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Hot Ion Buildup and Lifetime in LITE

FINAL REPORT

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ABSTRACT

An experimental investigation of hot ion buildup and lifetime in a small scale mirror device (LITE) is described. Hot ions were produced by 27 kV neutral beam injection into laser produced LiH plasmas and H plasmas produced by a washer gun. Hot H ion (12 kV) densities of $\approx 10^{12}$ cm^{-3} were produced with the LiH target plasmas and densities an order of magnitude lower were produced with the washer gun target plasmas. Hot ion dominant plasmas were not achieved in LITE. The experimental measurements and subsequent analysis using numerical models of the plasma buildup indicate that in small, unshielded mirror plasmas, careful control must be maintained over the transient background gas density in the vicinity of the plasma surface. The hot ion lifetime in LITE was set by the transient cold neutral background resulting from the washer gun or reflux from the target plasma striking the adjacent surfaces.

Hot Ion Buildup and Lifetime in LITE

I. INTRODUCTION

This report describes an experimental investigation of hot ion buildup in a small-scale magnetic mirror device and also examines some of the factors which limit the hot ion lifetime in this device. The experiments were conducted in the United Technologies Research Center LITE facility consisting of a minimum-B magnet coil, a titanium washer gun plasma source, a laser pellet target plasma source and a 27 kV neutral beam line.

Injection buildup to a hot ion dominant plasma was not achieved in the LITE experiments principally because the combined values of beam current density and neutral gas background required for successful sustenance were not attained. The experiments demonstrated that, for injection sustenance in a small scale unshielded mirror plasma, careful control must be maintained over the transient background gas density (charge exchange losses) in the vicinity of the plasma surface. In these experiments the initial neutral background density was sufficiently low so as not to limit the hot ion plasma lifetime.

To aid in the interpretation of experimental results an injection buildup computer model was formulated. This model was tested by application to other experiments and compared to the calculational model used to describe the 2XII experiment. Use of the model provided insight into the nature of the dominant loss mechanism.

The hot ion lifetime is determined by hot ion interactions with either the target plasma or the accompanying cold neutrals from the washer gun source. Simple electron drag does not appear to be the dominant loss mechanism because the observed lifetimes would imply an unreasonably low electron temperature ($\lesssim$ 1 eV) for the warm target plasma. Furthermore, observations of scattered neutrals at energies intermediate to the full and half energy of the neutral beam particles, and the lack of variation with the decay time suggests that electron drag does not limit hot ion buildup, but that the presence of a transient background of neutral gas effectively quenches the hot ion buildup.

This report describes the hot ion buildup and lifetime experiments together with a detailed rationale for the observed rapid hot ion decay. The LITE experimental system, as modified for the present study, is briefly described in Section II. A description of the numerical models, developed for the analysis of the target plasma and hot ion buildup by neutral beams, follows in Section III.

To demonstrate the validity of the models, numerical results are compared with experimental measurements of the decay of a LiH target plasma in LITE and with the decay of a washer gun plasma in the BBII-T experiment at the Lawrence Livermore Laboratory. Comparisons are also made between the LITE buildup code and a rate equation code which was used to model buildup in the 2XII experiment at Livermore. The model calculations are found to agree well with the experiments. Similarly, there is good agreement between the LITE code and the rate equation code.

In Section IV results of the hot ion experiments in LITE are presented. Hot ion buildup data are shown for neutral beam currents ranging from 200 mA to 10 A. Limited hot ion lifetime data are presented due to a failure in the neutral beam system which necessitated premature termination of these measurements.

The principal conclusions drawn from the lifetime data are presented in Section V. Here, evidence supporting the hypothesis that a transient neutral background was responsible for the observed decay is summarized.

II. LITE SYSTEM

The LITE experimental system, shown in Fig. 1, consists of a central vacuum chamber containing the minimum-B magnet coil, a titanium washer gun and a laser pellet irradiation target plasma source, the neutral beam source, and a beam dump tank. Initial evacuation to pressures $\lesssim 5 \times 10^{-8}$ torr are provided by oil diffusion pumps. Prior to experiment runs, titanium getter elements can be flashed to coat the surfaces of liquid nitrogen dewars lining the cylindrical chamber walls to achieve a base pressure of $2\text{-}4 \times 10^{-9}$ torr.

Beam defining apertures are used to remove large divergence components of the neutral beam and to reduce the streaming gas load from the source on the volume of confined plasma. Reflux from the beam dump is reduced by means of an aperture and alignment of the water-cooled titanium dump at an angle of 20^{o} relative to the beam axis.

A. Magnet

The confinement magnet is a spherical, baseball seam coil using liquid nitrogen prechilled copper windings. The minimum-B mirror magnetic field produced has a mirror ratio and well depth of 2, distance between mirror points of 31 cm, and a maximum center field intensity of 15 kG. The effective plasma confinement volume of $\sim$ 400 cm^3 has a diameter of $\sim$ 6 cm in the midplane and a cross-section area normal to the neutral beam of $\sim$ 100 cm^2.

B. Target Plasmas

The confined target plasma for these experiments was produced by laser beam heating of a LiH pellet suspended in vacuum at the magnet center (Ref. 1) or from the streaming plasma from a hydrogenated titanium washer gun (Ref. 2) mounted on the magnetic field axis above the magnet (Fig. 1). To generate the laser plasma target an $\sim$ 100 μm LiH pellet is electrically suspended at the center of the baseball coil and irradiated from two directions by an $\sim$ 40 Joule, 5 nsec Nd^{3+} laser pulse. The expanding plasma is then trapped in the magnetic field. As shown in Fig. 2a, the density of the laser initiated plasma is initially very high remaining above 1×10^{13} cm^{-3} for $\sim$ 100 μsec, and it decays to 1×10^{12} cm^{-3} in approximately 400 microseconds. Measured H^+ ion temperatures are 400 eV, and the electron temperature is $\sim$ 10 eV.

The washer gun is driven by a pulse forming network which, for these experiments, was configured to deliver a current pulse of $\sim$ 1 msec duration. Using a separately triggered ignitron as a crowbar switch, the gun arc current could be terminated at any desired point with a current decay time of $\sim$ 100 μsec. The confined plasma density from the washer gun is shown in Fig. 2b. The density rises to > 1 x 10^{13} cm^{-3} in approximately 200 microseconds and remains at this level for 800 μsec, at which time the gun is shut off and the plasma decays away. This plasma has ion energies of $\sim$ 200 eV and an electron temperature of $\sim$ 10 eV. These two target plasmas produce different background gas densities. Cold gas injected with the washer gun plasma can be of the order of 10 percent of the plasma density. For the laser initiated case there is a wall reflux which is typically $\sim$ 1 percent of the laser plasma density.

Variation in electron temperature during the decay of the laser target plasma was observed by a radiometer calibrated by Thomson scattering measurements at discrete times (densities) during the decay (Ref. 2). The electron temperature is observed to fall initially until the DCLC instability occurs at a density of $\sim$ 3 x 10^{12} cm^{-3}. The electron temperature then rises to a peak and subsequently decreases again for the remainder of the plasma decay. The point at which the electron temperature falls is coincident with large decays of the target plasma as observed on the microwave interferometer.

C. Neutral Beam

The source for the neutral beam is an ORNL 15-cm ion source with a cylindrical gas neutralizer tube (Ref. 3). The ion source extraction grids were designed to focus the beam onto the target plasma. Using a 50-cm long neutralizer, measurements showed that a 10-amp equivalent neutral current of one-half and one-third energy components of a 27-kV beam were focused onto a 100-cm^2 target area at a distance of 230 cm from the source.

A two-inch aperture was placed at a distance of 178 cm from the source to reduce the gas load on the plasma from the neutral beam. This aperture has the effect of sharply reducing the neutral current density beyond a 3-cm radius at the plasma location without affecting the central current density and leads to a calculated 8.6 A of neutral current within a 6-cm diameter at the plasma corresponding to a current density of 0.305 A/cm^2.

D. Diagnostics

The primary measurements of interest in the interaction of an energetic neutral injection beam with a confined high density target plasma are the time variation of the confined plasma density, the fraction of the neutral beam that interacts with the confined plasma, and the buildup rate and density of hot ions trapped in the mirror field.

A 4-mm microwave interferometer provides a measure of the electron density decay of the confined plasma for $n_e \lesssim 2 \times 10^{13}$ cm^{-3}. A secondary emission detector (SED) located at the end of the beam dump tank 300 cm from the plasma (530 cm from the ion source) is used to measure the attenuation of the neutral beam in the presence of the confined plasma and, thereby, provide a measure of the fraction of the beam trapped by the plasma.

The hot ion density is inferred from observations of the high energy neutrals escaping from the plasma as a result of charge exchange losses of trapped hot ions. A silicon barrier detector (SiD) of 8-mm diameter aperture located at 1.5 m from the plasma center observes the escaping neutrals directly and provides a measure of the total number of fast ions in the plasma. In addition, a fast atom detector (FAD) provides a measure of the hot ion energy. A small fraction of the escaping neutrals are reionized in a nitrogen gas stripping cell and are energy analyzed in a 90-degree, three-channel electrostatic analyzer with the three detector channels generally set centered on the full, one-half, and one-third energy components of the neutral beam. The energy analyzer uses channel electron multipliers as the detectors.

To interpret the measurements in terms of absolute measurements of hot ion population, both the SiD and the fast atom energy analyzer are calibrated by injecting the neutral beam onto a nitrogen gas target in the magnetic field and relating the observed signal to the calculated rate of production and loss of hot ions on the known density of nitrogen in the target volume viewed by the detectors.

III. COMPUTER MODELS OF TARGET PLASMAS AND HOT ION BUILDUP IN LITE

The computational methods used in the analysis of the target plasmas and plasma buildup by neutral beams in LITE were based on Fokker-Planck models of the kinetic theory of mirror-confined plasmas. Numerical solutions of the plasma Fokker-Planck equations yielded the velocity distributions of the electrons and plasma ions with sufficient accuracy for calculating classical mirror losses, charge exchange losses, charge exchange and ionization of the neutral beam and the growth and saturation of unstable waves driven by the loss cone distributions of the mirror-confined ions. Adaptations of two Livermore Fokker-Planck codes were used for this purpose: HYBRID-II, (Ref. 4) a two dimensional (v, θ) code and ISOTIONS (Ref. 5) a one-dimensional (v) code for which the angular distribution of ions is approximated by the lowest normal mode within the loss cone boundary. Extensive studies of the mirror-confined, laser-produced target decay were carried out with the modified HYBRID-II code for investigations of the effects of electron temperature and the enhanced scattering by the fluctuation levels of the convective loss cone instability (Ref. 6) and the drift cyclotron instability (Ref. 7). Calculations of the buildup of hot ion density by injection of a beam of energetic neutrals into the laser-produced target and washer gun target plasmas were made with the ISOTIONS code, modified to include self-consistent wall reflux and plasma losses by charge exchange with the neutrals of the vacuum background.

