224
1-22-80

SAND79-1011
Unlimited Release

LD. 548

MASTER

Particle Beam Fusion Progress Report April 1978 Through December 1978

Directorate of Pulsed Energy Programs

Sandia Laboratories
energy report

SAND79-1011
Unlimited Release

Distribution
Category UC-21

PARTICLE BEAM FUSION PROGRESS REPORT
APRIL 1978 THROUGH DECEMBER 1978

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

CONTENTS

	<u>Page</u>
INTRODUCTION	
TECHNICAL OVERVIEW (G. Yonas)	9
MANAGEMENT OVERVIEW (G. Yonas)	12
CHAPTER 1 FUSION TARGET STUDIES	
OVERVIEW	15
Calculation of Exploding Pusher Magnetic Targets (A. V. Farnsworth, Jr.)	15
Magnetohydrodynamic Behavior of Thermonuclear Fuel in a Preconditioned Electron Beam Target (M. M. Widner, I. R. Lindemuth)	17
Calculation Model for Radiant Energy Loss from a Hydrogen Plasma (L. Baker)	20
Low Power, High Gain Targets Employing Magnetic Thermoinsulation (M. A. Sweeney, A. V. Farnsworth, Jr.)	21
Beam-Target Coupling in an Expanding Thick-Shell Target (M. A. Sweeney)	22
Computational Methods to Study Beam-Fusion Ion Targets (T. A. Mehlhorn)	25
Line Radiation Diagnostic Code (L. Baker)	31
Melt and Yield Strength Determination for Brass and Ni/CH ₂ /Au Cylinders (M. A. Sweeney and F. C. Perry)	31
REFERENCES	32
CHAPTER 2 TARGET EXPERIMENTS	
OVERVIEW	35
Stability of Targets at High Dynamic Pressure for Inertial Confinement Fusion (F. C. Perry)	36
Enhanced Deposition of Electron Beam Energy in Thin Targets (E. J. T. Burns)	38
Soft X-ray and Vacuum Ultraviolet Spectroscopy of Ion Beam Heated Thin Targets (E. J. T. Burns)	42
Neutron, Time-of-Flight Spectrometer Development	46
Small Volume Tritium Filling Apparatus for DT Targets (J. T. Chang)	51
Power Deposition Experiment on Proto I Convolute (J. T. Chang)	52
Magnetic Targets: Preconditioning Test of $\phi 1$ and $\phi 11$ Targets (J. N. Olsen, J. T. Chang)	53
REFERENCES	57

CONTENTS (cont)

	<u>Page</u>
CHAPTER 3	
PARTICLE BEAM SOURCE DEVELOPMENT	
OVERVIEW.....	59
STANDOFF AND BEAM PROPAGATION.....	59
Electron Beam Propagation in Plasma Channels (J. R. Freeman, J. W. Poukey).....	59
MHD Studies of Plasma Channels (L. Baker, J. R. Freeman).....	62
Multichannel Particle Beam Transport (T. P. Wright).....	65
Analytic Ion Self-Pinch Formulas (T. P. Wright).....	68
Plasma Channel Thin-Foil Enhanced Electron Deposition (J. A. Malbleib, T. P. Wright).....	69
Current Density Enhancement Using a Converging Plasma Channel (J. W. Poukey, M. M. Widner).....	70
Inverse Diode Calculations (J. W. Poukey).....	70
PULSE POWER.....	71
Theory of Magnetically Insulated Flow (C. W. Mendel).....	71
Analysis of a Slipping Stream Instability for Magnetically Insulated Electron Flow (K. D. Bergeron).....	72
Beam Stability and Loss Mechanisms in Magnetic Insulation (K. D. Bergeron, J. W. Poukey).....	73
DIODE PHYSICS.....	75
Code Development (J. P. Quintenz, M. M. Widner).....	75
Proto I Enhanced Deposition Simulations (J. P. Quintenz, M. M. Widner).....	77
C-Diode Simulations (J. P. Quintenz, M. M. Widner).....	77
Ion Diode Studies (J. P. Quintenz, J. W. Poukey, D. J. Johnson).....	78
ACCELERATOR PHYSICS.....	79
Two-Dimensional Studies of Ion Beam Neutralization (J. W. Poukey, S. Humphries, Jr.).....	79
REFERENCES.....	82
CHAPTER 4	
PARTICLE BEAM EXPERIMENTS	
OVERVIEW.....	85
Five-Frame X-ray Camera Development (D. L. Fehl, P. A. Miller).....	85
Optimization of Electron Beam Pinching from Small R/d Cathodes for Thin Foil Enhanced Deposition Experiments on the Proto I Accelerator (S. A. Goldstein, M. M. Widner, E. J. T. Burns, J. P. Quintenz).....	90
Pulselac (S. Humphries).....	94
A Dual Current Feed Magnetically Insulated Light Ion Diode (D. J. Johnson, A. V. Farnsworth, Jr., D. L. Fehl, R. J. Leeper, C. W. Kuswa).....	99
Multiple Electron Beam Propagation Experiment on Proto I (P. A. Miller, L. P. Mix).....	108
REFERENCES.....	110

CONTENTS (cont)

	<u>Page</u>
CHAPTER 5	
PULSED POWER RESEARCH AND DEVELOPMENT	
OVERVIEW.....	113
POWER FLOW - MITE SELF MAGNETICALLY INSULATED LINE EXPERIMENTS.....	114
Power Flow Studies in Long Self-Magnetically Insulated Transmission Line (J. P. VanDevender, E. L. Neau, K. L. Brower).....	114
Load Line for a Self-Magnetically Insulated Line (J. P. VanDevender).....	115
Tapered Diode Feed and Diode Study (J. P. VanDevender).....	116
Vacuum Insulator Flashover Research (D. H. McDaniel).....	117
PULSED POWER RESEARCH IN SWITCHING.....	117
Water Dielectric Switching with Prepulse Suppression on Proto II (T. H. Martin)....	117
BFA I.....	118
Positive Polarity Option for EBFA I (J. P. VanDevender, D. L. Johnson).....	118
EBFA Monitor Development (E. L. Neau).....	118
BFA II.....	119
Supermite (D. L. Johnson).....	119
Supermite Marx Generator (D. L. Johnson).....	119
REFERENCES.....	120
CHAPTER 6	
PULSED POWER APPLICATIONS	
EP RATE PULSE POWER.....	121
Overview (K. R. Prestwich).....	121
Three Megavolt Transformer Development (G. J. Rohwein).....	121
Transformer Winding Tests (G. J. Rohwein).....	122
Switch Development (G. J. Rohwein).....	123
Repetitively Pulsed Marx Generator (M. T. Buttram, R. S. Clark).....	125
Repetitively Pulsed Diode (M. T. Buttram).....	127
Online Diagnostics for Repetitively Pulsed Diode Development (M. T. Buttram).....	129
REACTOR SYSTEM STUDIES.....	131
Overview (D. L. Cook, K. R. Prestwich).....	131
Design of a Gas-Filled Particle-Beam Reactor Chamber (M. A. Sweeney, D. L. Cook)...	131
First Wall Chemistry (D. L. Cook, K. Douglas).....	135
Hybrid Reactor Design Study (D. L. Cook).....	135
Synthetic Fuel Production (D. L. Cook).....	136

CONTENTS (cont)

	<u>Page</u>
ELECTRON BEAM SOURCES FOR GAS LASERS.....	137
Overview (K. R. Prestwich).....	137
Blade Field Emitters (J. J. Ramirez).....	138
Carbon Fiber-Brush Cathode Tests (J. J. Ramirez).....	139
Plasma Instability in Needle Cathode Diodes (M. T. Buttram).....	141
Plasma Injected, Microsecond Electron Beam Diodes (J. J. Ramirez, D. L. Cook).....	142
Terawatt Electron Beam for Gas Laser Excitation (J. J. Ramirez).....	145
Emission Suppression (R. S. Clark).....	147
REFERENCES.....	152
CHAPTER 7	
ELECTRON BEAM FUSION ACCELERATOR PROJECT	
EBFF.....	155
Overview (G. W. Barr).....	155
EBFA SUPPORTING SYSTEMS	155
Transformer Oil Transfer and Storage System (M. F. Aker).....	155
Deionized Water System (M. F. Aker).....	155
Insulating Gas Systems (M. F. Aker).....	155
EBFA Data Acquisition System (W. B. Boyer).....	155
Control/Monitor System (J. L. Harrison, EG&G).....	159
EBFA I.....	160
Overview (G. W. Barr).....	160
EBFA Tank Structure (M. F. Aker).....	161
Marx Generator (M. F. Aker).....	163
Charging System (R. A. White).....	163
Marx Generator Trigger System (R. A. White).....	163
Intermediate Stores (M. F. Aker).....	163
Trigatron Switches (M. F. Aker).....	165
Trigatron Trigger System (R. A. White).....	165
Isolation Inductors (R. A. White).....	165
Pulse Transfer Switches (R. A. White).....	165
Pulse Forming and Pulse Transforming Lines (M. F. Aker).....	166
Power Flow (M. F. Aker).....	166
Front End (M. F. Aker).....	166
Vacuum System (M. F. Aker, G. E. Staller).....	166
EBFA I (Summary) (R. A. White).....	166
EBFA II (G. W. Barr).....	167
PUBLICATIONS.....	169
PRESENTATIONS.....	171

INTRODUCTION

TECHNICAL OVERVIEW

During this period substantial improvements in the theoretical basis for particle beam fusion as well as the execution of critical experiments were instrumental in further definition of the optimum route to our goals of demonstrating scientific and practical feasibility. The major emphasis in the program continues to be focused primarily on issues of power concentration and energy deposition of intense particle beams in solid targets. This utilization of program resources is directed toward conducting significant target implosion and thermonuclear burn experiments using EBFA-I (1 MJ) in the 1981-1983 time period. This step, using EBFA-I, will then set the stage for net energy gain experiments to follow on EBFA-II (> 2 MJ) after 1985. Current program emphasis and activities differ substantially from those stressed in the laser approaches to inertial confinement fusion. Here the critical issues relate to delivering the needed power densities and energies to appropriate targets and to insure that the coupling of energy is efficient and matches target requirements.

Two important milestones were passed in our electron beam effort. The first achievement demonstrated focusing of e-beams at power densities of $\sim 3 \times 10^{13}$ W/cm² onto thin foil targets and confirmed our long standing predictions of magnetically enhanced electron deposition. This work also substantiated the Soviet results of deposition enhancement in thin foils which were reported for the first time in 1976. Our particle in-cell diode code simulations of beam focusing in high current diodes were combined with a collisional Monte Carlo electron deposition treatment to provide an in-depth understanding of this phenomenon. The thin foil temperature was diagnosed with arrays of x-ray diodes and soft x-ray spectroscopy with the data interpreted in terms of deposited power density using a sophisticated hydro code. Specific deposition enhancement factors of 3 to 5 for flat foils and > 10 for foils extended on a fine wire into the cathode were observed. Confirmation of our theoretical models gives us greater confidence in extrapolating to higher current levels. Further upgrading of Proto I resulted in current

densities of $\sim 20 \times 10^6$ A/cm² and additional target studies at these levels are planned.

The second electron beam achievement demonstrated the transport and overlap of multiple electron beams. Proto II was operated in a six-beam configuration to show for the first time that efficient injection transport, and overlap could be accomplished. Energy was transported from six diodes located at a radius of 46 cm onto a 1 cm radius central target with 90 percent efficiency. Multiple plasma channels formed using wire initiated high current discharges guided these beams to the target. An improved radiation treatment was added to our 1-D MHD code to study both channel formation and beam heating effects on channel dynamics and our beam overlap model was improved to include collisional effects at the target. The experimental results thus far agree with the single particle calculational approach and predict an upper limit of roughly a factor of three in electron power densification due to overlap. Further experiments with up to 12 beams and combination at smaller radii will test this model.

Predictions from beam overlap models using lower divergence angle ion beams indicate overlap factors as high as ten. When one takes these theoretical predictions together with estimates of a further factor of five increase in beam concentration through space time compression (beam bunching) we predict roughly an order of magnitude higher power density on target for ions than for electrons under conditions of long beam transport as needed for reactor applications.

When one compares the stringent requirements for magnetically enhanced electron deposition with the straightforward single particle nature of ion deposition (at least as we now perceive it) and we consider in addition the greater potential for ion beam power concentration using plasma channels, there is a strong motivation to demonstrate the needed ion beam current density and divergence requirements. Ion beam focusing is being investigated using two light ion diode approaches in collaboration with the Naval Research Laboratory and Cornell University. Using both approaches, remarkable progress has been made over the last few years in both ion diode efficiency and beam focusing. During this reporting period, studies using

our 2-D electron-ion code which solves for particle motion in self-consistent electric and magnetic fields, continued. Ion diode efficiency (~ 75 percent) and impedance levels were predicted and agree with experiment. Questions of effects of self-magnetic fields on beam focusing (in diodes with external field coils, current neutralization is incomplete) are being studied and compared with experiment. In addition to self-field deflection of ions, the intrinsic beam divergence due to anode plasma nonuniformity is being investigated and improvement has already been shown. Divergence angles of $\sim 2^\circ$ have been demonstrated for the first time and we are developing a more complete understanding of electron flow symmetry and stability requirements to minimize energy loss via electron flow.

Although target implosion experiments have not as yet reached a high level of significance in our program, it is clear that target issues must be integrated into program planning, diagnostic development, and target fabrication as the beam sources evolve. The program rationale being followed is to find an overlap between realistically projected source characteristics and target requirements. Thus, appropriate targets should benefit from the energy intensiveness of particle beams and be less dependent on high power densities or precise power pulse shaping as needed for achieving ultra high fuel compression. Our present strategy is to use high mass targets which implode at relatively low velocities but still reach ignition conditions. This has resulted in considerable emphasis on magnetically insulated targets over the last years.

These targets attracted interest at our lab as well as at the Lawrence Livermore Laboratory because they offer the prospect of reduced driver output power requirements with no loss in pellet gain if a (hot, low density) central region can be used to ignite adjacent dense cold material. The basic physical principle to be employed in such a target is the use of a magnetic field embedded in preheated fuel to inhibit electron thermal conduction energy loss to the imploding shell. In 1977, we reported thermonuclear neutron production with such a target using a relatively low power driver. Work since then has emphasized the detailed characterization of the preheat condition, development of precisely controlled fuel preconditioning methods, and the theoretical investigation of target scaling and multidimensional effects.

Target development and preconditioning methods are being studied with Schlieren imaging as well as streak and frame photography. Target fabrication for this effort is being carried out primarily at LASL with emphasis on compatibility with a compact, high current pre-discharge technique.

Clearly, such targets behave in a complex multidimensional manner and 2-D MHD simulations are being carried out. The ANIMAL code was used originally in collaboration with LLL and is continuing in collaboration with LASL. Such analysis predicts that vortices or eddies are formed during the implosion but the 2-D simulation of experimental conditions predict plasma conditions and neutron production in agreement with previous experiments. This analysis is being applied to conditions of higher implosion velocity to determine the relative importance of convection and electron heat conduction on fuel energy loss.

Both electron and ion approaches for EBFA rely on the use of magnetically insulated transmission lines (MITL) to transfer power from the low power density water vacuum interfaces to the diodes themselves. Our demonstration of efficient energy transport with long transmission lines together with development of methods to minimize losses in transition sections (as reported previously) are being extended to provide a test of the ultimate power concentration capabilities using the MITL technique. Theoretical models to describe the apparent instability launched from overly abrupt transitions are being developed and tested experimentally to provide a more complete understanding of the limits of applicability of this fundamental power concentration building block.

The construction of EBFA continued in the newly completed facility (Fig. 1) with the assembly of the Marx generators and the tank proceeding on schedule (Fig. 2). The schedule date for EBFA to become operational is July 1980.

Our efforts to concurrently develop the technology base needed for reliable high average power operation as demanded by reactor applications continued with important advances. Our resonant transformer demonstrator reached 3 MV with a 92 percent transfer efficiency and we began diode lifetime and conditioning investigations at current densities of several KA/cm^2 . These data are providing our first demonstrations that cold cathode

Fig. 1. Electron Beam Fusion Facility.

Fig. 2. Electron Beam Fusion Accelerator (EBFA) I.

	<u>75</u>	<u>76</u>	<u>77</u>	<u>78</u>	<u>79</u>
Operating (M\$)	3.7	4.8	6.5	8.7	9.2
Assigned Sandia Personnel	44	46	63	68	72
Construction (M\$)	0.3 ⁺	0.4 ⁺	9.1	4.4	1.0*

*P.E. & D
CP&D

Fig. 3. Sandia Particle Beam Fusion Program Resources.

diodes can satisfy our long term needs for reliable operation over extended periods. The gas-filled reactor approach continues to look favorable with chamber sizes determined by repetitive tensile loads in the first wall. Our preliminary theoretical investigation of the use of the resulting high temperature chamber gas for synthetic fuel production indicates this to be a valuable direction for further investigation with a primary question being tritium contamination of the synthetic fuel.

MANAGEMENT OVERVIEW

The historical program growth pattern is shown in Fig. 3. This growth has necessitated program reorganization with additional division level groups in target design,

operations, and beam experiments and the splitting of the program into two departments under Glenn Kuswa and Thomas Martin. The new organizational structure is shown in Fig. 4.

With the completion and occupation of EBFF the total program floor space has now grown to 74,800 ft² and our theoretical and experimental activities are now housed in close proximity to one another for the first time.

ORGANIZATION OF SANDIA PARTICLE BEAM FUSION PROGRAM

*Has accepted job offer but not on role.

Fig. 4.

CHAPTER 1 FUSION TARGET STUDIES

OVERVIEW

The target interaction theory group has studied particle beam target design, beam deposition physics, and reactor related calculations. Much of the near term experimental support and reactor calculations are included in separate sections of this report. The material reported here is primarily related to target design, and, in particular, to targets employing magnetic thermoinsulation.

The first section reports exploding pusher calculations with magnetic thermoinsulation for near term experiments designed to produce thermonuclear neutrons. Various target sizes with several fill densities are considered for the pulse and deposition characteristics of both Proto I and Hydra. These results indicate that the neutron yield should be somewhat higher for Proto I than for Hydra.

Next, calculations using the two-dimensional MHD code ANIMAL are shown for previously reported exploding pusher target experiments. The evolution during the preconditioning phase is in qualitative agreement with previously reported BEMAG calculations. During the implosion phase, the plasma wall interaction is seen to be important as is circulating eddy formation. In spite of these problems there was some degree of magnetic thermoinsulation and the calculated neutron yield $\sim 10^6$ was in agreement with previously reported experimental results.

A simple radiation energy loss model is discussed next, which is similar to the model used in the ANIMAL code and was developed for use with several Sandia codes. This type of model is particularly important for preconditioned targets in which the fuel density is spatially nonuniform.

A series of high gain (gain ~ 30) target calculations were done for electron and ion beam driven targets which employ a magnetically insulated central igniter. The fuel magnetization is assumed to be large enough to localize the alpha particle deposition in the central igniter.

The required beam powers are found to be 25 TW for proton targets and 90 TW for electron targets with beam intensity requirements $\leq 10^{14}$ W/cm².

The effect of target expansion on beam deposition is also being studied. It was found that large target blowoff extent can lead to reduced coupling to the target interior and to an increase in required beam power. There are also several potential advantages discussed such as reduced intensity requirements.

The next section deals with ion beam transport and a number of applications. The PCLLY code was upgraded to a two-temperature model with an ion beam deposition package for D⁺ ions. This permitted study of a wet wood burner concept which was found to require excessive beam current densities. Applications of beam target fusion neutron sources such as material studies, deposition studies, and fissile fuel production are also discussed. Work on the more general problem of ion beam transport, for arbitrary beam ions and arbitrary target material and state, is also beginning.

The last sections are related to interpretation of experimental results. First, a line radiation transport model is described to be used for interpreting experimental spectroscopy data. Second, calculations were done to infer material properties for cylindrical implosion experiments.

Calculation of Exploding Pusher Magnetic Targets

Recent work on the absorption of e-beam energy in thin targets, discussed elsewhere in this semiannual report, suggests the possibility of absorbing energy into an exploding shell magnetic target considerably more efficiently than has been possible previously, using either Hydra or Proto I. Since these two machines have comparable available energy but very different pulse characteristics, calculations have been

performed to determine which machine is preferable for maximizing neutron yields for the next set of experiments.

The targets considered are paralene shells of wall thickness .23 mm (9 mils), and inside diameters 1.59 mm, 2.38 mm, 3.175 mm, 4.76 mm, and 6.35 mm (1/16, 3/32, 1/8, 3/16, 1/4 inches). The fuel preheat temperature has been taken to be 15 eV for all targets considered, which is in reasonable agreement with the BEMAG calculations¹ and with preconditioning experiments.² Initial (preheated) density was varied from 3×10^{-6} g/cm³ to 10^{-4} g/cm³ to determine the optimum preconditionings. The initial density has been found to be a critical parameter by varying the initial fill pressure, the preconditioning current pulse, and electrode geometry. For this set of calculations, the preheat temperature was not varied, in part to reduce the number of computer runs, but also because the range of expected preheat temperatures is not so broad as is the range of preheated densities (factors of ~ 2 compared with factors of ~ 30).

The absorbed power for Proto I and Hydra were as follows: Hydra: 15 kJ absorbed, 75 ns FWHM, 15 ns risetime; Proto I: 15 kJ absorbed, 30 ns FWHM, 5 ns risetime. Not too surprisingly, the neutron yield obtained tends to favor Proto I (by $\sim$ factor of 5 in maximum neutron yield) as the accompanying yield curves (Figs. 1-2) indicate. The higher power of Proto I produces higher yields even though the total energy deposited is the same. Clearly, it is more advantageous to have the energy deposited early in time when the shell density is higher than to have energy being continuously deposited throughout the implosion. This effect is less important for larger radius targets for which the implosion time is much longer than the power pulse of either machine (250 ns for the k^0 target). It is noteworthy that the scaling with power seen here at constant total energy is much less than the $\sim$ cubic dependence that we reported at the San Diego ICF meeting³ where absorbed energy was allowed to increase with power.

From both the Proto I and Hydra neutron yield curves, we see that the curves at lower initial density are broader and

Fig. 1. Neutron yield vs. target diameter for the Proto I accelerator for several fuel fill densities.

Fig. 2. Neutron yield vs. target diameter for the Hydra accelerator for several fuel fill densities.

peaked further to the right than are the higher density curves. Lower density implies a lower radiative loss from the fuel, and therefore, a greater tolerance for the slow implosion velocity of the more massive shells. It may be desirable to operate experimentally in a lower density regime than that giving the highest yield seen here to insure radiative losses are not significant. We have also seen previously that the self-consistent yield vs. density curve has an abrupt drop with increasing density⁴ due to Ωt considerations.

These results were obtained using a hydrocode with a "fix" applied to the code that allows thermal conductivity to be reduced in the fuel without reducing it in the shell. Using another hydrocode without the fix gives somewhat higher yields ($\sim 3 \times 10^8$ neutrons for the 1/8" target on Proto I with fuel preconditions of $\rho_0 = 3 \times 10^{-5}$ g/cm³ and $T_0 = 15$ eV).

The results of these calculations suggest that the Proto I machine should be used in the next series of magnetic target experiments.

Magnetohydrodynamic Behavior of Thermo-nuclear Fuel in a Preconditioned Electron Beam Target

Two-dimensional magnetohydrodynamic numerical calculations have been performed to study the fuel behavior of a preconditioned relativistic electron beam target in which, experimentally, a portion of the beam current prepulse entered the target to provide fuel preheat and magnetothermoinsulation. The experimental conditions correspond to those previously reported by Chang, et al.^{4,5} for exploding shell targets irradiated on the REHYD accelerator (1 MeV, 250 kA, 100 nsec) for which $\sim 10^8$ neutrons were measured. The magnetohydrodynamic plasma model used includes radiation, thermal conduction, ionization, and resistive diffusion. The partial differential equations are solved by the ANIMAL⁶ computer code employing implicit finite-difference methods. Although the fuel is shown to develop counterstreaming vortices during the implosion phase, the computed neutron yield is in reasonable agreement with the experimental value, suggesting

the origin of the neutrons to be thermonuclear. The effect of both magnetothermoinsulation and preheat is examined.

For our computations of the plasma behavior, we use a magnetohydrodynamic model based on local thermodynamic equilibrium which is discussed in Ref. 6. In addition, we consider the magnetic field to consist of two components: $\vec{B}_p$, the field due to plasma currents, and $\vec{B}_b$, the field due to beam currents. The total field is the sum of the two components, i.e.,

$$\vec{B} = \vec{B}_p + \vec{B}_b$$

From Ampere's law with the usual neglect of displacement current we find that

$$\mu_0 \vec{J} = \nabla \times \vec{B}_b$$

and

$$\vec{B}_b = \frac{\mu_0 I(t)}{2\pi r} [1 - \exp(-r^2/r_b^2)] \vec{e}_\phi$$

which corresponds to a beam current I having a Gaussian pulse width r_b . During the prepulse, $\vec{B}_b = 0$.

During the prepulse, much of the gas is in general only partially ionized. Therefore, line radiation, both bound-bound and free-bound, becomes stronger than ordinary bremsstrahlung or free-free radiation. The enhanced radiation due to line emission is an important energy loss mechanism. Using the work of Griem,⁷ the radiative loss rate $\dot{\epsilon}_{\text{RAD}}$ is

$$\dot{\epsilon}_{\text{RAD}} = C_2 G(\rho, T) \rho^2 T^{1/2}$$

where C_2 is a constant and $G(\rho, T)$ is a density and temperature-dependent "total emission factor" which includes contributions from bremsstrahlung, bound-bound, and free-bound radiation. When $G(\rho, T)$ is equal to unity, $\dot{\epsilon}_{\text{RAD}}$ becomes the bremsstrahlung rate of Spitzer.⁸ In lieu of a more complete treatment of radiation, we ignore the contribution of Lyman- α radiation to $G(\rho, T)$.

This completes the discussion of the physical model and we are now ready to

define the particular problem of interest.

ANIMAL's representation of the fuel volume is depicted in Fig. 3. Throughout the computations, the volume remains spherical. The finite difference methods of ANIMAL are applied to the differential equations written in the spherical coordinate system, and a rectangular, orthogonal finite difference mesh in $r-\theta$ space has the quarter-circle mesh in real space shown in Fig. 3. During the prepulse, the end caps are treated as electrical conductors and the remainder of the pusher/fuel interface is treated as an ideal electrical conductor and the finite difference mesh contracts radially while retaining its sphericity and orthogonality. In the calculations reported here, non-uniform radial zoning is used to represent the boundary layers at the hot fuel/cold ($T=0$) pusher interface.

The initial condition prior to preconditioning for the computations reported here is a uniform plasma having a deuteron number density of $6 \times 10^{18}/\text{cm}^3$ and a temperature of 1 eV. The initial density corresponds to a room-temperature fill pressure of 100 Torr, and the temperature implies 2.5% ionization according to ANIMAL's equation-of-state. The initial radius is 1.5 mm and the end caps subtend a 15° half-angle. The prepulse current which provides the insulating boundary magnetic field boundary condition is a ramp function rising linearly to 12 kA in 1 μsec . The prepulse current and the initial conditions completely formulate the prepulse computations.

After 1 μsec , the outer radius is changed to an electrical conductor, and the finite difference mesh begins to contract. The pusher accelerates to 4 cm/ μsec in 0.008 μsec , after which the pusher velocity remains constant until the calculations are terminated. The main beam current which determines B_θ is a ramp function which rises linearly to 200 kA in 0.02 μsec and the pulse width τ_p is 0.18 μsec . The plasma configuration at the end of the prepulse, the pusher velocity, and the main beam current completely formulate the implosion computations.

During the prepulse, electrical current can enter the plasma fuel only through

Fig. 3. Finite difference mesh used to calculate the fuel behavior during: (a) prepulse, (b) implosion.

the end caps. Consequently, the current density is high at the end caps and decreases toward the midplane. There is thus strong localized ohmic heating and the temperature and pressure of the plasma at the end caps increases. The magnetic pinching force is smaller than the resultant pressure gradient, so the hot end cap plasma expands into the colder fuel, compressing it.

The plasma configuration at the end of the prepulse at 1 μsec is shown in Fig. 4a, where the first solid contour represents a value of $1.1 \times 10^{19}/\text{cm}^3$ and the contour increment is approximately $2.0 \times 10^{18}/\text{cm}^3$. One-half of the fuel mass is enclosed within the solid contour. Thus, at the start of the implosion, over one-half of the mass is over twofold compressed and is located in a double (only one-half is shown in the figures) toroidal dense core at the midplane or in the cold dense layer along the pusher. Fig. 4a also shows that relatively dense, cold material is penetrating the fuel volume along the axis. These results are in qualitative agreement with those reported in Ref. 4.

Fig. 4. (a) Plasma density contours at start of implosion, $t = 1.0 \mu\text{sec}$, maximum density $= 1.46 \times 10^{-4} \text{ gm/cm}^3$, minimum density $= 4.7 \times 10^{-6} \text{ gm/cm}^3$; (b) Plasma density contours during implosion at radial compression ratio $r_0/r = 15$, $t = 1.040 \mu\text{sec}$, maximum density $= 9.27 \times 10^{-1} \text{ gm/cm}^3$, minimum density $= 3.52 \times 10^{-2} \text{ gm/cm}^3$.

The plasma configuration at 1.04 μsec , 0.04 μsec into the implosion, is shown in Fig. 4b. At 1.04 μsec , the pusher radius is approximately 0.1 mm so a volume compression of over 3000 has occurred. In Fig. 4b, the mean density is $1.67 \times 10^{22}/\text{cm}^3$, and the contour increment is about $1.2 \times 10^{21}/\text{cm}^3$. By 1.04 μsec , the hottest, least dense plasma is located along the midplane. The cold, dense layer along the pusher persists, and along the axis, the cold material has penetrated a significant distance toward the midplane. A contributing reason for the axial penetration of cold material is the relatively low magnetothermoinsulation which occurs along the axis. However, the dominant reason is the counterstreaming convective motion characteristic of wall-confined plasmas in the presence of an azimuthal magnetic field, as reported by Lincum, Pettibone, et al.⁶ In the present case, magnetic field is convected toward the pusher as the plasma loses energy to the pusher by thermal conduction. The accumulated magnetic flux drives the counterstreaming vortices.

The temperature history during both the prepulse and implosion is summarized in Fig. 5 in terms of the maximum temperature which occurs within the fuel and the particle average temperature. At the start of the implosion, the preheated, magnetized fuel has maximum and average temperatures of 21 eV and 4.8 eV, respectively. At a compression ratio of 15 the maximum and average temperatures are 362 eV and 194 eV, respectively.

As shown in Fig. 5, some of the plasma fuel reaches a temperature of several hundred eV during the implosion. At such high temperatures, thermonuclear reactions would be expected to occur. Using the σv for a 50-50 deuterium-tritium mixture, we have calculated a neutron yield for the plasma configuration discussed in this section. In addition, we have computed the yield from an identically preheated, magnetized, and imploded plasma with $(\sigma T)_e$ artificially set to zero in the electron thermal conductivity during implosion. Finally, we calculated the yield from identically imploded, initially room temperature

Fig. 5. Temperature as a function of time during prepulse and radial compression ratio during implosion: (a) average, (b) maximum.

fuel in the absence of both preheat and magnetization; this latter calculation involved merely one-dimensional hydrodynamics. Our neutron yield calculations are plotted in Fig. 6. For our computations, intended to model the actual experiment, we find from Fig. 6a that at a compression ratio of 20, the neutron yield is 10^6 , which is the value quoted experimentally. As discussed in Ref. 4, a compression of about 20 could reasonably have been attained during the experiment. Therefore, our computations would suggest that the origin of the experimentally observed neutrons was indeed thermonuclear. The suggestion is strengthened in Figs. 6b and 6c. Fig. 6a shows that an artificial suppression of magnetothermoinsulation reduces the neutron yield by a factor of greater than 5 at the same compression; under such conditions, unreasonably high compression ratios are required to attain the experimental value of neutron yield. Finally, Fig. 6c would imply that in the absence of both preheat and magnetothermoinsulation, no measurable neutrons would have been detected

at experimentally achievable compression ratios.

Fig. 6. Thermonuclear neutron yield as a function of radial compression ratio: (a) basic calculation, (b) basic calculation except $(RT)_e$ artificially set to zero in the electron thermal conductivity during implosion, and (c) one-dimensional hydrodynamic implosion calculation in the absence of preheat and magnetic fields.

Calculation Model for Radiant Energy Loss from a Hydrogen Plasma

We require accurate treatment of energy loss rates from target fuel, especially for preconditioned targets as previously discussed. In the simulation of the implosion of such targets, this problem is complicated by the nonuniform nature of the temperature and density distributions. A simple subroutine to calculate such loss rates and designed for easy incorporation into current hydrocodes used in such target simulations has been developed. It assumes the plasma is optically thin over most of the spectral regime of interest in order

to treat the radiation as lost to the fuel once radiated. To economize on time and storage requirements, the subroutine does a tabular interpolation from data computed by another program. That program first computes the equilibrium plasma composition, including such species as the H^+ ion and the hydrogen molecular ion H_2^+ . Next, it computes the free-bound (recombination), free-free (bremsstrahlung), and bound-bound (line radiation) losses. Typical results for a deuterium ($A = 2$) plasma are shown in the accompanying figure, presented as the ratio G of the actual loss rate to the free-free loss rate. The effect of either including or not including the Lyman alpha line emission is shown in Fig. 7. Details of the code are contained in a Sandia report.⁹ This model should be of future usefulness in the CHARTB, BEHAG, and POLLY codes for analytic studies.

Fig. 7. Ratio of total plasma energy loss rate (ergs/sec/cm³) to the loss rate due to bremsstrahlung only. For a deuterium plasma at density 10^{-6} gm/cm³.

Low Power, High Gain Targets Employing Magnetic Thermoinsulation

Two previously reported magnetic target designs have given different results. One target design³ has a very low breakeven requirement (10 TW for protons, 50 TW for electrons), but gains above about 3 are not possible. The target has only one DT fuel region, and the magnetic field requirement is high—i.e., the field must be large enough to retain reaction-produced alpha particles within the low density fuel as well as to reduce thermal conductivity. The other target design^{10,11} produces high gain by the use of a cryogenic DT layer surrounding the magnetic field region, but required powers are higher (60 TW for protons, 375 TW for electrons). The magnetic field is assumed strong enough (30–60 kilogauss initially) to reduce conduction losses in the low-density fuel region but not to retain the alpha particles. If the constant-power voltage shaping previously reported¹² is utilized, power levels of 30 TW for protons and 200 TW for electrons are needed.

A recent target design combines the above concepts, requiring magnetic fields sufficient to trap alphas in the preheated, low-density fuel region (200–400 kilogauss initially). Ignition is produced in the surrounding cryogenic fuel mass by conduction processes rather than by alpha-particle deposition. A gain of 30 at 90 TW is possible with electrons and at 25 TW with protons. Constant-power voltage shaping reduces these power levels by about a factor of two.

The fuel physics was modeled on a hydro-code by assuming local, instantaneous trapping of alpha particles in the preheated, low-density fuel region and non-local, noninstantaneous alpha transport in the cryogenic DT layer. In reality, the presence of the magnetic field causes the alphas to undergo helical motion which significantly shortens their range, rather than causing them to deposit energy where and when it is produced. An actual magnetic central igniter is therefore expected to have a power requirement greater than 25 TW and less than 60 TW for protons, and greater than 90 TW but less than 375 TW for electrons.

Beam-Target Coupling in an Expanding Thick-Shell Target

The problem of energy coupling to the pusher region of an expanding, thick-shelled ICF target is being investigated. In analogy to a laser-driven target, material ablated by beam heating during an implosion can decouple a significant portion of the incident energy from the pusher via side scattering and geometric effects. Particularly for electron-beam heating, a reduction in driving efficiency is possible. This effect is being examined for electron and ion driven implosions.

In a pinched beam or beams, electrons behave as a hot gas and are not normally incident on the target surface. In a cold, dense target, even though backscattering coefficients for non-normal incidence are large, this makes little difference because an electron need only collide with a few absorbers to lose most of its energy. However, in a spherically expanding corona, many fewer absorbers are present in the azimuthal direction. An electron entering the expanded material therefore has a greater chance of escaping from the target region without depositing a significant portion of its energy if it enters non-normally or scatters azimuthally.

Thus far, no hydrodynamic calculations of electron-beam targets have included the effects of spherical target expansion on deposition.¹⁴ Most electron-beam target calculations, except for shock-focusing targets,¹⁵ have employed a planar, rather than a spherical deposition profile for the unexpanded shell material. To illustrate the effect of spherical expansion on a net-energy-gain target using the density distribution in the coronal layers, obtained from hydrodynamic calculations and a spherical-geometry Monte Carlo transport code,¹⁶ the target irradiated by pinched beams of 1 MeV electrons is a magnetic central igniter^{3,10} with an initial fuel radius of 0.3 cm and a shell composed of 0.0335 cm of iron and 0.01 cm of gold.

Planar expansion of a thick slab into a vacuum is self-similar for continuous in-depth energy deposition of a power-law driving source.¹⁷⁻¹⁹ The density distribution in the far blow-off region for a spherical power-driven expansion is also self-similar. The deposition can therefore be characterized by a similarity variable $\xi = R/R_0$, the ratio of the expanded to the initial target radius, rather than in terms of the time elapsed since expansion commenced.

Numerically, the blowoff extent is zoning dependent,¹⁹ although physically, its extent is limited by magnetic pressures generated at the edge of high v/γ beams and by the presence of background gas. We emphasize that our results thus depend on the model and target considered.

Figure 8 shows the fraction of energy absorbed in the target as a function of the similarity variable ξ . As the ablator material becomes more rarefied, a greater proportion of the energy escaping from the target is in the form of electrons which have lost only a small fraction of their energy before being backscattered. Deposition efficiency drops by about a factor of two by the time the target has doubled in size (roughly half the implosion time).

The expansion is characterized by a reduced amount of bremsstrahlung escaping the target (Fig. 9) and a reduced amount of bremsstrahlung deposited in the target (Fig. 10). The decrease in bremsstrahlung emitted is less than the decrease in deposition efficiency because radiation emitted by an electron scattered sideways is lost from both expanded and unexpanded targets, whereas electron energy is lost only from the expanded target.

As the target expands, more energy is deposited in the outer portion of the blowoff (Fig. 11). The electron practical range—the depth at which most of the energy is deposited—is reduced. The efficiency of coupling deposited energy to the pusher is then reduced.

The curve in Fig. 8 is well represented by the following function:

Fig. 8. Fraction of energy absorbed in an electron-beam target, in the absence of a restoring force, as a function of the similarity variable ξ .

Fig. 9. Energy emission in photons for an electron-beam target, in the absence of a restoring force, as a function of ξ .

Fig. 10. Bremsstrahlung deposition with respect to surface deposition, in the absence of a restoring force, versus ξ .

Fig. 11. Energy deposition vs. electron range without a restoring force; curves are labelled with the value of the similarity variable ξ .

$$f/E_0 = A \exp(-a \xi^2 - b \xi), \quad (1)$$

where f is the fraction deposited in the unexpanded target. For the particular target considered, spherical Monte Carlo transport calculations give the following values for the constants: $A = 2.0495$, $a = 0.6201295$, and $b = 0.69747$. Similar behavior is expected for other shell compositions, although in general higher- Z materials will have a larger total fraction of energy escaping for each ξ , reflecting the increased number of scatterers present and the increased bremsstrahlung produced.

The total energy deposited in the target as it expands from a radius R_0 to R , compared to the amount E_0 deposited if no additional electron energy is lost over that of the unexpanded amount, is then

$$E/E_0 = \frac{A(\pi/a)^{1/2}}{2(\xi-1)} \exp(b^2/4a)$$

$$\times \left\{ \operatorname{erf} \left[a^{1/2} (\xi + b/2a) \right] \right.$$

$$\left. - \operatorname{erf} \left[a^{1/2} (1 + b/2a) \right] \right\}.$$

Energy deposited after 3/4 of the implosion time is essentially unused,²⁰ since the implosion phase is over by the time the effect of the additional energy has propagated to the pusher. For our particular target, $\xi = 2.843$ at 3/4 of the implosion time, so $E/E_0 = 0.5374$. Without a restoring force to return electrons to the target, the total energy deposited is therefore about 1/2 the amount deposited if expansion is not taken into account. This estimate, however, ignores the effects of reduced bremsstrahlung heating and poorer coupling of deposited energy to the pusher late in the pulse will have on target performance.

To compensate for the decreased efficiency, higher powers may be necessary. A thin, high density layer slows the expansion, and the blowoff can be partly confined by magnetic pressures which, for net-energy-gain targets, can be comparable to ablation pressures.²¹ Less energy escapes from a smaller target of the same shell thickness, but beam radius and beam

overlap²² limitations can be more of a problem.

A realistic hydrodynamic calculation should account for other phenomena which can further alter the deposition efficiency and/or deposition profile shape in a thick-shell electron-beam target. Depending on the nature of electric and magnetic fields surrounding the target, escaping electrons could be returned to the target area so that they have an additional chance to deposit energy.^{23,24} This effect is estimated by assuming all escaping electrons are reflected back to the target region. No attempt is made to treat the electron trajectories self-consistently by solving the equation of motion in the beam self-field and the applied deuterium electric fields. Roughly 99% of the incident electron energy is deposited in the target; the rest passes out of the target region in the form of secondary bremsstrahlung photons.

As in the absence of a restoring force, deposition is enhanced in the outermost layers (Fig. 12) and bremsstrahlung heating of the pusher is reduced. However, with a restoring force, bremsstrahlung emission increases and a greater fraction of the escaping photons have energies < 0.1 MeV as target expansion proceeds. An even greater fraction of the electrons does not penetrate into the denser plasma layers. If the gyromotion of the electrons due to a magnetic field were included, the practical range would be further shortened,^{25,26} and decoupling of deposited beam energy from the high-density layers would be more pronounced.

One should be cautious about extending these results to pinched, overlapping beams striking a real target and to realistic self-fields, but the basic conclusions would be the same: without a restoring force, energy may escape at an increasing rate from an expanding target; with a restoring force, the energy deposited in the blowoff may be less useful because it is deposited at large radii.

Because less bremsstrahlung is deposited as a target expands, targets sensitive to bremsstrahlung heating may perform better than hydrodynamic calculations

employing unexpanded profiles imply. This may be particularly true because the effects of bremsstrahlung heating are more important late in the pulse during pusher compression. Expansion is also beneficial because the intensity required per beam is lower, offsetting the decrease in coupling and/or deposition efficiency.

Ions are not scattered much by matter, so expansion should have a lesser effect. However, ion deposition has a different though analogous problem. As an ion target expands, the region of peak deposition is at a smaller radius, especially if power amplification is employed, and tighter beam focusing would decrease ion peak power requirements.

Fig. 12. Energy deposition vs. range, with a non-self-consistent restoring force, for different values of ξ .

Computational Methods to Study Beam-Fusion Ion Targets

A. Code Development

It has been suggested in a recent paper by A. Birnboim, et al.²⁷ that it may be possible to utilize the previously introduced concept of a beam fusion "wet-wood burner" (e.g., see Dawson²⁸), which is currently being exploited to investigate the preignition physics regime of Tokamak reactors in the Princeton TFTR program, in the ICF program using an appropriately designed ion driven beam-fusion inertial confinement target.

The key idea of all wet-wood burner schemes is the same, namely to utilize the fusion reactions of an energetic beam of ions (e.g., deuterons) incident on a target where the plasma ions (e.g., tritium) are still "cold," but where the plasma electrons have been heated such that the relative magnitude of the fusion to the scattering cross sections is enhanced over that of a completely "cold" target. This enhancement occurs since the scattering cross section for the ions on electrons is a decreasing function of electron temperature.

To study the merits of using beam fusion reactions in an ion driven inertial confinement scheme, it was necessary to develop the capability to numerically simulate the dynamics of such a target. Specifically, we chose to modify the existing POLLY plasma hydrodynamic code to include the additional physics of ion beam transport and deposition, and beam fusion reaction calculations.

The energy loss of an ion when passing a distance dx in a plasma can be described by:

$$\frac{dE}{dx} = C_e (n_e, T_e) E^{\frac{1}{2}} - C_i (n_i) E^{-1} \quad (1)$$

where

$$C_e = \frac{8}{3} \sqrt{\pi} Z_b^2 e^4 \sqrt{\frac{M_e}{M_b}} \ln \Lambda \quad n_e T_e^{3/2} =$$

$$\frac{Z_b}{\alpha} n_e T_e^{3/2}$$

$$C_i = n_i \frac{M_b}{M_i} 2\pi (Z_b Z_i E)^2 \ln \Lambda_i$$

and E , Z_i , M_i refer to the energy, charge, and mass of the incident ion; M_e , N_e , T_e refer to the mass, density, and temperature of the plasma electrons; M_i , n_i , Z_i are the corresponding quantities for the plasma ions; and the $\ln\Lambda$ terms have the usual definitions.

The number of beam fusion reactions undergone by an ion beam of energy E_b while traversing a plasma of temperature T_e is

$$N = \frac{P(t)}{E_b} \int_{E_b}^{E(R)} \frac{\sigma(E) dE}{dE/n dx} = \left(\frac{P(t)}{E_b} \right) \frac{q}{2} \ln \Lambda \frac{3}{2} T_e^{3/2} \int_{E_b}^{E(R)} \sigma(E) E^{-1/2} dE \quad (2)$$

where $P(t)$ is the beam power incident on target, $\sigma(E)$ is the fusion cross section for the reaction of interest, and $E(R)$ is the beam energy at a distance R into the plasma as determined by the beam transport calculation. The integral in Eqn. (2) has been computed using parameterized fits²⁹ to the fusion cross section and using a Gaussian quadrature scheme. Presently, we have restricted our studies to the D-T and D-D reactions, although other reactions could easily be accommodated.

We have solved the deposition problem two ways. First, if one ignores the plasma ion contributions, Eqn. (1) can be analytically solved to find:

$$E(R)/E_b = \sqrt{1 - \frac{R^2}{\lambda^2}} \quad (3)$$

$$\text{where } \lambda = \frac{1}{n_e} \propto E_b^{1/2} T_e^{3/2}$$

This expression can be easily solved on a zone by zone basis to build up a deposition profile. Later reflection on the origins and applicability of Eqn. (1) led us to conclude that under certain circumstances ($T_e \leq M_i/M_e E_b$) the assumptions used to derive Eqn. (1) were invalid. Therefore, we have also included a routine using Euler's coupled with Newton's methods to solve the more exact slowing down equation. However, we have determined that although the details of the deposition profile can vary with the two methods, the ultimate performance of the target does not

change enough to justify the greatly increased computational costs of the more exact method. Therefore, future discussions will all assume a deposition calculation based on Eqn. (3).

A consistent $\ln\Lambda$ term has also been included in POLLY. Furthermore, since a two-temperature calculation was required, we found it necessary to rewrite the 2-T energy balance routine.

B. Computational Results of Beam-Fusion Target Scoping

After completing our modifications to POLLY as described in the previous section, we sought to understand and verify the physics of an ion beam driven wet-wood burner target as described by Birnboim, et al. The reference target was one that operated at a power level of 160 TW/cm², and was based on some early calculations done by Shearer.³⁰ Using the following parameters:

$$\begin{aligned} V &= 120 \text{ keV} \\ E &= 493 \text{ kJ in } 74.85 \text{ ns} \\ \text{Target Area} &= 0.125 \text{ cm}^2 \\ \text{Target Density} &= 5 \times 10^{20} \text{ cm}^{-3} \end{aligned}$$

We obtained an excellent agreement with Birnboim's results; a beam energy multiplication $Q = 0.92$ corresponding to a fusion neutron pulse of 1.5×10^{17} for a deuteron beam on a tritium target.

This calculation served as a benchmark to verify both the principle, in general, and the modified POLLY code in particular. At this point, one could identify the following attractive features of the scheme:

- (1) no pulse shaping has been assumed, or is required
- (2) the results are insensitive to the pulse length
- (3) only "classical" physics is involved, therefore, no new tricks need be invented.

One serious deficiency of the above calculation is that it assumes an ion beam of energy 120 keV (in order to operate near the D-T fusion cross section peak) while current pulse

power machines are being designed to operate in the megavolt regime. Table I summarizes some results obtained for calculations using megavolt deuterons on planar tritium targets of density $5 \times 10^{-4} \text{ gm/cm}^3$.

The last entry in the table dramatically demonstrates the fact that although the total neutron yield is essentially unchanged, the fusion/beam power gain is severely degraded since you are investing substantially more energy per particle while the fusion cross section is decreasing at these higher energies.

At this point a close look at our reference target parameters showed that the current density works out to be an incredible 1.3 GA/cm^2 ! This, of course, is unacceptably high since calculations indicate that traditional ablatively driven targets can be made to produce a net gain at current densities on the order of 10-100 MA. However, for the sake of completeness, we calculated the yield for the case of a 46.3 MJ/cm^2 in 35 ns (661 TW/cm^2 , 330 MA/cm^2) pulse of 1 MeV deuterons on a $.05 \text{ gm/cm}^3$ tritium target in a two-sided geometry and obtained a beam Q of .5 and a neutron yield of 5×10^{18} . This calculation utilized a two-sided arrangement of beams as depicted in Fig. 13. Since the performance of a wet-wood burner target improves with increasing electron temperature, such a scheme allows for a breakthrough at the center time to occur near the end of the pulse at which time the opposing beams propagate through the previously heated regions. One also has the possibility of shock wave formation leading to density peaking, shock heating, and thermonuclear ignition. Table II summarizes a study of the relative efficiency of various beam geometries. It is obvious that the best Q accrues to the two-sided geometry. Note that doubling the pulse length at constant power simply doubles the neutron yield, while doubling the power gives some enhancement of Q, although not as great as for two-sided illumination.

It should be noted that all these scoping calculations have been performed assuming a one-dimensional geometry. Two-dimensional effects will certainly degrade the ultimate performance and one would be led to attempt to restrict

these effects via the use of some cylindrical confinement arrangement. A more detailed study including 2-D effects might indicate that the loss of performance by these effects are to some extent mitigated by the beneficial effects of alpha particle heating which we have also ignored.

Fig. 13. Two-sided beam-fusion target injection geometry.

