[2] R. J. Goldston and H. H. Towner, Princeton Plasma Physics Laboratory Report No. PPPL-1637, 1980 (unpublished).

[3] A. H. Boozer, Phys. Fluids 23, 2283 (1980).

[4] B. V. Chirikov, Phys. Rep. 52, 265 (1980).

[5] C. F. F. Karney, Phys. Fluids 22, 2188 (1979).

Influence of Neutral-Beam Injection on Impurity Transport in the ISX-*B* Tokamak

R. C. Isler, L. E. Murray, S. Kasai,[(a)] D. E. Arnurius, S. C. Bates, E. C. Crume, J. L. Dunlap, P. H. Edmonds, E. A. Lazarus, M. Murakami, V. K. Pare, M. J. Saltmarsh, D. W. Swain, and C. E. Thomas
Fusion Energy Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

(Received 15 May 1981)

Observations of radiation from iron and from argon used as a test gas indicate that co-injection inhibits impurity accumulation in the interior of ISX-*B* (impurity study experiment) tokamak discharges, but counter-injection enhances accumulation. These results agree qualitatively with recent theoretical calculations.

PACS numbers: 52.25.Fi, 52.40.Mj, 52.55.Kc

One of the major impediments to achieving net power production from a fusion device may be the presence of impurities than can adversely affect the plasma. Because of this potential problem, a great deal of attention has been focused on methods of controlling the generation of impurities or of minimizing the transport of contaminants into the plasma. Some novel theoretical ideas within the framework of neoclassical theory have emerged recently showing that co-injection of neutral beams (beam current in the same direction as plasma current) can reduce the usual inward transport, whereas counter-injection can produce the opposite behavior.[1,2] These effects should be strongest near the center of the plasma where the momentum transfer from the beams and the plasma rotation are the largest. In this paper we discuss experimental results indicating that impurity behavior consistent with these theories is seen in the ISX-*B* (impurity study experiment) tokamak, although close quantitative comparisons are not yet possible.

Impurity transport in tokamaks is a notoriously complicated problem. In addition to the well understood classical and neoclassical processes,[3] which by themselves would cause impurities to accumulate in the interior of Ohmically heated plasmas, it is usually necessary to invoke an empirical, anomalous diffusion process to explain why accumulation proceeds slowly[4] or why it does not occur at all. If the anomalous transport is large enough, it is not expected that neoclassical, beam-induced effects can be detected. But in the ISX-*B* tokamak impurities do accumulate in Ohmically heated deuterium discharges,[5] and as a result, distinct changes of transport resulting from neutral-beam injection can be observed.[6] Similar changes take place in hydrogen discharges, but they are less distinctive. Anomalous transport is apparently more important in hydrogen discharges than in deuterium ones because accumulation does not occur in Ohmically heated hydrogen plasmas; i.e., the impurity confinement time is shorter than the duration of the discharge.

Typical results for the radiation of argon introduced as a test gas during Ohmically heated discharges are shown in Fig. 1. These data provide a reference for later comparison with the results obtained when using neutral-beam injection. The

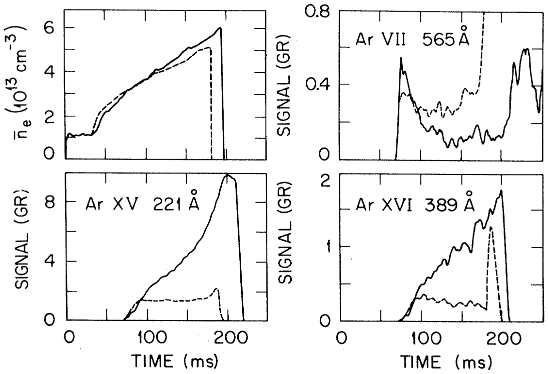

FIG. 1. Line-averaged electron densities and argon line radiation for Ohmically heated discharges in deuterium (solid lines) and in hydrogen (dashed lines). Argon is introduced in a 4-ms pulse at 60 ms.

