DENSITY LIMIT INVESTIGATIONS NEAR AND SIGNIFICANTLY ABOVE THE GREENWALD LIMIT ON THE TOKAMAKS TEXTOR-94 AND RTP

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Abstract

Ignition scenarios like those developed for ITER require plasma densities which will be close or above the Greenwald limit. Generally it is observed that exceeding this limit may lead to a degradation of plasma confinement or to a violent end of the discharge. The achievable density limit and the related processes, such as radiative instabilities and MHD phenomena, which eventually lead to disruption, have been investigated in the limiter tokamaks TEXTOR-94 and RTP.

1. EXCEEDING THE GREENWALD LIMIT ON TEXTOR-94

Two types of radiative instabilities have been observed prior to density limit disruptions in TEXTOR-94 ($R = 1.75$m, $a = 0.46$m): (i) in strongly polluted plasmas the density limit is reached when the radiation power, dominated by impurity radiation, equals the heating power in a poloidally symmetric way, while (ii) in clean tokamak discharges with high heating power another type of density limit usually sets in, leading to the so-called Greenwald limit. This second type of the density limit is characterized by a MARFE precursor, which is a thermal instability resulting from a nonlinear poloidally asymmetric radiation cooling mechanism.

In TEXTOR-94 the supression of MARFE's resulted in the possibility to exceed the Greenwald limit. Although the Greenwald limit does not reveal any dependency on the heating power, the onset of the MARFE can be delayed by higher input powers. Moreover, the development is influenced by recycling on the high-field-side [1]. It has been shown that by a position shift to the low-field-side and powerfull NBI heating it was possible to exceed the Greenwald limit by a factor of 2 using regular gas feed. The disruption and confinement properties of these high density discharges will be described.

An example of a disruption of such a high density discharge is shown in Fig. 1a for $q_a = 3.6$. The density is increased up to two times the Greenwald limit ($N^{GW} = \overline{n}_e/\overline{n}_e^{GW} = 2$). At the time of the disruption the radiated power reaches the input power. Just prior to the disruption a reduction of the particle fluxes at the toroidal belt limiter is observed, indicating a decrease of the convective heat flux. The higher the safety factor q_a the stronger the reduction in the particle fluxes (Fig. 1b). This detachment is not seen in the total radiation profiles. Usually radiative instabilities trigger various MHD-modes [2,3]. The detachment leads to the development of $m/n = 2/1$ MHD-modes. Their growth leads to a rapid loss of energy, and finally to a current quench. More detailed observations on MHD phenomena are shown later in the RTP experiments.

The disruption in these high density discharges resemble the first type of density limit disruption. Strong indications of a poloidal symmetric radiative collapse are found, if the MARFE

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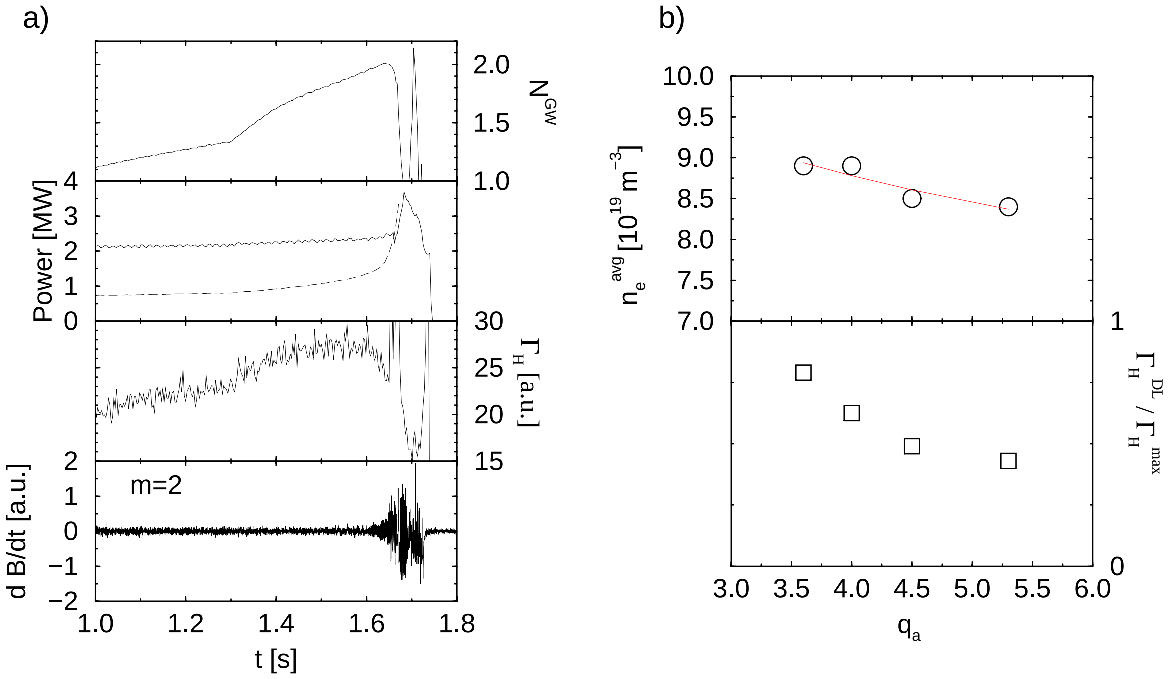