C. Applications of Beam-Fusion Ion Targets

Our studies of wet-wood burner targets using megavolt ion beams has indicated that the power multiplication is generally quite poor. This leads us to conclude that the economic production of power using a D-T beam-fusion reaction target is unlikely. Since the decrease of the D-T fusion cross section with increasing energy over 120 keV is the primary factor in this unsuitability, we have also given some thought to the use of alternate reactions. The D-D fusion cross section increases in the megavolt range, but the peak is an order of magnitude lower; thus it is also unsuitable. What is required is a fusion cross section that peaks around 1 to 5 MeV and has a suitably large peak value. One potential candidate is the D-Li reactions; however, we have not been able to obtain sufficient detailed cross section data to date to properly evaluate this option.

The other possible applications of the beam-fusion targets involve using the neutrons that are produced. One can see that we are predicting a potential yield of about 10^{12} D-T fusion neutrons per pulse per square centimeter of irradiated target (or about 7×10^{10} D-D neutrons) for a Proto I level machine. This can be compared to

TABLE I

Beam-Fusion Ion Target Performance at Various Beam Power Levels

<u>Machine</u>	<u>Ion Power on Target (TW/cm²)</u>	<u>Voltage (MV)</u>	<u>Pulse Length (ns)</u>	<u>Q</u>	<u>Neutron Yield cm²</u>
Proto I	.06	1.2	25	8.9×10^{-4}	10^{12}
Proto I*	.2-.4	2.0	25	8.6×10^{-4}	6×10^{12}
Proto II	.6	2.0	25-50	1.2×10^{-3}	2×10^{13}
Longer-Range	10.	~2.0	~50	6.5×10^{-3}	10^{15}
Birnboim	160.	~2.0	~50	.035	10^{17}

TABLE II

Dependence of Target Yield on Injection Geometry, Pulse Length, and Power Level

<u>Injection Option</u>	<u>Q</u>	<u>Neutron Yield</u>
1-sided	2.15×10^{-3}	1.5×10^{13}
1-sided - 2 x Energy	2.15×10^{-3}	3×10^{13}
1-sided - 2 x Power	3.0×10^{-3}	4×10^{13}
2-sided	3.71×10^{-3}	4×10^{13}

the approximately 2.7×10^{10} neutrons which is the current ICF record set by the SHIVA laser at LLL. We have currently identified three potential neutron utilizing options.

(1) ICF Materials Studies

It is well known that the radiation environment of an ICF reactor will present many new and difficult challenges to the materials community. There is a need to study the mechanisms of material damage and first wall response in the uniquely time dependent regime of currently envisioned ICF reactors. Since it is only logical to attempt to test candidate materials prior to the realization of the necessary driver and target technology such that all facets of the potential reactor will be defined at the same time, it is necessary to develop radiation sources (primarily fusion neutron sources) to allow for such testing (e.g., see proposals for a D-Li neutron source based on a neutron stripping reaction).³¹

The desirable characteristics of such a source are:

- (1) Neutron spectrum similar to that of 14 MeV D-T neutrons.
- (2) Pulsed in nature since most of the unique ICF effects will be attributable to the short pulse lengths involved.
- (3) Flux of about 10^{14} neutrons/cm²/sec which is equivalent to a neutron wall loading of 1 MW/m².
- (4) Availability of a reasonable experimental volume.

Referring back to Table I, we see that a rep-rated version of Proto II (5-10 Hz) would probably be capable, with a suitable design, of providing the desired neutron source. Moreover, the x-ray spectrum and fast ion fluxes might also be useful to simulate those anticipated in full-scale reactors. Such a facility could be interfaced with the proposed Systems Integration Facility and would not only provide materials testing data, but also engineering information about long term diode operation, target injection injection, cooling, reactor chamber gas

injection, cooling, reactor chamber gas dynamics, etc.

(2) Ion Deposition Studies

Since details of ion beam energy deposition profiles in various standard ICF targets can have a profound effect on target performance, it is desirable to have a high degree of confidence in one's ability to numerically simulate and understand the process. It would seem that a study to correlate experimental results using beam-fusion targets and numerical simulations could develop such an ability. By using materials having different Z and material properties, it should be possible to characterize ion beam transport and energy deposition in all the relevant regimes (namely bound electron, free electron, and ion contributions) with machines of modest power; such as Proto I.

(3) Fissile Fuel Production

The final option that we have considered is the so-called Fission Fuel Factory. As implied by the name, such a system would be used to produce primarily fissile fuel for a light water reactor based economy. This option was suggested to us not only because of interest in hybrid fusion reactors, but also due to a seeming resurgence of interest in the possibility of an accelerator breeder.³² It seemed that if one could consider using a spallation neutron source driven by a linear accelerator operating at a beam current of less than one ampere, that a beam fusion neutron source driven by a pulsed-power accelerator operating at 100-1000 kA might be both more effective and less expensive.

For our scoping analysis, we used a previous analysis³³ of the performance of a fusion hybrid operating in symbiosis with a converter LWR fuel cycle as our base model. Our analysis assumed the use of the Th²³²/U²³³ fuel cycle although the results for the U²³⁸/Pu²³⁹ fuel cycle would be essentially the same (you would have a somewhat higher blanket power multiplication with a smaller overall reactor support capability). The parameters we used were:

Blanket: Fissile production rate: $0.75 \text{ U}^{233}/\text{fusion neutron}$

Blanket multiplication: $M = 1$

LWR: Fuel conversion ratio: 0.85

Specific fuel inventory: $0.75 \text{ kg U}^{233}/M_w(\text{thermal})$

Thermal efficiency: 0.35

A capacity factor of 80% is used throughout. With the above parameters, one can calculate that the a mass balance, or support ratio of $51.5 M_w(\text{thermal})$ of LWR power for every $M_w(\text{thermal})$ of fusion power. Noting then that 1 GW of electrical power requires 2.86 GW of thermal power using the above thermal efficiency, this implies that one needs $2.86 \text{ GW} / 1.5 = 1.91 M_w(\text{thermal})$ of thermal fusion power to have the breeding capacity to supply all the makeup requirements for a 1 GW electric, fission power plant. At a pulse-repetition rate of 10 Hz this translates to a total neutron yield of 4×10^{18} neutrons/pulse which is also equivalent to a yield of 5.6 MJ/pulse. Of course, this analysis would hold for any pulsed fusion neutron source, and in particular we estimate, based on our calculations, that one would require an intensity of about 100 TW/cm^2 on a beam-fusion target to achieve such a yield.

D. A Consistent Ion Transport-Deposition Package

It was felt that a new and internally consistent ion beam transport and deposition package was needed both for stand alone studies and for eventual incorporation into hydrodynamic codes. We have therefore undertaken to write such a routine.

Our plan calls for describing the transport via the governing equation:

$$\frac{d\zeta}{dx} = \sum_f \frac{2\pi e^4 \bar{z}_f^2 \bar{z}^2}{\zeta} r_f^2 \left(\frac{M_f}{M_T} \right) N_f \lambda n \lambda \left\{ \text{erf}(\sqrt{\zeta}) - 2 \sqrt{\frac{\zeta}{\pi}} e^{-\zeta} \right\} \quad (1)$$

where ζ is a normalized energy $\zeta = \eta_f \xi$

$$\eta_f = \frac{M_f}{M_T \theta_f}$$

and $\bar{z}_T, M_T$ are the equilibrium charge state and mass of the incoming beam while $\bar{z}_f, M_f, N_f, \theta_f$ are the equilibrium charge state, mass, density and temperature of the field particle " f ," and the summation runs over all field particles; bound electrons, free electrons, and plasma ions.

The crux of our solution scheme centers around the idea that in a typical hydrodynamics calculation, the plasma temperature, density, and equilibrium charge state are always constant within a zone. Moreover the spatial mesh is usually chosen to resolve the deposition profile. With the additional assumption that the equilibrium charge state and $\lambda n \lambda$ term are essentially constant within any individual zone, one can in principle solve Eqn. (1) for the general case, obtain a universal solution depending only on normalized parameters, and incorporate this solution into a computer code. This results in a package that combines the accuracy of a general Fokker-Planck treatment with a great efficiency in computational effort.

We are also including subroutines to determine the equilibrium charge state of the ion beam due to collisional ionization and recombination, the Saha ionization state of the plasma (for use where this information is not already available), and the average ionization potential of the bound electrons which determines the $\lambda n \lambda$ term for the bound electrons.

Work has progressed to the point where the basic standalone program, dubbed LASION, is being tested against

published experimental results and refinements of the atomic physics model are being made. Relativistic corrections will be included in the near future. Moreover, work to incorporate the package into the hydrodynamic codes should begin shortly.

Line Radiation Diagnostic Code

Future high temperature plasma experiments are expected to use both grazing incidence and crystal spectrometers as diagnostics. These instruments will measure both continuum and line intensities. In order to interpret these observations in terms of plasma temperatures and densities, code development has been undertaken to model line formation and transport as well as continuum transport.

One program has been developed to treat the line formation in the "two-level" approximation. This is sufficient if the interconnecting lines and adjacent continuum are thin. The Eddington approximation is used for transporting the line at a number of frequency values. This enables the code to treat plane-parallel, cylindrical, and spherical geometries. The Eddington approximation has been shown to be accurate for such line transport problems.³⁴ The line source function is assumed to be independent of frequency and angle, which has also been shown to be a good approximation.³⁵ The computer code has been tested (for plane-parallel geometry) against the results of Hearn.³⁶ The code predicts the observed line's intensity and shape (distribution of intensity as a function of frequency) for arbitrary viewing angle. It is therefore of sufficient flexibility for detailed comparison with observation.

A more ambitious code is under development. It is intended to be capable of treating problems with interconnecting lines and continuum of arbitrary optical depths. This code will rely on the technique of "complete linearization"³⁷ to speed convergence.

Melt and Yield Strength Determinations for Brass and Ni/CH₂/Au Cylinders

Energy deposition and one-dimensional hydrodynamic calculations have been correlated with experimental data from the implosion³⁸ of brass and Ni/CH₂/Au cylindrical shells on the Hydra accelerator.

Electron energy deposition was determined using the two-dimensional Monte Carlo transport code CYLTRAN.³⁹ The pinched 1.1 MeV electron beam was assumed to have a radius equal to the outer cylinder radius (0.3175 cm for the brass cylinder, 0.3023 cm for the Ni/CH₂/Au cylinder). The hot pinched beam was modelled by a 2v cosine law source perpendicular to the cylinder axis.

For the brass cylindrical shell (1/4" O.D., 1/8" I.D.), the deposition at the inner surface is $\sim 4 \times 10^{-5}$ below the surface deposition. The deposition at the inner surface of the Ni/CH₂/Au cylindrical shell (0.127 cm Ni thickness, 0.0305 cm CH₂ thickness, 0.0015 cm Au thickness) is $\sim 7.5 \times 10^{-5}$ below the surface deposition. Preheating of the pusher by bremsstrahlung has minimal effect on the implosion: the temperature of the inner surface of both shells at the end of the 100 nsec deposition period is predicted to be $\sim 75^\circ\text{C}$.

The average implosion velocities of 0.7 cm/ μsec for the brass cylinder and 0.9 cm/ μsec for the Ni/CH₂/Au cylinder imply a power deposition of $\sim 1.5 \text{ TW/g}$. The hydrodynamic calculations indicate a temperature of $\sim 1560^\circ\text{C}$, well above the melt temperature of 850°C , for the inner surface of the brass when isentropic release to zero pressure occurs. The gold temperature is well below melt at isentropic release ($\sim 180^\circ\text{C}$), but the yield strength of gold is exceeded about 45 ns after energy deposition ends, before isentropic release. For both cylindrical systems a fluid treatment of Rayleigh-Taylor instability should therefore be adequate as soon as the inner surface begins moving inward.

REFERENCES

1. L. Baker, in Particle Beam Fusion Progress Report for October 1977 - March 1978, SAND-79-0002, February 1979.
2. J. N. Olsen, M. M. Widner, J. Chang, and L. Baker, J. Appl. Phys., April 1979.
3. A. V. Farnsworth, Jr., M. M. Widner, J. Chang, R. J. Leeper, L. Baker, and J. N. Olsen, Inertial Confinement Fusion, Technical Digest of Topical Meeting on ICF, February 1978, San Diego, Calif., ThC8.
4. M. M. Widner, Bull. Am. Phys. Soc. 22, 1139 (1977).
5. J. Chang, M. M. Widner, A. V. Farnsworth, R. J. Leeper, T. S. Prevender, L. Baker, and J. N. Olsen, Proc. 2nd Int. Conf. on High Power Electron and Ion Beam Research and Technology, Cornell University, Ithaca, NY, October 1977, Vol. 1, p. 195.
6. I. R. Lindemuth, J. S. Pettibone, J. C. Stevens, R. C. Harding, D. M. Kraybill, and L. J. Suter, Phys. Flu. 21, 1723 (1978); I. R. Lindemuth and T. R. Jarboe, Nuc. Fus. 18, 929 (1978); R. C. Harding, D. M. Kraybill, I. R. Lindemuth, J. S. Pettibone, J. C. Stevens, and L. J. Suter, submitted for publication; I. R. Lindemuth, "The ANIMAL Code," University of California/Lawrence Livermore Laboratory Report UCRL-52492 (1978).
7. H. R. Griem, Plasma Spectroscopy, McGraw-Hill, New York (1964).
8. I. Spitzer, Physics of Fully Ionized Gases, Interscience, New York, 1962, 2nd edition.
9. L. Baker and M. M. Widner, "Calculation of Radiation Energy Loss from a Hydrogen Plasma for Use in Hydrodynamic Codes," Internal Memorandum RS 4241/1006, July 1978, unclassified.
10. R. O. Bangerter and D. J. Meeker, in Proceedings of the Second International Topical Conference on High Power Electron and Ion Beam Research and Technology, Cornell University, Ithaca, NY, October 1977, Vol. 1, p. 183.
11. M. A. Sweeney and A. V. Farnsworth, Jr., Proceedings of the 1978 IEEE International Conference on Plasma Science, May 15-17, 1978, p. 170.
12. M. A. Sweeney and M. J. Clauser, Bull. Am. Phys. Soc. 22, 1061 (1977).
13. Reference deleted.
14. Z. Zinamon, E. Nardi, and E. Peleg, Phys. Rev. Lett. 34, 1262 (1975) have considered the effects of the two-dimensional, cylindrically-symmetric hydrodynamic expansion of a slab target on deposition. A considerable reduction of energy, deposition efficiency in the initial focal region results.
15. The shell of a shock-focus target is thick compared to the target radius initially, so a spherical deposition profile is necessary before target expansion occurs. M. A. Sweeney and M. M. Widner, Nucl. Fus. 18, 429 (1978).
16. J. A. Halbleib, Sr., "SPHERE: A Spherical-Geometry Multimaterial Electron/Photon Monte Carlo Transport Code," Sandia Laboratories Report SAND-77-0832, June 1977.
17. V. E. Neuvazhaev, Soviet Physics-Doklady 6, 1055 (1962).

18. V. E. Neuvazhaev, Proc. Steklov Inst. Math. 122, 23 (1973).
19. A. V. Farnsworth, Jr., M. M. Widner, M. J. Clauser, and K. E. Lonngren, Bull. Amer. Phys. Soc. 22, 1084 (1977).
20. M. J. Clauser, Phys. Rev. Lett. 34, 570 (1975).
21. L. Baker, J. R. Freeman, and S. L. Thompson, Bull. Amer. Phys. Soc. 21, 1146 (1976).
22. T. P. Wright, J. Appl. Phys. 49, 3842 (1978).
23. C. Yonas, J. W. Poukey, K. R. Prestwich, J. R. Freeman, A. J. Toepfer, and M. J. Clauser, Nucl. Fus. 14, 731 (1974).
24. J. A. Halbleib, Sr. and W. H. Vandevender, IEEE Trans. Nucl. Sci. NS-22, 2356 (1975).
25. D. Mosher and I. B. Bernstein, Phys. Rev. Lett. 38, 1483 (1977).
26. P. Gilad, Z. Kaplan, S. Miller, E. Nardi, E. Peleg, and Z. Zinamon, Proc. 2nd Intl. Top. Conf. on High Power Electron and Ion Beam Res. and Tech., Cornell University, Ithaca, NY, Vol. 1, p. 207.
27. A. Birnboim, E. Greenspan, D. Shvarts, Nuclear Research Center-Negev, unpublished.
28. J. M. Dawson, H. P. Furth, and F. H. Tenney, Phys. Rev. Lett. 26, 1156 (1971).
29. B. H. Duane, "Fusion Cross Section Theory," in BNWL-1685, Battelle, N. W. Laboratories, 1972, p. 57.
30. J. W. Shearer, Nucl. Fusion 15, 5 (1975).
31. ENL-20159 (1976).
32. C. M. Ban Atta, J. D. Lee, and W. Hecknotte, UCRL-52144 (1976).
33. D. J. Bender, UCRL-80589 (1978).
34. S. Cuperman, F. Engleman, and J. Oxenius, Phys. Fluids 6, 108 (1963) and 7, 428 (1964).
35. A. G. Hearn, Proc. Phys. Soc. (London) 84, 11 (1964).
36. A. G. Hearn, Proc. Phys. Soc. (London) 81, 648 (1936).
37. D. Mihalis, Stellar Atmospheres (San Francisco, W. H. Freeman & Co.), 1978, p. 396 ff.
38. F. C. Perry, L. P. Mix, A. J. Toepfer, accepted for publication in Appl. Phys. Lett. 1979; F. C. Perry, L. P. Mix, L. Baker, A. J. Toepfer, and R. Mah, Bull. Amer. Phys. Soc. 23, 854 (1978).
39. J. A. Halbleib, Sr. and W. H. Vandevender, Sandia Laboratories Report SAND-74-0030, March 1975.

CHAPTER 2 TARGET EXPERIMENTS

OVERVIEW

The goal of this division is to provide the experimental basis of target performance. Elements of this effort are target fabrication, deposition physics, experiments on stability of imploding systems, implosion physics, and diagnostics development.

During this reporting period, we developed improved fabrication techniques for magnetic thermoinsulated targets and conducted controlled bench tests of several versions of this class of target to simulate and measure preheat conditions obtained during irradiation with intense beams. Measurements made both on the Rehyd accelerator and with bench tests have improved our understanding of these targets.

Stability measurements of targets undergoing acceleration from high dynamic pressure have been carried out as part of our continuing effort to optimize target design and fabrication criteria. The technique employed cylindrical targets which allowed detailed measurements to be made of the imploding inner surface, and considerable information regarding the effect of manufacturing imperfections on implosions was obtained.

Enhanced deposition of electron beam energy in targets is important for near term studies. For this goal, we have studied deposition of electrons in a stalk-mounted configuration useful for target experiments on present machines and in flat targets mounted on the anode. The work reported here describes the application of spectroscopic measuring techniques which confirm enhancement factors up to 10-50 over classical values, and specific power deposition up to 100 TW/gram. A similar package of diagnostics was used to measure the deposition on ion beams in targets, and this work is also described.

The diagnostics of neutron output from targets irradiated by electrons require shielding to attenuate x-rays. As part of the continuing program to improve the accuracy and reliability of time-of-flight detectors, calculations predicting the effect of shielding on TOP waveforms were made, and are reported here.

NEUTRON TIME-OF-FLIGHT SPECTROMETER DEVELOPMENT

Neutron spectrometry will be a vital component of the EBFA target diagnostics, as well as for Proto II. The unique feature of this system, which must operate in an intense pulsed x-ray environment, are described, and detailed calculations predicting total system performance are presented.

ENHANCED ELECTRON ENERGY DEPOSITION IN THIN TARGETS - STUDIES CONDUCTED WITH SOFT X-RAY VACUUM ULTRAVIOLET SPECTROSCOPY

Efforts to improve electron beam energy coupling to targets irradiated within e-beam diodes have been in progress for several years. Recently, the specific power deposited in targets has increased markedly from previous values of 4 TW/gram to current values of 50-100 TW/gram. This section describes the target experiments and the specific diagnostics and calculations employed.

STABILITY OF TARGETS AT HIGH DYNAMIC PRESSURE FOR INERTIAL CONFINEMENT FUSION

Stability of imploding systems is a key factor in designing the most effective beam-pellet combination. Studies of stability in cylindrical geometry targets of various designs, including both exploding and ablative pushers driven by electrons have been carried out. The efforts caused by changes in designs and by manufacturing irregularities have been examined in this continuing effort toward optimizing target performance.

ION BEAM HEATED THIN TARGETS - SOFT X-RAY AND VACUUM ULTRAVIOLET SPECTROSCOPY

The first use of ion beams to implode related targets is described in this report. This section describes the spectroscopic tools used to determine temperatures of thin targets. During the period of this report, ion current densities of 25-35 kA/cm² were reported, and subsequently much higher values have been attained.

STABILITY OF TARGETS AT HIGH DYNAMIC PRESSURE
FOR INERTIAL CONFINEMENT FUSION

One of the most important considerations in the design of pellets for inertial confinement fusion is the sensitivity of the imploding system to fluid instabilities (Rayleigh-Taylor). Present research aimed at determining the feasibility of different driver-electrons ions or lasers - for ICF has increasingly indicated that pellet designs with high thermonuclear gain (100-1000) will be important considerations in the selection of complete driver-pellet systems.¹ High-gain targets are necessarily complex - generally such designs contain multiple shells and/or low density and cryogenic materials. High compressions can be obtained with shell structures with high aspect ratios (e.g. $r/R = 10^2$). According to present theories of instability growth, this results in stringent fabrication requirements ($< 10 \text{ \AA}$ surface smoothness) to avoid disastrous growth of Rayleigh-Taylor instabilities.

We are investigating experimentally the development of fluid instabilities and related hydrodynamic phenomena such as jetting and shock structure and convergence in multi-shell structures. The technique employs a relativistic electron beam (the Hydra accelerator—1 MeV, 300 kA, 100 ns) to implode specially fabricated cylindrical targets. The advantages of cylindrical targets have previously outlined.²

A REB diode has been designed permitting a single beam irradiation and subsequent energy deposition around the periphery of a cylindrical target (see Fig. 1 for a diagram of the experimental arrangement and associated diagnostics). Typically, the beam focuses around a circumference (diameter ~ 6 mm) and along

the axis of the cylinder ~ 4 mm. Experiments with single shell brass ($\rho=8.5$ g/cm³) cylinders indicate an energy deposition ~ 10 kJ in a shell defined by the area of beam focus and the depth of penetration of 1 MeV electrons (~ 0.73 mm). This results in temperatures of a few electron volts and the generation of thermal pressures in the range 2-5 Mbar. In these ablatively driven implosions the outer portion of the cylinder is evaporated, and a shock wave is formed in the shell and propagates radially to the inner surface of the cylinder. Reflection of the shock occurs at the initially cold inner surface, and one observes experimentally the subsequent implosion of pusher material. In general, the deposition is not symmetric around the circumference of the shell and varies approximately as $\cos(\Theta/n)$ where $n > 2$. Consequently, the implosion of material into the central volume is not symmetric. Methods have been developed which utilize diode parameter optimization and target shimming² to improve the symmetry of these implosions.

Multiple shell targets have been fabricated,³ and initial perturbations in surface smoothness and symmetry have been characterized. Experiments were performed using cylinders with nickel outer shell (ablator) followed by a polyethylene buffer and gold inner shell (pusher) with aspect ratios $(r/r_{Au})=100$ and $(r/r_{CH_2})=5$. In Fig. 2 are shown enlarged metallographic cross sections of gold and polyethylene shells. These cross-sections indicate a scallop-type initial perturbation on the CH_2 -Au and Au-void interfaces. The dominant wavelength and initial amplitude of the perturbation were determined to be about 0.2 and 0.01 mm, respectively. Because of the finite sampling procedure used in the characterization, it is possible that significant deviations in the above values could occur.

The amplitudes and wavelengths in implosions of the Ni-CH₂-Au systems as recorded in several shots by the 4-pulse holographic interferometer ranged in value as follows: $\eta \sim 0.1 - 0.5 \text{ mm}$ and $\lambda \sim 0.1 - 0.3 \text{ mm}$. Implosion times were approximately 200 ns; inner pusher velocities were $\sim 1 \text{ cm/us}$ and driver pressures were a few megabars as verified by one and two-dimensional hydrodynamic calculations.

Fig. 1. Diagram of the experimental arrangement and diagnostics.

Fig. 2. Initial Scallop Perturbation

Figure 3 shows the implosion sequence for one (shot 7211) of the Ni-CH₂-Au targets, and in

Fig. 3. Implosion sequence for high aspect ratio, multiple shell target. The interframe time is 26 ns, pulse duration is 3 ns.

Fig. 4 we show the radius - time diagram calculated by the CHART-D code for the experimental conditions of shot 7211. The

Fig. 4. Radius-time diagram (calculated by CHART-D) for the experimental conditions of Shot 7211 (Fig. 3).

experiment and calculations imply a power deposition of 1.5 TW/g, peak pressures of 2.3 Mbar and implosion velocity of 0.9 cm/μs. The calculations also imply that there is no significant preheat of the gold pusher by bremsstrahlung, and the temperature of the gold upon isentropic release from the high pressure state is well below the melt temperature. However, the yield strength of the gold is greatly exceeded under shock loading.

It is interesting to apply the results of the classical, incompressible Rayleigh-Taylor growth-rate theory to the present case. For an interface between two materials which is accelerated impulsively by a shock wave Richtmyer⁴ has shown that the amplitude η of a perturbation at time t following the impulse is given simply by

$$\eta = \eta_0 (1 + V_{fs} A k t)$$

where η_0 is the initial amplitude of the perturbation, V_{fs} is the free surface velocity of the interface and k is the wave number ($2\pi/\lambda$). For $\eta_0 = 0.01$ mm, $V_{fs} = 1.0$ cm/μs, $\lambda = 0.2$ mm, A , the Atwood number, is 0.9 (corresponding to CH₂ and Au) and $t = 150$ ns, there results $\eta = 0.4$ mm. This value lies within the experimentally observed range of final amplitudes.

The description of the detailed behavior of the implosions as observed in these experiments is beyond the above simple theoretical treatment. The data indicate both "fluid-like" and "non-fluid-like" disturbances, and in some instances the "fluid-like" crests and troughs tended to merge as the implosion proceeded. Possible explanations for the latter phenomenon include shell thickening, viscosity and wave interaction (multi-dimensional). "Non-fluid-like" disturbances appear to correlate with lower pressure states, since they are observed to originate from the low deposition side of the targets. These protrusions in some cases broke into discrete fragments.

A central gas core in the Ni-CH₂-Au targets (see Fig. 5 for the hologram sequence) revealed a converging shock in the gas.

Fig. 5. Implosion sequence for multiple shell target with central core of air (1 atm). The interframe time is 26 ns, pulse duration is 3 ns.

Initial corrugations in the shock front were observed, and these disturbances tended to damp out in the latter stage of shock wave convergence. Implosions of a Ni-Au target (no CH₂ buffer) were relatively smooth (see Fig. 6) - correlating with the reduced Atwood number.

For the purpose of reducing the holographic implosion data to a form suitable for theoretical analysis we have initiated the use of image processing techniques (D. Ghiglia, 2623). These methods are presently being employed to determine the harmonic content and phase characteristics as well as the displacement vector map of the imploding material (or shock) boundary.

Fig. 6. Implosion sequence for a Ni-Au target (no CH₂ buffer). The interframe time is 26 ns, pulse duration is 3 ns.

Future experiments are being designed to obtain additional direct information in density gradients (within the imploding material) and temperatures. In addition, we will determine the effects of aspect ratios on growth rates, material properties of the shells (including melt temperature) wave tailoring and preheat. These experiments are to be performed for both planar and cylindrical targets with well characterized initial perturbations. By using both planar and cylindrical geometry, the effects of convergence can be examined independently of the above parameters. As target fabrication techniques improve, initial perturbations with well-defined wavelength and amplitude can be designed into the structures. Such improvements would aid significantly in the theoretical analyses of the experiments.

ENHANCED DEPOSITION OF ELECTRON BEAM ENERGY IN THIN TARGETS

Enhanced deposition of electron energy is required to make electron driven fusion feasible. We describe recent results which extend both our understanding and our ability to deposit high power density in targets.

Soft x-ray, vacuum ultraviolet spectroscopy utilizing a one-meter grazing incidence spectrograph and photoelectric diodes have been used to measure electron and brightness temperatures in 6 μm gold targets, thin to a classical electron range. These temperatures when compared with radiation hydrodynamic calculations have been used to determine the energy deposition from two relativistic electron beam accelerators in two different distinct geometries. Specific power (power per unit mass) of 50 TW/gm and 100 TW/gm have been achieved in the two different geometries, respectively.

Recent considerable progress has been made in the specific power deposition (power per unit mass) over classical deposition for relativistic electron beam (REB) deposition in targets thin to an electron range. Enhanced deposition factors as high as 5 and 50 have been reported for two different experimental configurations.^{5,6} We report here the first high resolution, soft x-ray, vacuum ultraviolet (XUV) spectra above 60 eV for REB heated targets. XUV spectroscopy ($E > 8$ eV) has been used to diagnose the response of thin planar targets in 2 different geometries as shown in Fig. 7, to tightly focused, high v/y electron beams. In particular, electron temperatures have been deduced from spectral data from a high resolution ($E/\Delta E > 10^3$), split grating 1200 lines/mm, and 2400 lines/mm, 10 μm slit width, one meter grazing incidence spectrograph.⁷ Brightness temperatures and total radiated powers have been deduced from low resolution ($E/\Delta E > 1$), triplet array of photoelectric diodes or x-ray diodes (XRDs). These measurements have been compared with theoretical, coupled radiation-hydrodynamic calculations. From these calculations, we deduce the absorbed specific power. The absorbed

specific power when compared with classical electron beam deposition where the influence of self-electric and magnetic fields is minimal yield enhancement factors much greater than one.⁸

Total radiated power, electron and brightness temperature deduced from spectroscopic measurements were compared with one-dimensional hydrodynamic calculations. The temporal behavior of the specific power was taken from the incident power pulse as measured by the voltage and current diagnostics. This temporal behavior is well approximated by a trapezoid. For the case of uniform electron deposition in a 6 μm gold target as in the C-DIODE experiments (Fig. 7b), the electron temperature is approximately equal to the radiation temperature assuming local thermodynamic equilibrium (LTE) for this three-temperature calculation. At the time of maximum specific power deposition, the code indicates the electron density falls over two orders of magnitude in less than 2 mm from the original target surface. Similarly, the electron temperature drops a factor of two. Beyond 2 mm from the source, the electron temperature is approximately constant at the time of maximum power deposition. From opacity calculations in gold, 1/e transmission factors for 60 eV and 200 eV photons are between 10^{19} and 10^{20} ion density, respectively.¹⁰ Therefore, spatially integrated, spectroscopic measurements are indicative of electron densities up to a few $10^{20}/\text{cm}^3$.

The spectrum from the diode side of the 6 μm gold foil in the anode-foil experiment, (Fig. 7a) on the Proto I accelerator (1.5 MV, 250 kA, 20 ns) is shown in Fig. 8a. Spectra above 60 eV (below 200 nm) in energy (wave length) are characterized by four distinct features: (1) no observable continuum; (2) unidentified line spectra possibly belonging to various ionization states of gold; (3) silicon contamination SiV-SiVIII line spectra from diffusion pump oil; and (4) oxygen OV and OVI lines associated with various contaminants and oxygen adsorption. Numerous unidentified line spectra appear between 12.4 and 15.1 nm. Two of the gold line radiations have been identified with 5d-5p and 6s-5p transitions in Au XII.¹¹ On the side of the foil away from the diode, only oxygen lines were observed. The absence of any continuum radiation, and the presence of significant gold line radiation, suggest heating of a low density plasma ($n_e < 10^{20}/\text{cm}^3$) from low energy electrons

Fig. 7. Target geometry for: (a) anode-foil experiments; and (b) C-DIODE experiments.

Fig. 8. XUV spectra above 60 eV (less than 20 nm) for: (a) anode-foil experiments, and (b) C-diode experiments.

< 0.5 MeV, during the time that the voltage in the diode is near zero (see Ref. 9), for the anode-foil experiment.

Figure 8b shows the XUV spectrum above 60 eV on the same shot for both 1200 and 2400 lines/mm gratings for a 6 μ m gold target for the C-DIODE experiment, Fig. 7b, on the MITE accelerator (1.8 MV, 270 kA are 40 ns). The spectra are characterized by: (1) emission lines from the glass stalk coated with carbon consisting of silicon, oxygen and carbon ionization states; (2) continuum emission below 200 eV photon energy; and (3) absorption lines superimposed in the continuum below 150 eV photon energy; and (4) the absence of emission line spectra below 150 eV photon energy. Due to the lack of diagnostic access on the foil side of the C-DIODE on the MITE accelerator, C-DIODE experiments were also conducted on the Proto I accelerator. We verified that the emission lines come only from the stalk by observing only continuum and absorption lines and structure from the foil side of the C-DIODE on the Proto I accelerator. The emission lines from the stalk consisted of 2p-1s resonant line transitions from OVII, CVI, and CV and 3p-1s transitions from CVI and CV. No satellite structure was discernible above background. Superimposed upon the continuum emission were numerous absorption lines and edges with structure below 150 eV photon energy for 6 μ m thick gold targets. The identifiable absorption lines consisted of SiV-VI and OV. Above 200 eV photon energy, only emission lines were observable above background. There appeared numerous emission lines from 3d-2p and 3s-1p transitions in Si VI-Si XII. Emission lines from O VI were also observed. By the absence of emission lines and the existence of significant absorption structure in the continuum below 150 eV photon energy for 6 μ m gold, there appears to be a high density ($n_e > 10^{20}/\text{cm}^3$) hot plasma with a colder plasma in front which absorbs sizeable amounts of continuum radiation.

75 μ m gold foils were also irradiated in the C-DIODE configuration on the MITE accelerator. Absorption structure and lines were observed below 90 eV photon energy. Emission lines, however, were observed above 60 eV. Above 150 eV photon energy, only emission lines were observed above background. There was less continuum radiation for 75 μ m gold than for 6 μ m gold foils in the C-DIODE configurations.

The electron temperature from the anode foil experiments (Fig. 7a), was deduced from line intensity ratios from successive ionization states of OV and OVI for the 3p-2s transitions

at 17.22 and 15.01 nm. Relative calibration of the photographic film was accomplished with both a visible light source and a sliding spark source in the VUV assuming shot-to-shot reproducibility. This ratio measured T is claimed to be indicative of the temperature in the high density target because the transient populations of OV and OVI are 'frozen' into the plasma at the highest density due to the rapid decrease in electron density and consequent falloff in recombination rates of the expanding low density plasma. An electron density of $10^{20}/\text{cm}^3$ was estimated from opacity considerations as given by the hydrodynamic code calculations as discussed above. An upper limit on the electron density for line widths due to Stark broadening in OV and OVI is $4 \times 10^{20}/\text{cm}^3$.¹² Collision and ionization equilibrium should be established for electron densities of $10^{20}/\text{cm}^3$. Similarly for OVI, the collision limit is approximately at the $n=2$ energy quantum level. Therefore, the use of an LTE approximation should be reasonably valid for these transitions. If we assume a constant grating efficiency between these lines, we obtain an electron temperature of 17 ± 3 eV. This is consistent with XRD brightness temperature measurements on similar shots.

Electron temperatures for the gold targets on the C-DIODE experiment were deduced from the slope of the continuum and was consistent with an optically thin continuum between 150-200 eV and 90-150 eV for 6 μ m and 75 μ m gold targets, respectively, assuming a constant grating efficiency. The electron temperature was approximately 30 ± 6 eV for both the 75 μ m and 6 μ m gold foils, on the MITE accelerator although the brightness temperatures differed by at least a factor of 2. That is, the total radiated power for the 6 μ m gold was greater by a factor of 10 than for the 75 μ m gold target. Theoretical comparisons with 75 μ m gold were not possible since the deposition profile is unknown. However, based on total radiated power, the deposition in 75 μ m gold appears to be classical. Typical brightness temperatures were 27 eV for 6 μ m gold targets on the MITE accelerator. The fact that similar electron temperatures were deduced from the optically thin continua in 6 μ m and 75 μ m gold implies some heating of a low density plasma. However, in the case of the 6 μ m gold target, this radiation is small compared to the total radiated power. Stalk temperatures were estimated from line intensity ratios from hydrogen-like and helium-like 3p-1s carbon

lines to minimize the effects of line opacity. If the plasma is in LTE, then the electron temperature of the stalk is > 30 eV depending on the electron density.

Electron temperatures of 17 ± 3 eV for the anode-foil experiments are consistent with brightness temperatures of 20 eV and total radiated power based on the XRD measurements.⁵ These measurements imply specific power depositions as high as 50 TW/gm with enhancement factors of 3-5 over classical, depending upon the angular distribution of the incident electron flux.

Electron temperatures of 30 ± 6 eV for 6 μ m gold targets on the C-DIODE experiments on the MITE accelerator are consistent with brightness temperature as high as 27 eV based on XRD measurements. These measurements imply specific power as high as 100 TW/gm with enhancement factors of 10-50 over classical, depending on the angular distribution of the incident electron flux. The higher specific powers and uniform deposition of the C-DIODE when compared with the anode-foil experiments on the same accelerator may be attributable to a combination of magnetic stopping and electrostatic reflexing. Since the target is mounted into the hollow portion of the cathode with a negative potential on three sides, this potential well could help the electrons to multipass through the foil many times.

SOFT X-RAY AND VACUUM ULTRAVIOLET SPECTROSCOPY OF ION BEAM HEATED THIN TARGETS

XUV spectroscopy utilizing a one meter grazing incidence spectrograph and photoelectric diodes is used to determine the response of approximately one proton range thick planar targets to an intense beam of hydrogen and carbon ions. Electron temperature, brightness temperature, and total radiated power are then compared with radiation-hydrodynamic calculations to determine the ion beam energy deposition and incident current density. Incident current densities of 25-35 kA/cm² with 80% proton current and 20% singly ionized carbon ion current are consistent with the spectroscopic measurements.

Recently a magnetically insulated diode which produces a 0.5 TW ion beam, has been studied as part of an effort to develop a suitable ion beam for inertial confinement fusion.¹³ We report the first, high resolution, soft x-ray and vacuum ultraviolet (XUV) spectra from intense ion beam deposition. In this experiment we diagnose the response of planar irradiated targets with XUV spectroscopy (8-300 eV). Electron temperatures were deduced from a high

resolution ($E/\Delta E > 10^3$) 1200 lines/mm grating, 10 μ m slit width, 1 meter, grazing incidence spectrograph.¹⁴ Brightness temperatures and total radiated power were determined with low resolution ($E/\Delta E > 1$) XUV spectroscopy utilizing a triplet array of photoelectric diodes or x-ray diodes (XRDs).¹⁵ This data was used in conjunction with coupled radiation-hydrodynamic calculations to deduce the incident ion current density.

The Proto I magnetically insulated ion diode¹³ produced a radially converging peak current of 360 kA at voltages of 0.8 to 1.4 MV. The target geometry and beam configuration are shown in Fig. 9. The ion beam was partially blocked by the diode structure and therefore arrived at the target in six segments. A variety of thin targets, approximately one proton range thick, were utilized. These included 25 μ m thick polyethylene, 4 μ m and 8 μ m aluminum, 2 μ m and 5 μ m nickel, and 2.5 μ m gold. The temporal behavior of the ion current incident upon the targets was measured with dB/dt probes. A typical target current monitor signal is presented in Fig. 10a along with a signal from a 2 μ m polycarbonate filtered XRD, which was sensitive to photons between 100 and 284 eV. This target current was compared with calculated target currents for various ion species assuming time-of-flight dispersion over the 15 cm flight path, according to the experimental diode current and voltage characteristics. Good agreement was obtained early in time when the ion current was assumed to be protons. However, the late time behavior of the target current monitor signals could not be attributed to protons. The late-time behavior of the current pulse is, however, consistent with singly ionized carbon ions accelerated simultaneously with the protons. Similarly, as shown in Fig. 10a, a substantial amount of target heating appears very late in the current monitor pulse. The maximum in the polycarbonate XRD signal coincides with the maximum in the time-of-flight arrival of the diode current monitor signal, assuming singly ionized carbon ions. Recent experiments¹⁶ on the Hydra accelerator, using a variant of the magnetically ion diode, with an 80 ns duration pulse, suggest that early in the pulse the beam is composed of approximately 80% protons plus 20% C⁴⁺, but that later progressively larger amounts of more highly ionized carbon ions are accelerated. Because of the greater stopping power for carbon,

Fig. 9. Schematic of the target geometry and deposition.

Fig. 10. (a) Comparison of the target current monitor and 2 μ m Kimfoil filtered XRD. Target current monitor is consistent with protons throughout much of the pulse. Late-time behavior of the target current monitor, however, is consistent with singly ionized carbon ions.

(b) T_e and T_r are electron and radiation surface temperatures, respectively, from a radiation hydrodynamic code assuming 20% carbon component of the ion beam.

a substantial amount of target surface heating is attributed to these carbon ions, but for only a very shallow depth.

Figure 11 are spectra taken with the 1200 lines/mm grating with 25 μ m thick CH₃ 8 μ m thick Al, and 5 μ m thick nickel targets. Spectra above 60 eV (below 200 nm) in energy are characterized by three distinct features: (1) characteristic spectra associated with ionization species of the target, (2) silicon contamination spectra associated with diffusion pump oil used in the vacuum pump and to coat the insulator in the ion diode, (3) oxygen ion spectra associated with various contaminants such as water vapor and oxides of the target material. In the case of the carbon target, only the resonant line of CV(C⁴⁺), 2p-1s, was discernible above 60 eV. The silicon contaminant lines associated with the carbon target

were the 3d-2p transitions in Si VI. The primary oxygen lines associated with all targets were O V and O VI with the O VI lines generally the strongest in intensity. These lines included the ground state transitions 5p-2s, 4p-2s, and 3p-2s and the excited state transitions 6d-2p, 5d-2p, 4d-2p, and 3d-2p in O VI. In the aluminum targets, the most intense lines are the 3d-2p and 3s-2p transitions in Al VI and A V. Ground state transitions from Al IX through Al IV were observed in this region. In the nickel target, 4f-3d transitions were observed in Ni IX and Ni X. The most intense transitions were 3d-3p transitions in Ni X-Ni XI and 4p-3d transition in Ni VIII. Only oxygen lines were observed on the gold target above 60 eV.

These data have been interpreted, using density profiles for the expanding foil material calculated by a radiation hydrodynamic code. The ion species assumed were protons and singly ionized carbon ions, which were transported self-consistently over the 15 cm flight path, according to the actual diode voltage time history. The penetration of C II ions into the already expanded aluminum foil is such that at maximum temperature, the density heated by the penetrating ions is no higher than 10^{-3} g/cm³. Ranges of the carbon ions were $5-8 \times 10^{-5}$ g/cm² at these angles and voltages. The calculated result is that the surface electron temperature abruptly exceeds the surface radiation temperature beginning at the time of arrival of the carbon ions as seen in Fig. 10b. The carbon ion deposition takes place in an optically thin expanded plasma, which strongly effects the electron temperature. However, the radiation temperature, as measured by the XRDs, is dominated by the material temperature behind the surface. At the time of maximum specific power (power per unit mass) deposition, the plasma drops over two orders of magnitude in electron density 3 mm from the original surface. However, the calculated temperatures are relatively constant as a function of distance normal to the surface.

Due to rapid decrease in electron density from the surface of the target during the expansion phase, the populations of the ionization stages from the target are effectively 'frozen' as they drift out of the high density region into a region where longer recombination rates are associated with the expanding plasma of low electron density.¹⁸ Consequently temperatures

Fig. 11.

Spectra of 25 μm carbon, 8 μm aluminum, and 2 μm thick nickel planar targets taken with 1200 lines/mm, one meter, grazing incidence spectrograph mounted 33° from the target normal, 75 cm away on a single shot. Film is Kodak 101-01.

deduced from line intensity ratios reflect the high density regime. Similarly, an upper limit on the electron density for line widths due to Stark broadening in OV and OVI is $10^{20}/\text{cm}^3$.¹⁸ For OVI at a density of approximately $10^{20}/\text{cm}^3$, the collision limit is approximately the $n = 2$ energy quantum level. Therefore, LTE should be an adequate approximation for determining electron temperatures from the line intensity measurements from successive ionization stages for transitions between the $n = 3$ and $n = 2$ states. Steady state models are justified since equipartition times between electrons and between ions are less than a 100 psec. Similarly, ionization equilibrium is established for times less than 2 ns, for densities greater than 10^{19} and energy levels above $n = 2$.¹⁹ Line intensities from successive ionization states utilizing the 3p-2s transition in OVI and OV, the 4d-zp transitions in Al VII and Al VI for the aluminum target, and the 4f-3d transition in Ni X and Ni IX for the nickel target yield surface electron temperatures of 15 ± 2 eV for 25 μm polyethylene, 8 μm aluminum, and 2 μm nickel. In the case of the gold target, the 3p-2s transitions in OVI and OV, suggest an electron temperature of 10^{+2} eV.

Brightness temperatures, based on a blackbody spectrum, as measured by XRDs, suggest temperatures of 10 ± 2 eV for the polyethylene, aluminum and nickel targets. Only 7 ± 2 eV brightness temperature was measured for the gold target. This observation is consistent with the calculations in that a higher electron temperature is indicated by the line intensities seen in emission from the optically thin, carbon-heated region, than is indicated by the XRD measurements which respond primarily to the background continuum radiation. Thus, the presence of an optically thin (to continuum radiation) higher temperature region tends to confirm the expectation of a significant (20%) carbon component of the beam.

NEUTRON, TIME-OF-FLIGHT SPECTROMETER DEVELOPMENT

This report describes a Monte Carlo simulation of a neutron time-of-flight (TOF) system which is capable of measuring the ion temperature in particle beam fusion target experiments. In this system, the ion temperature is inferred from a measurement of the FWHM width of the Doppler broadened neutron pulse.^{20,21} The novel feature that distinguishes our spectrometer from others²² is its use of high Z-Pb filters in the neutron flight path to attenuate the intense bremsstrahlung x-ray background that is characteristic of electron beam target experiments. These backgrounds can

range up to some $10^{11} - 10^{12}$ Rads/sec at 1 m. In the case of ion beam target experiments, bremsstrahlung will still be produced by "leakage" electrons, but the level entering a TOF spectrometer would be at least ten times less than for electron beam targets. Backgrounds at these levels are sufficiently intense to saturate both the photomultiplier and the plastic scintillator in neutron scintillator detectors typically employed to measure the neutron pulse.²³⁻²⁶ Specifically, this study addresses questions related to neutron attenuation and neutron pulse shape broadening due to the material geometry of the line-of-sight (LOS) pipe, and the introduction of high Z lead filters in the neutron flight path. The basic approach used was to model the material geometry of a typical particle beam accelerator and then use the 3-D neutron Monte Carlo code SORS²⁷ to simulate the neutron pulse and its propagation down the flight path to the detector.

Model Parameters

Using the material zoning provisions of the SORS Monte Carlo code, a model of the LOS spectrometer has been developed. This model attempts to simulate, as closely as possible and practical, the geometry available in the EBFA facility under construction and in the Proto II accelerator. These machines contain a pellet within an air-filled diode chamber which is surrounded by a cylindrical water shell which serves as a dielectric. This in turn, is surrounded by the Marx generator capacitor bank which is in an oil bath.

Therefore, we decided that beyond the basic necessities of source, pipe, and detector, the model should have air, water, and oil zones concentric to the source. Although cylindrical in actuality, SORS limitations forced modeling these as cut off spheres. To complete the picture, a concrete floor, wall, dirt (outside wall), and collimators were added. Specific dimensions of the machine are similar to Proto II, but small changes will extend the results to EBFA. The critical dimension of the length of the flight path was a compromise. Whereas an actual LOS pipe will likely be over 100 meters in length, statistics limitations forced using a shorter distance in this model. Too short a length would have invited undesired effects of being too close to the oil and water tanks. We choose 20 meters as a compromise; this distance was found to be sufficient to remove the short-

distance effects of the geometry near the source. The lead filters used were 10.2 and 20.3 cm thick disks which were compared to runs with no lead (the 0.0 cm case).

Statistics Problems

Very early in the study we discovered that even with the compromise 20 meter flight path, obtaining adequate statistics would be a serious problem. In order to have Monte Carlo runs of appropriate statistics ($< 10\%$ for 0.0 and 10.2 cm cases and of not more than 5 hours of CPU time, several timesaving measures available in the SORS code had to be used.

First, since the detector subtends a small solid angle ($\Omega = 2.52 \times 10^{-6}$ of 4π or 0.36° of arc), the source was modeled as a cone of neutrons ($\Omega = 0.01$ of 4π) centered on the Z axis. Whereas the collimator edge extends to 1.4° from the axis, the source neutrons extend to 11.5° . To verify that this source reproduces the effect of an isotropic source, numerous comparisons were made. With varying amounts of lead shielding (0.0, 10.2, and 20.3 cm), the two types of sources produced the same results in regions of interest, well within a standard deviation.

Second, much computer time was spent following trajectories of neutrons in the oil and water tanks that never reach the detector region; these could be eliminated to save time without affecting results. The SORS code has two provisions to do just that. Zones near the source were weighted so that neutrons crossing into these zones were reduced by factors of 2 and 4. In addition to this reduction, neutrons in the zones near the source were eliminated when their velocities fell sufficiently low so that they could not reach the detector area until at least 100 nsec beyond the arrival time of the main pulse (284.5 - 387.5). Again comparisons were made in early runs with and without these timesaving options. Within 1/2 of a standard deviation, use of these options had no effect.

Final Model

After incorporating the above considerations, we arrived at the model used in the study. Figure 12 shows the horizontal view of this model.

The air, water, and oil spheres surrounding the source are cut off by an air space 1.2 meters above the y-z plane and a concrete floor 1.2 meters below the plane. Beyond the 15.2 cm thick concrete wall is dirt (composition data

Fig. 12. Model diagram showing zones of low weighting, velocity cutoff, and regions of interest.

furnished by Prof. John Hustler-UNM, Geo-Chemist). The model has considerable flexibility, especially regarding placement of the lead filters, seen in Section III.

