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The performance of improved H-modes at ASDEX Upgrade and projection to ITER

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Abstract
At ASDEX Upgrade, stationary discharges with improved confinement ($H_{98}(y,2) > 1$) and improved stability ($\beta_N > 2.5$) have been developed since 1998. New results presented here concentrate on extending the operational range of these improved H-modes at ASDEX Upgrade and extrapolating the results to ITER. The performance is optimised for q_{95} ranging from 3 to 5, using real time control of β_N and ECCD to suppress NTM activity at low β_N ~2. Discharges are obtained at different values of collisionality, at high density, and with a first wall predominantly covered by tungsten coated carbon tiles. For the extrapolation to ITER, the fusion power is estimated using $\beta_{N,th}$ and kinetic profile shapes as obtained in ASDEX Upgrade and $\langle n_e\rangle/n_{GW}=0.85$. The fusion gain that could be obtained is evaluated using different confinement scalings. These ASDEX Upgrade results indicate that improved H-modes are a candidate for an ITER hybrid scenario or could extend ITER operation beyond what is currently foreseen using standard H-modes.

1. Introduction

The principal reference scenario for ITER [1] is based on H-mode operation. It provides the basis for achieving ITER's primary goal of operation at Q=10 at a fusion power P_{fus}~400MW (with Q defined as the ratio of fusion power to external input power). An estimate for the energy confinement in ITER is based on the empirical IPB98(y,2) [1] scaling. The average density in ITER should be as high as possible, and is chosen to be 85% of the Greenwald density for H-mode operation, $n_{GW} = 10^{20}\ I_p[MA]/\pi a[m]^2$ [2], where I_p is the plasma current, a is the plasma minor radius. The operational space of the inductive reference scenario at 15 MA has been assessed for a range of $H_{98}(y,2)$ factors to determine the 'envelope' of performance within ITER's capabilities and physical constraints [3]. These show a strong dependence of Q and P_{fus} with $H_{98}(y,2)$, average plasma density and impurity concentration. Hence, a significant increase in ITER performance could be achieved with a relatively small improvement in energy confinement. Discharges that achieve $H_{98}(y,2) > 1$, and operate at higher beta compared to the ITER reference scenario, $\beta_N > 2$ can, when realised in ITER, be used to increase the performance at 15 MA ($\beta_N = \langle\beta\rangle aB_T/I_p$, with $\langle\beta\rangle$, the volume averaged normalised pressure (p) in the tokamak). Alternatively these discharges can be utilised for ITER operation at I_p=11-14 MA, while keeping Q=5-10. This so called hybrid scenario is designed to achieve long pulse operation with I_p driven by a combination of inductive and non-inductive currents. This would maximise the neutron fluence (neutron wall load x pulse length) in ITER for material testing.

At ASDEX Upgrade [4,5,6,7] stationary H-mode discharges have been developed which achieve the required level of confinement and stability for improving ITER's performance at full current (P_{fus} > 400 MW and Q > 10) or for hybrid operation at reduced current. These 'improved H-modes' are characterized by a q-profile with low magnetic shear in the centre and $q_0 \sim 1$, typically obtained by applying heating during the current rise phase of the discharge. Also other experiments (DIII-D [8], JT-60U [9] and JET [10]) have shown rapid progress in the development of this operational scenario in the past few years.

The new results presented here concentrate on extending the operational range of improved H-modes at ASDEX Upgrade. The performance is optimised for q_{95} ranging from 3 to 5, for different values of ν^* and at high density. The requirements for operation and control of high beta plasmas are given. The fusion performance in ITER is estimated by scaling the kinetic profiles obtained in ASDEX Upgrade, keeping the $\beta_{N,th}$ as obtained in ASDEX Upgrade and setting $\langle n_e \rangle / n_{GW}=0.85$ ($\langle n_e \rangle$, line averaged electron density). The fusion gain that could be obtained is evaluated using different confinement scalings.

2. Improved H-modes at ASDEX Upgrade

During the current rise phase of improved H-modes at ASDEX Upgrade a lower single null divertor configuration is used (formed at t ~ 0.5s). This allows operation at low plasma density (< 3×10^{19} m^{-3}) and a control of the impurity content. Additional heating is applied to slow down the current diffusion. By using such a scenario, a low magnetic shear in the centre is obtained at the beginning of the flat top phase of improved H-modes. Contrary to what one would expect on the basis of neoclassical current diffusion, the q-profile remains stationary with low central shear throughout the discharge. MHD modes are thought to be responsible for keeping q fixed. Typically (3,2) NTMs (combined with higher m/n activity) or fishbone activity in the core are observed in improved H-modes. [4]

Table I: Overview of discharges used. Ranges are given, values in brackets are average values.

