MHD phenomena at the β-limit in discharges with improved confinement by edge radiation cooling on TEXTOR-94

H. R. Koslowski†, G. Fuchs†, R. Jaspers‡, A. Krämer-Flecken†, A. Messiaen§, J. Ongena§, J. Rapp†, M. Tokar†

Trilateral Euregio Cluster:
†*Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, EURATOM Association, D-52425 Jülich, Germany*
‡*FOM Instituut voor Plasmafysica Rijnhuizen, EURATOM Association, Postbus 1207, NL-3430 BE Nieuwegein, The Netherlands*
§*Laboratoire de Physique des Plasmas / Laboratorium voor Plasmafysica, EURATOM Association, B-1000 Brussels, Belgium*

It is a common observation in present day tokamaks that the maximum normalized plasma pressure, $\beta_N = \beta_t/(I/aB)$, $\beta_t = \langle p \rangle/(B_t^2/2\mu_0)$, in stationary discharges is smaller than can be achieved transiently and is below the prediction based on ideal MHD theory [1]. The limitation of the plasma pressure is found to be caused by the onset of tearing modes which grow although the tearing parameter Δ' is negative. An explanation is given within the framework of the so-called neoclassical theory of tearing modes, where additional contributions driven by the plasma pressure are taken into account [2]. These are (i) destabilizing due to the flattened pressure profile across the magnetic island which leads to a lack of bootstrap current in the O-point reinforcing the growth of the tearing mode, as well as (ii) a stabilizing contribution arising from the ion polarization current in the island.

In the following we present experimental details on spontaneous transitions from higher to lower confinement which are observed when the stored energy in the plasma is increased until the β-limit is reached [3]. The experiments were performed on the circular shaped limiter tokamak TEXTOR-94 (R = 1.75m, a = 0.46m). The radiative improved mode (RI-mode) where the energy confinement is increased due to the feedback controlled seeding of Neon served as the target plasma for these investigations. Under these plasma conditions a high energy confinement, high densities, enhancement factors f_{H93} in excess of one, and a large fraction (> 50%) of radiative power exhaust are simultaneously reached under quasi-stationary conditions [4].

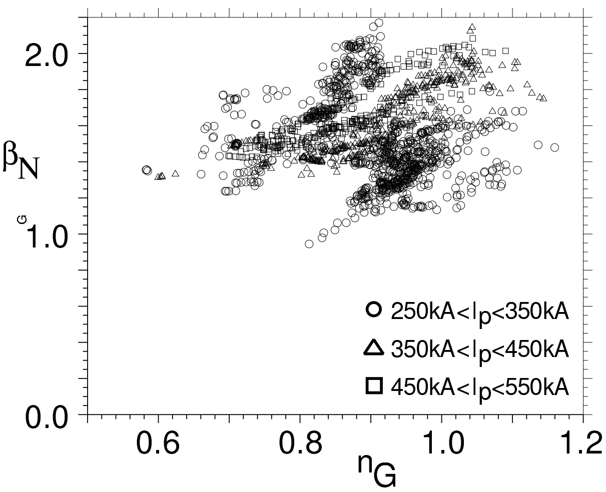


Figure 1: Normalized plasma pressure vs the Greenwald number.

An overview on the achieved values for β_N is given in figure 1. The maximum β_N for RI-mode discharges is about 2.2, β_p reaches values up to 1.5.

In general, it is found, that the limitation of the plasma pressure, i.e. the deterioration of confinement, is preceded by a characteristic change in the MHD activity in the plasma core. The sawtooth activity, normally present in these discharges, is stabilized and instead central MHD activity ($m = 1$) sets on when the β-limit is approached. The deterioration of the energy confinement, which reduces the stored energy by approximately 25%, is found to be well correlated with the onset of mode oscillations which have either the mode numbers $m/n = 3/2$ $m/n = 2/1$, depending on the plasma conditions. Frequently a successive onset of both modes, each accompanied by a reduction of the energy confinement can be observed.

