CONFINEMENT OF INJECTED SILICON IN THE ALCATOR A TOKAMAK

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Abstract

Results of injected impurity transport studies on the Alcator A tokamak are presented. We find that injected silicon diffuses throughout the plasma and is then observed, contrary to the predictions of neoclassical theory, to leave the discharge, having confinement times much shorter than the discharge length. There is no observed build-up of silicon on the axis of the device. The impurity confinement is found to increase with plasma current and background ion mass. Scalings with electron density and toroidal field are also discussed.

Impurities can profoundly influence tokamak plasmas through radiation and its contribution to power balance,[1-4] enhanced resistivity and the resulting changes in power input,[5] and dilution of the working gas. A review of impurity transport studies can be found in Ref. (6). Investigations utilizing intrinsic impurities are plagued by unknown source functions. Experiments with pulsed gas injection of impurities[7,8] are influenced by recycling, leading again to unknown source functions. Injection of non-recycling metallic impurities[9,10] overcomes this source problem, but in none of these previous experiments have the highest ionization states, which exist in the hot core of the plasma, been followed spectroscopically. In addition, the majority of such studies have been carried out in relatively dirty plasmas, where comparisons with collisional diffusion theories are difficult. With $Z_{eff} \gtrsim 2$ (typically due to light impurities such as O and C), the transport, as predicted by theory, is dominated by collisions among impurity species and not by collisions with the working gas ions.[11] Since the light impurities are fully stripped over much of the plasma cross section, it is extremely difficult to measure their density profiles. These profiles are crucial for any comparison with theory of the transport of artificially introduced trace impurities.

We report the results of silicon transport studies in the clean ($Z_{eff} < 1.2$)[12] high field Alcator A tokamak.[13] Figure 1 shows the time history of a typical deuterium plasma into which Si has been injected. Macroscopic parameters for the steady state portion of this discharge are: $B_T = 6.0T$, $I_p = 175$ kA, $q_\ell = 3.2$, $T_{eo} \approx 850$ eV, and $\bar{n}_e = 3.5 \times 10^{14} cm^{-3}$. Silicon is introduced into the edge of the plasma using the laser induced thin film desorption technique.[14] The neutral Si is ionized at the edge of the plasma and subsequently moves along and across field lines, ionizing to higher states as the silicon penetrates to hotter portions of the plasma. Si emissions are mainly monitored with a spatially imaging EUV monochromator[15] which simultaneously views 22 radial chords, and a single chord flat crystal x-ray monochromator. Lines observed are at 458Å, 303Å, 499Å, 6.65Å and 6.18Å for Si IV, XI, XII, XIII and XIV (H-like) respectively. In addition, an array of x-ray photodiodes also detects Si emission, without energy resolution. Results for normalized midplane line integral birghtnesses of Si XII, XIII, and XIV for discharges similar to that of Fig. 1 are shown in Fig. 2. Radial profiles of Si XII show that this state exists in a shell of width ≈ 2 cm FWHM at the radial location r/a = 0.6.

These results have been compared with a one-dimensional computer code[16] which integrates the coupled equations:

$$\frac{\partial n_j}{\partial t} = - \frac{1}{r} \frac{\partial\ r\Gamma_j}{\partial r} + A_j \qquad j = 1, \ldots , 14$$

where n_j is the density for the jth ionization state, Γ_j is the diffusional flux, and A_j represents the ionization and recombination terms. Results of inferred brightness time histories using the flux derived for neoclassical theory in the extreme Pfirsch-Schluter regime[6] including only silicon-deuteron collisions are shown in Fig. 3(a). This model predicts that the silicon accumulates at the center of the discharge with the emission from all three ionization states reaching a steady state level, in complete disagreement with the experimentally observed decays. By adding an anomalous term to the diffusion, enhancing the "self-diffusional" flux (proportional to the silicon density gradient) a factor of about 10 over the neoclassical, the results of Fig. 3(b) are obtained. In this case, agreement with the experiment is reasonable, particularly during the time the signals are decaying. In the code, the Si is assumed to have zero recycling coefficient, and the decay of each state is due to loss of the Si at the edge of the plasma. We interpret the empirical decay also as a loss of Si from the plasma. Coronal equilibrium calculations including electron impact ionization and radiative and dielectronic recombination imply that the fractional abundances of Si XIII, XIV, and XV (fully stripped) for T_e = 800 eV are .45, .45, and .1 respectively. For the lowest T_e cases, no H-like Si is observed. The decay of Si XIV and Si XIII therefore cannot be due to further ionization. The central broadband x-ray surface barrier diode (SBD) signal of Fig. 1 shows an increase of about a factor of 2 due to the Si. The amplitude of the sawtooth oscillations on this signal also increases by about the same factor, implying that the Si contribution to this emission comes predominently from the center of the plasma, inside the q = 1 surface. A preliminary shot by shot radial scan of the Si XIII emission confirms this. Thus it is the loss of Si from the core of the plasma which leads to the decay of the signals. By fitting an exponential to the Si XIII decay, a Si-particle confinement time (τ_{Si}) is inferred. When the decay times are shorter than about 10 msec, agreement, within experimental error, is found for such fits among the three highest observed ionization states. However, for τ_{Si} > 10 msec, the Li-like state tends to decay more rapidly, with the discrepancy increasing with τ_{Si}. This may be due to the influence on the observed

Si XII brightness time history of changing profiles in the outer half of the plasma.

