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** See annex of F. Romanelli et al, “Overview of JET Results”,*
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INTRODUCTION

Over the past 10 years a new scenario has emerged on the mid-size tokamaks ASDEX-Upgrade [1, 2, 3] and DIII-D [4, 5] which combines a higher q_{95} operation with improved confinement compared to the $H_{98,\mathrm{y2}}$ scaling law called hybrid scenario or improved H-mode. Could this kind of scenario be reproduced on ITER, new possibilities would arise, i.e. high Q operation at reduced I_P [6, 7]. Hybrid scenario plasmas can have significantly improved confinement above the standard $H_{98,\mathrm{y2}}$ H-mode scaling but the physics basis remains somewhat unclear. At JET [8] similar discharges have been carried out before the 2008/9 campaigns and most of the characteristics i.e. the stability against Neoclassical Tearing Modes (NTM) have been reproduced but the confinement was not improved significantly over the $H_{98,\mathrm{y2}}$ scaling. Recent JET experiments with a low triangularity magnetic configuration at low density focused on modification of the q-profile. First, the central part of the q-profile has been modified by early NBI heating, early off-axis ICRH heating and different current ramp rates. All these different target q-profiles (q-profile at the start of the main heating) did not result in a significant change in the global confinement. Analysis with the transport codes ASTRA and TRANSP have indicated that all these methods do not produce a q-profile which is as broad as on ASDEX Upgrade measured by the radius of the $q = 1.5$ surface as seen as 3/2 NTM position. Therefore a current ramp down after a short plateau was introduced (a current “overshoot”) to change the outer part of the q-profile (see figure 1 with the plasma current trace in black). The effect of reducing the current density in the outer third of the plasma by ramping the current down produced improved confinement up to $H_{98,\mathrm{y2}} = 1.4$ transiently. By small modifications to the qprofile the MHD stability and the improved performance could be extended to about 5s, only limited by the technical constrains on the NBI usage for these plasmas. In figure 1 some of the characteristic data of such a pulse (Pulse No: 75225) in comparison to a pulse without strong q-profile modification (Pulse No: 74826) is shown. The line averaged densities are similar, the same plasma shape is used and the NBI heating starts at the same time. One consequence of the change in target q-profile are different n-number NTMs in the plasma but also the global confinement as measured by the $H_{98,\mathrm{y2}}$ factor is different. In figure 2 the q-profile from a MSE and pressure (including fast ion pressure) constrained EFIT equilibrium 2.45s after start of the heating is shown. The q-profile of Pulse No: 75225 has a large low shear region up to $R = 3.4m$ compared to Pulse No: 74826. Also the positions of the critical rational q surfaces for NTM stability (as indicated in figure 2) are moved significantly outward in Pulse No:75225.

The density in Pulse No: 75225 is higher at $t = 6s$ but relaxing later in the pulse to the same values as in Pulse No; 74826 at $t = 5.6$s . Because of the 3/2 NTMin Pulse No: 74826 it is difficult to judge the time dependence because many parameters are dominated by the existence of this mode. The electron and ion temperature (see figure 3) in Pulse No: 75225 are higher for any radius and the electron density is higher as well for any radius compared to Pulse No: 74826. The differences clearly start in the H-mode pedestal and are then propagated towards the centre. The ion temperature and its profile are not constant during the pulse. Even the the ion temperature gradient length varies with time and radius therefore it is difficult to make a straight conclusion on changes of transport. For the profiles shown in figure 3 the R/L_{Ti} is 7.15±0.65 at R=3.4m for Pulse No: 75225 and 7.8±0.7 at R=3.4m for Pulse No: 74826. At the same time and radius the Mach number $S = \sqrt{\frac{m}{e}}\frac{v}{\sqrt{T_i}}$ is M = 0.49 for Pulse No: 75225 and M = 0.4 for Pulse No: 74826 showing a high rotation speed for the pulse with better confinement.

The same current overshoot technique has been applied to a high triangularity magnetic configuration (δ = 0.4) and to higher density. An example (Pulse No: 75598) is shown in figure 4. A confinement improvement factor of $H_{98,y2}$ = 1.35 is reached but degrades rapidly 1.5s after start of the NBI heating because of a 3/2 NTM in this case. The high triangularity plasma achieves a line averaged density of $\bar{n}_e = 4.6\times10^{19}$ m^{-3} compared to $\bar{n}_e = 3.6\times10^{19}$ m^{-3} in Pulse No: 75225. The higher density results in lower and less peaked temperatures. The magnetic configuration leads to larger ELMs with lower frequency which can in some cases be strong enough to excite NTMs in the absence of sawteeth. On the other hand the stored energy and the absolute energy confinement is higher for the same $H_{98,y2}$ factor.

