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Electron Beam Fusion Progress Report April Through September 1977

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ELECTRON BEAM FUSION PROGRESS REPORT
APRIL THROUGH SEPTEMBER 1977

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TITLE: Technical and management overview

INTRODUCTION

TECHNICAL OVERVIEW

General Discussion

The key milestones achieved during this reporting period are as follows:

1. Detailed measurements and further analysis of magnetic thermoinsulation targets which support the conclusion that the neutron production observed is of thermonuclear nature and not due to ion acceleration.
2. Continued measurements and analysis of beam propagation in preformed channels to define requirements for Proto II, EBFA, and eventually reactor experiments.
3. Operation of Proto II at the 8-TW power level thus demonstrating most of the pulsed power components for EBFA.
4. Initial tests of the EBFA module (MITE) with preliminary data on the critical aspects of magnetically insulated vacuum transmission lines.
5. Completion of theoretical and experimental electron beam focusing and target studies on Proto I demonstrating 5 to 10 MA/cm² and power densities of ~ 5 TW/g and ~10 to 15 TW/g in thin Au and Al foils, respectively, in agreement with theory which predicts enhanced deposition due to multiple electron interactions.
6. Demonstration of the high rep-rate test facility with over 10⁷ shots yielding data on switch reliability and lifetime.
7. Substantial progress on the construction of the Electron Beam Fusion Facility indicating that the completion schedule can be met and also completion of EBFA preliminary design involving 36 separate modules.

As a result of these steps we have been able to narrow our option matrix leading toward a candidate driver system for an experimental power reactor. The diagram from the previous progress report showing these options is reproduced here to indicate this narrowing process (Fig. 1).

Fig. 1. Particle Beam Fusion Program options.

Success in electron beam focusing with > 1-Ω diodes on Proto I together with beam propagation in plasma channels and demonstration of enhanced electron deposition have led to the adoption of this combination as our base line approach. The need for complex targets involving a central ignitor, such as a magnetically insulated region, became more clear as our analysis of simple targets came to an end.

With the definition of an experimental and theoretical program at NRL to pursue the self-magnetic field approach to electron suppression in ion diodes, we were able to narrow our attention at Sandia to use of external fields. This diode approach for light ions has also been adopted for a multistage ion accelerator which would be necessary for medium or heavy ions. This similarity in the light ion and heavy ion programs further simplifies our program. A revised option matrix is shown in Fig. 2.

Developments in these areas are summarized below.

Fig. 2. Option matrix as of October 1978.

Pulsed Power

Proto II became fully operational during this period following completion of switch testing and modification. The accelerator has operated over a wide range of pulse durations from 20 ns to 80 ns producing up to 8 TW at the input to the diode. This wide range of pulse durations is easily achieved simply by varying the water switch arrangement. The switch behavior is now as initially expected and beam focusing work is beginning. The five-fold power increase sought in EBFA will require either substantial improvements in vacuum breakdown if the Proto II disc vacuum feed approach is to be used, or the use of separate modules and magnetically insulated vacuum lines must be followed. At this time, the latter approach has been adopted with the final design definition planned for January 1978. The MITE apparatus became operational during this period and as a result of theoretical target studies which have indicated the need for higher energies in longer pulses, we decided to adopt the use of the 40 ns Proto II-type strip lines instead of the shorter pulse Blumleins originally considered for EBFA.

This use of longer pulse should permit higher efficiency operation with a projected EBFA output of ~1 MJ at a peak power of 30 TW. Initial vacuum insulation experiments on MITE indicated energy losses for azimuthally non-uniform lines as opposed to a coaxial line and the need for a "closed triplate" design was defined. Two-dimensional particle in cell simulations for long magnetically insulated lines were encouraging in that the only losses appear to exist at the pulse front with efficient and stable energy propagation during the major part of the pulse. At the end of this reporting period the hardware to fully test the long modified triplate approach on MITE was on order and tests are planned for the end of the year.

Theory

Target theory during this period emphasized the preheat and scaling aspects of magnetically thermoinsulated targets and the effects of beam stagnation on enhanced energy deposition in thin foils. Predictions for magnetic targets continue to be encouraging with the goal of 10^7 to 10^9 UT neutrons from Proto II remaining as a conservative estimate. The importance of both electrostatic and magnetic effects in enhanced deposition in thin foils was predicted and compared with experiments on Hydra and Proto I. The detrimental effect of scattering on enhanced deposition in high-Z foils was shown to be due to radial diffusion of the beam at v/γ values ~1. This analysis also indicated that higher v/γ beams should achieve substantial enhancement with factors proportional to $1/\gamma$. In particular, we expect that a $v/\gamma = 3$ beams with a radius of 1.5 mm should achieve a deposition enhancement factor of ~6 in a 6- μ thick planar Au foil. On the other hand, the enhancement factor is predicted to not be readily detectable for currents of 50 to 75 kA which have been obtained typically in the Hydra pinch. One way to improve the enhancement factor is through reduced scattering with low-Z foils and theory indicates that with v/γ of only 2 and the use of a 6- μ Al foil that an enhancement factor of ~2 to 3 should be expected. Experiments on Proto I have supported these predictions.

Further work on the use of channels for beam propagation emphasized the development of a 1-D MHD code to define channel conditions and to provide a design tool for scale up experiments. In addition, beam overlap analysis and reactor chamber overpressure calculations continued to indicate the viability of this approach to solve the stand off problem. This multiple channel approach may also be useful for the guiding of light ion beams and this possibility is under consideration also. The diode code was improved to handle nonuniform and nonplanar diodes and this code is in use in design of diodes for Proto II and EBFA.

Particle Beam Source Development

Beam focusing studies emphasized aspects of ion suppression and methods for improvement of beam reproducibility and focusing efficiency using heated anodes and segmented cathodes. Multiple beam research emphasized detailed diagnosis of preformed channels,

initial beam combination experiments on Hydra, and design of a 12-beam Proto II experiment. Ion experiments using external magnetic field suppression of electron flow were carried out on Hermes indicating large electron leakage and also showing the need for a symmetric power feed which is available with the two-sided machines such as Proto I and Proto II. Ion diode hardware for these accelerators was designed and fabrication of a Proto I experiment began. The use of external fields in a multistage accelerator for medium and heavy ions was studied analytically and promising theoretical results have led to the initiation of an experiment to test these concepts. Further diagnostic development continued with substantial improvement in a pulsed X-ray source for use in flash X-radiography.

Target Interaction

Experiments using preheated fuel and magnetic thermoinsulation with exploding pusher spherical targets continued. In order to further investigate the nature of this neutron output a comprehensive series of null experiments, as well as detailed neutron time-of-flight experiments, tended to confirm our original interpretation of these neutrons as being a result of implosion and not due to ion acceleration. Experiments with a glass shell filled with DT gas as well as separate experiments to diagnose preheat conditions were begun during this period. Enhanced deposition experiments on Hydra and Proto I were completed during this period showing that due to the limited focusing used in deposition experiments on Hydra ($J < 10^6$ A/cm²) and the marginal values of v/γ available on Proto I, substantially enhanced deposition in thin planar high-Z foils could not be obtained. On the other hand, by employing Al instead of Au this enhanced deposition effect was observed as predicted. The two-beam irradiation of spherical high-Z thin pellets on Proto I was carried out showing good symmetry of irradiation could be achieved with sufficient care but this experiment was discontinued due to the low deposition obtained. These results indicated the validity of the two-beam irradiation approach, but showed the need for higher currents such as that available on Proto II. Optical diagnostic techniques were demonstrated for use with open sided imploding targets and these diagnostics will be employed in future studies to investigate the growth of Rayleigh-Taylor instabilities. The first evidence of pusher breakup (fluff formation) of the inner

surface of an imploding target was obtained. Neutron signature experiments using a new pulsed neutron source and analysis showed that the heavily shielded scintillator photomultiplier in use could readily differentiate between the long pulse beam-target neutrons commonly produced in high current diodes and the short pulse neutron pulses expected from valid implosion produced thermonuclear conditions.

Applications

Operation of the 30 kW average power rep-rate test experiment began during this period with data collected on system reproducibility and lifetime. Individual experiments in excess of 5×10^5 shots were limited by the lifetime of the high current switch electrodes and lack of adequate flow rate in the output switch to provide for arc quenching. Redesign of these components is underway to improve performance and lower flow requirements. UV illumination of the output switch was found useful in achieving stable operation at low rep-rates but was found to be unnecessary at rep-rates of 20 to 30 pps. Additional studies on hydrodynamics of flow in various switch geometries are underway to improve arc quenching and electrode cooling with the lowest possible flow rates.

An economic model has been employed to define optimum design parameters for the high efficiency and low cost particle beam driver approaches. The basic difference from similar laser analyses is that a relatively low gain pellet (< 100) has applicability here. Our analysis has included both pure fusion and hybrid cases and indicates that pellet fabrication cost plays a strong economic role as long as the (driver efficiency) $\times$ (focusing efficiency) is greater than ~ 20 percent for a pure fusion reactor and ~ 10 percent for a hybrid reactor. If the pellet fabrication cost is $< \$0.10$, then the pellet gain can be < 50 for pure fusion and as low as 3 for hybrid Reactors (blanket gain of 25). If the pellet cost can be $\$0.01$, then the gain 3 pellet is compatible with a gain 10 hybrid blanket. This study has clearly identified the need for realistic estimates of the mass production costs of pellets. If these costs can be as low as a few cents per pellet, then economically attractive hybrid scenarios can be envisioned for low cost and efficient particle beam drivers which could be readily built after the net energy gain goal has been moderately exceeded. This type of economic model can

also allow one to create a scenario for the evaluation of technology and its impact on power cost. An arbitrarily chosen evolution of technology is hypothesized showing how improvements of various kinds can lead to reduced power costs. The numbers shown (on the right of Fig. 3) give the similar laser projections for a pure fusion reactor based on high gain pellets.

As technology improves with mass production methods and the unit costs are decreased, the cost of power would decrease with time which is in contrast to the situation that exists today where the cost of ever scarcer fuel drives the cost of energy up with time.

MANAGEMENT OVERVIEW

EBFA Project Status

This is the first full reporting period for the EBF Project since the start of construction at the EBFF site on January 21, 1977 and the initiation of the engineering design of the EBFA-I on January 4, 1977.

The construction activity at the EBFF site has progressed at a slightly slower than anticipated rate between March and October 1977. An aerial photograph showing the status of construction as of October 23, 1977 is shown in Fig. 5. However from this photo, one can see that the entire floor of the laboratory building including the trenches covered with gratings in the high bay portion has been completed. At this point the contractor, R. E. McKee, Inc., is ahead of the contracts construction Milestone No. 1 of having the laboratory building floor completed by November 3, 1977. The process oil tank storage farm can be seen nearing completion on the southeast corner of the laboratory building. Each tank has a capacity of 250,000 gallons of transformer oil for the electrical insulation of the energy storage section of EBFA. The upgraded EBFA-II will require 430,000 gallons of transformer oil. The EBFA will also use approximately 385,000 gallons of deionized water with a resistivity $< 1 \text{ M}\Omega/\text{cm}$. The deionized water system will be designed by the A/E, W. C. Kruger and Associates with the main storage tanks located due south of the two oil storage tanks. In the photo, the southeast corner of the laboratory which comprises the mechanical equipment room and diode preparation room on the first level and main pumps for the oil and water transfer systems in

the basement has been completely enclosed. The hexagonal pit and tunnels to the mechanical pump room and beneath the control room are completed. The 2 ten-ton capacity platform lifts have been installed. It can be seen that several sections of the high bay laboratory walls have been erected and that the high bay concrete door frames are in place. The entire laboratory building is to be constructed of precast concrete, double tee sections, both walls and roofs. The laboratory is expected to be completely enclosed by Thanksgiving 1977 so that the inside finish work can be accomplished during the winter. At this time, everything still appears on schedule for acquiring beneficial occupancy of the High Bay Laboratory to start the installation of the EBFA tank on the scheduled Milestone No. 3, i.e., August 11, 1978.

A "Baseline" design configuration of EBFA-I was established during July 1977 as a result of the progress made in the research areas of power flow and beam generation/transport during the reporting period. The elements of the EBFA "Baseline" design which are based on technical considerations were established primarily as a project management tool to facilitate planning, tracking, and reporting. This allows the EBF Project to make realistic estimates of the schedule, cost, and manpower necessary to support the project "End of Construction" date. The "Baseline" approach does not preclude necessary changes to the overall design of EBFA, however, if a change occurs after the scheduled design freeze of a particular element, a delay in the end of construction and an increase in total cost may be the result.

The EBFA will consist essentially of 36 independent particle beam accelerators arranged in a radial configuration within a single integrated tank structure. A preliminary design sketch of the EBFA-I "July 77 Baseline" is shown in Fig. 6. For discussion purposes, a single accelerator line can be divided into four separate sections: (1) the energy storage section, (2) the pulse forming section, (3) the power flow section, and (4) the front-end experimental section. The energy storage section consists of a 112 kJ Marx generator module, solid dielectric intermediate storage capacitors, and a triggered gas switch submerged in transformer oil for electrical insulation. The energy is transferred on command through a high voltage barrier into the water insulated pulse forming section. This consists of back-to-back Blumleins used to shape the pulse to 20-ns FWHM and a set

Fig. 3. REB Fusion Experimental Power Reactor Performance.

Fig. 4. REB Hybrid Experimental Power Reactor Performance.

Fig. 5. Electron Beam Fusion Facility Site - October 1977.

Fig. 6. EBFA-I preliminary design.

of transformer lines designed to match the impedance of the output load. The Magnetically Insulated-Vacuum Transmission Line (MI-VTL) concept of power flow is used to transmit the energy the last 18.5 ft. into the central or front-end section of the accelerator where the electron beams are generated. The MI-VTL concept is presently being investigated using the pulsed power test bed in Area V, called MITE, and by a research contract with Physics International. Preliminary experimental results have been encouraging. Also, theoretically, the MI-VTL power flow concept is scalable to much higher power levels than EBFA-I. This makes it a principle candidate for EBFA-II, the 2 MJ accelerator proposed to be built in the 1982-1983 time frame, which will be used to achieve net energy gain with a standoff capability. This approach circumvents the insulator flashover problem, which would require a major improvement in breakdown strength of the insulator surface to allow extrapolation of the Proto II approach to higher power levels. The design freeze for the EBFA power flow concept is scheduled for December 1977.

The most promising front-end concept for the generation, focusing and transport of the electron beam for pellet irradiation is the Multiple Electron Beam (MEB) configuration. The MEB concept involves using the central conductor of the MI-VTL pulse charged negative with respect to ground. Thirty-six individual electron beams are generated from two inch diameter cylindrical cathodes located

approximately 18 inches from the center of the pellet chamber. The tightly pinched electron beam then penetrates a thin anode foil and follows a low-density preionized channel in the background gas to the pellet. The low-density channel is established by exploding a wire between the anode foil and the pellet just prior to the arrival of the electromagnetic wave at the cathode.

The central portion of EBFA is being designed using a modular philosophy which will allow for the easy insertion of alternate front-end concepts. Several different pellet irradiation concepts are presently under investigation. The design freeze for the front-end concept is presently scheduled for July 1978.

The overall design of EBFA-I is proceeding on or slightly ahead of schedule. A major milestone in the engineering design was reached during June with the final design of the EBFA tank structure approved by the PBF Program personnel. The detailed fabrication drawings were being prepared with a target date of September 1, 1977 to start the procurement procedure. However in August, the results of MITE engineering evaluation tests of the solid dielectric capacitors to be used as the intermediate stores indicated a limited life expectancy at the EBFA-I operating voltage. It was decided at this time to use water capacitors for the intermediate stores based on the high reliability and excellent performance characteristics experienced with the Proto II water capacitors. It was decided to locate the intermediate stores on the water insulated side of the H. V. barrier in the pulse forming section instead of in the oil insulated energy storage section of the accelerator. With this decision, the intermediate store could be configured as an open, flat plate capacitor using the deionized water in the pulse forming section for electrical insulation and energy storage, thereby simplifying the capacitor geometry. This configuration also eliminates the possibility of gas trapping and electrical breakdown.

The intermediate stores decision resulted in a slight reconfiguration of the EBFA tank to enlarge the pulse forming section and reduce the energy storage section accordingly. This caused a one-month slip in starting the procurement action on the EBFA-I tank structure. A "Request for Quote" was sent to six prospective bidders on October 25, 1977 with a pre-bidders conference scheduled for November 7, 1977 at Sandia. The bids will be opened in

early January 1978 with a contract to be awarded in February 1978. Installation of the EBFA tank structure in the High Bay Laboratory Building at the EBFF site is scheduled to start on August 11, 1978.

Research results in the areas of target physics and beam interaction led to a reevaluation of the basic parameters for the EBFA-I during this period. It was decided to change the pulse length of the accelerator from 20 ns to 40 ns in order to improve the overall system efficiency and energy output. Based on preliminary experimental results obtained in the MITE accelerator on this longer pulse length, the beam energy should increase from 500 kJ to 1.0 MJ with the total power decreased from 40 TW to approximately 30 TW. Also, during these initial longer pulse experiments on MITE, it was determined that improved system efficiency could be achieved with the proven flat-plate Proto II-type pulse forming lines.

The redesign and cost analysis of the Proto II Marx generator connecting hardware for use in EBFA was completed in June 1977. A total redesign was undertaken to reduce the per unit cost of the hardware to be used in EBFA by pursuing alternate mass production techniques. The present plan is to use 36 of these redesigned Marx generators in EBFA initially and to double the number of generators in the upgraded configuration, EBFA-II. Procurement of a sufficient amount of this redesigned connecting and hanging hardware to build a single, full-scale EBFA Marx generator mock-up was initiated in June. The engineering evaluation of this mock-up will include the mechanical fit of the assembled unit, the quality of manufactured hardware, the handling characteristics of the entire modular unit, and finally, the electrical characteristics of the redesigned Marx generator. All aspects of the procedure will be checked out to verify that the specialized handling equipment, presently being designed, will satisfy the assembly/transportation/maintenance plan which has been developed for the 36 EBFA Marx generators.

In summary, during the reporting period the EBFA-I design experienced several changes dictated by the results of the various research efforts and the engineering evaluation tests on the single EBFA module. The present EBFA-I configuration consists of 36 identical modules as before with the energy storage section consisting of 36, 112 kJ Marx generators housed in a single annular tank. The deionized water filled pulse forming

section now consists of a flat plate intermediate storage capacitor, a triggered gas switch, a flat plate transmission line-type pulse forming section and a transformer section to the vacuum interface. The power flow section consists of the MI-VTL immersed in water (for radiation shielding purposes only) with the pellet irradiation candidate based on the MEB concept. The EBFA tank structure parameters are presented in Table I.

TABLE I

EBFA Tank Structure Parameters

1. Energy Storage Section - Oil Insulated
100' O.D. x 64' I.D. x 14' high-mild steel
Oil Capacity: I = 300,000 gal.;
II = 430,000 gal.
2. Pulse Forming Section - Water Insulated
64' O.D. x 40' I.D. x 15.5' high-stainless steel
Water Capacity: I = 135,000 gal.;
II = 225,000 gal.
3. Power Flow Section - Vacuum/Water
40' O.D. x 12' I.D. x 15.5' high-stainless steel/aluminum
Water Capacity: I = 65,000 gal.;
II = 110,000 gal.
4. Front-end Pellet Chamber Modules -
Vacuum/Pressure
8' diameter - aluminum

The EBFF/EBFA Installation Schedule has been established and is presented in Fig. 7. This schedule consists of many parallel activities that must be accomplished to meet the June 30, 1980 operational date. It is anticipated that a two-shift assembly operation will be started on EBFA as soon as the tank structure is complete. This schedule has helped to establish the manpower needed to perform the entire EBFF/EBFA assembly.

Fig. 7. EBFF EBFA Installation Schedule.

Personnel and Operating Budget

The operating budget for FY'78 is as follows:

	<u>Man Years</u>	<u>Total K\$</u>
Source Development	38	
Target Research	24	
Applications	10	
TOTAL	72	8700

PULSED POWER

OVERVIEW

Options for EBFA-I were narrowed as data became available from Proto II, MITE and power flow research. The solid dielectric capacitors proposed for intermediate stores have been eliminated for EBFA because of low reliability. Water capacitors based on data from Proto II and Hydra will be used on EBFA. These capacitors will be located inside the main water tank which will allow more flexibility in pulse outputs and switching. The discovery of a new prepulse prevention scheme has allowed stacking of strip lines to provide the same energy store as Blumleins at the same diameter and to provide better efficiency. The EBFA pulse duration and energy were increased to 35 ns and 1 MJ to provide a more optimum output from 40 to 30 TW. This allows elimination of one pulse forming stage. Improved SF-6 switching data from Proto II shows that present parameters are adequate for EBFA. A switch jitter of 3 ns with reliability exceeding 0.986 was demonstrated.

Proto II has achieved the design output and is now a user oriented accelerator. Several desirable features of the disc accelerator were proven.

Initial magnetic insulation experiments on a 1.5 m-long-tripole show small energy and power losses. Theoretical understanding of magnetic insulation was greatly enhanced and agreement between projections and experiment were obtained. It is expected that the longer pulse chosen for EBFA will simplify the long magnetic line application. The 7-m line will be tested during the next report period.

Magnetic flashover inhibition results from Ripple and Qmen promise very low inductance close in diodes for Proto II - EBFA-type accelerators and could allow greater power densities than are now being achieved.

EBFA-I

Results from Proto II and MITE along with modified target requirements have reshaped EBFA-I.

The EBFA design can be chosen from a wide variety of hardware. Strip lines or Blumleins either

stacked or unstacked have been demonstrated to operate. This provides a wide range of voltages and pulse lengths. The Marx generators and intermediate storage capacitors are operating well in Proto II and SF₆ switching difficulties have been resolved. A variety of pulse durations has been demonstrated on Proto II which could accommodate a wide variety of EBFA fusion experiments. The disc-shaped accelerator is operating well and has several operational advantages over concentric coaxial line type of accelerators. Magnetic insulation is being investigated and will be used to alleviate the vacuum interface flash-over problem. Combining the above, the present EBFA design is shown in Fig. 1. The 30.5-m-diameter tank will contain 36 modules. Each module will contain a Proto II-type Marx, an intermediate storage capacitor, a strip line pulse forming network, transmission lines, a single diode and a 4-m-long magnetically insulated transmission line leading to a common experimental chamber.

Changes since the last report have occurred primarily in the intermediate storage capacitors which have been changed to water energy stores located inside the main water tank. This was done to provide better capacitor reliability and to provide a faster charge time for the pulse forming lines. The pulse forming lines will be strip lines with an output pulse length of 35 ns at the half power points.

As found from the Proto II data included in this report a rather modest decrease in peak power can result in a large increase in output energy because another pulse compression stage can be eliminated. Subsequently the output parameters of EBFA were modified to increase the energy output from 0.5 MJ to 1 MJ total and to modify the power output to 30 TW peak. The projected outputs are 2 MV and 15 MA but these values could be modified pending future results from MITE.

PROTO II

Summary

Proto II has met the original design objectives and is being used for experimental studies.

Fig. 1. Electron Beam Fusion Accelerator (EBFA).

With the completion of the pulsed power testing, the accelerator can now be scheduled and used for a variety of experimental purposes including power flow. Proto II is now the world's most powerful (~ 8 TW) low-impedance ($\sim 1/8 \Omega$) accelerator.

Proto II has proven to be, for its size and complexity, a highly reliable and easily maintained accelerator. The new flat disc design had some variance from conventional accelerators but provided a multitude of advantages. The following pulsed power problems have been greatly reduced by the design:

- Trapped air in the water causing voltage breakdowns - Once the water is placed in the accelerator and the bubbles eliminated, switch gap changing, monitor calibration and servicing can be performed from the top of the lines. The water is removed only for major changes in accelerator configuration.

- Variable output voltages and impedances - The disc type line transformers were successful and easily adjusted. This eliminates the need for a separate set of large expensive close tolerance stainless steel cylinders to change the conventional accelerator output impedance.

- Multiple Marx generator operation and reliability - The Proto II Marx's are continuing to operate with very low jitter (~ 10 ns) and few prefires. The design provides safety switches for the generator which connects the Marx either to a dump resistor or the water capacitors. This fact allows the Marx's to be tested prior to every experiment to ascertain if they are running properly. This procedure checks the higher failure components. During the experiment, the Marx's are connected to the load for only a few seconds after being charged thus further narrowing the time window when a prefire could damage the experiment.

- Water intermediate storage capacitors - The water capacitors have proven very reliable after initial problems with gas bubble generation. Intermediate storage capacitors are a vital portion of any multiple channel water switching accelerator.

- Low diode inductance - The Proto II diode inductance is about 6 nh per diode or a total machine diode inductance of 3 nh. The diode has withstood a voltage of 2 MV which results in an inductance of 1.5 nh/MV. The natural diode grading inherent in the concept eliminates the need for field shaping and greatly

perturbing the equipotential lines in the diode area. New developments in MFI reported elsewhere show even lower inductances are possible.

- Varying pulse durations - Proto II has shown that several pulse widths are possible. Changing the pulse duration is possible without dumping the water and can be accomplished in less than four hours to provide 80, 60, 45, or 20 ns outputs. On conventional accelerators pulse width variation is difficult if not impossible over this range.

- Untriggered water switching - Data from Proto II shows 3 ns water switching jitter and indicates that this low value could be further decreased. Untriggered water switching should extrapolate to far larger accelerators.

Accelerator Description

Reference 1 has an in-depth description of Proto II, a later paper² detailed the slower pulsed power data. A photograph of Proto II is shown in Fig. 2. Eight Marx generators, tested to 1 MJ, are located in an annulus formed between a central 7.9-m-diameter tank and the outer 13.4-m-diameter tank. The tanks are 2.8 m high. Low jitter 400 kV trigger units synchronize the eight Marx generators and tests indicate less than 20 ns jitter for the entire Marx and trigger system. After triggering, the Marx generators transfer their energy to 16 intermediate water dielectric storage capacitors which are then switched through the eight 1.2-m-diameter high voltage feedthrough located around the inner tank wall by SF₆ trigatrons. The triggered SF₆ switches provide time synchronization for the accelerator and transfer the energy into the first water line in about 300 ns. A series of rod switches (16 to 80) then discharge the first water line into the second water line which in turn self-breaks through a sharp edge switch in typically 150 to 200 channels and provides a short rise time pulse into the radially converging transmission lines. Circumferential interconnections between the first water lines average voltage and time differences between the water capacitors and SF₆ switches. The radially converging lines join to two back-to-back low inductance diodes which provide two oppositely directed 1-m-diameter ring electron beams. The lines also provide a transformer with a 0.125 ohm input and a 0.25 ohm output for this series of tests. The output of the transformer section attaches

Fig. 2. Proto II accelerator.

to the back-to-back diode that has been described.¹ This diode was designed to have an inductance of 4.1 nH within the insulator envelope. The effective inductance, determined by short circuit shots in all pulse modes, was found to be within 10 percent of the design value. The short circuit shots provided a cross-check of the monitor calibration, calculated inductance, and effective output impedance of the accelerator. The electron beam was generated with a 1-m-diameter razor blade cathode and a 24 segment prepulse switch, consisting of 1.27 cm by 1.27 cm cylinders and was installed at a 1.32 m diameter. This increased the effective diode inductance by 1.5 nH and reduced the prepulse by a factor of 5 for the 50 ns pulse mode as shown by the traces in Fig. 3.

Fig. 3. Proto II prepulse voltages.

Twenty Nanosecond Mode Operation

Sixteen sharpened rods are used between the first water line and the second water line in this mode of operation. The small number of switching points provides inductive isolation between the two lines and exchanges the line energy in a lumped constant fashion. The energy transfers with a typical voltage of $V = V_0 (1 - \cos \omega t)/2$ waveshapes with a zero to peak of 70 ns. When line two is charging,

a voltage is applied across the second switch which is a sharp edge blade. A photograph of the channels obtained is shown as Fig. 4.

Fig. 4. Photograph of Proto II switching arc channels.

Note the large number of channels per radial section that were obtained. As expected, the switch rise time is limited by the water switch resistive phase and the total switch jitter. Voltage monitors are located opposite line 1, line 2, and the entrance to the radial transmission line. The voltage on line 1 rises to 2.1 MV in 240 ns, then the rod switches break down and charge line 2 in about 40 ns and subsequently cause a prepulse voltage at the transmission line input. After line 2 switches the output peaks at 1 MV or 3.9 TW in 12 ns with an energy of 60 kJ per side. The pulse then passes thru the transmission line transformer sections where the impedance changes and the voltage is increased by 1.4 before impinging on the diode. Each diode has four B monitors and V monitors. These are integrated, averaged then compared to the opposite diode. The data provides power, energy, and the inductively corrected voltages for the electron beam. The power and energy are shown in Fig. 5.

PII OUTPUT

Fig. 5. a. Proto II output power.
b. Proto II output energy.

The generated pulses arrive at the diode in a slightly asymmetric manner. They average to provide the diode current and voltages. A typical combined current trace is shown in Fig. 6 for monitors 1 m from center and 90° apart. The currents and voltages average out for a small diameter cathode but a large diameter cathode probably emits preferentially. If the arrival time differs by a spread of Δt , then the apparent rise time increase to the diode will be $\sim \Delta t/3$. Therefore, a spread of 15 ns will add 5 ns to the diode rise time. The spread originates primarily in the SF₆ switches and first set of water switches. An analysis of the switch data is shown in Table I. The switching appears to operate as predicted. The larger spreads are caused when one or two gas switches fire early. The cause of these early firings is being investigated.

TABLE I

Proto II - Switch Data

	Spread ns	1 σ Deviation ns	Predicted Deviation ns
SF ₆ Trigratron	25.0	6.8	5.0
Untriggered Rod Switch	10.5	3.2-6	2-6.4

PII CURRENTS

Fig. 6. Proto II diode currents.

Varying Pulse Width Mode

Due to the three pulse forming networks and the large number of water switches, several different pulse lengths can be obtained from this type of accelerator. The simplest PPN is described² and consists of dumping the water capacitors into a load. Approximately 2 TW peak was generated by charging water line 1 and using 1, 3, or 5 rod switches to shape the pulse. In this mode, 80, 60, or 35 ns pulses can be obtained. The line 2 switch is shorted to the transmission line during these tests. A summary of the normalized accelerator outputs in this mode is shown in Fig. 7.

SF-6 Trigratron Switching

While Proto II achieved its output parameters the SF-6 Trigratron switches exhibited a spread up to 50 ns or a jitter of about 16 ns on several experiments. On Proto II this time spread was reduced to about one-half by the voltage averaging on line 1 and its water switches. For instance, the 16 ns SF-6 jitter would correspond to a jitter of 8 ns in the water switching. A program was initiated to improve the SF-6 switch performance during September.

PROTO II OUTPUT VS POWER PULSE 1/2 WIDTH

Fig. 7. Proto II output vs. power pulse one-half width.

Precise timing measurements showed that the trigatron switch spread was caused by a few switches breaking down slightly before the trigger signal arrived. A few of the eight switches would break and then the rest would trigger as expected. The switches were operating at about 0.8 reliability. The SF-6 gas was checked and found to be acceptable. Three other probable causes were electrode damage, electrode material, and arc debris. A series of tests showed that all played a part in the early firing. New electrodes of 304 stainless steel were installed and the switch reliability was > 0.986 for an extended series of experiments on Proto II. Subsequent user experiments have proven this initial data and the SF-6 switch operational level should be adequate for EBFA.

Prepulse Prevention

The suppression of prepulse on super power accelerators is a major problem. A new approach for preventing the prepulse from reaching problematical levels has been developed and tested on the Ripple accelerator. A ground plane with several holes in it is inserted between the electrodes in the water dielectric switches as shown in Fig. 8. The switch electrodes from the output line

extend through the holes and face points on the opposite pulse forming line (PFL). The capacity from the PFL to the output line is reduced by approximately 90 percent and hence the prepulse is lowered by the same fraction. The energy formerly stored in that capacity and formerly dissipated in the switch, is now available for use in the accelerator. After the main pulse has passed through the ground planes, the gap between the holes and the switch electrodes breaks down and protects the pulse forming network from the pulse reflections from the diode.

Fig. 8. Cut away views of water dielectric switches are shown without (a) and with (b) the prepulse reducing ground plane.

The tests on the Ripple accelerator show that the prepulse can be reduced to approximately 6 kV into the transmission line for a 3 MV charge on line 2 (the worst case for prepulse).

An additional, water dielectric prepulse switch based on the same concept can reduce that to approximately 2.5 kV. Vacuum flash-over prepulse switches or plasma erosion switches in the diode can further reduce the prepulse to < 500 V. These types of switches have been designed for Proto II operation and are being fabricated.

MITE

Summary

The MITE (Magnetically Insulated Transmission Experiment) is a one module (1/36) version of EBFA. Because of the multiple diode approach proposed for EBFA, a test bed was needed to

test several of the modified Proto II components and the vacuum insulated line transport efficiency. The MITE pulser uses the same type of Marx as Proto II which charges solid dielectric intermediate storage capacitors. The intermediate storage capacitor initially charged back-to-back water insulated Blumlein transmission lines. The solid dielectric capacitors were investigated as an alternative to the water insulated intermediate energy storage capacitors. These new capacitors offer some distinct advantages over the water capacitors: no polarity effect as in water; compact packaging; no deionized water system. The primary uncertainty is the capacitor lifetime. Lifetime tests conducted during this report period indicated a reliability problem and are detailed below.

Solid Dielectric Capacitor Testing

Testing of the solid dielectric intermediate storage capacitors has continued on MITE. Four simultaneous capacitor failures occurred after 180 shots in a voltage range of 1.5 MV to 2.8 MV. An equivalent number of shots of 109 was calculated for an EBFA operating voltage of 2.5 MV by using the 8th power scaling law. After an additional 10 to 2.5 MV shots, four more capacitors failed.

The capacitors are made up of 123 paper-aluminum foil windings connected in series. An examination of some of the failed capacitors showed that an arc had punched through the paper insulation totally shorting some capacitors and partially shorting others. The partially shorted capacitors can be identified by an increase in capacitance. A capacitor was defined as having failed if its capacity had increased by 10 percent.

While a Wiebull analysis of the capacitor failure may not be entirely correct due to synergistic effects, a mean failure rate of ~150 shots at 2.5 MV is predicted. On EBFA if all capacitors would be replaced after 100 shots (~10 percent failures) the cost would amount to ~\$5000 per shot.

Blumlein

The initial MITE Blumlein pulse-forming lines are shown in Fig. 9. The line 1 sections are pulse charged to ~2.5 MV in 250 ns. The energy stored in line 1 is then transferred to line 2 through self-breakdown single channel water switches. The line 2 sections

reach a peak voltage of 2.5 MV in 70 ns. At that time, the knife edged Blumlein switches launch two pulses down the water-insulated transmission lines to the vacuum envelope. Monitors at positions 1, 2, and 3 as well as at the vacuum envelope are used to measure voltages and arrival times of the pulses. Measurements of pulse simultaneity showed a mean difference of 3.8 ns.

Fig. 9. MITE Blumlein pulse forming lines.

The charging waveforms at positions 1 and 2 are similar to those for Proto II. The Blumlein output waveform at position 3 is shown in Fig. 10. The power waveform shown is for both sides of MITE and was determined from the Blumlein output and line impedance at that point.

MITE OUTPUT

Fig. 10. a. MITE Blumlein output voltage.
b. MITE Blumlein output power.

Strip Lines

The discovery of a new prepulse isolation method has allowed stacking of the Proto II-type strip lines for EBFA. A new set of pulse lines were reconfigured from the Blumlein parts and comparative experiments were made. Initial results indicate more efficient strip line operation. The strip lines have a larger output current, lower voltage, and a simpler configuration than the Blumlein. A higher efficiency at lower cost make the strip line preferable for EBFA. Outputs and pulse shapes will be obtained for the next progress report.

Diode

The initial vacuum envelope used was a shortened (22-cm insulator length) version of a REBA³ diode. The measured inductance of 80 nH is much greater than the intended EBFA envelope. Vacuum triplate magnetically insulated vacuum transmission lines were connected to the diode to allow experiments to be performed prior to the intended diode delivery. The 28-cm-wide vacuum lines are spread 1 cm apart with the outer lines held at ground potential and the center line pulsed positively. A 1.2-m set of vacuum lines has been tested and a set of 7-m long is on order. Experimental results of the lines are presented in the MITE section.

The intended vacuum insulator interface for EBFA was designed and constructed for use on the MITE accelerator. This interface assembly, designed using the JASON field plotting code, uses standard 45° Lucite insulators and Gask-O-Seal grading rings. The diode is sized such that no interface will fail on a given shot when 36 such interfaces are operated in parallel in EBFA. The insulator rings are circular in shape with internal metal field shapers which convert from the circular input geometry to the racetrack geometry required for the magnetically insulated triplate transmission line output. The combination of rectangular and semicircular geometries required a number of assumptions during the design process to arrive at the calculated inductance of 36 nH to the beginning of the magnetically insulated transmission line. Inductance measurements have been made on the interface assembly using a 5-ohm fast pulse generator and uniform resistive load. Four different current feed geometries were used to simulate possible current feed geometries in the MITE

accelerator. All four current feeds gave measured inductance values within 1 nH of the calculated value of 36 nH. The interface is now undergoing high voltage testing in the MITE accelerator.

POWER FLOW - SELF MAGNETICALLY INSULATED TRANSMISSION LINES

Introduction

In the Electron Beam Fusion Accelerator (EBFA)⁴, 36 magnetically insulated vacuum transmission lines are to be used and each is approximately 7 m long. Since the transit time through the line is approximately the pulse duration, the electron flow must be magnetically insulated by the self-limiting impedance of the line, which is a much more stringent criterion than encountered in conventional load dominated lines.⁵

Both coaxial and triplate transmission lines have been considered for EBFA. With mean stresses of 2.4 MV/cm, power can be transported to within 1.1 m and 0.45 m of the pellet in EBFA for coax and triplate configurations, respectively. Consequently, the triplate configuration is being pursued because of its advantageous power flow capability.

The magnetic insulation program has been a cooperative venture with Physics International Company. Experiments have been performed at Physics International on coaxial⁶ and triplate⁷ configurations. Additional experiments are now in progress on the coaxial configuration. At Sandia, experimental work was undertaken on coaxial lines and semiempirical theory was developed to explain the input impedance of magnetically insulated transmission lines.⁵ Two numerical codes have been developed to study power flow in long self-magnetically insulated transmission lines^{8,9} and have been useful in interpreting the experimental results. Recently, experimental work has begun on the MITE accelerator⁴ using a 1.5-m-long triplate transmission line with a geometrical impedance of 8 ohms. The results of the numerical computations and the results of the MITE experiments will be discussed in this section, and related to the design of EBFA.

Computational Results

Two time-dependent numerical codes have been developed to study the properties of magnetic insulation.^{8,9} Results will first be discussed for the two-dimensional, time-dependent, fully self-consistent, particle-in-cell computer code. A voltage waveform is applied to the input of the simulated transmission line, and the time history of the pulse propagation and electron flow is computed. Figure 11 shows the voltage waveform for a 7-m-long, 8- Ω vacuum coax. The input voltage waveform was a trapezoid with a 10 ns rise to a 2.4 MV level and then constant; this shape was chosen to approximate the MITT voltage pulse. The voltage pulse without the magnetic insulation effects is shown by the dotted line in Fig. 11. The apparent input impedance $Z = V/I$ of the coax for this case was 5.4 Ω , which is 67 percent the geometrical impedance. The pulse rise time has sharpened, and the front of the pulse has been eroded. The average velocity of the front is 2.2×10^8 m/sec. Peak power is transported with 11 percent efficiency. Since electrons are lost to the anode during the rise time of the pulse, the average energy of the electrons reaching the anode is typically 11 percent of the maximum potential across the transmission lines. Electrons in the cutoff region behind the front are confined to a sheath which is relatively close to the anode; there is no leakage of electrons out and gap in the cutoff region. The current flowing in the negative inner conductor and the total current has been computed for peak voltages between 1 and 10 MV and the results agree within 1 percent with that computed from the minimum current allowed by the potential¹⁰ theory.

Another simulation was developed in the circuit analysis code SCITRI. The physics of electron emission and magnetic insulation are introduced via a conductance and an equivalent distributed network approximation of a lossy transmission line. The numerical dependences of the conductance on the local voltage and current are semiempirical fits to experimental data on short line measurements. The results of this code agree very well with the particle-in-cell and with experiments with coaxial lines.⁸ The advantage of this code is that it is possible to study the effects of various load configurations and simulate loss currents behind the pulse front.

Recent experiments on the triplate line Physics International have shown that

Fig. 11. 2-D time-dependent P.I.C. simulation of magnetic insulation.

resulting in a nearly linear voltage drop along the length of the triplate line. The code has been modified to include a small conductance behind the pulse front. Simple consideration of power balance for a line with a voltage loss yields an expression for the conductance per unit length of

$$g = \frac{1}{2V} \frac{dV}{dz}. \quad \text{For the PI results this}$$

suggests an equivalent loss current density of 12 A/cm^2 or 1.2 percent of the possible (Child's law, space charge limited value for this geometry. The solid dots with error bars in Fig. 12 are the experimental values for the peak voltage as a function of length and the open squares are the code results using the 12 A/cm^2 loss current. Hence the azimuthal asymmetries inherent in triplate lines may cause a low level leakage current to flow in the self-magnetically insulated triplate line. Recent 4-chlorostyrene measurements of the emission pattern confirm that the losses are predominantly in the regions with reduced E and B fields.

Sandia Triplate Experiment

A single module of EBFA has been designed and is being fabricated. The module consists of a 7-m-long, 3- Ω vacuum triplate line with a low inductance, 36 nH insulator.

Fig. 12. Voltage loss as a function of length for a simple triplate.

A 1.5-m-long, 8- Ω triplate was adapted to the MITE pulse forming network using a modified RFEA diode with an inductance of 8 nH. Figure 13 shows the triplate transmission line and some of its diagnostics. The centerline was constructed of two lines 25.4 cm wide, spaced 5.08 cm apart and connected electrically. The outer lines were 30.5 cm wide and connected electrically. The outer lines were 30.5 cm wide and were spaced 1 cm from the inner set of lines. The lines were terminated in a field emission diode in which the anode is a carbon calorimeter and the cathode is 20 cm of 5 mill thick stainless steel. Input voltage and current are measured on each side of the diode. B-dots are mounted on the input, middle, and output of the inner and outer conductors of the transmission line. Experiments have been conducted with positive polarity on the center conductor. The monitors on the inner line measure total current and those on the outer line measure boundary current, which is total current minus the electron current. Since B-dot monitors suffer from the effects of nonuniform current flow and emission, reliable data were taken only after the uniformity of emission was improved by coating the lines with graphite. A magnetic energy analyzer is mounted within the anode and uses 4-chlorostyrene to record time-integrated electron energy distribution at the load. The azimuthal symmetry of electron loss current is measured with 4-chloro placed around the circumference of the inner

Fig. 13. MITE vacuum transmission lines and diagnostics.

transmission line. A Faraday cup is installed in the middle of the centerline to measure loss current density to the side of the line. The cup measured losses of between 10 A/cm² and 2 A/cm² during the pulse rise time, and much less than 4 A/cm² during the rest of the pulse.

The initial shots were performed with bare aluminum lines and damage was severe and spotty. Four-chloro showed damage patterns that were teardrop shaped (6 mm x 12 mm) shaped with doses in excess of 2×10^6 rads. More uniform emission was obtained by coating the outer lines with Aerodag. The dose at the top and bottom of the lines was 30 to 50 percent larger than the dose on the sides. Voltage, $L di/dt$, and corrected voltage waveforms are shown in Fig. 14 for a charge level of 2.4 MV on the Blumlein. The high inductance of the diode made it difficult to calculate the corrected voltage available at the input of the transmission line with the fast 15 ns FWHM pulse. These waveforms were taken when the transmission line was running at its self-limiting impedance, i.e., the A-K gap was not drawing sufficient current to insulate the transmission line. The input impedance for this case is 4 Ω at peak power.

In order to obtain data at higher voltages while we awaited delivery of the low-inductance tube, the switching configuration in the MITE pulse forming network was changed from that in Ref. 4. Figure 15 shows the configuration used

Fig. 14. Voltage waveforms for short pulse operation.