As the first step in an attempt to understand the physical processes which lead to the transport of the injected Si, we have studied the scaling of τ_{Si} with several discharge parameters: electron density ($0.5 \times 10^{14}\mathrm{cm}^{-3} < \bar{n}_e < 5.5 \times 10^{14}\mathrm{cm}^{-3}$), plasma current ($55\ \mathrm{kA} < I_p < 230\ \mathrm{kA}$), toroidal field ($3.6\mathrm{T} < B_T < 7.9\mathrm{T}$), and working gas ($H_2$, D_2, ^{3}He and ^{4}He). Several clear experimental trends have emerged. For injection into deuterium plasmas with $B_T = 6.0$ T, Fig. 4 shows τ_{Si} vs. $\bar{n}_e$. This density scan shows a general increase in impurity confinement up to $\bar{n}_e \simeq 3.5 \times 10^{14}\mathrm{cm}^{-3}$. At higher densities, τ_{Si} levels off or perhaps decreases slightly. It has been conjectured [17] that at high density, impurity transport ought to approach the neoclassical, with accumulation at the center of the discharge. We find, even at the highest densities studied ($n_{e_o} \simeq 8 \times 10^{14}\mathrm{cm}^{-3}$), that this is not the case.

Scaling of τ_{Si} with current at fixed density has also been studied for H_2, D_2, ^{3}He and ^{4}He working gas discharges. The results for these gases are shown in Fig. 5. τ_{Si} increases in each case with increasing plasma current (with the possible exception of the H_2 results), the effect becoming more marked as background ion mass increases. Figure 6 shows the average of all data for $150\ \mathrm{kA} < I_p < 175\ \mathrm{kA}$ and $2 \times 10^{14}\mathrm{cm}^{-3} < \bar{n}_e < 3 \times 10^{14}\mathrm{cm}^{-3}$ in each of the four working gases. It would appear from these data that τ_{Si} is proportional to the mass of the background ion. In considering these data, it must be pointed out that other plasma parameters, most notably T_e and T_i and their profiles do not remain constant as $\bar{n}_e$, I_p and working gas are changed.

While sufficient data have not yet been gathered to allow definitive conclusions regarding the scaling of τ_{Si} with B_T, initial D_2 results are consistent with $\tau_{Si} \propto B_T^{-1}$ at fixed I_p. This, coupled with the current scaling results, would imply that τ_{Si} is a function of the safety factor, q, (or its profile) rather than the central electron or ion temperatures, which increase with both increasing plasma current and toroidal field.

The lowest current cases ($I_p < 60$ kA) exhibit no sawtooth oscillations on the central SBD signals. Since the fastest impurity diffusion is found in just these discharges, we conclude that the $m = 1$ instability inside the $q = 1$ surface is not the key mechanism leading to finite impurity confinement. In addition, a comparison of discharges with similar density and current, but about a factor of 10 difference in the magnitudes of $m = 2$ and $m = 3$ oscillations as observed on external pick-up loops, yields no significant change in τ_{Si}.

We summarize our main conclusions as follows: (i) injected Si diffuses throughout the plasma and is then observed to leave the discharge, with confinement times of the same order as those of global energy; (ii) there is no build-up of Si on axis, and the observed transport is not consistent with predictions based on neoclassical theory; (iii) scalings of τ_{Si} indicate that τ_{Si} increases with I_p, and with increasing working gas ion mass; (iv) preliminary studies of τ_{Si} vs. B_T in D_2, coupled with the current scaling results, imply that τ_{Si} decreases with increasing q.

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Figure Captions

Fig. 1. Time history of discharge parameters for a typical Si injection case.

Fig. 2. Line integral brightness time histories of observed UV and X-ray emission from Li-like, He-like and H-like silicon after injection.

Fig. 3. Predicted line integral brightness time histories for the states of Fig. 2 from (a) pure neoclassical diffusion, (b) neoclassical + anomalous diffusion.

Fig. 4. Scaling of τ_{Si} with electron density.

Fig. 5. τ_{Si} vs. plasma current at fixed electron density in the four different working gases, H_2, D_2, ^{3}He and ^{4}He.

