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[9]It may be difficult to observe the shifts directly as these are very small as compared to the frequency of radiation, and the superfluorescence pulses are very shortlived (~1 ns). These shifts can, however, be detected in quantum beat experiments because these shifts are not so small in comparison with the beat frequency.

[10]We work in the natural system of units $c=\hbar=1$.

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[13]At small times, the frequency-time uncertainty gives large frequency widths in the radiations generated by the two transitions which obviously have a wide band of overlapping frequencies. But, this does not give any interference as the emitting upper levels are uncorrelated. This is explicitly seen in perturbation calculations. Correlation comes in higher orders when the interaction of initially uncorrelated two-level systems with each other through the common radiation field is taken into account.

Suppression of Metallic Impurities by Electron Injection in a Tokamak

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We found that the sheath potential plays a dominant role in the plasma-wall interaction in the Macrotor tokamak. An increase in the sheath potential, produced by removing electrons from the plasma, results in the enhancement of the metal influx. When the sheath potential is reduced by electron injection, the metal influx is suppressed. This mechanism may be used as a tool in controlling metallic impurities in tokamaks.

Impurity control will be essential for fusion reactors. In tokamaks, low-Z impurity control has been achieved by the removal or by the trapping of impurities on the wall. These results have been reported elsewhere.[1,2] Techniques for reduction of metallic impurities have not yet been developed. Divertor[3] and nondivertor[4] schemes presently are being studied. We are reporting here new observations which indicate that the acceleration of ions by the sheath potential and not the ion temperature (through charge exchange) is the primary mechanism for metallic impurity generation in the Macrotor tokamak.

Figure 1 shows the experimental arrangement used for enhancement of the metal influx due to an *increase* in the sheath potential. Here, the toridal chamber is separated into two halves in a poloidal plane, forming two electric gaps. One of these gaps is normally used to allow the penetration of the poloidal flux needed for the plasma current. In the present experiment, both gaps are used for the superposition of the electrostatic fields around the plasma boundary. For the purpose of this discussion, the plasma is assumed to have a highly conducting core which forms a ring around the torus surrounded by a sheath region where ion-electron charge separation takes place.

When a dc potential is applied between the conducting shells, diffusive electron and ion fluxes flow to A and B halves of the chamber, respectively. Particularly, when B is made negative (200 V), practically all the ions leaving the plasma are collected by it. At the same time, A extracts the corresponding electron current. In this sense, the chamber halves behave as large Langmuir probes. Figure 2 shows the V-I characteristics of the two halves in the presence of tokamak plasmas. The change in the plasma potential relative to A is also shown. A large sheath drop develops only on the negative side. On the positive side, electrons tend to short circuit the

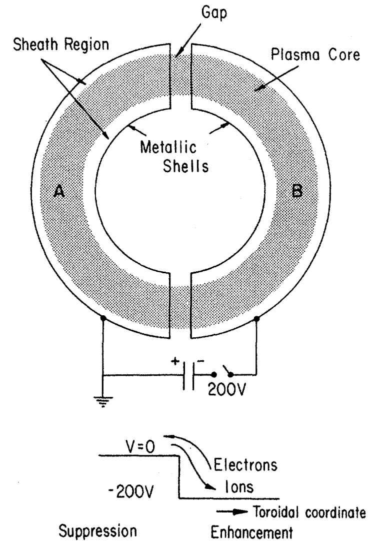

FIG. 1. Experimental arrangement for enhancement of the impurity influx. The negative half of the chamber accelerates the escaping ions through the sheath. This results in sputtering.

plasma to the chamber as if the plasma was not magnetized, or had open field lines to the wall (i.e., as in a "Q" machine).

