High-beta NTM in JET hybrid scenario at different toroidal magnetic fields

G. Pucella[1], L. Frassinetti[2], D.B. King[3], C.D. Challis[3], E. Alessi[4], E. Giovannozzi[1], C. Giroud[3], S. Wiesen[5], F. Auriemma[6], D. Brunetti[3], I.S. Carvalho[7], P. Carvalho[3], S.N. Gerasimov[3], A. Kappatou[8], D. Keeling[3], C. Perez von Thun[9], H.J. Sun[3], N. Vianello[6], M. Wischmeier[8], JET Contributors*, and the EUROfusion Tokamak Exploitation Team**

[1]*ENEA, Fusion and Nuclear Safety Department, Frascati, Italy*
[2]*EECS, KTH Royal Institute of Technology, Stockholm, Sweden*
[3]*UKAEA, Culham Campus, Abingdon, United Kingdom*
[4]*ISTP, Consiglio Nazionale delle Ricerche, Milano, Italy*
[5]*Dutch Institute for Fundamental Energy Research, Eindhoven, The Netherlands*
[6]*Consorzio RFX, ISTP-CNR, Padova, Italy*
[7]*ITER Organization, St Paul Lez Durance Cedex, France*
[8]*Max Planck Institute for Plasma Physics, Garching, Germany*
[9]*Institute of Plasma Physics and Laser Microfusion (IPPLM), Warsaw, Poland*

**See the author list of C.F. Maggi et al 2024 Nucl. Fusion (10.1088/1741-4326/ad3e16)*
***See the author list of E.H. Joffrin et al 2024 Nucl. Fusion (10.1088/1741-4326/ad2be4)*

1. Introduction.

Neoclassical Tearing Modes are often observed in high-β plasmas [1-6], with a strong correlation between their onset and the presence of saw-teeth, ELMs, or fishbones, even if "triggerless" modes are also observed at relatively high β values [7-8]. The reduction of the confinement time associated with saturated islands is well descripted by the "belt" model [9], but the possible effect on core accumulation of high-Z impurities must be considered [10]. The MHD stability of high-β plasmas (normalized beta up to $\beta_N = 4$) has been studied on a series of 43 pulses carried out at JET ($R_0 = 3.0$ m, $a = 0.9$ m, $k = 1.6$) to investigate the properties of peeling limited pedestals at very low collisionality [11]. The experiments were performed in the so-called JET hybrid scenario [12] at relatively low plasma current ($I_p = 1.4$ MA) and moderate heating power ($P_{NBI}+P_{ICRH} \approx 24$ MW), with a wide range of toroidal magnetic field (B_T = 1.7-3.4 T), and a different timing for the auxiliary heating switch-on (see Fig.1), depending on the B_T value [13], to keep the safety factor on-axis roughly the same, with $q_0 > 1$, in the main heating phase.

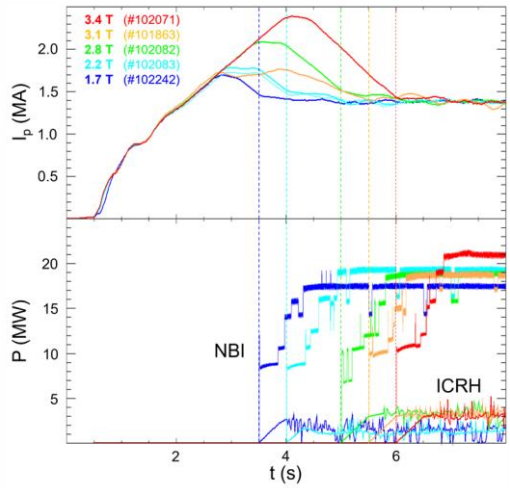

Fig. 1. Plasma current (top) and auxiliary heating (bottom) waveforms for JET hybrid pulses at different toroidal magnetic field.

2. MHD phenomenology.

The experiments started with pulses at 3.1 T. Considering the obtained results, some adjustments were made regarding the plasma current waveform for pulses at 3.4 T and 2.8 T. Further adjustments, also regarding the density in the Ohmic phase, were implemented for pulses with the lowest magnetic field, i.e. 2.2 T and 1.7 T. The main experimental evidence from the MHD point of view is reported below.

(i) *Higher magnetic field values*. 4 pulses out of 7 at 3.1 T ($q_{95} \approx 6.9$) were characterized by moderate 3/2 NTM, not affecting the plasma performance, with $\beta_N \approx 1.9$ - 2.1. The other 3 pulses showed strong 2/1 NTM, affecting the plasma performance, with $\beta_N \approx 2.2$ - 2.3 before the mode onset. Considering that the likelihood of 2/1 NTM is increased by the operation at high q_{95}, which brings the 2/1 surface to a smaller minor radius location where it is more unstable due to the high core pressure / pressure gradient [14], an increase in the height of the current overshoot has been implemented after the first pulses at 3.1 T to have a broader q-profile and increase the radius of the 2/1 surface. After these adjustments, no 2/1 NTM were observed at 3.4 T. A gas rate scan was performed at this field, showing 8 pulses out of 10 with moderate 3/2 NTM, at low and medium Deuterium flow rate, with maximum $\beta_N \approx 2.1$, and 2 pulses with mild 4/3 NTM, at the highest Deuterium flow rate and early density, with maximum $\beta_N \approx 1.7$. Only 2 pulses were performed at 2.8 T, with 3/2, 4/3 and 5/3 modes.

(ii) *Lower magnetic field values*. Locked modes in the overshoot ramp-down were observed in 3 out of 4 of the first attempts at 2.2 T. No locked modes were observed in the new two pulses performed with increased density in the Ohmic phase and reduced peak current in the overshoot waveform, which were characterized by moderate 3/2, mild 4/3 and 5/3, and strong 2/1 NTM inducing a core impurity accumulation and a confinement degradation. The β_N increase and the current diffusion could help to explain the late 2/1 destabilization [15]. 7 pulses with initial core n=1 activity and subsequent 3/2 NTM were performed at 1.7 T, with a final 2/1 NTM not observed at higher Deuterium flow rate values. It is worth noting that the onset of "triggerless" 3/2 NTM in two pulses occurred at $\beta_N \approx 4 \times l_i$ (l_i is the plasma internal inductance), which is usually a rough estimate of the ideal no-wall beta-limit. A further advance of the NBI heating (necessarily reducing the current overshoot) would be necessary to avoid the presence of fishbones and saw-teeth at the beginning of the pulse, sometime triggering a 3/2 NTM.