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THE LMF TRIAXIAL MITL VOLTAGE ADDER SYSTEM*

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Abstract

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

The basic pulsed power circuit is a Marx generator which, through appropriate pulse power conditioning, provides the necessary voltage pulse to the series accelerating gaps of each module. Although a module design with 2.6-MV cavities has been considered, the entire Laboratory Microfusion Facility (LMF) accelerator can be built with components identical to those presently used in the HERMES-III accelerator.

The inductively isolated cavity gaps permit voltage addition along the positive center conductor while the sheath electrons flow closer to the outer cathode electrode. Each module is envisioned to power a separate two-stage extraction diode which will generate a low divergence ion beam. A triaxial adder system is designed to provide the two separate voltage pulses required by the diode for each module. The voltage addition occurs in two separate self-magnetically insulated transmission lines (MITLs) where the center hollow cylinder (anode) of the second-stage MITL also serves as the outer cathode electrode for the first-stage MITL. The voltage of the second stage is about twice that of the first stage. The multiple 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 develop high gain (~ 500 MJ yield) Inertial Confinement Fusion (ICF) targets to study nuclear weapon physics and to provide an improved simulation source for nuclear weapon effects studies. 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 ~ 10 MJ to the ICF target in a controlled pulse shape.

The light-ion LMF pre-conceptual design[1] is based upon the ion beam input requirements for a 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 B modules, arrives at the target 40 ns later with a 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.

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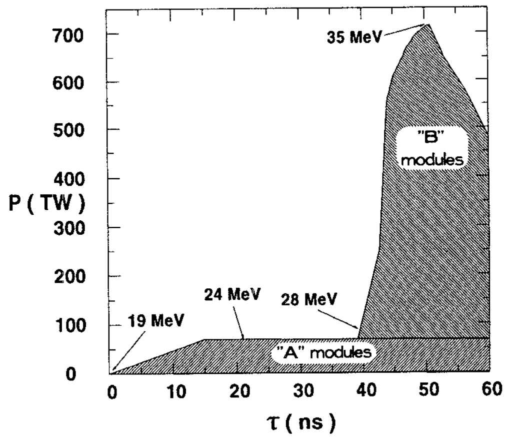


Figure 1. ICF Target Power Requirement for a 500-MJ Yield

II. The LMF Accelerator

The LMF pulsed power accelerator (Figure 2) is based on the successful HERMES-III[3] 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.[3] This technology is fairly simple and couples the self-magnetically insulated transmission line (MITL)[4] principle with the induction linac[5] to generate a new family of linear induction accelerators such as HELIA,[6] HERMES III,[3] RADLAC/SMILE,[7] and SABRE,[8] 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

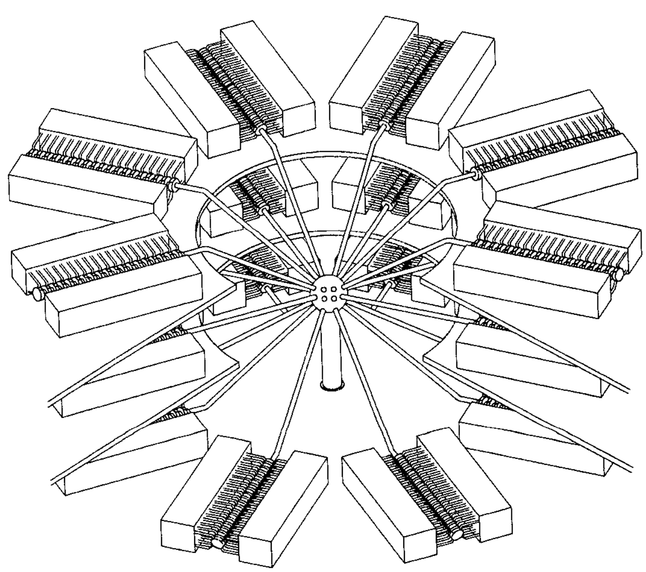


Figure 2. Cutaway View of the Light-Ion Microfusion Accelerator

(Figures 3 and 4) to produce negatively or positively charged particle beams. 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.[9] SABRE has a positive polarity inductive voltage adder (Figure 4). The LMF voltage adders also are of positive polarity, and the beam particles produced by the diodes are singly charged positive lithium ions.