dataset	#	q_{95}	n_e $\times 10^{19}$	$\langle n_e \rangle / n_{GW}$	$H_{98}(y,2)$	β_N	l_i
Type I ELMy H-modes*	944	2.9-5.5 (4.1)	2.6-14 (7.0)	0.25-1.1 (0.60)	0.5-1.6 (1.08)	0.7-3.5 (1.89)	0.75-1.3 (0.95)
Improved H-modes	259	2.8-5.4 (4.0)	4.0-12 (6.6)	0.3-0.97 (0.54)	0.8-1.5 (1.21)	1.4-3.6 (2.43)	0.75-1.1 (0.89)

*: This dataset also contains discharges with low magnetic shear in the centre

H-mode operation at ASDEX Upgrade is achieved for a wide range of plasma conditions. For the analyses presented in this paper, two H-mode datasets are created with I_p=0.6-1.4MA and B_T=1.6-3.0T, the values obtained are averaged for the time window selected. The first dataset contains all type I ELMy H-modes with q_{95} < 5.5 that are stationary for more than 0.2 seconds (grey symbols in Fig. 1a). A second dataset includes all improved H-mode discharges that are stationary for more than 0.5 seconds (red symbols in Fig. 1a), and not a mere selection of the best discharges realized at ASDEX Upgrade. The two sets of data are

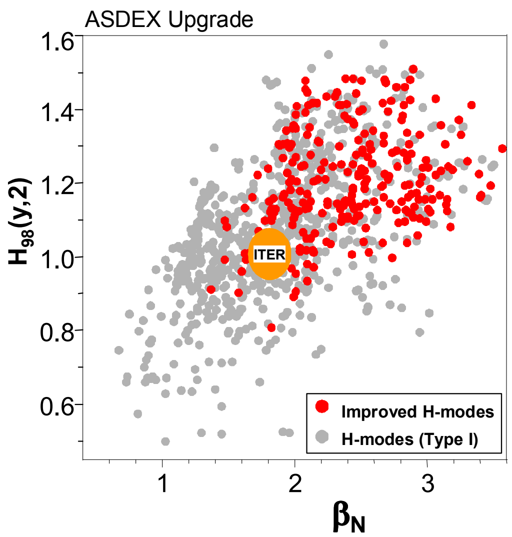

Fig. 1a: H-mode operation at ASDEX Upgrade achieves a wide range of $H_{98}(y,2,)$ vs β_N

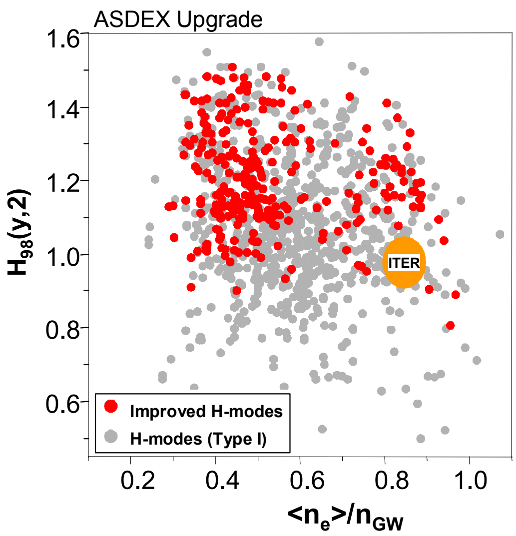

Fig.1b: H-mode operation at ASDEX Upgrade over a range of $\langle n_e \rangle / n_{GW}$

compared in Fig. 1 and Table I. Recently improved H-modes have also been obtained in discharges $q_{95} > 4$ without preheating [12]. Also these discharges (marked as red symbols) are included in Fig. 1. On average improved H-mode discharges achieve higher $H_{98}(y,2)$ at higher β_N compared to standard H-modes. By using early heating the average value of the plasma inductance (l_i) is lower (l_i=0.89), compared to the averaged l_i=0.95 for ELMy H-modes. Magnetic measurements are used to evaluate l_i (no MSE data before 2005), leading to large scatter of the values obtained. Hence, physics based selection criteria, using for example l_i<0.95 to identify improved H-modes, are not used here. Improved H-modes do not exclusively occupy the domain $H_{98}(y,2) > 1$ at $\beta_N > 2$-3. Standard H-modes that achieve high beta may have developed a q-profile with low magnetic shear in the centre, as the pedestal has a significant contribution to the beta achieved [13], giving a significant bootstrap current at the edge of the plasma. As a result the type I ELMy H-mode discharges at high beta would be similar to improved H-modes. So far it has not been possible to check all type I ELMy discharges in the dataset. For comparison, H-mode discharges from ASDEX Upgrade submitted to the ITER confinement database (DB3v5) have an average value of $H_{98}(y,2)$=1.0, rather than the average of $H_{98}(y,2)$=1.08 of the type I ELMy H-modes in the dataset used here, indicating some higher confinement discharges (improved H-modes) are included in the ELMy H-mode dataset.

