Long-Time Impurity Confinement as a Precursor to Disruptions in Ohmically Heated Tokamaks

R. C. Isler
Fusion Energy Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee 37830

and

W. L. Rowan and W. L. Hodge
Fusion Research Center, University of Texas at Austin, Austin, Texas 78712

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The confinement times of impurities in Ohmically heated tokamaks are shown to lengthen considerably as the density-limit boundary is approached and exceeded either by the increase of n_e itself or by the lowering of B_T or I_p. Observations made on the Texas tokamak indicate that a change in the balance of diffusion and inward convection mechanisms governing impurity transport precedes the onset of partial or major disruptions. These studies also explain the reason for the wide differences of impurity behavior previously observed among various tokamaks.

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The controllable parameters for producing Ohmically heated (OH) tokamak plasmas are the torodial field (B_T), the plasma current (I_p), and the electron density (n_e). In terms of these variables, the space over which a tokamak can be made to operate is limited by the appearance of disruptive instabilities, which either destroy the integrity of flux surfaces, leading to poor confinement properties, or terminate the current pulse completely. It is common to exhibit the region of stability for a given machine on a plot of $1/q_l$, the inverse safety factor, versus the Murakami parameter, $\bar{n}_e R_0/B_T$.[1,2] These regions typically occupy a somewhat triangular area on such a plot, as illustrated by the shaded portion of Fig. 1.

It is well known that impurities play an important role in setting the operating limits in OH plasmas since the right-hand boundary shown in Fig. 1, which is usually characterized as the density limit, can be extended significantly by the use of gettering to reduce the sources of low-Z elements. In a simple approximation, the increment of the volume-averaged impurity density beginning at some time t_0 is given by

$$\bar{n}_z=\Gamma_z\tau_z(S/V)[1-e^{-(t-t_0)/\tau_z}], \tag{1}$$

where the impurity confinement time, τ_z, and the influx per unit area, Γ_z, are constant in time. S is the total surface area of the plasma and V is its volume.

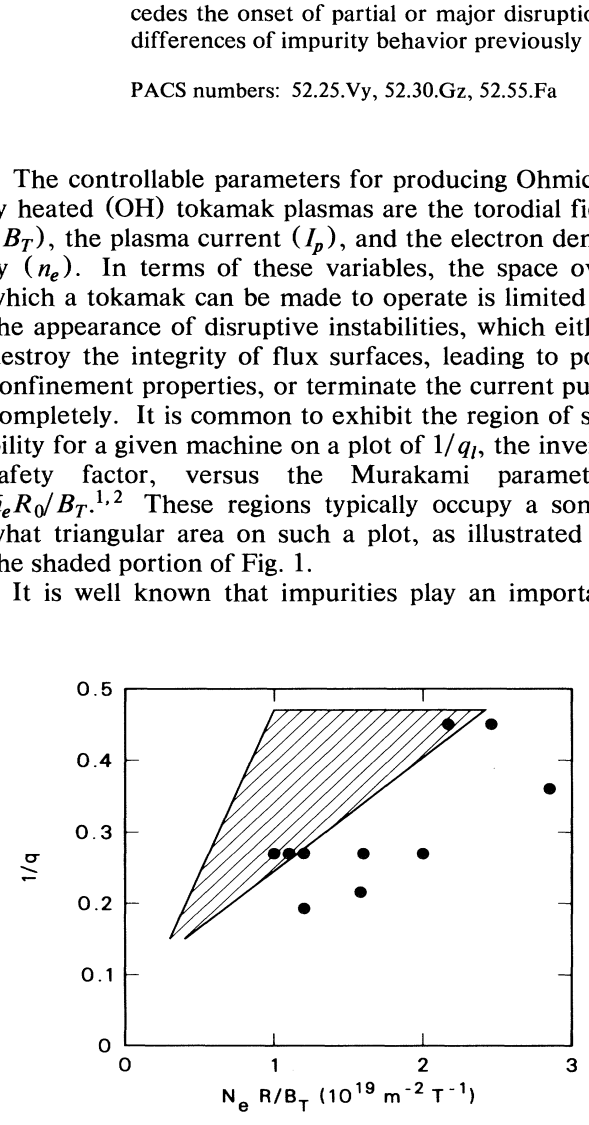

FIG. 1. Illustration of the region of stability in a tokamak. The shaded area is intended to depict a typical operating range. The points represent regions explored in the present work.