A. Decay of the Laser-Produced Target Plasma

The HYBRID-II code, developed at Livermore for the calculation of collisional relaxation of the two dimensional (v, θ) velocity distributions of ions in a multispecies plasma, was used, with modifications, for the analysis of the time behavior of mirror-confined, laser-produced LiH plasmas. The mirror losses are calculated by solving a coupled set of Fokker-Planck equations stepwise in time, subject to the boundary condition that the ion distribution functions vanish on a boundary defined by the loss cone angle and the plasma ambipolar potential. The ambipolar potential arises because of the large difference in the electron and ion masses and, hence, in their rates of scattering into the mirror loss cones. Electrons with energies less than $e\varphi$ are electrostatically trapped and are nearly isotropic and Maxwellian. Hence the electron velocity distribution is treated as a function of v alone and the electron loss rate depends, essentially, on the rate at which their energies are raised above the value $e\varphi$

Good agreement was found between HYBRID-II results and the observed decay of the laser-produced LiH plasmas between 100 and 200 μsec after firing the laser in the high-field ($B \geq 10^4$ G) experiments, for the following initial conditions:

Electrons,	$n_e(0)$	$= 10^{14}$ cm^{-3}	$T(0)$ =	17 eV
Protons,	$n_H(0)$	$= 2.5 \times 10^{13}$ cm^{-3}	$E_H(0)$ =	255 eV
Li^{3+},	$n_{Li}(0)$	$= 2.5 \times 10^{13}$ cm^{-3}	$E_{Li}(0)$ =	1785 eV

and by clamping the electron temperature at its initial value during the plasma decay. The assumed initial electron density is consistent with the cutoff microwave interferometer signal at early times. The ratio of H^+ and Li^{3+} energies 1:7 is consistent with particle energies observed in free plasma expansion, and the assumed value of electron temperature is of the order of the temperatures measured (10 to 15 eV) by Thomson scattering. The fact that the observed plasma decay could be fit with a t^{-1} time-dependent curve between 100 and 200 μsec implied that energies of the electrons and ions should be constant during this time and motivated the clamping of the electron temperature in the calculation. It is also noteworthy that when the calculation is repeated with Li^+ or Li^{2+} substituted for Li^{3+}, all other initial conditions being the same, the calculated density decay was much slower than the observed plasma decay. It would have been necessary to reduce the assumed value of the electron temperature below 1 eV, far below the values measured by Thomson scattering in order to obtain agreement with experiment.

Thus, two-dimension Fokker-Planck calculations for a mirror-confined H^+-Li^{3+} plasma with an electron temperature near the observed values yielded $n\tau$ values in agreement with the high magnetic field experiments for decay times up to 200-250 μsec. The laser target plasma characteristically emitted bursts of rf at the lithium ion cyclotron frequencies starting at 200 to 250 μsec, at which times the plasma decay was accelerated. To study the laser target plasma behavior beyond that time it was necessary to add enhanced diffusion terms to the HYBRID-II code to model the effects of the fluctuation levels of the convective loss cone and the drift cyclotron loss cone instabilities on the ion loss rates. It was found the convective loss cone mode fluctuation level (Baldwin-Callen effect) had an entirely negligible effect on the calculated ion loss rate. The quasi-linear growth rate of the DCLC mode, on the other hand, was calculated to be so rapid as to prevent the kind of classical decay of the laser target observed between 100 and 200 μsec. Hence, it was suggested that the ionization or charge exchange of the reflux of cold neutrals from the magnet walls might provide enough cold plasma to stabilize the DCLC mode. The luminosity of the central region of the plasma is most intense between 100 and 250 μsec. On the assumption that the optical radiation is emitted when cold neutrals from the magnet walls cross into the plasma region, the quasilinear calculations were repeated with a cold plasma source term having the observed time dependence of the central plasma luminosity. In this case the cold plasma component, $\leq$ 5 percent of the target plasma density, effectively suppressed the wave buildup between 100 μsec and 250 μsec and the calculated results were again in agreement with the observed decay in that time interval. Furthermore, as the cold plasma source strength diminished and the cold ion density decayed, quasilinear growth of the DCLC mode measured between 200 and 250 μsec, resulting in an acceleration of the calculated ion loss rate after 250 μsec as observed in the target plasma experiments.

Since the cold-ion-stabilized target plasma decay is essentially classical with constant electron temperature the two dimensional HYBRID-II results were duplicated with the classical model of the one-dimensional ISOTIONS Fokker-Planck code. On the assumption that the DCLC mode would be stabilized by a cold plasma stream, the simpler ISOTIONS code was used for the buildup calculations.

B. Buildup of Hot Plasma with a Neutral Beam

a. Buildup Model

ISOTIONS, a one-dimensional multispecies Fokker-Planck code developed at Livermore was adapted for the buildup calculations. Iteration subroutines were modified to eliminate negative values of the distribution functions; source terms representing injection of energetic neutral beams were altered to allow for possible attenuation by the target plasma; a subroutine was added to model the buildup and pumping of neutrals in the vacuum background and plasma losses by charge exchange with those and with the cold neutrals streaming down the beam line; and subroutines were added to facilitate the conversion of energy-dependent cross sections to distribution- and source-averaged rate coefficients. After these modifications, the code was renamed LITE to distinguish it from the original ISOTIONS code.

For the purpose of calculating the buildup of neutral densities in the vacuum surrounding the plasma, the vacuum chamber was considered to consist of two vacuum regions partitioned by the baseball magnet coil. To approximate the impedance of the baseball coil to particle flow between them, the interface between the two regions was taken as half the area of a sphere with a 16-cm radius. In the outer region the vacuum background neutrals are cold H_2 molecules which, because of the large volume of the region, were assumed to have constant density. In the inner region, adjacent to the plasma, the vacuum background consists of fast and Franck-Condon atoms (H) and slow neutral molecules (H_2). The fast neutrals and Franck-Condons are pumped only by ionization or charge exchange in the plasma or by adsorption at the magnet surfaces. The sources of fast neutrals are charge exchange of plasma ions with fast neutral beam atoms, cold neutrals streaming from the source and with vacuum background neutrals. Franck-Condon neutrals are produced by a mode of ionization of H_2 that leaves the H_2^+ in an excited repulsive state which dissociates into an ion and a Franck-Condon neutral with about 10 eV energy. Since these neutrals are more penetrating than cold H_2 in dense plasmas, it was assumed, conservatively, that all H_2^+ production leads to Franck-Condon neutrals. Cold background neutrals are produced by collisions of fast neutrals and Franck-Condons with the magnet coils. They are pumped by streaming between magnet coils to the outer vacuum region, by adsorption on gettered surfaces and by ionization or charge exchange in the plasma.

The actual spatial distributions of the neutral densities in the plasma volume may be slowing varying, as for the fast neutrals which have relatively large reaction mean free paths in the plasma, or rapidly attenuated, as in the case of cold neutrals which have small charge exchange mean free paths in the denser plasmas. In either case, spatial average densities of the neutrals in the plasma volume were used to calculate the plasma charge exchange loss rates. The type of spatial average that yields the correct reaction rate is related to the corresponding neutral density in the vacuum region adjacent to the plasma through the particle escape probability, a function of the mean free path of the particle and the mean chord length of the plasma. The mean chord length is, in turn, a function of the plasma size.

Plasma volume changes occur as the result of competing effects of erosion by charge exchange with cold neutrals near the plasma surface and buildup by ionization of the neutral beam near the surface. In this calculation, the plasma was assumed to be axisymmetric and only the plasma radius was allowed to vary. The plasma buildup rate is the total rate of ionization of the neutral beam in an annulus one ion gyroradius in thickness at the plasma surface. The rate of erosion of the plasma is the total flux of cold neutrals incident on the plasma surface times the ratio of the charge exchange cross section to the sum of the charge exchange and ionization cross sections. The minimum allowable plasma radius is two ion gyroradii and, if the plasma radius is reduced to this value, the erosion term is set equal to zero.

The neutral beam contains a small fraction, about 1 percent, of cold neutrals that stream down the beam line from the ion source and neutralizer directly into the plasma. Since they are mostly H_2 molecules with thermal speeds, their contributions to the plasma density losses and plasma volume erosion are accounted for by adding the flux of streaming neutrals to the flux of cold background neutrals at the plasma surface.

The processes involved in the interaction between the neutrals and the plasma are ionization of the neutrals by ion and electron collisions, charge exchange between plasma ions and Franck-Condon and fast atoms and charge exchange between plasma ions and cold H_2. The cross sections used for calculations of the rate coefficients are the standard ones for hydrogen. Cross sections for the corresponding reactions involving lithium ions, being unavailable, are roughly approximated by assuming Li^{3+} values to be of the same order as the H^+ cross sections and those of the lower charge states Li^{2+}, Li^+ to be much smaller. The rate coefficients are obtained as averages over the calculated plasma ion and electron velocity distributions. In the interaction of the plasma with the energetic neutral beams, charge exchange with the plasma ions and ionization by collisions with ions and electrons are the important reaction processes. The energy distribution of the beam neutrals consists of any number of delta functions at specified energies, usually three, at the full energy, half energy and one third energy of the beam. The rate coefficient for electron collision ionization was an average over the plasma electron velocity distributions. Rate coefficients for the other reactions were evaluated at the velocity of the beam component involved.

Three options for the time dependence of electron temperature are available: classical Fokker-Planck, constant temperature at a specified value, or a time-dependence which accounts for the energy drain by the stream of cold ions required for stabilizing the DCLC mode. Options for target plasma density time-dependence are classical Fokker-Planck or a specified time-dependent density corresponding to the observed washer-gun target density.

b. Comparisons with Livermore Results

Test problems were run to compare the predictions of the LITE code with calculated results of a Livermore buildup code (Ref. 8) developed by B. Stallard and with experimental results of the buildup experiment in Baseball II-T (Ref. 9). Unlike LITE, Stallard's code is not a Fokker-Planck code but solves rate equations for the plasma buildup using estimated $n\tau$ and reaction rate coefficients. Since it has been used extensively for studies of buildup of 2XII, there exits a high confidence level for its predictions. With both codes, buildup by neutral injection into a pure hydrogen target plasma with a time-dependent density typical of the LITE laser-produced plasmas was calculated for a beam current of 10 amperes, 38 percent at 15 keV and 62 percent at 7.5 keV. The cold neutral fraction streaming down the beam line was taken to be .002 and the initial cold neutral density surrounding the plasma was $n_o = 10^9\ cm^{-3}$. Other parameters were assigned values that are characteristic of the LITE experiment. Both calculations predicted buildup of the plasma to a steady state. The steady state conditions predicted by the two codes are listed in Table I for comparison.

