Confinement of Injected Silicon in the Alcator-*A* Tokamak

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Results of injected-impurity transport studies on the Alcator-*A* tokamak are presented. It is found 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 buildup 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.

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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 the work of Hawryluk, Suckewer, and Hirshman.[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 nonrecycling 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 $Z_{\text{eff}} \gtrsim 2$ (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 $(Z_{\text{eff}} < 1.2)$[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 $B_T = 6.0$ T, $I_p = 175$ kA, $q_l = 3.2$, $T_{e0} \approx 850$ eV, and $\bar{n}_e = 3.5 \times 10^{14}$ cm^{-3}. Silicon is introduced into the edge of the plasma by using the laser-induced–thin-film–desorption technique.[14] The neutral Si (average energy of approximately 3 eV/particle) is ionized at the edge of the plasma and subsequently moves along and across the 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 extreme-ultraviolet monochromator[15] which simultaneously views 22 radial chords, and a single-chord flat-crystal x-ray monochromator. Lines observed are at 458, 303, 499, 6.65, and 6.18 Å for Si IV, Si XI, Si XII, Si XIII, and Si XIV (H-like), respectively. Results for normalized midplane line-integral brightnesses of Si XII, Si XIII, and Si XIV

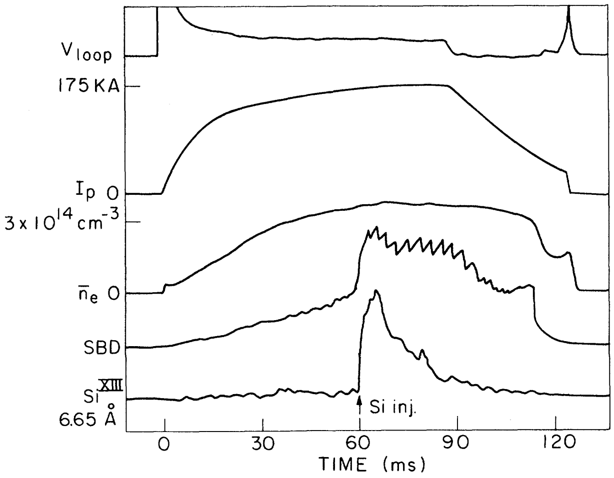

FIG. 1. Time history of discharge parameters for a typical Si-injection case.

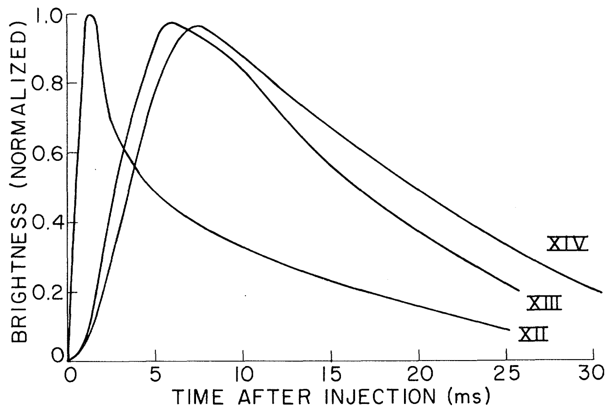

FIG. 2. Line-integral brightness time histories of observed uv and x-ray emission from Li-like, He-like, and H-like silicon after injection.

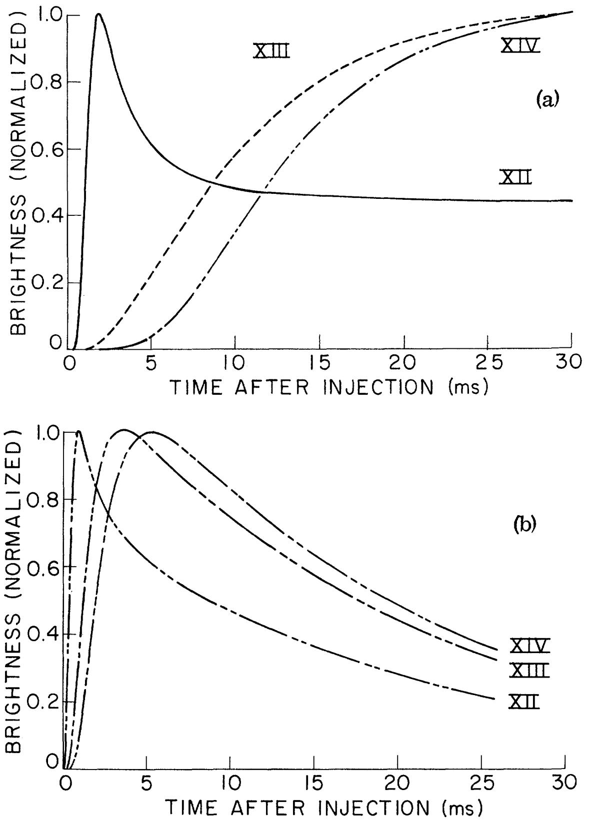

FIG. 3. Predicted line-integral brightness time histories for the states of Fig. 2 from (a) pure neoclassical diffusion, (b) neoclassical plus anomalous diffusion.