Figure 1: a) Temporal evolution of density limit discharge ($I_p = 256$kA, $B_t = 1.78$T, $a = 0.43$m): Greenwald number, radiated power (dashed line), heating power (solid line), hydrogen flux, Mirnov coil signal; b) Scaling with respect to edge safety factor (B_t variation): density limit, reduction in hydrogen fluxes just prior disruption

is suppressed. A critical density for the development of this radiative collapse should be given. For a density limit discharge with $q_a = 5.1$, $P_{in} = 2.6$MW and $Z_{eff} = 2.4$ the predicted critical density for a radiative collapse, given by $(\overline{n}_e^{cr} \propto q_a^{3/4} \, P_{in}^{1/2}/(Z_{eff} - 1)^{1/2} \, (q_a - 2)^{1/2})$ [3] is $\overline{n}_e^{cr} = 1.1 \times 10^{20}\mathrm{m}^{-3}$. This is larger than the experimentally observed maximum density of $\overline{n}_e = 8.1 \times 10^{19}\mathrm{m}^{-3}$. Furthermore, a scaling of the experimental found density limit [4] with respect to global parameters delivered the following dependencies of $\overline{n}_e^{cr} \propto I_p \times P_{in}^{0.44}/B_t^{0.17}$ The scaling with the magnetic field and the heating power is close to the one predicted [3]. However, the almost linear proportionality on the plasma current cannot be explained. Usually this linear dependence is only found in predictions of critical densities for the onset of MARFEs [5,6].

The confinement properties of stationary and transient high density discharges, significantly above the Greenwald limit, are different from those observations made in Radiative Improved mode (RI-mode) discharges. The RI-mode is an operational regime, which features high energy confinement and strong edge radiation cooling due to line radiation from seeded impurities [7]. Due to the linear scaling of the confinement enhancement factor $f_{H93} = \tau_E/\tau_E^{ITER93H}$ with respect to the Greenwald number, operation at high densities is favourable in this regime. However, a specific feature of the RI-mode, which is often observed, is the degradation of confinement after excessive gas puffing (Fig. 2a). It is therefore difficult to exceed the Greenwald limit significantly in RI-mode. In Fig. 2b a scaling of the f_{H93} with respect to N^{GW} is shown. For densities much larger than N^{GW} (triangles and squares) the scaling of f_{H93} does not follow the linear scaling of the RI-mode discharges (dots). This confinement degradation is qualitatively similar to SOC discharges and H-mode discharges in diverted plasmas [8]. Interesting to note that the product of $N^{GW} \times f_{H93}$ is almost constant. In RI-mode discharges, which exceed $N^{GW} = 1.2$ slightly, the density profile steepens. This leads to a ramp up of the density without gas puffing and finally a disruption. With this a significant increase in the central radiation losses prior the disruption was observed. However a local power balance for those RI-mode

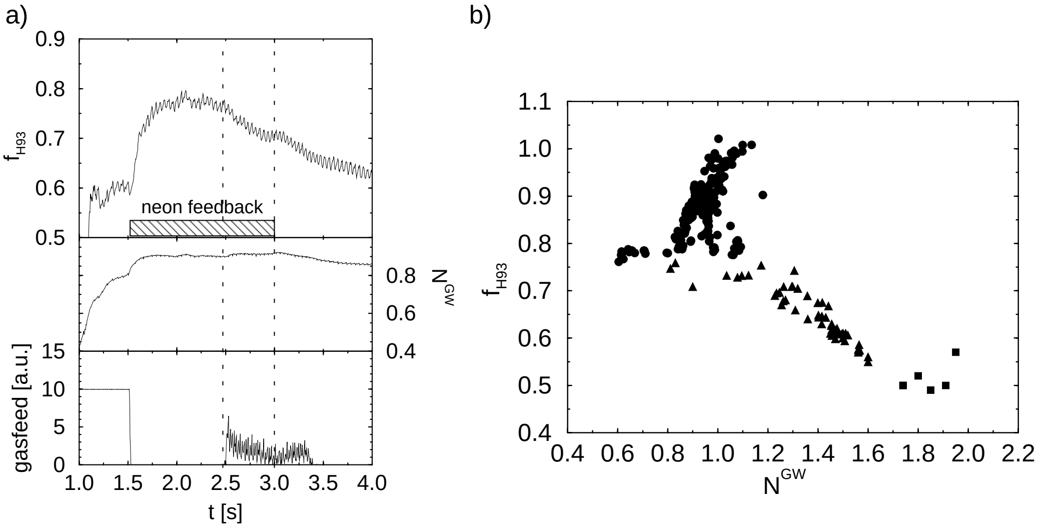

Figure 2: a) Confinement degradation with gas puff (I_p = 290kA, B_t = 2.25T, a = 0.43m): f_{H93}, Greenwald number, gasfeed; b) Confinement scaling factor f_{H93} versus the Greenwald number N^{GW} (non-disrupted discharges); RI-mode discharges, I_p = 290kA (circles); discharges with gas fuelling; D→D NBI, I_p = 290kA, with and without impurity seeding (triangles), H→D NBI, $I_p = 230 - 270$kA without impurity seeding (squares).