TABLE I

	LITE Code	LLL Code	
Density	6.91×10^{12}	2.56×10^{12}	cm^{-3}
Ion Energy	5.77	7.07	keV
Electron Energy	67.8	40.3	eV
Radius	4.1	3.7	cm
Volume	530	505	cm^{-3}
$n\tau$	6.2×10^{10}	(Est. 1.6×10^{10})	cm^{-3} - sec
τ_{ex}	1.2×10^{-2}	1.3×10^{-2}	sec

The results are in best agreement for those parameters that depend mainly on the plasma reaction rates with background neutrals, plasma radius, volume and charge exchange lifetime. This agreement is not surprising since the Livermore code was designed to treat those processes in detail. The plasma density and energies calculated by the Fokker-Planck methods of the LITE code may be more reliable since they do not require an estimate of $n\tau$ and energy exchange between ions and electrons is explicitly calculated.

A calculation was also made with the LITE code of the washer-gun target neutral injection experiment which had been performed at Livermore on Baseball II-T (Ref. 9). For this calculation, the vacuum parameters of Baseball II-T were used. The washer-gun target was assigned a density of 3×10^{13} cm^{-3}, as in the experiment. The initial ion energy was 250 eV (experimental $\sim$ 280 eV) and the electron energy was held constant at 30 eV. The neutral beam current was 33 amperes, 26 percent 17 keV, 53 percent 8.5 keV and 21 percent 5.7 keV for an average energy of 10 keV, as in the experiment. The cold neutral fraction streaming down the beam line was assumed to be 2 percent and the initial value of background neutral density was $n_o = 10^{10}$ cm^{-3}. For a target density of 3×10^{13} cm^{-3} a peak value of hot ion density observed in the experiment was $3(\pm 1) \times 10^{12}$ cm^{-3}. The hot ion density predicted by the LITE code was 7.7 $\times 10^{12}$ cm^{-3} about a factor-of-two larger. The calculated attenuation of the neutral beam by the target plasma is in much better agreement with experiment: The calculated reduction of the beam current was 11 percent compared with the measured value of 12 percent. These results are consistent with the difference in plasma diameters: $\sim$ 13 cm in the experiment versus 6 cm calculated.

While it has not been possible to pinpoint sources of disagreement, these comparisons provide a rough gauge of the confidence with which we view the predictions of the LITE code. Generally, such calculations predict trends in parameter values with changes in input more successfully than they predict the values themselves, although the calculations seem dependable for factor-of-two accuracy.

c. Sustenance Requirements for the LITE Experiment

Survey calculations were performed with the LITE code to determine the combinations of experiment parameters required to sustain a $\sim$ 10-keV plasma by injection of an energetic neutral beam into a laser produced LiH target plasma. The condition of sustenance was defined as one in which the trapped hot ion density is higher than 10^{12} cm^{-3} for 100 msec or longer. The critical parameters for achieving this condition are (1) neutral beam current density, (2) ambient density of cold neutrals, (3) current of cold neutrals in the beam, and (4) electron energy. In this study, the effects of the ambient neutrals and the cold neutrals in the beam could be combined by noting that, for the neutral beam current density chosen, 120 mA/cm^2, a 1 percent fraction of cold neutrals in the beam produces the same charge exchange plasma loss as a background neutral density of 5 x 10^{10} cm^{-3}. The current density of 120 mA/cm^2 was the design goal of the nominal 10 ampere neutral beam. (Actual performance in later experiments was almost a factor of three better than that.) The three energy components of the neutral beam were 26 percent 27 keV, 53 percent 13.5 keV, and 21 percent 9 keV. Since the adiabatic energy limit of the LITE magnetic field is less than 27 keV and it was thought that such ions would be lost soon after trapping, the 27 keV group was not assumed to be trapped. Hot ions at 13.5 keV and 9 keV were trapped by charge exchange with Li^{3+} and H^+ and ionization of the neutral beam in collisions with Li^{3+}, H^+ and electrons. The electron temperatures were calculated with the LITE code option that accounts for the energy drain caused by an external stream of cold ions required for stabilizing the DCLC mode. Figure 3 summarizes the results of these survey calculations by displaying the initial ambient neutral density required for a given initial electron energy to sustain the hot ion plasma density above 10^{12} cm^{-3} for three time durations: 1.0, 10. and 100 msec.

The sustenance condition corresponds to the region under the 100 millisecond curve in Fig. 3. Thus, at the design value of the injected current density, the initial value of the electron energy must be at least 40 eV and the combined densities of the ambient neutrals and cold neutrals streaming down the beam line must not exceed 8 x 10^{10} cm^{-3}. The point labeled LITE in Fig. 3 is included for reference to the initial conditions of the laser produced LiH target plasma (10-eV electron temperature (15-eV energy), 10^{10} cm^{-3} ambient neutral density plus 2 percent neutral streaming from the beam line).

IV. EXPERIMENTAL RESULTS

The results of hot ion buildup experiments with washer gun and laser plasma targets are summarized in Tables II and III. With the laser plasma target, attenuation measurements which allow the most direct interpretation resulted in average hot ion densities of 1.35 x 10^{12} cm^{-3}. The silicon detector results on the same plasmas averaged 0.96 x 10^{12} cm^{-3} and 0.82 x 10^{12} cm^{-3}, the first number analyzed in the gas calibration model, and the latter analyzed through considerations of the absolute gain of the detector. Both agree moderately well with the attenuation measurements. The results from the FAD measurements ranged from less than, to greater than, those obtained from the other diagnostics. This appears to be due to the highly nonlinear response of the channel electron multipliers at high count rates and the results from this diagnostic are not considered quantitative. The experiments on injection onto the washer gun target plasma resulted in hot ion densities a factor of 10-20 below those of the laser produced target plasma. Attenuation of the neutral beam was not observed in the washer gun tests, consistent with the lower densities observed by other diagnostics. For neither target was a hot ion dominant plasma ($n_{hot} > n_{target}$) achieved. Analysis of the target plasma evolution and of the hot ion buildup, are discussed in the following paragraphs.

A. Hot Ion Buildup in LITE

a. 200 mA Injection

Data are shown in Fig. 4 for the density of 12-keV ions measured during the injection of a 12-keV neutral H beam into a 5-cm diameter laser-produced LiH target. The aperture area of the beam was $\sim$ 40 cm^2 and its equivalent current density was 5 mA/cm^2, corresponding to the total current of 200 mA. The peak value of the density occurs at 50 μsec. Its value, 4 x 10^9 cm^{-3}, was obtained from the charge exchange rate n/τ_{cx}, determined from the calibrated fast atom detector signal, and the charge exchange lifetime, τ_{cx} = 20 μsec, corresponding to the ambient background neutral density n_o = 3.8 x 10^{11} cm^{-3} of the experiment. Also shown as the solid curves in Fig. 4 are results of LITE code calculations of the hot ion density for 200 mA, 5 mA/cm^2, injection of 10-keV H atoms into a laser produced LiH target plasma with initial conditions:

$$n_e(0) = 10^{14}\ cm^{-3} \qquad T_e(0) = 17\ eV$$

$$n_H(0) = 2.5 \times 10^{13}\ cm^{-3} \qquad E_H(0) = 254\ eV$$

$$n_{Li}(0) = 2.5 \times 10^{13}\ cm^{-3} \qquad E_{Li}(0) = 1770\ ev$$

The electron temperature was clamped at its initial value, since that was the option which successfully reproduced the observed target plasma decay for the

TABLE II

HOT ION DENSITIES-WASHER GUN TARGET

SHOT NO.	FAD	SiD	SiD (Gas Calibration)	ATTENUATION $n\sigma\ell$
WG 6	7.5×10^{10}			
WG 7	4.2×10^{10}			
WG 8	3.5×10^{10}			
WG 9	3.3×10^{10}			
WG 17		1.3×10^{11}	1.3×10^{11}	
WG 19		1.3×10^{11}	1.3×10^{11}	
WG 20		1.3×10^{11}	1.3×10^{11}	

TABLE III

HOT ION DENSITIES-LASER PLASMA TARGET

SHOT NO.	FAD	SiD	SiD (Gas Calibration)	ATTENUATION $n\sigma\ell$
3450	$>4.6 \times 10^{11}$			2.2×10^{12}
3451	$>9.0 \times 10^{11}$	$>1.2 \times 10^{12}$	$>1.4 \times 10^{12}$	1.2×10^{12}
3452	$>3.9 \times 10^{11}$	3.7×10^{11}	4.3×10^{11}	5.9×10^{11}
3453	$>1.4 \times 10^{12}$	7.6×10^{11}	8.9×10^{11}	1.8×10^{12}
3454	$>7.6 \times 10^{13}$	6.6×10^{11}	7.7×10^{11}	1.1×10^{12}
3455	1.4×10^{14}	1.1×10^{12}	1.3×10^{12}	1.2×10^{12}

first 200 μsec. Trapping of the hot ions was assumed to occur through charge exchange of the neutral beam with the target H^+ and ionization by collision with H^+ and electrons. Since the target plasma diameter of 4 cm gives a radius only twice the gyroradius of 10-keV ions, the hot ions were assumed to be unshielded from charge exchange with ambient cold neutrals. The three calculated curves are labelled with the corresponding initial values of background neutral density: 10^{11}, 4×10^{11} and 10^{12} cm^{-3}. Of the three, the $n_o = 4 \times 10^{11}$ cm^{-3} curve has its maximum closest to 50 μsec and its slope at later times corresponds to the observed decay time $\tau_{cx} = 20$ μsec. The factor of 3 difference between the measured and calculated densities was attributed to the neglect of the trapping effectiveness of the target plasma Li^{3+} ions. In subsequent buildup calculations, this effect was included.

b. 1.0 Ampere Injection

Before upgrading of the performance of the ORNL 15-cm source had been completed, some data from injection at a nominal 1 ampere of neutral current was obtained. In these experiments the maximum energy was 14.3 keV, and the current density at the target was 12 mA/cm^2. The data points shown in Fig. 5 represent the measured density of trapped ions due to injection into the laser-produced LiH target plasma. Values of the parameters used in the buildup calculations closely approximate the conditions of the experiment. The energies of the three components of the neutral beam were 14.3, 7.1, and 4.4 keV, representing 26.6 percent, 52.5 percent and 20.9 percent of the 12-mA/cm^2 current density at the target plasma. Another fraction, 0.02 of the total current, consisting of cold neutrals streaming from the source and neutralizer was incident on the target plasma. But their flux into the plasma was small compared with that of the ambient cold neutrals at their density of 7×10^{11} cm^{-3}. Hot ions were again assumed to be unshielded from charge exchange with cold neutrals because the plasma radius and hot ion gyroradius were comparable in size. Trapping of the hot ions occurred by charge exchange and ionization of the neutral beam with Li^{3+} and H^+ and ionization by electrons. The electron temperature was clamped at 10 eV, since that was the value obtained from Thomson scattering temperature measurements on the target plasma electrons. The calculated maximum of the hot ion density, 5×10^{10} cm^{-3} is in fairly good agreement with the measured value. This improvement was attributed to the inclusion of the trapping effects of Li^{3+}.

