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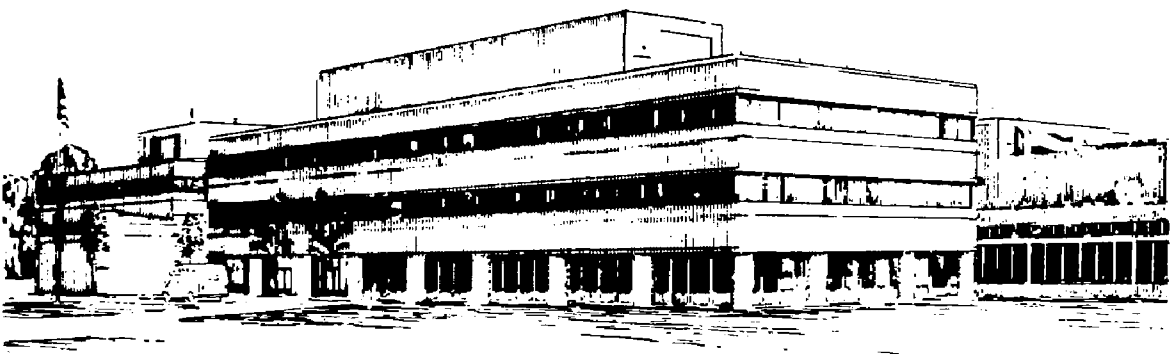

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Neutral Beam Heating of Detached Plasmas in TFTR

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Abstract

Detached plasmas on TFTR have been heated with neutral beam auxiliary power for the first time. At beam powers above 2 MW the detached plasmas in TFTR expand and reattach to the limiters. Deuterium and/or impurity gas puffing can be used to maintain plasmas in the detached state at powers of over 5 MW. Transient events were observed in a number of these plasmas, including a confinement-related delay in evolution of the edge emissivity and some phenomena which appear similar to those seen in the H-mode.

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A new plasma regime[1-5] called detached plasmas has been studied in TFTR. The main feature of a detached plasma is that nearly all of the input power is lost as radiation from the plasma edge[1] and the plasma edge is itself separated from the tokamak walls and limiters. There are three reasons for studying the neutral beam heating of detached plasmas: First, the detached plasma has rather uniform thermal loading of interior machine components and this would be advantageous in a fusion reactor. It is, therefore, interesting to determine the maximum heating power that can be applied while maintaining the detached state. Second, the dominance of radiation in the power balance of detached plasmas means that the response of the bolometer signal provides a diagnostic for direct observation of the total power lost by these plasmas, and of the global energy confinement, τ_E. And third, enhanced confinement regimes such as the H-mode[6] and Z-mode[7] provide evidence that τ_E can be influenced by edge conditions. The edge conditions for detached plasmas are unique, with neither limiter contact nor a divertor. Edge phenomena similar to those associated with divertor and limiter H-modes[8] have been observed in several detached (limiterless) plasmas heated by neutral beam injection. Here we discuss the first experimental observations of neutral-beam-heated detached plasmas and the transport-related effects in them.

The plasmas studied here were detached from the limiter in the ohmic phase by reducing the plasma current in the manner described in Ref. 1 more than 1 s prior to beam heating. About 40 such plasmas which remained detached during beam heating are examined here. These deuterium plasmas had currents, $I_p = 0.5 - 1.2$ MA, toroidal magnetic fields, $B_{tor} = 3.5 - 5.0$ T, and line-averaged densities, $\overline{n_e} = 2.5 - 7.0 \times 10^{19}/m^3$. The plasma major radius was 2.45 to 2.65 m and plasma minor radius 0.45 to 0.80 m, while the inner wall limiter radius was 0.83 m for a major radius of 2.50 m. Beam powers of up to 8.5 MW with a pulse duration of 0.5 s were used in these experiments.

