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ION CONFINEMENT AND RADIATION LOSSES IN THE ADVANCED TOROIDAL FACILITY

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Introduction

Collapses of stored energy are typically observed in low-density ($\bar{n}_e \approx 10^{13}$ cm^{-3}) extensively gettered ATF plasmas when the electron density rises to the ECH cutoff point, and the central heating is supplied only by neutral-beam-injection (NBI). However, the decline of stored energy can be avoided if the density is raised rapidly to about 5×10^{13}cm^{-3}. Three mechanisms have been proposed to explain the collapses: (1) impurity radiation, (2) excitation of an electron instability driven by the neutral beams, or (3) poor coupling of the beam ions to the thermal plasmas. Detailed spectroscopic studies of plasma cleanliness as a function of the gettering procedure have shown that radiation is an unlikely candidate for initiating collapses,[1] although it may become an important loss mechanism once the electron temperature has fallen to a low level. No specific electron instability has yet been identified with injection, but recent experimental and computational work indicates that losses by shinethrough and charge exchange strongly influence the evolution of low-density plasmas.[2]

Monte Carlo calculations have been performed for both high-density and low-density plasmas to determine the slowing down and charge exchange times. At high densities ($\bar{n}_e = 10^{14}$cm^{-3}), the characteristic slowing down time for the neutral beam ions (full energy of 30 keV) is approximately 1 ms and is much shorter than the characteristic time for charge exchange. Most of the fast-ion energy is delivered to the electrons before it can be lost by charge exchange. However, at low densities ($\bar{n}_e = 10^{13}$cm^{-3}), the slowing down time is approximately 80 ms and is eight times longer than the charge exchange time. The full- and half-energy beam ions are lost by charge exchange before they can transfer significant fractions of power to the plasmas. Only the one-third energy ions slow down to the critical energy where they pitch-angle scatter, and even so, their orbits then extend to the plasma boundary where the probability of charge exchange increases.

Theoretical calculations indicate that ion orbits in stellarators are more omnigenous when the plasmas are positioned slightly inside the axis of the helical field coils and the thermal ions should, therefore, be better confined.[3] Measurements of central ion temperatures as a function of plasma position are consistent with these predictions.

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Beam Particle Losses

Figure 1 shows the time histories of $\bar{n}_e$ and $T_e(0)$ for a typical collapsing discharge. The plasma is initially formed by 400 kW of ECH power, then 550 kW of neutral-beam power is injected from 260-400 ms. The electron density rises, and the temperature drops from the time injection begins. The average density reaches the ECH cutoff limit, $9 \times 10^{12}\text{cm}^{-3}$, at 300 ms.

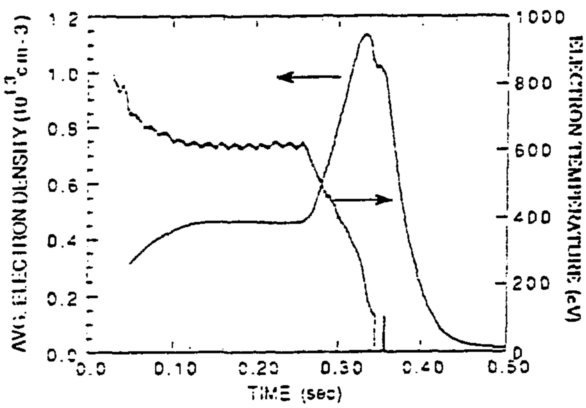

Fig. 1. Time histories of average electron densities and central electron temperatures in a low-density discharge employing NBI from 260 - 400 ms.

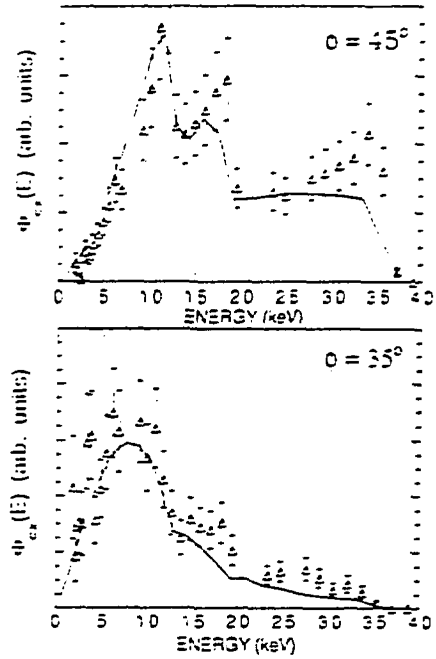

Fig. 2. Fast ion spectra at two different observation angles. The 0° observation angle is along a major radius.