Several theoretical papers have ascribed the density limit as resulting directly from radiative cooling exceeding the Ohmic input in the main current channel,[3] or from instabilities induced as the result of strong edge cooling.[4-9] It should be noted from Eq. (1) that even if Γ_z and τ_z are too large to maintain long-pulse operation, it is possible to produce short-pulse discharges of several hundred milliseconds so long as $t-t_0$ remains much less than τ_z. In this paper we emphasize the influence of confinement times, as distinct from the influxes, on establishing the extent of the stable operating space. In particular, we show that the onset of instabilities is associated with a change of impurity confinement from a short-time, diffusion-dominated process to a long-time, convection-dominated phenomenon. The transition can be achieved by independent alteration of any of the three parameters $\bar{n}_e$, B_T, or I_p. These results provide a link between previous work on the low-field ($B_t \leq 15$ kG), low-current ($I_p \leq 200$ kA) impurity-study-experiment-B (ISX-B) tokamak, where long confinement times and accumulation were normally observed in deuterium plasmas,[10-12] with investigations on other machines where τ_z was always less than the length of the discharges.[13–15]

Impurity confinement times have been examined under several operating conditions in the Texas tokamak (TEXT) by the monitoring of the decay of laser-injected scandium ions. The test ions do not seriously perturb the plasmas, except in borderline operating conditions when they may cause disruptions to appear at slightly lower densities than normal. The major and minor radii of this machine are 100 and 28 cm, respectively, and the maximum toroidal field is 28 kG. Discharges are characterized as unstable if they cannot be maintained without a partial or a major disruption for the full 500-ms capability of the OH power supply. All the results which we illustrate are for deuterium plasmas. The operating range investigated is shown by the points in Fig. 1. (The shaded area of Fig. 1 should not be interpreted as the extent of the stability region in TEXT. Only the right-hand boundary has been partially delineated from the work that we describe here.)

The time behaviors of several stages of scandium are compared in Fig. 2 for operating conditions having the maximum (solid lines) and minimum (dashed lines) values of $\bar{n}_e/B_T I_p$ in these studies. The discharges with the small value of this parameter are stable for the full 500-ms pulse length, and the decay times of the scandium signals are comparable to those observed in the extensive scaling studies on the Alcator tokamaks.[14] Because all the emissions decay to zero for the full-length discharges, the data are interpreted from the *e*-folding times as showing that the confinement times of interior ions are about 30 ms. For the large value of $\bar{n}_e/B_T I_p$, disruptions occur around 205 ms, and the scandium signals do not decay uniformly. In fact, the Sc XVI and Sc XIII emissions are actually increasing as the Sc XIX and Sc XVII disappear. Similar behavior of titanium in the ISX-B tokamak was analyzed as showing that few, if any, of the test ions actually diffused out of the plasmas. The temporal evolution was completely attributable to recombination, rather than transport, as the plasmas cooled from intrinsic impurity accumulation.[12] Impurity confinement times may be of the order of seconds in such discharges.[11]

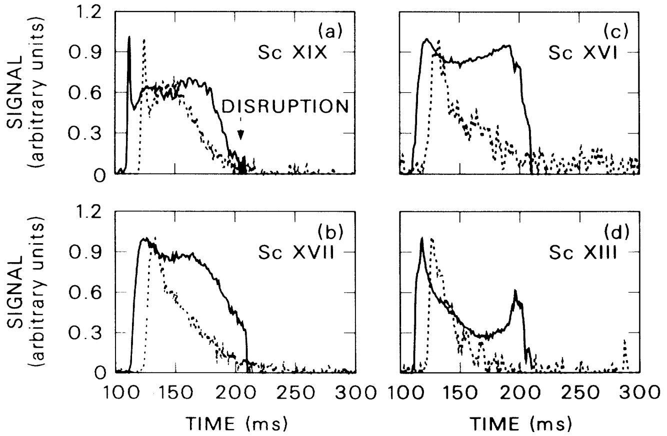

FIG. 2. Time histories of injected scandium ions for the maximum (solid) and minimum (dashed) values of $\bar{n}_e/B_T I_p$ explored in the present work. Solid curves: injection at 110 ms, $B_T = 15$ kG, $I_p = 150$ kA, and $\bar{n}_e = 3 \times 10^{13}/\mathrm{cm}^3$. Dashed curves: injection at 120 ms, $B_T = 20$ kG, $I_p = 200$ kA, and $\bar{n}_e = 1.6 \times 10^{13}/\mathrm{cm}^3$. The initial spike on the Sc XIX signals originates from a low ionization stage.

