Development of magnetic island near the density limit on FTU

G. Pucella, A.Botrugno, P. Buratti, E. Giovannozzi, M. Marinucci, O. Tudisco and FTU team*

C.R. ENEA, Assoc. Euratom-ENEA, Via E. Fermi 45, I-00044 Frascati, Italy

Introduction

Due to the strong dependence of fusion power on plasma density, the tokamak density limit has been the subject of intense study over several decades [1]. Density limit disruptions are usually ascribed to a thermal instability occurring when the radiation loss near the edge region overcomes the heat flux from the core. The ensuing contraction of the temperature profile leads to a shrinkage of the current profile that drives unstable a global MHD mode, such as the tearing mode [2], leading to disruption if the density continues to grow. Whereas this explanation for the appearance of a low-order tearing mode (usually of poloidal mode number $m = 2$ and toroidal mode number $n = 1$) when the density increases towards the limit is correct, it has proved difficult to obtain a robust onset criterion based on the linear instability. Dedicated density limit experiments were performed on FTU ($R = 0.935$ m, $a = 0.3$ m, $B_T = 2.5 - 8.0$ T, $I_p < 1.6$ MA) in a wide range of plasma current and toroidal magnetic field values [3]. In this paper the linear stability of the standard tearing mode has been analyzed to derive a condition for the onset of the MHD activity in high density ohmic plasma.

MHD activity

The magnetic activity on FTU is analyzed by means of poloidal and toroidal arrays of magnetic pick-up coils. All the investigated discharges present a very similar MHD phenomenology, as illustrated in Figure 1, where the time traces of some relevant quantities are reported for a discharge with $B_T = 8.0$ T and $I_p = 900$ kA. The onset of a $m/n = 2/1$ mode is identified at $t = 0.89$ s, when the frequency takes a well-defined value of 6 kHz. At first, the mode grows algebraically and its frequency remains constant. Subsequently, the amplitude shows a quasi-periodic modulation, with the maximum value reached during each period still increasing algebraically (a detailed description of this complex behaviour will be reported elsewhere). In the last phase, the mode growth speeds up and the frequency decreases to zero [4]).

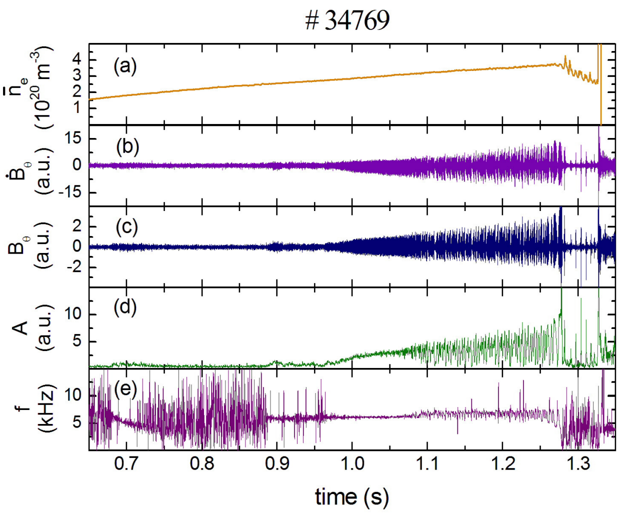

Figure 1. Time traces of some relevant quantities for the MHD activity on FTU: (a) central line-averaged density, (b) output from the pick-up coil, (c) poloidal magnetic perturbation, (d) mode amplitude, (e) mode frequency.

*See the appendix of P. Buratti et al., Proceedings of the 24th IAEA Fusion Energy Conf., San Diego, USA,2012

Linear stability and nonlinear evolution of the tearing mode

The classical tearing stability parameter Δ'_J associated to the current density profile can be calculated solving the marginal stability equation [2] with the current density profile obtained from the JETTO transport code, considering the electron temperature profile from the ECE diagnostic and assuming Spitzer resistivity. In Figure 2 (left) the safety factor and the current density profiles are reported, for different times up to the density limit disruption. The current profile peaks as the density limit is approached; in particular, from the zoom on the right we note a change of the derivative of the current density at the mode resonant surface, and also a continuous decrease of the value of the current density at the mode resonant surface. The linear theory also includes a stabilizing toroidal term Δ'_C associated to field line curvature [5], so the stability criterion can be written as (drift effects can be neglected because of the high collisionality):