c. 10 Ampere Injection

In the case of the actual 10-ampere injection experiments the current density was 305 mA/cm^2, of which 21.3 percent was at 27 keV, 55.2 percent at 13.5 keV and 23.5 percent at 9 keV. All three energy components were assumed to be trapped either by charge exchange with Li^{3+} and H^+ or by ionization in collisions with Li^{3+}, H^+ and electrons. The fast atom energy analyzer data provided the experimental evidence for the trapping of the 27-keV component. The electron temperature was clamped at 10 eV. In the experiments, there was also an observable attenuation of the beam by the target plasma averaging 18 percent over the first 35 μsec. The charge exchange component of the hot ion trapping source terms in the Fokker-Planck equations were adjusted to give the same calculated beam attenuation in the first 35 μsec. Cold neutrals streaming from the source and neutralizer had a current density of 3 mA/cm^2 (1 percent streaming) at the target plasma. The flux of these cold neutrals was not negligible compared with the flux of the ambient neutrals, as was the case for the 1-ampere injection experiment, but exceeded the background neutral flux. The trapped hot ions were assumed to be unshielded for both background neutrals and streaming neutrals. The time-dependent hot ion densities calculated for assumed initial values of the ambient cold neutral density of 10^{10} and 10^{11} cm^{-3} are shown in Fig. 6. The dashed curve, representing the case of 0.5 percent streaming shows that it would be necessary to reduce the streaming fraction to this value in order to build up a hot ion density exceeding the target plasma density. It also illustrates the point that the cold neutrals streaming down the beam line can cause more charge exchange losses than the ambient neutrals. In the 10^{10} cm^{-3}, 1 percent streaming case, the maximum value of the cold neutral density transient was 6 x 10^{10} cm^{-3}. Hence the 10^{11} curve provides a bound on the possible effect of the ambient neutrals on charge exchange losses in this set of calculations. The cause of the poor agreement of this curve with the measured decay of the hot ion density, also shown in Fig. 6, is uncertain. It might be attributed to a streaming fraction several times larger than the assumed value of 1 percent.

Tests were also carried out using the washer gun target plasma. Buildup to 1-2 x 10^{11} cm^{-3} peak density, with loss times of 20 μsec were achieved. The presence of the washer gun source itself significantly increased the background vacuum conditions from that of the laser plasma target, and lead to the reduced loss time. The washer gun injection tests were performed without the neutral beam aperture which was present in the laser target measurements. The lack of the aperture significantly degrades the vacuum environment, and the experimental data on washer gun injection are not presented. Using the LITE code, which agreed well with the laser target experimental data where the aperture was employed, calculations were run to predict buildup with the washer gun target. These results are presented in Fig. 7. As with the laser plasma target, by improving the vacuum conditions the hot ion dominant regime can be reached as shown in Fig. 7. The calculated washer gun target density and the hot ion density are shown for various values of the background gas density. All the calculations are for a 1-percent cold stream, as in Fig. 6 for the laser plasma target. The calculations indicate that for a background gas density of 8 x 10^{11} cm^{-3} (the density present during the experimental tests) the hot ion dominant regime could not be achieved. For a background gas density of 2 x 10^{11} cm^{-3} the hot ion density can exceed the target plasma density after ∿ 0.6 msec in the decay; this background density represents a less severe restriction than required for the laser target plasma due to the longer duration of the washer gun plasma.

B. Hot Ion Lifetime

Experiments to study the decay of the hot ion component of the plasma produced by neutral beam injection into a washer gun target plasma were undertaken to determine the factors limiting the lifetime of the hot ions. A simple rate equation model of the injection beam/target plasma interaction is described and the experimental results are compared to the predicted behavior.

a. Rate Equation Model

The hot ion plasma density produced by injection of an energetic neutral beam onto a mirror confined warm target plasma is given by

$$\frac{dn_H}{dt} = n_w J \sigma_{cx} - \frac{n_H}{\tau} \tag{1}$$

where n_w = warm target plasma density

J = neutral beam injection current density

σ_{cx} = beam charge exchange cross-section on target plasma

τ = hot ion loss time

It is assumed that ionization of the beam on the confined hot ions can be neglected. Since $\sigma_i << \sigma_{cx}$ ionization on the warm target ions will always be small compared with $n_w J \sigma_{cx}$. For injection conditions such that $n_H << n_w$, with a square pulse injection beam

$$J = \begin{cases} 0 & t < t_0 \\ J & t_0 \leq t \leq T \\ 0 & T < t \end{cases} \tag{2}$$

incident on a steady state (externally maintained) target, the hot ion density has the form

$$n_H = n_w J \sigma_{cx} \tau \left[1 - e^{-(t-t_0)/\tau}\right] \quad t_0 \leq t \leq T$$

$$= n_w J \sigma_{cx} \tau e^{\frac{-(t-T)}{\tau}} \quad T < t \tag{3}$$

The hot ion density is observed using an energy discriminating neutral particle detector to measure the fast atom flux from the plasma. For injection current and vacuum background conditions such that charge exchange scattering by the energetic beam is much greater than that due to the low energy neutrals, i.e.,

$$n_w J \sigma_{cx} V \gg \frac{n_o V}{4} S \tag{4}$$

where V = target plasma volume

n_o = cold neutral background density

v = cold neutral velocity

S = target plasma surface area

then the fast neutral flux to the detector is proportional to

$$F \propto n_H J \sigma_{cx}$$

and the fast neutral detector signal has the form

$$S_F \propto n_w (J \sigma_{cx})^2 \tau \left[1 - e^{-(t-t_0)/\tau} \right] \qquad t_0 \leq t \leq T \tag{5}$$

Equation 5 for the fast neutral detector signal is plotted in Fig. 8 along with the target plasma density, the injection beam current pulse (Eq. 2), and the confined hot ion buildup density (Eq. 3). Measurement of the risetime of the fast neutral signal provides a direct measure of the hot ion lifetime and from Eq. 1 can be used to determine the equilibrium hot ion buildup density

$$n_H = n_w J \sigma_{cx} \tau ; \qquad \frac{dn_H}{dt} = 0 \tag{6}$$

b. Lifetime Measurements

Typical data from the experiments is shown in Fig. 9. The injection current, measured with a 1-in. dia calorimeter target located at the target plasma position, was 40 mA/cm^2, and, for the shot shown in Fig. 9, the background gas density was 3 x 10^{-8} torr. From the microwave interferometer measurements, the equilibrium target plasma density established by the washer gun plasma source was 10^{13} cm^{-3}, and the charge exchange scattering by the beam

$$n_w J \sigma_{cx} V = 1.6 \times 10^{17} \text{ sec}^{-1}$$

compared with the cold neutral scattering

$$\frac{n_o V}{4} S = 1.8 \times 10^{15} \text{ sec}^{-1}$$

meets the conditions for beam dominated scattering of Eq. 4. Even considering the effect of the ∿ 1 percent cold neutrals accompanying the energetic beam, the cold neutral charge exchange

$$J_0 A = 4.7 \times 10^{16} \text{ sec}^{-1}$$

is less than that due to the energetic beam neutrals.

From the microwave transmission measurements the target plasma density reaches its equilibrium value at ∿ 400 μsec. At earlier times the calculated electron density is displayed at larger values but it is clear from the transmission data that this is an artifact and is the result of the inability of the interferometer to accurately track the phase shift at high attenuations as the electron density is evaluated working backwards in time from the asymptotic value in the plasma decay. At 400 μsec the accel voltage of the injection source is pulsed on. Secondary emission detector measurements show that the injection current rises rapidly in ∿ 6 μsec to a value which remains nearly constant throughout the pulse and when turned off at 750 μsec decreases to zero in ∿ 10 μsec. The washer gun target plasma source is turned off using the same timing pulse as the injection beam termination; however, from the microwave data the target plasma decays on the same time scale as the washer gun arc current, ∿ 100 μsec, long compared with the rate of decrease of the injection beam.

The fast atom flux is measured with the silicon barrier detector which is sensitive only to particles with energies above ∿ 0.5 keV and thus selectively discriminates against scattered warm target plasma ions. The silicon detector signal shows a 10-90 percent risetime of 31 μsec which corresponds to an e-folding time of 14 μsec. Using the experimental e-folding time in Eq. 6 yields $n_H = 3.4 \times 10^{10} << n_w$, as assumed in the derivation of Eq. 3. Measurements of the e-folding time have been carried out for different values of background pressure with the results shown in Fig. 10. At pressures below 10^{-6} torr, the e-folding time approaches a limiting value and the initial background pressure has little effect. Thus, we conclude that for the conditions of these experiments the hot ions within the target plasma are subject to a loss with a time constant of ∿ 15 μsec, independent of the initial pressure. Additional measurements have been made at high vacuum with different target plasma densities produced by operating the washer gun at reduced voltage. Although only limited data is available, it is clear from Fig. 11 that the limiting hot ion loss time depends inversely on the warm target plasma density. Assuming a 100 eV ion temperature for the warm target plasma, the charge exchange mean free path for cold background neutrals incident on the target plasma is ∿ 1 cm. If the limiting loss time was the result of background neutrals, the screening provided by the target plasma would be reduced for lower target plasma densities, and the inverse dependence of Fig. 11 would not be obtained. It appears, therefore, that the limiting loss is the result of interaction of the hot ions with the warm target plasma or with streaming cold neutrals produced by the washer gun along with the warm plasma.

Because the hot ion component is a small fraction of the warm target plasma density, it may be assumed that the electron temperature is unaffected by the injection and is fixed at the value determined by the washer gun stream. Assuming that the primary interaction of the hot ions is with the electrons of the warm target plasma, i.e., electron drag, the temperature of the target plasma electrons can be determined from the limiting loss time. From Spitzer (Ref. 10), neglecting the effects of the warm plasma ions, the energy decay time is

$$\tau_E = \frac{3 m_I m_e k^{3/2}}{8(2\pi)^{1/2} n z^2 z_o^2 e^4 \ln\Lambda} \left[\frac{T_e}{M_e}\right]^{3/2} = \frac{2.2 \times 10^7}{n} T_e^{3/2}$$

and the loss time for ions to be dragged into the ambipolar hole is

$$\tau_d = \tau_E \ln\left[E_i/E_h\right] = \frac{2.2 \times 10^7}{n} T_e^{3/2} \ln\left[T_i/3T_e\right]$$

using the assumption that the ambipolar space potential $\phi \approx 3\ T_e$. For an average ion injection energy of 13.5 keV (half energy beam component), T_i = 9 keV, and setting τ_d equal to the limiting loss time gives an electron temperature of .89 eV. This value of the electron temperature appears unreasonably low in light of the electron temperatures of $\gtrsim$ 10 eV which were measured for washer gun target plasmas in earlier experiments using Thomson scattering diagnostics.

Observations were also made of the fast neutral flux in discrete energy channels using the fast atom detector. The signals at the full, half and one-third energies displayed the same time history as the silicon barrier detector signal with virtually identical risetimes. Preliminary measurements were also carried out at other energies. As expected, for detector energies above the full injection energy no scattered signal was observed. However, in a limited number of measurements at intermediate energies the anticipated time delay for the ions to be dragged down in energy was not found, a result which would be consistent with low values of electron temperature but which may also be the result of overlap of the detection channels with the injection components.

