THE LIGHT ION FUSION EXPERIMENT (LIFE) ACCELERATOR SYSTEM FOR ICF*

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ABSTRACT

A Light Ion Fusion Experiment (LIFE) accelerator system is under study as a driver for ICF. The system consists of separate functional elements. Light ions are extracted from a pulsed cold plasma source and accelerated in multi-grid and multi-aperture accelerator structures, with provision for strong compression of beam pulses. D or He ion beams, 20 kA, 1-10 MeV, will be made to ballistically propagate in 10^{-4} torr gas by externally generated co-moving electrons which provide space-charge and current neutralization. The propagation method is relevant to the Heavy Ion Fusion program and helps to reduce the large number of heavy ion beams entering a reactor to a manageable few. The system is also a useful test bed to perform several propagation experiments in the near term. The reactor requirements in Heavy Ion Fusion and LIFE are identical.

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INTRODUCTION

A novel light ion-accelerator system was conceived(1) at TRW to serve as a driver in ICF, and a study is now in progress to validate some of the key concepts in the system. The LIFE accelerator system is different in many respects from the mainline light ion driver approach at Sandia Laboratories(2) which consists of magnetically insulated diodes to produce MA level beam currents and propagate in preformed plasma channels, typically in a 50 torr ambient gas pressure. Because of the differences to be described, the LIFE system can best be viewed as an alternate-back up to the light ion mainline system and also as a useful test bed, to perform several propagation experiments in the near term which are relevant to the Heavy Ion Fusion program. Such propagation experiments appear to be critically needed to provide the experimental feedback on detailed "particle-in-cell" simulations such as the one presented by D.S. Lemons(3) for the LASL-TRW collaborative effort.

CONCEPT DESCRIPTION

The LIFE accelerator is based on the use of separate function hardware elements and the system is optimized to fulfill the requirements of an ICF ion beam driver. Considerations of potential ICF reactor scenarios and the state-of-the-art in pulse power technologies have also been made in the conception of the LIFE system. Separate hardware provisions are made to provide the following functional elements:

1. <u>Generation of Intense Cold Ions:</u> A pulsed intense cold plasma ion source is under development in which plasma induction occurs by pulsed RF power coupling in a large area. Ion extraction is timed to occur in the near afterglow regime of the plasma, about 2 μs after RF power is terminated. In this regime, ion density is high but ion temperature has cooled by ion-neutral atomic collisions. Light ions, D or He at densities of $n_i = 5 \times 10^{12} \text{cm}^{-3}$, and temperatures of $T_i \approx 0.1$ eV can be obtained over a 2 m diameter area by 1 MW, 1 ms, RF power at 300 kHz.

2. Intense Beam Acceleration: The LIFE accelerator concept is based on beam stacking by a multi-aperture multi-grid accelerator structure in which each beamlet is channel focused by shaped electrostatic fields. A different example of this principle is the recent MEQALAC accelerator system by A.W. Maschke.(4) Current densities of $J_b \simeq 1$ A/cm^2 are extracted and accelerated in a multi-grid sector with constant applied voltage, V_1, over a pulse duration of $t_p \sim 1$ μs. Beamlets are further accelerated in a following sector with time dependent applied voltage, $V_2 + V(t)$, such that $V_o = V_1 + V_2$ is the final energy of particles in the beam front. $V(t) = V_0\,[(t_0/t_0 - t)^2 - 1]$, for $t < t_0$ where t_0 is the flight time of the slowest particles at the beam front, in post-acceleration ballistic drift. Typically, a total current of $I_{acc} \simeq 20$ kA, constant to within a few percent will be accelerated with $V_0 \sim 1$ MV and $V(t)_{max} \sim 10$ MV, for $0 < t < t_p$. Beamlet extraction and initial acceleration must be performed with constant applied voltages to preserve a well defined perveance condition and Child's law at the level of the plasma sheath. In this sector with $V_1 \sim 0.3$ MV, beamlet optics are designed to focus extracted beams of $r_b \sim 6$ mm down to a few mm, so that paraxial optics will apply in the subsequent time dependent acceleration. An example of the multi-aperture electrostatic focusing accelerator structure is shown in Figure 1. The optics of radial apertures as the one shown or hole geometries are under investigation with use of the codes(5) EGUN and EBQ. Figure 2 presents the manner whereby the accelator structure is energized.

3. Strong Time Compression: Provisions are made to program strong time compression of beam pulses at the level of 100:1 or 50:1, to deliver 1-2 MA beam currents at a target as 1 μs, 20 kA beam pulses from the accelerator are compressed to 10 ns in a ballistic transport distance of 10-15 m. Strong pulse compression is not feasible in single gap diode accelerators without introducing also strong beam defocusing effects; for these, pulse compression is confined to the level of 3:1 to 5:1 and MA currents need to be accelerated in order to deliver MA beams at targets. Accordingly, one of the main advantage in the LIFE system will be the use of relatively low power technology to energize the multi-grid accelerator structures. A flexible, programmable and highly efficient pulse power method(6)

is conceived by I. Smith for this project whereby the desired V(t) waveform can be tuned with a few tenth of a percent regularity.

4. Focusing: In addition to beamlet channel electrostatic focusing, the accelerator grid planes are spherically shaped with a radius of 10-15 m to provide the radial focusing of the entire beam. Provisions are made independently to apply systematic corrections of trajectories by shaped electrodes, both as a function of beam pulse time and overall beam radius.