We have previously reported the observation of increased impurity influx on the negative (ion) side.[5] Additional experiments were made with a small target plate, where the short circuiting by electrons is limited, allowing a local reversal

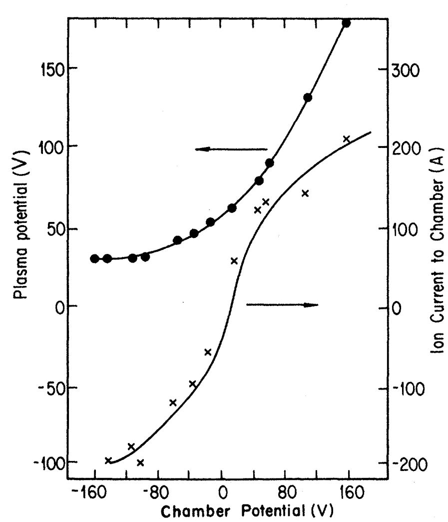

FIG. 2. The V-I characteristics of the tokamak chamber showing that the plasma is short circuited to the positive half of the chamber. On the negative half, the sheath drop increases with potential. ($V_{\text{sheath}} = V_{\text{plasma}} - V_{\text{chamber}}$.)

of the sheath potential. Reduction of the impurity influx was observed. Similar results were observed with an Al target placed in the divertor chamber of DIVA.[6] The possibility appeared that if the whole plasma could be biased negatively with respect to the wall, thus reducing the bombarding energy of the ions, the impurity influx would also be reduced.

We have recently succeeded in reducing the space (and, consequently, the sheath) potential by electron injection from tungsten filaments in the Macrotor tokamak. Figure 3 shows the experimental arrangement. Here, both halves of the chamber are used as one electrode by shorting one of the gaps. A total of 16 filaments (10 cm in length, and 1 mm in diameter) were placed 10 cm away from the wall. The plasms radius is 45 cm. The filaments are pulsed negative (100–300 V) with respect to the chamber for a short time in the quiescent phase of the discharge. The floating and the space potentials are monitored by Langmuir probes at the plasma edge. (These are swept in voltage, and the potentials are determined from V-I characteristics.) When electrons are injected, both the floating and the space potentials become more negative, reducing the energy of escaping ions. Spectroscopic observations of the Cr I (4254 Å) line show the reduction in the influx of the chromium by an order of magnitude. The Fe I influx behaves similarly.

Figure 4 shows the dynamics of the discharge during the application of the cold electron current I_e. The top trace represents the typical plasma current I_p. The change in the floating potential V_f is related to the abrupt application of the electron current. This results in a corresponding decrease in the Cr I radiation almost

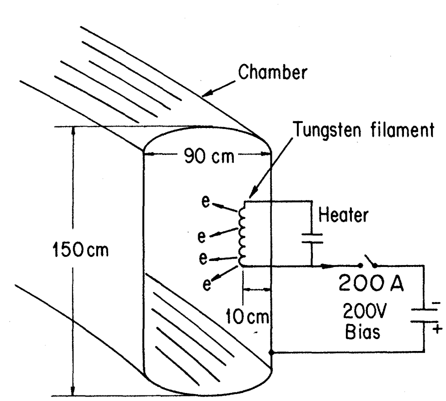

FIG. 3. Experimental arrangement for the injection of electrons into a tokamak from tungsten filaments placed at the plasma edge.

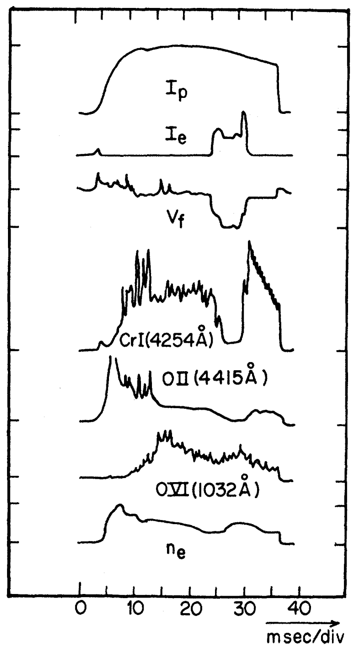

FIG. 4. The temporal signals observed in connection with the suppression of chromium influx due to electron injection. Note the large reduction factor obtained in the chromium trace. Possible background radiation near the chromium line has not been removed. ($I_p = 50$ kA; $I_e = 200$ A; $V_f = -150$ V; $n_e = 3\times10^{12}$ cm^{-3}; radiation in arbitrary units.)

