Technical Progress Report

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The Study of the Acceleration, Focussing and Bunching of Ions by Electronic Space Charge for Pellet Fusion

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MASTER

by

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A. Introduction

In our proposal of 1976, we had indicated three areas of work on this contract.

1. A low energy (1-10 kV) experiment to demonstrate focussing and to clarify the physics of bunching.
2. An experiment at high energy (100-500 kV) to scale our prior results.
3. A theoretical effort to formulate a self-consistent transient analysis of the virtual cathode - plasma interaction.

At the time of the writing of that proposal, the Nereus electron beam accelerator had just arrived. As we suspected, the high energy experiment with the Nereus was a "new world" to us, and some time was spent in becoming acquainted with that world. Although we are now operating regularly in that environment, it did necessitate emphasizing the high energy experiment at the expense of the low energy one. Consequently, the following summarizes the progress made on the last two items.

B. High Energy Experiment

Our initial experiments with the Nereus Accelerator were designed to demonstrate a number of items. More to the point, the experiments were designed to answer some pressing questions as to whether this concept was adaptable to voltages and power levels envisioned for pellet fusion.

Recall that our proposed scheme calls for the efficient transfer of energy from the injected electron beam to the plasma ions, and these ions are to be focussed on to a small target and "bunched" in their arrival at the target. However, there are some non-trivial questions to be answered; a partial listing is given below.

(a) Will the high voltage diode tolerate the presence of a pre-formed low density plasma?

(b) Does the injection of the electron beam into the plasma generate a host of beam-plasma instabilities?

(c) Can one form the target plasma in a convenient manner?

(d) Can one extract ions from this pre-formed plasma?

A negative answer to any of these questions would place a considerable damper on this scheme for ion-pellet fusion.

To answer these questions, we modified the front-end of the Nereus in the manner shown in Fig. PR-1. The water-line is charged positive so that a positive pulse drives the screen anode above ground. This is an important difference between our experiments and the usual e-beam operation with the cathode being pulsed negative.

With the cathode being pulsed negative, everything else becomes an anode and collects electrons - thereby reducing the electronic space charge available to accelerate the ions. If the anode is pulsed positive, only the screen collects electrons and the lifetime of the electrons is enhanced.