The initial response of the plasma to the beam heating is to expand. This can be seen in Fig.1 which is a time history of the total radiated power, P_{rad}, the power density in the radiating layer, Q_{rad}, and the minor radius, ap, of the radiating layer. a_p is taken to be the width (from the center of the plasma) at the half-maximum of the Q_{rad} profile provided by data from the bolometer arrays. Data are included for two detached plasmas, both of which were heated with about 1.2 MW of beam power. Figures1(a) and 1(c) illustrate two characteristic delayed responses of P_{rad} observed with beam heating of detached plasmas; a slow rise (for the initial 100 ms of beam heating), 1(a), and a delayed rise ($\Delta t \approx 100$ ms), 1(c). The parameter ap is used to monitor the plasma minor radius expansion. For beam powers less than about 2 MW, the plasma does not expand out to the limiter and therefore remains detached. For powers greater than 2 MW and without simultaneous gas puffing, the expansion was sufficient for the plasma to become reattached to the limiter. When plasmas reattach with significant plasma/limiter interaction, the edge radiation pattern becomes localized (poloidally asymmetric) at the limiter and the total radiative losses fall below the total input power. In some cases the plasma remains detached, with a symmetric radiation profile, even though the minor radius of the radiating layer is only slightly smaller than the limiter radius.

Volume emission profiles for detached plasmas with 1.75 MW of beam power and simultaneous puffing of deuterium, and with 4.85 MW of beam power and simultaneous puffing of neon are shown in Fig. 2 . Also shown is the profile for the ohmic target plasmas. It is possible to keep plasmas detached at beam powers of up to 3.5 MW by simultaneously puffing in deuterium gas at flow rates of up to 50 Torr-liters/s. At higher beam powers, impurity gas puffing is needed to keep the plasma from reattaching. Plasmas could be kept detached for beam powers up to 8.5 MW by simultaneously puffing neon. Short, high flow rate deuterium or neon gas puffs coincident with the start of beam heating were effective in keeping the plasma detached. Gas puffing was more than sufficient in both instances in Fig. 2 to make a_p smaller than it was during the ohmic phase. For the 1.75 MW beam-heated case, the plasma remained detached before, during, and after the beam pulse. The profile for the 4.85 MW case was taken about 150 ms after beam turn on and the plasma energy content had reached a plateau. Apparently the neon puff was too strong, causing the plasma to constrict and thus terminate at $\approx$ 300 ms after beam turn on. Similar behavior was observed with up to 8.5 MW of beam power.

The beam-heated detached plasmas of Fig. 2 were characterized by an annulus of impurity radiation, as are ohmic detached plasmas, and by negligible values of Q_{rad} within the inner $\approx$ 35 cm radius core. Thus the power deposited in the core of the plasma, for these virtually idealized cases, must be transported to the edge plasma before it can then be lost as impurity radiation by the low Z impurities at the edge. Both ohmic and beam-heated TFTR detached plasmas are nearly devoid of metallic impurities and often had $Z_{eff} < 2$ (the impurity was predominantly carbon from the graphite limiters). Since the detached plasma is not coupled to the limiters and walls, all of the input power is accounted for in the radiated power. The bolometric measurement can, therefore, serve as a diagnostic for both the magnitude and time behavior of the power that reaches the edge. Hence, the delay in the rise of the total radiated power evident in Figs. 1a and 1c, is a manifestation of τ_E . In contrast to the slow rate of rise of P_{rad}, the plasma energy content, E_{Tot}, from diamagnetic measurements increases rapidly from the instant the beams are turned on. The beam particles are deposited in the plasma core where they slow down by transferring their energy to the bulk plasma which then transports this energy to the edge in a time τ_E . The bolometric measurement together with a kinetic analysis (obtained using the SNAP[9] code) show that the neutral-beam-heated detached plasmas of Figs. 1 and 2 are well approximated by a model of a heated core surrounded by a thin radiating edge. The heating profile obtained from the kinetic analysis shows that almost 80% of the input power is deposited within the inner 45 cm minor radius. The bolometrically determined Q_{rad}, on the other hand, shows that more than 80% of the radiation (and thus of the total input power) is emitted outside this radius. These profiles are appealing for reactor considerations since the radiating shell would deposit the power losses fairly uniformly on the walls of the reactor.