As shown in Fig 1b, improved H-mode discharges typically operate at low density, $\langle n_e \rangle / n_{GW}$ = 0.35-0.6. Improved H-modes at higher density are obtained at ASDEX Upgrade by increasing the density after the formation of the q-profile, together with an increase in heating power. The highest values of $\langle n_e \rangle / n_{GW}$ = 0.85, with good confinement $H_{98}(y,2) \sim 1.2$ are obtained using a configuration at high triangularity, δ=0.4 (see section 4).

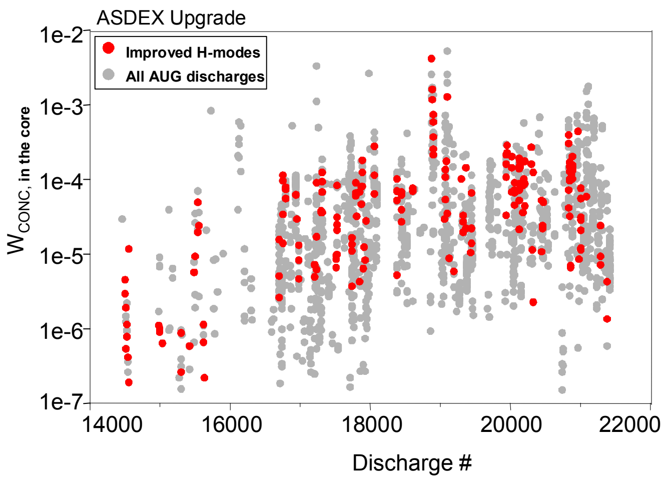

Fig.2: The concentration of tungsten in the centre for # 14000 (March 2001) to # 21500 (May 2006).

Control of the impurity influxes is of particular importance with the progressive increase in the area of the first wall covered by tungsten coated carbon tiles at ASDEX Upgrade. The tungsten concentration in the core of the plasma shows a steady rise in all plasmas since 2001, with the increase in surface covered by tungsten to 36 m^2 in 2006 (90% of the first wall surfaces, not the divertor). This is shown in Fig 2. The tungsten concentration is measured spectroscopically for the plasma region that has T_e~2-4keV (central part). Most H-modes, including improved H-modes, have central tungsten concentrations below 10^{-4}. This is considered acceptable for a reactor, with the tungsten concentration at the plasma edge below 10^{-5}. However, for all H-modes at ASDEX Upgrade central heating with ICRH or ECRH is required to avoid impurity accumulation. Operation at the lowest plasma densities (4-6x10^{19} m^{-3}) requires a boronisation prior to the experiments to minimise tungsten influxes.

More detailed investigations at ASDEX Upgrade, on the role of the q-profile in improved H-modes [12], on the documentation of the edge pedestal in these discharges [14] and on the role of pedestal in improved confinement discharges for various experiments [13] are ongoing to establish a physics basis for extrapolation of these results to ITER. Most of this research is coordinated by the International Tokamak Physics Activity (ITPA). Results obtained at ASDEX Upgrade form an essential part of these international collaborations.

3. Operation at q_{95} = 3-5

In recent studies q_{95} was varied from 3 to 5.5 by changing the plasma current (as would be the case in ITER), in contrast to previous studies where the toroidal field was changed at I_p=1MA. Discharges at q_{95}~5 (0.8MA/2.1T) have similar MHD behaviour, stability and confinement compared to pulses at somewhat lower q_{95} [6]. These discharges achieve high values for beta poloidal (~2). ASTRA code analysis of the kinetic data, including models for the bootstrap current and beam driven current, estimate a 0.73 non-inductive current drive fraction (I_{BS}/I_p=0.4, I_{NBCD}/I_p=0.33). The non-inductive current contributions alone sustain the central q above 1. Discharges at q_{95} > 5 would allow operation closer to fully non-inductive conditions. However, in H-modes the overall confinement, performance and capability to operate at sufficiently high densities all scale with I_p, so that these plasmas are deemed not ITER relevant.

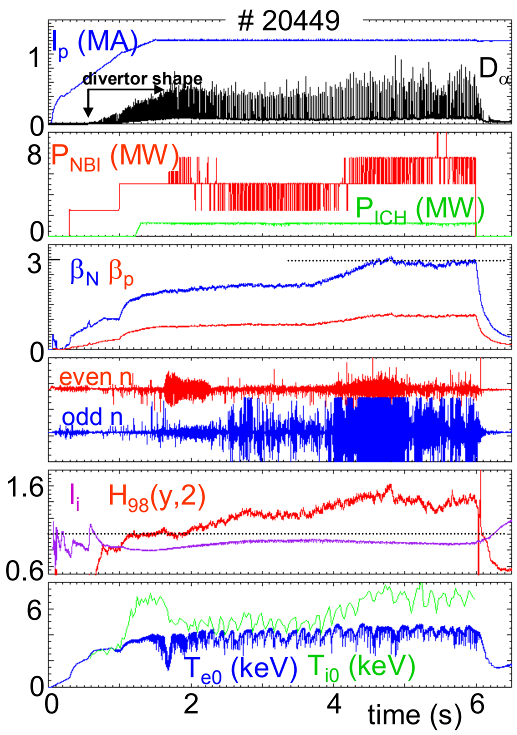

Fig.3: Improved H-mode at q_{95}=3.17.