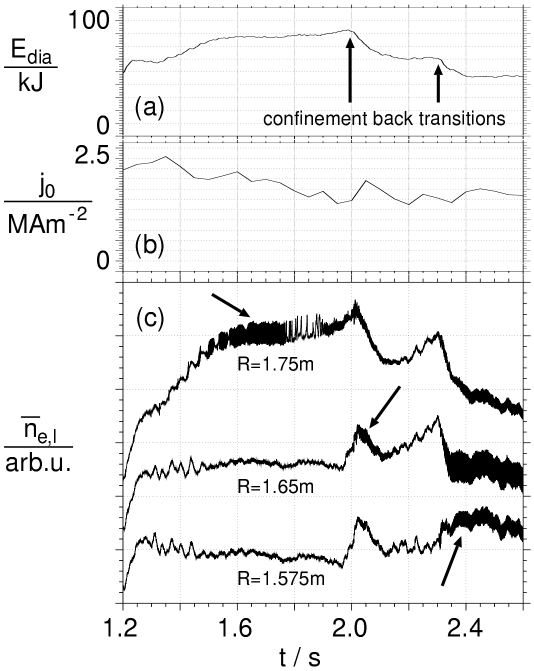


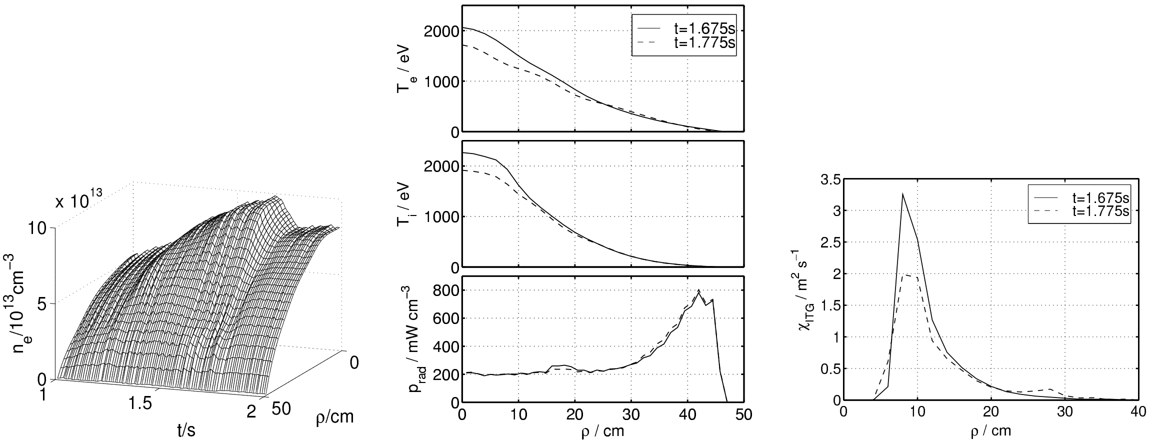
Figure 2: RI-mode discharge with two confinement back transitions correlated with the onset of MHD mode activity.

An example of a confinement back transition is shown in figure 2. At $t = 2$s and $t = 2.3$s the stored energy (a) shows a sudden decrease. The line integrated electron densities at various radial positions (c) indicate the onset of MHD activity. At $t = 2$s a $m/n = 3/2$ mode and later at $t = 2.3$s an additional $m/n = 2/1$ mode are destabilized. Measurements of the current profile prior to the onset of the $m > 1$ modes show that the current density on axis decreases (b), indicating a broadening of the plasma current distribution. The central q-value is still below unity when the sawteeth are suppressed and pronounced $m = 1$ activity in the plasma center becomes visible.