V. CONCLUSIONS

This report describes a set of experiments studying neutral beam injection into a plasma in a small scale mirror device. Requirements for hot ion dominance were delineated in a study of sustenance as summarized in Fig. 5. Neutral beam injection tests were carried out in several steps of increasing beam intensity. The initial tests served as a check on the understanding of the relevant physics and the ability of the model to accurately predict experimental results. The information obtained was incorporated in the model to improve predictions of the next level of experiments. The final hot ion buildup experiments utilized the highest beam intensity available (305 mA/cm^2) although ion dominance was not achieved with either the laser produced target plasma or the washer gun target. Analysis of the peak hot ion density achieved and hot ion lifetimes indicated that vacuum conditions were limiting the achievement of hot ion dominance. The mean free path for background neutrals incident on the plasma is small; however, the ion motion averages the interactions over an effective boundary region of one ion larmor diameter thickness (Ref. 11). For a plasma size large compared with the boundary thickness, the plasma interior is shielded from losses due to background gas charge exchange. With a plasma size comparable with the hot ion larmor diameter, the plasma is unshielded and cold neutral charge exchange interactions limit the plasma density throughout the plasma volume. For such an unshielded plasma more stringent injection/background conditions are required to achieve hot ion dominance and sustenance. Based on the model projections from the LITE injection experiments, a ratio of beam current/cold neutral flux (background gas plus streaming associated with the energetic beam) into the plasma of 180 would be required to achieve hot ion dominance with a decaying laser plasma target. This ratio is essentially independent of beam energy (within adiabatic limits) since the principal losses at threshold are charge exchange losses which depend only weakly on confined plasma energy. With a washer gun target, where the target can initially be maintained until equilibrium is established (as distinguished from the laser plasma target where hot ion buildup must occur before the target decays), the beam current/cold neutral flux required would be 50. Thus, for a given injection beam flux, a factor of $\sim$ 3.5 greater background density can be tolerated with the longer lived washer gun target.

Measurements of the lifetime of hot ions in a mirror confined warm plasma were carried out by observations of the hot ion buildup time obtained with energetic neutral beam injection. The initial background vacuum was sufficiently low as not to be a limitation on the hot ion plasma lifetime in these experiments. The hot ion lifetime scales inversely with the warm target plasma density and thus is determined by interaction of the hot ions with the target plasma or accompanying cold neutrals from the washer gun source. Assuming that the hot ion lifetime is limited primarily by electron drag gives a warm plasma electron temperature less than 1 eV, a factor of 10 lower than obtained in earlier experiments from Thomson scattering measurements. Observations of scattered neutrals from the plasma at energies between the full, half and one-third energy components of the beam have not shown the initial time delay which would be expected with an electron drag dominated loss with electron temperatures of $\sim$ 10 eV, for which the energy decay time is > 50 μsec. These measurements indicate that the hot ion lifetime is determined not by electron drag, but by the transient cold neutral background that results from the washer gun or cold neutral reflux produced by target plasma ions striking the adjacent surfaces (e.g., magnet walls).

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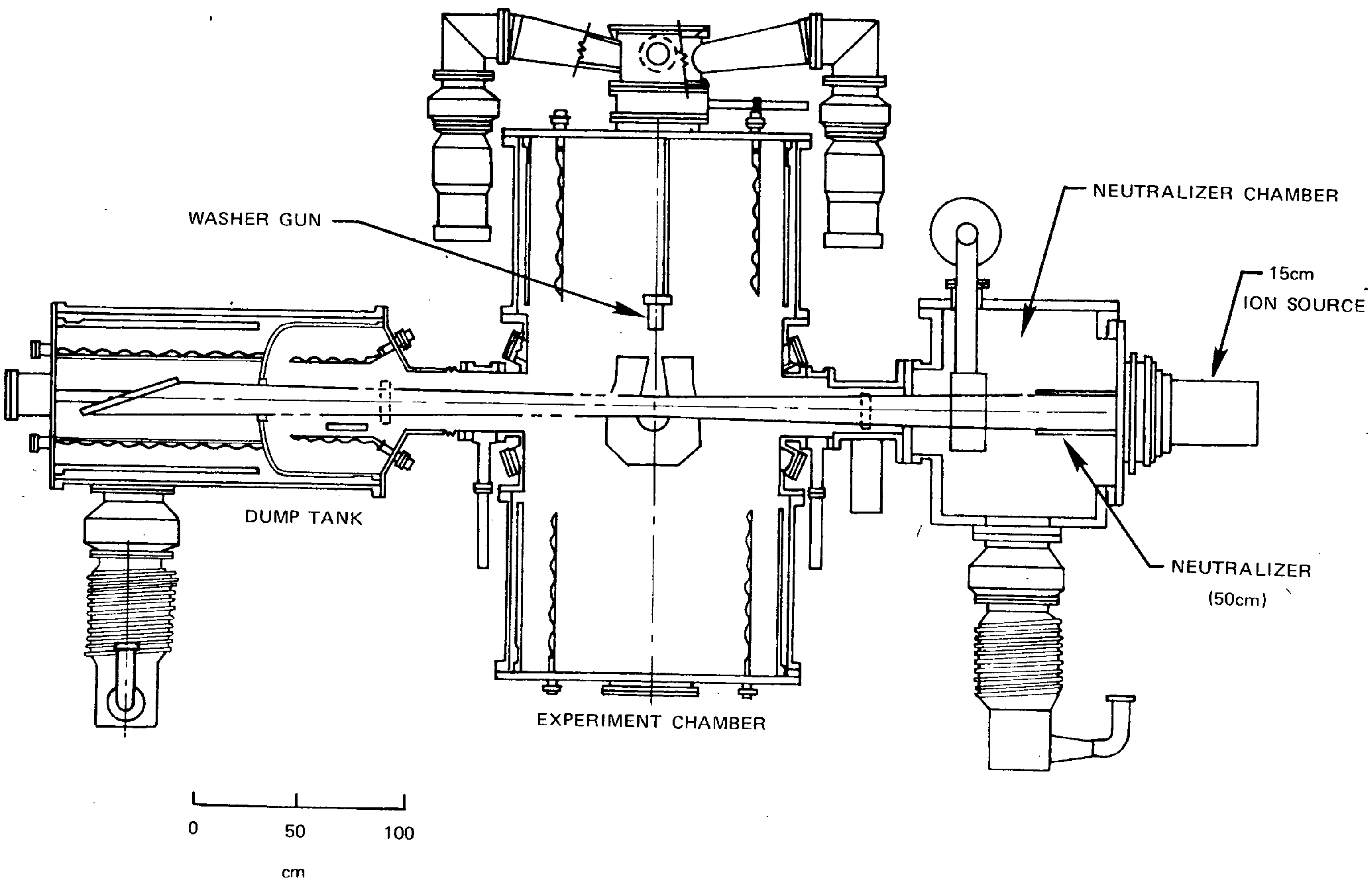
LIST OF FIGURES

LITE FACILITY FOR 10A INJECTION



78-05-98-2

FIG. 1

NEUTRAL BEAM INJECTION TARGET PLASMAS

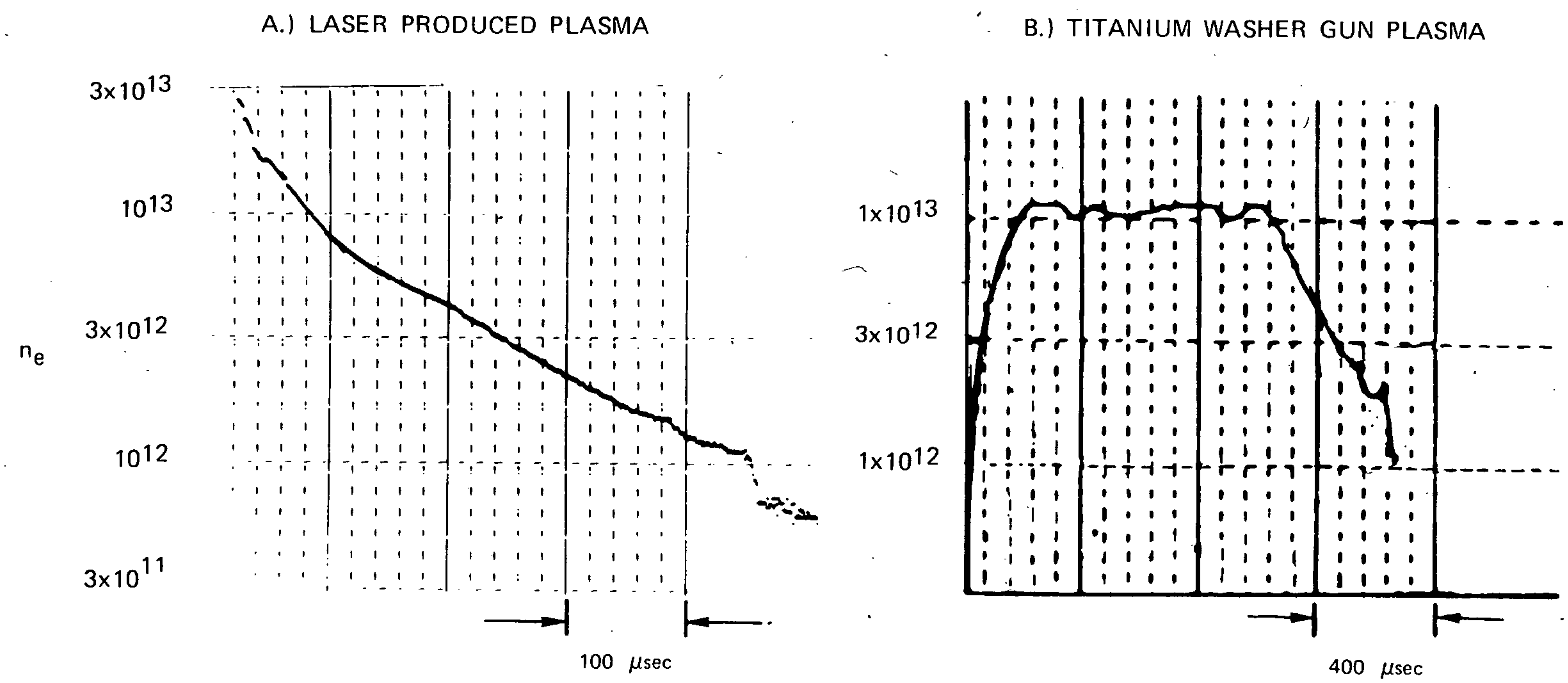
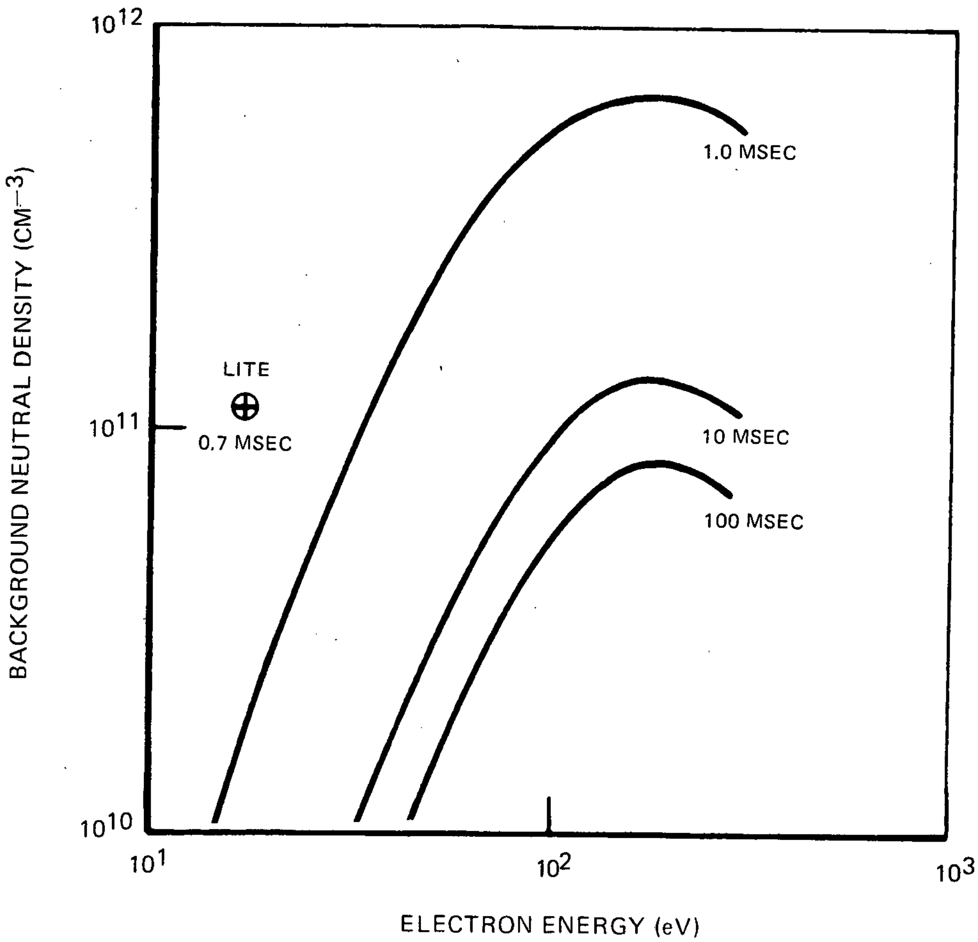