The delay in response, Δt, of P_{rad} for the two cases is not very different from the value of τ_E obtained from the kinetic analysis, thus supporting the argument that at low beam power Δt is a measure of τ_E. The change in the time behavior of P_{rad} for both plasmas occurs at $\Delta t \approx$ 100 ms after beam turn on, while SNAP calculations give $\tau_E \approx 140$ ms for the discharge of Fig. 1a and $\tau_E \approx 110$ ms for Fig. 1c. The two spikes on P_{rad} in Fig. 1c, between 2.8 and 3.0 s, are due to short bursts of MARFE[10,11] activity. In fact, for both cases the change in P_{rad} time behavior at $\Delta t \approx 100$ ms is accompanied by appearance of MARFE activity. This is consistent with the idea of additional energy (transported from the core) becoming available at the edge to heat the plasma there and change its radiation characteristics. At high power, the delayed rise of P_{rad} is not quite as distinct since multiple beams and strong gas puffing both lead to broader and more complicated heating and radiation profiles.

Two types of events were observed for a few of the discharges reported here. Sudden changes in D_α light and edge T_e and n_e values characterize these events and this activity is similar to that observed during transitions from the L- to the H-mode. Figures 3-5 show data for several such discharges. The first type, Fig. 3, showed several rapid cycles of such phenomena. Beam power was 1.75 MW and the radiated power profile for this discharge is included in Fig. 2. Figure 3a shows several drops in the D_α signal which are followed by more gradual increases. Correlated with the D_α activity are sudden increases (also quickly followed by gradual decreases) in edge n_e and T_e and a decrease in P_{rad} (Figs. 3b-d). These events, followed by relaxation within 10 to 20 ms (with no net improvement in τ_E), have been observed in a number of the beam-heated detached plasmas. It has been pointed out[12] that this cyclic behavior is suggestive of locked modes (non-rotating MHD modes).[13] However, close examination of the $\tilde{B}_\theta$ signal for Fig. 3 did not show evidence that this is the case.

In the second type of behavior, a single event occurs which is preceded by a period of poor confinement, followed by a 130 ms period of recovery or improved (and possibly enhanced) confinement. This is indicated in Fig. 4 which includes the time variation of the total electron energy content, E_e, and time-resolved contour plots of T_e, for a plasma heated with 3.5 MW of counter-injected beam power. This event leads to the drop in E_e at 4.295 s which appears to be accompanied (or possibly triggered) by a sawtooth fall[14] in $T_e(0)$, a sudden change in D_α light, reduced MHD activity and the appearance of a detached MARFE on the upper outer major radius side of the plasma. Except for the MARFE, similar changes are observed during L- to H-mode transitions in other tokamaks.[6,8]

The electron energy content (and probably E_{Tot}) begins to rise immediately as the beams and gas puff come on simultaneously, and saturates about 110 ms later. Global energy confinement times are difficult to measure for these plasmas due to difficulty in interpreting the effect of minor and major radius variations on the diamagnetic signal. The minor radius in the OH phase was about 0.57 m and gas puffing restricted Δa_p to an increase of only $\approx$ 10 cm by 4.1 s. The plasma then began to shrink (as is clear from the T_e contour plot of Fig. 4 beginning at 4.1 s) and continued to do so until the event at 4.295 s, at which time $a_p \approx 0.50$ m. Since $a_{lim} = 0.85$ m, the plasma was well separated from the limiter at the time of the event (and the appearance of the detached MARFE). The apparent deterioration in confinement from 4.12 to 4.29 s correlated with the increased MHD activity. At 4.16 s, Mirnov loop data showed a turn on of low frequency, $\approx$ 160 Hz, oscillations (probably m = 5). Oscillations of the same frequency were found in the edge density as measured by the multichannel far-infrared laser interferometer (MIRI).[15] Just before the event at 4.29 s, a burst of m:n = 3:1 ($\approx$ 2 kHz) MHD activity occurred. After this event, no coherent MHD activity was measurable for the remainder of the beam pulse. For the OH detached plasma $q_{edge} \approx 5.0$ just before beam turn on at 4.0 s. It increased to 7.0 by 4.1 s, decreased to 3.8 by the time of the event and then increased for the remainder of the beam pulse (q_{lim} = constant = 11). The density profile is broad with a central value of $9 \times 10^{19}/m^3$ at the time of maximum E_e (at 4.45 s) and this is rather dense for a 600 kA, 4.6 T plasma heated with a modest 3.5 MW of beam power. The improvement in confinement after 4.3 s is reflected mostly in the n_e profile which is broad and relatively steep at the edges. T_e increases very little at the center and somewhat more at the edge. The most extreme development of n_e and T_e profiles occurred in a similar discharge (Fig. 5) with similar dynamics and beam power. These profiles, from Thomson scattering and MIRI, show that $n_e(r)$ is flat with $n_e(0) \approx 8 \times 10^{19}/m^3$.

