisite output switches, a transformer, vacuum interface, long magnetically self-insulated power-flow lines, and a particle-beam diode. All modules are designed to deliver their power pulse to the diodes with a simultaneity of 12.3 ns. This jitter is primarily determined by the jitters of the gas and water switches, and secondarily by the Marx-generator jitter.

The PBFA I, modular, pulsed-power technology relies on building identical components and subsystems, and triggering them simultaneously. Proto II tested the concept with eight Marx generators. The initial PBFA I test of the Marx generators shows that the modular, primary pulsed-power concept is a sound one. The Marx generator will be tested at full power on February 1, 1980 when the diagnostic software is ready.

The details of the assembly is discussed elsewhere in this progress report under the PBFA I project report

Figure 104. PBFA I.

Effect of Module Jitter on Output-Power (D. L. Johnson)

A statistical analysis of the PBFA I module simultaneity was performed. Measured values of gas- and water-switch jitter were used to predict PBFA module jitter and machine simultaneity. The module jitter was then used to predict the PBFA I output power and pulse shape.

MITE experiments showed that the rms jitter or standard deviation of a single water switch was 6 ns. Each module has 10 water switches in parallel. A time-of-closure (t_s) of 5 of the 10 switches was selected as the random variable to be studied and was defined as the water switch closure time. Each of the 10 switches was assumed to be independent; this assumption, while not entirely correct, is acceptable since the switches are transient-time isolated from one another. The standard deviation of t_s was calculated using the 5th order statistic for a normal distribution and for a Weibull distribution. The results are: $\sigma_{\text{normal}} = 2.33$ ns and $\sigma_{\text{Weibull}} = 2.4$ ns. These values are close so a normal distribution was assumed for the remaining calculations.

The module-output time is equal to the sum of the times to closure of the gas and water switches plus a fixed delay.

$$T_{\text{out}} = t_{\text{gas switch}} + t_{\text{water switch}} + \text{constant}$$

Measurements of the trigatron switch timing on HydraMITE yielded a 1.64 ns standard deviation for the gas switch time. The standard deviation of T_{out} is then

$$\sigma_{\text{out}} = \sqrt{\sigma_{\text{gas}}^2 + \sigma_{\text{water}}^2}$$

$$\sigma_{\text{out}} = \sqrt{(1.64)^2 + (2.4)^2} = 2.9 \text{ ns}$$

The expected values of the range of firing times ($R = T_{\text{last}} - T_{\text{first}}$) for PBFA I and PBFA II are

$$E(R) = 4.24 \times \sigma_{\text{out}} = 12.3 \text{ ns (PBFA I)}$$

$$E(R) = 4.78 \times \sigma_{\text{out}} = 13.9 \text{ ns (PBFA II)}$$

The effect of the module jitter on output power was calculated assuming a distribution of firing times of normally distributed random variables with $\sigma = 2.9$ ns and using $\sin^2 \omega t$ waveshape for the power pulse with a FWHM of 40 ns. For both PBFA I and PBFA II, the power reduction was less than 2%.

Since ion bunching is being considered, calculations of output powers were made assuming a time compression of 4 (i.e., a 10-ns FWHM pulse) on the output power pulse of each module. The output power was reduced, in this case, by 17% from the maximum power available. Figure 105 shows the normalized pulses with and without module jitter.

Figure 105. Normalized PBFA II Output Power With and Without Module Jitter. Each module has a $\sin^2(t-t_0)$ pulse shape with a 10-ns full width at half-maximum.

Sensitivity of Output Power to Gas-Switch Timing (J. T. Crow)

Analysis of the HydraMITE data shows that the energy to the water-vacuum interface is a sensitive function of the timing of the gas switch between the intermediate storage capacitor and the pulse-forming lines.

Output energy versus gas-switch timing is plotted in Figure 106 for 25 shots. Energy was calculated using a program that integrates the outputs of two D-dot and three B-dot monitors at the vacuum interface to obtain voltage and current values; they are then corrected for inductive effects, multiplied together, and again integrated with respect to time. Gas-switch timing was varied by using a self-break switch over a range of gas pressures. Examination of

the plot indicates that 50 ns early firing (out of ~620 ns optimum charging time for the intermediate-storage capacitor) results in a loss of 3 to 5 kJ and firing 100 ns early will decrease the output nearly 10 kJ or one-third the potential output.

Figure 106. Energy to Diode vs Gas Switch Timing (Intermediate-Storage Capacitor Charging Duration).

A possible error exists in the calculation of the output energy in that small baseline uncertainties in the D-dot and B-dot monitors become large when integrated two times. An improved system of energy measurement is being developed.

Positive-Polarity Power Transport in the HydraMITE Power-Flow Lines (J. T. Crow, J. S. Seamen, and J. P. VanDevender)

Successful testing of the HydraMITE facility in the negative polarity configuration was reported in the last Semiannual Progress Report. Testing with positive polarity shows that power transport through the injector and MITL is 100%, within experimental error.

Polarity reversal is accomplished in the water section by crossover bars installed between pulse-forming lines 1 and 2.¹ Operation of the Marx generator intermediate-storage capacitor and line 1 remains the same as in the negative-polarity case.

Current transport is measured by comparing the current at the vacuum interface between the water and MITL line (I_{in}) with the current at a point 4.5 m toward the load (I_{out}). Figure 107 shows I_{in} and I_{out} for a typical self-limited case (HydraMITE shot No. 41), time-shifted to show amplitude correspondence. Figure 108 (shot No. 47) shows the two currents for a short-circuit load located 80 cm from the I_{out} monitor. The peak of I_{in} is 420 kA, and the first (forward) peak of I_{out} is 440 kA, within the accuracy of the monitors.

Figure 107. MITL Input and Output Current for Self-Limited Line.

Figure 108. MITL Input and Output Current for Short-Circuit Load.

The peak value of I_{out} under short circuit conditions can be calculated by the formula

$$I_{out} = I_{in} \left(\frac{4\alpha}{1 + \alpha} \right)$$

where α is the ratio of the MITL impedance under matched conditions (self-limited) to the vacuum impedance. For HydraMITE at 2 MV, $\alpha = 0.63$, and here $I_{in} = 420$ kA. Then $I_{out} = 650$ kA calculated, with a measured value of 680 kA.

Measurements of transport efficiencies in HydraMITE will continue as the facility is further used for testing various loads.

Magnetically Self-Insulated Output-Convolute

(J. P. VanDevender, D. B. Seidel and J. T. Crow)

Each magnetically self-insulated transmission line on PBFA I ends in a tapered transition from a

closed triplate line to a coaxial line. The coax is then connected to the diode. We previously reported that the output transition was lossy in the negative-polarity mode, and that the electron loss was predominately on the top and bottom parts of the convolute. We have taken more extensive data on the MITE and HydraMITE accelerators in both polarities. Although the analysis of the data is critically dependent on the model used to infer the voltage from the measured currents, the data indicates that the negative-polarity convolute is indeed lossy for a load impedance $> 3\Omega$. The positive-polarity data indicates the losses are somewhat less. The design of the convolute has been altered to relieve the electrical stress in the region of the loss. The modification on a similar convolute on MITE reduced the losses in the negative-polarity mode. The modified design has been ordered for installation on PBFA I. The significance of this work is that a diode that requires a positive-polarity mode would be advantageous. However, the modified design should allow an acceptable power transport in the negative mode.

Figure 109. Schematic Diagram of the MITE Output Transition Between the Triplate and Coax Lines. The distributed element network that approximates the transition is also shown.

The geometry of the output convolute and its equivalent circuit representation are shown schematically in Figure 109. The total and boundary currents I_T and I_B are measured before the convolute. The total current I_{out} is measured after the convolute. The A-K gap is varied and the data is reduced to give the efficiency of current-transport $N = I_{out}/I_T$ for a given ratio of the load impedance Z to the vacuum-wave impedance Z_o of the triplate line.

If the load impedance is larger than the self-limited impedance $Z_{SL} \approx 0.63 Z_o$, then the total current is the self-limited value, the voltage is $V = 0.63 Z_o I_T$ and $Z/Z_o = V/I_{out} Z_o = 0.63 I_T/I_{out}$. If Z is significantly less than Z_{SL} , the reflected wave collapses the electron flow and the load line for the magnetically self-insulated line² can be used to infer Z/Z_o as

$$Z/Z_o = \frac{I_{sc} - I_T}{I_{out}}$$

where I_{sc} is the short-circuit current. The appropriate expression to use in the analysis of a particular shot is determined by the values of I_T and I_B and the geometry of the load.

The data is shown in Figure 110 with the theoretical values calculated from an equivalent circuit simulation³ of the convolute geometry. The losses are significant unless the impedance is low. The mismatched load results in a significant reduction in the output power and energy, as shown in Figures 111 and 112.

Collimated thermoluminescent detectors were used on the top and side of the convolute to map the losses. The approximate time-averaged loss-current densities were computed from the dose measurement and are shown in Figure 113. The location and severity of the damage to the anode in the convolutes agree qualitatively with the inferred-current densities. The negative-polarity data shows severe losses on the top and bottom. The data suggests that the electron flow became detached from the cathode in the convolute, suffered a severe perturbation at the edge of the convolute, and was lost to the anode. The losses are both less and more uniform for the positive-polarity convolute. Apparently, the nature and severity of the perturbation is altered when the flow goes into the concave cathode at the top and bottom of a positive-polarity convolute. The physics and implications of the test results are still being investigated.

Figure 110. The Data From Positive (+) and Negative (0) Inner-Conductor Experiments is Shown With the Simulation Results.

Figure 111. The Calculated Power Absorbed in the Load as a Function of the Load Impedance R_L for a Well-Behaved Transition.

Figure 112. The Calculated Energy Deposited in the Load as a Function of the Load Impedance R_L for a Well-Behaved Transition.

Figure 113. Approximate Time-Averaged Loss-Current Densities. TLD's are placed as shown in the schematic. The current densities are calculated from the TLD measurements on the top and side of the output transition. The solid lines are for a negative inner conductor and the "S" and "T" data points are side and top measurements for a positive inner conductor.

An additional source of loss appeared on several of the higher impedance negative-polarity shots. After ~ 20 ns, a low impedance ($Z \approx 2$ ohms) loss occurred at some location in the convolute. The nature and cause of this loss has not been identified. If the lower impedance loss is caused by initiating ion flow from an anode plasma in the convolute, then the anode plasma must be formed by electron deposition of ~ 200 J/g, which is usually too low to cause anode plasma formation. Additional investigations will be conducted on the modified convolute.

Magnetically Self-Insulated Coaxial to Triaxial Convolute (CTC)

(J. T. Crow and G. D. Peterson)

The external B-field, extractor ion diode designed by D. J. Johnson requires a triaxial feed. A coaxial-to-triaxial magnetically self-insulated convolute has been tested on MITE with low-impedance loads from short circuit to a calculated 3 ohms. Current transport efficiency on most shots was near 100%, and current division between inner and outer lines of the triax could be adjusted by varying the impedance of the inner line.

A diagram of the tested configuration is shown in Figure 114. The outer housing and center rod are negative polarity and are connected together by four 3.3-mm dia pins passing through holes in the positive conductor. With this configuration, a region of zero B field can be expected 5 to 8 mm on the load side of the pins. It appears that no significant loss is caused by this field zero. Locations of the B-dot current monitors are shown schematically. The two inner monitors are actually rotated 90° from the two outer monitors. Spacers adjust the anode-cathode gap.

Figure 114. Coax-to-Triax Convolute.

The MITE triplate line has a vacuum impedance of 7.6Ω operating at 4.8Ω , and the tapered triplate-to-coax convolute has an impedance at the output of 20Ω . The inner and outer lines of the triax section are each 25Ω . The outer diameter permits packing 36 units on a 60-cm-radius circle, appropriate to PBFA I.

A Rogowski coil, located at the input of the MITE tapered convolute, was calibrated using a 10-kV pulser; then the B-dot monitors were calibrated against this Rogowski using short-circuit machine shots with and without the pins connecting the center rod. Current transport efficiency was calculated as the sum of the currents measured in the inner-and-outer triax lines, divided by the current at the Rogowski coil. Transport losses, therefore, include those in the taper convolute. A plot of current transport is shown in Figure 115 for shots with A-K gaps between 1.8 and 4.4 mm. Short-circuit shots used for verifying calibrations are not included. The average current transport for all shots plotted is 85%. If shots 6, 7, 8, 9, and 10 are excluded, the average transport is 99% (within an estimated accuracy of $\pm 15\%$) with a high of 103% and low of 85%. Shots 6 through 10 were taken after complete disassembly of both the MITE

tapered convolute and the CTC, and after opening the MITL for cleaning of the vacuum interface. Shots 6 through 8 were at 4.2 mm A-K gaps, shot 9 at 2.5 mm, and shot 10 at 3.3 mm. The reasons for the poor transport in these shots is not clear, but may be due to some misalignment on reassembly, or poor electrical connections somewhere in the MITL or convolutes. By shot 11, current transport had returned to 100%.

Figure 115. Current Transport Efficiency $\eta = I_{in}/I_{out}$ in Convolute.

Vacuum leaks were discovered near the load end of the MITE line after ~25 total shots (including short circuits). The two leaks were repaired and a previous shot configuration repeated. Gate valves in the diffusion-pump stacks are closed a few seconds before each shot, and line pressure at the time of firing can only be estimated. Using observed rates of pressure rise after closing the valves, the estimated pressure at the time of firing was $\sim 1 \times 10^{-1}$ Pa before the leak repair, and $\sim 2 \times 10^{-2}$ Pa after. The repeated shot indicated no difference in the transport, either in the MITE line or in the CTC, at the two pressures. The A-K gap in the two shots was small, so that the load impedance was a fraction of an ohm, approximately short-circuit conditions.

The load impedance on the MITE line was calculated for several shots using $Z_L = Z_o(I_{sc} - I_{in})/I_L$, where Z_o is the MITE-line vacuum impedance; I_{sc} , the short circuit current; I_{in} , the current at the Rogowski coil; and I_L , the current in the load measured by the triax B-dot monitors. Since I_{sc}

and I_{in} are approximately the same value, uncertainties are large. However, the calculation indicates that the load impedance is a fraction of an ohm for A-K gaps below 3.5 mm and rises rapidly to about 3Ω at 4.5 mm.

The percentage of total current transported by the outer line of the CTC is plotted in Figure 116 for the same shots as Figure 115. Crosses in Figures 115 and 116 are for shots using a 1.84-cm dia center rod (25 Ω line) and circles are for shots using a 1.32-cm dia center rod (45 Ω centerline impedance). The current division using the 25 Ω center line is ~55% in the outer line and 45% in the innerline. Using the 45 Ω center line produces about 65% outer and 35% innerline currents. For the last seven shots plotted, including the five with the 45 Ω center line, a new cathode was installed consisting of two rings of 3.2 and 6.4 cm diameters, 2.5 mm wide, separated by a 2.25-cm deep channel. This was done to increase the isolation between the inner and outer lines and to closer approximate the final ion diode to be used. There was no significant difference in operation between the ring cathode and the planar cathode with the A-K gaps used.

Figure 116. Ratio of Current in Triax Outer Line (I_o) to Total Transmitted Current (I_{out}).

There was very little physical damage during the shots near 100% transport, except for the expected damage to the removable carbon anodes. During the few low efficiency shots, the damage was primarily on the positive conductor around the through holes (particularly near the center rod). Losses and damage in the outer line due to the magnetic field zero near the pins failed to materialize. There was essentially no damage to the connecting pins.

Signs of loss around the holes and on the center rod tended to appear for A-K gaps over 4 mm and were accompanied by indications of reduced current in the centerline; these signs may be associated with electron-current pinching in the A-K gap. A shot with no center rod or pins at A-K = 0.34 cm showed essentially no current past the inner B-dot monitors; a similar shot at A-K = 0.42 cm produced 100 kA propagating back into the centerline cavity. The total current in each of the shots was 360 kA. Calculations of the critical current for electron-beam pinching in the A-K gap using $I_c = 17,000 \beta \gamma r / 2d$ with $r = 6.4$ cm (outer-cathode ring diameter) and d equal to the gap spacing shows the total current equal to $1.3 I_c$ for the 0.34 cm A-K gap and equal to $1.6 I_c$ for the 0.42 cm gap.

Performance of the convolute in these tests was very encouraging. Expected losses due to magnetic-field zeros did not appear. Current transport was (within experimental error) 100% in most cases, and it appears possible to adjust the current division between inner and outer lines of the triax by changing the center-rod diameter. Testing of the extractor diode with this convolute is scheduled for HydraMITE beginning in February 1980.

PBFA II

SuperMITE (D. L. Johnson)

SuperMITE will be a four-module prototype of PBFA II, as shown in Figure 117. Construction of the tankage is complete and one module is being developed. The 208-kJ Marx generator has been fabricated and installed; testing will begin in early January. A new design of the intermediate storage capacitor is complete, and a capacitor is ordered, with delivery scheduled for mid-January. The new SuperMITE water capacitor differs from the PBFA I design in that the trigatron gas switch is recessed 12 in. into the center cylinder of the capacitor. The trigatron-isolation inductor has also been modified to take up less space in the water-tank section. Instead of the helical PBFA I design, the SuperMITE inductor will be a planar spiral coil. These modifications add 2 ft of space in the water section allowing more room for the pulse-forming network.

Figure 117. SuperMITE, the Four-Module Prototype of PBFA II.

The tests on MITE of a 4-MV PFN design have been delayed until January. Consequently, the PFN design for SuperMITE has been delayed, but the delay will not result in any schedule slippage in the PBFA II program.

Gas Switch Program (D. L. Johnson)

The upgrade from the PBFA I to a 4-MV, 100-TW PBFA II places greater demands on gas-switch performance. Increased current and charge-transfer capabilities with lower jitter and greater reliability are required. While the present trigatron switch performance is adequate for initial PBFA I tests, this switch is not satisfactory for long-term PBFA I or for PBFA II use. Proto II switching data show that, after 30 to 100 shots, PBFA I type trigation degrade to unacceptable simultaneity. A gas switch improvement program has been initiated to develop a more reliable, low-jitter, long-lifetime switch for the PBFA accelerators. The program includes material studies, investigations of breakdown processes in SF₆, and small- and full-scale testing of improved trigatron switches and alternatives to trigatron switches. Two alternative switches are being investigated at Sandia: a laser-triggered switch and an x-ray-triggered switch. In addition, switches under development by industry are being considered as alternatives to the trigatron.

The trigatron experiments are directed towards improving the reliability and lifetime of the trigatrons and, therefore, improving the performance of Proto II and PBFA I. Towards this goal, experiments on HydraMITE, SuperMITE, and Proto II are planned for FY 80. Erosion of electrodes and degradation of switch jitter will be measured using several different electrode materials. The trigatron geometry (e.g., hole and trigger-pin sizes and shapes) will be varied in an attempt to reduce the increase in switch jitter caused by electrode erosion.

A 1-MV, transformer-driven test stand will provide voltage to study the breakdown physics in SF₆ insulated trigatrons. A basic understanding of the breakdown processes should lead to improved trigatron design.

Successful experiments by LLL⁴ on laser-triggered switching of a SF₆-insulated gap using a few megajoule KrF laser has prompted an investigation by Sandia into laser-triggered switching for the PBFA Program.

Studies of UV absorption, laser-induced excitation, ionization, and their effects on the dielectric properties of pure SF₆, commercial-grade SF₆, and SF₆ with selected trace additives are planned for FY 80. In addition, large-scale testing on SuperMITE of a KrF-triggered switch is also scheduled.

Preliminary X-Ray-Triggering Studies of SF₆ Insulated Gaps (E. L. Neau)

Several alternate triggering methods are being investigated for low-jitter, pressurized SF₆-insulated, high-voltage spark gaps for use in PBFA I and II. One possibility, which has the advantage of being located outside the electrode area and subsequent current-carrying plasma channel, is to use a flash x-ray source to generate ionization within the gas volume to initiate and/or enhance low-jitter gas breakdown. Two series of experiments have been conducted using a 600-kV Febetron flash x-ray source to investigate SF₆ breakdown in both high and low E/P breakdown regions.

The initial experiment used a pulsed-charged, SF₆-insulated, 1.83-mm, uniform field gap pressurized to 25 psia. The calculated dc-breakdown voltage for this gas pressure was 27.4 kV while the pulsed breakdown, with an applied waveform that rose to peak in 1.1-μs, was 56 kV. Breakdown of this gap was initiated with the Febetron source located 5 cm behind the 3.2-mm thick aluminum cathode. A Cyltran⁵ code simulation for these conditions predicted an ion density in the gas of 4×10^{13} pairs/cm³. The timing of the flash x-ray source was adjusted to cause breakdown at 35 kV on the pulsed waveform that corresponds to an applied field of 191 kV/cm and an E/P ratio of 1.12 V/cm-Pa; this is well above the value of 0.89 V/cm-Pa that gives equal ion generation and attachment coefficients in SF₆.⁶ The standard deviation in gap closure, as measured from the start of the pin-diode signal which monitored the x-ray output, was 1.3 ns with a total spread in 12 shots of 3 ns and a delay of 2 ns. The intensity of the source was then reduced by approximately 9 orders of magnitude that increased the delay in breakdown to 10 ns while maintaining nanosecond jitter in gap closure.

The second series of experiments used the same 600-kV Febetron source and a trigatron gap identical to those used in PBFA I, except the trigatron electrode was replaced by a hemispherical electrode with no

trigger pin. The self-break curve, for a 600-ns charge-time waveform, was established in the MITE facility and an operating point of 2.4 MV with a gap pressure of 72 psia was used in all x-ray triggering experiments. The Febetron source was located perpendicularly to the switch axis and the x-rays traveled through 60 cm of air and 40 cm of oil before reaching the switch housing. Less than 0.1 mrad per shot reached the switch volume in this configuration. Calculations are being made to determine the level of ionization produced within the SF₆ in this geometry. No low-jitter breakdown region was observed with the x-ray source applied within a window of from 20 to 200 ns before self breakdown.

Breakdown of these SF₆-insulated gaps can be modeled as the appearance of a free electron which multiplies through the Townsend primary ionization effect in the gas to form an electron avalanche with a number density of about 10⁸ ion pairs/cm³ at the tip. The field at the avalanche tip approximately equals the applied field and the avalanche converts to cathode- and anode-directed streamers moving 2 orders of magnitude or more faster than the drift velocity in the avalanche stage. Data on ionization and attachment coefficients have been published by Bhalla and Craggs⁷ as a function of E/P and a polynomial fit of this data has been combined with measurements of spark formative times in SF₆ by Felsenthal and Proud⁸ to give the following equation for the drift velocity in the avalanche stage.

$$V_d = 2.386 \times 10^7 + 1.488 \times 10^5 E/P \text{ cm/s}$$

Measurements of spark-formative times presented by Felsenthal and Proud were made in uniform field gaps with E/P held constant during the growth of the avalanche. The effective ionization coefficient data from Bhalla and Craggs and the drift-velocity equation for SF₆ have been used in a computer model to calculate the growth of the electron avalanche in the two series of x-ray triggering experiments with the time varying applied field; in the case of the PBFA I switch a field enhancement factor of 1.64 has been used in the region of the anode and cathode. The field-enhancement factors for the PBFA I switch, as mounted in the MITE accelerator, were determined with the electrostatic Poisson solver JASON.⁹ The code results for the 1.83-mm gap experiment show that the applied voltage has to be 29 kV for the avalanche to grow to the critical density of 10⁸

pairs/cm³ within the 1.83-mm distance between the anode and cathode which agrees with the measured value of 30 kV. The calculated formative time for the 1.83-mm gap is 9 ns at 30 kV on the pulsed waveform. The calculated avalanche-to-streamer growth distance in the 9.1-cm gap of the PBFA I switch is 5.8 mm with a formative time of 13 ns.

The calculated formative times predict gap closure ~10 ns after the pulsed waveform rises above the dc-breakdown level. The measured delay was 300 to 400 ns with the 1.83-mm gap, while the 9.1-cm gap closed within 10 ns of the dc-breakdown value. These results can be reconciled in the following manner. The time taken for a given gap to close consists of the formative time (as calculated above) plus a statistical time delay due to appearance of the initial electron which starts the avalanche. The pulsed self-breakdown field at the cathode of the 1.83-mm gap and the 9.1-cm gap are 306 kV/cm and 433 kV/cm. These fields, with local microscopic field enhancement, are sufficient to cause direct field emission of electrons from the cathode material that can start avalanches. The 9.1-cm gap, at its dc-breakdown level, has a cathode field high enough to field-emit electrons; therefore, the pulsed breakdown and dc breakdown occur at the same level. Any electrons injected into the gap by an x-ray source below the dc-breakdown level do not give rise to avalanches because the attachment coefficient exceeds the ionization coefficient. The cathode field in the 1.83-mm gap at dc breakdown is 164 kV/cm, which is insufficient to cause field emission; however, any electrons scattered from the cathode by x-rays can start the avalanche phase.

