Conf-930616--13

RECEIVED

JUL 27 1993

OSTI

THE LMF TRIAXIAL MITL VOLTAGE ADDER SYSTEM*

M. G. Mazarakis, D. L. Smith, L. F. Bennett, T. R. Lockner, R. E. Olson, and J. W. Poukey
Sandia National Laboratories
P. O. Box 5800, Albuquerque, NM 87185-5800

Abstract

The light-ion microfusion driver design consists of multiple accelerating modules fired in coincidence and sequentially in order to provide the desired ion energy, power pulse shape and energy deposition uniformity on an Inertial Confinement Fusion (ICF) target.

The basic energy source is a number of Marx generators which, through the appropriate pulse power conditioning, provide the necessary voltage pulse wave form to the accelerating gaps or feeds of each module.[1] Although we have considered an alternative module design with 2.6-MV cavities, the entire LMF accelerator can be built with components identical to those of HERMES III.

The cavity gaps are inductively isolated, and the voltage addition occurs in the center conductor of the voltage adder which is the positive electrode while the electrons of the sheath flow closer to the outer cylinder which is the magnetically insulated cathode electrode. Each module powers a separate two-stage extraction diode which provides a low divergence ion beam.[2] In order to provide the two separate voltage pulses required by the diode, a triaxial adder system is designed for each module. The voltage addition occurs in two separate MITLs. The center hollow cylinder (anode) of the second MITL also serves as the outer cathode electrode for the extension of the first voltage adder MITL. The voltage of the second stage is about twice that of the first stage. The cavities are connected in series to form the outer cylinder of each module. The accelerating modules are positioned radially in a symmetrical way around the fusion chamber.

A preliminary conceptual design of the LMF modules with emphasis on the voltage adders and extension MITLs will be presented and discussed.

I. Introduction

The Laboratory Microfusion Facility has both near and long-term goals. The near-term goals are to study high gain Inertial Confinement Fusion (ICF) targets with yields of the order of 500 MJ, to study nuclear weapon physics, and to provide an improved nuclear weapon simulation source. Among the long-term goals, the most important is to provide the technical development necessary to demonstrate scientific feasibility for fusion energy production. To achieve these goals, the LMF driver must deliver to the ICF target energies equal to or higher than 10 MJ with the ability to vary the magnitude and pulse shape of the deposited energy as a function of time.

The light-ion LMF pre-conceptual design[3] is based upon the ion beam input requirements of the 500-MJ yield ICF target. These requirements are established by a combination of numerical calculations and the existing ICF database. The driver design is modular and consists of 24 modules of two different types: A and B. These modules are fired in a two-step sequence to provide the desired power pulse shape on the target (Figure 1). We have chosen lithium singly charged ion beams produced in two-stage extraction diodes.[2] The first pulse to arrive at the target, generated by the 12 A modules, has a 65-TW flat top and a 60-ns duration. The main pulse, delivered by the 12 modules B, arrives at the target 40 ns later. It has higher peak power (650 TW) but shorter duration (20 ns). The pulses overlap during the last 20 ns to provide the target with the required 715 TW peak power.