In figure 5 time traces of q for Pulse No's: 75598 and75596 (very similar to Pulse No's: 75598) and 75225 at rtor = 0.6 from a Faraday polarisation, a MSE constrained equilibrium, a interpretative TRANSP calculation and a interpretative CRONOS run are plotted. The TRANSP and CRONOS calculations usemeasured density profile from HRTS diagnostic, temperature profile information from the ECE radiometer diagnostic and ion temperature and Z_{eff} profiles froma CXRS diagnostic (see also figure 3). As the starting point for the calculation a q-profile from the Faraday rotation constrained EFIT equilibriumis taken at t = 3s. In the discussed plasma the confinement improvement appears to be triggered if not caused by a modification of the outer part of the q-profile by utilising a current overshoot technique. Naturally the fast change of q will disappear on a similar time scale as introduced with a delay caused by the increased temperature due to the applied strong heating. The time traces in figure 5 show that indeed most of the change in q has been removed by current diffusion after about 2s indepen dent of the triangularity or density, however the confinement for #75225 remains high. There is some small trend left for the rest of the heating period - the q-profile does not reach an equilibrium during the heating period. Qualitatively the TRANSP and CRONOS calculations reproduce the trend for both pulses and show that classical current diffusion is sufficient to explain the changes in q within the measurement uncertainties.

SUMMARY

Experiments were performed on JET to scan the q-profile with a central q around 1 to see if a domain could be found where the confinement can be improved significantly compared to a H-mode with a non modified q-profile. Different methods have been tried to change the q-profile mainly changing the central part of the q-profile based on the assumption that a low shear in the centre allows the hybrid scenario to reach higher confinement. This approach was not successful on

JET and instead a change in the outer part of the *q*-profile was necessary to improve the confinement significantly. On JET the chosen method up to now is a small current ramp down after a fast current ramp up and immediate strong heating following.

The confinement improvement affects the whole profile and is not localised. An improved pedestal pressure seems to play a key role for the low triangularity discharges. The confinement enhancement survives the decay of the change in current profile by current diffusion by a significant amount of time in the low triangularity configuration. Calculations by TRANSP and CRONOS can follow the experimental *q*-profile evolution indicating that classical current diffusion is enough to explain *q* evolution. This scenario operates at high normalised beta and a main difficulty are NTMs. By carefully changing a few parameters like β_N being beta controlled, a small amount of gas fuelling from the edge and small differences in NBI timing a relatively stable regime has been reached at low triangularity with only 5/4 or 4/3 NTMs. If these kind of plasmas have a close relationship to the ASDEX-Upgrade and DIII-D hybrid plasma then the scenario has been shown to be extendable to lower ρ^*, breaking the trend reported in [9] and hence show potential to be ported to ITER. Remaining problems are mainly MHD related and would be less severe for ITER because of its ECCD capability allowing NTM stabilisation. However, many physics questions remain open including how the scenario can be used at higher densities with impurity seeding and whether continuous current drive would be necessary to maintain it.

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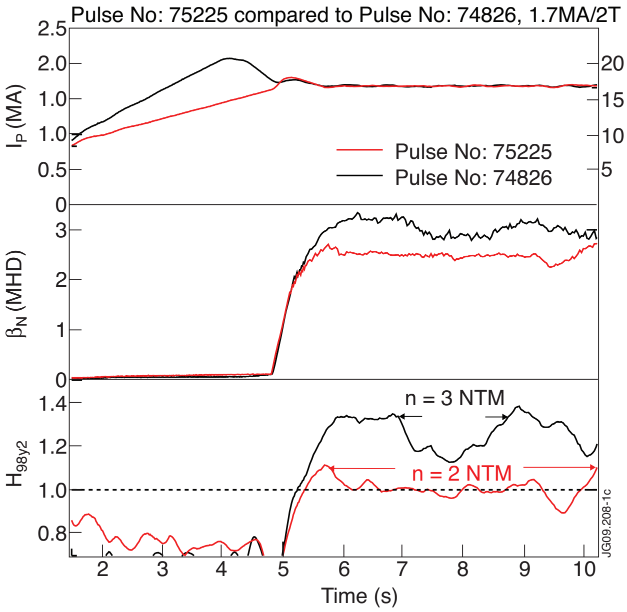