Fig. 15. Pulse forming line configuration for long pulse.

to obtain the long pulse. The Blumlein switch on line 2 and the transfer switches between line 1 and line 2 were removed and a three-point Blumlein switch was installed on line 1. Typical output, current, and corrected voltage waveforms and the output of the magnetic energy analyzer are shown in Fig. 16 for a charge voltage of 1.7 MV on the Blumlein. The $L \, dI/dt$ correction to the voltage is now much lower, allowing a more reliable calculation of input voltage. The input impedance of the transmission line is $4 \, \Omega$, and is the same self-limiting value as that obtained with the short pulse. The magnetic energy analyzer data and the A-K gap geometry indicate the gap impedance to be $7 \, \Omega$. Hence, although the current transport was 100 percent to the end of the transmission line, only a third of the current was flowing to the anode from the cathode. The rest must be flowing directly to the anode in the last 2.5 between the last B-dot on the cathode and the load A-K gap. Figure 17a shows plots of the total current as a function of corrected voltage with curves for minimum parapotential current and saturated parapotential current. These curves are similar to those obtained in the P.I. experiments. Figure 17b shows plots of the boundary current vs. corrected

voltage along with curves for the boundary current necessary for saturated parapotential and minimum parapotential electron flow. The boundary current and the total current are equal up to the arrow. The total current begins to rise at a faster rate and exceeds the value for minimum parapotential current near the end of the pulse. The voltage decreases as the current remains high at the end of the pulse which indicates that the magnetically insulated line is not a constant resistive load for an accelerator. The current transport was excellent for case and the current loss density was between 10 and 50 A/cm² on the top and bottom of the line and $< 2 \, \text{A/cm}^2$ on the sides between plates

A summary of the loss current density for various experiments is shown in Table II. The values of the losses have been normalized to the space charge limited current densities for the various configurations. The experiments above the dotted line were all for uniform coaxial geometry. The values of loss current are very low and the power transport was excellent for these experiments. The 2-D PIC simulations have indicated no loss current in uniform geometries and is consistent with experiments. Experiments involving nonuniform

(a)

(b)

Fig. 16. Typical electrical and magnetic energy analyzer data for the long pulse.

(a)

(b)

Fig. 17. Total current and boundary current V-I plots for a magnetically insulated line.

TABLE II
Loss Current Density Summary

Experiment	Z Ohms	(J_L/J_{CL}) %	Aerodag Coating Negative Electrode
Hydra Coax	11	≤ 0.2	No
Pi - Short	24 to 49	$\leq 0.2 \pm 0.1$	No
PI - Long	49	$\leq 0.03 \pm 0.02$	No
Curved Coax Hydra	11	3.0 (1/4 area)	No
PI Triplate	24	0.5 (1/3 area)	Yes/No
MITE Triplate	8	5.0 to 10.0 (1/6 area)	Yes

geometries are listed below the dotted line. The fraction of the anode area over which the loss current was observed is also indicated. These experiments indicate that current is lost in the regions in which the ratio of the vacuum fields E_r/B_z at the anode is well above the average E_r/B_z in the lines. Consequently, although the loss currents in a simple triplate line result in an unacceptably low transport efficiency for EBFA, a line designed for a nearly constant value of E/B should be much more efficient. An oval shaped or "closed triplate" cross section line approximately satisfies this criterion and will be tested in the near future.

MAGNETIC FLASHOVER INHIBITION (MFI) WITH SELF-FIELDS

The study on magnetic inhibition of vacuum flashover with self-magnetic fields was extended to higher electric fields on the 0.3- Ω Ripple accelerator. The experiments indicated that the average flashover electric field along the insulator surface E_{11} is proportional to the magnetic field B_0 perpendicular to E_{11} , as has been predicted,¹¹ and the flashover strength of a MFI insulator can exceed that of the standard +45° acrylic insulator.

The Ripple diode used in the experiments is shown schematically in Fig. 18. The diode was shorted with inductive shorts ranging from 0.47 nH to 1.8 nH in most of the tests.

Fig. 18. Schematic of Ripple diode. The radius of the aluminum cylinder is changed to vary the inductance or the cylinder is replaced with an A-K gap for a particle beam load.

Shots were also taken with particle beam loads with a plasma erosion switch,¹² in which the impedance was initially zero and then increased to $\sim 0.1 \Omega$ after the current was established.

Tests were conducted with $+45^\circ$, -45° , and 0° acrylic insulators lightly coated with silicon diffusion pump oil. The voltage across the insulator was measured with an integrated $\bar{D}$ monitor, and the currents inside and outside the insulator were monitored with integrated B probes. Flashover was determined to have occurred when the current inside the insulator was crowbarred to a constant value and that outside the insulator continued to increase. Typical voltage and current waveforms are shown in Fig. 19. The values of E_{11} and B_0 at flashover for the three insulator geometries are shown in Fig. 20 with the low B_0 values obtained by other experiments.¹³

For $+45^\circ$ insulators, in which the electrons are geometrically inhibited from striking the insulator, the flashover strength was not strongly dependent on the magnetic field. This result is consistent with the earlier observation of McDaniel, et al.¹⁴ with externally applied B_0 . For -45° and 0° insulators the flashover strength was approximately proportional to the value of B_0 and was approximately given by

$$E_{11} = 0.045 B_0 c$$

$$= V/d (\cos\theta)$$

where B_0 is the magnetic field in Tesla, $c = 3 \times 10^8$ m/sec, V is the voltage across the insulator in volts, d is the separation between the electrodes in meters, and θ is the insulator angle. This value of E_{11} is consistent with the -45° data with an externally applied B_0 in Ref. 14.

The presence of UV and X-ray radiation from the anode and cathode with a particle beam load did not degrade the flashover strength.

The scaling of the flashover strength with magnetic field B_0 reverses the usual dependence of the tube inductance or the insulator radius. If the tube is made small enough for MFI to be useful and the ratio of the tube height to the length of the vacuum feed is a constant, then the inductance varies as $1/r$. The limiting radius of

the insulator is then determined by water breakdown. With water dielectric convoluted feeds to the diode¹⁵ and the short pulse breakdown strength of water,¹⁶ then MFI double diodes for Proto II and EBFA-I could be built with tube radii of only 0.28 m and 0.54 m, respectively, with inductances of 0.56 nH and 0.3 nH, respectively.

However, the Ripple diode has a small area (45 cm^2) insulator. There is a well-known dependence of flashover strength E on area for $+45^\circ$ insulators with $Ea^{0.1}$ so that the flashover strength could be degraded in a larger diode. This area dependence is related to the width of the probability distribution for flashover. The fact that there were more than ten flashover channels per shot and they were uniformly distributed around the insulator indicate that the width of the flashover probability distribution in these experiments was very small and, hence, the area dependence very weak. Nevertheless, a full-scale test of MFI is required to confirm the utility of the approach in superpower accelerators, and that experiment is being planned for Proto II.

A second obvious use of MFI is in preventing restrike of the insulator during the current rise in Z-pinches. That approach has been successfully tested on the Ripple accelerator and is reported under the heading "Superfast Z-Pinch."

MAGNETIC FLASHOVER INHIBITION USING AN EXTERNALLY APPLIED MAGNETIC FIELD

Magnetic deflection and trapping of electron trajectories has been employed to develop vacuum pulse power transmission lines operating at more than 1.5 MV/cm. Theoretical predictions of improvement in vacuum insulator performance have been developed.^{17,18} The principle has been, experimentally, investigated as a method of improving the voltage hold off characteristics of vacuum-dielectric interfaces used in electron beam machine diodes for shallow insulator angles using an externally applied magnetic field.

The experiment consists of a polymethacrylate disk insulator with an area of 116 cm^2 between metal field shaping electrodes which create a 14° angle between the field lines and the disk surface. The disk is lightly oiled with DC 704 silicon oil and subjected to 36 ns wide pulses of up to 500-kV amplitude from the 2- Ω coaxial

Fig. 19. The current waveforms outside the insulator ($-I_{out}$) and inside the insulator (I_{in}) are shown at 0.56 MA/div and 10 ns/div in A and B, respectively. Flashover of this -45° insulator occurred upon voltage reversal. The voltage waveform is shown in C at 50 kV/div and 10 ns/div.

THOR accelerator providing mean fields at the disk surface up to 20 MV/M. A separate 20 kV, 215 μ fd capacitor bank is used to provide variable amplitude and polarity magnetic fields at the insulator surface of up to 1.3 Tesla. A 155 nH inductor across the normal A-K gap is used to carry the bank current while maintaining voltage across the disk surface. The experiment is shown schematically in Fig. 21. The inductor across the A-K gap causes the voltage waveform to depart, with an L/Z droop, from the normal rectangular shape. An integrated D-dot pick-off probe is used to monitor the voltage at the disk while an integrated B-dot coil, oriented to ignore the symmetric fields produced by the coaxial line, is used to monitor the current due to the non-symmetric breakdown across the disk surface.

The voltage pulse amplitude applied to the insulator disk was raised in steps until breakdown was observed approximately 5 ns after the initial voltage peak at a mean field of 15 MV/M. First experiments with magnetic fields

Fig. 20. E_b vs. B at breakdown for A: 0° (●) and -45° (●) insulators and B: $+45^\circ$ insulators (▲). A completely shaded symbol indicates breakdown, an open one indicates no breakdown, and a partially shaded symbol indicates late time breakdown. The points at $B = 0$ are from Ref. 13 with electron initiating points at the anode or cathode to remove the area dependence. The highest stressed points in each case were obtained with a particle beam load.

Fig. 21. Schematic of the THOR experiment. The isolation inductors keep the fast pulse out of the slow capacitor bank circuit while maintaining a circuit for the bank current.

on the order of 0.2 Tesla deflecting electrons from the cathode surface into the insulator surface caused breakdown on the rising voltage waveform as expected. With the magnetic field reversed to cause electrons to deflect away from the insulator surface, no breakdown was observed during the full 36 ns wide pulse. Breakdown did occur as soon as the voltage pulse reversed polarity which made the outer metal surface a cathode and electrons were directed into the insulator surface. Typical disk voltage and integrated B-dot waveforms are shown in Figs. 22a through 22d for breakdown with and without an externally applied B_0 field. A plot of mean electric field at the insulator surface achieved for various values of B_0 is given in Fig. 23. The ratio of magnetic field needed to inhibit a surface flashover at a given mean electric field is given by the relationship

$$\frac{E}{CB} < 0.1$$

External magnetic fields have been employed to improve shallow angle insulator flashover field strength by more than a factor of two which is the limit observable in the present experiment. Comparison of the results of this experiment and an experiment using self

generated fields¹⁹ show the external field to be a factor of two more effective in raising breakdown strength which may be a result of having the magnetic field present before saturation of the electron avalanche.

OPTICAL CALIBRATOR

A compact optical calibrator for fast electronic streak cameras has been constructed using a pulsed nitrogen laser as the input light source and a fiber optic bundle array to develop five optically delayed outputs.

A coaxial EG&G nitrogen laser is driven with a Kappa Scientific 30-kV pulser to generate a 450 psec risetime, 3.3-ns FWHM light pulse with an overall system jitter of less than 1 ns. A disk of Pilot-B scintillator is used to convert the 337 nm laser radiation to 408 nm emission for transmission through a Galileo fiber optic bundle has 5 outputs each delayed in 5 ns increments as well as an optical to reference output which is internally coupled to a photodiode to provide a 1.5 volt electrical to signal. This assembly has provided adequate light output for calibration of the 20 ns sweep of an STL image converter camera. The coaxial laser head used in this calibrator can also provide a 200 psec wide pulse when

Fig. 22. The voltage and integrated B-dot waveforms shown in 22a and 22b were taken with no external applied B field. Figures 22c and 22d were taken with an applied field of 0.46 Tesla with all other conditions held constant. Voltage at 118 kV/div, integrated B-dot at 1 volt/div and 20 ns/div time sweep for all traces.

Fig. 23. Peak mean electric fields at the insulator surface vs. externally applied B_0 for $+14^\circ$ insulators. ■ indicates early breakdown, with 5 ns of voltage peak, ● indicates breakdown on the falling portion of the applied voltage waveform, and □ indicates no breakdown during the full 36 ns pulse.

can also provide a 200 psec wide pulse when filled with neon which will be investigated for calibration of an Ima-Con image converter camera using a shorter delay increment fiber optic bundle.

VOLTAGE MONITORS

A new D type monitor has been developed for more reliable voltage measurements in water dielectric pulse forming lines. The monitor uses a plastic dielectric across the lines and avoids the following problems formerly associated with water dielectric D monitors: (a) bubbles on the pick-off electrode, (b) oxide coating on the pick-off, (c) streamer initiation and electrical breakdown between the pick-off electrode and the ground plane, (d) nonlinear behavior of the shunt resistor, and (e) reduced frequency response by the stray capacity to ground. The monitor has

been used on the Ripple accelerator to measure voltages up to 2.5 MV, at rates of change of voltage up to 8×10^{13} V/sec, in electric fields of up to 500 kV/cm.

The monitors are now installed on the MITE accelerator for evaluation for EBFA.

Fig. 24. Schematic drawing of nylon dielectric D voltage monitor for water dielectric transmission lines.

SUPERFAST Z-PINCH

The development of magnetic flashover inhibition (MFI) suggests that the restrike problem in plasma devices may be overcome. The 0.3-Ω Ripple accelerator was used to pinch a 0.5 torr D_2 gas-filled pinch with $I_{max} = 2.0$ MA. Streak photographs and current and voltage measurements were obtained on pinches with initial radius $r_0 = 2$ cm and length $l = 2$ cm. When the current pulse was not crowbarred, the insulator restrieked upon current restrike. At no time did restrike occur during the current rise when MFI should be effective. The pinch impedance Z was approximately 0.15 Ω and was reasonably well matched to the accelerator.

The Z-pinch configuration is shown schematically in Fig. 25. Current (B) monitors and voltage (D) monitors are in the acrylic insulator feed to the pinch. The voltage V and the rate of change of current I are shown in Fig. 26 and the integrals of V and I are shown in Fig. 27. The resistance R from electron-neutral collisions, electron-ion collisions, and ion-ion collisions was calculated to be < 0.01 Ω. Since R is much less than the line impedance

Fig. 25. Schematic of Z-pinch experiment.

Fig. 27. The current I and the integral of the voltage LI are shown in a and b, respectively.

Fig. 26. The derivative of the current with respect to time $\dot{I}$ and the voltage V are shown in a and b, respectively.

Z_0 or the ratio of V/I across the plasma, R is assumed to be zero in the analysis. The inductance vs. time is obtained in Fig. 28a from

$$L = \frac{\int V dt}{\int I dt} = \frac{LI}{I}.$$

An aluminum cylinder is inserted into the pinch volume and the inductance that is obtained on that short circuit shot is shown in Fig. 28b. After the signal gets above the noise level, the short circuit inductance of 2 nH agrees with the calculated value to

Fig. 28. The inductance $L = LI/I$ with a plasma load and a short circuit are shown in a and b, respectively.

within 10 percent. However, the initial inductance in the Z-pinch shot is low by 30 to 50 percent from shot to shot, which is not well understood.

The pinch radius is computed from the change of the inductance ΔL as

$$r = r_0 / \exp \left(\frac{2\pi \Delta L}{\mu_0} \right).$$

The radius r and velocity $U = \dot{r}$ of the current sheath are shown in Figs. 29a and 29b, respectively. The radius apparently collapses to $\sim 0.3 r_0$, and the peak velocity of the sheath

Fig. 29. The current sheath radius R and sheath velocity U inferred from the inductance vs. time curve are shown in a and b, respectively.

is ~ 60 cm/ μ sec when one averages through the oscillations. The power $\dot{W}_p$ delivered to the plasma is given by

$$\dot{W}_p = \frac{1}{2} L \dot{I}^2.$$

$\dot{W}_p$ and the energy $W_p = \int_0^t \dot{W}_p dt$ are shown in Figs. 30a and 30b, respectively. The 3 kJ of plasma energy corresponds to 7 keV for each electron and ion in the initial gas. The pinch radius stopped at $0.30 r_0$ when the current was crowbarred at $I = 600$ kA. The final ion number density was, therefore, $\sim 5 \times 10^{17}/\text{cm}^3$. The ion line number density was $\sim 5 \times 10^{17}/\text{cm}$ and the temperature obtained from the Bennett relation is 1 keV at equilibrium. The piston velocity obtained from the inductance measurement is consistent with a shock velocity of > 80 cm/ μ sec and a temperature behind the reflected shock of > 1.3 keV. The energy containment times from ion loss are 66 ns and 25 ns for $T_i = 1$ keV and 7 keV, respectively. The calculated neutron yield for these extremes of T_i are 3×10^6 and 3×10^9 for $T_i = 1$ keV and 7 keV, respectively. An attempt to measure the neutron yield through 30 cm of H_2O and 100 cm of air produced no significant counts on a Ag-detector. This null result gives an approximate upper bound on the T_i of 2.5 keV. Additional work is in progress to increase the crowbarred current and to improve the diagnostics on the pinched plasma. The suitability of this plasma as a plasma simulator will then be examined.

Fig. 30. The power $\dot{W}_p$ and energy W_p delivered to the plasma are shown in a and b, respectively.

EBFA DATA ACQUISITION FACILITY

Studies to determine computer system requirements for the EBFA Data Acquisition and Control/Monitor systems indicate that a single large minicomputer should be able to handle both jobs. More detailed studies are currently being made on control system requirements to verify this. Preliminary specifications have been written to define the CPU, peripherals, and operating system requirements for the data acquisition computer system. A preliminary DOE 1830 implementation plan has also been written. The computer RFO will be released as soon as the control monitor specifications are ready.

We are currently in the preliminary stages of defining the EBFA data acquisition hardware, i.e., oscilloscopes and waveform digitizers. Some alternatives to Tektronix R7912 transient digitizers are being examined. One possible alternate digitizer is the updated version of the R7912, the 7912AD. This device is superior to its predecessor in the following respects: the main frame and plug-ins are fully programmable, and it communicates with the computer via a microprocessor-controlled IEEE 488 standard interface. The disadvantages are: (1) it costs \$6 K more than its predecessor, and (2) the programmable vertical plug-in available only has a bandwidth of 200 MHz. Tektronix is also developing a lower speed device called a 7612 transient digitizer. This is fully programmable dual channel device that can sample each channel as fast as every 5 ns. Both Sandia and Lawrence

Livermore Laboratory are developing Charge Coupled Device (CCD) transient digitizers. The CCD's are used as analog shift registers to store a waveform in real time so it can be digitized later at a slower rate. Both developmental projects have sampling rates in the 5 to 10 ns range. There are proposals for developing 1-ns sample rate CCD digitizers. The current problem areas in CCD digitizers are linearity, transfer efficiency, and CCD channel matching. We are presently pursuing the possibility of utilizing the newly developing CCD technology to obtain a multichannel, high-speed, low-amplitude resolution transient digitizer which could be used to record switch simultaneity information from EBFA. We are currently following the progress of all types of new transient digitizers described above. The decision on the initial EBFA configuration will not be made until spring of 1978.

We have examined several cable shielding options for EBFA and have tentatively decided to construct a shielded cable raceway between the bottom of the EBFA tank and the main radial I-beam supports by welding plates to the bottoms of the beams to form an RF tight enclosure. The cables would then be routed around the tank in the 8 inch space above the I-beams from the main junction box in the pit under the accelerator to the desired energy point into the tank. Based on MITE experiments we have decided to feed all diagnostic cables for the Marx banks, pulse forming lines and transmission lines through bulkhead feedthroughs in the bottom of the tank. This should result in much quieter signals and preliminary design for the main junction box in the pit has also been completed. This box will contain patch panels for jumping cables from all EBFA diagnostics to either the screen room or instrumentation trailers parked outside the building.

The EBFA diagnostic screen room will be designed by Sandia Plant Engineering. They have completed a preliminary design including specifications and drawings. The data acquisition portion of the screen room will be 15' x 65'. One end of the screen room will be isolated from the data acquisition system for use by the laser holography pellet diagnostics. The need for another shielded area for the control room is currently being evaluated. The design should be finalized and an RFQ let early in 1978. Construction will begin as soon as the building is ready for occupancy.

HYDRA, PROTO I, PROTO II - DATA ACQUISITION FACILITY

The number of R7912 transient digitizers in the data acquisition facility for Hydra, Proto I and Proto II has been increased from 15 to 29. The additional 7912 channels required extensive modifications to the applications software. The changes have been made and the new software system is operational. The number of addressable output data records on disc was increased from 80 to 120 for all three accelerators.

The capabilities of the interactive data reduction program FAWTEK have been greatly enhanced. We have included the ability to write programs in the simple FAWTEK language and then store them on disc. Users can then run these programs whenever desired. This eliminates the job of typing the same sequences of commands after every shot.

We have also added new commands to perform a number of common diode analysis functions. For instance, a single command will compute and plot corrected diode voltage, integrated B, impedance, power and energy. Other commands do signal averaging, baseline adjusts, and multiple overlay plots. Finally, we have included the ability to address signals on disc by their output header names in addition to their record numbers.

The shot archive tape software has been modified to reduce mistakes. Checks have been included to:

1. Prevent same shot from being taped twice.
2. Insure taped shot numbers are sequential.
3. Prevent reading a shot off tape onto disc over a shot that has not been taped.
4. Prevent firing a new shot before last shot has been taped.

IMAGE PROCESSING

We are currently in the midst of a project to develop a general image processing capability. A comprehensive package of image processing subroutines, LADIES, has been obtained from Los Alamos. This system is now operational on the CDC 7600 after a rather involved

process. The only facility at Sandia for displaying computer generated images is the Comtal device on the high-performance interactive graphic system. This system is interfaced to one of the CDC 6600's via a PDP-9 minicomputer. We have successfully displayed images and their Fourier transforms on the Comtal. The Comtal has two nice internal features for enhancing images. One is a pseudo-color mapping of black-white intensities into different colors on the display screen. The second is a function memory which allows interactive nonlinear intensity mappings. We are currently using this system to enhance holograms of cylindrical implosions on Hydra.

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THEORETICAL RESEARCH

OVERVIEW

The goals of the particle beam fusion program include the development of pulsed power drivers for fusion reactors and the application of these drivers in fusion target experiments. The theoretical program has continued to provide target design information for near-term experiments, including the recently reported neutron-producing magnetic targets, as well as designs for Proto II and future drivers, such as EBFA I. The traditional 1-D Lagrangian hydrocode design calculations for magnetic targets were complemented by 2-D MHD code studies of the initial fuel preheat phase using the BEMAG code developed at Sandia. Results from these computations verified the preheating of a small fraction of the fuel mass and the establishment of the magnetic field required for thermal insulation.

The baseline design for EBFA I presently employs magnetic insulation of the vacuum lines and the propagation of multiple pinched beams in neutralizing plasma channels. The beams are to be combined at a central target chamber, possibly using enhanced electron deposition in a target. Theoretical work was done to study the production and characteristics of current-carrying plasma channels in air, initiated by an exploding wire. Particle trajectory calculations were carried out to determine the efficiency of recombination of multiple beams near a target chamber. Our understanding of enhanced electron deposition in thin foils was advanced by a combined program of theoretical and experimental work on Proto I and Hydra. Hydrodynamic and diode code results were consistent with the measured deposition levels of ~ 10 TW/gm on Proto I.

Fusion reactors with standoff based on multiple beam propagation in background gases are faced with questions of target-produced shock-loading at the first wall. Hydrocode calculations of this problem have provided input data for reactor systems studies.

Theoretical studies of magnetic insulation of vacuum transmission lines were continued and compared with experiment. A new time-dependent electromagnetic particle-in-cell code was written to study the evolution of magnetic insulation in coaxial transmission lines that are longer than the electromagnetic pulse length. A good transport efficiency was predicted by the code, in agreement with experimental data for both 0.5 MV and 3.3 MV.

Our understanding of electron and ion beam production and focusing has been greatly assisted by the use of large-scale direct simulation computer codes. A newly modified code was completed to provide a complete variable zoning capability. This flexibility was combined with a new method for treating particle emission from tapered cylindrically symmetric surfaces to provide a tool for studying tapered, hollow cathodes, including "parapotential" cathodes, a Soviet design for the Angara I accelerator, and a cathode proposed for an upgrade of the Los Alamos PHERMEX machine.

FUSION TARGET PHYSICS

Single-Shell Fusion Pellets for EBFA with Electron or Ion Ablative Drivers

We are investigating ablatively-driven electron and ion-beam fusion targets for the EBFA accelerator, which has been designed¹ for multiple diodes and beam combination.

Nominal parameters used for the multi-module EBFA in the calculations are 2 MeV, 60 ns pulse length, 0.4 MJ deposited. A 6.67 TW average power is assumed since it is estimated conservatively that the peak power deposited will be about 10 TW, with a pulse rise time and fall of 20 ns.

A. Electron-Beam Targets

Figure 1 shows the optimal shell thicknesses for different outer-shell compositions with 2 MeV electron beams. A low-Z ablator (iron or carbon) is preferable because of the decreased bremsstrahlung heating of the pusher and the lower pellet cost. Electron-beam energy deposition was determined using functions² obtained from least squares fits to TIGER³ planar deposition profiles for gold over the voltage range 0.2-3 MeV, instead of performing separate least squares fits for various materials at 2 MeV beam voltage. Using the deposition profile of iron/gold or carbon/gold at 1 MeV, these gold deposition functions have been rescaled at 2 MeV to account for the broader profile and lower bremsstrahlung characteristic of energy deposition in a low-Z/high-Z composite material compared to a high-Z material. The accuracy of this procedure has been checked by comparing the least squares solution for a 0.725 MeV carbon/gold deposition profile with the profile as obtained from the rescaled gold functions. The scaled solution has the same general shape but the profile is broader and the bremsstrahlung tail is 5% higher at the csda range than in the least squares solution. Target behavior has previously been found to depend on the level of the bremsstrahlung tail, and to be independent of the precise shape of the major portion of the deposition profile.⁴

Fig. 1. Pie diagrams showing optimized shell configurations for 2 MeV electrons at EBFA power levels.

The carbon/gold shell thickness has been only roughly optimized, by assuming that the total shell or is about the same fraction of the csda range as for 1 MeV electrons³ (0.93) and that the gold/carbon mass ratio is 1/3-3/4.⁴ The carbon/gold target requires a fuel diameter of 1 cm or greater for efficient transfer of beam energy to the pusher.⁵

Figure 2 indicates the expected sharp drop in neutron yield as target diameter is increased or the symmetry requirement becomes less stringent. The compression ratio R_0/R_f , where R_0 is the initial outer shell radius and R_f is the fuel radius at maximum compression, gives a measure of the irradiation symmetry required^{6,7} ($\sim 2\%$ for $R_0/R_f = 50$, $\sim 4\%$ for $R_0/R_f = 30$). For targets with diameters exceeding about 0.8 cm, an irradiation symmetry requirement of 2-4% implies a DT fuel mass exceeding 25 μg . A longer machine pulse length would be preferable for these large-diameter electron-beam targets; implosion times are 100-350 ns for target diameters of 0.5-1.0 cm.

For the same compression ratio R_0/R_f , target diameter, and total energy deposited, Fig. 2 shows that iron-ablator targets have a yield two orders of magnitude higher than gold-shell targets. In contrast, breakeven calculations at 1 MeV and small target diameters have indicated⁶ that iron-ablator targets are

better than gold-shell targets of the same diameter only for higher compression ratios.

Fig. 2. Neutron yield versus target diameter for iron- and gold- ablator targets at EBFA power levels. Curves are for constant compression ratio R_0/R_f .

Magnetic thermoinsulation^{8,11} has not been included in these calculations; such calculations are planned and it is expected that the yield will increase significantly.

B. Ion-Beam Targets

Figure 3 shows the optimal shell thickness for an Li⁷D-shell target with 2 MeV ion beams. A low-Z material must be used for the absorption region, in spite of the reduced tamping effect of the outer part of the shell, to reduce radiation in the form of thermal x-rays⁹ and to improve tolerance to Rayleigh-Taylor instabilities.^{6,7} A range-energy relation in lithium for protons with energies less than or equal to 2 MeV, given approximately by¹⁰ $E_p = 40.7X^{0.64}$, where E_p is the proton energy in MeV and X is the range in g/cm², has been used in the calculations.

Fig. 3. Pie diagram showing optimized shell configuration for 2 MeV protons at EBFA power levels.

Figure 4 indicates the variation in neutron yield with target diameter for fixed compression ratio R_0/R_f and the variation in yield with DT fuel mass. For target diameters exceeding 1 cm, there appears to be little improvement in yield unless one goes to a larger compression ratio. An irradiation symmetry of 3-5% requires a fuel mass exceeding 50 μ g for target diameters in excess of 0.8 cm. The gain (energy produced/energy deposited) is 0.001-0.006 for these targets with 6.67 TW deposited; 50-80% of the thermonuclear yield occurs by the free-fall time. The aspect ratios for these targets (10-40) may be a problem unless an energy spread on the driving source is employed¹¹ to reduce sensitivity to fluid instabilities.

A machine pulse length of 60 ns is a closer match to the implosion time for these targets as opposed to the electron-beam targets. The 1 cm diameter targets have an implosion time of 60 ns; the 0.6 cm diameter targets have an implosion time of 30 ns.

Calculations with magnetic thermoinsulation^{8,11} are planned.

Fig. 4. (a) Neutron yield versus target diameter for EBFA ion-beam target of Fig. 3. Curves are for constant compression ratio R_p/R_f . (b) Neutron yield versus DT fuel mass. Curves are for constant target diameter.

C. Scaling to Breakeven

We assume that machine scaling to higher powers is such that the beam pulse length would be the same as for EBFA and that the pinch radius would be the same or larger than expected for EBFA.

A breakeven graphite-carbon-ablator target (cf. Fig. 1) for 2 MeV electrons has been modelled on CLYDE. The fuel diameter is 1 cm, fuel mass is 600 μg , implosion time is 67 ns, beam power is 2000 TW, 100 MJ of energy is deposited, and the compression ratio implies 3% uniformity of beam deposition and shell thickness. A gain of about ten would require 5000 TW of power. The major factor contributing to the high power requirement is target size rather than beam voltage. It seems obvious that one must look elsewhere--to magnetic thermonuclear^{8,11} or other advanced target concepts--for achievable breakeven designs.

Multiple-Shell Fusion Pellets for EBFA

We have begun an investigation of double-shell ablative targets for EBFA. The purpose of the study is (1) to determine neutron yields possible with double shells for electron-beams and ion-beams and (2) to determine some guidelines for optimization of multiple-shell targets.

Our major concentration so far has been on an electron-beam target, though a number of the guidelines we obtain should be applicable to ion-beams as well, in spite of differences in the energy deposition. The electron-beam target being studied is shown schematically in Fig. 5. Nominal EBFA parameters are the same as for the single-shell designs described elsewhere in this report. We have not used a high-melt-energy material such as tungsten for the inner shell in our initial study, in spite of the fact that the detrimental effects of bremsstrahlung preheat are reduced,¹² and we have not considered the possibility of a magnetic-thermoinsulation target.¹³ Both concepts are inappropriate for a parameter study since computer costs are increased considerably.

Fig. 5. Schematic diagram of double-shell electron-beam target under study for EBFA parameters.

All the CLYDE calculations assume a DT fuel mass of 10 μg . The buffer mass M_b , inner shell mass M_i , and buffer to inner shell thickness ratio $\Delta R_b/\Delta R_i$ are varied to maximize neutron yield, subject to the following constraints: (1) $\Delta R_b/\Delta R_i \lesssim 8$. One-dimensional (planar) analysis¹⁴ has indicated that a buffer to inner shell thickness ratio of 8 or less requires 1% uniformity of surface finish to limit the growth of instabilities. (2) $R_{DT}/\Delta R_i \lesssim 20$ for shell stability.^{15,16} (3) The ratio of the radius of the outermost shell to the final fuel radius $R_o/R_f \lesssim 50$ so that symmetry requirements are not too restrictive.

We have chosen to express our guidelines in terms of the mass ratios M_b/M_i and M_i/M_b and the thickness ratio $\Delta R_b/\Delta R_i$ since these parameters immediately characterize the fabricated design. However, a more judicious choice of parameters could provide better insight into why target performance is better in some cases. For example, the ratio of the minimum thickness of the buffer to the inner shell thickness¹⁷ may be a more relevant parameter than $\Delta R_b/\Delta R_i$. For an accelerating shell to extract the most internal energy from the buffer, the inner shell should be thin compared to the minimum gas thickness.¹⁷

Our best preliminary design to date has $M_b/M_i = 10$, $M_i/M_b = 9$, and $\Delta R_b/\Delta R_i = 7$. Neutron yield is 1.5×10^9 , $R_{DT}/\Delta R_i = 8.1$, $R_o/R_f \sim 55$.

Voltage Shaping with Electron Beam Fusion Targets

As an ablatively-driven implosion proceeds, the shell pr increases and energy is deposited further out in the ablator and is therefore used less efficiently late in time. If one increases the electron-beam voltage during the pulse,¹⁸ energy penetrates deeper into the shell late in the pulse (Fig. 6), giving better coupling into the target and faster inward acceleration of the shell. We have continued our analysis¹⁹ of voltage shaping with electron beams (the method is also applicable to ions) as a means of improving target performance. The CLYDE²⁰ computer code has been used and

we have restricted our study to targets with a simple gold shell filled with gaseous or levitated-cryogenic DT in order to reduce the number of parameters. The two questions we have addressed in the study are:

(1) Does voltage shaping increase the beam impedance needed for breakeven and gain?

(2) Does voltage shaping increase burn efficiency (the fuel burn-up fraction) and target ρr ?

Fig. 6. Schematic diagram showing variation in power deposition per mass with radial depth in an e-beam target, with and without voltage shaping.

An increase in impedance is desirable since, for a single low-impedance, large-aspect ratio diode, a substantial fraction of the total current is in ions and, even if ion flow is suppressed, pinch stability, gap closure, and radial compression impose a lower limit of 0.1-1 ohms on the impedance.¹ Multiple diode geometries²² are therefore necessary to keep the impedance Z_d of each diode high while keeping the impedance of the

combined beams (Z_p /number of diodes) small. We find that the impedance increase of a factor of 2 to 4 obtained by voltage shaping is of the same order as that obtained with simple design improvements (iron ablator,⁴ velocity multiplication,⁹ reduced deposition lengths and reduced bremsstrahlung at high currents²³). The use of voltage shaping with one of these schemes or with more complicated target concepts which allow even higher beam impedances (magnetic thermoinsulation,¹³ small central ignitor²⁴) will further reduce the number of diodes required in a multiple-diode geometry.

Figure 7 shows a typical voltage pulse shape for an electron-beam-driven target. The effectiveness of voltage shaping is quite sensitive to the time shape of the beam pulse with respect to the dynamics of the metal shell. If the voltage rise is more rapid than shown in the figure, excessive shell preheat occurs, reducing peak shell density and degrading target performance; if the voltage rises more slowly than shown, energy doesn't penetrate deeply enough and the advantage of voltage shaping is lost.

Fig. 7. Typical voltage pulse shape for an electron-beam-fusion target.

There is some possibility of independently varying voltage and current, so we have investigated two types of voltage shaping (cf. Table I). For variable-impedance

voltage shaping, the optimal shell thickness is the same as with an unshaped pulse; for constant-impedance voltage shaping the optimal shell thickness for a given initial voltage V_i is greater than for an unshaped design with constant beam voltage V_i . The choice of which type of voltage shaping to use depends on whether a lower breakeven current and the same or a lower power are desirable. Constant-impedance voltage shaping produces the greater increase in impedance, but increases the peak power and current. Variable-impedance voltage shaping produces a smaller increase in impedance but reduces the power.

Both of the advanced target concepts mentioned above (magnetic thermoinsulation and central ignitor) have the disadvantages that burn efficiency and target pr are reduced.²⁴ Figure 8 indicates that voltage shaping can increase burn efficiency and target pr at breakeven levels for a simple gold-shell target filled with gaseous or cryogenic DT. The targets--with and without voltage shaping--have higher target pr and increased burn efficiency for greater energy deposited (corresponding to higher initial voltages). At higher voltage the shell is thicker, ablation pressures are higher, and the shock wave starts further out, preventing the shock from entering the fuel and shock heating it until later in the implosion. The performance of cryogenic-DT targets is improved by voltage shaping. Proper pulse shaping delays the arrival time of the inner edge of the fuel at the target center by generating a weak initial shock at low voltage and low power.

Similar improvement in burn efficiency and target pr can be expected with the advanced targets. Such a study of magnetic-thermoinulation targets is in progress.

TABLE I
Current and Impedance Requirements with Voltage Shaping

Type of Voltage Shaping	Breakeven Current Compared to "Unshaped"	Breakeven Impedance Compared to Unshaped
1. Constant-impedance (Power $\propto$ Voltage ²)	Same	$\sim 3-4$ higher
2. Variable-impedance (Power is constant, linear, or trapezoidal function of time)	$\sim 2/3$	~ 1.5 higher

Fig. 8. Burn efficiency and maximum target pr versus the deposited energy necessary to produce breakeven with and without voltage shaping. A larger amount of energy deposited corresponds to a larger voltage and greater shell thickness.

Proto II Magnetic Targets

Calculations have been performed to project the performance of targets containing preheated fuel and magnetic fields, assuming the power absorbed in the shell is consistent with that which might be expected from Proto II (.25-4 TW absorbed). The present target preserved the shell $\langle \rho R \rangle$ of the targets successfully employed in the REHYD experiments (.3 g/cm²), but was sized to provide an implosion time consistent with the ~ 50 ns current pulse mode of Proto II. A target inside diameter of 7 mm was chosen.

For magnetic targets, the fuel density is the single most important parameter governing the convergence ratio of the implosion. A DT fuel density of ~ 10⁵ g/cm³ for the 7 mm target and a modest assumed preheat of 15 eV were found to produce substantial neutron yields (10⁹-10¹³) with moderate convergence ratios (10-15), for a variety of levels of absorbed power. The results of a series of target calculations is found in Table II. Thermal conductivity was assumed reduced by a factor of 36, to the ion conduction level for DT.

Magnetic Target Preheat Calculations

The principle of magnetic thermal insulation has been successfully employed in electron beam fusion targets. (A discussion of recent experiments is found elsewhere in this report.) Reduced thermal conduction and fuel preheat lead to much lower driver power levels than would otherwise be needed. The technique has promise not only for near term targets but also for high-gain advanced targets.¹¹ For these reasons the design of such targets are of great interest. There are two basic phases in the operation of a magnetic target. The first of these is the preheat phase, in which a discharge current is passed through the central region to heat the fuel and to establish the magnetic field required for thermal insulation. The second phase is the implosion of the target by the main beam pulse. This latter phase is usually studied using 1-D Lagrangian target design codes.

The BEMAG 2-D Eulerian MHD code, described in an earlier report,²⁵ was used to compute the fuel behavior during the preheat phase for the magnetic targets used in the recent experiments. The results for a typical gas discharge case are shown in Fig. 9. The figure plots density contours at four different times in the preheat phase. Contours for 0.25 ρ_0 and 1.0 ρ_0 , where ρ_0 is the initial fuel density, are plotted at each time. The flat horizontal electrode at the top of the target collects electrons emitted from the cathode in the prepulse phase. This in turn drives a discharge current through the fuel region to the anode, represented by the cross-hatched region at the base of the target. Since the outer shell containing the fuel is constructed of an insulating material, the current flows down the center electrode supporting the collector and then around the outside of the fuel. As the field diffuses in, the highest current density (and ohmic heating rate) is present near the electrode. This is seen in the first portion of the figure at $t = 0.2$ μ sec. By $t = 0.4$ μ sec, the ohmic heating near the electrode has resulted in a flow of hot fuel towards the center of the sphere. This in turn leads to a pile-up of cold, dense fuel at the outer surface where it contacts the insulating container. At later times the volume occupied by the hot, low density fuel increases. By $t = 0.8$ μ sec, the central region contains only about 10% of the initial fuel which does, however, have a temperature of 15-20 eV. This fractional fuel mass heating is an essential feature of the preheat phase.

In addition to heating the fuel, the prepulse current also must establish the magnetic field required for insulation. This can only happen, however, if the diffusion time of the field into the fuel is shorter than the prepulse time. That this occurs is shown clearly in Fig. 10, which plots contours of total enclosed current at $t = 0.8$ μ sec. Most of the current flows in the central fuel region and the later target implosion by the main pulse is fast enough to keep the field frozen into the fuel plasma.

TABLE II

Specific Power (TW/g)	Total Power (TW)	Yield (no. of neutrons)	Convergence Ratio (R_o/R_f)	$T_{\max}$ (eV)	$(\rho R)_{\max}$ (g/cm ²)
5	.27	4.7×10^9	10.3	740	3.3×10^{-4}
10	.53	2.8×10^{10}	11.2	980	4.0×10^{-4}
20	1.07	2.0×10^{11}	12.1	1360	4.6×10^{-4}
40	2.13	1.7×10^{12}	12.8	1930	5.0×10^{-4}
80	4.26	1.4×10^{13}	13.5	2960	5.2×10^{-4}

Fig. 9. Density contours ($0.25 \rho_0$ and $1.0 \rho_0$) at four different times in the preheat phase.**MAGNETIC FIELD PENETRATES ON PREPULSE TIME SCALE** Fig. 10. Iso-current lines at $t = 0.8 \mu\text{sec}$.

Hydrodynamics of Power-Deposition Driven Expansions

Analytical and numerical studies have been performed to model the expansion of material under the influence of continuous, in-depth deposition of power, such as power deposition by high energy particle beams (see Fig. 11). The governing hydrodynamic equations have been studied and found to reduce to a self-similar set for the two planar cases: (1) ablation from the surface of a thick wall, and (2) the expansion of a finite mass foil of negligible thickness. For each case, an ideal gas equation of state is employed and negligible initial internal energy is assumed. Self-similarity is obtained for a time dependent, spatially uniform power deposition function of the form $P = \epsilon(1 + \alpha) t^\alpha$.

The equations of continuity, momentum, energy, and state employed are:

$$\text{Continuity} \quad \frac{\partial \rho}{\partial t} + \rho \frac{\partial v}{\partial x} + v \frac{\partial \rho}{\partial x} = 0$$

$$\text{Momentum} \quad \frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} + \frac{1}{\rho} \frac{\partial p}{\partial x} = 0$$

$$\text{Energy} \quad \frac{\partial e}{\partial t} + v \frac{\partial e}{\partial x} + \frac{p}{\rho} \frac{\partial v}{\partial x} = \epsilon(1 + \alpha) t^\alpha$$

$$\text{E.O.S.} \quad \frac{p}{\rho} = (\gamma - 1) e$$

It has been found convenient to eliminate the pressure, p , in favor of density, ρ , and internal energy, e , and to normalize these parameters and the velocity, v , to the internal energy, e_0 , speed of sound, c_0 , and initial density, ρ_0 , for case 1 or mass per unit area divided by magnitude of the expansion wave position x_0 , for case 2 (see Fig. 12). The independent position variable x is also normalized to x_0 , which is obtained by integrating the speed of sound c_0 with respect to time. The normalization variables are

$$e_0 = \epsilon t^{1+\alpha} \quad \text{Energy}$$

$$c_0 = [\gamma(\gamma - 1)\epsilon]^{1/2} t^{\frac{1+\alpha}{2}} \quad \text{Speed of Sound}$$

$$x_0 = \frac{[\gamma(\gamma - 1)\epsilon]^{1/2} t^{\frac{3+\alpha}{2}}}{\frac{3}{2} + \frac{\alpha}{2}} \quad \text{Expansion Wave Position}$$

$$\rho_0 = \rho_0 \quad (\text{Case 1}) \quad \text{Density}$$

$$\rho_0 = \frac{M}{\Lambda x_0} \quad (\text{Case 2}) \quad \text{Density}$$

Case 1. Ablating Wall

Case 2. Exploding Foil

Fig. 11. Energy deposition from particle beam into a thick wall (Case 1) or thin foil (Case 2).

Fig. 12. Expansion wave from an ablating thick wall.