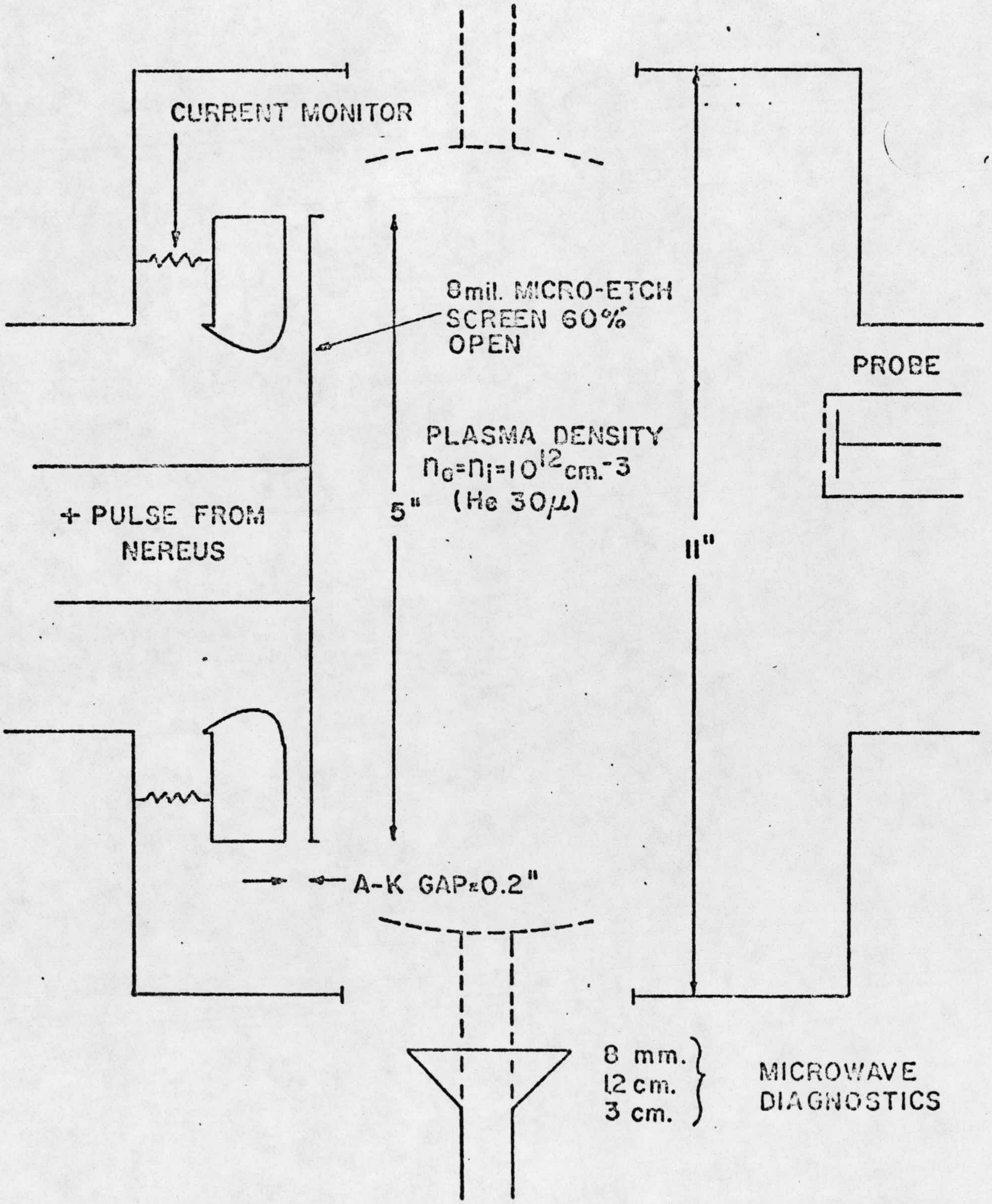


Fig. PR-1. Modification of the Nereus.

The pre-formed plasma was formed by running a low pressure discharge between the grounded aluminum shell and another electrode located on top of the machine. Thus the interior of the aluminum can was the negative glow region of a hollow cathode discharge. One of the pleasant surprises of this research was the ease by which we could produce a well-behaved target plasma for the electron beam.

This discharge could be run either D-C (for plasma densities in range 10^{9}-10^{10} cm^{-3}) or pulsed with a high current (100-400 amp) for the higher densities (10^{11}-10^{12} cm) for pressures greater than 10 microns. In the latter case, one can always choose a lower density by firing the Nereus pulse at a selected time in the afterglow.

This method of producing the target plasma is quite simple and convenient and appears to be scalable to the larger volumes envisioned for pellet fusion. Indeed everything seemed to be in its favor to work even better there.

Since it is the negative glow region of a discharge, it is an electron beam produced plasma with the low energy electron beam coming from ground walls of the container and accelerated by the cathode fall potential (1-3 kV). Thus the majority of the plasma is field-free and not prone to the host of discharge instabilities. Based upon present knowledge of the hollow cathode discharge, this technique should be scalable to larger volumes at even lower pressures.

Another pleasant surprise was that fact that not only did the high voltage A-k gap tolerate the presence of the pre-formed plasma, it seemed to prefer it. We were leary of the possibility of the pre-formed plasma initiating diode closure. As shown in Fig. PR-2, the cathode current in a typical pulse is slightly higher (than with no plasma) but far from short-circuit value of $\sim$ 70 k Amp.

In retrospect, one can explain this preference for the presence of the low density plasma in the following way. For operation in a vacuum, one depends upon the formation of a cathode plasma to supply the electrons for the diode. Thus the presence of a prior plasma tends to make the cathode plasma form earlier and more uniformly.

As shown in Fig. PR-1, we also had the capability of measuring the microwave emission from the beam - plasma system at the wavelengths indicates. Figure PR-3 shows a typical microwave emission during the Nereus pulse. The significance to be attributed to this figure is in the minute amount of power radiated considering that nearly a 100 megawatts of power was being switched. The conclusion to be drawn here is that the beam - plasma interaction is not violently unstable.

Our greatest source of difficulty during the past year lies with item (d) - could we extract ions from a pre-formed plasma with energies comparable to the applied voltage. Even though difficulties have been encountered, there are problems with the diagnostics rather than that of the physics.