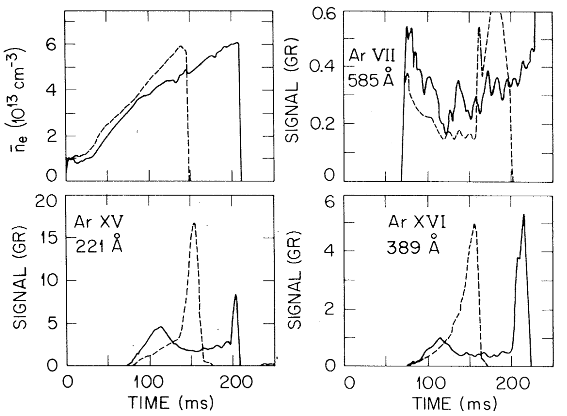

FIG. 2. Line-averaged electron densities and argon line radiation in co-injection (solid lines) and in counter-injection (dashed lines) deuterium discharges. Argon is introduced in a 4-ms pulse at 60 ms and neutral beam injection lasts from 100 to 200 ms.

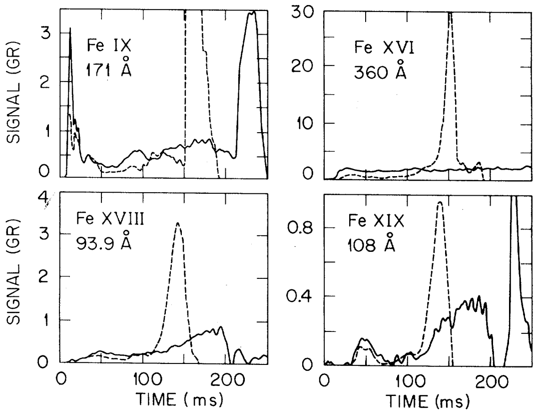

FIG. 3. Iron line radiation in co-injection (solid lines) and counter-injection (dashed lines) discharges in deuterium. Neutral beam injection lasts from 100 to 200 ms.

controlled use of argon for investigating transport phenomena obviates variations of source rates during the discharge; such variations can lead to ambiguities if only the intrinsic impurities are used to investigate particle fluxes. The argon is introduced in a pulse of 4 ms duration at 60 ms after the discharge begins. After 30 ms, the radiation in a hydrogen discharge changes only slowly for all of the ionization stages that are shown. For comparable parameters in deuterium, the radiation from Ar XV and Ar XVI ions in the interior of the plasma continually increases at a rate that is significantly greater than the rate of increase of the electron density, while the radiation from Ar VII on the outside of the plasma column decreases to 15%–20% of its peak value (the behavior is similar if n_e is held constant). The plasma conditions are nearly the same in both cases, exhibiting "sawtooth" behavior but showing only weak activity from modes with $m \geqslant 2$. These results clearly indicate that the argon concentration becomes much more centrally peaked in deuterium than in hydrogen.

Figures 2 and 3 illustrate typical signals from argon and iron in deuterium plasmas when using 600 kW of neutral-beam injection. The evolution of the argon line emission is similar to that from the Ohmically heated discharges up to 100 ms when injection begins (less argon was used in the counter-injection shots than in the other two sequences). The plasma parameters are kept as nearly the same as possible up to this time as evidenced by traces of $\bar{n}_e$ in Fig. 2 and by the central-chord, soft x-ray signals shown in Fig. 4. The plasma current is 200 kA and the toroidal field is 12.9 kG. The central temperatures just prior to injection are assumed to be the same as measured in the Ohmically heated discharges, 400–450 eV. After 120 ms, the time dependence of the radiation from deuterium plasmas differs markedly among the three cases shown in Figs. 1 and 2, although profiles of the electron temperatures and densities, taken at 190 ms and at 130 ms for the co-injection and counter-injection discharges, respectively, are very similar with $T_e(0) \simeq 700$ eV.

In order to interpret the spectroscopic data, it is first necessary to assess the changes that electron heating would have on the line radiation if the impurity concentration were to remain unchanged by injection. Modeling calculations using

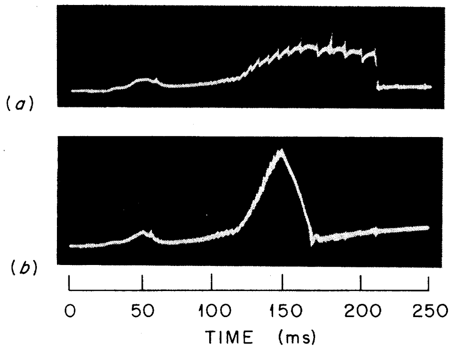

FIG. 4. Soft x-ray (p-i-n diode) signals during (a) co-injection and (b) counter-injection discharges in deuterium.