The normalized, self-similar variables are

$$\xi = \frac{x}{x_0},$$

$$V = \frac{v}{c_0},$$

$$E = \frac{e}{e_0},$$

$$R = \frac{p}{p_0}.$$

The self-similar equations are

Energy

$$\beta E - \xi \frac{dE}{d\xi} + V \frac{dE}{d\xi} + (\gamma - 1) E \frac{dV}{d\xi} = \beta$$

Momentum

$$\frac{\beta}{2} V - \xi \frac{dV}{d\xi} + V \frac{dV}{d\xi} + \frac{1}{\gamma} \frac{dE}{d\xi} - \frac{1}{\gamma} \frac{E}{R} \frac{dR}{d\xi} = 0$$

Continuity

$$(V - \xi) \frac{dR}{d\xi} + R \frac{dV}{d\xi} = 0 \quad \text{Case 1 (wall)}$$

or

$$\frac{d}{d\xi} [R(V - \xi)] = 0 \quad \text{Case 2 (foil)}$$

with boundary conditions for Case 1

$$V(-1) = 0$$

$$E(-1) = 1$$

$$R(-1) = 1$$

and for Case 2

$$V(0) = 0$$

$$\int_{-\infty}^{\infty} R(\xi) d\xi = 1$$

where

$$\beta = \frac{2(1 + \alpha)}{3 + \alpha}$$

The solution for Case 2 is

$$V = \xi$$

$$E = \frac{\beta}{\beta + (\gamma - 1)}$$

$$R = \sqrt{\frac{\beta \gamma}{4\pi}} \exp\left(\frac{\beta \gamma \xi^2}{4}\right),$$

for which plots are shown in Fig. 13.

Fig. 13. Solution for exploding foil expansion.

In terms of dimensional variables, the solution for Case 2, the exploding foil, is

$$v = \left(\frac{3}{2 + \alpha} \right) \frac{x}{t},$$

$$e = \frac{\varepsilon t (1 + \alpha)}{1 + \left(\frac{\gamma + 1}{\beta} \right)},$$

and

$$\rho = \frac{m}{A} \sqrt{\frac{(1 + \alpha)(3 + \alpha)}{8\pi(\gamma - 1) \varepsilon t^{(3 + \alpha)}}}$$

$$\exp \left[- \frac{(1 + \alpha)(3 + \alpha) x^2}{8(\gamma - 1) \varepsilon t^{(3 + \alpha)}} \right]$$

An asymptotic solution of the Case 1 equations, for large values of ξ , is

$$V \sim \frac{\xi}{2} + \sqrt{\left(\frac{\xi}{2}\right)^2 + L},$$

$$E \sim \frac{\beta \left(1 + \frac{L}{\xi^2}\right)}{\beta \left(1 + \frac{L}{\xi^2}\right) + (\gamma - 1)},$$

and

$$R \sim R_r \exp \left[-\frac{\xi \sqrt{\xi^2 + 4L} + \xi^2}{4L} \right],$$

where

$$L = \frac{\gamma}{\gamma(\gamma - 1) + \beta\gamma}.$$

The full solution for Case 1 is shown in Fig. 14, which is obtained numerically.

Fig. 14. Solution for ablating wall expansion.

An interesting feature of the power driven expansions studied here is the unbounded domain of the solution, which results from the assumption of uniform power deposition per unit mass and the continuum formulation. This compares with the bounded domain of the adiabatic expansion solution for which the driving energy is the non-zero initial energy of the material. Numerically, using Lagrangian hydrodynamic codes, the unbounded solution for power driven expansions is manifested in an ever-

increasing leading edge velocity as a function of increasingly fine zoning of the leading edge. In real flows, when the collision time, τ , exceeds the time scale t in the far blowoff region, the continuum formulation of hydrodynamics breaks down and a kinetic theory approach is appropriate.

Another significant feature of these solutions is the nearly uniform temperature implied by $E \rightarrow \text{const}$ for large ξ . This suggests that even at high temperatures, conduction energy transport will be small, because of small temperature gradients. Finally, it is noteworthy that for $t < \tau_{1/2}$ the Case 1 solution applies to finite thickness foils, where $\tau_{1/2}$ is the time for the expansion wave to reach the center of the foil, from each surface. For $t \gg \tau_{1/2}$, the Case 2 solution applies.

REACTOR AND STANDOFF RESEARCH

Plasma Channels for REB Propagation

The propagation of multiple pinched electron beams^{1,26} to a target chamber has many attractive features, including a standoff capability for a reactor and reduced pulsed power requirements compared with ultra-high-current single or double diode configurations. A summary of recent work in this area is described elsewhere in this report. A key element of the propagation scheme is the formation of a long uniform plasma channel to neutralize the space charge and current of the injected beam. This plasma channel also carries an externally supplied discharge current to confine the beam electrons to the channel.

Present experiments have used an exploding tungsten wire to initiate a capacitor bank driven air discharge. It is felt that the exact mechanism for initiation of the discharge is unimportant, so that a laser preionization could be used for a reactor based on beam propagation. We have constructed a 1-D MHD code to study the evolution of the discharge. These code computations have been used to provide a comparison with density and temperature measurements of the channel,

as well as providing a design tool for Proto II and EBFA scale experiments.

The code, entitled CHART-B, combines a 1-D Lagrangian hydrocode (with radiation diffusion) with a magnetic field solver. The hydrocode is described in the aforementioned summary contained elsewhere in this report. The most recent modification of the code is the incorporation of a circuit equation to describe the electrical coupling of the channel and the capacitor bank. The peak channel currents computed compare with the measured values to about 10-20%. In addition, the treatment of the electrical conductivity has been improved by incorporating theoretical data published by Viegas and Peng²⁷ for the conductivity of air at low temperatures ($2000^\circ\text{K} \leq T \leq 20000^\circ\text{K}$).

REB Combination

The general problem of REB overlap is to determine a plasma and field geometry which achieves efficient beam superposition at a target and is consistent with target requirements. As a first step, we have analyzed a single, simple case and have neglected specific target requirements.

Of the many possible channel transport and overlap schemes, the one considered consists of 40 uniform current-carrying channels (radii r_c) arranged circumferentially around the target with return current channels forming the axle of a wagonwheel configuration.²⁸ Figure 15 shows one concept of how such a wire configuration would fit in the front end of a multi-beam accelerator. For a given plasma channel radius, r_c , the converging channels begin to overlap at a radial distance R_0 from the center of the configuration. The plasma current along a beam channel is assumed to be constant in as far as the channel overlap radius (R_0), where it linearly decays over a specified distance as the individual currents merge into a disk current. A channel current of 20 kA was chosen for 1 MeV electrons to provide good containment of the beam, while remaining below the Alfvén-Lawson critical current of about 50 kA. The two axial return current channels are assumed to have expanded to twice the radius of the beam channels.

In this study, an injected electron distribution was sampled by varying the initial phase space coordinates, calculating the 3-D trajectories, and recording the distance of closest approach to the center of the configuration ($r = 0, z = 0$). Note that the assumption of current neutralization implies that the electron trajectories are noninteracting and therefore simple superposition occurs in the beam overlap region. Scattering and electric fields are assumed negligible and symmetry of target irradiation is not evaluated.

The variation in the distance of closest approach to the center of the configuration ($R_{\min}$) attained for different injection conditions is shown in Figure 16. The results of Figure 16, when weighted with a realistic, non-hollow, injected beam distribution should actually produce better beam concentration than apparent in the figure. In Figure 16a, 1 MeV electrons were injected at the channel radius (r_c) with a velocity nearly parallel to the channel axis. The electrons execute betatron oscillations approximately in the injection plane of the channel. Inside the channel overlap region there is cylindrical symmetry, so that when the injection plane is aligned with the x-y plane ($\alpha = 0$), all of the betatron oscillation can go into angular momentum (p_θ) in the overlap region. However, for $\alpha = 90^\circ$, none of the betatron motion appears in p_θ when the electron passes into the overlap region. Figure 16b shows the result of varying the amplitude of the betatron oscillation for an intermediate injection plane angle ($\alpha = 45^\circ$). In Figure 16c, the axial variation of the electron distribution is obtained by moving the injection point ($r = r_c, \alpha = 45^\circ$) along the channel for a betatron cycle. In Figure 16d, electrons are injected at the channel edge with an increasing non-axial velocity component.

From these results, it appears that most of the injected electrons from a realistic beam can get inside a radius roughly one-quarter of the channel overlap radius at the hub of the configuration, regardless of the length of the channels. An estimate of the beam concentration (current density gain G) in these calculations is obtained by comparing the net current density crossing the cylindrical region of radius $R_{\min}$ and height $2r_c$ with the current

density in a single channel:

$$G = j_{\text{net}}/j_c = 10 r_c/R_{\text{min}} \approx 5.$$

This result depends sensitively on the actual plasma current configuration near the center of the system. We should note that the channel studies reported here have not been optimized, and higher gains may be obtained by reducing the overlap radius using different channel configurations and/or smaller channels.

Fig. 15. Concept for multi-beam front end for EBFA.

Fig. 16. Summary of point-of-closest-approach results from 40 beam calculation.

Electron Deposition in Thin Targets

Recent interest in electron deposition has centered on enhancement of collisional deposition resulting from particle dynamics in strong self beam and/or diode macroscopic fields. The increase in deposited power per unit mass is simply the result of an increased path length in a given amount of material which can be caused by electrostatic reflexing^{2,3} or by magnetic beam stagnation²⁹⁻³⁰ or diffusion.³¹

In general, electron deposition can be described as

$$P_M = \int_0^{\epsilon_{MAX}} e f(\epsilon) \beta c S(\epsilon) d\epsilon, \quad (1)$$

where P_M = deposited power/mass (w/gm), $e = 1.6 \times 10^{-19}$ col, $f(\epsilon)$ = electron density/energy (cm^{-3} Volt⁻¹), βc = electron speed (cm/sec), and $S(\epsilon)$ = stopping power (Volt/gm/cm²). The beam density n_b is given as

$$n_b = \int_0^{\epsilon_{MAX}} f(\epsilon) d\epsilon. \quad (2)$$

For a monoenergetic beam $P_M = e n_b \beta c S(\epsilon_0)$. In the energy range of interest 1-10 MeV, $\beta \approx 1$ and $S \approx 10^6$ Volts/gm/cm² and depends weakly on material. Therefore to increase P_M the beam density must increase. If we reference P_M to a cold, normally incident beam with current density J (amps/cm²), then an enhancement factor χ can be defined as $\chi \equiv n_b e \beta c J^{-1} = \beta/\beta_N$, where $\beta_N = \langle V_N \rangle / c$ and $\langle V_N \rangle$ = average normal velocity. One can further relate the normal drift velocity due to curvature and grad B drifts, assuming $B \propto r$ or $B \propto r^{-1}$, such that $\chi \approx I/I_A$, where I is the enclosed current and $I_A = 17000$ Gy. This enhancement results from magnetic stagnation for large v/γ beams since the beam density increases as the beam drift velocity becomes small.

The computational models used for studying enhanced deposition include both (1) Monte Carlo models and (2) diode codes. Versions of the Monte Carlo models are (A) collisions only, (B) collisions with non-self-consistent E and B fields, and (C) collisions with self-consistent B fields.⁴ The Monte Carlo model is useful

for studying magnetically enhanced deposition in targets of arbitrary thickness. The diode code can predict deposition (A) in the limit of negligible beam target interaction or (B) with a simplified scattering and energy loss model. This model contains self-consistent E and B fields and is useful for computing deposition in very thin foils in realistic diode geometries.

Theoretical predictions of deposition for the Hydra experiment are shown in Fig. 17. Plotted is specific power deposited in the focal volume vs. I_p = current enclosed within pinch radius r_p . The focal volume is the region in the foil with $r < r_p$ and r_p is 1/2 of the FWHM of the current density profile. The voltage is 1 MeV, $r_p = .15$ cm, and the foil is a 6 μm thick, planar Au foil. The upper two curves are Monte Carlo code predictions with non-self-consistent E and B fields for either isotropic or normal incidence to the foil. A gaussian J and n_b profile, truncated at $r = r_p$, is assumed with $E = 10^6$ v/cm in front of the foil and $E = 0$ behind the foil. It is also assumed that B penetrates the foil. Note the increase in P_M as I_p increases for $I_p > I_A = 47.4$ kA, reflecting deposition enhancement. Also shown are analytic estimates obtained from $P_M = e n_b \beta c S$ for charge neutralized Hammer-Rostoker³³ equilibrium beam and for a Bennett equilibrium beam. For these estimates one obtains n_b from the equilibrium beam conditions with the remaining parameters fixed by the beam voltage. It is seen then that enhanced beam density is implicit to high current beam equilibria and that deposition estimates are somewhat reduced from the non-self-consistent Monte Carlo calculations. For these estimates it is assumed that the beam equilibria is not significantly modified by the interaction with the foil. The variation in the upper four curves is thought to qualitatively represent the theoretical uncertainty due to uncertainty in the source beam. The lower line represents the reference deposition level of a cold, paraxial beam.

Examples of solutions using the Monte Carlo model with self-consistent magnetic forces are shown in Fig. 18. A Hammer-Rostoker beam with charge neutralization is injected from the

left boundary and propagated into a foil as shown. Plotted are a few representative particle trajectories for a beam with energy 1 MeV, radius = .15 cm and total current = 94.8 kA ($v/\gamma = 2$). The case on the left is for gold foil of areal density $1.93 \times 10^{-3} \text{ gm/cm}^2$ expanded to .01 cm. The dot density plotted within the foil is proportional to the local P_M . For this very thin case the beam is not significantly perturbed by the foil and uniform deposition of $\sim 4 \text{ TW/gm}$ is calculated within the beam radius, which is consistent with that given by the unperturbed beam density and particle energy. The example on the right is similar except that a foil with areal density of $1.93 \times 10^{-2} \text{ gm/cm}^2$ is assumed. For this case, scattering is more pronounced and there is some reduction in P_M near the beam axis which results. The deposition averaged over the focal volume is $\sim 3.2 \text{ TW/gm}$ which represents only a 20% reduction of the unperturbed beam case. Since these parameters approximate the conditions of the Hydra experiment, we would not expect substantial reductions in P_M due to modifications in B due to scattering in the foil.

Examples of diode code calculations for the Hydra parameters are shown in Fig. 19. Figure 19a shows a diode configuration with a planar hollow cathode. The anode consists of an absorbing boundary at 720 kV which approximates a carbon anode in the experiment. A typical electron trajectory is shown. The diode code predicts a pinch with FWHM ≈ 1.5 -2 mm which approximates the experiment although the current density was ~ 2 -4 x higher than in the deposition experiment. Figure 19b shows a similar diode except that a thin 6 μm Au foil, backed by vacuum, is located near the axis. This configuration is similar to the thin foil deposition experiment. Note that this model indicates an increase in beam density on axis for the thin foil case. The deposition level inferred from the peak beam density is $\sim 6 \text{ TW/gm}$ which is qualitatively in agreement with the Monte Carlo calculation for pinch radius of .15 cm and pinch current of 100 kA.

Comparisons between calculations and experiments were also made. A planar anode foil experiment was performed with a tapered (10°) hollow cathode o.d. 7.6 cm and i.d. 3.56 cm was used with a thick carbon anode (.635 cm) with a hole of 2.54 cm dia. in the center. Various foils were then mounted over the anode hole in the plane of the anode. There was vacuum on both sides of the foil. Surface temperature of the rear surface of the foil was measured using x-ray diodes, optical diodes, and spectroscopy. The beam was also diagnosed using time-integrated x-ray pinhole photography and a collimated PIN detector.

Fig. 17. Theoretical predictions for Hydra experiments.

Fig. 18. Beam-foil interaction with $v/\gamma = 2$ using Monte Carlo model with self-consistent B fields. Beam with Hammer-Rostoker equilibrium injected from left.

Fig. 19. Diode code solutions for Hydra diode.

Figure 20 shows results of this experiment and is a plot of temperature vs. time for shot #5706 for which a 6 μm Au foil was used. Calculated solutions (---) as well as experimental data using XRD measurements (—) and optical diode measurements (—) are shown. The calculated solutions are obtained using the CHARTD code³⁴ with planar geometry which assumes the foil is optically thick. The deposited power/mass is constant in time and space at the level indicated. The hydrodynamic calculations indicate a temperature profile which is peaked at the center of the foil and which decreases to some plateau near the outer portion of the blow-off. Both the optical and soft x-ray depth are such that temperatures in the plateau region are measured and both diagnostics should measure essentially the same temperature. The XRD data corresponds to spatially averaged black body temperature associated with the hot focal region of the beam. The associated error bars correspond to uncertainties in sensitivity of the detector and the source area. The optical diode data results from an absolutely calibrated photo diode. Spectroscopy was also employed to insure that strong line radiation was not emitted in the range observed by the photo diode. Both measurements are consistent and indicate $P_M \sim 1 \text{ TW/gm}$. The data here are typical of many shots for which temperatures $\leq 5 \text{ eV}$ were measured.

If we take the most optimistic values for current density and pinch radius as that given by x-ray pinhole data for a thick carbon anode, then the peak J is only 600 kA/cm^2 and the pinch current $I_p = 45 \text{ kA}$. This implies deposition levels of about 1 TW/gm (see Fig. 17) which indicates little enhancement and which is consistent with experimental measurements.

Another series of experiments was performed on the Proto I accelerator. The diode physics are different than that of Hydra since a much smaller cathode ($\sim 2.5 \text{ cm}$ diameter) is used in a plasma filled diode. A much tighter pinch is produced with higher J and with a large fraction of the total current enclosed. X-ray pinhole photography indicates that a single beam incident on a thick carbon anode produces peak J $\approx 5 \text{ MA/cm}^2$

with $\text{FWHM} \approx .16-.2 \text{ cm}$. For these conditions we would expect $P_M \approx 10 \text{ TW/gm}$ from previously discussed theoretical models.

Fig. 20. Temperature vs. time for Hydra experiment.

Results of surface temperature measurements and hydrodynamic calculations are shown in Fig. 21. Plotted is temperature vs. time for (A) a 6 μm Al foil and (B) a 6 μm Au foil. For the calculations, the CHARTD code was used with planar geometry and the temperature obtained at a depth of 10^{-4} gm/cm^2 from the front surface corresponding to the maximum depth observed by the soft x-ray temperature measurements. The deposition was assumed uniform in space and constant in time with $t = 0$ corresponding to pinch formation time. Radiation losses were assumed negligible. Note that calculations predict that for a given deposition level a higher temperature is produced in the gold foil than for the aluminum foil which is a result of greater foil inertia, and less expansion cooling, for the gold.

Fig. 21. Temperature vs. time for Proto I experiment.

Also shown are surface temperature measurements obtained from x-ray diodes for the respective foils using a single side of Proto I. Time = 0 corresponds to the pinch formation time. Again uncertainties in the emission area lead to uncertainties in the measured temperature. The Al foil data, however, is pessimistic in that the entire apertured area is assumed to determine the lower temperature bound. For the Au foil, x-ray pinhole photography and PIN detectors were used to estimate the emission area. From this data we conclude $P_M \approx 4-6$ TW/gm for a $6 \mu\text{m}$ Au foil and $P_M \approx 8-16$ TW/gm for the $6 \mu\text{m}$ Al foil.

Diode code calculations for the above conditions indicate that scattering in the gold foil tends to reduce the deposition over that of a $6 \mu\text{m}$ Al foil where scattering is negligible. We feel this and differences in ion diode current due to the ion mass may explain the differences in deposition levels between Al and Au.

Preliminary Studies of Blast Loading at the First Wall of an Electron Beam Reactor Chamber

Estimates of the blast wave pressure at the first wall of a gas-filled electron-beam reactor chamber have been determined from the CHARTD³⁴ code, using the Lockheed tables³⁵ for the radiative properties of air, and analytic point source solutions for a spherical blast wave. Such a model has previously been used to study atmospheric weapon effects³⁶⁻³⁷ (i.e., fireball growth and shock propagation from nuclear explosions), which is analogous to the problem studied here. The pressure pulse at the first wall was obtained as a function of the energy from the pellet implosion, the ambient air pressure in the chamber, and the chamber radius. The energy from the pellet implosion is the energy deposited in the pellet plus the energy in the DT fuel and in x-rays after thermonuclear burn; neutrons will not contribute to the growth of the blast wave.

Calculations were done on CHARTD for two hypothetical pellet implosions, with 1 atmosphere chamber fill pressure, using the energy partition of M. J. Clauser's³⁸ 2.4 mm diameter gold/DT electron-beam pellet. Characteristics of the energy in these two pellet implosions are given in Table III, based on CLYDE calculations for Au/DT³⁸ and Fe/Au/DT⁴ ablative pellets. At the onset of a CHARTD calculation, energy is deposited on the pellet to simulate the energy deposition; at the implosion time 1/5-1/4 of the thermonuclear energy produced is deposited in the fuel to simulate the results of the burn.

Figure 22 shows the growth of the fireball and the blast wave for Pellet #1. Rapid radiative growth of the fireball occurs on a time scale of 10 ns due to beam deposition. The fireball sits at about 10 cm until debris expansion from the pellet implosion reaches the fireball at about 1 μsec and the fireball begins to "shock up" and grow by compressing and doing work on the surrounding air.

We conclude that for these pellets, the reactor chamber radius will be determined by the neutron flux because the reflected shock overpressure from the pellet debris decays rapidly with distance and is << 100 atmospheres at 2 meters for pellet gains of interest (≤ 50). The peak value of the reflected shock overpressure with 1 atmo chamber fill pressure P_0 is about 144 atmo at 1 m, 12 atmo at 2 m, and 1.8 atmo at 4 m for Pellet #1; for Pellet #2, it is 137 atmo at 1 m, 22.5 atmo at 2 m, 2.6 atmo at 4 m. Figure 23 shows shock overpressure ΔP and time elapsed since energy deposition in the pellet began versus reactor chamber radius for Pellet #2. Reflected overpressure ΔP_r is obtained from ΔP using the Rankine-Hugoniot equation,

$$\Delta P_r = 2 \Delta P + \frac{(\gamma+1) \Delta P^2}{2\gamma P_0 + (\gamma-1) \Delta P}$$

TABLE III
Energy of Fictionalized Pellets

Pellet #	Energy Deposited (MJ)	Thermonuclear Energy Released (MJ)	Energy in Ions and X-Rays		Energy in Neutrons	
			(MJ)	(%)	(MJ)	(%)
1	4	40	8	20	32	80
2	3	60	15	25	45	75

Fig. 22. Growth of fireball and blast wave with time since the pellet implosion for Pellet #1 (cf. Table III).

Fig. 23. Shock overpressure and time elapsed since the pellet implosion versus reactor chamber radius for Pellet #2 (cf. Table III).

At increasing distance from a finite but sudden source of energy, the resulting blast wave appears more and more like that of a point source. Equations for the point source spherical blast wave are 36, 39-40

Shock overpressure ΔP :

$$(1) \quad \Delta P/P_o = \frac{2\gamma}{\gamma+1} \left[\frac{4}{25} X^{-3} \right] \text{ for } \Delta P/P_o \geq 10$$

$$(2) \quad \Delta P/P_o = \frac{2\gamma}{\gamma+1} [0.14 X^{-3} + 0.115 X^{-2} + 0.244 X^{-1} - 0.016] \text{ for } 0.1 \leq \Delta P/P_o \leq 10$$

time:

$$(3) \quad t = R_o/C_o X^{5/2} \text{ for } \Delta P/P_o \geq 10$$

$$(4) \quad t = 0.543 R_o/C_o [(1 + 4.61 X^{5/2})^{2/5} - 1] \text{ for } 0.1 \leq \Delta P/P_o < 10$$

where $X = R/R_o$

$$(5) \quad R_c = 211.97 \left[\frac{25}{4B\gamma} \frac{E_o}{P_o} \right]^{1/3} \text{ cm}$$

$B = 5.33$ for $\gamma = 1.4$

E_o = energy, in MJ, deposited in pellet plus energy in ions and x-rays

P_o = ambient air pressure in atmospheres

C_o = sound speed

The dashed lines on Fig. 23 indicate the point source solution obtained by matching the CHARTD solution to the point source equations at a pressure of about 15 atmospheres, using $\gamma = 1.4$, the value for room temperature air. Such an adiabatic γ of 1.4 gives a reasonable fit to the CHARTD results. For Pellet #2, R_o from CHARTD calculations is 524.6 cm; from equation (5) using $\gamma = 1.4$, it is 523.6 cm.

From the point source solutions we can obtain estimates of how the shock overpressure varies as a function of E_o , reactor chamber radius R_c , and fill gas pressure in the chamber P_o . These results are tabulated in Tables IV and V.

TABLE IV

Shock Overpressure as a Function of Reactor Radius R_c and Energy E_o

$$P_o = 1 \text{ atm}$$

$$\gamma = 1.4$$

$E_o \backslash R_c$	1 m	2 m	4 m	5 m
5 MJ	9	2	0.4	0.3
10 MJ	15	3	0.6	0.5
20 MJ	30	5	1	0.7
40 MJ		9	2	1
100 MJ		19	3	2

TABLE V

Shock Overpressure as a Function of Reactor Radius R_c and Fill Pressure P_o

$$E_o = 20 \text{ MJ}$$

$$\gamma = 1.4$$

$P_o \backslash R_c$	1 m	2 m	4 m	5 m
0.1		4	0.6	0.3
0.2		4	0.7	0.4
0.5		5	0.8	0.5
1	30	5	1	0.7
2	30	6	1	1
5	37	7	2	1
10	42	9	3	2

The impulse of the blast wave can be a significant parameter in predicting damage to the chamber wall. For Pellet #2, the pressure pulse duration is estimated to be 0.1-1 millisecond for pressure loading at a fixed point. This estimate is made by using the pressure pulse width (FWHM) at a given time and dividing by the shock velocity.

Work is in progress to extend the CHARTD shock calculation to study shock interaction with a 1 cm steel wall at 4 m. The purpose of such a calculation is to determine what the dynamic stresses on the wall are as a result of the ion and x-ray fluences and to determine whether radiative transport to the wall can be recovered by wall heating.

POWER FLOW THEORY AND DIODE PHYSICS

Magnetic Insulation of Vacuum Transmission Lines

The use of magnetic insulation by means of the self-magnetic field of the line current in vacuum transmission lines continues to be a vital technique for power flow development. There are two important cases which should be distinguished. There is first the "short pulse" case when the pulse duration or its risetime is short compared to the transit time from the input of the line to the load, and we are interested in the propagation of the pulse before it reaches the load. Secondly, there is the "short line" case in which the time scale for voltage changes is long compared to the propagation time, so that we can treat the load and line as being held at a fixed voltage. It is important to make this distinction, because in the crucial transition zone between the region in which electrons can cross the gap and the region in which they are trapped near the cathode the orbits of the electrons could be quite different; in the short pulse problem they experience dB/dt and dd/dt effects which are unimportant in the long pulse problem.

Magnetic Insulation of Vacuum Transmission Lines - The Short Line Problem

A comparative analysis has been made of a number of theoretical predictions for the self-limiting current and of experiments of Shope and Toepfer on Hydra,⁴¹ and of VanDevender on Hermes.⁴² Five different theoretical models were studied and compared with the data. They are tabulated in Table VI. One of them was the single particle model which neglects

the effects of space charge on the fields. Three others were based on the parapotential model of Ref. 43, and a fourth was based on the steady state model of Ref. 44. The parapotential model predicts different values of the line impedance Z_s depending on what voltage, V_m , is specified at the edge of the electron sheath. Defining $\gamma = 1 + eV/mc^2$,

$$Z_s/Z_0 = (\gamma_0 - 1) \left(\gamma \left\{ \ln[\gamma_m + (\gamma_m^2 - 1)^{1/2}] + \frac{\gamma_0 - \gamma_m}{1/2} \right\} \right)^{-1}, \quad (1)$$

where Z_0 is the free space line impedance.

These predictions are plotted in Figures 24a and 24b. As can be seen, the "saturated" theories (2 and 3) describe the data fairly well for voltages less than .9 MV, but at higher voltages, the "boundary current" theory (#4), proposed by McDaniel,⁴² is the most successful, although the minimum parapotential current theory (#5) is roughly correct. Also shown in Figures 24a and 24b (circles) are the results of computer simulations using a PIC code in coaxial geometry which was developed specifically for this problem. As can be seen, the agreement between the simulations and curve #4 and the data is quite good.

The success of the nonsaturated theories leads us to suspect that a much smaller portion of the current is carried in space charge close to the anode than the saturated theories would suggest. The computer simulations also support this conclusion. This is considered an advantage from the point of view of transport efficiency because there is less likelihood in most configurations of large losses occurring in the transition region between the line and the load.

TABLE VI
Theoretical Predictions for Self-Limiting Current

CURVE	MODEL	SELF-LIMITING IMPEDANCE
1	Single Particle (Non Self-Consistent)	$Z_s = Z_o \left(\frac{\gamma_o - 1}{\gamma_o + 1} \right)^{1/2}$
2	Saturated Parapotential	Eq. (1) with $\gamma_m = \gamma_o$
3	Saturated ⁴⁴ Steady State (Self-Consistent)	$Z_s^{SS} = Z_s^{PP} (F/G)$ (See Reference 45 for values of F/G)
4	Boundary Current	Eq. (1) with $\gamma_m = Z_o/Z$
5	Minimum Parapotential	Eq. (1) with $\frac{\partial I}{\partial \gamma_m} = 0$

Fig. 24. Self-limiting impedance of coaxial line. Solid curves are theoretical predictions identified in Table VI. Circles are computer simulations. (a) Data is from Hermes, operating with a 139 Ω (geometrical impedance) coax; (b) data is from Hydra with a nominal 11 Ω impedance. Triangles are for a curved coax.

Magnetic Insulation of Vacuum Transmission Lines - The Short Pulse Problem

We now consider the problem when the line length L is longer than the pulse length ($L > cr$, where τ is pulse time). A schematic of the problem is shown in Fig. 25. A voltage pulse $V(t)$ enters a coax at $z = 0$. The inner boundary ($r = a$) is assumed capable of emitting space charge limited electrons. The problem is to calculate $V(z,t)$ for $z > 0$. Cylindrical symmetry is assumed.

Fig. 25. Schematic of coax line problem. A = anode, K = cathode.

Our first approach to this problem was to use the equivalent circuit code SCEPTR, ⁴⁶ by using nonlinear circuit elements, one can model many of the qualitative features which have been observed in experiments, such as pulse front sharpening and erosion. In our second approach, a fully time-dependent electromagnetic field solver was written and tested (by comparing with analytic solutions for simple problems), and a nonlinear conductivity (including magnetic cutoff) was included. Results were compared with those obtained using SCEPTR, and excellent agreement was found. We thus proceeded to include a cool fluid model, in which charge and current densities are determined from

the potentials via conservation laws. Although this yielded some interesting results, the model soon became so complex that we turned to our final and most general approach, a 2-D, time dependent, particle-in-cell code which allows us to study the details of the electron behavior. The electron emission is handled using a Gauss' law technique valid for time-dependent fields, ^{47,48} All results given below in this section were obtained with this particle simulation code.

To illustrate the results, we consider the case $L = 5$ m, $a = 6.35$ cm, $b = 10.58$ cm, and a pulse which rises linearly in 4 ns to $V_0 = 5$ MV, remains constant at 5 MV for 7 ns, then falls linearly to zero in 4 ns. The solution at $t = 15$ ns is shown in Fig. 26. $V(z)$ at this time is plotted with the beam envelope curve (E) to show that the leakage current (40 kA here) flows only in a narrow region at the pulse front. The average electron energy reaching $r = b$ is 1.5 MeV (not 5 MeV). It is also important to note that the electrons in the "cutoff" region behind the front do not turn near the anode; they are confined to a sheath which is relatively close to the cathode. This may account for the absence of leakage behind the front region and has beneficial implications for transport efficiency through regions of nonuniform electrode structure (e.g., the diode-transmission line interface region). Another feature of this solution is that the front of the pulse sharpens as the pulse propagates; at $t = 0$ the 10-90 risetime is 3.2 ns, while at $t = 15$ ns, it is 1.5 ns. In addition, it is found that the front propagates at a velocity less than c , while the pulse rear propagates at c . This front erosion, as well as the front sharpening, were also observed in experiments ^{49,50} and in the equivalent circuit analysis. ⁴⁶

We have also studied the case where electron emission is delayed until a threshold E_r is reached at the cathode. For the case shown in Fig. 27, this threshold was .7 MV/cm. The resulting behavior is similar to the above except that the high voltage part of the pulse is eroded more rapidly at first, and a precursor pulse moves at c ahead of the main pulse, as shown in the figure.

This behavior is, again, qualitatively similar to the experimental and circuit analysis results.

Fig. 26. Simulation results at $t = 15$ ns for a 5 MV pulse propagating down a 5 m line with $Z_0 = 31 \Omega$. E is the envelope of particle trajectories of which three are shown.

Fig. 27. Voltage V vs. z , showing effect of delaying emission until $E_r(K) > E_c$.

Results for a number of runs are summarized in Table VII. Several interesting features are evident. First, it appears that I_T and I_B scale quite closely with Z_0 at fixed V_0 , whereas there seems to be a different dependence of I_L , the conduction current which actually leaks to the anode, on line parameters. There may also be a weak dependence of the front velocity, $v_f = c\beta_f$, on the dimensions of the line (compare runs 4, 5, and 6). The proportion of leakage current total current is seen to decrease dramatically with increasing voltage. This is in accord with the approach of β_f to 1 as voltage increases because energy transport efficiency becomes very good as v_f approaches c , so losses must decrease. The transport efficiency (as defined in Eq. 9 of Ref. 46) for the 11 nsec pulse after 3 meters ranged from 66% at 1 MV to 96% at 10 MV.

It is interesting to compare these results with the parapotential theory of Ref. 45 for I_T , defined by $I_T = V_0/Z_S$ with Z_S given in Eq. (1). The flow pattern of Fig. 26 suggests that $V_m = V_0$ ("saturated parapotential theory") would not be appropriate, so we need a prescription for the choice of V_m . Since we have I_B , we can use another result from the parapotential theory, $V_m = I_T/I_B$, to determine if these results are consistent with it. As seen in Table VII, the agreement between I_B calculated in this way and I_T is remarkably good, especially in view of the fact that the electron orbits are known to be quite different from those assumed in the parapotential theory. It should also be noted that the simulation results are within 10% of the minimum parapotential current, I_{min} , discussed in Ref. 45.

* Fig. 28, two of the quantities from Table VII are plotted against voltage and compared with the function $((V_0 - 1)/(V_0 + 1))^{1/2}$. If space charge is neglected, one obtains this expression, both for Z/Z_0 , and as presented in Ref. 50, for β_f . One would expect these to be correct at low voltages, but it is very interesting that the agreement for β_f is also quite good at high voltages. Also shown are two experimental points for β_f , which are in good agreement with the simulations. On the other hand, Z/Z_0 appears to reach a plateau below the solid line in a manner similar to

that which has been observed in short coax (steady state) experiments and simulations.⁵¹

The particle code was also used to simulate a coaxial line with the same geometric impedance as the triplate line in the present MITE experiments. The results of this work are discussed elsewhere in this report.

Double Sheaths in Plasmas

Under certain circumstances a plasma may respond to an applied electric field by forming a narrow, non-neutral region in the body of the plasma across which essentially the entire potential drop occurs. These structures are referred to as double layers or double sheaths. They are of current interest for several reasons; they may play a role in electron emission processes from sharp points and edges,⁵² in plasma-filled diodes, and in the FOSIL fast-opening switch concept.⁴²

Using analytic models, several features of double sheaths have been investigated. One of the most important questions is under what circumstances double sheaths will form. We have obtained a simple expression for the critical density which marks the transition from double sheath behavior to a turbulent discharge (in which the field is essentially constant across the plasma). We have also obtained an expression for the maximum plasma density for which the plasma is unstable to the growth of density perturbations, a process which is thought to lead to the nucleation of a double sheath. What is interesting is that both expressions can be put in the same form: in cgs units,

$$n_c \equiv \eta^{-2} \frac{m_i}{m_e} \frac{E_0^2}{12\pi kT^*} \quad (1)$$

Here, η is a measure of the effective collision frequency referred to the ion plasma frequency, $\nu_{eff} = \eta \omega_{pi}$; E_0 is the applied field; and T^* is an effective temperature whose form depends on whether we are discussing the nucleation condition or the sheath maintenance condition. In many cases, $T^* = T_e$, the electron temperature.

TABLE VII

Summary of results from the time-dependent particle code. Z_0 is the geometrical impedance, $60 \ln b/a$; I_T is the total current flowing in the line while Z is V/I_T ; I_L is the conduction leakage current which actually intercepts the anode; I_B is the "boundary current" which flows within $r < a$; I_p is the parapotential current calculated as described in the text and should be compared with I_T ; β_f is the front velocity (measured at $2/3 V$) relative to c .

Run	V_0 (MV)	Z_0 (Ω)	I_T (kA)	Z/Z_0	I_L/I_T	I_B/I_T	I_p (kA)	β_f
1	1.	31.	59.	.57	.42	.54	59.	.66
2	2.4	8.	450.	.67	.38	.51	440.	.75
3	3.	31.	140.	.70	.29	.46	140.	.79
4	5.	4.	1670.	.75	.35	.43	1640.	.82
5	5.	31.	220.	.73	.20	.42	215.	.87
6	5.	72.	93.	.74	.14	.41	91.	.87
7	6.	31.	260.	.75	.14	.38	260.	.90
8	10.	31.	410.	.80	.10	.37	400.	.95

Fig. 28. Reduced front velocity, $\beta_f = v_f/c$ (open triangles) and reduced running impedance, Z/Z_0 (open circles) vs. voltage from the simulations. The solid line is an expression for both quantities from a single particle analysis. Also shown are two experimental measurements of β_f (solid triangles), one at 460 kV⁴⁹ and one at 3.4 MV⁵⁰.

In Figure 29, we have compared Eq. (1) with some results for the transition density taken from the experimental work of Lutsenko, et al.⁵³ the value of η chosen was .86, which is the value predicted by Buneman⁵⁴ and verified in reference 55. The agreement is quite good, considering how simple the model is for such a complex system. Better agreement is obtained by increasing η to 1.2, as shown by the dashed line. This value of η is well within the uncertainties, since the experiments on anomalous resistivity in this parameter domain are not all in good agreement. However, even with $\eta = .86$ we get the dashed line with $T = 8$ eV rather than 4 eV. This is also plausible because the 4 eV value quoted by Lutsenko, et al. is the initial value, and a good deal of electron heating can be expected in the plasma.

Fig. 29. Critical density for transition from double sheath to turbulent discharge. Data is from Ref. 53. Theoretical curves are from Eq. 1 with $T = 4$ eV and a nitrogen plasma.

Another aspect of double sheaths which has been studied is the balance of electrostatic forces among the various species (electrons and ions in the beams and in the plasmas). A model which treats the beams as cold fluids and the

plasmas as having isothermal distributions has been used to determine thermal effects on the beam current densities. This in turn affects the balance of forces among the species. It is found that there are no net forces on the sheath even when there is a pressure difference between the plasmas on opposite sides of the sheath. This may explain why double sheaths have been observed to be remarkably stationary in some experiments.

Electron Emission from Cathode Plasmas in Relativistic Diodes

The mechanism of high current electron emission from cathodes of relativistic electron beam (REB) diodes is a process which has only recently begun to be understood in a detailed manner. Much attention has been paid in the recent literature to the initiatory phase of the transition to space charge limited flow. This is in part because for many applications, the goal is to prevent vacuum breakdown. Several experiments have observed the process of explosion of microscopic metal particles at the cathode surfaces. It is assumed generally that when enough such points have exploded in an REB diode, the plasma flares coalesce to form a relatively uniform expanding plasma front, which has been photographed holographically. If the plasma is sufficiently dense, one expects and observes the space charge limited current.

However, there is still a missing element in this analysis, which is to explain how current continuity is maintained across the metal/plasma interface at the cathode. It is proposed that it is not necessary to assume electrons cross the metal/plasma boundary. Instead, current continuity can be maintained by a flux of positive ions from a high density plasma region across a positive sheath into the metal lattice.

It turns out that there are two requirements on the plasma: it must be sufficiently thick. The density requirement is found to be

$$n_c = 1.48 \times 10^9 (V^3 A / T_e)^{1/2} d^{-2}$$

where A is the ion atomic number per charge, T_e is in eV and all other units are SI. For $T_e = 3$ eV, $d = .005$ m, $V = 1$ MV, $A = 1$, we find $n_c = 3.5 \times 10^{22} \text{ m}^{-3}$, which corresponds to 9.3 kA/cm^2 . The thickness requirement is obtained by setting the number of ions in the thickness τ equal to the number of electrons delivered to the anode. For the same parameters it is found that $\tau = 2$ mm. Both of these conditions are expected to be easily met. Several other consistency checks have also been made.⁵⁹ There are a number of conclusions one can draw if this hypothesis is correct. For one thing, the uniformity of electron emission is determined primarily by the extent of the cathode over which a plasma with density greater than n_c has formed. This depends on the dynamics of lateral plasma motion. In addition, it answers the question of how dense a preformed plasma need be to act as a space charge limited emitter.

Theory of Radial Power Flow

Calculations of the radially inward propagation of a voltage pulse are of interest for several reasons. First, such studies are relevant to present work on Proto II to produce a low impedance diode for power concentration. Second, we wish to know more about magnetic insulation in a radial disk vacuum transmission line. And, most generally, the calculations may teach us something about how to concentrate power in the form of electromagnetic waves.

Thus, a new version of the time dependent, 2-D, cylindrically symmetric, electromagnetic particle code was written to study the problem of a voltage pulse propagating radially between two parallel plates, with one plate emitting space charge limited electrons. There are several restrictions on the present form of the code; it cannot treat tapered geometries (i.e., a spacing between the plates which varies in r), and (assuming the pulse enters the system at $r = R$ at $t = 0$) it is only valid for a time $2R/c$. The code was checked against analytic vacuum solutions, which show that the pulse amplitude increases sharply as the axis ($r = 0$) is approached. The obtaining of these analytic solutions

was itself an interesting problem, because the eigenfunctions of the cylindrical wave equation are Bessel functions rather than trigonometric functions, as in the planar case. The orthogonality of these eigenfunctions could not be used and the inverse Laplace transform had to be performed explicitly in an integral which contained the Bessel functions. Careful attention had to be paid to the singularities in the integral (at the zeros of the Bessel function) of which there were an infinite number.

Studies using this code are still rather preliminary, but several interesting results have emerged. (1) the effect of the emission (if the entire cathode face turns on) is to cause $V(r)$ to decrease as $r \rightarrow 0$, rather than the increase found in the vacuum case. (2) Runs with an emission threshold (i.e., no electron emission until a critical field is reached at the cathode surface) look interesting (at least for the case studied, where V rises linearly in 4 ns to 2 MV in a 2 m diameter system with 1 cm gap) in that the region near $r = 0$ turns on rather suddenly, so that currents in the MA range are produced in times of less than 1 ns. (It should be mentioned that the currents in this first study were not well focused, and a critical field was required which may be somewhat higher than physical.) (3) Adding a B_θ from an external source (e.g., wire on axis) did not help, since it insulates most near $r = 0$ without shutting off emission at large r . Also, the pinching was not helped appreciably, as also observed with the steady state diode code.⁶⁰ (We are assuming that these times of < 10 ns are too short for appreciable ion production.) What seems to be needed to make this scheme of power concentration work well is to insulate with an externally applied B_r field (e.g., from a cusp), although we have not yet studied this possibility with the code.

DIODE CODE DEVELOPMENT AND APPLICATION

Variable Zoning Diode Code

A new version of the diode code⁶⁰ has recently been written which increases the code's accuracy and flexibility in treating different diode geometries. The new version couples nonuniform mesh and slanted surface capabilities resulting in a very flexible diode code.⁶¹ A time dependent emission scheme has also been added to the code as a first step in investigating time dependent effects in diodes.⁴⁸

The ability to treat diode regions with a nonuniform mesh is of importance in many simulation problems. A nonuniform mesh enables one to have refined zoning in areas of interest within the diode (such as near emission surfaces, in target regions, or in the pinch region) without extending this same fine zoning over the entire diode. Thus problems can now be considered which would have previously required an excessively large mesh size. A judicious choice of zoning can also improve the code accuracy. Figure 30 shows the percent error in the computed current density for a 1-D, monopolar, nonrelativistic space charge limited flow when both a uniform mesh and a nonuniform mesh with the same number of zones and particles are used. The nonuniform mesh has fine zoning near the emission surface resulting in a smoother current density across the gap and much less error.

The new code version was written to include slanted surfaces so that tapered cathodes could be properly handled. The slanted surface capability also has application to conical anode configurations or piecewise linear approximations to other surfaces not lying on constant r or z surfaces in the diode. The slanted surface is restricted to pass through mesh points (diagonals of rectangular mesh zones), however, coupled with the non-uniform mesh capability this can still result in quite general surface descriptions. The key to successfully treating slanted surfaces in the new code was in the interpolation scheme used in the zone containing the slanted surface. If the usual rectangular area weighting were used in this zone, a staircase effect on the

equipotential lines as shown in Fig. 31a would result. If instead a triangular area weighting is used in this zone, the correct equipotentials, as shown in Fig. 31b, result. An example of a slanted mesh simulation is given in a following section.