The results of these two series of experiments and computer calculations indicate two areas of investigation for an x-ray-triggered 3-MV switch with nanosecond jitter required for PBFA I and II. One possibility is to develop a switch with many short gaps (comparable to the 1.83-mm gap) in series to achieve the 3-MV holdoff capability. The x-ray source would provide the initiating electrons required throughout a large number of the small gaps. The second possibility would be to operate the gap with the cathode-electric field greater than the dc-breakdown level but less than the level required for field emission. The x-ray pulse then provides the initial electron and triggers the gap. Lower energy x-ray sources, at the 100 to 150 kV level, will also be investigated since voltage pulses at this level could be delivered with standard coaxial cables to 5-cm dia commercially-available x-ray or electron-beam tubes close to the switching electrodes.

Voltage Addition With Parallel-Plate Lines

(T. H. Martin and J. P. VanDevender)

Convolute, water dielectric transmission lines have reduced prepulse, provided pulse-forming line stacking in parallel, and reversed the output polarity in high-current accelerators. In each application, the power efficiently passes through holes, turns around right-angle corners, or inverts polarity. A new convolute design stacks modules in series to provide accelerator voltage of tens of megavolts.

Flat-plate pulse-forming lines provide equal and oppositely directed electric fields when switched into the two back-to-back transmission lines. If one side of the line has a polarity-reversal convolute, as shown in Figure 118, then the electric fields of the two waves (top and bottom) will be in the same direction, and a traveling-voltage wave of twice the amplitude and impedance will be transmitted downstream from the convolute. This procedure is extendable, so that several modules may be added together.

Figure 118. Schematic of High-Voltage Experiment

An experiment was designed for MITE to check the efficiency of wave additions with triplate, water-dielectric lines. The initial pulse-forming line geometry is similar to the PBFA I design. PBFA I pulse-forming lines provide a two-sided, 1.2-MV, 0.8-TW, 40-ns output into the transmission lines. One side of this output was inverted, and both sides were transformed to higher voltage and impedance and then added. The convolute used is shown in Figure 118; it is one meter long. A 2.54-cm dia by 90-cm long pipe connected each output terminal to the tank wall.

These pipes simulated the beam-drift tubes on a linear accelerator. Different resistive were then connected directly across the high-voltage terminals and the accelerator-load line was determined. These load characteristics are shown in Figure 119. The open circuit voltage was 8.0 MV and the matched power output was 3.8 MV, 220 kA at 0.83 TW. At 6.4 MV, about 100 kA could be provided to the load. The convolute was efficient and showed that high voltages can be obtained in small volumes. The output impedance of this voltage stacker is 18 ohms, the feasibility of this convolute for a 4-MV power conditioner for PBFA II has been demonstrated.

Figure 119. Load Line From the MITE High-Voltage Experiment

Superfast High-Energy Density Pinches

The research in this reporting period attempted to solve the azimuthally-asymmetric power-flow problem in Proto II and to study foil and wire-array initiation with holography. The power-asymmetry problems were solved as described under Proto II Optimization at 11 TW (see pg. 32). The output of Proto II is now 11 TW and 320 kJ. The voltage arrives at the diode with a temporal spread of 10 ns at different azimuthal positions. This study showed that the power-flow problems were caused by timing asymmetries and the large

azimuthal asymmetry of the power pulse at the diode. The asymmetry has been corrected and power flow at the 4-MA level with the improved quartz-gauge, current diagnostic located at 0.2-cm from the load is beginning. The "Foil Initiation Studies" section reports on the difference between plasmas formed by foils and wire arrays at dI/dt 's of 10^{13} A/s. This dI/dt level is two orders of magnitude larger than the Proto II prepulse, and duplicates the leading edge of the main pulse when the foil or wire array becomes a plasma. Foils initiate uniformly with an annular-plasma sheath that does not expand to the return-current wall. Wires have large instabilities and hot spots that would short-out the load.

Foil-Initiation Studies (R. W. Stinnett)

Experiments were conducted to determine the initial state of the annular plasma formed when acylindrical foil initiates during the main pulse of Proto II. These experiments are important for several reasons:

1. The initial state of an imploding liner plasma assists in determining the effect of instabilities on the implosion.
2. The extent to which the annular plasma expands radially determines the minimum foil-wall gap required and thus determines the minimum inductance of the current feed.
3. Physics studies of foil initiation will provide a data base that may be used to design foils for optimum implosions.

Initiation studies using both foils and wire arrays compare the relative merits of various configurations.

The experimental accelerator used for these experiments is called THOR which consists of a Marx generator feeding a 2-ohm coaxial water line. The line, which includes a solid dielectric switch, terminates in a 28-nH vacuum-feed section containing a foil or wire array. This configuration produces a 30-ns, 0.5-MV pulse which drives a 0.25-MA current in the foil or wire array with a peak dI/dt of 1×10^{13} A/s. Figure 120 shows a schematic of the front end of THOR. Figure 121 shows the dI/dt level in the early portion of the Proto II main pulse. The "x" marks the point at which a standard, 2-cm-long, 1.26-cm-dia foil would initiate. This point falls on the leading edge of the pulse at a dI/dt of $1-2 \times 10^{13}$ A/s. Since this approximately matches the first part of the THOR current pulse (shown in Figure 122), the results of initiation studies of THOR should be directly applicable to foil and wire array initiation on Proto II.

Figure 120. Schematic of THOR's Front End.

Figure 121. dI/dt in the Early Part of the Proto II Pulse.

Figure 122. THOR's Current Pulse.

Diagnostics

Initial experiments studying foil and wire breakdown on THOR were conducted using three basic diagnostics: Faraday cups, holography, and visible light photography using streak- and open-shutter cameras. The Faraday cups, mounted inside and outside of the foils and wire arrays, had 0.034-cm dia apertures and were biased at +300 V. They were typically located from 0.18 to 0.4 cm from the wire or foil and were inductively isolated to prevent arcing to them during the time of interest. Streak photography measured the plasma uniformity. This technique also looked axially at foils and wire arrays to determine when plasma reached the center.

Holography showed the density contours around foils and wire arrays during the first 50 ns of the pulse. This is a 4-frame system with each frame separated by 27 ns. It produces one fringe for a density-path length product of $3 \times 10^{17} \text{ cm}^{-3}$.

Results

The foil-initiation results are enlightening and encouraging. Foils initiate very uniformly, producing an annular sheath that does not expand to the feed wall during the time of interest. Wire arrays, however, initiate nonuniformly, show evidence of hot spots and instabilities, and expand rapidly to the wall.

Faraday-cup experiments show a radially outward plasma expansion velocity of 5 to 7 cm/ μs for foils and 10 to 12 cm/ μs for wires at the 10^{15} cm^{-3} density level. Preliminary results indicate a comparable inward expansion of the foil and wire-array sheaths at a

similar density level. Streak-camera traces of foil initiation indicate that wrinkled foils preferentially initiate at the wrinkles. Streaks from wire experiments show an expansion of the luminous portion of the wire-plasma columns that is primarily inward at 3 to 5 cm/ μs . Axial streaks from wire shots show light on axis within 20 to 30 ns after the beginning of the current pulse.

Holography was a very useful tool for studying foil and wire initiation. The sensitivity is very different for foils and wires because the effective length of the laser and plasma interaction is different in both cases. If the minimum detectable density level is taken to be one-quarter of a fringe, the minimum, detectable, chord-averaged, plasma density is about $8 \times 10^{16} \text{ cm}^{-3}$ for 1.90-cm dia foils, and it is $1.5 \times 10^{18} \text{ cm}^{-3}$ for wires. The foils consisted of 1400 to 1800 Å of aluminum vapor deposited on 6000 Å of parylene. Various 1.27-cm dia wire-array configurations were studied, including four- and six-wire arrays of 7.6- μm -dia, stainless-steel wire, six- and twelve-wire arrays of 25.4- μm dia, stainless-steel wire, and four- and six-wire arrays of 15.2- μm dia aluminum wires.

Foil-initiation experiments show that foils consistently initiated uniformly, and formed a current-carrying sheath. The plasma thickness at the $8 \times 10^{16} \text{ cm}^{-3}$ density contour is only 0.11 cm. Figure 123 shows data on outward-foil expansion. After 15 ns into the current pulse, the magnetic-field pressure causes the sheath to stop expanding and to begin imploding. The sheath has compressed back to a radius of 0.08 cm by 30 to 40 ns. This data indicates that a foil-wall gap of about 0.15 cm can be used in future current-feed designs. This will be a distinct advantage in designing future, low-inductance, MFI diodes.

Figure 123. Foil Plasma Sheath Expansion.

Results from wire-array initiation experiments show that each wire in the array expands nonuniformly with hot spots occurring within a period of about 0.05 cm. Several different wire-array configurations were studied, using both aluminum and stainless-steel wires. The mass per unit length of the array was varied from 14 to 430 $\mu\text{g}/\text{cm}$ with no systematic change occurring in the expanding plasma columns formed during initiation. Figure 124 shows some typical data on wire-plasma column expansions. During the first 20 to 30 ns, the wire-plasma columns expanded with a velocity $V = 2.3 \pm 0.6$ cm/ μs perpendicular to the radial-implosion direction. The radially-outward expansion velocity V_{out} was about $2/3 V$ while the inward-expansion velocity V_{in} was about $1.5 V$. The expansion slows down after 20 to 30 ns to about 40% of the earlier value for V and V_{out} ; however, V_{in} is decreased only to 60% its earlier value.

Figure 124. Wire Plasma Column Expansion.

These wire-plasma expansion velocities were measured at an electron-density level of $1.5 \times 10^{18} \text{ cm}^{-3}$. This density level is higher by a factor of 20 than the level at which expanding-foil plasma were studied because of the much shorter path length through the wire plasma. This makes a direct comparison between foil and wire plasma expansion very difficult and subject to large errors. However, a tentative observation may be made. Since wire plasmas expand at the 10^{15} cm^{-3} density level almost twice as fast as foil plasmas and expand at nearly the same velocity at a density level of $1.5 \times 10^{18} \text{ cm}^{-3}$ as foil plasmas do at a

density level of $3 \times 10^{17} \text{ cm}^{-3}$, it is reasonable to expect wire-plasma columns to expand faster than foil plasmas at all density levels from $10^{15} - 10^{18} \text{ cm}^{-3}$.

The data from Faraday-cup measurements and holography indicate that foils initiate uniformly. A well-defined sheath is formed and expands less than 0.15 cm in 12 ns before being swept back toward the initial foil position by the magnetic pressure arising from the current in the sheath. There is also a plasma front that expands radially inward from the initial foil position. At a density of 10^{15} cm^{-3} , this plasma moves toward the axis with a velocity of $\sim 7 \text{ cm}/\mu\text{s}$. This inward-expansion velocity at larger plasma densities is at present undetermined.

Wire-array experiments show nonuniform wire initiation with hot spots and plasma-expansion velocities of 10 to 12 cm/ μs at the 10^{15} cm^{-3} density level. Varying the wire-array mass and material did not have a significant effect on the plasma columns formed during initiation.

Further experiments on foil and wire array initiation are necessary to determine the plasma-sheath expansion at a density of $2.5 \times 10^{16} \text{ cm}^{-3}$ for both foils and wires. This density level is important because a plasma of this density filling the foil-wall gap could shunt the current to the foil for an appreciable length of time before being swept out of the gap. A laser system is being constructed that will address this problem using schlieren techniques. More holography data will also be necessary to confirm and extend the preliminary data already obtained on foil initiation.

Spectroscopic techniques will be used to determine plasma temperatures during initiation. This will also provide data on the initiation and layer mixing of different materials in layered foils.

It is very important that the interior of foils be studied during initiation to determine the expansion of the inner edge of the sheath and the effect of plastic substrates on the sheath. New hardware is being designed that will allow actual Proto II foils to be mounted vertically in THOR. Both the foils and the liquid Indium-Gallium contact scheme used on Proto II can then be examined. Using the new hardware, it will be possible to study both the interior and exterior surfaces of foils with holography, schlieren, and spectroscopic techniques.

In summary, the experiments show that foils initiate uniformly and expand slowly; wires initiate nonuniformly and expand rapidly to adjacent walls. Foils are potentially superior to wire arrays for producing an energetic, dense plasma because the initial plasma is better defined and the parasitic inductance near the plasma is less for the foil.

Proto II Optimization at 11 TW (D. H. McDaniel)

During the period from August to November 1979, the power flow on Proto II was increased from 5 TW, 100 kJ to 11 TW, 320 kJ. The need for more output became evident when the imploding-foil experiments¹⁰ were unable to reach the 4-MA level. Calculation of the equivalent, matched electrical power during the foil-implosion experiments agreed with that measured during the multiple-electron beam experiments.¹¹ The accelerator is now ready for full-power experiments.

The above modifications increased the output of Proto II to 320 kJ at a peak power of 11 TW. The full-width half-maximum of the forward-going voltage waveform is now 40 ns. The spread at the diode for the 16 pulse-forming sections is never more than 10 ns and more typically 5 ns.

This increase in energy and power should be compared to the original design goals (which were met in 1977) of 100 kJ at 8 TW with a 20-ns forward-going voltage pulse. This increase in power will allow studies of magnetic insulation in load-dominated vacuum transmission lines to begin at the 4-MA level. The new power level should also provide an interesting source for testing the scaling of the ion diodes.

Magnetically Self-Insulated Ion Diode

Magnetically self-insulated electron flow in a tapered transmission line has been applied to the production of light ions for near-term experiments in particle-beam fusion. Experiments on the MITE accelerator have been performed, and the concept has been investigated with 2-D simulations and analytical theory. The results show that a structure of vacuum-wave impedance (Z_0) will operate at $Z = V/I = 0.25 Z_0$ and the ion-current density is approximately twice the simple space charge-limited value without electron flow. The scaling of the diode to Proto II and PBFA I results in small radius diodes with 40% to 50% ion-production efficiency. Average-power densities on target are calculated up to 10 TW/cm² for PBFA I. The results of this investigation are that the quasi-spherical diode is promising for near-term ion-beam driven-target experiments. However, the development of a well-defined ion source over relatively large (2000 cm²) areas and the development of the thin cathode must be accomplished before meaningful experiments can be performed. The staff which

would do this work is presently committed to designing the PBFA I convolute from the 36-output lines to a common diode feed. Since such a convolute is required for several ion-diode candidates, it has the higher priority and the quasi-spherical diode is inactive.

Quasi-Planar, Magnetically Self-Insulated Ion-Diode Experiment (J. P. VanDevender, J. P. Quintenz, R. J. Leeper, and D. J. Johnson)

The diode shown in Figure 125 was investigated in an experiment called SMAUG at the end of a 6-m-long, magnetically self-insulated transmission line on the MITE accelerator.¹² The accelerator is similar to one module of the Particle-Beam-Fusion Accelerator (PBFA) I that is currently being fabricated for inertial-confinement fusion experiments. The 2-MV, 400-kA, 35-ns power pulse is shaped by the electromagnetic shock effect¹³ to give a 2-ns rise-time pulse with $\dot{I} \approx 2 \times 10^{14}$ A/s and $\dot{V} \approx 10^{15}$ V/s at the input to a magnetically insulated vacuum transition. The experiment is the first to investigate the characteristics of ion diodes under conditions (dI/dt , dV/dt , V , and I) appropriate to a particle-beam-fusion accelerator.

Figure 125. Schematic of the SMAUG Diode.

The operation of the diode proceeds as follows. The voltage is applied to the cathode, and current flows into the diode through a tapered magnetically self-insulated, coaxial, vacuum-transmission line with a cathode radius of $r_c = 0.5$ cm and an anode radius of $r_a = 1.0$ cm at the output. The large applied electric field causes the 6- μ m thick aluminized mylar

foil to undergo explosive emission and plasma formation within 4 ns. The structure acts like a short, radially diverging, magnetically self-insulated vacuum-transmission line. The vacuum wave impedance Z_0 equals $60 d/r$ ohms; d is the separation between the anode and the cathode at a radius r . Earlier experiments with lines of uniform cross section have shown that the self-limited voltage and current in a line with vacuum-wave impedance Z_0 are related by $V/IZ_0 = \alpha_e(V)$ and is independent of Z_0 .¹⁴ We have verified that a similar relation holds for the tapered line.

After a formative delay time, the anode plasma emits ions that are accelerated across the A-K gap and through the cathode. The ion space charge should be partially neutralized by a cloud of electrons; the cloud is extracted from the cathode plasma. The electrons and ions then drift across a 0.15-m-long, vacuum-filled drift region to a carbon-activation array as shown in Figure 125.

The results of the experiment are compared with the simulations in the section entitled "Numerical Simulation of the SMAUG Ion Diode."

In summary, the experiment showed that a magnetically self-insulated transmission line with a plasma on the anode can be used to generate a light-ion beam. The structure operates at $V/IZ_0 = 0.25$ and the ion current is enhanced by a factor of ~ 2 . The electron losses are small and occur at large radii, as expected, and cause no damage. However, the efficiency is only 10% and is unacceptable. The basic problem with the quasi-planar diode shown in Figure 125 is that the magnetic field, which is necessary to trap the electrons, decreases as the radius is increased. As a result, the A-K gap d must also increase with radius to keep the electrons trapped. Since the ion-current density is proportional to $1/d^2$, it decreases very rapidly with increasing radius. Therefore, only the portion of the diode near the axis produces significant ion current, and the diode is inefficient. This deficiency is not present in a quasi-spherical geometry that is discussed in the next section.

Theory for Magnetically Self-Insulated Focusing Diode (J. P. VanDevender)

The experiments and simulations of the quasi-planar diode provided the necessary information for investigating the scaling of these results to an ideal quasi-spherical geometry that avoids the inefficiency problem of the quasi-planar diode. We have derived¹⁵

expressions for the electrode shapes, the ion-production efficiency, and the sensitivity of the ion flow to variations in the A-K gap parameters. The results indicate that the ion diode should be an efficient source of ions from a small radius source and the power on target is relatively insensitive to $\pm 10\%$ variations of the diode parameters.

The quasi-spherical diode is shown schematically in Figure 126; and it resembles the geometry of various other magnetically self-insulated ion diodes proposed previously.¹⁶⁻¹⁹ This diode has the following advantages: the electron flow is controlled more adequately, the ion current density is more uniform, and the magnetic deflection of the ion beam is corrected.

Figure 126. Schematic of Quasi-Spherical Diode.

Application to Current Particle Beam Fusion Accelerators (J. P. VanDevender and J. T. Crow)

The theory of the quasi-spherical ion diode is applied to two accelerators in the particle beam fusion program at Sandia. We assume that each accelerator is operated in the 2-MV mode for protons to provide a satisfactory ion range in the target.²⁰ The voltage (V_0) diode impedance V_0/I_0 , total current I_0 , and pulse duration of Proto II and PBFA I are shown in Table 5. The choice of the initial A-K gap d_0 is made so that the average electric field is 660 MV/m; i.e., 3-mm at 2-MV.

Table 5. Parameters for Each Hemisphere of Proto II and PBFA I

System	V_o (MV)	V_o/I_o (ohms)	I_o (MA)	τ (ns)
Long-Pulse Proto II	2	0.74	2.7	40
PBFA I	2	0.266	7.5	40

The choice is justified by successful experiments at this stress on MITE and corresponds to a rather conservative ion-current density of <4 kA/cm². The final A-K gap is chosen to be either the same as the initial gap or the A-K gap required for magnetic insulation at $\phi = 1.5$ rad; whichever gap is larger.

The initial radius (r_o) is chosen by using d_o , V_o/I_o , to compute the radius at which the A-K gap forms a matched impedance transmission line for the power pulse,

$$r_o = \frac{I_o}{V_o} \frac{60\alpha d_o}{\alpha}$$

where $\alpha = 0.25$. The initial ϕ_o is chosen to give a reasonable (1 to 5 cm) thickness to the center MITL conductor. The parameters for each accelerator are listed in Table 6. The calculated values of η , r_a , r_c , d , I_{ion} , and at the final value of ϕ are shown in Table 6. The efficiencies of 25% to 48% are encouraging, and the relatively small diode radii are similarly encouraging. The increased efficiency for the larger accelerator reflects a desirable feature of the scaling.

The power density in watts/steradian is given by

$$P = j V_o r_c^2 / \sin \theta$$

for an ion-current density (j) and varies between 0.26 and 0.45 TW/sr for Proto II and between 1.3 and 1.9 TW/sr for PBFA. P is peaked at ϕ and ϕ_r , and has a minimum at $0.3 < \phi < 0.5$. The relatively weak variation of P vs ϕ is desirable for providing reasonably uniform target irradiation. A small amount of beam divergence will almost certainly cause the power density to be very uniform.

Since the A-K gap is relatively large and since the drift region is free of applied magnetic fields, the beam divergence should be very small.

The average power-per-unit area on a target of radius (r_t) with $1 \text{ mm} \leq r_t \leq 5 \text{ mm}$ for Proto II and PBFA I ion beams with divergences between 0.5° and 4° (full width at half maximum) is plotted in Figure 127. Clearly, the ability to produce low divergence ion beams is the key to a high-power density on target. The scattering of ions as they pass through the cathode foils is an unavoidable source of divergence for this type of diode.

Measurements by H Bichsel²¹ on scattering of 0.7- to 4.8-MeV protons by thin foils indicate that the theoretical description of multiple scattering by Moliere is correct within 5% in this range. The scattering of a 2-MeV proton beam was calculated for foils of aluminum, graphite, mylar, and parylene N. For mylar and parylene, the scattering angle θ_{FWHM} listed is the square root of the sum of the squares of θ_{FWHM} for each atomic component taken separately.

Since the cathode foil is mostly mylar or parylene and is between 2 and 6 μm thick, the distribution of scattered ions will have θ_{FWHM} of 0.5° to 1.0° . This amount of divergence is significantly only for very small ion targets with radii less than 1.5 mm. Consequently, ion scattering by the cathode foil does not severely limit the utility of the magnetically self-insulated ion diode for near-term experiments.

The beam deflection under nonideal conditions for the two accelerators is calculated. The variation of δ , the displacement of the ion-beam trajectory from the center of the target as it crosses the Z axis, with ϕ for $V = 0.8 V_o$, $0.9 V_o$, $1.1 V_o$, and $1.2 V_o$ has been calculated for Proto II and PBFA. The deflection was always less than 1.4 mm for Proto II and 2.3 mm for PBFA I. The size of the target determines the maximum-allowable value of δ , and hence the allowable tolerance for V_o . Voltage variations of $\pm 20\%$ are probably acceptable for targets with diameter larger than 3-mm on Proto II and 5-mm on PBFA I.

The beam-deflection Ω from a variation ψ in the A-K gap separation d for $V_o = 2 \times 10^6 \text{ V}$, $Z = 1$, $A = 1$, and $\alpha = 0.25$ is $\Omega = 0.1333 \psi/d$. For $\psi/d = 10\%$, $\Omega = 13.3 \times 10^{-3} \text{ rad}$ or 0.762° . Even for small targets, these deflections are not disastrous. Since ψ/d is likely to be largest at $\phi = 0.75$ rad, the deviations δ of the ion trajectories from the target center for the two accelerator systems and for $\psi/d = 10\%$ at $\phi = 0.75$ rad are 1.3-mm and 2.0-mm for Proto II and PBFA I, respectively. The mechanical requirements of $\psi/r_c \approx 0.1 d/r_c$ at $\phi = 0.75$ are 0.4% and 0.2% for the two accelerators, respectively. The mechanical requirement is stringent but not necessarily prohibitive.

Table 6. Ion Diode Parameters for Sandia Accelerators

System	α	ϕ_0 (rad)	$\phi = \phi_0$	r_0 (m)	d_0 (m)	η %	r_a (m)	$\phi = \phi_f$		I_{ion} MA	ϕ_f (rad)
			θ (rad)					r_c (m)	d (m)		
Long-Pulse Proto II	0.25	0.103	1.4370	0.0972	0.003	25	0.0868	0.0836	0.003	0.7	0.98
PBFA-I	0.25	0.06	1.4370	0.169	0.003	48	0.150	0.147	0.003	3.6	0.95

Figure 127. Calculated Power Density on Target of Radius R_T for (a) PBFA I and (b) Proto II vs Target Radius for a Given-Beam Divergence θ_{FWHM} .

The diode consists of an anode surface that is machined to ± 0.1 -mm, which is well within the capability of today's technology. The surface is an ion source that provides a single ion species with a low ($< 0.5^\circ$) divergence. Since none of the present ion sources fulfill this requirement, considerable re-

search will have to be performed to find a satisfactory surface. The cathode is a preformed mylar "balloon" that consists of two identical halves affixed to mounting rings as shown in Figure 126. The mylar is first fixed onto a mounting ring and then shaped by a recently developed technique.²²

The shape of the final surface is determined by the shape of the mandrel and the pressure differential between the inside and outside of the cathode. The tolerance that is achievable and the pressure differential that is required must be determined by experiments. The minimum pressure differential is that required to support the foil mass and is $\sim 10^{-6}$ atm, but a pressure of $\sim 10^{-3}$ atm should be used to assist in space charge and current neutralization of the ion beam in the drift section.