5. Current Neutralization: The provision of current neutralization of intense light ion beamlets will be made at the exit end of the accelerator structure. It is required to produce co-moving and co-located electron-ion beams in order to have space-charge and current neutralized ballistic propagation over distances of 10-15 m in an ambient gas pressure of 10^{-4} torr. A detailed calculation(7) of the single and multiple scattering of ions off the nuclear coulomb field and ion energy straggling due to atomic ionization of a medium produced the 10^{-4} torr requirement, so that 1-10 MeV D or He ions will not spread more than ± 2 mm in 10 m of transport in N_2 gas. Therefore, beam neutralization by the ionization of ambient gas at 0.1 - 1 torr pressures is not acceptable and externally prepared co-moving electrons must be provided to the ion beam. The alternate propagation scheme is through pre-formed high return current plasma channels which are not considered here. A method of generating co-moving electrons is sketched in Figure 3. These electrons must become co-located with the ions within 20-50 cm of travel, otherwise the electrostatic field among electron and ion beamlets will raise the temperature of electrons causing a pressure which limits the amount of ballistic focusing of ions. Co-location is made possible by cusp magnetic fields which fan out co-moving electrons to quickly mingle with the ion beamlets and become trapped in their potential wells. A special test bed is being prepared at TRW to address experimentally the issues of current neutralization of intense and energetic ion beams.

6. Beam Power Profile Shaping: The flexibility in the LIFE accelerator concept in principle makes it possible to deliver a desired beam pulse profile from each beamline while providing also a strong beam

pulse compression at the target focus. Ordinarily, in a multibeam target compression arrangement each beam would be programmed to fill a specified portion of the power profile, so that the totality of beams but no each beamline provide the power shape desired by target designers. Starting with one of the target design cases presented by R.O. Bangerter,(8) a smooth power raise from ∿ 10% to 100% in 14 ns and flat top for 6 ns (see Figure 4), the time varying acceleration voltage waveform in the LIFE system can be programmed(9) according to the shape displayed in Figure 5 to deliver also a current amplified beam of 66:1 at the target focus, as shown in Figure 6. The accelerator will produce a nearly constant current source of 20 kA and in the above case, each beamline will impart 60 kJ energy at the target. A configuration of 34 beamlines is envisaged for a 150 TW, 2 MJ, 300 TW/cm^2 LIFE driver.

STRONG BEAM PULSE COMPRESSION TEST

Since strong beam pulse compression is one of the key features of the LIFE system, a small scale experiment was performed at TRW using most of the ingredients in the concept, to explore some of the issues of technical feasibility and hardware requirements. The experimental setup is given in Figure 7 and details are reported elsewhere.(10) The time varying acceleration voltage waveform was shaped by a 20 channel circuit, to accelerate and pulse compress He$^+$ ions up to 7 keV. A beam current of 0.6 mA was extracted at constant voltage and subsequently, a 1 μs duration pulse compressing voltage was applied in the following accelerator grids. The pulse compression time focus was located 66 cm downstream from the end of the accelerator. After careful shaping of the time varying voltage waveform, the 1 μs beam pulse was compressed to 8 ns at the time focus. Figures 8 and 9 show a collection of measurements in the temporal behavior of the detected beam current as a function of axial position from the accelerator. Voltage waveform tuning was accomplished by a variety of diagnostic techniques including the behavior of the beam itself. Once the desired waveform was tuned, highly reproducible results were obtained over long periods in time. No attempts were made to provide externally current neutralization electrons or to design a good spatially focusing accelerator structure. The achieved beam pulse time compression is 125:1 in 66 cm of travel.

A test facility is being upgraded at TRW to scale up these measurements to the 500 keV level with 500 A, 1 μs, He^+ beams produced in a pre-prototype LIFE accelerator system.