Fig. 30. Comparison of uniform vs. nonuniform zoning error in computed current density for a test case.

Fig. 31. Computed equipotentials using two different interpolation schemes.

A time dependent emission law has also been investigated and included in the diode code. The emission law, based on Gauss' law, is similar to that used by Lee & Goldstein.⁶² The time dependent scheme has been used to investigate ion emission threshold effects on electron beam pinch development in the Sandia accelerators.⁴⁸ These studies were somewhat similar to the work of Miller & Zinamon.⁶³

Foil Anode Effects

The effect of thin foil anodes in diodes has received much attention lately. The diode code has been applied in support of enhanced deposition and pinching foil experiments on several accelerators. The foil is simulated as a constant potential surface in the diode. A simple small angle scatter and stopping power routine, written by M. M. Widner (5241), has been added to the code to treat the effects of scattering and deposition in these thin foils.

1. Proto I

In an attempt to understand the recent Proto I experiments with thin foils, a series of diode code runs were made. The first diode configuration considered was that of a hollow cathode of inner radius 0.635 cm and outer radius 1.27 cm. The diode voltage was 1.5 MV and the total diode current was 160-200 kA per side. Four different foil cases were considered and the runs are summarized in Table VIII. The infinitely thin foil case is a foil with no scattering or deposition. The solid anode case is a perfectly absorbing boundary (no back scattering). It should be noted that the 50 μ m thick foil case is probably stretching the applicability of the scattering and deposition models which are valid only for thin foils.

The first thing to note from this table is that the electron density near the foil center was higher for the thinner foils and highest for the zero thickness case. The peak of the radial distribution of absorbed power moved farther away from the axis with decreasing foil thickness. The current density j_e , defined here as current/area absorbed by the foil, and

also the absorbed power in the foil near the axis, decreases with decreasing foil thickness. We draw the important conclusion that a thin foil does not really "destroy the pinch," as has been suggested, but is simply unable to absorb a significant fraction of an electron's energy during the few passes it makes through the foil. In other words, to get a large fraction of the diode energy absorbed on axis, one must have electric and magnetic fields which can keep the electrons near the focal region for many passes as well as something there which collects the charge.

A few Proto I simulations were also done for a single sided case at 1.5 MV with the same cathode as described above. The foil in these simulations was mounted over a hole in the anode of radius 4.76 mm and depth 4.96 mm. Three different foils were considered and the results are summarized in Table IX. This series of simulations investigates the results of going from low Z to high Z foils and the effect of changing the ion species. The results demonstrate that lowering the foil Z increases the electron density (by a factor of two for this case) at the foil as expected. Changing the ion species slightly lowers the density, mainly by decreasing the total current.

2. Hydra

Simulations of foils in Hydra diodes were done to investigate the effects of scattering in the foil and also the effect of varying the medium properties in the hole in the anode over which the foil was mounted. Three simulations were done with the same geometry of a foil mounted over a .95 cm radius hole in the anode. The cathode inner radius was 1.59 cm, the outer radius was 3.81 cm and the diode voltage was 720 kV. The three foils considered were perfectly absorbing, 6 μ m gold with no scattering, and 6 μ m gold with scattering. The electron particle map for the third case is shown in Fig. 32. The resulting maximum electron densities at the foils were $.5 \times 10^{15} \text{ cm}^{-3}$, $1.3 \times 10^{15} \text{ cm}^{-3}$, and $1.2 \times 10^{15} \text{ cm}^{-3}$, respectively. Scattering is seen to have little effect on the maximum electron density since magnetic field effects dominate for this case.

TABLE VIII

Summary of 2-Sided Proto I Foil Simulation Results

Foil Type	I_e (kA)	I_i (kA)	Current Density in $r < .4$ mm (MA/cm ²)	Maximum Electron Density at Foil (cm ⁻³)	Power Absorbed in $r < .8$ mm (W)
Infinitely thin	150	60	-	12×10^{15}	0
6 μ m Au	115	45	< .1	2×10^{15}	2×10^9
50 μ m Au	150	30	4	6×10^{15}	8×10^{10}
Solid Anode	175	35	13	7×10^{14}	1.3×10^{11}

TABLE IX

Summary of One-Sided Proto I Foil Simulations

Foil Type	Ion Species	I_e (kA)	I_i (kA)	Maximum Electron Density at Foil (cm ⁻³)
6 μ m Au	H ⁺	170	35	3.4×10^{15}
6 μ m Al	H ⁺	180	35	6.2×10^{15}
6 μ m Al	Al ⁺	170	5	4.2×10^{15}

Fig. 32. Electron particle map of 6 μ m gold foil in a Hydra diode.

A second Hydra diode configuration consisting of a hollow cathode of inner radius 1.90 cm, outer radius 6.35 cm, A-K gap of .89 cm, and diode voltage of 1 MV was simulated to investigate the effects of various fills in a 1.60 cm radius hole in the anode over which an infinitely thin foil was mounted. The results of these simulations show that a plasma filled ($E = 0$) hole behind the foil produces a maximum electron density at the foil greater than twice that which results if the region is perfectly absorbing (solid anode). Further, if the hole is not plasma filled but allowed to have full E and B fields and form its own potential well, the electron density is enhanced by a factor of 4 over the solid anode case. The pinching in these three cases varied only slightly. The conclusion is that the foil always enhances the electron density over a solid anode case.

3. Thin Foil NRL Diodes

A series of runs was made for a small, $R/d = 6$, Hydra type diode to examine the idea of using a thin planar foil placed parallel to the anode and connected to it by a stalk on axis. (This idea was proposed by Shyke Goldstein, NRL.) A sample case is shown in Fig. 33, where the dots are simulation electrons, and K, F, A, and S stand for cathode, foil, anode, and stalk, respectively. Electrons absorbed in the foil pass through S to the anode, contributing to B_0 in F-A. Table X shows results from five of the most interesting runs. The most important column is the electron power deposited in the foil in $r < 3$ mm. The presence of a "target" in run #3 means that an electron absorber of radius 3 mm was located at the foil; this run gave the best results of the foil cases, having the most power deposited and the least leakage to the anode. This case was done with and without a charge neutralizing plasma in F-A, with no substantial difference found. Run #4 had no foil, the F-A region being anode plasma; j (pinch) was 2.4 MA/cm². Run #5 had no foil or anode plasma; j (pinch) was 1.5 MA/cm². Adding a $B_z = 1$ kG to these cases destroyed the pinch.

In run #3, the total power is distributed as: target 50%, ions 30%, anode 15%, foil 5%. Since l_i is so large, there does not seem to be much point in increasing R/d. Even if one is willing to live with 30% in ions, one should be able to obtain a better pinch using plasma injection. Our conclusion from this work is that this type of diode does not seem very promising, and this conclusion is consistent with the preliminary results obtained by D. J. Johnson (5244) on Hydra. It is important to point out, however, that the poor pinches obtained with these thin foils do not mean that the absorbed power/mass is low, and in fact the calculated density near the foils was generally large. As shown by runs 2 and 3, the problem is to get the electron energy into the foil during its 2 or 3 passes.

4. Foil Diodes with B_z

The diode code was used to study the effect of an applied uniform B_z on a double sided, KAAK diode. Each anode A consists of a foil F. Figure 34 shows a sample calculation (only the left half of the symmetric system is shown). Ions were neglected, and the region between foils was vacuum. Some electron orbits (or parts thereof) are shown; note the scattering in the 10^{-3} cm Au foil. The average electron makes 14 passes through the foil and deposits 70 keV per pass. The B_z effectively prevents much pinching. One can tailor the energy/pass and the region of the foil where the deposition takes place by varying foil thickness and B_z . This result is interesting mainly because of the large number of passes per electron.

5. Conclusion on Foil Effects

Some general conclusions can be drawn from the above foil simulations. It is seen that thin foils consistently increase the maximum electron density at the foil position over that which would obtain if the foil were replaced by an absorbing anode. The thinner the foil, the greater this enhancement. The low absorbed powers observed in the simulations does not imply that the absorbed power/mass is low but rather that the electrons do not deposit much energy into the foil during their few passes.

Finally, an applied B_z field can increase the number of passes an electron makes in the foil, thus increasing the deposited power/mass ratio. The applied B_z , of course, prevents much electron pinching.

Proto II Diode Studies

A low voltage simulation of a Proto II diode provided information on expected current densities in the first pinching experiments on the machine. The diode considered consisted of a hollow cathode with an applied voltage of 500 kV.

Fig. 33. Electron particle map from a .95 MV thin foil (F) diode. K-F = 4 mm, F-A = 2 mm, outer (inner) cathode (K) radius = 3.8 cm (1.6 cm).

TABLE X

Summary of Thin Foil "Shyke" Diode Simulations

Run	Foil	Target	I_e (kA)	I_i (kA)	Passes/e	Power (TW) Deposited $r < 3$ mm	% e Lost to A, $r < 3$ mm
1	10 μ m	No	240	95	2.5	.01	31
2	1 μ m	No	250	100	3.2	.002	50
3	1 μ m	Yes	240	100	2.4	.17	35
4	0	No	240	80	---	.20	11
5	"	---	250	100	1	.14	43

Fig. 34. Sample electron trajectories from a diode code run with 10 μ m Au foil and applied $B_z = 1$ kG. K = cathode, F = foil (anode). Only the left half of the symmetric KAK system is shown. K-F = 2 mm, F-A = 1 mm, $V = 1.5$ MV, and outer cathode radius = 1.2 cm.

The dimensions in this simulation are $R_{out} = 6.35$ cm, $R_{in} = 2.47$ cm, and $d = 1.5$ mm resulting in an R/d of 42. An infinitely thin anode plasma is assumed to allow the emission of ions over the entire anode surface for $r < R_{out}$. The cathode emits electrons from the face, top and bottom shanks, and corners.

The steady state results for the above simulation are an electron current of 475 kA, and an ion current of 640 kA. This total current of 1.115 MA is slightly higher than the predicted parapotential current of $I_p = 950$ kA because of the inclusion of shank and corner emission. The electron beam undergoes a moderate pinch with 35% of the electron current hitting the anode in $r < 3.5$ mm. The resulting current density in this area is .43 MA/cm². One half of the total electron current arrives at the anode in $r < 1.96$ cm, and 85% in $r < 2.47$ cm. While the low voltage current density

on axis was low, it was expected that the results would improve with increasing voltage.

Higher voltage results have been recently obtained which suggest a very tight pinch is obtainable under certain diode configurations. A 63.5 cm outer radius, 15.2 cm inner radius, tapered cathode with a .254 cm cathode tip-to-anode gap was simulated with a 1.5 MV diode voltage. Various combinations of ion emission, wire on axis, taper angle and a special solid cathode were considered and are summarized in Table XI. In this table j_1 and $\%_1$ represent the current density and percent of the total electron current hitting the anode in $r < 1.9$ cm. Case A represents a tapered cathode (1° taper) and Case B represents a flat cathode (0° taper). In both of these cases, ions are emitted only over the range $0 < r < 15.2$ cm. Cases C and D are for a special cathode consisting of the tapered cathode of Case A but with the cathode extended from the tip to the axis resulting in a solid cathode instead of a hollow one. In Case C ions are emitted as above. In Case D, the ions are replaced by an $I_w = 1$ MA wire current on axis. Perhaps the most interesting cases shown in Table XI are A and C. Case A demonstrates that a large fraction of the electron current can be pinched from a large cathode radius to a relatively small area on the anode. In Case C almost all of the electron current arrives at the anode in the 1.9 cm radius area with the sacrifice of the energy devoted to ion current. Case A has a smaller I_1 than case C because the E_z field near the axis is lower (the cathode is hollow). Case B has a still lower I_1 because of the lack of electron pinching. Figure 35 is an electron particle map for case C. In summary, these results show that a tapered cathode pinches better than a flat one, and that a line current from a wire cannot replace the distributed ion flow.⁶⁰ It should be pointed out that these are steady state simulations; time dependent effects can play an important role in pinch development. However, these steady state runs should correspond reasonably well to the behavior of the diode at the peak of the voltage pulse.

TABLE XI
Proto II Large R/d Simulations

	I_w (MA)	I_e (MA)	I_i (MA)	j_1 (MA/cm ²)	η_1
A	0	3.3	0.7	0.1	25
B	0	4.6	0.2	0.0	6
C	0	0.9	2.2	0.1	96
D	1.0	1.6	0	0.0	1

Fig. 35. Electron particle map from a
Proto II diode, case C. $R_0 =$
64 cm, $R_i = 15$ cm, $d_0 = 1.1$ cm,
 $d_i = 2.5$ mm, $V = 1.5$ MV.

Los Alamos PHERMEX Diode Simulation

In response to a request from F. VanHaften at Los Alamos, the newest version of the particle code was used to simulate a proposed diode for the PHERMEX facility. The diode consists of a 30° tapered hollow cathode with 5 mm A-K gap, $R_{inner} = .35$ mm, and $R_{outer} = 1.27$ cm. The simulations were run with 1 MV and 2 MV across the diode. The resulting current densities on axis were respectively 1.8 MA/cm² and 3.5 MA/cm². The 1 MV case is shown in Fig. 36. The results of these simulations indicate that it is not unreasonable to assume that the desired 1 to 2 mm spot size containing 50% of the total electron current can be achieved, at least at early times in the pulse. Plasma motion at later times may change this result, possibly for the better.

Fig. 36. Electron particle map from a proposed Los Alamos PHERMEX diode.

Large Diode Simulation

A large diode has been simulated to investigate electron beam pinching from hollow ($R_{outer} = 32$ cm, $R_{inner} = 28$ cm) large aspect ratio diodes ($R/d = 80$). The assumed voltage is 1 MV. The simulation has importance in understanding Proto II diode operation. The simulation model assumes that an infinitely thin plasma covers the anode from which ions are emitted over the range $0 < r < R_{outer}$. Electrons are emitted over the entire cathode including both inner and outer shanks, corners, and face. The simulation is steady state in that it includes no time dependent effects such as time dependent emission, plasma formation, or $\partial B/\partial t$ effects. The results of this simulation are an electron current of 525 kA and an ion current of 3.1 MA. This total current of 3.6 MA implies an impedance of 0.3Ω . Of the total electron current, about 90% hits the anode within a 1 cm radius of the axis, resulting in a pinch containing an average current density of 0.15 MA/cm². This value of total current is in good agreement with the parapotential theory which predicts a current of $I_p = 3.5$ MA. The theoretical ratio of ion to electron current $I_i/I_e = 3.9$ is slightly lower than the simulation value of 5.6, but the Goldstein formula does not strictly apply to this case of a very hollow cathode. Dividing the parapotential current according to the theoretical ratio of I_i/I_e yields an ion current of $I_i = 2.8$ MA and an electron current of 700 kA, in fair agreement with the simulation.

The pinch formation time is expected to be quite long, and it is not clear whether the large anode area πR_{outer}^2 can really be covered with dense plasma, as this might require a considerable fraction of the beam energy.

Hermes II Ion Diode Studies

Two different diode geometries were simulated for the Hermes accelerator in an effort to determine if they could produce an anomalously high ion current, as suggested by some preliminary experimental results.⁶⁴ The first simulation consisted of a 7.62 cm

radius spherically tipped cathode opposite a flat anode with a 28.6 cm A-K gap. The applied voltage was 10 MV. The second geometry considered was a hemispherical cathode of radius 7.62 cm opposite a hemispherical anode of radius 22.9 cm. The applied voltage in this case was 7 MV.

Both of the above described simulations predicted that only about 10% of the total diode current would be in ions. Other possible mechanisms for producing higher ion currents were examined. No plausible mechanism was found which produced much more than 10% in ions, except for a small possibility of electron reflexing in some of the experiments. The conclusion that we draw is that Hermes II in these configurations should not produce an anomalously high ion current.

Angara Cathode

An early time simulation of the Angara cathode, used at the Kurchatov Institute, has been done using the newest version of the diode code. An electron particle map for this cathode is shown in Fig. 37. The cathode tip radius is 1 mm and the outer radius is 5 mm. The tip to anode gap is 2 mm and the diode voltage is 500 kV. The steady state simulation results are an electron current of 30 kA and an ion current of 1 kA with 12% of the electron current arriving at the anode within a radius of 1 mm resulting in a current density over that area of 0.1 MA/cm². The simulation validity is restricted to early times in the voltage pulse because plasma motion is neglected. There is very strong experimental evidence that much greater total currents and current densities are achieved with this diode and that the diode behavior is very much dependent upon prepulse conditions. This suggests that plasma motion plays an important role in this diode.

Parapotential Cathode Simulation

The slanted surface capability of the new diode code version has been applied to the investigation of the behavior of tapered "parapotential" cathodes. A particular Hydra diode is considered

in which the cathode has $R_0 = 3.87$ cm, $R_1 = 1.59$ cm, and the diode voltage is 950 kV. Three A-K gaps are considered. The first is a tapered (parapotential) cathode with 10° taper angle. (See Fig. 38. The other two cathodes are both flat faced (0° taper angle) with different A-K gaps. The results of these three simulations are presented in Table XII.

Fig. 37. Electron particle map of Angara cathode early time behavior.

The results indicate that the parapotential cathode pinches as well as the flat cathode when the former runs at a much lower current level. It also pinches better than a flat cathode whose A-K gap has been adjusted to provide the same total current. The pinch is better for the parapotential cathode because the emission is predominantly from the inner part of the cathode face, as opposed to the flat cathodes where the emission is much more uniform over the entire face.

Fig. 38. Parapotential cathode electron particle map

TABLE XII

Summary of Parapotential vs. Flat Cathodes

Cathode	A-K Gap (mm)	I_e (kA)	I_i (kA)	j_1 MA/cm ²
Parapotential	2.7	180	35	2.0
Flat	5.0	240	80	2.0
Flat	6.5	160	40	1.5

PARTICLE BEAM SOURCE DEVELOPMENT AND THEORY

Collective Ion Acceleration

A collective acceleration program is in progress which is designed to demonstrate feasibility of the Ionization Front Accelerator (IFA).^{65,66} The three main goals of the experimental feasibility phase of this program are summarized in Table VIII. The status of this program as of September 1977 is also indicated in this table. Note that the full IFA system (IREB, dye laser, fast shutter, frequency-doubled ruby laser, and heated Cs experimental chamber) is now operational for the first time. Following Table VIII, we will now briefly summarize progress on the IFA experiments to date.

Goal I of this program was to demonstrate that Cs is a feasible working gas. This involved IREB stopping and transport experiments in air and in Cs (see previous semiannual report). The results of these experiments clearly demonstrated the pressure threshold for IREB-induced ionization of Cs and showed that for a reduced Cs pressure of ≤ 30 microns, IREB-induced ionization processes should not interfere with the IFA operation.⁶⁷ The Cs density can therefore be up to 10^{15} cm^{-3} , which is 10^3 times larger than the typical IREB density of 10^{12} cm^{-3} . This means that the Cs has to be ionized only 0.1% to control the potential well motion in the IFA.

Goal II of this program involves experiments to demonstrate laser-controlled IREB beam front motion. To achieve this goal, the five prerequisite problems listed in Table XIII had to be solved. The first four problems have now been solved, and the fifth is near solution:

(i) transparent/conducting drift tube studies. All of our earlier IREB transport studies in air and in Cs were performed in a drift tube with "perfectly-conducting boundary conditions" (i.e., a metal tube). For the IFA, it is of course necessary to have windows along the drift tube for the swept dye laser light to enter. Therefore, it was necessary to develop a "transparent/

conducting" drift tube. It was quickly found that a purely transparent tube (e.g., quartz) drastically and unfavorably altered the IREB propagation characteristics from those that occur in a metallic tube. A number of hybrid drift tubes were then constructed containing various combinations of glass (quartz, pyrex), conductive coatings, and metal (brass, copper, etc.). After substantial experimentation, a suitable "transparent/conducting" drift tube was created that does reproduce the IREB transport properties of a metal tube, yet also has windows along the sides for use in the IFA.⁶⁸

(ii) laser sweep. The dye laser beam is to be injected into a light pipe array to produce a swept light front along the IFA drift tube. To demonstrate that such a swept light front can be made, and to examine the actual uniformity of the front, a series of streak camera experiments were performed. In these experiments, the dye laser output (8521 Å) was made visible to the streak camera (P-11 photocathode) by the use of a frequency-doubling crystal. The streak pictures obtained clearly demonstrate that the light pipe array does produce an accurately-programmed light sweep. In addition, use of the fast shutter assembly (optical risetime $\sim 1 \text{ nsec}$) demonstrated that a very sharp swept light front can be made.⁶⁸

(iii) scintillator/streak beam front diagnostic. To observe the beam front motion in our controlled beam front experiments, it was necessary to develop a new time-resolved beam front diagnostic. This consists of a scintillator lining the inside of the drift tube which is excited by the IREB electrons hitting the drift tube walls. The emitted light is then recorded by a streak camera. This technique has now been perfected so that we can readily see, with subnanosecond resolution, e.g., stopped IREB's (for injection into vacuum) and fully-propagating IREB's (at optimum transport pressures).⁶⁸

(iv) high temperature modification. Because the experimental chamber must be heated to $\sim 250^\circ\text{C}$ to achieve the desired Cs operating pressure, a number

of complications arose concerning materials problems. These problems have been adequately solved and we are now able to operate at the required temperatures rather routinely.

(v) low jitter synchronization of lasers and IREB. To achieve the required synchronization of the lasers and the IREB for the IFA, it is necessary to minimize the jitter and delay times as much as possible. The commercially available trigger-to-Pockel pulse delay times of 300-400 nsec were reduced to ~ 50 nsec by developing and constructing special Pockel cell drivers. Our present jitter measurements yield standard deviation values of ~ 6 nsec for the IREB (start of blumlein charging to diode pulse), < 4 nsec for the lasers (trigger to laser pulse out), and ~ 1 nsec for the fast shutter (trigger to shutter pulse out). We have had some laser pretriggering problems caused by Marx generator noise. We are in the process of solving these problems and ensuring as accurate a synchronization as possible.

The first system shots have been taken without the fast shutter, so the swept dye laser pulse has a rather long risetime. Nonetheless, in some of our first shots the synchronization was favorable: the streak pictures did roughly indicate that the beam front was controlled by the lasers.⁶⁸ We await further tests, and use of the fast shutter, to finalize this conclusion.

In summary, the key results of the IFA experimental program to date are that we have:

- (1) demonstrated Cs is a feasible working gas.
- (2) demonstrated transparent/conducting drift tube.
- (3) demonstrated accurately-programmed laser sweep.
- (4) demonstrated diagnostic that accurately shows time-resolved beam front motion.

We are just now beginning full system shots, and the study of laser-controlled beam front motion.

This program is jointly sponsored by DOE and AFOSR.

Calculations of Ion Beam Neutralization

This work was done in support of the pulsed linear ion accelerator experiments of S. Humphries. A crucial problem in such a device is the neutralization by electrons of the ion beam, since even a relatively small degree of non-neutralization would cause beam spreading in the long drift regions. The calculations were made with a 1-D relativistic electrostatic particle code. A uniform ion background $n_i = 10^{12} \text{ cm}^{-3}$ was introduced into an $L = 1$ cm gap with a .5 ns risetime. Space charge limited electrons were emitted self-consistently from the walls. The exact numbers chosen are not important, since potentials scale like $n_i L^2$. The solution after .5 ns oscillates about an equilibrium in which the ions are overneutralized near the walls, underneutralized in the middle. The maximum potential is 40 kV (for no neutralization, it would be 225 kV), which is bad since the ions would see a defocusing field of order 10^5 V/cm .

As pointed out by Humphries,⁶⁹ in a real device there will always be effects which give the electrons a velocity component parallel to the wall, which prevents them from returning to the wall, and allows more complete neutralization. This was modeled in the 1-D code by simply reducing the velocity (perpendicular to the wall) by a fixed fraction f each time an electron crosses the midplane. Both $f = .9$ and $f = .7$ fairly well. The .9 case reduced the maximum potential to $< 2 \text{ kV}$ in 1.5 ns, while the .7 case took only 1 ns. To within the accuracy of the code, good neutralization was achieved everywhere. These results seem to confirm the idea⁶⁹ that cold electron neutralization can occur provided the electrons can gain a velocity parallel to the walls.

TABLE XIII
IFA Feasibility Experiments

<u>I. Demonstrate Cs is a feasible working gas</u>	
IREB stopping and transport in air	} completed March, 1977
IREB stopping and transport in Cs	
<u>II. Demonstrate laser-controlled IREB beam front motion</u>	
transparent/conducting drift tube	} completed September, 1977
laser sweep	
scintillator/streak beam front diagnostic	
high temperature (250°C) modifications	
low jitter synchronization of lasers and IREB	} first system shots
<u>III. Demonstrate collective ion acceleration</u>	
ion diagnostics	

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PARTICLE BEAM SOURCE DEVELOPMENT

OVERVIEW

Electron beam research directed toward providing improved in-diode pinched beam sources and establishing the efficiency and feasibility for superposition of many beams progressed in three major areas.

It was established that heating of the anode to $\sim 1000^\circ\text{C}$ is a useful means for reducing hydrogen content of anode plasmas. The consequent reduction in proton current can allow a reduction factor of 2 to 3 in the energy lost to ions in large aspect ratio diodes and allows more flexibility in the design of future systems for in-diode pinch target experiments.

Focusing stability has been improved from large effective aspect ratio (radius/gap of emitting surface) diodes. The means used is to split cathode surfaces into segments isolated one from another by their own self-inductance. A central cathode is adjusted to provide a bias current which guides the current produced by the outer ring of cathodes into the central region. Since the beam does not strike the anode as it sweeps inward toward the center, producing plasma on the anode surface as was the case for previous diodes, ion current loss is reduced by a large factor, and the formation speed and stability of pinches were enhanced. The principles involved have been demonstrated on Hydra and Proto I, but the full benefit remains to be determined in lower impedance operation on Proto II. An additional development made by the Pulse Power Group showed that, using self-magnetic insulation, electromagnetic energy could be transmitted to within about 20 cm of the axis of Proto II with minimal loss. This development will very likely result in improved formation of pinches at Proto II power levels, either with conventional cathodes or the segmented cathode approach.

Substantial progress toward establishing the feasibility of combining beams guided along ionized current-carrying channels has been made. Two beams have been transported, and overlaid on a target. Theoretical and experimental measurements on channel formation have resulted in specifications for the capacitor bank channel initiation system for a 12 beam combination experiment on Proto II, and hardware for this experiment is being procured.

An additional area of beam research has been the development of a small pulsed X-ray source to yield high quality flash X-radiography of pellets. A source yielding $\sim 100\text{-}\mu\text{m}$ resolution of objects has been demonstrated and work continues to improve the convenience and reliability of this source.

The effort to extend the capability of higher power conventional pulse power generators to accelerate ions (rather than electrons), and assess the feasibility of this technology variation for target experiments and reactors has progressed. We have focused our efforts on the use of externally applied magnetic fields to suppress electron flow and completed an exploratory set of experiments on Hermes-II. We identified a source of energy loss caused by electron flow and have nearly completed design of a follow-on experiment on Proto I which should eliminate the electron loss and allow us to test other critical factors affecting ion beam focusability.

Progress toward development of a multistage accelerator for ions with pulse power technology centered on development of a new laboratory facility and design and procurement of hardware for a five-stage test apparatus for the Pulsac concept. In addition, we obtained encouraging theoretical results indicating that effective space charge neutralization will exist between acceleration stages of Pulsac. Other theoretical results indicated that the limits required for gap voltage stability to maintain longitudinal beam focus should be obtainable for realistic parameters of experimental hardware.

IMPEDANCE CHARACTERISTICS OF HEATED REB DIODES

Recently, considerable emphasis has been placed upon the use of low-impedance relativistic electron beam (REB) diodes to produce a source of electrons for inertial confinement fusion experiments.¹ At diode power below 10^{12} W and impedance above 1 ohm, these diodes generate a tightly pinched electron beam focus with peak current density of approximately 1 MA/cm². However, for applications requiring higher power and lower impedance a rapid collapse² of the diode

impedance occurs prior to the termination of the electrical pulse. The investigation³ of plasma formation in 15 ohm diodes with pulsed holographic techniques has demonstrated that although copious supplies of anode and cathode plasma with densities $\geq 5 \times 10^{16}$ electron/cm³ are produced, the impedance is specified by even lower density plasmas which are unobservable with holography. Therefore, although the impedance collapse is thought to be caused by the rapid motion of diode plasma which effectively closes the diode gap during the pulse, the relative importance of anode and cathode plasma is uncertain and the gap closure velocity is only inferred by modeling¹ the diode impedance. A second mechanism which accentuates the impedance collapse is the increasing efficiency with which ion current is generated⁵ as the diode aspect ratio R/D increases. This work reports a successful attempt to reduce the impedance collapse due to these mechanisms by heating the anode to a temperature of approximately 1000°C which is adequate to remove all but the last one or two monolayers of absorbed hydrogen.⁶ The data obtained are consistent with recent observations⁷ of a reduction in the rate of impedance collapse for anodes heated to 400°C.

Measurements were made with the Hydra accelerator⁸ which was operated with the central electrode in positive polarity. A hot cathode (filament) electron beam was used to heat thin foil anodes and the inner edge of the REB cathode for 30 minutes prior to and during data acquisition. The heating apparatus, anode foil stretcher, and REB diode used are shown in Fig. 1. The anode and cathode temperatures were estimated to be 1000° and 200°, respectively, based upon an equation of the electrical powers delivered to the radiation and conduction heat losses. The use of thermocouples or an optical pyrometer for temperature measurements was determined to be impractical because of the high voltage and luminosity of the 2500°C filament.

Diagnostics included the electrical characteristics of the REB diode, signals from biased ion collectors,⁹ collimated and uncollimated X-ray flux measurements,¹⁰ and X-ray pinhole photographs. The ion collectors were configured with 10-3 cm² apertures and located at 17 to 40 cm from the anode. The collectors were mounted in pairs at radial positions of approximately 1.2 cm on opposite sides to the diode center line to ascertain the ion beam symmetry. The collimated X-ray flux was obtained with a silicon PIN diode which observed a 1-cm-diameter region at the center of the anode. The uncollimated PIN diode observed

the X-ray flux emitted through the 50-mm-diameter hole in the cathode.

Fig. 1. A cross-section view of the pinched electron beam diode and anode heating apparatus.

As has been previously observed,⁴ it was noted in this experiment that the diode current for a pinched REB with cold anode could be expressed approximately by $I = I_e + I_i$. In this expression the ion current is given by $I_i(A) = I_e \times (eV/2m_i c^2)^{1/2}$ R/D and the electron current by $I_e(A) = 9 \times 10^3 (\gamma^2 - 1)^{3/2} R/D$. The relationship for ion current is based upon a simple argument that the space charge of the ion beam should equal that of the electron beam for electrons that pinch to the diode axis. The electron current is functionally similar to the critical electron current for self-pinch $I_c(A) = 8.5 \times 10^3 (\gamma^2 - 1)^{3/2} R/D$. In these relations γ is the relativistic electron mass correction, c is the velocity of light, m_i is the mass of an ion in the ion beam (taken to be the mass of a proton for a cold anode), and R/D is the diode aspect ratio. The diode gap is taken to be $D = D_0 - vt$, where v is a fit parameter ($v \approx 2.3$ cm/usec for cold anodes in this experiment) which is assumed to relate to the motion of anode and cathode plasma which begins at current initiation. In this model the diode aspect

ratio is chosen to be the larger of the two ratios determined from the inner and outer radii of the cathode. The data shown in Fig. 2 are the total diode current, corrected voltage, and impedance for Shot 6095 with heated tantalum anode. Also shown are the calculated ion current and diode impedance. These curves were obtained using the inner cathode radius aspect ratio and $v = 1.75$ cm/psec. The value of m_i was assumed to be that for C^{+2} on the basis of time-of-flight analysis of the emitted ion beam. This has reduced the calculated ion current by a factor of 2.5 and raised the calculated impedance by approximately 20 percent with respect to the values obtained for proton flow.

Fig. 2. The continuous curves are the corrected diode voltage, total diode current, and impedance for Shot 6095. The dotted curves are the calculated ion current and impedance assuming a C^{+2} ion beam. See text for details of these calculations.

The results shown in Fig. 3 are the ion collector signal for Shot 6095 obtained at 17 cm from the anode, and calculated currents at the collector location for C^{+2} and Ta^{+2} ion beams. The calculated currents were obtained numerically. This was done by dividing I_i into approximately 0.4 ns

duration time steps and by dispersing the current at each step according to the simultaneous diode voltage. The resultant discrete current was smoothed with a 6 db low-pass filter between 30 and 60 MHz. The very low-intensity ion collector signal beginning at 70 ns in Fig. 3 is coincident with the expected arrival time of protons. When cold anodes were used this time coincided with the onset of a large signal which continued until approximately 50 ns, in agreement with the calculated current for proton flow. At 200 ns the signal increases rapidly and agrees on a "first order" basis with the calculated current for C^{+2} . The discrepancy observed in Fig. 3 between the calculated and measured ion currents is attributed to the presence of ions other than C^{+2} in the ion flow. After 200 ns, the signal increases again suggesting a component of the current due to Ta^{+2} . The discrepancy between the observed and calculated ion current varied considerably from shot to shot and was often different for the pair of collectors. However, the general trend was always consistent with the assumption of weakly ionized carbon and proton emission for the hot and cold anodes, respectively. The absolute magnitude of the ion collector signals could not be used to verify the calculated reduction in ion current for the heated anode shots because of the possible variation in collector efficiency as a function of ion species. A few shots taken with 125- μ m-thick copper foils at room temperature and approximately 500°C gave the same general behavior with more of a tendency for C^{+1} and Cu^{+1} emission for hot anodes.

The X-ray measurements were of little assistance in diagnosing the heated diode behavior. Although it was expected that the hollow electron beam collapse¹¹ velocity would be decreased with a heated anode, because of the requirement of the beam to heat the anode to extreme temperatures to create high-Z ions, the collimated PIN diode signals did not indicate such a decrease. The X-ray pinhole photographs did indicate a difference in the azimuthal electron beam symmetry however. For hot electrodes, eight well-defined radial spokes were noted which correlated with pie-shaped sections removed from the anode near the outer edge of the cathode. This suggests that the warmer inner edge of the cathode, which no longer retains an abundant supply of absorbed hydrogenous material¹¹ ($> 5 \times 10^{16}$ atoms/cm²) suitable for conversion to plasma during cathode whisker explosions, plays a less important role in electron emission for the heated diode.

Fig. 3. The continuous curve is an ion collector signal from Shot 6095 obtained 17 cm from the anode. The dotted curves are calculated ion currents for this collector position assuming C^{+2} and Ta^{+1} ion beams.

In conclusion, it was observed that although impedance collapse is not as rapid for heated diodes, extremely hot electrodes do not prevent the collapse. It was not possible to establish with certainty the origin of the plasma causing the impedance collapse because the electrodes were not independently heated. The reduced ion current striking the inner edge of the cathode for the heated diode would probably not result in less cathode plasma being formed if the quantity of absorbed gas were unchanged because of the higher stopping power of the high-Z ion beam. It can therefore be inferred from the X-ray photographs that heating the cathode affected the quantity of cathode plasma produced by whisker explosions and at least partially assisted in minimizing the impedance collapse. This indicates that the impedance collapse perhaps could be further reduced by use of cathodes heated to 1000°C.

ELECTRON BEAM PINCHING FROM DISCRETE LARGE DIAMETER CATHODES

Over the last few years, attempts to produce high power density pinches from multimegamp electron beams have met with a number of problems. For MeV energies, these beams must

be generated at low impedance (≤ 0.5 ohms); for parapotential electron flow¹² this necessitates employing diodes with large radius cathodes and small anode-cathode gaps. Pinch size, however, has been seen to increase with both increasing cathode radius¹³ and radius to gap ratio (R/d). A beam compression ratio (radius of cathode/half-current radius of the pinch) of about 10 at R/d of 5 has represented the maximum pinch "quality" for some time.¹⁴ At R/d greater than about 10, difficulty in turning on large area annular cathodes uniformly over their emitting surface and possible instabilities in the radial flow of very thin sheet beams result in the generation of highly filamented beams which, because of poor symmetry, generate magnetic fields which preclude the formation of reproducible well-centered pinches and often result in early impedance collapse due to off-axis gap closure by plasmas. In addition, loss of one-half or more of the total diode power to either electrons striking the anode at large radius or to the generation and flow of large ion currents¹⁵ frequently occurs.

In an attempt to alleviate these problems, we have investigated an alternate technique for generating high current electron beams at low impedances. By employing arrays of discrete cathode elements located on circles of successively larger radii, and a single axially mounted cathode of the proper design to establish the boundary condition for parapotential flow,¹² we have been able to generate pinches from relatively large diameter (from 12 cm to 1.2 m), large R/d (11 to 47) cathodes with improved beam compression ratios and significantly reduced ion currents. Here we report on preliminary experiments done at relatively high impedance (e.g., 1 to 5 ohms), which characterize the production of multiple electron beams, their radial propagation, and their combination on the diode axis. These multiple cathode arrays shortly will be employed in Proto II pinching experiments at 0.25 to 0.5 ohms.

The use of biased arrays of segmented cathode has several advantages over a single, large, very hollow annular cathode. Since the latter operates in an "ion induced pinch" model¹⁶ (i.e., ions from anode plasma locally reduce the diode E field, thereby enhancing radial direction of the $E \times B$ drift), a significant amount of energy is lost to ion generation and in certain cases the pinch sweep-in rate is partially controlled by

the anode composition and rate of ion production.¹⁷ The former cathode configuration, however, operates in the "bias current pinch" mode,¹⁸ for which early in the beam pulse, radial flow is enhanced by increasing the magnetic field with an axial current. Although anode plasma may still be necessary for tight pinch formation,¹⁹ it will be shown later than ion flow can be localized to a small area in the axial region and power loss to ions is significantly less than that previously predicted.¹⁵

Discrete cathode arrays also exhibit better large scale turn-on uniformity than a large annulus, partly because of field enhancement effects at the ends of the emitting surfaces and partly due to inductive isolation of each cathode within a circle. For typical geometries and current rise rates used in these experiments, a discrete cathode which had not yet turned on would have from 100 kV to 200 kV more voltage drop to the anode than would a cathode which had turned on. The formation of nonreproducible beam filamentation and large angular momentum beams by annular cathodes of $R/d > 1$ can thus be alleviated by using this technique of "forcing" the turn on of each cathode segment. Although multiple rather than a single beam exists in the diode, the number of beams now is controlled by the number of cathodes (N) and the magnetic field possesses N fold symmetry. As will be shown, proper shaping of the emitting surface of the discrete cathodes for generation of a purely radially directed beam can reduce the angular momentum of the beams.

In previous work with a biased hollow annular cathode,¹⁵ the bias current was supplied by resistively or inductively isolated axial loads (rods or solid cathodes). Although increases in pinch sweep-in velocity by factors of 3 to 6 were attained, major improvement in pinching was not realized, for several possible reasons. First, to establish the boundary condition for parapotential flow of electrons from a single outer cathode, the axial load must supply the current $I_{\text{bias}} \geq (1/\gamma)I_{\text{total}}$, but for the work reported in Ref. 13, only 10 to 20 percent of the requisite I_{bias} was

achieved. Second, the temporal response of bias current should satisfy the previous condition throughout the power pulse. But for the small rods used, their inductance resulted in slow current rise early in the pulse; the outer electrons therefore were being underbiased during this time and for the larger solid cathodes, rapid gap shorting

by plasmas produced an overbiased condition leading to magnetic cutoff of the outer cathode emission and possibly drawing the pinching electrons off the anode surface since the bias cathode was now very near anode potential. Third, none of the bias cathodes used actually produced a pinching beam itself. The outer electrons therefore would not follow parapotential flow once they penetrated the center current sheet, and may have struck the anode across the inner cathode. And fourth, the outer cathode, a single-tapered annulus (10 cm O.D., 8 cm I.D., 50 taper) operating at R/d of 11, generated a highly filamented beam with poor azimuthal symmetry (observable in X-ray pinhole pictures) and highly variable direction in which the beams were launched. Here we show that the use of biased discrete cathode arrays can greatly reduce many of these initial problems.

Diagnostics and Apparatus

For this series of experiments, the Proto I and Hydra accelerators were undermatched to progressively approach low impedance operation. Proto I (nominally 7 ohms/side) were operated single sided from 3 to 5 ohms with typical beam parameters of 1.0 MW, 300 kA, 24 ns; Hydra (nominally 2 ohms) was operated both normal polarity for X-ray diagnostics and reversed polarity for ion diagnostics with typical beam parameters for both cases of 900 kV, 450 kA, 100 ns.

Various tip geometries used for discrete outer cathodes are shown in Fig. 4. Except for the cylindrical tip (B), all others were made with straight or slightly curved single-edged emitting surfaces in an attempt to generate beams with a radially inward trajectory and as little azimuthal velocity as possible. In this way we hoped to be able to use the multicathode approach and to incorporate the recently described paravector-potential diode.¹⁸ Small cylindrical tapered cathodes were used for providing axial bias current. The following dimensions were used: either 2.5 cm O.D., 1.3 cm I.D., 15° taper, or 3.8 cm O.D., 2.5 cm I.D., 10° taper, run at inner edge R/d_0 of 1.4 and 2.5, respectively. Beams from these cathodes have been studied previously²⁰ and were found to pinch rapidly (within 15 ns) and tightly (2 to 4 mm FWHM). Depending on the current they are required to supply (they run at relatively flat impedance typically for 25 to 60 ns) the duration of most of the experiments of interest here. Fig. 5a shows a diode setup

Fig. 4. Emitting surface geometries for outer cathode tips:

- A. Hemispherical edge, concave or convex.
- B. Cylindrical, 15° taper.
- C. Concave curved edge.
- D. Straight edge.

Fig. 5a. Diode setup for Proto I experiments. Cathode dish with discrete cathode arrays is above, anode plate with central witness plate is below. Note six-sided damage pattern and axial hole blown through witness plate.

for Proto I employing a small diameter bias cathode on axis and a circle of six outer cathodes on a 13-cm-diameter circle; the latter are operated at an R/d_0 of 9 to 13, depending upon the desired impedance.

Fig. 5b shows the cathode insert plate for a Hydra experiment where eight outer cathodes on a 20-cm-diameter circle (run at R/d_0 of 20 to 28) surround a larger diameter axial cathode. Also shown just outside the outer discrete cathodes is a single hollow annulus (23 cm diameter) used to generate beams for comparison with the discrete cathode case. The electrical characteristics of each circle of cathode elements was monitored by azimuthally spaced arrays of dI/dt loops at various radii and with one or more voltage monitors at the edge of the diode. Besides monitoring the current feed symmetry, the current loops were used to determine the current bias relationship between the cathode arrays and the time-dependent characteristics of each circle. Beam formation and propagation were diagnosed by recording the bremsstrahlung from anodes of either graphite or aluminum of at least one residual range thickness. X-ray pinhole photography at various magnifications provided time-integrated information on individual beam structure and

Fig. 5b. Cathode insert plate for Hydra experiments.

their combination on axis. Three silicon PIN diodes provided time-resolved data on the dose to the anode; two diodes were used with 0.48-cm-diameter aperture lead collimators to observe radiation from the axis and from just inside one of the outer cathodes, while the third diode measured total radiation. Arrays of biased charge collectors⁹ were used to estimate the localized current density of ions from the anode plasma, to examine the ion front profile, and to determine the effect of the current biasing condition on ion production. Either 3 or 4 detectors were mounted at various radial and azimuthal positions and observed ions through various holes and slots in the cathode mounting plate (visible in Fig. 5b). A negative bias of 50 to 100 volts and flight path of 7.5 cm from anode to detector were used.

Most results on pinch quality reported here are qualitative; techniques for more quantitative measurement of pinch size, current density, fraction of total beam energy within the pinch region, and sweep-in velocity presently are being developed.

Experimental Results

The bias conditions for three Hydra shots are shown in Fig. 6. In these plots, when the current ratio $I_{\text{total}}/I_{\text{bias}}$ falls just under the γ plot and has about the same temporal shape, the outer electrons are properly biased during the entire machine pulse. The

Fig. 6. Bias condition, i.e., current ratio plots of $I_{\text{total}}/I_{\text{bias}}$, and electron γ plotted vs. time for three cases: underbiased annulus (top), overbiased annulus (center), discrete cathode array (bottom).

three cases to be compared are an underbiased hollow annulus (top), an overbiased annulus (center), and an array with 8 discrete outer cathodes (bottom). The time-dependent impedances of each cathode for these cases are plotted in Fig. 7, and the ion signals detected at $r = 0, 5$, and 10 cm (the latter being just inside the emitting edge of the outer annulus or discrete cathode) are shown in Fig. 8.