As the highest expected burn time on particle beam fusion machines is 3-5 ns and this would be the worst case for measuring ion temperatures using FWHM pulse measurements, the model uses a source of a 3 ns wide burst of neutrons. Whereas, ion temperatures should eventually reach 5-10 keV, the present model uses a Gaussian neutron energy distribution corresponding to a 1 keV ion temperature, which is more difficult to measure. The SORS code limits tallies of data to five time edits which were separated in our study by 1.5 ns time intervals (compared to ~ 3.5 ns resolution typical of current detection systems). With the Monte Carlo model determined, we proceeded to study the effects of the lead shielding and material geometry.

Section III

Lead Shielding Effects

As was noted in the introduction, the large x-ray pulse necessitates use of lead (or other high-Z material) shielding between the source and the detector. Using Monte Carlo runs with the model described above the effects of this shielding on pulse shape (FWHM) and peak attenuation were examined. Disks of lead were placed at

five positions in the LOS (refer to Fig. 12): 10 cm from source; 730 cm from source, just beyond the oil tank; 970 cm from source, in front of the wall; 1500 cm from source; and 1970 cm from source, adjacent to the scintillator. Figures 13-17 show the time history of the energy deposited in the scintillator in

Fig. 13. Scintillator energy deposition with lead filter 10 cm from source.

MeV per neutron emitted in 4π per 1.5 nsec. Each plot shows the pulse at a given placement for the cases of 0.0, 10.2, and 20.3 cm of lead shielding. Figure 18 is a plot of the attenuation factors versus the distance of the 10 cm lead disk from the source.

The result displayed in Fig. 18 may be understood from the following considerations. When the lead filter is located close to the neutron source small angle neutrons are elastically "inscattered" down the LOS pipe. Since the energy loss for a small angle elastic scattering in lead is very small ($1.6 \times 10^{-8}\%$ for 10 scatter), the scattered neutron has virtually the same energy as unscattered ones and subsequently arrives at the scintillator in time with the main neutron pulse. The result is a neutron pulse of higher pulse height. As the lead filter is moved towards the midpoint of the LOS pipe, this effect falls off as the solid angle of lead filter decreases. Moving the lead closer to the detector brings in more

Fig. 14. Scintillator energy deposition with lead filter 730 cm from source.

Fig. 15. Scintillator energy deposition with lead filter 980 cm from source.

small angle elastically scattered neutron due to the detector subtending a greater solid angle relative to the filter. Again these neutrons arrive at the detector in time with the main neutron pulse and contribute to the energy deposition in the detector.

Fig. 16. Scintillator energy deposition with lead filter 1500 cm from source.

As the lead filter is moved very close to the scintillator, non-elastically scattered neutrons tend to make contributions to the energy deposition in the scintillator. In the case of lead, for 14 MeV incident neutrons, the inelastically scattered neutrons produced are isotropic in angle and Maxwellian in energy with a peak at 1.0 ± 0.1 MeV.²⁸ Neutrons produced in (n,2n) reactions in the lead also form a similar distribution of low energy neutrons.²⁸ Thus, unless scattering occurs in lead near the detector, very few non-elastics will reach the detector, and those that do will arrive later than the primary neutron pulse. Consequently, non-elastically scattered neutrons deposit little energy in the peak of the main neutron pulse. They also tend to broaden the pulse. These effects may be seen in Fig. 13-17.

Pulse Shape of Disk Filters

As noted above, only non-elastics disturb the pulse shape. In this study, the pulse width

Fig. 17. Scintillator energy deposition with lead filter 1980 cm from source.

Fig. 18. Leading edge attenuation factor versus lead filter placement.

is expected to be a combination of width due to (1) finite burn time, $(\Delta t)_b$, (2) finite length of the scintillator, $(\Delta t)_l$. In the present calculations $(\Delta t)_b = 3$ ns, and for the 12.7 cm scintillator $(\Delta t)_l = 1.71$ ns. As yields increase, shorter length scintillators became possible, hence, decreasing $(\Delta t)_l$ and making ion

temperature measurement less difficult. And (3), broadening due to the ion temperature. The line width at the scintillator $(\Delta t)_{\text{temp}}$ is proportional to the Gaussian ΔE_0 of the neutrons at the source due to the assumed Maxwellian distribution of reacting ions; $\Delta t = (t/2E_0)\Delta E$ and $\Delta E = 177 \sqrt{0.1}^{20}$. The model uses a neutron source corresponding to a 1 keV ion temperature. An actual spectrometer using a longer flight path would have a higher $t/2E_0$ and thus an easier-to-measure higher $(\Delta t)_{\text{temp}}$. Also, in an actual system, there would be a broadening $(\Delta t)_{\text{pmt}}$ due to the response of the photomultiplier tube.

These time widths are related by,

$$\Delta t = \sqrt{(\Delta t)_{\text{burn}}^2 + (\Delta t)_{\text{length}}^2 + (\Delta t)_{\text{temp}}^2 + (\Delta t)_{\text{pmt}}^2}$$

For this model $\Delta t = \sqrt{3^2 + (1.71)^2 + (2.44)^2} = 4.23$ ns. The results of fitting the data to Gaussians and extracting the FWHM for the lead placements are shown in Fig. 19. To check that the model reproduces the results of adding in quadrature, additional runs were made.

Fig. 19. Pulse broadening versus lead filter placement.

Without an energy distribution $\{(\Delta t)_{\text{temp}} = 0\}$ the addition in quadrature predicts $\Delta t = 3.45$ ns, while the code generated $\Delta t = 3.6 \pm 0.3$ ns. With a point-time source $\{(\Delta t)_{\text{burn}} = 0\}$, adding in quadrature predicts $\Delta t = 2.98$ ns. The model generated data giving $\Delta t = 3.0 \pm 0.3$ ns.

Extra Lead Around Detector

Whereas placing the small disk of lead at the scintillator produced a large contribution due to non-elastic scattering, the pulse broadening was small. Placing more lead near the detector

should increase both effects. Figure 12 shows the geometry of extra lead shielding around the detector. The 10.2 and 20.3 cm runs of disk filters were rerun with additional lead placed on the sides and back of the scintillator. Results appear in Fig. 20. Since this configuration had the extra lead shielding in turn shielded by the water collimator, the next step was to remove the Z material around the detector can be very detrimental to the pulse width; but if the high-Z material is shielded by low Z, the effect is greatly reduced.

Fig. 20. Scintillator energy deposition with extra lead shielding surrounding detector (water collimator present).

Final Results

Table I summarizes the results for the five disk placements as well as the two cases with extra lead around the detector. It contains the peak heights, attenuation factors and FWHM for each case.

The main conclusions from the study are that (1) attenuation is less than that predicted by total cross section, (2) the best placement for the filter is near the source since attenuation is less without pulse broadening (3) unless lead shielding is near the detector the neutron pulse is not broader thus ion temperature measurements are possible,

and (4) if forced to have much lead near the scintillator, non-elastics cause trouble, but shielding at the lead by the water greatly reduces the effect.

Fig. 21. Scintillator energy deposition with extra lead shielding surrounding detector (no water collimator present).

TABLE 1
Summary of Data from Experiments

Run	Time (ms)	Energy (MeV)	Rate (MeV/ms)	Pressure (Torr)	DT (mg)	DT (g)	DT (kg)
1	384.5	0.40	0.40	1.0	0.001	0.001	0.001
2	386.0	4.0	4.0	1.0	0.001	0.001	0.001
3	387.5	4.5	4.5	1.0	0.001	0.001	0.001
4	389.0	5.8	5.8	1.0	0.001	0.001	0.001
5	390.5	5.8	5.8	1.0	0.001	0.001	0.001
6	392.0	5.8	5.8	1.0	0.001	0.001	0.001
7	393.5	5.8	5.8	1.0	0.001	0.001	0.001
8	395.0	5.8	5.8	1.0	0.001	0.001	0.001

SMALL VOLUME TRITIUM FILLING APPARATUS FOR DT TARGETS

In previous TN neutron experiments no attempts were made to measure precisely the target fill pressure when the target was shot. The uncertainty in the target fill pressure made subsequent data analysis, quite difficult. To remedy this situation, we have built a fill-in-place apparatus such that seconds before the shot a small vial containing DT gas is punctured to fill the target. Included in this fill-in-place apparatus is a novel tritium

pressure monitor which is used to measure the pressure in the filling chamber. Such an apparatus is shown in Fig. 22. The total volume of this apparatus is 0.095 cm³ which, depending on the target size, is 1-7 times the target volume. With this volume ratio,

Fig. 22. Fill-in-place apparatus (total volume 0.095 cm³).

we can keep the tritium inventory small ranging from 20-75 mCi. During operation the filling volume and the target is first pumped out through the pneumatic valve. A short time before the shot is to take place, the valve closes and the DT reservoir is punctured by a solenoid actuated needle to release the DT gas and to fill the target. Pressure in the chamber during this time is continually measured by the tritium pressure monitor and any leak will be detected.

The tritium pressure monitor consists of a small plastic scintillator (Pilot-B) coupled by a fiber optical cable to a RCA 8575 photomultiplier tube. β^- 's emitted from the decaying tritium atoms are counted and by keeping the scintillator geometry constant, counting rate can be calibrated against fill pressure. The output of the photomultiplier is fed into a EG&G T105/N fast discriminator (nominal threshold = 50 mV) and scaled on an ORTEC 772 counter. In calibration runs performed at CNB-3 division at LASL it was found that the output of the detector was linear with tritium pressure and that 1000 counts above background in a 10 second counting interval corresponded to a 100 Torr pressure of 50-50% DT gas. Figure 23 shows such a calibration curve.

Fig. 23. Calibration curve for tritium pressure monitor.

To make certain that pressure equilibrium is reached between the target and the fill chamber, which are connected by a 2-inch long 0.002" I.D. fill tube, we placed another scintillator in the target volume to allow simultaneous pressure monitoring of the target and the fill chamber. This test verified that pressure equilibrium between the target and the fill chamber can be reached in less than 1 second. Leaks in the target can also be monitored by this technique as a leak will manifest as a continual decrease in β^- counting rate.

In summary, we now have the capability to precisely determine the target DT fill pressure and to continually monitor for leaks until the shot is made.

POWER DEPOSITION EXPERIMENT ON PROTO I CONVOLUTE

Recently experiments have been carried out on Proto I Convolute to determine how much power can be delivered to a hollow gold sphere whose diameter and total mass is identical to a Φ -III target. In this experiment only the C-DIODE is used. XRD's are used to measure soft x-ray output from the targets and these measurements are used in conjunction with hydrodynamic calculations to infer the specific power delivered on target. Gold targets 3 mm diameter with wall thickness of 7.6 μ m and 16.2 μ m were mounted on 50 μ m glass fiber stalks which varied in length from 7-12 mm. The cathode is a hollow brass cylinder 1.125" O.D. and 0.3" or 0.375" I.D. The cathode face has a 15° taper. Best results were achieved with 0.375 I.D. cathode and 9 mm long stalk. Since the A-K gap is $\sim$ 3 mm

the target is situated 6 mm inside the hollow region of the cathode.

Data from two shots #1958 and #1959 are presented here. Shot #1958 used a target with 7.6 μ m wall and 4.1 mg total mass and shot #1959 used a target with 16.2 μ m wall and 8.8 mg total mass. Results of these two shots and their deposition rates inferred from hydrodynamic calculations are tabulated in Table 1.

Table 1

Shot	Target XRD Mass (V) (mg)	Specific Power (TW/g)	Power Absorbed (TW)	Efficient
1958	13 4.1	20-25	0.1	18%
1959	7 8.8	17	0.15	25%

The detailed time-dependent behavior of these two shots are shown in Figs. 24 and 25.

Fig. 24. Shot #1958

In summary, we find gold spheres in size and mass comparable to Φ -III targets can achieve a specific deposition rates of 17 TW/g and a coupling efficiency of 25%. These represent a factor of 4 improvement over the old Rehyd results.

Fig. 25. Wave forms from Proto I Convolute Shot #1959

MAGNETIC TARGETS: PRECONDITIONING TEST OF $\emptyset I$ AND $\emptyset III$ TARGETS

Introduction

The magnetic target program involves preconditioning an electron beam target by passage of an ohmic heating current through the fuel prior to compression by the electron beam. A magnetic field is thereby established in the target interior which inhibits thermal conduction from the heated fuel to the target walls throughout the compression pulse. An understanding of the preconditioning phase is essential for target design and actual compression experiments. This section is a report of investigations of the preconditioning phase of two magnetic target types,²⁹ $\emptyset I$ and $\emptyset III$, shown in Fig. 26.

The $\emptyset I$ targets were preheated by the prepulse machine voltage from the accelerator itself, the thin hat acting to draw several kA of prepulse current. The fuel was a 1 mil CD_2 filament. Compression experiments with these targets have already been reported²⁹ as yielding thermonuclear neutrons in a series of shots on the Rehyd accelerator. The present work confirms that the CD_2 filament does indeed vaporize and expand during the machine prepulse time as earlier hypothesized. Luminosity and schlieren experiments will be presented which also provide estimates of filament temperatures during this phase.

Fig. 26. Electron beam $\emptyset I$ and $\emptyset III$ targets. $\emptyset$ targets are 3 mm in diameter. $\emptyset III$ targets may be somewhat larger depending upon power available in the REB accelerator to be used.

The $\emptyset III$ targets are of a newer design which has not been extensively tested yet in compression experiments. A gaseous DT fuel is used and the preheat current is driven by an external supply, passing through the fuel and returning via the outer conducting coating. Target operation tests are reported here which show that the present $\emptyset III$ targets suffer from a partial disassembly problem during the preconditioning phase. It is not known how damaging this degree of disassembly would be in a compression experiment; design changes are being pursued to avoid disassembly in future $\emptyset III$ targets in any case.

Filament Preheating for $\emptyset I$ Targets

These experiments were carried out on the same accelerator, Rehyd, as used for the neutron production tests. With the prepulse switches bypassed the machine prepulse voltage ranged from 40-120 kV during the 0.7 μs Marx erection time as observed earlier. The target chamber, current monitors, and targets were those used previously.

The filament behavior during the prepulse time was observed in two modes, both utilizing a fast streak camera. In the simplest, luminosity of the filament and target walls was observed with a large aperture imaging system. The emission was so weak that l:l imaging was required and thus poor spatial resolution resulted; plans for spectroscopic analysis were abandoned. In the second scheme, a large CW laser was used to obtain high resolution (10-20 μm) schlieren imaging of the filament. The optical system was

similar to that used for gas discharge studies³⁰ except that a 12.5:1 image magnification was obtained.

The behavior of the accelerator monitors is shown in Fig. 27 for a typical shot. This shot, #2190, was with a $\emptyset$ target cut away on one side for viewing access. Rehyd was charged to 75 kV with an A-K gap of 0.523". The Marx erection time, top signal, is 0.7 μ sec; a pick-off from this triggers the streak camera, as shown in the next trace, for a 0.5 μ sec streak. The integrated V and B signals for the machine prepulse are given next. The traces are discontinued when the probes went off-scale at 0.48 and 0.64 μ sec, respectively. A peak voltage of 64 kV was seen just before the current underwent a large increase to ≥ 10 kA. Presumably most of the current was collected by the thin aluminum disc on the top of the $\emptyset$ target.

Fig. 27. Accelerator performance in large prepulse mode. From top to bottom the signals depict (a) Marx erection, (b) streak camera gating, (c) integrated V monitor, and (d) integrated B monitor, respectively. Arrows indicate times of initiation of wall and filament light with respect to the current signal.

Light emitted from the target is shown in Fig. 28 as obtained with the streak camera. The walls appear first at 0.34 μ sec followed at 0.58 μ sec by the filament. This latter time is close to the time of steep current increase. The timing of wall and filament flashing varied but the filament never preceded the wall light. The current increase was always close to the filament starting time; however, no estimate of the filament/wall current ratio can be made from this data. The filament temperature may be estimated under a blackbody assumption through analysis of the instrumental sensitivities; $T \geq 0.35$ eV. There was the possibility in these results that the filament was not heated but was merely reflecting light emitted by the target walls. For this reason we turned to the schlieren technique.

Fig. 28. Light emission from the $\emptyset$ target with 1:1 imaging. The streak duration is 500 with 10 ns resolution.

A schlieren streak of the 1 mil filament is shown in Fig. 29 for shot #2200. In this shot the prepulse voltage peaked at 35 kV at 0.24 μ sec. The current underwent a characteristic steep increase at 0.38 μ sec to 5 kA at 0.45 μ sec; however, the filament did not start to expand until 0.50 μ sec. Observation of filament vaporization via the schlieren technique always showed a 100-200 ns lag from the time of current increase (in contrast, the luminosity measurements showed no time lag). The radial expansion velocity here is 2×10^5 cm/sec, the slowest of all those observed. In this particular case, the prepulse current stopped after 200 ns when the prepulse voltage went through zero.

with the result that the expansion stagnated. Vaporization of the target walls is evidenced in plasma coming in from the sides, a result expected from the luminosity measurements.

Fig. 29. Schlieren imaging of the 1 mil CD_2 filament. Spatial and temporal resolutions are 10-20 μm and 25 ns, respectively.

Discussion of Filament Preconditioning

These experiments suggest two phases in the filament preheating: (a) Luminous phase. In the luminous phase, the filament is emitting visible light but no plasma shows in the schlieren system. This phase begins with the steep increase in the prepulse current and is after the peak prepulse voltage (40-120 kV). After initiation, the voltage and current monitors ring off-scale with large amplitude oscillations. (b) Plasma phase. With a 100-250 ns delay after the increase of prepulse current (and beginning of luminous phase), a plasma forms around the CD_2 filament which is observable in the schlieren apparatus. The radial expansion velocity is in the range of $2-9 \times 10^5$ cm/sec.

The current carrying mechanisms during the two phases are probably different. At the beginning of the luminous phase an electric field of 100-200 kV/cm occurs between electrodes inside the target. This is sufficient for flashover³¹ along the CD_2 filament and/or field emission directly from the electrode. We assume then that the luminous phase is a flash-over phenomenon. Appearance of a plasma is delayed by the length of time required for flashover to heat the filament to the point of gas desorption, at which time avalanche ignition

may occur. After creation of a surface plasma ohmic heating drives the plasma expansion observed in the schlieren data.

The data were further analyzed in an attempt to estimate temperature and density of the resultant plasma. During the luminous phase before plasma expansion, a blackbody assumption yields $T \geq 0.35$ eV. Later during the schlieren-observed plasma phase the expansion velocities, $2-9 \times 10^5$ cm/sec, were indicative of $0.2 < T < 1.8$ eV. This is consistent with $T \sim 1$ eV being required for ionization to produce an observable plasma. The question of whether the entire filament or only desorbed surface gas is heated is not answered here. The sensitivity of the schlieren system was good enough that either plasma would have been recorded, given reasonable density scale lengths.

ØIII Target Integrity

Prototype ØIII targets were tested with a 9 kA external driver for integrity during the preconditioning phase. The targets were mounted as they would be during a compression experiment, in vacuum on a graphite anode with a 100 torr gas fill. Light emitted by the target was photographed with a framing camera and also a still camera.

The current passing through the driving circuit is shown in Fig. 30 with timing marks for the framing camera. Three frames were

Fig. 30. ØIII driving current and framing camera monitor. The current is displayed at 5 kA/cm and the time sweep for both is 500 nsec/cm.

obtained in the 700 ns required for the current to rise to 9 kA. The framing photos are presented in Fig. 31 along with schematic clarifications. Both the stem and the cap poles light up; however, the problem is worst at the cap pole. This also appears in

the still camera photograph of Fig. 32.

Fig. 31. ØIII target during preheat. Schematically shown at right are position and orientation of target with respect to framing record. Exposure time is 20 ns; the target was 4.8 mm in diameter.

the rise to peak current but partial disassembly may be occurring at the poles.

Two-dimensional simulations are planned to establish the seriousness of polar disassembly with respect to compression symmetry. In the meantime further development of the target is aimed at avoiding excessive local heating. A special target is being fabricated which will allow a pole-to-equator resistance ($0.4 \text{ m}\Omega$) measurement in case the aluminum overcoat, which provides the current return path, has been nonuniformly applied, leading to larger resistance and local heating. Since one out of the five targets tested did survive, it is presumed that this is basically a fabrication problem.

Fig. 32. Time integrated photograph of ØIII target during preheat. Anode and stem are on the bottom; cap is on the top. This is the same shot as shown in framing record of Fig. 31.

Comparison of the photographs shows that gross disassembly of the shell does not occur during

REFERENCES

1. J. H. Nuckolls, R. O. Bangerter, J. D. Lindle, W. C. Mead and Y. L. Pan, "High Performance Inertial Fusion Targets," Lawrence Livermore Laboratory, paper presented at the European Conference on Laser Interaction with Matter, Oxford, England.
2. F. C. Perry, L. P. Mix and A. J. Toepfer, "Shock Focusing in Implosions of Inertial Fusion Targets," accepted for publication in Appl. Phys. Lett.
3. These multiple shell cylindrical targets were fabricated by Los Alamos Scientific Laboratory.
4. R. Richtmyer and D. Taylor, "The Instability in Shock Acceleration of Compressible Fluids," Commun. Pure and Applied Math, Vol. 13, 297 (1960).
5. M. M. Widner, Steven A. Goldstein, C. W. Mendel, Jr., E. J. T. Burns, J. P. Quintenz, and A. V. Farnsworth, Jr., submitted to Phys. Rev. Lett.
6. J. Chang, J. P. VanDevender, A. V. Farnsworth, Jr., M. M. Widner, E. J. T. Burns, and J. P. Quintenz, Bull. Am. Phys. Soc., 23 763 (1978); also to be published.
7. D. L. Garrett and R. Tousey, Appl. Opt. 16, 898 (1977).
8. M. M. Widner, J. W. Poukey, and J. A. Halbleib, Sr., Phys. Rev. Lett. 38, 548 (1977).
9. Reference deleted.
10. E. J. T. Burns, S. A. Goldstein, J. A. Halbleib, Sr., L. P. Mix, J. N. Olsen, J. W. Poukey, J. P. Quintenz and M. M. Widner, Sandia Report No. 78-2-026, unpublished.
11. V. Kaufman and J. Sugar, J. Opt. Soc. Am. 66, 1019 (1976).
12. D. D. Burgess, B. C. Fawcett, and N. J. Peacock, Proc. Phys. Soc. 92, 805 (1967).
13. D. J. Johnson, G. W. Kuswa, A. V. Farnsworth, Jr., J. P. Quintenz, R. J. Leeper, E. J. T. Burns, and S. Humphries, Phys. Rev. Lett, to be published.
14. D. L. Garrett and R. Tousey, Appl. Opt. 16, 898 (1977).
15. J. R. Kerns and D. J. Johnson, J. Appl. Phys. 45, 52254 (1974).
16. D. J. Johnson, A. V. Farnsworth, Jr., D. L. Fehl, R. J. Leeper, and G. W. Kuswa, submitted to J. Appl. Phys.
17. Reference deleted.
18. D. D. Burgess, B. C. Fawcett, and N. J. Peacock, Proc. Phys. Soc. 92, 805 (1967).
19. Hans R. Grien, Plasma Spectroscopy (McGraw-Hill Book Co., New York, 1964), Chap. 6, p. 153. R. W. P. McWhirter in Plasma Diagnostic Techniques edited by R. H. Huddleston and S. L. Leonard (Academic Press, New York, 1965), Chap. 5, p. 216.
20. H. Brysk, Plasma Physics 15, 611 (1973).
21. G. Lehner and F. Pohl, Z. Phys. 207, 83 (1967).
22. R. A. Lerche, L. W. Coleman, J. W. Houghton, D. R. Speck, and E. K. Storm, Appl. Phys. Lett 31, 645 (1977).
23. J. A. Harvey and N. W. Hill, to be published as a special volume of Nuclear Instruments and methods.
24. J. Kirtbridge, E. C. Yates, and D. G. Crandall, Nucl. Instr. and Meth. 52, 293 (1967).

25. C. W. Sandifer and D. G. Crandall, EG&G Report 1183-2331, EG&G Santa Barbara Operations Coleta, California (1975).
26. D. G. Crandall, EG&G Santa Barbara Operations, private communication.
27. J. Kimlinger and E. F. Plechaty, Lawrence Livermore Report UCRL-50532, October 1968.
28. H. Goldstein, Fundamental Aspects of Reactor Shielding, Addison-Wesley Publishing Company, Inc., Reading, Mass., 1959.
29. J. Chang, M. M. Widner, A. V. Farnsworth, Jr., R. J. Leeper, T. S. Prevender, L. Baker, and J. N. Olsen, Proc. of the 2nd Int'l Conf. on High Power Electron and Ion Beam REsearch and Technology, Ithaca, NY, Oct. 3-5, 1977.
30. J. N. Olsen, M. M. Widner, J. Chang, and L. Baker, Submitted to J. Appl. Phys. Sept. 1978.
31. K. D. Bergeron, J. Appl. Phys. 48, 3073 (1977).

OVERVIEW

Electron and ion beam propagation in current-carrying plasma channels is a method for providing standoff in particle beam driven ICF experiments and reactors. The channels are part of a configuration for combining many separate beams at a central target chamber. Theoretical and computational work in this area has concentrated on increasing the accuracy of our physical models for channel formation. The models now include both the effect of the various channel fields on electron beam propagation and the self-consistent channel heating caused by the return current which is generated as the beam propagates. Earlier studies of beam dynamics in the overlap region near the target chamber have been extended to configurations where the beams are injected in several separate planes to increase the beam concentration. New calculations for ion beam overlap have also been computed. All of these studies are aimed at providing information both for the present twelve beam experiment on Proto-II and for scaling to EBFA-I.

Theoretical work in the pulse power area has continued to concentrate on phenomena related to magnetic insulation. A new non-laminar theory has been developed to provide a simple analytic model for comparison with experiments on MITE. An evaluation of the slipping stream instability in a magnetically insulated flow was carried out to determine if it might explain current losses seen on MITE. Another approach to the same problem studied the trajectories of electrons injected into magnetically insulated lines. These additional particles represented untrapped electrons which could be created by geometry perturbations or instabilities. It was found that most of the injected electrons were lost from the system and had little effect on the current flow.

Electron beam focusing and deposition in thin targets is affected both by the usual electric and magnetic fields in the diode and by electron scattering.

A simulation code which treats these effects self-consistently was used to study the enhanced deposition experiments carried out on Proto-I using both flat anodes and the C-diode configuration. A good agreement was obtained with the experimental results. Another version of the code, without scattering, was used to study the dynamics of ions produced in the Proto-I radially converging ion diode experiment. The results were in qualitative agreement with the experiment and indicated the importance of studying beam space charge and current neutralization in the short drift region between the cathode and the target region.

STANDOFF AND BEAM PROPAGATION

Electron Beam Propagation in Plasma Channels

Inertial confinement fusion reactors based on multiple beams of relativistic electrons have been proposed^{1,2} to overcome impedance, focusing, and ion generation difficulties associated with power levels in the 10-100 TW range. Some of these designs³ incorporate a gas fill to reduce the x-ray damage to the first wall. Since the conceptual reactor chambers have radii of about 3-4 m, it is necessary to provide a means for transporting the tightly focused beams to the central target region. One such method² is to use an external capacitor bank power supply to strike a narrow discharge channel from the diode to the target. The discharge could be initiated by a laser⁴ for reactor applications, although present experiments have used a fine axial wire. As the discharge is ohmically heated, a pressure imbalance occurs. This drives a shock wave radially outwards, leaving behind it a channel of reduced density and high temperature. The density and electrical conductivity must be high enough to neutralize the self-fields of the

injected beam of electrons. To confine them to the channel further requires that the discharge current be of the order of the Alfvén current, $I_A = 17000 \text{ By A}$, to provide a radial confining force. A final requirement is that the mass of the channel be high enough to prevent significant channel expansion by the beam on the beam time frame. Air at an initial pressure of 0.1-1.0 atm and a final temperature of a few eV satisfies these requirements in present experiments. Discharges^{2,5,6} driven with currents reaching 60-80 kA in a few microseconds have been used successfully to propagate ~ 100-200 kA electron beams for distances of 50-100 cm. Application of the concept for intense light ion beams has been discussed by Goldstein, et al.⁶

A single electron injected off axis at zero angle into a channel carrying a uniform current density will execute sinusoidal betatron oscillations if the channel current $I_c \ll I_A$. At the higher channel currents required to confine the hotter electrons characteristic of a focused beam, the exact orbits are more complex, since the axial velocity V_z isn't constant. At the high beam current densities of interest, an axial return current almost completely cancelling the beam magnetic field is generated.⁷ This can be seen by assuming a Bessel function dependence $J_0(r)$ for the beam current and a constant conductivity σ inside the channel of radius r_c , with zero conductivity between r_c and a wall at R . Solving the relevant diffusion equation for a beam which rises linearly in a time τ to a value I_B , and then remains constant, gives

$$I_{\text{net}} = I_B \left[1 - \frac{\tau_d}{\tau} e^{-\tau/\tau_d} \left(e^{\tau/\tau_d} - 1 \right) \right],$$

for $\tau \geq \tau_d$,

where the diffusion time $\tau_d = \mu_0 g/b^2$ and b is found from $J_0(b r_c) = J_0(R/r_c)$ or $J_1(b r_c)$. For parameters of interest, the maximum degree of current non-neutralization I_{net}/I_B is only a few percent.

The return current is driven by an electric field which tends to retard

the beam electrons and to further alter their trajectories. At high current densities and long propagation lengths, this return current electric field effect can result in a potentially serious loss of beam energy and a further loss in beam fluence at the target by increasing the beam radius. The remainder of this note describes trajectory calculations in the channel fields and presents estimates of beam spreading and energy loss for reactor conditions.

Figure 1 shows schematically the configuration which was studied. MHD code studies⁸ of the evolution of the discharge channel current density have shown that it is approximately uniform in the radial direction before the beam enters the channel. Although an electron beam of sufficiently high current density could alter this distribution, a uniform discharge current density will be assumed. The exact trajectory equations are given by

$$\frac{dV_z}{dt} = \frac{e}{m\gamma} \frac{V_z}{c} \frac{V_z}{c} E_z + \frac{e}{m\gamma} V_z B_\theta, \quad (1a)$$

$$\frac{dV_z}{dt} \frac{z}{c} = -\frac{e}{m\gamma} E_z + \frac{e}{m\gamma} \frac{V_z}{c} E_z - \frac{e}{m\gamma} V_z B_\theta \quad (1b)$$

where we assume that E_z and B_θ are constant in space and time, and that $V_\theta = 0$. Scattering in the reduced density channels at electron energies greater than 1 MeV is negligible over the distances under consideration.

A simple approximate solution can be obtained from Eq. (1a) by letting $V_z = c$; since $B_\theta = -\kappa r$, where κ is a constant, one obtains for an electron injected at a radius r_0 with zero angle,

$$r = r_0 e^{\alpha t} \cos \omega t, \quad (2)$$

where $\alpha = eE_z/2m\gamma c$ and $\omega = (e\kappa c/m\gamma - \alpha^2)^{1/2}$. The condition $\omega \gg \alpha$ is easily satisfied for this application. It is further true that $\alpha \ll 1$ on the beam time scale so that the amplitude of the oscillation as a function of axial distance z down the channel is given by

$$A = r_0 (1 + \alpha z/c). \quad (3)$$

Fig. 1. Plasma channel configuration showing a typical trajectory with an increasing amplitude.

Eqs. (2) and (3) describe a trajectory with the usual betatron frequency ω and an amplitude which grows slowly with distance. This behavior is shown schematically in Fig. 1. If an electron is injected with an initial angle θ_0 , Eq. (3) is replaced by

$$A = A_0 (1 + az/c), \quad (4)$$

where

$$A_0 = \sqrt{r_0^2 + \left(\frac{c \tan \theta_0}{\omega} \right)^2}$$

The exact electron motion in channels of interest is more complicated. The electron loses energy at a rate given by

$$\dot{\gamma} = \gamma_0 - \frac{eE_z z}{mc^2} \quad (5)$$

This relation can be combined with Eq. (1) to yield the following exact trajectory equation,

$$\frac{d^2 r}{dz^2} - \frac{eE_z}{mc^2} \frac{z}{r^2} \left[1 + \left(\frac{dr}{dz} \right)^2 \right] \frac{dr}{dz} + \frac{\omega^2}{mc^2} \left[1 + \left(\frac{dr}{dz} \right)^2 \right]^{3/2} \frac{r}{\sqrt{\gamma^2 - 1}} = 0 \quad (6)$$

This equation has been numerically integrated using a standard Adams-Peace method. The results show that the betatron wavelength decreases as the electron loses energy to electric field. The trajectories also become distinctly non-sinusoidal over sufficiently long distances.

A third method used to study the problem was a particle-in-cell approach similar to those used to study diode focusing.⁸ This method has the advantages of being able to treat more general models of the channel, including varying field distributions and particle loss from the channel; it can also conveniently treat a beam with a distribution of initial conditions, including a hot beam characteristic of a diode pinch. The results for single particles agreed well with the results from the exact equation, Eq. (6).

Using the particle-in-cell code, parameter studies were done for cases relevant to electron accelerators at Sandia Laboratories: (initial) energy ~ 2 MeV, channel current ~ 50 -100 kA, channel radius 4 mm, channel length 50 cm. The code results for energy loss and beam spreading agreed fairly well with Eqs. (3) and (5). For cases with $I_c < I_A$, the beam spreading is essentially independent of I_c , but for cases with $I_c > I_A$, electrons injected at larger r_0 turn around in z (i.e., do not propagate down the channel). At larger values of E_z , the betatron wavelength is shorter as expected, since the exact paraxial result for ω is $(ekc/m\gamma - \omega^2)^{1/2}$. As expected, for E_z values small enough that γ doesn't change substantially, the linear dependence of the beam spreading on E_z suggested by Eq. (3) is correct. However, the increase in amplitude of a particular trajectory (which starts at r_0) increases somewhat faster than linearly with r_0 (at larger r_0 the paraxial result of Eq. (3) is a poorer approximation). An electron which is injected with an initial angle θ_0 merely moves on an expanding sine wave of different amplitude, roughly as given by Eq. (4). An analogous expression can be derived easily for ions. The mass dependence of Eq. (4) greatly reduces the importance of spreading, but the electric field could affect power compression in schemes which rely on ion bunching.

To estimate the importance of the beam spreading, it is helpful to look at

a few examples. Initial results were recently reported⁹ for beam propagation using the Proto II accelerator at Sandia Laboratories. The parameters in the twelve beam experiment were an electron energy of 1.25 MeV, a current per beam $I_B = 300$ kA, a channel current $I_C = 60$ kA, a channel length $l = 50$ cm, and a channel radius $r_C = 0.85$ cm. For complete current neutralization, $E_z = j/\sigma \sim I_B/\pi r_C^2 \rho_0$. For air at 2.5 eV and $\rho \sim 0.20 \rho_0$, $\sigma \sim 200$ mho/cm so that $E_z = 0.7$ kV/cm. (The total electric field E_z also includes a smaller contribution from the capacitor bank which drives the discharge phase.) If these parameters are used with Eq. (3), the amplitude $A = 1.01 r_0$ at $z = 50$ cm. This low degree of spreading is due both to the low average transported current density, ~ 140 kA/cm², and the relatively short propagation distance.

Modules for the EBFA-I accelerator,¹⁰ which becomes operational in 1980, are designed to produce $I_B = 500$ kA at $E = 2$ MeV. Typical target radii¹¹ are in the range of a few millimeters, so that channel radii $r_C \sim 0.2$ cm would be desirable for compatibility. Although EBFA-I is not designed to resemble a reactor (and thus has only a 25 to 50 cm beam transport stage), it is nevertheless of interest to examine the expansion of such a beam over a longer distance characteristic of a reactor,³ $z \sim 3$ m. It is seen immediately that a much higher electrical conductivity of the background gas is desirable; $\sigma \sim 4000$ mho/cm would limit the electric field to a value of about $E = 1$ kV/cm. This would require a gas temperature of several tens of eV, which would be difficult to achieve using direct discharge heating of the air at 0.1-1.0 atm. At lower pressures, return current heating,^{8,12} of the channel plasma becomes more efficient, especially for lower atomic weight media such as hydrogen or helium. This mode of heating could be used to supplement the discharge phase.

If an electric field $E_z = 1$ kV/cm is achieved, Eq. (3) predicts a beam spreading of $A = 1.06 r_0$ for a 3 m beam transport. This corresponds to a reduction in the current density $j \sim A^{-2}$, so that $j/j_0 = 0.89$. At the same time the electrons are losing energy at the rate $\dot{\gamma} = \gamma_0 - eE_z/mc^2$, so that

$\gamma/\gamma_0 = 0.89$. The net reduction in beam fluence F thus becomes $F \sim (\gamma-1)/(\gamma_0-1)$ $j_0 = 0.77$, which is an acceptable reduction of 23%. A larger electric field would lead to unacceptable losses in transport efficiency.

To summarize, it has been found that a beam injected into a current-carrying plasma channel induces a return current almost equal to the beam current. The electric field which drives this beam current spreads the beam radius in addition to reducing the beam electron energy; both of these effects reduce the transported fluence. These effects have been shown to be small for present day experiments which use relatively short channels and modest current densities. For reactor level parameters, a channel electric field of less than 1 kV/cm will be required. This electric field is achievable with high channel temperatures and conductivities, but these will probably require lower pressure, lower atomic weight background gases to enhance the efficiency of return current heating.

MHD Studies of Plasma Channels

Current-carrying plasma channels are required to transport focused electron or ion beams from multiple diodes to a central target region. An experiment was performed recently on Proto II which combined six channels at a cylindrical target. An improved version of the CHART-B 1-D MHD code was used to study the channel production theoretically and to compute the self-consistent return current heating produced by the beam. The code was also used to provide the Naval Research Laboratory with correct initial conditions to improve their studies of low density channels for light ion propagation. The range of air pressures for which the code is valid was extended by generalizing the radiation treatment to a multigroup diffusion.

The basic code has been described in detail in previous progress reports. The most recent modifications include a fully self-consistent calculation of the plasma return current which is then used to compute ohmic heating and Lorentz force effects in the plasma. (Our earlier

calculations assumed complete current neutralization.) The channel current calculation also includes the coupling to an external circuit self-consistently. A typical code run is divided into two time scales. The initial part computes the capacitor discharge phase, using as input the external circuit inductance, resistance, capacitance, and voltage, plus an assumed density, temperature, and radius representing the initial breakdown. The magnetohydrodynamic calculation of the channel variables proceeds until the beam injection time. The code then requires the input beam current density profile as a function of time as additional input. The return current growth and the channel heating and expansion which occur on the beam time frame are then computed.

Figure 2 shows the results for the channel production phase of the calculation for the Proto-11 experiment. The initial conditions were an external inductance of 250 nH, a resistance of 0.05 Ω , a capacitance of 10 μF , and a bank voltage of 100 kV. Six channels in air at 1 atm were assumed to be driven in parallel. The beam was to be injected at a time $t \approx 1.5 \mu\text{s}$, when the channel current was about 50-60 kA and the temperature was 2.2 eV.

Figure 3 shows the response of the channel on the beam time scale. A uniform current density 300 kA, 60 ns, 1.25 MeV beam with the trapezoidal pulse shape shown was used as input. The temperature had increased to 3 eV by 40 ns as measured in the beam time frame. This increase is helpful in reducing the ohmic loss and the spreading of the beam described in the previous section, but a higher temperature (and electrical conductivity) would be required for propagation of higher current density beams over several meters. The problem was not severe for Proto 11 because of the 0.5 m propagation length and the low injected current density. The electric field j_{p0} is plotted in Fig. 3, and is seen to have an average value of only 1 kV/cm.

The degree of current neutralization was very high, on the order of 99%. This can be understood by examining the L/R time constant which governs changes in the net current. Although the parallel connection reduces the effective channel

Fig. 2. Channel discharge phase.

Fig. 3. Beam injection phase.

inductance (and resistance), the external circuit inductance remains high and precludes rapid changes in the net current. Although not shown explicitly in Fig. 3, the density profile was substantially unchanged from that shown in Fig. 2, indicating that no serious expansion of the channel occurred.

One channel calculation was carried out for a lower density hydrogen channel appropriate for ion transport. Only the initial discharge phase was performed. The purpose of the work was to provide the Naval Research Laboratory with initial conditions which could be employed in the ion beam injection phase using their own MHD code. For realistic circuit parameters, a channel current rising to 18 kA in 4 μ s was achieved. At that time the channel radius was 0.55 cm and the channel temperature was 2.5 eV, as desired. It was found that in order to achieve the desired channel plasma ion number density of about $2 \times 10^{18} \text{ cm}^{-3}$, an initial fill density of molecular hydrogen at 10^{-3} g/cm^3 was required. This corresponds to a number density of about $3 \times 10^{20} \text{ cm}^{-3}$, so that the channel density was reduced by over a factor of one hundred by the discharge. This is to be contrasted with the density ratio of about five to ten seen in calculations for 1 atm air, and it occurs because of the lower ionization energy and higher specific heat of hydrogen.

Until recently, the radiation flow in the air plasma channels was treated by a phenomenological conduction model first used by Pavlovskii. This model was very easy to incorporate in the code and had a remarkably good comparison with experimental measurements of the channel density profile, the expansion velocity and the central temperature. Interest in extending the model to lower pressures resulted in an effort to replace the Pavlovskii formula with a proper multigroup diffusion treatment. An algorithm was developed for the code and spectrally resolved opacity data was obtained from R. Johnston at Science Application Incorporated.

Figures 4 and 5 compare the fringe shifts computed with the new version of the code with data taken last year

Fig. 4. Comparison of computed and measured interferometry fringe profiles at $t \approx 1 \mu$ s.

Fig. 5. Comparison of computed and measured interferometry fringe profiles at $t \approx 6 \mu$ s.

in channel experiments using the HYDRA accelerator. The example shown used an eight band model with boundaries at 0, 1, 3, 5, 7, 9, 12, 50, and 500 eV. The Schuman-Runge band for the oxygen molecule is included within the 9-12 eV bin. Opacity contributions for photon energies of less than 0.5 eV were neglected because of a lack of reliable data. The comparison is quite good at both times shown, and represents a significant improvement over the results using the simpler model. Very similar profiles were obtained with a five-band model. The initial conditions in the calculations assume that the air

discharge has just been initiated and that the wire plays no further significant role. It is thus necessary to time correlate the computed evolution of the channel with the experiment. The correlation for this comparison was done by matching the times at which the current reached its maximum value with the entire current pulse. The quality of the comparison suggests that the multigroup model should be useful for pressure scaling studies.

Multi-Channel Particle Beam Transport Theory

Several improvements in the single particle trajectory code were made to make the coding more efficient. The collisionless trajectory code was modified from a single trajectory calculation to a Monte Carlo version with many histories. Cosine and isotropic velocity distributions are provided within a solid angle specified by the user. The code was further modified to include the capability of using stacked disks of channels to study reactor scenarios. The code is interactive on the timesharing system and immediate trajectory plots can be generated at the terminal using either a graphics terminal or a digital plotter. Figures 8-10 were produced interactively.

The first multi-channel overlap calculations were performed for 40 and 36 electron beams in a wagonwheel disk arrangement.¹³ Since the injected beam current per channel exceeds the Alfvén-Lawson critical current for electrons, the channel must contain a highly conducting plasma to cancel the beam current. The injected beam particles are contained in the channel through the application of a plasma current over a timescale much longer than the beam pulse time. The net magnetic field is obtained from superposition of the individual channel magnetic fields.¹³

The first part of the work reported here is concerned with channel configurations and electron or ion beams relevant to the Proto 11 accelerator. The basic wagonwheel configuration in this case has 12 channel "spokes." Two discharge return current configurations will be discussed. The first consists

of two axial channels perpendicular to and fed by the 12 beam channels, in the standard wagonwheel (with axial) configuration. The second configuration alternates beam and return channels, so that there are 6 beam channels and 6 plasma discharge return current channels in the same plane. The first configuration leads to larger net magnetic fields as the plasma current flowing in the axial channels strengthens the superimposed beam channel fields. The net magnetic field at the edges of the channels is a minimum in the plane of the disk for the standard configuration, whereas for the alternating configuration, the net field between channels in the plane of the disk is a maximum. Thus, for the standard configuration, the individual beams merge to a disk beam at the overlap radius, whereas the alternating configuration keeps the beams from mixing azimuthally while allowing them to spread axially.

The first cases presented will be electron and ion beams injected into the standard wagonwheel configuration. Figure 6 shows the minimum radius achieved by several sample trajectories for 1.5 MV electrons for two cases where the individual channel radii (r_c) were 5 mm and 3 mm. In both cases, the mean value of the minimum radius (R_m) is about one-fourth of the overlap radius ($R_o = r_c / \sin(\pi/N)$), as seen previously,¹³ and the current density gain is a factor of 3 above that in a single channel. We note that 12 channels is an optimum of sorts for a single disk since $R_o \approx 4r_c$ so that $R_m \approx r_c$ for a 12 beam electron configuration. These results are further confirmation of the statement¹³ that the overlap results for electrons are relatively insensitive to geometrical configurations such as the number or size of channels.

Next, a series of proton calculations were performed for the same configuration. Higher overlap current density gains should be achievable with ions since their larger mass results in less bending in the channel fields, leading to colder beams. In fact, the initial proton divergence angle is expected to play an important role in the degree of overlap attainable. Two sets of ion trajectories were run with initial divergence half-angle 16° in 1.5 cm diameter channels to compare the effect of increasing the

Fig. 6. Points of closest approach ($R_{\min}$) to wagonwheel center for several trajectories in 5 mm and 3 mm radius channels.

channel current from 50 kA to 100 kA per channel. At 50 kA the overlap current density gain was 4.32 and it only increased 5% to 4.56 for 100 kA. The ion divergence angle was then decreased to 8° and 2° in successive runs. The results are shown in Fig. 7 where the current density gain saturates between 6 and 7 for small divergence angles. This saturation value depends on the number of channels and the ion divergence angle, as discussed below.

Fig. 7. Current density gain as a function of proton beam angular spread.

Figures 8 and 9 show the difference in the r-z trajectories of electrons in the standard configuration and in the alternating channel configuration. Without the fields due to the axial return currents, the electrons in the alternating configuration makes essentially force-free transits of the central region and escape radially or axially after a single pass. Figure 10 shows a comparison in the distribution of distance of closest approach to the center of the system for the two configurations. The alternating configuration is considerably broader, and principally because only half of the channels are being used to transport beams, the overlap gain drops to 1.5 from 3.4 for the standard configuration. Similar results were found for ions with 8° divergence angle: the current density gain dropped from 6.1 to 2.8 in the alternating configuration.

Fig. 8. R-Z projection of 3-D electron orbits in standard wagonwheel configuration. Predominant escape mechanism is axial grad in B drift.

Fig. 9. R-Z projection of 3-D electron orbits in alternating configuration. Predominant escape is radially up a return current channel.

Single disk overlap current density gain estimates for electrons and ions in uniform current density plasma channels can be obtained from the formula derived earlier¹³ for N beams converging on a cylindrical surface of radius R_m and height $2r_c$:

$$G = \frac{EN}{4} \sin\left(\frac{\pi}{N}\right) \approx \frac{\pi E}{4}, \quad (1)$$

where the approximation is for large $N(>10)$, and the parameter $\epsilon = R_0/R_m$ is a measure of the effective beam divergence at the end of the channel. For electrons, the channel current is close to the Alfvén current, so the beams come out of the channels hot and the trajectory calculations showed that $\epsilon \approx 4$, independent of the number or size of channels, provided that $R_0 > 4r_c$. If $R_0 < 4r_c$ ($N < 12$), then $R_m \approx r_c$ and $\epsilon \approx 1/\sin(\pi/N)$. Therefore, for a single disk system of N electron beams, the current density gain can be expressed as

$$G_e \approx \begin{cases} 3 & N > 12 \\ N/4 & N < 12 \end{cases}. \quad (2)$$

Fig. 10. Comparison of R_{min} distributions for electrons in alternating and standard wagonwheel configurations.

By going to multi-disk electron configurations to keep R_0 small, a net current density gain of 10 (3 disks) seems to be feasible.

Higher gains seem possible for ions because they are more massive and have a lower effective temperature which causes them to spread more slowly than electrons inside the overlap radius. For a given maximum injection angle θ_m of ions at a radial position r_i in a channel of radius r_c , the channel current can be picked to just contain the ion beam. This preserves the initial ion temperature during the channel transport so θ_m remains as the important parameter in the overlap estimate. If the effective ion temperature is large enough that the ion beam can spread more than a channel radius in the distance R , then $R_m \approx R_0 \tan \theta_m$. Of more interest are high brightness ion beams where $R_0 \tan \theta_m < r_c$ and $R_m \approx r_c$. The beam divergence parameter in Eq. (1) becomes

$$\epsilon_1 = \begin{cases} \cot \theta_m & \text{for } \tan \theta_m > \sin(\pi/N) \\ \frac{1}{2}(\theta_m) \csc\left(\frac{\pi}{N}\right) & \text{for } \tan \theta_m < \sin(\pi/N) \end{cases} \quad (3)$$

The trajectory calculations have shown that $f(\theta_m)$ increases from 1 for $\theta_m \approx \pi/N$ to 2 for $\theta_m \ll \pi/N$. Note that the transition in ϵ_1 occurs near $N\theta_m = \pi$, which gives $\theta_m = 15^\circ$ for $N = 12$ and 2° for $N = 90$. The current density gain factor for ion overlap becomes

$$G_1 = \begin{cases} \frac{1}{2} N f(\theta_m) & \text{for } N\theta_m < \pi \\ \frac{\pi}{N\theta_m} & \text{for } N\theta_m > \pi \end{cases} \quad (4)$$

Thus, for $N = 12$ and $\theta_m = 2^\circ$, $G_1 \approx 6$ as seen in Fig. 7. For $N = 90$ and $\theta_m = 2^\circ$, $G_1 = 22$. Higher overlap current density gains may be achievable by using multi-disk arrangements for ion beams.

Some multi-disk calculations for electrons in cylindrical geometry were undertaken which show effects on electron transport not found in single-disk systems. Five wagonwheel disks were stacked together with the combined discharge return currents flowing out along the axis of the system. Eighteen channels per disk gave a total of 90 beams. The superimposed magnetic fields proved to be too large to allow electron transport in all but the center disk which includes the $z = 0$ plane. One way to diminish this effect is to use conducting radial disks interleaved between the channel wagonwheels to carry the return current. This configuration isolates each wagonwheel between two conducting return current disks and allows efficient electron propagation to the overlap radius. A possible remaining problem is that the net field in the overlap region remains low and thus the electron reflexing required for enhanced deposition will be reduced.