The magnetically self-insulated ion diode in the quasi-spherical geometry should efficiently produce intense ion beams for near-term target experiments on Proto II and PBFA I. However, the development of large area, uniform, and spatially well-defined anode plasmas and the development of the thin-foil cathode must be done before meaningful experiments can be conducted. Because of these problems and the existence of more currently developed ion-diode concepts, this quasi-spherical diode work is presently inactive.

Advanced Pulsed-Power Studies

INTREPID - Fast-Opening, High-Current Switch

(G. L. Sauve, W. B. Duggin, E. L. Neau and J. P. VanDevender)

A. I. Pavlovskii and others²³ reported that they had successfully operated an explosively actuated opening switch that interrupted 7.3 MA and delivered 4 MA into a 30-nH load with an effective e-folding rise time of 350 ns. The goal of the INTREPID program is two-fold: verifying the results obtained by Pavlovskii and determining the operating principles of the device so that larger and/or faster opening switches may be designed using this technology. A 100-MA switch of this type could deliver about 100 MJ and a peak power of 10^{14} W over a time scale of about 1 μ s. One significant advantage that this technology has over exploding conductors (fuses) is that the energy for operating the device is not extracted from the electrical circuit. This leads to higher switch efficiency and makes switch-timing independent of the electrical circuit.

A small-scale switch device has been designed, and investigations into the switch physics have begun. The small-scale device uses a plane-polar geometry, whereas the Pavlovskii device uses a cylindrical geometry; however, the essential switch physics in

the two devices is similar. A schematic of the experiment is shown in Figure 128. The switching occurs when the plasma is compressed by (and mixed with) the explosive products. The current waveform, corrected voltage, and switch resistance are shown in Figures 129-131. In the first experiment, there was no load to absorb the stored energy. Approximately 35 kJ were deposited in the 0.6 cm³ switch volume while the switch remained open. There was no sign of breakdown. The first test interrupted 830 kA developing 14 kV across the 1-cm switch with an effective e-folding risetime of 450 ns. The switch resistivity, opening time, and electrical stress were within a factor of 2 of the values reported by Pavlovskii.

One-dimensional computer simulations indicate that the plasma/pusher interface is Rayleigh-Taylor unstable and the linear-growth rate is consistent with the switch-opening time as discussed under "Studies of INTREPID Plasma Switch Operation" in the theory section of this progress report. In this model, the fast, irreversible change in resistance is caused by plasma/interface mixing.

Figure 128. Schematic Diagram of the Small-Scale Switch Device.

Figure 129. Current Waveform in INTREPID Experiment.

Figure 130. Voltage Across the INTREPID Switch.

Figure 131. Resistance of the INTREPID Switch.

There may be other contributing effects, such as a divergence from Spitzer resistivity under high-density and low-temperature plasma conditions when there is less than one particle per Debye sphere. The mixing model requires that the explosive products have a much lower conductivity than that of the plasma channel and a high dielectric strength. Russian literature indicates that electrical conductivities²⁴ of $1\Omega^{-1}\text{ cm}^{-1}$ and breakdown strengths²⁵ of 100 kV/cm are typical in explosive products. A set of experiments are being planned to determine the electrical conductivity and dielectric strength of the explosive EL 506C, which is similar to the explosive Pavlovskii most likely used.

In addition to the explosive products data, several additional, small-scale experiments are planned. They will have an inductive load that will be switched into a current path in parallel with the switch. SCEPTRE²⁶ simulations for the second set of experiments show that the energy input to the foil plasma will be approximately the same as in the first experiment up to the time of peak-plasma compression. The power input to the plasma then decreases as current flows through the inductive load; the plasma resistivity is expected to increase beyond that obtained in the first experiment. The experimental program includes developing and testing a set of 10-MA switches during 1980.

Nanosecond Surface Flashover Studies in Vacuum (D. H. McDaniel)

This work was conducted under contract to Texas Technical University with a subcontract to the University of South Carolina. The prime investigators were M. Kristiansen and J. E. Thompson, respectively.

When an electric field is applied to a vacuum insulator interface, a secondary electron avalanche occurs along the insulator surface.^{27 28} If the electric field is present for sufficient time, electrical breakdown occurs along the insulator surface. Both of these events modify the electric field along the insulator vacuum interface on a nanosecond time scale. The object of this work was to time-resolve the change in the electric-field distribution along a vacuum insulator interface during the application of high voltage. Experiments were performed with the angle between the insulator and the electrode surface of 0° and $\pm 45^\circ$. The data should provide insight into how flashover occurs and how lower inductance can be designed.

These experiments employed a new diagnostic,²⁹ which makes use of the Pockells or Kerr effect, to spatially resolve the electric field as a function of time at a vacuum-insulator interface. From the measured electric field, the surface-charge density can be calculated. The experiments were successful in measuring changes in the electric field along 0° angled insulators; however, difficulties were encountered with $\pm 45^\circ$ angled insulators. The results show that the electric-field modification due to surface charging begins at the cathode and propagates to the anode at 1 cm/ns. In cases where electrical breakdown does not occur at the end of the charging process, the field

distortion is seen to disappear. This effect is attributed to saturation of the secondary-electron avalanche. Breakdown usually occurs in the intergap region on the insulator surface and propagates at 2.5 cm/ns. In some cases the breakdown originates at the cathode. These are the first set of experiments to measure the time dependence of the secondary-electron avalanche and subsequent electrical breakdown. The experiment substantiates the model for vacuum-insulator surface breakdown for 0° angled insulators.³⁰

The problems of measuring the electric field for 45°-angled insulators have now been resolved. There is no physical model that explains the breakdown process for +45°-angled insulators. This diagnostic technique will provide experimental information that will enable a model for electrical breakdown at +45° to be developed. In order to proceed with experiments, a follow-on contract has been placed with J. E. Thompson. The final report of the present contract is published under Sandia Laboratories Report SAND80-7041 and can be obtained from Division 4252.

References

1. J. P. VanDevender, D. L. Johnson, *Particle-Beam Fusion Progress Report, April-December 1978*, SAND79-1011 (Albuquerque: Sandia Laboratories, 1979), p 118.
2. *Ibid.*, p 115.
3. K. D. Bergeron, *J of Appl Phys*, 48:3065, 1977.
4. W. R. Rapport, Lawrence Livermore Laboratory, submitted for publication.
5. J. A. Halbleib, Sr. and W. H. VanDevender, *CYLTRAN: A Cylindrical Geometry Multimaterial Electron/Photon Monte Carlo Transport Code*, SAND74-0030 (Albuquerque: Sandia Laboratories, 1975).
6. R. Geballe and M. L. Reeves, *Phys Rev*, 92(4):867, 1953.
7. M. S. Bhalla and J. D. Craggs, *Proc of the Phys Soc*, 80:151, 1962.
8. P. Felsenthal and J. M. Proud, *Phys Rev*, 139(6A):A1796, 1965.
9. S. J. Sackett, *JASON - A Code for Solving General Electrostatics Problems*, UCID-17814 (1978).
10. D. H. McDaniel and R. W. Stinnett, "The Effect of Simultaneity on Peak Current Delivered to an Inductive Load," *Particle Beam Fusion Progress Report*, January 1-June 30, 1979, (Albuquerque: Sandia Laboratories, 1979).
11. P. A. Miller and L. P. Mix, "Multiple Electron Beam Transport Experiment on Proto II," *Particle Beam Fusion Progress Report*, (Albuquerque: Sandia Laboratories, 1979).
12. J. P. VanDevender, *J Appl Phys*, 50:3928, 1979.
13. I. G. Kataev, *Electromagnetic Shock Waves*, Sovetskoye Radio, Moscow (1963) (London: Iliffe Books Ltd., 1966), p 39.
14. S. L. Shope, J. W. Poukey, K. D. Bergeron, D. H. McDaniel, A. J. Toepfer, and J. P. VanDevender, *J Appl Phys*, 49:3675, 1978.
15. J. P. VanDevender, J. P. Quintenz, R. J. Leeper, D. J. Johnson, and J. T. Crow, Sandia Laboratories, submitted for publication.
16. J. W. Poukey, J. R. Freeman, M. J. Clauser, and G. Yonas, *Phys Rev Lett*, 35:1806, 1975.
17. D. J. Johnson and G. W. Kuswa, "High Power Ion Diodes for Inertial Confinement Fusion Experiments," Sandia Laboratories internal memorandum RS5244/1003, unpublished.
18. S. Humphries, *Plasma Phys*, 19:399, 1977.
19. S. A. Goldstein and J. Guillory, *Phys Rev Lett*, 35:1160, 1975.
20. T. A. Melhorn, Sandia Laboratories, private communication.
21. H. Bichsel, *Phys Rev*, 112:182, 1958.
22. R. Lagasse and A. Kraynik, Sandia Laboratories, Albuquerque, NM, private communication.
23. A. I. Pavlovskii, V. A. Vasyukov, and A. S. Russkov, *Sov Tech Phys Lett*, 3:320, 1977.
24. A. A. Brish, M. S. Tarasov, and V. A. Tsukerman, *Sov Phys JETP*, 37:1095, 1960.
25. V. L. Korolkov, M. A. McInikov, and A. P. Tsyplenko, *Sov Tech Phys*, 19:1569, 1975.
26. J. C. Bowers and S. R. Sedore, *SCEPTRE: A Computer Program for Circuit and System Analysis*, (Englewood Cliffs, NJ: Prentice Hall, 1971).
27. A. Watson, *J. of Appl Phys*, 38:2019, 1967.
28. O. Milton, *IEEE Trans Elec Insul*, 9:EI-7, 1972.
29. J. E. Thompson, et al, *IEEE Trans of Instr and Measurement*, 1:IM-25, 1976.
30. R. A. Anderson and J. Brainard, 8th Int'l Symposium on Discharges and Electrical Insulation in Vacuum, D4, (Albuquerque: Sandia Laboratories, September 1978).

Chapter 6. Pulsed Power Applications

Overview

Research associated with long range goals of the ICF program are discussed in this chapter; reactor systems studies, repetitive pulse power, and electron beam sources for gas lasers are the three major areas. Substantial progress has been achieved in each of these activities.

Design issues associated with gas-filled reactors and the engineering test facility (ETF) are being addressed in the system studies. With the progress made during the reporting period, design implications of the gas-filled reactor approach are better understood.

The advantages and disadvantages associated with pellet injection and beam aiming in a gaseous environment were further quantified. The physical limits on pellet velocity and beam aiming are sufficiently detailed for a full conceptual design. The nature of the hydrodynamic shock and thermal-energy transport in noble as well as molecular gases is now better defined.

The cavity-wall impulse from the pellet thermal energy was computed for PBFA based on the reactor-hydroshock studies. This item must be included even in near-term experimental machines. The first-wall design issues were examined in a contract with the University of Wisconsin. A conservative wall-design approach appears adequate and straightforward. The scoping study of a particle-beam ETF has been extended. Several long lead time development needs were identified. The feasibility study on laser-initiated channels is complete. Various laser-produced ionization techniques were rank-ordered. Resonant atomic absorption that leads to electron collisional de-excitation (run away) and molecular absorption that causes thermal ionization are the most attractive. Finally, a joint study of a target development facility for single-shot testing of targets has been initiated.

Extensive technology development will be required for all drivers that are under consideration for reactor systems. A study completed by the Physics International Company identifies pulse-power technology needed for production of electricity with inertial confinement fusion.¹ Development plans

were outlined for short-range and long-range programs. A low-level effort to develop components and test facilities for repetitively operated, pulse-power systems continued at Sandia during this period.

The 1.5-MV transformer system was operated continuously for 2×10^4 shots at full voltage. A low-inductance spark gap was developed for plus/minus charged capacitor banks in the transformer primary. Extensive data was collected on oil breakdown from bubbles formed at the electric field-enhanced region. The small-area dielectric strength of several paraffin-based oils was measured and found to be higher than transformer oil for gap spacings greater than 0.6 cm. After an initial breakdown, subsequent breakdowns were substantially lower than transformer oil. The 1-MV Marx generator was operated at half-voltage and 5 Hz for several minutes. Some difficulties have been encountered with the pulse-charging system; further work is required in this area. Spark gaps for this system have been tested extensively and efforts to minimize the gas-flow rates are underway. Light-ion-beam diodes require 1-kA/cm² electron-beam sources to form virtual cathodes and enhance ion flow. With plain metal cathodes in repetitive operation, the turn-on time (plasma-formation time) gradually increases with the total number of pulses. However, with cathodes made from Oilite-bearing stock, the impedance characteristics remain constant for greater than 300,000 pulses.

Virtually all of the high-power gas lasers that are being considered for ICF-reactor applications require electron beams in the pumping process. These large area beams are presently generated from cold-cathode diodes. For microsecond pulse duration, the electric fields at the cathode are low and it is difficult to achieve uniform current densities. Techniques to preform the cathode plasma with surface flashover boards were investigated. A 1000-cm² cathode has produced a beam with $\pm 16\%$ current-density uniformity. The apparent anode-cathode gap closure velocity was 3 cm/ μ s.

During the previous reporting period, a 1-TW, 20-ns dual-transverse electron-beam accelerator that could drive a 10-kJ HF laser was conceived; much of the design was completed and fabrication was initiated. Subsequently, decisions were made to stop work

on the HF program and to concentrate on the short-wavelength rare gas halogen lasers. Fabrication of RAYO was stopped and the design is being modified to match the requirements for power-conditioning studies for large excimer laser systems. The new accelerator RAYITO will produce a 1-MV, 500-kA electron beam with pulse durations of either 50 or 200 ns.

The expected overall electrical efficiency of a KrF laser is ~5%. For ICF application, light outputs per module would be at least 50 kJ, implying a 1-MJ energy storage. Electron-beam excitation-pulse lengths from 100 to 500 ns are being considered. A study to explore pulse-power trade-offs indicated Marx generator (pulse-forming transmission line) diode systems are substantially less complex than arrays of pulse-forming networks.

Reactor System Studies

Pellet Injection, Tracking, and Targeting (D. L. Cook)

The pellet injection, tracking, and targeting problem in a gas-filled, particle-beam reactor cavity is very different from that of a vacuum, laser-reactor cavity. Some aspects of this problem were reported in the last semiannual.² The problem has been more fully investigated during the last period, and many limits have been quantified.³

Basic pieces of the problem are illustrated graphically in Figure 132. The pellet must be accelerated rapidly enough that the acceleration time and accelerator length are reasonable, but slowly enough that the forces do not damage the pellet. The pellet's velocity must be sufficient to ensure that the pellet will not be damaged by heating on the way to the vessel center, but slow enough to ensure that the tracking and beam-aiming problems are solvable. The level of hydrodynamic motion of the buffer gas, which can alter the pellet trajectory, must be considered. The targeting problem is dependent on all of these elements, as well as the beam-aiming method and geometrical limitations.

Figure 132. Pellet Injection Considerations

Beam-Aiming Method (D. L. Cook)

The beam-aiming method is shown in Figure 133. The guiding laser beam enters the cavity collinear with the beamline through the ion diode, plasma channel electrode (ion focus), and isolation-valve assembly. The laser path, which determines the ion-beam path, is controlled by a movable mirror outside of the pellet's direct line-of-sight and the neutron field. Beam-aiming and mirror-rotation considerations are shown in Figure 134. Equations (1) and (2) give the actuator stroke needed for a tracking distance (X_t) and the maximum limit on pellet injection velocity that is determined by active beam tracking and targeting.

$$d = A\theta = A \frac{X_t}{R_1 + R_2 + R_c} \quad (1)$$

$$V_M = \left[\frac{8 W_{act}}{M_m A^2} \right]^{1/2} (R_1 + R_2 + R_c) \quad (2)$$

In these equations, X_i is the tracking distance; W_{act} is the actuator energy capability; M_m is the mirror mass; and A is the mirror radius. The velocity limit is due to a limited mirror actuator energy capability. A numerical example is given later in this section. The largest energy capability of a fast ($<100 \mu s$) actuator currently produced is 0.1 J.

Figure 133. Beam Aiming Technique

Figure 134. Channel Laser Mirror Response

Beam Incidence and Timing (D. L. Cook)

The accuracy with which the beam can be made to strike the pellet depends on the accuracy of tracking and on the driver jitter. Also needed for timing the beam-target interaction are the driver response time and the channel formation time (including current rise).

The pellet velocity limits are determined by the required value of beam incidence. The geometrical

loss fraction, which is dependent on this incidence error, is given in Figure 135 and Eq (3),

$$F_L = \frac{2}{\pi} [\delta(1 - \delta)^{1/2} + \sin^{-1}(\delta)] \quad (3)$$

where $\delta = \text{axis displacement/target diameter} = \Delta X/D$ and the beam diameter is equal to the target diameter. The driver jitter and response times are shown with their sources in Figure 136. The important sources of jitter are the pulse-forming line input and output gas switches. The important sources of delay are the primary voltage-multiplying elements (Marx generator or transformer).

Figure 135. Beam Incidence Error

Figure 136. Driver Jitter and Response Time

Pulse Repetition Rate and Reactor Power Level (D. L. Cook)

The considerations which set an upper limit on pellet velocity are the beam-aiming method, beam incidence and timing errors, and pellet acceleration. Considerations that set a lower limit on velocity include the pulse repetition rate, the pellet yield, the cavity size, the reactor power level, heating of the pellet, and the effect of hydromotion on the pellet trajectory. For the gas-filled cavity design, there is a unique relation between cavity radius and pellet yield for a fixed level of stress in a first wall of constant thickness.⁴ This relation is given by Eq (4)

$$Y = K_1 R_c^{5/2} \quad (4)$$

where $K_1 = 4 \text{ MJ/M}^{5/2}$. The reactor power level, given by Eq (5),

$$P = Y \cdot \text{PRF} \quad (5)$$

is simply the product of pulse rate and pellet yield. A fixed fraction of interpulse time (F_i) is allowed for pellet injection (after gas pumping that may be needed and after attenuation of gas hydromotion has been allowed to take place); these relations are coupled in the form of Eq (6) which determines a minimum pellet velocity. The result is rewritten in terms of power and size in Eq (7).

$$V_{\min} = \frac{R_c \cdot \text{PRF}}{F_i} \quad (6)$$

$$V_{\min} = \frac{P R_c^{-3/2}}{K_1 F_i} \quad (7)$$

Pellet Lifetime in the Reactor Cavity (D. L. Cook)

If a cryogenic pellet is employed, survivability during the cavity transit must be assured. With a deuterium protective layer external to the pellet, a very large temperature gradient which is ablation-supported can exist to protect the cryogenic pellet from the hot buffer gas. Under the assumption of free-streaming convective heat transfer (a worst case), there is a relation between the gas density and temperature, the deuterium layer thickness and physical properties, the cavity radius and the pellet velocity. This minimum velocity condition is given in Eq (8)

$$V_{\min} = \frac{N_g [8k_b T / \pi m_g]^{1/2} 1.5 k_b T R_c}{4 \rho_a \Delta E_{\text{sub}} \epsilon} \quad (8)$$

where

$N_g T$	= buffer-gas density, temperature
m_g	= buffer-gas atomic mass
ρ_a	= ablative layer density = ρ_{D2}
ΔE_{sub}	= deuterium sublimation energy (4 to 20 K)
ϵ	= ablative layer initial thickness

Effect of Hydrodynamic Motion on the Pellet Trajectory (D. L. Cook)

The effect of buffer-gas hydrodynamic motion on the pellet trajectory was estimated in two limits. In the first limit, the disturbance is assumed to have been randomized in direction (e.g., by wall reflections) but not decreased in strength after the first-wall reflection. The result of a diffusion calculation is given by

$$V_{\min} = R_c \left\{ \frac{3U}{r_p} \frac{\left(\frac{C_D \rho_g \pi r_p^4}{M_p} \right)^2}{(\Delta x)^2} \right\} \quad (9)$$

In obtaining this result, a fluctuating drag force

$$F = \frac{1}{2} C_D \rho_g U^2 \pi r_p^2 \quad (10)$$

was assumed, where C_D is the drag coefficient. This leads to a diffusion coefficient with the form

$$D = \left[\frac{C_D \rho_g \pi r_p^4}{M_p} \right]^2 \cdot \frac{U}{2r_p} \quad (11)$$

The result predicts a very small effect on the trajectory. In the second limit, the disturbance is assumed unidirectional and active over the entire pellet flight. The result, given by Eq (12), predicts a large perturbation of the trajectory.

$$V_{\min} = R_c \left\{ \frac{C_D \rho_g U^2 \pi r_p^2}{4 M_p \Delta x} \right\}^{1/2} \quad (12)$$

From this, it is concluded that some steps (possibly passive ones, such as wall design) should be taken either to randomize or attenuate the gas overpressure seen by the pellet at injection time. Since, typically, the overpressure is reduced by the fraction of wall taken in ports, some reduction will occur naturally. However, a nonspherical cavity may be desirable.

Example of Pellet-Injection Parameter Values and Velocity Limits (D. L. Cook)

A list of values assigned to the parameters involved in the pellet-injection considerations already discussed is given in Table 7. These were chosen to gain a better understanding of the critical limits and are certainly subject to change. The relations that describe the velocity minima and maxima are listed in Table 8 and are graphically presented in Figure 137 for the particular parameters chosen. The form of these relations has been selected to show explicitly the limits in such a space. The area in which all limits are satisfied is denoted by "window for pellet injection."

Summary of Pellet-Injection, Tracking and Targeting Investigation (D. L. Cook)

Based on current information, the following statements can be made regarding pellet injection, tracking, and targeting in a gas-filled particle-beam-reactor cavity:

1. Targeting can be accomplished using small (~ 0.2 kg) mirrors to reorient the laser beams that guide the plasma channels.
2. There is a sizable window in V_p, R_c space for pellet injection and targeting that is bounded on the upper side by allowable pellet acceleration and pellet accelerator length, by driver characteristic times, and by the beam-aiming mirror actuation. On the lower side, this window is bounded by the pulse-repetition rate and reactor power level, and by cryogenic pellet heating in the buffer gas.
3. For near-term test facilities, the window expands downward due to the absence of repetition-rate constraints (single-pulse) and the anticipated use of gases at room temperature as propagation media.

4. Although no serious physical limits were uncovered in this investigation, further quantification of the known limits will require detailed numerical calculations for particular pellet and cavity designs, especially in the case of the heating and hydromotion constraints.

Table 7. Example of Injection Parameter Values

Gas Type	Neon
Gas Density	$1.8 \times 10^{24} \text{ m}^{-3}$
Gas Temperature	800 K
Pellet Radius	$5 \times 10^{-3} \text{ m}$
Pellet Mass	$5 \times 10^{-4} \text{ kg}$
Deuterium-Layer Thickness	$1.5 \times 10^{-3} \text{ m}$
Allowable Beam Incidence	
Error	$1 \times 10^{-3} \text{ m}$
Driver-Firing Jitter	$1 \times 10^{-8} \text{ s}$
Driver-Response Time	$1.5 \times 10^{-6} \text{ s}$
Pulse-Repetition Rate	10/s
Fraction of Interpulse Time	
Devoted to Pellet Injection	0.1
Channel Laser Mirror Mass	0.2 kg
Channel Laser Mirror Radius	$5 \times 10^{-2} \text{ m}$
Nominal Mirror Actuator	
Energy	1 J
Tracking Distance	0.1 m
Distance from Channel-Laser Mirror to Cavity Wall	10 m

Table 8. Examples of Injection Velocity Limits

Minimum Limits

$$\begin{aligned} \text{Pellet Lifetime: } V_{\min} &= 54.5 R_c \\ \text{Repetition Rate and} \\ \text{Reactor-Power Level: } V_{\min} &= 2.5 \times 10^{-6} P_R R_c^{-3/2} \\ \text{Residual Hydromotion:} \\ 739 R_c &> V_{\min} > 6 \times 10^{-3} R_c \end{aligned}$$

Maximum Limits

$$\begin{aligned} \text{Pellet Acceleration and} \\ \text{Pellet-Accelerator Length: } V_{\max} &= \sqrt{2AS} \\ \text{For } \Lambda = 1000 \text{ G, } V_{\max} &= 140 \text{ S}^{1/2} \\ \text{Channel-Mirror Actuation: } V_{\max} &= 63 (10 + R_c) \\ \text{Driver-Firing Jitter} \\ \text{(Quasi-predictable trajectory): } V_{\max} &= 10^5 \text{ m/s} \\ \text{Driver-Response Time (For highly-unpredictable} \\ \text{trajectory): } V_{\max} &= 670 \text{ m/s} \end{aligned}$$

Figure 137. Pellet Injection Window

Thermal Transport in a Reactor Chamber Filled With an Inert Gas (M. A. Sweeney and D. L. Cook)

Calculations have been performed using the CHARTB⁵ code to determine the effect of several noble gases (helium, neon, and argon) on the transport of nonneutronic energy to the vessel wall of a particle-beam reactor using frequency-dependent opacity data. In the study, we are particularly concerned with how the composition, density, and temperature of a transport/buffer gas affect the first-wall lifetime and the lifetime of other critical elements such as beamline components, diagnostics, and the pellet-injection system by altering blastwave kinetics and thermal transport in the chamber. Previous studies³ of an air-filled chamber (without frequency-dependent data) concluded that the reradiation of thermal energy to the first wall was very slow, principally because of the presence of molecular rotational and vibrational transitions at low temperatures which effectively stopped low-energy photons. Because of the slow thermal transport, considerable pumping power will be necessary to return the air, between microexplosions, to conditions compatible with laser initiation of highly conducting magnetized-plasma channels needed for beam propagation. It was assumed that, by using an inert gas, the rate of thermal transport would be increased so that the pumping requirement would not be excessive. Use of an inert gas would have an added advantage because the absence of chemical reactivity reduces wall-corrosion damage and the higher ionization energy

in the case of helium and neon implies larger mean free paths at low temperatures. By using multigroup opacities, a more accurate treatment of the thermal transport can be obtained than through the use of one absorption mean for all photon energies.