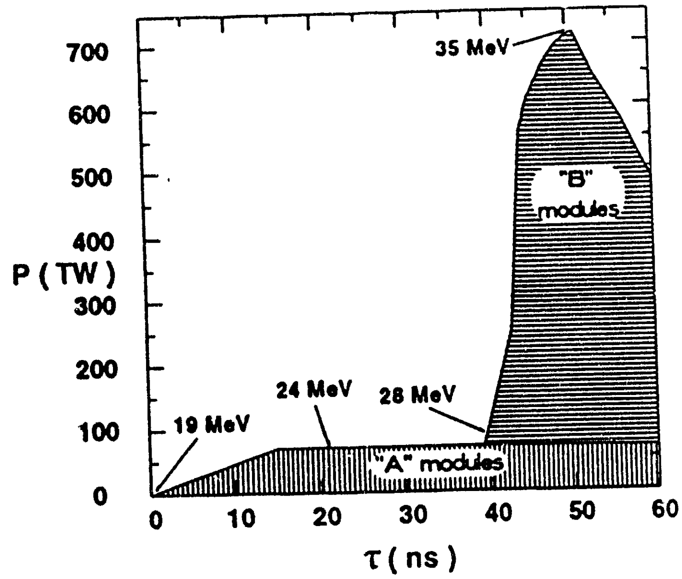


Figure 1. ICF Target Power Requirement for a 500-MJ Yield

II. The LMF Accelerator

The LMF pulsed power accelerator (Figure 2) is based on the successful HERMES-III[4] technology developed in Sandia during the last ten years in collaboration with Pulsed Science Inc. Each of the 24 modules of Figure 2 are similar or identical to HERMES III.[4] This technology is fairly simple and couples the self-magnetically insulated transmission line (MITL)[5] principle with the N.

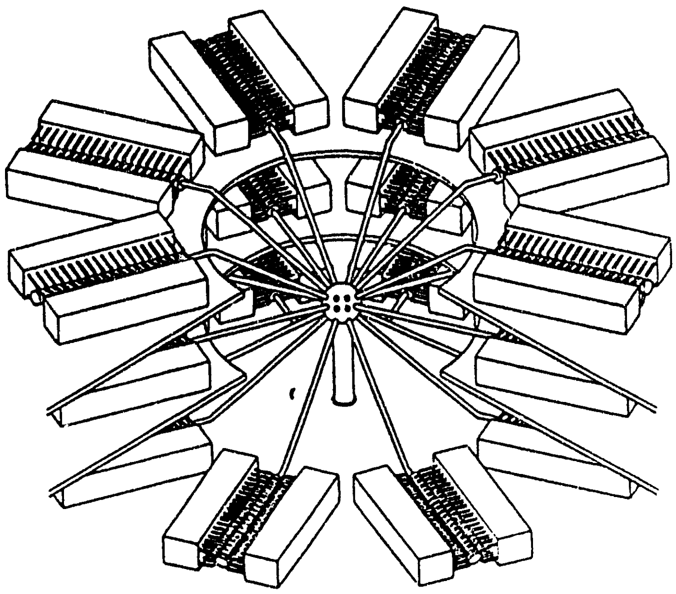


Figure 2. Cutaway View of the Light-Ion Microfusion Accelerator

*This research was supported by the U. S. Department of Energy under contract DE-AC04-76DP00789.

Christophilos invention of the induction linac[6] to generate a new family of linear induction accelerators, such as HELIA,[7] HERMES III, RADLAC/SMILE,[8] and SABRE,[9] which we call linear inductive voltage adders. In these accelerators there is no beam drifting through the multiple cavities as is the case with conventional induction linacs. The place of the beam is taken by a central conductor which extends along the entire length of the device and effectuates the voltage addition of the accelerating cavities. The beam is produced at the end of the voltage adder in a single or multistage diode. These devices can operate in either polarity (Figure 3) to produce negatively or positively charged particle beams. In a positive

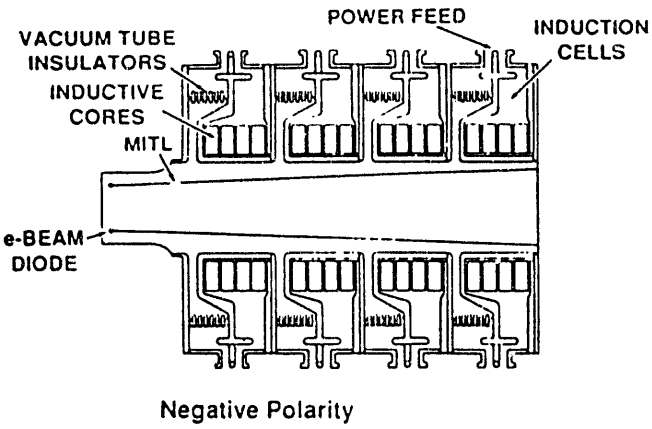


Figure 3. A Four-Cavity Negative Voltage Adder of the HELIA Type Providing Power to an Electron Diode