Fig. 6. Averages of all τ_{Si} measurements for $150\ \mathrm{kA} < I_p < 175\ \mathrm{kA}$ as a function of background ion mass.

FIGURE 1

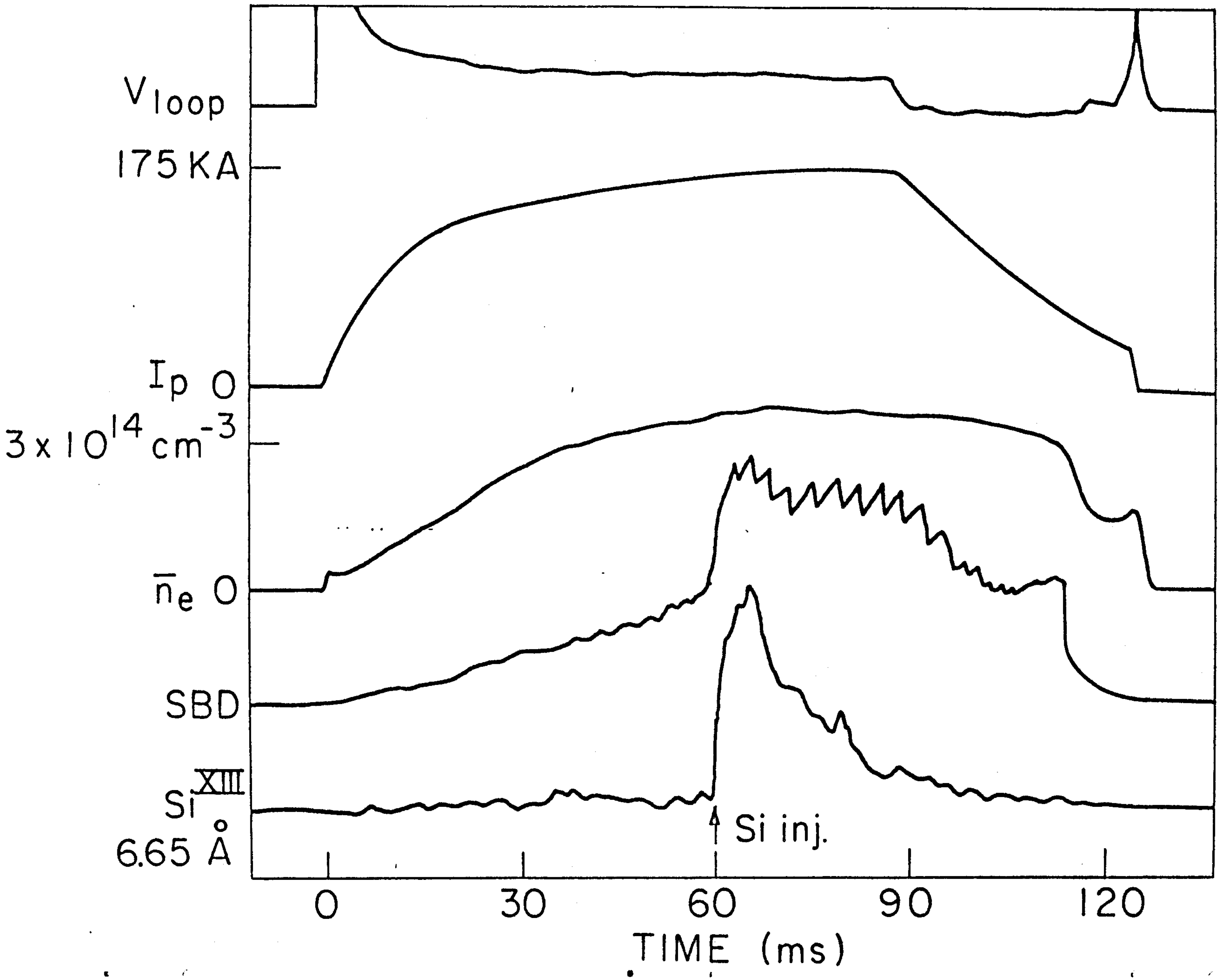

V_{loop}
175 KA
I_p 0
3×10^{14} cm^{-3}
$\bar{n}_e$ 0
SBD
Si XIII
6.65 Å
Si inj.
0
30
60
90
120
TIME (ms)