The assumptions of the thermal transport/hydrodynamic calculations are: (1) a one-fluid, two-temperature approximation of the gas-radiation system ($T_r, T_e = T_i$), (2) multifrequency radiation transport with harmonic (Rosseland) mean of each band, (3) flux-limited-diffusion approximation, and (4) local thermodynamic equilibrium.

A considerable amount of effort was spent in analyzing the frequency-dependent data supplied by LASL,⁶ in developing a program to generate group-mean opacities from the data (including analytic cross sections⁷ at photon energies above those supplied on the tapes (<13 eV at 5000 K for argon)), and on checking out and making changes to the multigroup-opacity-routing corrections for gases other than air that had not been run on a problem before.

Our major conclusion⁴ from the calculations is that the usefulness of a pure noble gas is of questionable benefit because of the unacceptably high-thermal stresses with 23.5 MJ in nonneutronic energy (corresponding to a particle-beam target with a gain of ~ 20) unless the wall radius is assumed to be considerably >4 m. A typical calculation assumed 66 kPa (at 0°C) of neon, with an initial cavity-gas temperature of 750 K, a 1-ns absorption-pulse length, a 41.6-cm initial radius for the fireball, and 54 photon-energy bands from 0 to 5000 eV. The rapid removal of energy from the gas (in about 60 ns, Figure 138) via reradiation to the first wall reduces the first-wall overpressure by a factor of about 4. With a noble gas, the radiant energy is released to the first wall before the shock wave reaches the first wall, as opposed to the situation for air, where optical depths are comparatively small and the shock wave transfers a large impulse to the wall before significant energy can be removed by reradiation.

The results obtained in the one-group Wisconsin study⁸ with noble gases are qualitatively similar. However, their results imply lower (but still unacceptably high) thermal stresses. The Wisconsin calculations assume $T_e = T_i = T_r$ initially, whereas our calculations do not. CHARTB is currently being altered so that this is a possible initial condition. A better comparison can then be made between the two results. In addition, a multigroup air calculation will be performed; these results will then be compared with our previous one-group calculation.

In the next reporting period, we intend to investigate the possibility of seeding the cavity gas with a

high-Z material in order to increase the opacity and thus reduce the thermal stresses experienced. The following gas combination is being contemplated: 66 kPa of argon or neon with 130 Pa of sodium or potassium. We also intend to consider a buffer gas such as NH_3 . The seeded inert gas has the advantage of a lower average ionization energy; with the NH_3 , the presence of molecules will increase the opacity. Both choices also provide a gas type desirable from the standpoint of plasma-channel formation by atomic or molecular absorption.⁹

Figure 138. Fraction of Deposited Energy Removed From 66 kPa Neon Gas as Function of Time

Impulse and Overpressure on PBFA Pellet Chamber (D. L. Cook)

The impulse (in the case of a vacuum) and the overpressure (in the case of a gas fill) that are presented to a cavity wall by the disassembly of a target with significant thermal energy have been computed for PBFA based on the reactor hydrodynamic shock studies. The computations indicate that the loading in both the vacuum case and in the strong-shock limit of the gas-filled case scale similarly and are comparable in magnitude. Table 9 gives some results of the investigation in tabular form. These are the incident overpressure, the overpressure arrival time, and the overpressure duration as functions of radius for a rapid 1-MJ point energy release in the presence of 66

kPa (0°C) of air. The values tabulated have been calculated using strong-shock theory, which, for these parameter values, is valid to $R = 1.3$ m.

The principal result of this study was that because of the scaling of the wall loads ($\sim E/R^3$), impulse and overpressure due to targets having no measurable gain are important considerations in near-term as well as far-term facility vessel and diagnostic design.

Table 9. Incident Overpressure, Arrival Time, and Duration Shown as a Function of Distance From a Rapid 1-MJ Point Energy Release in 66 kPa of Air

Radius (m)	Overpres- sure (ΔP) (atmo)	Shock Arrival Time (μs)	Shock Duration (μs)
0.1	1540.0	0.8	0.1
0.2	193.0	4.8	0.7
0.3	57.1	13.2	1.8
0.4	24.1	27.2	3.7
0.5	12.3	47.5	6.5
0.6	7.1	74.9	10.3
0.7	4.5	110.0	15.2
0.8	3.0	153.7	21.2
0.9	2.1	206.3	28.5
1.0	1.5	268.4	37.0
1.1	1.2	340.6	47.0
1.2	0.9	423.4	58.4
1.3	0.7	517.2	71.4

First Wall-Design Study (D. L. Cook)

The design study of a particle-beam-reactor cavity first wall, carried out in collaboration with the University of Wisconsin, has been completed.¹⁰ The object of this study was to investigate the first-wall design issues for a large (~ 4 -m radius) gas-filled reactor cavity. The important parts of the problem included energy transport through the buffer gas, hydrodynamic loading of the cavity wall, and blanket neutronics. A number of detailed reports have been written on topics that were central to this investigation.^{8,11-13}

The type of first-wall configuration analyzed is shown in Figure 139. The panel receives the most severe loadings of any part of the cavity-wall structure. It is referred to as the "first" wall since it faces the microexplosion. A proposed panel geometry is shown in Figure 140. The behavior of such a panel was analyzed. The stress analysis was done, using varying sets of assumptions; the results were evaluated and compared. The boundary conditions for a

simply supported and partially clamped plate analysis are shown in Figure 141. Rectangular plates were assumed to describe trapezoidal ones to first order.

Figure 139. First Wall Panel

Figure 140. First Wall Panel Topology

The results of the stress analyses are presented in Tables 10 through 12. Definitions of parameters not given in these tables can be found in Figures 139 and 140. In Table 10, design parameters for a first wall with a stress limit of 20 ksi are listed. The lower part of the table presents nine combinations of panel size and number of panels per hemisphere. In Table 11,

design parameters are given for a wall with a 10-ksi stress limit. A summary of the front plate and total panel thicknesses is presented in Table 12 for the two stress limits of 32 panels per hemisphere. The values given can be accommodated within a conservative wall design.

SIMPLY SUPPORTED AND CLAMPED PLATES

SIMPLY SUPPORTED PLATE

$$\frac{\partial W}{\partial x}(0,y) = \frac{\partial W}{\partial x}(a,y) = \frac{\partial W}{\partial y}(x,0) = \frac{\partial W}{\partial y}(x,b) = 0$$

PARTIALLY CLAMPED PLATE

$$\frac{\partial W}{\partial y}(x,0) = \frac{\partial W}{\partial y}(x,b) = 0, \quad w(0,y) = w(a,y) = 0$$

Figure 141. Stress Analysis Boundary Conditions

Table 10. Design Parameters for First Wall With 20-ksi Stress Limit

Cavity Radius	= 400 cm
Circumference	= 2513.27 cm
Gas Duct Radius	= 170 cm
Plate Height (b)	= 420 cm
Maximum Stress	= 20 ksi
Maximum P_w	= 4 atm = 58.784 psi
$\sigma_{max}/P_{w max}$	= 340

	No. of Panels/ Hemisphere	a(cm)	b/a	a^2/td	t	d
(1)	8	314	1.34	4640	0.5	42.54
(2)	16	157	2.67	2880	0.5	17.13
(3)	32	78	5.35	2200	0.5	5.61
(4)	8	314	1.34	4640	0.75	28.36
(5)	16	157	2.67	2880	0.75	11.42
(6)	32	78	5.35	2200	0.75	3.74
(7)	8	314	1.34	4640	1.0	21.27
(8)	16	157	2.67	2880	1.0	8.57
(9)	32	78	5.35	2200	1.0	2.80

Table 11. Design Parameters for First Wall With 10-ksi Stress Limit

Cavity Radius	=	400 cm
Circumference	=	2513 cm
Gas Duct Radius	=	170 cm
Plate Height (b)	=	420 cm
Maximum Stress	=	10 ksi
Maximum P_w	=	58.8 psi
$\sigma_{max}/P_{w max}$	=	170
No. of Panels/ Hemisphere		a(cm) b/a a ² /td t d
(1)	32	78.5 5.3 1040 0.5 11.8
(2)	32	78.5 5.3 1040 0.75 7.9
(3)	32	78.5 5.3 1040 1.0 5.9

Table 12. First Wall Mechanical Design Parameters

Cavity Radius	=	400 cm
Gas Duct Radius	=	170 cm
Plate Height	=	420 cm
Maximum P_w	=	58.8 psi
No. of Panels/ Hemisphere	Front Plate Thickness (cm)	Total Plate Thickness (cm) 20-ksi 10-ksi
32	0.5	5.61 11.86
32	0.75	3.74 7.91
32	1.0	2.80 5.93

The major conclusion of the first-wall study is that particle-beam-fusion reactor first walls can be designed to withstand the hydrodynamic overpressure from the pellet explosion using standard engineering design techniques, conventional materials such as steels, and very conservative engineering design factors. Realistic designs are possible using a stress limit of 5 times less than the yield strength, assuming a maximum overpressure on the wall of twice that predicted by computer hydrocalculations. This represents a full order of magnitude in conservative design criteria. Furthermore, this result is for the simplest wall design from a fabrication point of view. This conclusion is most important because it allows for large margins of error in areas of uncertainty without jeopardizing the viability of the wall design. An example of this uncertainty is the effect of pulsed-neutron damage.

ETF Scoping Study (D. L. Cook)

A scoping study of a particle-beam ETF which was briefly described in the last report has been extended during this period. Requirements in several areas have been further quantified. These areas include driver isolation, pellet injection, pellet tracking, beam aiming, cooling, pellet production, and

blanket-section replacement. The following data present in simplest form the assumptions made in each of these areas and the resultant requirements.

ETF Driver Isolation Requirements

- 66 kPa $\rightarrow$ 10^{-1} Pa
- 2-cm aperture
- 200- μ s aperture-open time
- 10 shots/s

Need: $\sim 10^4$ l/s-beamline

or

Two 10-in. diffusion pumps/beamline

ETF Pellet Injector Requirements

- 5-m pellet travel
- 10-ms maximum travel time
- Final position error $< 1/2$ cm

Need: $\rightarrow \sim 500$ m/s muzzle velocity

$\rightarrow \sim 1$ mrad divergence

$\rightarrow$ Cryogenic system including the accelerator

$\rightarrow$ 13-m acceleration barrel at 1000 g's

$\rightarrow$ No jamming at 10 Hz for 1000 s

ETF Pellet Tracking System Requirements

- $< 10\%$ error (dia) at strike
- Rapid-position acquisition
- Pellet-fracture detection

Need: $\rightarrow \sim 2$ - μ s position determination

$\rightarrow \sim 1$ -mm position determination at 5 m distance

$\rightarrow$ Fracture detection/safing system

$\rightarrow$ Protection from blast

ETF Beam Aiming System Requirements

- ~ 10 -cm tracking distance
- ~ 1 -cm position variation
- ~ 10 -m correction arm

Need: $\rightarrow$ 10-mrad tracking angle

$\rightarrow$ 1-mrad rapid correction capability

$\rightarrow$ 5-J, < 100 - μ s actuator

$\rightarrow$ 10-Hz operation; 100-ms reset

Cooling System Requirements

- 2-Mw/m² loading
- 1-m cavity radius
- <12 blanket sections
- ~4 coolants

Need: → ~4 cooling systems (nuclear grade)

- ~2-Mw/m² capability
- ~6-Mw capacity/loop
- Versatile connections
- Include H₂O, liquid metals, gases

ETF Pellet Production Needs

- Test runs are 10⁴ shots (1000 s, 10 Hz)
- Tests are 3 mo. apart

Need: On average, 100 "good" pellets per day

ETF Blanket Section Replacement Times

- ~1 x 1 x 1 m in size
- Single header, <50 tubes
- ~10% structural material
- ~90% coolant

Need: → Handling capability for 2 tonne modules

- 1-mo. cooling time
- 1-mo. pretesting time
- 2 wks. for disassembly
- 2 wks. for assembly
- 3 mo. between test runs

The generic design of the type of module that will be tested in an ETF is depicted in Figure 142. Important parts are the inlet and outlet tubes, separated-flow channels, a realistic first wall, and a shield section for biological shielding consistent with minimal remote handling. A candidate vessel and structure arrangement into which a module of this type would fit is shown in Figure 143. In this design, the upper and lower caps are relatively permanent, as are the attachments to them and the coolant headers. The beams enter through beam modules that are independently cooled and are not changed with the blanket modules. The module shape has been chosen to permit rapid installation and replacement.

Figure 142. ETF Module

Figure 143. ETF Cavity Assembly

Laser-Channel Study

(D. L. Cook)

In the previous reporting period, a study of laser-initiated channel feasibility was begun in collaboration with the University of New Mexico.¹⁴ This study consisted of an examination of a number of possible mechanisms for the guiding of a discharge by a laser. The object of the study was to make a preliminary determination of the applicability of these various approaches for particle-beam-reactor, plasma-channel initiation.

Initially, it was recognized that most of the literature dealt with gas breakdown. Although breakdown is an option for channel initiation, it is both power and energy intensive. A more attractive approach is to provide only the level of ionization needed to guide a discharge; this area served as the focus of the study.

Study results were a scoping of scientific feasibility of an approach including a determination of laser peak-power and energy requirements. Some of the practical requirements in implementation of these schemes were not considered in detail. Therefore, the conclusions may be altered when implementation issues are taken into account.

The output of this study was a rank-ordering of potential laser-produced ionization techniques. Resonant atomic absorption, leading to electron-collisional de-excitation (runaway), and molecular-vibrational excitation, leading to thermal ionization or production of a rarefaction region, were ranked as most attractive. These have the common advantages of a very low threshold; low laser-energy requirements (1 to 10 J); and moderate laser-power requirements. In addition, they are potentially fast and can produce a small channel. Potential problems in this category include the necessity for short wavelength lasers, use of an alkali in the reactor vessel, molecular and atomic-level matching, and molecular opacities.

Direct ionization fell into the moderately-attractive category, with energy requirements limiting the technique to a very narrow range of laser and gas choices. A possible combination would be a UV laser and an alkali.

Full laser-induced gas breakdown processes were categorized as least attractive. These include aerosol-initiated ionization, multiphoton ionization, and cascade ionization. These suffer from similar, serious disadvantages: a distinct threshold, high laser-energy requirements, high laser-power requirements, and possibly large discharge-channel radii. One of the few advantages they do offer is that they are essentially wavelength and gas-type independent.

A follow-on investigation was initiated to determine the nature and magnitude of the implementation problems mentioned earlier. Only the most

promising options are being considered in the development of a preliminary conceptual design of a channel-initiation system.

Target-Development Facility Design Study

(D. L. Cook)

A joint design study of a target-development facility has been initiated. This study, involving Sandia National Laboratories, the University of Wisconsin, and the University of New Mexico, has as its objective the preliminary conceptual design of a facility that will enable testing and development of fusion targets needed for the engineering test facility, fission-fusion hybrids, and pure fusion reactors. The facility will provide a significant simulation capability. The initial-design calculations have begun and a straw-man list of parameters has been selected.

Repetitive Pulse – Power Development

Pulse-Power Development Plan for Inertial Confinement Fusion

(K. R. Prestwich)

A study by the Physics International Company¹ identifies pulse-power technology that must be developed for commercial applications of inertial confinement-fusion reactors. Six major facilities for resolving specific engineering issues had previously been identified in a Department of Energy, Office of Inertial Fusion long-range planning exercise.¹⁵ These six facilities with their major purpose are listed in Table 13.

All of the facilities in Table 13 require repetitive operation except the SPTF. The Physics International study defined the technology needed for the repetitively operated facilities. Although substantial uncertainty exists in the various research and development programs, a specific set of operating parameters were determined and supplied to Physics International to define the scope of their work. These specifications are listed in Table 14 and the ICF drivers are tabulated in Table 15. The study defined the state-of-the-art for the pulse power and the technology requirements for each driver. Substantial commonality exists in the needs for the gas lasers, light-ions and linear-induction accelerators for heavy ions. Since

design data for the SIF and the ETF is needed in a relatively short time according to the schedule given in Table 14, these facilities must be built from extensions of existing technology. The requirements for these two facilities were defined as a near-term program by Physics International, and detailed development plans were derived with an estimated cost for completion of \$24.3 million.

The technology for the remainder of the facilities was denoted as the far-term program. The operational lifetime of these facilities requires a large extrapolation in either lifetime or peak power from present-day systems. Although this extrapolation made it difficult to arrive at a detailed program plan, a scheme was scoped in somewhat less detail than was given the near-term plan. A preliminary estimate of the research and development costs is \$28 million.

1.5-MV Resonant Transformer System (G. J. Rohwein)

The 1.5-MV, repetitively pulsed, transformer system was tested to full voltage at pulse rates up to 10 pps. In another series of tests, it was operated at 1.2 MV and 20 pps for sustained runs up to 100,000 shots. Throughout the testing, no difficulties were encountered with the transformer, capacitor bank, or switches. The system consistently operated with a transfer efficiency of 91%.

During full-voltage testing, a problem with corona generation in the switch-tank oil developed. Puffs of tiny bubbles on each shot were observed to originate from higher-stress points around the high-voltage components in the tank. With repetitive pulsing, the bubble puffs would expand into the bulk volume forming a cloud around the point of origin. The size of the bubble clouds seemed limited by partial coalescence into larger bubbles that rose to the surface and burst. It was interesting that at pulse rates over 3 pps, the bubble production could be varied

from essentially zero with the system operating at 1.2 MV to a brisk-boiling condition at 1.5 MV.

Typically, random streamers began to appear out of the bubble clouds after a number of shots; they could vary from less than ten to several hundred, depending upon the bubble production per shot. The appearance of random streamers always leads eventually to an arc breakdown in the oil, although the partial-discharge condition would sometimes exist for over a thousand shots before breakdown actually occurred.

What has been demonstrated by these early repetitive tests over 1 MV is that the corona-inception voltage (CIV) rather than field and time-dependent breakdown relationships is the dominant failure criteria for repetitively stressed oil dielectrics. The tests also provide an interesting comparison between breakdown stresses for single-shot and rep-rate operation. When the system was tested in the single-shot

Table 13. ICF Facilities

Facility	Major Purpose
Single Pulse Test Facility (SPTF)	High-gain pellet development
Systems Integration Facility (SIF)	Beam focusing and guiding integrated with pellet injection and tracking
Engineering Test Facility (ETF)	First-wall blanket and thermal-system development
Materials Test Facility (MTF)	First-wall and blanket life-time studies
Fusion Pilot Power Plant (FPPP)	Complete power-plant system integrations
Prototype Fusion Power Plant (PFPP)	Production of electricity for the power grid

Table 14. Facility Specifications

Facility	Driver Energy (MJ)	Repetition Rate (Hz)	Pulse Lifetime	Construction Date
SIF	0.030-0.10	1-10	10 ⁷	1986
ETF	0.5	1-10	10 ⁷	1990
MTF	0.5	1-10	10 ⁹	1992
FPP	1.0	1-10	2 x 10 ⁸	1995
PFPP	1.0-5.0	1-10	10 ⁹	2002

Table 15. ICF Drivers

Lasers	Particle Beams
CO ₂	Electrons
KrF	Light Ions
HF	Heavy Ions

mode, occasional oil breakdowns did not occur until the peak voltage approached 3 MV. With the system in the same configuration but rep-rated above 3 pps, corona-induced breakdowns began around 1.4 MV, over a factor of 2 lower than single-shot breakdowns.

Since the problem of corona generation was encountered, higher stress points were carefully graded so that no part of the system operated over about 300 kV/cm. This grading and a continuous slow recirculation of the oil in the switch tank to disperse and mix any local accumulation of bubbles into the bulk oil volume has greatly reduced the breakdown problem. Runs as long as 20,000 shots have been made at full voltage without breakdown but, at the conclusion of these runs, the entire oil volume would be lightly clouded with pin-point bubbles indicating that some corona production was still present.

To control the concentration and buildup of small bubbles, a continuous-flow evacuation system has been designed that will recirculate 5 to 8 gpm of transformer oil, and remove not only the entrained gas in the oil, but also maintain the moisture and absorbed gas concentrations below saturation so that the oil has the capacity to absorb small amounts of gas produced by partial discharges. In addition to vacuum processing, a series of experiments are planned to measure the corona-inception voltage of transformer oil under conditions of partial- and full-gas saturation.

Oil Breakdown Tests (G. J. Rohwein)

A series of tests were conducted on the REPIT facility to measure the bulk-breakdown characteristics of three paraffin-base oils that may be useful in certain applications as an alternative to mineral transformer oils. The oils tested include ordinary motor oil (Pennzoil, 20 W); a Teflon-loaded oil (Lubri-lon); and RTEmp, a commercial insulating oil. The results of the tests are plotted in Figure 144. The plot also shows for comparison the breakdown characteristics of mineral-transformer oil and x-ray oil previously tested under identical conditions. All the paraffin oils showed a higher breakdown strength than transformer oil for electrode spacings greater than 0.6 to

0.75 cm. Not shown is the apparent tolerance for carbon contamination. After the first breakdown in a given oil sample, subsequent breakdowns occurred at ~50% lower voltage than the first breakdown in Lubri-lon and about 70% of the first breakdown in motor oil. RTEmp usually recovered to nearly 90% of first breakdown for at least three to four subsequent shots. In all cases the electrodes were wiped clean between breakdown and the carbon residue was mixed into the bulk volume of the oil sample.

Figure 144. Breakdown Strength of Various Oils

In general, transformer oil (and especially x-ray oil, exhibited a much better dielectric-recovery characteristic than any of the paraffin-base oils. X-ray oil would recover to virtually 100% of its initial strength between breakdown shots until the bulk volume was perceptibly blackened from the breakdown products.

Probably the significant difference in dielectric recovery between mineral- and paraffin-base oils is that oxidation inhibitors are usually added to electrical-grade mineral oils which limit the amount of carbon and gas produced from arc or partial discharges. Possibly, RTEmp, a paraffin oil developed for high-voltage insulation, is better than motor oil in terms of dielectric recovery because it too has an oxidation inhibitor.

The present oil tests show that there is no apparent advantage in loading an oil with a high dielectric-strength, solid powder such as the Teflon in Lubri-lon. Second, paraffin-base oils, such as motor oil, can be a useful insulating media where no breakdowns or partial discharges are expected. Finally, the prospect exists that (with fine filtering and the addition of

oxidation inhibitors) motor oil would be useful in large-volume insulating applications.

Spark Gap for Plus/Minus Capacitor Banks (G. J. Rohwein)

A new low-inductance spark-gap switch has been developed for plus/minus charged capacitor banks in an air environment. This gap (shown in Figure 145) is called the half-switch, and consists of two identical two-electrode sections with one section attached directly to the insulator bushing and high-voltage terminal of each capacitor. The output electrodes are interconnected by an external plate or strip that bridges the distance between the gap and is biased to ground during the charge cycle. This arrangement avoids the dc-insulation, flashover problems that often arise with single switches which require exposed connection plates and must be charged to high dc voltages along with the capacitors.

Figure 145. A Half-Switch

The half-switch is triggered by applying a fast-rising, high-voltage pulse to the electrically common-output electrodes. However, since there is no direct UV communication between the two sections of the gap, problems in reliable triggering were encountered when the trigger pulse was applied to the center of the connector strip. These problems were overcome by feeding a separate trigger line to

each section of the gap. One parallel line was connected to each gap section through a spark plug inserted in the side of the housings so that the plugs fired before the trigger pulse reached the main electrodes. The sparks from the plugs thereby illuminated the main gaps with UV, and simultaneously provided some pulse sharpening. With this triggering arrangement, the half-switch could be triggered from ± 300 V to ± 25 kV with up to 35-psi air pressure in the gaps, indicating simultaneous breakdown of both gap sections over that range. In the simultaneous breakdown mode, the breakdown jitter between the two gap sections was unmeasurable with 2-ns resolution over a 100-shot sequence. Normally, the system is operated with an 80-kV trigger voltage, which is sufficiently high to assure simultaneous gap breakdown over the range of 0 to ± 25 kV.