polarity voltage adder (Figure 4), the center conductor is positively charged relative to the outer conductor which is interrupted at regular intervals by the cavity gaps. The HERMES-III voltage adder is of negative polarity. A linear inductive voltage adder can be converted from negative to positive polarity and vice versa by a rotation of 180° around a vertical axis of the center conductor or equivalently of each of the accelerating cavities. This was demonstrated on HERMES-III which operated with equal success in positive and negative polarity.[10] SABRE has a positive polarity inductive voltage adder. The LMF voltage adders also are of positive polarity, and the beam particles produced by the diodes are singly charged positive lithium ions.

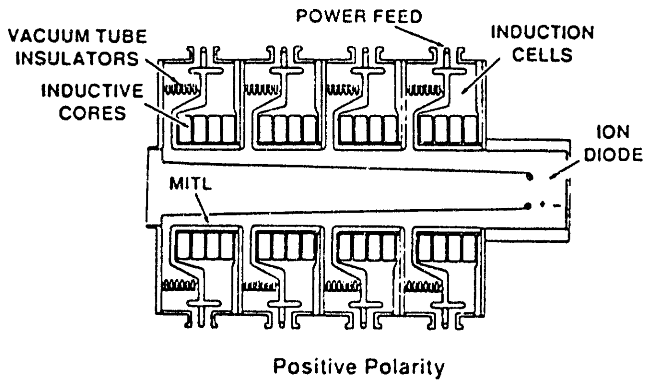


Figure 4. A Simple Positive Voltage Adder of the SABRE Type Providing Power to a Single Stage Ion Diode

The selected number of modules, 24, is a trade-off between cost, pulse uniformity on the target, and number of diodes that can be fit at the 4 m radius outside wall of the interaction chamber. Each module has its own diode, producing the 24 separate ion beams focused on the ICF target. The beams propagate fully space charged and current neutralized in a 1 Torr helium atmosphere. In the first 3 meters of transport the beam annular cross section remains constant with the particle trajectories being slightly divergent. The principal focusing occurs in a main solenoidal lens 1 meter from the 1 cm radius ICF target. The beam transport system is achromatic.[11] The achromaticity is achieved by combining the final focusing solenoid with the self-filled focusing effect at the ion diode. The ion trajectories are ballistic between the diode and the lens and between the lens and the target.

The power and kinetic energy of the ions delivered to the target are shown in Figure 1. The electrical power delivered by the voltage adders to the diodes is somewhat higher due to certain inefficiencies in the diode and in the transport system. We assume a 70% peak power efficiency from the diode to the target. Hence, the modules A deliver to the diodes at total peak electrical power of 91 TW and the modules B of 457 TW. Table 1 summarizes the electrical output parameters for both types of modules.

The beams from the modules B are bunched by a factor of 2 during transport to the target, driven by a ramped voltage pulse provided to the second stage gap by the inductive voltage adders. Bunching doubles the peak ion power delivered to the target and shortens the pulse duration from 40 ns (Table 1) to 20 ns (Figure 1).

Table 1
Electrical Output Parameters per Module

	Module A	Module B
P(TW)	7.6	38
V(MV)	24.7	36
I(MA)	0.31	1.06
τ(ns)	60	40
W(MJ)	0.46	0.83

III. Triaxial Voltage Adder and Extension MITL Design

In designing the triaxial voltage adder and the extension MITL the following constraints were imposed by the target requirements and the diode design: the accelerating voltage of the first stage should be 10 MV. The sum of the voltage of both stages for each module A and B must be 25 and 36 MV, respectively (Figure 1), and the currents of each diode stage should be the same and equal to 0.31 MA and 1.06 MA (Table 1).

