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Improved H-mode Identity Experiments in JET and ASDEX Upgrade

A.C.C. Sips[1], E. Joffrin[2], M. de Baar[3], R. Barnsley[4], R. Budny[4], R.J. Buttery[5], C.D. Challis[5], C. Giroud[2], O.Gruber[1], T.C. Hender[4], J. Hobirk[1], X. Litaudon[2], C.F. Maggi[1], Y-S Na[1], S.D. Pinches[1], A. Stäbler[1], the ASDEX Upgrade Team and the EFDA-JET contributors*.

[1]*Max-Planck-Institut für Plasmaphysik, Boltzmannstrasse 2, D-85748, Germany.*
[2]*Association EURATOM-CEA, CEA Cadarache, F13108, St. Paul lez Durance, France.*
[3]*Associatie EURATOM-FOM, FOM Rijnhuizen, P.O. Box 1207, 3430 BE, The Netherlands.*
[4]*Plasma Physics Laboratory, Princeton University, Princeton, USA.*
[5]*EURATOM-UKAEA Association, Culham Science Centre, OX14 3EA, Abingdon, UK.*

1. Introduction

Advanced scenarios in tokamaks aim at achieving improved confinement and stability over standard ELMy H-modes, with $H_{98}(y,2) \geq 1.2$ and $\beta_N \geq 2.5$. This would allow an improvement of Q, or, at fixed Q, discharges at reduced plasma current, substantially increasing the pulse length of the tokamak. Key to obtaining these conditions is operation at different current density profiles compared to standard H-modes. Most experiments concentrate on plasmas with (strongly) reversed magnetic shear in the centre, allowing formation of internal transport barriers. However, these q-profiles are only maintained in stationary conditions at low $\beta_N < 2$ [1], while the required values for $H_{98}(y,2)$ and β_N are only obtained transiently. An alternative approach is offered in discharges with magnetic shear in the centre close to zero, $q_0 \sim 1$, and q_{95} near 4, a hybrid of the reversed q profiles and standard q-profiles in a tokamak. This scenario has been developed at ASDEX Upgrade [2]

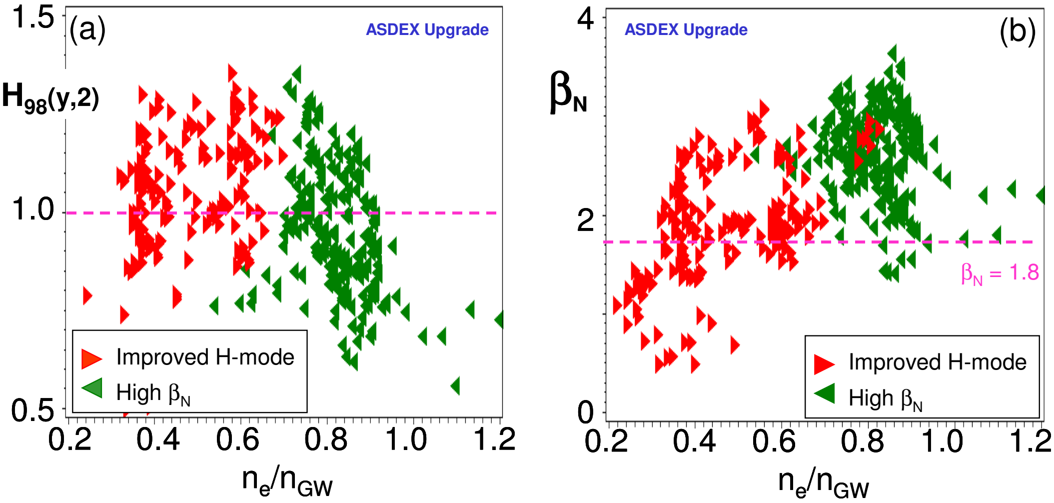

Figure 1: Overview of $H_{98}(y,2)$ and β_N values obtained at ASDEX Upgrade,for improved H-modes at low density and high beta plasmas at higher density. Both scenarios have a hybrid q-profile.

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* See appendix J. Pamela et al., Fusion Energy 2002 (Proc. 19th Int. Conf. Lyon 2002) IAEA, Vienna.

and DIII-D [3]. These plasmas have no sawteeth and the current density profile is stationary due to small MHD modes in the centre. Figure 1 gives an overview of the results obtained at ASDEX Upgrade. These indicate that the required values for $H_{98}(y,2) \geq 1.2$ and $\beta_N \geq 2.5$ can be obtained at ASDEX Upgrade for a range of q_{95} values from 3.3 to 4.5. Presented here are experiments to demonstrate this scenario in JET and to study it in a wider range of dimensionless parameters.