the RECYCL code[7] with fixed functional forms for T_e profiles and with average impurity transport velocities of 1.2 cm/ms, to agree with the velocities inferred from the Ohmically heated discharges, indicate that the Ar XV radiation should decrease by about 20% if $T_e(0)$ changes from 450 to 700 eV, but that the Ar XVI emission should increase by a factor of 2. Similar calculations show that broadening of the electron temperature profiles, within the range that generally occurs during injection, should affect radiation from either stage by less than 10%. Therefore, the factor of 2 decrease of the emissions following co-injection cannot result from variations of the temperature or of the shape of its radial profile. Instead, it indicates that the argon concentration in the interior of the plasma does not continue to build up throughout the discharge as it does with Ohmic heating alone, but that it actually decreases. Also, the reversal after 120 ms in the declining Ar VII signal is directly opposite to the behavior expected for a fixed total argon profile during electron heating, and these data are interpreted as indicating that the argon depletion from the exterior of the plasma is halted or reversed during co-injection. The same type of analysis shows that the rapid increase of intensity following counter-injection reflects a very strong accumulation in the interior. In summation, all of the data indicate that argon accumulation is inhibited by co-injection and enhanced by counter-injection. It should be noted that attempts to observe similar effects on the Princeton Large Torus tokamak have indicated little difference of the argon influx during Ohmic heating or co-injection; the influx was, however, larger during counter-injection.[8]

The interpretation of the iron emission is similar to that of the argon. If the changes of the electron temperature and density during injection are taken into account, the general evolutions of the Fe XVI, Fe XVIII and Fe XIX lines during co-injection are consistent with the iron content of the plasma remaining constant. The accumulation that occurs during Ohmic heating is halted. The fact that the iron concentration in the interior does not actually appear to decrease, as does the argon, may reflect an additional influx caused by plasma heating; in some experiments decreases have been observed.[6] In contrast, the influx to the center during counter-injection is so fast that the plasma begins to cool at about 130 ms. This cooling is accompanied by recombination into lower stages of the iron, and as the Fe XVIII and Fe XIX line intensities decrease, Fe XVI and Fe XV begin to radiate strongly. The discharge then disrupts around 160 ms. The temporal behavior of the soft x-ray signals in Fig. 4 corroborates the conclusions about impurity transport drawn from the spectral data. For the same values of $T_e(0)$ and $n_e(0)$, these signals are proportional to the impurity content in the center of the plasma. They show that following the electron heating by co-injection no long-term impurity accumulation takes place but rapid accumulation takes place initially during counter-injection. The loss of signal after 150 ms in the counter-injection discharges reflects the decrease of $T_e(0)$ caused by radiative losses.

The strong increase of iron radiation cannot be explained by assuming that poorly confined hot ions formed during counter-injection are introducing significant amounts of additional iron. Enhanced emission does not appear in all the ionization stages as it would if the increase were solely caused by additional iron being brought into the discharge without a simultaneous change of the transport rates. In fact, after an initial rise, the Fe IX signal actually decreases as the radiation from the interior ions rise. It has been known for several years that impurity problems are more severe with counter-injection than with co-injection, but that simultaneous injection in the two directions often produced radiative losses that were smaller than with counter-injection alone.[7,9,10] This result is understandable in terms of beam-induced effects on impurity transport, but is not understandable in terms of source changes. The fact that argon, which is not produced by a plasma-wall interaction, behaves the same as the iron strengthens the conclusion that the rapid rise of the iron emission during counter-injection results from changes of transport.

The differences between impurity behavior in Ohmically heated, co-injection, and counter-injection discharges in deuterium are consistent with the theories mentioned previously,[1,2] but it is necessary to address the question of whether anomalous diffusive effects not contained in these theories could account for the present observations. The buildup of impurities in the interior of the plasma during counter-injection cannot result from an increase of the anomalous diffusive mechanisms because these would produce flatter, rather than more peaked, impurity profiles. Therefore, we can only conclude that the accumulative processes are enhanced by the neutral beams, and that any concomitant increase of the anomalous transport is relatively small. The results of counter-injection experiments in hydrogen support these conclusions. They also show that the argon radiation from the interior increases, although the maximum emission is a factor of 3–5 lower than in deuterium.