The loss of fast beam ions before they slow down appreciably can be seen in the neutral particle spectra of Fig. 2 where the points are measured data from a neutral-particle analyzer. The 45° observation angle is nearly tangential to the magnetic axis, and the peaks at the full, one-half, and one-third beam energy stand out distinctly. In a typical spectrum where the fast ions are not lost, the slowing-down distribution observed at this angle populates the intervals between the beam energy peaks such that a monotonically rising distribution is observed from the full beam energy down to the critical energy where pitch-angle scattering rapidly increases. The fact that the spectrum between these peaks show deficits in the population indicates that the slowing down ions are being lost. Deficits of counts can also be seen at the 35° angle of observation, where particles are observed only after they have pitch-angle scattered, but the steps in the spectrum are less distinct. By the time a high-velocity particle has pitch-angle scattered it has already lost a certain amount of energy to the electrons, so ions with energies close to those of the three beam components are unlikely to be observed at 35°.

The fast ion spectra are modelled with a Fokker-Planck code by assuming a neutral-particle density that gives the best fit to the experimental data as shown by the solid lines in Fig. 2. This neutral-particle density is then used in the PROCTR code to model the power balance. Figure 3 indicates the fractions of beam input power that is lost through various channels. At 270 ms, 80% of the beam power is lost by shinethrough and charge exchange; only 10% is coupled to the electrons, and this fraction is insufficient to maintain the electron temperature at the preinjection value since the electron density has risen over 20%. By 320 ms the density has reached the cutoff value for the 53 GHz ECH, and the plasmas are sustained primarily by the 40% of the beam power, 220 kW, that is coupled to the electrons. As the temperature decreases, the radiation rises strongly. Analysis of spectroscopic data implies that the fraction of power lost through radiation is only 25-30% of the input power both during the ECH phase and the NBI phase. However, when the shinethrough and charge-exchange losses are taken into account, radiation can account for 50-75% of the power that is actually coupled to the plasmas in this period, and a complete collapse ensues. At high densities where the shinethrough and charge-exchange losses are smaller, the coupling of the neutral-beam power is sufficient to sustain the plasmas even though the radiation levels are comparable to those of low-density discharges.[1]

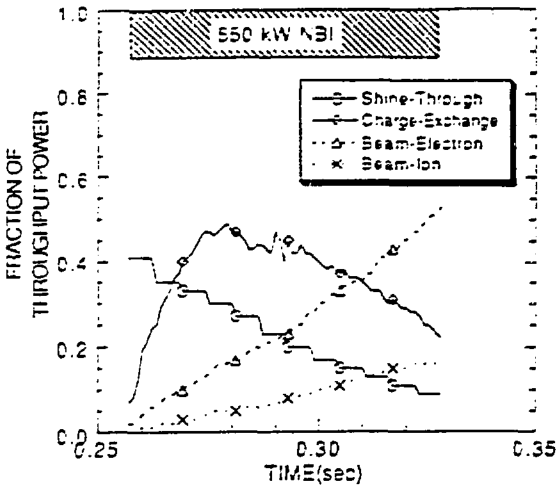

Fig. 3. Calculated fast-ion energy losses as a function of time for the discharge characterized in Fig. 1

Thermal Ions

Transient ion heating is observed in plasmas which collapse despite the fact that most beam particles are lost before slowing down to the critical energy where they begin to pitch-angle scatter and transfer heat effectively to the ions. Figure 3 indicates that up to 14% of the input power is transfered from the hydrogen beams to the plasma deuterons at 320 ms when the stored energy collapse begins. The effect on the thermal ions is shown is shown in Fig. 4 for two different positions of the magnetic axis. The major radius of the helical coils is 210 cm, but the plasma can be shifted by adjusting the dipole component of the vertical field. The ions start to heat at the time neutral-beam injection is initiated; their temperature reaches a maximum in about 30 ms, then begins to decay concurrently with the stored energy. The seemingly contradictory rise of the ion temperature at the same time the electron temperature is falling can be modeled consistently by the PROCTR code.