In summary, we have described preliminary results of neutral beam heating of detached plasmas in TFTR. It was found that the plasmas tend to expand and attach to the limiter for $P_b >$ 2 MW. The plasmas can, however, be kept in the detached state by puffing of deuterium and/or impurity gases. However, the necessary control at high power has yet to be attained. These experiments demonstrate that it is possible to increase the edge emissivity significantly and maintain uniform power loading at the walls. This will be especially important as reactor level neutral beam heating powers are approached. If the edge emissivity could be increased to the level observed in MARFEs,[16] then plasmas in TFTR could remain detached with input powers of up to 35 MW and reactor scenarios involving detached plasmas might be possible. In such experiments, the edge emissivity would have to be carefully controlled in order to avoid plasma contraction and disruptions which seem to occur when q(edge) $\approx$ 2.[1] Interesting transients were observed in the radiating layer including a confinement-related delay in the edge emissivity and some phenomena which have similarities with the H-mode.

Acknowledgments

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Figure Captions

Figure 1. Response of a detached plasma to two low power (1.2 MW) beam heating cases showing; 1(a,b) a slow initial rise in P_{rad} and 1(c,d) a delay, $\Delta t \approx 100$ ms, in rise of P_{rad} . Also shown are a_p, plasma minor radius (a_{lim} = 83 cm), and Q_{rad}, the peak plasma emissivity as functions of time. $n_e l$(center) and $T_e(0)$ for the OH target plasmas were significantly different for the two cases; (a,b) 2.4 x $10^{19}/m^2$ and 3.3 keV and (c,d) 4.0 x $10^{19}/m^2$ and 1.35 keV, respectively.

Figure 2. Volume emission profiles, $Q_{rad}(r)$, for three levels of heating of detached plasmas; OH, $P_b \approx 1.75$ MW and $P_b \approx 4.85$ MW .

Figure 3. Beam-heated detached plasma showing a series of H-mode-like transition events. Shown are time variation of D_α, edge T_e and n_e, and P_{rad}. P_b was 1.75 MW and the beam and gas puff (50 Torr liters/s) were turned on at t = 4.0 s.

Figure 4. Neutral-beam-heated detached plasma showing improved confinement after a single event at $t \approx$ 4.295 s. The time variation of E_e, $n_e l$(center), and contours of T_e are shown. Beam and gas puff (50 Torr liters/s) on at t = 4.0 s. $P_b \approx 3.5$ MW and a_{lim} = 85 cm.

Figure 5. T_e and n_e profiles for a plasma, heated with 3.15 MW of beam power, which exhibited a single event similar to that of Fig.4. The profiles were taken at 4.4 s, near the end of the beam pulse.

