A LIGHT ION BEAM DRIVER FOR THE LABORATORY MICROFUSION FACILITY+

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ABSTRACT

The Laboratory Microfusion Facility (LMF) is being planned to develop high-gain, high-yield (200 MJ-1000 MJ) ICF targets for applications to nuclear weapons effects simulation, thermonuclear weapons physics, and energy production. It is expected that a 1000-MJ yield will require ~10-20 MJ input energy to the target. The light-ion beam driver concept for the LMF consists of 36 accelerator modules that drive independent Li^+ ion diodes. Each ion beam is extracted from an annular ion diode and propagated to a solenoidal lens located near the wall of the target chamber. This magnetic lens focuses the beam on to the pellet located at the center of the target chamber. The temporal shape of the power pulse delivered to the target is controlled by the synchronized firing of the accelerator modules. This paper presents a status of the light-ion beam LMF driver concept.

I. INTRODUCTION

The light-ion beam LMF driver concept consists of multiple accelerators that can be fired sequentially to provide the desired energy, pulse-shape variability and energy deposition uniformity on the ICF target.[1] As presently conceived, 36 lithium-ion beams will be generated, and delivered to the pellet as shown in Fig. 1. The thirty-six accelerators consist of twelve Hermes-III-sized modules that produce a 40-ns ion beam with energy ramping from 18 to 20 MeV and current from 0.46 MA to 0.72 MA, and twenty-four high-energy modules that deliver a 40-ns ion-beam pulse with energy ramping from 26 MeV to 32 MeV and current from 0.8 MA to 1.2 MA. The ramped velocity imparted to the ions cause each beam to bunch during the 4.0-m transport to the target, thus decreasing the power pulse duration at the target to 15 ns. Preliminary results from a detailed analysis of the beam transport and focusing system indicate that the individual beams deposit either ~250 kJ or ~560 kJ within a 2-cm diameter for a total of ~16 MJ delivered to the target. The shape of the power pulse delivered to the target is controlled by the synchronized firing of various module groups. The baseline concept uses a 6-6-24 firing sequence to deliver three separate power pulses to the target with the 12 Hermes-III size modules delivering the first two pulses. The uniformity of the driving pulse at the target is a critical concern. Six beams impinging on the target at one given time may not provide adequate uniformity. This modular design concept is readily adaptable, however, to a different firing sequence as might be required by drive uniformity requirements.

II. ACCELERATOR MODULES

The lithium-ion beams are generated by an accelerator module similar in design to Hermes III, a 22-MV, 730-kA, 40-ns electron beam generator shown in Fig. 2.[2,3] Hermes III generates its output pulse by adding the pulses produced by eighty pulse forming modules in a specific parallel/series combination. The eighty individual 1.1-MV, 220-kA pulses are first added in groups of four to develop twenty 1.1-MV, 730-kA pulses which are then fed through high-power linear induction accelerator cavities. The induction cavities feed power along the length of a self-magnetically insulated vacuum transmission line (MITL) which adds the cavity outputs to generate the 22-MV, 730-kA, 40-ns pulse. The output of this "adder MITL" is delivered to the diode by an "extension MITL". Figure 3 shows a cut-out view of the cavity/MITL system.

For the LMF concept, each accelerator module will power an extraction-geometry Li^+ ion diode similar to that shown in Fig. 4. The ion diode is located at the end of a long "extension MITL" just outside the shielded target chamber and ~4 m from the pellet as shown in Fig. 5. For this application, the MITLs must operate in positive polarity; that is, with the center conductor positive with respect to the "grounded" outer conductor of the coaxial line. The power flow in a positive polarity MITL is significantly more complex than in negative polarity.

Initial experiments have been conducted on Hermes III and HELIA[4] in positive polarity operation.[5,6] The configuration was obtained simply by removing the cantilevered shank, rotating the twenty induction cavities 180 degrees about a vertical axis, and reinserting the shank. The current delivered by the induction cavities was efficiently transported through the adder and extension MITLs to a reverse polarity e-beam diode load. Although we did not obtain a time resolved measurement of the voltage waveform at the load, peak voltages inferred from H^- ion range measurements indicate efficient voltage addition.

Power amplification by beam velocity bunching during transport to the target requires a ramped voltage pulse at the ion diode. This is simply accomplished by changing the configuration of each coaxial pulse forming line (PFL).[7] A constant impedance PFL module produces a "flat top" output pulse. By tapering the diameter of the inner electrode, the impedance can be adjusted along the length of the PFL which results in the ramped output pulse required for beam bunching, as shown in Fig. 6.

Precise synchronization of the LMF accelerator modules requires very low "jitter", or inter-module timing variation, operation. The Hermes III output is representative of the average of a large number of low-jitter modules. An analysis performed using demonstrated Hermes III performance indicates that the 24 "high power" LMF modules, intended to be fired simultaneously, can be synchronized to within an acceptable 2 ns window.

III. Li^+ ION DIODE

The baseline Li^+ ion diode for the LMF module is an extraction geometry, applied magnetic field (applied-B) diode.[8] Although it has many features in common with other ion diodes, the extraction applied-B ion diode needed for LMF has several features which distinguish it from the diodes developed on other Sandia accelerators. The operating impedance of the LMF diode, 25-32 Ω, is higher than that at which other high power ion diodes have been tested. The LMF diode voltage, 27-32 MV, is beyond the existing experimental data base and will require the use of both larger anode-cathode gaps and higher insulating magnetic fields than are presently used. Finally, although an ion beam microdivergence of ~14 mradians is acceptable for an ignition experiment on PBFA II[9], the baseline LMF design concept that delivers ~16 MJ to the target requires a microdivergence of ~6 mradians.