FIGURE 2

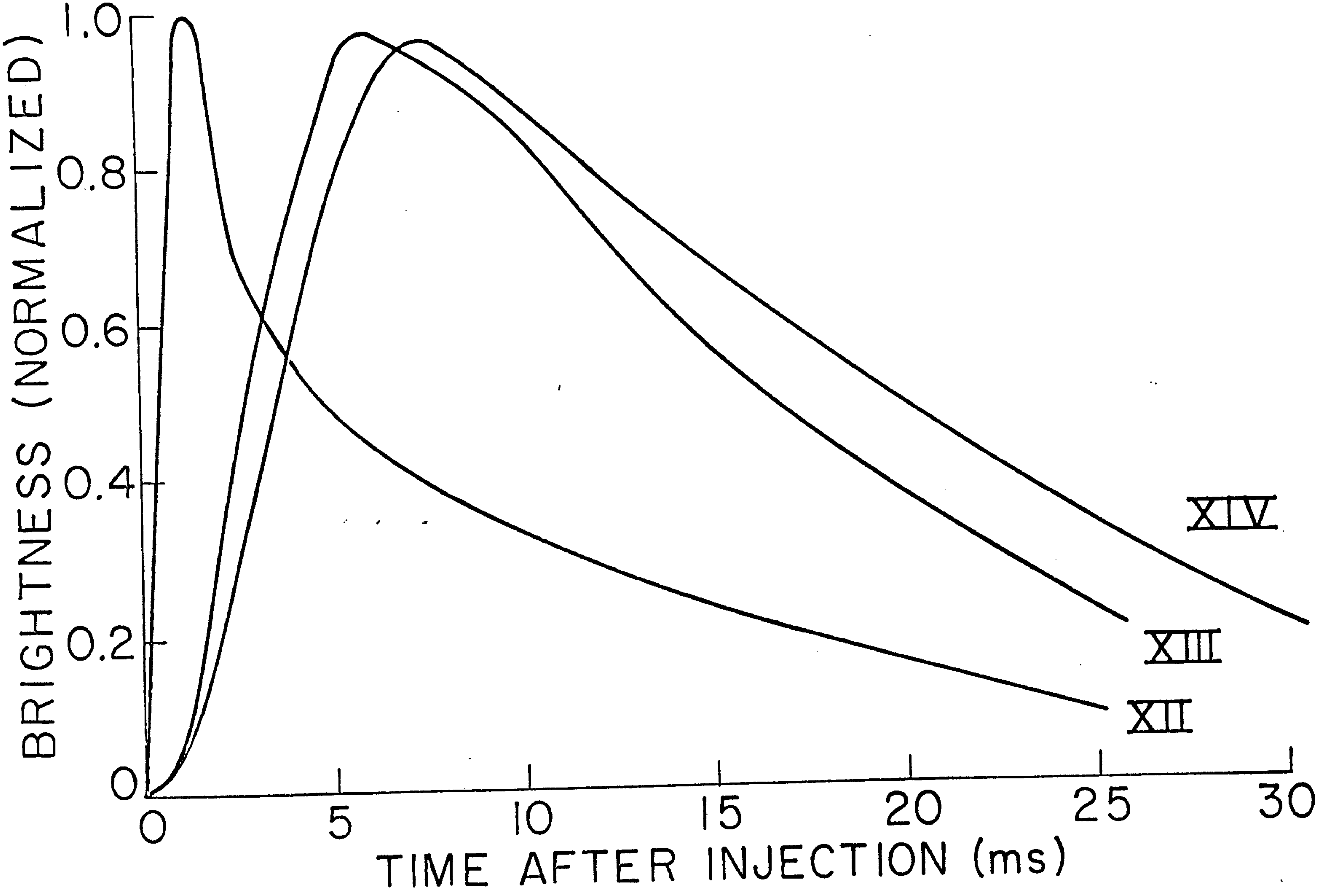

BRIGHTNESS (NORMALIZED)
1.0
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
TIME AFTER INJECTION (ms)
XIV
XIII
XII

FIGURE 3(a)