The sensitivity of confinement properties to controllable parameters are illustrated in Figs. 3–5 for certain ionization stages of scandium. The erratic emissions subsequent to partial disruptions have been suppressed in these figures in order to make the results clearer. Sc XVII emissions from a toroidal-field scan having $I_p = 200$ kA and $\bar{n}_e = (3.5\text{–}4.3) \times 10^{13}/\mathrm{cm}^3$ are shown in Fig. 3. The 28-kG case is on the borderline of operating for the full 500 ms, but it does disrupt between 400 and 450 ms. As the magnetic field is reduced the disruption occurs at the successively earlier times of 290, 260, and 220 ms. The decay of the test ions cannot be characterized by a single confinement time throughout the discharges. Although it appears that essentially all injected ions are lost from the system in nondisruptive situations, the concentrations do not decay completely for the disruptive cases. Instead, they fall only to some nonzero level which is not dissipated by recycling to the limiter. The level becomes higher as B_T is decreased, and at 15 kG most of the scandium is retained. These data suggest that the relative importance of diffusion and convection changes strongly as a function of B_T and that the transition may actually occur during the course of a discharge. In the frequently used empirical model of impurity transport where the diffusion coefficient is

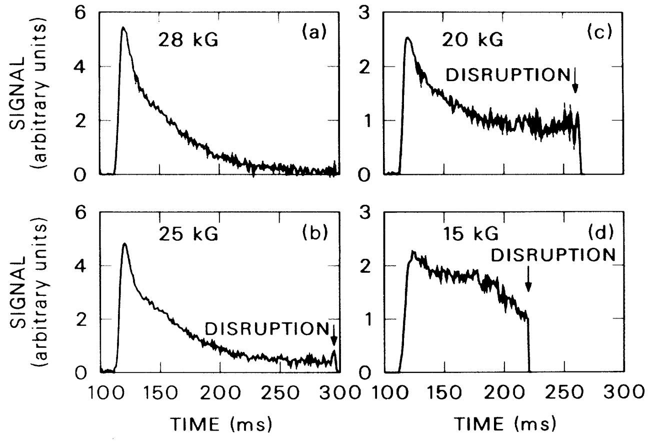

FIG. 3. Time behavior of Sc XVII for the toroidal-field scan. Deuterium plasmas with $I_p = 200$ kA, $\bar{n}_e(\max) = (3.5\text{–}4.3) \times 10^{13}/\mathrm{cm}^3$.

assumed to be constant and the magnitude of the inward convection coefficient is taken as $V_c = V_0 r/a$, the steady-state solution of the continuity equation is a Gaussian profile with a width proportional to V_0/D.[16] The increasing retention of highly ionized stages as a function of $1/B_T$ is believed to indicate that steeper impurity gradients are maintained between the plasma interior and its edge as V_0/D increases. Experiments in ISX-B, using nitrogen as a test gas for pump-limiter studies, have indeed shown that little interchange of impurities occurs between the main plasma and the scrape-off layer under conditions where partial entrapment of N^{7+} is observed[17]; i.e., there appears to be a barrier to radial diffusion in the vicinity of the limiter tip.

Large changes of τ_z are also reflected in the spectral-line histories from a current scan (Fig. 4) and from a density scan (Fig. 5). The 250-kA case shown in Fig. 4 is barely within the stable region. The Sc XVII decays are seen to be 3–4 times longer than the low-density case depicted in Fig. 2. Nevertheless, most of the test ions are lost from the plasmas within 110–120 ms. The confinement times are much longer at the lower currents, and disruptions occur between 200 and 300 ms. Figure 5(a) illustrates the decay of Sc XIX from the lowest (dashed curve) and highest (solid curve) densities studied during an $\bar{n}_e$ scan at constant q_l. An intermediate case is shown in Fig. 5(b). For the lowest density, the Sc XIX emission disappears quickly. As $\bar{n}_e$ is raised the decay time gradually lengthens, and the period of stability shortens. The intermediate-density case [Fig. 5(b)], which disrupts at 370 ms, is very revealing. Scandium from the periphery begins to accumulate in the interior after 300 ms. This reversal of net flow supports the inference that the transport coefficients are altered during a discharge such that the diffusive losses begin to be counterbalanced by inward convection.

Because the impurity confinement times become very long, it is natural to inquire whether accumulation and radiative losses from intrinsic contaminants in the plasma core set the stability limits or whether they result from unfavorable current profiles without reach-