IV. BEAM TRANSPORT AND FOCUSING

The diode produces an annular ion beam which is transported ballistically and focused onto the target as shown schematically in Figs. 5 and 7. A background gas provides charge and current neutralization during transport. The self-magnetic field of the ion beam in the diode acts in conjunction with the 30-cm-long, solenoidal-focusing lens located 1.5 m from the target as a "two lens" achromatic focusing system.[10] The optimal distance from the focusing lens to the target is determined by the beam microdivergence. The ion beam microdivergence must be ≤ 6 mrad to achieve the required focal spot with the solenoidal lens centered at 1.65 m. The required beam divergence scales inversely with this distance for constant energy on target.

Optimization of the focused ion power on target requires tradeoffs between competing system parameters. Beam focus degradation mechanisms include: (1) ion envelope expansion and mean orbit deflection from E&B fields during transport, due either to inadequate charge and current neutralization or (2) scattering and dE/dx energy loss in the gas transport region, (3) instabilities (e.g., filamentation and ion-electron, two-stream instability), and (4) E_z drive return current. The gas pressure must be chosen high enough to provide good charge neutralization and a high plasma conductivity: this will minimize the effects of (1), (4), and (5). On the other hand, the gas pressure must be chosen low enough to minimize losses due to (2) and (3). Calculations indicate that 1 Torr of helium gas satisfies these constraints although efficient ballistic beam transport and focusing needs to be demonstrated at LMF parameters.

The performance of the two-lens focusing system has been modeled using the particle-in-cell (PIC) code PICDIAG[11] which follows the ion trajectories through the focusing system. The simulations include the self-pinch fields in the diode and the fields produced by a realistic magnetic lens. For a solid beam, the system is achromatic at every radial location. For an annular beam (as used for LMF), the ions at the inner radial edge see no self-magnetic field in the diode and, therefore, the inner radius trajectories are not achromatic. In the simulations, the shape of the diode can be adjusted to optimize the focusing of the inner ions over the pulse length.

Preliminary simulations have been performed for a variety of cases. The LMF parameters used in the simulations include a 4 meter transport length, ramped voltage (26-32 MV) and current (0.8-1.2 MA) pulses, a solenoid lens of length 30 cm with nominal axial magnetic field of 20 kG, and a lens-center to target distance of 1.65 m. The ion beam outer (inner) radius is 15 cm (7.5 cm) and the pellet radius is 1 cm. Including self-field effects, realistic lens fields, and some diode shaping, the model predicts 90% energy transport efficiency and 148% power transport efficiency for a zero microdivergence beam. For a HWHM microdivergence of 6 mrad, initial results indicate 60% energy transport efficiency and 106% power transport efficiency. These ongoing simulations will be used to optimize the system performance and to study the sensitivity of this transport scheme to the various beam and transport parameters. This study will allow us to study the output of each each accelerator module to obtain the desired power and energy on target.

Alternate transpo... schemes under consideration for LMF include low-mass, wall-confined, Z-discharge channels and wire-guided transport.[12] Both schemes have been demonstrated in proton beam experiments on the GAMBLE II accelerator at NRL. Extensive theoretical analysis of the solenoid lens, low-mass, wall-confined channel, and wire-guided transport systems will be used to select an optimum ion transport scheme for LMF.

V. TARGET CHAMBER

The x-rays from the thermonuclear explosion pass through the background 1 Torr helium gas with negligible absorption and deposit their energy in the inner wall of the target chamber. The structural wall would be protected by a carbon liner. Calculations indicate that, for a 1-gigajoule pellet yield, ~1 kg of material is vaporized from the liner surface and results in a shock overpressure of ~75 GPa. A long-life chamber design requires that this overpressure be reduced to ~0.2 GPa at the structural wall. An initial analysis suggests that a 1.5-m radius target chamber may be possible.[13]

The 1.5-m radius target chamber design locates the solenoidal focusing lens at the inner wall of the target chamber consistent with the "two-lens" focusing system. An alternate concept is being investigated and is shown in Fig. 8. It uses a larger radius target chamber and re-entrant beam transport tubes which locate the focusing solenoidal lenses at the desired 1.5-m radius. This larger chamber sees a significantly reduced x-ray loading on the inner wall. The beam transport tubes are robust structures but must also be protected from the x-rays. Future analyses will emphasize this target chamber concept as the larger chamber volume is better suited for nuclear weapons effects simulation experiments.

VI. TECHNOLOGY VALIDATION PROGRAM

We have initiated a research program to validate the light-ion beam LMF driver concept. The goal is to demonstrate the integrated system performance on Hermes-III with LMF-scale parameters. Near term research will be conducted on SABRE, a 10-MV, 250-kA, 40-ns accelerator being built for the technology validation program (Fig. 9).

Applied-B extraction ion diode experiments have been conducted on SABRE at ~3 MV. Initial results indicate that the diode performance is described by the theoretical model that also describes the performance of the Applied-B barrel diode on PBFA II.[14,15] The SABRE diode was observed to transition rapidly (<5 ns) to enhanced ion flow conditions faster than observed in previous experiments. Such rapid transition is required for efficient diode operation. The SABRE results are not fully understood, but might be a consequence of the unique saturated electron flow conditions that exist in the positive polarity MITL feed. Preliminary experiments have been performed on SABRE using the LEVIS lithium source where behavior similar to that obtained on PBFA II was observed. SABRE will be operational at 10 MeV by December 1990 and will enable us to perform well diagnosed Li^+ ion beam experiments. These experiments will emphasize obtaining high-efficiency, high-purity Li^+ beams with low, ~6 mrad, beam divergence. A successful, sub-scale test of the integrated system performance on SABRE would be followed by a full-scale demonstration experiment on Hermes III.