Above 35 psi, the gap goes into a cascade breakdown mode above ± 7.5 -kV charge. This accounts for the peculiar wedge-shaped triggering-threshold curves in the lower right-hand region of Figure 146 which is a plot of triggering range. The wedge will shift to the right or left on the graph depending on the trigger voltage.

Physically, the half-switch is an extremely rugged device. The main electrodes are flat, 10-cm dia, water-cooled, copper disks which breakdown randomly over the 70-cm² effective switching area. The electrodes, housing, subplate, and covers were designed to minimize material and fabrication costs by using standard-size plates and tubes where possible. The combined features of simplicity and superior-switching performance as far experienced quality the half-switch as the most likely candidate for future capacitor banks requiring many parallel switches.

Figure 146. Triggering Range of Half-Switch

Repetitively Pulsed Marx Generator Development

(M. T. Buttram)

The repetitively pulsed Marx generator development program has three objectives: (1) to establish the efficiency and lifetime of a reasonably high-powered Marx generator in repetitive service, (2) to examine the characteristics of slowly purged gas switches, and (3) to provide repetitive high-voltage pulses at substantially higher energy per pulse (~ 10 kJ) than is currently available at Sandia. When the third objective is attained, a variety of pulse-forming lines, high-voltage switches, and diode experiments can begin.

To implement this program, a 11.5-kJ, 1-MV inductively coupled Marx generator and several smaller experiments have been built. The large Marx generator has been operated at half-voltage and 5 Hz for periods of several minutes. A primary limitation on this work has come from the charging system. The original work done with a 30-kV, 120-kW power supply was limited by the low voltage available (the Marx needs a 65-kV charge), and by overloading the supply which caused the final Marx-charge voltage to vary from pulse to pulse. This situation should be somewhat improved with the installation of three-quarters of a 80-kV, 2-MW dc supply. (The remainder was returned to the factory for repair of faults found in the initial testing.) The power available in this new supply has some drawbacks. Faults which were inconsequential with the previous supply are now catastrophic. There is a need for careful design of a good pulse-charging control system. For the present, resistive charging is being used.

The Marx generator has eight three-element spark gaps. A prototype gap with air dielectric was operated to 50 kV and 50 pps for long runs. A purged gas flow of 600 SCFH was used. Spark gaps are purged to restore their dielectric strength between shots. Purging cools the electrodes and mixes cool gas with the hot gas in the spark channel. At low repetition rates (less than 50 Hz), purging is needed primarily as a supplement to natural cooling which restores at least 80% of the dielectric strength of most gaps within 20 ms after a single shot. Purging is required to prevent long-term heat buildup. Two experiments confirm this fact. The RTF-I pulser rail gap has been operated for several minutes at rates to 40 Hz with no gas flow. The run had to be terminated before the gap got hot enough to melt its plastic housing; however, it did not prefire, so the gas had not lost its dielectric strength. The second experiment was done in a burst-mode Marx generator where gas flow (substantially

below 50 SCFH) was sufficient to maintain gap strength for 1 s at 50 Hz in a 20-kA discharge. Experiments currently in progress will raise the voltage per switch and the current to values comparable with the inductively coupled Marx (130 kV, 50 kA). Preliminary data indicate that very minimal gas (SF_6) flow (~ 100 SCFH per switch) will suffice at rates above 10 Hz for periods of several seconds. This gives one reason to believe that Marx-generator switches may be cooled effectively without significant gas flow. This alternative cooling technique (e.g., immersion in an oil bath) will be used as a partial substitute for gas cooling to maintain an acceptable thermal equilibrium in the switches in the inductively coupled Marx.

Currently the Marx generator is being operated within a 200- Ω resistive load. A water Blumlein has been designed for future pulse compression for single-shot operation at 1 MV. Experiments will establish how far the voltage must be reduced for repetitive service. The designed Blumlein output will be 1-MV, 50-ns pulses into 6 Ω . The line has been modeled with SCEPTRE as a pair of two-dimensional LC networks properly switched and terminated in a resistive load. The predicted output voltage is 95 to 100% of the theoretical with a 14-ns 10 to 90 risetime, a 38-ns flat top, and a 26-ns 90 to 10 fall. The 14 ns is consistent with $2.2 L/Z$ where L is the inductance of the switch and Z is the line impedance. The full width at half-maximum is 58 ns. Hardware for this experiment should be delivered during the next reporting period.

Repetitively Pulsed Electron-Beam Diode

(J. W. Ginn and M. T. Buttram)

Experiments were performed to gain information regarding the behavior of electron-beam vacuum diodes in a repetitively pulsed environment. Methods of improving the lifetime and the stability of diodes in such an environment were investigated by varying the material and geometry of the cathode. Use of an oil-impregnated cathode material resulted in a constant diode behavior for over 3×10^5 shots.

The experiments used the RTF-I high-voltage, repetitive-pulsed generator.¹⁶ RTF-I is driven by a transformer which charges a 9.5 Ω , oil-insulated, coaxial, pulse-forming line (PFL) to as much as 700 kV. Up to 350 kV can be impressed across a matched load for the 30-ns pulse length. In this experiment, the cathode diameter was 6.4 cm and the beam area was 32 cm². The anode to cathode (A-K) gap required to

match the diode impedance to the PFL can be roughly calculated from the equation for the space-charge-limited flow:

$$Z = \frac{137\pi}{\sqrt{V}} \frac{d^2}{A} \quad (13)$$

where V is the diode voltage in MV, d is the A-K spacing in centimeters, and A is the beam area in cm^2 . For the typical operating voltages of 250 kV, a 9.5- Ω impedance implies a spacing of roughly 0.5 cm. This appeared to match the line fairly well. The anode consists of an aluminum plate with a jacket of circulating tap water behind it for cooling purposes. Although the RTF-I has been operated to rates of 100 pps, anode cooling requirements limited rates to under 35 pps for prolonged runs.

Diode current was measured with an annular, low-inductance, in-line 0.135- Ω -resistive shunt (CVR). The CVR was calibrated against a standard foil CVR. Further, when the PFL was dc-charged to a known voltage, and subsequently discharged into a resistive load, analysis of the current waveform using the equation:

$$Q = C_{\text{PFL}} V_{\text{PFL}} = \int i \, dt \quad (14)$$

verified the CVR calibration. C_{PFL} was measured with impedance bridges and verified by ringing the PFL through a known inductance and measuring the ringing frequency.

Attempts were made to calibrate the capacitive monitor used to measure voltage on the PFL by isolating the line and ringing it up to 50 kV, but results varied by a factor of 2 from day to day. The capacitive monitor was moved from the top to the side of the PFL to reduce the likelihood of air in the pickoff section; the monitor was calibrated using the current waveform and conservation of charge. Diode voltage was measured with an integrated dv/dt monitor. It was calibrated by performing an energy balance using the equation:

$$W = \frac{1}{2} C_{\text{PFL}} V_{\text{PFL}}^2 = \int v i \, dt \quad (15)$$

Inductive voltage corrections were assumed to be negligible.

A second-load voltage probe exists in the pickoff section of an annular water resistor. This resistor is between the output switch and the diode, and serves

primarily to suppress prepulses from capacitive voltage division before the output switch is fired. SCEPTRE¹⁷ calculations indicate that the annular water resistor absorbs roughly 15% of the energy stored on the line. The resistor is therefore filled with recirculating tap water for cooling purposes. The resistive monitor produces a much higher voltage than the dv/dt monitor and has therefore been used for digitizing the waveform. However, although it reproduces the shape of the pulse very well, its calibration does not appear to remain constant, possibly because of the day-to-day fluctuation in tap-water resistivity. The ratio of the signal from the resistive monitor to that of the dv/dt monitor varies from 960 when the resistor is filled with 227- Ω/cm salt water to 440 using 2-k Ω/cm tap water to 152 with 5-M Ω/cm deionized water. Assuming purely resistive division, the difference between the salt and tap-water results should be 15%. The origin of the problem is apparent from a comparison of the salt water versus deionized water results. In the former case, the monitor is a resistive divider; in the latter, it is capacitive. The disparity between the results indicates that the probe-attenuation factor is changing at a time characteristic of RC decay through the water (20 ns for the case of tap water). This model does not explain why the probe waveform matches the dv/dt monitor waveform, but it does suggest that $\rho = 2500\text{-}\Omega/\text{cm}$ water is not suitable for fast-pulse monitors. Because of this inconsistent calibration, diode voltages to be discussed were measured from the output of the dv/dt monitor.

After thousands of shots, aging (i.e., degradation of cathode emission characteristics) is manifested in the following ways:

1. The time required for the formation of a plasma on the cathode surface increases, resulting in a higher voltage spike on the leading edge of the waveform, since a nonemitting cathode presents an open circuit to the PFL;
2. The diode current during the main pulse is reduced in amplitude.

Figure 147 shows waveforms typical of a new cathode and an old one. One useful way of comparing the emission characteristics of cathodes on various shots is to compare their impedances at the time of turn-on (i.e., at the time when the voltage has its greatest value). As a cathode ages and initiation of emission becomes more difficult, this impedance rises.

Efforts were concentrated upon two cathode-surface geometries. The cathode in Figure 148 has concentric rings machined into its surface. Emission is from the edges of the rings as evidenced by erosion

at those edges and the appearance of a corresponding beam pattern upon the anode surface after many thousands of shots. We studied another cathode-emitting surface which employed an array of steel-roll pins (0.16-cm-dia hollow cylinders mounted on the cathode-backing metal). The field enhancements are more pronounced on the roll-pin cathode; furthermore, these enhancements are still present after considerable cathode erosion. This can be seen in Figure 149 which contrasts new and used roll-pin cathodes.

a. Typical new cathode waveforms, 20 ns/cm. Upper trace: Voltage, 120 kV/cm. Lower trace: current, 15 kA/cm

b. Typical aged cathode waveforms, same scale as a.

Figure 147. Waveforms for a Brass-Ring Cathode

Figure 148. Oilite Ring Cathode After 300,000 Shots

Figure 149. Roll-Pin Cathodes: (L) New Brass; (R) Oilite After 300,000 Shots

Data from an early run using a brass-ring cathode is presented in Figure 150, which shows a plot of the diode impedance at the voltage peak versus the cumulative number of shots. The impedance rises sharply after only a few thousand shots. After some 20,000 shots into the run, the diode was opened and the cathode surface lightly coated with diffusion-pump oil. This has the effect of both increasing diode current and lowering the voltage peak. The cathode ages much more slowly until it is again oiled some 100,000 shots later. Voltage and current waveforms before oiling and on the first and second events after oiling are shown in Figure 147. After a few thousand shots, the cathode was sprayed with a coating of Aerodag. With this carbon coating the diode achieved its lowest turn on impedance of the run. Operation was terminated after roughly 10,000 shots with this coating before aging data could be obtained.

Figure 150. Normalized Diode Impedance at Turn On versus Elapsed Events for a Brass-Ring Cathode

Figure 151 is a plot of the normalized diode turn-on impedance versus the number of shots accumulated for five cathodes, including the brass-ring cathode just discussed. There was a more rapid initial aging of the brass-roll-pin cathode than there had been with the ring cathode. When the pin tips were oiled after some 71,000 shots, a similar drop in impedance occurred, followed by aging at a rate comparable to that observed initially. A second brass-ring cathode was run without oiling the surface at any time. The turn-on impedance doubled after fewer than ten thousand shots and continued to rise rapidly. As Figure 151 shows, when the run was terminated due to a punctured anode, the "turn-on" impedance had risen by almost an order of magnitude. Figure 152 shows the voltage and current waveforms at the beginning and end of the run, as well as the voltage from an open-circuit diode shot wherein the only load fed by the 9.5- Ω PFL is the 130- Ω water resistor. As emission becomes more difficult, the diode-voltage waveform is seen to approach that of the open-circuit condition. The energy delivered to the diode during the main pulse is down to slightly over 50% of that delivered early in the cathode's life.

The rejuvenation of brass cathodes by application of oil or carbon coatings suggested the use of a material impregnated with oil. Both ring- and roll-pin cathodes were fabricated from a bearing material manufactured under the trade name Oilite. The Oilite

used was sintered bronze that had been vacuum-impregnated with an SAE 30 oil. As Figure 151 indicates, both Oilite cathodes exhibited a virtually constant turn-on impedance throughout the course of a 300,000-shot run. Three sets of waveforms separated by 100,000 shots using the Oilite roll-pin cathode are shown in Figure 153. The emission characteristics are virtually unchanged over this range. The Oilite cathodes are shown in Figures 148 and 149. In addition, a ring cathode was fabricated from carbon. However, the carbon cathode began to outgas and destroyed the diode vacuum before significant aging data could be obtained.

Without oiling, roll-pin and ring cathodes appeared to age at comparable rates for the first few thousand shots. The roll-pin cathode's aging slowed, whereas that of the ring cathode apparently continued toward a nonemitting condition. This difference may be due to the retention of field enhancements by the roll-pin cathode. Although some of its outer pins were worn down by as much as 0.3 cm, many highly field-enhanced sites of potential emission remain. Oiling the emitting surface rejuvenates the cathode. After oiling, aging is more rapid in the case of the roll-pin cathode as compared to the ring cathode, probably because less emitting surface area is oiled. With either geometry, a continuous supply of oil permits relatively constant diode characteristics. The turn-on impedance of the Oilite-ring cathode actually decreased by 20% after 300,000 shots.

The phenomenon of cathode aging is closely related to the initiation of electron emission. The presence of a layer of carbon on the cathode surface facilitates emission. Diode behavior immediately subsequent to oiling suggests that penetrating the oil layer and carbonizing the oil are the prerequisites for renewed emission. Referring to Figure 151, since the field enhancements are unchanged, the voltage must initially rise to the same peak required prior to oiling. Once the layer is penetrated and the cathode emitted, current is higher than before the oiling. Subsequent shots require lower voltages and achieve still higher currents. No surface film is assumed in the classic Fowler-Nordheim¹⁸ derivation of field emission. It is widely accepted that field emission originates at highly field-enhanced microscopic projections¹⁹, although different hypotheses have been advanced for the manner in which breakdown then proceeds.²⁰ From the present results, it appears that the emissive behavior of carbon- and hydrocarbon-surface films warrants closer study, particularly since an adsorbed layer of oil may often be present unintentionally.

Figure 151. Normalized Impedance at Turn-On versus Number of Events for Five Cathodes

a. Brass-ring cathode waveforms after 200,000 shots, 20 ns/cm

b. Voltage waveform for a nonemitting cathode, 20 ns/cm, 125 kV/cm

Figure 152. Extreme Aging of a Brass-Ring Cathode and a Voltage Waveform of a Nonemitting Cathode

a. After 100,000 event

b. After 200,000 event

c. After 300,000 event

Figure 153. Oilite Roll-Pin Cathode Waveforms Showing Consistent Impedance Characteristics. 20 ns/cm, upper trace: voltage, 100 kV/cm; lower trace: current, 5.9 kA/cm

Future studies are planned for better understanding of the aging phenomenon. Examinations of the cathode surface at various stages of the aging process will be made by a scanning-electron microscope. Attempts will be made to identify potential sites of emission and to observe changes in the number and condition of such sites during the life of the cathode. From a practical standpoint, the type of oil with which the Oilite cathodes were impregnated tended to blacken the diode chamber and, more importantly, to create difficulties in pumping a good vacuum (typically 10^{-4} Pa) once the chamber had been opened to air. This is probably due to the adsorption of air molecules by the oil. On the other hand, the oil apparently protected the aluminum-anode material since anode erosion was much reduced from that using the brass cathodes. One option is to remove the

oil by means of a cold trap built into the diffusion pump. An experiment is planned using a cathode of the same sintered bronze material, but impregnated with diffusion-pump oil.

Electron Beam Sources for Gas Lasers

Plasma-Injected Microsecond Diode Studies (J. J. Ramirez)

A study of a microsecond diode, in which an injected plasma was allowed to fill the anode-cathode gap volume prior to the application of the high-voltage pulse, was discussed in a previous progress report. These studies have been extended to the regime where the preformed plasma was constrained to be near the cathode surface when the high-voltage pulse was applied to the diode.

The surface-flashover plasma board used for the experiments in which the plasma was constrained to be on or near the cathode surface is similar in concept to the one employed by Gary K. Loda.²¹ This board is shown schematically in Figure 154 and consists of a pattern of circles etched on a printed circuit board. These circles define a large number of circular islands (metal pads) that are separated from the remaining metal in the circuit board by an insulating gap. A voltage is applied to the circuit board as shown in Figure 154. This voltage is divided capacitively across C_1 and C_2 . The voltage across C_2 causes a flashover along the insulating gap on the surface of the printed circuit board which discharges C_2 . Since only the capacity associated with a given pad is discharged when the gap flashes over, the voltage on the remaining gaps is not significantly affected. In this manner all of the gaps on the printed circuit board are made to flashover. This design allows a very high-density packing of plasma blobs on the surface of the cathode which then act as zero-work function emitters. In order to effectively flashover the insulating gaps, C_2 must be smaller than C_1 . This condition results in a practical limitation in the packing density of the emitting sites possible with this type of plasma board.

An attempt was made to characterize the plasmas produced by these boards with a biased Langmuir probe, but the collected current was below the threshold of our instrumentation. Possibly a cold, dense plasma is produced due to the small values of

the capacity driving each arc; typically 10^{-14} - 10^{-15} F. As a consequence, it was found that the high voltage from the PFN had to be applied immediately after flashing over the plasma board; otherwise, the arcs appeared to extinguish and no current was drawn across the diode. A precise determination of the simultaneity required was not made but it was <200 ns.

Figure 154. Surface Flashover Board Cathode

Plasma boards with arc densities of 8 and 16 cm^{-2} (referred to as large and small circles, respectively) were tested. In order to facilitate timing requirements, the output of the PFN itself was used to drive the plasma board for these tests. Since these boards arc over with a 20-kV input pulse, the plasma on the cathode surface was formed within a few nanoseconds from the start of the voltage pulse.

Figure 155 shows a set of diode waveforms obtained with an 18- by 36-cm cathode using printed circuit boards with the small circles. The anode-cathode gap was 8.6 cm. Apertured Faraday cups indicate that the entire board emitted uniformly over its full area. The time-integrated measurement of the current density at the anode yields a beam measuring 25 by 40 cm. This indicates some divergence of the beam. Two scans across the beam at the anode are shown in Figure 156. They indicate a variation of $\pm 16\%$ in the anode-current density.

Figure 155. (a) Voltage and Current Waveforms, (b) Power and Impedance Waveforms for a Typical Plasma

Figure 156. Scans of Radiochromic Film Indicating Relative Current Density at the Anode

A plot of the effective anode cathode gap spacing as a function of time is shown in Figure 157. It was obtained from the diode waveforms shown in Figure 155 and used the space charge limited relationship

$$ZV^{3/4} = \frac{427 (X_{eff})^2}{A} \quad (16)$$

where V is the diode voltage in megavolts and A is the area of the beam at the anode. The approximation made for these calculations is that A is the beam area determined with the radiochromic dosimetry and is constant in time. The slope of the line drawn through the data yields a closure velocity of $3 \text{ cm}/\mu\text{s}$. These data also indicate that the diode does not reach space-charge-limited flow over all of the measured beam area until about 75 ns into the voltage pulse. At this time the calculated X_{eff} equals the actual anode-cathode spacing. Although the board flashed over within a few nanoseconds after the beginning of the voltage pulse, the resulting plasma was incapable of supporting a space-charge-limited flow early in the power pulse.

Figure 157. Effective Anode Cathode Gap Spacing versus Time for Plasma Cathode

Table 16 summarizes data for various experimental conditions. Note that the plasma boards with the small circles gave lower closure velocities. The arrangements with smaller anode-cathode gaps also yielded smaller closure velocities. Loda quotes closure velocities as low as $1 \text{ cm}/\mu\text{s}$.²² Possibly this low value was achieved because his diode operated in a

repetitively pulsed mode. The repetitive pulsing would result in a conditioning of the cathode by driving the low-Z material off its surface; otherwise it would give rise to the high velocities observed here.

Table 16. Apparent Gap-Closure Velocities Obtained for Various Experimental Conditions

Cathode Type	Anode-Cathode	
	Gap (cm)	Closure Velocity (cm/ μ s)
Small circles	8.6	$3.0 \pm .3$
Small circles	6.0	$2.0 \pm .3$
Large circles	8.6	$3.5 \pm .3$
Large circles	6.0	$2.5 \pm .3$

The uniformity of the beam at the anode and the collapse of the diode impedance are two of the primary concerns in generating electron beams for applications to laser excitation. The uniformity results from the requirement to evenly excite the laser medium, and the collapse affects the efficiency with which the stored energy is coupled to the laser medium. It also has some practical consequences in anode-foil survivability. Cathodes that emit uniformly over their entire surface area are required to obtain a uniform beam at the anode. The surface-flashover cathode with a high-arc density provides a uniform emission surface.

The collapse of the diode impedance can result from both an increase of the beam area and a decrease of the anode-cathode gap. In a uniformly emitting cathode the beam area increases only as a result of the motion of electrode plasmas. This plasma motion also reduces the effective anode-cathode spacing. It is reasonable to expect that the expansion velocity of these plasmas is controlled by the ion species; i.e., low-Z plasmas yield higher velocities. A repetitively pulsed diode, where the adsorbed low-Z materials have been removed, would thus exhibit a smaller impedance collapse. It is likely that a significant portion of the collapse, which has been observed in many low-current density diodes, is due to an increase in the beam area as increasingly more of the cathode area starts emitting. With a uniformly emitting cathode this contribution to the impedance collapse is minimized. What remains is the result of the closure of the anode-cathode gap by electrode plasmas. This gap-closure velocity could possibly be reduced by controlling the ion species involved.

RAYITO (J. J. Ramirez)

The original RAYO concept which was to be the driver for a 10-kJ, H-F laser has been replaced by RAYITO, a facility for studying power-conditioning problems associated with large excimer laser systems. Since present day concepts for these laser systems encompass a wide range of parameters, the RAYITO facility must be flexible enough to allow investigation over this wide-parameter space. The performance requirements and design concepts for this facility are discussed below.

RAYITO is to be a single-diode, 0.8 to 1.0 MV, 50- and 200-ns, 2- and 4- Ω accelerator. Due to budgetary and time constraints, maximum use must be made of components designed for the original RAYO project. The initial concept for the 50-ns mode of operation was patterned after the Mite design.²³ The 1-MV, 2- Ω , PFL would produce an output waveform similar to the MITE output with a 24-ns 10/90 risetime and a 6 to 8-ns system jitter. It was deemed necessary to reduce this risetime in order to improve the experimental capabilities. A second design, which reduced the risetime to ~ 12 ns but increased the jitter to ~ 20 ns, was also unacceptable. The problem with simultaneously meeting both jitter and risetime requirements arises from the properties of the self-breaking water switches used in these designs. The risetime is controlled by the resistive phase in the water switches; and the jitter, by the charge time of the lines.

In order to meet both the jitter and risetime requirements, the final design concept employs two intermediate energy stores. A block diagram of the accelerator in the 50-ns output mode is shown in Figure 158. The Marx generator is a PBFA-type module that uses 1.0- μ F capacitors. This higher energy unit is required for the 200-ns, 4- Ω mode of operation that has been tested in the MITE facility. The Marx charges an intermediate energy store, which consists of two Proto II water capacitors, in 700 to 800 ns. These capacitors are discharged via a triggered gas switch into the 150-ns line. In the 50-ns output mode this line acts as a second intermediate store. It gets charged in ~ 300 ns and is discharged by self-breaking water switches into the 50-ns, pulse-forming line (PFL). With this arrangement, the PFL can be charged fast enough to allow an output-pulse risetime of ~ 12 ns using a second set of self-breaking water switches. The output of the PFL is sent to the diode via a transmission line and convolute arrangement. A third set of self-breaking water switches is used to

reduce the amplitude of the prepulse applied to the diode. In this design, the system jitter is dominated by the jitter of the water switches in the 150-ns line. A total jitter of 6 to 8 ns should be achieved.

Figure 158. Block Diagram of RAYITO

In order to obtain a 200-ns output pulse, the two water capacitors are removed from the system, the 150- and 50-ns lines are tied together and are charged directly by the Marx generator in $\sim 1 \mu\text{s}$. An output risetime of ~ 50 ns would be obtained using self-breaking water switches. The jitter of the Marx generator and output switches would combine to produce a total-system jitter estimated at 23 ns. Triggered gas switches would be required to improve on these parameters. The water tankage is to be made long enough so that this option might be retrofitted at some later date if such an improvement is found to be essential.