A first cut of the design is being done utilizing Creedon's[5] analytical formalism of parapotential electron flow in self-magnetic insulated transmission lines (MITL). The design is further validated with particle-in-cell numerical simulations utilizing the MAGIC code.[12] The available parapotential flow[5] and pressure balance[13] model theories are for negative polarity voltage adders. The electron flow in a positive polarity adder is more complicated, and there is not as yet a simple analytical theory to describe the flow and to provide mathematical expression for designing the MITL. However, experiments with HERMES III[10] and SABRE[9] accelerators along with numerical simulations have demonstrated that a positive polarity voltage adder can be designed as a negative one with its polarity inverted in the actual assembly. The LMF modules' design, presented here, is not yet validated with numerical simulations.

First, we select the current and the voltage of the cavities we want to use. The current is the most critical parameter because it must be close to the current requirements of the diode. The number of cavities of each voltage adder is then defined by the voltage at the diode and the amount of undermatching required at the downstream end of the extension MITL. It is an iterative process and requires a few trials and errors before the voltage adder, the extension MITL and the diode load have the right peak voltage and current pulse flowing through them in a self-consistent way. The solution must simultaneously satisfy circuit models such as SCREAMER[14] and the parapotential flow or pressure model theory. The undermatching of the MITL to the load is necessary in order to improve the efficiency of the power coupling. In an MITL as opposed to a vacuum transmission line where all the electron current flows on the surface of the conductors, part of the electron flow occurs in the vacuum gap between the two conductors. Actually in a "matched" voltage adder, that is in a voltage adder of an operating impedance equal to the characteristic impedance of the cavities, more than half of the current is carried by the electrons in the vacuum gap which are emitted from the negative polarity electrode and form a sheath near it. If we do not undermatch the MITL at the load, all these electrons and the current associated with them will be lost at the diode anode. This is especially true in a positive ion diode.

The analytical theories predict that undermatching the MITL at the load causes a new operating regime to be established where the amount of current flowing at the electrode surface (boundary current) is match larger than the sheath current. The ratio of boundary current to sheath current increases with the amount of undermatching and depends on the voltage and the particular MITL geometry. Experiments with HERMES III[4] and numerous code simulations[15] are in full agreement with the theoretical predictions.

For practical purposes, a good rule of thumb to follow in designing the voltage adder and extension MITL is the following: a 30%-35% undermatch at the load brings up the power coupling efficiency to 80%-85%.

We have followed the above described methodology in the design of the four separate LMF voltage adders and extension MITLs (two for the modules A and two for the modules B). Actually for the modules B we designed four MITLs and voltage adders: two for the HERMES-III cavities and two for the 2.6 cavities (Table 2). As an example, Figure 5 presents the design of the module "B" voltage adders and extension MITLs. Numerical simulation for each voltage adder similar to those of Figure 6 are under way.

Table 2
Design Options for the B Modules

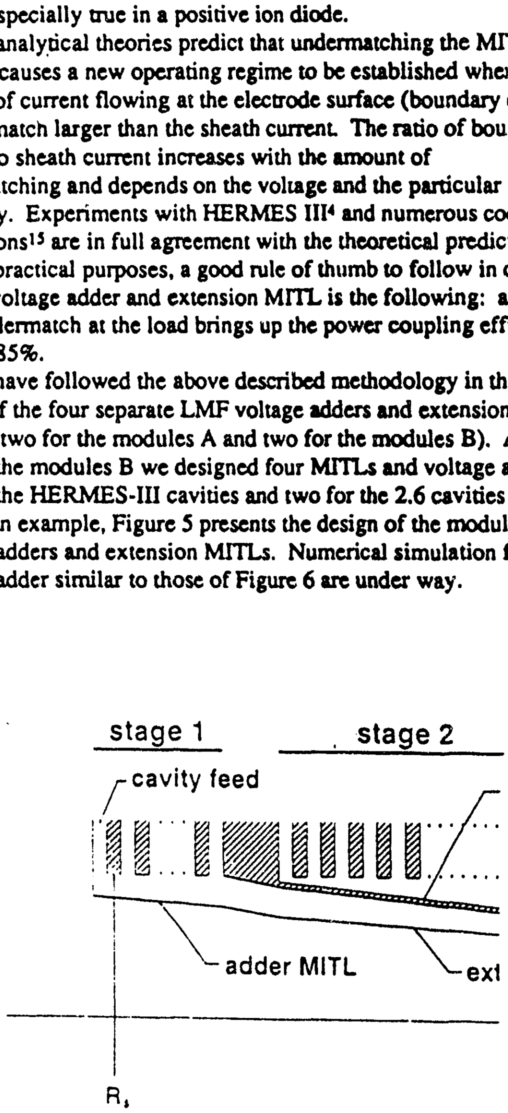
	HERMES-III Option	2.6 MV Cavity Option
Cavity Voltage (MV)	1.1	2.6
Number of Cavities	40	17
PFLs/Cavity	4	4
PFL Impedance (Ω)	5	8
I matched (MA)	0.88	1.15