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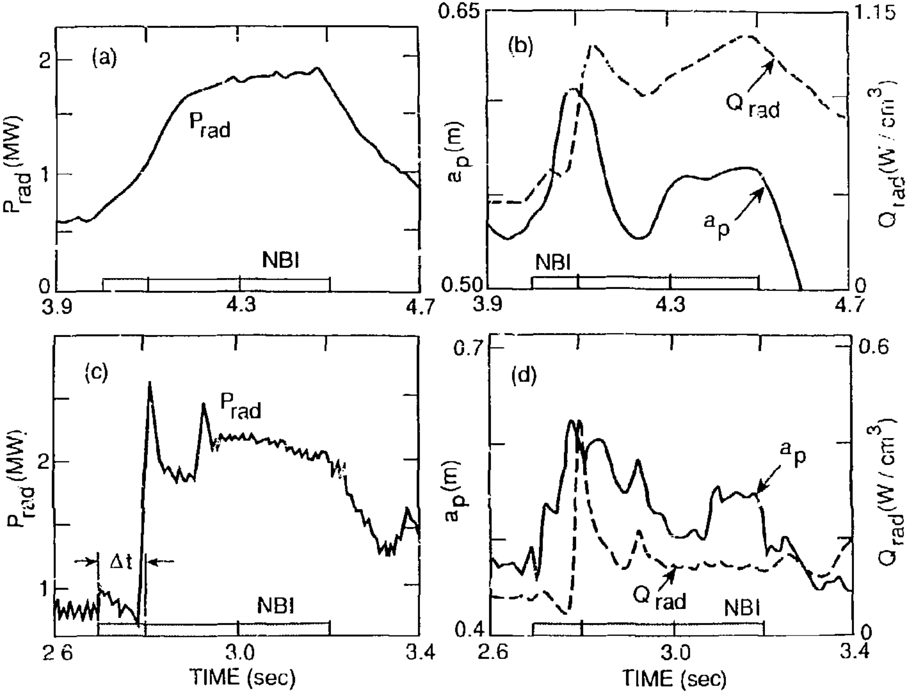