For the underbiased condition, the annulus impedance falls during most of the power pulse at a rate consistent with a gap closure velocity²³ of 4 to 4.5 cm/μsec. Although the ion flow is peaked on axis, the signal across from the annulus is still one-fifth the axial value. The fast closure and relatively flat ion profile suggest that the diode is operating similarly to one employing a single unbiased annulus.²² In the early overbiased case, when the inner impedance begins to rapidly fall as a consequence of axial gap closure, the annulus becomes magnetically cut-off; experimentally its impedance appears to rapidly increase, but the annulus never actually stops emitting electrons as will be explained shortly. The ion signals show the ion (and consequently the electron) current density to be very peaked on axis. For the near-optimum biased cathode array, the outer cathodes emit with nearly constant impedance for almost 60 ns and exhibit little or no closure (0 to 1.5 cm/μsec). The axial cathode impedance reaches a plateau then increases, probably due to space charge repulsion between the axial cathode electrons and those from the outer cathodes, i.e., this hump in the impedance curve indicates success in drawing the outer electrons in toward the axis. The ion signals still show an axially peaked ion profile. Compared to the underbiased case, the signals at 10 cm radius are comparable in amplitude; however, since the ion signal is non-zero only across from the discrete cathode tips, the total ion current at large radius is actually reduced by the ratio of cathode emitting areas, in this case by a factor of 4, while the axial value has increased by a factor of 7.5.

The data in Fig. 8 suggests that ion flow occurs in two different regimes in the diode. On axis, where the inner and outer electron beams combine, the ion current density is on the order of the space-charge limited value, but across from outer cathodes signals only a few percent of the axial value are detected under proper bias conditions. Thus, a large area of source-limited ion flow exists at large radius. For underbiased

cases, the flatter ion profile is a result of electron loss and energy deposition at large radius, as can be seen in Fig. 9. Here collimated PIN diode signals from X-rays emitted within a 0.18 cm² are on axis and just inside an outer cathode are plotted for underbiased and properly biased cathode arrays. The increase in the axial PIN signal and decrease in the radial signal under proper bias is apparent especially at late times. These results correspond to a reduction by a factor of 5 in the anode dose at large radius.

Several time-integrated X-ray pinhole photographs of discrete cathode array pinches are shown in Fig. 10. In 10a and b, the electron loss pattern across the outer cathodes and the expansion as the beams sweep inward can be seen to differ for different tip geometries and bias conditions. Where the individual beams overlap, electrons appear to be lost at localized regions on the anode, as evidenced by a symmetric pattern of circular and "petal" shaped X-ray emission sites in the pinhole pictures and small regions of spall between the cathodes on the witness plate. This beam loss may be due to partial cancellation of the magnetic field, with electrons consequently crossing equipotential lines and striking the anode, or it may be a result of electrostatic repulsion when the beams combine and the charge density increases, since this occurs in a region devoid of ions for charge neutralization. It therefore appears to be desirable to keep the beams separate as they sweep radially inward. Under higher magnification (10c), the beams can be seen to propagate into the region of the bias cathode pinch and eventually coalesce on axis.

Conclusions

Our understanding of the operation of biased discrete cathode arrays can be summarized using a simple diode model shown in Fig. 11. With little or no bias current, electrons from an outer cathode will follow a trajectory similar to No. 1, i.e., weakly pinch, deposit most of their energy at large radii, generate a large ion current, and sweep in at a few mm/ns radial velocity. This happens because, just as in an ion induced pinch, the electrons need the increased magnetic field from ion flow to achieve parapotential flow. Under proper bias condition, which has been determined experimentally to be $I_{\text{bias}} \sim (1/\gamma)I_{\text{total}}$ throughout the pulse, outer electrons will flow radially inward at a significantly higher velocity than for the ion induced case and combine

Fig. 7. Time-dependent impedances of the outer cathode(s), inner cathode, and total diode for the three cases of Fig. 6.

Fig. 8. Signals from biased ion collectors at three radial positions for the cases of Fig. 6. Signals, not corrected for 7.5-cm flight path, are mainly from H^+ and C^+ .

Fig. 9. Signals from collimated PIN diodes looking on axis and just inside outer discrete cathode for two bias cases. Area under curves is proportional to dose delivered to anode at that position.

Fig. 10a. X-ray pinhole photograph of pinch using 8 cathodes "A" of Fig. 4.

Fig. 10b. X-ray pinhole photograph of pinch using 8 cathodes "C".

Fig. 10c. X-ray pinhole photograph of Proto I pinch using 6 cathodes "D", at higher magnification. Diffuse circular ring in center is 24 mm diameter.

with the other outer beams and electrons from the axial cathode on the diode axis, where the magnetic field rapidly drops (path No. 2). If the outer electron flow is initially over-biased or becomes so during the pulse because the axial A-K gap closes too rapidly from plasma motion, electrons will follow path No. 3, strike the axial cathode, and eventually be emitted toward the anode but at the much smaller R/d of the center cathode, i.e., at higher impedance and inductance. With greater overbias, outer electrons will be magnetically cutoff so fast (path No. 4) that they return to the cathode plate outside the inner BDOT position and contribute to the power flow into the axial cathode. Since the outer cathode current is obtained by measuring the difference between inner and outer BDOT signals, path 4 gives zero outer current (though outer cathode emission is not zero) and explains why the impedance appears to rapidly rise at late time in Fig. 7.

For highest power deposition on axis and low-impedance, low-inductance operation, diode conditions for the approaching Proto II experiments will be optimized for beam focusing from a path No. 2 type mechanism.

Fig. 11. Cross section of diode showing possible electron trajectories from outer cathode(s).

REB PROPAGATION AND COMBINATION IN PLASMA CHANNELS

The ignition of thermonuclear pellets by relativistic electron beams (REB's) will require the development of sources capable of delivering tens or hundreds of terrawatts of electrons at voltages near one megavolt and at very high current densities. While the use of self-pinched electron diodes is a promising approach to this problem, one encounters significant difficulties in going beyond the one terrawatt level in a single diode. These difficulties include the following: (1) power loss approaching 50 percent at the one megavolt, one megamp level can occur in a diode by the generation of a counter-streaming ion beam if suppression measures are not employed; (2) radial compression ratio limits of only 10:1 are commonly seen for efficient, intense pinch generation; (3) anode-cathode gaps tend to short circuit with effective gap closure velocities of a few cm/ μ s; and (4) pinch stability becomes poor for diode aspect ratios above 20:1. Taken together, these restrictions imply a practical limit of near one terrawatt at a few ohms for the generation of efficient, intense pinches by a single REB diode. While these restrictions can be overcome somewhat, a substantial breakthrough is required to obtain useful pinches well above the one-terrawatt level. Consequently, in the pursuit of fusion by electrons one is led to approaches involving the generation of many independent pinched beams and their subsequent combination.^{23,24} In this section, we present results of preliminary studies of such a system. In the arrangement under consideration, dozens of separate pinched beams are to be transported via plasma channels from diodes to a target region. At the target, suitable beam overlap must be achieved and suitable incidence on the target must occur. The distinct elements of the problem to be discussed are (1) pinch formation in the diode, (2) REB injection into the plasma channel, (3) channel formation and beam propagation, and (4) beam overlap at the target.

Pinch Formation

In the course of other work, a simple anode-cathode geometry was developed for the Hydra accelerator²⁵ which has characteristics suitable for the present study. The cathode was a 76 mm O.D., 33 mm I.D., hollow brass cylindrical cathode with a 10° taper. The front face of the cathode had a series of

concentric grooves with sharp edges machined into it. The grooves in the cathode face caused rapid turn-on and uniform emission to occur. For pinch diagnostics, thin, flat carbon anodes were employed. They allowed highly resolved X-ray pinhole photography to be performed and the anode blow off generally did only minor damage to the cathode face. Anode-cathode gaps of 2 to 4 mm were usually used, with impedances in the range ≈ 2 to 6 ohms resulting.

X-ray diagnostics of the pinched beam were performed with an X-ray pinhole camera (time-integrated) and spatially apertured PIN diode measurements of the latter type (described elsewhere)²⁴ indicated that, once the pinch was formed, all (> 90 percent) of the X-rays produced came from within a 10-mm-diameter region on axis. From this information and densitometer traces of pinhole pictures we infer that the pinch was 3-mm in diameter with a peak current density of 3 MA/cm², when the diode power was 0.4 TW. For work described below, two separate anodes and cathodes were driven by a single Hydra line, so that only about 0.25 TW were available per cathode. Under these conditions, the available pinch intensity was reduced substantially.

REB Injection Into Channels

Once a satisfactory pinch has been obtained, the REB must be successfully injected into a channel. The channel is a current-carrying plasma which provides for beam current and charge neutralization. Ideally, the channel properties are chosen so that once a beam electron enters the channel, it should drift freely down the channel under the influence only of the channel fields. The beam electron should experience no collective forces. Consequently, a simple abrupt transition from the diode to the channel plasma and fields should provide satisfactory injection. A particle simulation of this process has been performed and reported elsewhere.²⁴ Note that for beams injected with large transverse energy, some electrons will experience excursions beyond their initial radius of injection. As a result, the beam current density in the channel may be lower than at the anode plane.

In experiments, the channel termination at the anode plane can produce problems. The channels used in this work were formed by wire-initiated discharges in the ambient air. The 2.54 x 10⁻³ cm diameter tungsten wires were attached either directly to thin foil anodes or to wire bridge:

directly behind the anode. The thin anodes served as electrical grounds for the diode fields, as return current paths for wire and channel currents, as mechanical wire supports, and as pressure windows. In all cases tried, substantial radial beam blowup was experienced at the injection point, so that the transported beam was of much lower current density than available at the anode plane. In addition, some beam loss occurred at the injection point. In the best cases, 80 percent injection efficiency was obtained. A radial blowup factor of two or three was common because the channel size was several times larger than the pinch diameter.

REB Transport in Plasma Channels

The channels used to transport the REB's from the diodes to the target vicinity are current-carrying, highly conducting, plasma discharges. They satisfy the need for a small diameter column which is charge and current neutralizing and has a "rigid" imbedded magnetic field. The channels could, in principle, be formed in many ways. In this work, they were initiated by air by fine tungsten wires which were driven by a 20 kV, 15 pF bank. The tungsten wires play mainly a formative role in the discharge process, with the wire material remaining on axis while the cylindrical discharge column expands in air about the wire. Holograms of the channel are shown in Fig. 12 for an early time and near peak current (50 kA).

A 1-D magnetohydrodynamic (MHD) model has been used to provide a means for comparison with the experimental results and estimates of channel parameters required for beam propagation models. The model is quite similar to one described by Aleksandrov, et al.²⁶ and Pavlovskii, et al.²⁷ The conservation equations governing mass, momentum, energy, and magnetic field intensity in cylindrical coordinates (practical cgs units) are:

$$\frac{dp}{dt} = - \frac{p}{r} \frac{\partial}{\partial r} (ru), \quad (1)$$

$$\rho \frac{du}{dt} = - \frac{\partial}{\partial r} (p + q) - 0.1 jH, \quad (2)$$

$$\rho \frac{dr_m}{dt} = - \frac{(p + q)}{r} \frac{\partial}{\partial r} (ru) - \frac{1}{r} \frac{\partial}{\partial r} \left(r\kappa \frac{\partial T}{\partial r} \right) + 10^7 j^2/\sigma, \quad (3)$$

$$\frac{dH}{dt} = \frac{\partial}{\partial r} \left[\frac{10^9}{4\pi r\sigma} \frac{\partial}{\partial r} (rH) \right] - H \frac{\partial u}{\partial r}, \quad (4)$$

where

$$\frac{d}{dt} = \frac{\partial}{\partial t} + u \frac{\partial}{\partial r}.$$

The parameters, ρ , u , p , T , and E_m are the air density, radial velocity, pressure, temperature, and specific energy, while q is the usual artificial viscosity. The magnetic field H is assumed to be azimuthal and the current density axial. A simple Ohm's law and Maxwell's equations were used to obtain Eq. (4).

The set of equations was closed by the addition of a tabular equation of state (which included ionization effects) relating the specific energy to the pressure and temperature. Magnetic field boundary conditions were provided by specifying the total current carried by the channel as a function of time, using values measured experimentally. It was assumed that the wire served only to initiate the air discharge and its presence was not included in the calculations. The initial conditions required included the temperature and radius of the discharge at the start of the computations. These were not known from experiment, and values of $T_0 \sim 0.6$ eV and $r_0 \sim 0.06$ cm were used. A solution to the set of equations was obtained by modifying the existing CHART-D 1-D Lagrangian hydrocode.²⁸ These modifications included adding the Lorentz force term, ohmic heating and a magnetic field solver.

The solution to the equations also required specification of the transport properties, σ , the electrical conductivity, and κ , the radiative diffusivity. The conductivity σ included contributions from both electron ion²⁹ and electron-neutral collisions. The

Fig. 12a. Hologram of channel at 1 μ s.

Fig. 12b. Hologram of channel at 6 μ s.

commonly available tabular Rosseland mean free paths λ_R (required to determine the radiative diffusivity) are not suitable for these calculations because they neglect absorption of the more energetic photons. Aleksandrov, et al.²⁶ and Pavlovskii, et al.²⁷ used an approximate $\lambda_R = 6 \times 10^{-5} T^{1.33}/\rho$ (T in eV).

The present computations studied both the Pavlovskii approximation and a simplified multigroup radiation approach where an effective λ_R diffusion approximation was used for the short-wavelength photons ($T > 7$ eV) and a loss term $E = 4\sigma_0 T^4/\rho\lambda_p$ was used for longer wavelength photons ($T < 7$ eV). The parameter λ_p is the Planck mean free path and σ_0 is the Stefan-Boltzmann constant. In general, the code predicts the existence of a high temperature (few eV), low-mass-density channel core, surrounded by a cold, high-density tube of gas. This is seen in the comparison of integrated refractivities in Fig. 13, where the Pavlovskii λ_R was used for these calculations. The comparison of both the channel boundary expansion velocity and refractivity is good. The calculated current density distributions are nearly uniform in the hot core.

Fig. 13. Radial profiles of fringe shift count from holograms in Fig. 12 and corresponding theoretical predictions.

Simple estimates may be made of REB-induced effects on channel dynamics. Using conductivity, mass distribution, and energy deposition information such as calculated above, one may estimate REB energy loss, degree of current neutralization, and beam-induced channel expansion. Such estimates show that adverse effects should not be prohibitive with air channels near 1 m long at REB currents near 1 MA at densities of several MA/cm². For the case of very much more intense REB's strong beam-channel coupling could occur, and variation of gas species and channel formation technique would need to be considered.

REB Overlap

The general problem of REB overlap is to determine a plasma and field geometry which achieves large beam superposition at a target and is consistent with target requirements. As a first step, we have analyzed a single, simple case and have neglected specific target requirements.

Of the many possible transport and overlap schemes, the one considered consists of 40 uniform current-carrying channels (radii r_c) arranged circumferentially around the target with return current channels forming the axle of a wagonwheel configuration.³⁰ Fig. 14 shows one concept of how such a wire configuration would fit in the front end of a multi-beam accelerator. For a given plasma channel radius, r_c , the converging channels begin to overlap at a radial distance R_0 from the center of the configuration. The plasma current along a beam channel is assumed to be constant in as far as the channel overlap radius (R_0), where it linearly decays over a specified distance as the individual currents merge into a disk current. A channel current of 20 kA was chosen for 1 MeV electrons to provide good containment of the beam, while remaining below the Alfvén-Lawson critical current of about 50 kA. The two axial return current channels are assumed to have expanded to twice the radius of the beam channels. In this study, an injected electron distribution was sampled by varying the initial phase space coordinates, calculating the 3-D trajectories, and recording the distance of closest approach to the center of the configuration ($r = 0, z = 0$). Note that the assumption of current neutralization implies that the electron trajectories are noninteracting and therefore simple superposition occurs in the beam overlap region. Scattering and electric fields are assumed negligible and symmetry of target irradiation is not evaluated.

Fig. 14. Concept for multibeam front end for EBFA.

The variation in the distance of closest approach to the center of the configuration ($R_{\min}$) attained for different injection conditions is shown in Fig. 15. The results of Fig. 15, when weighed with a realistic, non-hollow, injected beam distribution should actually produce better beam concentration than apparent in the figure. In Fig. 15a, 1 MeV electrons were injected at the channel radius (r_c) with a velocity nearly parallel to the channel axis. The electrons execute betatron oscillations approximately in the injection plane of the channel. Inside the channel overlap region there is cylindrical symmetry, so that when the injection plane is aligned with the x-y plane ($\alpha = 0$) all of the betatron oscillation can go into angular momentum (p_θ) in the overlap region. However, for $\alpha = 90^\circ$, none of the betatron motion appears in p_θ when the electron passes into the overlap region. Figure 15b shows the result of varying the amplitude of the betatron oscillation for an intermediate injection plane angle ($\alpha = 45^\circ$). In Fig. 15c, the axial variation of the electron distribution is obtained by moving the injection point ($r = r_c$, $\alpha = 45^\circ$) along the channel for a betatron cycle. In Fig. 15d, electrons are injected at the channel edge with an increasing nonaxial velocity component.

From these results, it appears that most of the injected electrons from a realistic beam can get inside a radius roughly one-quarter of the channel overlap radius at the hub of the configuration, regardless of the length of the channels. An estimate of the beam concentration (current density gain G) in these calculations is obtained by comparing the net current density crossing the cylindrical region of radius $R_{\min}$ and height $2r_c$ with the current density in a single channel:

$$G = j_{\text{net}}/j_c = 10 r_c/R_{\min} \approx \pi$$

This result depends sensitively on the actual plasma current configuration near the center of the system. We should note that the channel studies reported here have not been optimized, and higher gains may be obtained by reducing the overlap radius using different channel configurations and/or smaller channels. In fact, recent preliminary results predict that gains of ~ 10 can be attained, and the ultimate gain possible has not been determined but could be even greater.

Thus far, experiments have addressed several parts of the multiple beam combination problem. The efficient generation and transport of a single beam has been reported previously.³⁰ More recently, a dual diode front-end was constructed for the Hydra accelerator. It was used to generate two independent beams driven by a single Hydra line. The interaction of the two beams at a combination region was then studied.

The total energy available to the two anodes was 50 kJ. Total power and net impedance behavior is shown in Fig. 16a. The two diodes were generally balanced in energy to within 10 percent. A top view of the experimental arrangement is indicated in Fig. 16b. The flat carbon target was pulsed positive by the bank and the two wires were driven in parallel (60 kA total peak current). X-ray pinhole photographs were taken with the camera in the position shown, so that images of the anodes, wire support structures, wires, and target were all recorded. Two types of shots were taken: first, the wires were displaced vertically from each other at the target; second, the wires were attached to a common point at the target. X-ray images such as in Fig. 17 were obtained. The anode assembly image is relatively bright because of the presence of high-Z material and because the injection efficiency was poorer than that reported previously.³⁰ On some shots, the

Fig. 15. Summary of point-of-closest-approach results from 40 beam calculation.

Fig. 16a. Total diode power and net impedance for dual diode experiment.

Fig. 16b. Schematic top view of dual diode experiments showing pinhole camera position used for Fig. 17. Wires were staggered vertically as target for some shots.

Fig. 17. X-ray pinhole images showing anode structures, wires, and target. Spacing between anodes = 11.5 cm; wire lengths = 31 cm; spacing between spots at target in top image = 6 cm.

high density tube of air at the channel edge was visible in the X-ray photograph.

From this experiment, we conclude that no gross problems arise at the intersection of two beams and channels at a target. Some current density enhancement was obtained at the overlap region, but no calculations have yet been performed for this configuration which are useful for quantitative comparison.

Summary

Initial studies of the basic elements of the multiple REB combination scheme have been carried out. Results of theoretical analyses and experiments concerning beam pinching, injection, transport, and combination via plasma channels are encouraging. Ultimate limits to power density achievable by the technique have not yet been determined.

A HIGH RESOLUTION TIME RESOLVABLE FLASH X-RADIOGRAPHY SYSTEM

Hydrodynamic instabilities have been predicted for Relativistic Electron Beam (REB) inertial confinement fusion targets during implosion. Due to the high density target materials used, for example gold or iron, observations of the target implosion dynamics and instabilities are only possible with flash X-radiography (FXR) techniques. The FXR system resolution and penetrating power required for observing the different instabilities are listed in the following table.

In addition, a unique requirement of the FXR system arises from the necessity to discriminate against the background REB bremsstrahlung pulse. We have been successful in developing an FXR system that will for the first time resolve sufficient details to begin the experimental examination of instabilities. It consists of a 600 kV, $\sim 100 \mu\text{m}$ diameter and 3 ns FXR source and a time resolvable duo-microchannel plate X-ray camera that can be pulse actuated to discriminate against the background REB X-ray pulse.

A 3 ns, 600 kV commercially available FXR source has been modified to produce a X-ray spot size of $\sim 100 \mu\text{m}$. With this small source, magnification flash X-radiography of small objects several mm in size can be achieved. This is demonstrated in Fig. 18. The objects in this radiograph consist of 0.02", 0.01", and 0.005" tungsten wires spaced 0.02", 0.01", and 0.005" apart, and four gold spheres, two with 3 mm diameter and 0.002" wall thickness (note the small dent on one of these), and two 4 mm diameter with 0.008" wall thickness. The object to source distance was 10 cm and the object to film distance was 30 cm. This arrangement gave an image magnification of three.

Figure 19 shows a schematic diagram of a duo-microchannel plate X-ray camera. The input channel plate performs as an X-ray converter and a preamplifier with a gain of ~ 300 . It serves to convert the incident photon image to an electron image which is accelerated by the gridless electrode to the second channel

TABLE I
CHARACTERISTIC LENGTHS AND AERIAL DENSITIES

<u>INSTABILITIES</u>	<u>CHARACTERISTIC LENGTH (cm)</u>	<u>PENETRATING POWER (g/cm²)</u>
Gross Instability resulting from target and/or irradiation asymmetry	0.1	< 0.25
Ablator-pusher Rayleigh-Taylor	0.02	$\sim 0.25 - 1.5$
Pusher-fuel Rayleigh-Taylor	0.001	$\sim 1.0 - 4.0$

Fig. 18. X-radiograph made with the 100 μ m source.

Fig. 19. Duo-microchannel plate X-ray camera.

plate. During transit the electron image quality is preserved by a 4-k gauss magnetic field. The gyro-diameter (0.2 mm) of the electrons in this field defines the intrinsic resolution of this camera. After further amplification (~ 300) by the second channel plates the image is rendered visible by a phosphor screen and recorded onto film via contact printing. Since the channel plates can be operated in the pulsed mode, by pulsing on the bias voltage for the channel plates, the camera can operate with a shutter speed as fast as 10 ns.

A second version of this camera with multiple framing capability has also been constructed and is now undergoing tests. In this version, the input stage consists of five separately gated channel plates. In this way, five consecutive 10-ns X-radiographs with variable

framing intervals can be achieved. In addition to projection X-radiography, this version can be used in conjunction with a pinhole arrangement to provide time resolvable X-ray pinhole photography.

Coupling the FXR source with the duo-channel plate camera, the system can be used to record the target behavior after the REB pulse. Synchronizing the gating pulses with the FXR pulses after the REB X-ray pulse eliminates the background bremsstrahlung from the image. Using a projection arrangement to provide a magnification factor of three, the system resolution is unaffected by the camera resolution and only determined by the projection geometry. The system spatial resolution is $\sim 100 \mu$ m and temporal resolution is potentially 1 ns. The penetrating power of this system as determined by a Au stepwedge is $\approx 1.5 \text{ gm/cm}^2$. This system provides us a useful tool to study most of the possible instabilities with the exception of those occurring in the pusher-fuel interface.

HIGH POWER MAGNETICALLY INSULATED RADIAL DIODE

It has long been recognized by workers in ICF that the creation of intense focused ion beams would best satisfy pellet ignition requirements, but the requisite sources were discerned to be improbable. Recently, as a result of the development of potentially suitable ion beam ignition source technology, calculations predicated upon ion beams have been published.³²⁻³⁴ We report here progress toward extending previous ion diode results to create an intense ion beam which will be useful in pellet fusion studies. The final goal is to utilize pulse-power technology to create a beam which will be useful in pellet fusion studies. The final goal is to utilize pulse-power technology to create a beam which can deposit $\sim 10^{14} \text{ W/cm}^2$ symmetrically upon a pellet while maintaining good impedance match with the power source for the duration of the pulse.

Principles of Operation

The nominal 10 MeV 140 kA Hermes³⁵ accelerator was employed as the pulse-power source for the experiment described; the diode is shown in Fig. 20. Magnetic insulation to suppress radial electron flow was provided by pulsed coils with a period of 10 milliseconds to allow nearly unimpeded penetration of the field lines through the stainless steel

Fig. 20. Radial ion diode apparatus.

housing. The calculated field plot is shown in Fig. 21; measurements confirmed that eddy currents did not alter the field configuration. The magnetic field lines were nearly perpendicular to the electric field in the highly stressed portions of the anode and cathode to reduce electron leakage current, and the path length along lines connecting the anode and cathode was made as long as possible for the same reason. The gap spacing and the area of the ion-emitting source were chosen by assuming Child-Langmuir limited flow of protons with an applied voltage of 7.5 MeV. Other factors considered were possible plasma closure of the gap during the 800 ns prepulse and the magnetic field limit of about 20 kG which could be produced with easily constructed coils and available energy storage. The ion source was a piece of nylon plastic window screen placed in contact with the stainless steel anode surface. During the voltage rise capacitive energy is stored within the plastic and eventually the surface breakdown strength is exceeded causing the stored energy to dissipate in a surface plasma. We have not yet attempted to analyze this process in detail or to optimize the plasma layer formation. For several shots, a layer of deuterated polyethylene powder suspended in a volatile liquid was coated over the screen. We assumed that hydrocarbon contamination in the diode would cause at least half of the ion flux to be protons, rather than deuterons, consistent with previously reported data.³⁶ A 10-cm length of

polycarbonate plastic was inserted in the cathode shank to serve as a prepulse suppressor giving a capacitive division ratio of $> 4:1$ to the 800-kV prepulse.

Diagnostics and Results

Three B loops were positioned 120° apart on the input and output faces to estimate current flowing in the diode. Azimuthal variations of the B signals were insignificant. A pinhole X-ray camera was used to image the ends of the diode to determine the position of the electron leakage and thermoluminescent detectors (TLD's) and PIN diodes were used to compare the X-ray flux levels from different shots at several locations. Fig. 22 shows an example of electron leakage measurements at the drift tube end of the diode obtained with the pinhole camera for $B = B_{crit}^*$. It is apparent from the white patches on the drift tube wall in the figure that a substantial current of electrons was lost in radial flow along the field lines in the forward direction. The faint elliptical pattern surrounding the cathode indicates a small electron loss to the anode where it joins the drift tube wall. The pinhole camera viewing the input region of the diode indicated that < 10 percent of the leakage current appeared in this region and this was confirmed by TLD's. This is expected because the radial electric field and azimuthal magnetic field due to current in the cathode shank results in an axial drift force on electrons so that radial leakage would be in the forward direction.

The targets were either polyethylene or aluminum sheets, or conic sections which served both as witness plates and as targets for neutron production. The purpose of the conic sections was to determine the azimuthal uniformity of the ion flux; no azimuthal structure larger than the cathode screen mesh size was in evidence. Damage patterns on plates showed clear outlines of the perforations in the cathode screen (Fig. 23), indicating that space charge neutralization of the ion stream was rapid and nearly complete and that ion beam divergence was at most a few degrees. Electron transport along the B field lines within the cathode

* B_{crit} is the field for which an electron gyroradius equals the gap spacing.

Fig. 21. Plot of magnetic lines of force in gap.

Fig. 22. Pinhole photograph of electron leakage current in forward direction.

and field emission from the regions where these lines intersect the cathode is the means postulated for neutralization. It was also noted that the intense region of ion emission was restricted to areas covered by the plastic mesh.

Based upon current measurements and neutron output, we estimate that approximately 20 percent of the current was carried by protons. The balance of the current consisted of electrons which were diffusely deposited on the drift chamber wall. The peak diode voltage, corrected for inductance, was ~ 4 MV, and the total diode current was 160 kA. A plot of diode voltage and current for a typical diode is shown in Fig. 24. Since the inductive correction to the voltage was > 50 percent, errors in calculating the impedance are considerable. Nevertheless, we note that the impedance appears to drop considerably toward the end of the pulse. The impedance would be expected to stay fairly constant over the 100 ns power pulse because the gap is > 2 cm and plasma closure at 3 cm/ μ sec would change the effective gap by less than 10 percent. Measurements by others³⁷ have shown that the presence of magnetic fields $> B_{crit}$ tends to hold back plasma expansion and hold the impedance constant. It is likely that either plasma generated during the prepulse or increased electron leakage, perhaps from field emitted electrons on the cathode end are responsible for the fall in impedance.

Because of the extreme potentials developed by Hermes and the high diode feed inductance (~ 1600 nH) it was impractical to incorporate leads to an external electrical recording system in the cathode. Therefore, calorimetry was attempted by using a liquid crystal thermometer attached to a box behind an aperture. This device was to be photographed a few seconds after the shot. Unfortunately, hot vapor from the diode appeared to damage the liquid crystal surface and may also have contributed to the deposited energy in the box. We expect that the new ion diode outlined below will be more accessible to calorimetry. Additional ion production data was obtained by measuring the neutron output and energy from several combinations of ion source and target during the course of the experiment. A deuterated polyethylene coating was employed on the ion source screen together with a CH_2 target to produce the $C^{12}(d,n)N^{13}$ and $C^{13}(d,n)N^{14}$ reactions. For a few shots, a thin CD_2 coating was used over the CH_2 target in an attempt to superpose some yield from the

$d(d,n)He^3$ reaction. In the absence of CD_2 , it was possible to study proton induced reactions. The neutron detectors included two silver activation counters³⁸ and two scintillation time-of-flight (STF) detectors³⁹ placed 8.8 and 17.9 meters from the diode. The STF's had a linear response and peak current ratings of 0.6 and 1.2 A, and were shielded with 20.3 cm of lead.

An example of STF data obtained from the detector located 8.8 m from the diode is shown in Fig. 25. (A CD_2 source and a CH_2 target were employed.) The first peak is caused by bremsstrahlung from leakage electrons. The leading edge of the second peak is attributed primarily to fast neutrons from the $C^{13}(d,n)N^{14}$ reaction. The change in slope at 475 ns after the X-ray signal may be caused by the peak production of neutrons from the $C^{12}(d,n)N^{13}$ reaction. Of course, complications caused by other reactions which can occur for the materials in the diode in the 4 to 6 MeV ion energy range available, and the 100 ns neutron production interval make precise measurements difficult to carry out.

For a CD_2 -coated ion source and a CH_2 target, the neutron flux recorded on the silver detectors was 5×10^9 to 7×10^{10} . Using the value 4.2 MV for corrected diode voltage and total neutron yield cross-sections,⁴⁰ we calculate the diode current to be 20 kA of ions. We assumed in this calculation that about 50 percent of the ions accelerated were protons from diode contamination, in agreement with previous data.³⁶ Since the reaction cross-sections have a large functional dependence on voltage, the ion current inferences may be in error by as much as a factor of two.

This experiment differs from a previously reported radial ion diode experiment⁴¹ for which 60 percent generation efficiency was measured. In the previous work, the exclusion of field lines from the cathode would have caused a bulge in the field pattern in the vicinity of the end of the cathode. The flow of electrons would have been inhibited because E and B would be approximately orthogonal, a condition less well preserved in this experiment. In addition, it is possible that the glass insulator in the previous experiment could have reflected some of the electrons. If a single current feed such as employed in our experiment were used in the future, we would suggest using a B field modified to be mirror-like at the open end for the purpose of reducing leakage current.

Fig. 23. Aluminum witness plate showing damage pattern. The structure is due to the pattern of the perforations in the cathode mesh.

Fig. 24. Ion diode voltage and current (inductance corrected).

Fig. 25. A typical oscilloscope trace on the 8.8-m TOF detector showing the X-ray bremsstrahlung signal and the ion-beam target neutrons. The horizontal sweep rate was 200 ns/div and the vertical sensitivity was 4 volts/div.

Similarities in observations of beam quality, integrity of the acceleration gap and ion source after many shots, space-charge neutralization, and insulation against electron flow across the annular region of the gap give us confidence in the utility of extending this technique for fusion research.

Direction of Future Research

The defects of end leakage of electrons and magnetic deflection of the protons to an off-axis locus can be circumvented, by using the design conceptually sketched in Fig. 26. In this design, the magnetic coils are placed within the cathode structure, which is magnetically transparent. The anode is a good conductor which expels the field so that magnetic lines of force are tangential to the anode surface. The total magnetic flux traversed by a particle moving from the anode to the center is zero, so that ions undergo no net deflection. Since the lines of force close around the cathode structure and drifts are inward from both ends, electron leakage should be small. For the sketch shown, the Sandia Proto I and II accelerators rated at 2 and 8 terrawatts are ideally configured with two grounded radial feeds with a positive

radial feed interposed. This allows the magnetic coils to be readily connected to a capacitor bank and keeps the target at ground potential providing easy diagnostic access. The azimuthal magnetic fields caused by the diode current itself will perturb the focal spot size. This effect can be partially compensated by shaping the gap cathode, so that the original velocity of the ions is altered in a manner which causes the ions to converge for a particular diode current.

Fig. 26. Next generation two-sided feed, quasispherical, ion diode experiment.

Certain questions will be addressed to assess the utility of ion diodes for fusion research. We will, for instance, explore the dependence of beam quality on cathode mesh size and ion source design. We will find out whether electrons moving freely along field lines will allow those lines to effectively smooth out potential variations so that the field lines can be viewed as equipotentials. To operate at small gap spacing and low impedance, we will have to confirm and extend previous results showing that B fields can delay plasma closure of the gap so that a good impedance match can exist through the pulse. The diode self-magnetic fields may further aid in reducing electron leakage as high powers are attained. The spherical focus experiment now being planned for the 1 to 2 TW Proto I machine is expected to provide answers to many of these questions during the next year. A cross-sectional view is shown in Fig. 27.

Fig. 27. Proto I ion diode in cross section.

HIGH INTENSITY PULSED LINEAR ION ACCELERATORS

A relatively small (1 staff and 1 technical assistant) experimental program has been underway since spring 1977 to develop linear ion accelerators with vastly increased pulsed output capabilities compared to conventional devices. The experiments are aimed at a demonstration of the principles of space charge neutralized ion beam transport described in Ref. 42. In this report, the relevance of this work to the inertial confinement program will first be discussed, followed by a brief review of the physical principles of the device. The work done to date is listed. To conclude, experiments planned for the next six months are outlined.

The advantages of ions for initiating fusion burns of fuel pellets are well-known.⁴³ Two possibilities for the production of the required ion energy fluxes have been proposed, light ion diodes⁴⁴ and heavy ion beams from conventional accelerators.⁴⁵ Light ion diodes, an outgrowth of recent progress in the ability to produce proton beams using the technology developed for relativistic electron beams, can be designed for high power levels in the voltage range appropriate for protons (1 to 10 MeV). Consideration of heavy ions (U^{+}) is a consequence of severe current transport limitations in conventional accelerators; to achieve the required power at low current levels (1 kA) very high beam energies (100 GeV) must be used. Even so,

this heavy ion current represents a 10^4 extrapolation over present experience with light ion beams. If multistage linear accelerators could be developed with increased current carrying capacity, a vast parameter space of intermediate mass ions would be accessible which could have great practical advantages over the two extreme cases considered. The energy of the intermediate mass beam would be chosen to fulfill two requirements: (1) the beam current should be easily handled using conservative pulsed voltage technology, (2) the acceleration of the beam must reduce the beam divergence enough to achieve the required standoff distance from the final lens. A 1.5 TW module using 50 kA of O^{+} at 300 MeV with 3-m standoff from the target would be well suited to reactor studies and is theoretically possible.⁴⁶

Compared to light ion diodes, multistage intense accelerators would have the following advantages for fusion applications: (a) the decreased divergence angle from acceleration of the initial injector distribution would allow standoff from the target, (b) physical electrodes are not necessary; therefore, there is the potential for high duty cycle operation, and (c) the requirements on power flow in the conversion of electrical energy to beam kinetic energy, are reduced since the conversion process is spread out in space and time. The advantages over conventional accelerators using heavy ions are: (a) the ability to operate at lower beam energy makes the accelerator system more compact, less complex and much less expensive, (b) the possibility of using strong electrostatic beam focusing eliminates the vast magnetic field energy that would be needed to contain heavy ion beams, (c) the system is modular, so that tests can be made on devices costing a small fraction of the cost of a demonstration plant, (d) the requirements on the injector and low velocity acceleration section can theoretically be met, (e) the accelerator has a basically uniform design throughout its length and no complex switching and transport elements are needed for current multiplication, and (f) magnetically insulated diodes driven by pulse lines have a demonstrated high efficiency.

The theoretical basis for multistage magnetically insulated ion accelerators are described in detail in Refs. 42 and 47. Referring to Fig. 28 the accelerator consists of a number of annular drift tubes

separated by narrow acceleration gaps permeated by radial magnetic fields. Inside the drift spaces, which form the bulk of the accelerator length, the beam can be neutralized by cold electrons since the magnetic fields prevent the backflow of electrons, allowing the interior of the tubes to be at uniform potential. Sources of cold electrons line the tube walls and, consistent with experiment observations, these electrons can rapidly flow into the beam causing an almost complete cancellation of space charge fields. In the acceleration gap, the beam will be unneutralized, but the magnetic insulation allows strong fields to be impressed on the gap (MV/cm) eliminating longitudinal space charge effects. In addition, if the magnetic fields are shaped as is shown in Fig. 28, the electrostatic equipotentials will be similarly shaped since the magnetic field lines determine the location of virtual electrodes. Thus, transverse electric fields can be impressed which are large enough to overcome transverse space charge effects. An additional use of the insulating magnetic fields is that they can allow controlled, voltage dependent electron flow which can decouple the gap voltage from the instantaneous ion current and prevent klystron instabilities, as described below.

Fig. 28. Magnetically insulated acceleration gap. System is symmetric about centerline. (Calculated field courtesy of J. Freeman.)

The initial theoretical work for the magnetically insulated multistage ion accelerator was performed at Cornell University (Ref. 42). Additional theoretical work has been performed at Sandia Laboratories and was

presented in Ref. 47. It was suspected that nonrelativistic beams accelerated by loaded pulse lines would be subject to instabilities resulting in filamentation of the longitudinal phase space, degradation of the current profile and, hence, difficulties in matching and controlling the beam in downstream sections. The instability comes about because voltage variations in upstream gaps (which are inevitable if the beam is to draw significant energy from the pulse line) produce extrusions of the longitudinal phase space. These can velocity bunch so that current spikes are produced in downstream gaps. These produce larger voltage variations, and hence the process bootstraps. In order to investigate the severity of this problem, a computer simulation code (PILAC) was developed to trace particle orbits through multigap systems driven by realistic pulse line models. The code allows arbitrary initial phase distributions, addition of shunt circuit elements, and adjustment of the pulse charge, characteristic impedance, and timing of the various acceleration stages. Testing was done at low beam loading with a positive ramp in the applied voltage (controlled by shunt circuit elements) and, as expected, the beam behavior was similar to that of an RF driven linear accelerator. At higher loading, bunching instabilities set in very quickly, as shown in Fig. 29. It appeared that for reasonable efficiencies (10 percent or greater), broadening of the velocity spread of the injected beam could not prevent the growth of bunches, although the onset was somewhat delayed.

A possible cure for klystron instabilities is the use of controlled electron flow in downstream gaps to decouple the gap voltage from ion current variations. Magnetically insulated gaps, if run near the critical cut-off magnetic field, exhibit many of the properties of zener diodes. Electrons will flow until the gap voltage is depressed below that needed to allow electron crossing. If the magnetic field is adjusted to maintain the gap voltage at $V(\text{pulse line})/2$, then the voltage will be clamped near this value as long as the maximum ion current is less than $V(\text{pulse line})/2Z_{\text{line}}$; as ions flow in, they slightly depress the voltage which has a large effect on the electron current, and hence the electrons are replaced with ions. When the V-I electron curves for the annular gaps of the accelerator are obtained experimentally, they will be incorporated into PILAC to investigate the utility of this method.

Fig. 29. Typical PILAC run. Gaps powered by 50 ohms pulse lines charged to 1 MV with a 30 nH series inductance and a 100 ohm shunt resistor. Initial phase space distribution is rectangular.

- (a) Emerging phase distribution ($v_z - 2$) and gap voltage (dotted) and current (solid) profiles for Gap 1.
- (b) Emerging phase distribution (note change of scale) and voltage and current profiles for Gap 2.

Other theoretical work included studies of transverse focusing of ion beams using imperfect lenses with negligible space charge forces. The computer program developed will be useful to provide a baseline against which to compare experimental results on beam focusing. Members of the theoretical group have contributed to an understanding of the accelerator concept. Magnetic field solutions for the experiment under construction were provided by J. Freeman (see Fig. 28). The process of beam neutralization by cold electrons has been studied by J. Poukey with very encouraging results. These studies will continue with more complex models for the electron dynamics.

The major thrust of work in the last six months has been in the design of an initial five-stage accelerator, Pulselac, to investigate the critical concepts of high current beam transport. A complete machine design

has evolved and is currently under construction. A sketch of the initial stages of Pulselac is given in Fig. 30. A list of design and testing work follows:

1. An unused Marx generator assembly (including oil tank, oil, switches and capacitors) was located and rebuilt to yield 25 kJ at 450 kV. A fast, high reliability switch was installed, and the Marx was successfully tested at maximum voltage into a high resistance load.

2. Cable for the cable Blumlein lines of Pulselac were tested to 400 kV. In order to fire the Blumlein with low jitter, trigatron switches were designed. A low-inductance, multi-output trigger Marx generator was designed, built, and successfully tested to 100 kV.

3. Multielement wall flashboards to supply the cold electrons for beam neutralization were designed. A twelve output capacitor bank for flash initiation was built and tested

4. Vacuum chambers, vacuum insulators, drift tube assemblies, and magnet coils for the accelerator were designed. Delivery is expected in January 1978.

5. The main magnetic field banks were designed and are being assembled. The total stored energy is 30 kJ.

6. Two complete vacuum systems with controllers were built.

7. A fast pulsed gas valve was built and successfully tested.

At the same time, a new laboratory was set up specifically for multistage ion accelerator experiments.

To the present, the bulk of the time has been devoted to design, construction and testing of subsystems. Experiments will be initiated in early 1978. The Pulselac is designed for 300 to 400 kV/stage. The design is modular so any number of coupled stages can be investigated up to a maximum of 5. The injector should be able to supply 10 kA of protons. The maximum degree of tunability has been incorporated into the device. Gap spacing and effective magnetic field curvature as well as the pulse length and characteristic impedance of the cable Blumlein lines can be varied. In addition to the primary goal of obtaining

PULSELAC Modules 1 and 2

Fig. 30. Initial stages of Pulselac experiment.

the maximum ion current at the highest brightness, the following areas will be studied:

1. Effectiveness of cold electron neutralization. Measurements of time-dependent transverse phase distributions as beam propagates through magnetic field.
2. Measurements of phase distributions from injector.
3. Experiments with gas and pulsed plasma ion sources for injector.
4. Determination of focal lengths of electrostatic lenses.
5. Experiments in pulse shaping using shunt circuit elements in pulse lines.
6. Confirmation of velocity bunching instabilities predicted by PILAC.
7. Attempts to cure velocity bunching by electron clamping.
8. Experiments with plasma-filled magnetic lenses to bring output beams to high intensity focus.

SLOT REFLECTOMETRY FOR DIAGNOSING DIODE PLASMAS

Slot reflectometry is a diagnostic method for measuring electron density and collision rate by looking at the conductivity of a plasma which is terminating a waveguide. The diagnostic is best suited to measuring plasmas near a metal surface. It has been used in the past to measure anode plasmas on a Nereus diode, prepulse plasmas on the Proto 1 accelerator and gun plasmas stagnating against metal plates. While the last measurement was originally used to characterize the guns used in plasma-filled diode work, there is another region where slot reflectometry will be of value. The ion diode work uses plasma covered surfaces as ion sources. At present, there are metal-dielectric structures which flash to make plasmas. In addition, the use of gun plasmas stagnating against the anode offers potential as a uniform source of ions in self-pinch diodes (for diodes employing external magnetic fields the flow of plasma across the field must be considered). Guns presently used yield 10^{15} cm^{-3} at the surface where the plasma stagnates and 10^{13} cm^{-3} away from the surface.