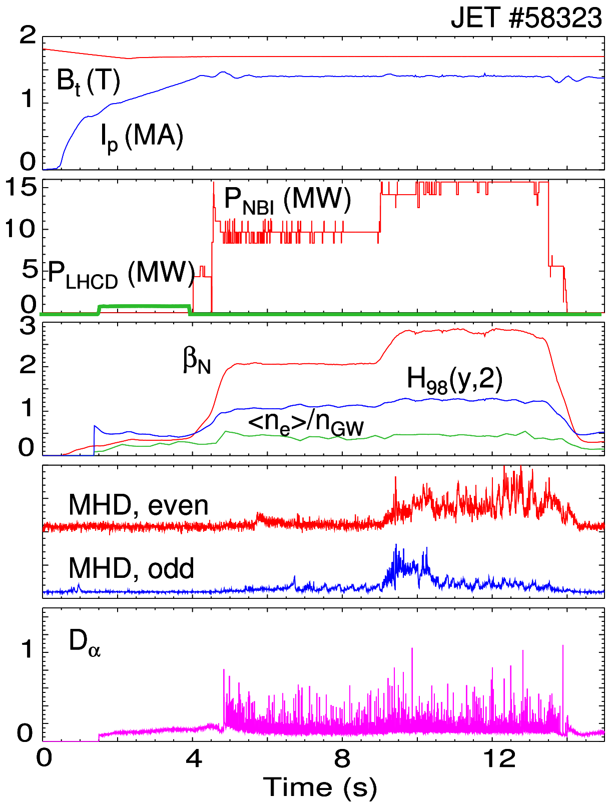

Figure 2: Pulse 58323 at JET is similar to improved H-modes obtained at ASDEX Upgrade

2. Experiments at JET

The aims of the experiments at JET are: (i) to establish improved H-mode conditions at 1.4MA/1.7T (q_{95}=3.9), with similar non-dimensional parameters (for example: ρ^* and q-profile) compared to ASDEX Upgrade, (ii) to produce stationary discharges, and (iii) to document differences (if any) when going to lower ρ^*, using 2.8MA/3.4T. In the experiments plasma shapes with a low triangularity δ=0.2 and δ=0.44 are used, matching configurations used in ASDEX Upgrade. In setting up the conditions to obtain the desired q-profile, the current rise was optimised for low inductance (not a reversed q-profile), to provide a target q-profile close to a profile required for stationary conditions. By timing of the NBI and using LHCD preheat, sawteeth are avoided at the start of the main heating phase (NBI) while q_0 is close to 1. In these discharges the sawteeth are suppressed throughout the heating phase when enough power is applied (beta poloidal ≥ 0.9). At JET the maximum NBI heating time is 10 seconds. Figure 2 gives an overview of pulse 58323, where the initial NBI heating phase uses feedback control to maintain β_N near 2 [4]. This is a standard technique used in this scenario to provide initially enough heating to set-up the hybrid q-profile, after which it is safe to increase the beta further. After 4.5 seconds the request for β_N is increased to 2.8, just within reach of the maximum available heating power, obtaining Ti_0 = 11 keV and Te_0 = 5 keV at $<n_e>/n_{GW}$ = 0.5. Neoclassical tearing modes at q=3/2 and 4/3 or fishbone activity in the core occur without degrading the confinement. The discharges in JET at 1.4MA/1.7T obtain $\rho^* = 7 \times 10^{-3}$, close to the values for ASDEX Upgrade ($6 \cdot 10^{-3} < \rho^* < 9 \cdot 10^{-3}$). In these conditions a linear increase of β_N with power is observed (see Figure 4a). β_N values up to 2.8 are obtained at 16 MW NBI heating with $H_{98}(y,2) \sim 1.2$. In the computation of $H_{98}(y,2)$, the thermal stored energy from TRANSP calculations has been used (for pulse 58323, 70% of total stored energy during the NBI heating phase). The experiments at δ=0.2 and δ=0.44 show that peaked density profiles are obtained with $n_{e0}/\langle n_e\rangle \sim 1.3$. At δ=0.44 discharges reach $\langle n_e\rangle / n_{GW} = 0.87$ while maintaining a peaked density profile. The electron density profiles and ion temperature profiles at 1.4MA/1.7T are similar to profiles observed in ASDEX Upgrade (no internal transport barrier). TRANSP calculations of the q-profile and the contributions to the current density profile are given in Figure 3. The calculated non inductive current contributions add up to 46% of the total plasma current. Important here is that the bootstrap current profile is rather flat over the entire plasma radius, supporting the low central shear. This is in agreement with results from ASDEX Upgrade, which obtain non-inductively driven current fractions in the range 40%-60% [5].