Fig. 1

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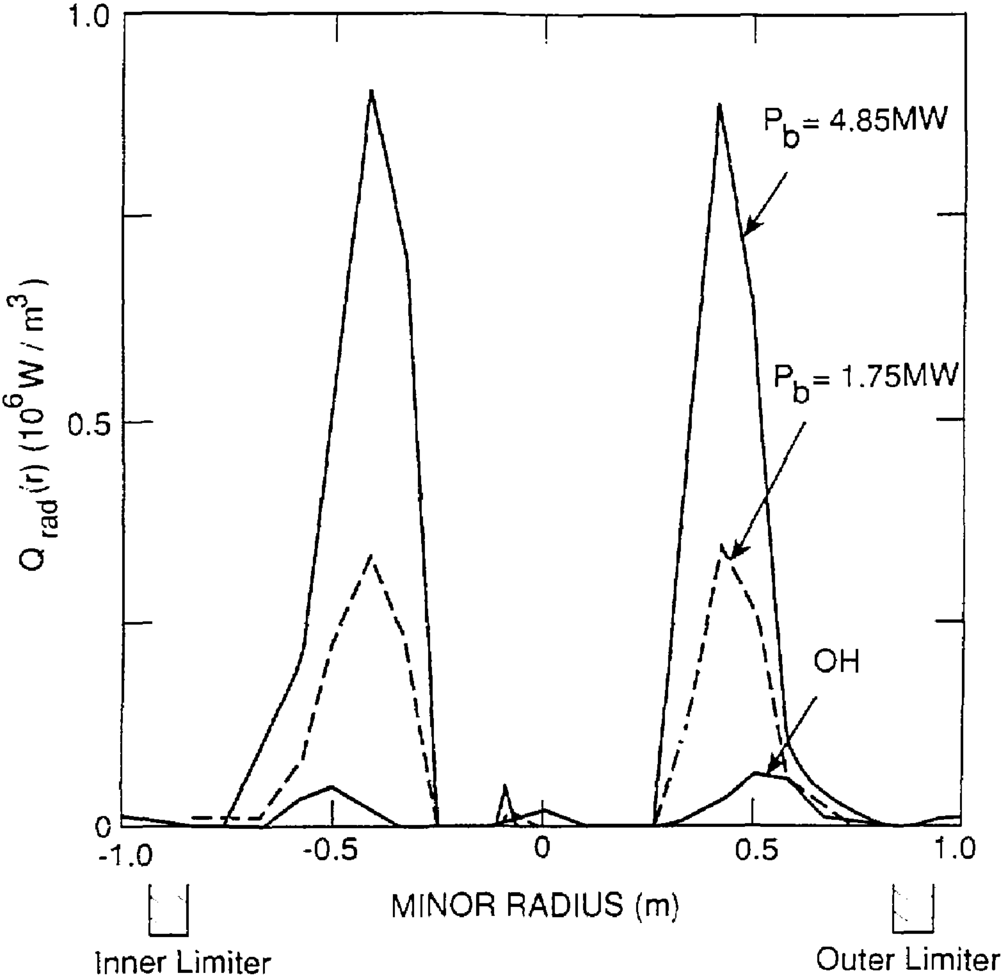
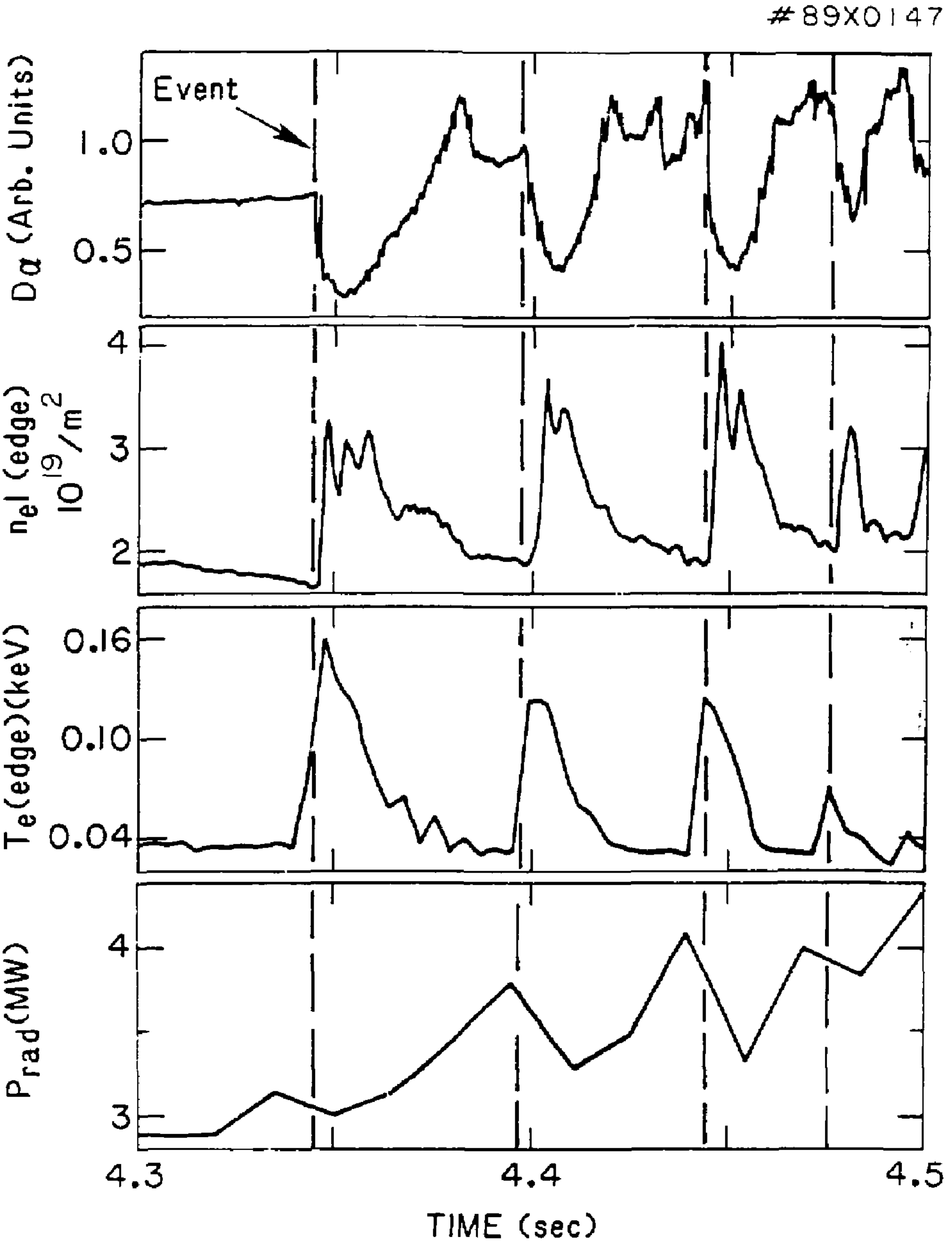