FIG. 2

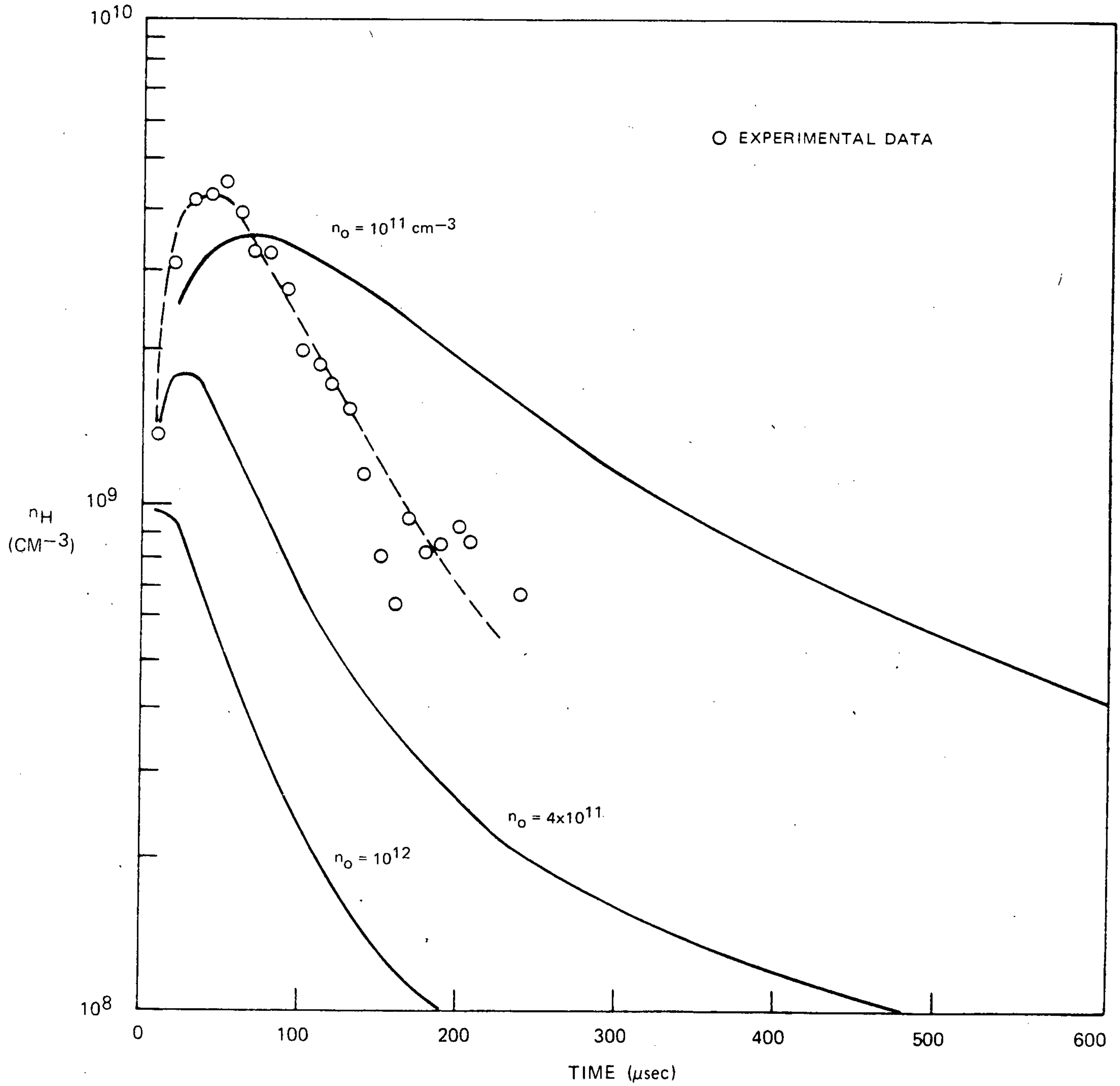
78–05–98–4

SUSTENANCE REQUIREMENTS FOR 10 AMPERE, 27 keV INJECTION



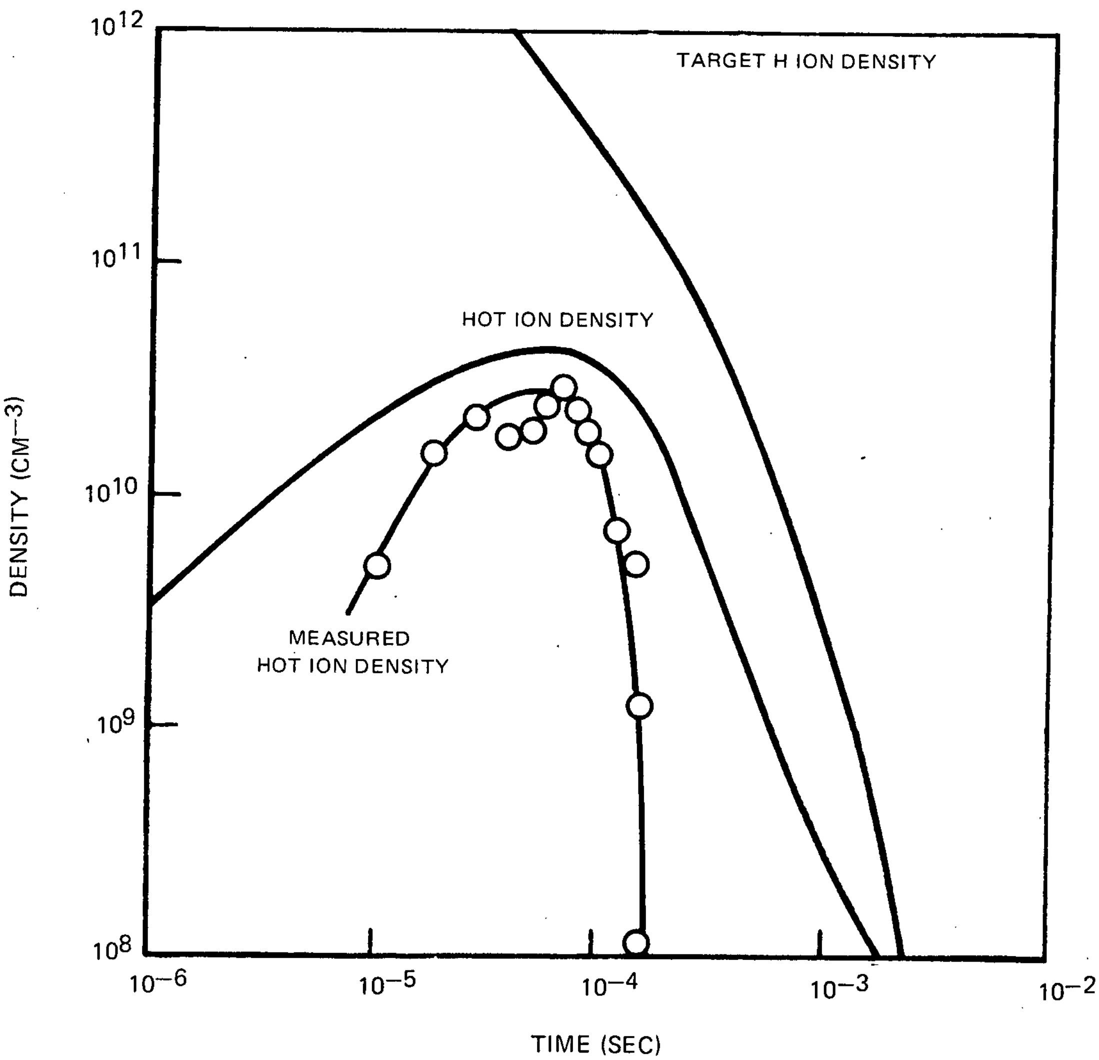
78–09–180–4

CALCULATED DENSITY OF TRAPPED HOT IONS VS TIME



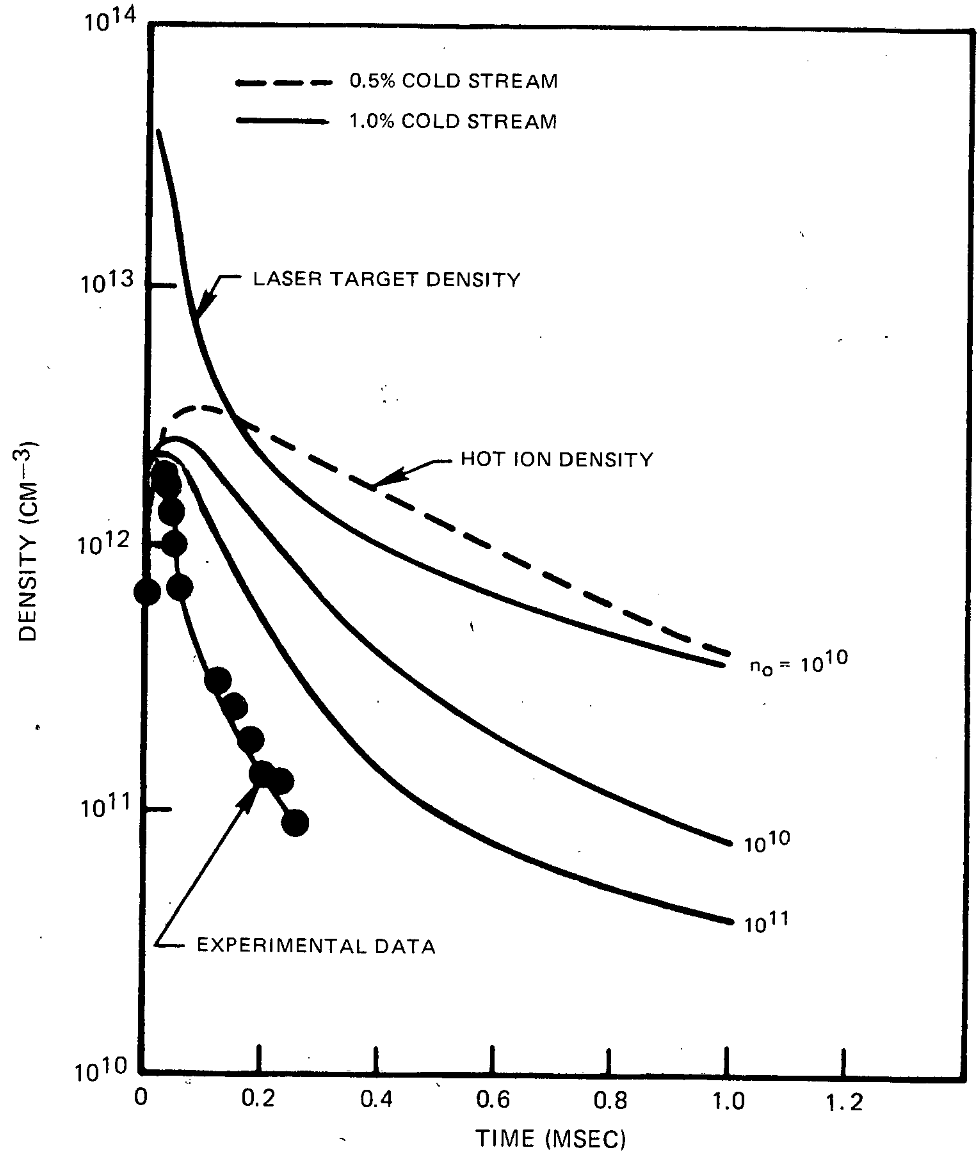
HOT ION BUILDUP

1 AMPERE INJECTION



78–09–180–2

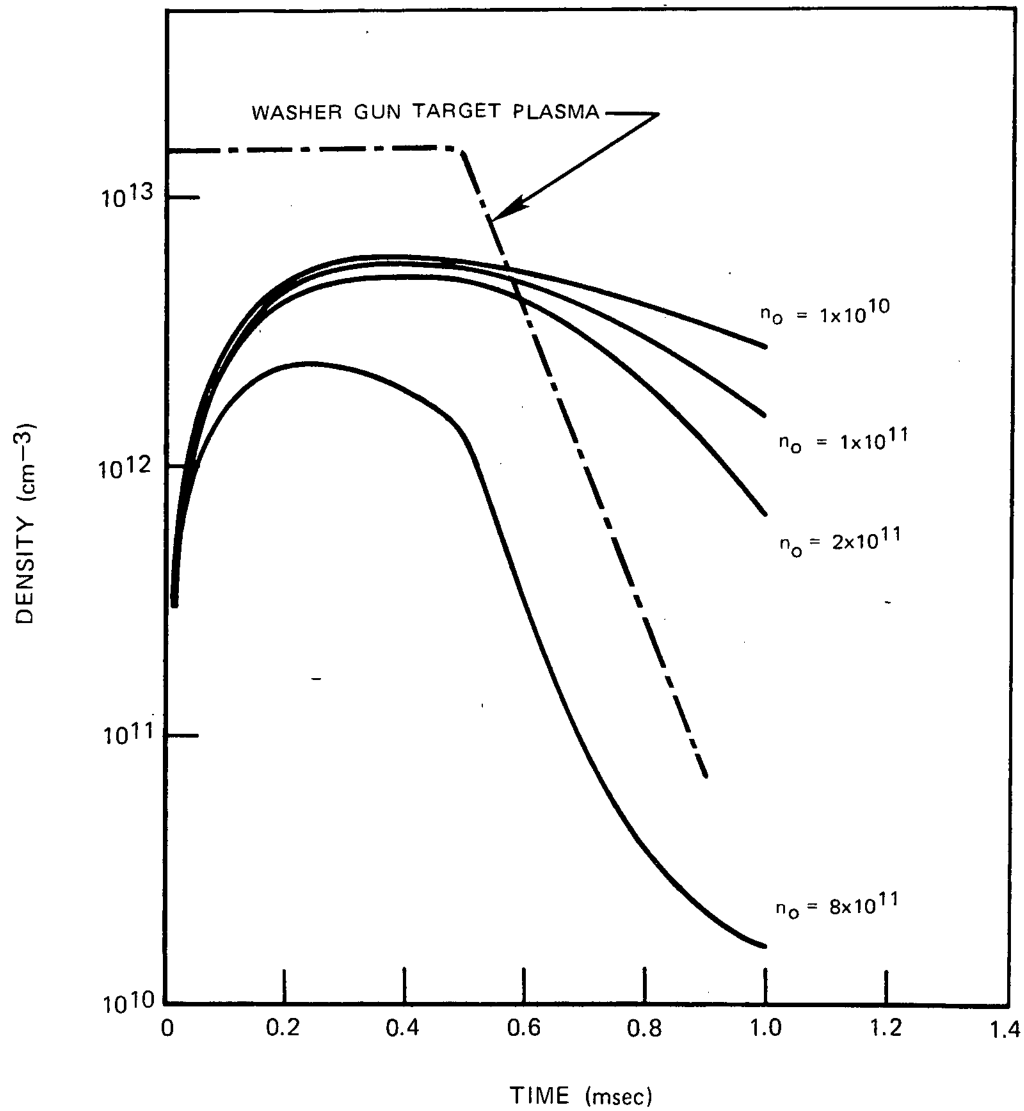
HOT ION BUILDUP LASER PLASMA TARGET