These multi-disk results point out the need for careful design in future multiple beam configurations. The systems should provide good electron transport to the target and also allow for multiple electron passes if enhanced deposition in thin foils is to be obtained. Work will continue to optimize electron and ion transport.

Analytic Ion Self-Pinch Formulas

The interest in ions as ICF drivers has led to many ion diode designs which produce geometrically different ion beams. A set of analytical formulas have been derived for estimating self-pinch phenomena in four cases of interest, as shown in Fig. 11. The models are similar to those originally used by Lawson for electron pinches. The equation of motion for an ion at the beam edge is converted to an envelope equation which is solved using the paraxial approximation. This procedure assumes that orbit crossing is negligible, which is reasonable for ions at beam currents and energies of interest for ICF. Space-charge neutralization is assumed, so that only magnetic effects are considered.

For an axially injected solid cylindrical beam of initial radius r_0 and carrying net current I_n , the focal distance is given by

$$z_f = \left(\frac{\pi I_n}{4 I_n} \right)^{1/2} r_0 \quad (1)$$

with the critical ion current given by $I_n = 1.4(AV/Z)^{1/2}$ megamperes, and A = atomic number, Z = charge state, V = accelerating voltage in megavolts. For a typical proton beam $I_n = 35$ kA, $V = .8$ MV, $r_0 = 6.4$ cm, and $z_f = 34$ cm.

For a solid cylindrical beam with a geometrical focal angle θ_m , the focal distance is

$$z_f = \left(\frac{\pi I_n}{4 I_n} \cos \theta_m \right)^{1/2} r_0 \exp(\alpha^2) \operatorname{erfc}(\alpha) \quad (2)$$

with $\alpha^2 = (I_n/4 I_n) \sin \theta_m \tan \theta_m$. This reduces to Eq. (1) for $\theta_m = 0$, and has the asymptotic expansion $z_f = z_g [1 - 2(2\alpha)^{-2} + 12(2\alpha)^{-4}]$ with $z_g = r_0 \cot \theta_m$ the geometrical focal distance. For the same beam parameters as before and with $\theta_m = 21.6^\circ$, Eq. (2) gives $z_f = 12.8$ cm.

An axially injected hollow cylindrical beam with inner and outer return current conductors will pinch to a cylindrical sheet instead of collapsing on the axis since the ions at the inner edge of the beam are deflected outward to larger radii.

Fig. 11. Representation of beam envelopes for four different geometries: (A) solid beam, axial injection; (B) solid converging beam; (C) hollow beam, axial injection; (D) radially converging disk beam.

There are separate focal lengths for the inner and outer beam edges and their ratio depends only on the beam aspect ratio (r_o/r_i). For $r_o = 2r_i$, the focal distance for the inner beam edge is

$$\ell_i = .4(I_c/I_n)^{1/2} r_o. \quad (3)$$

with I_n equal to half of the unneutralized beam current. The focal distance of the outer beam edge is equal to $1.1 \ell_i$. For a reasonable set of proton beam parameters, $V = 1.2$ MV, $I_p = 200$ kA, $r_o = 5.4$ cm, which gives $\ell_i = 6$ cm.

A radially converging disk beam will also pinch to a sheet disk as it moves inward from its initial position r_o . To find the radial position r_p where this pinch occurs, it is necessary to invert the equation

$$\frac{r_p}{r_o} \left[1 - \ell_n \left(\frac{r_p}{r_o} \right) \right] = 1 - \ell_n \frac{I_c}{I_n}, \quad (4)$$

where d is the initial disk thickness and I_n is again half of the unneutralized ion beam current. For a 1.2 MV, 200 kA beam with $r_o = 15$ cm and $d = 5$ cm, we find $r_p = 1.7$ cm.

Since these formulas contain A , Z , and I_n , they should be useful in estimating focal distances or net currents (when focal distance is experimentally

determined) for arbitrary ion species.

Plasma Channel Thin-Foil Enhanced Electron Deposition

The magnetic field subroutine for multi-channels was incorporated into a version of the CYLEM¹⁴ Monte Carlo electron-photon transport code so that electron deposition in multi-channel configurations could be studied. The purpose of using thin foils is to increase the specific deposition above the classical value of 10^{12} W/cm²/gm-MA by causing several electron transits through the same section of foil. Several cases of axial injection into single plasma channels with a planar 12 μ m thick tantalum foil were run with magnetic fields corresponding to various plasma currents on both sides of the foil. Inside the beam radius, deposition enhancement was found to be between $8-12 \times 10^{12}$ W/gm-MA, which is 3-4 times the classical value. Several electron passes through the foil were obtained, but some of these occurred outside the beam radius and did not contribute to the enhanced deposition inside the beam radius. It was found that the gradient and curvature drifts in this configuration were not favorable in terms of returning electrons to the foil.

Radial injection of azimuthally uniform disk beams and azimuthally non-uniform multi-channel beams between two planar foils and cylindrical targets having dimensions of the order of the channel radii was studied next. Most of the runs produced classical deposition and again suffered from unfavorable particle drifts away from the foils. Also, relatively large target foil areas reduced the specific deposition. Deposition levels of 4×10^{12} W/gm-MA were obtained by making the return current channel radii equal to the beam channel radii.

These calculations have demonstrated the importance of the electron drift motion and foil area on the deposition enhancement, and further studies are underway.

Current Density Enhancement Using a Converging Plasma Channel

The behavior of a charge and current neutralized e-beam in a converging plasma channel has been modeled analytically and numerically. The purpose of the work was to study the possibility of focusing an electron beam (e.g., to a target) using an insulating, rigid, tapered wall to control the plasma current density (and hence the B_θ field) which in turn determines the beam motion. If the channel current density is uniform in radius r out to the wall radius r_0 , and increases with axial distance z like r_0^{-2} , where $r_0 = a(1-z/L)$, then for typical conditions (betatron wavelength $\ll L$) a WKB solution can be done and gives j_z (beam) $\propto r_0^{-1}$, or beam current $I(z) = I_0(1-z/L)$, where I_0 = injected beam current. This means the convergence is less than geometric (due to electron loss at r_0), but still conceivably of interest near the overlap region of EBFA.

The problem was also studied using a particle code, and for initially cold beams the code agrees well with the WKB solution. A typical trajectory is shown in Fig. 12, for $a = 5$ mm, $L = 6$ cm. Generally speaking, the current density enhancement for an initially cold beam will be about a factor of four over the first 3/4 of this 6 cm channel, and will be somewhat less for an initially hot beam. Adding a reflecting wall (due to a sheath current) for $z < 3/4 L$ did not help (electrons turned around and went back out the entrance plane), and adding the B_θ of a current on the axis gave a j_z enhancement of < 1 . Further work on other configurations may be tried, but the factor of four enhancement seems now to be the upper limit.

Inverse Diode Calculations

The diode simulation code has been used to study the 2-D inverse diode problem, for the purpose of studying the efficiency of conversion of power from a directed e-beam (e.g., emerging from a channel) to V-I in a small-diameter diode.¹³ The system actually simulated is sketched in Fig. 13. Space charge limited electrons were emitted from the cathode K (including shank), and ions

Fig. 12. Electron trajectory in a converging plasma channel.

Fig. 13. Inverse diode electron trajectories.

from anode A. The injected e-beam had uniform density (for $r < 7.5$ mm), an energy of 2 MeV, and was cold.

The results are given in Table I. Here V is applied voltage, I_{inj} is beam current injected through the anode plane, $I_{e,K}$ is electron current to the cathode, I_i is ion current, R is $V/I_{e,K}$, and η is the power efficiency = $(I_{e,K}/I_{inj}) \cdot (V/2 \text{ MeV})$.

Note for the 300 kA runs that $I_{e,K}$ decreases monotonically with V , while η peaks at about 30% near $V = 1$ MV. In these runs the beam current dominates so $B_0 > 0$ and the typical trajectory is A in Fig. 13. For the 100 kA runs, however, the diode current dominates so $B_0 > 0$ and the typical trajectory is B. In the 1 MA run, both types of trajectories are seen and in addition some of the $I_{e,K}$ is carried by types C and D. Still more complex trajectories are found in the 2 MA run. Conclusion: beams of 0.3 to 1 MA give the best η . The inverse diode is still not promising in this parameter range, but other parameter ranges could be more interesting. Studies to explore the feasibility of using an inverse diode to power a compact ion diode or an inverse diode which itself is powered by an ion beam have not yet been undertaken.

TABLE I.

$V(\text{MV})$	$I_{in}(\text{kA})$	$I_{e,K}(\text{kA})$	$I_A(\text{kA})$	$R(\Omega)$	η
0	300	300	0	0	0
.7	300	200	10	3.5	.25
1.0	300	180	13	5.6	.3
1.2	300	150	16	8.0	.3
1.5	300	0	30	< 0	0
1.0	100	0	24	< 0	0
1.5	100	0	70	< 0	0
1.0	1000	400	52	2.5	.2
1.0	2000	500	128	2.0	.13

PULSE POWER

Theory of Magnetically Insulated Flow

A general theory of planar, one-dimensional magnetically insulated flows has been developed. The theory assumes a distribution of electron canonical momenta (and energies if necessary) and reduces the problem to a single second order differential equation. Within the constraints of the model (i.e., planar, 1-D, time-dependent) the solutions are exact. The model is readily expanded to coaxial geometry which, however, requires two simultaneous second order differential equations to be solved. The quasi-laminar theories of Lovelace and Ott¹⁶ and Ron, Mondelli, and Restoker¹⁷ are limits of the general theory wherein the distributions are delta functions. The general

theory predicts that the flow must consist of at most a finite number of layers. The laminar theories of Creedon¹⁸ and others are limits as this number of layers goes to infinity. In spite of the value of laminar theories for understanding these flows, all laminar flows are unstable.¹⁹

In the case of relativistic, magnetically insulated flows, no laminar flow is set up, so the general theory is applicable. Several general theorems about these flows follow from the theory.

- (1) The electric field at the anode plane depends only on the total and boundary currents, and not directly upon the line voltage.
- (2) The average drift velocity of the electrons can be determined from the total and boundary currents.

- (3) The minimum bias current to total current ratio is given by the saturated quasi-laminar and laminar expression, i.e.,

$$I_{\text{Bias}}/I_{\text{Total}} \geq \left(1 + \frac{eV}{mc^2}\right)^{-1}$$

In addition, two hypotheses are expected to apply to relativistic flows.

- (1) The flow probably consists of a single layer or stream with all electrons gyrating about a common plane.

- (2) Excessive negative momentum electron components result in large bias current requirements.

Comparison of the theory with experiments indicates that the total and bias currents could be used to determine line voltage using the formula

$$\frac{eV}{mc^2} = I_A \left(\frac{2\pi I_b a}{I_A w} \right)^2,$$

where a/w is the ratio of plate separation to width, $I_A = 8.5$ kA, and I_b is the cathode current. An example of this is shown in Fig. 14, where the model was used to compute the time-dependent voltage using the experimental current trace from the Physics International triplate experiment.²⁰ An excellent comparison was obtained for this case.

Fig. 14. Example of voltage calculation from boundary current. Data is from the Physics International triplate experiment.

Analysis of a Slipping Stream Instability for Magnetically Insulated Electron Flow

Thin (sheet-like) unneutralized electron beams which have a shear in the electron fluid velocity across the layer are known to be susceptible to an instability whereby a wave on one surface interacts electrostatically with a wave on the opposite surface. This has been termed the slipping stream instability or the diocotron instability.¹⁹

A slightly different situation occurs in another class of beam problems in which there is velocity shear: magnetically insulated flow in vacuum between electrodes supporting a high electric field. It was suggested by VanDevender²¹ that current losses observed in experiments on the MITE accelerator might be attributable to a diocotron-like instability. The one missing ingredient in the magnetic

insulation case is a second beam/vacuum interface, since the beam is confined by the cathode on one side. With only one surface wave the instability cannot occur, which is fortunate from the point of view of practical applications because the growth rate of the instability is very rapid.

The motivation for the present work, however, is the observation that as cathode plasma develops, there is a second surface between it and the beam. (See Fig. 15.) This is equivalent to an ion-vacuum interface superimposed on the electron background, so a diocotron instability was possible, and we have investigated the dispersion relation which results when the beam/plasma layer is treated more realistically. The analysis may be relevant to anomalous current leakage in magnetically insulated vacuum gaps, when enough time has elapsed that the plasma layer is reasonably thick, and also to the problem of plasma closure and subsequent shorting of the gap, a process which may represent the practical limitation of high stress magnetic insulation. The exact form of the dispersion relation depends on the model chosen for the electron beam. Two cases were considered: the laminar (or parapotential) model in which electrons flow parallel to the surfaces, and the quasi-laminar or two-stream model in which electrons perform horseshoe-like orbits between the cathode plasma and the beam edge.

Fig. 15. Model for the modified diocotron analysis. Electrode effects are neglected.

The laminar flow model has a complex ω , real k behavior similar to the conventional diocotron theory, but the characteristic frequency is much lower (closer to the geometric mean of the ion and electron

cyclotron frequencies) (Fig. 16). There is however, no low frequency convective instability. The quasi-laminar model, on the other hand, exhibits such a convective (real ω , complex k) instability (Fig. 17), though k diverges at $\omega = \omega_c \sqrt{e/2}$, where $e \equiv m_e/m_i$. The quasi-laminar model also has the complex ω , real k behavior similar to the laminar flow model results (Fig. 18). Neither theory explains the apparent standing wave behavior seen in the MITE experiments, but these instabilities may be important in the late time behavior of magnetic insulation when plasma closure is an important breakdown mechanism. The details of this work have been published in a Sandia Internal Memorandum.²²

Fig. 16. Complex ω , real k dispersion relation for the laminar flow (parapotential) model. $e = 1/1836$ is assumed, corresponding to a hydrogen plasma.

Beam Stability and Loss Mechanisms in Magnetic Insulation

The 2-D electromagnetic particle code²³ has been used to investigate the effect on magnetic insulation of a beam of electrons injected longitudinally into a coaxial vacuum gap. Previous investi-

Fig. 17. Dispersion relation for the convective instability for the quasi-laminar case. Since the replacement $\text{Im } g^{\pm} \rightarrow -\text{Im } g^{\pm}$ is allowed but $\text{Re } g^{\pm} \rightarrow -\text{Re } g^{\pm}$ is not, there are actually four branches, of which only two are shown.

gations of magnetic insulation with this code have included only electrons emitted from the cathode cylinder. For the most part, agreement with experiment has been very good. For example, in Ref. 24, we have made a detailed comparison with experimental results for a 10 m long magnetically insulated coaxial line. This was an excellent opportunity to make such a comparison because there were current monitors for both total current and boundary current at three intermediate positions along the line. The overall agreement between the simulation and experimental results was very good.

However, there was one feature that appeared in this experiment (and in several others) which was not predicted by the code. This was a measurable loss (15%) in peak current between 2.5 and 5 m due to leakage to the anode behind the front. It was first pointed out by VanDevender²¹ that such losses

appear to be stimulated by geometry perturbations at the line input. In order to help understand this process, we have investigated simulations in which a beam is injected into the transmission line region at the input, yet in which space charge limited emission from the cathode surface is still allowed.

The first case considered was an injected beam with a parapotential profile.²⁵ The parameters used were appropriate for the NITE accelerator. If the parapotential beam were stable then we would expect the beam to flow the length of the transmission line and there would be no electron emission from the cathode. In fact, what is seen is that the parapotential beam leaks to the anode after a short distance, to be replaced by a beam of emitted electrons similar to the solution in the case of no injected beam. The current density at $z = 0$ and at $z = 1.5$ m (half the length of the line) at a time well past the front arrival time are shown in Fig. 19. For comparison, the beam profile in the absence of injection is also shown. (Fluctuations have been smoothed in the simulation results by averaging over several hundred time steps.) It is clear that the injected parapotential beam has essentially been transformed into an emitted beam with a very slight increase in beam density at large radii.

We conclude from these results that the parapotential beam is disrupted, apparently due to instability, within a short distance from the injection plane, resulting in a substantial current loss within the first 0.25 m. Many of the remaining injected electrons are, in the process, launched into orbits which have a relatively long lifetime (hundreds of cyclotron orbits), but which eventually drift to the anode (or cathode) to be replaced by emitted electrons.

The purpose of the second injected beam simulation is to study these long-life-time orbits with the idea in mind that they may explain the downstream losses seen in experiments. A very hollow beam was chosen with a total current (20 kA) which is small compared to the emitted beam current. The actual beam parameters are indicated in Fig. 20. The peak voltage was as before, 2.5 MV. Also shown in this figure is the current

Fig. 18. Same as Fig. 16 but for the quasi-laminar model. The geometric mean of the ion and electron cyclotron frequencies in both figures corresponds to $f = .023$.

Fig. 19. Current density at $z = 0$ and 1.5 m from the simulation with and without an injected beam of parapotential profile.

Fig. 20. Leakage current to the anode vs. position for the simulation with a hollow injected beam as shown in the insert (total injected current = 20 kA). Note that most of the current loss to the anode occurs between .5 and 1.5 m.

leakage to the anode in the form of total current incident between zero and z . Note that most of the beam loss to the anode occurs between .5 and 1.5 m. It is interesting that the anode losses in the MITE experiments (which had the same voltage and vacuum impedance) were confined to approximately the same region. In another run with the same beam parameters but with the beam centered at 7.75 cm, the entire 20 kA was lost to the anode between 0. and 2. m and, in contrast to the previous result, a substantial proportion (42%) of this occurred in the first 0.5 m.

In Ref. 26, we have considered the possibility that this low level leakage is a result of a diffusion-like process due to random variations in the trajectory parameters as field fluctuations are experienced by the electrons. There it is pointed out that, as in the case of plasma loss in Tokamaks, one class of particles may contribute disproportionately to the leakage. In our case these are "trapped particles" which neither intersect the anode nor the cathode during one gyropeniod.

Another question considered in Ref. 26 is by what mechanism such a beam of trapped particles might be generated. (See Fig. 21.) It is concluded that if, as in the non-relativistic case, the (self E) $\times$ B

drift is larger than the VB drift, such a beam could be generated in the injection region where the transmission line tapers down from the insulator. For a more complete analysis, the best approach would probably be to use a steady state particle code. However, it is important to point out that even with a knowledge of the beam profile, we cannot gain any better quantitative understanding of the beam diffusion problem with the electromagnetic particle code because the spectrum of field fluctuations is expected to be considerably different than for the physical system.

Fig. 21. Field lines and drifts due to electrode and space charge non-uniformities in a magnetically insulated transmission line. The output or load is to the right of the figure. Trapped particle beams might originate from region "a."

DIODE PHYSICS

Code Development

The most recent development in the diode code has been the coupling of the particle-in-cell (PIC) code with a collisional Monte Carlo model. This combined code allows the investigation of electromagnetic interactions in realistic diode geometries. The Monte Carlo model has

been described in detail elsewhere.²⁷ Electron energy loss is accounted for in the continuous-slowing-down approximation and multiple elastic scattering is described using the theory of Goudsmit and Saunderson.²⁸ Beam electron bremsstrahlung is computed and assumed to escape the problem (no photon transport is computed).

Preliminary results using this model to simulate the effects of varying anode material on beam pinching were reported earlier.²⁹ In this section more recent results with an improved combined code are presented. Figures 22a-22c are electron particle maps for the same Proto I diode configuration but with different anode materials. The diode voltage is 1.1 MV, and electron and ion currents are $I_e \sim 235$ kA, $I_i \sim 80$ kA for all three cases. Figure 22a shows the electron particle map for the case where the anode is perfectly absorbing. Any electron which encounters the anode is assumed absorbed by the anode at that radius. This corresponds to the results which are obtained with the PIC code by itself without any Monte Carlo included. In Fig. 22b the anode material is carbon. New electrons can be seen to penetrate into the anode material. This penetration depth is consistent with a 1.1 MeV electron's practical range in carbon. The beam pinch in this case is broadened over that obtained for the perfectly absorbing anode primarily due to the increased path length in the carbon. An electron entering at a small radius with a large angle can travel out to a larger radius before stopping and contributing its charge to the radial current density profile. In Fig. 22c the anode material is gold. Now the penetration depth is much smaller than for carbon and the backscatter fraction is higher. The beam pinch is broadened here due to this backscatter.

The following sections describe simulations of foil and C-diode experiments on the Proto I accelerator. These simulations use the combined PIC-Monte Carlo code in an attempt to predict specific deposition levels which are observed experimentally.

Fig. 22. Electron particle maps for different anode materials.

Proto I Enhanced Deposition Simulations

The enhanced deposition experiment which was performed on the Proto I accelerator using thin foils mounted over holes in the anode³⁰ was simulated with the combined PIC-Monte Carlo code described above. The diode configuration was first simulated in the usual manner with a solid anode. In the experiment a major effort was made to suppress the machine prepulse. The resulting low level of prepulse coupled with the small cathode size and short machine pulse length made the simulation and experiment agree very well. In fact the total current and current density profile predicted by the simulation were in very good agreement with experimental results even though no A-K gap closure was assumed.³¹ This suggests that the lower than usual prepulse level prevented significant plasma motion before the main pulse. The smaller cathode size reduced some of the time dependent effects which are not treated in the steady state diode code such as anode plasma production and pinch formation. These things taken together made the experiment behave much as the simulation would predict using the physical A-K gap. With the code and the experiment in agreement for the solid anode case, the effect of adding a foil mounted over a hole in the anode was next considered.

Figure 23 shows an electron particle map of the enhanced deposition simulation. The diode voltage was 1.1 MV. The anode material was carbon. The foil was a 6 μ m thick gold foil which was assumed to expand uniformly to a thickness of 0.10 mm. The hole in the anode was assumed to be completely space charge neutral with the total beam self-magnetic field included there. The results of this simulation were an electron current of $I_e \sim 210$ kA, an ion current of $I_i \sim 80$ kA, and a specific deposition in a 2 mm diameter spot of the foil of ~ 28 TW/gm. These results are again in very good agreement with the experimental results.³⁰

C-Diode Simulations

The C-diode concept in which a target is mounted on a stalk which extends

Fig. 23. Electron particle map and sample electron trajectory for enhanced deposition simulation.

to a point within a hollow cathode's inner radius has been investigated by computer simulation recently. First results were for the case of a solid density target and stalk mounted in the Proto I accelerator. These simulations described the important role which ions play in the operation of the C-diode in this configuration. The ions were shown to increase the electron emission, and hence current, and the distributed ion current produced a B-field more favorable to beam pinching into the target region.^{29,32}

The combined PIC-Monte Carlo code has been used to study the effect of lowering the target and stalk total mass while maintaining their size in the diode. This simulates the effect of to successively thinner targets and smaller stalks. The target and stalk size is maintained constant to simulate the target expansion. This method of attacking the problem assures that the only variables from run to run are the target and stalk mass densities. It was found that the coupled code becomes numerically unstable when the amount of energy that an electron loses in a given pass through the target becomes comparable with the diode potential fluctuations near the target.

This occurs at a density of about 1.0 gm/cm^3 for the gold foil considered. This corresponds to an unexpanded foil thickness of $\sim 90 \text{ }\mu\text{m}$. This imposes a limit on the thickness of foils which can be treated with this version of the diode code. This thickness limit is less than a practical range for the 1.5 MV electrons considered here and hence some trends towards even thinner foils (for example the $6 \text{ }\mu\text{m}$ thick foil considered experimentally) can be seen.

Figures 24a and 24b show electron particle maps for two different target densities. The Fig. 24a is for a normal density (19.3 gm/cm^3) gold target. Very little target penetration is seen in this case. In Fig. 24b the target is an expanded gold target with a density of 2.0 gm/cm^3 . The thickness is less than a practical range and the electrons make several passes through the target. These two simulations illustrate the trend in going to thinner and thinner foils. The diode flow pattern remains essentially the same until the thickness is reduced below the practical range. The flow pattern is modified for the thinner targets as a result of increased electron space charge and enhanced ion emission due to electron reflexing. The additional ion current leads to enhanced electron emission from the cathode inner shank and less emission from the cathode face. Work is in progress to study thinner foils and also beam propagation using the C-diode concept.

Ion Diode Studies

The Proto I radially converging ion diode experiment has been simulated with the diode code.^{33,34} The code is two-dimensional, steady state, and treats electron and ion motion in self-consistent electric and magnetic fields. The applied and self-magnetic fields, which are excluded from the anode but fully penetrate the thin disc cathodes, are computed by solving the one component vector potential equation with the proper boundary conditions. Figure 25 is the result of one such simulation, assuming cylindrical symmetry for the diode. The figure contains an ion simulation particle map at an instant in time in one quadrant. Lines of equal

Fig. 24. Electron particle maps for Proto I, C-diode simulation for (a) 19.3 gm/cm^3 target density and (b) 2.0 gm/cm^3 target density.

intensity B_{app} are shown in a second quadrant with the x and z axes being the axes of symmetry. The assumed diode voltage is 1.2 MV and the B_{app} in the anode-cathode gap is approximately 13 kG. A typical electron trajectory is shown at the position of the virtual cathode near one B_{app} field line. The ions are accelerated across the gap from the anode to the virtual cathode and then travel in a reduced electric field region toward the axis. In the simulation shown in Fig. 25, complete space charge neutralization was assumed between the discs and hence the only electric field which exists there is the small amount which penetrates the virtual cathode. The magnetic field component in this region due to the ion return current on axis causes the nearly laminar self-pinch ion flow shown by the ion map in Fig. 25. When the space charge electric field between the discs was not set equal to zero in an attempt to numerically simulate the neutralization process, large fluctuating potential wells developed between the discs. In this case only approximately 10% of the beam was transported to the diode center-line. This must be compared to a 90% transport efficiency for the simulation with complete space charge neutralization. There is experimental evidence that these space-charge-produced wells do not occur. The presence of a low density background gas (not included in this simulation) can in fact help the neutralization. Possible sheath structure not resolvable in the simulation can also help to account for the large calculated potentials (with space charge neutralization not assumed) which are not observed experimentally. The simulation of Fig. 25 predicts a total ion current of approximately 270 kA and an electron current of approximately 100 kA.

It has been shown experimentally that a high intensity ion beam can be extracted from this magnetically insulated ion diode and focused at the diode center-line. The observed 75% ion production efficiency agrees with the numerical simulation value although a 37% smaller diode gap was used in the simulation. This is at least partially attributable to a 1 mm reduction in the 8 mm experimental gap due to gap closure (5 cm/ μ sec was required to explain the observed time dependent impedance) and also a

Fig. 25. Radially converging ion diode: ion particle map and applied magnetic field lines.

2 mm reduction in gap due to the anode plasma thickness. As stated above, in the simulation with perfect neutralization 90% of the beam arrived at the diode center-line, whereas only 10% arrived in the attempt to numerically simulate the neutralization process. This must be compared to 25% (ignoring geometric considerations) in the experiment, suggesting that the actual neutralization is between the two simulations. The simulation effort on this diode is continuing with the inclusion of a background gas in the diode region.

ACCELERATOR PHYSICS

Two-Dimensional Studies of Ion Beam Neutralization

A crucial problem in the acceleration of intense ion beams by linear accelerators is providing enough low energy electrons for space charge neutralization.³⁵ Using a 2-D PIC simulation, we have studied this problem for an ion beam in the 2-20 kA range as it passes through a single accelerating gap. The configuration studied is relevant to the PULSELAC device, in which insulating cusp-like magnetic fields are present in the gaps,³⁶ as shown in Fig. 26. The typical $|B|$ is several kG.

Fig. 26. Single accelerating gap of a linear ion accelerator, showing lines of the applied B field. Radius of outer boundary is 20 cm, z-length considered is 24 cm.

The necessity for electron neutralization is illustrated by Fig. 27, which shows the spreading of a completely unneutralized 3.4 MeV, 20 kA proton beam accelerated through 1 MV. If we emit electrons from the bottom surfaces, and in the gap, and inject a charge and current neutral ion beam, the electron particle map is shown in Fig. 28. The applied B (Fig. 26) insulates the gap, electrons entering with the ions tend to mirror in the cusp, and electrons from the left side in the figure are picked up and carried out with the exiting ions. There is a non-neutral region near the center, however, and in passing through this region the ions will acquire a transverse energy. The amount of ion spreading will depend on the ion current and energy.

The motion of a 2 kA, 3 MeV proton beam with electron neutralization is shown in Fig. 29. This solution is for parameters not unlike the envisioned early gaps in PULSELAC, and we see the optimistic result that the ions receive only a tiny perturbation in passing through a single gap. Figure 30 shows

Fig. 27. Space charge blowup of an unneutralized ion beam. Beam moves from right to left.

Fig. 28. Electron particle map from a PIC simulation.

Fig. 29. 3 MeV, 2 kA proton beam with electron neutralization.

Fig. 10. 3 MeV, 20 kA proton beam with electron neutralization.

that a 20 kA beam (with the other parameters unchanged), however, acquires considerable transverse energy, and is certainly above the practicable current limit for these parameters, unless further electron neutralization is provided by some means not included in the present simulation model (several possibilities are being considered).

This work, when combined with the 1-D studies reported earlier,³⁵ leads us to conclude that electron neutralization of intense ion beams in linear accelerators should be easily achievable to a high enough degree to allow acceleration of kA ion beams through at least a few gaps without undue radial spreading. The code is expected to be of use in further studies of space charge effects and gap insulation in linear ion accelerators.

REFERENCES

1. L. I. Rudakov and M. V. Babykin, in Proc. Seventh Eur. Conf. on Cont. Fusion and Plasma Physics, Lausanne, Switzerland (1975).
2. 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 (1977).
3. D. L. Cook and M. A. Sweeney, Proc. of Third ANS Topical Meeting on Tech. of Cont. Nuc. Fusion, Santa Fe, New Mexico, 1978.
4. J. R. Greig, D. W. Koopman, R. F. Fernsler, R. E. Pechacek, I. M. Vitkovitsky, and A. W. Ali, Phys. Rev. Lett. 41, 174 (1978).
5. P. Miller, L. Baker, J. R. Freeman, L. P. Mix, J. W. Poukey, and T. P. Wright, Proc. of 2nd Int. Topical Conf. on High Power Electron and Ion Beam Res. and Tech., Cornell University, Ithaca, NY, October 1977.
6. S. A. Goldstein, D. P. Bacon, D. Mosher, and G. Cooperstein, Proc. of 2nd Int. Topical Conf. on High Power Electron and Ion Beam Res. and Tech., Cornell University, Ithaca, NY, October 1977.
7. J. R. Freeman, P. A. Miller, L. Baker, J. P. Quintenz, T. P. Wright, J. W. Poukey, L. P. Mix, and M. M. Widner, 1978 IEEE Int. Conf. on Plasma Science, Monterey, Calif., May 1978.
8. J. P. Quintenz and J. W. Poukey, J. Appl. Phys. 48, 2287 (1977).
9. P. A. Miller and L. P. Mix, Bull. Am. Phys. Soc. 23, 853 (1978).
10. T. H. Martin, D. L. Johnson, and D. H. McDaniel, 2nd Intl. Topical Conf. on High Power Electron and Ion Beam Res. and Tech., Ithaca, NY, 1977.
11. M. J. Clauser, Phys. Rev. Lett. 34, 570 (1975).
12. D. Mosher, D. G. Colombant, S. A. Goldstein, and Roswell Lee, 1978 IEEE Int. Conf. on Plasma Science, Monterey, Calif., May 1978.
13. T. P. Wright, J. Appl. Phys. 49, 3842 (1978).
14. J. A. Halbleib, Sr. and W. H. Vandevender, J. Appl. Phys. 48, 2312 (1977).
15. Physics International Report, PIFR-959, September 1977.
16. R. V. Lovelace and Edward Ott, Phys. of Fluids 17, 1263 (1974).
17. A. Ron, A. A. Mondelli, and N. Rostoker, IEEE Trans. on Plasma Sci. PSI-1, 85 (1973).
18. John M. Creedon, JAP 46, 2946 (1975).
19. O. Buneman, R. H. Levy, and L. M. Linson, JAP 37, 3203 (1966).
20. M. Di Capua and D. G. Pellinen, Physics International Report PIFR-1009, March 1978.
21. J. P. VanDevender and D. H. McDaniel, Proc. of the VIII Intl. Symp. on Discharges and Electrical Insulation in Vacuum (Albuquerque, New Mexico, September 1978).

22. K. D. Bergeron, Sandia Laboratories Internal Memorandum RS 4241/1005, October 1978, Unclassified.
23. J. W. Poukey and K. D. Bergeron, J. Appl. Phys. 32, 8 (1978).
24. K. D. Bergeron, J. W. Poukey, M. S. Di Capua, and D. G. Pellinen, Proc. of the VIII Intl. Symp. on Discharges and Electrical Insulation in Vacuum (Albuquerque, New Mexico, September 1978).
25. J. M. Creedon, J. Appl. Phys. 46, 2946 (1975); 48, 1070 (1977).
26. K. D. Bergeron and J. W. Poukey, SAND-78-2234J, submitted to J. Appl. Phys.
27. M. M. Widner, J. W. Poukey, and J. A. Halbleib, Sr., Phys. Rev. Lett. 38, 548 (1977).
28. S. Goudsmit and J. L. Sanderson, Phys. Rev. 57, 24 (1940).
29. J. P. Quintenz and M. M. Widner, Particle Beam Fusion Progress Report - October 1977 through March 1978, SAND-79-0002, Sandia Laboratories, Albuquerque, New Mexico (March 1979).
30. M. M. Widner, S. A. Goldstein, C. W. Mendel, E. J. T. Burns, J. P. Quintenz, and A. V. Farnsworth, Jr., submitted for publication.
31. S. A. Goldstein, C. W. Mendel, and J. P. Quintenz, Bull. of APS 23, 763 (1978).
32. J. Chang, J. P. VanDevender, A. V. Farnsworth, Jr., M. M. Widner, E. J. T. Burns, and J. P. Quintenz, Bull. of APS 23, 763 (1978).
33. J. P. Quintenz, J. W. Poukey, and D. J. Johnson, Conference Record - IEEE International Conference on Plasma Science, Monterey, California, 174 (1978).
34. D. J. Johnson, G. W. Kuswa, A. V. Farnsworth, Jr., J. P. Quintenz, R. J. Leeper, E. J. T. Burns, and S. Humphries, Jr., to be published.
35. J. W. Poukey and S. Humphries, Jr., Appl. Phys. Lett. 33, 122 (1978).
36. S. Humphries, Jr., J. Appl. Phys. 49, 501 (1978).

CHAPTER 4 PARTICLE BEAM EXPERIMENTS

OVERVIEW

The following abstracts summarize the content of this section:

Five-Frame X-ray Camera Development

A variety of improvements have been made to the five-channel time-resolved x-ray camera. It has been used for XUV measurements on ion driven targets as well as with REB targets.

Optimization of Electron Beam Pinching from Small R/d Cathodes for Thin Foil Enhanced Deposition Experiments on the Proto I Accelerator

A modification to the Proto I accelerator and pinch development work have resulted in a diode capable of delivering 20 MA/cm^2 to a planar target. Thin foil targets irradiated at the 10 MA/cm^2 level have been studied. Deposition of $5 \times 10^{13} \text{ W/gm}$ have been measured; this is in agreement with diode-Monte Carlo simulations and with analytic theory.

Pulselac

Work has continued on the Pulselac program. Ion sources providing up to 30 kA of protons and 2 kA of carbon ions have been developed. Magnetic gap insulation, neutralization of the transported ion beam, and post-acceleration have been demonstrated.

A Dual Current Feed Magnetically Insulated Light Ion Diode

A modular ion diode has been developed and tested on Hydra. The diode uses an externally driven coil system to provide electron insulation. A proton beam with half-angle divergence of 2 degrees and peak intensity of 60 kA/cm^2 was obtained. A cogenerated carbon ion beam was also observed and diagnosed and will be the object of future experimental studies.

Multiple Electron Beam Propagation Experiment on Proto II

Initial results have been obtained with the Proto II twelve-beam system. Six of the 12 beams have been transported 46 cm to a cylindrical target with a radius of 1 cm with

efficiency of roughly 90 percent. This is in agreement with theory. More detailed measurements will be performed on a variety of targets in the immediate future.

FIVE-FRAME X-RAY CAMERA DEVELOPMENT

A number of processes associated with particle beam fusion produce radiation in the XUV to hard x-ray region. Such phenomena include bremsstrahlung production, atomic excitation, and thermal emission. A five-frame, time-resolved x-ray camera is being developed which is sensitive in this region for studies of the transport and focus of electron and ion beams, the interaction of these particle beams with targets, and the subsequent motion of such targets during irradiation: These events represent luminous objects; the camera is also being adapted for studies of targets using a radiographic technique with a single time-resolved frame.

The necessity to protect the final image stage of the camera, a phosphor, from hard x-rays and to look directly at the object dictate the basic camera design shown in Fig. 1. A five pinhole array focuses continuously changing x-ray images on five, independently gated microchannel plates where

PHYSICAL DESCRIPTION

Fig. 1. Schematic diagram of gated x-ray camera.

time-resolved electron images are formed in a predetermined time sequence. These electron images are then transported out of the x-ray beam by a curved magnetic field to another microchannel plate where the images are amplified. The images then strike a phosphor, the emitted optical light is transported outside the vacuum region through fiber optics, and the final images are recorded on Polaroid film.

Improvements

The following determinations and improvements have been made since the last progress report:

- (1) The prototype camera has yielded useful information for beam experiments on large accelerators such as Rehyd and Hydra. These results are summarized below.
- (2) The pinhole optics has been improved so that the field of view at the object is 1.9 cm, and the resolution is presently limited by the pinhole diameter.
- (3) The resolution at the object for hard x-rays is approximately 0.46 mm.
- (4) The sources for several image distortions have been identified and eliminated. Figure 2 shows the images of the front microchannel plates as uniformly illuminated before and after correction. In Fig. 2a, rounding compression and off axis drifts are visible; the image size in Fig. 2b should be compared with the actual detector size in Fig. 2c. The variation in size is approximately 10 percent. (A chipped plate is visible in Fig. 2b.) Distortion due to dynamic sources, such as EMP, still need investigation.
- (5) The shutter pulse monitoring system has been improved. Although typical, voltage gate pulses are approximately 900 V high and approximately 10 ns (FWHM) wide, the actual image may be determined by a shorter pulse. This idea is illustrated in Fig. 3. A 12 ns (FWHM) voltage pulse is shown in Fig. 3a. This pulse, after correction for the accelerator voltage, modulates the gain of the microchannel plate which is extremely nonlinear (Fig. 3b). The result is a gain pulse of approximately 2 ns FWHM duration (Fig. 3c). The intensity of the electron images is determined by the gain of the

Fig. 2a. Distortion due to induced currents in aperture plate as B-field rises. This distortion was eliminated by increasing the B-field rise time by 3X.

Fig. 2b. Corrected images.

Fig. 2c. Actual detector size.

microchannel plate during exposure. Experiments are planned to test this analysis.

Applications to Particle Beam Experiments

In the hard x-ray regime the camera has examined the interaction of a relativistic electron beam with a spherical target in the "C" diode configuration. Figure 4a shows a schematic of the physical arrangement, and Fig. 4b is an example of a time-integrated picture of the event. Time-resolved x-ray pictures of the interaction are shown in Fig. 5 together with a correlation of the accelerator power pulse and the shutter time. The information gained in this experiment was useful in determining how uniformly the electron beam irradiated the target and if the focus of the beam wandered appreciably with time.

Fig. 3a. Typical detector gate signal; 12 ns (FWHM).

Fig. 3b. Typical gain-voltage characteristic for microchannel plate. X's mark calibration points. Dotted line indicates approximation.

Fig. 3c. Computed gain pulse; 2 ns (FWHM).

Fig. 4a. Physical configuration for Hydra shot = 7405.

Fig. 4b. Time-integrated picture.

In the soft x-ray and XUV regime the camera has examined the focus of a multicomponent ion beam on an aluminum plate. The time-resolved images suggest three distinct, but time-overlapping, events in the operation of the diode. First, at early times electron-produced bremsstrahlung produces a uniform haze on the images, which could be reduced with thicker shielding of the camera. Second, just as the hard x-ray signal is decaying away, a focus of approximately 5 mm diameter and 20 ns duration is visible in the images corresponding to the arrival of the proton beam. Third, broad and spatially shifted focuses appear in the field of view and correspond with the arrival of C^{14} ions. A composite photograph of these events is shown in Fig. 6. Such studies graphically revealed the complexity of the ion beam composition and transport in this diode which could not be addressed previously.

Summary and Future Plans

Thus far, the five-frame camera has demonstrated its feasibility for use in particle beam accelerator environments and yielded some qualitative data in electron and ion diode experiments. Such applications are planned to continue, but attention must also be paid to calibrating the response and exposure of the instrument, determining its dynamic range, obtaining its ultimate resolution, and removing the remaining distortions. A small, proximity-focused camera for soft x-ray studies is also under development. Finally, the application of the camera to target experiments in radiographic mode will be expanded.

A(57ns) B(87 ns) C(100ns) D(110 ns) E(133 ns)

Fig. 5. Comparison of x-ray images to diode power history. The indicated times mark the peak of the voltage pulses to the camera. In these photographs the anode and stalk (not visible) lie to the right. Original photographs taken with Type 55 Polaroid film.

Fig. 6. Time-resolved pinhole photographs of the proton and carbon beam foci obtained with the five frame CEMA camera. The continuous curves are B loop data obtained behind target apertures at locations P and C. The dotted curves are XRD signals obtained viewing a 9 mm diameter region of the target between the gas injection jets.

OPTIMIZATION OF ELECTRON BEAM PINCHING FROM SMALL R/d CATHODES FOR THIN FOIL ENHANCED DEPOSITION EXPERIMENTS ON THE PROTO I ACCELERATOR

For the last several years, the electron beam pinch work performed on Proto 1 has been directed toward obtaining the highest power density beam generated by a single, small R/d cathode for use in deposition physics and target irradiation studies. The single beam optimization work commenced by shorting one half of the Proto 1 double diode (to reduce prepulse voltage and the consequent early production of diode plasmas) and operating the other half with an anode-cathode gap adjusted to run a 7 ohm diode impedance to match the characteristic impedance of the accelerator. With a corrected voltage, $V_d = 2$ MV, and a total diode current, $I_d = 250$ kA, typical axial electron current densities (ion flow taken into account) on thick targets evaluated from time-integrated x-ray pinhole photographs of 5-7 MA/cm² were obtained. An improvement to this operating mode was made by employing a capacitive division, cathode shank mounted, flashover switch to further suppress prepulse allowing diode operation at a smaller A-K gap and lower impedance (≤ 4 ohms).² In raising the total diode current from 250 to 340 kA (undermatching the accelerator impedance), an increase in axial current density to 8-12 MA/cm² was obtained. Diode current and voltage parameters and the resultant current density profile for a sample shot are shown in Figs. 7 and 8, respectively. A diode-Monte Carlo code was used to model the performance of the diode in this configuration. When using the measured corrected voltage and actual vacuum A-K gap as fixed variables, the current density profile from the code (Fig. 9) was found to be in reasonable agreement in both shape and amplitude with the experimentally determined profile.

A final improvement in pinch quality was obtained by convoluting the electrical feed in the pulse forming section to allow the energy stored in both halves of the accelerator to be delivered in parallel to a single diode while simultaneously decreasing the amount of prepulse.² In lowering the characteristic impedance to 3.5 ohms, both the voltage and current into the diode were increased (see Fig. 10); since the pinch remained approximately in the same area, the axial electron current density was raised to 18-20 MA/cm² (Fig. 11).

With these sequential increases in beam current, and current density (and hence pinch

Fig. 7. Sample corrected voltage, total diode current, impedance, power, energy, and prepulse voltage vs. time for diode operation at 4 ohms. Actual A-K gap prepulse was 0.3 times the waveform shown due to the capacitive division of the cathode prepulse switch.

Fig. 8. Current density profile (J_e) and electron current (I_e) vs. radius plots for the diode conditions of Fig. 7. Solid line is from left half of scan of x-ray photograph, dotted line is from right half; comparison is an indication of circular symmetry of pinch.

Fig. 9. Theoretical j_e and I_e vs. radius plots from a diode-Monte Carlo code using the same experimental conditions as the shot in Fig. 8. Poor agreement between theoretical and experimental I_e plots is a result of zone size and statistics of the code.

V/Y), it became feasible to study the effect and scaling of enhanced deposition mechanisms by directing the pinched beams onto thin foil targets. This approach was first suggested by Yonas et al.³ and later studied experimentally by Rudakov and co-workers.⁴ Additional theoretical^{5,6} and experimental^{7,8} results were subsequently reported. The subsequent experiment⁷ reported lower deposition rates than those of Ref. 4 although diagnostics, pinched beam conditions, and diode-target geometry were different.

The enhanced deposition experiments reported here were performed before final diode optimization by convoluting the power feed, so that typically J (current density) ≈ 10 MA/cm² on axis for thick graphite anode. The experimental geometry, shown in Fig. 12, consisted of a hollow, tapered, brass cathode and a graphite anode whose thickness outside the pinch region exceeded the range of 1.1 MV electrons. The target itself was a 6.4 μ m thick gold foil whose diameter (3 mm) was

Fig. 10. Corrected voltage, total current, impedance, power, energy, and prepulse voltage for a sample shot after convoluting the power feed.

selected to be only slightly larger than the region irradiated by the beam during its tightly pinched phase. Use of thin foils much bigger than the pinch area caused spreading of the beam compared to the thick target case, presumably due to scattering within the foil and undesirable reflexing mechanisms, and resulted in significantly lower deposition rates. Note that it was possible to view both the front (diode side) of the foil through the hollow cathode, and the rear side of the foil through the hole in the graphite portion of the anode.

Diagnostics consisted of a time-integrated x-ray pinhole camera, x-ray photoelectric diodes (XRD), and accelerator voltage, current, and switching simultaneity monitors. Several different diagnostic configurations were used: (1) XRD on front and x-ray camera on rear; (2) x-ray camera on front and XRD on rear; and (3) V.O.s on both sides with no x-ray camera. The time-integrated x-ray pinhole camera was

Fig. 11. J_e and I_e vs. radius plots after convoluting the power feed.

sensitive to hard x-rays with photon energy $\geq 30 \text{ keV}$ and was used to determine the pinched beam size and location with respect to the target. The pinhole resolution ($\leq 0.05 \text{ cm}$ for $\sim 2\times$ magnification) was significantly higher than the measured pinch diameter. Surface temperature measurements were made using x-ray diodes with aluminum photocathodes. A set of three diodes were mounted at the end of a cylindrical, baffled tube at a distance of 268 cm from the foil. Each of the three diodes was sensitive to a different portion of the spectrum: (1) unfiltered-peak sensitivity $\sim 20 \text{ eV}$, range 8–30 eV; (2) $0.8 \mu\text{m}$ aluminum filter-peak sensitivity $\sim 40 \text{ eV}$, range 30–70 eV, and (3) $0.33 \mu\text{m}$ parylene plastic filter-peak sensitivity $\sim 150 \text{ eV}$, range 70–380 eV. Permanent magnets were used to prevent electrons and fast ions from entering the XRD's.

Of the 29 successful shots in this data set, XRD measurements were made on the front side on 15 shots, on the back side for 12 shots, and on both sides for 2 shots. The average value of the peak XRD signal for the unfiltered channel was 17 volts for the front surface and 1.4 volts for the rear surface. A

Fig. 12. Diode configuration for enhanced deposition experiments. A tapered hollow, brass cathode, C, a carbon anode, A, and a thin gold target covering the through-hole in the anode are shown.

surface temperature can be inferred from these signals given detector response, detector geometry, emitting spot size, and source spectrum. For spot diameters of 0.2 cm, which corresponded to the pinch full-width-half-maximum as determined by thin target x-ray pinhole photograph, and average peak surface temperature of 20 eV was obtained for the front surface and 6.7 eV for the rear surface for an assumed black body spectrum. The inferred temperatures obtained from the Al and parylene filtered channels were within 10% of the unfiltered channel value averaged over all the shots for which data were available.

When the timing of the XRD signal was compared with the machine voltage pulse, the XRD signal peaked as the voltage dropped to zero or within 10 nsec thereafter. This timing relationship was consistent with magnetically enhanced deposition, with deposition enhancement factor^{4,5} (X) proportional to I/I_A . Peaking slightly after the voltage crossed zero

may be due to diode plasma stagnation, increased emitting area due to radial expansion, or to late time diode shorting phenomena as a consequence of plasma motion.

One can estimate deposition rates in the region of B-field penetration as^{5,6}

$$P_M = \gamma J \frac{1}{\rho} \frac{\partial x}{\partial t} \quad (1)$$

where $\chi \equiv$ enhancement factor ~ 2 for $I_p < I_A$, $\chi = 2 I_p / I_A$ for $I_p > I_A$, $P_M =$ power deposited/mass (W/gm), $J = I_p / \pi r_b^2$ (amps/cm²), $I_p =$ pinch current (amps), $I_A = 17000$ B (amps), $r_b =$ pinch radius (cm), and $\rho = 1.8 \times 10^{-6}$ g/cm³ = stopping power (electron volts/gm/cm²) $\sim 10^6$. To correctly calculate I_p , given the diode voltage = V and current = I , one must subtract the ion current from I (typically a 40% correction for present voltage and current conditions) and subtract the electron current for $r > r_b$. A probable lower bound on the electron current is $I_e = I(1 + I/I_A)^{-1}$, where $I = 1.58 \times 10^5 A^{1/2} (\gamma + 1)^{1/2} \ln(\gamma + (\gamma^2 - 1)^{1/2})$ and $A =$ atomic mass (AMU) (see Ref. 10). The fraction of the electron current in the pinch was determined from the radial deposition profile measured using x-ray pinhole photography on thick targets. For these Proto I experiments, $I_p = F I_e$ where $F \sim 0.5$ to 0.6 .

The above formulas with $A = 1$ were then applied to the measured $V(t)$ and $I(t)$ from a Proto I shot to estimate $P_M(t)$ from Eq. 1. The resulting pulse shape of $P_M(t)$ was to a very good approximation a ramp function given as $P_M = P_{Mx} t/30$ for $t < 30$, $P_M = P_{Mx} (35-t)/5$ for $30 < t < 35$, and $P_M = 0$ for $t > 35$, where t is in ns. In addition, to allow for finite pinch formation time, $P_M = 0$ for $t < 5-10$ ns. Using the measured V and I and with $F = 0.6$ and $r_b = 0.075$ cm (from experimental measurements), $P_{Mx} = 6 \times 10^{13}$ W/gm.