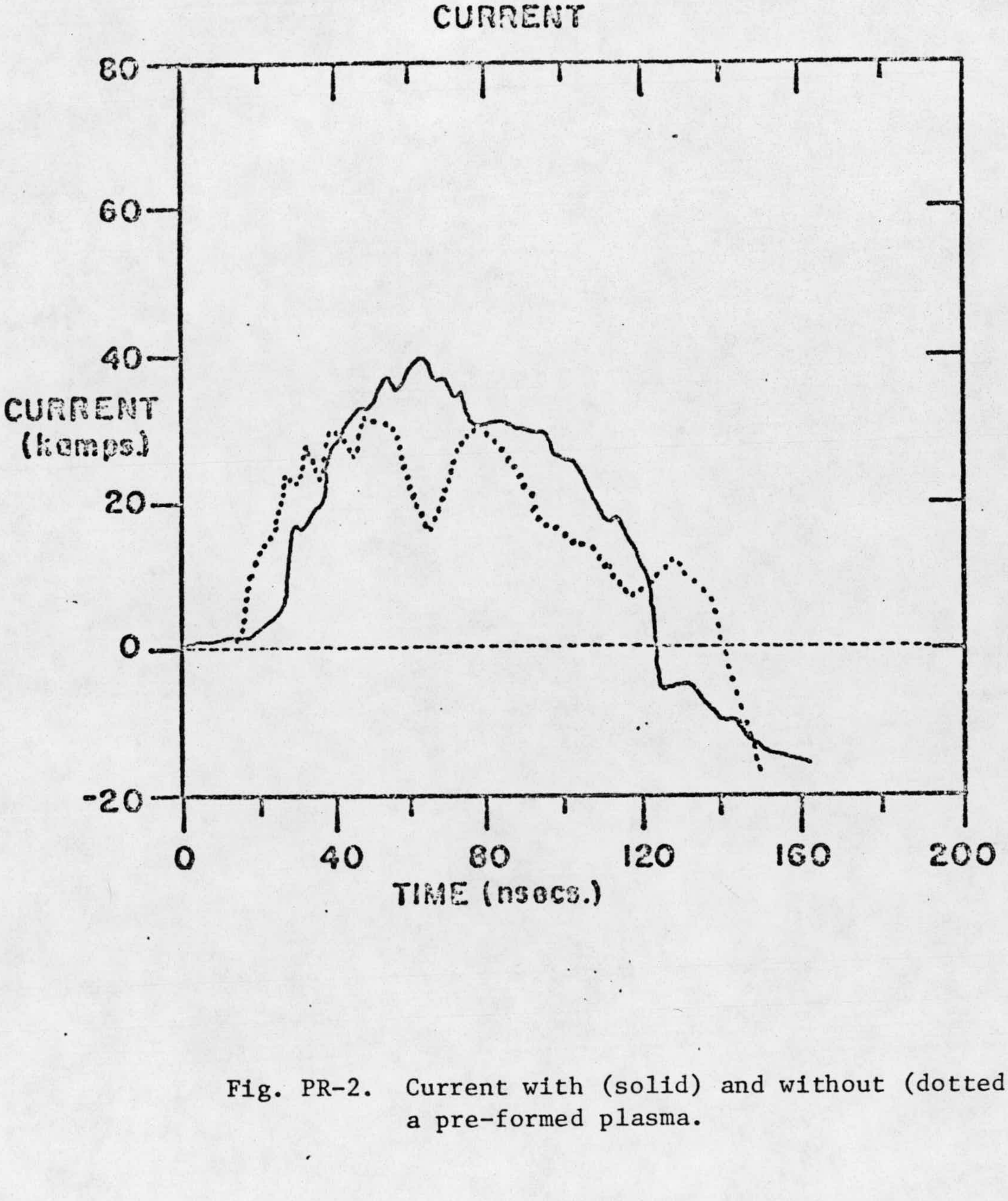


Fig. PR-2. Current with (solid) and without (dotted) a pre-formed plasma.