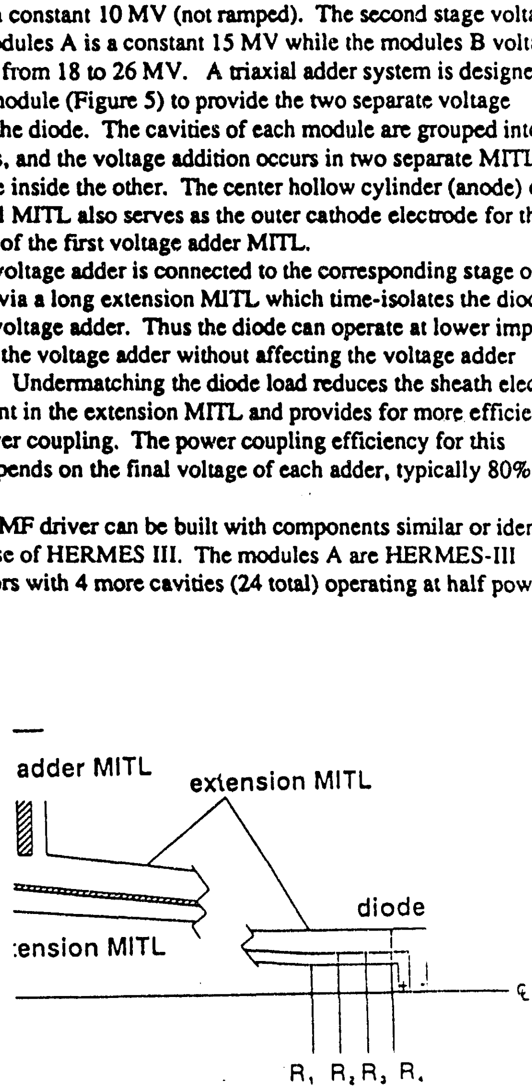
IV. Accelerating Module Design

The accelerating voltage of the first stage for both A and B diodes is a constant 10 MV (not ramped). The second stage voltage for the modules A is a constant 15 MV while the modules B voltage is ramped from 18 to 26 MV. A triaxial adder system is designed for each module (Figure 5) to provide the two separate voltage pulses to the diode. The cavities of each module are grouped into two stages, and the voltage addition occurs in two separate MITLs nested one inside the other. The center hollow cylinder (anode) of the second MITL also serves as the outer cathode electrode for the extension of the first voltage adder MITL.

Each voltage adder is connected to the corresponding stage of the diode via a long extension MITL which time-isolates the diode from the voltage adder. Thus the diode can operate at lower impedance than the voltage adder without affecting the voltage adder operation. Undermatching the diode load reduces the sheath electron current in the extension MITL and provides for more efficient pulse power coupling. The power coupling efficiency for this design depends on the final voltage of each adder, typically 80% to 85%.