The improvement of the energy confinement in RI-mode discharges is attributed to a reduction of ITG mode turbulence in a large part of the plasma [5]. Figures 3(a) and 3(b) show the electron density and the temperature profiles in the plasma before and after the confinement back transition. It is clearly visible that the profiles in the plasma center exhibit a large drop, whereas in the outer half of the plasma nearly no change is detectable. In addition, the radial distribution of the radiated power density caused by neon feedback (figure 3(b) bottom) is not affected by the drop in confinement. The energy transport due to the ITG mode (figure 3(c)) is even decreased because the gradients in the state with reduced confinement are lower. This result is in good agreement with calculations of the confinement degradation due to neoclassical tearing modes on ASDEX-U [6], where the losses are attributed to the enhanced transport across the islands.

Measurements of the plasma current distribution performed with polarimetry [7] indicate for many cases where these confinement degradation is observed a flattening of the current profile within the $q = 1$ surface, i.e. the peaking of the plasma current is reduced, which has been found to be a feature of the radiative improved confinement.

In figure 4 the value of the tearing parameter Δ' is plotted versus the time before the onset of an $m/n = 3/2$ mode for a series of similar discharges. Within the uncertainty of the measurement Δ' is below unity, and shows no temporal change before the mode starts. The increase after the onset of the mode oscillation might be an artefact of the reconstruction procedure. In principal, the line integrated measurements done by polarimetry cannot detect local small scale modifications of the poloidal magnetic field which may have a rather large influence on the tearing parameter.



(a) Electron density profile.

(b) T_e (top), T_i (middle), and P_{rad} (bottom) profiles.

(c) Energy diffusion due to ITG mode turbulence.

Figure 3: Comparison of the plasma profiles before and after the confinement degradation due to the onset of an 3/2 mode.

A further feature which is characteristic for the growth of the island due to neoclassical effects is shown in figure 5. Here several channels of the HCN-interferometer measuring the line integrated electron density with high time resolution are displayed. The sawteeth in the plasma core are replaced by $m = 1$ mode oscillations seen on the central channels. Although the sawteeth in general are stabilized, irregular crash events in the core occur, as can be seen from inverted sawteeth on the outer channels. One of this core crashes acts as a trigger for the $m/n = 3/2$ mode starting at $t = 2.226$s.

The MHD modes leading to the reduction of β show a hysteresis behaviour. After the drop of the plasma pressure below the critical value where they are excited the modes do not disappear.

The resistive growth time for tearing modes at the rational surface, $\gamma^{-1} \approx \tau_R^{3/5}\tau_A^{2/5} \approx 3$ms is shorter than the observed growth time of the order of $10 - 20$ms.

The theory of neoclassical tearing modes includes a stabilizing contribution from the ion polarization current in the island [2], which should be even more effective in regimes

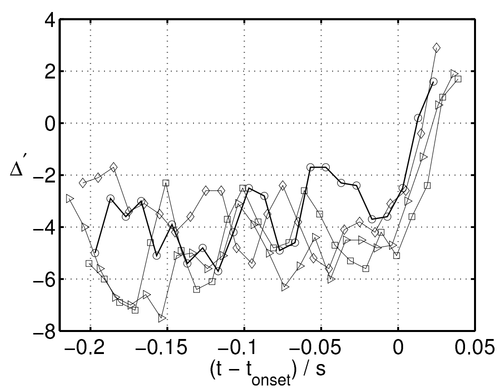


Figure 4: Tearing parameter Δ' before the onset of MHD mode activity.

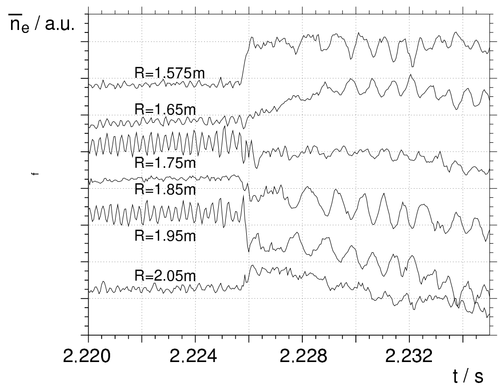


Figure 5: A crash event in the plasma center triggers the 3/2 mode.