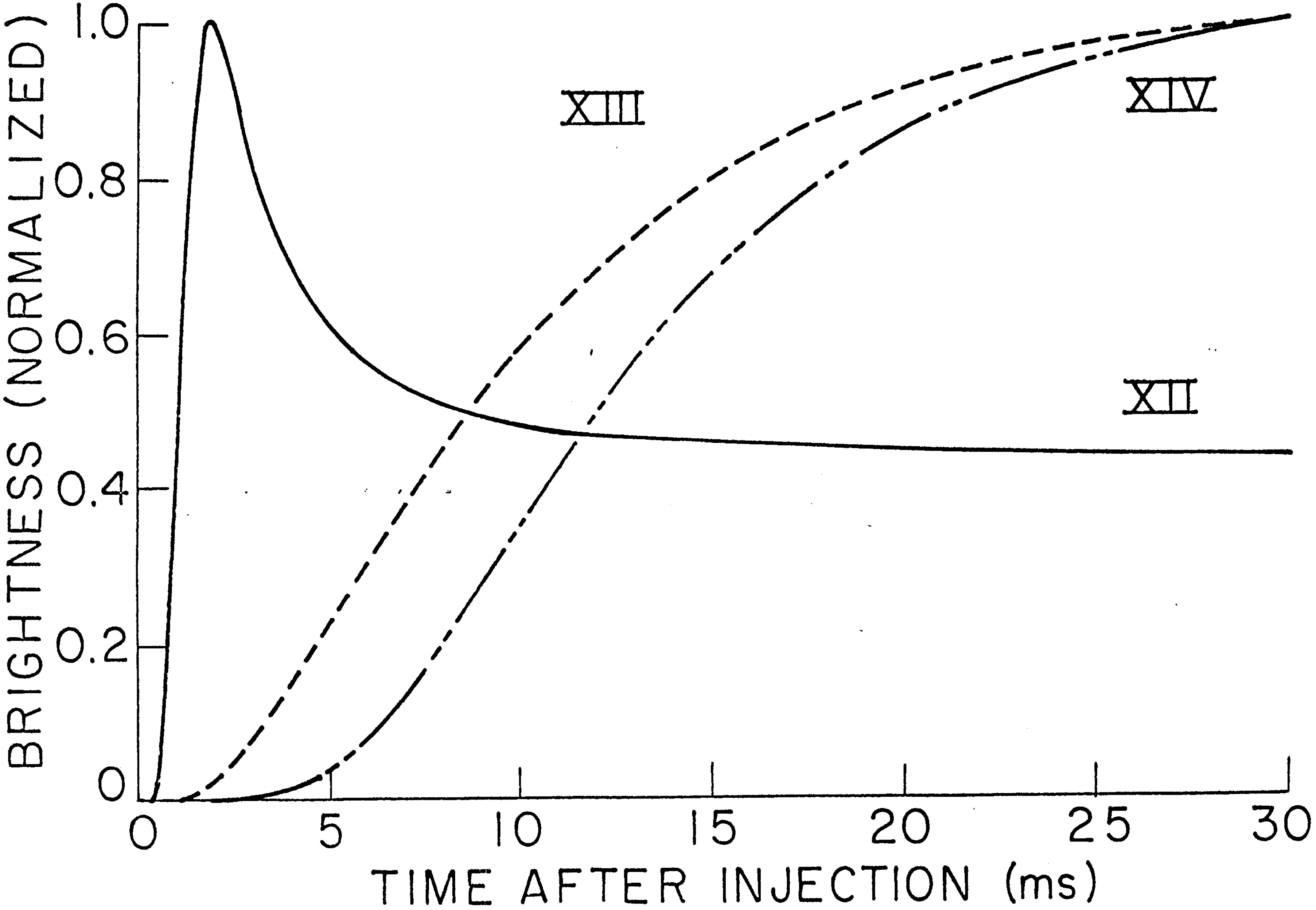

XIII
XIV
XII
1.0
0.8
0.6
0.4
0.2
0
BRIGHTNESS (NORMALIZED)
0
5
10
15
20
25
30
TIME AFTER INJECTION (ms)

FIGURE 3(b)