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L.I.F.E

MULTI-GRID, MULTI-APERTURE ACCELERATOR STRUCTURE

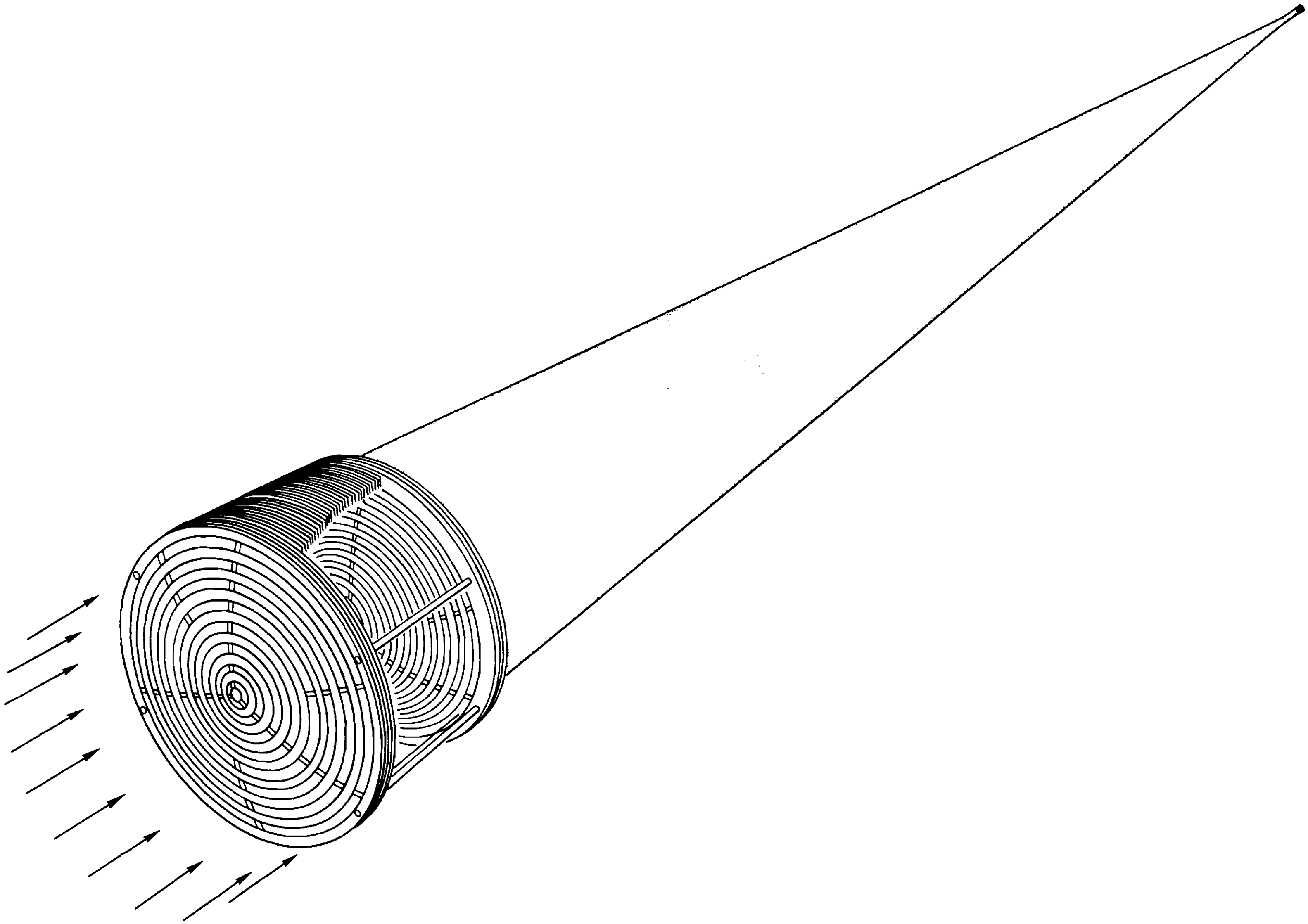


FIGURE 1

L.I.F.E.
MULTIGRID ACCELERATOR VOLTAGE DISTRIBUTION CHAIN

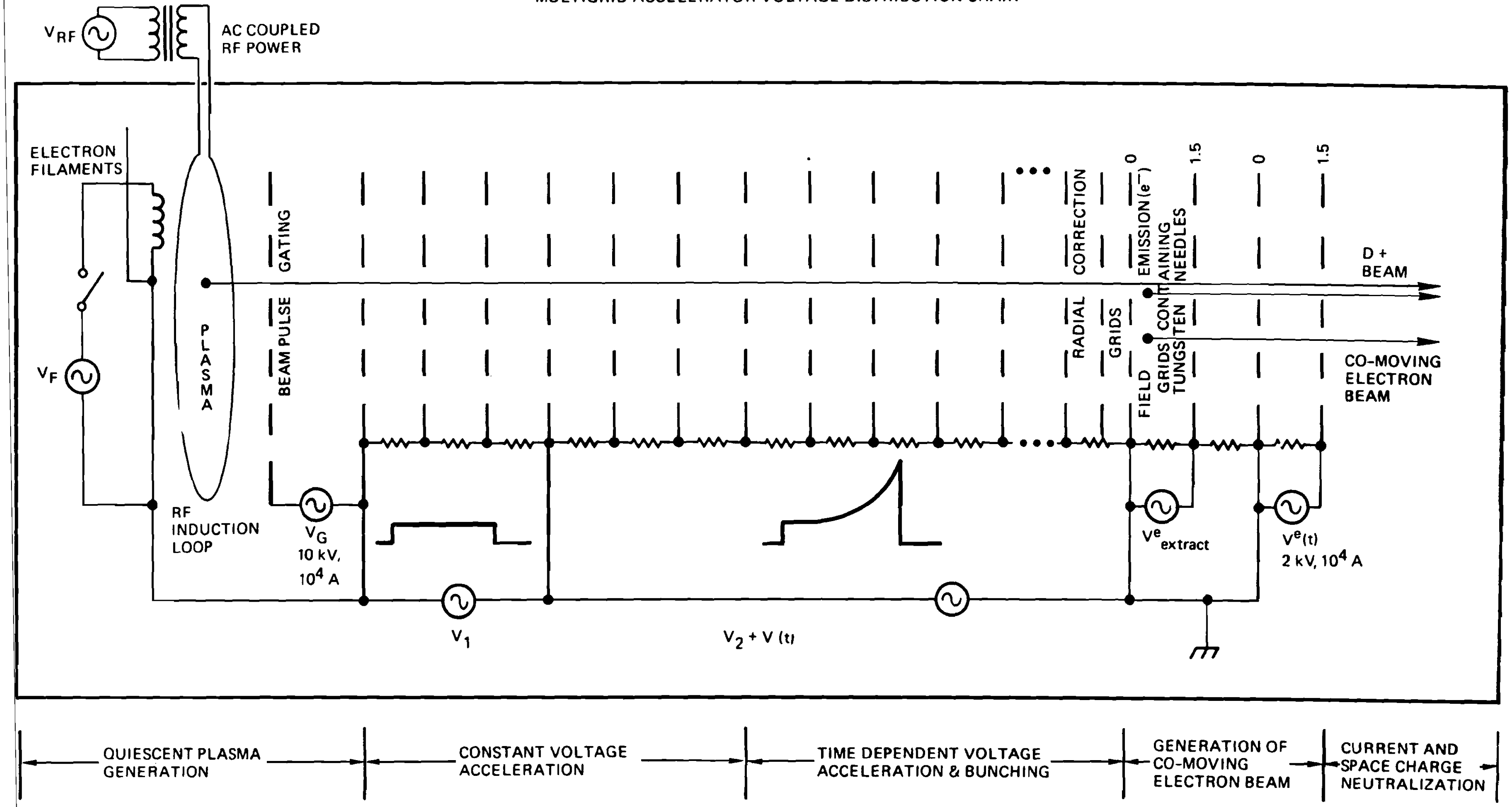
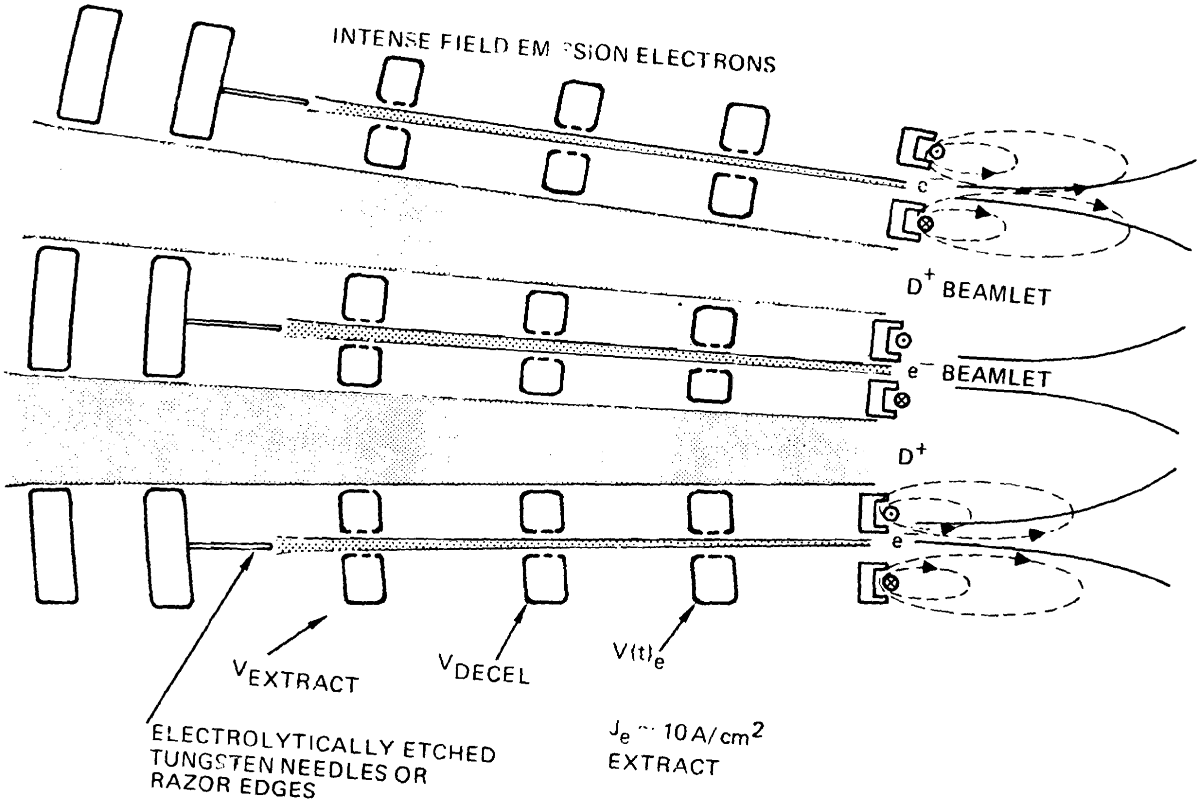


FIGURE 2



$$\left.\begin{array}{ll} v_e(t) = v_i(t) & \text{CURRENT} \\ n_e = n_D & \text{CHARGE} \end{array}\right\} \text{NEUTRALIZATION}$$

$$E_e(t) = \frac{m_e}{M_D} E_b(t)$$

$$E_e\text{MAX} = 1.32\ (\text{keV})$$

GENERATION OF CO-MOVING ELECTRON BEAM FOR CURRENT & CHARGE NEUTRALIZATION OF ACCELERATED DEUTERONS

FIGURE 3

FIGURE 4

L.I.F.E

SINGLE BEAM POWER PROFILE AT TARGET

$\int P(t)dt = 60$ kJ

POWER RISE TO 4.4 TW IN 14 ns (50%), FLAT FOR 6 ns (50%). POWER PROFILE ACCORDING TO R.O. BANGERTER (LLL) TARGET CALCULATIONS.