Evaluation of the co-injection results is not so straightforward, because either reductions of the accumulative mechanisms or enhancement of anomalous diffusion can prevent the accumulation. But the fact that neoclassical, beam-induced effects seem to increase the accumulation rates of impurities during counter-injection, even in hydrogen discharges where the anomalous processes are relatively large, provides a strong argument that the same mechanisms inhibit the impurity influx during co-injection. In addition, the magnetohydrodynamic activity, which often serves as an indicator of changes in the anomalous impurity transport, remains at a very low level. It is not significantly intensified by injection. Therefore, it appears that increases of anomalous transport are of secondary importance in the experiments we describe here, and the lack of accumulation during co-injection is caused by reductions of the neoclassical effects.

In summary, the present results from the ISX-*B* tokamak indicate that co-injection inhibits inward impurity transport and counter-injection enhances it, in qualitative agreement with recent theories.[1,2] The capability of making these observations requires that anomalous diffusive effects do not overwhelm neoclassical mechanisms and that increases of impurity influxes during injection do not obscure transport changes.

We would like to acknowledge the cooperation and help of the entire ISX group during these studies. Special thanks are also due to D. J. Sigmar and K. H. Burrell for several helpful discussions. This research was sponsored by the Office of Fusion Energy, U. S. Department of Energy, under Contract No. W-7405-ENG-26 with the Union Carbide Corporation.

---

[a] Visitor from Japan Atomic Energy Research Institute, Tokai, Ibaraki, Japan.

[1] W. M. Stacey and D. J. Sigmar, Nucl. Fusion 19, 1665 (1979).

[2] K. H. Burrell, T. Ohkawa, and S. K. Wong, General Atomic Company Report No. GA-A16082, 1980 (unpublished).

[3] S. I. Braginskii, in *Reviews of Plasma Physics*, edited by M. A. Leontovich (Consultants Bureau, New York, 1965), Vol. 1; L. Spitzer, Jr., Astrophys. J. 116, 299 (1952); J. B. Taylor, Phys. Fluids 4, 1142 (1961).

[4] E. C. Crume, D. E. Arnurius, and R. C. Isler, Bull. Am. Phys. Soc. 25, 867 (1980).

[5] R. C. Isler, S. Kasai, L. E. Murray, M. Saltmarsh, and M. Murakami, Phys. Rev. Lett. 47, 333 (1981).

[6] R. C. Isler, E. C. Crume, D. E. Arnurius, and L. E. Murray, Oak Ridge National Laboratory Technical Memorandum No. ORNL/TM-7472, 1980 (unpublished).

[7] R. C. Isler, E. C. Crume, and H. C. Howe, Nucl. Fusion 19, 727 (1979).

[8] K. Brau, Bull. Am. Phys. Soc. 24, 1107 (1979).

[9] L. Grisham, H. Hsuan, and G. Schmidt, Bull. Am. Phys. Soc. 23, 797 (1978).

[10] E. Hinnov, K. Bol, H. Eubank, R. Hawryluk, J. Hosea, E. Meservy, and S. Suckewer, Bull. Am. Phys. Soc. 23, 874 (1978).

Apparent and Real Thermal Inhibition in Laser-Produced Plasmas

R. J. Mason
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 10 February 1981)

Laser-driven thermal-electron-transport inhibition is studied with use of a self-consistent Monte Carlo model for all the electrons. Comparison is made with the results of flux-limited single-group–diffusion calculations. The need for severe flux limiters is traced to deficiencies in the classical diffusion modeling that can excessively heat the overdense surface matter of a pellet, ignore coronal decoupling of the thermals electrons, and neglect the effects of electric-fields for a return current through density gradients.

PACS numbers: 52.25.Fi, 52.50.Jm, 52.65.+z

For some time it has been recognized[1,2] that severe flux limitation must be imposed on thermal electron diffusion for accurate modeling of laser-plasma interactions. The implied thermal inhibition has been ascribed to ion-acoustic turbulence,[3] suprathermal and thermal counter-

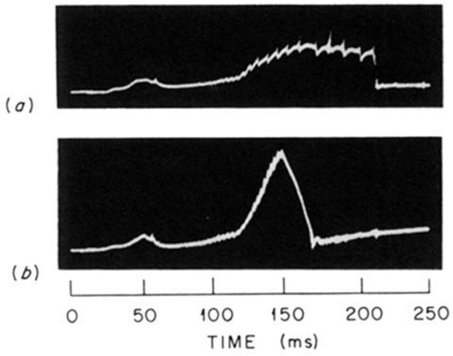

FIG. 4. Soft x-ray (p-i-n diode) signals during (a) co-injection and (b) counter-injection discharges in deuterium.