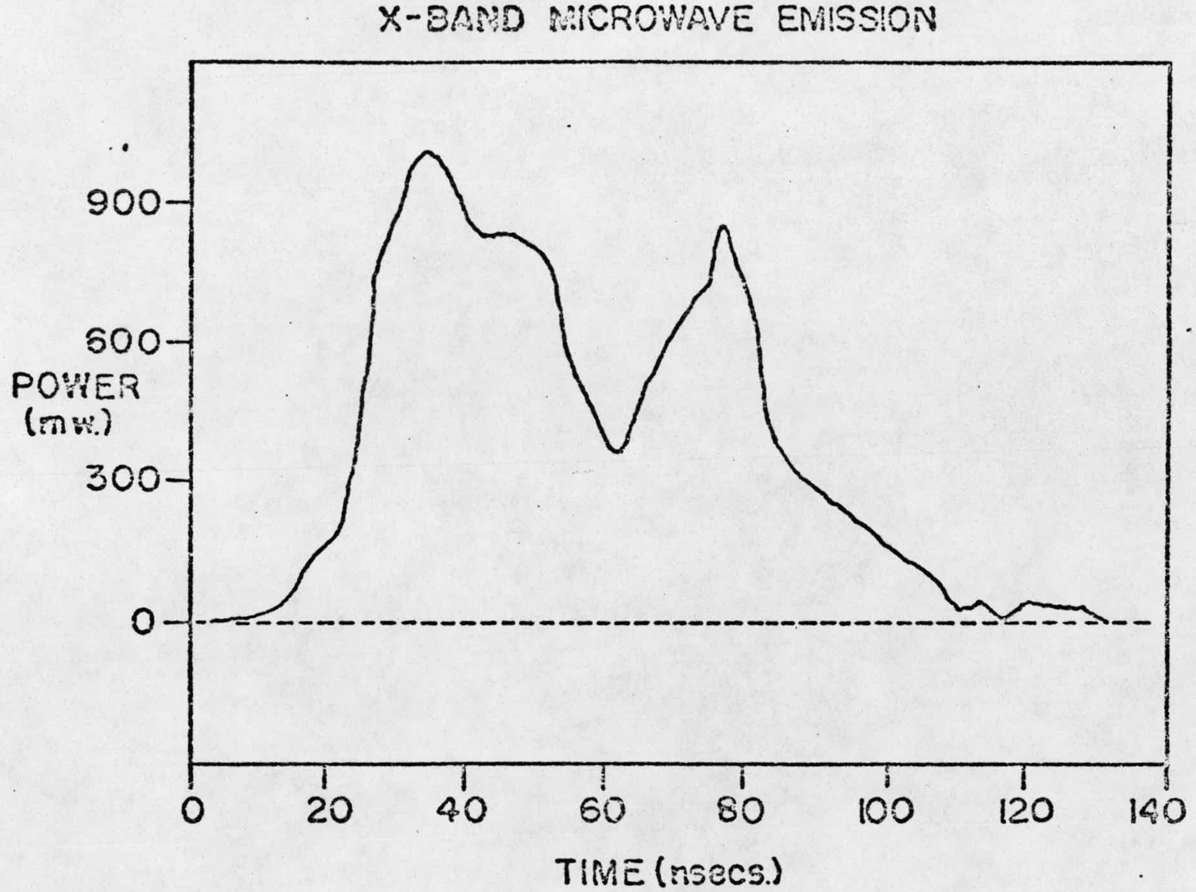


Fig. PR-3. Microwave Emission at X-Band.

Figures PR-4 and PR-5 illustrate some of the successes in answering item (d). Figure 4 shows the display of two probes located 10 cm apart downstream from the anode. The initial pulse is the marker pulse to indicate the time at which the anode is pulsed, and the sharp breaks (positive) indicate the arrival of the accelerated ions. By measuring the difference in time-of-flight one can infer the energy of the ions and extrapolate backwards to infer the time (or position) when they were accelerated.

However, it should be noted that these were detected with a low density ($\leq 5 \times 10^9$ cm^{-3}) background plasma, which necessarily limits the ion current to a small value of $\sim$ 1-2 $^A/cm^2$.

As we attempted to use a higher value of initial plasma density (and thereby increase the ion current density), the pre-formed plasma tended to short-circuit our probes and render the subsequent ion pulse meaningless.

It must be emphasized that this difficulty is one of electronic circuitry - not of the physics of the ion acceleration. It can and will be cured by the simple expedient of pulsing the probes from a low impedance source.

To summarize the progress made so far this year, we have allayed many of the nagging practical questions about this scheme of ion pellet fusion, and at the same time we have become acquainted with the techniques of high power pulsed technology. Based upon these results, we hope to address the more interesting problems of focussing and bunching of the ions.