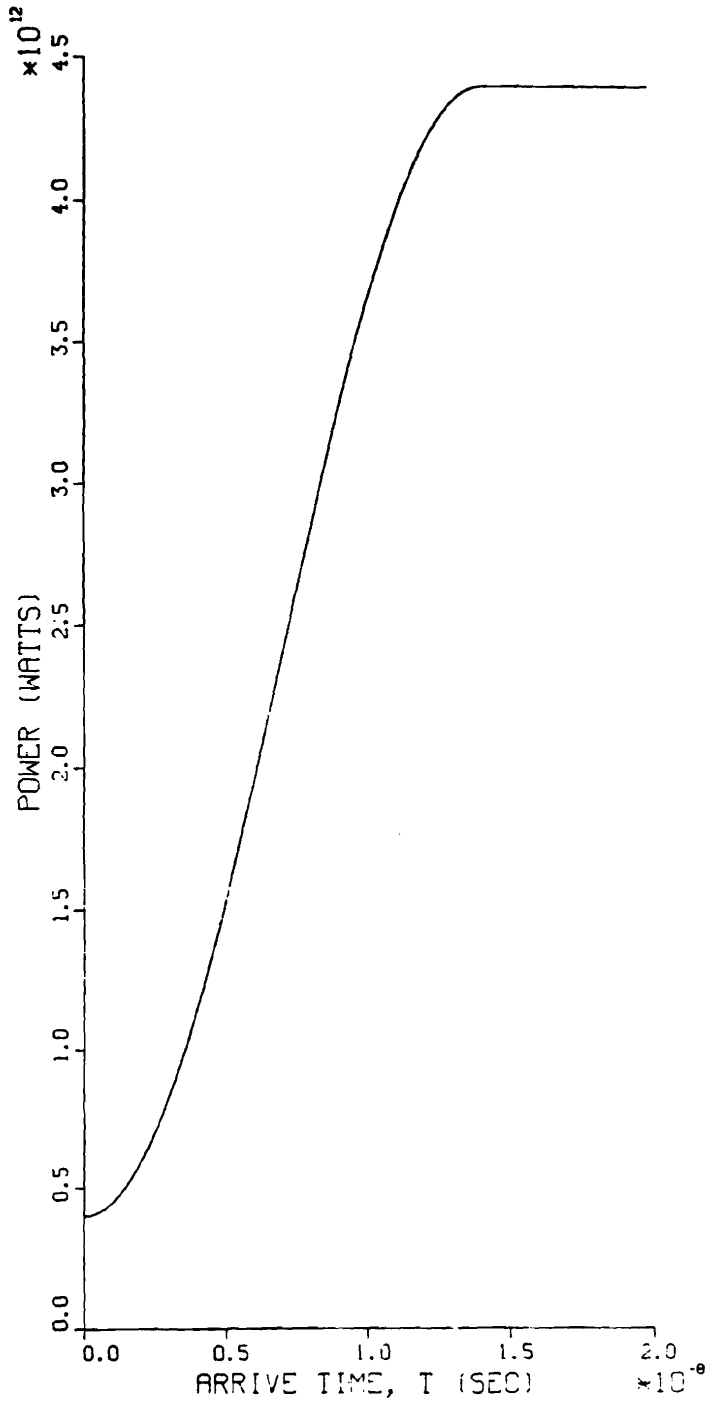
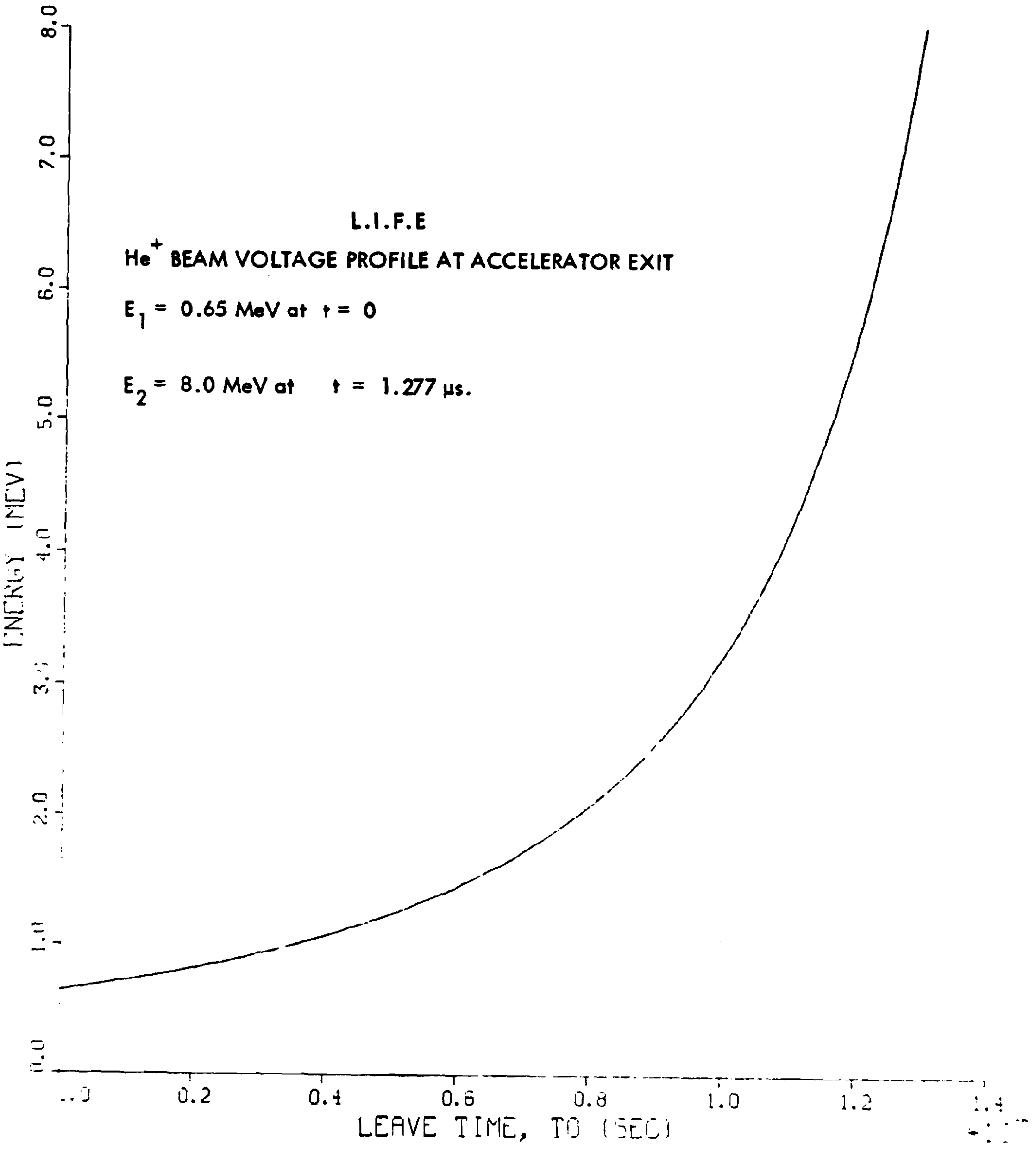