Results of one-dimensional hydrodynamic calculations of planar foil expansion are shown in Fig. 13 for the previously described pulse shape for several P_{Mx} values. Also shown are plots of inferred temperature vs. time obtained from XRD data for two spot diameters: 2 mm, corresponding to the "full width half-maximum" of the x-ray pinhole profile and 3 mm, corresponding to the foil diameter. The emission area is thought to be bracketed by these two sizes. A conservative estimate of the deposition rate is then $\geq 5 \times 10^{13}$ W/gm.

Fig. 13. Front surface temperature vs. time plot. Calculated plots (----) for various peak deposition rates are compared with temperature plots (—) inferred from the unfiltered XRD channel for two assumed spot diameters.

For the pinched beam conditions 7×10^6 A/cm², averaged over the focal volume, and $V = 1.1$ MV, we would expect deposition rates with no enhancement of ~ 1 to 1.5×10^{13} W/gm depending on the angle of incidence. This implies an enhancement of ~ 3 to 5 .

The significantly lower rear surface temperatures measured are thought to be due to radial beam spreading in the foil interior where the B-field is weak. This effect can be roughly estimated assuming unmagnetized electrons in the foil interior for distances from the surface greater than a skin depth δ . For typical parameters, $\delta =$ expanded foil thickness $= 0.1$ cm, $\delta = 0.02$ cm, average electron angle $\theta = 45^\circ$, and $r_b = 0.1$ cm, we would expect the rear surface deposition to be about half of the front surface deposition. This deposition rate is approximately consistent with the observed rear surface temperature which is $\sim 7-10$ eV. To increase P_M on the rear, one would need to increase $r_b \gg (\delta - \delta) / \cos \theta$.

To calculate the deposition rate, a combined diode-Monte Carlo code was used which is a combination of previously reported codes.² Results from such a calculation are shown in Fig. 14 for which the particle dynamics are self-consistent with diode E and B fields as

Fig. 14. Combined diode-Monte Carlo calculation showing diode geometry, electron positions, and a typical trajectory.

well as with collisional energy loss and scattering in the anode material. The thick anode material was solid carbon and foil material expanded gold with $\rho = 0.0124$ g/cm³. The B-field was assumed to penetrate the foil. The voltage was 1.1 MV, total current was 295 kA and $I_e = 200$ kA, corresponding to the diode conditions midway in the power pulse. The calculation predicts 2.4×10^{13} W/gm within a radius of 0.1 cm which corresponds to the experimental focal volume. This deposition rate is in good agreement with the analytic result which estimates $\sim 3 \times 10^{12}$ W/gm midway in the power pulse.

In summary, magnetically enhanced deposition with a tightly pinched beam has been observed; front surface temperatures of ~ 15 -20 eV have been measured. The corresponding deposition rate was $\sim 5 \times 10^{13}$ W/gm and an enhancement of ~ 3 -5 times that given by a single electron pass was inferred. Rear surface deposition was reduced due to beam spreading and to range shortening which occurs near the end of the power pulse when the voltage is low.

These results are all consistent with both analytic theory and diode-Monte Carlo simulations.

Future deposition experiments, conducted with the convoluted diode feed, will examine the scaling of magnetically enhanced deposition with current. Deposition rates $> 10^{14}$ W/gm are expected.

PULSELAC

The purpose of the Pulselac program is to investigate the feasibility of multiple stage accelerators¹² of intense ion beams. Proceeding to a multiple stage system is one method of alleviating the problems of high intensity ion diodes for inertial fusion applications. Post-acceleration can decrease the divergence angle of a beam (and hence increase standoff) and significantly reduce the requirements for instantaneous power and energy flux to attain the necessary final beam power.^{13,14} This is a valuable property for high repetition rate devices. The Sandia approach differs from that envisioned for conventional accelerators¹⁵ in that beam neutralization by electrons will be used within the accelerator volume. Nonetheless, many of the problems encountered are common to all multiple stage systems, although the resolution of these problems involves unique approaches dictated by the high current levels used. Areas of particular interest for the Pulselac program are the development of high brightness sources of intermediate mass ions, the transverse confinement and stability of high current beams, and the longitudinal stability of beams driven by loaded pulselines. Over the last six months, encouraging progress has been made in these areas. A brief review of the status of Pulselac experiment and theory will be given, followed by more detailed descriptions of work performed.

A number of significant goals were accomplished. The standard design, magnetically insulated gap with radial fields was built and successfully tested, both at high voltage for short pulses (300 kV for 60 ns) and long pulses approaching a microsecond. In the absence of injected ions, permeance reductions of up to 700 from unimpeded electron flow were measured. The gaps were used as proton injectors for short pulses, and showed the classical behavior of magnetically insulated ion diodes, even though the geometry departed radically from past experience. With a long pulse generator, the proton gap exhibited unstable but reproducible behavior which

allowed the extraction of very high fluxes of protons. Experiments were also performed on carbon ion injectors (with C. W. Mendell). These experiments represented two important milestones: the first intense ion injector of ions other than p^+ and d^+ , and the first magnetically insulated ion diode using an active plasma source decoupled from the extraction gap. Another experiment performed was the use of a second magnetically insulated gap to post-accelerate the beam. Approximately 500 A of protons were given an energy increment of 200 kV over a pulse length of 200 ns. A significant demonstration in these studies was the electrostatic focusing effect of the shaped acceleration gap, supporting the feasibility of electrostatic transport for intense ion beams. Two major theoretical studies were undertaken. The first (with J. W. Poukey), treated the propagation of ion beams in nonlinear transport systems. Criteria were established for confinement and stability of the beam as well as the transverse beam energy limits in a nonlinear system. The second study treated the growth of velocity bunching instabilities in accelerators of nonrelativistic particles using pulse line drive. These instabilities were found to depend on the properties of the driving circuit, and were stabilized by sufficient longitudinal velocity spread in the beam. The major problem encountered in experimental work was the difficulty in keeping the beam confined transversely in the initial stages of the accelerator. A better theoretical understanding of beam transport showed that the gaps were too far apart for the focusing effects of the gaps to control the slow moving beam. The present experiment was based on a resonant electrostatic excitation of the acceleration gaps with a 50 ns pulse length; this method constrained the drift tube lengths. Another problem encountered with this system was the high demands on manpower to assemble and debug the ambitious arrangement of floating cable Blumlein lines. On the other hand, experience with injectors and acceleration gaps operating on a microsecond time scale gained this year suggested a new approach, where the initial gaps would be activated simultaneously and situated as close together as possible to control the beam during its initial acceleration. Such an accelerator would also minimize construction and testing. Thus, the goal of operating a five stage accelerator has been postponed until the completion of the new, high gradient unit.

The Pulselac gap is shown in Fig. 15. The radial magnetic fields¹⁶ are produced by four

Fig. 15. Standard Pulselac acceleration gap.

carefully designed coils. They prevent electrons from crossing the gap and give them a self-connected azimuthal drift motion. A number of tests were performed to investigate the magnetic insulation properties of this gap, which forms the basis for the entire acceleration scheme. Short pulse results with no ions showed an electron permeance reduction of over 600 from the unimpeded case, one of the best results obtained to date with any magnetically insulated gap. This result indicated that the electron residence time in the gap was very long, and electron orbits were for the most part stable, even in this unusual geometry which had a large radial variation in the strength of the magnetic field. Results with a long pulse generator (where the gap was powered directly by a Marx generator) showed the behavior indicated in Fig. 16. Shown are three time-dependent permeance plots for a) no applied field, b) a field close to the critical insulating field, and c) one about 2 times higher than the critical. The dotted line shows the theoretical permeance needed to obtain a 50 percent efficiency for the extraction of zero velocity protons. The rise in permeance in curve "c" is probably not due to current in the diode, but rather leakage currents, which could be reduced by expanding the dimensions of the vacuum wall surrounding the diode. With a

Fig. 17. Magnetic insulation experiments with Pulselac gap. Spacing between triggers equal 1 cm. Perveance ($I/V^{1.5}$) vs. time. a: No applied field, b: $B/B^* = 1$, c: $B/B^* = 2$.

modified design, it should be possible to extend the useful lifetime of the post-acceleration gaps to about a microsecond.

Proton injection experiments were initially done using a 60 nsec Blumlein line and a standard surface flashover proton source.¹⁷ Typical results are shown in Fig. 17. The pulse line produced a flat voltage pulse, and the diode had a fairly constant impedance with fast turn on. Probe measurements near the extraction cathode showed a well-defined beam pulse, and a time-of-flight detector gave a clear indication of the extracted proton beam. Note the azimuthal nonuniformity of the ion signals; this was characteristic of difficulties in achieving an accurate alignment across the 25 cm diode dimension. The major problem with this mode of operation was the unacceptable level of beam divergence ($\sim 7^\circ$) caused by space charge effects in the extraction gap. Attempts to alleviate this

Fig. 17. Oscilloscopes for typical short pulse proton injection shot. Bottom photographs show three diode current density monitors at different azimuthal positions, and a time-of-flight detector.

by shaping the anode failed because the flashboard produced plasma preferentially on the anode edges. The problem was solved by the fortuitous observation that if the gap was pulsed for a longer length of time by direct connection to the Marx generator, it evolved into a different mode of behavior where currents far in excess of the Child-Langmuir value for the mechanical gap without plasma closure could be obtained with an acceptable degree of beam divergence (3°). Currents up to 30 kA were obtained at voltages around 100 kV for pulse lengths approaching 1 microsecond. Typical oscilloscopes are shown in Fig. 18. Note the ion current density probes, which show a nonuniform Child-Langmuir mode

Shot 729

Fig. 18. Oscillographs for typical long pulse proton injection shot. Bottom photograph shows outputs from diode monitors which take a radial average of current density at two different azimuthal positions.

early in time which evolves to a high current density state. This late time behavior is believed to be governed by a weak instability of the rotating cathode electron cloud. The mode is characterized by high reproducibility and azimuthal uniformity of emission. Initial measurements on the diode are given in Ref. 18. Since this was written, improvements in the voltage supply have doubled the diode output, and further progress is expected.

Another improvement in injector performance was the operation of a carbon ion injector at current levels up to 2 kA. An array of six carbon plasma guns was located 20 cm from the injection gap. The guns were fired a few nanoseconds before the main voltage pulse.

Using field excluders, the gap was reconfigured so that the magnetic field did not extend upstream of the gap; the plasma stagnated upon reaching this magnetic boundary. Current and voltage traces for a typical shot are shown in Fig. 19. The gap starts in a low impedance clearing phase, after which the current drops and the voltage rises quickly to a high value determined by the inductive overshoot. After this, it settles into an equilibrium mode with ion current about 5 times that predicted by the Child-Langmuir law. The late time breakdown again takes place outside the diode. Figure 19 shows typical time-of-flight data, indicating a beam composed primarily of C^{+} and C^{++} , in agreement with measurements of the properties of the plasma gun. Note the spikes caused by the rising portions of the oscillating voltage. It was possible to change the shape of the voltage pulse. For instance, a triangular pulse was obtained by adding a shunt capacitor across the acceleration gap. Changes in the voltage form were well reproduced by changes in the time-of-flight signals.

In the post-acceleration experiments, the proton diode was used to inject ions into a second gap. In the configuration used, the gap was 60 cm downstream. Because of the beam divergence and a slight aiming error, only 500 A of current reached this gap. A separate Marx generator was used to provide a 200 kV pulse about 200 ns in duration when the current had risen to a maximum. The higher energy component could easily be seen in time-of-flight detectors downstream of the second gap. Of greatest importance was the fact that the post-acceleration gap could be used to focus the high energy portion of the beam to a thin ring focus, and the effective focal length could be changed by adjusting the magnetic field line curvature of the gap. Thin scintillator sheets downstream of the second gap showed a uniform level of excitation with no post-acceleration.

When the second gap is fired, the high energy ions could be seen as a brighter component with a definite radial variation. A number of shots such as these identified the effective focal length of the gap to be roughly in agreement with theory.

Theoretical work includes a treatment of beam propagation in nonlinear focusing systems, studies of longitudinal beam stability, and two conference papers on fusion reactor applications and parameters of high current multi-stage accelerators.^{3,14} The major results of the first work are:

Fig. 19. Typical results from carbon injector. Top: Current and voltage history. Total current is shown. Breakdown at 700 ns occurs outside the diode. Bottom: Time-of-flight current density measurements for the same shot, at 60 cm. Also shown is a prediction of the monitor response using the voltage and current measurements and assuming equal current densities of C^+ and C^{++} .

- (1) The orbits of particles in a transport system consisting of a number of discrete nonlinear focusing elements can be made analogous to those in a nonparabolic potential well.
- (2) This approximation can be used for first order design of an optical system.
- (3) The nonlinearities of the transport system give particles a spread in oscillation frequencies which makes them resistant to parametric instabilities.
- (4) Characteristics of the transport system and self-fields of the beam set a minimum limit on transverse beam temperature which cannot be tuned away.

This work is significant since high current ion beams will have strong self-field interactions that are far from the linear approximation used for theoretical work appropriate to conventional accelerators. The transverse beam energy is of prime importance since it determines the minimum focal size of the beam.

The second work also addresses problems unique to the Pulselac approach; the longitudinal stability of pulse line driven accelerators of nonrelativistic particles (existing pulse line accelerators have used relativistic electrons). The major results of this work are:

- (1) Voltage oscillations can be amplified by velocity bunching to produce a strong beam instability which increases the longitudinal velocity spread, as shown in the phase plots of Fig. 20.
- (2) A sufficient velocity spread (determined by the properties of the pulse line driving circuit) can provide stability.
- (3) An unstable beam becomes self-stabilized when the velocity spread reaches the required limit.
- (4) In order to avoid growth of the effective longitudinal phase area, the beam must be accelerated with constant axial length rather than constant gap pulse-length.
- (5) The velocity spread required for stability does not preclude beam confinement and possibly an order of magnitude temporal bunching after leaving the accelerator.

Fig. 20. Phase space history of a beam unstable to velocity bunching instabilities in a pulse line driven accelerator. The beam passes through four gaps between each plot. Periodic boundary conditions are applied, so there is no change in the longitudinal beam width. The black bar indicates a constant velocity width equal to that of the initial distribution. (Plots are scaled by the computer printout routine.)

Plans for the next year include optimization of the proton injector and second gap experiments up to about 2 kA. In particular, as a result of experience in microsecond injectors and post-acceleration gaps, a new, high gradient five-stage accelerator is being built. The close spacing of the acceleration gaps should allow transverse control of the beam according to the theory of Ref. 19.

A DUAL CURRENT FEED MAGNETICALLY INSULATED LIGHT ION DIODE

Inertial confinement fusion schemes require a power density of $10^{13} - 10^{15}$ W/cm² on target.²⁰ In addition, for ion beams, an upper limit to the usable ion energy is specified by the associated ion range in the target. For protons, this limit is approximately 10 MeV; therefore, at least 10 MA of beam current must be accelerated, undergo current neutralization, and be focused onto the target. The ion diode development undertaken here is part of an effort to produce ion beams that can be focused and overlapped upon

a target with the aim of reaching the power range required for fusion applications.

The focus data obtained are first interpreted with respect to the problem of obtaining a charge and current neutralized low- Z ion beam in the presence of a strong transverse B-field. The transverse B-field, which is always present to some degree in the drift region of a magnetically insulated diode, hampers the ease of current neutralization but is used to advantage here in producing a spatial separation of the focal of the proton and various higher Z ions in the beam. This allows a detailed analysis of the make up of the ion beam, which is used to gain understanding of the anode plasma formation and evolution throughout the pulse.

Apparatus

The ion diode is shown in Fig. 21 with a partial schematic of the diagnostics used. The ion beam originates from a plasma which quickly forms on a dielectric material on the anode during the pulse. The acceleration of the beam occurs between the anode, which is pulsed positive, and a virtual cathode¹² formed by the motion of electrons along B_{app} field lines. These electrons originate from the real cathode, positioned across from and along the perimeter of the spherical anode surface, and form uniform equipotential surfaces across the diode face for every choice of anode curvature. The ions then undergo "S" shaped trajectories when passing through the positive and reversed B_{app} -field before being geometrically focused at the target.

Fig. 21. Artist's conception of the diode and a schematic of some of the beam diagnostics.

The anode was fabricated from aluminum to exclude the 70 μ s risetime (1.5 mm skin depth) insulating B_{app} -field and conform the field to the 16 cm radius spherical surface of the anode. The cathode consisted of a 3 mm thick stainless steel plate with a 13 cm diameter aperture centered upon the spherical anode surface. Velvet cloth was mounted upon the anode, opposed to the cathode aperture, which provided the lowest divergence ion beam plasma source tested. A 10 cm wide nylon mesh was joined to the top and bottom of the velvet and formed a continuous source of anode plasma around the anode. This was necessary to produce a continuous ion beam which extended to the rear of the anode and resulted in a more stable electron containment. The diode gap was typically 4 mm at the top and 7.5 mm at the bottom to provide uniform ion emission across the diode face, despite electron accumulation at the bottom due to the downward $E \times B_{app}$ electron drift direction. This configuration resulted in the maximum focusable ion current. A 0.5 mm thick, 4 cm wide stainless steel vane was mounted vertically along the beam center line and assisted in space charge neutralizing the ion beam near the virtual cathode. The 10 B_{app} -field coil bars were positioned 2 cm from the anode which reduced bumpiness of the virtual cathode to approximately 2%. A coil current of 45 kA/bar gave a field of 13.5 kG in the diode gap. The diode was coupled to the Hydra accelerator²⁴ (1 MV, 300 kA) by splitting the output pulse line at the accelerator diode into two

15 cm long, 20 ohm, self-magnetically insulated transmission lines. These transmission lines were operated in the positive polarity and fed current to each end of the 15 cm tall anode plates. Three calibrated magnetic pickup (B) loops were mounted along the outer conductor of each line to measure the line leakage and diode current. The corrected diode voltage was obtained using the diode inductance measured with a 15 μ m diameter short circuit between the anode and cathode plate.

The target was positioned 1.6 cm below the diode center line, as shown in Fig. 21, in a 15 cm diameter, 8 port target chamber. This centered the target at the proton beam focus when the downward deflecting B_{app} -field was set at 11 kG in the diode gap. Since the B_{app} -field was normally 13.5 kG the proton beam focus was deflected 2 cm (800 keV proton energy) and C^{+2} and C^{+3} foci, 0.9 and 1.1 cm, respectively. A gas puff valve²⁵ allowed injection of gas plumes from two jets mounted near the target, at 22.5° on either side of the pinhole camera, as shown in Fig. 21. This system injected a helium, air or argon plume in 800 μ s, which was concentrated at the target and preferentially directed into the ion beam. The pressure of the gas was typically 0.02 torr, 4 cm from the anode, as measured by an exposed 6AH6 vacuum gauge tube,²⁶ and estimated to be 1 to 3 torr at the target, based upon an extrapolation of other gauge tube data. These plumes were used to study ion beam space charge and current neutralization processes in the transverse B_{app} -field. A pair of calibrated target B loops (see Fig. 21) measured the ion beam current and were shielded from the gas plume by a target shroud.

The ion beam diagnostics used are listed in Table I. The proton fluence was determined by measuring the activation²⁷ of carbon samples which intercepted the beam. The decay of N^{13} from the $C^{12}(p,\gamma)N^{13}$ and $C^{12}(d,n)N^{13}$ reactions was related to the fluence, taking into consideration the activation cross sections specified for a given diode voltage. Three 34% transmission stainless steel flux screens were used in series to attenuate the beam and avoid carbon blow off. A time-integrated x-ray pinhole camera was used to spatially measure the proton beam profile by observation of aluminum K-line radiation produced by atomic excitation. The proton fluence was also determined with this technique using numerically calculated x-ray production efficiencies for the voltage and relative current throughout the pulse, the current geometry used, and the sensitivity²⁸

of the Kodak No Screen x-ray film used. This camera utilized a 0.4 mm pinhole and gave 0.8 mm resolution. The presence of proton and carbon ion species in the beam was indicated on a time-integrated basis by a Thomson mass spectrometer²⁹ with channel electron multiplier array (CEMA) detector.

Active ion beam diagnostics consisted of charge collectors,³⁰ and B loops located behind 2 mm diameter apertures in the target near the proton and carbon foci. Data were also taken with a time-resolved x-ray pinhole camera,³¹ which observed the proton induced atomic excitation emission, in addition to the thermal VUV emission from the target. This camera used five pinholes to produce images on five independently gated CEMA detectors. (The effective exposure times were less than 5 ns.) The resulting electron images were transported along a 2 kG, pulsed toroidal magnetic field, amplified in a second CEMA plate, then accelerated into a phosphor to produce visible images. These light images were transported by a fiber optic plate directly to Polaroid film. The 0.5 mm diameter pinholes were covered by 8 μ m aluminum which separated the vacua of the camera and target chamber. The image resolution was pinhole limited to 1 mm. The thermal VUV and XUV emission from the target was also observed on a time-resolved basis with aluminum cathode photo diodes (XRD's) operated bare or with a 2 μ m polycarbonate (Kimfol) filter. These detectors observed the central 9 mm diameter region of the target and responded to 10 to 30 eV and 170 to 270 eV emission, when bare and filtered, respectively.

Additional diagnostics consisted of carbon activation samples mounted in pill boxes,³² to retain carbon blow off material, and neutron diagnostics using anodes coated with TiD. These diagnostics were primarily used to measure the ion emission from the rear of the anode. A silicon PIN diode and time integrated x-ray pinhole camera observed thick target electron bremsstrahlung due to lost electron current.

Current Flow Patterns in the Diode

Typical electrical characteristics of the diode are shown in Fig. 22. The total current is the current observed by the rear B loops located in the Hydra diode. This current agreed to $\pm 7\%$ with that measured by a current viewing resistor across the water vacuum insulator of the Hydra diode. The current lost along the transmission lines and/or

Table I.

<u>Diagnostic</u>	<u>Quantity Observed</u>	<u>Accuracy</u>	<u>Used to obtain</u>
Carbon Activation	Proton Fluence	$\pm 20\%$	Proton focus with 6 mm resolution
Atomic Excitation	Proton Fluence	$\pm 20\%$	Proton focus with 1 mm resolution
CEMA Camera	X-ray and VUV Flux	uncalibrated	Time resolved H^+ and C^+ focii
Photo Diodes	VUV and XUV Flux	$\pm 20\%$	Target Temperature
Thomson Spectrograph	H^+ and C^+ Ions	uncalibrated	Presence of various ion species
Charge Collectors	H^+ and C^+ current density	$\pm 20\%$	Ion time-of-flight
Target Aperture & Loops	H^+ and C^+ current density	uncalibrated	Ion time-of-flight
Target Chamber & Loops	H^+ and C^+ current	$\pm 20\%$	Unneutralized beam current

Fig. 22. Corrected diode voltage and total current (including current lost in the transmission lines) delivered to the diode. The smaller currents are those measured at the target with and without the gas puff plume.

transported into the diode as self magnetically trapped electron current³³ was estimated to be approximately 20% of the total current based upon the ratios of the signals from the current viewing resistor in the Hydra diode and the three B loops located along each transmission line at the positions shown in Fig. 23. This result was observed for diffusion pump oil and Aerodag coated walls at electric field stresses of 500 and 350 kV/cm, respectively (the highest electric fields utilized in this experiment). The minimal amount of magnetically trapped current is attributed to the reinforcement of the self B-fields by the B_{app} -fields in the transmission lines.

Because of the geometry of this diode, the ratios of the three B loop signals can be taken as an indicator of the fraction of the current passing through the cathode plate. By virtue of calibrations employing shorts at the front and rear of the diode, we infer $\geq 80\%$ of the diode current was carried through the diode plate when the puff gas system was used. This value was reduced somewhat for noncurrent neutralized beams because the preferential current return of the ion beam was no longer through the cathode. The target current shown in Fig. 22 as $I_{1, Puff}$, is the ion current measured in the target chamber using a tapered diode gap but no gas puff or cathode vane to provide current neutralization. (Experiments with a parallel

Fig. 23. A cross sectional view looking down at the diode together with a photograph of the diode taken before the rear portion of the B_{app} -field coils were encapsulated in epoxy. Pin-hole photographs of the thick target electron bremsstrahlung from the top and front of the diode are also shown. Note that the emission from the front of the anode is obscured by a stainless steel diode flange in the top view.

diode gap or no source of rear anode plasma displayed premature impedance collapse and severe damage to the lower edge of the anode. This occurred because the ion beam was enhanced near the lower edge of the diode due to space charge from piled up electrons. This caused electron loss from the cancellation of the B_{app} -field near the lower edge of the diode by the self B-fields of the ion and electron beams.) The tapered gap gave uniform ion emission across the curved anode surface as observed by witness plate damage. The ion current density was enhanced by approximately a factor of three over the Child-Langmuir value assuming a 4 mm gap and a 2 cm/ μ s gap closure velocity. The value of the target current was reduced 15% due to occultation by the B_{app} -field coil bars and 15% due to time-of-flight debunching from the value emitted through the cathode aperture. The total diode impedance was defined by the top front diode gap and nearly independent of the rear gap, D_r , even though the backward ion current scaled as D_r^{-2} when D_r was varied from 10 to 20 mm. This is consistent with the preferential injection of electrons into the diode near the upper portion of the tapered gap, which then pile up across the front diode gap near the upper portion of the tapered gap,

which then pile up across the front diode face due to the decreasing $E \times B_{app}$ drift velocity. Most of these electrons are lost but serve to enhance the forward ion current. The portion of this electron current which arrived at the lower edge of the diode was quickly lost on the rear side for large rear gaps, but transported around to the front face gap, for small rear gaps. However, when the electron current was transported across the rear gap the backward ion current was enhanced, explaining the observation that approximately the same net current was lost for small or large rear gaps.

The above observations, together with measurements of the ratio of forward to backward ion current (made with carbon activation pill boxes and neutron diagnostics), and analysis of thick target x-ray pinhole camera photographs, such as are shown in Fig. 23, indicate the following division of the diode current: 33% focus current directed through the cathode aperture (including current lost upon the magnet bars), 10% forward ion current which strikes the cathode, 25% electron current loss originating from the cathode, and approximately 17% backward directed ion current or electron loss originating from the rear of the diode housing. The remaining 15% of the current is lost along the transmission lines. We attribute the low transmission line loss to the strong magnetic field shear where the B_{app} -field lines cross the transmission lines abruptly. This shear is due to the self B-field from the diode current.

Ion Beam Composition

The diode was first operated with a planar anode (at approximately half the diode power shown in Fig. 22 with peak corrected voltage of 650 kV) to allow examination of the ion species being accelerated with the Thomson mass spectrometer. The data obtained show an abundance of proton and carbon ions and to a lesser extent oxygen ions. The carbon ions were accelerated primarily as C^{+2} and C^{+3} with some C^{+4} also present, but many displayed a lesser charge during spectrometer analysis, due to charge exchange with the estimated 0.02 torr gas between the spectrometer collimators. This is expected because of the approximately 10^{-16} cm² charge exchange cross section for these ions and the fact that the mean charge for carbon ions passing through matter is approximately +2 at 0.9 MeV and +3 at 2.4 MeV.²⁴ (Charge exchange for ions accelerated as C^{+3} is downward or upward for diode voltages ≤ 800 kV and ≥ 800 kV, respectively.)

This proliferation of ion species adds to the complexity of diagnosing the focus characteristics. Fortunately we are aided in our data reduction by the transverse B_{app} -field in the diode which spatially separates the proton and higher-Z foci. The signals from the charge collectors and B loops responding to a carbon beam, especially one transported through a background gas, must be interpreted with care because of secondary electron emission and charge exchange effects. Also atomic excitation photography is impractical for carbon ions in this energy range because their velocity is insufficient to excite K-shell electrons for low-Z targets with their modest fluorescence yields and because L-shell fluorescence yields of these targets is very small. We therefore diagnosed these beams from observation of target heating, which is difficult also because low energy carbon ions produce an optically thin plasma⁵ for target temperatures above a few eV. In our data reduction we therefore put most emphasis upon proton measurements and simply check to ascertain that the remainder of the beam is consistent with carbon or oxygen ions.

Ion Beam Focus

Initial focus studies were made 14 cm from the curved anode without the gas puff or cathode vane. These were added later to assist in space charge and current neutralizing the beam. The total focusable proton yield (beam transported past cathode and B_{app} -field coil bars) was measured with a large array of carbon activation samples. These were located over a 15 cm diameter region centered on the proton focus in a plane normal to the diode center line. The fluence profile obtained is shown in Fig. 24 and represents a total yield of 3.2×10^{16} protons when integrated over radial distance (50 kA for a 75 ns pulse). The FWHM of this profile is approximately 20% broader than that for the focus measured with the time-integrated atomic excitation pinhole camera (approximated by $r = R/0.8$ cm in Fig. 24) which observed the proton beam striking an aluminum target mounted at 45° to the beam direction. This is attributed to a slightly tighter focus earlier in time to which the camera responds with increasing sensitivity. This occurs because the camera sensitivity drops by a factor of two for proton energies between 800 and 600 keV and four between 800 and 450 keV, whereas the activation sample response is nearly equal for protons with energies between 800 and 450 keV.

A gas plume was injected into the ion drift region to assist in space charge neutralizing

Fig. 24. Proton fluence measured with a large array of carbon activation sample 14 cm from the anode when no attempt was made to space charge or current neutralize the beam.

the beam and resulted in a much tighter focus. However, premature diode impedance collapse occurred when gas was allowed in the diode gap. This problem was circumvented by substituting the cathode vane (which injected electrons near the virtual cathode) for that portion of the gas plume near the diode gap. These methods of achieving space charge neutralization were necessary because of the 7 to 12 cm distances over which electrons must normally be supplied along B_{app} -field lines. Since the space charge potential voltage in this situation is proportional to the square of this distance⁶ a significant reduction in the beam blow up was realized. A good focus was also achieved without the gas plume by using a vane which extended to the target although approximately 20% of the beam was lost on the vane.

The gas plume also produced a partially current neutralized ion beam which resulted in a

lower observed target current, $I_{T, \text{Puff}}$, as shown in Fig. 22, but greatly increased peak focus current density. By adjusting gas plume pressure, timing, and atomic number, it was possible to freeze the target current at a nearly constant value, from 20 to 100% of the unneutralized value. (Higher pressures and atomic numbers gave lower target current.) A fraction of this reduction is no doubt caused by carbon charge exchange in the drift region and possible stopping of the lower energy carbon ions directly in the gas. However, since the effect is also observed early in time, prior to the arrival of the carbon beam to the target, other mechanisms are also important. It appears that near the target, where the gas and beam current density are highest, sufficient momentum transfer occurs between gas molecules, electrons, beam and backstreaming ions to allow a return current across the transverse B_{app} -field which freezes the self B-field. In regions where the beam is not current neutralized, such as immediately behind the virtual cathode, the current necessary for downstream current neutralization was supplied by the motion of electrons along B_{app} -field lines between the beam and cathode vane, target chamber or diode walls.

The time-integrated atomic excitation photograph shown in Fig. 25 was obtained at a focus

Fig. 25. At atomic excitation pinhole photograph of the proton beam obtained with gas puff neutralization using a typical air plume. A vertical densitometer scan through the photograph is shown to the right.

13.2 cm from the anode, with a typical air plume. The gas injection jets shadow the focus at the right and left edges of the photograph. The current density profile of this focus is approximately $50 \text{ e}^-/\text{R}/4 \text{ cm}$ KA/cm^2 , assuming the total proton current of 50 kA, noted above, when integrating over all R. This proton beam focus has sufficient power to produce 5 mm diameter holes in 0.5 mm thick 6061-T6 aluminum plates oriented at 45°

to the beam direction. Rear surface spall was registered upon similarly oriented aluminum plates 1 mm thick. The lateral focus position was reproducible to $\pm 1 \text{ mm}$.

The time history of this focus was examined using the five frame CENA camera to observe the atomic excitation emission. Typical data obtained are shown in Fig. 26, where the target and target chamber were rotated 90° around

Fig. 26. Time-resolved pinhole photographs of the proton and carbon foci obtained with the five frame CENA camera. The continuous curves are B loop data obtained behind target apertures at locations P and C. The dotted curves are XRD signals obtained viewing a 9 mm diameter region of the target between the gas injection jets.

the ion beam center line. The proton focus occurs near the lower gas injection jet and the carbon focus near the upper jet. These photographs show that the proton focus occurs between 35 and 105 ns. During this period the ion beam current measured with the target chamber B loops (of which $> 90\%$ was incident upon the 7.5 cm diameter target) is approximately 35 kA. This represents a self B-field sufficient to bend the proton trajectories so that the beam will focus 13 cm from the anode^{27,38} (a distance 3 cm shorter than the anode radius). The optical density

exposure of the time integrated atomic excitation photographs indicate a peak current density of 60 kA/cm², based upon the 20 ns focus duration and the diode voltage when the protons were accelerated. This is in reasonable agreement with the value obtained by setting the integral of the focus profile over R equal to 50 kA, but suggests that the wings of the focus, which are too low in intensity to observe with the CEMA camera gain setting used, may accumulate faster than the core of the focus late in the pulse. The complete disappearance of the proton focus after 110 ns can not be entirely explained by the reduction in the atomic excitation efficiency with voltage, but is consistent with a proton beam held rather constant at 50 kA throughout the pulse which defocuses slightly after 110 ns. This defocusing is expected because of the rise of the target current above 35 kA and the lower diode voltage which move the focus closer to the anode. The constant proton current is necessary to account for the magnitude of the carbon activation signal noted previously. The angular divergence of this proton beam (half angle of the cone which includes half of the beam current) is $2.1 \pm 0.3^\circ$.

The carbon beam focus was observed after 120 ns by the CEMA camera, first near the upper gas injection jet, as shown in Fig. 26. The image is due to aluminum L-line radiation from an optically thin plasma with temperature > 15 eV, which is transmitted through the 8 μ m aluminum window separating the camera from the target chamber. The transmission occurs between 40 and 75 eV where the transmission coefficient is only 3×10^{-4} but the CEMA sensitivity is approximately 10 times greater than in the region above 1 keV.^{39,40}

The position of the carbon focus (> 12 mm deflection) is consistent with $C^{+3,+4}$ ions, accelerated by 600 kV, which undergo one unit of downward charge exchange in the drift region. Since the charge exchange is more probable in the reversed B_{app} -field region (where the gas density is higher) and ions which have less charge experience less trajectory bending, these ions would display more deflection at the target than those which did not charge exchange. Because various ion species are involved and charge exchange occurs all along the ion trajectories a broad vertical spread to the focus would occur, as noted. The same discontinuous trajectory production mechanism would prevent an extremely tight horizontal focus, although the self R-field for the approximately 50 kA target current, which occurs at 130 ns, is optimum to focus these carbon ions at 13 cm.

Other mechanisms such as late time bumpiness in the anode plasma due to nonuniform anode plasma motion may also contribute to the poor carbon focus noted. Carbon ions appear to carry $> 70\%$ of the target current after 130 ns. (A limited amount of data obtained with nylon mesh anode plasma sources show qualitatively similar behavior but with some reduction in the amount of carbon current.)

The thermal spectrum to which the bare XRD responds is heavily filtered by the gas plume making precise interpretation of this signal difficult. However, the Kinfol filtered XRD observes emission in a transmission window through air and gives data (see Fig. 26) useful for estimating target temperature. These data are in qualitative agreement with the CEMA camera photograph and indicate a peak target radiation temperature at the carbon focus of 18 ± 2 eV. This is reasonably consistent with the optically thin electron plasma temperature of 22 eV calculated with LASNEX⁴¹ assuming a 1.8 MeV, 10 kA/cm², 40 ns duration carbon focus. A similar calculation for a 800 keV, 60 kA/cm², 20 ns duration proton focus gave a 6 eV temperature which could not be measured because of the background gas.

The δ loop data taken behind target apertures, at locations C and P, shown in Fig. 26 and charge collector data (not shown) were also used to determine the arrival time of the beam at each focus. A comparison of the leading edge of these data and calculated time-of-flight current traces indicates that the protons are preferentially accelerated early in the diode current pulse and that carbon ions with charge $+2$ are accelerated > 20 ns later. The C^{+1} ions are assumed to retain their charge state when drifting to the target, and therefore would have insufficient deflection to be detected by these δ loops early in the pulse.

Anode Plasma

Focusing experiments were performed using a nylon mesh anode surface material in addition to the velvet to note the effect on beam focus quality. The fairly coarse (approximately 1.5 mm grid spacing) nylon mesh was found to produce a beam focus with FWHM of 13 mm. The rayon velvet cloth with approximately 2×10^4 fibers/cm² and a uniformity of fiber height of ± 0.1 mm produced a FWHM of 10 mm with a similar diode configuration. (These data were acquired with a single gas jet which did not create a gas plume asymmetric with the beam center line. Consequently,

larger foci were noted which can not be compared with those previously described.) We interpret these results to imply that the plasma surface uniformity obtained on the anode has an effect on the beam quality in this experiment and that initial perturbations on the anode surface may be preserved on the emitting plasma for the duration of our pulse.

The choice of a fibrous or textured dielectric surface for the anode was made to obtain a well emitting anode plasma early in the machine pulse. It was observed that smooth homogeneous conducting or dielectric surfaces did not produce a satisfactory anode plasma. This suggests a mechanism of anode plasma production related to that of surface flashover⁴² or an electron avalanche process along the dielectric surface, presumably initiated by a few leakage electrons. The plasma thus created is then heated by the flow of current through it.

The presence of the +3 and +4 charge states of carbon in the ion beam suggests a temperature of at least 6 eV in the emitting region of the anode plasma based upon a coronal model ionization distribution⁴³ for a high temperature carbon plasma. This rather high temperature is consistent with the 1 kA/cm^2 anode current density observed here, provided the ions originate in a low density region where n is approximately 10^{16} cm^{-3} . In this situation with a B_{app} -field of 13.5 kG the electron cyclotron frequency exceeds the collision frequency by an order of magnitude (at $n_e = 10^{16}$, $T_e = 6 \text{ eV}$, $B = 13.5 \text{ kG}$; $\omega_{ce} = 12$). Since this low density seems probable for the emitting plasma front (lower densities would be quickly eroded away in supplying the particles in the beam), we conclude that the high charge states of carbon observed in this experiment are the result of enhanced local heating of the expanding plasma front, caused by the applied magnetic field. We note that for a diode similar to the one used here, operated at an anode current density of 100 A/cm^2 , approximately equal quantities of protons and C^{+3} were observed,⁴⁴ which is consistent with an anode plasma temperature of approximately 1 eV.

The results described above indicate an ion beam comprised of $\geq 75\%$ proton current for the first 20 ns of the pulse but increasing amounts of highly ionized carbon species later in time. This is consistent with the expected emission from a 10^{16} cm^{-3} anode plasma with approximately equal isotopic abundance of hydrogen and carbon. Since the ion emission rate⁴⁵ is related to $Z_i e (kT_i/m_i)^{1/2}$ such a

plasma at a temperature of 1 eV (equal abundances of H^{+1} and C^{+3}) would initially result in 78% proton current. As the H^{+1} ions are removed from the surface of the plasma we expect the beam eventually to stabilize at 50% proton current since the H^{+1} mobility is probably insufficient to replace ions removed in the time scale required. However, when the plasma temperature is raised to 6 eV, $\geq 75\%$ of the current would be carried by C^{+3} and C^{+4} ions even though 50% of the beam particles are still comprised of protons.

Conclusions

A low impedance modular ion diode with externally applied B-field, to suppress electron flow has been tested and its fundamental properties examined. The diode produced extremely reliable operation with lateral focus position reproducible to $\pm 1 \text{ mm}$, at a distance of 13 cm from the anode. Although the total proton current was only 50 kA, a peak proton focus current density of 60 kA/cm^2 was achieved at this distance. This beam has a divergence half-angle of 2.1° which is the lowest divergence reported to date. The anode plasma source quality appears to influence this divergence although self B-field bending effects undoubtedly also broaden the focus.

It was also shown that an asymmetrical magnetically insulated ion diode powered by self magnetically insulated transmission lines, can achieve an ion production efficiency of 33%. It would be possible to increase this efficiency to 50% with the elimination of lost forward ion current, which strikes the cathode in the present design, and more careful control of electron injection and accumulation across the diode face. It remains to be seen whether diodes powered by longer self magnetically insulated transmission lines, where the B_{app} -field does not partially assist in the transmission line insulation process will be as efficient as presently demonstrated.

The diode demonstrated that flashover sources of anode plasma produce significant quantities of carbon ions when driven at anode current densities of approximately 1 kA/cm^2 for longer than 20 ns. This accounted for the low total proton current observed. It is expected that at anode current densities of approximately 10 kA/cm^2 even higher anode plasma temperatures will be reached, allowing for the first time the acceleration of relatively pure, high intensity carbon beams. Because a carbon plasma at any temperature between 10 and 70 eV is comprised primarily

of C^{+4} ion species, a stable beam with 80% of the current carried by C^{+4} ions (assuming an equal isotopic abundance of hydrogen and carbon in the anode plasma) could result over a broad duration power pulse and anode current density range. This would be very desirable since the diode voltage and impedance could be effectively increased by a factor of approximately five over that for protons (20 times greater carbon energy) with little change in the ion range in the target. Such a beam also would display considerably less self B-field defocusing effects.

Acknowledgments

The authors wish to thank D. F. Wenger and R. L. Noack for their valuable experimental assistance and S. Humphries, Jr. and J. P. Quintenz for useful discussions. The B_{app} field calculations of J. R. Hadley were used in the design of the diode.

MULTIPLE ELECTRON BEAM PROPAGATION EXPERIMENT ON PROTO II

In the past, the concept of using ionized current-carrying channels, to propagate a large number of focused beams to a single target has been tested on Hydra in single and dual beam experiments.^{46,47} Recently, the first experiments using Proto II and many beams has been carried out. In this work, a system eventually capable of a 12 beam transport experiment was tested with 6 beams transported and 6 beams terminated at witness plate anodes. The latter six were used to assess pinch quality and bremsstrahlung dose data for use in determining the transport efficiency of the other beams from the diode to the target. Fig. 27 shows a dummy test shot in which 12 channels were formed. The diode hardware is partially visible. The channels are 46 cm long, have a 0.8 cm radius, and are driven by a system incorporating a Maxwell Laboratories capacitor bank. The channel driver system has effective output parameters of 100 kV maximum, 20.6 μ F, and 230 nH. This should be adequate to transport 12 Proto II beams at roughly 1 MA/cm² peak.

The accelerator output waveforms obtained in this experiment are shown in Fig. 28. Target cylinders having radii equal to the overlap radius of the channels, r_0 ($r_0 = r_c/\sin(\pi/N)$, where r_c is the channel radius and N is the number of channels) and equal to 60% r_0 were studied. The azimuthal variation of the

Fig. 27. Photograph showing channels in air. This view is normally blocked by vacuum chamber hardware.

Fig. 28. Waveforms from a Proto II beam propagation shot. Both raw and inductively corrected voltage waveforms are shown on VTAV plot. ITOT and PTOT are total diode current and power.

deposition in the cylinder was determined with an x-ray pinhole camera. The x-ray pinhole photographs indicated discrete areas of deposition in the target cylinder corresponding to the points at which each channel intersected the cylinder in the case where $r = r_0 = 1.6$ cm; when $r = 60\% r_0$ a uniform

azimuthal x-ray pattern is observed. This azimuthal averaging in the case of smaller cylinders could be extremely important for any multi-beam reactor approach since the target loading asymmetries due to low output from one beam would be greatly reduced. The transport efficiency was determined by comparing the dose to CaF_2 TLD's located directly behind the witness-plate anodes to those located at one end of the target cylinder. The electron-photon Monte Carlo transport code CYLTRAN⁴⁸ was used to normalize the results for the two geometries. Although the absolute value of the TLD dose was a sensitive function of the assumed value of the incident electron energy, the relative dose for the two geometries was only a weak function. Assuming an electron energy of ~ 1 MeV, we obtained estimates of 94% and 91% efficiency for electron transport to cylinders with $r = r_0$ and $r = 60\% r_0$, respectively. These figures include the losses due to pinch formation time, channel injection, and beam propagation in the channel. Ion losses are not included. The strong voltage scaling of the inferred deposition tends to emphasize the transport of higher energy electrons. Figure 29 displays these

two data points along with a theoretically predicted curve of relative dose vs. radius.⁴⁹

A further experimental test of this MES concept will be carried out in the spring to obtain more data. The utility of the stem to carry out cylindrical target implosion experiments and to provide a simulation source will be determined. Tests of an electron-ion hybrid target concept will be carried out if ongoing theoretical calculations are encouraging.

BEAM COMBINATION EFFICIENCY

Fig. 29. Normalised beam transport efficiency. Solid line is calculated and points are data based on TLD measurements for 1.6 and 0.95 cm radius targets.

REFERENCES

1. S. A. Goldstein, C. W. Mendel, Jr., Electron Beam Fusion Progress Report, Oct. 1976 thru March 1977, p. 103, SAND77-1414.
2. S. A. Goldstein, C. W. Mendel, Jr., Electron Beam Fusion Progress Report, April thru Dec. 1978.
3. G. Yonas, J. W. Poukey, K. R. Prestwich, J. R. Freeman, A. J. Toepfer, and M. J. Clauser, Nucl. Fusion 14, 731 (1974).
4. S. L. Bogolyubskii, B. P. Gerasimov, V. I. Liksonov, Yu. P. Popov, I. I. Rudakov, A. A. Samarskii, V. P. Smirnov, and L. I. Uzunskuev, Pis'ma Zh. Eksp. Teor. Fiz. 24, 202 (1976) JETP Lett. 24, 178 (1976).
5. M. M. Widner, J. W. Poukey, and J. A. Halbleib, Sr., Phys. Rev. Lett. 38, 548 (1977).
6. D. Mosher and I. B. Bernstein, Phys. Rev. Lett. 38, 1483 (1977).
7. M. J. Clauser, L. P. Mix, J. W. Poukey, J. P. Quintenz, and A. J. Toepfer, Phys. Rev. Lett. 28, 398 (1977).
8. M. M. Widner, E. J. T. Burns, M. J. Clauser, S. A. Goldstein, J. A. Halbleib, Sr., L. P. Mix, J. N. Olsen, F. C. Perry, J. W. Poukey, J. P. Quintenz, and A. J. Toepfer, Proc. of the 2nd Int'l Conf. on High Power Electron and Ion Beam Research and Technology, Cornell Univ. Ithaca, NY, Oct. 1977, p. 287.
9. E. J. T. Burns et al., Relativistic Electron Beam Energy Deposition in Thin Gold and Aluminum Targets, SAND78-2026, Jan. 1979.
10. J. W. Poukey, Proc. of the 1st Int'l Topical Conf. on Electron Beam Research and Technology, Albuquerque, NM, Nov. 1976, p. 247.
11. Reference deleted.
12. S. Humphries, J. Appl. Phys. 49, (2), 501 (1978); and S. Humphries, "Proc. of 2nd Int'l Topical Conf. on High Power Electron and Ion Beam Research and Technology," edited by J. A. Nation and R. N. Sudan (Laboratory of Plasma Studies, Cornell University, 1977), 83.
13. S. Humphries, J. Poukey and G. Yonas, "Proc. of the 3rd Int'l Conf. on Collective Methods of Acceleration," to be published.
14. S. Humphries, "Proc. of the Heavy Ion Fusion Workshop" (Argonne, IL, 1978), to be published.
15. See, for instance, "EROA Summer Study of Heavy Ions for Inertial Fusion," edited by R. O. Bangerter, W. B. Hermannsfeldt, D. L. Judd and L. Smith (Lawrence Berkeley Laboratory, LBL-5543, 1976), and "Proc. of the Heavy Ion Fusion Workshop," edited by Lyle W. Smith (Brookhaven National Laboratory, BNL-50769, 1977).
16. Field calculations by J. F. Freeman.
17. P. Dreike, C. Eichenberger, S. Humphries, and R. N. Sudan, J. Appl. Phys. 47, 85 (1976).
18. S. Humphries and G. W. Kruhn, accepted for publication, Appl. Phys. Lett.
19. S. Humphries and J. W. Poukey, submitted to Particle Accelerators.
20. M. J. Clauser, Phys. Rev. Lett. 35, 848 (1975).
21. S. Humphries, Jr., R. N. Sudan, and L. Wiley, J. Appl. Phys. 47, 2382 (1976).

22. D. J. Johnson, G. W. Kuswa, A. V. Farnsworth, Jr., J. P. Quintenz, R. J. Leeper, E. J. T. Burns, and S. Humphries, Jr., (to be published).
23. T. H. Martin, D. L. Johnson, and D. H. McDaniel, "Proc. of the 2nd Int'l Topical Conf. on Electron Beam Research and Tech.," Cornell Univ. Ithaca, NY, 1977, (unpublished).
24. T. H. Martin, IEEE Trans. Nucl. Sci. NS-20, 289 (1973).
25. G. W. Kuswa, C. Stallings, and A. Stamm, Rev. Sci. Instrum. 41, 1362 (1970).
26. I. Henins and J. Marshall, Rev. Sci. Instrum. 40, 875 (1969).
27. F. C. Young, J. Golden, and C. A. Kapetanakis, Rev. Sci. Instrum. 48, 432 (1977).
28. G. M. Dozier, D. B. Brown, L. S. Birks, P. B. Lyons, and R. F. Benjamin, J. Appl. Phys. 47, 1449n (1977).
29. J. N. Olsen, G. W. Kuswa, and E. D. Jones, J. Appl. Phys. 44, 2275 (1973).
30. C. Eichenberger, S. Humphries, Jr., J. Maenchen, and R. N. Sudan, J. Appl. Phys. 48, 1449 (1977).
31. D. L. FehI, J. Chang, G. W. Kuswa, and C. W. Mendel, (to be published).
32. A. E. Blaugrund and S. J. Stephanakis, Rev. Sci. Instrum. 49, 866 (1978).
33. S. Shope, J. W. Poukey, K. D. Bergeron, D. H. McDaniel, A. J. Toepfer, and J. P. VanDevender, J. Appl. Phys. 49, 3675 (1978).
34. J. B. Marion and F. C. Young, "Nuclear Reaction Analysis" (North-Holland, Amsterdam, 1968), p. 41.
35. A. V. Farnsworth, Jr., D. J. Johnson, G. W. Kuswa, and R. J. Leeper, Bull. Am. Phys. Soc. 23, 816 (1978).
36. J. W. Poukey and S. Humphries, Jr., Appl. Phys. Letts. 33, 122 (1978).
37. T. P. Wright, (to be published).
38. D. Mosher, (private communications).
39. J. P. Rager, Laboratori Gas Ionizzati Report No. LGI 72-12-E, Frascati, Rome, Italy, 1972 (unpublished).
40. C. Gahwiller, F. C. Brown, and H. Fujita, Rev. Sci. Instrum. 41, 1275 (1970).
41. G. B. Zimmerman, W. L. Kruer, Comments Plas. Phys. 2, 51 (1975).
42. S. Humphries, Jr., J. Appl. Phys. 49, 501 (1978).
43. D. Mosher, Phys. Rev. A. 10, 2330 (1974).
44. J. M. Neri, M. A. Greenspan, D. A. Hammer, and R. N. Sudan, Bull. Am. Phys. Soc. 23, 902 (1978).
45. L. Valyi, "Atomic and Ion Sources" (John Wiley & Sons, NY, 1977), p. 346.
46. P. A. Miller et al., Phys. Rev. Lett. 39, 92 (1977).
47. P. A. Miller et al., "Proc. 2nd Topical Conf. on High Power Electron and Ion Beam Research and Tech.," 393, Oct. 3-5, 1977, Cornell, Ithaca, NY.