where the ion collision frequency normalized to the electron diamagnetic drift frequency, $\nu_{ii}/m\epsilon\omega_e^*$ (ϵ is the inverse aspect ratio of the rational surface), exceeds a certain threshold. The normalized plasma pressure, β_N, scales approximately linearly with the poloidal ion gyro radius, ρ_p^*, in good agreement with the assumption, that stabilization of the neoclassical tearing modes is primarily due to the ion polarization current. A similar observation is reported from ASDEX-U [6], where in addition the collisionality dependence for the excitation of neoclassical tearing modes shows a good agreement with the theory [8]. For the high densities in the RI-mode plasmas this stabilizing term should be by a factor $\epsilon^{-3/2}$ larger, because the collisionality is one order of magnitude above the critical value as determined on ASDEX-U. There are several indications for the neoclassical nature of the MHD modes observed at the β-limit in TEXTOR-94, however, the present state of the theory would predict a strong stabilization of neoclassical modes due to the rather high collisionality. Further work seems to be required in order to find out the collisionality dependence of the polarization term [9].

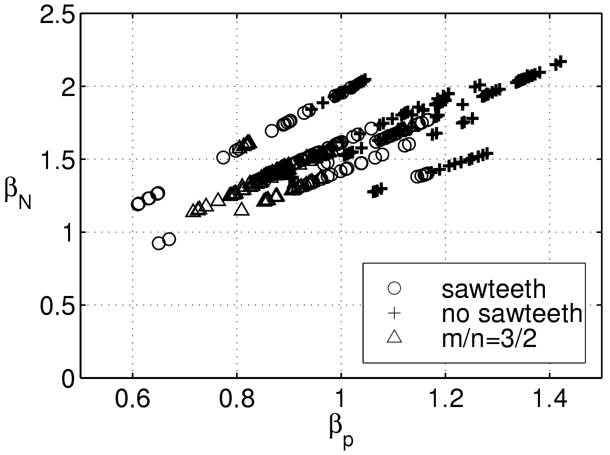


Figure 6: Plot of β_N vs β_p. The data are sorted by the type of MHD activity in the plasma.

Figure 6 shows a plot of β_N versus β_p where the points in the database have been marked by the kind of observed MHD activity. The evolution from a sawtoothing plasma with good energy confinement into a state with rather poor confinement and strong mode activity can be observed in many discharges where the β-limit has been encountered. It can be seen that the 3/2-mode strongly reduces the confinement. The best values have been achieved with a stabilization of the sawtooth oscillations, but core MHD activity might be still present. Although the $m = 1$ mode seems not to have a strong influence on the confinement quality of the plasma, stationary conditions are difficult to reach once the sawtooth activity is stabilized. A stable sawtoothing discharge with a confinement enhancement factor with respect to H-Mode $f_{H93} > 0.95$ and a flat top time of 6.8s = $160\tau_{\mathrm{E}}$, similar to the ratio of burn time to energy confinement time foreseen for ITER, has been achieved.

[1] F. Troyon et al. (1984) *Plasma Phys. Control. Fusion* **26** 209
[2] O. Sauter et al. (1997) *Phys. Plasmas* **4** 1654
[3] J. Ongena et al. (1996) *Plasma Phys. Control. Fusion* **38** 279
[4] G. Wolf et al. (1997) *in Plasma Physics and Controlled Nuclear Fusion Research 1996* (Proc. 16th Int. Conf. Montreal, 1996), Vol. 1, IAEA, Vienna 177
[5] M. Z. Tokar et al. (1999) *Plasma Phys. Control. Fusion* **41** L9
[6] S. Günter et al. (1999) *to appear in Nuclear Fusion*
[7] H. R. Koslowski and H. Soltwisch (1997) *Fusion Engineering and Design* **34-35** 143
[8] M. Maraschek et al. (1999) *Plasma Phys. Control. Fusion* **41** L1
[9] S. Günter et al. (1999) *this conference, to be published in Plasma Phys. Control. Fusion*