$$\Delta'_{lin} = \Delta'_J + \Delta'_C < 0 \qquad (1)$$

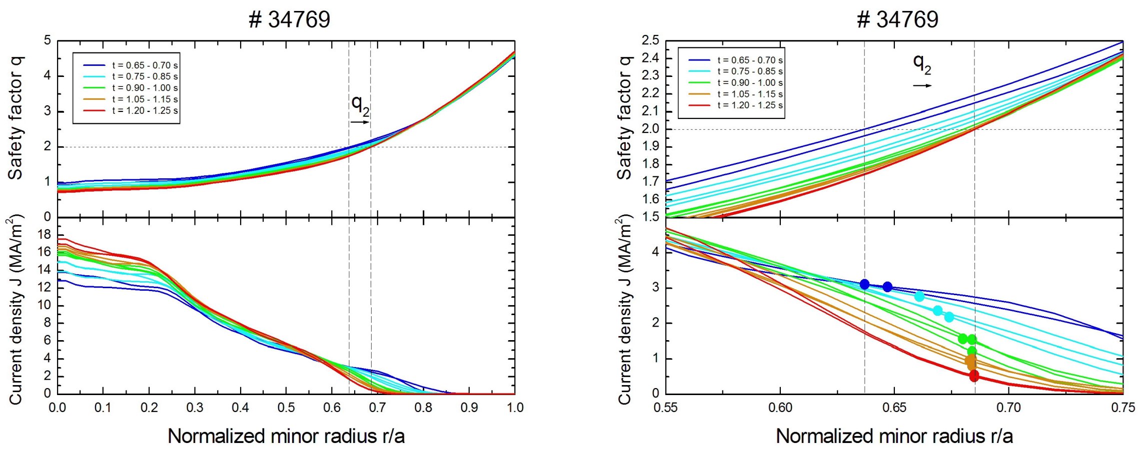

Figure 2. Safety factor and current density profiles at different times during the current flat-top and the density ramp-up up to the density limit disruption.

In Figure 3 the time evolution of the three terms Δ'_J, Δ'_C, and Δ'_{lin} is reported for the complete current flat-top time interval up to the density limit disruption (b). As we can see, the stabilizing toroidal term associated to the field line curvature is approximately constant during the time evolution, with a slight decrease of its absolute value associated with the increase of the tearing layer width with increasing resistivity. Regarding the classical tearing parameter, it increases with increasing peaking of the current density profile. Therefore, from the linear stability criterion expressed in equation (1), the tearing mode results unstable starting from $t = 0.86$ s, which is in good agreement with the experimental

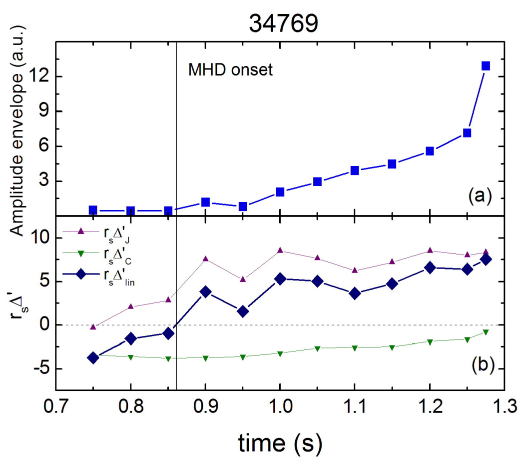

Figure 3. Time traces of the mode amplitude envelope (a) and of the three terms in the linear stability criterion (b).

observation (a). A more accurate analysis could be done considering the development of the magnetic island inside the plasma. The radial field perturbation at the mode resonant surface r_s is proportional to the poloidal field perturbation at pick-up coils (at $r_c = 0.33$ m), $B_{r1}(r_s) = k \quad B_{\theta 1}(r_c)$. Rather than employing the usual analytical estimate based on neglecting plasma current outside r_s, the factor k is calculated numerically using the cylindrical approximation and the current density profile from JETTO with an ideal wall at $r_w = 0.33$ m. At mode onset, the resulting k differs by 40% from the analytical estimate and converges to the latter going towards the density limit. Finally, considering the well-known expression for the island width, we have:

$$w = 4\sqrt{\left.\frac{rqB_{r1}}{mq'B_\theta}\right|_{r=r_s}} = 4\sqrt{\frac{Rr_s}{n\,B_z s_s}\cdot k\cdot B_{\theta 1}(\,r_c\,)} \qquad (2)$$

In Figure 4 the time evolution of the island width as evaluated from equation (2) is reported in arbitrary units (given the difficulty to have an absolute calibration of the pick-up coils) for the analyzed discharge, showing that the island width increases algebraically with time, with a last phase where it seems to grow more quickly. To make a comparison, we can try to estimate the expected island width considering the nonlinear island evolution as described by the so-called Rutherford equation [6]. In particular, taking into account the effect associated to the island width [7], we can derive the saturation amplitude of the island, considering that for typical current profiles the island reaches saturation in a small fraction of a resistive time, after which the saturated state adiabatically follows the changing current profile. The resulting values of the saturated island width, corresponding to the condition $dw/dt = 0$ in the Rutherford equation, are reported in Figure 4 in arbitrary unit, showing that also the predicted island width increases with increasing peaking of the current density profile. After $t = 1.15$ s the Rutherford equation does not predict saturation, probably given to the high values of the linear tearing parameter at shrunk current profiles.