VII. SUMMARY

The light-ion beam LMF driver concept consists of multiple accelerator modules that can be fired sequentially to provide the desired energy, pulse-shape variability and energy deposition uniformity on target. The accelerator modules are based on the very reliable, low-cost Hermes III accelerator technology. The design concept is very flexible and will evolve to include results from the on-going system study and the technology validation program. The goal of this program is to demonstrate the integrated system performance of an LMF-scale accelerator module on Hermes III.

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FIGURE CAPTIONS

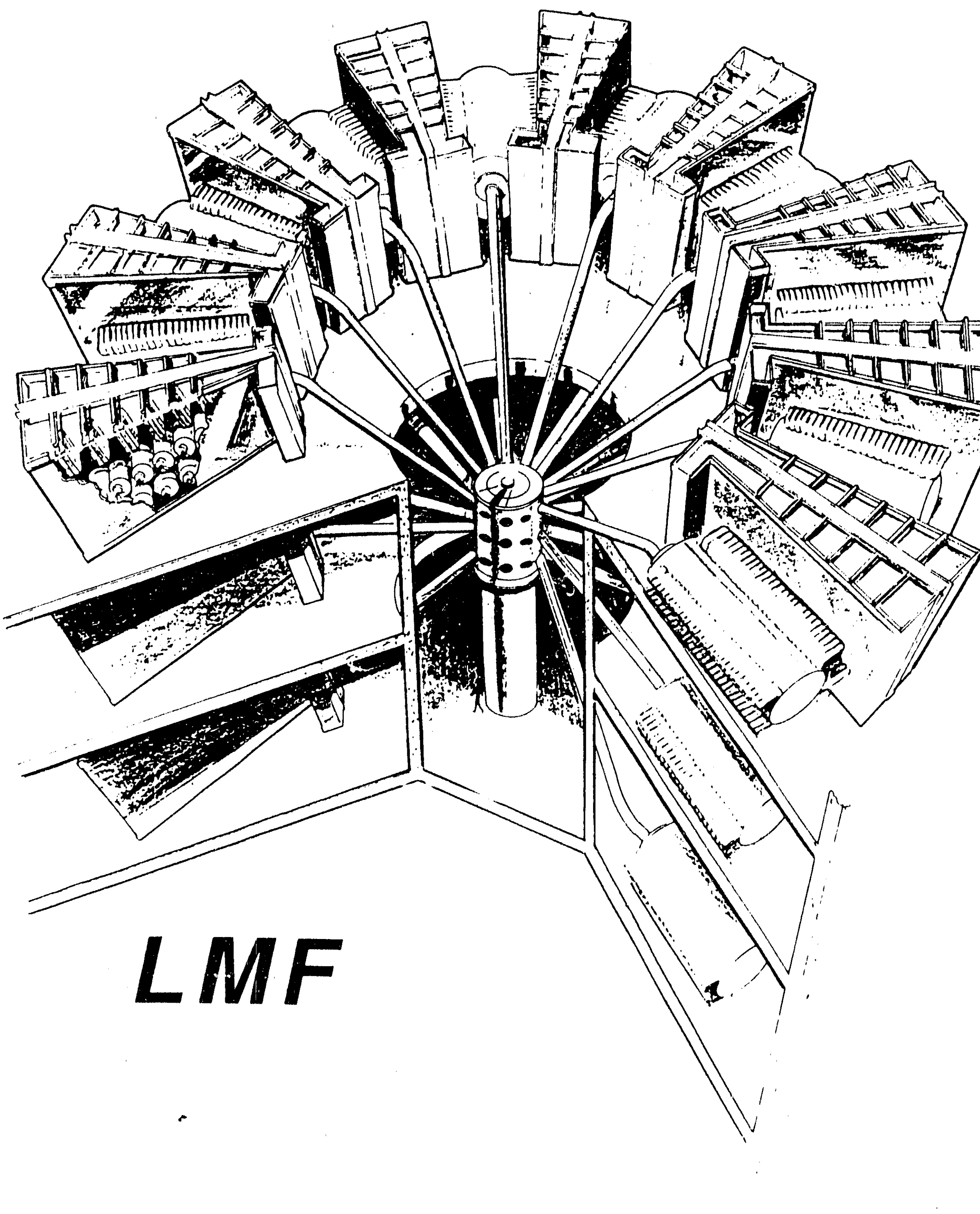

FIGURE 1.