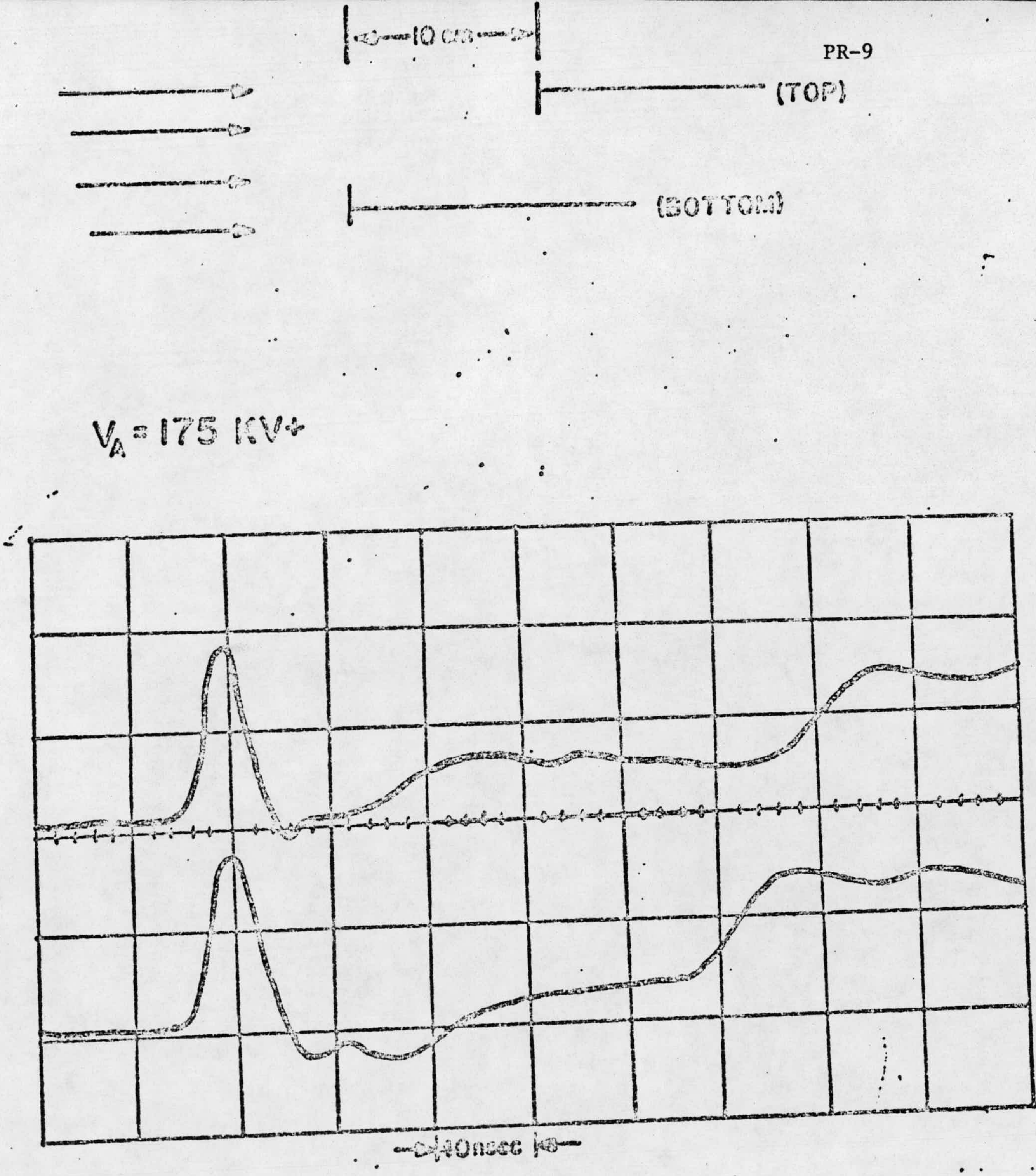


Fig. PR-4. Ion signals measured by two probes.