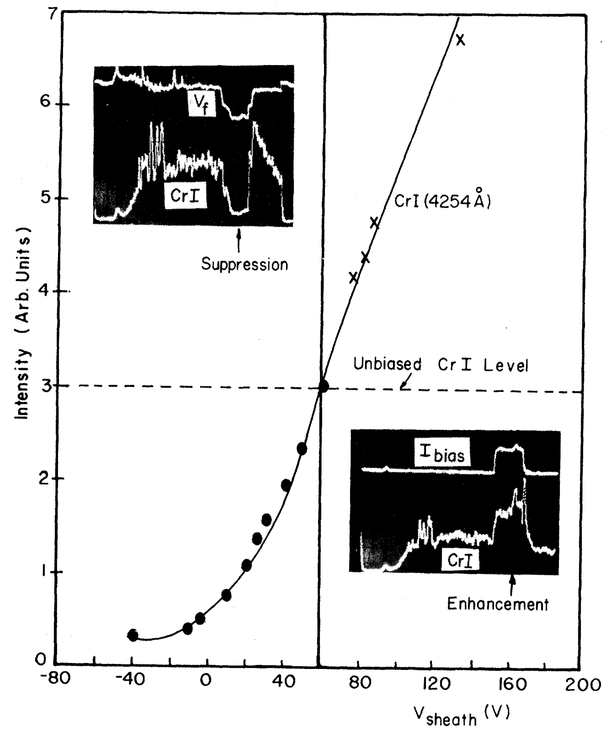

FIG. 5. Suppression and enhancement in the chromium influx as a function of the sheath potential in the Macrotor tokamak. The insets show typical raw data in the case of large suppression and enhancement.

to zero level uniformly around the total surface of the plasma channel. The O II radiation also decreases. No significant change is seen in the Cr II line (not shown), excluding the presence of large spectroscopic anomalies.

There is a slight increase in the electron line density n_e (monitored by a microwave interferometer) and the O VI radiation. The latter changes may be related to the 50% increase in the power input (≅ 40 kW) due to electron injection. The variations obtained in the Cr influx as a function of the sheath (plasma potential) are shown in Fig. 5 for both suppression and enhancement experiments. (The abscissa has been inferred from voltage-swept Langmuir-probe traces.) It is apparent that the reduction of Cr influx takes place for space potentials negative with respect to the wall.

The insets show observed increase (decrease) in the Cr I radiation. Cr II behaves similarly. The external current used for the sheath modifications in both suppression and enhancement experiments was about 200 A. No significant changes in the plasma equilibrium were observed for short pulse durations. The injected electrons tend to slightly cool the plasma edge (10–20%), which does not account for the large change in the Cr I signals. Furthermore, in the injection experiments where the sheath potential did not change (due to unfavorable plasma-wall contact) a slight *increase* was observed on all line radiation, excluding the possibility of interference from the presence of filaments. The metal (Cr, Fe) radiation was *reduced only if* the sheath potential *decreased* during electron injection.

In conclusion, we have shown that the sheath potential plays a dominant role in the Macrotor tokamak in stimulating the influx of metallic impurities. The injection of cold electrons into a tokamak can reduce the sheath potential and decelerate the ions before they hit the wall. This results in suppression of impurities through reduction of sputtering. Neutral-particle sputtering does not yet play a dominant role. The experiments were conducted in a device where the metallic influx was not from a localized limiter. These results may be of interest for divertor applications, where it is desirable to have a low sheath potential.[7] In a reactor, electrons may be injected into a plasma from large limiter plates with good secondary electron yields to keep the sheath potential low.