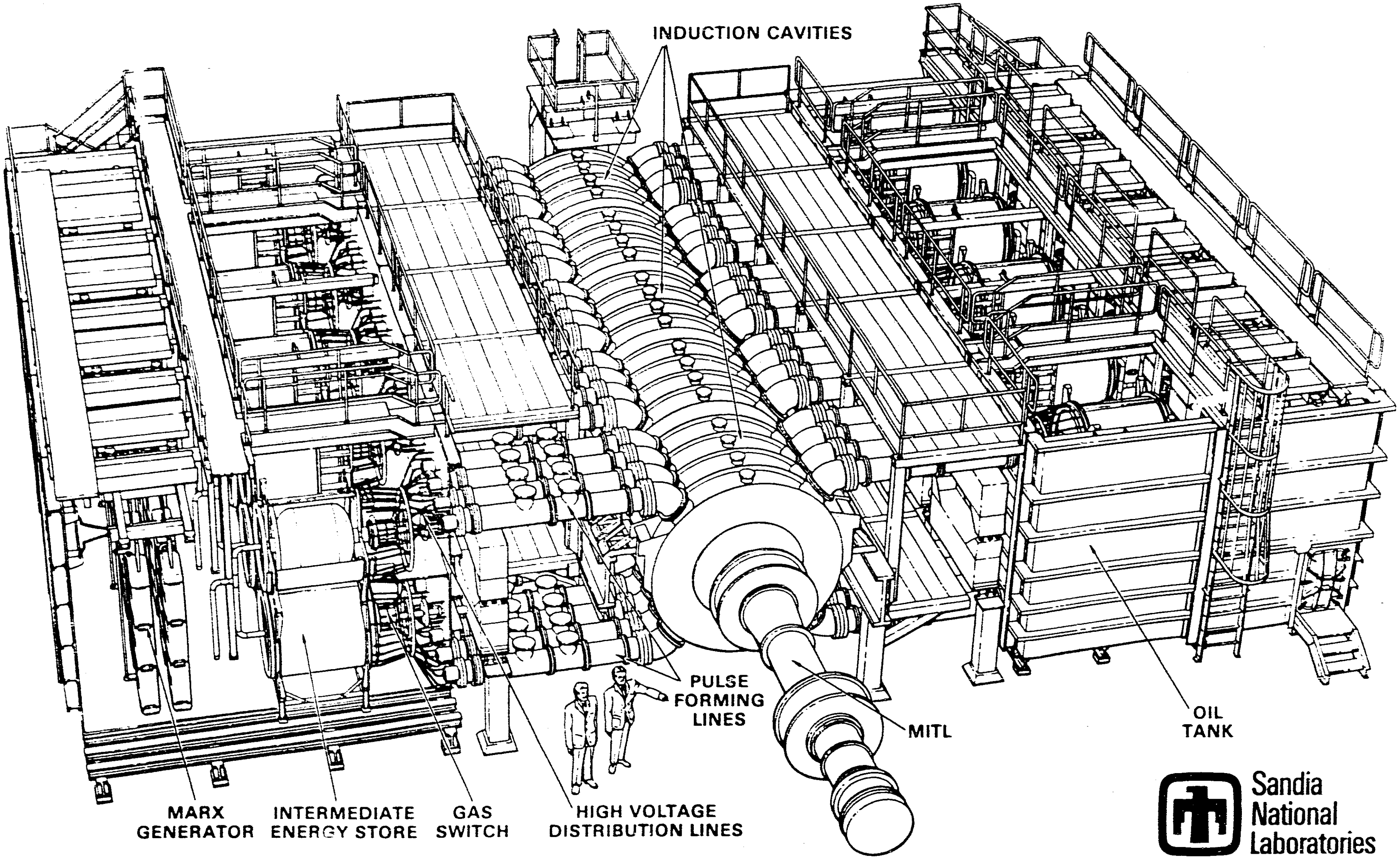

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FIGURE 2.