discharges just prior disruption did not show a local radiation collapse in the plasma core.

2. DISRUPTION STUDIES ON RTP

At RTP ($R_0 = 0.72$m, $a = 0.164$m), density limit disruptions develop following two distinct types of evolution. In the first type, sawtooth oscillations are observed. After the last sawtooth crash an $m/n = 2/1$ mode develops in less than 2ms just before the onset of the disruption. On the other type of precursor, there are no sawteeth. At the beginning of the current plateau an $m/n = 2/1$ mode develops and saturates. For a time that can go up to 100ms the amplitude of the mode increases slowly until the onset of the disruption. High densities, up to the Greenwald limit (in RTP with $q_a = 4, \overline{n}_e^{GW} = 1.2 \times 10^{20}\mathrm{m}^{-3}$), can be reached only in discharges that show the first type of precursor, and have low impurity content. Once the $m = 2$ mode appears in the second type of evolution the density stops increasing. The maximum observed density was $\approx 0.5 \times \overline{n}_e^{GW}$. In both cases it is clear that an $m/n = 1/1$ mode is phase locked to the $m/n = 2/1$ mode. By correlating the observation of this two modes with a 20 channel ECE radiometer and a high resolution Thomson scattering, a $m/n = 3/2$ mode was detected in the precursor about 160μs before the onset of the disruption. Fig. 3 shows electron temperature Thomson scattering profiles during the two phases of the energy quench. The first phase (Fig. 3a) that lasts for $\approx 100\mu$s is characterized by the total loss of energy confinement in the core of the plasma. The heat that flows from the core is distributed through all the plasma volume as is indicated by the flat T_{e2} profile. After this, during the second phase (Fig. 3b), confinement of energy is also lost at the edge of the plasma with the consequent decrease of the edge temperature as T_{e3} profile shows.

3. SUMMARY

The density limit originates in the development of radiative instabilities at the plasma edge and a subsequent onset of MHD-modes which eventually destroy the plasma confinement. In TEXTOR-94 it was shown that one can exceed the Greenwald limit by a factor of 2, if MARFEs are suppressed. However the energy confinement is degraded for densities significantly higher

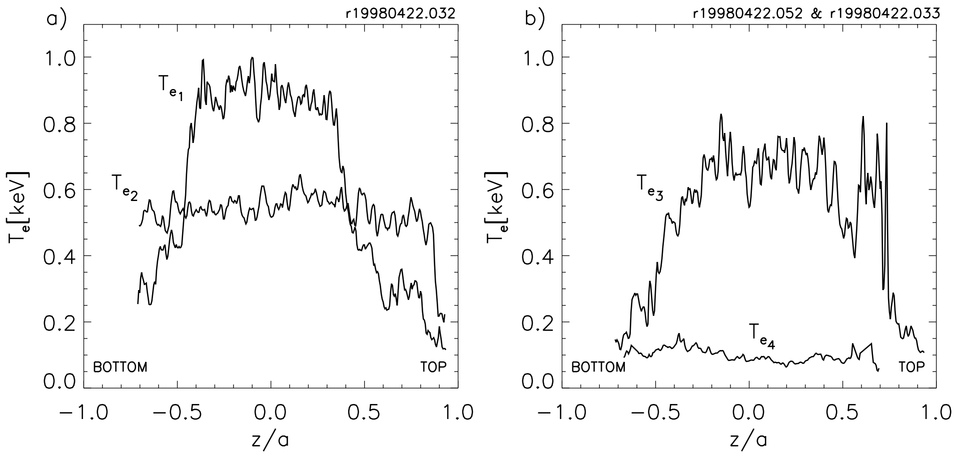

Figure 3: Electron temperature profiles during the energy quench (EQ) of discharges with saw teeth. a) T_e profiles, in the same discharge separated by 100μs, at the onset and at the end of the first phase of the EQ. b) second phase of the EQ. T_{e3} is 150μs and T_{e4} is 700μs after the onset of the energy quench.

than the Greenwald limit. This was observed with and without additionally seeded impurities. Thomson scattering electron temperature profiles were obtained, at RTP, during the two phases of the energy quench. A flattening of the T_e-profile at the end of the first phase is followed by total loss of confinement in the second phase.

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