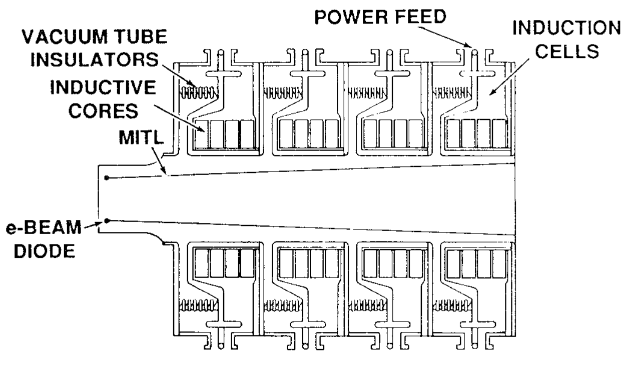


Figure 3. A Four-Cavity Negative Voltage Adder of the HELIA Type Providing Power to an Electron Diode

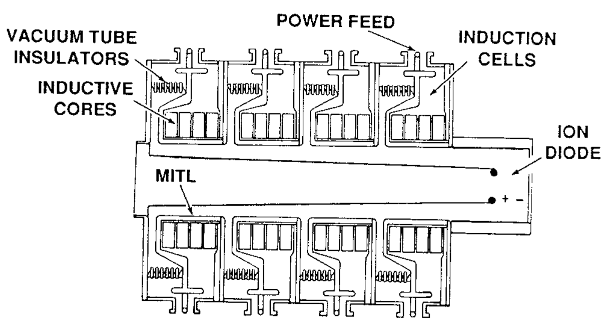


Figure 4. A Simple Positive Voltage Adder of the SABRE Type Providing Power to a Single Stage Ion Diode

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 charge and current neutralized in a 1-Torr helium atmosphere. In the first 3 meters of transport the beam annular cross section remains constant with slightly divergent particle trajectories. The principal focusing occurs in a main solenoidal lens 1 meter from the 1-cm radius ICF target. The beam transport system is achromatic,[10] achieved by combining the final focusing solenoid with the self-field 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 inefficiencies in the diode and in the transport system. A 70% peak power coupling efficiency from the diode to the target is assumed. Hence, the A modules drive the diodes with 91 TW and the B modules with 457 TW. Table 1 summarizes the electrical output parameters for both types of modules.

The beams from the B modules are velocity 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

	A Module	B Module
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 A and B module 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 preliminary design utilized an analytic formalism of parapotential electron flow in self-magnetic insulated transmission lines,[4] validated with MAGIC[11] particle-in-cell numerical simulations. The available parapotential flow[4] and pressure balance[12] model theories are for negative polarity voltage adders. The electron flow in a positive polarity adder is more complicated, and no simple analytical theory exists to describe the flow and to design the MITL. However, experiments with HERMES III[9] and SABRE[8] accelerators along with numerical simulations have demonstrated that a positive polarity voltage adder can be generally 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, the current and the voltage of the cavities are chosen. The current is the most critical parameter since it must match the diode requirements. The number of voltage adding cavities is determined by the voltage needed at the diode and the MITL/diode mismatch. This iterative process requires a few cycles before the voltage adder the extension MITL, and the diode load have appropriate self-consistent voltage and current pulses. The solution must simultaneously satisfy circuit models such as SCREAMER[13] and the parapotential flow or pressure balance theories. The MITL must be undermatched by the load to optimize the power coupling efficiency In an MITL, as opposed to a vacuum transmission line where all the current flows on the surface of the conductors, a part of the current is in vacuum electron flow between the conductors. In a typical "matched" voltage adder (a voltage adder of an operating impedance equal to the characteristic impedance of the cavities) more than half of the current is carried by electrons emitted from the negative polarity electrode flowing in the vacuum gap. If the load does not undermatch the MITL, all these electrons and the current associated with them will be lost before the diode.

The analytical theories predict that the reflected wave from a load impedance undermatching the MITL creates a new operating regime where the amount of current flowing in the electrode surface (boundary current) is much 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[3] and numerous code simulations[14] support the analytical 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 increases the power coupling efficiency to 80%-85%.

The above methodology has been used to design the four separate LMF voltage adders and extension MITLs (two for the A modules and two for the B modules). Actually for the B modules four MITLs and voltage adders were designed: two for the HERMES-III cavities and two for the 2.6-MV cavities (Table 2). As an example, Figure 5 presents the design of the "B" module 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