HOT ION BUILDUP

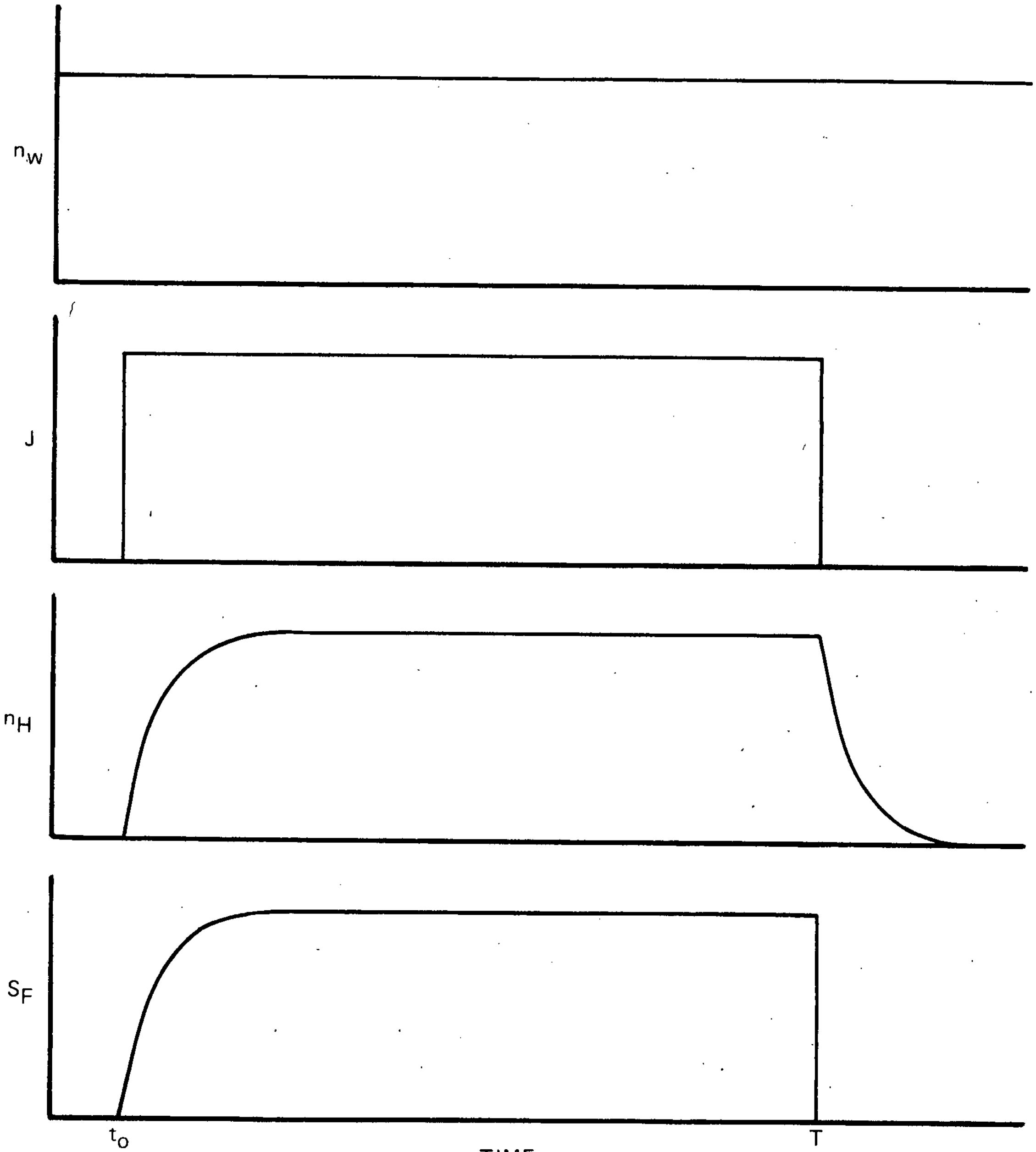
WASHER GUN PLASMA TARGET

10 A INJECTION



78–05–98–6

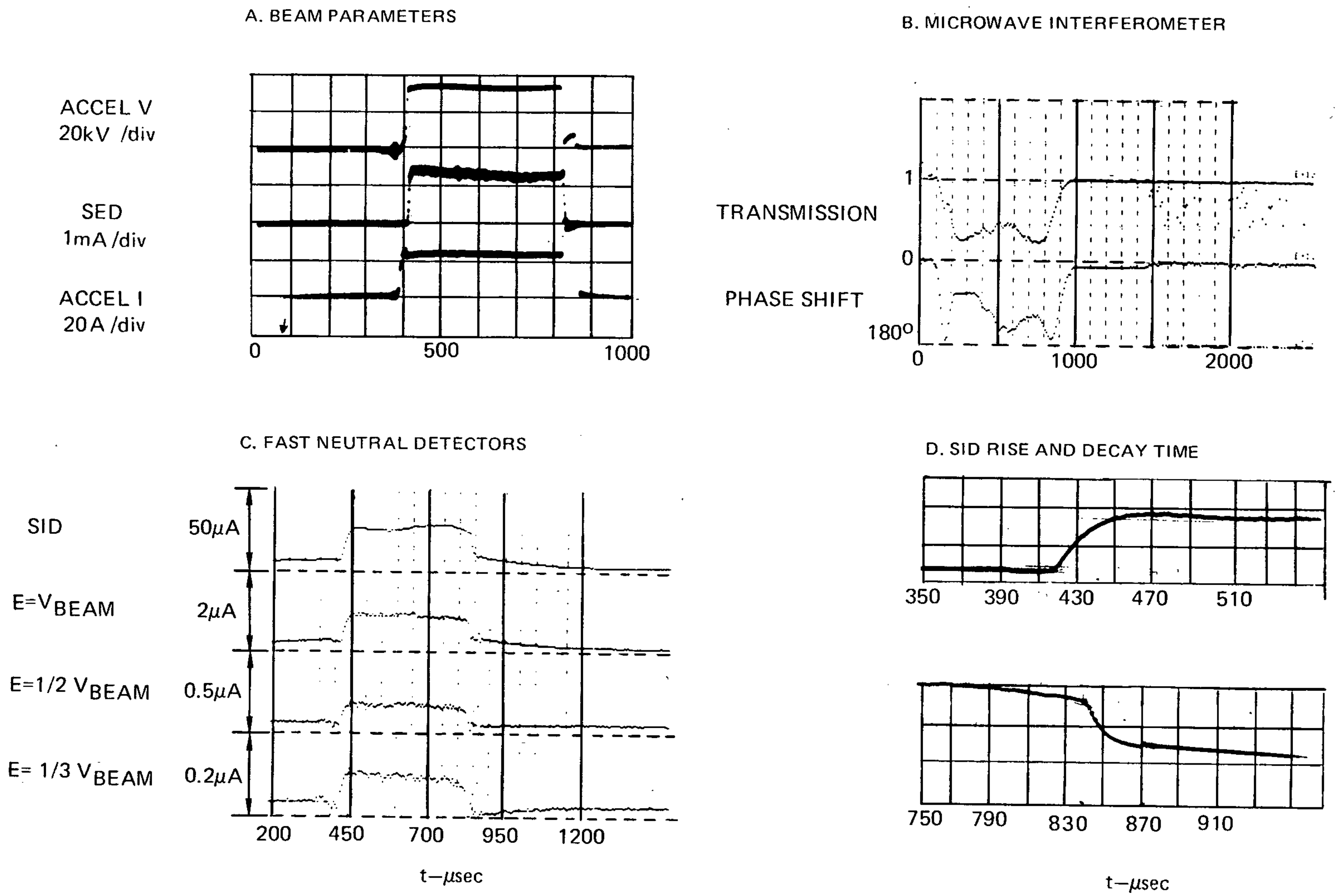
VARIATION OF HOT ION DENSITY (n_H) AND FAST NEUTRAL SIGNAL (S_F) FROM MODEL



77–12–180–1

TYPICAL DATA FOR NOMINAL 30kV BEAM INJECTION ON WASHER GUN TARGET PLASMA

$P_o = 3.0\times10^{-8}$ TORR   t = 0 @ WASHER GUN TRIGGER