Discharges at lower q_{95} (~3) are achieved by increasing the plasma current to 1.2MA. Operating at 2.0T, ICRF H-minority heating with a resonance in the centre is used to allow control of the central impurity content and the density peaking. Fig. 3 shows an example of a discharge at q_{95}=3.17 (#20449). Feedback control of beta (β_N) is used (with P_{NBI} as actuator) to avoid early MHD modes and the formation of an internal transport barrier (which poses a risk of a disruption). In this discharge equal amounts of central and off-axis neutral beam heating (current drive) are used. The tungsten concentration in the centre is 2.5×10^{-5}, for $\langle n_e \rangle = 6.4 \times 10^{19} m^{-3}$ and $\langle n_e \rangle / n_{GW}$=0.42. The discharge reaches β_N = 2.9, stationary for 1.5s (10 energy confinement times), limited by the duration of the additional heating. After 2 seconds, n=1 activity is observed, dominated by fishbone activity lasting throughout the high power heating phase, indicating that q ~ 1 in the centre. Also (4,3) NTM activity is observed and no sawteeth are present throughout discharge. It is reported in [12] that in improved H-modes without (3,2) NTM activity, $H_{98}(y,2)$ is typically higher. With the increase of beta during the pulse, $H_{98}(y,2)$ continues to rise until it reaches 1.4 at β_N=2.9. Hence, this pulse displays a significant increase in H-mode performance.

4. Operation over a wide range in normalised collisionality (ν*).

ASDEX Upgrade has shown [5] that improved H-modes at I_p=800kA can operate at high plasma density. This is achieved by carefully adjusting the heating power and the gas puff rate in a high triangularity (δ=0.45) plasma configuration near double null, with q_{95} = 3.5-4 at $\langle n_e \rangle / n_{GW}$ = 0.88 and $H_{98}(y,2)$=1.3. These discharges are included in Fig 1b. With the first wall covered by tungsten coated carbon tiles, it is important to achieve H-modes at high edge density ($n_{e,ped}$) to minimise the tungsten influxes over a wide operational range. Recent improved H-mode experiments have extended high density operation to a plasma current of 1MA (q_{95}=4), achieving $\langle n_e \rangle = 1.1 \times 10^{20} m^{-3}$ ($\langle n_e \rangle / n_{GW}$ =0.85-0.9). This goes beyond the absolute densities required for ITER while maintaining high performance: $H_{98}(y,2)$=1.2, β_N=3.0. The density profile is moderately peaked, with $n_{e,ped} \sim 9.2 \times 10^{19} m^{-3}$ and n_{e0} ~

$1.3x10^{20}m^{-3}$. At these high densities in the core the electron and ion temperatures are equal $T_{i0}=T_{e0}=3keV$.

The results presented here can be extrapolated to ITER using the normalised collisionality ($\nu^* \sim a^7<n_e>^3\kappa^2/\varepsilon^3W^2$, with W the total stored energy). Devices smaller than ITER, like ASDEX Upgrade, operate at densities relevant for exhaust ($<n_e>/n_{GW}$ =0.85-0.9) at relatively high collisionality, $\nu^*/\nu^*_{ITER} \sim 10$. Hence, it is important to document the confinement improvement over IPB98(y,2) scaling in ASDEX Upgrade versus ν^*/ν^*_{ITER} for standard H-modes and improved H-modes covering a range of electron densities from $0.4x10^{20}$ m^{-3} to $1.1x10^{20}$ m^{-3} (Fig. 4). The highest values of $H_{98}(y,2)$ are obtained at ITER relevant ν^*. Improved H-mode discharges operate typically close to ITER collisionality values and occupy the upper envelope of the operating space in Fig. 4

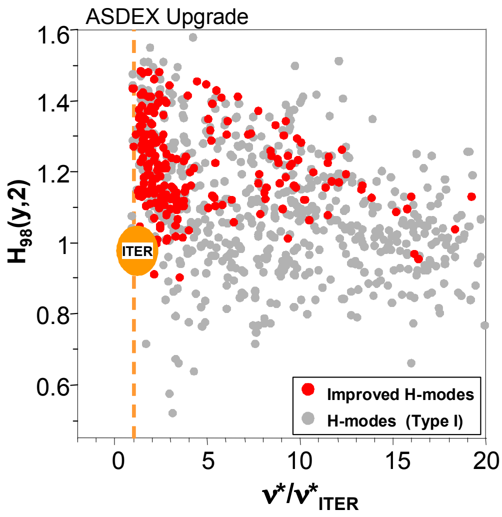

Fig. 4: $H_{98}(y,2,)$ vs. collisionality, normalised to the ITER collisionality (ν^*/ν^*_{ITER}).