48. J. A. Halbleib, Sr. and W. H. Vandeveder, "CYLTRAN: A Cylindrical Geometry Multi-material Electron/Photon Monte Carlo Transport Code," SAND74-0030, Sandia Laboratories (March, 1975).
49. T. P. Wright, J. Appl. Phys. 49, 3842 (1978).

CHAPTER 5 PULSED POWER RESEARCH AND DEVELOPMENT

OVERVIEW

This reporting period was directed toward preparing for the EBFA I construction and pulsed power tests, improving our understanding of the basic physics of vacuum flashover and of self-magnetically insulated power flow through vacuum transmission lines, and developing the technology base for EBFA II.

EBFA I activities in pulsed power research were centered on the prefabrication of the EBFA I Marx generators and on the design of the EBFA I module Hydramite. Significant improvements over the MITE design have been incorporated into Hydramite in the following areas: the Marx hanging hardware, the intermediate energy store, the water immersed SF_6 switch and its triggering system, the shorter pulse-transformer, the new field shaper for the vacuum power flow injector, and the new closed triplate geometry which has been incorporated into the power flow lines and tapered transition to the anode/cathode gap. With each improvement, there are associated risks. Since the EBFA I schedule allows only the minimal period of time between the Hydramite test and the EBFA I procurement, a great deal of our effort has been expended in assuring that the tests will proceed expeditiously. The MITE experiment was used to test the new field shaper and the new current and voltage diagnostics and calibration procedures. The new Marx configuration has been successfully tested on Hydramite, the rest of the features will be tested before May 1979.

Experiments in the physics of vacuum flashover were carried out in a contract with Texas Tech and University of South Carolina. The work investigated the physics of the electron and/or ion avalanche before electric breakdown. Understanding this process is important in the design of low inductance vacuum insulators for ICF accelerators, especially for advanced designs employing magnetically inhibited flashover.

Our understanding of magnetic insulation advanced during this reporting period through the following: a) the MITE experiments on the tapered A-K feed, b) the Proto II experiments with short radial vacuum lines, c) the MITE experiments with the advanced field

shaper, d) the generalized 1-D theory of self-magnetically insulated flow by C. W. Mendel (4244), e) the 2-D electromagnetic and PIC computations by K.D. Bergeron and J.W. Poukey (4241) on the effect that an injected beam has on the electron flow in a self-magnetically insulated line, and f) the clarification by K. D. Bergeron of the role that a possible modified diocotron instability may have on electron flow. As a result of these efforts, the importance of any convolute in self-magnetically insulated flow has been recognized. In this context, a convolute is a section of line in which the Lagrangian of an electron depends on the direction x of electron drift. Under such circumstances, the canonical momentum P_x is not conserved and in principle, a species of electrons that travels for many Larmor orbits without re-intersecting the cathode, can be formed. We have hypothesized that this second species of electrons is responsible for the apparent instability in magnetic insulation that was identified and cured in the previous reporting period. Experiments and calculations to explore and develop this hypothesis are planned for the rest of FY 79 and FY 80.

EBFA I will be a multimodular particle beam accelerator that will operate at a power density of 34 TW/sr. EBFA II will be an electron or ion accelerator and could operate at 50 to 60 TW/sr. The research that will produce the required technology base for the EBFA II options has begun. The problem of polarity reversal was successfully addressed on MITE. The first higher energy density Marx generator was successfully tested on MITE and an even higher energy density version is being procured. The EBFA II module, Supermite, is in the various stages of concept definition, detailed design definition, and hardware procurement. The research will continue, so that when the output option for EBFA II is determined, the required technology base will be available.

POWER FLOW - NITE SELF-MAGNETICALLY INSULATED LINE EXPERIMENTS

Power Flow Studies in Long Self-Magnetically Insulated Transmission Lines

In the progress report covering October 1977 through March 1978, we reported the efficient transport of energy through the 6.0 m long MITE lines. The transport efficiency was strongly dependent on the geometry of the transition section between the vacuum insulator and the transmission line itself. Specifically, for a gap spacing d between conductors as a function of the coordinate x along the direction of propagation, the variation of d with respect to x is $\delta d/\delta x$. If $\delta d/\delta x = 0.25$ the transport was 60 percent efficient. If $\delta d/\delta x = 0.07$, the transport was 100 percent efficient. The result suggested $\delta d/\delta x \leq 0.07$ was sufficient for efficient power transport. However, all the geometries studies had a negative inner conductor and had a magnetic field on that conductor that was independent of x .

The results for negative polarity were not necessarily usable for positive polarity. The geometry had to be changed so that the electromagnetic field variation in the x direction was small for both positive and negative polarity geometries. This geometry change required that $dB/dx = 0$ restraint be relaxed. Consequently, the criterion of $\delta d/\delta x \leq 0.07$ for a parallel plate line can be generalized to be

$$\frac{d}{Z_0} \frac{\delta Z_0}{\delta x} \leq 0.07 \quad (1)$$

where d is the gap separation and Z_0 is the vacuum wave impedance of the line. In practice, the geometry is complicated and the criterion must be applied locally. For a given geometry, the structure is pulsed in situ and the gap separation and magnetic field B are measured at each position x . The effective width W_{eff} of the line is then given by

$$W_{eff} = 4 \times 10^{-7} I/B \quad (2)$$

where I is the current in the line in amperes. The effective impedance of the line is then

$$Z_c = \frac{377d}{W_{eff}} \quad (3)$$

where d is the gap between conductors of position x . The line geometry is changed until the criterion is satisfied. Three profiles of $Z_0(x)$ were investigated during the development of the transition section and they are shown in Fig. 1. Profile A has a section in which the impedance is much too low. There was appreciable damage to the lines at a distance ~ 15 cm downstream from the minimum impedance section. Profile B is somewhat better, but the energy transport was only 75 percent. Profile C was generated by the final geometry. With Profile C, the total currents I_T and boundary currents I_B at the input and output were $I_{T,in} = 0.44$ MA, $I_{B,in} = 0.25$ MA, $I_{T,out} = 0.47$ MA, $I_{B,out} = 0.30$ MA, respectively, into a slightly under-matched load. The short circuit current at the output of the line was 0.66 MA for an input current of 0.43 MA, which agrees well with the calculated value of 0.69 MA in a 100 percent efficient self-magnetically insulated line as discussed later in this report. The voltage inferred from the line geometry, I_T and the ratio of I_T/I_B at the output was 2.1 MV for the self-limited load compared to 2.2 MV at the input. Each of these measurements indicate ~ 100 percent power transport. A calorimeter at the output indicated only 60 to 70 percent transport, however, the calorimeter was always damaged

Fig. 1. Profiles A, B, and C of the vacuum wave impedance Z_0 as a function of distance x into the MITE injector. The earlier study indicated the "Lossy" profile was too severe and the "Efficient" profile was satisfactory.

by a pinched beam. Hence the radiative losses are quite large and the calorimeter could not be expected to read the full value of deposited energy.

The efficient propagation is consistent with the generalized criterion for the injector. It also appears to be important for $\delta Z_0/\delta x \leq 0$, i.e., the vacuum wave impedance should continually decrease or be constant in the transition section.

Load Line for a Self-Magnetically Insulated Line

The self-limited impedance of the self-magnetically insulated line $Z_{\text{self}} = V/I$ and is always less than the vacuum wave impedance Z_0 . For $V = 2$ MV, $\alpha = Z_{\text{self}}/Z_0 = 0.63$. The reduced impedance is caused by the E field distortion and the current transport of the electrons flowing between the conductors. Since the position and electromagnetic properties of the electron sheath change with the voltage, total current, and boundary current in the line, the effective line impedance also depends on V , I_1 , and I_0 . The variable impedance Z_1 of the line causes the load voltage V_2 to depart from the usual well known relation

$$V_2 = \frac{2V_1 Z_2}{(Z_2 + Z_1)}$$

where V_1 is the voltage of the incident wave. For $Z_2 \geq Z_1$, the section of magnetically insulated line immediately surrounding acts as part of the load. The current that does not pass through the load is lost to the anode across the vacuum gap. Consequently, the line is a constant voltage source and $V_2 = V_1$. If $Z_2 < Z_1$, the situation is more complex. The current I_2 is greater than I_1 and the voltage V_2 is less than V_1 . The reflected wave increases the magnetic field in the vacuum gap and decreases the electric field. Consequently, the electron sheath is constrained to flow closer to the anode. In practice a small reflection drives the flow very close to the cathode and hence Z_1 approaches Z_0 rather quickly. By assuming the reflected wave drives the line impedance to $Z = Z_0$, we can approximate the power transport through a simple model.

The incident wave has a voltage V_1 from an impedance Z_1 and propagates into an impedance Z_0 . The transmitted wave has a voltage V_3 and propagates through a line of impedance

Z_0 to a load impedance $Z_2 \ll Z_0$. The transmitted voltage V_3 is

$$V_3 = V_1 \quad (4)$$

if the mismatch acts like an over matched self-magnetically insulated line, or

$$V_3 = \frac{2V_1 Z_0}{Z_0 + Z_1} \quad (5)$$

if the excess magnetic field traps the electron in the line at the intersection of the two waves.

The load voltage is

$$V_2 = \frac{2V_3 Z_2}{Z_2 + Z_0}$$

in either case. The assumptions (1) and (2) give different load lines as shown in fig. 2. The data points are from the DiCapua and Pellinen¹ (O) normalized to the experiments where $Z_1 = Z_2$ or the MITE experiment (Δ). The data are consistent with the second assumption. The power efficiency $I_2 V_2 / I_1 V_1$ for a self-magnetically insulated line as a function of Z_2/Z_1 shown in Fig. 3. The dotted line represents the power efficiency from a constant impedance line.

Fig. 2. Load lines of output voltage V_2 vs. load impedance Z_2 normalized to input voltage V_1 and vacuum wave impedance Z_0 for assumption (A) in Eq. 4 and (B) Eq. 5 respectively.

Fig. 3. Power efficiency P/P_0 vs. load impedance mismatch for a long, self-magnetically insulated transmission line.

The short line problem is similar if $Z_2 > Z_{1min}$ where Z_{1min} is the minimum value of Z_1 anywhere in the magnetically insulated feed. For a radial disk feed $Z_{1min} = 60 \text{ d/r}$. For $Z_2 < Z_{1min}$, the load voltage is determined by the impedance of the nonmagnetically insulated ordinary line feeding the diode.

Tapered Diode Feed and Diode Study

The MITE self-magnetically insulated line is shown in Fig. 4. Approximately 0.5 meters before the anode/cathode diode, the triplate line is convoluted into a coaxial line. The convolute geometry is such that the magnetic field H_c on the inner conductor is everywhere greater than or equal to the magnetic field in the uniform field region of the triplate line when the structure is pulsed with a low voltage pulse. This criterion does not consider the distortions created by the electron flow.

The plot of the vacuum wave impedance Z_0 versus the axial direction x is shown in Fig. 5. Since the excess magnetic field over traps the electron flow in the taper. The convolute must be terminated in an impedance $Z_2 < Z_1$ which was 4.8Ω in the MITE experiment to trap the electrons. The variation of Z_0 - 60 d/r of a typical A-K gap is also shown for comparison.

Various cathode configurations were used. Flat faced cathodes saturated parapotential⁴

Fig. 4. Schematic of the six meter long MITE self-magnetically insulated transmission line. The line is terminated in a tapered section followed by the A-K gap. Total (I_T) and boundary (I_B) current monitors are shown with voltage monitor V_0 and Faraday cups (FC).

Fig. 5. Vacuum wave impedance Z_0 as a function of the distance into the tapered output convolute and A-K gap.

cathodes with $\gamma_m = \gamma_0$, minimum parapotential cathodes with $\gamma_m \approx 2$, C-DIODES⁵ and Bat cathodes⁶ were tested. Each cathode was characterized by its minimum geometric impedance $Z_0 = \min(60 \text{ d/r})$ where d is the anode to cathode spacing at a radius r . All of the cathodes showed some focused flow behavior. The Babykin and parapotential cathodes produced craters 1 to 1.3 cm deep in aluminum 6061-T6 anodes.

The voltage V was inferred from the total current IT2 and boundary current I82 before the convolute and the A-K current was inferred from the current I83 on the inner conductor immediately behind the A-K gap, as shown in Fig. 4. The plot of $Z = V/I$ for these cathodes is shown in Fig. 5. The prepulse consisted of a ~ 200 ns pulse at ~ 6 kV followed by a ~ 15 ns pulse at ~ 300 kV immediately prior to the main pulse. No cathode operated stably at Z less than the 4.8Ω required for complete trapping of the current in the convolute. The cathodes operated closer to the minimum parapotential impedance than to the usual saturated value, as shown in Fig. 6. Evidently, the Babykin cathodes operate in a different regime than the tapered cathodes. The apparent low impedance behavior is not well understood. Since the voltage measurement is an indirect one and relies on a 1-D theory under less than ideal circumstances, it must be suspect. In addition, the current monitor I83 measures

FIG. 6. The impedance vs. the minimum value of $60 d/r$ in the A-K gap for A-K studies at the output of the long self-magnetically insulated line on MITF. The (X) symbols are Babykin cathodes; the (O) symbols are 15° tapered cathodes with a 5.08 cm O.D. and 2 cm I.D.; the (Δ) symbols are 5.08 cm O.D. flat faced cathodes; the ($\square$) symbols are 2.54 cm O.D., 1.0 cm I.D., 6° tapered cathodes; the ($\diamond$) is a C diode configuration similar to (O) cathodes. Approximations to the minimum and saturated parapotential relations are shown for comparison.

boundary current, not total current. However, since the geometrical impedance of the A-K feed was 20Ω , the total and boundary current should have been the same to within 10 percent in these experiments for $Z_2 < 8 \Omega$ and voltages less than 2 MV. More adequate total current monitors have since been developed and the total and boundary currents at that position are equal under similar experimental conditions.

These results will be reinvestigated when more adequate voltage monitors are available.

Vacuum Insulator Flashover Research

The successful application of magnetic flashover inhibition to low inductance vacuum insulator design requires an improved understanding of the role of electron and/or ion avalanches in surface flashover. Experiments to provide that information were conducted under a contract with Texas Tech University and the University of South Carolina. A paper describing their initial progress was given at the 1978 International Symposium on Vacuum Discharges.

PULSED POWER RESEARCH IN SWITCHING

Water Dielectric Switching with Prepulse Suppression on Proto II

The suppression of prepulse is a major problem in pulsed power. A new technology to lower prepulse and prevent reflected energy from damaging the accelerator was developed. The technology was tested on the Ripple accelerator and later installed and tested on the Proto II accelerator.

A ground plane with several holes in it is inserted between the water switch electrodes. The switch electrodes from the output line extend through the holes and face points on the opposite pulse forming line. The capacity between the PFL and the output transmission line is reduced by about 90 percent and the prepulse is lowered by a similar amount. The energy stored in that capacity and formerly dissipated in the switch is now available for the output pulse. After the main pulse has passed through the ground planes, the gaps between the hole and switch electrode break and prevent pulse reflections from the diode from damaging the Marx generator and PFN supports.

Tests on Proto II verified the switch performance as predicted on Ripple. The prepulse on Proto II was lowered to ~ 5 kV. When a

vacuum prepulse switch was used, it was further reduced to ~ 750 V. Subsequently, tests into short circuit loads at full power were made with no damage to Proto II. These rugged, relatively inexpensive, metal prepulse shields should replace large, expensive solid dielectric barriers which may fail. The switch concept will be used on EBFA to perform the above tasks and to allow PFN stacking and hence a higher energy density accelerator.

EBFA I

Positive Polarity Option for EBFA I

The pulse forming network for EBFA I is designed for the negative polarity, electron beam option. The polarity effect in water-dielectric breakdown would limit the output power to approximately 50 percent of negative polarity power if the voltage on the Marx generator were simply reversed. Consequently, a polarity inverting convolute, shown schematically in Fig. 7, was designed for the output transformer and was tested on MITE. After the negative pulse was formed, the convolute inverted its polarity with > 90 percent efficiency. The polarity inverter provides a simple, efficient method of obtaining the positive polarity option for an ion EBFA I.

Fig. 7. A schematic of the polarity inverting convolute in the MITE water dielectric transmission line is shown. A prepulse gap has been incorporated. The crossover structure consists of 8 sets of cross-overs for 1.4Ω line.

EBFA Monitor Development

E-field and B-field monitors for use on EBFA, some of which are shown in Fig. 8, have been developed using the MITE and Proto II electron beam machines. The E-field monitors are based on an extended dielectric rod form of capacitive pickoff, and the B-field monitors are electrostatically shielded and encapsulated pickup loops. Fidelity and linearity of both types of monitors have been verified for fields ranging from the low calibration level through the operational level expected in EBFA. Development effort focused on cross calibration between different types of voltage monitors, short circuit machine shot comparisons of E-and B-field monitors, and comparison of E-and B-field monitor signals in pulse lines of known geometrical impedance. A copper sulfate voltage monitor, using a Kel-F housing to eliminate long term bubble formation, was also developed for use on the EBFA vacuum interface. Monitors will be procured for EBFA following final testing on Hydramite.

Fig. 8. Representative E-field and B-field monitors to measure current and voltage on EBFA.

There are more than 350 monitor locations on EBFA. The large numbers of monitors involved requires both new methods of data acquisition and monitor manufacture and calibration. All monitors are being obtained with physical tolerances which give individual calibration

factors within 5 percent of a given value for that type of monitor. Each monitor will be individually calibrated in calibration fixtures which have the same E-or B-field distributions that the actual EBFA lines have. Provisions are also incorporated in EBFA for in-situ calibration of monitors using adjacent signal cables and reference monitors.

A portable calibration source for EBFA monitors has been developed. This unit provides a 10 kV pulse with a 50 ns width and 2 ns risetime into loads between 2 and 31 ohms. A second unit has also been developed which can charge the intermediate stores in EBFA to 90 kV in times comparable to operational charging times for in-place calibration of voltage monitors.

EBFA II

Supernite

An EBFA II pulse power test facility called Supernite is being designed. Tankage has been designed to hold four EBFA modules (a 20° sector of EBFA II). Development of Supernite will proceed in two phases. In the first phase, pulse power research, development, and testing will be conducted in the areas of increased Marx generator energy storage, lower impedance/higher power pulse forming lines, positive-polarity, triplate transformer lines, and a triaxial vacuum interface.

In the second phase, four modules of a design based on results from the first phase will be constructed, installed, and tested. The object is to have a demonstration in which design problems peculiar to EBFA II geometry could be eliminated or minimized so that the conversion from EBFA I to EBFA II could be accomplished with a minimum of difficulty.

Supernite Marx Generator

Two types of Marx generator capacitors are being considered for increasing the module energy in Supernite. The first, a 1.0 μF , 100 kV capacitor would give a 43 percent increase in stored energy and the second, a 1.3 μF , 100 kV capacitor would store 86 percent more energy. These would give EBFA II a total Marx energy storage of 11.5 MJ and 15 MJ respectively. Since these capacitors have dimensions identical to those for EBFA I, all EBFA I Marx generator hardware could be utilized in EBFA II.

The MITE Marx generator was replaced with one containing the 1.0 μF capacitors. Initial tests show a 30 percent increase in energy delivered to the vacuum interface. A larger increase would be expected for the EBFA system since the solid dielectric intermediate store on MITE has a greater loss than the water insulated intermediate store on EBFA.

Tests of the 1.3 μF capacitors are planned for Supernite as well as lifetime tests of both the 1.0 μF and 1.3 μF capacitors.

REFERENCES

1. S. L. Shope, J. W. Poukey, K. D. Bergeron, D. H. McDaniel, A. J. Toepfer and J. P. VanDevender, J. Appl. Physics, 49, 3675 (1978).
2. J. W. Poukey and K. D. Bergeron, Appl. Phys. Lett., 32, 8-10 (1978).
3. M. S. DiCapua and D. G. Pellineo, to be published. Also in PIFR-1009, Physics International, San Leandro, CA (1978).
4. J. M. Creedon, J. Appl. Physics, 46, 2946 (1975) and J. Appl. Phys., 48, 1070 (1977).
5. J. Chang, J. P. VanDevender, A. V. Farnsworth, M. M. Widner, E. J. T. Burns and J. P. Quinten Bull. Am. Phys. Soc. 23, 763 (1978) to be published.
6. L. I. Rudakov, Transport of a Relativistic Electron Beam to a Thermonuclear Target-Translation, Translation SAND77-6011, June 1977.
7. J. P. VanDevender, accepted for publication in J. Appl. Physics (1978).
8. J. P. VanDevender, Electron Beam Fusion Progress Report, April through September 1977, SAND78-0080, p. 27 (1978).

CHAPTER 6 PULSED POWER APPLICATIONS

REP RATE PULSE POWER

Overview

After significant energy gain from an inertially confined fusion reaction, a number of difficult engineering problems must be solved before commercial power can be realized. Many problems can not be investigated until preceding problems are solved (i.e., reactor wall lifetime can be investigated only when a reliable driver, a pellet factory, and a pellet injection and guiding system have been developed). These series problems extend the engineering development period to twenty years. The first element in the sequential chain is the rep rate pulse power system. A pulse power module of a full reactor system is needed in the mid 80's to start the development process. Results from the low level program at Sandia to develop this experimental capability are described.

The peak voltage level for resonant transformer systems is now extended from 1 MV to 3 MV with a 92 percent energy transfer efficiency. The design of a 10 kJ, 10 pps Marx generator was completed and the major portion of the parts fabricated. Initial experiments defining the pulse to pulse voltage and current reproducibility of a cold cathode diode operating at 30 pps are described.

Three Megavolt Transformer Development

An air core transformer shown in Fig. 1 was designed, built and tested to demonstrate the feasibility of multi-megavolt operation. The transformer was successfully tested to 2.2 MV in an off resonance single swing charging mode and to 3 MV in a dual resonance charging mode. The energy transfer efficiency for the two modes of operation were 56 and 92 percent, respectively.

The transformer, a ring shielded spiral strip design, has a 60 cm diameter single turn primary surrounding a 42-turn copper strip secondary winding with oil impregnated polyester film interturn insulation. The active width of both windings is 30 cm. The case and flanges of the transformer are filament wound fiberglass-polyester composition which provides a rigid structural assembly and free penetration of the magnetic field. The concentric rings that are attached

Fig. 1. Three megavolt transformer.

to the core and case across the margins of the secondary winding, maintain a coaxial electric field shape in those regions to prevent breakdown from the inner turns of the secondary.

A capacitor bank to provide primary pulsed power for the transformer test was designed and built. The load section is a high voltage water capacitor, a spark gap switch and a water load resistor. A sketch of the system is shown in Fig. 2. The primary capacitor bank consisted of two 1.85 μF capacitors arranged in an over-under configuration and connected to be charged to ± 50 kV. At ± 50 kV the bank stores 4.6 kJ. A single rail gap

Fig. 2. Cross section of three megavolt transformer test assembly.

between the high voltage terminals of the capacitors discharges the energy through the transformer primary. Energy coupled through the transformer is fed to the 1 nF load capacitor. Near the peak of the secondary voltage excursion, the self-breaking gas spark gap between the capacitor and load resistor closes and the energy in the secondary capacitor is subsequently dissipated in the load resistor.

For the first series of tests the transformer output was direct coupled to the load capacitor and maximum charge transfer occurred at the peak of the first voltage excursion. Under these conditions the secondary capacitor reached a maximum of 2.2 MV in 1 μ s with a charge of + 50 kV on the primary bank. The energy transfer efficiency was 58 percent. Following the single swing tests the system was converted to a dual resonance charge cycle by adding tuning inductors to the primary-secondary sections of the circuit and changing the load capacitor to 0.76 nF. This change matches the frequencies of both sides of the system and reduces the effective coupling coefficient of the transformer to 0.6. In the dual resonance mode the total transfer time was 3 μ s which was the time to the peak of the reverse voltage excursion on the secondary. The system was taken to a full 3 MV with the primary capacitor bank charged to + 45 kV. This corresponded to an energy transfer efficiency of 92 percent. The energy transfer efficiencies for both charge cycles include all losses which were principally in the primary spark gap and the water capacitor.

The only difficulties encountered during the testing were two minor breakdowns along structural supports inside the transformer above 2 MV and occasional breakdowns in the water capacitor between 2.5 MV and 3 MV. A simple modification to the supports that corrected the breakdown problems in the transformer and improved voltage grading on the center conductor of the water capacitor raised the breakdown voltage sufficiently to reach 3 MV.

The results of these experiments clearly demonstrate the feasibility of multimegavolt transformer operation. They also provided the operating experience to allow the design and operation of higher energy repetitively pulsed transformer systems in successive program phases.

Transformer Winding Tests

A spiral strip transformer was designed and tested to failure and the results compared with the dielectric strength data obtained from oil-mylar laminate tests. Flat laminate tests have been used to simulate spiral windings for the purpose of evaluating various oil-mylar combinations. The core and primary turn were designed with the same length and edge curvature as the flat plate laminate test electrodes to duplicate the edge conditions (see Fig. 3).

Fig. 3. Sketch of transformer and flat plate laminate test assemblies.

The transformer, shown in Fig. 4, has a single turn primary and a 41-turn copper strip secondary winding with mylar and oil insulation. The width of the copper strip is 10 cm and has a thickness of 0.025 cm. The case consists of a single piece of 30 cm diameter acrylic tube partially slit along one side to provide space for feeding the primary turn ends. It connects to the acrylic face plate by means of a flange and bolts. The opposite end of the tube is capped with another acrylic plate. The pitch of the secondary winding is 0.063 cm. With 41 turns, the total winding thickness is 2.55 cm which is approximately 2.5 times the thickness of the test laminates. The transformer windings were impregnated with x-ray oil.

Fig. 4. Spiral strip transformer.

The transformer was mounted on the REPIT tank² and connected on the primary side to a $1.5 \mu\text{F}$ capacitor. The secondary was loaded with a 0.15 nF capacitor which discharges through a 250 ohm load resistor for energy dissipation. In the first series of tests the transformer was operated up to 1 MV in progressively higher voltage steps. Approximately $10,000$ shots at 10 pps were fired at each voltage increment. Above 1 MV the transformer was single shot tested in voltage increments of 100 kV . At 1.5 MV a breakdown occurred between the outer ring of the core and the primary which perforated approximately half the thickness of the mylar in the margin. The mean breakdown stress at 1.5 MV was 590 kV/cm , identical to the 590 kV/cm breakdown field measured with mylar and x-ray oil in the laminate tests. This result validates the laminate tests to simulate the electric strength of composite solid-liquid insulating systems for transformers. As an added benefit, the simple inexpensive transformer built for this experiment could be a useful design for small to medium sized, high-voltage systems where low cost is an important factor.

Switch Development

Two spark gap switches operating between of 10 to 30 kV were investigated during this report period. One is a cylindrical, flat-button three electrode spark gap with a ceramic liner inside a polycarbonate housing. Figure 5 is a sketch of this switch.

Fig. 5. Cylindrical, flat-button, three electrode spark gap.

switch triggered breakdowns occur randomly, spaced between the flat surfaces of the electrodes. The other spark gap is a low inductance flat plate switch with an in-line circular switching area in the plane of the plates as shown in Fig. 6. The plates are insulated from each other by a thin ceramic disk 0.37 cm thick. A cylindrical trigger electrode which is centered in the switching area is supported by housing caps on either side of the plates. Triggered spark discharges occur in the annular gap between the trigger electrode and the main electrodes. Because of its configuration, this spark gap is called a CAP switch (Cylindrical-Annular-Plate Switch).

Fig. 6. Cylindrical-Annular-Plate (CAP) Switch.

The flat button switch is cooled by both air and water. Water is circulated through a small volume outside each main electrode backing plate. The water volume surrounds the exhaust port from each electrode thereby removing heat from the exhaust products. The interior volume of the switch is cooled by a high speed vortex air flow. Air is injected into the switch volume through a convergent-divergent nozzle which generates a supersonic air stream tangent to the maximum inside diameter of the ceramic insulator. As it enters the switch volume, the air stream is split by the trigger blade and a high speed vortex is formed on both sides of the trigger blade which converges to the center across the switching area of the electrodes. Heated air and debris are exhausted from the switch through the centers of both main electrodes.

In this switch, the high speed vortex has a dramatic effect on switch performance in terms of stable operation at high pulse rates (up to 200 pps), and uniform electrode erosion and debris removal. For all testing which included a range between 300 J at 20 pps and 25 J at 200 pps no evidence could be found that the plasma ever expanded beyond the electrode profile. This conclusion is based on the complete lack of smoke traces or discoloration beyond the actual switching region. The electrode surfaces after approximately one million shots were exceedingly smooth and uniform. Although perceptible erosion of the Elkonite had occurred, roughness from hot spots where an arc had "settled out" was not detectable. There was no evidence of small bead-like debris deposited anywhere inside the switch or on the electrodes which is typical of many rep rate switches. During the testing, the pulse rate could not be increased beyond 200 pps due to power supply limitations. Therefore, the maximum operating limit of the switch is not presently known.

This switch has a wide triggering range when operated with a high impedance, 40 kV, transformer trigger source. Figure 7 is a plot of the triggering range of the switch as a function of voltage and pressure.

The CAP switch was tested to a maximum pulse rate of 20 pps on the REPIT facility with most runs at a rate of 8 pps. Maximum energy transfer was 550 J. The triggering characteristics of the switch are shown in Fig. 8. The air flow pattern through this switch was not optimum for high pulse rates. It is currently being modified to incorporate a high speed vortex flow generated around the

Fig. 7. Triggering range of flat button switch.

Fig. 8. Triggering characteristics of the CAP switch.

Two important facts have been demonstrated from the current switch development. First, cylindrical gap configurations can be designed with greater overall electrode switching area in a package less than one third the size of equivalent rail gaps. With a configuration like the GAP switch, the inductance can be as low or lower than a rail gap. Second, high speed rotational gas flow sweeping the entire electrode region maintains a much more consistent air quality in the electrode region for all repetition rates and current discharge levels while requiring air volumes only half that of switches incorporating soft flow techniques. There is strong evidence that high velocity gas flow improves switch break-down uniformity over large area electrodes, an important requirement for minimum erosion in rep rated switches.

Component acquisition is nearly complete and component testing is beginning for the repetitively pulsed Marx generator facility, RTF-II (1 MW, 10 kJ per pulse, 10 to 100 Hz). RTF-II is designed to study electron beam accelerator components at a time averaged throughput power level exceeding 100 kW. A resonant charging scheme coupled with inductive isolation between stages will be used to maximize the throughput efficiency of the device. SCPTRE³ computer modeling indicates that an overall efficiency of 90-95 percent should be possible. While this will be a significant accomplishment, it still leaves a 5 to 10 percent of the energy for the Marx generator components to absorb. This ranges from 5 kW under the best circumstances to 100 kW at a throughput power of 1 MW. All components must be designed to survive this extreme thermal loading.

[illegible]

are charged as pairs, eliminating the normal interconnection between the terminals held at ground during the charging phase. A large (greater than 10 k Ω) resistor which has no effect on the operation of the generator will be added to safely discharge the capacitors when the generator is turned off for maintenance. Fifteen stages (rather than 16) will be used because the last stage cannot be utilized efficiently. To charge a 16th stage requires either a fairly large resistor to ground (which absorbs at least 3 percent of the generators throughput power) or a multi-Henry megawatt inductor. Neither option is reasonable. Water cooling is used throughout using tap water (resistivity typically 20000 Ω -cm) piped through the generator via the isolation inductors and trigger coupling resistors. The 135 μ H inductors are made of 0.6 cm diameter copper tubing wound on a 25 cm diameter, 23 cm long threaded acrylic tube. Energy stored in these inductors after Marx erection represents the major inefficiency of the generator. To avoid deposition of this energy in the capacitors, a small resistor (4 to 10 Ω depending on the resistivity of the cooling water) is added in series with each inductor. SCEPTRE results show that this resistor absorbs the energy remaining in the inductors after the Marx has discharged without appreciably reducing the overall generator efficiency.

The inductors and their associated resistors have been designed and parts procured. Special care was taken to prevent accumulation of air bubbles in the resistors to maintain their dielectric strength. The resistors have been assembled and leak tested. The inductors remain to be assembled.

The pulse discharge capacitors have been procured. They are $0.35 \mu\text{F}$, 70 kV variety designed for repetitive pulse service. A single $18 \text{ cm} \times 36 \text{ cm} \times 61 \text{ cm}$, 20 nH capacitor will be used for each stage with the option to parallel two or more to increase the energy per shot.

The Marx switches have been assembled (Fig. 10) and testing has begun. They have a self-break voltage of 1 kV per absolute pound of air pressure. Each electrode is cooled with a water jacket located behind a 0.3 cm thick replaceable copper arc surface. A coaxial design is employed with large electrodes areas to maximize switch lifetime. This lifetime is probably limited by erosion. The switches are designed for 130 kV bipolar operation with a peak current of 50 kA in a $1 \mu\text{s}$ pulse. Minimum grace time between shots will be 4 ms at 100 Hz.

Fig. 10. High power Marx generator spark gap.

Triggering is via the outer (center) element in Fig. 10. A 13 turn transformer trigger generator with a gain of 7 has been developed. The trigger pulse can be made to greatly exceed the switch operating voltage, a condition which improves the triggering range of the switch. A large triggering range allows the switch to be operated at a voltage well below the self-breakdown level. This in turn allows the switch to continue to operate without adjustment as the self-breakdown threshold drops due to heat buildup during repetitive operation.

The switch and trigger system have been tested in 50 kV unipolar operation at 50 Hz. No problems have been encountered with this switch. Currently a conversion to allow bipolar testing is underway.

A primary power source to operate this Marx generator facility (and other high power systems currently under construction) has been defined and a contract for procurement has been placed. The source is a dc power supply operating from the 4160 volt three phase power lines available in Sandia Laboratories, Area III. Switch gear has been installed to allow the power lines currently used by the Sandia Laboratories Radiant Heat facility to be shared by the repetitive pulser development program. The power supply itself is under construction with installation and testing at Sandia projected for mid February 1979.

The power supply is a multimode device capable of being configured six different ways as detailed in Table I

TABLE I

2 MW Power Supply Characteristics

Mode	Maximum Voltage (kV)	Maximum Current (A)
Bipolar-Series	80	12.5
Bipolar-(Series-Parallel)	40	25
Bipolar-Parallel	20	50
Unipolar-Series	80	25
Unipolar-(Series-Parallel)	40	50
Unipolar-Parallel	20	100

Switching between modes will be made by changing the interconnection between the four identical output transformer-rectifier section. Maximum output power in each mode is 2 MW.

A tank (3 meters square by 1.5 meters deep) has been acquired for the Marx generator. Oil storage (20,000 gal.) is being constructed. Two gas systems, one a closed loop SF_6 system and the second consisting of a gasoline powered air compressor with a dryer-filter have been installed. Assembly of the Marx generator will begin when fabrication of the inductors is complete. Operation is scheduled to begin in March.

Repetitively Pulsed Diode

Information about cold cathode electron beam diodes operating in repetitive pulse conditions for extended runs is sparse, particularly at higher current densities. To explore electron beam generation in this region, a diode has been added to the RTF-I pulser. Primary objectives of this work are to identify failure modes under repetitive pulse conditions and to determine which diode operating parameters must be degraded from single shot limits for repetitive pulse operation. It is anticipated that damage to the anode and cathode and accumulation of debris on the vacuum insulator will be problems. Outgassing which increases the diode pressure sufficiently for a low pressure arc to form could also adversely affect repetitive operation.

The diode designed for RTF-I is shown in Fig. 11. It has a diaphragm type vacuum interface with minimal shielding against transport of debris or UV from the A-K gap region. The anode is a water-cooled, 0.3 cm thick aluminum plate. Various cathodes have been used. The most successful is a flat waffled surface. The A-K gap is adjustable to 1 cm to match the diode impedance to the 10 Ω output of RTF-I. Current in the diode is monitored with a low inductance resistive shunt (CVR) and voltage with a capacitive divider (V) and with a pickoff section in the annular resistor shown in Fig. 11. This resistor is constructed of lexan annuli holding a resistive solution between the center (HV) electrode and ground. Tap water (resistivity approximately 2000 $\Omega\text{-cm}$) is used as the resistive medium because it may be flowed freely through the resistor for cooling. Use of a more common electrolyte, e.g., CuSO_4 , would require a cooling and recirculation system.

Fig. 11. RTF-I diode.

The resistor also provides prepulse suppression necessary for successful diode operation. For 10 Ω diode operation, the annular resistor was typically operated between 60 and 90 Ω . Good prepulse suppression is particularly important on RTF-I which has a rather long (6 μs) PFL charging waveform. Symmetry is also important. If the annular resistor is replaced by a single tube, the output waveforms are badly distorted. Because of its rather low impedance the annular resistor absorbs more than 10 percent of the total RTF-I power necessitating the cooling previously mentioned. Future plans call for operation of high impedance A-K geometries in this diode. At that point it will be necessary to operate the annular resistor at 10 Ω and absorb most of the RTF-I output power. A CuSO_4 solution in a cooled recirculating system will be installed at that time.

Voltage and current waveforms are displayed in Fig. 12. Their duration is 30 ns FWHM. The voltage peaks at 200 kV and the current at 20 kA. The computed impedance waveform is shown as the solid circles in Fig. 13. (The solid line is a hand drawn line through

Fig. 12. Voltage (a) and current (b) waveforms for RTF-I diode. Upper traces first 10 shots of 5000 shot run at 20 Hz. Lower trace final 10 shot of that run. Sweep 20 ns/div.

Fig. 13. Impedance plot for RTF-I diode.

the data.) For a planar diode the space charge limited impedance is given by

$$Z = \frac{137}{V^{1/2}} \left(\frac{d}{r} \right)^2$$

where V is in megavolts, d and r are the A-K gap spacing and cathode radius respectively. For the data of Figs. 12 and 13, d is 0.37 cm and r is 1.9 cm, giving the Z equal to 11 Ω , the dashed line in Fig. 13.

Clearly the diode is behaving like a normal single shot device even though these data were taken during 20 pps operation. Each waveform is a composite of approximately 10 consecutive shots demonstrating excellent pulse-to-pulse stability. In addition the lower waveforms in Fig. 12 were taken approximately 5000 shots at 20 Hz after the upper waveforms and no aging is apparent. This is particularly important as the diode under these conditions is operating near the power absorption limit of the anode and considerable debris is being generated.

These data are part of a 17,000 shot run at various rates as listed in Table II.

TABLE II

Rep Rate Diode Date

Repetition Rate (Hz)	Accumulated Consecutive Shots
2.2	300
5.9	1000
10	3000
20	5000
<u>30</u>	<u>8000</u>
Total	17,300

Following this run the anode was deeply pitted but intact. The run was terminated by a failure of the vacuum interface which broke down on the oil side. Most probably this resulted from partial discharges in air bubbles accumulated at the oil-lucite interface. Formation of air bubbles in highly stressed areas may represent a major problem in producing long lived repetitively pulsed systems.

The maximum diode repetition rate is determined by the ability of the anode to absorb beam power. As an example, for 150 joules per pulse of 250 KeV electrons the aluminum anode is expected to melt near 25 Hz in this geometry. These electrons penetrate 0.03 cm into aluminum and on a single shot will melt the anode unless dispersed over an area of more than 4.4 cm². Under repetitive conditions heat builds up at the anode surface. At 25 Hz assuming 1-dimensional heat flow

into the anode, the computed temperature rise after many shots is 2.4 times the single shot temperature. Therefore the beam area must be expanded to 10.5 cm^2 . The experimentally observed beam spot is 11 cm^2 , thus these data are near the melting limit. In fact, the beam is not uniform and slow erosion of the anode is observed which becomes catastrophic in the 20 to 30 Hz range. At increased voltage the depth of penetration in the anode and heated anode volume increases in proportion to the voltage. Total energy (assuming diode impedance is held constant) increases as voltage squared. Thus energy per gram deposited and temperature rise both increase in proportion to the voltage. Higher voltages and/or repetition rates will require redesign of the cathode to produce a larger anode beam spot.

Online Diagnostics for Repetitively Pulsed Diode Development

Online diagnostics for RTF-I have been augmented to monitor the output current and voltage waveforms during data taking. Samples are taken simultaneously from each of the two waveforms at 4 ns intervals using gated fast sampling analog-to-digital converters (ADC's). Sampling begins approximately 8 ns before the start of the current waveform and continues until 24 samples covering 92 ns have been taken. The ADC's are unipolar, thus only negative portions of the waveforms are digitized.

Figure 14 illustrates the technique used in the sampling. Current and voltage waveforms are divided into 24 separate signals using high fidelity resistive splitters. These signals are input to 24 ADC's through delay cables ranging from 8 to 100 ns in 4 ns steps. A gate timed to the start of the current

Fig. 14. Sampling technique for on-line data acquisition for the voltage and current waveforms for the RTF-I diode.

pulse selects the time at which the sample is taken. As shown in Fig. 14, the gate comes 8 ns before the latest pulse and somewhat after the earliest pulse. Thus the entire waveform plus a baseline are measured. Any positive going afterpulse is ignored by the digitizers which are a unipolar design.

The effective gate width inside the ADC's is nominally 4 ns less than the input gate signal. If the gate is driven by a 16 mA (into 50 Ω) external gate signal, a width of 5.5 to 6 ns is required to get reliable sampling. Doubling to 32 mA allows the external gate signal to be reduced to 4 ns. The actual sampling gate may be inferred from the ADC output which is nominally 0.25 picocoulombs per count. A 73 volt signal split 24 ways gives a count of 775 for a 4 ns gate. Since the ADC input impedance is 50 Ω , this corresponds to a 3 ns effective gate. For the 5.5 ns external gate, the internal gate increases by only 10 percent. In terms of fidelity of reproduction of the input pulse by the sampling technique, the difference is inconsequential. Data to be presented were taken with the 5.5 ns FWHM gate.

Figure 15 is a logic diagram of the sampling system appropriate to the 5.5 ns gate. The voltage signal is split using a power tee and then further divided into 24 parts with two twelve-for-one resistive splitters. Fidelity of the splitter system, checked by splitting the gate signal, was found to be adequate. A 10 percent voltage signal derived from an inductive pickoff is used to display the signal being sampled on a fast oscilloscope. The current signal is handled in the same way. In addition a 10 percent signal is picked off to produce the gate. A discriminator produces an external trigger for the oscilloscope, a stop for the time digitizer (used to monitor the firing of the RTF-I output switch), a master trigger and the 4 ADC gates in time from the leading edge of the current pulse.

The master trigger is the computer signal that an event has occurred. Upon receipt of the trigger, data are input to the computer memory and analysed as rapidly as possible. In addition all the data are transferred to tape for subsequent detailed off line processing.

Each data word is multiplied by a conversion factor relating ADC counts to voltage or current as appropriate. These constants can be computed during a calibration phase at the start of a run. First data with no

Fig. 15. Logic diagram for sampling system for RTF-1.

Input waveform are processed to compute the offset (pedestal) of the ADC's (typically 1 count for a fast gate). Next a standard effectively DC voltage is digitized. The final calibration constant is the calibration factor for the voltage or current probe multiplied by the standard voltage divided by the calibration digital signal corrected for pedestal. The whole process is done automatically using the same gate signal and splitting/sampling hardware as are used in the actual data acquisition phase. Thus the only effects not allowed for in calibration are anomalous response of the ADC to a fast pulsed signal (not observed to date) and non-linearity which has been measured by the manufacturer to be small over the voltage range of interest.

Figures 16 through 19 show the response of the sampling system to standard pulses. The waveform of Fig. 16 was fed to both the current and voltage inputs of the sampling system. Fig. 17 compares the computer output (with error bars giving the standard deviation of the shot-to-shot variation) with a solid curve through hand measured points. The agreement is reasonable. Figure 18 shows a faster pulse for which samples by hand (curve)

and by the computer are shown in Fig. 19. With the exception of a general broadening the pulse is reasonably reproduced. A 3 ns gate may be expected to increase the pulse width by approximately 3 ns. In fact the input and sampled waveforms are both 25 ns wide at half maximum and the sampling distortion is in the form of a tail on both the leading and trailing edges of the waveform and a lack of definition of the sharp corners.

Fig. 16. Slow waveform fed to sampling system.

Fig. 17. Comparison of computer output to curve drawn from digitized data.

Fig. 18. Fast waveform fed to sampling system.

Fig. 19. Comparison of computer output to curve generated from digitized data.

The bulk of the waveform is reproduced with reasonable fidelity. Thus the impedance, power and energy for each pulse can be computed and compared to other pulses. Since the ADC's need signals of several volts amplitude, the waveforms before splitting need to be 50 to 100 volts in amplitude effectively eliminating probes requiring integrators (such as $\dot{B}$ or $\dot{V}$ probes) which suffer large voltage reduction upon integration. A CVR and a high time averaged power water resistor have been developed and checked for pulse fidelity on RTF-I. They will be used for online data acquisition in the near future.

REACTOR SYSTEM STUDIES

Overview

Significant progress was made during this period in reactor physics and conceptual design. Preliminary evaluation of the design criteria in the gas-filled reactor concept is underway and a better understanding of the energy transport in the central vessel is in hand. Several factors affecting the choice of the transport/buffer gas have been identified. The interaction of pellet materials and a hot buffer gas with the cavity walls has been studied. Estimates of wall erosion rates and a determination of reactor products were made. Bechtel National has completed the final capital cost estimate of a large particle-beam-driven fusion-fission power plant. An investigation of the potential for synthetic fuel production in the reactor cavity has been initiated. This possibility is unique to particle beam systems. The use of chemical exchange reactions is most promising for use with DT-containing pellets, while dissociation reactions are attractive for use with advanced-fuel pellets.

Design of a Gas-Filled Particle-Beam Reactor Chamber

Technological feasibility of a commercial fusion power plant utilizing particle beams depends in part upon two requirements of reactor chamber design. First, the inner cavity walls must be capable of withstanding frequent pulses on the order of 10 Hz of x-rays, energetic charged particles, and neutrons. Second, the electron or ion beams must be repetitively transported to the center of the reactor chamber and focussed on pellets about a cm in diameter.

If the chamber is filled with a background gas of several tens of torr for electrons and

several torr for ions, beam-current neutralization and pinched-mode propagation are possible with an azimuthal field in a highly conducting plasma channel.⁹ The dense gas effectively shields the first wall from most of the low-energy x-rays and ion debris (Fig. 20). These would otherwise be stopped in the first few microns of the wall, causing steep temperature gradients, ablation, sputtering, and spall. For 100 torr of air, most x-rays are stopped⁷ in 10 cm and most heavy ions in 1 cm. With the presence of a gas in the chamber, the structure must withstand blast loading rather than the short-range, short-duration deposition of x-rays and ions. Because of the much longer spread in arrival of a blast wave, the stress felt by the wall should be less damaging.

Fig. 20. Schematic diagram of a particle-beam reactor chamber with and without gas protection.

Energy partition and spectra of a pellet implosion are functions of pellet design, voltage, and fusion gain. For a gold-shell ablatively-driven target with a fusion gain of about 25 (Fig. 21), roughly 17.5 percent of the energy release is in neutrons, with the remainder in x-rays and ion debris.¹⁰ The 14.1 MeV neutrons lose about 1.5 MeV in traversing the compressed fuel and high-Z pusher. The x-ray spectrum is characteristic of a 350 eV blackbody, and most of the gold ions have energies of 100-600 keV.¹⁰

The shock overpressure for the implosion decays to about 0.8 atm at a radius of 4 m in a 100 torr background gas (Fig. 22). The dependence of overpressure on gas prefill pressure is weak at this radius, increasing only 60 percent for a ten-fold increase in gas pressure.

Fig. 21. Energy partition and pellet spectra of a typical gold-shell pellet implosion for electron beams.

Fig. 22. Shock overpressure and time arrival vs. chamber radius for the target of Fig. 21 for a 100 torr N_2 chamber prefill.

More than 2 ms elapse after microexplosion before the shock reaches a 4 m radius first wall. The sound speed in a hot plasma channel is roughly 10 times that in the background gas and the pressure is more than 20 times higher, implying an arrival time of greater than 0.6 ms for a shock traveling up a channel to a diode. This may not be sufficient time for a rep-rated solenoid valve to close,¹¹ protecting the driver from the blast wave, but a rep-rated rotating vane should be able to close in 0.1 ms. About 1-2 ms is needed for the channel to mix turbulently with the background gas.¹² This estimate does not take into account the effects of a microexplosion on channel survival or expansion, so it appears that diode protection is not a problem.

The radius of a gas-filled chamber is limited by the difficulty of producing long ionized channels and propagating beams along these channels. The minimum radius depends upon economic neutron and blast-wave wall loadings (see Fig. 23). The chamber radii determined by a 10 ksi peak hoop stress are consistent with economic values¹³ of neutron wall loading at a rep rate of 10 Hz. A 110 MWe hybrid requires a 1.3 m radius chamber; a 1200 MWe hybrid, 4 m. Furthermore, for the higher pellet yields, chamber radii are rather insensitive to energy deposited and yield.

