

Role of the q-profile in improved H-modes at ASDEX Upgrade

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1. Introduction

At ASDEX Upgrade, stationary improved H-mode discharges are obtained with low magnetic shear in the centre and q_0 near 1. This allows operation at high beta and good confinement. An investigation on the role of the q-profile in improved H-modes is presented here. The current rise can be controlled at ASDEX Upgrade to provide a range of values for the plasma internal inductance (q-profile) in improved H-modes (Figure 1). The heating power available allows operation at high (poloidal) beta over a wide range of plasma conditions. At ASDEX Upgrade, the current density profile is calculated by the CLISTE [1] equilibrium code, supported by MSE diagnostic measurements, available again in 2006.

2. Improved H-modes at $q_{95} = 3$

In recent years the current rise phase of improved H-modes has been modified from the original use of a limiter configuration up to 1 MA to a scenario with an early formation of a lower single null divertor shape. This allows control of the plasma density and impurity content. In addition a range of heating powers can be used during the current rise phase. Improved H-modes typically operate with $q_{95} = 4-4.5$ at 1MA. Discharges at lower q_{95} (~ 3) have been set up by increasing the plasma current to 1.2MA at 2.0T, rather than lowering the toroidal field at 1MA. At 2.0T ICRF using H-minority heating with a resonance in the centre can be used. This allows control of the central impurity content and the density peaking at ASDEX Upgrade. Figure 2 shows an example of a discharge at $q_{95}=3.1$. No MSE measurements are available for this discharge. A strong increase of the central ion temperature is observed at beginning of flat top phase (1.1-1.5 seconds). Feedback control of normalised beta (β_N) is used to avoid formation of an internal transport barrier (ITB) while the ITB poses a risk of a disruption at low beta. Sawteeth are only observed after 2 seconds, mixed with fishbone activity lasting throughout the high power heating phase, indicating that q approaches 1 in the centre. No large (3,2) NTMs are triggered by these sawteeth, similar to observations in Hybrid scenario experiments in DIII-D [2] and JT-60U [3] with q_{95} near or below 3. The (3,2) NTM mode seen on the MHD measurements from 1.7 to 2.3 seconds is

reproducible and in some case grows in amplitude deteriorating confinement. Recent experiments demonstrate that ECCD can be used successfully to suppress this (3,2) NTM activity. β_N is increased slowly and maintained at 3 from 4.5 to 6 seconds (10 energy confinement times). During the rise in beta, the confinement enhancement factor increases to reach $H_{98}(y,2) = 1.4$ at $\beta_N=3$. This behaviour is typical of improved H-modes at ASDEX Upgrade [4,5] and is achieved using equal amounts (power) of central and off-axis neutral beam heating and current drive. The confinement and stability achieved in these improved H-modes at $q_{95}=3.1$ exceed the values required for ITER operation at $Q=10$ [6] ($H_{98}(y,2) = 1.0$ and $\beta_N=1.8$ at $q_{95}=3$). The extrapolation of these results to ITER is in progress [7].

3. Early heating vs. late heating of improved H-modes

Stationary improved H-mode discharges in ASDEX Upgrade can exhibit different MHD behaviour, separating into two distinct groups: (i) Discharges with an early X-point configuration, 2.5MW NBI heating during the current rise and $q_{95} > 3.5$ predominately observe (3,2) NTM activity during the main heating phase, and reliably achieve high values of $\beta_N \sim 3$. (ii) Discharges with a current rise in limiter configuration (faster current penetration) or discharges without preheating or at low $q_{95} \sim 3$ observe mainly fishbone activity, in some cases a sawtooth phase evolves to fishbone activity. During this initial sawtooth phase, the discharges are prone to develop large (3,2) NTM modes, strongly deteriorating performance. The discharges with sawteeth and fishbone activity have good energy confinement. These observations have encouraged a dedicated set of experiments at fixed plasma current (1MA) and field (2.4T), with the start of the additional heating varied at constant $q_{95} \sim 4.5$ (see Figure 3). The discharges were kept at rather low beta ($\beta_N=2-2.3$) to study the q-profile evolution and confinement. The ICRF heating waveform has notches lasting 100ms, compensated by an increase in NBI, every 0.5 seconds. This obtains the best MSE measurements as typically the MSE system is disturbed by ICRH. In these conditions the early heated pulses show NTM activity; while in the late heated pulses a sawtooth phase evolve to fishbone activity. For the early heated pulses, the q-profile measurements (Figure 4) show central q values starting at 2 after the current rise phase, dropping slowly to 1, while the NTM activity starts. The late heated pulses on the other hand start with $q(0)$ below one, rising towards 1 when beta increases. Both types of discharges reach steady state conditions on a current diffusion time scale as reported in [8]. The stationary q-profiles are different for early and late heated discharges (Figure 4), maybe caused by the distinct MHD behaviour, although these differences are within the error bars of the analysis of the MSE data. Both electron temperature and ion temperature are higher in late heated pulses, despite the higher plasma density. Typically, the edge pedestal pressure is higher in late heated discharges [9]. Transport analyses are in progress to determine if there is an additional improvement in core confinement. The late heated pulses obtain $H_{98}(y,2)=1.5$ for 30 energy