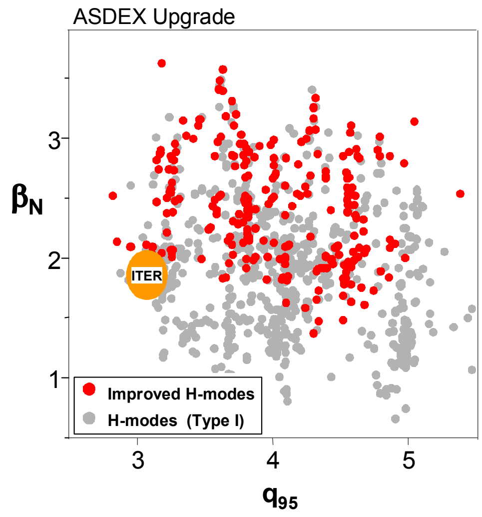

Fig. 5: The beta (β_N) achieved in H-mode discharges in ADSEX Upgrade for q_{95}=3-5.5.

5. Operation at high beta: Limits and control of NTMs

High beta, $\beta_N \sim 3$, can be achieved in nearly all experimental conditions explored so far for improved H-modes Fig. 5 shows that the maximum values for β_N obtained have no dependence on q_{95}. The maximum values of β_N achieved are in most cases near the no wall beta limit ($\beta_N=4l_i$) over the range of q_{95} explored. The beta limit in (improved) H-modes manifests itself as a (2,1) NTM [6].

The improved H-modes at low q_{95} have fishbone activity at high beta (β_N~2.5-3). These discharges are prone to develop large (3,2) NTM modes, strongly deteriorating confinement, during the first few seconds when β_N is increased above 2. A characteristic of (3,2) NTM activity at low q_{95} < 3.5 is that the impact on confinement is generally stronger compared to improved H-mode discharges at higher q_{95} [15]. In the example given before at q_{95}=3.17 (Fig. 3) the (3,2) NTM mode is seen on the MHD measurements from 1.7 to 2.3 seconds. This NTM behaviour is reproducible using the same discharge set-up and in some cases grows in amplitude leading to a (2,1) NTM.

For two similar discharges at 1.2MA/2.0T (#21269 and #21272) the conditions of #20449 were repeated. Co-ECCD was applied at 1 MW in #21269 at ρ_{pol}=0.77, while in #21272 no ECCD was applied. In both pulses the (3,2) NTM started spontaneously (without sawteeth trigger) at around 1 second, growing in size until 2.0 s. The (3,2) NTM is stabilised rapidly in #21269 when ECCD is applied from 2.0 s. (Fig. 6). Fig. 7 shows how the kinetic profiles recover when the NTM is stabilised. These profiles are obtained from fits to various diagnostic measurements available at ASDEX Upgrade. After the (3,2) NTM stabilisation, the discharge continues and is subsequently heated to reach β_N=2.5, and $H_{98}(y,2)$=1.2. Without ECCD (#21272), the (3,2) NTM remains, deteriorates the plasma confinement, leading to a (2,1) NTM that grows and locks. When this occurs, the plasma protection triggers an impurity gas injection to induce a mild disruption.

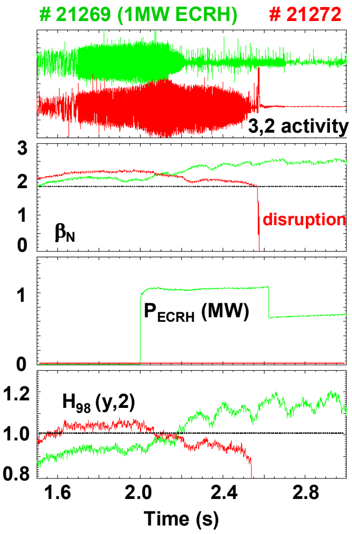

Fig.6: Two similar discharges at 1.2MA. #21269 uses ECRH to stabilise the (3,2) NTM.