The chamber radii in Fig. 23 are not absolute minima. With a thicker liner, a lower chamber prefill, internal liquid metal cooling to limit thermal stresses and reduce the hoop stress, or more frequent first wall replacement, i.e., higher neutron and blastwave wall loadings--chamber size could be further reduced.

The chamber gas acts as an AC-DC thermal power converter (Fig. 24). The absorption and transport of x-ray and ion debris energy in the gas smoothes out over many milliseconds the pellet energy which would otherwise appear at the first wall as fast transients accompanied by large thermal stresses.

The choice of the proper buffer gas is important for system efficiency. Attenuation data (Table III) for 350 eV x-rays in gases⁷ indicates that any gas except helium stops most x-rays in an electron-beam reactor chamber. For an ion-beam reactor the highly nonlocal nature of the absorption of a 500 eV blackbody spectrum in air¹⁴ indicates it may be necessary to account for deposition volume in sizing the chamber based on blast loading. The particle beam will lose energy in traversing a plasma channel. Except for

xenon, the energy loss⁸ of a 2 MeV proton beam over 4 m is less than 10 percent (Table IV); for protons of higher energy less energy is lost.

Fig. 23. Sizing of a particle-beam reactor chamber based upon reflected overpressure from a blast wave and neutron wall loading. A pellet coupling efficiency of 0.65 was assumed. Overpressure values are based on a constant ks: blast loading of a 1.0 cm-thick liner and a 100 torr chamber prefill.

Fig. 24. Percentage of non-neutronic energy from the 75 MJ pellet of Fig. 21 transported from 100 torr of air to a 4 meter-radius chamber wall as a function of time after equilibrium is established.

TABLE III

Mean Free Path in Gases for 350 eV X-rays

Gas	MFP at 1 Atm (cm)	MFP at 100 torr (cm)
H ₂	55.3	420.1
He	3.7	28.3
Li	0.65	4.9
N ₂	0.4	3.0
Ne	0.14	1.05
Ar	0.03	0.21
Xe	0.05	0.38

For adequate x-ray attenuation, about 3 mean free paths should be obtained in the chamber radius.

TABLE IV

Energy Loss of Protons in a 4-Meter Long Plasma Channel of Density = 2/760 Atmospheric (corresponds to 10 torr chamber prefill)

Gas	Energy Loss For 2 MeV Proton (MeV)	Energy Loss For 4 MeV Proton (MeV)	Energy Loss For 10 MeV Proton (MeV)
He	0.032	0.018	0.0082
Li	0.048	0.028	0.013
N ₂	0.18	0.11	0.052
Ne	0.11	0.072	0.035
Ar	0.18	0.11	0.057
Xe	0.34	0.24	0.13

The reradiation time of the absorbed energy to the first wall and the equilibrium temperature of the chamber gas also influence gas choice. For a typical pellet implosion--24.8 MJ in x-rays and ion debris, 75 MJ yield--CHARTD calculations reveal that the reradiation time at a 10 Hz rep rate varies between 0.4 and 10 seconds for chamber prefills of 7.5 to 200 torr air and the equilibrium air temperature varies between about 0.5 and 0.9 eV. A 0.5 eV temperature is tolerable for channel initiation since the air is unionized, but 0.72 eV (corresponding to 75 torr) is not, since the free electrons inhibit cascading.

There are a number of possible solutions to the relatively long reradiation times and high equilibrium temperatures. If the chamber gas is seeded with a gas such as SF₆, electrons are attached quickly and the gas should have sufficient dielectric strength for channel formation. A lower Z gas would increase transport to the walls and reduce channel expansion because of lower radiative opacities and electrical resistivities. However, calculation of energy transport to the walls for gases other than air requires opacity data below an eV; such opacity data is not generally available. Group T-4 at LASL is providing frequency-dependent opacity data for He, Ar, and Ne at temperatures above 0.4-0.5 eV, and for H at temperatures about 0.13 eV. Gas recirculation might still be necessary, especially for the higher-pressure electron-beam chamber, to restore the cavity to conditions favorable for channel initiation and beam propagation. Some electrical energy of the power plant would then be needed for gas pumping. For example, 5 MWe is needed to replace 100 torr of gas in 0.2 sec using a 2 m² flow area.

First-Wall Chemistry

The potential for first wall chemical corrosion damage due to wall interactions with a high-temperature buffer gas and with pellet debris materials have been studied. The corrosion rates of two candidate wall materials, type 316 stainless steel and carbon (isotropic graphite, pyrolytic graphite and carbon/carbon composites), when subjected to the debris of a particular pellet (0.3 cm in radius, having a lead coating 0.043 cm thick and containing 990 micrograms of an equimolar DT mixture) and one of several high temperature buffer gases were investigated. The gases studied were hydrogen, nitrogen, and impure helium (10 ppm O_2).

The study was carried out in two parts. In the first part, an extensive literature search was used to determine the chemical reactions most likely to lead to significant wall corrosion. The production of methane, acetylene, and cyanogen eliminated the potential use of hydrogen and nitrogen (e.g., as air) with a carbon first wall. The rapid oxidation of a pure #316 stainless steel wall by the impure helium eliminated that combination. The second part of the study involved the use of an equilibrium thermo-chemistry program, ACE,¹⁵ previously used at Sandia for the calculation of nose cone ablation and erosion rates. This code allows a quantitative evaluation of wall/buffer-gas/pellet-material combinations to be made.

Results indicate that for a particular reference design, the erosion of a carbon wall in impure helium (10 ppm O_2) would be 2-3 mm/yr (commercial-grade helium generally contains 0.1-0.5 ppm O_2). The erosion due to unburned pellet DT alone is about 4×10^{-2} mm/yr. This, then, may be a usable wall/gas combination. Other results indicate that while pure stainless steel is very rapidly eroded by oxidation, the thin Cr_2O_3 layer found on most stainless steels routinely exposed to air presents a very effective barrier to oxidation by impure helium. The combination of stainless steel with impure noble gases may, therefore, also be a usable wall/buffer gas combination at high temperatures.

Hybrid Reactor Design Study

The Bechtel National engineering design and final cost estimate of a conceptual 1075 MWe (net) electron beam fusion-fission power plant have been completed. Some of the parameters of the design are listed in

Table V. This is a large power reactor which produces, at modest values of pellet gain (18), blanket energy gain (6), and recirculating power fraction (12 percent), enough fissile fuel per year to power six light water reactors of equivalent electrical output.

TABLE V
Electron Beam Fusion-Fission
Reactor Design Parameters

DT fusion power	720 MW
Total thermal power	3440 MW
Gross electrical output	1227 MW
Net electrical output	1075 MW
Pulse rate	10 Hz
DT target yield	72 MJ
Electron beam energy	4 MJ
Target gain	18
Number of electron beams	32
Reactor cavity diameter	10 m
Reactor cavity height	13.5 m
Reactor cavity gas	100 torr N_2

The major part of the capital cost estimate, for the heat transfer system on, is based on a Bechtel breeder reactor study and is, therefore, quite detailed. The reactor and electron beam costs are more detailed than comparable items in any previous Bechtel fusion system study, including UWMAC III.¹⁶ A summary of the cost estimate is presented in Table VI.

The value for construction cost does not include the owner's costs, interest during construction, or escalation. When these are included, the total capital cost is 3422×10^6 1988 dollars, or 1823×10^6 1978 dollars. At a fixed charge of $\$300 \times 10^6$ /yr and a fuel revenue of $\$95 \times 10^6$ /yr, the estimated electrical generation cost is ~ 35 mills/kWh.

TABLE VI
Capital Cost Estimate Summary
(\$10⁶, 1978)

Nuclear Steam Supply System	353
Balance of Plant	<u>518</u>
Direct Cost	871
Field Distributable Expenses	174
Engineering and Services	209
Contingency (20 percent)	<u>251</u>
Construction Cost	1505

Based on this estimate and updated costs for the Bechtel/LLI laser hybrid, a cost comparison with a standard (1075 MWe) light water fission reactor (LWR) can be made. Table VII shows this comparison in 1978 dollars.

TABLE VII
Cost Estimate Comparison for a Fission Reactor and Two Hybrid Reactors (\$ 1978)

	Fission LWR	Bechtel/SLA E-beam Hybrid	Bechtel/LLI Laser Hybrid
Driver Cost	NA	\$80 x 10 ⁶	\$280 x 10 ⁶
Installed Cost	\$918/MWe	\$169/MWe	\$2385/MWe
Cost/LWR Cost	1.00	1.85	2.60

Synthetic Fuel Production

At the pressures needed for beam propagation in the gas-filled reactor concept (> 50 torr), the energy in x-rays and debris ions from the pellet is fully absorbed by the gas. If the gas is not recirculated, its temperature equilibrates in the 0.5-1.0 eV range, determined by the pellet non-neutronic power output and by the rate of thermal conduction, convection, and radiation to the walls. If the gas is recirculated, the temperature is lower. At room temperature, the time needed to transport 25 MJ (the non-neutronic output of a 75 MJ-yield pellet) through 4 meters of 100 torr air is greater than 5 seconds. As a result, the chamber gas acts as a large thermal "capacitor", and the gas flow rate determines both the gas temperature and the amount of thermal power transported to the cavity walls.

The potential of raising large amounts of gas to the temperatures described above leads to the possibility of synthetic fuel production on a massive scale. For example, in a spherical 4-m radius cavity filled to a density of $3.6 \times 10^{18}/\text{cm}^3$ (100 torr at 273°K), more than 28 kg of H₂O or 68 kg of CO₂ would be in the cavity at any one time.

In addition to the anticipated need for synthetic fuels at the time such a fusion reactor might be constructed, there are at least two other reactor-related reasons for pursuing this possibility: (1) The possible conversion efficiency from thermal energy to chemical energy (fuels) is much higher than for conversion to electricity. Figure 25 shows that the pellet thermal energy can have an end use value comparable to that of the neutrons. (2) The conversion to fuels (stored chemical energy) could, if needed, provide for electrical production even during reactor shutdown, with an additional investment in a boiler, but little in turbo-generating machinery.

Fig. 25. Comparison of efficiency of conversion of thermal energy to fuels and neutron energy to electricity.

A pilot study was carried out in conjunction with the University of New Mexico to determine the most attractive fuel-producing reactions.¹⁷ Estimated values of some of the parameters of these reactions are listed in Table VIII. A large range of operating temperatures, particle densities, and operating pressures is encompassed and the values shown are not necessarily optimal. In the calculations, 75 MJ-yield pellets being imploded at 10 Hz in a 4-m radius cavity were assumed to be the energy source (240 MW_{th}). The energy values of the chemical products are given in Table IX, and the estimated dollar values of these products near maximum yield are

presented in Table X. Currently, a more detailed study is underway which will produce more solid estimates of chemical reaction rates, recombination rates, and product yields.

TABLE VIII
Summary of Estimates

Process Number	Reaction	Time (s)	Temperature (K)	Pressure (atm)	Energy (kcal/gm-mole)	Gas (g)	Notes
1.	H_2	770/100 CF	12,000	10	68.32	0.27	
2.	H_2	770/100 CF	12,000	10	68.32	1.53	
3.	C_2H_2 & H_2	770/100 CF	12,000	10	310.61 & 68.32	0.45	
4.b.	CO	770/100 CF	12,000	10	67.63	1.93	
4.b.	H_2 & CO	770/100 CF	12,000	10	68.32 & 67.63	1.96	

TABLE IX
Energy Value of Products

Process Number	Gas	Energy Value (kcal/gm-mole)	Total Energy Value/Day (Btu) $\times 10^{10}$
1.	H_2	68.32	0.27
2.	H_2	68.32	1.53
3.	C_2H_2 & H_2	310.61 & 68.32	0.45
4.b.	CO	67.63	1.93
4.b.	H_2 & CO	68.32 & 67.63	1.96

TABLE X

Current Wholesale Value of Gas Products

Process Number	Gas	Rate (lb/day)	Value (1955)	Notes
1.	H_2	770/100 CF	\$2,000.00	
2.	H_2	770/100 CF	\$2,000.00	
3.	C_2H_2 & H_2	770/100 CF	\$2,000.00	
4.b.	CO	770/100 CF	\$2,000.00	
4.b.	H_2 & CO	770/100 CF	\$2,000.00	

A number of problems have been identified in these studies. If the flow rate of hot gases from the vessel is large, high-temperature refractory materials may be needed. While these can be developed, the time and expense may be significant. This has been one of the pacing items in the coal gasification program. A second potential problem is contamination of the fill gas by the unburned tritium from the pellet. Separation of T from hydrogen and water vapor is relatively routine using successive diffusion stages, centrifuging, electrolysis, and molecular sieves. The difficulty arises in separating tritiated high-molecular-weight products such as acetylene. The use of exchange reactions as opposed to dissociation-recombination reactions for fuel production is promising and might circumvent the tritiated-product problem.

ELECTRON BEAM SOURCES FOR GAS LASERS

Overview

Virtually all of the high-power gas lasers that are being considered as drivers for ICF reactors require electron beams in the pumping process. These moderately high power beams perform one of the following three functions depending upon the particular laser being considered 1) provide control of a gas discharge, 2) provide direct excitation for either the laser or its photolytic drivers or 3) initiate chemical reactions. Low current density (1-40 A/cm²) beams with microsecond pulse durations are needed for

functions 1) and 2) for gas lasers that store energy. Non-storage gas lasers (such as HF or KrF systems) require large area, high current density (100-1000 A/cm²) beams with pulse durations in the 10-100 ns regime. Although present day electron beam generators satisfy the needs of experiments being performed today, a better understanding of the physics and engineering issues involved in beam generation, transport and deposition is required before substantially larger energy systems can be developed.

Low-current density beams for this application are usually formed with highly field enhanced cathodes. Carbon fiber cathodes provide a technique for controlling the density of cathode plasma spots in contrast to the randomness of blades. Impedance characteristics and plasma closure velocity for both types of cathodes have been measured. Electron beams generated from these sharp edged emitters exhibit substantial temporal variations in beam current density. Experiments were previously reported that defined the instability formation time as a function of current density. Experiments that were completed during this period indicated that the instabilities are caused by phenomena occurring in the volume of expanding plasma rather than at the cathode surface.

Plasma-filled diodes offer an attractive alternative to sharp-edged emitters for generating low-current density electron beams. Experiments initiated during the previous reporting period continued throughout this period. Plasma and diode conditions for maintaining a constant impedance throughout the one microsecond pulse have been established. Variation in initial plasma properties can result in widely different impedance characteristics.

In FY 79 the emphasis of the experimental program is shifting to the higher current density, short-pulse duration beams. A one terrawatt test facility (RAYO) is being designed and fabricated. The technology developed during the Proto II accelerator¹⁸ program is being heavily used during the design of this accelerator. The experimental program will establish the beam parameters (and the techniques for producing these parameters) required to optimize the system for driving a 10 kJ MF laser or a 0.5 kJ KrF laser.

Preventing emission from cathode support structures is an important consideration for obtaining efficient diode operation.

Experiments have demonstrated that the emission level can be kept below 0.5 A/cm² at mean electric fields of 470 kV/cm for 20 ns voltage pulses.

Blade Field Emitters

Highly field enhanced, thin blade cathodes have been used to generate high current density electron beams for a number of years. It has been shown¹⁹ that the Child-Langmuir limited impedance behavior of blade cathodes can be expressed as

$$Z_{\text{blade}} = \frac{433}{\sqrt{1/2}} \frac{x^2}{A} \quad (1)$$

where V is the applied voltage in kV, x is the anode-cathode gap and A is the area of the beam at the anode. The area is determined by the geometry shown in Fig. 26 and is given by

$$A = 2\Delta\omega \cdot l + 2\Delta l^2 \quad (2)$$

where l is the length of the blade and $\Delta\omega$ and Δl are the spreading of the beam along the axis perpendicular and parallel to the plane of the blade respectively. Experiments with high current density diodes have shown that $\Delta\omega$ and Δl are directly proportional to the anode-cathode spacing. Measurements of the spreading have indicated proportionality factors ranging from 0.6 to 1.0. This range in values may be due to differences of self-field effects in the various experiments.

Fig. 26. Blade field emitter and blade geometry.

An experiment was performed to check the validity of equations 1 and 2 for low current density microsecond diodes and to determine the spatial and temporal uniformity of the resulting current density at the anode. A schematic diagram of the experimental arrangement is shown in Fig. 27. A 30.3 cm long, .0025 cm thick titanium blade was clamped in an aluminum support structure. The tip of the blade was located 1 cm above the aluminum plate. The edges of the blade were rounded to prevent a preferential field enhancement at the edges. Open shutter photographs of the blade during a shot showed a uniform glow along the tip of the blade only. This indication that only the blade tip emitted was confirmed by a series of shots using the blade support structure without a blade. Since these measurements reproduced the experimental conditions existing during the blade measurements and since no diode current was observed, it was concluded that all of the measured current was due to the blade and not to any of the support structures.

Fig. 27. Experimental geometry for blade cathode.

Results of these measurements are shown in Fig. 28. The open circles represent the blade impedances 120 ns into the voltage pulse. The filled circles represent the blade impedances 160 ns into the voltage pulse. The solid line was obtained from equations 1 and 2 assuming that $\Delta\omega = \Delta I = \gamma$. Each data point is an average of 13-15 shots. The macroscopic (V/x) electric fields investigated ranged from 10 to 60 kV/cm. These data show that the empirical relations give an adequate description of the diode impedance behavior. Differences between calculated and measured impedances appear to be due to: a) cathode turn-on and b) impedance collapse due to closure of the anode-cathode gap resulting from plasma motion. For gaps greater than 7 cm the diode has not reached space-charge limited flow at 120 ns into the voltage pulse but by 160 ns, it has reached this value.

Fig. 28. Impedance characteristics of blade cathode.

For smaller gap spacings the diode reaches space-charge limited flow earlier in time and gap closure has brought the impedance below the line which was calculated assuming the full anode-cathode gap. Measurement of the impedance collapse for a 6 cm gap yields an apparent gap closure rate of ~ 3 cm/ μ s.

Measurements of the time integrated current density at the anode using passive radiochromic dosimetry techniques showed the presence of beam striations. These appeared as strips of higher current density spaced at regular intervals and running perpendicular to the plane of the blade. These arise from a tearing mode instability of the cathode plasma²⁰ and have been observed in all blade field emitters. In the presence of these striations the local current density can differ by a factor of ± 25 percent. Apertured Faraday cup measurements showed the existence of sharp fluctuations in the anode current density. An investigation into these temporal instabilities is described in a different section of this report.

Carbon Fiber-Brush Cathode Tests

Carbon filaments have been used as low voltage dc field emitters. In these studies a single carbon filament was operated stably for a period of several hours with currents up to 1 mA.²¹ The performance characteristics of these filaments were observed to be superior to those of the traditional tungsten emitters.

A brush-type cathode consisting of bundles of $\sim 10\text{ }\mu\text{m}$ diameter carbon fibers was built to test their applicability to low current density, microsecond electron beam diodes. The bundles consisted of several hundred individual fibers and were arranged in a grid pattern 1.25 cm apart. The assembled cathode is shown in Fig. 29. The tip of the carbon fiber bundles protruded $\sim 1\text{ cm}$ above the aluminum backing plate. No attempt was made to make the bundle heights exactly equal or to assure that they were perpendicular to the surface of the backing plate.

Fig. 29. Carbon fiber brush cathode.

This cathode was installed in the LEGS diode.¹ The distance between the anode and the tip of the carbon fiber bundles was $\sim 9.3\text{ cm}$. Figure 30 shows the diode voltage and current waveforms when the cathode was subjected to fields (V/d) of approximately 10 kV/cm and 20 kV/cm . It can be seen that the cathode emits readily at these fields. The diode reaches space charge limited flow early in the power pulse and exhibits an apparent gap

Fig. 30. Diode voltage and current waveforms at two voltage levels.

closure of about $1.5\text{ cm}/\mu\text{s}$. The apparent gap closure velocity was significantly higher at times and was related to the formation of emission sites on the surface of the aluminum backing plate. This phenomenon is apparent on Fig. 31 where two shots with the same diode parameters are shown. The waveforms on the left have a closure velocity of $2\text{ cm}/\mu\text{s}$ whereas those on the right have an apparent closure velocity of $5\text{ cm}/\mu\text{s}$. The open shutter photographs taken of the cathode during these shots show significantly more emission from the aluminum plate for the $5\text{ cm}/\mu\text{s}$ case. If the cathode support structure could be prevented from emitting, the carbon fiber brush cathode would make a superior field emitter for low current density electron beam diodes since it emits well at fields of 10 kV/cm and exhibits apparent gap closure velocities of about $1.5\text{ cm}/\mu\text{s}$.

Apertured Faraday cup measurements showed that the anode current density exhibits temporal instabilities similar to that displayed by blade cathodes. A quantitative measurement of the anode current density spatial uniformity were not made. It was qualitatively similar to that obtained with an array of blade emitters. Another advantage this cathode may have over blade emitters is in repetitive pulsed applications. Since each bundle is made of a very large number of individual fibers, the destruction or erosion of any one fiber would not affect the operation of the diode in subsequent shots. Very long lifetimes may thus be a characteristic of this type cathode.

Fig. 31. Diode voltage and current waveforms for two shots at same voltage level with corresponding open shutter photographs of cathode.

Plasma Instability in Needle Cathode Diodes

An experiment has been performed to improve our understanding of the formation of current bursts of the type shown in Fig. 32 from needle and blade cathode diodes. For the few tens of nanosecond duration of these bursts the local current density may exceed the ambient space charge limited value by a factor of five or more.²² Data strongly suggest that the burst instability occurs only after the cathode plasma becomes too diffuse to sustain the current density allowed by the space charge limit. The question has been raised whether the burst is actually triggered by the explosion of microscopic whiskers at the metallic cathode surface after formation of the original plasma. Data have been offered to support this model.²³ They prove that the burst can be triggered by a relatively large spark at the cathode tip but do not prove that the bursts are actually driven from the cathode surface.

On the contrary data discussed below demonstrate that the bursts are independent of the cathode surface. By using a 2.5 cm dielectric needle, the metallic surface, where whiskers presumably explode, can be

Fig. 32. Typical event, 2.5 cm A-K gap 100 ns/cm base for each oscilloscope trace.
a. Voltage waveform 32.2 kV/div.
b. Total diode current (CVR) waveform 3.1 kA/div.
c. Axial current density (Faraday cup) waveform 32 A/cm²/div.

transit time isolated from the emitting front of the cathode plasma. If the model of Ref. 23 were correct, bursts should occur approximately 1 μ s later than would be expected from an equivalent diode with a metallic needle if at all. In fact they occur as if the cathode were a metallic needle suggesting that the burst formation is a property of the cathode plasma, not the cathode surface.

Data were taken using dielectric needles 2.5 cm long with a 50 μ m tip diameter. The A-K spacing was varied from 1.3 to 2.5 cm. Voltage pulses 1.5 μ s in duration and 200 kV in amplitude (into a matched load) were applied using a Nereus Marx generator²⁴ incorporated in a three section Guillemin Type A pulse forming network.²⁵ Total diode current was measured with a 0.1 Ω low inductance shunt (CVR) and current density on the needle axis was monitored with an apertured Faraday cup. Voltage was measured with one resistive divider in the diode and a second at the PFN output.

Open shutter photographs of the diode were taken for each event. In contrast to photographs of metallic needles where most of the light comes from the emitting tip, a glowing plasma appears along the entire length of the dielectric needle. Bright spots are confined to the triple point as would be expected for a surface flashover cathode.

Metallic cathodes emit current almost immediately (on the microsecond time scale of this experiment) upon application of the voltage pulse. The dielectric cathodes do not emit measurable current until a field of approximately 30 kV/cm is reached at the triple point. After the surface flashover, the total current rises precipitously; (Fig. 32) to 500 A in less than 10 ns. This current is interpreted as emission from the plasma along the needle shank. The total current increases until the generator short circuit value is reached at 0.5 μ s into the current pulse. This time to reach a short circuit condition implies a mean plasma closure speed of 5 cm/ μ s (a speed typical of metallic needle cathodes for this A-K spacing and voltage also). There is some emission without the needle. It begins after a time delay similar to the turn on delay with a dielectric needle in place. It rises slowly with time never exceeding 150 A and thus represents a small background to the current with the dielectric needle. Clearly the bulk of the observed emission is from the surface plasma of the dielectric cathode.

Emission along the needle axis rises gradually from zero in a manner characteristic of gap closure. For the event in Fig. 32 the current density becomes unstable rather early, at 120 ns into the current pulse, with a 20 ns burst reaching 3 times the ambient value of 20 A/cm². In this case the burst is not apparent in the total current. Bursts do, however, appear in the total current in 70 percent of the events.

For this particular event it is clear that the change to a dielectric needle has not delayed the onset of instability appreciably. To quantify this point, the onset of instability may be compared to the empirical relationship $t_{CR} = 880/j_{CR}^{0.43}$ which according to Ref. 26 relates the current density at the start of a burst j_{CR} (A/cm²) to the time from the start of current flow t_{CR} (microseconds). This formula is a fit to data on the range 10^3 A/cm² < j_{CR} < 10^4 A/cm². The time to instability varies considerably from shot to shot with either type of cathode, but if averaged over 10 shots for a given geometry, this relationship is found to hold for dielectric needles also. Figure 33 shows j_{CR} vs. t_{CR} for several gap settings. The points are the new data and the solid line is the equation. Agreement is quite good indicating that the dielectric needle cathode has not delayed the onset of bursts relative to what would be expected from a metallic needle by more than the typical measurement error, 20 ns.

Fig. 33. Critical (burst) time vs. axial current density at burst onset.

These data imply that the model of current instabilities triggered by mass bursts from the cathode surface is not correct. The results of Ref. 26 prove that current bursts can be generated by cathode surface phenomena but do not rule out other mechanisms. The present data demonstrate that the mechanism leading to the instability is not dependent on the type of cathode used and they are difficult to accommodate with the model of Ref. 26. Instead the present data indicate that the mechanism which generates the current bursts is intrinsic to the cathode plasma and independent of the cathode surface.

Plasma Injected, Microsecond Electron Beam Diodes

In the preceding progress report, the initiation of a project to study the interaction of externally generated low density plasmas with microsecond electron beam diodes was discussed.² The impetus for this study was to obtain external control of the impedance behavior of low current density, microsecond

associated with field emitting cathodes such as slow current "turn-on", diode impedance collapse and poor spatial and temporal uniformities of the current density at the anode. The study has been continued. We report here on the characterization of the plasma sources used in this study and on further plasma injected diode studies.

Surface Flashover Plasma Boards

One of the large area plasma sources being used for this study consists of a pattern of rows etched on a printed circuit board. Each row consists of a number of metallic pads separated from each other by a 0.5 mm gap. In this application a voltage pulse is applied to one end of the row while the other end is held at local ground. A ground plane beneath the board makes each pad act as a capacitor which is charged by the applied voltage pulse and which discharges itself into the next capacitor along the row by arcing over the gap separating them. In this way all of the gaps of a row are made to flashover. A large area plasma source can be made by using a number of rows as shown in Fig. 34. Measurements were made of the characteristics of the plasma produced by a flashover board similar to that shown in Fig. 34 using a biased Langmuir probe. With the probe in front of the board, a 2-3 μ s plasma pulse was seen traveling past the probe at a velocity of ~ 5 cm/ μ s. At 15 cm

Fig. 34. Vacuum surface flashover plasma board.

in front of the board the peak number density was 10^{11} cm $^{-3}$. The electron temperature was measured at ~ 3 eV. The individual plasma spots coalescing into a uniform plasma front can be seen in Fig. 35. This is a scan 6 cm from the board with a 14 cm by 18 cm aperture placed 2 cm in front of the board. The peak number density drops rapidly with distance from the board as can be seen in Fig. 36. These measurements also showed that applying a positive voltage pulse to the flashover board resulted in a plasma burst with twice the peak number density obtained with a negative voltage pulse; all other plasma parameters remained the same. The reasons for this observed difference has not been explained at this time.

Fig. 35. Peak number density vs. position 6 cm in front of plasma board.

Fig. 36. Peak number density at center of plasma board vs. distance from source.

Plasma Guns

The second type of plasma source used for the diode studies is shown in Fig. 37 together with its driving circuit. These guns were developed by C. W. Mendel²⁷ and work by flashing over an insulator at the tip of the gun. They emit a plasma which is typically a few microseconds wide with a bulk velocity of $\sim 5 \text{ cm}/\mu\text{s}$ and a density of $10^{13}/\text{cm}^3$ at a distance 20 cm from the gun exit. The angle of divergence of the plasma is controlled by the angle of the helical, cone shaped ground plane at the tip of the gun.

Fig. 37. Plasma gun and driving circuit.

Diode Studies

The plasma-injected diode studies were conducted on the LEGS electron beam accelerator. This pulser consists of a four-stage pulse forming network which supplies a $1 \mu\text{s}$ voltage pulse to the diode. A schematic of the pulse forming network is shown in Fig. 38 together with the output voltage waveform across a resistive load.

Previously we reported that significant control of low current density, microsecond electron beam diodes could be obtained by injecting a low density plasma into the diode. The strongest control on the diode impedance was obtained by varying the time between the injection of the plasma and the application of the high voltage pulse to the diode. It was felt that this impedance control was obtained by the formation of a double sheath within the diode. The thickness of such a

sheath is controlled by the plasma density and temperature. Longer delay times correspond to lower densities which give rise to larger sheaths and thus to higher diode impedances. Although it is not certain that sheath formation does occur in plasma injected diodes, it is apparent that high density plasmas formed within the diode do occur and play a strong role in determining the behavior of the diode.

Fig. 38. Electrical schematic of LEGS pulser together with the output waveform across a resistive load.

Data taken over a wide range of parameters show that three types of diode waveforms can be obtained with plasma injection. These are shown in Fig. 39. The first type of waveform is characterized by a slowly rising current and a corresponding drooping voltage. These are observed at very long time delays or when plasma has not been injected into the diode. They may be explained by the formation of a dense electrode plasma which expands into the anode-cathode gap and results in a collapse of the diode impedance throughout the voltage pulse. The second type of waveforms is characterized by a double peaked current waveform. The first peak is controlled by the injected plasma and the second peak by the dense electrode plasmas. The last type of waveforms observed is characterized by flat voltage and current waveforms. Two explanations for this case are possible; either a stable sheath has been formed in the diode or the two peaks which are observed in the second type of waveforms have been exactly balanced to give a flat current pulse. The data at this time are insufficient to determine which of these two possible explanations is correct.

Fig. 39. Schematic characterization of the three types of waveforms obtained with plasma injected diode.

Some evidence exists that the second peak observed in the current waveform is due mainly to a nonuniform dense cathode plasma. In experiments where the field-enhanced high voltage electrode is pulsed positive, the current pulse more closely resembles the third type of waveforms. The second peak in the current waveform is much reduced or not observable. It may be that under these conditions a dense electrode plasma does not form on the surface of the grounded cathode. Time-integrated radiochromic dosimetry measurements of the anode current density do not show the presence of highly localized non-uniformities or beam striations. In the case where the field enhanced high voltage electrode is pulsed negative, highly localized nonuniformities in the anode current density are observed which seem to correlate with bright emission spots on the cathode as seen with open shutter photography.

The injection of externally generated low density plasmas holds significant promise for improving the performance of low current density, microsecond electron beam diodes. To realize this promise we must improve our understanding of how dense electrode plasmas are formed under high voltage conditions when

a low density plasma has been injected into the diode. It appears that in order to take full advantage of this technique we must learn to prevent or control the formation of nonuniform, dense cathode plasmas.

Terrawatt Electron Beam Source for Ge₃ Laser Excitation

Non-energy storing, high power gas lasers will require the development of suitable high power excitation sources. Electron beams have been shown to be efficient laser drivers and are capable of providing the high power requirements. In response to the increasing need for higher power electron beam drivers, a program was initiated during the first quarter of FY 79 to design and build a terrawatt electron beam accelerator (RAYO) with its near term application as the driver for a 10 kJ H-F amplifier.

RAYO is a 1 MV, 20 ns, 20 kJ accelerator. It will generate two beams from opposing diodes to enable the use of the double-transverse excitation geometry. This geometry allows for the efficient coupling of the incident electron beam energy to the laser gas while making possible a more uniform energy deposition profile in the gas than can be obtained with the single-transverse excitation geometry. Figure 40 shows a schematic of the single transverse excitation geometry with its characteristic energy deposition profile. Because only a limited degree of non-uniformity in the energy deposition profile can be tolerated across the active laser medium, most systems utilizing the single transverse geometry deposit only a small fraction of the incident beam energy into the gas medium; the remaining beam energy is simply dumped into the opposite wall of the laser chamber. In the double-transverse excitation scheme, the individual profiles of the opposing beams can be added to give a more uniform profile while depositing the majority of the electron beam energy incident on the gas. This can be seen schematically in Fig. 41.

RAYO is an application of the high power water-dielectric accelerator technology developed at Sandia for the particle beam fusion program.^{18,28} A block diagram of the accelerator is shown in Fig. 42. The Marx generator²⁸ is the type used in Proto II¹⁸ and EBFA I.²⁸ It consists of 32 each 0.7 μ F, 100 kV capacitors in a low inductance configuration. At maximum charge it stores 112 kJ at 3.2 MV but for this application it will be operated at a reduced charge level. The

Marx pulse-charges an intermediate energy store consisting of two water capacitors similar to those used in Proto II¹⁸ in about 750 ns. A high voltage pressurized gas switch is used to discharge the energy out of the intermediate store. The output is fed via 40 Ω , oil dielectric transmission lines to two sets of water dielectric transmission lines contained in separate 1.5 m x 1.2 m x 2.4 m tanks which are located on opposite sides of the laser chamber. Passing through an oil-water interface, the pulse is fed to line 1. Line 1 acts as a 9 nF capacitor and is charged in about 250 ns. In turn, it charges line 2 in 70-80 ns via self-breaking water switches.¹⁸ Line 2 is a 2 Ω , 20 ns (two-way transit)

1 MEV. ELECTRONS IN F_2 GAS

Fig. 40. Schematic of single-transverse excitation geometry and characteristic energy deposition.

(a)

(b)

Fig. 41. Schematic of double-transverse excitation geometry and characteristic energy deposition.

pulse forming transmission line which is charged to 2 MV. A second set of self-breaking water switches discharges line 2 into a 2 Ω transmission line (line 3). A third set of water switches is used to reduce the level of the prepulse fed to the diode via the 2 Ω transmission line (line 4). The 1 MV electro magnetic pulse from line 4 passes through a water-vacuum interface into the diode. This feedthrough is an acrylic racetrack, diaphragm interface designed to hold 1.5 MV for 20 ns. This provides a safety margin to account for the overvoltage resulting from the inductive voltage spike. Each diode generates a 0.5 MA beam over a 0.3 m x 1.0 m area. Provision has been made for an externally applied magnetic field to prevent beam pinching in the diode and laser gas medium.

Fig. 42. Block diagram of RAYO accelerator.

In going from the vacuum diode to the laser cell the electron beam must pass through a thin foil. In order to contain the high gas pressures in the laser cell, this foil must be backed by a rigid support structure (Hibachi). In the case of the H-F laser application, the foil must also withstand an extreme overpressure due to the chemical reaction, up to ten times the original pressure. The design of Hibachi-foil assembly to allow penetration of the applied magnetic field through this structure presents considerable difficulties. A base design for one such structure has been developed, however the optimum configuration for beam transport to the laser cell will remain to be determined in the course of the experimental program.

The electrical design definition of RAYO has been completed. Mechanical design of the various components has begun. Delivery and installation of components are expected to be completed around the end of the 3rd quarter of FY 79. Pulse power tests and diode studies will begin during the last quarter of FY 79. The experimental program will emphasize efficient beam generation, beam transport through the Hibachi-foil structure and electron beam energy deposition in the laser gas while maintaining a uniform energy deposition profile through the gas volume.

Emission Suppression

Substantial electron emission from cathode support structures will decrease the efficiency, distort the accelerator waveform, and could result in damage to the diode insulators. Previous data^{1,2} taken with a one microsecond pulse duration indicated bare metal surfaces will emit greater than 1 A/cm^2 at electric fields above 70 kV/cm . Dielectric coating (e.g., acrylic or epoxy) can increase the field at which no emission occurs to 250 kV/cm .

Emission suppression for pulses of substantially shorter duration has now been investigated. The lumped constant pulse forming network used for the work described in Ref. 1 has been replaced with a pulse forming line (PFL) insulated with either water or ethylene glycol corresponding to pulse durations of 35 and 25 ns respectively. The PFL was terminated using a 5 ohm electron beam diode mounted in the same vacuum housing with the test gap (see Fig. 43).

Fig. 43. Experimental test set-up.

Experiments were conducted using a uniform field (10y curvature) cathode with an area of 180 cm^2 as shown in Fig. 44. Bare metal (aluminum, brass, and stainless steel) cathodes and dielectric coated (stainless steel substrate) cathodes were investigated. A Faraday cup was used to detect emission current densities greater than 0.1 A/cm^2 and to time correlate the currents with the voltage pulse.

Fig. 44. Uniform field cathode.

With a test gap spacing of 0.95 cm, a polished stainless steel cathode exhibited an emission current density of 2 A/cm^2 when subjected to an electric field of 360 kV/cm (see Table XI). Below this field, there were spurious emissions of less than 0.5 A/cm^2 occurring randomly with each increase of field. During a second series of tests, this cathode reached a field of 360 kV/cm without detectable emission occurring during the tests. In order to reach higher fields, the test gap spacing was reduced to 0.64 cm. Spurious emissions of 2 A/cm^2 or less were measured as the fields were increased from 300 kV/cm to 526 kV/cm. At 560 kV/cm, the current density was greater than 10 A/cm^2 .

Two stainless steel cathodes were coated with epoxy paint (Rustoleum Company). Cathode A, referring to Table XII, reached electric fields of 325 kV/cm with no emission when spaced at 0.95 cm. The test gap spacing was reduced to 0.64 cm and a field of 490 kV/cm was reached when 0.5 A/cm^2 was observed. Several small craters were created in the epoxy during this shot. Without repairing the cathode, the voltage was reduced and another series of tests were performed. Fields of 593 kV/cm were obtained without detectable emission. One shot at a reduced spacing of 0.32 cm yielded emission currents greater than 10 A/cm^2 when a field of 633 kV/cm was applied. Again without cathode repair, the spacing was increased to 0.64 cm and emission currents of 1.5 A/cm^2 were

TABLE XI

Stainless Steel Cathode with Mirror Finish

Test Number	Gap Spacing (cm)	Electric Field (kV/cm)	Current Density (A/cm^2)
119	0.95	200	
120		202	
121		212	0.3
122		266	
123		277	
124		277	0.3
125		310	0.1
126		335	1.2
127		360	2.0

Reduced Electric Field and Re-tested

128	265
129	288
130	310
131	332
132	360

Reduced Gap Spacing

133	0.64	300	
134		315	1.8
135		345	1.7
136		345	
137		361	1.0
138		428	1.5
139		477	2.0
140		486	1.9
141		526	
142		560	> 10.0

TABLE XII

Epoxy Paint Coated Stainless Steel Cathode "A"

Test Number	Gap Spacing (cm)	Electric Field (kV/cm)	Current Density (A/cm ²)
145	0.95	288	
146		310	
147		325	

Reduced Gap Spacing

148	0.64	280	
149		312	
150		329	
151		378	
152		427	
153		444	
154		480	
155		490	0.5

Reduced Electric Field and Retested

156		443	
157		477	
158		518	
159		593	

Reduced Gap Spacing

160	0.32	653	> 10.0
-----	------	-----	--------

Increased Gap Spacing

161	0.64	313	1.5
-----	------	-----	-----

Increased Gap Spacing

162	0.95	211	
163		200	
164		232	
165		243	
166		277	
167		288	
168		310	
169		343	
170		366	

observed at 313 kV/cm. By increasing the gap spacing to 0.95 cm, a field of 366 kV/cm was applied with no detectable emission. Cathode B was installed with a spacing of 0.79 cm and emission did not occur with fields of 440 kV/cm except 0.5 A/cm² were observed at 260 kV/cm as seen in Table XIII. A decreased spacing of 0.64 kV/cm produced fields of 542 kV/cm without emission. Currents much greater than 10 A/cm² were measured at 395 kV/cm when the spacing was reduced to 0.48 cm.

TABLE XIII

Epoxy Paint Coated Stainless Steel Cathode "B"

Test Number	Gap Spacing (cm)	Electric Field (kV/cm)	Current Density (A/cm ²)
256	0.79	241	
257		253	
258		260	0.5
259		279	
260		292	
261		307	
262		332	
263		353	
264		399	
265		440	

Reduced Gap Spacing

266	0.64	280	
267		299	
268		329	
269		345	
270		361	
271		378	
272		427	
273		444	
274		542	

Reduced Gap Spacing

275	0.48	395	>> 10.0
-----	------	-----	---------

A stainless steel cathode, coated with krylon acrylic (Borden Chemical Co.) withstood fields of 425 kV/cm without emission when spaced at 0.95 cm (Table XIVa). However, when subjected to a retest, greater than 2 A/cm² were detected at this field. The damage to the dielectric was evaluated and the cathode re-installed without repairs for retesting under the same conditions although several small craters were evident across the cathode surface. Electric fields of 425 kV/cm

did not produce detectable emission during this retest. The gap spacing was reduced to 0.79 cm and fields of 445 kV/cm were obtained. Then the spacing was reduced to 0.64 cm. When 550 kV/cm was reached, 3.4 A/cm² were emitted. At a later date, this cathode was tested again to determine the effects of the craters created by the previous tests. Tests were conducted with spacings of 0.95 cm, 0.79 cm, and 0.64 cm with electric fields of 366 kV/cm, 426 kV/cm, and 378 kV/cm, respectively, being the maximum fields reached. No detectable emissions occurred until 378 kV/cm was applied to the 0.64 cm spacing. At this point, 4.3 A/cm² was measured as shown in Table XIVb.

All of the uncoated cathodes produced similar results. Several shots would produce emission and then no detectable emission was measured for the next several shots. The results of these tests are shown in Tables XV, XVI, and XVII for brass, polished brass, and polished aluminum. These tables indicate that the polished samples were superior to the unpolished samples and that stainless steel (Table XI) was somewhat superior to the other metals. It is obvious that a conditioning process is taking place on the cathode surface as the applied electric fields are increased.

TABLE XIVa

Acrylic Coated Stainless Steel Cathode
(1st Series)

Test* Group	Gap Spacing (cm)	Electric Field (kV/cm)	Current Density (A/cm ²)
----------------	------------------------	------------------------------	--

1	0.95	200-425	0
---	------	---------	---

Reduced Electric Field and Retested

2	0.95	200-425	>2.0 @ 425 kV/cm
---	------	---------	------------------

Reduced Electric Field and Retested without repairs to cathode

3	0.95	200-425	0
---	------	---------	---

Reduced Gap Spacing

4	0.79	325-445	0
---	------	---------	---

Reduced Gap Spacing

5	0.64	325-550	3.4 @ 550 kV/cm
---	------	---------	-----------------

*For clarity the tests have been arranged in groups due to the large number of shots involved in this test.

TABLE XIVb

Acrylic Coated Stainless Steel Cathode
(2nd Series)

Test* Group	Gap Spacing (cm)	Electric Field (kV/cm)	Current Density (A/cm ²)
1	0.95	366	0
Reduced Gap Spacing			
2	0.79	426	0
Reduced Gap Spacing			
3		378	4.3

*For clarity the tests have been arranged in groups due to the large number of shots involved in this test.

TABLE XV

Brass Cathode

Shot Number	Gap Spacing (cm)	Electric Field (kV/cm)	Current Density (A/cm ²)
201	0.95	281	
202		292	1.2
203		315	
204		331	
205		353	1.1
206		376	1.2

Decrease Gap Spacing

207	0.79	265	
208		292	
209		305	0.6
210		338	0.4
211		365	1.4
212		365	1.0
213		371	1.0
214		411	2.2
215		418	1.7

Increased Gap Spacing

216	0.64	299	0.5
217		315	1.2
218		365	
219		422	2.2
220		398	6.0
221		431	6.0
222		439	Gap Closure
223		480	Gap Closure

TABLE XVI

Brass Cathode with Mirror Finish

Shot Number	Gap Spacing (cm)	Electric Field (kV/cm)	Current Density (A/cm ²)
224	0.64	315	0.7
225		348	0.7
226		365	0.9
227		389	2.4
228		406	2.2
229		431	1.5
230		481	
231		481	
232		498	>> 10.0
233		531	>> 10.0
234		513	>> 10.0

One epoxy coated cathode (stainless steel substrate) was tested with the 25 ns pulse duration pulse generator output. With a 0.48 cm test gap, there was no detectable emission at 442 kV/cm; however, a field of 482 kV/cm produced sufficient emission to cause gap closure. When the fields were lowered back to 442 kV/cm, emission did not occur.

These tests have demonstrated that dielectric coatings can inhibit electron emission. The conditioning effect found in bare metal cathode is not as pronounced when the metal has been coated which indicates the dielectric acts to minimize surface irregularities. Emission occurring through the dielectric do cause permanent damage; however, this damage does not necessarily degrade the cathode emission hold-off down to the point of the bare metal.

TABLE XVII

Aluminum Cathode with Mirror Finish

Shot Number	Gap Spacing (cm)	Electric Field (kV/cm)	Current Density (A/cm ²)
35	0.95	200	
36		205	
37		211	
38		237	
239		254	
240		272	
241		288	
242		320	
243		342	1.1

Reduced Gap Spacing

244	0.79	253	
245		275	
246		294	
247		332	0.7
248		345	1.2
249		371	2.2
250		391	2.4
251		393	2.5
252		451	0.5
253		437	
254		41	3.7
255		451	11.0

REFERENCES

1. Particle Beam Fusion Progress Report October 1977 through March 1978, SAND79-0002.
2. Electron Beam Fusion Progress Report October 76 through March 77, SAND77-1414.
3. J. C. Bower and S. C. Sedore, Sceptre, A Computer Program for Circuit and Systems Analysis, Prentice Hall, Inc., Englewood Cliff, NY, 1971.
4. D. L. Johnson and K. R. Prestwich, An 18 MV Marx Generator, IEEE Trans. Nucl. Sci., Vol. NS-16, No. 3 June 1969.
5. M. T. Buttram and G. J. Rohwein, Operation of a 300 kV, 100 Hz, 30 kW Average Power Pulser, 13th Pulse Power Modulator Symposium, Buffalo, NY, June 20-22, 1978.
6. P. A. Miller, et al., Phys. Rev. Lett. 39, 92 (1977); P. A. Miller, private communication.
7. F. Biggs and R. Lighthill, "Analytical Approximations for X-Ray Cross Sections II," Sandia Laboratories Report SC-RR-71-0507.
8. W. Whaling, Handbuch der Physik, 1957, Vol. 34, p. 193-217.
9. Particle Beam Fusion Progress Report October 1977 through March 1978, SAND79-0002.
10. S. G. Varnado and G. A. Carlson, Nuclear Tech. 29, 415 (1976).
11. G. J. Rohwein, private communication.
12. J. R. Grieg, et al., Phys. Rev. Lett. 41, 174 (1978).
13. G. L. Kulcinski, "Progress in Materials Research for Fusion Reactors," University of Wisconsin Report UWFD-228, October 1977.
14. F. Biggs, "Tables for the Attenuation of Blackbody X-Rays in Air," Sandia Laboratories Report SC-RR-64-1702.
15. C. B. Moyer, B. F. Blackwell, P. C. Kaestner, A User's Manual for the Two-Dimensional Axisymmetric Transient Heat Conduction Material Ablation Computer Program (ASTHMA), SC-DR-70-510, December 1979.
16. B. Badger, et al., "UWMAK-III, A Noncircular Tokamak Power Reactor Design", EPRI Report ER-368, July 1976.
17. D. Woodall and J. Fisk, The Feasibility of Synthetic Fuel Production in an Electron-Beam-Driven Inertial Confinement Fusion Reactor Chamber, University of New Mexico Dept. of Nucl. Energy Report NE-53(78) Sandia-665-1 (1978).

18. T. H. Martin, J. P. VanDevender, D. L. Johnson, D. H. McDaniel and M. Aker, Proc. of the Int'l. Topical Conf. on Electron Beam Res. and Tech., Vol. 1, p. 450, Albuquerque, NM, November 3-5, 1975.
19. T. H. Martin and L. P. Bradley, Bull. Am. Phys. Soc. 16, 1229 (1971).
20. A. J. Toepfer and L. P. Bradley, J. Appl. Phys. 43, 3033 (1972).
21. F. S. Baker, A. R. Osborn and J. Williams, J. Phys. D. 7, 105 (1974).
22. A. A. Plyutto, K. V. Suladze, E. D. Korop and V. N. Ryshkov, Discharges and Electrical Insulation in Vacuum, Proc. of 5th Int'l. Symposium, Poznan, Poland (1972), p.145.
23. G. P. Bazhenov, O. B. Ladyzhenskii, E. A. Litvenov and S. M. Chesnokov Sov. Phys. Tech. Phys. 22, 212 (1977).
24. R. S. Clark, Nereus Marx Generator, A 600 kV-1.5 kJ Unit, SC-DR-71 0216 Sandia Laboratories, March 1971 (unpublished).
25. Glasoe and Lebacqz, Pulse Generators, Radiation Laboratory Series, Vol. 5, McGraw Hill, 1948.
26. D. I. Proskurovskii, V. P. Rotshtein, A. F. Shubin and E. B. Yankilevitch, Sov. Phys. Tech. Phys. 20, 1342 (1976).
27. C. W. Mendel and S. A. Goldstein, J. Appl. Phys., Vol. 48, p. 1004 (1977).
28. T. H. Martin, D. L. Johnson and D. H. McDaniel, Proc. of 2nd Int'l. Topical Conf. on High Power Electron and Ion Beam Res. and Tech., Vol. 1, p. 807, Cornell University, October 3-5, 1977.