The LMF driver can be built with components similar or identical to those of HERMES III. The modules A are HERMES-III accelerators with 4 more cavities (24 total) operating at half power,





Two alternative designs of module "B"

$R_5 \geq R_4$ ($R_5^{HERMES\ III} = 38$ cm)

Cavity Type	# Cavities Stage 1	# Cavities Stage 2	# Cavities Total
2.6 MV	5	12	17
1.1 MV	14	26	40

R_1 cm	R_2 cm	R_3 cm	R_4 cm	V_1 MV	V_2 MV	I_{diode} MA	P TW
20	24.5	25	39.3	9.6	27.6	1.06	39.5
14	20.5	21	38	10.2	25.8	1.06	38.3

Figure 5. The Triaxial Voltage Adder Configuration for the Two-Stage Extraction Diodes of the LMF Accelerator.

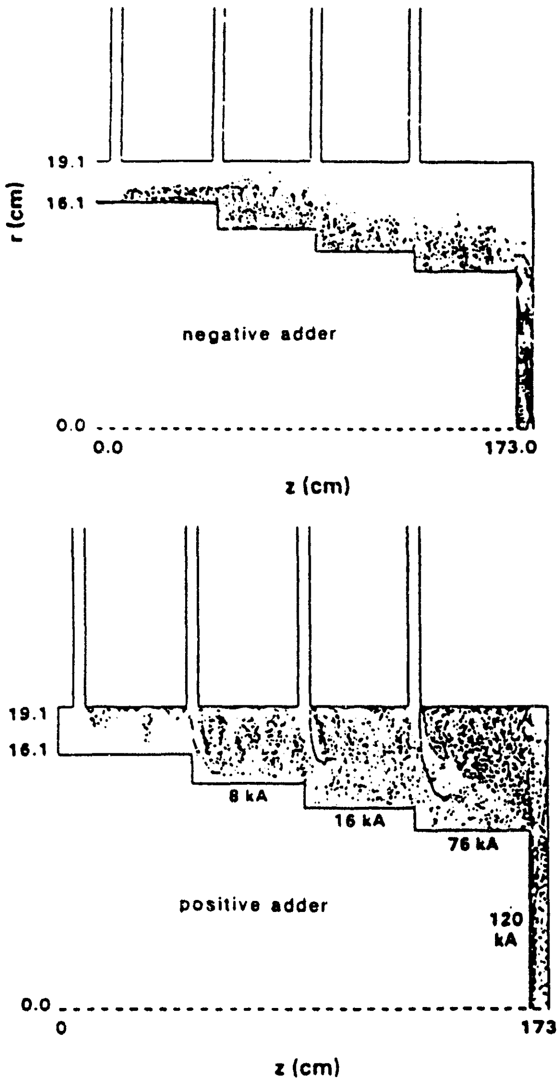


Figure 6. MAGIC Simulations of the Electron Flow for a negative and positive polarity. Here the impedance of the voltage adder increases in a step-wise fashion as opposed to the smooth variation of Figures 3 and 4. Most of our accelerators have voltage adders with step-wise variation of the radius of the center conductor.

using half of the 5 W pulse-forming and transmission lines that power each of the HERMES-III cavities. (Figure 7)

There are two design options for the modules B: one that is again composed solely of HERMES-III components and the other made up of 2.6 MV cavities of entirely new design. The modules B

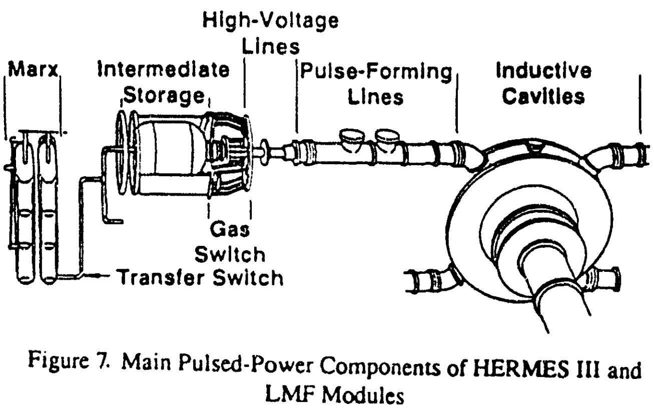


Figure 7. Main Pulsed-Power Components of HERMES III and LMF Modules

can be built by two HERMES-III accelerators connected in series (40 cavities in total) or by seventeen 2.6-MV cavities. Table 2 summaries the two design options for the B modules.