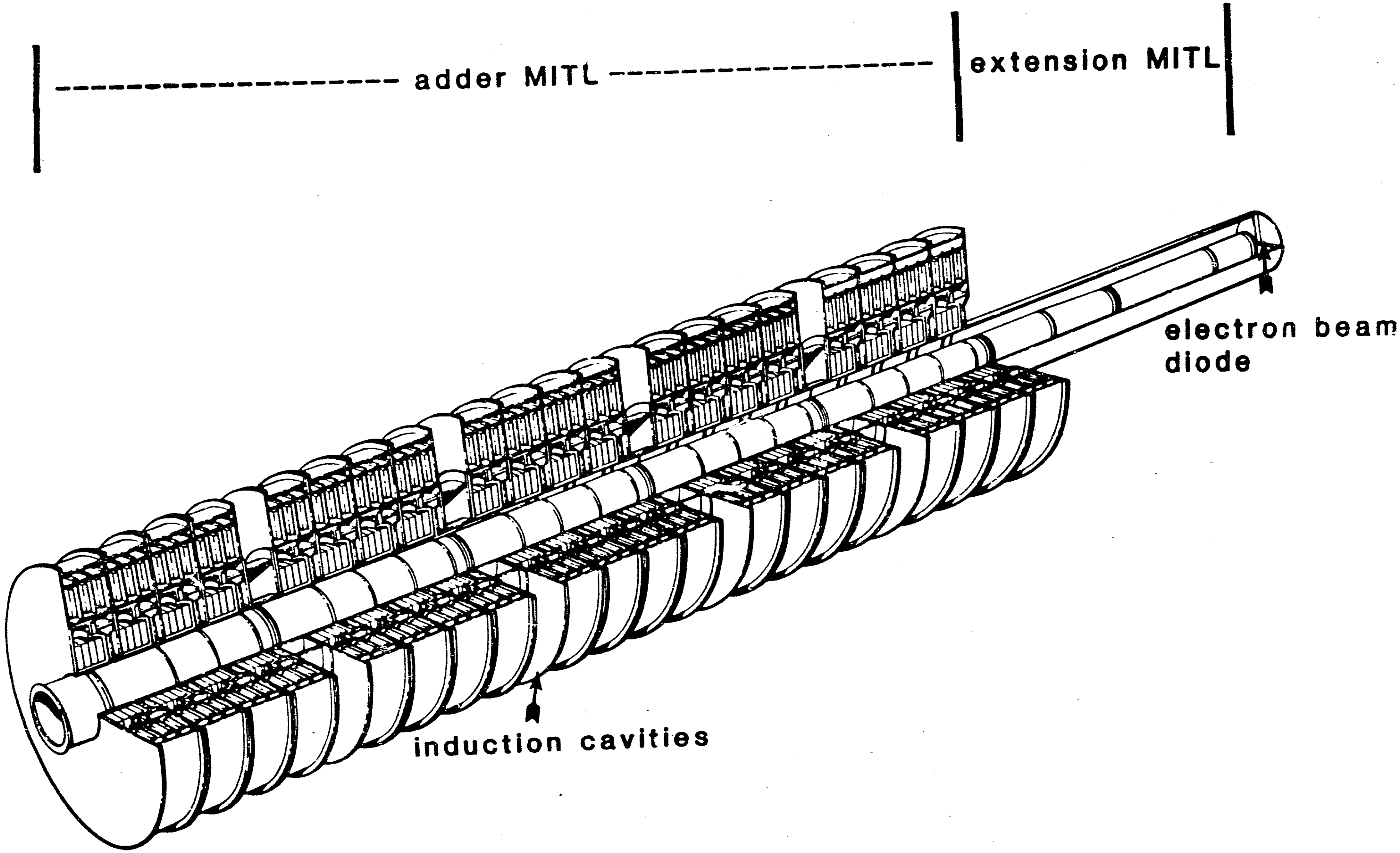
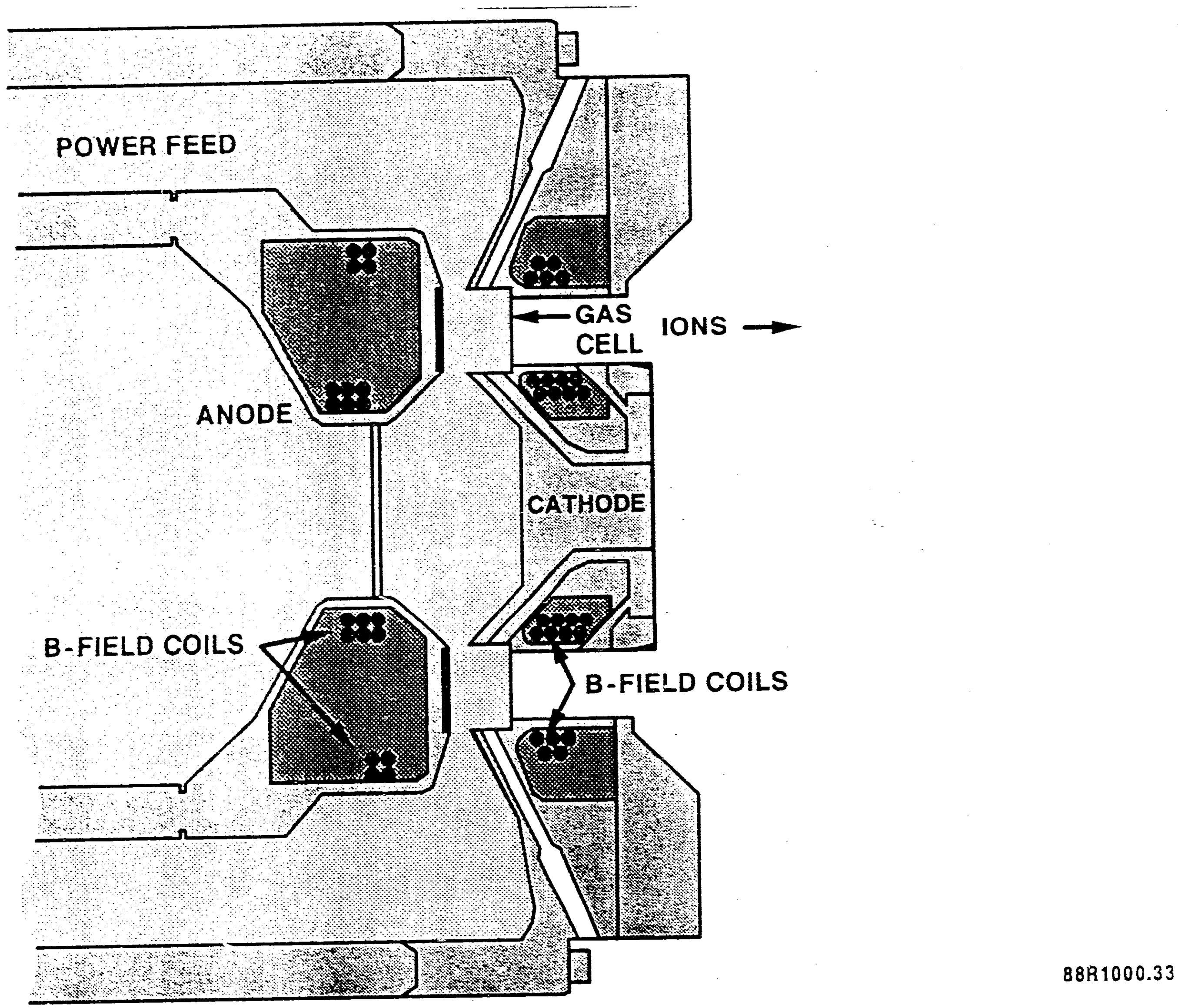

adder MITL
extension MITL
electron beam
diode
induction cavities

FIGURE 3.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GAS
CELL
IONS
ANODE
CATHODE
B-FIELD COILS
B-FIELD COILS
88R1000.33

FIGURE 4.