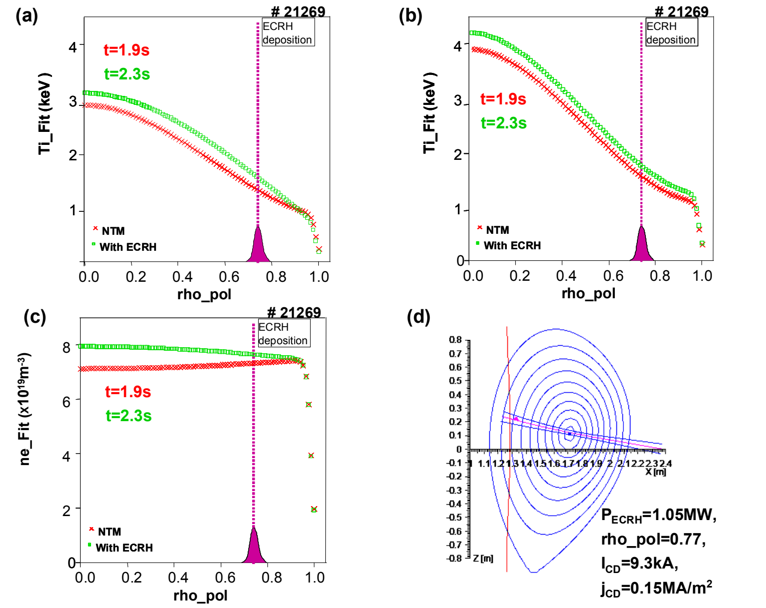

Fig. 7: #21269: 1MW ECRH is applied at ρ_{pol}=0.77 to stabilise the (3,2) NTM. Te, Ti and n_e are given before (red) and after NTM stabilisation (green).

6. Extrapolation to ITER

The prediction of the fusion performance in ITER presented here is based on an extrapolation using the ASTRA transport code starting from experimental profiles. Results are calculated for 68 ASDEX Upgrade discharges, conventional and improved H-modes with q_{95}=3.15-4.8, $H_{98}(y,2)$=0.95-1.65 and β_N=1.7-3.5. For these discharges the density and temperature profiles are obtained from a fit to the data of several diagnostics. The thermal beta calculated from the kinetic profiles ($\beta_{N,th}$) is typically 0.8-0.9 β_N.

Some assumptions are made to scale ASDEX Upgrade experiments to ITER [16]. A similar method has been used for DIII-D discharges [17]. The choice is, of course, not unique. The toroidal field (5.3T) and the equilibrium boundary are taken from the ITER design [1]. The plasma current in ITER is chosen to match the q_{95} used in ASDEX Upgrade, and varies from I_p=14.2MA down to I_p=9.4MA for the range of q_{95}=3.15-4.8. The density profile shape is kept and its value is adjusted to achieve $\langle n_e \rangle$=0.85n_{GW} in ITER (Fig 8a). At ASDEX Upgrade H-modes obtain good confinement over a range of $\langle n_e \rangle / n_{GW}$ (see Fig.2). As a result choosing $\langle n_e \rangle$=0.85n_{GW} is valid, especially considering ITER

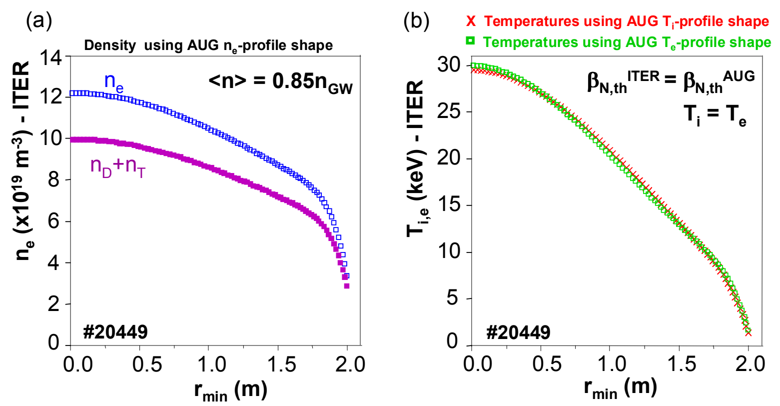

Fig 8: The density and temperature profiles in ITER scaled from #20449. In these conditions *P_{fus}=1070 MW, Q=∞.*

uses a plasma configuration at δ~0.5. Electron and ion temperature profiles are assumed to be the same in ITER. The shape of the temperature profiles is taken to be equal to the ion temperature profile in ASDEX Upgrade when $T_{e0}<T_{i0}$ or taken equal to the electron temperature profile when $T_{e0}\geq T_{i0}$. Usually, the temperature gradient lengths are quite close to each other in H-mode plasmas (Fig 8b), some differences are observed at the lowest plasma densities (at high T_{i0}). The scaling factor for the temperature profiles is determined by the $\beta_{N;th}$ value obtained in the ASDEX Upgrade discharges. It is assumed that similar $\beta_{N;th}$ values can be achieved, although the normalised Larmor radius ρ* is substantially lower in ITER, which could make discharges more susceptible to NTM activity [15]. The deuterium and tritium concentrations are assumed to be equal. Impurity concentrations are taken from the ITER design: Be 2 %, Ar 0.12 %, He 4.3 %. As a result, the volume averaged Z_{eff} is approximately 1.65 in all simulations, and the dilution of the tritium and deuterium fuel is ~0.8 as shown in Fig 8a.