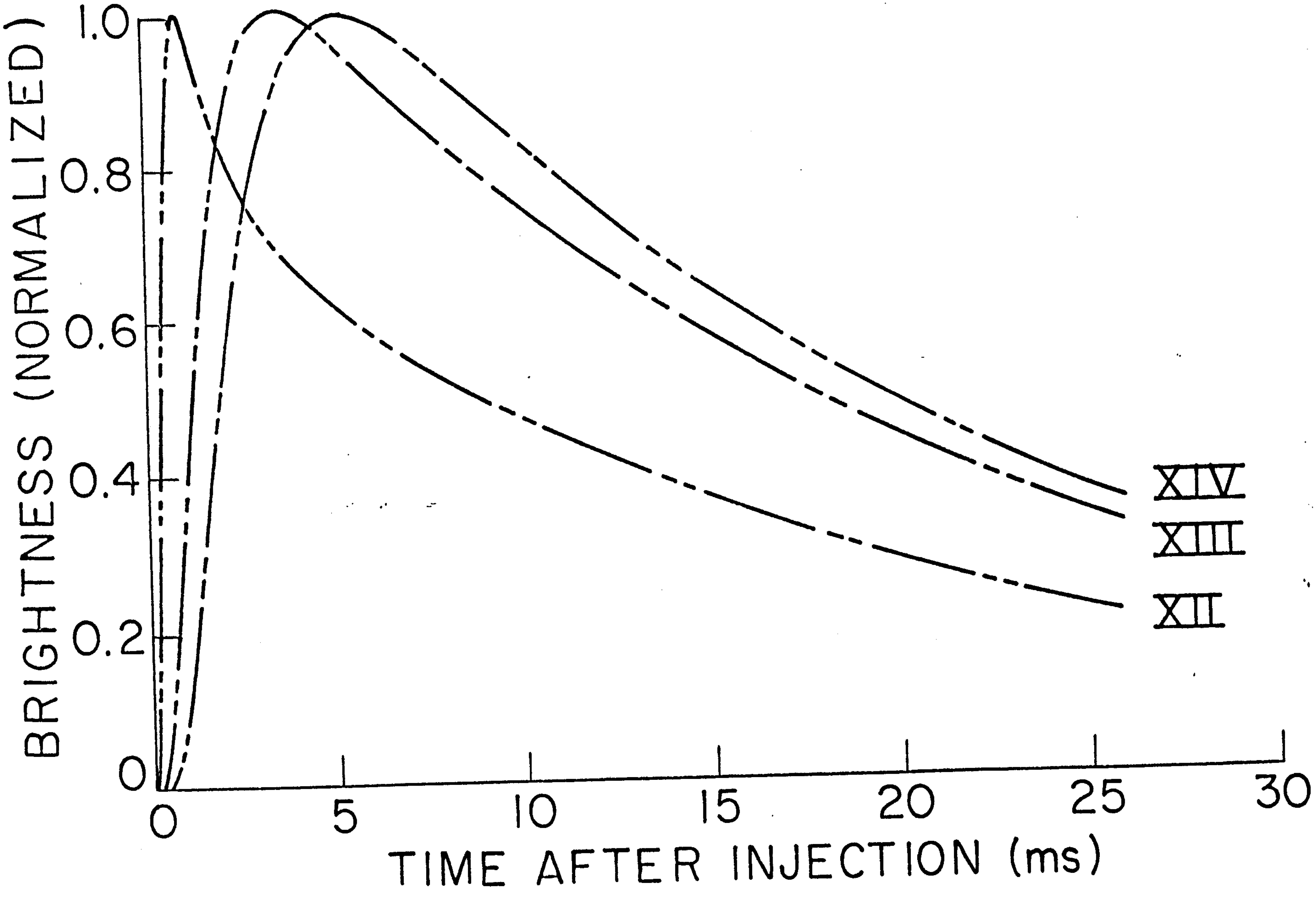

BRIGHTNESS (NORMALIZED)
1.0
0.8
0.6
0.4
0.2
0
0
5
10
15
20
25
30
TIME AFTER INJECTION (ms)
XIV
XIII
XII

FIGURE 4

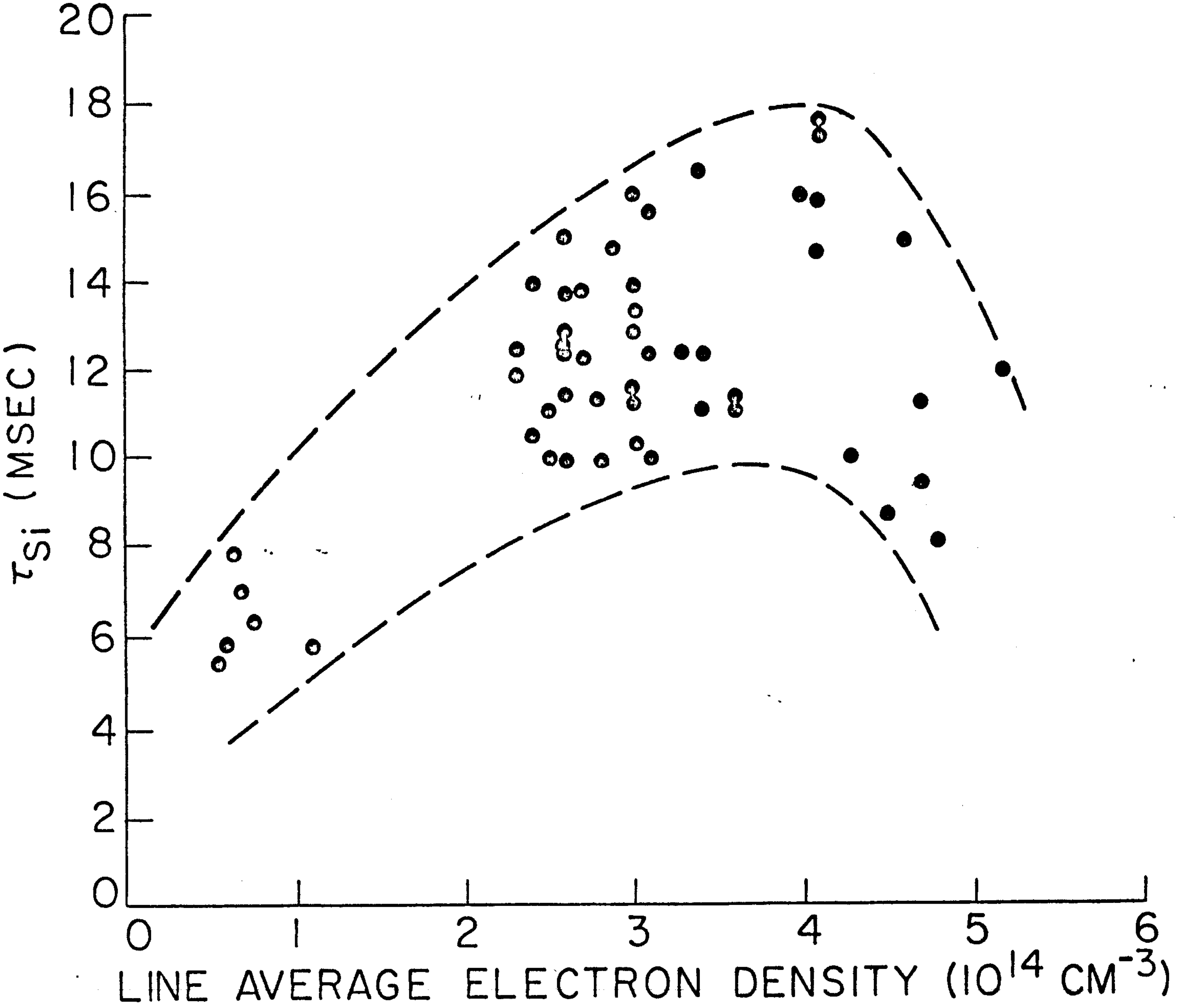