Moving the plasma inward from the 210 cm position by 2.5 cm makes a dramatic difference in the maximum ion temperature, from 400 eV to 800 eV. This observation is consistent with theoretical results that predict an inward displacement reduces the rate of thermal ion losses by ameliorating the deviations of orbits from flux surfaces and by increasing the fraction of trapped thermal particles that are contained within the confined plasma boundary.

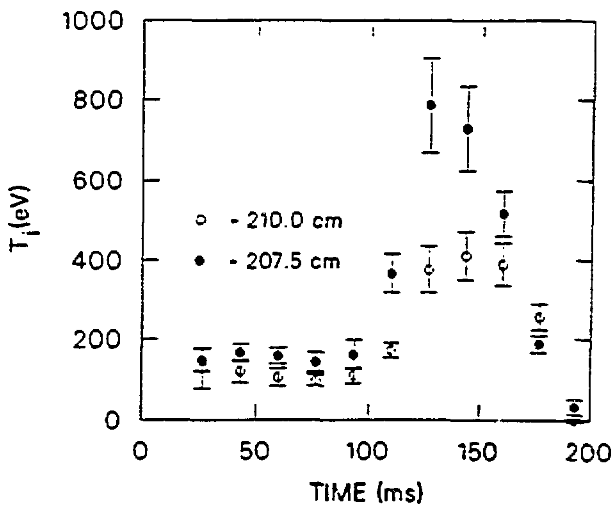

Fig. 4. Thermal-ion temperatures (O VII) as a function of time for two different plasma positions. Neutral injection lasts from 100 ms to 200 ms.

Evolution of Radiation Profiles

As already noted, spectroscopic studies have indicated that collapses are not likely to be initiated by impurity emissions in low-density plasmas employing extensive titanium gettering, although the radiation can become an increasingly important loss factor as the electron temperature falls. It is known, however, that radiation is the primary cause of collapse in poorly conditioned discharges where the low-Z impurity level is relatively high. In order to further our understanding of impurity effects, neon was injected into ECH plasmas and into moderate-density NBI plasmas, which would otherwise have remained quasistationary, until collapses were actually initiated. Narrowing of the temperature profiles was observed with neon injection, and the NBI plasmas collapsed when the total radiation, as inferred from spectroscopic analysis, reached 32%-35% of the input power. These results correlated well with picture of radiative collapse developed using the PROCTR code.[4]

Estimates of the profiles and total radiated power from spectroscopic data are subject to many uncertainties, therefore a fifteen-channel bolometer array was installed to obtain more direct measurements. Figure 5 shows the evolution of the radiation profile determined from the bolometer data for plasmas similar to those analysed for the spectroscopic studies. Before neon injection, the medium-density plasma is quasisteady. After neon injection at 350 ms, an intense radiation peak develops in the edge, and a thermal collapse begins at 360 ms. The neon radiation comes primarily from the Be-like and Li-like stages; it gradually moves inward as the plasma cools until the low ionization stages appear in the plasma center, rather than at the edge. The total radiated power is 30% of the heating power when the neon is injected, thus, the data from the bolometer array provide a strong confirmation of the picture developed from the spectroscopic analysis.

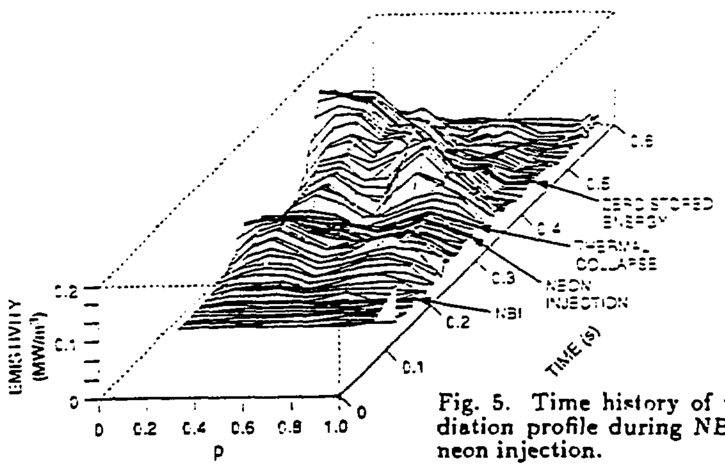

Fig. 5. Time history of the radiation profile during NBI with neon injection.

Acknowledgement

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