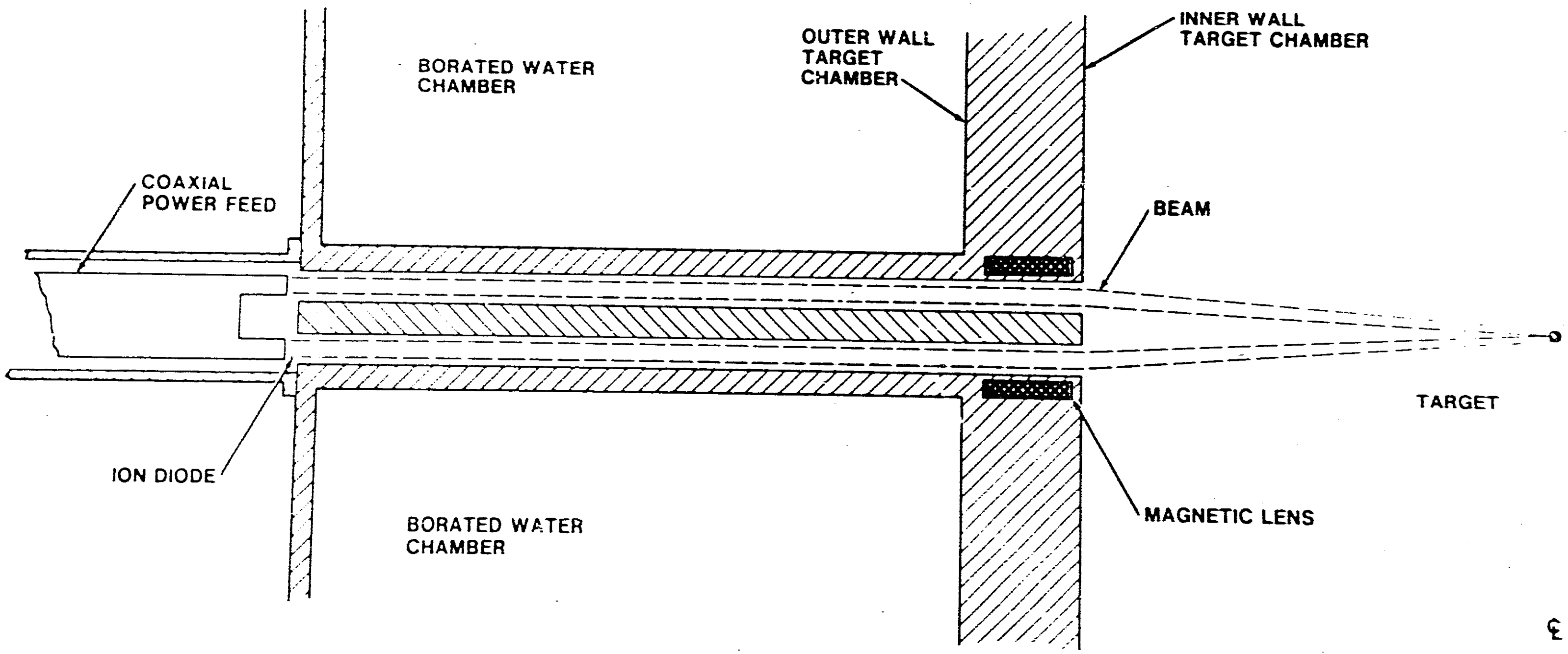

INNER WALL
TARGET CHAMBER
OUTER WALL
TARGET
CHAMBER
BORATED WATER
CHAMBER
COAXIAL
POWER FEED
BEAM
TARGET
ION DIODE
BORATED WATER
CHAMBER
MAGNETIC LENS
℄

FIGURE 5.