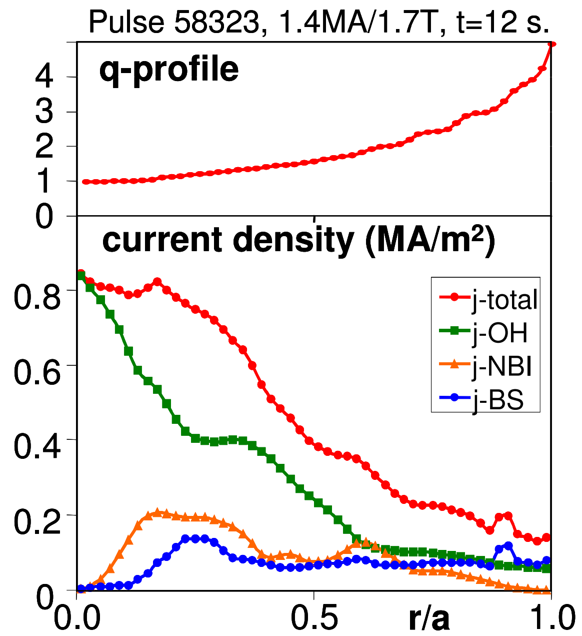

Figure 3: The q-profile, from TRANSP calcualations, plotted with the contributions to the current density profile. NBI and the bootstrap contribute 23% each to the total current.

At 2.8MA/3.4T, and thus lower ρ^*, which is important for a better extrapolation of this scenario to ITER, the general features of this regime could be reproduced. However, at low triangularity not enough input power (≤ 17 MW) was available to create type I ELM's and only type III ELM's were achieved. Moreover, transport barriers are formed in the core, near q=1. This may be due to the low target densities used, $\langle n_e\rangle / n_{GW} = 0.25$, in agreement with findings at low density in ASDEX Upgrade and in previous experiments at JET [6]. Transport analysis of these discharges shows a clear reduction of the ion diffusivity near the centre compared to improved H-mode discharges at 1.4MA/1.7T. At 2.8MA/3.4T $\beta_{pol} = 0.6$ and β_N=1.1 are obtained, with the bootstrap current contribution peaking near r/a=0.1, providing only 9 % of the total current.

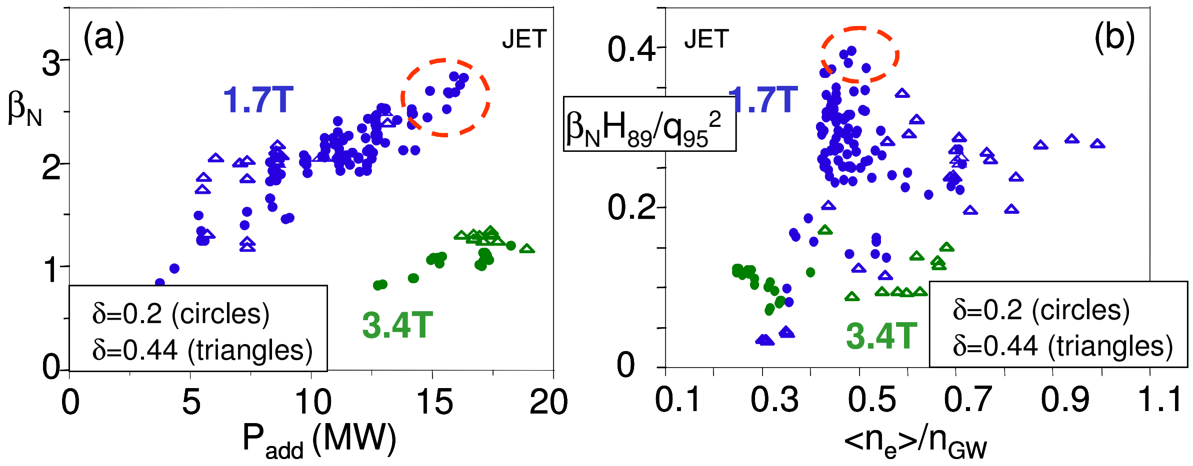

Figure 4: Overview of β_N values obtained at JET, showing a linear increase with heating power. At δ=0.2 values for $H^{89}\beta_N/q_{95}^2$ reach 0.42 the requirement for Q=10 in ITER.

3. Conclusions

By matching plasma shape, q-profile and ρ* of ASDEX Upgrade, an improved H-mode scenario has been obtained at JET at 1.4MA/1.7T. Stationary conditions are achieved with small NTM and fishbone activity in the core with similar β_N, H-factor, MHD and profiles as improved H-modes at ASDEX Upgrade. However, at lower ρ* in JET (2.8MA/3.4T), ITB´s form at low density. Also, these discharges only obtain Type III ELM´s at the edge of the plasma. Experiments at higher input power (> 17 MW) are required to verify if improved H-mode conditions can be obtained at lower ρ* by going to higher density and higher beta. In addition experiments are needed to document the beta limit at JET at 1.4MA/1.7T and to optimise operation at δ =0.44. The figure of merit for fusion gain, $H^{89}\beta_N/q_{95}^2$, reaches values up to 0.42 in JET at q_{95}=3.85 (see figure 4b), in line with the results from ASDEX Upgrade and DIII-D at similar q_{95} [2,3]. This figure of merit is required to achieve Q=10 in ITER (the reference scenario at q_{95}=3.0 has $H^{89}\beta_N/q_{95}^2$ = 0.42). The JET experiments, in combination with detailed parameter scans at ASDEX Upgrade and DIII-D [7], have been given high priority by the ITPA for collaborative experiments in 2003.

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