FIGURE 5



L.I.F.E

He^+ BEAM VOLTAGE PROFILE AT ACCELERATOR EXIT

E_1 = 0.65 MeV at t = 0

E_2 = 8.0 MeV at t = 1.277 μs.

FIGURE 6

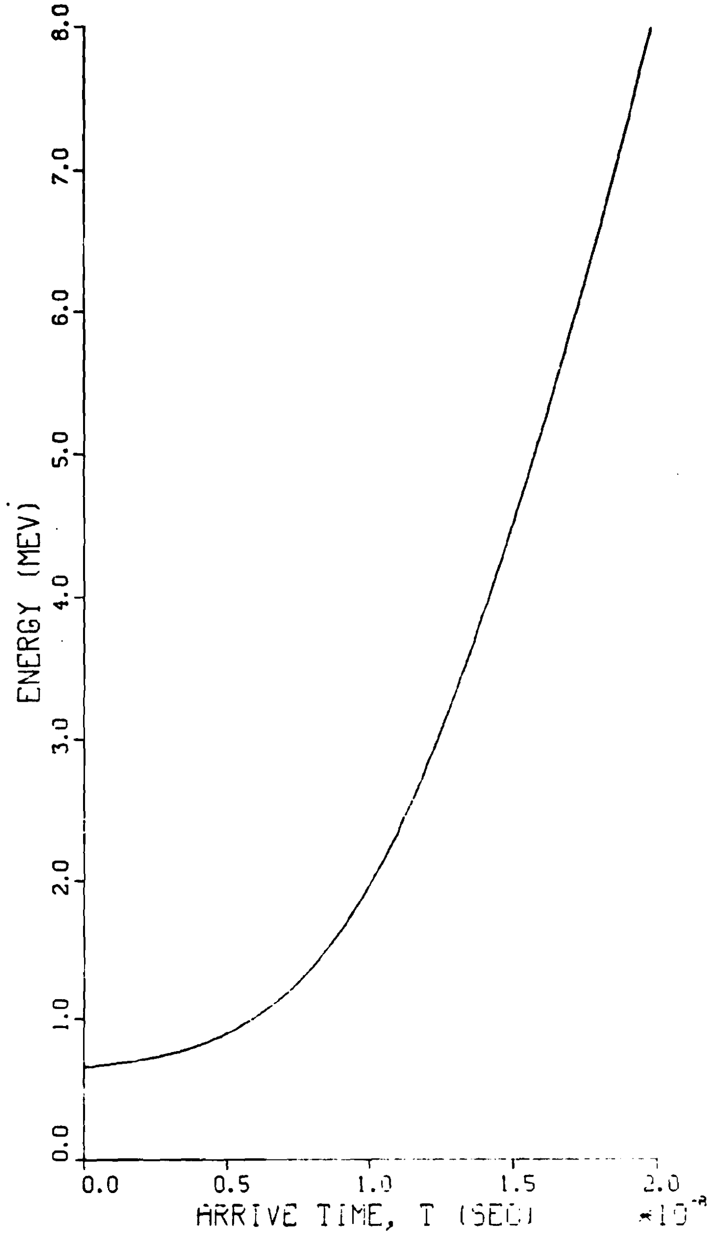
L.I.F.E

He^+ BEAM VOLTAGE PROFILE AT TARGET

I_{accel} = 20 kA, t_{accel} = 1.28 μs, CA = 65.6