confinement times, while the early heated pulses achieve $H_{98}(y,2)=1.2$. Surveying all improved H-mode data for ASDEX Upgrade in recent years, discharges at low internal inductance ($l_i < 0.9$), never obtain $H_{98}(y,2)$ above 1.3. At the highest beta values, both early and late heated pulse tend to evolve towards similar values for l_i and hence confinement, although the difference in MHD behaviour (and $q(r)$?) remain.

4. Control of the initial current rise phase

A more detailed investigation of the initial current rise phase of improved H-modes was performed. By varying the plasma density and amount of NBI heating during the current rise, the q-profile at the start of the main heating phase can be changed to the profiles shown in Figure 5, with $q(0)$ ranging from 0.9-2.0. Table I gives an overview of the conditions during the current rise and the resulting MHD during the plasma flat top phase. In a series of 8 discharges the complete spectrum of types of improved H-modes obtained in the past 7 years at ASDEX Upgrade could be reproduced: From ITB formation in discharges at low density and 2.5MW heating, to sawtoothed plasmas at high density or no preheating at all (late heating pulses). Future experiments will complete this documentation of the current rise phase including the use of ICRH and ECRH.

5. Conclusions and discussion

Improved H-modes are a candidate for ITER Hybrid operation. How to achieve discharge with low magnetic shear in the centre in ITER relies on the use of the various heating systems available (or planned). This paper presents results are relevant for ITER, in particular improved H-modes at $q_{95}\sim 4.5$ without the need for preheating, which in addition achieve higher confinement at moderate beta ($\beta_N=2-2.3$). Future investigations at ASDEX Upgrade will concentrate on (i) documenting the reason for the confinement improvement in the late heating pulses, (ii) late heated pulses at lower q_{95} values ($q_{95}=3-4.5$), (iii) the differences (if any) between early heated and late heated discharges at the maximum stable beta ($\beta_N\sim .3$), and a documentation on the role of the MHD activity. Through the International Tokamak Physics Activity (ITPA), a coordinated research with other experiments is planned on the role of the q-profile in improved H-modes.

References

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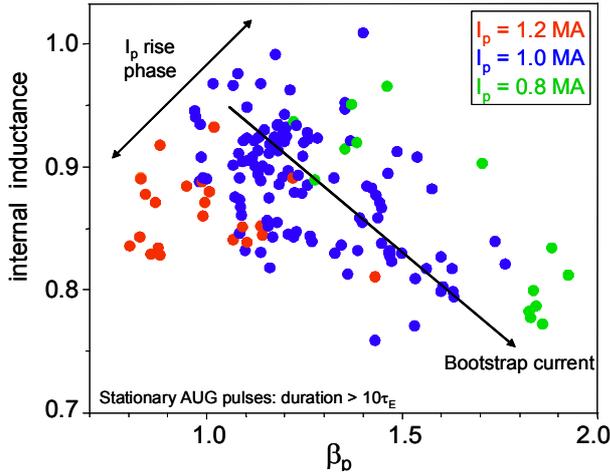


Figure 1: The evolution in the internal inductance in improved H-modes at ASDEX Upgrade for a range of plasma currents. At low beta, l_i is determined by the current rise phase, while at higher beta the current density profile has a significant contribution from the bootstrap current.

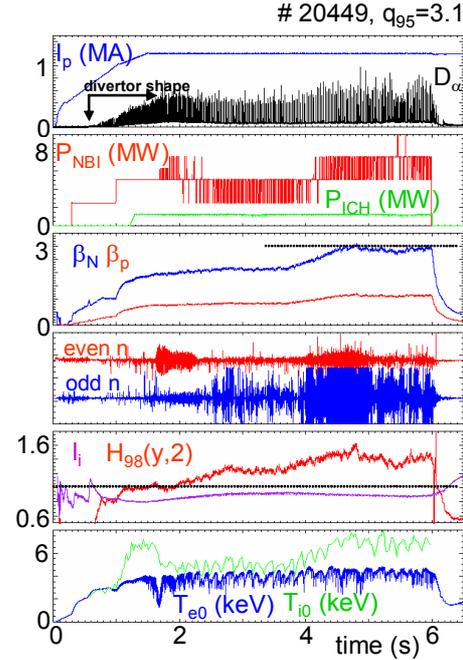


Figure 2: Improved H-mode at $q_{95}=3.15$. Control of beta (β_N) is used to achieve $\beta_N \sim 3$.