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Behavior of Persistent Currents under Conditions of Strong Decay

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We report observations of the decay of persistent currents of thin superfluid ^{4}He films for which the superfluid velocity deviates strongly from the previously observed log$t$ behavior. We present data which document the evolution of this behavior as a function of film thickness. The Iordanskii-Langer-Fisher theory does not accurately describe our observations.

Superfluid ^{4}He has the remarkable ability to attain a state of macroscopic persistent flow. It is generally assumed that such flow is, in fact, only metastable. In some cases the instability is weak enough to render the flow persistent over laboratory lifetimes. In other cases the metastability becomes clearly apparent. Previous to this report[1] all studies of the degradation in time of these persistent currents yielded results which could be adequately described by

$$v(t) = a - b \log t, \qquad (1)$$

where $v(t)$ is the macroscopic velocity of the flow at time t and a and b are empirical parameters. In particular, Kojima *et al.*,[2] Kukich, Henkel, and Reppy,[3] and Langer and Reppy[4] have observed that the flow of bulk ^{4}He in restricted geometries (compressed powders, Vycor, etc.) obeys Eq. (1). The Iordanskii-Langer-Fisher[5,6] (ILF) model of persistent-current decay generally predicts Eq. (1) under conditions for which the superfluid velocity makes small deviations from a critical velocity, v_c.

Telschow and Hallock[7] have also reported general agreement with Eq. (1) in studies of persistent flow in thin ^{4}He films, but they observed this behavior to be obeyed even for changes in the velocity of as much as 60% away from the initial[8] velocity, v_0. We present results here of studies of persistent currents in ^{4}He films for which the decays in some cases appear to cause the complete extinction of the flow. Our results as a function of film thickness show clearly for the first time the evolution of deviations from Eq. (1).

The apparatus used for the present work is an improved version of that used[7,9] earlier in this laboratory. Persistent currents are generated on a Pyrex annular ring without rotation using a thermal technique.[7] The speed of the persistent flow is measured using the well-known techniques of Doppler-shifted third sound.[10] We have observed that the strength and nature of the velocity decays does not depend on the presence of the third sound necessary to make the measurements. Film thickness values are determined[11] from the temperature and vapor pressure and are consistent to within a few percent with thickness values deduced[11] from the observed third-sound velocity. Changes in the film thickness due to the flow of the film are observable[12] but are too small to be relevant here.

Data on the decay of the persistent currents are

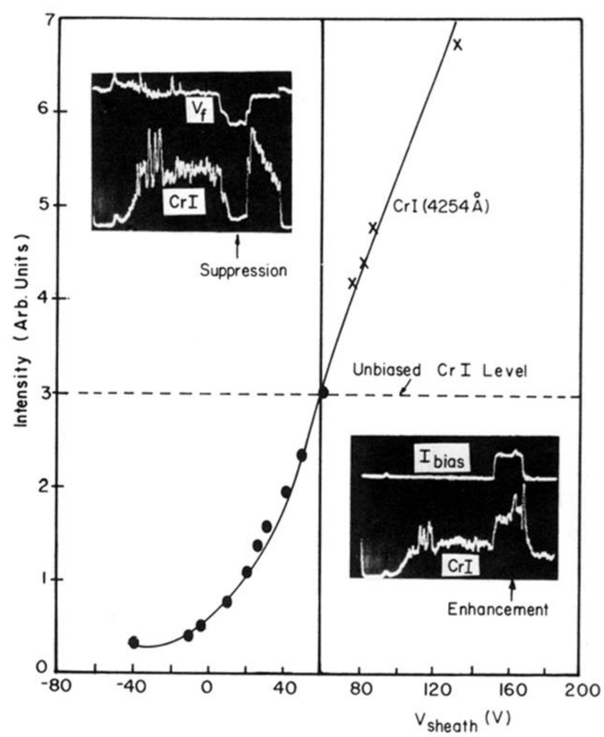

FIG. 5. Suppression and enhancement in the chromium influx as a function of the sheath potential in the Macrotor tokamak. The insets show typical raw data in the case of large suppression and enhancement.