77–12–185–1

FIG. 9

RISE AND DECAY TIMES (e–FOLD) OF SILICON DETECTOR SIGNAL AS A FUNCTION OF INITIAL AMBIENT PRESSURE

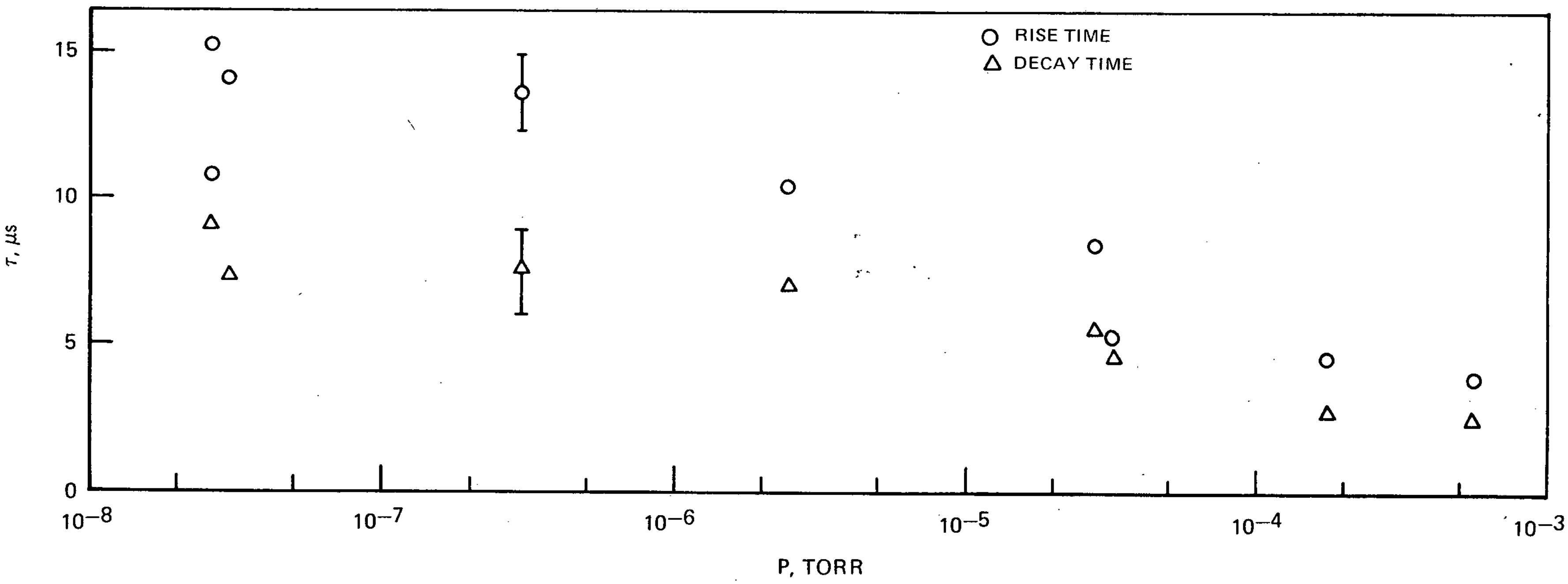
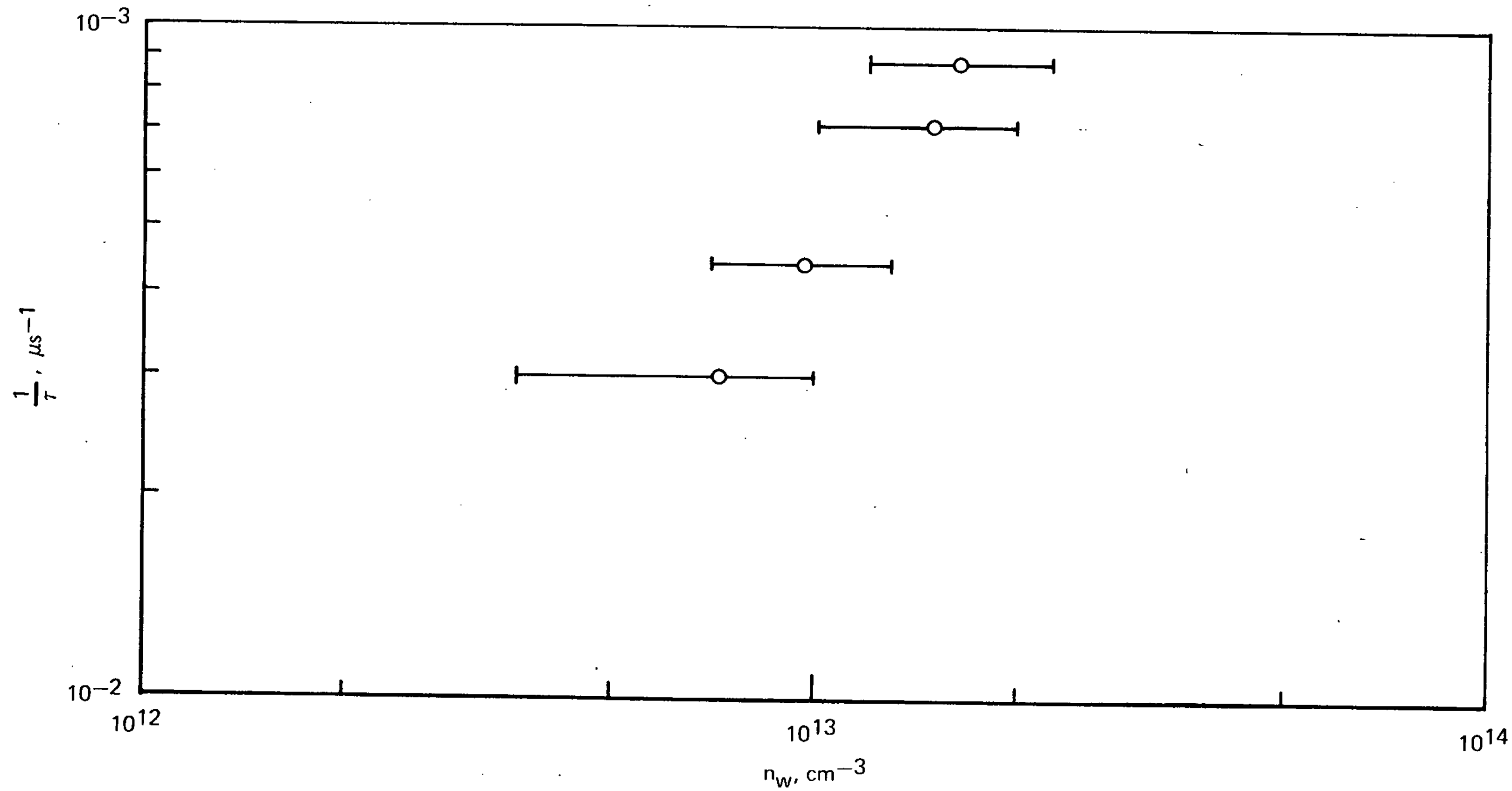


FIG. 10

77–12–187–2

RISE TIME OF SILICON DETECTOR SIGNAL AS A FUNCTION OF TARGET PLASMA DENSITY

$P_o \approx 3 \times 10^{-8}$ TORR



77–12–187–1

FIG. 11