I_{target} = 1.3 MA, E_{target} = 60 kJ, T_{ave} = 3 MeV

R_{accel} = 1 m, A = 10 m, R_{focus} = 4 mm, A_{focus} = 0.5 cm^2



LIGHT ION BEAM COMPRESSION EXPERIMENT

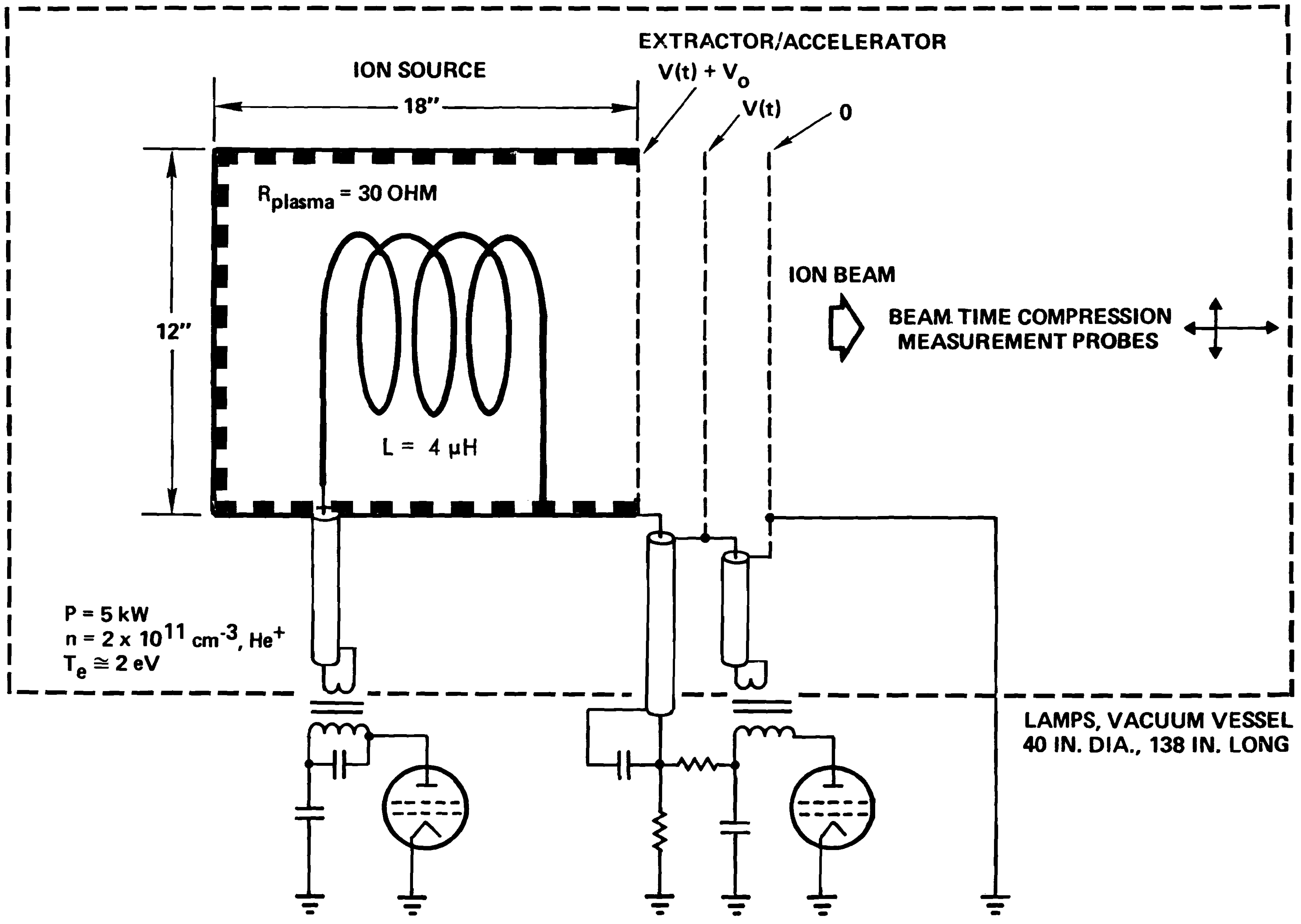
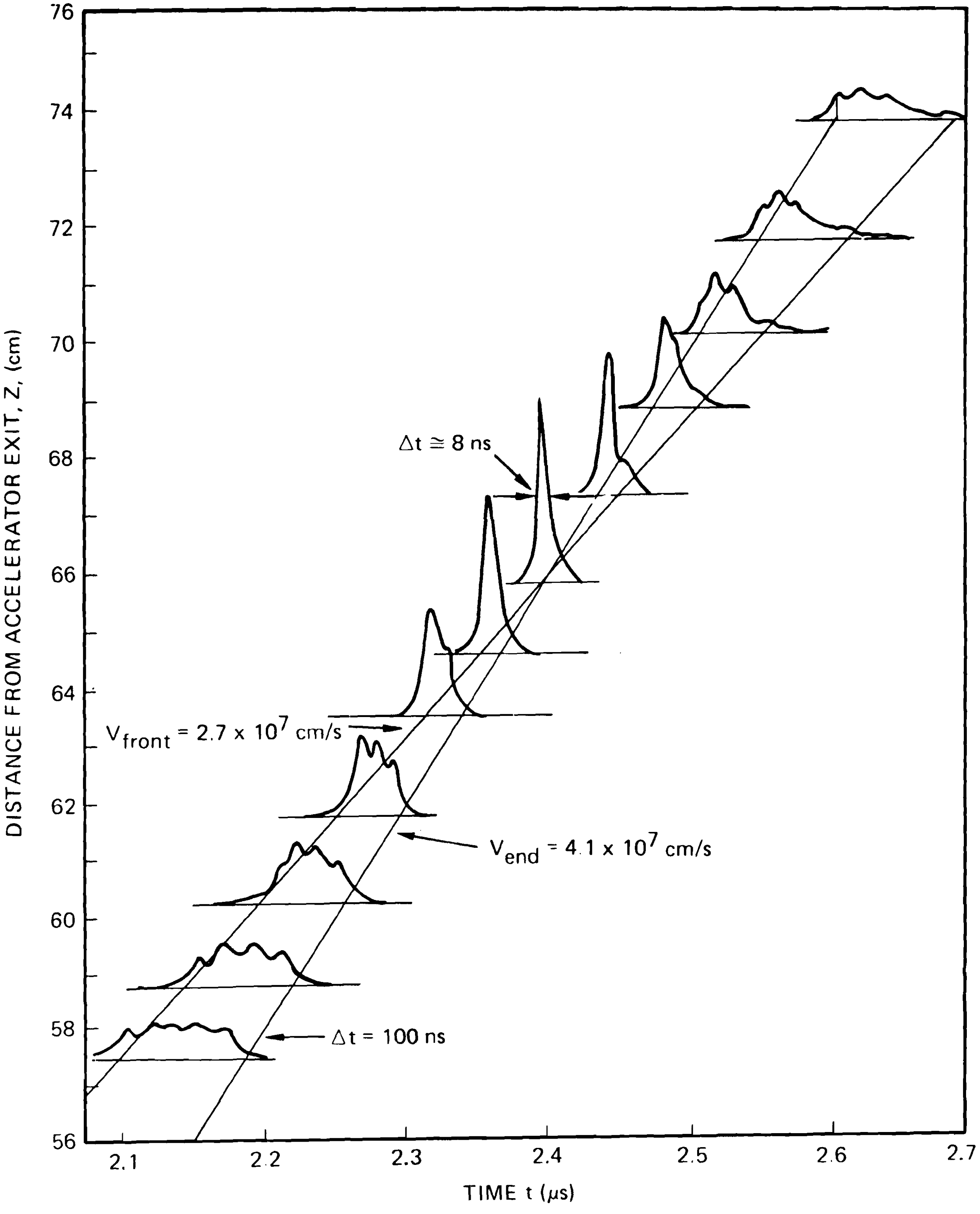