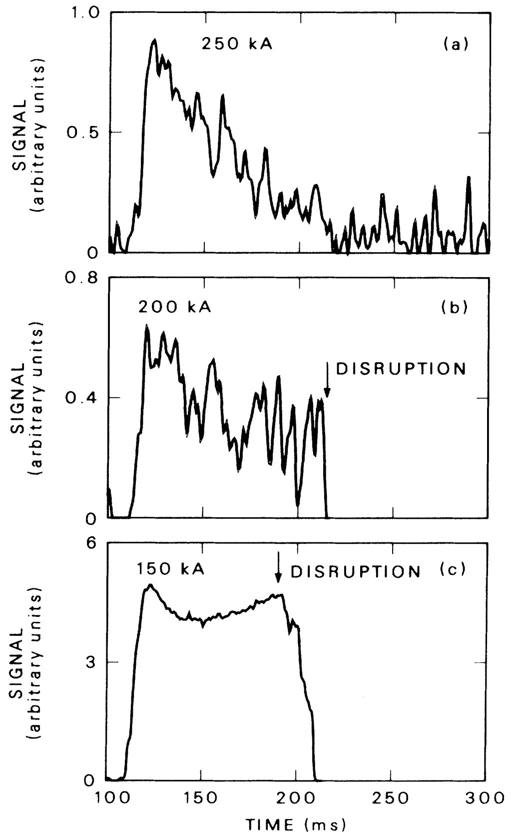

FIG. 4. Comparison of Sc XVI signals for the current scan. Deuterium plasmas with $B_T = 15$ kG and $\bar{n}_e(\max) = (3.5\text{–}4.3)\times 10^{13}/\text{cm}^3$.

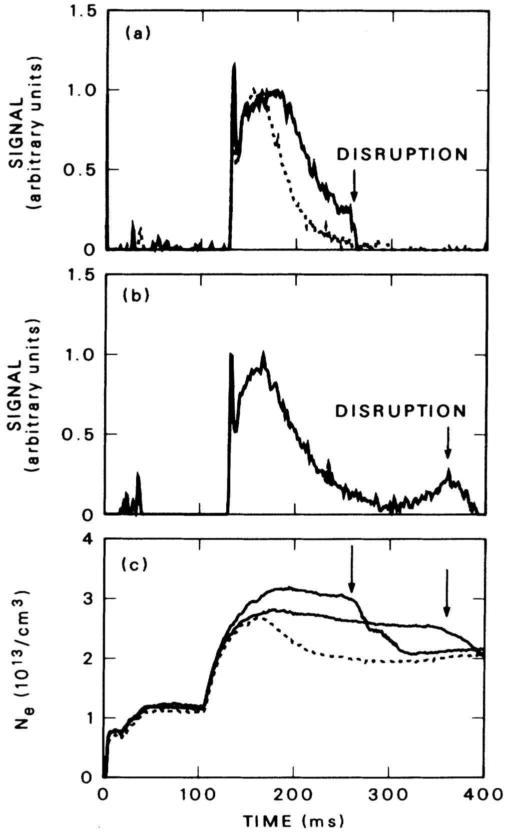

FIG. 5. (a),(b) Sc XIX emissions and (c) $\bar{n}_e$ histories during the density-scan sequence. Deuterium plasmas with $B_T = 20$ kG and $I_p = 200$ kA. (a) Radiation observed during the highest (solid line) and lowest (dashed line) density shots studied. (b) Intermediate-density case where peripheral scandium starts to flow back into the interior after 300 ms.

ing the radiative limits in the main current channel. Two of the seven discharge conditions studied terminated in hard disruptions which were preceded by a growth in the MHD activity. The other five had partial disruptions, and did not evidence significant enhancment of MHD activity prior to this event. For these five sequences, the central-chord soft-x-ray signals indicate that the Ohmic power input is insufficient to sustain the radiated losses. Prominent sawtooth behavior is evident until 10 to 30 ms before the disruption. The sawtooth behavior then ceases, and immediately before the disruption the signal level begins to drop, an indication that $T_e(0)$ is also falling. For the sequences farthest from the stability boundary, rapid accumulation of intrinsic impurity ions is observed both from the rising soft-x-ray signals and from vacuum-ultraviolet lines *during* the sawtooth period. The sawtooth behavior most likely prevents the development of narrow central peaks in the impurity distribution, but it does not forestall the buildup of the average concentrations in the interior of the plasmas. No strong evidence of intrinsic metallic accumulation in the core of the plasmas is observed for the sequence nearest the stability boundary, but the reclustering of the test ions is evident in Fig. 5(b).

In summary, we have shown that long-time impurity confinement characterizes the unstable regions of tokamak operation in contrast to the short-time confinement observed during stable discharges. The farther the operation is from the density limit, the longer τ_z is and the more likely it is that interior impurity accumulation and consequent radiative cooling leads to a partial disruption if enhanced MHD activity does not prematurely terminate the current flow. A most important aspect of the results is that even in cases where radiative cooling is of minor importance, the change in the nature of the impurity confinement, and possibly of the working-gas confinement, appears to trigger disruptions. Although the results presented here relate to Ohmically heated plasmas, they are also expected to apply to nonrotating, neutral-beam–heated discharges. Achieving long-pulse deuterium densities greater than $10^{14}/\mathrm{cm}^3$ in machines having modest values of R_0/B_T and operating without net momentum input may well require that the impurity influxes be kept extremely low or that the trapping be relieved by the deliberate inducing of edge fluctuations.[18]

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