The theory of slot reflectometry has been done rigorously and the calculation of electron density and collision rate is readily accomplished either graphically or by small programmable calculator. The experimental apparatus has been refined to yield the highest possible accuracy for fast time scales (rise times of a few ns). The measurement range (0.5×10^{13} to 10^{15} for present apparatus) is unavailable with our other diagnostics.

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TARGET INTERACTION

OVERVIEW

Target interaction and implosion physics research has continued on the Hydra and Proto I accelerators. Diagnostic development of optical X-ray, XUV, and neutron detection methods was also carried out as part of the target interaction program.

Measurements of the interaction of a tightly focused REB with planar and spherical gold targets were made on the Proto I accelerator (2 beams, each typically 1.8 MV, 200 kA, 20 ns). Irradiation symmetry to better than 10 percent has been routinely obtained with ~ 50 percent of the electrons reaching the target region. Due to the low v/v of the Proto I beam, only a small fraction of the incident flux is absorbed in the target in good agreement with theoretical calculations. Preliminary calculations for a focused 1.5-MV, 2-MA Proto II beam, indicate that order of magnitude increases in the energy deposition are likely due to recirculation of electrons in the intense self-fields of the beam. The Proto I experiments underscore the necessity of both considering the electron focusing efficiency and the efficiency with which the electrons couple to a target when estimates of target energy deposition are made.

Radiation temperature measurements associated with XUV (soft X-ray vacuum ultraviolet) photoelectric diodes or, commonly called, X-ray diodes (XRD's) imply that electrons incident on 6 micron thick, than a single pass through the foil. Defining the concept of enhancement as that of a given electron making more than a single pass, we found enhancement factors of 2 for the above foils. We have found a geometrical dependence on the enhancement, namely, the diameter of the hole behind the foil. Independent of geometry, we found no enhancement for gold and aluminum foil thicknesses greater than 12 microns. Current density and energy deposition are not inconsistent with a beam stagnation model.

Research on implosion dynamics of ablatively driven targets has resulted in the development of experimental techniques and optical diagnostics to measure implosion time, pusher temperature, and implosion symmetry. By utilization of shock convergence, pusher temperatures of 5 to 10 eV and pusher velocities of ~ 3 cm/us have been obtained on Hydra, corresponding to

peak pressures of 10 Mbar in tungsten. Lower pusher temperatures (2 to 3 eV) have been correlated with nonuniform loading, in particular target configurations. Ablatively driven cylindrical targets (brass) have been driven up to 1.3 Mbar pressures, and optical holography indicates jet formation during the final stages of implosion due to nonuniform loading. The formation of ejecta (fluff) from shock loading of the pusher free surface has been observed in experiments with cylindrical targets.

Development of time-of-flight neutron diagnostics has continued. The thermonuclear neutron "signature" from an ICF target has been established using a fast plastic scintillator-photomultiplier combination shielded by several cm of lead in conjunction with a 2-ns-wide neutron source which directly simulates the expected thermonuclear neutron pulse from a REB imploded target. In addition, neutron Monte Carlo calculations have been carried out to predict the response of a SPM to a burst of thermonuclear neutrons. In both cases, the thermonuclear neutron pulse shape is found to have a sharp leading edge of a few nanoseconds, a rather narrow FWHM of the order of some twenty to thirty nanoseconds, and a long tail that can extend for up to one hundred nanoseconds.

Details of our research on preheated fuel targets which rely on magnetic thermoinsulation to permit the use of laser beam power are also reported here. We have carried out experiments which have produced $\sim 10^6$ DD neutrons and our analysis indicates that a fuel temperature ≈ 1 keV and a fuel density of 1.6×10^{-2} g/cm³ has been achieved. Since our analysis is one dimensional, this conclusion must await scaling experiments for verification.

BEAM-TARGET INTERACTION MEASUREMENTS ON PROTO I

A series of experiments which were designed to assess the feasibility of implosion studies on DT-filled spherical pellets were performed on Proto I (2 diodes, each 1.6 MV, 200 kA, 20 ns). Preliminary measurements of the Proto I pinch on thick-flat targets indicated that about 50 percent of the current could be focused to the target region ($r < 0.8$ mm) which was in agreement with PIC calculations

of J. P. Quintenz. If all this energy were uniformly deposited in a DT-filled thin gold sphere, calculations¹ indicated thermonuclear neutron yields greater than 10^6 would be obtained. The experiments described in this report investigated the uniformity which could be obtained on spherical pellets with the tightly focused beams of Proto I, and the coupling efficiency of the focused beam to the targets. The diagnostics included quantitative X-ray pinhole photography, visible radiometry (5070 ± 50 Å) and VUV radiometry (8 to 80 eV). By comparison with PIC diode simulation which included an approximate model of the beam-target interaction as well as Monte Carlo calculations which coupled the pinch profiles from the PIC simulations with a more exact treatment of the beam-target coupling, a clear picture of the beam-target interaction was obtained. The theory as well as experiment indicated that insufficient energy was coupled to the target to obtain neutron yields of 10^6 even though irradiation symmetry of 10 percent could be routinely obtained. The details of these experiments will now be considered.

Irradiation Symmetry Measurements

The first measurements were designed to evaluate the dependence of irradiation symmetry on the target mounting geometry. For these experiments 1.5 mm diameter gold pellets with both 25 μ and 50 μ wall thicknesses were mounted in 0.8 mm thick aluminum anodes and positioned in the mid-plane between two 2.54 cm diameter tapered hollow cathodes having dielectric flashover switches in their base as shown schematically in Fig. 1. The cathodes were aligned with the pellets to an accuracy of 0.2 mm. The gold pellets were mounted in the anode using several geometries.² Two examples are shown in Fig. 2. In the first, the central portion of the aluminum was tapered over a distance of 3 mm to a central hole the diameter of the pellet. The pellet was then placed in the hole and connected to the aluminum using conductive epoxy around the equator of the pellet in the small gap between the gold pellet and the aluminum anode. To insure uniform return current paths, the entire assembly was then coated with 1- μ gold plating over the central 1.2 cm diameter of the anode. The second geometry involved supporting a pellet in the center of 1.2 cm diameter hole on three 0.2 mm diameter stainless steel tubes. As in the first case, a 1- μ gold plating was placed over the entire central portion of the anode.

The primary diagnostic for determining irradiation symmetry was X-ray pinhole photography.

EXPERIMENTAL GEOMETRY

X-ray pin hole photography
Visible Radiometry (5070 Å)
VUV Radiometry (8 eV - 80 eV)
X-ray Radiometry (30 keV - 180 keV)

Fig. 1. Experimental geometry for dual diode target measurements on Proto I.

Figure 3 shows an X-ray pinhole photograph and a microdensitometer scan across the image. The enhancement of the X-rays at the edge of the shell is due to limb brightening.³ On this shot, the symmetry is better than 5 percent around the circumference of the sphere. For both geometries described above, uniformities of 5 percent to 15 percent could be frequently obtained, however, the total X-ray intensity tended to be higher for the first geometry which provided for better grounding of the target. Although this technique provided good data on the variation of deposition with azimuth around the target, the variation from pole to equator could not be determined except by very crude estimates based on the ratio of the X-ray amplitude at the edge to that at the center. Since, as explained later, the total electron deposition appeared to be significantly less than that required for measurable thermonuclear neutrons, this aspect of the symmetry was not investigated further.

Energy Deposition Measurements

In assessing the feasibility of doing implosion studies, not only must the irradiation symmetry be determined, but also the

(a) Conducting epoxy suspension in chamfered A/anode.

(b) Spoke suspension in 1.2-cm hole in A/anode.

Fig. 2. Two of the pellet geometries investigated on Proto I.

Fig. 3. Typical X-ray pinhole data. Top is a microdensitometer scan across the diameter of X-ray pinhole photo shown below.

efficiency which the electron energy can be delivered to the target from the cathode. To answer this question, both the spherical targets, described above, and more easily fabricated, planar targets were used. Optical radiometry, VUV radiometry and quantitative X-ray pinhole photography provided estimates of the energy deposition in the targets. The radiometry data was converted to an equivalent blackbody temperature which was compared with the electron temperatures predicted by the coupled radiation-hydrodynamic code CHART-D. Figure 4a shows a comparison for typical optical data and Fig. 4b shows similar data for the VUV radiometry. In both cases, the diode power pulses were modeled with a trapezoid and the maximum amplitude adjusted to obtain agreement with the experimentally determined electron temperatures. For these data, good agreement is obtained when peak specific power deposition of 3 and 7.5 TW/gm are assumed in the calculations for the optical and VUV data, respectively. The measurements depended heavily on the deposition or temperature in the outer regions of the plasma with $\rho r \sim 10^{-4}$. The measured temperatures were found to be independent of the target thicknesses, to within ~ 30 percent over the range of 6μ to 100μ in agreement with theoretical calculations reported in the next section.

The total dose to the pellet was also inferred from the intensity of the images on calibrated X-ray film. The calibrations were performed at Sandia's Positron facility. Renormalization was obtained by comparison of the X-ray dose to the film with predictions of X-ray generation using coupled electron photon Monte Carlo codes.⁴ The pinhole images were filtered to provide 80 percent of the response (10 percent to 90 percent) in photons with energies of 30 to 160 keV. The X-ray intensities from the gold targets indicated depositions of order 5 TW/gm. The X-ray intensities were observed to scale with the thickness of the target for thin targets, indicating constant specific energy deposition (for the filtered pinholes, self-absorption was not a significant effect).

No significant differences in the deposition were observed between two-sided illumination of spherical targets and single-sides irradiation of planar targets. The reasons for this apparent discrepancy are twofold. In the case of the X-ray diagnostics, Monte Carlo calculations, described below, indicate little electron recirculation within the target region and a bremsstrahlung spectrum strongly peaked in the forward direction. In the case of the VUV and

and optical diagnostics, only the front surf of the target is observed. The 2:1 variatic observed in the deposition profile of the Monte Carlo calculations would change the factor of two effect to a 50 percent effect. The failure to observe this change could be due to either inadequate statistics on the deposition or to a 30 percent reduction in the pinched current.

Theoretical Calculations

The experimental results have been modeled using two main calculational approaches. Particle in a cell calculations (PIC) have been performed by J. P. Quintenz² (5241) and Monte Carlo calculations have been performed using several Sandia electron/photon transpo codes. The Monte-Carlo calculations relied heavily on the results of the PIC calculations, gave good agreement in the limits where both codes are believed accurate, and provided additional theoretical predictions in the intermediate regime where the approximations in the PIC scattering model are believed to be invalid.

The PIC calculations are described in some detail elsewhere.⁶ The calculations not only treat the self-consistent electric and magnetic fields but also treat the scattering and reflections from the anode with a macroscopic approximation written by M. M. Widner (5241). The results for Proto I parameters indicate that for a thick anode, no effects are observed due to the scattering in the anode. The current density averaged over a 0.4-mm radius was calculated to be 13 MA/cm² with half the energy deposited in a 0.8 mm radius. The thin target results for 6- μ gold targets indicated a radial diffusion of the deposition energy deposited in the 0.8-mm radius target region.

Coupled electron-photon Monte Carlo calculations were performed to look at the effect of scattering on the deposition in planar targets which are neither very thick nor very thin compared to a csda range. Both one-dimensional (TIGER)⁴ and two-dimensional (CYLEM)⁵ calculations were performed. For all the calculations, a cosinusoidal angular distribution for the incident electrons and a radial distribution consistent with the PIC calculations of Quintenz were assumed. A r^{-1} variation in the current density was assumed for each bin of the PIC simulation in order to smooth the discontinuities in the profile. The two-dimensional calculations included magnetic fields consistent

(a)

(b)

Fig. 4. Analysis of typical radiometry data.

- a. Visible data at $5070 \pm 30 \text{ \AA}$.
- b. VUV data at 8 to 80 eV.

with the current profile and electric fields which were roughly equal to the self-consistent fields calculated in the PIC simulations. Variation in the electric field by factors of 2 to 3 in the CYLEM resulted in negligible changes (~10 percent) in the energy deposited in the target region ($r < 0.75$ mm).

The two-dimensional calculations, with 51 percent of the incident electrons striking the target region, indicate that 0.8 percent, 2.2 percent, 10.4 percent and 40 percent of the incident energy will be deposited in target region on 6, 12, 50, and 250- μ gold foils, respectively. As in the PIC calculations, the fields were chosen to be symmetric about the anode for all but the 6- μ case. The reason for the slightly lower value (0.8 percent vs. 1.1 percent for the PIC simulations) for the 6- μ foil can probably be explained by the difference. In contrast to the PIC calculations of 100 percent efficiency, an efficiency of 80 to 90 percent was observed for energy deposition in thick anodes. For both the 6- μ and 50- μ foils, with no fields at the rear surfaces of the targets.

One-dimensional calculations were performed with the Monte Carlo code TIGER for the case of 6- μ and 50- μ gold targets and compared with two-dimensional calculations in which the fields at the rear of the anode were removed. The TIGER calculations were performed both by allowing all transmitted and reflected particles to escape and by allowing specular reflection of the reflected particles at the front surface of the target. The arithmetic mean of the two calculations predicted 0.8 percent and 9.2 percent compared with 0.8 percent and 9.7 percent for the two-dimensional calculations.

The very good agreement between the PIC calculations and Monte Carlo results for thin anodes suggests that the incident profile is not seriously modified by the reflexing of electrons in the anode. The good agreement between the one- and two-dimensional codes in the case where half the back scattered electrons are reintroduced indicate a relatively small enhancement due to recirculation in the diode field; about 80 percent of the dose is obtained if no recirculation occurs. The lack of recirculation is apparently a result of the relatively low value of beam v/γ , namely, of order 1. The observed lack of reflexing occurs only that the reflexing electrons tend to strike the anode at radii larger than the pinch region. Other data

in fact, is consistent with the average electron making about two passes through the foil before being lost at large radii.

Summary

Experiments to measure the interaction of the superpinched electron beam on the Proto I accelerator have been completed with both planar and spherical targets. Azimuthal symmetry to better than 10 percent has been observed for a number of target configurations and the specific energy deposition is measured to be independent of target thickness for thin gold targets and to range from 3 to 9 TW/gm depending on the particular diagnostic technique. The energy deposition predicted by the theoretical calculations and the experimentally determined values are summarized in Fig. 5. The specific energy deposition is a factor of 2 to 4 less than that predicted by the theory and about a factor of 3 to 5 less than that required for measurable yield of TN neutrons. The scaling of deposition with target thickness is an excellent agreement with calculations although the experimental pinch profile is slightly broader than predicted by the PIC simulation. Proto II, with powers of 8 TW and $v/\gamma \sim 50$ (vs. 0.7 TW and $v/\gamma \sim 2$) is nearing readiness. Preliminary estimates of the energy deposition in a $v/\gamma \sim 10$ pinch suggest that an order of magnitude increase in the energy deposition over that measured in Proto I due to recirculation of the electrons in the intense self-fields of the beam. Due to the enhanced capabilities of Proto II, DT-filled target experiments will not be performed on Proto I. On the other hand, Proto I parameters may lend themselves more readily to ion beam/target experiments, thus ion diode experiments are presently being planned.

ELECTRON DEPOSITION IN THIN GOLD AND ALUMINUM FOILS HEATED BY A RELATIVISTIC BEAM

Radiation temperature measurements associated with XUV (soft X-ray vacuum ultraviolet) photoelectric diodes or commonly called, X-ray diodes (XRD's) imply that electrons incident on 6-micron thick, unbacked, gold and aluminum foils make more than a single pass through the foil. We found electron energy depositions consistent with theoretical calculations which include the effects of self electric and magnetic fields in thin targets.

Fig. 5. Comparison of theoretical and experimental data on Proto I.

the diameter of the hole behind the foil. Independent of geometry, we found no enhancement of gold and aluminum foil thicknesses greater than 12 microns. Current density and energy deposition are not inconsistent with a beam stagnation model.

Current densities in these experiments were rather modest, less than 5 MA/cm² for the Proto I accelerator ($v/\gamma < 3$) and less than 0.6 MA/cm² for the Hydra accelerator ($v/\gamma < 7$).

Introduction

During the last six months we have been experimentally investigating electron energy deposition in thin, flat, anode foils. As has been proposed, if there were some means of efficiently coupling beam energy to thin targets, then targets with less mass could be used for electron beam fusion targets and power requirements from electron beam accelerators could be reduced. Recently Clauser, et al., have reported efficient coupling to a spherical shell extending from the anode on a stalk. The mechanism for coupling was beam stagnation which is a combination of magnetic stopping and electrostatic reflexing. In these series of experiments we wanted to investigate a simpler target design with particular emphasis on the effect of target thickness on energy deposition. In this section of the report, we describe a series of three experiments that were carried out to observe enhanced deposition: (1) 50.8, 25.4, 12.7, and 6.35 micron thick unbacked gold foils on the Hydra accelerator with an unbacked hole radius of 1 cm; (2) 50.8, 25.4, 12.7, and 6.35 micron thick gold foils and 6.35 micron thick aluminum foil on the Proto I accelerator with an unbacked hole radius of 0.5 cm; and (3) 205.7, 88.9, 38.1,

and 6.35 micron thick aluminum foils on the Proto I accelerator with an unbacked hole radius of 1 cm. Particular emphasis was placed on XUV radiation temperature measurements for describing energy deposition and hard X-ray measurements for determining total charge and electron density incident on the foils. Other sections of this report will describe optical temperature measurements, two-dimensional effects and detailed theoretical modeling of the above experiments.

Experimental Procedure

Figure 6 shows the experimental setups for the three series of experiments on the Hydra and Proto I accelerators. Tapered annular cathodes with inner and outer radii of 1.6 cm and 3.8 cm, and a cone half-angle of 80° were used with a cathode spacing of 0.27 cm; corresponding to an initial geometrical R/d of about 5.7 on the Hydra accelerator. Tapered annular cathodes with inner and outer radii of 0.64 and 1.27 cm and a cone half-angle of 75° were used with an anode-cathode spacing of 0.32 cm; corresponding to an initial geometrical R/d of about 2 on the Proto I accelerator. On the Hydra experiments, either optical photodiodes for optical temperature measurements on the grazing incident spectrograph for time-integrated, high-resolution XUV spectra was used on a given shot. On the Proto I experiments, only single-sided operation was used. On the series (2) experiments on Proto I, the bottom diode was used. On the series (3) experiments on Proto I, the top diode was used. This was done to allow both front and rear radiation temperature measurements to be made. Figure 7 shows typical accelerator operating characteristics for both the Hydra and Proto I accelerators. Typical parameters were 0.8 MV, 300 kA, 80 ns pulse width for the Hydra accelerator and 1.5 MV, 200 kA, 30 ns pulse width for the Proto I accelerator.

Radiation temperature measurements were made with a triplet array of XRD's⁸ and/or visible (~ 507 cm) photodiodes. Figure 8 shows the cathode response of XRD's as a function of incident photon energy and the sensitivity of XRD's to a blackbody radiation source as a function of blackbody temperature. Between 3 and 7-eV blackbody temperature, the response of the XRD varies only 20 percent, indicating its strong T⁴ dependence in this temperature regime. The detectors are insensitive to radiation temperatures below 2 eV. Filters were placed in front of two of the XRD's to view the shot on spectral regions of 30 to 70 eV (1-μm aluminum) and 70 to 284 eV (0.33-μm

Fig. 6. Experimental setup on Hydra and Proto I.

Hydra:

Fig. 7. Machine characteristics for Hydra and Proto I.

$$\bar{R} = \frac{\int_0^\infty R(E) S_{BB}(E, T) dE}{\int_0^\infty S_{BB}(E, T) dE}$$

$$= \frac{\int_0^\infty R(E) S(E, T) dE}{\sigma AT^4}$$

Fig. 8. Response of X-ray diodes (XRD's) to photons and as a function of blackbody temperature.

Parylene, C_8H_8). In measuring the blackbody temperature from a radiating disk at normal incidence, one finds that the power on the detector is given by

$$P_{BB} = 2\sigma AT^4 \left(\frac{d\Omega}{\Omega} \right)$$

and

$$\frac{d\Omega}{\Omega} = \frac{da_{det}}{2\pi R^2}$$

where da_{det} is the detector area, R is the distance from the source, and A is the source area. The aperture system for the XRD's (see Fig. 6), allowed a maximum viewing area of 2.85 cm^2 on the Hydra accelerator and 0.5 cm^2 on the Proto I accelerator. In estimating the temperature, the diameter of the energy deposition profile was chosen to be 2 mm greater than the FWHM of the hard X-ray profile.⁹ This is an extremely conservative estimate of the temperature, because of the T^4 dependence.

In measuring radiation temperature as a function of time, one is actually measuring the energy deposition in the foil as a function of time. In order to determine whether the energy deposition in the foil is due to multiple passes of an electron, one must assume average deposition energy for a given electron in a single pass. Figure 9 compares different angular electron distributions for a given photon flux incident on 6- μm thick gold. The number of electrons incident per unit solid angle chosen to be a constant gives the most reasonable energy deposition for pinched beam diodes. This means an average electron angle of incidence of 45° . Also, we have allowed the electric field in the diode to return all scattered electrons back to the anode at the same point of scattering, a one-dimensional analysis. This deposition profile is what we call the average deposition per electron.

It is clearly the maximum possible energy deposition per particle, and probably overestimates the deposition per particle by as much as 30 to 40 percent.¹⁰

Similarly, in order to estimate the total deposition in the foil, we must know the number

of incident particles per unit time on the foil. To determine the total current in the pinch, we utilized high band-pass filters in front of absolutely calibrated PIN's. The PIN's were absolutely calibrated using a DC electron beam source which produced normally incident monoenergetic beams between 0.4 and 1.1 MeV on 50- μm gold plus 0.5-cm-thick graphite targets and a one-dimensional electron photon transport code TIGER⁴ to calculate the resulting photon spectrum. The PIN's were calibrated behind 150- μm -thick uranium and 250- μm -thick erbium photon filters to allow an essentially flat response for incident radiation. Figure 10 shows the spectral and total energy response to the PIN's. In the case of the thinnest aluminum foils, the total current was estimated from absolutely calibrated photographic film.¹⁰

Temperature measurements were compared with calculations using the Lagrangian hydrodynamic code CHART-D.¹¹ This code, which includes complete equation-of-state, Saha ionization and thermal electron and radiation transport was used to calculate temperature and density as a function of time and position on both sides of the thin foil. CHART-D is a one-dimensional code. By inputting the average energy deposition per particle and electron number density, the radiation temperature as a function of time was found. We varied the electron number density holding the pulse length constant until it matched the experimentally measured temperature. A comparison was made with the integrated electron flux to the target as inferred from hard X-ray measurements. In all cases the two values of electron number density were in agreement. In the case of 6- μm thick targets the experimentally determined values of n_e when compared to diode current implied that the electrons made more than one pass through the target.

Results

Figure 11 shows a one-dimensional analysis for current density for 50, 25, 12, and 6- μm -thick gold foils and 0.32-cm range thick carbon as a function of radius from time-integrated pinhole photographs for the series of experiments on the Hydra accelerator. Peak current density never exceeded 0.6 MA/cm^2 for the gold foils. The pinch profile was normalized to the total current as given by the dB/dt monitors assuming 90 percent of

Fig. 9. Photon energy production for different incident electron angular distributions on 6- μ m gold foils.

Fig. 10. Response of high band-pass PIN's to incident photon energy. The buildup factor is the difference between experimental measured photon flux to the theoretically predicted photon flux.

Fig. 11. Shot 5691 0.32-cm-thick carbon - - - - -
 Shot 5692 50-μ-thick gold . . . . .
 Shot 5693 25-μ-thick gold - - - - -
 Shot 5694 12-μ-thick gold - - - - -
 Shot 5706 6-μ-thick gold —————

the current was in electrons (10 percent in ions). Total current in the pinch as a function of time was also inferred by the absolutely calibrated apertured PIN detector as shown in Fig. 12. In the case of the 6- μm thick gold, the inferred current appears to exceed the total current as measured by the dB/dt monitors. Figure 13 compares the experimentally measured temperature as a function of time to that of the temporal profile of temperature with a maximum current density of 0.5 MA/cm². Indeed, the experimental temperature profile corresponds to a profile with a maximum current density of 0.4 MA/cm² or 1 TW/g. From Fig. 11 we see that the maximum current density is 0.2 MA/cm² when the total current is normalized to the dB/dt monitors for 6.35- μm gold. This corresponds to a peak power of 0.5 TW/g, where $dE/dx = 2.54$ MeV-cm²/g. From this data we conclude that electron energy coupling to thin 6- μm gold targets was increased over that expected from electrons making a single pass in the target, by a factor of 2. Figure 14 shows the time integrated XUV spectrum. Very few emission lines appear in the spectral region (greater than 600 Å), suggesting that most of the radiation is due to continuum. The spectrograph is astigmatic and is therefore insensitive to continuum radiation. Figure 15 shows absorption lines appearing in the visible. However, these appear late in the power pulse. During the main part of the power pulse, the visible spectral region is dominated by continuum. Therefore, the assumption of a blackbody radiating source appears to be valid.

Figure 16 shows a one-dimensional analysis for current density for 50, 25, and 12- μ -thick gold foils and 25- μm -thick gold plus 0.635 cm range thick carbon with 0.635-cm gap between the carbon and the gold foil. Current density was inferred from apertured PIN detectors on the image plane of a pinhole camera. Current densities for the 6- μm gold and aluminum foils were taken from time-integrated pinhole photographs. The unbacked hole radius behind the foils were 0.5 cm. Peak current densities for 50- μ , 12.7- μ and 6- μ gold foils were 4.8, 1.8, 1.0 MA/cm², respectively. As in the Hydra case, there was a general broadening of the current profile, the thinner the foil. Peak current densities for 6- μm aluminum foils were approximately 2.1 MA/cm². Figure 17 shows experimentally measured temperature profiles compared with theoretical temperature profiles with a peak current density less than or equal to that experimentally measured. In the case of gold foils, we found no temperatures greater than the

maximum possible temperature profile to be expected from experimentally measured peak current densities. In the case of aluminum, we found temperatures consistent with a current density of greater than 4 MA/cm², whereas peak current densities inferred from hard X-ray profiles never exceeded 2 MA/cm² for 6- μm aluminum. Therefore, for 6- μm aluminum, more than a single pass was required to explain the observed energy deposition.

Conclusion

In a set of three experiments: (1) 50.8, 25.4, 12.7, and 6.35- μm -thick gold foils on Hydra with a 1-cm-radius holder; (2) 50.8, 25.4, 12.7, and 6.35- μm -thick gold foils and 6.35- μm -thick aluminum foil on Proto I with a 0.5-cm-radius holder; and (3) 205.7, 88.9, 38.1, and 6.35- μm -thick aluminum foils on Proto I; we observed a general broadening of the hard X-ray pinhole images as the foil was made thinner. If one assumes that the total diode current is included in the pinch with a current density profile given by the X-ray pinhole data, then the pinhole data would imply lower peak current density or axis with thinner foils. However, we have shown conclusively on the Hydra experiments that the number of electrons per unit time incident on the diode side of the foil is twice the current as measured by the integrated dB/dt monitors for 6- μm gold. Also in the case of 6- μm -thick gold foils on Hydra and 6- μm -thick aluminum foils on Proto I, the measured radiation temperatures are a factor of two greater than what can be expected when assuming the maximum possible current density incident on the foil. The mechanism for enhancement is consistent with the beam electrons making more than a single pass through the 6- μm -thick Au and Al targets.

Fig. 12. Total current in the Hydra diode from the integrated dI/dt loops and the number of electrons/sec incident from the diode side of the foil during the pinch phase.

Shot 5706 6- μ gold foil -----
 Shot 5694 12- μ gold foil - . . . . .
 Shot 5693 25- μ gold foil . . . . .
 Shot 5714 50- μ gold foil _____

Fig. 13. Comparison of experimental temperature profile with the CHART-D temperature profile for a peak current density of 0.5 MA/cm^2 . The experimental temperature is closer to that of a peak current density of 0.4 MA/cm^2 .

Fig. 14. Time-integrated spectra between 10 to 80 μm from a 2.2-m grazing incidence spectrograph. Many of the emission lines coincide with the spectral region of the 1- μm aluminum signal, these emission lines appear during impedance collapse, implying a low-density plasma.

Fig. 15. Time-resolved optical spectra from rear surface of gold foils. Wavelength range is 2450 Å - 3150 Å, spectral resolution is 4 Å, temporal resolution is 6 ns.

Fig. 16. Relative current density profiles for 50, 25, and 12- μ -thick gold foils and 25- μ m-thick gold plus 0.635-cm range thick carbon with a 0.635-cm gap between the carbon and the gold foil.

Fig. 17(a). Temperature measurements of 25, 12.7, 6.35- μ m-thick gold foils on Proto I. Comparisons were made with CHART-D¹¹ with a temporal profile as given by a trapezoid normalized to the total current density during the pinch.

Fig. 17(b). Temperature measurements for 6- μ m aluminum foils compared with CHART-D profiles. This corresponds to peak current densities of 3.8 and 5.4 MA/cm². X-ray pinhole photographs current densities on the 2 and 2.7 MA/cm², respectively.

MEASUREMENT OF THE TEMPERATURE OF A THIN FOIL USING OPTICAL AND VUV DETECTORS

Temperature measurements of thin gold foils heated by the Hydra relativistic electron beam have been carried out using optical and vacuum ultraviolet detectors in a blackbody assumption. The goals of the program were twofold: (1) show that blackbody radiation in these spectral ranges could be used as a reasonable diagnostic, and (2) compare observed temperatures with hydrodynamic simulations based upon classical or greater than classical deposition rates.¹² To this end, it was necessary to measure accurately the beam pinch enhanced current density. This was done with an absolutely calibrated high energy PIN detector and time-integrated X-ray pinhole camera using a 1-D photon transport code. Peak temperatures of 5 to 6 eV were obtained for the thinnest foils, 6 μm , consistent with classical deposition at 1 TW/gm.

The diagnostics are sketched in Fig. 18 for shots on the Hydra accelerator (1 MV, 300 kA, 80 ns). The foil backside temperature is measured by (1) an optical diode, filtered for $h\nu = 2.5$ eV, (2) a vacuum ultraviolet diode, $h\nu = 20$ eV, and (3) an ultraviolet streaking spectrometer, $4 < h\nu < 5$ eV.

An experimental detail concerning the emitting source area, A, which will affect the temperature via the blackbody emission

$$S(\nu) = \frac{2\pi h \nu^3 A}{c^2} [\exp(h\nu/kT) - 1]^{-1},$$

should be clarified. In the vacuum ultraviolet, the diode sees only $h\nu \geq kT$ and integration of the source diode response function, $R(\nu)$, for a signal voltage, $V(T)$

$$V(T) = \int R(\nu) S(\nu) d\nu$$

shows very nearly a T^4 dependence. Thus an error in the emitting area will not seriously affect the VUV result. (For example, a factor of 2 in the area gives a 19 percent error.) A source area is chosen somewhat larger than the pinch size as determined by the pinhole camera.¹³

The optical diode, however, is filtered to a 70-nm bandwidth at 507 nm and has a calculated $V(T) \sim T^{1.9}$ for our temperature range. The accuracy of the emitting area becomes more

critical; a Questar telescope is used to image the central 0.05 cm^2 of the pinch region through a pinhole to the optical diode so that the emitting area is accurately known.

The beam deposition was characterized by (1) an X-ray pinhole camera to measure deposition area, (2) an X-ray PIN diode to measure total pinch current using a Monte Carlo X-ray emission simulation, and (3) conventional B and V machine current and voltage monitors. The PIN diode was absolutely calibrated using a DC electron beam as a function of beam energy and angle. A 1-D electron-photon transport code (TIGER)⁴ was used then to calculate a total response to a pinched electron beam in terms of pinch current at a given beam voltage. The current density approaches 1 MA/cm^2 for thick foils (25 to 50 μm) and falls to 0.2 MA/cm^2 for the thinnest foils, 6 μm .

A summary of the measured temperatures is presented in Fig. 19, where only the highest temperature (in 5 shots) observed at each foil thickness is given. Peak values of 6 eV and 5 eV are found by the VUV and optical diodes, respectively. The large disagreement for the 25- μm -thick foil has not been explained. It may be related to aligning the optical system to where a pinch is expected; for thinner foils the pinch was broader and alignment would be less critical.

Agreement between the diagnostics is considered acceptable, considering the number of calibrations involved. In the optical system, for example, substantial deviations from expected performances were caused by near-field vignetting in the telescope and degraded sensitivity of the diode (as revealed by a tungsten lamp calibration at 507 nm¹⁴).

Validity of the blackbody assumption is a critical question in the analysis of these experiments. To this end, the foil heating and expansion was simulated with the CHART-D hydrodynamic code¹⁵ and compared with opacity calculations.¹⁶ The results of a typical case are displayed in Fig. 20 for a 25- μm -thick gold foil with a 1 TW/gm deposition rate. The temperature and density profile, measured from the foil center plane, are given as simulated at the end of the peak of the power pulse with values corresponding to the left-hand ordinate. Photon escape functions,

$$\exp \left[- \int_x^\infty K(\rho, T) dx \right],$$

Fig. 18. Blackbody measurements on the Hydra accelerator. Temperatures were measured by optical vacuum ultraviolet, and ultraviolet detectors. The electron beam was characterized by a pinhole camera, an X-ray diode, and (not shown) β and $\dot{V}$ monitors.

Fig. 19. Foil temperatures vs. thickness. Only best values are shown; five or more shots were made at each thickness.

Fig. 20. Hydrodynamic simulation of 25- μ m gold foil uniformly heated at 1 TW/gm. Comparison is made to opacity calculations.

right-hand scale, describe the percentage of optical (2.5 eV) or average VUV (20 eV) photons escaping from a given depth. It is clear that the expanded foil is still opaque for these photons and that both systems see into regions of the same temperature, although differing densities. These simulations also allow an estimate of the interior temperature, 8 eV, to be made based on surface measurements.

Agreement of simulated surface temperatures and measured values provide an estimate of the deposition rate, 1 TW/gm, appropriate for these experiments. Fig. 21 shows the time history of several simulations at varying depositions in comparison with a typical 25- μ m gold foil shot. It is seen that the observed temperature is a sensitive indicator of the deposition. Use of the TIGER electron transport code, at current densities given by PIN diode and pinhole camera analysis, shows that no unexpected phenomena are occurring; deposition is in accordance with classical mechanisms. It had been hoped that these shots would test a model of enhanced deposition in large self-magnetic fields in thin foils.¹² However, the pinches with thin foils were not as tight as previously measured¹⁷

Fig. 21. Temperature time history as viewed by optical and VUV detectors in comparison with surface temperatures simulated with various deposition rates, 0.2 to 4.5 TW/gm.

for thick anodes so that the high v/γ requirement was not satisfied for a conclusive test.

Time-resolved ultraviolet and optical spectra were also obtained with the spectrometer/streak camera combination sketched in Fig. 18. Spectral and temporal resolutions are 0.4 nm and 6 ns, respectively. In the ultraviolet (240 nm < λ < 300 nm), the spectrum consists of a continuum superimposed upon which numerous neutral and first ionized gold lines appear in absorption. The ion lines are more prolific for the thicker foils. These spectra are consistent with a model in which a cooler plasma of gold ions and neutrals exists between the detector and a much hotter blackbody source emitting the continuum. Given the energy levels involved, a vapor temperature of 0.5 to 2.0 eV is estimated. The opacity of this vapor in the spectral region viewed by the optical diode is largely undetermined. Tentative results in the visible, however, show no absorption lines and the photon escape functions of Fig. 20 also suggest that there should be no absorption problem.

These experiments in thin foil heating are continuing on Proto I where a higher current density, although at a lower v/γ , should provide higher foil temperatures. In the Proto I situation, the VUV and optical systems are mutually exclusive and require separate shots. Interesting results, suggesting enhanced deposition, have been obtained by the VUV system and are described elsewhere in this report. Optical data are too preliminary for comment.

We conclude from the Hydra experiments that surface temperatures of 5 to 6 eV imply depositions of 1 TW/gm, in agreement with classical deposition models. However, decreasing current densities with thinner foils may indicate that the necessary high v/γ values for enhanced deposition processes were obtained.

IMPLOSION PHYSICS

The performance of an ICF target can be characterized by (1) neutron yield, (2) fuel compression (pr), (3) temperature of pusher and fuel, and (4) velocity of pusher. Potential problems for practical ICF target designs (including high-gain multiple shell configurations) which could result in significant reductions of these figures-of-merit are (1) multidimensional phenomena, i.e., effects of loading and structural (pellet) nonuniformities, (2) Rayleigh-Taylor instabilities originating at material boundaries, (3) particle ejection from shocked interfaces, and (4) equation-of-state anomalies, i.e., viscosities, melt temperature and opacities which lie outside the normal extrapolations employed in calculations.

In closed spherical ICF targets, experiments designed to measure any of the above figures-of-merit other than neutron yield are difficult if not impossible to perform. We have, therefore, chosen open (but converging) model targets in order to perform thermo- and hydrodynamic experiments. These model targets consist of (1) open hemispheres, and (2) cylindrical sections. Experimentally determined thermo- and hydrodynamic quantities are compared with calculations for these geometries using one- and two-dimensional hydrocodes. Diagnostics include, at present, velocity and temperature measurements by optical methods (four-pulse holography, streak and framing photography and fast photo-multipliers) and in the future, flash X-radiography. The

performance and stability of the targets will provide a data base for fusion target design as well as an understanding of the roles of the above problem areas in ICF experiments.

It should be recognized that experiments performed in the pressure-velocity domain 1 to 10 Mbar, 1 to 3 cm/ μ s on the Hydra accelerator have practical value exceeding purely a demonstration of diagnostic capability. Severe multidimensional phenomena (from nonuniform loading). Rayleigh-Taylor instabilities and particle ejection from shocked surfaces are all known to occur at the 1 Mbar level and below. How exactly they affect the performance (as defined above) of an ICF implosion has not been established at any level. In addition, equations-of-state presently used in hydrodynamic - TN burn calculations have no experimental verification (for converging systems) in the megabar range or above.

Previous experiments were conducted on the Hydra accelerator with single ablatively driven hemispherical shells.¹⁸ In that work, the electron beam target coupling efficiency was established by comparisons of experimental implosion times and material jet velocities with the results of two-dimensional hydrodynamic calculations. More recently, pusher velocity and temperature measurements have been performed on Hydra for (1) double-shell hemispheres, and (2) thick-walled single-shell (shock focusing) hemispheres, and optical holographic data for cylindrical implosions have been obtained.

In Fig. 22 is shown the basic experimental arrangement for measurement of the material implosion time and jet velocity. The figure depicts a double-shell target, with an outer shell Au (wall thickness = 0.32 mm, diameter = 3.8 mm), and an inner shell of W (wall thickness = 0.2 mm and diameter = 1.4 mm) with water as the buffer material between the two shells. The inner shell and buffer thickness satisfy conditions calculated by Toepfer and Tiffany for stability. The two thin pellicles ($\sim 7 \mu$ m) are used along with a laser source and fast photomultiplier detector to measure the time of arrival of inner shell material at the equator (first pellicle) and arrival approximately one-centimeter downstream (second pellicle). For the arrangement shown in Fig. 22, the measured implosion time was approximately 300 ns and the material jet velocity was 1.6 cm/ μ s for a total diode energy of 22 kJ.

Fig. 22. Experimental arrangement for measurement of target implosion, time and jet velocity.

In addition to pusher velocities of double shells, we have performed time-resolved temperature measurements of the inner shell of the double shell system during implosion. In Fig. 23 are shown two oscillographs of a photomultiplier detector which recorded either (a) light with wavelength = 514 nm (a laser source) reflected from the inner tungsten surface or (b) light with wavelengths centered at 514 nm (bandpass = 100 Å) generated by the collapse of the inner wall. The purpose of illuminating the tungsten inner wall was to detect the time of shock wave arrival at the inner surface, a useful parameter in hydrodynamic analyses. A definite reduction in reflectivity is observed (a) and the occurrence of this change is interpreted to be the time of shock breakthrough. Following the reduction in intensity, the rapid rise in light intensity is thought to be associated with the luminosity of the converging shell. In (b), the shell was not illuminated, and the intensity is solely associated with self-luminosity. In this case, the calibrated optics and photomultiplier implied a peak temperature of approximately 0.5 eV. Although the complete structure of the light signal is not understood, the occurrence of the initial maximum at ~300 ns is in agreement with previous measurements of the implosion velocity. In fact, the rise of the luminosity signal is correlated with the time-resolved implosion velocity for the double-shell system.

● Jet Velocity Calculation and Measurement

Fig. 23. Measurement of implosion time and jet velocity for shock focusing target.

Hydrodynamic code calculations have not yet been performed for these double-shell configurations.

We have applied these techniques to the single shell, thick-wall or shock-focusing target system for which there are hydrocode calculations. Both gold and nickel ablaters have been used in experiments. Figure 24 gives the target dimensions. In Fig. 25 are shown the results of an implosion time-jet velocity measurement similar to that for the case of a double shell. The shock focusing single shell was multilayered, consisting of a thick outer layer of gold (thickness = 0.6 mm, diameter = 1.9 mm) and thin inner layer of tungsten (thickness = 0.094 mm). For the shot depicted in Fig. 25, total diode energy was 23 kJ. The first pellicle was placed slightly downstream from the shell equator. The light intensity trace indicates an initial reduction due to X-ray induced noise in the detector followed by a change at 130 ns due to arrival of material at the first pellicle. The initial change in reflected intensity from the second pellicle occurs at approximately 255 ns resulting in a jet velocity of 3.3 cm/μs. Also shown in the same figure is the calculated

Fig. 24. Shock focusing target temperature data. The negative signals are the output from calibrated photodiode detectors viewing optical emission at 514 nm from the pusher free surface. The positive signals are X-ray bremsstrahlung emission from the target.

Fig. 25. Measurement of implosion time and jet velocity for double shell target.

(from the two-dimensional hydrodynamic code CSQ¹⁹) velocity-time history for beam and target conditions similar to those of the experiment. The calculated implosion time and pellicle arrival times correspond well to the experimental data. The calculated pressure velocity and temperature profiles are shown in Fig. 26.

Temperature measurements were carried out employing both the Au-W and Ni-W shock focusing hemispheres. Examples of the results are shown in Fig. 27, where the ranges in measured temperatures and implosion times are listed along with the oscillograph traces. A significant experimental observation is that the temperature for the Ni-W configurations (5 to 10 eV) are approximately a factor of two higher than those for the Au-W hemispheres (2 to 4 eV). One also notes that the measured values for Au-W are considerably lower than that predicted by the CSQ calculation (~13 eV). To further study these phenomena, one-dimensional spherical implosion calculations²⁰ were performed for the actual experimental conditions for both the Au-W and Ni-W cases. These results indicated 10 to 15 eV for Ni-W and 15 to 20 eV for Au-W. The significant discrepancy between measured and predicted temperatures for Au-W may be associated with multidimensional effects and indicate the sensitivity of shock focusing target performance to uniformity of loading. Such effects might be expected to be more severe in Au-W than Ni-W because more smoothing of the implosion would occur for the thinner shell of Ni-W than for that of Au-W. In these experiments, target loading was observed by X-ray pinhole cameras to vary by 50 percent over the surface. The long risetime in the temperature profile observed in some Ni-W shots is probably attributable to preheating of the tungsten layer (by electrons) to thermodynamic states above vaporization. In general, however, preexpansion does not appear to be a significant problem for these targets (as evidenced by the rapidly rising temperature profiles and reasonable implosion times).