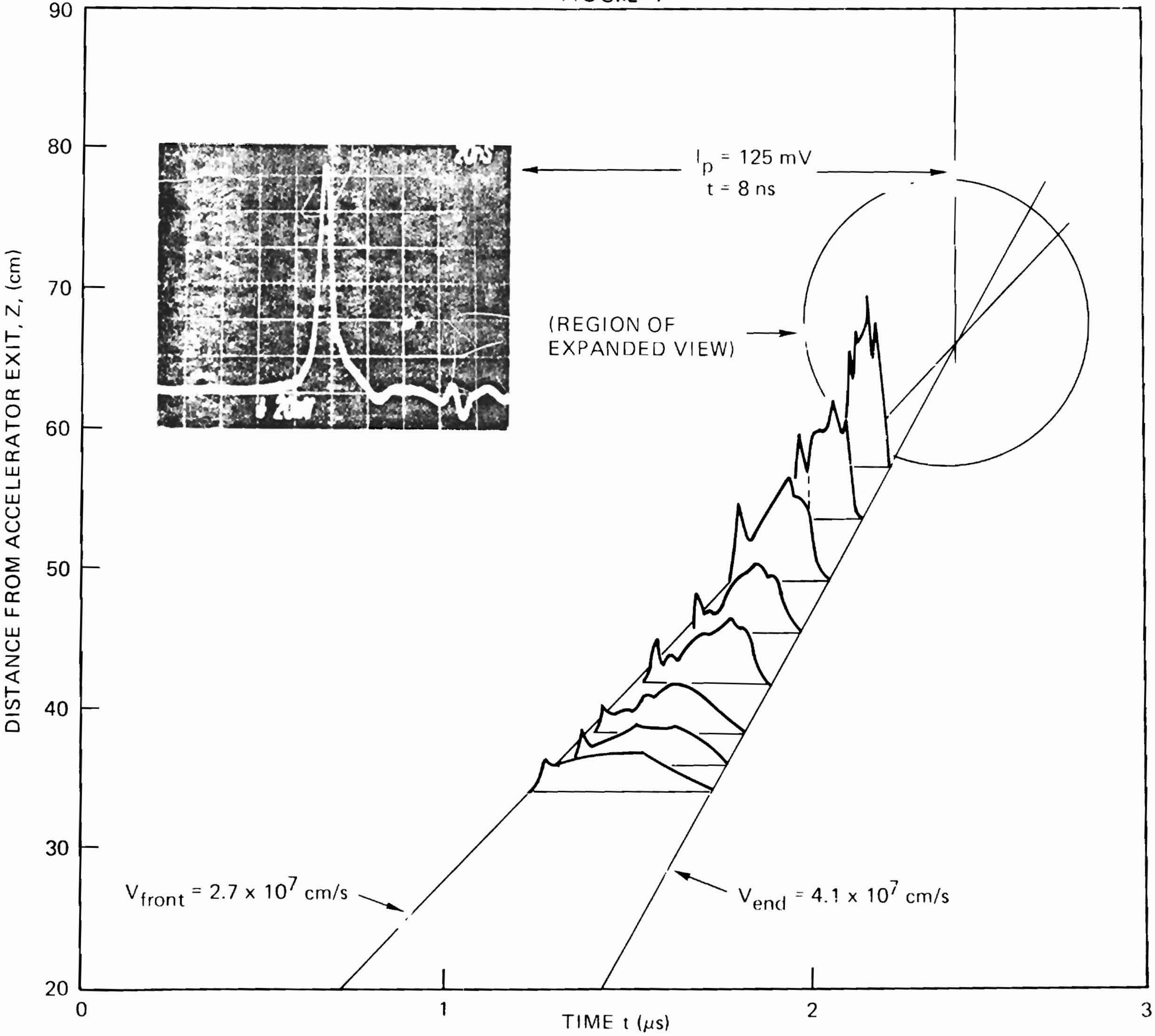
FIGURE 7



DISTANCE FROM ACCELERATOR EXIT, Z, (cm)
76
74
72
70
68
66
64
62
60
58
56
TIME t (μs)
2.1
2.2
2.3
2.4
2.5
2.6
2.7
Δt ≅ 8 ns
V_{front} = 2.7 x 10^7 cm/s
V_{end} = 4.1 x 10^7 cm/s
Δt = 100 ns

FIGURE 8

FIGURE 9



DISTANCE FROM ACCELERATOR EXIT, Z, (cm)
90
80
70
60
50
40
30
20
0
1
2
3
TIME t (μs)
I_p = 125 mV
t = 8 ns
(REGION OF
EXPANDED VIEW)
V_{front} = 2.7 x 10^7 cm/s
V_{end} = 4.1 x 10^7 cm/s