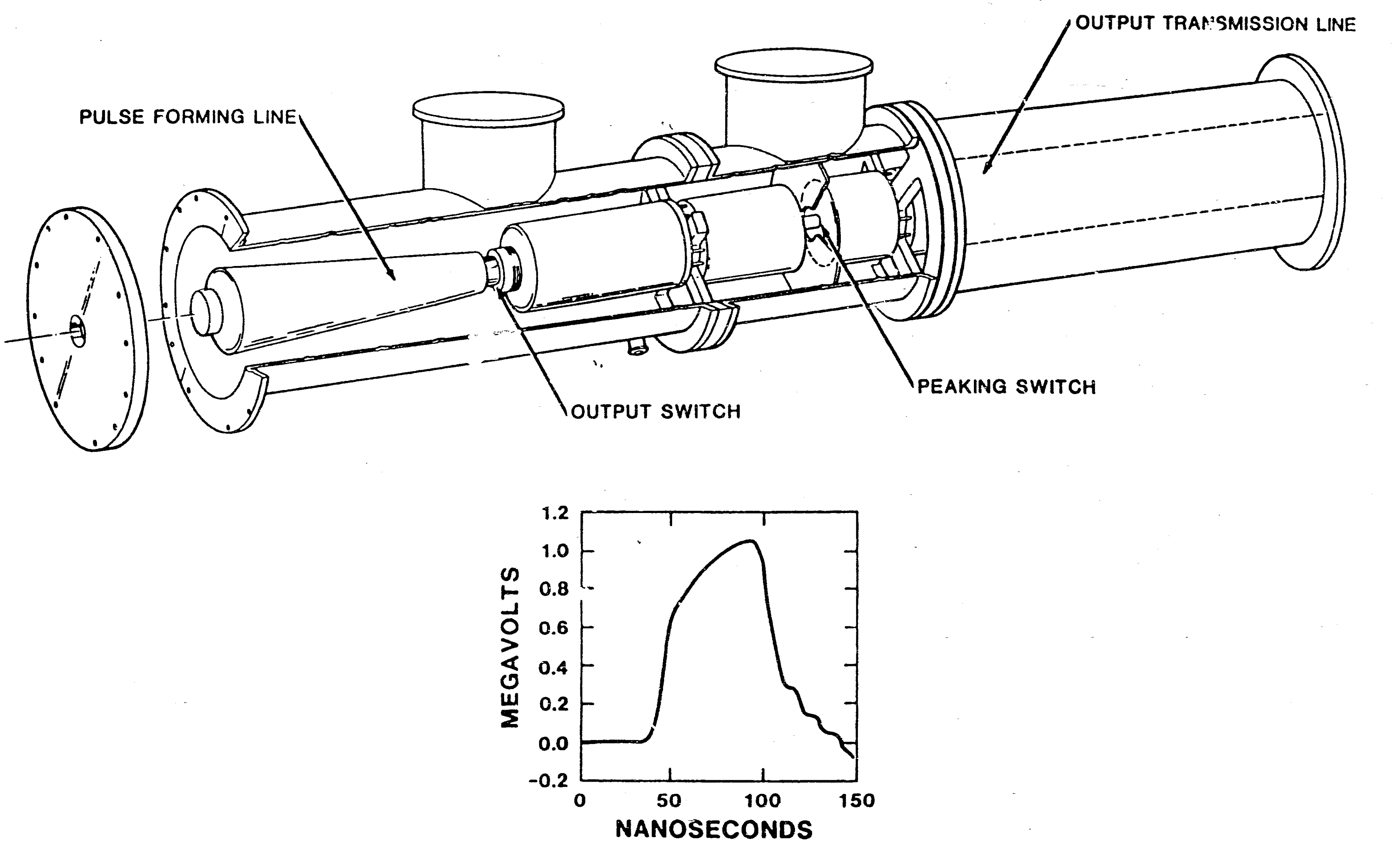
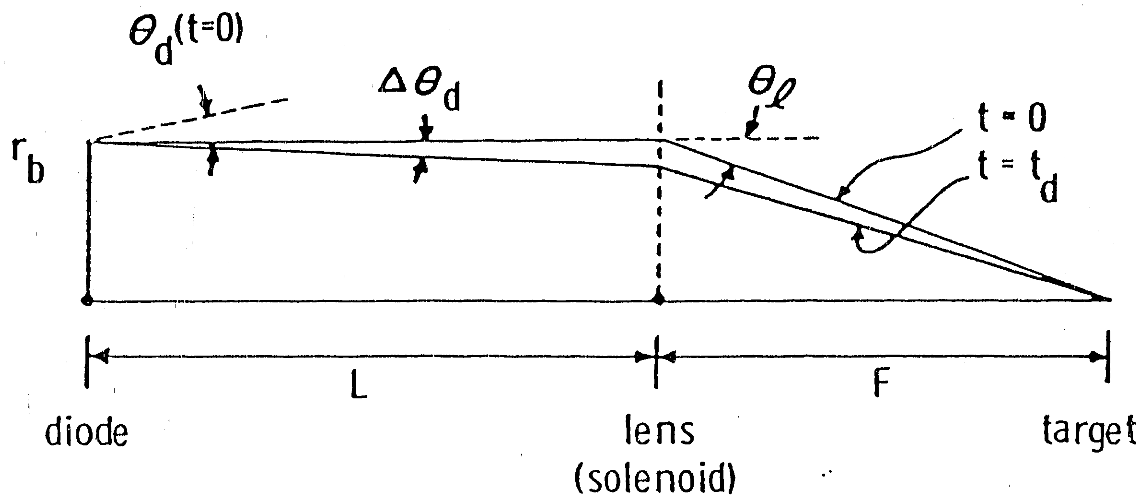

OUTPUT TRANSMISSION LINE
PULSE FORMING LINE
PEAKING SWITCH
OUTPUT SWITCH
1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
MEGAVOLTS
0
50
100
150
NANOSECONDS

FIGURE 6.



$\theta_d(t=0)$
$\Delta\theta_d$
θ_ℓ
r_b
t = 0
$t = t_d$
L
F
diode
lens
(solenoid)
target

FIGURE 7.