CHAPTER 7 ELECTRON BEAM FUSION ACCELERATOR PROJECT

EBFF

Overview

The initial construction phase on the Electron Beam Fusion Facility (EBFF) is nearing completion. On January 1, 1979, the DOE general contractor, R. E. McKee of El Paso, TX, stated the project was approximately 98% complete. The original construction phase of the project started on January 20, 1977, with a scheduled completion date of October 3, 1978. However, changes and/or additions to the original facility plans were requested by Sandia Laboratories. These modifications resulted in DOE/ALU granting a 41-day extension to November 15, 1978, to complete the construction and turn the entire facility over to Sandia's Plant Engineering organization. The original contractual agreement to have the High Bay portion of the laboratory building ready for beneficial occupancy by August 11, 1978, to begin installation of the EBFA tank structure remained unchanged. The High Bay was complete enough to start the EBFA tank fabrication on August 21, 1978. The official completion of construction and turnover to Sandia is presently estimated to be February 1979, and Sandia's contractors are already preparing for EBFF occupancy.

Office building and the light laboratory occupancy was started during December by Sandia's contractors. The light laboratories occupancy consists of running additional electrical power, installing cable trays, radiation shielding for the small Nereus accelerators, safety interlocks on laser laboratory doors, relocation of laboratory equipment from TA-V to EBFF, installation of the machine tools in the new machine shop, etc. This work is scheduled for completion by mid-January 1979. The schedule calls for initial personnel move-in by late February 1979. The office and laboratory public address systems will be installed along with the two 11-channel intercom systems for EBFA during the spring of 1979.

The 15' x 102' screen room to house the Control/Monitor System and the Data Acquisition/Data Processing System was started in November 1978 by Universal Shielding Corporation of Plainville, NY. This double-wall screen room protects sensitive computer and recording equipment from the EBFA EMP. The peak shielding effectiveness for the interference attenuation is specified at 110dB at 450 MHz. The

shield effectiveness of the completed screen room will be established by the screen room co-ordinator and verified by an independent testing firm, E-System, Melpar Division, Falls Church, VA. The screen room will be assembled, tested, painted, and ready to move into by March 1, 1979.

An EBFF photograph showing the mid-December 1978 status is shown in Fig. 1.

EBFA SUPPORTING SYSTEMS

An update on the status of the necessary supporting systems for EBFA, initially described in the previous progress report, is presented below.

Transformer Oil Transfer and Storage System

The oil transfer and storage system is ready for connection to the EBFA. Minor piping system modifications were aided to allow better access for the delivery trucks. Oil reserve sufficient for EBFA I is now in the 500,000 gal. storage tanks.

Deionized Water System

Title II drawings are nearing completion. A baseline system with provision to upgrade was chosen. The resin beds and skimmers will be installed under occupancy contracts.

Insulating Gas Systems

Designs of the various gas systems are complete and all components except the piping, which will be provided on the occupancy contracts, are ordered. In addition to the SF₆ and artificial air systems, a third gas system containing a mixture of SF₆ and argon will supply the Gas Switch Trigger system obtained from Maxwell Laboratories.

EBFA Data Acquisition System

Screen Room - The EBFA data acquisition system will be located in a 15' x 65' room of a 15' x 102' RFI shielded enclosure. The Control/Monitor system and a laser interferometer will occupy two other rooms. The screen room contract was awarded to Universal Shielding Corp. The enclosure is 60% complete as of January 1, 1979. Work should be finished by March 1. The room's electromagnetic shielding

FIG. 1. Construction of the Tashan Dam.

effectiveness will be tested by an independent contractor. E-Systems Nelpar Division has been selected to perform these tests. Equipment installation starts in March.

Computers - Hewlett-Packard minicomputers were selected for the Data Acquisition and Control/Monitor systems. Both cost and performance benchmark test results were considered during the selection. Benchmark tests evaluated computation speed, interactive response speed and FORTRAN compiler memory efficiency.

The Data Acquisition Computer System consists of the following equipment:

- HP 1000F/45 CPU with 256 K byte memory
- Moving Head Disc 20 M byte
- Floppy Discs (2)
- Magnetic Tape 9-track
- Card Reader
- Graphics Console Terminal
- Versatec 1000 lpm Printer/Plotter
- Tektronix 4014 Graphics Display
- Terminals (2)
- Tektronix Hard Copy Unit.

The computer system delivery date is March 15, 1979. It will be installed when the screen room is ready.

Data Recording Equipment - EBFA requires several resolution levels from data recording equipment. High resolution (7 bit, 0.2 ns) waveform recorders are required for accelerator checkout characterization and experiments. Low resolution (4-6 bit, 1-2 ns) waveform recorders are required for monitoring accelerator performance during experiments. Time digitizers with 1 ns resolution are required for monitoring module accelerator switch simultaneity. Peak detectors and gated integrators will monitor low speed power flow in the accelerator.

Tektronix 7912AD Programmable Transient Recorders will be used to meet the high resolution waveform requirements. Forty-four units are ordered. Deliveries begin in March 1979 and end by August 1979. The 7912's are interfaced to the computer via the standard IEEE 488 General Purpose Instrumentation Bus (GPIB). The H-P computer system supports the interface with both hardware and software.

A contract with Electronic Vision Division of Science Applications, Inc. will develop a prototype 40-channel, low resolution, high-speed transient recorder for the EBFA requirements. Each channel will meet the following specifications:

- Amplitude Resolution ... 6 bits
- Time Resolution 1-50 ns Variable
- Record Length 240 Samples
- Input Range + 1 V
- Input DC offset ± 1 V adjustable
- Computer Interface IEEE 488

All channels are swept simultaneously by a common time base signal generator. The projected production cost is \$80K-100K per unit for a cost of \$2K-2.5K per channel.

The prototype design is based on a standard EVC product, the Digicon tube. A block diagram is shown in Fig. 2. Each analog voltage input is converted to light and transported via fiber optics to the input face of the tube. This photocathode generates 40 independent electron beams (one for each channel). The beams are accelerated, focused, and deflected in the tube. The beams strike a phosphor screen, and the resulting light output is recorded by a CCD camera with 190 (wide) by 244 (long) resolution elements. Each channel is recorded redundantly by two adjacent rows in the CCD. The light level recorded in each CCD cell is proportional to the analog input signal. The analog data in the CCD is clocked out and digitized by a conventional moderate speed ADC. Digital data is stored in a local solid state memory for later readout by the computer. We anticipate eventually having five or six of these units to meet all low resolution waveform recording requirements for EBFA.

The switch simultaneity and slow speed power flow monitor recording requirements for EBFA will be met by standard off-the-shelf CAMAC compatible time digitizers, peak detectors, and gated integrators. We have ordered a trial system with stand-alone computing capability. The equipment will be evaluated on the MITE and Proto II accelerators. If these tests prove successful, we will incorporate a full system in the EBFA data acquisition facility.

Cable Plant - The EBFA data acquisition system cable plant has been designed to meet several severe requirements. These include high EMP levels ($\approx 10^{15}$ V/sec and A/sec), large number of possible monitor points (≈ 700), and wide band signals (≈ 300 MHz). The details of the various segments are described below. Shielded flexible jumper cables will run from each monitor to a local feedthrough panel in the floor of the accelerator. These jumpers will have RG-214 cable shielded by solid convolute tubing. Standard fittings are available for mating

Fig. 2. High Speed Multichannel Recorder.

the shield to type N and HN connectors. Ferrite sleeves will be placed over the cable inside the solid shield near each end of the assembly. The purpose of these sleeves is to absorb noise current on the RG 214 shield. The entire underside of the accelerator tank outside the experimental area will be plated over to form an RF tight cable raceway.

RG 331 1/2" foamflex cable will be run in the RF tight raceway from the feedthrough ports to a large junction box (15'H x 18'W x 7'D) in the pit area. The junction box will be used to jumper monitor signals to the screen room from EBFA and any other future accelerators which may be built in the facility. Three hundred RG 331 cables will be run from the junction box to the screen room in ten 6-inch conduit buried under the floor. Fiber optic links were considered for the cable plant. They were rejected because of high cost and poor analog bandwidth.

Control/Monitor System

Detailed design for the cableways and junction boxes for Control/Monitor cabling between the screen room and EBFF subsystems has started. Estimates were made and orders placed for Control/Monitor cables, terminal blocks and crimp-on lugs.

A standard relay panel for 24-volt relays was designed for the interface between the 110 volt high bay and the 24-volt control room equipment. Most of the components are on order.

A computerized cable numbering system was developed from LASL and entered into the Sandia computer. This system generates wire lists in several formats for wiring and troubleshooting, and also estimates cable requirements.

The Control/Monitor screen room filter panel electrical design has been made. All electrical components are on hand. Final mechanical design will start when the hole pattern dimensions are available.

Design, breadboard, and checkout of the IEEE-488 interface card for the microprocessor is 95% complete. The card includes the IEEE-488 interface, a 256 byte RAM, DMA capability between the microprocessor and IEEE-488 bus, an interrupt timer, a time out circuit, hexadecimal LED's for subsystem diagnostics, and buffers for input/output expansion. Printed wiring layout of this card will be

started shortly. The interface card will transmit 256 byte blocks of data to the minicomputer at 160 kilo bytes per second.

A standard 7" chassis design has been completed and one prototype 7" chassis fabricated. This chassis design will be used for most of the control room subsystem chassis. The 7" prototype is presently being used for checkout of the IEEE-488 card.

A standard 10-1/2" chassis design and fabrication of a prototype chassis is 90% complete. This design will be used for control room subsystems that need a larger panel, or where space for more microprocessor cards is needed. The 10-1/2" prototype chassis will be used to test the SF₆ system controls in the Proto II EMP environment.

A standard relay driver circuit card and a standard monitor interface card are being designed. They will be used in both chassis designs.

A microprocessor software development system was procured and preliminary software for the SF₆ system was written and emulated in the development system.

Preliminary "top-down" design of the minicomputer software has been carried out to ensure compatibility between subsystems. Detailed design definition of the transfer switch system was completed and is being reviewed by the Sandia users group.

Detailed design definition of the SF₆ system is 90% complete.

Detailed design is in process for modifications to the oil transfer system control console.

Preliminary design definition of the vacuum system has been completed to determine tank modifications and to identify long lead time items. Specifications for vacuum gages are being prepared. We now plan to use cold cathode ion gages in EBFA. A hot cathode ion gage was procured and tested to test its vulnerability to EMP. It was damaged, apparently by EMP, and repaired by the manufacturer. We have installed metal oxide varistors at critical points in the circuit and have resumed testing on MITE.

Preliminary Control/Monitor design definitions for the Marx charging, Marx firing, and Gas Switch Trigger Systems are in process.

A tank liquid level monitor has been installed

in an EMP enclosure. It will be used on an existing accelerator to evaluate the level monitor for use at EBFA and to obtain data on EMP levels on the power line and at penetrations into junction boxes.

A two-way fiber optics serial data link has been breadboarded. It will be used with the SF₆ prototype chassis to evaluate EMP protection systems.

EBFA I

Overview

The overall design definition of EBFA I was 95% complete during the reporting period. The project is presently in the procurement phase. Orders were placed to develop all charging and firing systems, i.e., the Marx generator capacitor charging system, the Marx generator firing system, and the Gas Switch Trigger system. The assembly of the EBFA tank structure is approximately 50% complete to date. The status of the tank fabrication as of January 4, 1979, is shown in Fig. 3. Orders for all electrical components in the pulse forming section, power flow section, and the initial front end were placed. As described in the previous progress report, one set of EBFA electrical components was ordered to assemble into a demonstration accelerator. This accelerator, called Hydramite, will verify the mechanical fit of all hardware and the as-built electrical characteristics before the authorization is given to fabricate the 36 identical sets of EBFA I components.

The Hydra accelerator modifications to Hydramite was started in December 1978. The south leg of Hydra was removed and a tank designed to simulate the water pulse forming section on EBFA was installed. The Hydra test cell was enlarged to accommodate the longer EBFA magnetically insulated transmission line and front end hardware. Additional deionized water storage tanks, piping, and transfer systems were installed. The HYDRA data acquisition system cable plant was completely redone. New junction boxes and steel conduits were installed to shield the new cables from EMP. Jumper cables in flexible metal shielding are used between the junction boxes and the diagnostic transducers. The EBFA Marx generator, installed in the Hydra accelerator for approximately one year, was disassembled and refurbished with modified EBFA Marx hardware after successfully surviving several thousand shots. Delays in receiving some EBFA components for Hydramite will postpone the initial pulsed

power tests until February 1979. After initial testing, the accelerator will be shutdown to install the remaining components. The full accelerator testing will start during March 1979 and continue for one month. The EBFA engineering staff has been working closely with the component fabricators to resolve discrepancies uncovered in the Hydramite manufacture and assembly of the first component for Hydramite. As expected, Hydramite has revealed many engineering, fabricating, and procurement problems before encountering them on EBFA I.

The Marx generator assembly started two months ahead of schedule (August 1978) in a hangar on Kirtland-West. The assembly activity was started early to allow the crew to assemble the accelerator. The early Marx assembly was hampered by slow arrival of the casting for the upper and lower corona shields. Even with these problems, the Marx generator assembly is ahead of the anticipated schedule. Twenty-eight of the 36 modular units were completed by January 1, 1979. All of the Marx generators will be assembled and ready for installation by the end of January 1979. The EBFA tank will accept the Marx units during June 1979. All Marx generator units are stored under individual protective covering to keep them clean as shown in Fig. 4.

The final Marx electrical connections with copper sulfate resistors will be delayed until just before transportation of the Marx generators to the EBFA site for installation in the accelerator tank structure. Two additional Marx generator modules, a left-hand and a right-hand unit, will be assembled as EBFA spares when additional connecting hardware is available. These two spare units will be stored in the Marx transportation frames and located adjacent to the EBFA tank structure for immediate use. The EBFA Marx generators have been designed to allow Marx generator removal without dumping the electrical insulating transformer oil from the tank. This capability should minimize the downtime and allow all Marx generator maintenance to be conducted external to the tank.

The "April 78 Baseline" design is essentially unchanged. The design now includes a dummy load and transfer switch located at the output of the gas switch and at the input to the pulse forming line. This switch will provide increased safety and operational convenience, and will allow all of the accelerator firing systems to be checked for simultaneity prior to an experimental shot. An over-voltage gap switch has also been added to the intermediate water capacitor to protect

Fig. 3. Electron Beam Fusion Accelerator.

Fig. 4. Marx Generator Units.

against an electrical breakdown between the inner and outer electrode of the storage capacitor in the event that the gas switch fails to fire. The shockwave induced in the water by such a breakdown could damage the high voltage barrier separating the water from the transformer oil in the energy storage section of EBFA. The updated status of each of the major components or subsystems of EBFA will be discussed in the following paragraphs of this section.

EBFA Tank Structure

The tank contractor completed all prefabrication activities and started on-site operation on August 21, 1978. Most floor level portions of the structure are in place and the walls are started. A modification package, which was originally planned to begin after completion of the basic tank structure, has been specified and awarded as a change to the contract. Work on the modification has started and will run concurrent with the original specification.

Marx Generator

Marx generators assembly is ahead of schedule. Twenty-eight of the required 36 are ready except for the copper sulfate resistors which will not be fabricated and installed until immediately before installation in the EBFA.

Charging System

The contract for the charging system was placed during this reporting period with Universal Voltronics Corporation. It is a center tapped 220 kilovolt DC supply capable of charging the capacitors in EBFA I or the much larger bank expected in EBFA II. It will charge each of the 1152 capacitors (EBFA I) to 100 kilovolts for a total stored energy in the energy storage section of 4.0 megajoules. This energy will be distributed to the 36 independent Marx circuit high voltage generators used in the energy storage section, providing each with 112 kilojoules. Total EBFA Marx weight is 140 tons.

The charging system design has two separate high voltage units located just outside of the 100-foot diameter wall of the energy storage section. The high voltage units are 180° apart (northeast and southwest sides) and either is designed to independently charge the entire machine. Normally both high voltage units will be operated together to provide faster charging and thus minimize the time at high voltage and reduce the possibility of a voltage breakdown.

The charging system has a power subsystem cabinet located northwest of the tank, near the control room and halfway between high voltage units. The triangular area shown in Fig. 5 will also contain equipment racks for the other high voltage systems. Three-phase 480 volt AC power for the charging system will be controlled by and distributed from this cabinet to the two high voltage units. In addition to motordriven variable output power transformers, the charging power subsystem will contain relays and other items needed to remotely control AC power in the system.

Remote control of these three major charging system components will be provided by a remote control panel in the EBFA radiation, RF and EMP shielded control room.

Marx Generator Trigger System

The contract for this system is at Maxwell Laboratories, Inc., and work on it was to be nearly completed at the end of December. Predelivery acceptance tests of this firing system are scheduled for late January, and system delivery is expected in February. Operation of this system will fire the 36 EBFA Marx generators and cause them to multiply driving voltage in the energy storage section to 3.2 megavolts as a part of the process of delivering the stored energy to the intermediate store capacitors in the water section. When this Marx trigger system fires, a total of 576 field distortion triggered spark gaps fire to change connections in the Marx generators. The parallel charged capacitors in each of the 36 Marx generators are reconnected into series discharge circuits by the conducting spark gaps. The firing system has nine separate main pulser units (MPU) under oil in the energy storage section. These nine MPU's are equally spaced around the tank and each one fires four EBFA I Marx generators.

Each of the MPU's in the Marx trigger system is itself a six-stage Marx generator. Equal cable lengths and simultaneous firing of the MPU's will provide simultaneous firing of all 36 Marx generators in the energy storage section.

Intermediate Stores

The contractor for the intermediate store capacitor has obtained material and is scheduling for production while awaiting go ahead after tests of the first units on the Hydramite accelerator. The polyurethane high voltage barriers are delivered and are undergoing inspection. The mounting rings are cast and clean-up machining is in progress.

Fig. 5. Floor plan showing high voltage equipment locations.

Trigatron Switches

A trigatron switch was received but minor flaws caused it to be sent back to the fabricator for correction. Production of the EBFA units will start upon successful tests in Hydramite.

Trigatron Trigger System

The contract for this system was placed with Maxwell Laboratories, Inc. This system will simultaneously trigger the 36 trigatron spark gaps used in the pulse forming, water section of the accelerator.

These three-electrode, gas insulated spark-gap switches are triggered when voltage on the intermediate store capacitors reaches a peak near three megavolts. The trigger to the trigatrons is the last pulsed power trigger applied to the accelerator. All of the water dielectric spark gaps downstream from the trigatrons are selfbreakdown switches.

The system was contracted to have nine output trigger units (OTU), each designed to trigger four trigatrons. Since then it has been decided that only six of the nine will be used in EBFA I and each OTU will trigger six trigatrons. This will result in slightly slower rise time of the voltage and current trigger pulse to each trigatron, but should provide adequate synchronization of the trigatrons. Each OTU will trigger six trigatrons equally spaced at 60° around the tank from each other in the water section of the tank. The six OTU's will be located on the upper portion of the pit walls. Each of these rail switched units are oil filled, will weigh about 900 pounds and will be charged to 150 kilovolts. The 150 kilovolt power supply to charge them will be located on the floor of the pit. Approximately 2 tons of RG 220/U cable will be connected between the OTU's and the trigatrons in the water section of the accelerator. Since the electrodes of each trigatron, including the trigger probe, rise to full voltage, a three megavolt isolation coil is used at the trigatron for connection of the trigger signal from the OTU. This isolation coil allows the majority of each trigger cable (sheath) and its driving OTU to be held to local ground potential, while at the trigatron the sheath of the trigger cable is allowed to rise to greater than 2.5 megavolts. Up to 5.4 kiloamps is available in the trigger spark for each trigatron; or total current delivered by the complete trigger system may range up to 194 kiloamps for EBFA I.

Isolation Inductors

Connection of grounded circuitry to the high voltage conductors in the water section of the accelerator is required at two places in each of the 36 modules. Inductors are used to achieve these connections. The first of these is the previously mentioned isolation inductor that connects the trigger signal to the trigatron. Three trigger isolation inductors have been delivered to support tests in Hydramite. This design is a free-standing coil of 1-1/8" copper tubing with approximately 50 feet of RG 218 coaxial cable inside of it. The coil has a nominal diameter of 1 foot and is about 4-feet long. This approach has been used before but not in the water section of a machine.

The second water section location in which an inductor is needed to prevent shorting the power pulse to ground is at the water side of the vacuum interface. Here an "S" shaped 2-1/2" diameter aluminum pipe is used to provide a cableway for data acquisition cables connected directly to the "hot" conductor of the magnetically insulated power flow lines. The length of this cableway is such that its two-way transient time (in water) allows the accelerator power pulse to pass before the shorting effect of the shunt path occurs. One cableway of this design will be available in January for performance confirmation tests in Hydramite.

Pulse Transfer Switches

Thirty-six pulse transfer switches located in the water section of the accelerator constitute a change to the baseline design described in the last reporting period. These previously mentioned switches will be located between the trigatron (three-electrode triggered spark-gap) switch and the first pulse forming line. These new transfer switches (one in each module) will normally be in the dummy load position. They will be changed to the through position when the machine is ready for a full shot to the front end. The location of these transfer switches allows an overvoltage protection gap for each intermediate store capacitor to be included in the switch design. The overvoltage protection gaps, volt-time breakdown characteristic, is designed to be less than that of the intermediate store capacitor. Most of the energy from any discharge through this protection spark gap will be dissipated in the dummy load resistors which are built into the transfer switch. This protection provided to the intermediate store capacitor will nearly eliminate any possibility of a flashover water

explosion that might rupture the three megavolt feedthrough insulator that also serves as an oil/water barrier.

Several factors, including location, make the design of this switch more difficult than the transfer switches in the oil insulated energy storage section.

Corrosion resistant hydraulic actuators for operation of the switch when water is used both as the hydraulic fluid and the surrounding environmental medium, are not readily available.

Design layout of the switch has progressed to the point of showing both feasibility and practicality of its features. Actuator suppliers have been contacted and likely suppliers capable of providing the special actuator design needed have been identified. As soon as actuators and parts can be obtained, testing will be done to confirm the design before EBFA switches are ordered. The addition of these pulse transfer switches to the design adds another budget item not previously included in cost estimates.

The decision to include the pulse transfer switches has come quite late in the accelerator pulsed power design. It may not be possible to include them in the early pulsed power tests of the EBFA I accelerator, but they are expected to be ready about the end of the year. It is planned that a prototype will be tested during the next reporting period.

Pulse Forming and Pulse Transforming Lines

The contractor has ordered all material and has started work on the first units for testing. Problems with corrosion of earlier lines similar to the EBFA units has lead to consideration of various chromate processes to protect surfaces. One proprietary process produces a variety of colors which might lead to a departure from the all brushed aluminum appearance.

Power Flow

The contractor for the power flow lines has been selected and has ordered the long lead time extrusions used for the inner and outer conductors. The test units to be used for design prove-out on Hydramite will be fabricated from an extrusion on hand for the inner conductor and a weldment for the outer conductor. A first attempt at fabrication of the weldment was rejected and will be rebuilt.

The vacuum interface fabrication has moved to an all out effort to produce all 36 units

required for EBFA without waiting for Hydramite confirmation after detailed discussion of production schedules with the contractor. This more risky approach was required to meet the scheduled date for EBFA operation.

Front End

Conceptual design is now complete and several front end components have been defined. The vacuum systems which were dependent on many details of the front end are detailed and ready for purchase. A baseline front end which allows experimental changes at various diameters from the center has been realized.

Vacuum System

Each of the 36 vacuum interface and power flow line combination will have an independent six-inch diffusion pump and valve assembly located near the vacuum interface. The anode-cathode region will have additional pumping from six 10-inch diffusion pumps connected through a ring manifold which also serves as a support for the inboard end of the power flow lines. The backing and roughing pumps will be located remote from the accelerator to alleviate the noise and vibration generated by mechanical pumps. Each of the vacuum transmission lines may be isolated from the rest of the accelerator in the event of individual line failures.

EBFA I (Summary)

ENERGY STORAGE SECTION (Oil Section)

36 high voltage Marx generators
1152 Capacitors
Each capacitor charged to + or - 100 kilovolts
Total weight of capacitors 140 tons
Total stored energy 4.0 megajoules
Marx output voltage 3.2 megavolts
Discharge current greater than 3 megamps
9 Trigger pulsers, each triggers 4 Marx generators
Each Marx generator 112 kilojoules.

PULSE FORMING (Initial)

36 Water dielectric intermediate storage capacitors
Stored energy before switching:
90 kilojoules in each
Total energy before switching:
3.2 megajoules
36 Three-electrode gas dielectric switches (trigatrons)
Triggered switching up to 2.9 to 3 megavolts
Additional pulse shaping by water dielectric

transmission lines and water spark gaps.

CHARGING SYSTEM

Two separate high voltage units containing a total of four 110 kilovolt DC power supplies

Constant current charging with current up to 1.5 amps

Charge time EBFA I (4.2 MJ) 75 seconds

Charge time EBFA II (10 MJ $\rightarrow$ 15 MJ)

90 to 135 seconds

MARX FIRING SYSTEM

9 Marx pulser units (MPU's)

Charged to 80 kilovolts

Each 6 stage Marx pulser multiplies

output to greater than 400 KV

Maximum timing spread 16 nanoseconds.

TRIGGER SYSTEM

6 Output trigger units, each triggers

6 trigatrons

Each OTU is contained in a 900# oil filled tank

OTU voltage 100 to 135 kilovolts

OTU output current at trigatrons 194

kiloamps total

Pulse time speed 5 nanoseconds max.

EBFA II

Plant Engineering and Design (PEDD) funds for FY79 were included in the Public Works bill that was vetoed by the President. When available, these funds will be used to do the preliminary design for EBFA II and provide the architectural design (Title I & II) for the new facilities. These funds will initially be used to design and procure an accelerator utilized as a pulsed power and power flow physics test bed.

Engineering design of a new multibeam accelerator has been underway for several months. Supermite will be the pulsed power and power flow physics test bed on which to do the basic research necessary to provide the criteria for the design of the EBFA II electrical components. The basic geometry of Supermite will simulate a 20° sector of EBFA. The initial proposal for EBFA II described a simple 2 times power and energy upgrade using EBFA I hardware arranged in a plane directly above the existing electrical components. However, several new developments in pulsed power technology lead us to believe that it may be possible to upgrade the capability of the modules. The

Supermite test bed will provide the capability to investigate much higher energy Marx generators, higher current pulse forming networks, transmission lines for both electrons and ions, etc. Later, Supermite will be a full sized mockup of EBFA II on which to investigate the mechanical packaging of the two layers or planes of electrical components. The Supermite accelerator will be located in the High Bay Laboratory (building 981) at EBFF just to the north of EBFA. The design of the Supermite tank has been completed and the procurement procedure has been initiated. Utilities to support this accelerator are presently being defined and will be installed along with the utilities to support EBFA. Initial pulsed power tests on a single higher energy Marx generator are scheduled to start in August/September 1979.

PUBLICATIONS

- RADIAL ELECTRON BEAM LASER EXCITATION, THE REBLE REPORT, J. J. Ramirez and K. R. Prestwich, SAND78-2005 (October 1978).
- PULSE POWER TECHNOLOGY FOR INERTIAL CONFINEMENT, K. R. Prestwich, D. L. Cook and G. Yonas, Proc. of the 3rd ANS Topical Meeting on Controlled Nuclear Fusion, Santa Fe, New Mexico, May 9-11, 1978.
- ONLINE DATA ACQUISITION SYSTEM FOR REPETITIVE PULSER DEVELOPMENT, M. T. Buttram, SAND78-1753 (September 1978).
- OPERATION OF A 300 kV, 100 Hz, 30 kW AVERAGE POWER PULSER, M. T. Buttram and G. J. Rohwein, SAND78-0933 (July 1978).
- CURRENT INSTABILITY IN ELECTRON BEAM DIODES WITH DIELECTRIC NEEDLE CATHODES, M. T. Buttram, SAND78-2142 (October 1978).
- TRANSPORT STUDIES OF CUSP AND MULTICHANNEL REB FUSION CONCEPTS, T. P. Wright, J. Appl. Phys. 49, 3842 (1978).
- FORCE BALANCE AND DENSITY CRITERIA FOR DOUBLE SHEATHS IN PLASMA, K. D. Bergeron and T. P. Wright, Phys. Fluids 21, 1578 (1978).
- HERMES-II BEAM EXTRACTION AND EMP EXPERIMENTS, P. E. Bolduc, R. I. Butler, T. P. Wright, R. B. Miller, M. B. Sandova, J. A. Halbleib, C. N. Vittitoe and W. Moril, SAND79-0238.
- NONUNIFORM MESH DIODE SIMULATION CODE, J. P. Quintenz, J. Appl. Phys. 49, 4377 (1978).
- PRODUCTION OF 0.5 TW PROTON PULSES WITH A SPHERICAL FOCUSING, MAGNETICALLY INSULATED DIODE, 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).
- RELATIVISTIC ELECTRON BEAM ENERGY DEPOSITION IN THIN GOLD AND ALUMINUM TARGETS, E. J. T. Burns, S. A. Goldstein, J. A. Halbleib, L. P. Mix, J. N. Olsen, J. W. Poukey, J. P. Quintenz and M. M. Widner, SAND78-2026 (January 1979).
- CALCULATIONS FOR THE RADIAL LINE ELECTRON ACCELERATOR, J. W. Poukey, RS 5241/240, Internal Memorandum (March 1978).
- FAST NEUTRALIZATION OF ION BEAMS IN THE PRESENCE OF TRANSVERSE MAGNETIC FIELDS, J. W. Poukey and S. Humphries, Jr., Appl. Phys. Lett. 33, 122 (1978).
- SPRINGER TRACTS IN MODERN PHYSICS, VOL. 84--COLLECTIVE ION ACCELERATION, published by Springer-Verlag, Heidelberg, 1979. Includes "Collective Ion Acceleration with Linear Electron Beams" by C. L. Olson, and "Collective Ion Acceleration with Electron Rings" by U. Schumacher (Max Planck Institut fur Plasma Physik, Garching).
- THE POWER BALANCE LIMIT IN COLLECTIVE ION ACCELERATION, C. L. Olson, Proc. of 3rd Intl. Conference on Collective Methods of Acceleration, Laguna Beach, California, May 22-25, 1978.
- EXPERIMENTS AND SCALING OF THE IFA, C. L. Olson, Proc. of 3rd Intl. Conference on Collective Methods of Acceleration, Laguna Beach, California, May 22-25, 1978.
- BEAM TARGET NEUTRON PRODUCTION IN REB DIODES, R. J. Leeper, J. T. Chang and L. P. Mix, Proceedings of 1978 IEEE International Conference on Plasma Science, Monterey, California May 15-17, 1978.

ADVANCED POWER FLOW TECHNOLOGY FOR HIGH CURRENT ICF ACCELERATORS, J. P. VanDevender and D. H. McDaniel, Proc. of the 8th International Symposium on Discharges and Electrical Insulation in Vacuum, Albuquerque, New Mexico, September 5-7, 1978.

DESIGN OF COMPACT PARTICLE-BEAM-DRIVEN INERTIAL CONFINEMENT FUSION REACTORS, D. L. Cook and M. A. Sweeney, Proc. of the 3rd ANS Topical Meeting on Controlled Nuclear Fusion, Santa Fe, New Mexico, May 9-11, 1978, Vol. 2, p. 1178 (1979).

SANDIA'S PARTICLE BEAM FUSION PROGRAM, M. A. Sweeney, Proc. of Fusion: Tomorrow's Energy Source, 16th Annual Symposium of the Idaho Section of ASME, Idaho Falls, Idaho, April 19, 1979.

A MEMO ON THE TEXT PROGRAM, T. A. Mehlhorn, RS 4247/8, Internal Memorandum (December 1978).

TARGETS FOR HEAVY ION FUSION, M. J. Clauser, Proc. of the Symposium on Relativistic Heavy Ion Research, Darmstadt, W. Germany, July 1978, p. 499.

CALCULATIONS OF RADIANT ENERGY LOSS FROM A HYDROGEN PLASMA FOR USE IN HYDROCODES, L. Baker and M. M. Widner, RS 4241/1006, Internal Memorandum (July 1978).

ROLE OF RADIATION TRANSPORT IN PLASMA CHANNEL MODELING, J. N. Olsen and L. Baker, RS 4244/1, Internal Memorandum (February 1979).

CHARTS MULTIGROUP RADIATION TRANSPORT, L. Baker, SAND79-0386 (March 1979).

HIGH CURRENT PULSED LINEAR ION ACCELERATORS FOR INERTIAL FUSION APPLICATIONS, S. Humphries, Jr., J. W. Poukey and G. Yonas, Proc. 3rd International Conference on Collective Methods of Acceleration, Laguna Beach, California May 22-25, 1978.

HIGH CURRENT LINEAR ION ACCELERATORS UTILIZING ELECTRON NEUTRALIZATION, S. Humphries, Jr., G. W. Kuswa and J. W. Poukey, Proc. '79 Particle Accelerator Conference, Bull. Am. Phys. Soc. 24, 170 (1979).

HIGH CURRENT LINEAR ION ACCELERATORS FOR INERTIAL FUSION, S. Humphries, Jr., Proc. of Heavy Ion Fusion Workshop at Argonne Labs., Chicago, Illinois, September 19-21, 1978.

FOCUSING EXPERIMENTS WITH LIGHT ION DIODES, D. J. Johnson, Proc. of Heavy Ion Fusion Workshop at Argonne Labs., Chicago, Illinois, September 19-21, 1978.

GENERAL PURPOSE INTENSE ION INJECTOR, S. Humphries, Jr., Proc. of APS 20th Annual Meeting, Bull. Am. Phys. Soc. 23, 815 (1978).

BUNCHING AND POWER FLOW IN PLASMA-FILLED ION DIODES, C. W. Mendel, RS 4244/2, Internal Memorandum (December 1978).

AZIMUTHAL SYMMETRY AND ION DIODES, C. W. Mendel, RS 4244/3, Internal Memorandum (December 1978).

FILAMENT PREHEATING FOR . TARGETS, J. N. Olsen, SAND78-2246 (February 1979).

ROLE OF RADIATION TRANSPORT IN PLASMA CHANNEL MODELING, J. N. Olsen and L. Baker, RS 0014/1, Internal Memorandum (February 1979).

PRESENTATIONS

NUMERICAL COMPUTATION OF PLASMA BEHAVIOR IN RELATIVISTIC ELECTRON BEAM TARGETS, I. R. Lindemuth and M. M. Widner, Annual Meeting on Theoretical Aspects of Controlled Thermonuclear Research, Gatlingburg, Tennessee, April 1978.

MULTIPLE BEAM REB FUSION, J. R. Freeman, P. A. Miller, L. Baker, J. P. Quintenz, T. P. Wright, J. W. Poukey, L. P. Max and M. M. Widner, 1978 IEEE International Conference on Plasma Science, Monterey, California, May 15-17, 1978.

ENHANCED ELECTRON DEPOSITION, M. M. Widner, 1978 Meeting on the Classified Inertial Confinement Targets, Las Vegas, Nevada, October 1978.

OBSERVATION OF ENHANCED ELECTRON DEPOSITION IN THIN FOILS, M. M. Widner, S. A. Goldsrein, C. W. Mendel, E. J. T. Burns, J. P. Quintenz and A. V. Farnsworth, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

THIN Au FOIL IRRADIATION WITH C-DIODE ON THE MITE ACCELERATOR, J. T. Chang, J. P. VanDevender, A. V. Farnsworth, M. M. Widner, E. J. T. Burns and J. P. Quintenz, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

XUV SPECTROSCOPY OF ION BEAM AND ELECTRON BEAM DEPOSITION IN THIN TARGETS, E. J. T. Burns, J. T. Chang, A. V. Farnsworth, S. A. Goldstein, D. J. Johnson, G. W. Kuswa, C. W. Mendel, J. P. VanDevender and M. M. Widner, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

A COMBINED MONTE CARLO-DIODE SIMULATION CODE, J. P. Quintenz and M. M. Widner, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

MHD FUEL BEHAVIOR IN ADVANCED REB TARGETS, I. R. Lindemuth and M. M. Widner, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

PLASMA CHANNELS FOR ELECTRON BEAM TRANSPORT, J. R. Freeman, L. Baker, J. W. Poukey and M. M. Widner, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

BEAM PRECONDITIONING OF ELECTRON BEAM FUSION TARGETS, L. Baker, M. M. Widner, A. V. Farnsworth and J. T. Chang, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

ENHANCED ELECTRON DEPOSITION, M. M. Widner, Second International Conference on Energy Storage, Compression and Switching, Venice, Italy, December 5-8, 1978.

NUMERICAL SIMULATION OF COMPRESSED MAGNETIC FLUX PULSE POWER GENERATORS, T. P. Wright, L. Baker, J. R. Freeman and M. Cowan, 1978 IEEE International Conference on Plasma Science, Monterey, California, May 15-17, 1978.

FUEL PRECONDITIONING STUDIES FOR ELECTRON BEAM FUSION, J. N. Olsen, M. M. Widner, L. Baker, and J. T. Chang, 1978 IEEE International Conference on Plasma Science, Monterey, California, May 15-17, 1978.

MAGNETIC IMPLOSION OF PLASMAS WITH SHORT PULSE, HIGH POWER GENERATORS, M. J. Clauser, L. Baker, D. H. McDaniel, R. W. Stinnett and A. J. Toepfer, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

HYDRODYNAMIC STABILITY OF MULTIPLE SHELL TARGETS, F. C. Perry, L. P. Mix, L. Baker and A. J. Toepfer, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

COMPUTER SIMULATION OF A PLASMA ARMATURE, T. P. Wright, L. Baker and J. R. Freeman, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

SANDIA'S PARTICLE BEAM FUSION PROGRAM, M. J. Clauser, Colloquium at Massachusetts Institute of Technology, Cambridge, Massachusetts, April 7, 1978.

SCORPIO THEORY, M. J. Clauser, DNA Advanced Concepts Review Meeting, Albuquerque, New Mexico, May 4, 1978.

NEAR-TERM PARTICLE BEAM FUSION TARGETS, M. J. Clauser, Heavy Ion Fusion Workshop, Argonne, Illinois, September 1978.

PULSE LINE DRIVEN ELECTROMAGNETICALLY IMPLoded PLASMA, D. H. McDaniel, E. J. T. Burns, M. J. Clauser, L. P. Mix, R. W. Stinnett, A. J. Toepfer, J. Dorman and R. Reinovsky, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

A COMPACT HYBRID USING AN INERTIALLY CONFINED ION BEAM WET-WOOD BURNER SCHEME, T. A. Mehlhorn and M. J. Clauser, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

CENTRAL IGNITER MAGNETIC TARGETS WITH VOLTAGE SHAPING, M. A. Sweeney and A. V. Farnsworth, Jr., 1978 IEEE International Conference on Plasma Science, Monterey, California, May 15-17, 1978.

AN ION BEAM DRIVEN CONICAL IMPLSION, A. V. Farnsworth, Jr., D. J. Johnson, and C. W. Kuswa, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

CHARGED PARTICLE TRANSPORT USING A SPACE AND TIME DEPENDENT FOKKER-PLANCK CODE, T. A. Mehlhorn and J. Duderstadt, 1978 IEEE International Conference on Plasma Science, Monterey, California, May 15-17, 1978.

PARTICLE BEAM FUSION, M. A. Sweeney, Career Stimulation Program, Sandia Laboratories, Albuquerque, New Mexico, April 17, 1978.

DESIGN OF COMPACT PARTICLE-BEAM-DRIVEN INERTIAL CONFINEMENT FUSION REACTORS, D. L. Cook and M. A. Sweeney, Third ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Santa Fe, New Mexico, May 9-11, 1978.

DESIGN OF A GAS-FILLED PARTICLE-BEAM REACTOR CHAMBER, M. A. Sweeney and D. L. Cook, 20th Annual Meeting of the American Physical Society Division of Plasma Physics, Colorado Springs, Colorado, October 1978.

POWER FLOW IN HIGH CURRENT PARTICLE ACCELERATORS FOR INERTIAL CONFINEMENT FUSION, J. P. VanDevender, 1978 IEEE International Conference on Plasma Science, Monterey, California, May 15-17, 1978.

JOWOG-6, J. P. VanDevender, Sandia Laboratories, Albuquerque, New Mexico, June 27-30, 1978.

ADVANCED POWER FLOW TECHNOLOGIES FOR HIGH CURRENT ICF ACCELERATORS, J. P. VanDevender and D. H. McDaniel, Eighth International Symposium on Discharges and Electrical Insulation in Vacuum, Albuquerque, New Mexico, September 5-7, 1978.

SELF-MAGNETIC INSULATION IN LONG TRIPLATE TRANSMISSION LINES, J. P. VanDevender, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

TEMPERATURE ESTIMATES FROM NEUTRON PRODUCTION IN A HIGH DENSITY PLASMA IMPLSION, R. W. Stinnett, D. H. McDaniel, R. J. Leeper and A. J. Toepfer, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

PREPULSE EFFECTS ON CYLINDRICAL FOILS AND ON WIRE ARRAYS, L. Baker, M. J. Clauser, R. W. Stinnett, A. J. Toepfer and D. H. McDaniel, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

MULTIPLE ELECTRON BEAM IRRADIATED TARGET DIAGNOSTICS, L. P. Mix and P. A. Miller, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

A MONTE CARLO STUDY OF A NEUTRON TIME-OF-FLIGHT SPECTROMETER SUITABLE FOR USE IN PARTICLE BEAM FUSION EXPERIMENTS, R. J. Leeper, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

BEAM TARGET NEUTRON PRODUCTION IN REB DIODES, 1978 IEEE International Conference on Plasma Science, R. J. Leeper, J. T. Chang and L. P. Mix, 1978 International Conference on Plasma Science, Monterey, California, May 15-17, 1978.

VACUUM ULTRAVIOLET SPECTROSCOPY OF CHARGED PARTICLE DEPOSITION IN THIN FOILS, E. J. T. Burns, S. A. Goldstein, D. J. Johnson, G. W. Kuswa and P. A. Miller, IX Summer School and Symposium on the Physics of Ionized Gases in Dubrovnik, Yugoslavia, August 28-September 2, 1978.

ELECTRON BEAM DRIVEN SHOCKS AND IMPLSIONS OF MODEL FUSION TARGETS, F. C. Perry, Gordon Conference, August 7-11, 1978.

SANDIA PULSED POWER PROGRAM, T. H. Martin, DNA Advanced Concepts Review Meeting, San Diego, California, May 3, 1978.

PROTO-II PROGRESS, T. H. Martin, JOWOC, Sandia Laboratories, Albuquerque, New Mexico, June 27-30, 1978.

STATUS OF PULSED POWER TECHNOLOGY, T. H. Martin, Mid-Con Meeting, Dallas, Texas, December 14, 1978.

PULSE POWER PARTICLE BEAM SOURCES AS FUSION DRIVERS, G. W. Kuswa, American Nuclear Society Meeting, San Diego, California, June 18-22, 1978.

APPLICATIONS OF PULSE POWER TECHNOLOGY TO INERTIAL FUSION, G. W. Kuswa, 1978 IEEE International Conference on Plasma Science, Monterey, California, May 17-19, 1978.

AIR CHANNEL MODELING AND HIGH v/γ BEAM TRANSPORT IN DISCHARGE CURRENT, J. R. Freeman, J. W. Poukey and L. Baker, Lawrence Livermore Laboratory, Livermore, California, September 18-21, 1978.

THE POWER BALANCE LIMIT IN COLLECTIVE ION ACCELERATION, C. L. Olson, Third International Conference on Collective Methods of Acceleration, Laguna Beach, California, May 22-25, 1978.

EXPERIMENTS AND SCALING OF THE IFA, C. L. Olson, Third International Conference on Collective Methods of Acceleration, Laguna Beach, California, May 22-25, 1978.

CONTROLLED BEAM FRONT MOTION AND COLLECTIVE ION ACCELERATION WITH THE IFA, C. L. Olson, 20th Annual Meeting of the American Physical Society Division of Plasma Physics, Colorado Springs, Colorado, October 1978.

CALCULATIONS OF MAGNETICALLY INSULATED ION DIODES, J. P. Quintenz, J. W. Poukey and D. J. Johnson, 1978 IEEE International Conference on Plasma Science, Monterey, California, May 15-17, 1978.

COMPUTATIONS OF CHARGE NEUTRALIZATION IN HIGH-CURRENT LINEAR ION ACCELERATORS, J. W. Poukey and S. Humphries, Jr., 20th Annual Meeting of the American Physical Society Division of Plasma Physics, Colorado Springs, Colorado, October 1978.

THE C-DIODE--A HIGHLY EFFICIENT REB DIODE FOR TARGET IRRADIATION, J. T. Chang, S. A. Goldstein, C. W. Mendel and J. P. Quintenz, IEEE International Conference on Plasma Science, Monterey, California, May 15-17, 1978.

OPTIMIZATION OF ELECTRON BEAM PINCHING FROM SMALL R/d CATHODES FOR THIN FILM ENHANCED DEPOSITION EXPERIMENTS, S. A. Goldstein, C. W. Mendel and J. P. Quintenz, 20th Annual Meeting of the American Physical Society Division of Plasma Physics, Colorado Springs, Colorado, October 1978.

A MODULAR LOW IMPEDANCE MAGNETICALLY INSULATED ION DIODE, D. J. Johnson, G. W. Kuswa, R. J. Leeper and J. P. Quintenz, 20th Annual Meeting of the American Physical Society Division of Plasma Physics, Colorado Springs, Colorado, October 1978.

HERMES III USING MAGNETIC CUSP TECHNIQUES, T. P. Wright and C. R. McClenahan, Joint JOWOG G/SUBWOG 268 Meeting, Sandia Laboratories, Albuquerque, New Mexico, June 27-29, 1978.

THE EXTRACTION OF A LOW v/y BEAM OVER MANY METERS/NEAR-FIELD EMP SIMULATION, P. E. Bolduc, C. N. Vittitoe and T. P. Wright, Joint JOWOG G/SUBWOG 268 Meeting, Sandia Laboratories, Albuquerque, New Mexico, June 27-29, 1978.

RELATIVISTIC ELECTRON BEAMS-THEORY AND APPLICATIONS, T. P. Wright, New Mexico State University, Physics Department Colloquium, Las Cruces, New Mexico, October 12, 1978.

LOW v/y REB PROPAGATION EXPERIMENTS IN THE PRESSURE RANGE 1-640 TORR, P. E. Bolduc, R. B. Miller, T. P. Wright, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

MULTIPLE-CHANNEL CHARGED-PARTICLE BEAM OVERLAP STUDIES, T. P. Wright, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

PULSED POWER TECHNOLOGY FOR INERTIAL CONFINEMENT, K. R. Prestwich, D. L. Cook and G. Yonas, Third ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, Santa Fe, New Mexico, May 9-11, 1978.

ELECTRON EMISSION STUDIES OF PLANAR DIODES FOR LOW CURRENT DENSITY, MICROSECOND E-BEAM ACCELERATORS, R. S. Clark, J. J. Ramirez and K. R. Prestwich, 1978 IEEE International Conference on Plasma Science, Monterey, California, May 15-17, 1978.

REPETITIVE PULSE POWER AND HIGH CURRENT LINEAR DEVELOPMENT AT SANDIA LABORATORIES, K. R. Prestwich, Naval Air Systems Command Pulse Power Technical Advisory Group Meeting, Kirtland AFB, New Mexico, October 23-24, 1978.

CURRENT INSTABILITY IN ELECTRON BEAM DIODES WITH BLADE AND NEEDLE CATHODES, M. T. Buttram, 1978 IEEE International Conference on Plasma Science, Monterey, California, May 15-17, 1978.

OPERATION OF A 300 kV, 100 Hz, 30 kW AVERAGE POWER PULSER, M. T. Buttram and G. J. Rohwein, 13th Pulse Power Modular Symposium, Buffalo, New York, June 20-22, 1978.

OPERATION OF A REPETITIVELY PULSED ELECTRON BEAM DIODE, M. T. Buttram, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

STUDIES OF MICROSECOND E-BEAM DIODES, J. J. Ramirez and D. L. Cook, 1978 IEEE International Conference on Plasma Science, Monterey, California, May 15-17, 1978.

MICROSECOND PLASMA-FILLED E-BEAM DIODE CHARACTERISTICS, D. L. Cook and J. J. Ramirez, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

COLLECTIVE-EFFECT ELECTRON ACCELERATION, R. E. Maller, Third International Conference on Collective Methods of Acceleration, Laguna Beach, California, May 22-25, 1978.

RADLAC-A HIGH ENERGY RADIAL LINE ELECTRON ACCELERATOR CONCEPT FOR VULNERABILITY, R. B. Miller, K. R. Prestwich, J. W. Poukey and G. Yonas, Fourth AIAA Joint Strategic Science Meeting, San Diego, California, September 13-15, 1978.

PROPAGATION OF HIGH CURRENT DIODE BEAMS, R. B. Miller, Propagation Physics Meeting, Lawrence Livermore Laboratory, Livermore, California, September 19-21, 1978.

PROTO-I AS A SHORT PULSE X-RAY SOURCE, S. L. Shope, JOWOG-6, Sandia Laboratories, Albuquerque, New Mexico, June 27-30, 1978.

PROGRESS IN THE DEVELOPMENT OF A FIVE-FRAME X-RAY CAMERA FOR E-BEAM FUSION STUDIES, D. L. Fehl, J. T. Chang and G. W. Xuswa, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

HIGH CURRENT PULSED LINEAR ION ACCELERATORS FOR INERTIAL FUSION APPLICATION, S. Humphries, Jr., J. W. Poukey and G. Yonas, Third International Conference on Collective Methods of Acceleration, Laguna Beach, California, May 22-25, 1978.

GENERAL PURPOSE INTENSE ION INJECTOR, S. Humphries, Jr., American Physical Society Meeting, Colorado Springs, Colorado, October 1978.

HIGH CURRENT LINEAR ION ACCELERATORS FOR INERTIAL FUSION, S. Humphries, Jr., Heavy Ion Fusion Workshop, Argonne Laboratories, Chicago, Illinois, September 1978.

FOCUSING EXPERIMENTS WITH LIGHT ION DIODES, D. J. Johnson, Heavy Ion Fusion Workshop, Argonne Laboratories, Chicago, Illinois, September 1978.

GENERAL 1-D RELATIVISTIC ELECTRON FLOW, C. W. Mendel, American Physical Society Meeting, Colorado Springs, Colorado, October 1978.