Figure 1: Time traces of a JET hybrid discharge with current ramp down before the main heating in black compared to a pulse without strong q*-profile modification in red. In the upper graph the traces of the plasma current and the NBI heating power are shown. In the middle the normalised beta bN and in the lower graph the* H98,y2*-factor is drawn.*

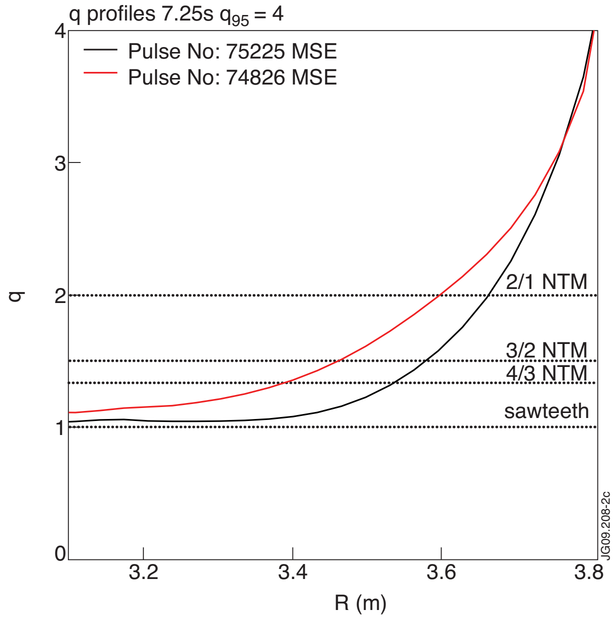

Figure 2: Equilibrium reconstructed q profile 2.45s after start of the main heating for a pulse with current overshoot and a pulse without.