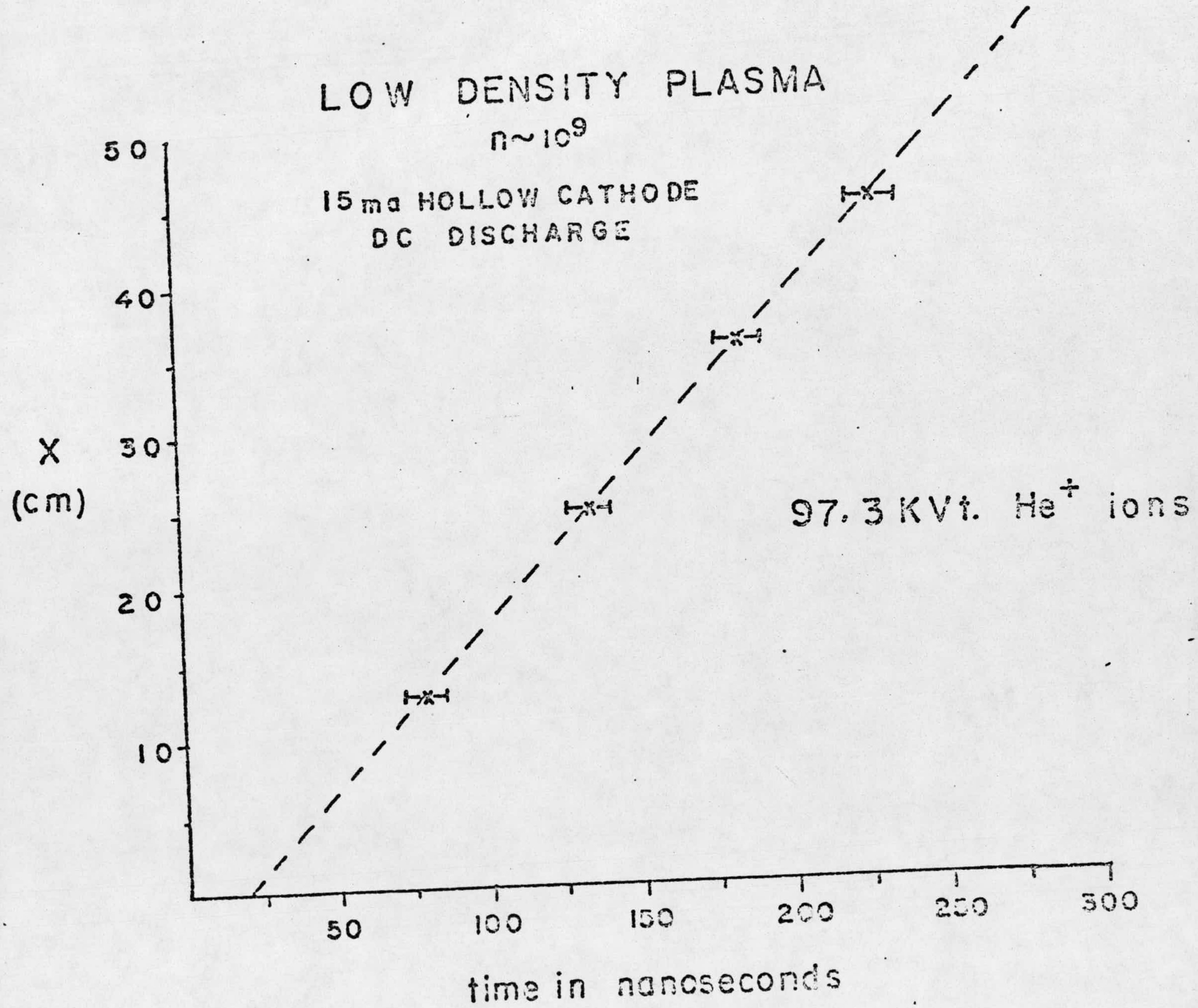


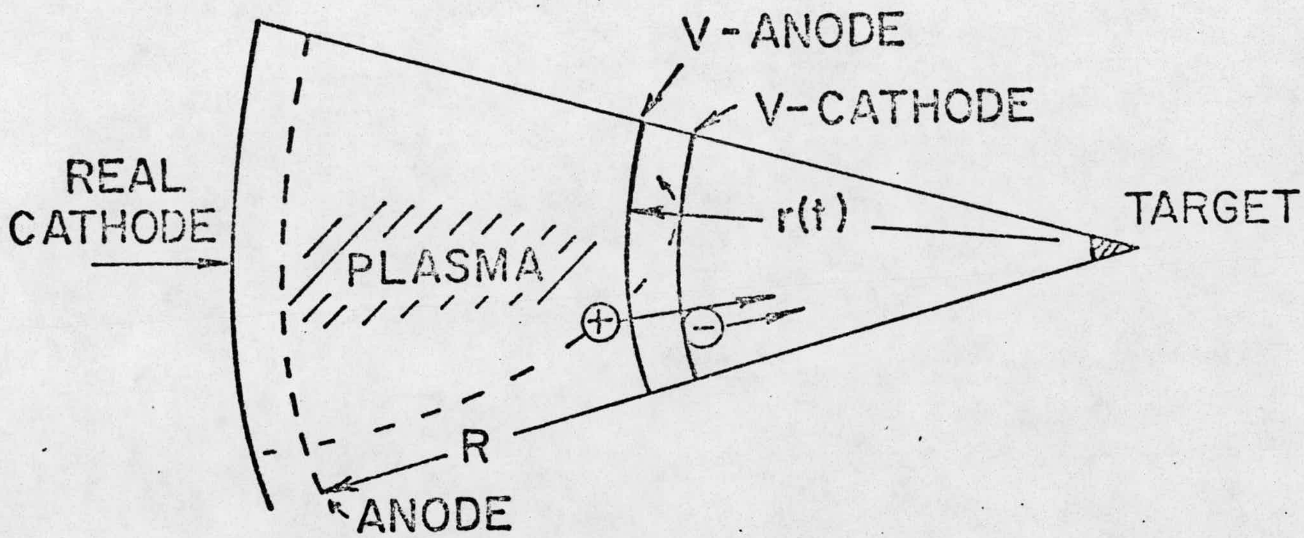
Fig. PR-5. Time of flight data for the accelerated ions.

C. Self-Consistent Transient Analysis of the Beam-Plasma Interaction

In all of the analyses used to date to predict bunching, the potential well was assumed to exist without regard to reaction of the plasma to the injection of the electron beam. Clearly this was a serious defect in the analysis and we have spent considerable effort in correcting this deficiency.

The situation is depicted in Fig. PR-6 where we consider an electron beam injected into a sector of a sphere filled with a pre-formed plasma. It takes little imagination to consider two limiting cases of a low plasma density and a high plasma density. If the plasma density is low, a virtual cathode will form at some radius - roughly that of the anode minus the exterior A-k gap distance. Since the initial ion density is low, little energy is focussed onto the target. At the other extreme of the plasma density high, the injected beam density would be a small perturbation on the background plasma density. Hence, the injected beam would propagate through the diameter of the sphere and the outward motion of the plasma electrons would compensate for the injected charge. Even though there are many ions, they would gain little kinetic energy from the (almost) non-existent space charge well, and little energy would be deposited on the target (located at the center).

Somewhere in between these two extremes lies the optimum case. Due to the natural convergent properties of the injected electron beam, its density can exceed the background plasma density at some point r_o. At radii larger than r_o, the beam density is smaller and the motion of the plasma electrons would tend to



$$\int_{r_0}^{r(t)} N(r) 4\pi r^2 dr = \int_0^t \frac{I_i}{e} dt$$

Fig. PR-6. Model for Theoretical Work.

shield the bulk of the plasma from any appreciable fields. Consequently, one would form a virtual A-k gap on the interior as shown in Fig. PR-7, where we have also allowed for the possibility of a finite rise-time.

Once this virtual gap is formed, it sweeps out the ions in the region r_o to $r_o + D$ accelerating them towards the center. In doing so, the virtual gap moves towards the real anode. Since the virtual gap is moving, the ions crossing it do not gain the full energy associated with the potential well - rather their velocity after passing the virtual cathode is given by:

$$v_a = - v_o + \sqrt{v_o^2 + u_o^2} \qquad (1)$$

where v_o = velocity of the A-k gap toward the real anode.

$$u_o = \sqrt{\frac{2e\, V_a(t)}{M}}.$$

Obviously, if the plasma density is comparatively large, the virtual gap barely moves; if the plasma density is small, the accelerating gap moves quickly towards the real anode. (This effect was seen in our low energy experiment - indeed the experiment was the inspiration for this theory).