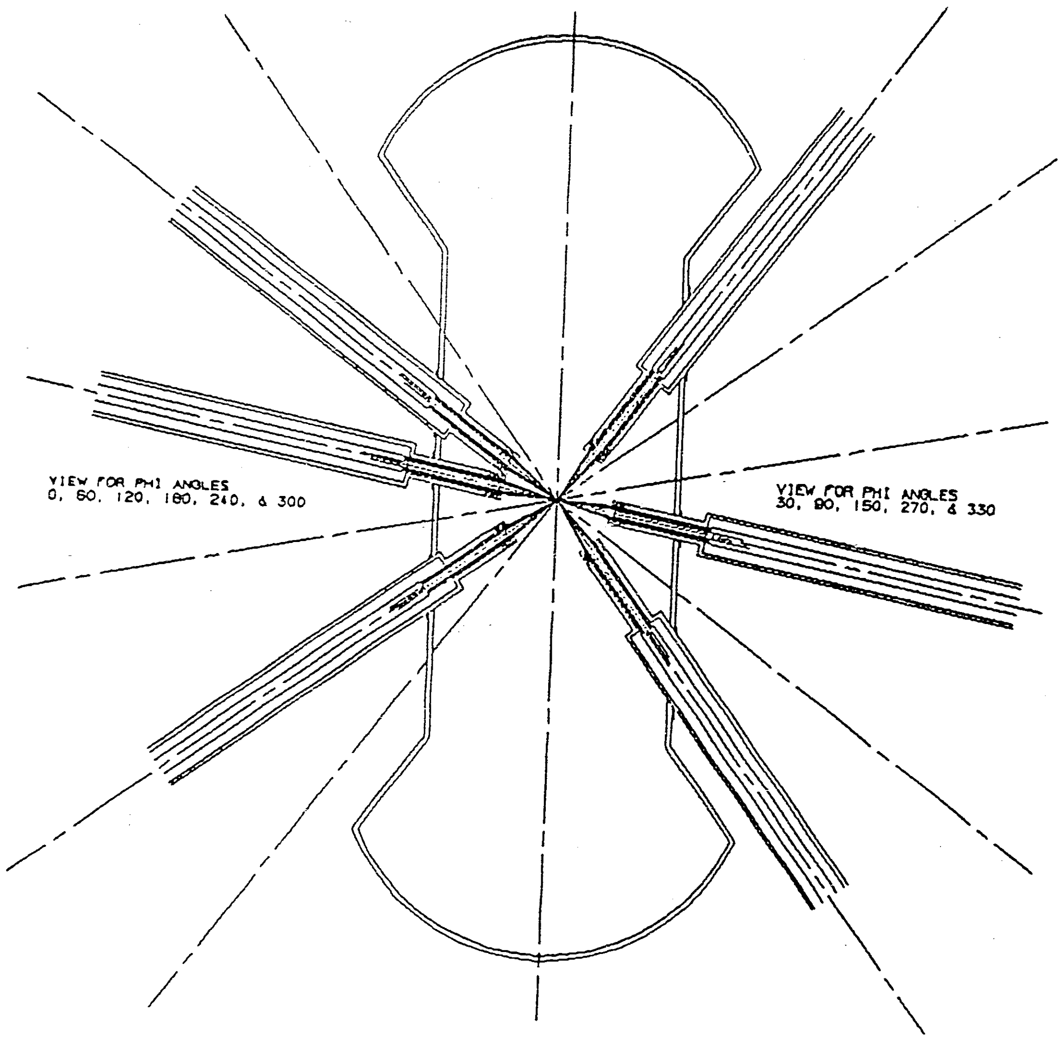

VIEW FOR PHI ANGLES
0, 60, 120, 180, 240, & 300
VIEW FOR PHI ANGLES
30, 90, 150, 270, & 330

FIGURE 8.

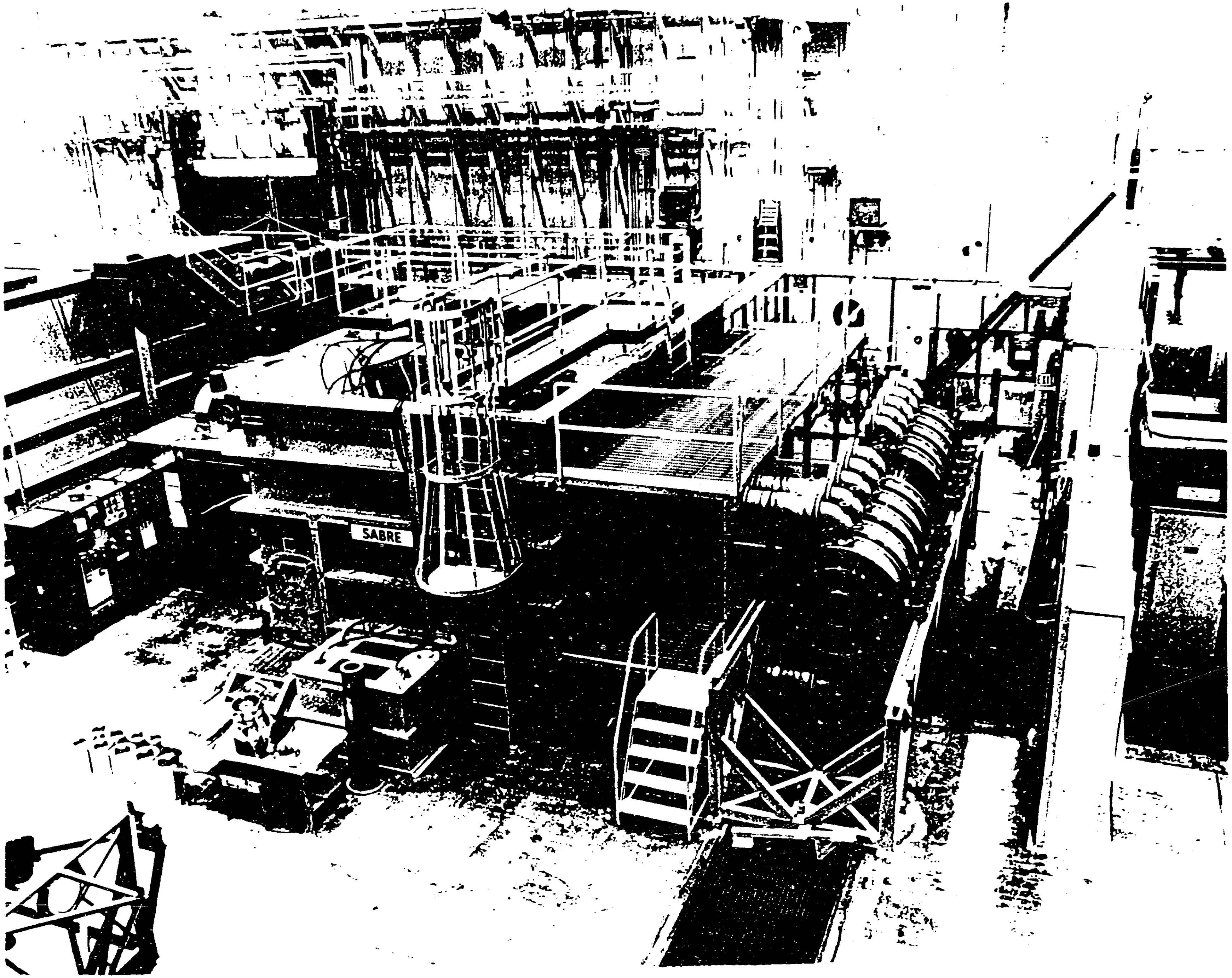


FIGURE 9.

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