The conversion of the accelerator impedance from 2 to 4 Ω would be accomplished by changing the electrode spacing of the transmission lines from 10 to 20 cm. This is usually done since the only hardware change required would be the installation of slightly different ground plane electrodes in the convolute section to the diode. Since the 200-ns PFL must be charged in $\sim 1 \mu\text{s}$ in order to properly equilibrate the transmission-line voltage, tracking of the nylon-support rods could possibly limit the amplitude of the output pulse for the 2 Ω configuration. This should not present a severe limitation to the planned experimental program.

The diode designed for the original RAYO concept will be used for RAYITO with some minor modifications. Calculations show that the diode insulator will hold off 1.3 MV and 1.0 MV for the 50-ns and 200-ns output pulse widths, respectively. No significant inductive overshoot will occur in the 200-ns mode and a maximum of 12% will be expected in the 50-ns, 2 Ω mode. At the desired output levels of 1 MV, 50 ns and 0.8 MV, 200 ns, this design provides an 18% to 20% safety factor in the insulator-breakdown strength.

The design concept described meets all the requirements established for RAYITO, and will provide a versatile facility for power-conditioning studies in large excimer laser systems. The design is based on proven pulse-power technology that will allow its implementation in a timely and cost-effective manner.

Pulse-Power Consideration for High-Energy KrF Lasers (K. R. Prestwich and J. J. Ramirez)

Preliminary design of large KrF-laser systems for ICF requires electron-beam drivers with pulse widths ranging from 100 to 500 ns. The PBFA technology has established the applicability of water-dielectric, PFL for the generation of high-power electron beams with pulsewidths of up to 100 ns. Pulse-forming networks (PFN) of various kinds are generally recognized as applicable to the generation of pulse widths $\geq 1 \mu\text{s}$. The requirements on the electron-beam drivers for KrF lasers fall between these two regimes. In choosing between PFL and PFN designs for these drivers, consideration must be given to system cost, efficiency, complexity, and reliability.

With dual transverse excitation and the pressure regimes of interest, 0.5 to 1.5 MeV electrons have the appropriate range. If a module has 50-kJ light output with 5% efficiency, the capacitor bank must store 1 MJ; therefore the effective output impedance of the

system is less than 1Ω . In the PFN case, the primary leg of the network must be a 1.0- to 3.0-MV Marx generator. Modern Marx generators have inductances in the 0.6- to 2.0- $\mu\text{H}/\text{MV}$ range. Since this inductance limits the nominal impedance for a given pulse width, a PFN type (where each stage has the largest value inductance) is the most appropriate. The Type C Guillemin voltage-fed network²⁴ shown in Figure 159 fulfills this need. Even with the Type C, pulse durations between 50 to 500 ns can not be achieved with sub-ohm impedances. Many PFNs must be operated in parallel to generate the total beam current. The exact number of components that would be required can be determined in the following manner. The pulse duration (T) is defined in terms of the primary leg capacitance (C_1) and inductance (L_1) in Eq (17).

Figure 159. Type C Guillemin Network

$$T = \pi \sqrt{L_1 C_1} \quad (17)$$

Rearranging this equation and substituting for L_1 gives

$$C_1 = \frac{T^2}{\pi^2} \frac{10^6}{LV_0} \quad (18)$$

where L is the Marx inductance in $\mu\text{H}/\text{MV}$ and V_0 is the Marx charge voltage. The values of C_n , the higher-frequency stage capacitance, are proportional to $1/\nu^2$ where $\nu = 3, 5, 7, \dots$. Thus if one considers a three-stage PFN, about 85% of the total energy is stored in the primary stage. From Eq (18), the energy stored in C_1 is given by

$$E_{C1} = \frac{T^2}{2\pi^2} \frac{10^6}{L} V_0 \quad (19)$$

The number of PFNs to be operated in parallel can be calculated using

$$N_{\text{PFN}} = \frac{0.85 E_T}{E_{C1}} \quad (20)$$

The number of capacitors per PFN is

$$N_{\text{cap/PFN}} = \frac{kV_0}{V_c} \quad (21)$$

where k is the number of legs in the PFN circuit and V_c is the capacitor charge voltage. Combining Eqs (18), (19), and (20) and letting $k = 3$, one obtains

$$N_{\text{cap}} = \frac{5 \times 10^{-5} E_T L}{T^2 V_c} \quad (22)$$

Figure 160 is a plot of this equation for $E_T = 1 \text{ MJ}$ showing upper and lower limits as a function of V_c and L . The Marx spark gaps and support hardware is directly proportional to the number of capacitors in a Marx PFL arrangement; the energy-storage capacitors fall in the range of 3.3 to 10 kJ. The additional charging stage decreases the efficiency so that the 1.0 MJ would become 1.1 to 1.35 MJ depending upon the exact switching arrangement. Therefore, the number of capacitors for a water PFL combination would vary from 110 to 409. For large energy storage and slow-charge time, the impedance of each transmission line would be about 6Ω . Six or seven triplate transmission-line structures would be required for each side of the dual-transverse system.

Figure 160. Number of Capacitors for 1-MJ PFN or PFL versus Pulse Width

Some concern has been raised that dispersive effects might limit the risetime obtainable with water-dielectric PFLs for pulse widths greater than 200 ns. A small bench-test experiment has been performed to address this issue for pulse widths ~ 500 ns. A sketch of the apparatus is shown in Figure 161.

A 7.3-m long ($\tau_{1\text{-way}} = 218$ ns), 6- Ω -water coaxial line was pulse charged by capacitor C1 through an inductance L1. The time required to charge the line was controlled by changing the value of this inductance. The line was discharged by a self-breaking air gap and the output pulse was observed across a resistive load (RL). For these tests, C1 was charged to ~ 10 kV. Typical results are shown in Figure 162. The top trace is the charging waveform, measured at the switch end of the line; the bottom trace is the output pulse across the load resistor. The FWHM of the output pulse is 435 ns, as calculated from its physical dimensions, and the risetime is ~ 30 ns. Essentially the same results were obtained when the line-charge time was reduced to 1 μ s. The postpulse observed in the output is the result of feeding energy from the C1 capacitor. This pulse was minimized when the output gap closed at the peak of the charging waveform. Early gap closure is also responsible for the slight ramping observed in the main output pulse. The low-voltage data indicates that dispersive effects should not play a dominant role in determining the risetime of output waveforms obtained with water-dielectric, pulse-forming lines for pulse widths up to 500 ns.

Figure 161. Experimental Setup for 435 ns PFL Test

Figure 162. Charging and Output Waveforms From 435-ns PFL

References

1. J. Benford, T. Naff, G. Simcox, O. Zucker, and R. Cooper, *A Unified Pulse Power Plan for Inertial Confinement Fusion*, Report PIFR-1299 (Physics International Company, August 1979).
2. D. L. Cook, *Particle-Beam Fusion Semiannual Progress Report, January-June, 1979*, SAND80-0974, (Albuquerque: Sandia National Laboratories, 1980).
3. D. L. Cook and M. A. Sweeney, *Bull Am Phys Soc*, 24 (8):1071 (1979).
4. D. L. Cook and M. A. Sweeney, *J Nucl Mat*, 86:127, 1979.
5. L. Baker, SAND79-0386 (Albuquerque: Sandia Laboratories, 1979).
6. W. F. Huebner, A. L. Merts, N. H. Magee, Jr., and M. F. Argo, Report LA-6760-M (Los Alamos: Los Alamos Scientific Laboratories, August 1977).
7. M. F. Argo, private communication; E. Storm and H. I. Israel, *Nucl Data Tables A7*:565-681, 1970; F. Biggs and R. Lighthill, Report SC-RR-71-0507 (Albuquerque: Sandia Laboratories, December 1971).
8. R. R. Peterson and G. A. Moses, Report UWFD-315 (Madison: University of Wisconsin, October 1979).
9. J. Olsen, Sandia National Laboratories, private communication.
10. G. A. Moses et al, *First Wall and Cavity Design Studies for a Light-Ion-Beam-Driven Fusion Reactor*, Report UWFD-320, (Madison: University of Wisconsin, September 1979).
11. R. R. Peterson and G. A. Moses, Report UWFD-307 (Madison: University of Wisconsin, June 1979).
12. M. H. Ragheb, G. A. Moses, and C. W. Maynard, Report UWFD-295 (Madison: University of Wisconsin, July 1979).
13. R. L. Engelstad and E. G. Lovell, Report UWFD-322 (Madison: University of Wisconsin, December 1979).
14. G. W. Cooper, *A Feasibility Study of Laser-Guided Discharges*, Report NE-74 (Albuquerque: University of New Mexico, October 1979).
15. T. G. Frank, Department of Energy, Office of Inertial Fusion, private communication.
16. M. T. Buttram and G. J. Rohwein, "Operation of a 300-kV, 100-Hz, 30-KW Average Power Pulser," *Proc of the 13th Pulse Power Modulator Symposium*, (Buffalo, NY, 1978), p 303.
17. J. C. Bowers and S. C. Sedore, *SCEPTRE, A Computer Program for Circuit and Systems Analysis*, (Englewood Cliff, NY: Prentice Hall, Inc., 1976).
18. R. H. Fowler and L. Nordheim, *Proc R Soc*, A119 (London, England: 1928), p 173.
19. R. L. Little and W. L. Whitney, *J Appl Phys*, 34:2430, 1963.
20. G. A. Mesyats, "The Role of Fast Processes in Vacuum Breakdown," *Proc of the 10th Int'l Conf on Phenomena in Ionized Gases* (Oxford, England, 1971), p 333.
21. G. K. Loda, *Electron Gun for High Average Power UV/Visible Lasers - Final Report*, Systems, Science and Software Co. Report SSS-79-11400-FR (Hayward, CA, January 1979).
22. G. K. Loda, private communication.
23. T. H. Martin, J. P. VanDevender, G. W. Barr, and D. L. Johnson, "PBFA - Pulse Power for Fusion," *3rd Int'l Topical Conf on High Power Electron and Ion Beams* (Novosibirsk, USSR: July 3-6, 1979).
24. G. N. Glasoe and L. V. Lebacqz, *Pulse Generators*, Vol 5 (McGraw Hill: Radiations Laboratory Series, 1948).

Chapter 7. Electron-Beam Fusion-Accelerator Project

PBFA I Project

Overview

Significant construction progress on PBFA I (Figure 163) and its supporting systems was made during this reporting period. The PBFA will initially operate in both the positive and negative polarity modes; this operation will provide the greatest flexibility for initial experiments without modifying the accelerator for different polarities. In the first configuration, 18 of the 36 lines will provide negative polarity pulses and 18 lines will provide positive polarity pulses. The slow pulse energy storage section of PBFA remains unchanged for either mode of operation; i.e., the Marx generators are charged negatively with respect to ground. The intermediate energy

storage, the gas switches, and the Pulse Forming Line (PFL) will operate as originally designed. The positive output pulse is provided in the water-insulated transition section by installing an electrical cross-over network. The vacuum-interface-insulation stack must be configured to allow the appropriate polarity operation. A polarity change requires several weeks to accomplish if hardware is interchanged. Both positive- and negative-polarity operations were demonstrated on HydraMITE, the PBFA Demonstration Experiment. Photographs showing modules in either polarity option are shown in Figures 164 and 165. Special anode/cathode hardware has been designed and procured to allow the initial phase of testing.

Figure 163. PBFA Accelerator in December 1979.

Figure 164. Negative Polarity Transition Between Output of the PFL and the Input of the Transformer Section.

Figure 165. Positive Polarity Cross-Over Network Located Between the Output of the PFL and the Input to the Transformer Section.

During construction, the PBFA assembly/installation schedule has been modified several times to accommodate construction-delivery delays in the project. The present installation schedule is shown in Figure 166. The tank turnover was delayed for several reasons. The fabricator experienced problems in sandblasting the stainless-steel portion of PBFA, and because of the strong interrelationship between the PBFA tank and the SuperMITE tank, both tanks required similar construction operation. Since the same contractor supplied both tanks, many of these operations were done in series. Before any electrical components could be installed in either tank, it was imperative that all tankage work in the building be complete. The PBFA tank completion was intentionally delayed to allow the PBFA utility contractor to install all of the electrical conduits for the power/control wiring on the PBFA tank before final painting. These interactions resulted in rescheduling the turnover of the PBFA tank until the first week in September 1979. Immediately after tank turnover, the entire high bay was cleaned to convert it from a construction site to a laboratory. Both PBFA and SuperMITE were then painted.

Component installation began the last week in September. After experiencing delays due to crane problems, the Marx generators were rapidly installed. Within six weeks, the energy-storage components were ready for testing. In November, the initial subsystems checkout for the Marx pulsed power tests was started. These tests exercised the major accelerator subsystems; i.e., the 36 Marx generator modules, the Marx generator charging system, the Marx generator firing system, the Marx firing system transfer switch, the resistive "dummy" loads to dissipate the stored energy, and the current and voltage monitors. Additional systems required to support these initial tests were the data acquisition/data-processing systems and the support system controls.

Facility related systems required for the initial pulsed power tests, such as the oil transfer system, the SF₆ insulating gas transfer and repurification systems, and the pressurized oil system to drive the transfer switches, were also tested. All of these systems experienced problems that were subsequently corrected.

The project team visited several fabricators during November 1979. The 36 pulse forming lines and the transformer sections being fabricated at Continental Machine in Albuquerque were scheduled to be delivered by November 15, 1979 and December 15, 1979, respectively. The fabricator did not meet this schedule. It was agreed that a delivery of 10 pulse forming lines per week would begin December 21, 1979 and continue until delivery was complete; under the same conditions, delivery of 10 transformer sections per week would begin on January 15, 1980. If this schedule is maintained, these items will not affect the assembly schedule. The accelerator assembly, critical path item is the central section and the lower spool of its target chamber which is now scheduled for a January 15, 1980 delivery. The intermediate storage capacitors which were rejected in October 1979 for having inferior welds should be delivered during February 1980.

The gas switch, lucite insulator rings exhibited crazing directly under the O-ring seal between the insulator and the grading ring. It is suspected that the insulators were cleaned with a solvent that weakened the lucite. All insulators will be replaced.

We installed the vacuum manifold, the diffusion-pump backing manifolds, and the structure to support the work platform, catwalks, and radiation

shielding at the center of PBFA; we are now installing the electrical power and control conduits to support the vacuum system.

The deionized water transfer and storage system acceptance test was conducted during the November 1979. Several fittings failed during the testing. New fittings were ordered and a second test is scheduled for January 1980. A contract was placed to convert 200,000 gal of water to deionized water when the acceptance tests are completed.

During December 1979, we proceeded with pulsed power tests of the PBFA energy storage sections. The distributed Marx generator trigger system checked out with all nine Marx Pulser Units (MPU's) operating at 500-kV output with less than a 10-ns spread. The first charging and firing of all 36 Marx generators was carried out successfully on December 21, 1979. This test was a significant milestone for the program. Approximately 1.0 MJ of energy was stored and simultaneously discharged into resistive loads for the 36 Marx generator modules. These tests verified the proper installation of the charging system and the circuitry of the Marx generator modules. The charging voltage of the Marx generator will be increased to 100 kV during January 1980 to complete the characterization tests. These tests will determine the erection time, simultaneity, and electrical characteristics of the 36 modules.

During December, we also began to install the accelerator catwalk. In the same month, we completed electrical power and control wiring in the center section of PBFA for the 36 diffusion pumps. Installation of the target chamber, the power flow lines, and the vacuum interfaces will begin in January. The RF panels that enclose the underside of the accelerator and the data acquisition cable splice room were installed.

Component fabrication and delivery are proceeding. As of January 1, 1980, all 36 vacuum interfaces and 26 of the power flow lines were received. The remaining ten power flow lines are scheduled by mid-January. Sixteen PFLs were assembled and inspected. The transformer section fabrication is on schedule and all units are expected by mid-February. The central section of the target chamber is finished. The lower spool of the target chamber should be completed by January 15. The power flow lines and vacuum interfaces will be installed and aligned to the target chamber starting in January. Acceptance tests

of the gas switch trigger system will be conducted at Maxwell Laboratories during January.

Tank Structure

The tank structure was completed during July 1979. The final acceptance test was conducted June 22-26 by filling the energy storage section of the tank with water to a depth of 16 ft. One small leak was detected and fixed; the structural integrity of the outer and middle walls was verified. The heavy steel structure shown in Figure 167 was installed around the 18-ft center section to support future radiation shielding as required. This central structure will also support a central donut-shaped work platform above the target chamber. Access catwalks are being installed around the top of this central structure, around the top of the 60-ft dia wall, and around the central structure at the power flow line level. The catwalks are connected with three radial catwalks $\sim 120^\circ$ apart. The two radial catwalks on the west side

connect to a work platform extending along the west side of the high bay between the main entrance into the high bay and the south wall of the building. The other radial catwalk extends to the northeast corner of the tank where a set of stairs will be installed to reach the floor level. Emergency escape ladders have been installed in the energy-storage section.

Energy Storage Section (Installation)

Energy Storage and Dummy Load System

Marx generator installation proceeded rapidly. Marx support saddles, positioned by the tank contractor, locate the generators. The polyurethane high voltage feed through barriers were installed in the oil/water wall. Three Marx generators were installed by September 27, and the installation of all 36 was complete on October 8, 1979. Two views of the Marx generator installation are shown in Figures 168 and 169.

Figure 167. Central Support Structure: Radiation Shielding and Catwalks.

Figure 168. Typical Marx Generator Module Installation.

Figure 169. Overhead View of the Energy Storage Section Showing the Marx Generator Installation.

Problems with the Marx transfer switches were identified during this reporting period. A redesign of this switch was started in July. The switch mounting was changed from the floor, supported on insulator legs, to a bracket attached to the Marx output corona-cap casting. This redesign was completed before installing the Marx dummy loads.

Sixteen dummy load assemblies were attached between pairs of Marx generators to alternate I-beams as shown in Figure 170. Each resistive load assembly has four copper sulfate-solution resistors to absorb energy from two Marx generators. This resistor provides each 116-kJ impulse generator with a 14-ohm check divertor load.

Figure 170. Marx Generator Dummy Load Resistor Assembly.

Marx Charging System

In October 1979, we completed the installation and check out of this Universal Voltronics system. All interconnections between the power supply subsystems are enclosed in electrical conduit. Both high voltage unit (HVV) tanks were cleaned and filled with transformer oil. Installation of the Marx

grounding relays and the 100-kV charging conductors within the tank proceeded well. Partial installation of these components is shown in Figure 171. Each of the two HVUs has a separate grounding relay assembly. Suppression of any Marx transients in the power supply high voltage units is provided by RC filtering and an overvoltage spark gap. The two SF₆ gas dielectric, field distortion, overvoltage spark gaps are identical to the Marx generator gaps. Easily removable, clip-on, copper-tubing interconnections were installed between Marx generators for charging. These provide continuous, positive and negative 100-kV bus rings all the way around the energy storage section of the accelerator by connecting all 36 Marx generators together. Removal of individual conductor segments from the ring allows arbitrary division of the charging and energy storage system.

Figure 171. Marx Generator/Charging System Interface Assembly: Overvoltage Protection Spark Gap, Grounding Relay, and Charging Connections.

Marx Firing System

We completed installation of this system in November. Delivery from Maxwell Laboratories, Inc. (MLI) was approximately 6 months behind schedule.

The Sandia performance requirements were more difficult to achieve than MLI had estimated.

For this system all power and interconnections outside of the accelerator tank are enclosed in conduit. Ten 100-kV trigger cables and nine 80-kV dc-charging cables are routed over the outside wall of the accelerator. These were routed around the upper inside of the outer wall to provide charging and triggering for each Main Pulser Unit (MPU). Each MPU shown in Figure 172 is a six-stage Marx impulse generator that erects to 10 nF and about 0.5 MV. Slack in the 177-ft equal length trigger cables was taken up wherever necessary by a single U-loop in the cables on the tank wall. Time-delay reflectometry (TDR) was used to confirm equal cable-time delay. Card-board templates of the drawing locations were used to position the MPUs, the MPU transfer switches, and MPU-to-Marx trigger contact plates. Hydraulic lines used to operate the MPU transfer switches and monitor the swing-arm position of each switch were routed and connected. Each MPU location was provided with a 100-ohm dummy load, a 3000-ohm referencing resistor, and a voltage monitor resistive divider. All of these firing-system resistors use a copper sulfate solution inside Tygon tubing. Sandia Marx-type, CuSO₄ voltage monitors were interchanged with the MLI monitors. Copper tubing was formed and installed 9 in. above the floor of the oil section to make two 0.5-MV pulse transmission lines for each MPU. Each of these nine transmission line pairs originate at the MPU switch-fire position and terminate at the trigger-contact plates of four energy storage impulse generators. A typical installation is shown in Figure 173. Minor shipping damage had to be repaired, bias resistors and other equipment installed, and spark-gap irradiation pin spacing adjusted on these impulse generators. Trigger generators, remote controllers, synthetic air system, power distribution, etc, associated with the firing system were installed and made operational without significant problems.

Energy-Storage Section (Pulsed Power Tests)

Testing and check out of individual subsystems and components related to the energy storage section began when the hardware was delivered. The energy storage section was charged to one-half voltage and discharged into dummy loads before the end of December 1979.

Figure 172. Marx Generator Firing System: Main Pulser Unit (MPU) Installation.

Figure 173. Marx Firing System: Typical MPU Installation With Transfer Switch, Dummy Load Resistors, and Transmission Lines.

Charging System

On August 3, dry-tank tests recommended by Universal Voltronics were conducted as shown on Figure 174. Power supply short-circuit, load tests with both high voltage units (HVV) were made to 800-mA total current (i.e., 400 mA each HVU). We tested the open-circuit to 20 kV with each HVU and with the transformer rectifier assemblies raised out of the HVU tanks. We also made a preliminary check of the remote control system. Charging system installation proceeded in parallel with other high bay activities.

Figure 174. Marx Generator Charging System: High Voltage Unit (HVU) Internal Structure.

Charging system installation, except for the Marx grounding relay and interconnections, was completed by October 25. HVU oil tanks were cleaned, filled, and connected; the power subsystem and its related ac-power conduit and wiring were installed; the remote controller was installed in the control room. Voltage on both HVUs was increased step-by-step to 100 kV in a 29-hr, continuous oil bake-out process. Short circuit tests using both HVUs were made up to 1.6 A. Sandia's Standards Laboratory personnel assisted in the high voltage calibration of the system. The

system performed well and the 36 Marx generators were charged to 50 kV at the end of December.

Firing System

Acceptance tests of the firing system were completed at Maxwell Laboratories, Inc. and the system shipped in August. Testing of the partially installed system commenced in November; good timing and low (6- to 10-ns spread) timing and jitter were measured for the installed system during December. The system fired all 36 Marx generators charged to half-of-full voltage at the end of December. We checked the remote-control operation of the MPU transfer switches during this same period, and the MPUs operated both into dummy loads and the pulse-transmission lines.

Energy Storage System Tests

The end of December tests allowed initial high-voltage checkout of the many subsystems, components, and interconnections. Many systems were proven when the half-voltage tests were completed. No component failures or high-voltage breakdowns were observed with 100 kV on 578 spark gaps and 50 kV on 1152 capacitors during these tests.

Pulse Forming Section

The water insulated section of the accelerator receives energy from the Marx generators in ~ 650 ns and compresses the pulse in time to ~ 40 ns. Components providing this time compression are the intermediate storage capacitor, the triggered gas switch, and the PFL with multipoint, self-breaking water switching. The 40 ns is then line transformed from 1.5 MV to the 2.0-MV voltage impressed across the vacuum interface. During this reporting period, these components are being fabricated. Manufacturing problems and delays were experienced, and the assembly schedule was modified to accommodate this delay.

Intermediate-Storage Capacitors

Nine inner electrodes and eight outer cylinders were rejected by Sandia due to poor workmanship. They were returned to the fabricator during November 1979. A trip to the fabricator showed similar problems with most intermediate storage capacitors; these were rejected. In addition, the first nine inner

bottles needed additional welds to strengthen the gas-switch mounting area. The present schedule calls for all units to be shipped by March 1980.

Gas Switches

All gas switches were received during September and October 1979 and stored in Building 481. Uncrating and inspection of the gas switches showed a major problem with the insulator stack. Approximately 75% of the gas switches had crazed insulator rings. An investigation was begun immediately (both chemical analysis and stress analysis), and another complete set of insulator rings were ordered. Preliminary findings indicated that cleaning fluid degraded the mechanical properties of the lucite insulator rings. When mechanical loads were applied to the lucite, crazing occurred directly under the O-ring, vacuum-seal pressure points. The rebuilt gas switches will be assembled by the PBFA assembly crew, and the problem should not delay the PBFA operational date.