Let us now ask the question fundamental to bunching: Can we choose the plasma density to control the motion of the virtual A-k gap to insure that all of the accelerated ions reach the target at r = o at the same time?

The answer is yes!

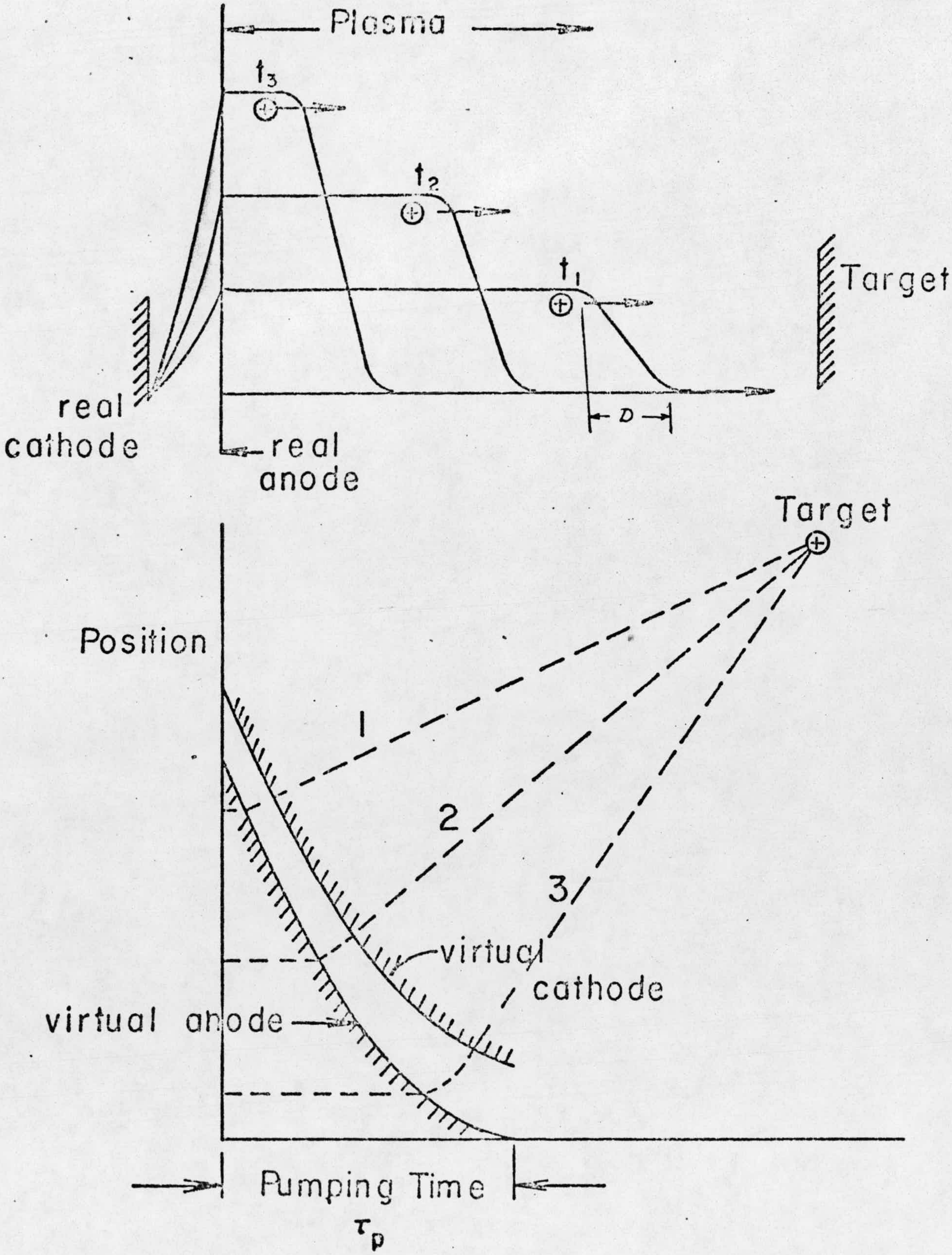


Fig. PR-7. Dynamics of the Virtual A-k Gap.

Furthermore, one can make the system tolerant of a finite rise-time.

Rather than give all of the mathematical details, let us summarize the major results; the details will be contained in a publication being prepared. If one assumes an infinitely fast-rise anode pulse and neglects the time for the ion to cross the virtual gap, then the equation for the motion of the gap to yield perfect bunching is given by:

$$\frac{r(t)}{R} = \{(1 - \frac{t}{T}) \ [(\frac{u_o T}{R})^2 \ (\frac{t}{T})^2 + (\frac{r_o}{R})^2]\}^{1/2} \qquad (2)$$

If one does not neglect the transit time of the ion across the virtual gap, then one must resort to the computer, but the answer is nearly the same. The main difference is that "perfect bunching" is no longer achieved. Furthermore, one can also tolerate a finite rise-time of the injected beam current of the form:

$$I(t) = I_a \ (1 - \exp - \frac{t}{\tau}) = I_a \ (1 - \exp - \frac{1}{a}\frac{t}{\tau_p}) \qquad (3)$$

where $a = \frac{\tau}{\tau_p}$: ratio of rise-time to the pump time.