Using these assumptions, the fusion power in ITER can be calculated directly from the scaled kinetic profiles. An overview of the results is given in Fig. 9. The maximum fusion power obtained ranges from 420MW (at $\beta_{N,th}$=2.6) at I_p=9.4 MA to 1070MW (at $\beta_{N,th}$=2.8, #20499, Fig. 3) at I_p=14.2 MA in ITER. An estimate for the required input power (P_{aux}) and Q depend on the energy confinement. In Fig. 9 the IPB98(y,2) scaling is used, assuming the same H_{98}(y,2) values are obtained in ITER and ASDEX Upgrade.

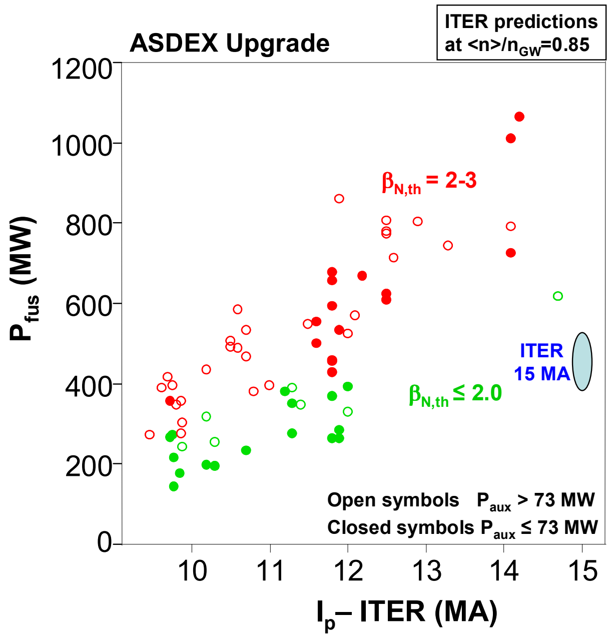

Fig. 9: The prediction of the fusion power in ITER by scaling the kinetic profiles data from ASDEX Upgrade. The power requirements (P_{aux}) to sustain the β_N,th use IBP98(y,2) scaling.

These extrapolations indicate that operation at high beta results in significant fusion power for I_p=9.5MA to I_p=12MA. The bootstrap current fraction at these plasma currents is f_{BS}~0.4 at β_N~3, while Q ranges from 6-15. Alternatively, the results at low q_{95}~3 (I_p=14-15 MA) indicate that the fusion power could be more than doubled compared to the ITER reference scenario, moreover these discharge would obtain ignition (Q=∞) in ITER. For the highest fusion power obtained at q_{95} ~ 3.1, the pedestal conditions $n_{e,ped}=6.8\times10^{19}m^{-3}$ and $T_{e,ped}=T_{i,ped}$=5.7 keV are within the ITER design parameters.

The fusion gain and input power (P_{aux}) required have been calculated for three different energy confinement scalings [1,18,19]. For each scaling the respective H-values obtained at ASDEX Upgrade are taken. The results are shown in Fig. 10. For the IPB98(y,2) scaling operation at high beta would require, in some cases, a value for P_{aux} which is above the maximum planned for the first stage in ITER (73MW). These are indicted by the open circles in Figs. 9, 10. This is a feature of the IPB98(y,2) scaling law which has a strong beta degradation ($B\tau_E\sim\beta^{-0.9}$), and maximises Q at the lowest possible beta. Especially for high q_{95} (I_p^{ITER} <11MA), the IPB98(y,2) scaling predicts discharges at β_N>2.5 to be inaccessible at $<n_e>=0.85n_{GW}$ even for H_{98}(y,2)=1.3-1.5. Far more optimistic values for P_{aux} and Q are obtained using a GyroBohm scaling [18] ($B\tau_E\sim\beta^0$). The scaling proposed by Cordey [19] ($B\tau_E\sim\beta^0$) would predict higher Q at high beta compared to the IPB98(y,2) scaling.