Pulse-Forming Lines

There was a delay in the production of the PFL because of design changes and design corrections to problems that became apparent after assembly of the first several units. These changes included modifications to the support-rod clamp assembly to insure positive clamping and proper positioning of the lines on the rods. Current schedules call for the final unit to be shipped the last week in February.

Pulse Transforming Line

The manufacturer of the pulse transforming line also manufactures the pulse-forming lines. Delays in delivery of the pulse forming line caused delivery delays of the transforming line. Presently, the first units will be delivered the last week in February with ~ 10 /wk thereafter. The controlling factor will be the corrosion resistant plating turn-around time.

Gas Switch Trigger System

The trigger system, which will simultaneously trigger all 36 gas switches, is behind schedule, the system is being developed by Maxwell Laboratories. High voltage resistor problems that caused the delay were corrected and acceptance tests are scheduled for January 1980. High voltage, trigger isolator coils needed for this trigger system were received from National Tube Company during November. TDR

measurements of electrical length have been made, and final cable trim will be done by the PBFA assembly crew.

Power Flow/Front End Section

The power flow section of PBFA is the center 40-ft-dia section of the accelerator containing the vacuum interface, the magnetically insulated transmission lines, the pellet chamber, the various vacuum manifolds, and the 42 diffusion pumps. The vacuum manifolds, the support structure to hold the catwalks and radiation shielding, and the electrical utilities (i.e., power, control, and monitor wiring) have been installed in the power flow section. The center section of the pellet chamber (the section that all 36 transmission lines bolt to) is complete and the lower spool that provides mounting capability for the pellet chamber vacuum system is in final machining. These two critical sections of the pellet chamber will be shipped to Sandia for immediate installation in PBFA by late January 1980. The vacuum interface and power flow line are approximately on time with the original fabrication schedule established during the fall of 1978. All 36 units will be ready for installation by February 1, 1980. The accelerator components will be installed and aligned from the center pellet chamber out to the PFL.

Accelerator Support Systems

Vacuum System

All major components for the vacuum system have been received. The mechanical roughing pumps have been installed and checked out. The diffusion pump backing manifolds and the central high vacuum manifold shown in Figure 175 have been installed, leak-tested, and approved. All fabricated components to be evacuated have been individually leak-tested and approved as subassemblies prior to shipment to Sandia. All ionization and thermocouple gauges and their respective controllers have been received and are being installed. All electrical and plumbing services for the vacuum system have been installed and the control/monitor system has been designed, approved, and installed. Some minor damage to components during shipping and storage, and minor manufacturing errors have been identified and repairs/corrections are being made.

Insulating Gas Systems

The SF_6 gas system for the Marx gap and main trigger switches was installed, checked out, and operated. This system consists of an SF_6 reclaimer shown in

Figure 176 for storage and repurification of the gas in a closed-loop operation. Due to the PVC pipe failure and results of initial tests, the entire system was upgraded by installing copper pipe to optimize the safety and operational requirements. These upgrades are being done in parallel with the old system to minimize the downtime. The synthetic air system for operation of the Marx switch firing system has been installed, verified, and operated. The synthetic air and argon/ SF_6 gas systems for the trigatron trigger units have been designed and are being fabricated.

Deionized Water System

The deionized (D.I.) water system installation is nearing completion. This system consists of four 50,000-gal, fiberglass, storage tanks; 16-in. dia fiberglass main transfer lines with two each 2,000-gpm transfer pumps; 6-in. dia fiberglass and PVC-deionization loop with two each 100-gpm pumps; and a 4-in. dia PVC surface-skimmer system.

During the last week of December 1979, a contract was awarded which provides 200,000 gal of 1-m Ω /cm water, resin bed maintenance for a year, water-borne organisms control, and a skimmer recovery system. Despite earlier problems with quality control of fiberglass pipe and fittings, final acceptance testing is scheduled for late January 1980. The system will deliver D.I. water to the PBFA accelerator when required. It is anticipated that the first fill with D.I. water will be about the middle of March 1980.

PBFA Data Acquisition System

Cable Plant

The fixed cable plant consists of ~75,000 ft of 792 RG-331 coax cables running from floor ports in the accelerator tank to a 6- x 18- x 15-ft splice room in the pit. The cables are routed through the main supporting structure of the accelerator tank as shown in Figure 177. This system has been made rf-tight by the installation of metal covers and RF-I gasketing shown in Figure 178 under the entire tank I-beam support structure. The splice room was made rf-tight by using a combination of continuously welded seams, gasketed—metal cover plates, and a commercial screen room door. Inside the splice room, short flexible jumper cables (RG214) connect the in-accelerator cable plant to the recording facility cables. This cable plant consists of 270 RG-331 cables installed in steel conduit.

Figure 175. Central High Vacuum Manifold From Below.

Figure 176. SF₆ Storage and Repurification System.

Figure 177. Data Acquisition Cable Installation Inside of the Accelerator Supporting Structure.

Figure 178. Underside of Accelerator With rf-Tight Metal Covers Installed.

Jumper cables between the tank ports and diagnostic monitors consist of RG-214 coax cable inside commercial, flexible, solid-convolute shield tubing. Specially designed and commercial fittings mate the tubing to the coax connectors and provide an rf-tight mechanically-sound connection. All 82 jumper cables for MPU of the Marx generator firing system and Marx generator diagnostics have been built and installed.

Data-Recording Equipment

All data-recording equipment is housed in a 15- x 65-ft screen room in the low bay area adjacent to the accelerator. Presently ten Tektronix 485 oscilloscopes and 44 Tektronix 7912AD Transient Digitizers have been installed. Trigger generator and fiducial time-maker systems are operational.

Science Applications, Inc., Las Vegas, provided a special fiducial time-marker generator. The marker pulse width is variable from 2 to 20 ns in 2-ns steps. Special high peak power fixed attenuators have been designed and are working in the system. They consist of 3-W low inductance precision resistors mounted on a 50- Ω printed circuit board in a commercial minibox with type-N connectors.

Initial check-out tests of the IEEE 488 interface between the 7912AD's and the Hewlett-Packard computer indicated that the two devices could communicate successfully. However, when more than seven or eight 7912's are placed on a controller card, the bus hangs up and communication is lost. Tektronix found a few potential problems with their interface; they are currently redesigning it. Additional controller cards have been purchased from Hewlett-Packard to back up the Tektronix redesign.

Software

Extensive software was developed to support the data acquisition system. An automatic data acquisition program is operational for the 7912AD digitizers and the coax signal switches. This program reads an input table of signals to be recorded and their characteristics. It uses the table information to set up and check out all the programmable hardware. It then arms each digitizer for the shot. After the shot, the program reads, calibrates, and stores each waveform on the disc.

An automatic calibration program is also operational. This program switches vertical and horizontal calibration signals to each recorder. It digitizes the signals and computes calibration factors. The calibration data is stored on disc. This data is then used by the automatic data acquisition program to set up digitizers and calibrate signals.

An interactive data-reduction program has also been developed. This program reads operator commands from a graphics terminal and performs requested operations. Commands are available for controlling all system hardware, reading and writing signal arrays to and from disc, performing mathematical operations on signal arrays, and plotting the arrays.

Control/Monitor System

Installation of the Control/Monitor screen room has been completed and the relay racks and operator console have been installed. The EMP filter panel has been installed and ~60% of the EMP filters have been connected.

Installation of junction boxes and Control/Monitor cables throughout the PBFA facility is ~95% complete. This includes junction boxes, solenoids, and pressure switches on the PBFA tank for the transfer switch system and for the SF₆ system. Three relay junction boxes have been installed in the tunnel with relay panels for control of various PBFA subsystems. Installation of power and control wiring in the center part of the PBFA tank for the vacuum system diffusion pumps and vacuum valves is about 80% complete. Control cabinets and relay cabinets for the vacuum system have been procured and set in place in the pit. An electrical contractor is on site to complete electrical hook-up for the vacuum system.

Manual control panels for the oil transfer systems and deionized water transfer system have been redesigned, fabricated, installed, and checked out. The manual controls for the oil transfer system are fully operational. The deionized water system installation is not complete, but the manual controls will be ready when needed.

Control panels for the Marx charging power supply and Marx firing system have been installed in the screen room. These systems are operational and are presently being used for pulsed power tests.

The high voltage interface chassis is being designed and is partly fabricated. This chassis will interface the Marx charging supply, Marx firing system, and the gas switch trigger system to the operator console and to the minicomputers.

The Marx transfer switch control chassis is completed and installed. This subsystem will be fully operational as soon as pressurized hydraulic oil is available.

The trigatron transfer switch control chassis is being redesigned. Junction boxes to house the solenoids and pressure switches are being fabricated.

Cable is already installed for this system and terminations of the cable at the PBFA tank end is underway.

The timing and firing system is presently being designed. This unit will interconnect all of the PBFA subsystems and generate the proper timing signals to fire the accelerator. Definition of the timing and firing unit was done late, awaiting the actual operational testing of the accelerator. The timing and firing unit will allow modifications to accommodate future requirements.

Delay generators have been ordered for the 10-ms delayed trigger system. NIM (Nuclear Instrumentation Module) bins have been received for this system.

A temporary SF₆ control chassis has been installed and is operational. This chassis will be used for the initial pulsed power tests. It will be replaced with a new control chassis after we have accumulated some operating experience with the SF₆ system.

Design of the control chassis for the synthetic air system is progressing. This system design will be finalized when we have some operating experience with the existing manual system and when detailed requirements for the output trigger systems are available.

Design and fabrication of the automatic control chassis for the oil-transfer system and for the deionized water transfer system are complete and checkout is in process. These two chassis will be redesigned to include slow drain and fill sequences. These new sequences were not anticipated originally and are being included to prevent air entrainment in the liquids due to geysering.

Ion gages and thermocouple gages are on hand for the vacuum system. Fabrication of mounting hardware for the gages is about 50% complete. Design of the vacuum control system is in process.

Most of the control chassis in the Control/Monitor screen room will use one of two standard chassis designs: a 7-in.-high chassis and a 10- $\frac{3}{4}$ -in.-high chassis. These standard designs use the same chassis sheet metal work, power supply installation, and microprocessor card file hardware. Five each of these standard chassis have been fabricated and are in stock.

The Control/Monitor minicomputer has been installed and interfaced to the transfer switch chassis and the SF₆ chassis. Minicomputer software to handle the subsystem interface and to input and output accelerator control and status information to the operator has been prepared. Final preparation and checkout of the minicomputer software will proceed when more subsystems are operating.

Microprocessor software for the SF₆ system and transfer switch system is complete. Microprocessor

software for the oil transfer system chassis and the deionized water transfer system chassis has been written, and is presently being debugged. This software will be changed to incorporate the slow fill and drain sequences.

The major subsystem remaining to design is the access control system. The access control system is directly related to the safe operation of the accelerator. Definitions of the access-control and safe operating procedures are presently in process.

PBFA II Project

Overview

A PBFA II program review was held on September 6, 1979 with E. Temple (DOE Controller Office) and T. Godlove (DOE/OIF) in attendance. During the technical review, a statement was made that it was possible to build the originally proposed EBFA II for the \$30M Total Estimated Cost (T.E.C.) and on the originally proposed schedule. The original T.E.C. was established in March 1978 in the EBFA II Conceptual Design Proposal. At that time, EBFA II was assumed, for the purpose of cost estimating, to be a simple two-times upgrade of EBFA I; i.e., 2.0 MV, 2.0 MJ, and 60 TW, employing 1978 pulsed power technology and requiring very little additional engineering design. However, during the last year and half, the Particle Beam Fusion Program has changed its main emphasis from electrons to light ions as the principal ICF driver source. In addition, developments in pulsed power technology have led to reevaluation of the design parameters for EBFA II (and incidentally a name change to PBFA II). The present criteria for PBFA II calls for a more powerful, higher energy accelerator to support the light ion experimental program; i.e., 4 MV, 3.5 MJ, and 100 TW, which has as its goal the demonstration of net energy gain. A

reappraisal of target designs and the degree of conservatism warranted at this time also has forced us to consider methods to deliver the greatest total energy to the pellet. The 3.5-MJ PBFA II design led to a higher cost than was estimated for EBFA II in March 1978. The PBFA I operational period was also extended to three years instead of the two years assumed in the EBFA II Conceptual Design proposal; the extended time increases the cost due to inflation. This additional operating period of PBFA I resulted from a reevaluation of the time required to prepare for the upgrade of PBFA I to PBFA II. A revised T.E.C. is under evaluation.

SuperMITE

The SuperMITE accelerator is being developed for (1) a test bed to develop higher voltage and current components for PBFA II, and (2) demonstration experiment to package four PBFA II lines into two 10° simulated sections of the PBFA tank. The accelerator tank was completed and painted during September 1979. The water-leak test was successfully completed during October. A single 208-kJ Marx generator using 1.3- μ F to 100-kV capacitors has been installed. A shield wall has been installed around an area in front of the water pulse forming section that will contain the power flow line and a simulated pellet chamber for beam extraction and transport experiments. The PBFA data acquisition system cable plant has been extended from the cable splice room in the pit under PBFA to a junction box mounted adjacent to the Supermite shield wall as shown in Figure 179. The sixty RG331 ½-in. foam flex data acquisition cables were installed and verified by the EG&G cable crew from the Nevada Test Site. The control console to charge and fire the Marx generator was installed in parallel with the construction activities. Initial pulse-power testing will start in January 1980 when electrical power and transformer oil are available.

Figure 179. SuperMITE Accelerator.

PRESENTATIONS

"Numerical Simulation of the Effects of an Injected B_z Field on an Imploding Hollow Plasma Liner." *Proceeding of Second International Conference of Megagauss Magnetic Field Generation & Related Topics*. December 1979.

"Simulation of Space-Charge Neutralization of Beams." J. W. Poukey and J. P. Quintenz. *Conference on Particle and Hybrid Codes for Fusion*. Napa, CA. December 10-11, 1979.

"Weak Field High Voltage Foilless Diode Experiments on Hermes II." C. R. McClenahan, J. W. Poukey, and B. G. Epstein. *American Physical Society Plasma Meeting*. Boston, MA. November 12-16, 1979.

"Two-Stage Acceleration of Intense Pulsed Ion Beams." S. Humphries, Jr., C. W. Mendel, and J. W. Poukey. *21st Annual Meeting of the Division of Plasma Physics, American Physical Society*. Boston, MA. November 12-16, 1979.

"Theory of Hollow E-Beams in Guide Fields." B. G. Epstein and J. W. Poukey. *21st Annual Meeting of the Division of Plasma Physics, American Physical Society*. Boston, MA. November 12-16, 1979.

"Simulations of a Self-Magnetically Insulated Ion Diode." J. P. Quintenz and J. P. VanDevender. *21st Annual Meeting of the Division of Plasma Physics of the American Physical Society*. Boston, MA. November 12-16, 1979.

"Self Magnetically Insulated Ion Diode." J. P. VanDevender, D. J. Johnson, R. J. Leeper, P. A. Miller, and D. L. Fehl. *21st APS Meeting*. Boston, MA. November 12-16, 1979.

"Power Flow to a Central Load in Modular, Super-Power Accelerators." D. B. Seidel, J. P. VanDevender, D. H. McDaniel, and D. L. Johnson. *21st APS Meeting*. Boston, MA. November 12-16, 1979.

"Plasma Injected Microsecond Electron Beam Diodes." J. J. Ramirez. *21st APS Meeting*. Boston, MA. November 12-16, 1979.

"The Pellet Injection Problem in a Gas-Filled Particle Beam Reactor." D. L. Cook and M. A. Sweeney. *21st Annual Meeting of the American Physical Society Division of Plasma Physics*. Boston, MA. November 12-16, 1979.

"Particle Beam Transport and Combination for ICF." P. A. Miller, L. P. Mix, and T. P. Wright. *21st Annual Meeting of the Division of Plasma Physics, American Physical Society*. Boston, MA. November 12-16, 1979.

"Optimized Multi-Channel, Multi-Disk Spherical Overlap and Deposition of REBS." T. P. Wright and J. A. Halbleib, Sr. *21st Annual Meeting of the Division of Plasma Physics, American Physical Society*. Boston, MA. November 12-16, 1979.

"Limits on Power Intensification in Magnetically Insulated Vacuum Transmission Lines." M. J. Clauser, B. G. Epstein, J. W. Poukey, and D. H. McDaniel. *21st Annual Meeting of the Division of Plasma Physics, American Physical Society*. Boston, MA. November 12-16, 1979.

"Ion Beam Targets for Near Term ICF Application." A. V. Farnsworth, M. M. Widner, and T. A. Mehlhorn. *21st Annual Meeting of the Division of Plasma Physics, American Physical Society*. Boston, MA. November 12-16, 1979.

"High Temperature, Superfast Z-Pinch." J. P. VanDevender. *21st APS Meeting*. Boston, MA. November 12-16, 1979.

"Gradient-Drift Enhancement of Energy Deposition and Bremsstrahlung Production in Thin Targets by Relativistic Electron Beams." J. A. Halbleib, T. P. Wright, and S. A. Goldstein. *21st Annual Meeting of the Division of Plasma Physics, American Physical Society*. Boston, MA. November 12-16, 1979.

"Fuel Energy Balance Studies of Pellet Ignition Requirements." M. M. Widner. *21st Annual Meeting of the Division of Plasma Physics, American Physical Society*. Boston, MA. November 12-16, 1979.

"Effects of Range Changing on the Efficiency of Ion Driven Hydrodynamic Implosions." T. A. Mehlhorn. *21st Annual Meeting of the Division of Plasma Physics, American Physical Society*. Boston, MA. November 12-16, 1979.

"Current Experimental Results and Development of Magnetically Insulated Ion Diodes." G. W. Mills, D. J. Johnson, and A. V. Farnsworth. *21st Annual Meeting of the Division of Plasma Physics, American Physical Society*. Boston, MA. November 12-16, 1979.

"Blast-Wave Kinetics and Thermal Transport in a Particle-Beam Reactor Chamber." M. A. Sweeney and D. L. Cook. *21st Annual Meeting of the Division of Plasma Physics, American Physical Society*. Boston, MA. November 12-16, 1979.

"An Experimental Study of Thin Aluminum Foil Initiation." R. W. Stinnett and D. H. McDaniel. *21st APS Meeting*. Boston, MA. November 12-16, 1979.

"A High Current Foilless Diode Generator." R. B. Miller and K. R. Prestwich. *21st APS Meeting*. Boston, MA. November 12-16, 1979.

"Self-Magnetically Insulated Electron Flow." J. P. VanDevender. *Nuclear Engineering Dept. Colloquium*. Columbia University, New York, NY. November 11, 1979.

"Particle Beam Fusion." J. P. VanDevender. *Physics Colloquium*. New Mexico State University, Las Cruces, NM. November 8, 1979.

"PBFA Mechanical Design." Society of Manufacturing Engineers, Albuquerque, NM. November 1979.

"PBFA Facilities & Future Programs." 1979 American Nuclear Society Meeting, San Francisco, CA. November 1979.

"Pulsed Power Systems for Inertial Confinement Fusion." J. P. VanDevender. *Energy Research Session of the Nat'l Electronics Conf. '79*. Chicago, IL. October 29-31, 1979.

"PULSELAC Program." S. Humphries, Jr., J. R. Freeman, G. W. Kuswa, C. W. Mendel, J. W. Poukey, and J. P. Quintenz. *Proc. Heavy Ion Fusion Workshop*. Berkeley, CA. October 28-30, 1979.

Presentation to Advanced Laser Concept Technical Review and Program Planning by K. R. Prestwich, Las Vegas, NV. October 18, 1979.

"Light Ion Target Consideration." M. M. Widner. *DOE-LASL/LLL Technical Planning Meeting*. Los Alamos, NM. October 11-12, 1979.

"Sandia Labs Particle Beam Fusion Program." Department of Mechanical Engineering, Energy Seminar - Invited Speaker, University of Kansas. October 1979.

"PBFA Construction Development." DOE-HQ - Controller Office, Construction Management Branch, Germantown, MD. October 1979.

"PBFA Design Engineering." University of New Mexico, School of Engineering, Albuquerque, NM. October 1979.

"Particle Beam Interactions With Plasmas and Their Application to Inertial Fusion." M. J. Clauser, E. J. T. Burns, J. Chang, A. V. Farnsworth, S. A. Goldstein, D. J. Johnson, G. W. Kuswa, T. A. Melhorn, C. W. Mendel, L. P. Mix, J. W. Poukey, J. P. Quintenz, M. A. Sweeney, J. P. VanDevender, and M. M. Widner. *14th International Conference on Phenomena in Ionized Gases*. Grenoble, France. July 9-13, 1979.

"Recent Developments in High Average Power Driver Technology." K. R. Prestwich, M. T. Buttram, and G. J. Rohwein. *3rd Int'l Topical Conf. on High Power Electron and Ion Beams*. Novosibirsk, USSR. July 3-6, 1979.

"Progress Toward Fusion Conditions With Light Ion Beams." G. W. Kuswa, E. J. T. Burns, A. V. Farnsworth, D. L. Fehl, S. Humphries, Jr., D. J. Johnson, R. J. Leeper, C. W. Mendel, P. A. Miller, L. P. Mix, J. W. Poukey, J. P. Quintenz, and T. P. Wright. *3rd International Topical Conference on High Power Electron and Ion Beams*. Novosibirsk, USSR. July 3-6, 1979.

"Electron and Ion Beam Transport to Fusion Targets." J. R. Freeman, J. W. Poukey, T. P. Wright, L. P. Mix, P. A. Miller, J. N. Olsen, and L. Baker. *Third International Topical Conference on High Power Electron and Ion Beam Research and Technology*. Novosibirsk, USSR. July 3-6, 1979.

"Shock Instability of Inertial Fusion Targets." F. C. Perry, L. Baker, D. Ghigla, L. P. Mix, M. A. Sweeney, and A. J. Toepfer. *APS Topical Conference on Shock Waves in Condensed Matter*. Pullman, WA. June 11-13, 1979.

"Ion Beam Energy Deposition in Matter." T. A. Melhorn, 1979 *IEEE International Conference on Plasma Science*. Montreal, Canada. June 4-6, 1979.

"Particle Beam Fusion - PBFA I/PBFA II." *National Tool Machining Association*. Albuquerque, NM. April 1979.

INVENTION DISCLOSURE

Gas Flow Stabilized Magavolt Spark Gap for Repetitive Pulse Application. SD-3868. December 1979.

PUBLICATIONS

"An Intense 3-ns Neutron Source." J. Chang and R. J. Leeper. *Rev. of Sci. Instrum.*, 51 (6), June 1980.

"Propagation of Light Ions in a Plasma Channel." J. N. Olsen, D. J. Johnson, and R. J. Leeper. *Appl. Phys. Lett.*, 36, 808. May 15, 1980.

"A Calorimeter Which is Rugged and Has a Fast Response." W. M. McMurtry and S. R. Dolce. *Proc. 26th Int'l Instrumentation Symposium*. Seattle, WA. May 5-8, 1980.

"Soft X-Ray, Vacuum Ultraviolet Spectroscopy of Thin Targets Heated by Enhanced Electron Energy Deposition." E. J. T. Burns, J. Chang, A. V. Farnsworth, J. P. VanDevender, M. M. Widner, S. A. Goldstein, C. W. Mendel, and J. P. Quintenz. *J. Appl. Phys.* To be published May 1980.

"Overlap of Intense Charged Particle Beams for ICF." J. A. Halbleib, P. A. Miller, L. P. Mix, and T. P. Wright. Submitted to *Nature*. Released March 6, 1980.

"An Applied-B₀ Magnetically Insulated Ion Diode." M. A. Greenspan, R. Pal, D. A. Hammer, R. N. Sudan, and S. Humphries, Jr. *Appl. Phys. Lett.* March 1980.

"An Essential Refinement for Accurate Voltage Monitors" (U). C. W. Mendel. Sandia Internal Memo RS4244/80/2, SRD, (April 1980).

"A Small Tritium Filling and Monitoring Apparatus for Particle Beam ICF Targets." J. Chang, R. J. Leeper, C. Martinez, and W. M. McMurtry. *Rev. Sci. Instrum. (Notes)* 51 (3), 398. March 1980.

Laser Heating of a Molecular Gas Channel, J. N. Olsen and L. Baker. SAND80-0154. Albuquerque: Sandia National Laboratories. February 1980.

"Multi-Photon Ionization of Molecules in Selectively Excited Rovibrational States." P. Esherick and R. J. Anderson. Submitted to *Chemical Physics Letters*. January 1980.

"Plasma-Polymerized Organosilanes as Protective Coatings for Solar Front-Surface Mirrors." K. W. Beig and K. B. Wischmann. Accepted for publication in *Solar Energy Materials*.

Intense Pulsed Ion Beams for Fusion Applications, S. Humphries, Jr. SAND80-0402. Albuquerque: Sandia National Laboratories, 1980; also submitted to *Nuclear Fusion*.