V. Conclusion

This LMF accelerator design is based on the HERMES-III robust technology. It has a flexible modular configuration which offers risk control by an anticipated staged construction. Half of the 24 modules are identical to HERMES III, and the other half can be built with HERMES-III or similar 2.6-MV components. This provides a confident base for realistic cost estimates and offers additional assurance for the success of the project.

References

[1] D. L. Smith, et al., "A Pulsed Power Design for the Linear Inductive Accelerator Modules for the Laboratory Microfusion Facility," This Conference.

[2] T. R. Lockner, et al., "Theoretical and Experimental Studies of the 2-Stage Diode," This Conference.

[3] M. G. Mazarakis, et al., "The Light-Ion Pulsed Power Induction Accelerator for the Laboratory of Microfusion Facility (LMF)," *Proc. of the 1993 IEEE Particle Accelerator Conference*, Washington, D. C., May 17-20, 1993, to be published; and *Bull. Am. Phys. Soc.* 38, No. 4, 1200 (1993).

[4] J. J. Ramirez, et al., "HERMES-III—A 16-TW, Short Pulse Gamma Ray Simulator," *Proc. 7th International Conf. on High Power Particle Beams*, Karlsruhe, Germany, July 4-8, 1988, pp. 148-157.

[5] J. H. Creedon, "Magnetic Cutoff in High-Current Diodes," *J. Appl. Phys.*, 48, No. 3, 1070 (1977).

[6] N. Christophilos, et al., "High Current Linear Induction Accelerator for Electrons," *Rev. Scient. Instrum.*, 35, No. 7, 886 (1964).

[7] J. J. Ramirez, et al., "The Four Stage HELIA Experiment," *Proc. 5th IEEE Pulsed Power Conf.*, Arlington, Virginia, June 10-12, 1985, p. 143-146, IEEE #85C2121-2.

[8] M. G. Mazarakis, et al., "SMILE—A New Version for the RADLAC II Linear Accelerator," *Proc. of the 1990 Linear Accelerator Conference*, Albuquerque, New Mexico, September 10-14, 1990, pp. 438-440, LA-12004-C.

[9] J. Corley, et al., "SABRE, A 10-MV Linear Induction Accelerator," *Proc. 8th IEEE Pulsed Power Conference*, San Diego, California, June 16-19, 1991, pp. 920-923, IEEE #91CH3052-8.

[10] D. L. Johnson, et al., "Hermes-III Positive Polarity Experiment," *Proc. 7th IEEE Pulsed Power Conference*, Monterey, California, June 11-14, 1989, pp. 32-35, IEEE #89CH2678-2.

[11] C. L. Olson, "Achromatic Magnetic Lens Systems for High Current Ion Beams," *Proc. of the 1988 Linear Accelerator Conference*, Williamsburg, Virginia, Oct. 3-7, 1989, pp. 34-37, CEBAF Report 89-001.

[12] B. Goplen, et al., Mission Research Corp. Report MRC/WDC-R-068, 1983.

[13] C. W. Mendel, et al., "A Simple Theory of Magnetic Insulation from Basic Physical Considerations," *Laser and Part. Beams*, 1, Part 3, 311 (1983).

[14] M. M. Widner, et al., "SCREAMER User's Guide," Sandia National Laboratories, June 26, 1991.

[15] J. W. Poukey, Private Communications.

DISCLAIMER

END

DATE FILMED

9/21/93