for discharges similar to that of Fig. 1 are shown in Fig. 2. Radial profiles of SiXII show that this state exists in a shell of width ≈2 cm full width at half maximum (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

$$\partial n_j/\partial t = -r^{-1}\,\partial(r\Gamma_j)/\partial r + A_j, \quad j = 1, \ldots, 14,$$

where n_j is the density of 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 with use of the flux derived for neoclassical theory in the extreme Pfirsch-Schluter regime[6] which includes 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. Uncertainties in temperature and density profiles cannot explain this disagreement. By adding an anomalous term to the diffusion, enhancing the "selfdiffusional" 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. The discrepancies during the rise of the signals are probably due to a combination of uncertainties in ionization rates and in the assumed initial conditions for the ionization of the incoming neutrals. 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, Si XIV, and Si XV (fully stripped) for $T_e = 800$ eV are 0.45, 0.45, and 0.1, 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. A shot-by-shot radial scan of the Si XIII brightness profile shows that the emission of Si XIII is peaked on axis with an inverted-profile full width at half height of 4 cm. 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, agree-

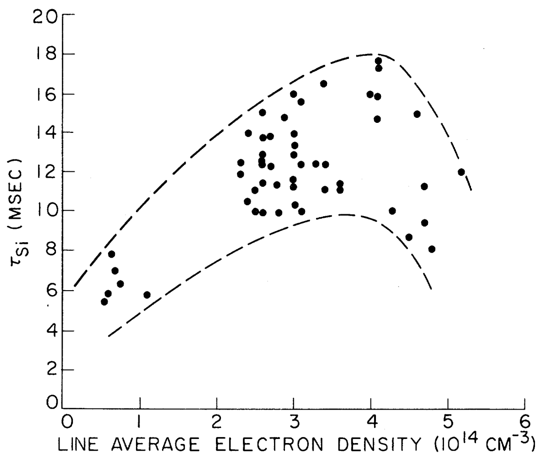

FIG. 4. Scaling of τ_{Si} with electron density.

ment, within experimental error, is found for such fits among the three highest observed ionization states. However, for $\tau_{Si} > 10$ 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. Changes in central T_e and n_e during the time of the Si XIII decay introduce uncertainties of order 15% into the central-particle-confinement times inferred from the brightness decay.

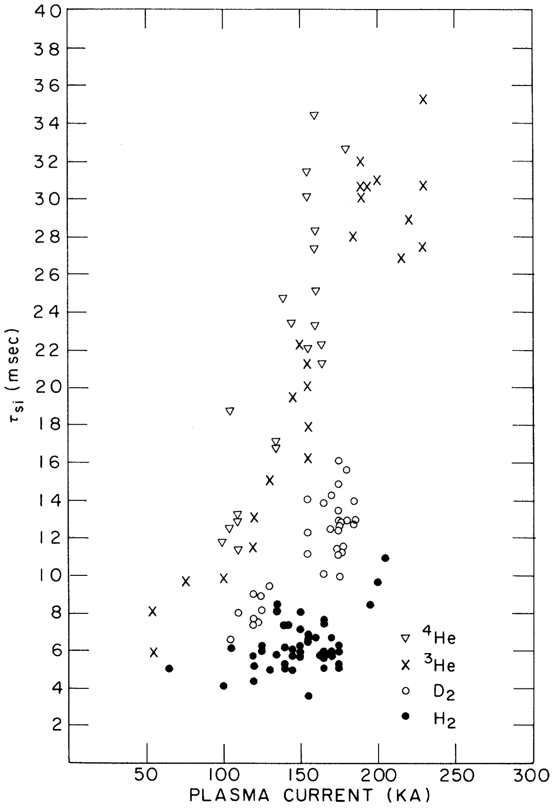

FIG. 5. τ_{Si} vs plasma current at fixed electron density in the four different working gases, H_2, D_2, ^{3}He, and ^{4}He.