Fig. 2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3
2
T_e(edge)(keV)
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0.10
0.04
P_{rad}(MW)
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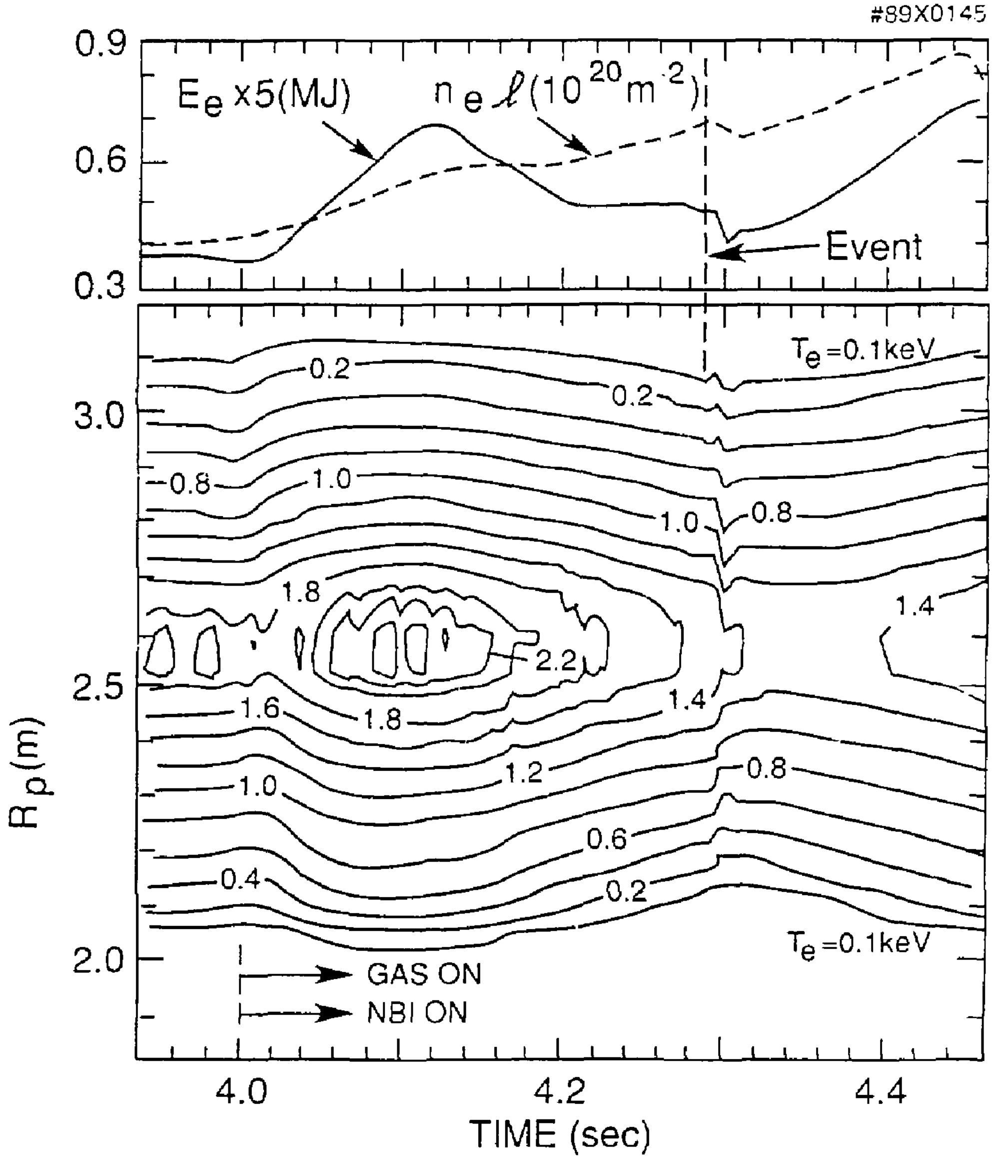
3
4.3
4.4
4.5
TIME (sec)