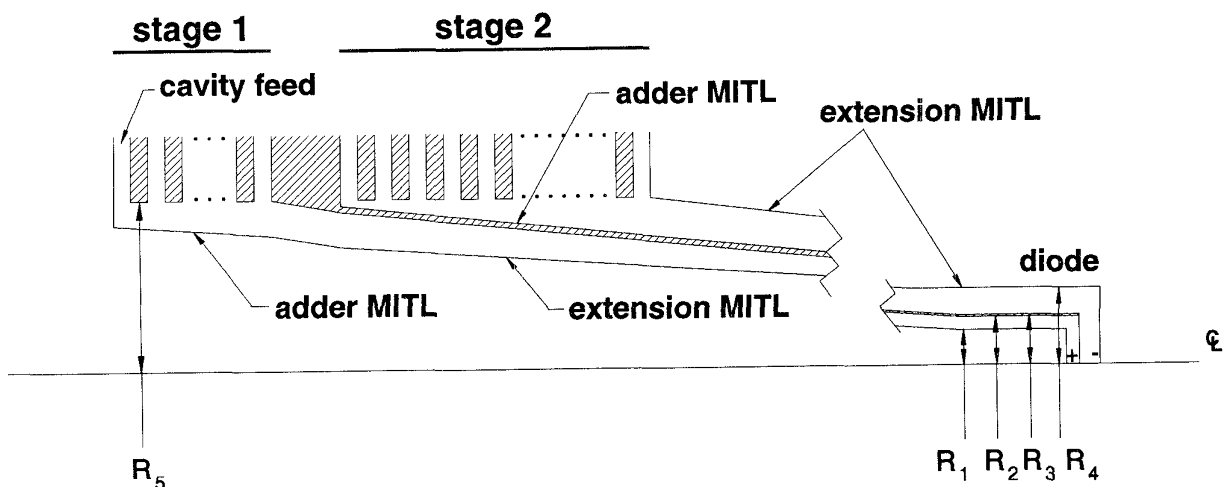
IV. Accelerating Module Design

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 A modules is a constant 15 MV while the B modules 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 stage MITL also serves as the outer cathode electrode for the extension of the first stage 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 accelerator 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 A modules are HERMES-III accelerators with 4 more cavities (24 total) operating at half power, using half of the 5-Ω pulse-forming and transmission lines that power each of the HERMES-III cavities. (Figure 7)

There are two design options for the B modules: one that is again composed solely of HERMES-III components and the other made up of 2.6-MV cavities of an entirely new design.[15] The B 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.

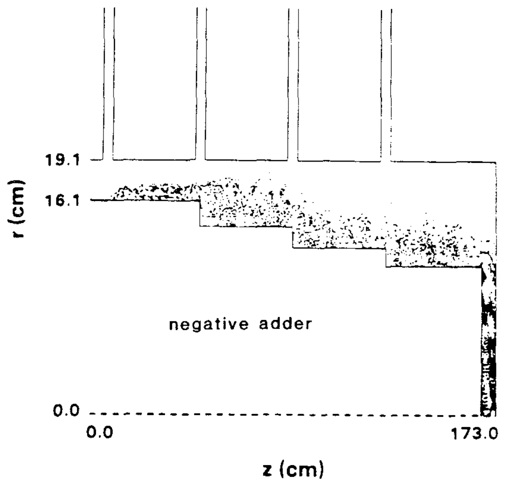


Two alternative designs of module "B"

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

Cavity Type	# Cavities Stage 1	# Cavities Stage 2	# Cavities Total	R_1 cm	R_2 cm	R_3 cm	R_4 cm	V_1 MV	V_2 MV	I_{diode} MA	P TW
2.6 MV	5	12	17	20	24.5	25	39.3	9.6	27.6	1.06	39.5
1.1 MV	14	26	40	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.



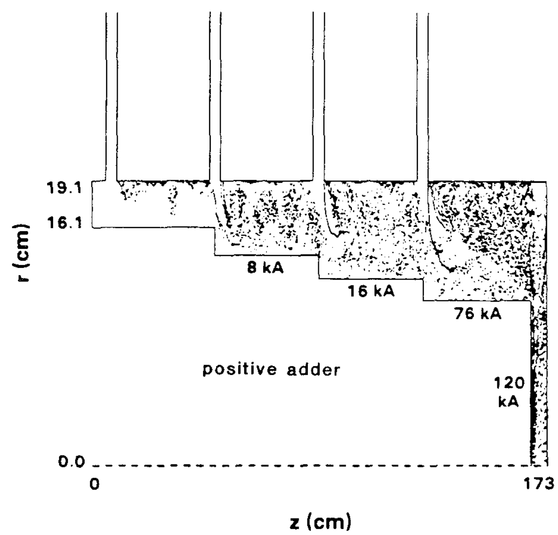


Figure 6. MAGIC Simulations of the Electron Flow for a negative and positive polarity. Here the impedance of the voltage adder increases in a step-wise fashion as opposed to the smooth variation of Figures 3 and 4. Most of our accelerators have voltage adders with step-wise variation of the radius of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

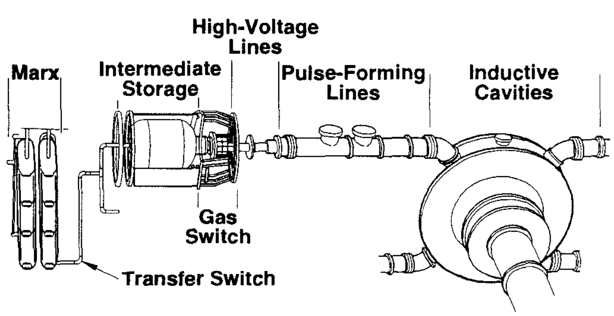


Figure 7. Main Pulsed-Power Components of HERMES III and LMF Modules

V. Conclusion

This LMF light-ion 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.

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