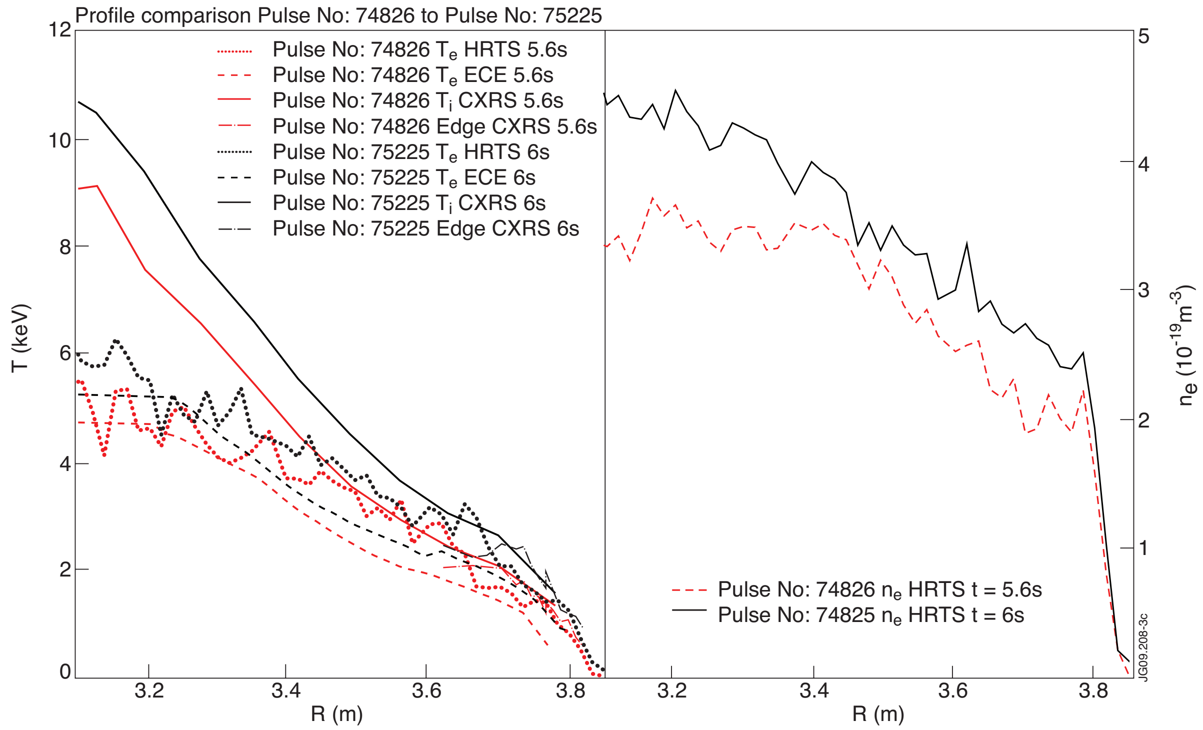

Figure 3: Temperature profiles from a pulse with modified q-profile in black and without modified qprofile in red. The profile in closed lines are ion temperatures measured by Charge Exchange Recombination Spectroscopy (CXRS). Dashed-Dotted lines are from the edge CXRS system. Dashed lines are electron temperatures measured by a Electron Cyclotron Emission (ECE) radiometer diagnostic and dotted lines are electron temperatures measured by the High Resolution Thomson Scattering (HRTS) diagnostic. On the right hand side the corresponding density profiles from HRTS.

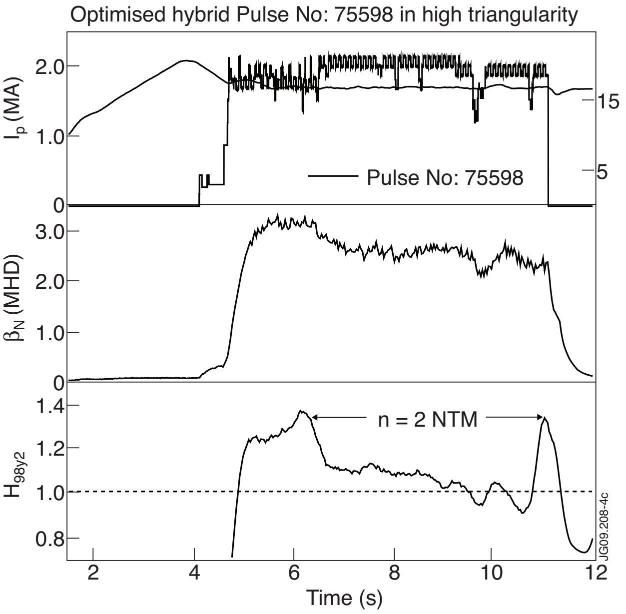

Figure 4: Time traces of a JET hybrid discharge with current ramp down before the main heating and high triangularity. In the upper graph the traces of the plasma current and the NBI heating power are shown. In the middle the normalised beta β_N and in the lower graph the $H_{98,y2}$-factor is drawn.

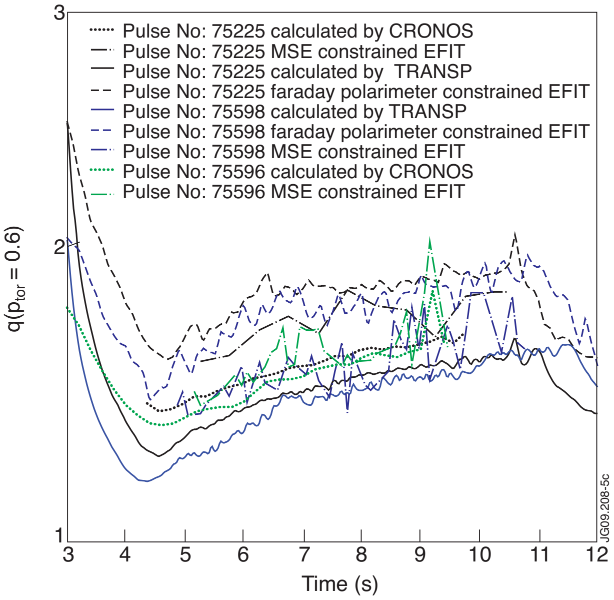

Figure 5: Time traces of q at ρ_{tor} = 0.6 for a low triangularity discharge in black and two high triangularity discharges in blue and green. All have modified q-profiles using current ramp downs. Dashed lines are from Faraday rotation constrained EFIT equilibrium constructions. The Dotted-Dashed lines represent MSE EFIT calculations, closed lines are from interpretative TRANSP calculations and double dashed and dotted lines are from CRONOS