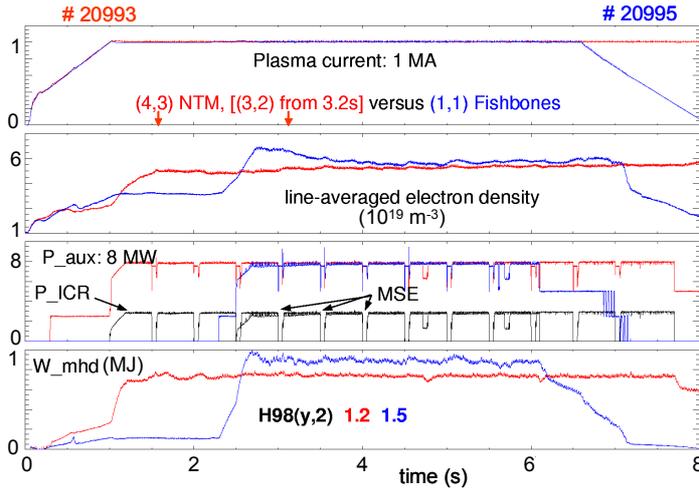


Figure 3: Early vs. late heating at 1MA/2.4T ($q_{95}=4.5$). The notches in the ICRH waveform are used to obtain reliable MSE measurements.

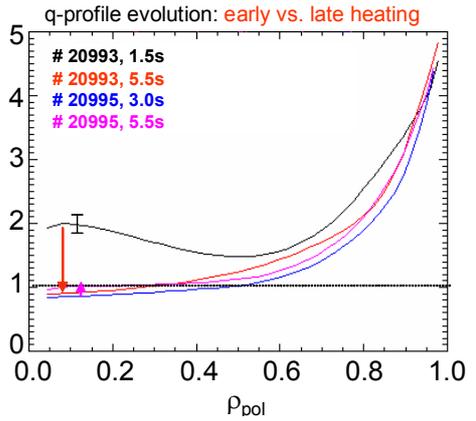


Figure 4: Evolution of the q-profile of the two cases presented in Figure 3.

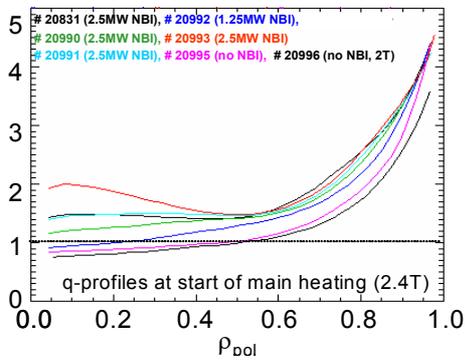


Figure 5: Variation of the q-profile for different current rise cases (Table I).

| # | T_e (1.0s) [keV] | $\langle n_e \rangle$ (1.0s) [10^{19} m^{-3}] | P_{NBI} preheat [MW] | q_0 (start of heating) | MHD behaviour |
|-------|--------------------------|---|-------------------------------------|--------------------------------|--|
| 20998 | 3.0 | 2.5 | 2.5 | 1.6 | Disrupts after ITB formation (2T)* |
| 20993 | 3.4 | 2.2 | 2.5 | 1.9 | 4/3 NTM \rightarrow 3/2 NTM at 3.2s. |
| 20831 | 3.1 | 2.6 | 2.5 | 1.9 | 4/3 NTM throughout |
| 20991 | 2.6 | 3.6 | 2.5 | 1.4 | 3/2 NTM at 2.3s. |
| 20990 | 2.2 | 5.5 | 2.5 | 1.2 | 3/2 NTM at 1.8s. |
| 20992 | 1.5 | 5.3 | 1.25 | 0.9 | 4/3 NTM throughout |
| 20995 | 1.6 | 2.9 | 0 | 0.8 | Fishbones throughout |
| 20996 | 1.1 | 2.9 | 0 | 0.8 | Sawteeth \rightarrow Fishbones |

Table I: Overview of different improved H-modes achieved by adjusting the preheating phase. Also includes late heating pulses (#20995 and #20996).