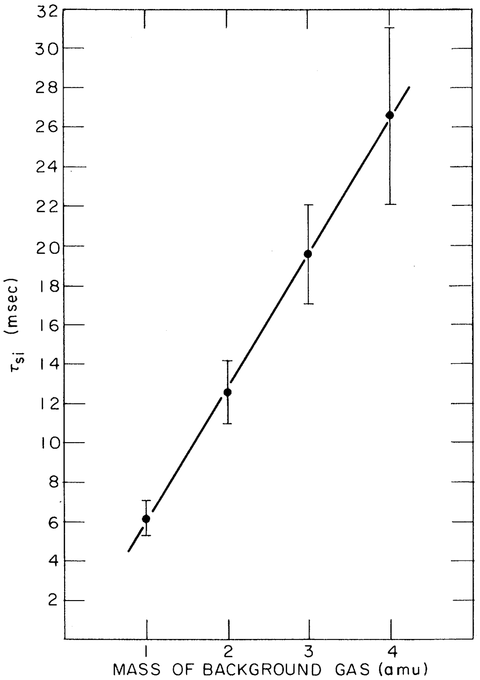

FIG. 6. Averages of all τ_{Si} measurements for 150 kA $< I_p <$ 175 kA as a function of background-ion mass.

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 (0.5×10^{14} cm^{-3} $< \bar{n}_e <$ 5.5×10^{14} cm^{-3}), plasma current (55 kA $< I_p <$ 230 kA), toroidal field (3.6 T $< B_T <$ 7.9 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 $\bar{n}_e \approx 3.5\times10^{14}$ 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 ($n_{e0} \approx 8\times10^{14}$ 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 kA $< I_p <$ 175 kA and 2×10^{14} cm$^{-3} < \bar{n}_e < 3 \times 10^{14}$ 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 the 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 $\tau_{\text{Si}} \propto B_T^{-1}$ 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 surface-barrier–diode 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 pickup loops, yields no significant change in τ_{Si}.

We summarize our main conclusions for Si transport in the low-Z_{eff} Alcator-*A* discharges studied, 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 buildup of Si on the 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. These results apply only directly to the trace Si in the plasma, and we cannot conlcude experimentally that the transport is the same for the intrinsic impurities in the plasma.

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[1] E. B. Meservey, N. Bretz, D. L. Dimock, and E. Hinnov, Nucl. Fusion 16, 593 (1976).

[2] J. Hugill *et al.*, in *Proceedings of the Eighth European Conference on Controlled Fusion and Plasma Physics, Prague, Czechoslovakia, 1977* (International Atomic Energy Agency, Vienna, Austria, 1978), Vol. I, p. 39.

[3] V. Arunasalam *et al.*, in *Proceedings of the Eighth European Conference on Controlled Fusion and Plasma Physics, Prague, Czechoslovakia, 1977* (International Atomic Energy Agency, Vienna, Austria, 1978), Vol. 2, p. 17.

[4] L. S. Scatturo and M. M. Pickrell, to be published.

[5] TFR Group, in *Proceedings of the Fifth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo, Japan, 1974* (International Atomic Energy Agency, Vienna, Austria, 1975), Vol. 1, p. 127.

[6] R. J. Hawryluk, S. Suckewer, and S. P. Hirshman, Nucl. Fusion 19, 607 (1979).

[7] K. Brau *et al.*, Bull. Am. Phys. Soc. 23, 901 (1978).

[8] TFR Group, Nucl. Fusion 16, 1297 (1977).

[9] S. A. Cohen, J. L. Cecchi, and E. S. Marmar, Phys. Rev. Lett. 35, 1507 (1975).

[10] K. H. Burrell *et al.*, Phys. Rev. Lett. 41, 1382 (1978).

[11] S. P. Hirshman, Phys. Fluids 20, 589 (1977).

[12] J. L. Terry *et al.*, Nucl. Fusion 18, 485 (1978).

[13] M. Gaudreau *et al.*, Phys. Rev. Lett. 39, 1266 (1977).

[14] E. S. Marmar, J. L. Cecchi, and S. A. Cohen, Rev. Sci. Instrum. 46, 1149 (1975).

[15] R. K. Richards, H. W. Moos, and S. L. Allen, Rev. Sci. Instrum. 51, 1 (1980).

[16] E. S. Marmar, Ph.D. thesis, Princeton University, 1976 (unpublished).

[17] W. Englehardt *et al.*, in *Proceedings of the Seventh International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Innsbruck, Austria, 1978* (International Atomic Energy Agency, Vienna, Austria, 1979), Vol. I, p. 123.