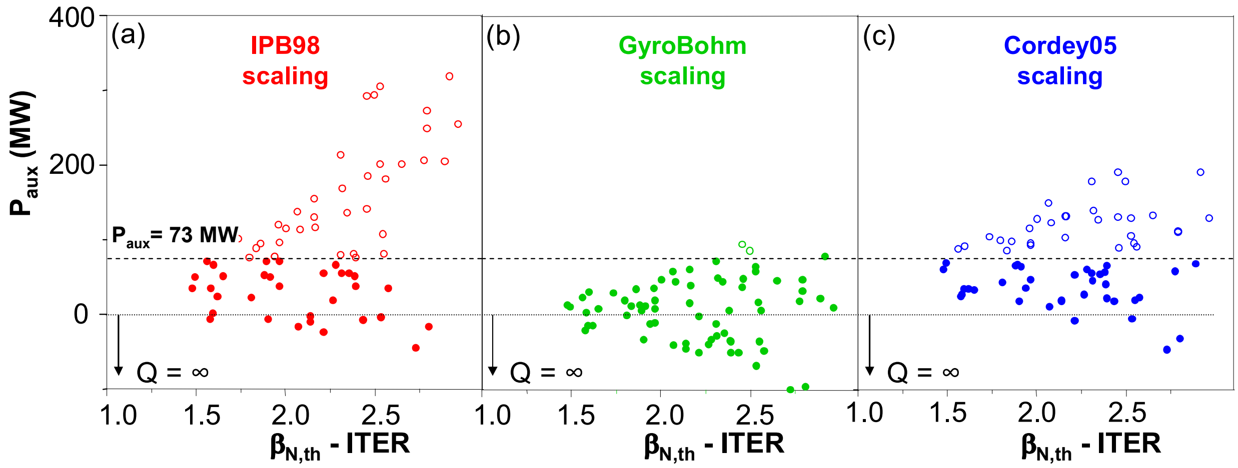

Fig. 10: Input power requirements (P_{aux}) to sustain the beta in ITER as obtained in ASDEX Upgrade for three different energy confinement scaling laws.

8. Conclusions

At ASDEX Upgrade, H-modes with low magnetic shear in the centre achieve $H_{98}(y,2)>1$ and $\beta_N=2\text{-}3$. The central tungsten concentration can be kept at acceptable levels ($<10^{-4}$) in these experiments at ASDEX Upgrade. Improved H-modes at $q_{95}=3.1$ achieve $H_{98}(y,2)=1.4$ at $\beta_N=2.9$, with fishbone activity in the core keeping the q-profile stationary. ECCD can be used to stabilise (3,2) NTM activity during the low beta ($\beta_N\sim2$) phase of these discharges. Operation at high density with $\langle n_e\rangle=1.1\text{x } 10^{20}$ m^{-3} ($\langle n_e\rangle/n_{GW}=0.85\text{-}0.9$) is demonstrated. However, the highest $H_{98}(y,2)$ values are achieved at ITER relevant ν^*. The kinetic profile shapes at ASDEX Upgrade are scaled to ITER (using ASTRA), setting $\langle n_e\rangle=0.85n_{GW}$ and keeping $\beta_{N,th}$. This predicts high fusion power for improved H-mode discharges at $q_{95}=3.1$ ($P_{fus}=1070$ MW, $Q=\infty$). In these conditions, the density and temperature at the edge are within ITER design parameters. At lower I_p in ITER (9.5MA-13MA), significant fusion power can be achieved ($P_{fus} \geq 400$ MW, Q=6-15). Using the IPB98(y,2) scaling, the auxiliary power requirements at high $\beta_N>2.5$ and at $I_p<11$MA may exceed the maximum P_{aux} planned for the first stage of ITER (73 MW).

References

[1] ITER Physics Basis 1999 *Nucl. Fusion* **39** 2137
[2] Greenwald M. *et al* 1988 *Nucl. Fusion* **28** 2199
[3] Shimada M. *et al* 2004 *Nucl. Fusion* **44** 350
[4] Gruber O. *et al* 1999 *Phys. Rev. Lett.* **83** 1787
[5] Sips A. C. C. *et al* 2002 *Plasma Phys. Control. Fusion* **44** B69
[6] Stäbler A. et al *2005 Nucl. Fusion* **45** 617
[7] Gruber O. et al *2005 Plasma Phys. Control. Fusion* **47** B135
[8] Luce T. C. et al *2005*, *Nucl. Fusion* **45** S86
[9] Ide S. et al *2005*, *Nucl. Fusion* **45** S48
[10] Joffrin E. et al *2005*, *Nucl. Fusion* **45** 626
[11] Pereverzev G. V. *et al* 1991 *Report IPP* 5/42
[12] Stober J. *et al* 2006 *this Conference, "Physics studies of the improved H-mode scenario in ASDEX Upgrade"*, (EX/P1-7)
[13] Maggi C. F. *et al* 2006 *this Conference, "Characteristics of the H-mode Pedestal in Improved Confinement Scenarios in ASDEX Upgrade, DIII-D, JET and JT-60U"*, (IT/P1-6)
[14] Suttrop W. *et al* 2006 *this Conference," Studies of the edge pedestal and behaviour of Edge Localised Modes in improved H-mode in ASDEX Upgrade"*, (EX/8-5)
[15] Zohm H. *et al* 2006 *this Conference, "Control of MHD Instabilities by ECCD: ASDEX Upgrade Results and Implications for ITER"*, (EX/4-1Rb)
[16] Tardini G. *et al* 2006 33rd EPS Conference, Rome 19-23 June 2006, P.112
[17] Luce T. C. *et al* 2004 *Phys. Plasmas* **11** 2627
[18] Petty G. *et al* 2003 Fusion Sci. Technol. **43** 1
[19] Cordey J. G. *et al* 2005 *Nucl. Fusion* **45** 1078