Additional experiments to study ablatively driven cylindrical targets have been carried out on Hydra. Diode parameters were nominally 4 Ω , > 0.3 TW, 30 kJ. Two anode configurations were tested, with target axes either parallel to the diode axis through the anode center, or perpendicular to the diode axis and above the anode surface. The targets were 6.32 mm O.D., 1.6 mm thick and 4.76 mm O.D., 0.80 mm thick brass tubing with an average density of 8.50

gm/cm³. The electron beam focused to a diameter comparable to the target O.D. Optical holography of transversely mounted tubes gave simultaneous measurements of pusher and ablator velocities. For the case of the thicker tubes which were total stopping to the < 1.2-MeV electrons, an ablator velocity of 1.5 cm/ μ sec was measured (Fig. 28). The particle velocity at the time of shock breakthrough at the pusher surface was inferred from the pusher velocity to be 0.25 cm/ μ sec. Using published Hugoniot data for brass, this corresponds to a shock pressure of 1.3 Mbar and shock velocity of 0.73 cm/ μ sec. In certain holograms, distortion of the reference fringes indicates the occurrence of fluff (particle ejection from the shocked inside surface). Asymmetric loading of the targets resulted in off-center convergence. Several shots were taken with air-filled cylinders optical emission measurements were made of the temperature attained from compressional heating. Temperatures $\approx$ 1 eV were observed. Future experiments will employ high aspect ratio pushers with low density buffers to study stability, and various pusher materials and surface finishes to study fluff. In addition, experiments will be performed to study the effects of altering the pusher shape to improve convergence for nonuniform loading.

SCINTILLATOR-PHOTOMULTIPLIER RESPONSE TO A SIMULATED REB GENERATED THERMONUCLEAR NEUTRON PULSE

Recent experiments have reported evidence of thermonuclear neutron production from relativistic electron beam (REB) imploded or heated targets,²¹⁻²³ the detection of thermonuclear neutrons from such targets is complicated by the possibility of background beam-target neutrons being produced. To measure thermonuclear neutron production all experiments to date have employed fast plastic scintillator-photomultiplier combinations (SPM) to determine neutron time-of-flight. Typically, the SPM's require some 10 to 20 cm of lead shielding to attenuate the intense bremsstrahlung pulse present in these experiments to a level that kept the SPM's from saturation. Such massive amounts of lead shielding attenuate and modify the neutron pulse shape.

Published calculations of REB imploded targets all indicate that thermonuclear neutron production should occur in < 3 ns.²⁴ This research report considers the response of a SPM shielded with various amounts of lead to

Fig. 26. Calculated pressure, velocity, and temperature in shock focusing targets.

Fig. 27. Shock focusing target dimensions.

Fig. 28. Electron beam driven ablation implosion of the brass cylinder in transverse diode.

a beam target produced 3-ns-wide burst of DD neutrons. In this way, the "signature" of a true burst of thermonuclear neutrons was established. Since background beam-target neutrons are produced throughout the power pulse of a REB accelerator (typically > 20 ns), it should be readily possible to distinguish the background neutron "signature" from the true thermonuclear neutron "signature."

Thermonuclear Neutron "Signature"

The pulsed power source used to produce the 3-ns neutron burst was a commercially available Febetron Model 706 electron beam accelerator. The Model 706 has a nominal voltage of 600 kV, an electron current of 10 kA, an impedance of 60 Ω , and a 3-ns-wide power pulse. The neutron production was monitored by a standard silver activation counter²⁵ and by an EG&G NPM-54 SPM detector.²⁶ A typical shot produced some 1×10^6 DD neutrons in a 3 ns burst yielding a neutron intensity of some 3.3×10^{14} neutrons/sec.

As an example of SPM response, Fig. 29 shows three DD neutron pulses detected through 1.9, 10.2, and 30.3 cm of leading shielding. The

NPM-54 SPM has a risetime of 2.2 ns and a FWHM response of 3.5 ns when used to observe a single instantaneous event such as a comic ray. In Fig. 29a, the prompt X-ray bremsstrahlung pulse of the Febetron as well as the neutron burst is observed through 1.9 cm of lead at a laboratory angle of 100° . The neutron time-of-flight from this trace is 46 ns consistent with 2.45 MeV DD neutrons. The neutron pulse has a risetime of 3 ns and a FWHM of about 6 ns. In Fig. 29b, the X-ray bremsstrahlung pulse is completely attenuated by the 10.2 cm of lead, and the neutron pulse is observed to have a 4 ns risetime and a FWHM of approximately 20.0 ns. In Fig. 29c, the neutron pulse is observed to have a 4 ns risetime and a FWHM of approximately 32 ns when detected through 20.3 cm of lead. It is clear that in both cases, the lead shielding is degrading the leading edge of the neutron pulses to a small extent, but its most notable effect is to create a large tail on the neutron waveforms. Consequently, it is possible over reasonable flight paths to use the leading edge of a neutron pulse as a timing marker to determine the time of arrival of a monoenergetic neutron group. It should also be noted that there is no need to make a shorter neutron burst since the fastest SPM detectors have integration times of the order of 3 ns.

- a. 2.5 volts/div, 20 ns/div. The detector was shielded by 1.9 cm of lead and the total neutron yield was 1.1×10^6 . Note the prompt X-ray pulse.

- b. 5.0 volts/div, 20 ns/div. The detector was shielded by 10.2 cm of lead and the total yield was 1.0×10^6 . The lead shielding completely attenuated the X-ray pulse.

- c. 2 volts/div, 20 ns/div. The detector was shielded by 20.3 cm of lead and the total yield was 8.8×10^5 . Once again the lead shielding completely attenuated the X-ray pulse.

Fig. 29. Oscilloscope traces comparing neutron scintillator - photomultiplier detector response to a 3-ns-wide DD neutron pulse when the neutron pulse is detected through 1.9, 10.2, and 20.3 cm of lead shielding.

As a further check on the neutron pulse shape presented in Fig. 29b, time-dependent Monte Carlo neutron transport studies were made using the code SORS developed at Lawrence Livermore Laboratory.²⁷ Figure 30 shows the good agreement between the neutron Monte Carlo generated pulse shape for a 3-ns-wide source and that obtained from the Febetron pulsed neutron source.

STABILITY OF MULTIPLE SHELL ICF CAPSULES

With a marginal driver, one method to achieve high pusher velocities is the utilization of velocity multiplication in a multiple shell target.²⁸ In this type of a target, the outer more massive shells, act on the inner shells hydrodynamically through the medium of a low-density buffer, which ideally acts as a perfect, massless spring to transmit momentum and energy. A major problem with this concept is that during acceleration of each inner shell by the buffer, the interface between the buffer and shell is Rayleigh-Taylor unstable.²⁹ We have considered the idealized problem of an infinitely massive piston (outer shell) acting on a thin foil (inner shell) to estimate regimes of buffer density, shell separation, and thickness which are less susceptible to instability during the acceleration phase.

Consider the problem in Fig. 31. An infinitely massive piston is assigned a constant velocity v_p , compressing the buffer gas, which in turn accelerates a thin foil. We analyze the acceleration history of the foil to determine the Rayleigh-Taylor instability growth. For ICF applications, the piston velocity is greater than the speed of sound in the uncompressed gas so that a shock wave is generated ahead of the piston. The shock travels to the foil where it is partially transmitted and reflected. As the gas is compressed further, the shock undergoes repeated reflections between the piston and the foil. After a few reflections, the gas is heated to a point where the piston velocity is subsonic and the gas undergoes an adiabatic compression. After maximum compression, the foil attains a velocity greater than that of the piston, resulting in expansion of the gas. For an ideal buffer, the maximum foil velocity obtained is $2 v_p$. Dissipation resulting from shock heating of the gas and foil results in less efficient momentum transfer and lower foil velocities.

A one-dimensional Lagrangian hydrocode POLLY³⁰ was used initially to calculate the foil motion. In this code, the piston was the left boundary of the system and was given a constant velocity. The gas, which was assumed to be ideal with $\gamma = 5/3$ was divided into fifty zones. The foil was treated as the right boundary of the system with a mass determined by its density and thickness. The velocity of the foil, shock position, and state of the gas were calculated as a function of time.

An analytic estimate of the foil motion was made by assuming the gas to undergo adiabatic compression, with initial conditions specified by the POLLY calculation when the reflected shock had returned to the piston for the first time. This model resulted in an analytic expression for the Rayleigh-Taylor growth. Foil motion as calculated by analytic model was compared in various cases with the resultant motion as calculated by the hydrocode. Foil mass, initial gas pressure, and piston velocity were varied in the calculations. Piston velocity varied between 0.2 and 1 cm/usec, initial gas pressure between 0.1 and 10 atmospheres, and foil mass between 0.008 and 0.8 gms/cm².

The analytic model consistently gave higher peak accelerations over shorter time intervals than the hydrocode. Peak foil velocities agreed to within a few percent. Since the amplitude of the Rayleigh-Taylor mode (linear regime) is

$$\delta(t) = \delta_0 \exp \int_0^t \sqrt{ka} \, A \, d\tau \quad (1)$$

where δ_0 is the initial perturbation, k the mode wave number, $a(\tau)$ the acceleration, and A the Atwood number, it follows that using $a(\tau)$ as calculated by the analytic model will result in a conservative estimate for $\delta(t)$. Thus, to explore the regime of parameters for which Rayleigh-Taylor instabilities could be come serious, we consider the analytic model.

$$p_s^\gamma = p_{s0}^\gamma \quad (2)$$

$$p = m\ddot{s} \quad (3)$$

SCINTILLATION NEUTRON DETECTOR SIGNATURE

Fig. 30. Comparison of the Monte Carlo generated neutron pulse shape for a 3-ns-wide source and that obtained from the Febetron pulsed neutron source. The smooth curve are the Monte Carlo generated data, and the dots are the data set obtained from the pulsed neutron source. The Monte Carlo generated data was peak normalized to the pulsed neutron source data.

Fig. 31. Geometry for model calculation of stability for accelerated foil.

$$\frac{1}{\gamma-1} p s + \frac{1}{2} m \dot{s}^2 = \frac{1}{\gamma-1} p_0 s_0 + \frac{1}{2} m \dot{s}_0^2. \quad (4)$$

Here s is the foil piston separation, p the gas pressure, m the (areal) mass of the foil, and dot denotes differentiation in time. The initial conditions p_0 , s_0 , $\dot{s}_0$ are specified at some time t_0 after the shock is reflected from the foil, with best agreement between the code calculations and analytic theory obtained when t_0 is taken to be the time at which the shock returns to the piston. The solution to Eqs. (2) - (4) can be parameterized by the ratio

$$x = 2p_0 s_0 / (\gamma-1) m \dot{s}_0^2 \quad (5)$$

of initial foil energy in the piston frame of reference to the initial energy stored in the gas. For the problem at hand, $\dot{s}_0 \approx v_p$.

The resulting expression for $\delta(t)$ is

$$\delta(t) = \delta_0 \exp \left\{ G(t) \sqrt{A s_0 / \lambda} \right\} \quad (6)$$

The function $G(t)$ can be evaluated in terms of elliptic integrals $F(\eta, v)$ and $E(\eta, v)$.³¹ Let t_m denote the time of closest approach between the foil and piston, then

$$G(t_m) = \sqrt{6\pi} \left(\frac{x}{1+x} \right)^{3/2} \left\{ \sqrt{2} F(\eta, \pi/4) - 2\sqrt{2} E(\eta, \pi/4) + 2(x + x^2)^{-1/2} \right\} \quad (7)$$

where $\eta = \sin^{-1} \sqrt{1 - [x/(1+x)]^{1/2}}$, (Fig. 32). At $t = 2t_m$ the foil has essentially escaped from the piston and $G(2t_m) = 2G(t_m)$.

The above theory has been applied to calculate the stability of double shell targets designed for EBFA (cf. pp. 48, 49). For the best design (neutron yield 1.5×10^9), the piston (outer shell) velocity is 0.827 cm/ μ s, and the reduced areal mass density of the piston and driven shell is 0.433 gm/cm². The pressure behind the reflected shock is 1.3 MBar and the distance between the inner shell and the outer shell when the reflected shock returns to the piston is ≈ 0.008 cm.

The corresponding value of the parameter x is 0.13 for which $G(t_m) \approx 1.8$. Hence, to assure stable acceleration of the inner shell, this requires a shell uniformity between one and ten percent.

NEUTRON PRODUCTION FROM ADVANCED REB FUSION TARGETS

During the past two years we have been investigating an advanced REB fusion target concept consisting of targets which contain preheated fuel and magnetic fields.³² The purpose of the preheat is to place the fuel onto a higher adiabat and the purpose of the magnetic field is to reduce fuel thermal conduction losses. An advantage to this approach is that high fuel temperatures can be obtained for relative slow implosion velocities, implying increased

Fig. 32. The function $G(t_m)$, where t_m refers to time of closest approach between piston and foil, vs. x , the ratio of initial foil kinetic energy in piston frame of reference to initial energy stored in buffer gas.

neutron production for targets irradiated with low power REB accelerators. In particular, Widner and Farnsworth³² have predicted measurable neutron yields ($\sim 10^6$ to 10^8) for modest REB accelerators (power ~ 0.2 TW). Additional 1-D calculations³² indicate this approach may also permit lower beam power for breakeven level targets, assuming negligible thermal conduction losses and deposition of α energy in the fuel. Others³³ have also indicated the advantage of using preheat and magnetic fields in inertially confined systems in the context of thin shell REB targets for which the beam, passing through the target, provides the preheat and magnetic field in the fuel.

Recently, we reported a target design³² which incorporated a preheated, magnetized fuel as is shown schematically in Fig. 33. Owing to its resemblance to the Greek letter " ϕ ", it was designated as the " ϕ " target. The target consists of an insulating spherical shell which contains the fuel (in this case a CD_2 wire), a thin metallic collector and two electrodes, one of which connects the collector to the shell, and the other connects the shell to the anode. The thin metallic collector serves to collect electric charge

Fig. 33. " ϕ " target configuration.

during the beam prepulse and during the main beam pulse until the electron range becomes greater than the collector thickness. This charge accumulation causes electrical breakdown to occur along the fuel wire and subsequent filament explosion. The resulting current flow provides ohmic heating of the fuel and a magnetic field inside the shell. In this way, the " ϕ " target makes use of the electron beam not only to drive the shell implosion but also to precondition the fuel.

The simplicity of this target design permits easy experimental implementation.

The " ϕ " targets used in these experiments consisted of plastic (polystyrene) shells 0.3 cm I.D. and 0.03 cm wall thickness, which contained a CD_2 filament ~ 25 to $50\ \mu\text{m}$ in diameter as shown in Fig. 33. These targets were irradiated by a single REB from the Hydra leg of the REB accelerator (called Rehyd) (1 MeV, 250 kA, and 100 ns). Energy deposition symmetry of the shell, as demonstrated previously³⁴ with spherical targets without collectors, was preserved by the choice of aluminum collectors thin to an electron range at full diode voltage. In the experiment, these targets were shot both with and without machine prepulse.

In addition, a number of null targets were shot. These include targets with large portions of one or both halves of the spherical shell cut away (Fig. 34a and b); targets with a thick plastic cylinder around the shell to prevent uniform energy deposition (Fig. 34c); and targets with the electric conduction path interrupted by an insulating plug between the CD_2 wire and the bottom electrode (Fig. 34d).

Fig. 34. Null target configuration.

The neutron diagnostics included a silver activation counter and two scintillation neutron time-of-flight detectors³⁵ placed at 4.28 m and 6.35 m away from the diode and at 10° and 32.7° respectively measured from the diode axis. With these detectors the neutron yield and the time of arrival that

high fuel temperatures can be obtained for relatively slow implosion velocities, implying increased neutron production for targets irradiated with low power REB accelerators. In particular, Widner and Farnsworth³² have predicted measurable yields ($\sim 10^6$ to 10^8) for modest REB accelerators (power $\sim 0.2\ \text{TW}$). Additional 1-D calculations³² indicate this approach may also permit lower beam power for breakeven level targets, assuming negligible thermal conduction losses and deposition of α energy in the fuel. Others³³ have also indicated the advantage of using preheat and magnetic fields in inertially confined system in the context of thin shell REB targets for which the beam, passing through the target, provides the preheat and magnetic field in the fuel.

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A total of 39 target shots were made, of which 24 were with null targets and 15 were with complete targets. No 2.5 MeV neutrons were produced by the null target shots. However, some of these have generated lower energy neutrons ($< 0.5\ \text{MeV}$) apparently from the $\text{C}^{12}(\text{d},\text{n})\text{N}^{13}$ reaction³⁶ arising from the deuterium in the diode and carbon on the anode. Of the 15 complete target shots, 7 shots failed to produce 2.5 MeV neutrons; 4 were due to low diode output, and the failure mode of the remaining 3 have not been identified.

Fig. 35. Experimental setup.

Eight target shots produced from 5×10^6 - 2.5×10^7 neutrons as measured by the Ag activation counter. The neutron energy are reduced from the time-of-flight data (see Fig. 36). It is clear two groups of neutrons are produced and they are well separated by the far detector. The slow group is attributed to background $C^{12}(d,n)N^{13}$ beam-target reactions and the leading edge of the fast neutron pulse is analyzed. These arrival times are plotted in Fig. 37 against the detector distance away from the diode. Curves a and b show TOF data of two different arrangements of detector position, they indicate $2.5 \text{ MeV} \pm 0.2 \text{ MeV}$ neutrons were produced during the last 30 ns of the beam voltage pulse. The corresponding implosion time for curve b is derived from optical streak data of the shell and shows agreement with the extrapolated neutron formation time. The total 2.5 MeV neutrons produced in these shots are bounded on the low side by the time-of-flight counter sensitivity, $\sim 10^6$, and on the high side of the Ag activation counter measurements, $\sim 10^7$, which includes both high and low energy neutron contributions, as is evident in Fig. 36b. Also plotted are the neutron arrival times at the near detector of shots made with incomplete spherical shells, and due to the low neutron yields ($\sim 10^6$) of these shots, no

signal was recorded by the far detector. These arrival times are much later than those of curves a and b.

The rate of expansion of the shell, as measured by the optical streak camera, has been compared to CHART-D computer code³⁷ results to estimate the specific power absorbed by the shell. This comparison, which assumes the light front approximately corresponds to a constant a real electron density of $\sim 10^{17} \text{ cm}^{-2}$,³⁸ indicates approximately 3 to 5 TW/g absorbed in the shell.

Neutron production from exploding shell targets without preconditioning of the fuel have been investigated by others.³⁹ Measurable neutron yields from such targets have been predicted, but have been shown to require substantially higher deposition levels than the $\sim 4 \text{ TW/g}$ observed here. We find this conclusion verified by the present result that the production of 2.5-MeV neutrons requires prepulse current.

Our present interpretation of the preconditioning of the fuel is that prepulse current ohmically heats and expands the CD_2 fuel filament during the 1 μsec , 5 to 10 kA prepulse, creating a nonuniform fuel density distribution. The

(a)

(b)

Fig. 36. Time-of-flight neutron detector signals for neutron detectors located at 0.56 m (a) and 4.45 m (b) from the target. Arrows indicate reference time and time of arrival of neutrons. The signal near time zero is from the X-ray pulse.

Fig. 37. Position vs. neutron arrival time. Time is referenced to the end of the voltage pulse.

lower density regions obtain higher temperature for a given current density and therefore, become less resistive, providing a preferential channel for current flow. The result is that a fraction of the wire mass is heated to a high temperature and contains suppression. Calculations made with a two-dimensional MHD computer code⁴⁰ including

radiative transport and Spitzer resistivity are in general agreement with this interpretation.⁴¹ For example, at a point in time just before the target starts to implode, calculations indicate central region conditions are: $\rho \sim 2 \times 10^{-6} \text{ g cm}^{-3}$, $T \approx 20 \text{ eV}$, $B \approx 10^4 \text{ gauss}$.

During the main beam pulse, the fuel and magnetic field are compressed, increasing the ωr of the low density central region. This leads to a substantial reduction of electron thermal conduction losses during the high temperature compression phase when such losses would otherwise dominate. Using the calculated preheat temperature, and fuel density, and assuming a thermal conductivity reduction factor consistent with the expected final magnetic field from flux conservation considerations, we have performed 1-D hydrodynamic and thermonuclear neutron calculations using CLYDE.⁴² These calculations show that after an implosion time of $\sim 80 \text{ ns}$ the fuel reaches $\sim 1 \text{ keV}$ and $1.6 \times 10^{-2} \text{ g cm}^{-3}$ in temperature and density and produces $\sim 10^6$ neutrons in 5 to 10 ns. We find that the calculated implosion time is consistent with the observed time of origin of the 2.5 MeV neutrons, and the predicted neutron yields are consistent with those observed.

TARGET PREHEAT EXPERIMENT

A central question in the electron-beam fusion experiments with preheated-fuel targets⁴³ is the exact condition of the fuel at the beginning of the implosion pulse. Separate experiments are being carried out which simulate the target preheating in a simpler, more accessible geometry. Fuel temperature is measured by spectroscopic comparison of OIII and OII line intensities. Electron density has been obtained both by broadening of D_α , D_β and various OII lines and also more directly with a laser interferometer.

The experimental arrangement for spectroscopic observations is shown in Fig. 38. A two-stage, 80-kV Marx bank provides an 8 kA, 500 ns heating pulse which closely approximates measured prepulse in the Rehyd target shots. The target itself is a 2 to 4-mm-diameter quartz tube with "in-situ" gas mixing which allows each target to be used with fresh gas for several shots. Streaked spectra are obtained with a Czerny-Turner spectrometer coupled to an ultraviolet-sensitive streak camera. Windows and lenses are of fused quartz since a principal line is the OIII at 326.5 nm. Temporal and spectral resolution are 30 ns and 0.6 nm, respectively.

Fig. 38. Experimental apparatus for time-resolved spectra. The preheat pulse is characterized by current monitors (B and CVR) and a voltage monitor across the target.

A microdensitometer trace of the spectrum between 310 nm and 390 nm is shown in the top trace of Fig. 39 for a 4-mm target filled to 100 torr of H_2 + 10 torr of O_2 . The OIII/OII

line ratio⁴⁴ gives a temperature of 3.9 eV if an electron density of 10^{18} cm^{-3} is assumed, consistent with line broadening estimates.⁴⁴ (Interferometric measurements also justify this; see below.) Variations of gas fill pressure show only weak dependence of temperature upon initial pressure: 3.8 eV for 50 torr fill.

Fig. 39. Microdensitometer scans of ultraviolet spectra; top, 4 mm target at 100 torr initial pressure and bottom, 2 mm target at 200 torr. OIII (326.5 nm) and OII (372.7 nm) were used for temperature estimates.

A slightly higher temperature, 4.1 eV, is found by decreasing the tube diameter to 2 mm. The spectrum in this case, lower trace in Fig. 39, shows continuum radiation dominating all but the reversed OIII line. Such a reversed line might be explained, for example, by a three-zone emission model: (1) a high temperature continuum-emitting core, (2) a lower temperature, high-density annulus around the core absorbing the continuum in a 4-nm band at the OIII line, and finally (3) a lower density outer shell emitting the OIII line in a 1.2-nm band. Spatial streaks with the slit transverse to the target axis do show a luminous front structure; however, more quantitative results are found with the interferometer.

The interferometric arrangement given by Fig. 40 is basically a Mach-Zender utilizing a CW HeNe laser and a gated photomultiplier.⁴⁵ Peculiar features are: (1) unequal path lengths, (2) a cylindrical lens to recollimate the beam after passage through the cylindrical target, and (3) a divergence matching telescope in the reference beam. Photomultiplier traces for the 4-mm target, filled to 200 torr, are displayed in Fig. 41 for probing across the target axis (top) and 1 mm off of the axis (bottom). The axial result shows a steady increase in density (2 oscillations), a stagnation, and then decay. The off-axis result, however, shows a gradual buildup of plasma, passage of a high-density front (1-1/2 oscillations), and then slower variations. Qualitatively this is consistent with the three zone spectroscopic model. The density of the front, $2 \times 10^{18} \text{ cm}^{-3}$, is also sufficient for absorption of the OIII line from the continuum emission.

The results to date include temperature and electron density measurements at constant current for variations in target diameter and gas fill pressure. At low pressure (50 torr) we measure $T_e = 3.8 \text{ eV}$ in a luminous front. The front may be optically thin but the core is too tenuous to be observed in comparison with the front. At higher pressure (200 torr) and smaller targets the temperature of the front increases by 10 percent and evidence of a blackbody core is seen.

Further measurements, both spectroscopic and interferometric, are in progress to complete the fuel preheat characterization. Numerical simulations are being initiated by the Plasma Theory Division to investigate whether our 4-eV luminous front is consistent with a significantly hotter interior as earlier postulated.⁴⁵

Fig. 40. Density measurements via laser-interferometry. Power in the two beams was matched by proper selection of beam splitters and insertion of neutral filters (0.0 to 0.3) as needed in the reference beam. The photomultiplier is encased in Mu-metal and has a double electrostatic shield.

Fig. 41. Interferometer signals for axial and off-axis probe beam alignments. One 2- π oscillation corresponds to a density line integral of $0.35 \times 10^{18} \text{ cm}^{-2}$.

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APPLICATIONS

REP-RATE PULSE POWER TECHNOLOGY STUDIES

Overview

The Rep-Rate Technology Program was initiated in FY'77 to develop the pulse power technology required for high average power drivers that will be necessary for either particle beam or laser initiated ICF reactors. During this period, fabrication of the 350-kV, 300-J, 100-pps test facility was completed and the facility is now being utilized to investigate the appropriate pulse power components. The effects of gas flow rates on the operation of high-voltage and low-voltage spark gaps are being investigated. Development of high-voltage, pulse transformers continued during this period. Design of a 1.0 to 1.5 MV test facility was initiated. Recent activities in our development of excitation sources for high pressure gas lasers are included here also.

Development of a 350-kV, 300-J, 100-pps Test Facility

The 100 pulse per second test facility^{1,2} has now achieved half power operation for extended runs and full power operation for periods of a few minutes. The facility is designed to generate 350-kV, 30-kA, 30-ns pulses at rates to 100 pps. Current extended runs have reached 400 kV, 14 kA at 70 pps and 350 kV, 12 kA at 100 pps. A total of more than 10^7 shots have been fired yielding data on performance of high, time-average power, repetitive spark gap switches and component lifetimes. Individual runs have exceeded 5×10^5 shots. The PFL has been charged to 1 MV on single shot tests.

An artist's drawing of the facility is shown in Fig. 1. It consists of a low-voltage modulator section, a voltage step-up transformer, a pulse-forming line (PFL), a high-voltage switch and a load resistor or diode. Fig. 2 is an electrical schematic of the system. The modulator converts DC power at 10 kV to primary pulsed power at 20 kV by resonant charging a 1.5- μ F capacitor from 14.5- μ F capacitor. When the 1.5- μ F capacitor is subsequently discharged through the primary of the voltage step-up transformer, the PFL is charged to 700 kV. Near the peak of the charge cycle, the output switch closes and energizes the load. At full voltage and 100 pps, the average power output of the system is 30 kW.

A dual resonance transformer was chosen for this repetitive pulser application because of the high-energy transfer efficiency.³⁻⁶ In the present system, 94 percent of the energy stored in the 1.5- μ F capacitor is transferred to the PFL. The 6 percent energy loss is dissipated in the 1.5- μ F capacitor (~ 1 percent), the switch (~ 4 percent), and the transformer (~ 1 percent).

Currently, the operating limits for the system are set by the lifetime of the high current switch in the transformer primary and by the ability to quench the output switch. The lifetime properties of the transformer switch should be improved with installation of tungsten alloy electrodes and a ceramic body. The output switch presently being tested requires a higher gas flow rate than is available from the laboratory compressors. Additional air supply or a design that utilize the air more efficiently will be required for stable operation.

Low Voltage Rail Gap Switch

It has been clearly established through experiments with the 100-pps modulator and later in testing of the 100-pps, 300-J accelerator system that flow patterns and gas velocity are the key factors in effective scavenging of residual ionization and debris in repeated spark gaps. It is further indicated that high velocity gas flow over the working electrode surfaces provides surface cooling between shots and consequently prevents or at least inhibits the occurrence of hot spots which enhance the probability of successive breakdowns at those same points. The effects of hot spot formation are progressively lower voltage holdoff and significantly increased electrode erosion at the hot spots.

To investigate this problem in the rail gap switch on the low-voltage, high-current discharge stage of the 100-pps modulator, a variety of slotted and perforated trigger tubes were tried. The arrangement that produced the widest electrical operating range and most efficient use of gas is shown in Fig. 3. This trigger electrode has a tubular base with a 6-mm square rib bonded to its side. A line of 0.5-mm-diameter holes were drilled into the tube on each side of the rib base such that air delivered to the tube from each end was forced through the gap

Fig. 3. Electrode configuration for the rail gap switch.

region from a series of high velocity jets produced by the small perforations. When triggered, the breakdown of the gap occurs between the main electrodes the top edge of the rib. With the high velocity air streams below the breakdown region, the plasma and debris is expelled into the top region of the gap housing where it is carried away through a hose. With this arrangement, air flows directly over the breakdown areas and provides rapid cooling of both the trigger electrode and main electrodes. The relative effectiveness of the various purging schemes was judged primarily by postmortem examination of erosion uniformity on the electrodes after extended runs and by visual observation of shot-to-shot arc movement during operation.

The rail gap switch is typically operated in a range of 10 kV to 25 kV with a total gap space of 8 mm. The switch is triggered by a cable discharge trigger source operated at 25 kV. The DC self-break level and triggering threshold characteristics are plotted in Fig. 4. Two points representing the dynamic self-break voltage and the triggering threshold at 50 pps are superimposed on the DC data curves. These points lie very close to the DC data. The low triggering threshold of the switch (approximately 30 percent of the self break) provides a wide range for stable operation. A further advantage of the wide triggering range is the ability to vary the pulse rate and voltage of the system without having to continually readjust the pressure in the switch.

High Voltage Switch

The switch between the PFL and the load is a 700 kV self-breaking, air-dielectric,

Fig. 4. Self-breakdown voltage and minimum trigger voltage or pressure for the rail gap switch.

spark gap shown in Fig. 5. (Air was chosen for reasons of economy.) When operating into a matched load, it conducts a peak current of 35 kA for 30 ns with a 10-ms recovery period between pulses. In eight hours of running (about 3×10^6 shots), it must pass 3000 coulombs without degradation in performance. Optimal power flow is achieved with the switch operating as close as possible to the peak of the PFL charging waveform. However ringovers, that is pulses on which the statistical fluctuation in breakdown voltage cause the switch not to close, must be minimized to avoid excessive heat dissipation in the transformer and second stage capacitor. The spread in breakdown voltage determines the fraction of PFL full voltage at which the switch must operate.

The switch operates at pressure up to 10 atm with a gap length of 3 to 6 cm. Its cylindrical acrylic housing (2) has a 20 cm inner diameter and is 19 cm long. Dried and filtered

Fig. 5. High voltage switch.

air is injected from the output (larger) electrode (4) through 8 ports (5) with a rotary flow pattern which sweeps and cleans the housing. Exhaust gas exits through the center of the same electrode passing through a copper cooling coil (8) located within the high voltage structure before entering nylon lines through the high field region. Both the input and output gas lines are connected to the output side of the switch to minimize the voltage standoff required. Because of a slight field enhancement, breakdown occurs over a 50 cm² band at the outer edge of the small electrode (1) during normal operation. Dispersion of the spark over large areas of the tungsten-copper electrode tips has reduced the electrode erosion for 2×10^6 shots to a negligible level.

The switch was operated for 2×10^5 shots at 1 to 5 pps and 1 kA peak on a repetitive impulse tester with a dual resonance waveform prior to the 2×10^6 shots in the present accelerator. Data from these experiments confirmed that the electric field vs. pressure curve for air is not sensitive to the first half cycle of the dual resonance waveform. The voltage breakdown distribution is observed to have a standard deviation equal to 3 to 5 percent of its mean. With ultraviolet illumination this deviation has been reduced below 1 percent. An arc from a needle positioned 1 cm from the smaller electrode and resistively coupled through 25 k Ω to the larger electrode generated the UV. Figure 6 shows 30

consecutive traces (spaced manually along the time axis to display voltage stability). The total voltage pulse lasts 1.65 μ sec, the positive swing 0.45 μ sec. Illumination occurs shortly after the zero crossing and breakdown occurs repeatedly at 450 kV, the peak of the waveform. Figure 7 displays 19 equivalent shots vertically spaced to display time jitter. The standard deviation of the breakdown time distribution is 15 ns.

Fig. 6. Sequence of high voltage switch tests showing voltage jitter, 190 kV/div, 0.5 μ s/div.

Fig. 7. Sequence of high voltage switch tests showing time jitter - 50 ns/div.

Experiments conducted at repetition rates above 5 pps have used a switch without UV illumination installed in the 100-pps facility. The charging waveform on the output switch is displayed in Fig. 8. It is bipolar, the peak positive voltage being approximately 60 percent of the peak negative value. Total pulse length is 5.6 μsec . The positive swing lasts 3 μsec and the negative 2.6 μsec . In the figure, the output switch fires near the peak of the negative voltage excursion.

Fig. 8. Charging voltage waveform on the PFL 300 kV/div, 2 μs /div.

For a given gas flow rate and a given pulse there is a maximum pulse repetition frequency (PRF) at which the switch operates stably. Instability may be marked by dispersion of the breakdown voltage on the negative voltage swing or by the appearance of breakdown near the peak of the positive voltage excursion with a stable negative breakdown level. Onset of jitter in the negative breakdown level may be observed from multiple shot photographs as in Fig. 9 which shows a sequence of shots. With sufficient gas flow, the switch stability at 20 to 30 pps with no UV illumination is comparable to the 1-pps stability with UV illumination. This is presumed to be due to the presence of remnant ionization and metastables which simulate the effect of UV pre-ionization.

The appearance of positive voltage breakdown is a more common sign that the switch is not adequately purged. Figure 10 presents a plot of the flow rate needed to suppress positive breakdown vs. repetition rate at

Fig. 9. A sequence of high voltage switch tests on the 350-kV facility showing voltage jitter 160 kV/div, 2 μs /div.

Fig. 10. Flow rate vs. repetition rate for stable operation of high voltage switch.

constant gap spacing, voltage, and peak current. The proportionality between flow and maximum pulse rate indicates that the product of time between pulses and the flow rate is equal to some function of the other variables in the

problem, e.g., voltage, peak current, and geometry. Experiments to establish this functional relationship are currently in progress.

Multichannel Surface Discharge Switch Experiment

Repetitively pulsed high energy systems will require multichannel spark gaps to avoid excessive electrode wear and in some cases achieve low inductance. In anticipation of this requirement a simple experiment was conducted to evaluate the merits of a surface discharge switch for these applications.

The experiment consisted of a 0.04 μF capacitor connected to a two-electrode rail gap (15 cm long) with an insulated trigger electrode placed between the two main electrodes (Fig. 11). The trigger electrode was made up of a 2-cm copper tube inserted inside a 2.5-cm alumina ceramic tube with the ends sealed off to prevent breakdown from the inside. The trigger pulse was supplied by a charged coaxial cable which was connected to the trigger electrode through an isolation capacitor and a pulse shaping spark gap.

The gap was unpressurized and operated over a range of 10 to 20 kV with visual observations made of the breakdown channels. Preliminary results showed that with a dry ceramic surface and a trigger voltage of at least 20 kV, the average channel population was no greater than 3 to 4. However, when the ceramic surface was lightly wiped with transformer oil, the average channel population increased to greater than 10 (Fig. 12). The high channel number would remain for 200 to 300 shots then fall to the original 3 or 4 within about 50 shots.

To renew the surface it was only necessary to dry wipe the surface of the ceramic and the channel number would again increase to greater than 10. In wiping the ceramic, the residue removed was barely perceptible which indicated that fouling of some sort was probably not responsible for the eventual reduction of breakdown channels. In fact, the role of the thin oil film itself in controlling the channel population is not known. Further experiments will be required to understand the surface effects.

If the appropriate operating conditions can be found, a surface discharge gap may offer a wide trigger range without trigger electrode erosion and be an attractive candidate for future high current multichannel switches.

Fig. 11. Surface discharge switch.

Fig. 12. Open shutter photograph of multichannel surface discharge switch.

Spark Gap Gas Flow Experiments

As repetitive spark gaps are required to pass higher energy and power levels it becomes increasingly important to utilize the gas flowing through the switch more efficiently. Switch configuration, flow volume, flow pattern and gas velocity all have pronounced effects on switch performance. The present experiments were conducted to study the flow characteristics through a variety of switch configurations and determine the relative merit of different scavenging methods.

Conventional repetitive spark gaps typically have in-line cylindrical electrodes with hollow centers through which gas delivered to the housing is exhausted along with the shot-to-shot ionization and debris. Occasionally, gas injected into the housing is given rotational motion to improve the mixing and clean out process, but in practically all cases the gas velocity is quite low (well below sonic speed) until it passes between the electrodes. Consequently, plasma from a high current discharge can expand freely into the low velocity region outside the electrodes and mix with the approaching cool gas. Total clean out of the ionization products requires displacement of a sizeable gas volume outside the electrode region in addition to the volume between the electrodes. The scavenging process would be considerably more efficient if the plasma were prevented from expanding into the approaching gas stream and the gas cooled as rapidly as possible by turbulent mixing in the regions between the electrodes and in the exhaust ports. The present experiments included both conventional purging schemes and three new techniques involving high velocity jet purging.

A total of six types of switch models were tested. These were configured as transparent two dimensional models through which gas flow could be observed in a schlieren optical field. The switch models are shown in Fig. 13. A test run typically consisted of flowing air through the model within the schlieren field and firing a plasma gun (20 J) into the gap region of the model to simulate a switching arc. The plasma gun discharge was synchronized with a high speed framing camera which recorded the discharge and subsequent sweep out of the plasma cloud by the flowing air. A six-frame sequence of one such test is shown in Fig. 14.

In summary, the results showed that the spherical electrode, tubular electrode and cone frustum models were fully cleared of ionization products within 2 to 2.5 ms with flow

volumes up to 35 SCFM. At the same flow rate the coaxial switch model cleared within 0.8 ms. In all of the above cases the air was delivered to the open volume of the housing and exhausted through the electrodes in the conventional manner of switch purging.

A more efficient sweep out of the spherical electrode model was achieved by placing a tubular center electrode with a simple nozzle in the plasma gun and supplying the nozzle with 100 psi air. The resulting jet velocity was approximately 335 m/sec ($\text{mach} \approx 1$). The jet was directed into the convergent section of a diffuser in the opposite electrode which formed a single stage jet pump. With 15 SCFM delivered through the nozzle, an additional 5 SCFM was drawn into the exhaust stream through the housing ports for a combined flow of 20 SCFM. This volume with the high velocity jet at the center reduced the total clean out time to about 1 ms. Compared to the original arrangement which required a full 2 ms with 33 SCFM.

The high speed vortex switch and the linear rail gap models represent two new techniques of scavenging which showed marked improvements over all other methods. With the high speed vortex model the plasma did not expand beyond the electrode diameter of 2.5 cm with a total flow of 4 SCFM. Total clean out was estimated to be less than 0.75 ms. At higher flow rates the expansion diameter was less and was blocked from view by the electrodes. However, in the spherical, tubular, and cone frustum models the plasma expanded to at least 5 cm with flow rates up to 35 SCFM which illustrates the effectiveness of the high speed vortex.

The linear jet purged rail gap also showed good clean out efficiency. With less than 3 SCFM the clean out time was no greater than 0.6 ms. The exceptionally fast clean out time of this gap is attributed to the supersonic air stream through the gap regions. Furthermore, in this and the high speed vortex model the high velocity was generated outside the gap region and projected through it which prevented the typical back blast of expanding plasma into the open volume of the switch.

At this point, the results of these experiments must be regarded as largely qualitative. However, the dramatic improvements in switch scavenging with the new low volume, high velocity models illustrates that substantial gains can be made over conventional designs. Further experiments are planned with actual

Fig. 13. Gas flow experiment spark gap models.

Fig. 14. Six frames from gas flow experiment.

prototype switches and flow models as an ongoing effort to improve high power switch performance and efficiency.

High Voltage Transformer Development

A new high voltage transformer (Fig. 15) has been designed and constructed. It is a spiral strip design with a single turn primary and a 48-turn secondary winding. The margins of the transformer on both the core and case are graded with split rings similar in principal to most previous designs. It has, however, several features which reduce the cost of the unit and improve its performance in repetitive pulse applications.

Cost reduction features include use of standard tube sizes for all cylindrical sections, commercially available duct transitions for the end flares and insulated No. 12 gauge electrical wire for grading rings on the core. The case rings are inserted in grooves in the case and do not require a vacuum encapsulation process to secure them in place.

This transformer has an externally exposed primary turn which facilitates heat removal in repetitive pulse applications. The exposed primary has flanges connecting the two case sections which simplifies the assembly of the unit and allows it to be easily disassembled for winding changes or service.

The transformer has undergone preliminary testing up to 800 kV on the REPIT facility¹ and has been operated at approximately 10 pps for shot periods at approximately 500 kV. No internal problems have been detected. The transformer will be tested to 2 MV in the near future to determine whether windings can be operated with voltage stresses in the range of 400 kV/cm. Before the tests can be completed, however, the load capacitor and switch in the REPIT tank must be modified to accommodate the higher voltages.

Marx Generator Design Studies

Conceptual design of a Marx generator for a high-voltage, high-power test facility (1 MV, 10 kJ per pulse, 10 to 100 pps) has been completed. This facility will be used to study electron beam generator components at higher voltages and at average power levels approximately one order of magnitude greater than those of the present repetitive pulse test facility. Because of the high average

Fig. 15. Pulse transformer.

power, it will be necessary to closely control energy losses in the Marx generator. Resistive isolation between stages, resulting in significant energy loss during the Marx charging, must be replaced by inductive isolation.

As presently envisioned the Marx would have 16 stages with plus/minus charging. A charging voltage of approximately 60 kV per stage would be required for one megavolt operation. The 60 kV would be achieved by LC ring-up from a 30 to 40 kV primary energy source. Capacitance per stage for 10 kJ operation at 60 kV would be 0.35 μF for a total Marx charging time capacitance of 5.6 μF . To charge the Marx in 10 msec the input inductance would be 1.8 H. The maximum charge current would be only 106 A. Thus, ring and hold charging using semiconductor diodes is entirely reasonable. Studies using the SCEPTRE network analysis program⁸ demonstrate that the Marx capacitors can be uniformly charged in this fashion.

Upon erection, the Marx generator energy must be delivered to its load. The equivalent circuit for the erected Marx and its load is shown in Fig. 16. An analysis of this circuit with SCEPTRE shows that the energy can be transferred to the load in about 1 μs . Most of the energy loss goes into the interstage inductances, L_I . Assuming $L_I = 30 \mu\text{H}$, the energy transfer efficiency to the load is 86 percent. Doubling L_I cuts the loss in

Fig. 16. Marx generator equivalent circuit.

half giving a transfer efficiency of 92 percent. In this model, the energy transfer efficiency may be increased to better than 99 percent with appropriately large inductors; however, the effects of stray capacitance not included in the simulation will limit what may be achieved in practice.

The peak output current from the erected Marx generator will approach 50 kA. The development of a 50 kA, 120 kV, 100 pps spark gap switch suitable for this Marx represents a major challenge. Eight such switches must be erected simultaneously and quenched in 10 msec. For comparison, the primary input and output switches of the prototype facility currently operate at 20 kA, 20 kV and 13 kA, 600 kV, respectively.

The primary energy store for this test facility will be a DC power supply. Specifications for the device have been written and switch gear for connection to the 4160-V power mains is being installed.

LOW CURRENT DENSITY DIODE STUDIES

Overview

Large area low-current density ($1\text{--}40\text{ A/cm}^2$) electron beams are required for direct excitation of low-gain lasers or photolytic sources. Generally sharp-edged electron emitters are used to provide the field enhancement necessary to form the cathode plasma and

initiate space charge limited electron flow.⁹ The mean electric field of 17 to 50 kV/cm are required to achieve the low-current density, space-charge limited electron flow. With this type of cathode it is difficult to achieve uniform current densities at the anode¹⁰ and substantial temporal fluctuations in the current density are caused by cathode plasma instabilities.¹⁻¹⁵ For efficient operation of these diodes, it is necessary to suppress emission from cathode support structures.

During this period, investigations of the cathode plasma instabilities, emission enhancement, and emission suppression techniques have been underway. Development of a 400-kV, 1-psec electron beam source for these studies was completed.

Cathode Plasma Instability Studies

In certain operating regimes electron beams from diodes of the type commonly used for direct excitation of gas lasers or to sustain discharge lasers (blade cathode, planar anode) show large local current density fluctuations. Since these fluctuations could have a negative effect on the efficiency and operation of the laser, experiments to study the physics underlying these instabilities and to search for stable diode operating regimes have been performed during this period. These fluctuations are characterized by current density increases to several times the ambient space charge limited value in bursts lasting a few tens of

nanoseconds. In general, the current density after the burst is unaffected by the occurrence of the burst, and subsequent bursts may occur aperiodically.