Figure PR-8 shows that a practical finite rise-time could give a greater power magnification ratio ($\tau_p/\Delta t$) than an infinitely fast current pulse. Here we plot the power magnification ratio, $\tau_p/\Delta t$, as a function of the ratio of the current rise-time to the pump time, for the case where the initial virtual gap starts at 0.75 of the anode radius. The various curves are for different percentages of the total energy carried by the ions. For instance, if the normalized rise-time were 0.1, then 70% of the total energy carried by the ion arrives with $^{1}/560$ of the pump duration.

This theory has progressed to the point where it is in the stage of being prepared for publication.

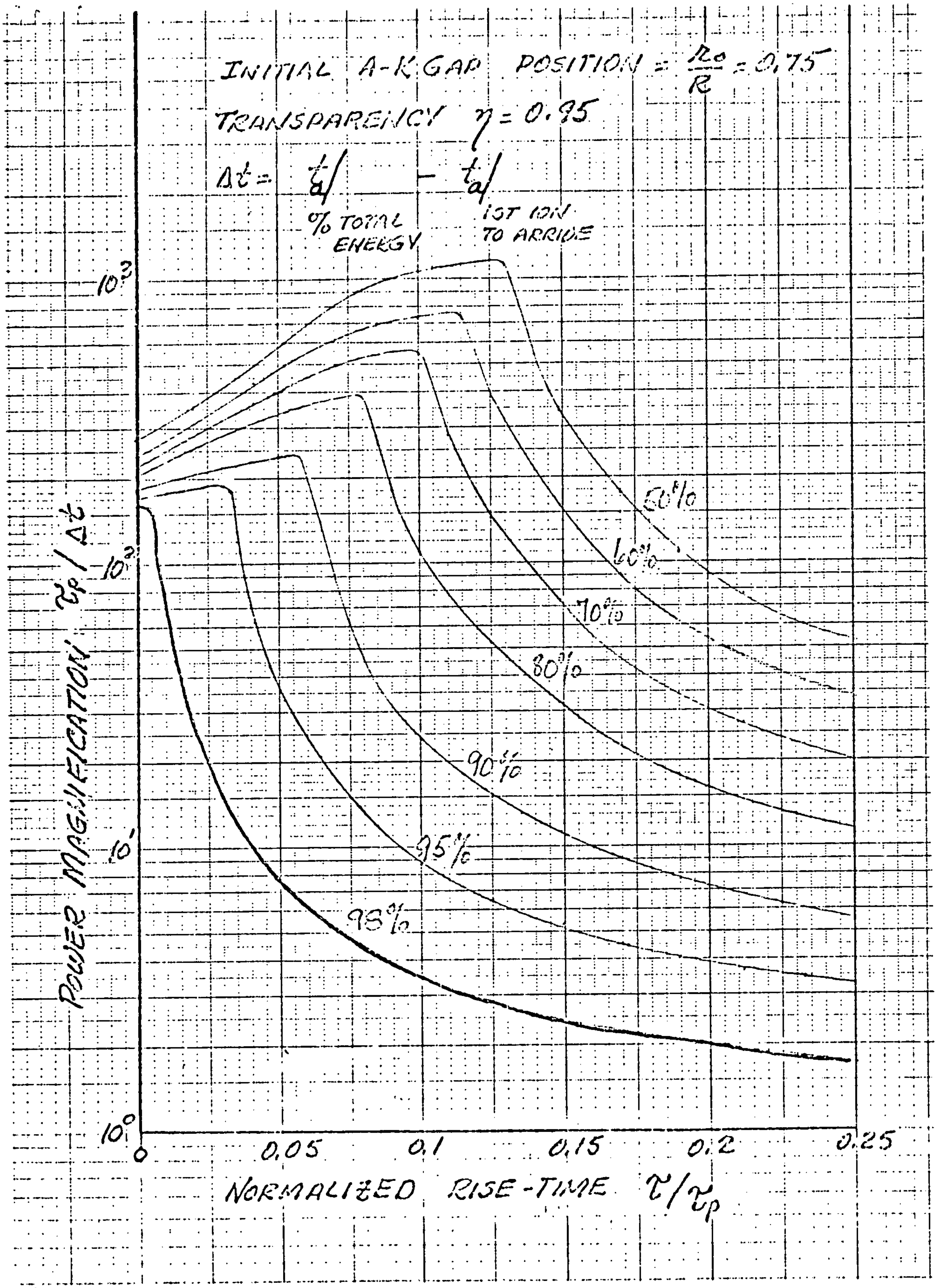


Fig. PR-8. Power magnification as a function of the ratio of rise-time to pump time.