Fig. 3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$n_e\ell(10^{20}m^{-2})$
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1.0
1.8
2.2
1.4
1.6
1.2
0.6
0.4
R_p(m)
GAS ON
NBI ON
TIME (sec)

Fig. 4

89X3104

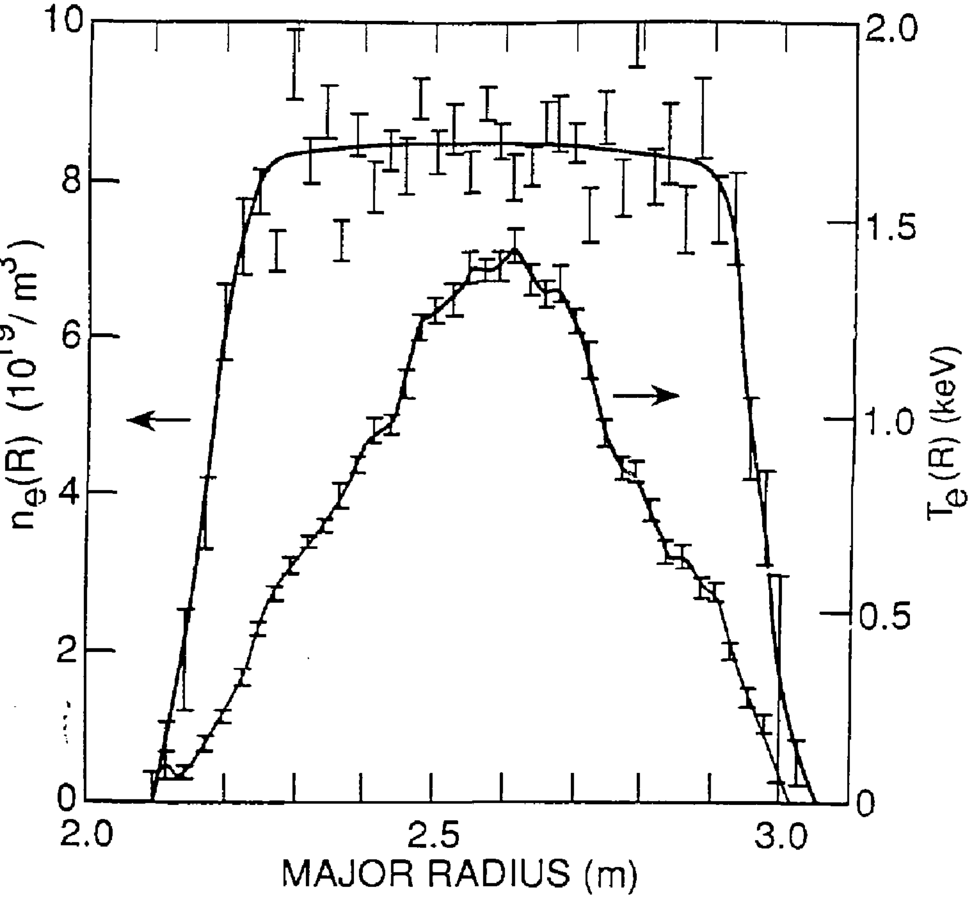

Fig. 5

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