A similar phenomenon has been studied extensively in the single needle cathode geometry where aperiodic current bursts exceeding five times the ambient space charge limited current have been observed¹¹ together with microbeam formation, ion acceleration to energies in excess of the diode voltage,^{12,13} and dispersion of the electron energies.¹⁴ Assuming that the instability arises because the expanding cathode plasma can not sustain the diode current density, a model relating the current density just before the instability, j_{CR} , to the onset time of the instability, t_{CR} , has been derived and tested for $10^4 \text{ A/cm}^2 < j_{CR} < 10^5 \text{ A/cm}^2$ with good agreement with data.¹⁵ Data collected during this period indicate that within certain limits the model may also be correct for j_{CR} as small as 2 A/cm^2 .^{16,17} This model further postulates a turbulent plasma between the cathode and the anode which disperses the electron energies. Microwave emission from the diode at the time of the instability has been found to be consistent with such turbulence.¹⁸ With the modifications described below, this needle cathode model also seems to apply to blade data. This is reasonable since the fluctuations in current density are qualitatively similar in both cases. The blade data shows that the instabilities on the average occur later in time for a given current density than the needle instabilities which is consistent with the model. However, microwave emission has not been observed in the blade experiments, indicating the absence of a turbulent mid-gap plasma. This has yet to be explained theoretically.

Along with the LPN accelerator, a pulse generator, a lumped-constant, pulse-forming network (PFN).^{1,16} An electrical schematic of the LPN is shown in Fig. 17 together with the open circuit (no-load) output pulse. The no-load pulse is 1.1 μsec long with 0.2 μsec rise and fall times. (Because of the 30- Ω resistor in parallel with the diode, the no-load condition actually corresponds to the generator driving a matched load.) For the data presented the no-load voltage would have been 200 kV, but the actual peak diode voltage was typically somewhat smaller due to loading of the generator by the diode.

The cylindrical 75 nH LPN diode, Fig. 18, was adapted to mount needle, blade, or dome cathodes with anode-cathode (A-K) spacings

Fig. 17. Electrical schematic of the LPN accelerator. Superimposed waveform corresponds to an open circuit at the diode.

Fig. 18. LPN diode schematic.

from 0.5 to 6 cm on a variable length shank. Current density and total diode current were monitored with the Faraday cup and CVR shown in Fig. 18. Typically the Faraday cup was covered by a copper foil more than an electron range thick with a 2-cm-diameter hole on axis for current density measurements. Diode voltage was monitored with a copper sulfate resistive divider at the output of the PFN. Microwave measurements were made through three ports 90° apart in the diode sidewall as shown in Fig. 18. All microwave data were taken at 90° to the diode axis.

A typical needle event is shown in Fig. 19 where Fig. 19A is a combination of the voltage waveform (upper trace), and current density (lower trace), and Fig. 19b is the total current. The maximum mean stress is 58 kV/cm over a 2.7 cm gap. The peak current, after the diode has shorted is 12.5 kA. The CVR current spike reaching 75 percent of the short circuit current at 20 ns into the pulse is accompanied by a "notch" in the voltage pulse and an instability going off scale in the current density measurement. Fig. 20 is a plot of j_{CR} vs. t_{CR} averaged over 10 shots per point typically. The dashed curve is a fit to the data of Proskurovskii, et al.¹⁵ at higher j_{CR} . Note that the points at lower j_{CR} fall on the curve while the points above 20 A/cm² are significantly above it indicating that the instability does not occur on the rising portion of the waveform. At smaller A-K gaps the instability tends to occur at the peak of the loaded generator waveform, a time slightly earlier than the no-load peak (Fig. 17) but significantly later than the theoretical prediction. This result combined with observation that a small instability often occurs at the time of the small voltage drop 80 ns into the voltage pulse (Fig. 17), leads to the speculation that the diode, in general, will remain stable as long as the voltage is increasing. A corollary would be that a constant falling voltage eventually produces an unstable current regime.

The initial instability occurs before closure of the A-K gap by the expanding cathode plasma. In the event of Fig. 19, the initial instability occurs at t_{CR} equal to 200 ns whereas gap closure as measured by the fall of the gap voltage to zero occurs at t_{close} equal to 420 ns. Assuming constant closure speed during the pulse, the original 2.7 cm gap has been reduced to 1.3 cm at 200 ns. For the total data sample $0.3 < t_{CR}/t_{close} < 0.5$, corresponding to less

than 50 percent gap closure at t_{CR} . As discussed below, a comparison of the blade cathode impedance data with a model based on the Child-Langmuir theory for a cylindrical diode, indicates that closure speed is constant and in reasonable agreement with the zero voltage calculation. Such detailed comparisons have failed thus far for the case of the needle data and indeed an inspection of the total current waveform of Fig. 19b, suggests that the closure speed may increase following the initial instability. If it does the increase might be due to the generation of anode plasma by anode heating during the instability as described in Ref. 15.

Plasma motion has been monitored for a needle cathode with a 2.6-cm A-K gap using interferometry on forward scattered 25 GHz microwaves. A constant gap closure by a dense ($> 7 \times 10^{12}$ cm⁻³) plasma is observed but the interferometric data does not indicate any structure associated with the current bursts. Microwave emission from the diode plasma, however, shows a burst structure simultaneous with the current density bursts (Fig. 21). The microwave data are consistent with a model in which a sheath is created in the cathode plasma.¹¹ A beam is formed in the sheath which reacts with the plasma on its anode side to produce plasma oscillation (turbulence) and thus microwaves. Assuming that the sheath becomes so dense that the density of the expanding cathode plasma becomes too small to support the diode current density, the time at which instability occurs, t_{CR} , should be proportional to $j_{CR}^{-0.5}$. To understand this relationship, assume that at $t = 0$ a whisker on the cathode tip explodes. A cathode plasma forms when debris from the explosion is ionized by electrons emitted from the cathode. Subsequently, additional material is vaporized from the cathode by the action of joule heating and ion bombardment. This material is fed into the cathode plasma at a rate of R atoms per second. The cathode plasma generated at the needle tip expands into the evacuated diode volume with assumed spherical symmetry at a plasma front speed v . As the plasma expands its total mass increases as Rt and its volume increases even more rapidly, as $\frac{4}{3} \pi (vt)^3$. Thus the mean plasma density, ρ , decreases as does the maximum current density, j , which the plasma can stably conduct $\frac{1}{r}$ (e is the electron charge and s is the electron thermal speed in the plasma). Simultaneously, the current density being drawn from the plasma increases

(a)

(b)

Fig. 19. Typical needle cathode shot, time base 100 ns/cm.

- a. Diode voltage, 87 kV/cm (upper trace).
Current density on axis, 60 A/cm²/cm (lower trace.)
- b. Total diode current, 3 kA/cm.

Fig. 20. Current density vs. instability onset time curve from blade and needle cathode data.

due to closure of the A-K gap. A critical condition is reached when

$$j = \frac{1}{4} \rho_{es} = \frac{1}{4} \left(\frac{Rt}{\frac{4}{3} \pi (vt)^3} \right) es.$$

Solving for t , the instability condition becomes $t \propto \frac{1}{j^{0.5}}$. For future reference note that if the plasma were to expand cylindrically, as from a blade (line) source, the volume term would be $\pi l (vt)^2$, l being the blade length. Instability occurs at a time $t \propto 1/j$. Finally for a parallel plate geometry where the only volume increase is due to linear expansion across the gap the volume increases in proportion to time. The time factors cancel in the instability equation and instability at constant j is the prediction.

It has been noted that $t_{CR} \propto j^{-0.4}$ fits the data on the intervals $10^2 \text{ A/cm}^2 < j_{CR} < 10^4$

Fig. 21. Microwave bursts correlated with total current bursts for a needle shot.

A/cm^2 and $2 \text{ A/cm}^2 < j_{CR} \leq 20 \text{ A/cm}^2$. At intermediate values the data are ambiguous.

Blade data were taken in the same apparatus with a 50- μm thick, 10-cm-long stainless steel foil blade with edges rounded to reduce field enhancement. Voltage and current traces for a typical shot are shown in Fig. 22. Open shutter photographs showed a relatively uniform density of emission sites along the blade. The peak mean stress is 120 kV/cm over a 1-cm gap. The instability in current density (lower trace, Fig. 22) 250 ns into the pulse is not observed in either the voltage waveform (Fig. 22a, upper trace) or total current (Fig. 22b). Thus, neither voltage nor total current may be relied upon to detect instability from blade cathodes.

Both t_{CR} and the time to diode closure, t_{close} , are significantly longer for a given A-K gap and voltage when the cathode is a blade compared to a needle. The relationship between t_{CR} and j_{CR} for blades is also shown in Fig. 20. The $t_{CR} \propto j_{CR}^{-1.3}$ behavior correlates reasonably well with the model used to explain

(a)

(b)

Fig. 22. Typical blade cathode shot, time base 100 ns/cm.

- a. Diode voltage, 87 kV/cm (upper trace).
Current density 60 A/cm²/cm (lower trace).
- b. Total current, 3 kA/cm.

the needle data. If the cathode plasma expansion is cylindrical (as from a blade) rather than spherical (needle) the theoretical relation is $t_{CR} \propto j_{CR}^{-1.0}$, which for the sophistication of the model is adequate agreement.

Nothing can be said based on the blade data concerning the affect of a rising voltage on stability because in the parameter range accessible, t_{CR} always occurred on the flat portion of the LPN voltage waveform. Microwave emission is very seldom observed in the blade experiments. It is never associated with the first instability and when seen occurs about the time the diode shorts.

As with the needle data, the initial instability occurs well before gap closure. Fig. 23 shows the diode impedance for a blade shot with a 2-cm gap and a maximum mean stress of 70 kV/cm. The dots are a rough fit to a model based on the Child-Langmuir formula for space charge limited flow between coaxial cylinders. Two variable parameters were used, the overall normalization and the cathode plasma closure speed. It is not remarkable that a two parameter fit can match a relatively linear curve, independent of the function being fit. However, the closure speed deduced from the fit is sufficiently close to that computed from the diode voltage collapse (as shown in Fig. 24) to lend credence to the model. It is interesting that the fit implies a constant closure speed across the entire A-K gap.

Data were also taken from a dome cathode (radius, 2 cm) at A-K spacings < 1 cm. This is a good approximation to a parallel plate geometry with enough field enhancement to insure that breakdown occurs on axis where it can be seen by the Faraday cup. Fig. 25 shows a typical shot; note the presence in the current density of bursts similar to those seen from blades and needles. Microwave emission is not observed.

The data are not, as yet, good enough to establish a relation between t_{CR} and j_{CR} . Note, however, that the model which has been successful in reproducing the relationship between t_{CR} and j_{CR} for needles and blades predicts t_{CR} to be independent of j_{CR} for a parallel plate geometry.

Fig. 23. Impedance characteristic for a blade shot (solid curve) compared with Child-Langmuir cylindrical diode model calculations (dots).

Fig. 24. A-K closure speed vs. gap spacing for blade and needle data.

Fig. 25. Typical dome cathode shot, time base 100 ns/cm. Voltage at 87 kV/cm (upper trace). Current density at 300 A/cm²/cm (lower trace).

Emission Enhancement Experiments

The electron emission characteristics of three materials have been investigated as part of the continuing study of low current density, one microsecond diodes. The test cathodes were subjected to low electric fields (20 to 114 kV/cm) while observing the emission quality and uniformity across the cathode surface. Diagnostic measurements included open shutter photographs of the cathode, radiochromic dosimetry at the anode, and diode voltage and current waveforms.

A 10.2-diameter cathode with a graphite-felt emitting surface was tested on the LPN accelerator^{1,16} using the parameters in Fig. 17. Graphite felt is a material of density packed graphite fibers with the fiber ends position in a random direction. Mean electric fields of 20 to 45 kV/cm were applied between the cathode and anode. At 20 kV/cm, cathode plasma formed at discrete locations as shown by the open shutter photograph of Fig. 26a. These photographs are reflections of the cathode from a metallic anode. The current and voltage waveforms shown in Figs. 27a and 27b indicate that the current lagged the voltage rise by a few tens of

nanoseconds. As the mean electric field was increased to 45 kV/cm, the current turn-on time decreased as shown in Figs. 28a and 28b; however, Fig. 26e indicates that the same discrete cathode plasma patterns were produced. Radiochromic dosimetry indicated that the spatial anode current density variations were ± 25 percent from the mean value. Uniformity of the current density should be improved if the same electric field is applied to a large A-K gap spacing. A 2.5-cm-diameter graphite felt cathode behaved in a similar manner with the exception of showing a higher impedance.

A 10.2-cm-diameter cathode of solid graphite cross-hatched with 0.16-cm-wide and 0.16-cm-deep grooves spaced 0.16 cm apart, was tested under the same conditions. With fields of 25 to 35 kV/cm, the electron emission was non-reproducible with long current turn-on times or no turn-on at all. Above 35 kV/cm, the current turn-on time was reduced from hundreds of nanoseconds to tens of nanoseconds. Open shutter photographs of the cathode showed a relatively small number of emission spots which were randomly located (shot-to-shot) across the cathode face.

A small sample of metal-oxide matrix¹⁹ material was tested on the LEGS accelerator (described

Fig. 26. Open shutter photographs of a graphite felt cathode with varying electric fields.

- a. 20 kV/cm.
- b. 25 kV/cm.
- c. 30 kV/cm.
- d. 35 kV/cm.
- e. 45 kV/cm.

Fig. 27. Diode waveforms for a low electric field (20 kV/cm) graphite felt cathode.

- a. Voltage at 500 ns per division.
- b. Current at 500 ns per division.

Fig. 28. Diode waveforms for a high electric field (45 kV/cm) graphite felt cathode.

- a. Voltage at 500 ns per division.
- b. Current at 500 ns per division.

elsewhere in this report) using the parameters given in Table I.

TABLE I

LEGS Pulser Parameters

Output Voltage	460 kV
10/90 Risettime	40 ns
Pulse Width	1 μ s
Impedance	40 ohms
Cathode Area	1000 cm ²

The experimental setup and two photographs of the surface with magnification of 6,000 and 1,500 are shown in Fig. 29. As indicated by the photographs, the material consists of an array of tungsten needles less than 1 micron in diameter that protrude from the surrounding surface 10 to 15 microns. The needle density is approximately 4×10^6 cm⁻² of sample surface area. A brass sample of the same macroscopic geometry was used to compare the emitting properties of the array. At electric fields of 48 to 72 kV/cm, emission was not detected by a Faraday cup and radiochromic film dosimetry. With the electric field 114 kV/cm, the sample emitted at 300 ns into the voltage pulse and the diode had developed a short by 800 ns. The emission from the brass sample was similar to the tungsten array. Possibly, the high density of the tungsten needles causes the array to appear as a smooth surface thus reducing the field enhancement and making it comparable to a smooth brass surface with its macroscopic surface perturbations.

Emission Suppression Experiments

For efficient operation of electron beam diodes for laser excitation, methods must be developed to suppress electron emission that occurs from cathode support structures of low-current density electron beam diodes with a one microsecond pulse duration. Initial experiments involving electron emission suppression using dielectric coated cathodes were performed on the LPN accelerator and reported in Ref. 1.

Additional experiments have now been performed using the LEGS accelerator. Bare metal and dielectric coated cathodes were investigated with the test setup shown in Fig. 30. All cathodes had a 32 machine finish with the surface polished with 600 grit sandpaper and diamond polish (15-1 micron paste). Dielectric coatings were applied to this substrate by either aerosol spray or dipping. The thickness of the coating was not controlled; however, they were typically 50 microns thick. Instrumentation was adjusted to detect current emissions of 0.1 amp/cm² or greater being emitted by the 45 cm² cathode.

Tables II, III, and IV show the results of these tests. The electric fields shown in the tables are mean fields at which no detectable emission occurred. It should be noted, however, that the fields are taken at the

TABLE II

Emission Suppression Results
1.15 cm A-K Spacing

<u>Cathode Type</u>	<u>Electric Field (kV/cm)</u>	<u>Remarks</u>
Unpolished brass	> 63	Lower machine limit
Polished brass	94, 67, 72	
Silicone oil-aluminum	119	
Silicone oil-brass	125	
Polished aluminum	156, 127	
Nitrocellulose-aluminum	165	
Polystyrene-aluminum	175	
Acrylic #2-aluminum	194	
Teflon-aluminum	203	
Anodized-aluminum	211, 228, 197	
Clyptal-aluminum	233	
Epoxy-aluminum	275	
Acrylic #1-anodized aluminum	> 330	Upper machine limit
Acrylic #1-aluminum	> 330	Upper machine limit
Acrylic #1-brass	> 330	Upper machine limit

TABLE III

Emission Suppression Results
0.48 cm A-K Spacing

<u>Cathode Type</u>	<u>Electric Field (kV/cm)</u>
Acrylic #1-anodized-aluminum	206
Acrylic #1-brass	271
Acrylic #1-aluminum	349

TABLE IV

Emission Suppression Results
1.78 cm A-K Spacing

<u>Cathode Type</u>	<u>Electric Field (kV/cm)</u>
Polished brass	66
Polished aluminum	73
Silicone oil-brass	147
Silicone oil-aluminum	162

Fig. 29. Metal-oxide matrix experimental cathode.

Fig. 30. LEGS diode test setup.

average applied voltage and does not reflect the higher voltage excursion at the beginning of the pulse (refer to Fig. 34). The cathodes actually experienced 10 to 15 percent higher fields during the first 200 ns of the pulse. When emission occurred, it was observed during the first 400 ns for the majority of the cathodes.

All dielectric coatings with the possible exception of silicone oil, acted to suppress electron emission to some extent. Silicone oil, the product employed by most researchers to inhibit emission, gave the poorest results. It seemed to improve the brass cathodes but its value on polished aluminum cathodes at 1 cm spacings is questionable until further tests are conducted. One coating, acrylic #1, was far superior to the others and could be used to repair damage and imperfections in other coatings without interfering with test results. Acrylic #2, of different manufacture, could only be classified as average in its suppression properties.

In vacuum breakdown, an A-K gap spacing dependency is known but the extent of the dependency is unknown. For this reason, it is difficult to correlate the results

between different spacings as shown in Tables II, III, and IV. Discrepancies between results at different spacings can also be attributed to sample preparation. Attempts will be made to understand the somewhat ambiguous results that were obtained when the A-K spacings were changed.

LEGS, A Test Facility for Large Area, Microsecond Diode Studies

A design study for a microsecond e-beam generator suitable for large area ($\sim 1000 \text{ cm}^2$), low-current density ($\sim 1\text{-}20 \text{ A/cm}^2$) diode investigations was reported in the last semiannual report. The equivalent circuit for the pulser (LEGS) is shown in Fig. 31 and consists of a four-stage Type-A Guillemin network (PFN). The triggered crowbar switch can be used to obtain diode pulsewidths shorter than the PFN pulsewidth; it also reduces the pulse fall time to $\sim 60 \text{ ns}$. The pulser was assembled and has undergone considerable testing.

The Marx generator, shown in Fig. 32, consists of sixteen, $\pm 50\text{-kV}$, $0.22\text{-}\mu\text{F}$ capacitors and eight low inductance, low jitter 100-kV spark gaps with a midplane trigger electrode. The first two gaps are triggered by an externally applied pulse. The midplane electrode in the remainder of the gaps are coupled to ground via $10\text{-k}\Omega$ resistors. The output parameters of the Marx generator are given in Table V.

TABLE V

Marx Generator Output Parameters

Capacitance:	13.8 nF
Inductance:	1.5 μH
Series Resistance:	2.3 Ω
Maximum Voltage:	800 kV
Maximum Stored Energy:	4.4 kJ

The remaining stages of pulse-forming network (PFN) can be seen in Fig. 33. Also seen in this figure are the crowbar switch, the Marx generator and the diode vacuum feedthrough. The capacitance inductance values for these last three stages are given in Table VI.

TABLE VI

Nominal Values for PFN Elements

2nd Stage:	$C11 = C12 = C13 = 2.8 \text{ nF}$ $L1 = 3.0 \mu\text{H}$
3rd Stage:	$C21 = C22 = C23 = 2.8 \text{ nF}$ $L2 = 0.7 \mu\text{H}$
4th Stage:	$C31 = C32 = 4.1 \text{ nF}$ $L3 = 0.2 \mu\text{H}$

In testing the generator, the values of $L1$, $L2$, $L3$, and LM were adjusted to obtain the desired waveform. Substantial flexibility in the shape of the output waveform was demonstrated by making changes in the values of these elements. Fig. 34 shows the pulser output waveforms into a matched resistive load (40 ohms). The $10/90$ risetime is 40 ns with a full width at half maximum (FWHM) of $1.2 \mu\text{s}$.

Small area cathode studies are underway. A large area diode chamber that will allow the study of beams up to $\sim 1000 \text{ cm}^2$ has been designed and ordered. Delivery is expected in early December. A Hibachi anode and gas chamber has also been ordered. It will be used for beam transport and energy deposition measurement.

Fig. 31. Equivalent circuit for LEGS pulser.

Fig. 32. Photograph of Marx generator

Fig. 33. Photograph of PFN.

Fig. 34. Output voltage for LEGS pulser.

RADIAL ELECTRON BEAM LASER EXCITATION

Total and Spatially Resolved Energy Deposition Measurements

Measurements of energy deposition by the radially converging e-beam from the REBLE accelerator²⁰ were conducted for nitrogen, argon, krypton, xenon and SF₆ gases at fill pressures ranging up to three atmospheres.¹⁶ The REBLE diode and typical diode current, voltage, power and impedance waveforms are shown in Fig. 35. The 20-cm-diameter, 30-cm-long anode was a 0.005-cm-thick stainless steel foil. For these measurements the peak voltage was nominally 750 kV.

Spatially resolved deposition measurements were made using the radiochromic film package shown in Fig. 36. The package was ~1 cm wide and 30 cm long; it was placed at a given radial position inside the gas chamber and ran the length of the volume. The black paper on either side of the film assured that the deposition in the film was from the high energy electron beam. After placement of the film package, the chamber was evacuated, pressurized and irradiated by the incident radial e-beam. By scanning the film with a

densitometer, a spatially resolved measurement of the energy deposited in the film was obtained.

The experimentally determined dose delivered to the radiochromic film was compared with detailed Monte Carlo code calculations using the CYLEM code.^{21,22} CYLEM is a derivative of the CYLTRAN²³ Monte Carlo code and allows the inclusion of externally applied, static electromagnetic fields. The applied e-fields are restricted to void regions. Fig. 37 shows the geometry used for the code calculations. Only the radial electric field in the diode gap was used in the calculations. This allowed electrons which had random-walked out into the diode gap to be reflected back into the material region. By sampling the incident electron spectrum obtained from the diode voltage and current waveforms, both the initial energy of the primary electron and the radial electric field applicable during that primary electron history were obtained. The incident electron axial distribution was measured and approximated by a triangular source distribution symmetric about its midplane. All primary electrons were started normally incident to the anode foil. Because the code assumes a cylindrically

Fig. 35. Radial diode and typical diode waveforms.

Fig. 36. Radiochromic film package.

Fig. 37. CYLEM code geometry employed for calculations.

symmetric materials geometry, the radiochromic package was modeled by a complete cylindrical package. Since the measurements were conducted using ~1-cm-wide strips, an experiment was conducted and verified that the dose measured with the strips was not significantly different from that which would be obtained using a complete cylindrical package.

Figures 38a and 38b show a comparison of the experimental and calculated dose when the chamber was pressurized with xenon gas at 1200 torr and 2400 torr, respectively. The solid lines are the experimental dose and the histograms are the Monte Carlo calculations. The code results were converted into joules/gram by using the total incident beam energy as obtained from the diode voltage and current waveforms. The cross-hatched area indicates the total error in the calculations including both the statistical error and the uncertainty in the determination of the total incident beam energy. The disagreement between theory and experiment near the "wings" of the distributions is primarily due to the slight inaccuracy of the model used for the axial and angular distribution of the incident beam electrons.

Quantitative agreement similar to that shown in Figs. 38a and 38b was obtained for argon and krypton gas fills over the entire pressure range measured. Fig. 39 shows comparisons for nitrogen gas fills of 400 and 600 torr. In Fig. 40 comparisons are shown for gas fills of 400 and 1000 torr SF₆. Although reasonable agreement was obtained at 400 torr of SF₆, the calculated dose is about four times higher than the measured dose at 1000 torr and R = 1.4 cm. This discrepancy in calculated and measured dose delivered to the film at the R = 1.4 cm position occurs for SF₆ at all gas fill pressures above 600 torr.

Since agreement between experiment and calculations was obtained for all gases and pressures except SF₆, one can postulate that this discrepancy is due to the strong electro-negative nature of SF₆. Electrons are attached leaving low mobility negative ions with an associated space charge buildup which prevents the beam from penetrating to the center of the chamber. Although other mechanisms cannot be ruled out, this scenario described above seems to be a reasonable explanation for the disagreement between experiment and the Monte Carlo calculations since collective effects, such as space charge buildup, cannot be included in the calculations.

The total energy deposited in the gas as a function of pressure was determined by measuring the pressure rise inside the chamber after exposure to the radial e-beam. These measurements are compared to the Monte Carlo results in Fig. 41 for nitrogen, xenon and SF₆ gases. For the cases of argon and krypton gas fills agreement similar to that shown for xenon was obtained.

Radial Diode Impedance Characteristics

Studies of various cathode materials and geometries revealed that cathodes made of thin annular metal foils exhibited the shortest turn-on times, gave more uniform current emission, and had better shot-to-shot reproducibility than any other cathode types investigated. A study was made to determine the impedance characteristics of the radial diode using annular blades.

The diode impedance from a single annular blade cathode can be expressed as

$$Z(1\text{-blade}) = \frac{KX^2}{V^2 A} \quad (1)$$

where X is the anode-cathode gap spacing in cm, A is the area in cm² covered by the beam at the anode surface, and V is the diode voltage in MV.²⁴ The area is 2 R₀h where R₀ is the radius of the anode and h is the height of the beam at the anode surface. The height of the beam was experimentally determined to be within 10 percent of twice the A-K gap. Substituting and rewriting

$$ZV^2(1\text{-blade}) = \frac{K}{4\pi R_0} X. \quad (2)$$

Impedance data obtained for a single blade cathode is shown in Fig. 42. The dots are the experimental points and the solid line was obtained using equation 2 with K = 675. This constant gave an accurate representation of the data for both a 10 cm and 5 cm radius anode. It was also determined that, when no significant overlap existed between the individual beamlets, the impedance of an N-blade cathode was given by Z(1-blade)/N. When significant overlap between the individual beamlets existed, the impedance of the

(a)

(b)

Fig. 38. Comparison of experimental and calculated dose for xenon gas fills of 1200 torr and 2400 torr.

Fig. 39. Comparison of experimental and calculated dose for nitrogen gas fills of 400 torr and 1600 torr.

Fig. 40. Comparison of experimental and calculated dose for SF_6 gas fills of 400 torr and 1000 torr.

Fig. 41. Percentage of total incident beam energy deposited in gas as a function of fill pressure.

Fig. 42. Impedance of a single annular blade cathode of radius $R_0 + X$.

Fig. 43. Hibachi support structure.

multiblade cathode was not easily calculable but was always larger than that obtained with no overlap of the beamlets.

Hibachi - Anode Investigations

In the e-beam excited lasers the maximum working pressure of the gas chamber is determined by the strength of the thin-foil anode. For maximum energy transfer through the anode foil a high strength, low-Z metal foil is desirable, e.g., a high strength titanium alloy. In order to extend the working pressure beyond the capabilities of a self-supporting foil, a stiff support structure (Hibachi) may be used. Here some transport efficiency is lost due to absorption and scattering of incident electrons by the ribs of the support structure; furthermore this lost efficiency is not necessarily given by the optical transparency of the structure.

The Hibachi-type anode shown in Fig. 43 was designed for the REBLE facility to investigate the effect of the structure on the diode operating characteristics and to measure the transparency of the structure to the radial e-beam for various anode-cathode configurations. The calculated optical transparency

of the structure was 78 percent. Measurements of the beam energy transported through this anode structure were made using a 0.005 cm stainless steel liner in order to compare with measurements using a self-supporting anode of similar construction to the liner.

Measurements using the Hibachi anode indicate that the holes in the support structure had little or no effect on the impedance characteristics of the radial diode for A-K gap spacings of 2.5 cm or larger, i.e., the diode impedance behavior was essentially the same as that obtained with a solid anode of diameter equal to that of the support structure.

The beam transport efficiency through the Hibachi anode was obtained by measuring the maximum energy delivered to SF_6 gas as a percentage of the total incident beam energy; this is compared to the equivalent measurements using a self-supporting foil anode. Measurements were conducted for various A-K gap spacings and for support structures with wall thicknesses of 0.32 cm and 0.64 cm. Results are summarized in Table VII.

TABLE VII

Beam Energy Transport Through Hibachi Structure
With 0.005 cm Thick Stainless Steel Foil

A-K Gap (cm)	Wall Thickness (cm)	Maximum Percentage of Total Incident Energy Deposited in SF ₆ Gas
1.59	0.635	28
2.54	0.635	35
3.81	0.635	36
2.54	0.318	47
3.81	0.318	57

These results are to be compared with a self-supporting 0.005-cm-thick stainless steel foil which gives a maximum of ~ 70 percent of the total incident beam deposited in the SF₆ gas.

As was expected, the structure with the thinner wall transmits more of the beam energy. Another feature evident from this data is that more of the beam energy is transmitted at the larger gap spacings. This is related to the effect of the gap spacing on the electron trajectories as they approach the apertures. It can be seen from the last two rows in this table that under these conditions the structure approaches the calculated optical transparency.

The Hibachi anode with 0.32-cm wall thickness and 0.005-cm stainless steel foil was pressure tested and determined to be capable of operating at pressures up to five atmospheres. The self-supporting foil of equivalent dimensions failed consistently at ~ 3 atmospheres gas pressure.

AN INDUCTIVE GENERATOR FOR FUSION POWER GENERATION

Introduction

An inductive generator called Pulsar is being developed for possible future application as a prime power source of "topping stage" for pellet fusion reactors. This generator employs a direct current superconducting magnet to provide magnetic flux for a generator coil. In a laser-driven reactor this could be accomplished by allowing plasma produced by

the pellet explosion to expand within the generator coil. In a charged particle beam reactor the burst-heated atmosphere within the pellet chamber could be allowed to drive a metallic fixed-radius piston axially through the coil. In either case, electric energy is generated with relatively high conversion efficiency compared to that achieved with steam-turbine generators.

Energy partition for the pellet explosion would determine the fraction of plant power produced by this direct and inexpensive means. If enough energy could be converted to drive the Pulsar generator, the reactor could provide its own operational pulse power plus an additional amount for commercial use. A relatively small steam-turbine "bottoming stage" could then provide the remainder of the commercial power generated.

An experimental program has been conducted utilizing a 200-kJ superconducting magnet with a 0.45-m bore. Experiments carried out to date with metallic pistons or plasma as the active elements (armatures) have confirmed expectations. A one-meter diameter 400 kJ superconducting magnet is being prepared to test scaling predictions for larger sizes.

During this period work was carried out to develop explosively generated plasma armatures suitable for use in both the 0.45-m and 1-m magnets and preparations were made for the refrigeration system which is needed for the 1-m magnet. Progress was made on an MHD code to simulate operation with plasma armatures.

Plasma Armature Code Development

To date, the computer code used to model performance with expanding metallic armatures has also provided the only means to estimate performance with plasma armatures (MHD code). This is a lumped parameter circuit model where the armature is segmented into n elements to simulate diffusion and proximity effects in the induced current distribution. By inputting measured plasma dimensions and velocities from actual experimental shots into the code and changing the plasma conductivity until the computed load current agrees with the experimental measurement, the average plasma temperature achieved during an experiment can be estimated. By this means it has been established that experimental plasma armatures produced with high explosive have had temperatures up to 4 eV. Fig. 44, constructed from this lumped parameter model, compares Pulsar generator performance with lossless, metallic, and 4-eV plasma armatures. It shows how the ratio of energy in the pulse to energy stored in the superconducting magnet (E/E_{max}) depends on the radius of the generator coil. In view of the assumptions implicit in the application of this code to plasma armatures the plasma curve must be considered to be a crude estimate. Still, with fusion reactor scale of a few meters and with plasma produced by a nuclear burst one could expect that pulse energy would exceed stored magnet energy, and that energy conversion efficiency (kinetic-to-electric) would be very high (~ 1).

Fig. 44. Scaled Pulsar output.

For more accurate estimates of the effect of scale on performance of plasma armatures a one-dimensional magnetohydrodynamic (MHD) code is being developed. The code is based on the CHART-D radiation-hydrodynamics code with magnetic fields included self-consistently. The basic geometry includes a massive cold piston (high explosive detonation products) which expands at high velocity into the gas which can be either preionized or neutral. A shock forms in front of the piston and compresses the magnetic field against a perfectly conducting generator coil. The radiative diffusivity will be turned off for the first runs but will be added later. Other features to be added as the code develops are: magnetic diffusion into the metallic walls, additional circuits such as the load and superconducting magnetic, and explosive debris simulation. The code will eventually model output waveforms so that direct comparison with actual experiments may be carried out. Test cases for magnetic compression and diffusion which can be compared to analytical solutions should be completed in January.

The 1-m Magnet

The next phase of the Pulsar study involves an increase in scale of the experimental generator. The original superconducting magnet with a warm bore of 0.45 m and 200 kJ storage is shown on the right in Fig. 45. On the left is the superconducting winding for the next magnet. This new magnet will store only twice the energy but will have a warm bore only slightly less than 1 m. The dewar for this magnet is nearing completion. Experiments with the larger magnet will allow experimental verification of the effect of scale on Pulsar performance.

SYSTEMS STUDIES

Overview

The block diagram of a systems model that simulates the technical and economic performance of the conceptual reactor design is shown in Fig. 46. A computer optimization routine is utilized to select the optimal reactor configuration based on cost of the product. Both hybrid reactors and pure fusion reactors have been investigated and will be discussed here.

Fig. 45. The 0.5 and 1.0 meter magnets.

Fig. 46. Power generation characteristics for a REB fusion reactor.

The basis for the model is a power balance analysis which treats the power production loop on a per pulse basis. The loop comprises the energy delivery system (Marx generator, transmission lines, and diode), the fuel pellet, the energy conversion blanket, and the electrical power generating system. Parametric curves for the efficiencies and capital costs for each of these subsystems are assumed and used to evaluate the cost of generating electricity with the system.

Parametric Analysis of a REB Fusion Reactor

The results obtained for the fusion baseline system are shown in Table VIII. One megajoule of energy is assumed to be absorbed by the pellet, resulting in a 100-MJ thermonuclear yield. Five vessels are combined to arrive at a total capacity of 1020 MW_e. The modularity provided by the five 200 MW_e vessels appears to be a desirable characteristic. The system reliability should be enhanced by the redundancy, and reactor development is possible in smaller steps that entail less risk. The pulse rate per vessel is less than 5 Hz, which is a desirable operating regime for the REB accelerator system. Pellet fabrication costs are unknown so that a relatively high cost was assumed. We do not believe that \$0.01 pellets are likely although this area must be investigated further. The resulting power generation costs are approximately twice that of current light water reactor costs and are comparable to costs associated with alternate future energy sources.

Using the baseline fusion reactor as an operating point, the sensitivity of the leveled busbar energy cost (BBEC) to variations in component cost and performance are tested. In Fig. 47, BBEC is plotted as a function of the driver cost in \$/J. Power generation costs increase 25 percent when driver costs are increased from 0 to \$100/J. Driver costs are currently estimated at \$20/J. In this cost range, driver costs do not appear to be a dominant factor in determining plant economic viability. The BBEC is plotted as a function of the driver efficiency in Fig. 48. The curve is relatively flat above 30 percent. Although the driver efficiency is arbitrarily taken to be 58 percent, there is little penalty in choosing an efficiency of 30 percent. If the driver efficiency is less than 20 percent, the pellet yield must be higher than the 100 MJ yield proposed here.

TABLE VIII

REB Fusion Reactor - Baseline System

System Characteristics	
Pellet Gain	100
Beam Energy	1.4 MJ
Driver Efficiency	0.58
Focusing Efficiency	0.7
Blanket Gain	1.3
Pellet Cost	\$0.40
Circulating Power Fraction	9%
Chamber Radius	5.3 m
Number of Vessels	5
Plant Capacity	1020 MW _e
Pulse Rate per Vessel	4.5 Hz
BBEC (1976\$)	55 mills/kW _{hr}

The sensitivity of BBEC to the pellet fabrication cost is illustrated in Fig. 49 for several pellet thermonuclear yields. The energy absorbed by the pellet is fixed at 1 MJ and the pellet yield varies from 50 to 300 MJ. For pellet fabrication costs of less than \$0.10 per pellet, all of the systems are economically viable. As the pellet yield is increased, proportionally higher pellet fabrication costs are acceptable. In Fig. 50, the allowable pellet fabrication cost is calculated as a function of pellet yield for the BBEC fixed at 50 mills/kW_{hr}. At a yield of 300 MJ, over \$1 per pellet is acceptable. A fixed pellet gain of 100 is assumed for the second curve in Fig. 50. The energy absorbed by the pellet is varied to change the pellet yield. The two systems are equivalent for a pellet yield of 100. Pellet yield is the dominant factor in determining allowable pellet costs. As the pellet yield increases, the requirements for other reactor parameters become less stringent. Pellet gain is a secondary effect primarily because the high efficiency of the REB driver minimizes the effect that circulating power fraction has on BBEC.

Based upon the estimates presented, a pure fusion REB driven reactor appears to be reasonable with the base case parameters. The driver costs if less than \$100/J do not appear limiting. The driver efficiencies should be above 20 to 30 percent for the system to be economically viable with a 100-MJ pellet yield. Lower pellet yields and pellet gains are acceptable if the pellet fabrication costs are low (< \$0.10). The proposed pellet

Fig. 47. Sensitivity of $\overline{BBEC}$ to driver cost - baseline fusion system.

Fig. 48. Sensitivity of $\overline{BBEC}$ to the driver efficiency - fusion baseline system.

Fig. 49. Sensitivity of $\overline{BBEC}$ to pellet fabrication cost - baseline fusion system.

Fig. 50. Sensitivity of allowable pellet cost to pellet yield - fusion baseline system.

costs of \$0.40 per pellet is an upper limit on acceptable costs. Modular systems, such as this one have attractive features but need more study. The penalties associated with this type of relatively low yield modular system are relatively unknown compared to the cited advantages, such as higher reliability and easier system development.

Parametric Analysis of a REB Hybrid Reactor

The pellet chosen for the baseline hybrid reactor system has a gain of 20 at 3 MJ of absorbed energy. The driver efficiency is assumed to be 58 percent with 70 percent of the beam energy effectively coupled to the pellet to drive the implosion. A fast fissioning blanket that provides an energy multiplication of 7 and produces 1.4 fissile atoms per fusion is used. The selling price of the fissile fuel is assumed to be \$30 per gram fissile. The chamber radius, which is 4.6 meters, is determined by the first wall X-ray loading. If the reactor vessel is at atmospheric pressure, the blast effects size the vessel at approximately 4 meters. The power plant consists of one reactor vessel and produces 990 MWe. The vessel pulse rate is 7.7 Hz which is within the bounds of projected pulsed power technology.

The system operates with a circulating power fraction of less than 10 percent of which 4 percent is for auxiliary power requirements and the remaining 6 percent is used to charge the Marx generators. Over 2000 Kg of plutonium are produced each year which account for 25 percent of the system revenues. The other 75 percent of the revenue is from selling power at a BBEC of 33 mills/kWhr.

The efficiency requirements for the baseline hybrid reactor are similar to those of the baseline fusion system. Driver efficiency increases above 30 percent have almost no effect on power generation costs while if the efficiency drops below 10 percent, the power generation costs quickly become unacceptably high.

In Fig. 51, the relationship between BBEC and pellet gain are shown for two driver and beam/pellet focusing efficiencies. Case 1 is the base case assumption where 41 percent of the energy into the Marx generator is effectively coupled into the pellet; in Case 2 that efficiency is 20 percent. The power generation costs for the two systems are very similar. The main effect that

driver efficiency has on power generation cost is through the circulating power fraction. The circulating power fraction resulting from charging the Marx generator is low enough for the base case (~ 5.5 percent) that doubling that fraction does not have serious consequences. Pellet gains above 15 are required for both systems and gains between 20 and 30 are desirable. Pellet gains above 30 do not significantly improve the system's economic performance.

Pellet fabrication costs have a significant impact on the BBEC for the baseline hybrid system, Fig. 52. Pellet costs can be as high as \$1.00/pellet if one assumes 50 mills/kWhr as a maximum acceptable power generation cost. If the pellet fabrication costs are \$0.10 each the BBEC is cut in half to 25 mills/kWhr. Reasonable estimates for pellet costs are currently unavailable so that each analyst must rely on his own intuition. Pellet fabrication costs have a significant impact on the choice of reactor design. If costs are negligible, an important constraint on high repetition rate systems is removed. However, if the pellet costs are not negligible compared to the value of the power generated, these systems are unacceptable. This area will be difficult to determine accurately because of the lack of experience in pellet mass production and rapidly changing pellet design. The involvement of knowledgeable people in the cost estimation is necessary even to make order magnitude estimates of pellet cost.

A second hybrid system, described in Table IX, was investigated to determine the effects of a very low gain pellet on reactor economics. The system uses a gain 3 pellet that requires 1 MJ of absorbed energy to initiate the implosion. A thermal fission blanket with a gain of 25 is employed to compensate for the low pellet gain and yield. The fissile fuel production of the thermal fissioning blanket is approximately 1 fissile atom/fusion, which is half that of the previously used fast fissioning blanket. The pellet cost is chosen to be \$0.10. The plant consists of 4 vessels 1.4 meters in radius that combine for a total plant capacity of 880 MWe. 400 kg of plutonium are produced each year and the levelized busbar energy cost is 46 mills/kWhr.

The sensitivity of the BBEC to pellet fabrication costs is shown in Fig. 53 for several blanket designs. When the pellet costs are low (~ \$0.01/pellet), the differences between the systems are minimized. The system with a gain 10 fast fissioning blanket produces power

Fig. 51. Sensitivity of $\overline{BBEC}$ to pellet gain - baseline hybrid system.

Fig. 52. Sensitivity of $\overline{BBEC}$ to pellet cost - baseline hybrid system.

TABLE IX

HYBRID SYSTEM - MAGNETIC PELLET

Systems Inputs

Pellet Gain	3
Beam Energy	1.4 MJ
Driver Efficiency	0.58
Focusing Efficiency	0.7
Blanket Gain	25
Pellet Cost	\$0.10
Fissile Fuel Selling Price	\$30/GM

System Characteristics

Circulating Power Fraction	14%
Chamber Radius	1.4 M
Number of Vessels	4
Plant Capacity	800 MW _e
Pulse Rate per Vessel	10.3 Hz
Fissile Fuel Production Rate	400 kg/yr
BREC (1976\$)	46 mills/kWhr

Fig. 53. Sensitivity of $\overline{BREC}$ to pellet fabrication cost - magnetic pellet.

that is only a few mills per kWhr more expensive than the gain 25 blanket and both appear to be economically acceptable. As pellet cost increase, the low gain blanket systems quickly become unacceptable.

Conclusions

Efforts are underway to construct the accelerators needed to achieve scientific breakeven from a particle-beam-driven, inertially-confined, fusion reaction. In the near term (by 1985), it is expected that net energy gain will be achieved from such a reaction if several physics questions are resolved favorably. The difficulty of achieving very high gain pellet physics is even more problematical and we have therefore concentrated our attention on gains less than 100. High efficiency, low cost, particle-beam drivers can be effectively utilized with these relatively low gain pellets and hybrid blankets to construct an experimental or demonstration power reactor. Successful construction of such a device would provide impetus to the commercialization of fusion technology. A system having a driver efficiency of 20 percent or higher, a driver cost of \$40/J and a pellet cost of \$1 each would be attractive for use with gain 20 pellets. If pellets can be manufactured in quantity for less than a few cents each, the high efficiency of the REB driver makes the system using a gain 3 pellet economically feasible (as compared with other long range energy solutions). The pure fusion systems appear economically acceptable when a few megajoules of energy can become coupled to a pellet to yield 100 to 200 MJ of energy. This, too, appears as a reasonable extension of present technology given positive physics results. In the future, the decision of whether to build hybrid or fusion reactors will probably depend on the relative demand for energy or fissile fuel, rather than being determined by technical constraints.

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