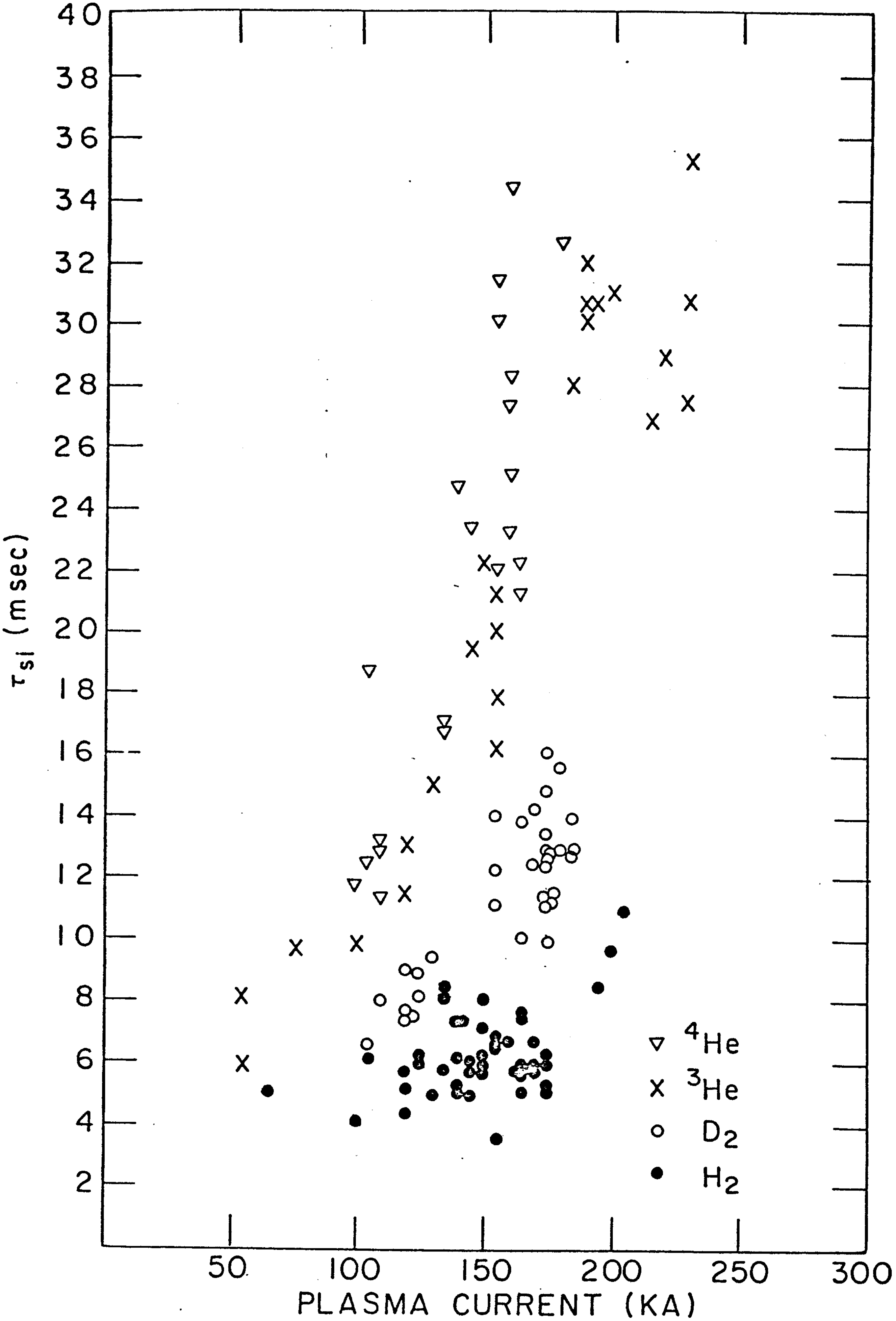
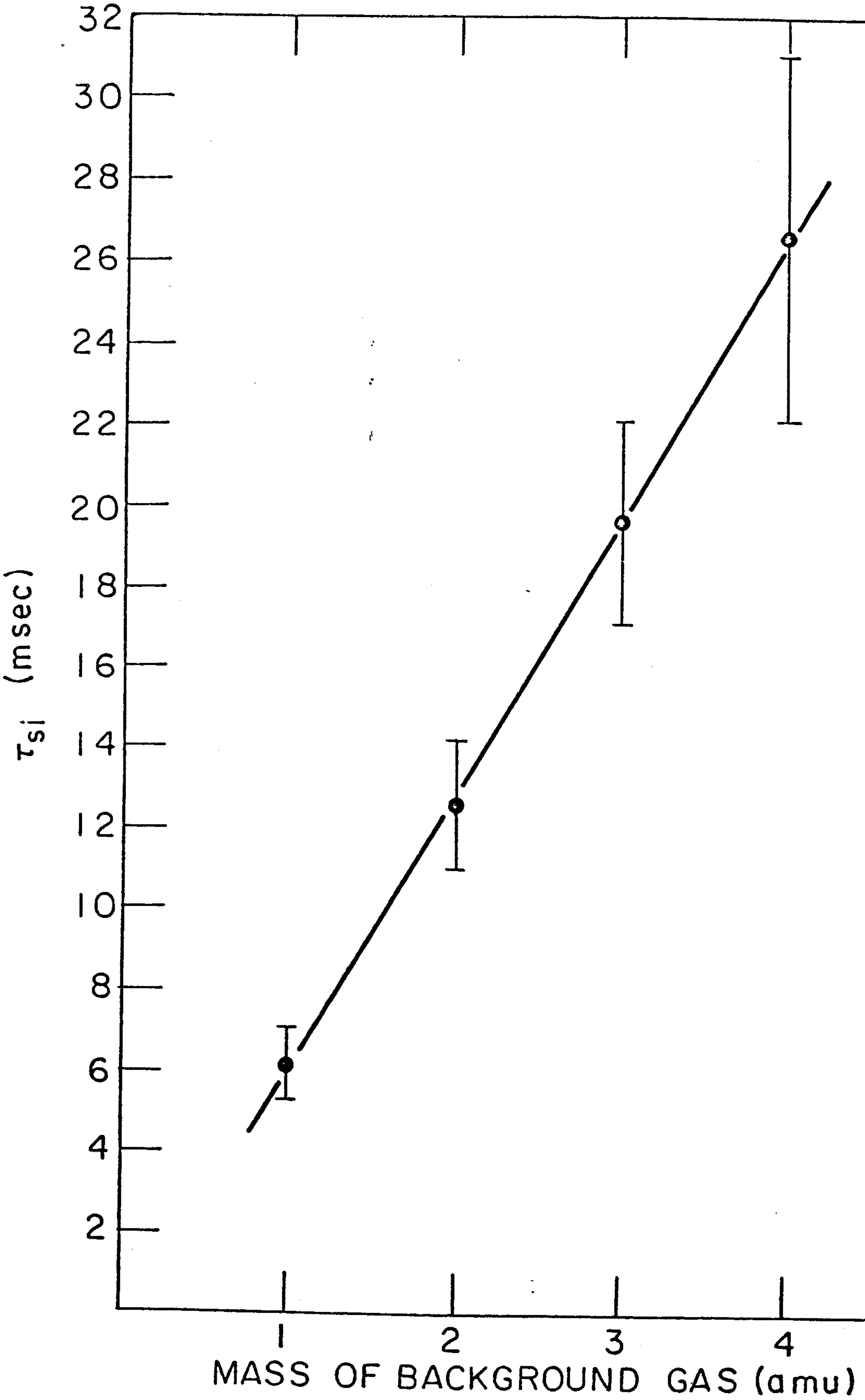

τ_{Si} (MSEC)
20
18
16
14
12
10
8
6
4
2
0
0
1
2
3
4
5
6
LINE AVERAGE ELECTRON DENSITY (10^{14} CM^{-3})

FIGURE 5



τ_{sl} (msec)
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
50
100
150
200
250
300
PLASMA CURRENT (KA)
▽ ^4He
X ^3He
○ D_2
● H_2

FIGURE 6


32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
τ_{si} (msec)
1
2
3
4
MASS OF BACKGROUND GAS (amu)