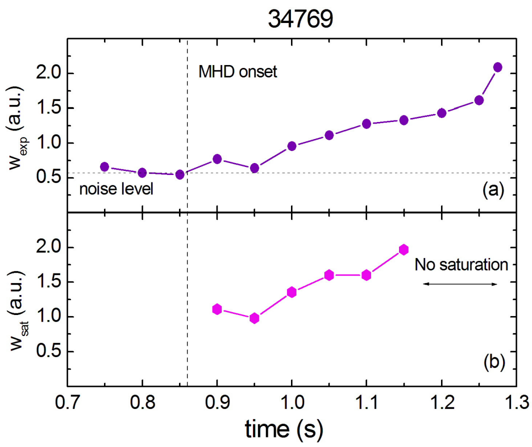

Figure 4. Time traces of the island width evaluated starting from the pick-up signals (a) and from the Rutherford equation (b).

Discussion

We have shown that the tearing mode onset in a density limit discharge is associated to the peaking of the current density profile and the MHD onset time can be estimated starting from the linear stability criterion expressed by equation (1). The current profile peaking is usually parameterized by the normalized internal inductance of the plasma l_i (as defined in [8]). In Figure 5 (left) the time traces of the internal inductance are reported for three discharges with $B_T = 8.0$ T and different values of plasma current ($I_p = 500$, 700, 900 kA). As we can see, during the density ramp-up the internal inductance continuously increases and the values of l_i (namely the peaking of the density current profile) at the MHD onset (corresponding to the

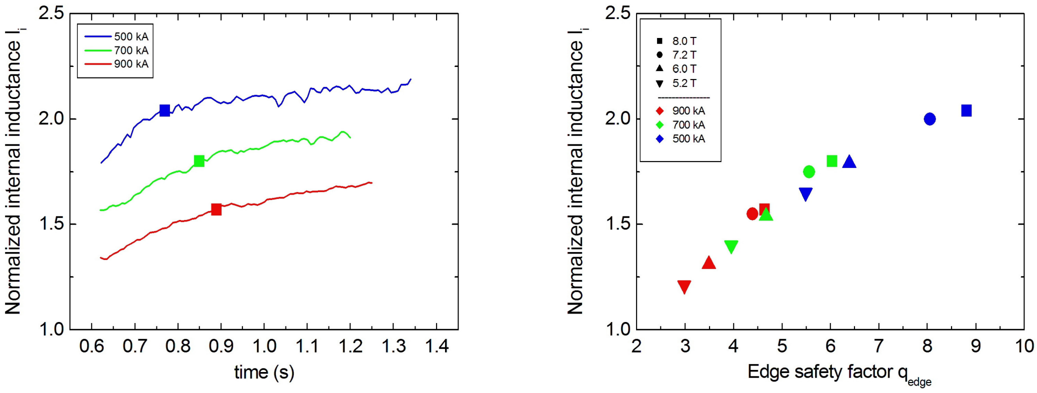

Figure 5. (Left) Time traces of the internal inductance for three discharges with $B_T = 8.0$ T and different values of plasma current (see legend). The squares in the figure correspond to the MHD onset. (Right) Internal inductance at the MHD onset as a function of the edge safety factor for 12 different discharges in a wide range of values of plasma current and toroidal magnetic field (see legend).

squares in the figure) are higher for lower plasma current. To complete our analysis we have studied the MHD activity of 12 discharges in a wide range of values of plasma current (I_p = 500-900 kA) and toroidal magnetic field (B_T = 5.2-8.0 T) and for each discharge we have derived the value of the internal inductance at the onset of the MHD activity. The results of this analysis are reported in Figure 5 (right) as a function of the edge safety factor q_{edge}, showing that at the MHD onset l_i is a function of q_{edge}.

Conclusions

The usual explanation for the appearance of a low-order tearing mode when the density increases towards the limit is correlated to a contraction of the current density profile. In order to obtain a condition for the onset of the MHD activity, the linear stability of the classical tearing mode has been analyzed for a specific discharge, confirming a destabilization with increasing peaking of the density current profile. Furthermore, from the nonlinear island evolution described by the Rutherford equation we have noted that the critical phase preceding the density limit corresponds to the lack of prediction of a saturated island width. Finally, considering different discharges, a general relation was obtained at the MHD onset between the normalized internal inductance of the plasma and the edge safety factor.

Acknowledgements

This work was supported by the Euratom Communities under the contract of Association between EURATOM-ENEA. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] M. Greenwald, Plasma Phys. Control. Fusion **44**, R27-R80 (2002)
[2] H. P. Furth, P. H. Rutherford, and H. Selberg, Phys. Fluids **16**, 1054 (1973)
[3] G. Pucella, O. Tudisco, et al., Nucl. Fusion **53**, 023007 (2013)
[4] M. M. F. Nave and J. Wesson, Nucl. Fusion **30**, 2575 (1990)
[5] A. H. Glasser, J. M. Greene, and L. Johnson, Phys. Fluids **19**, 567 (1976)
[6] P. H. Rutherford, Phys. Fluids **16**, 1903 (1973)
[7] R. B. White, D. A. Monticello, M. N. Rosenbluth, and B. V. Waddell, Phys. Fluids **20**, 800 (1977)
[8] J. A. Wesson, et al., Nucl. Fusion **29**, 641 (1989)