"A Five-Frame, X-Ray Camera for Charged Particle, Inertial Confinement Fusion Studies." D. L. Fehl, J. Chang, G. W. Kuswa, and C. W. Mendel. *Rev. Sci. Instrum.*, 51, 292 (1980).

"Degradation of Elastomers in Geothermal Environments." C. Arnold, Jr., K. W. Bieg, and J. A. Coquat. Accepted for publication in *ASTM Special Technical Journal*.

"Use of Glow Discharge Polymerization to Improve the Environmental Resistance and Lubricity of Elastomers for Use in Deep Sour Gas Wells." C. Arnold, Jr. and K. W. Bieg. *Polymer Preprints*, 21 (1), 97 (1980).

"Production and Postacceleration of Intense Ion Beams in Magnetically Insulated Gaps." S. Humphries, Jr., J. R. Freeman, J. Greenly, G. W. Kuswa, C. W. Mendel, J. W. Poukey, and D. W. Woodall. *J. Appl. Phys.*, 51, 1876 (1980).

"Transport of Ions in Linear Accelerators Utilizing Electron Neutralization." S. Humphries, Jr. and J. W. Poukey. *Particle Accel.*, 10, 107, 1980.

"Production of Annular Electron Beams by Foilless Diodes." R. B. Miller, K. R. Prestwich, J. W. Poukey, and S. L. Shope. *J. of Appl. Phys.*, submitted December 1979.

"High Power Laser Optical Components Meeting." *Proceedings of High Power Laser Optical Components Meeting*. Boulder, CO. November 1979.

Characterization and Properties of Plasma Polymerized 2-Vinylpyridine, K. W. Beig, D. K. Ottesen, and K. L. Brower. SAND79-1798. Albuquerque: Sandia Laboratories. November 1979.

"Pulselac Program." S. Humphries, Jr., J. R. Freeman, G. W. Kuswa, C. W. Mendel, J. W. Poukey, and J. P. Quintenz. *Proc. of Heavy Ion Fusion Workshop*. Berkeley, CA. October 28-30, 1979.

"Operation of a 300 kV, 100 Hz, 300 kW Average Power Pulser." M. T. Buttram and G. J. Rohwein. *IEEE Trans. on Electron Devices*. Vol. ED-26, No. 10. October 1979.

"Relativistic-Electron-Beam/Target Interaction in Plasma Channels." J. A. Halbleib, and T. P. Wright. Submitted to *The Physics of Fluids*. October 12, 1979.

"Theoretical Multiple Beam Overlap From Channel Transport of Intense Particle Beams." T. P. Wright and J. A. Halbleib, Sr. Submitted to *The Physics of Fluids*. October 12, 1979.

Optimization of the Particle Pusher in a Diode Simulation Code. M. M. Theimer and J. P. Quintenz, September 1979, SAND79-1748.

"The Effects of Strong Excitation-Photon Coupling on Mixed Crystal Spectra: Diphenylmethylen in Benzophenone." R. J. Anderson, B. E. Kohler, and J. M. Stevenson. *J. Chem. Phys.*, 71, 1559. August 1979.

Production and Postacceleration of Intense Ion Beams in Magnetically Insulated Gaps. S. Humphries, Jr., J. R. Freeman, J. Greenly, G. W. Kuswa, C. W. Mendel, J. W. Poukey, and D. W. Woodall. August 1979, SAND79-1673.

"Observation of Magnetically Enhanced Electron Beam Deposition." M. M. Widner, S. A. Goldstein, C. W. Mendel, E. J. T. Burns, J. P. Quintenz, and A. V. Farnsworth, Jr. *Phys. Rev. Lett.*, 43, 357, July 30, 1979.

"Soft X-ray Vacuum Ultraviolet Spectroscopy of Ion Beam Heated Thin Targets." E. J. T. Burns, D. J. Johnson, A. V. Farnsworth, Jr., G. W. Kuswa, G. A. Doschek, and U. Feldman. *Appl. Phys. Lett.* 35, 140, July 15, 1979.

"Electron and Ion Beam Transport to Fusion Targets." J. R. Freeman, J. W. Poukey, T. P. Wright, L. P. Mix, P. A. Miller, J. N. Olsen, and L. Baker. *Third International Topical Conference on High Power Electron and Ion Beam Research and Technology*. Novosibirsk, USSR. July 3-6, 1979.

"Progress Toward Fusion With Particle Beams." G. W. Kuswa, K. W. Bieg, E. J. T. Burns, J. T. Chang, M. J. Clauser, A. V. Farnsworth, D. L. Fehl, S. Humphries, Jr., D. J. Johnson, R. J. Leeper, C. W. Mendel, P. A. Miller, L. P. Mix, J. N. Olsen, F. C. Perry, J. W. Poukey, J. P. Quintenz, and T. P. Wright. *Proc. 3rd International Topical Conference on High Power Electron and Ion Beams*. Novosibirsk, USSR. July 3-6, 1979.

"Production and Postacceleration of Intense Ion Beams in Magnetically Insulated Gaps." S. Humphries, Jr., J. R. Freeman, J. Greenly, G. W. Kuswa, C. W. Mendel, J. W. Poukey, and D. W. Woodall. *J. Appl. Phys.* July 3, 1979, and Sandia Rpt. SAND79-1673. August 1979.

"Recent Developments in High Average Power Driver Technology." K. R. Prestwich, M. T. Buttram, and G. J. Rohwein. *3rd Int'l Topical Conf. on High Power Electron and Ion Beams*. Novosibirsk, USSR. July 3-6, 1979.

"A Dual Current Feed Magnetically Insulated Light Ion Diode." D. J. Johnson, A. V. Farnsworth, Jr., D. J. Fehl, R. J. Leeper, and G. W. Kuswa. *J. Appl. Phys.* 50, 4524, July 1979.

"Investigations of the Radial Electron Beam Diode for Gas Laser Excitation." J. J. Ramirez and K. R. Prestwich. *J. of Appl. Physics*, 50, p 4988 (July 1979).

"Determination of Line Voltage in Self-Magnetically Insulated Flows." C. W. Mendel, J. P. VanDevender, and G. W. Kuswa. *Proc. of IEEE 2nd Int'l Pulsed Power Conference*. Lubbock, TX. June 12-14, 1979.

"Particle Beam Interactions with Plasmas and Their Application to Inertial Fusion." M. J. Clauser, E. J. T. Burns, J. Chang, A. V. Farnsworth, S. A. Goldstein, D. J. Johnson, G. W. Kuswa, T. A. Mehlhorn, C. W. Mendel, L. P. Mix, J. W. Poukey, J. P. Quintenz, M. A. Sweeney, J. P. VanDevender, and M. M. Widner. *Journal de Physique*, No. 7, Tome 40, Juillet 1979, p C7-81.

"Two-Photon Absorptivities of the all Trans α , ω Diphenylpolyenes from Stilbene to Diphenyloctatetraene Via Three Wave Mixing." R. J. Anderson, G. R. Holtom, and Wm. M. McClain. *J. Chem. Phys.*, 70, 4310. May 1979.

"Radial Stability of Critical-Surface Density Profiles." G. R. Montry and R. L. Berger. *Nuc. Fusion*, 19-5, 659. May 1979.

"Multiple-Component Materials Test Facilities for Magnetic Fusion Energy: Sandia Laboratories Conceptual Designs." A report to MFE/DOE by F. L. Vook, W. Beezhold, G. J. Lockwood, L. Posey, T. P. Wright, and R. Kerst. January 1979.

"Fuel Preconditioning Studies for E-Beam Fusion Targets." J. N. Olsen, M. M. Widner, J. Chang, and L. Baker. *J. Appl. Phys.* 50, 3224, 1979.

"Light Ion and Electron Beams for Inertial Fusion." P. A. Miller, D. J. Johnson, T. P. Wright, G. W. Kuswa, and G. Yonas. *Comments on Plasma Physics and Controlled Fusion*, 5, 95-103 (1979).

"Observation of Magnetically Enhanced Electron Beam Deposition." M. M. Widner, S. A. Goldstein, C. W. Mendel, E. J. T. Burns, J. P. Quintenz, and A. V. Farnsworth. *Phys. Rev. Lett.* 43, 357, 1979.

"Fourier Transform Infrared Analysis of Plasma Polymerized 2-Vinylpyridine Thin Films." K. W. Beig and D. K. Ottesen. *Plasma Polymerization*. M. Shen and A. T. Bell, eds. American Chemical Society, Washington, DC, 1979.

"Particle Beam Interactions With Plasmas and Their Application to Inertial Fusion." M. J. Clauser, M. A. Sweeney, et al. *Journal De Physique*. Suppl. No. 7, C7-81, 1979.

"Self-Similar Power-Driven Expansion Into Vacuum." A. V. Farnsworth, M. M. Widner, M. J. Clauser, P. J. McDaniel, and K. E. Lonngren. *Phys. Fluids*, 22, 859, 1979.

Particle Beam Fusion Progress Report - October 1977 Through March 1978.

"Breakeven and High Gain Magnetic Targets," A. V. Farnsworth, Jr., p 47.

"Central Igniter Magnetic Targets With Voltage Shaping," M. A. Sweeney and A. V. Farnsworth, Jr., p 48, SAND79-0002.

"Particle Beam Fusion Progress Report, April 1978 Through December 1978." Gerald Yonas. March 1979. SAND79-1011.

"A Preliminary Ion Beam Fusion Target Design." G. O. Allshouse. 1979. SAND79-2275.

"ICF Target Ion Deposition. Scaling Study." S. A. Slutz. 1979. SAND79-2276.

"Fuel Energy Balance Studies of Pellet Ignition Requirements." M. M. Widner. 1979. SAND79-2454.

DISTRIBUTION:

TID 4500 R68 UC 21 (191)

US Department of Energy (2)
Office of Assistant Secretary for
Defense Programs
Mail Station 5F-066
Washington, DC 20545
Attn: Dr. R. Morgan
J. W. Culpepper

US Department of Energy (3)
Office of Military Application
Mail Station A-362
Washington, DC 20545
Attn: Maj. Gen. W. W. Hoover, USAF
Cdr. F. Hughes, USN
P. O. Matthews

US Department of Energy (9)
Office of Inertial Fusion
Mail Station C 101
Washington, DC 20545
Attn: T. F. Godlove
C. B. Hilland
S. L. Kahalas
K. Gilbert
L. E. Killion
R. L. Schriever (?)
T. H. Walsh
S. Barrish

US Department of Energy (2)
Office of Fusion Energy
Mail Station G-234
Washington, DC 20545
Attn: J. F. Decker
E. E. Kinter

US Department of Energy
Office of High Energy and
Nuclear Physics
Mail Station J-309
Washington, DC 20545
Attn: J. E. Leiss

US Department of Energy
Office of Classification
Mail Station A2-3220
Washington, DC 20545
Attn: R. T. Duff

US Department of Energy
San Francisco Operations Office
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Air Force Weapons Laboratory (CC)
Kirtland AFB, NM 87117
Attn: Col. B. L. Francis

Air Force Weapons Laboratory (DYP) (4)
Kirtland AFB, NM 87117
Attn: W. Baker
Maj. H. Dogliani
A. H. Guenther
D. Straw

Air Force Weapons Laboratory
Technical Library
Mail Stop SUL
Kirtland AFB, NM 87117

Argonne National Laboratory
9700 South Cass Avenue
Argonne, IL 60439
Attn: R. I. Martin

Avco-Everett Research Laboratory, Inc.
2385 Revere Beach Parkway
Everett, MA 02149
Attn: R. Dougherty

Ballistic Missile Defense
Advanced Technology Center
P. O. Box 1500
Huntsville, AL 34807
Attn: L. Havard

Ballistic Research Laboratory
Aberdeen Proving Ground, MD 21005
Attn: D. Eccleshall

Battelle Memorial Institute
DOE Library
505 King Avenue
Columbus, OH 43201

Bechtel Corporation
50 Beale St.
San Francisco, CA 94105
Attn: W. O. Allen

Bell Telephone Laboratories
Murray Hill, NJ 07974
Attn: A. M. Clogston

Bell Telephone Laboratories
Holmdel, NJ 07733
Attn: S. J. Buchsbaum

Brookhaven National Laboratory
Upton, L. I., NY 11973
Attn: A. W. Maschke

DISTRIBUTION (Cont):

Bendix Corp.
Southfield, MI 48037
Attn: A. D. VanRennes

California Institute of Technology (2)
Pasadena, CA 91125
Attn: H. W. Liepmann
R. W. Gould

Columbia University
Engineering & Applied Science Dept.
New York, NY 10027
Attn: R. A. Gross

Combustion Engineering, Inc.
1000 Prospect Hill Rd.
Windsor, CT 06095
Attn: M. Clark

Cornell University
Ithaca, NY 14853
Attn: R. N. Sudan

Defense Advanced Research Projects Agency (2)
1400 Wilson Blvd.
Arlington, VA 22209
Attn: J. Mangano
J. Bayless

Defense Nuclear Agency (2)
Washington, DC 20305
Attn: E. Conrad (2)

Desert Research Institute
University of Nevada System
Laboratory of Atmospheric Physics
Sage Building, Stead Campus
Reno, NV 89507
Attn: F. Winterberg

Harry Diamond Laboratories (2)
US Army Electronics Research
and Development Command
Adelphi, MD 20783
Attn: S. E. Graybill
P. A. Caldwell

Electric Power Research Institute (3)
3412 Hillview Avenue
Palo Alto, CA 94304
Attn: N. A. Amherd
K. Billman
F. R. Scott

JAYCOR, Inc. (2)
20550 S. Whiting Street
Suite 500
Alexandria, VA 22304
Attn: D. A. Tidman
J. U. Guillory

KMS Fusion, Inc.
3941 Research Park Dr.
Ann Arbor, MI 48106
Attn: A. J. Glass

Lawrence Berkeley Laboratory (3)
University of California
Berkeley, CA 94720
Attn: D. Keefe
A. M. Sessler
A. Faltens

Lawrence Livermore National Laboratory (9)
University of California
P. O. Box 808
Livermore, CA 94550
Attn: R. J. Briggs
J. L. Emmett (2)
C. D. Henricks
D. J. Meeker
J. H. Nuckolls
R. O. Bangerter
R. E. Kidder
T. K. Fowler

Los Alamos National Laboratory (10)
University of California
P. O. Box 1663
Los Alamos, NM 87544
Attn: D. M. Kerr
H. Dreicer
C. A. Fenstermacher
D. Giovanielli
D. J. Sandstrom
T. F. Stratton
S. Rockwood (2)
T. Keyworth
R. W. Selden

Massachusetts Institute of Technology
Mechanical Engineering
Mudd Building, Room 236
Cambridge, MA 02139
Attn: G. Bekefi

DISTRIBUTION (Cont):

Massachusetts Institute of Technology
167 Albany St.
Bldg. NW16
Cambridge, MA 02139
Attn: R. C. Davidson

Mathematical Sciences Northwest, Inc.
P. O. Box 1887
Bellevue, WA 98009
Attn: P. Rose

Maxwell Laboratories, Inc. (2)
8835 Balboa Avenue
San Diego, CA 92123
Attn: A. C. Kolb (2)

Mission Research Corporation
P. O. Box 1209
La Jolla, CA 92038
Attn: V. A. Vanlint

Mission Research Corporation
P. O. Drawer 719
Santa Barbara, CA 93102
Attn: C. L. Longmire

Mission Research Corp.
1400 San Mateo Blvd. SE
Suite A
Albuquerque, NM 87108
Attn: B. Godfrey

Naval Air Systems Command
Headquarters
Washington, DC 21360
Attn: R. Wasneski

Naval Research Laboratory (5)
4555 Overlook Avenue SW
Washington, DC 20390
Attn: T. P. Coffey
G. Cooperstein
D. Mosher
S. A. Goldstein
S. E. Bodner

Naval Surface Weapons Center
White Oak Code RI
Silver Spring, MD 20910
Attn: R. B. Fiorito

Naval Surface Weapons Center
Dahlgren, VA 22448
Attn: M. F. Rose, Code F102

North Carolina State Univ. at Raleigh
P. O. Box 5342
Raleigh, NC 27607
Attn: Prof. W. O. Doggett
Physics Department

Oak Ridge National Labs.
Oak Ridge, TN 37830
Attn: D. Swain

Occidental Research Corporation
P. O. Box 19601
Irvine, CA 92713
Attn: D. Chang

Pacific Gas & Electric Company (2)
77 Beale Street
San Francisco, CA 94106
Attn: C. P. Ashworth
S. Smith

Physics International (2)
2700 Merced St.
San Leandro, CA 94577
Attn: J. Martinez (2)

Public Service Electric & Gas Company
80 Park Place
Newark, NJ 07101
Attn: R. A. Huse

Pulsar Associates, Inc. (2)
11491 Sorrento Valley Rd.
San Diego, CA 92121
Attn: C. Jones
W. F. Crewson

R&D Associates
P. O. Box 9695
Marina Del Rey, CA 92091
Attn: C. A. McDonald

Rand Corporation
2100 "M" Street
Washington, DC 20037
Attn: S. Kassel

W. J. Schafer & Associates, Inc.
1901 No. Fort Myer Drive
Suite 800
Arlington, VA 22209
Attn: E. T. Gerry

DISTRIBUTION (Cont):

W. J. Schafer & Associates, Inc.
1261 Prospect St.
Suite 9
P. O. Box 800
La Jolla, CA 92038
Attn: M. R. Dowe, Jr.

Science Applications, Inc. (2)
5 Palo Alto Square
Palo Alto, CA 94304
Attn: R. Johnson
J. Siambis

Ian D. Smith, Inc. (3)
3115 Gibbons Drive
Alameda, CA 94501
Attn: I. D. Smith
S. Putnam
P. Spence

Stanford University (3)
P. O. Box 4349
Stanford, CA 94305
Attn: A. E. Siegman
S. E. Harris
A. L. Schawlow

Stanford Linear Accelerator Center (2)
Stanford University
P. O. Box 4349
Stanford, CA 94305
Attn: W. B. Herrmannsfeldt
B. Richter

Texas Tech University
Department of Electrical Engineering
Lubbock, TX 79409
Attn: M. Kristiansen

TRW, Inc. (2)
Advanced Technology Lab.
One Space Park
Redondo Beach, CA 92078
Attn: Z. G. T. Guiragossian, R1/1070
J. Maniscalco

University of Arizona (3)
Tucson, AZ 85721
Attn: M. O. Scully
R. L. Morse
P. Franken

University of California-Irvine
Physics Department
Irvine, CA 92717
Attn: N. Rostoker

University of California-Los Angeles (2)
Physics Department
Los Angeles, CA 90024
Attn: J. Dawson
B. D. Fried

University of California-San Diego
Physics Department
La Jolla, CA 92093
Attn: K. A. Brueckner

University of Illinois (3)
Urbana, IL 61801
Attn: J. Verdeyen
G. H. Miley
B. E. Cherrington

University of Rochester
River Station
Rochester, NY 14627
Attn: M. J. Lubin

University of Texas (2)
Austin, TX 78712
Attn: W. Drummond
M. Rosenbluth

University of Utah
Department of Electrical Engineering
Salt Lake City, UT 84112
Attn: R. W. Grow

University of Wisconsin (2)
Nuclear Engineering Department
Engineering Research Building
1500 Johnson Drive
Madison, WI 53706
Attn: G. Kulcinski
G. Moses

Westinghouse Electric Corporation
Breeder Reactor Division
P. O. Box 355
Pittsburgh, PA 15222
Attn: Z. M. Shapiro

DISTRIBUTION (Cont):

Westinghouse Research Labs.
Churchill Boro
1310 Beutah Rd.
Pittsburgh, PA 15235
Attn: W. P. Kovacik

Office of Director of Defense
Research and Engineering
Room 3E1006
The Pentagon
Washington, DC 20301
Attn: R. Cooper

Directed Energy Technology
(OUSDRE)
Rm. 3D106/
The Pentagon
Washington, DC 20301
Attn: J. R. Airey

Assistant for Director of the
Directed Energy Program
Office of the Deputy Undersecretary
for Research & Advanced Technology
The Pentagon
Washington, DC 20301
Attn: G. Gamota

Rensselaer Polytechnic Institute (3)
Department of Nuclear Engineering
Troy, NY 12181
Attn: R. T. Lahey, Jr.
R. C. Block
D. R. Harris

University of California-Los Angeles
Chemical, Nuclear & Thermal Engineering Dept.
6291 Boelter Hall
Los Angeles, CA 90024
Attn: R. W. Conn

Fusion Power Associates
Science Applications, Inc.
2 Professional Dr.
Suite 248
Gaithersburg, MD 20760
Attn: S. O. Dean

Science Research Laboratory
West Point, NY 10996
Attn: Maj. T. H. Johnson

R&D Associates
1401 Wilson Blvd.
Arlington, VA 22209
Attn: P. Turchi

TRW, Inc.
23555 Euclid Avenue
Cleveland, OH 44117
Attn: J. S. Foster, Jr.

Atomic Weapons Research Establishment (5)
Bldg. H36
Aldermaston, Reading, RG7 4PR
Berkshire, ENGLAND
Attn: J. C. Martin
J. W. Weale
D. Dracot
D. Foster
M. Goodman

Culham Laboratory (2)
UKAEA Research Group
Abingdon Oxfordshire OX 14 3DB
ENGLAND
Attn: Ms. M. King
R. S. Pease

Imperial College of Science & Technology
London, ENGLAND
Attn: S. A. Ramsden

Centre D'Etudes de Valduc
Commissariat a L'Energie Atomique
B.P. 14-21/IS-Sur Tille
FRANCE
Attn: C. Patou

Laboratoire de Physique
des Milieux Ionises
Ecole Polytechnique
91120 Palaiseau, FRANCE
Attn: H. J. Doucet

Commissariat a L'Energie Atomique
Centre D'Etudes De Limeil
Boite Postale 27
94190 Villeneuve St. Georges
FRANCE
Attn: J. P. Watteau

Commissariat a L'Energie
B.P. No. 6, 92260
Fontaney Aux Roses, FRANCE
Attn: F. Bottiglioni

Institut de Physique Nucleaire (2)
B.P. No. 1
91406 Orsay Cedex
FRANCE
Attn: H. Flocard
J. Peter

DISTRIBUTION (Cont):

The Weizmann Institute of Science (3)
Rehovot, ISRAEL
Attn: E. Blaugrund
E. Nardi
Z. Zinamon

Institute of Laser Engineering (2)
Osaka University
Yamada-Kami, Suita
Osaka, 565, JAPAN
Attn: S. Nakai
C. Yamanaka

Kernforschungszentrum Karlsruhe GmbH
Institut für Technische Physik
Postfach 3640
7500 Karlsruhe 1
WEST GERMANY
Attn: Prof. Dr. W. Heinz

Max-Planck-Institut für Plasmaphysik
8046 Garching Bei München
WEST GERMANY
Attn: Ruth Lengyel, Bibliothek

Kernforschungszentrum Karlsruhe GmbH
Institut für Neutronenphysik
und Reaktortechnik
Postfach 3640
7500 Karlsruhe 1
WEST GERMANY
Attn: G. Kessler
H. U. Karow

Institute of Plasma Physics
Nagoya University
Nagoya, JAPAN
Attn: M. Masuzaki

Science Research Council
Rutherford Laboratory,
Chilton, Didcot
Oxfordshire OX110QX
ENGLAND
Attn: J. D. Lawson

Plasma Physics Section
Government of India
Trombay
Trombay 400 085
INDIA
Attn: A. S. Paithankar

Physical Research Lab
Navrangpura
Ahmedabad 380 009
INDIA
Attn: Surjalal Sharma, 471

1 M. Sparks
400 C. Winter
1000 G. A. Fowler
2000 E. D. Reed
3145 R. B. Craner
3312 T. N. Simmons
3600 R. W. Hunnicutt
4000 A. Narath
4200 G. Yonas (15)
4201 G. W. Barr
4210 J. B. Gerardo
4211 E. J. McGuire
4212 R. A. Gerber
4214 E. D. Jones
4216 A. W. Johnson
4218 J. K. Rice
4220 M. Cowan
4230 J. E. Powell
4231 T. P. Wright
4232 W. Beezhold
4233 G. A. Zawadzka
4234 D. H. McDaniel
4240 G. W. Kuswa (15)
4241 J. R. Freeman
4242 L. P. Mix
4243 J. Chang
4244 P. A. Miller
4247 M. M. Widner
4250 T. H. Martin (15)
4251 T. H. Martin (Actg)
4252 J. P. VanDevender
4253 K. R. Prestwich
4254 S. A. Goldstein
5000 J. K. Galt
8000 T. B. Cook, Jr.
8214 M. A. Pound
3141 L. J. Erickson (5)
3151 W. L. Garner (3)
for DOE/TIC (Unlimited Release)

[illegible]

* Recipient must initial on classified documents.