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ITER performance of scaled ASDEX Upgrade discharges

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1 Introduction

Several approaches can be employed to predict the fusion performance of the ITER burning plasma. Scaling laws have been derived on a common database of discharges from the existing tokamak devices, delivering an estimate for the energy confinement in ITER. Those fits have been extended and refined progressively.

The most commonly used empirical scaling for conventional H-mode plasmas is IPB98(y,2) [1]. In the past decade new parameter ranges have been explored and alternative scenarios have been developed, aiming in particular to an optimum compromise between long pulse operation and high performance, within the constraints of the auxiliary heating capability. Moreover, several experimentss have highlighted different dependences of the energy confinement time on plasma parameters than assumed so far, in particular the β dependence [2] [3] [4] , which is only partly explained by errors-in-variable regression [5]. Theory based fluid models, validated on exixsting tokamaks [6], have been applied in order to simulate ITER discharges in terms of dimensionless physics [7] [8]. It should be noted that the predicted fusion performance is strongly sensitive to the density and temperature values at the top of the pedestal, which can be predicted only with significant uncertainties, and to the model's stiffness [8] [9].

The approach of this work is to scale existing ASDEX Upgrade discharges to ITER dimensions, following some assumptions on dimensionless parameters and the shape of the kinetic profiles. For this purpose the ASTRA transport code is used [10]. The calculations are benchmarked with existing predictions of the fusion power and fusion gain for several ITER scenarios. Results for extrapolated ASDEX Upgrade discharges are shown both for conventional as well as improved H-mode scenarios, for several Greenwald density fractions and $\beta_{N,th}$ values. Finally, the main dependences of the fusion gain are highlighted in the framework of the IPB98(y,2) scaling law.

2 Scaling setup and assumptions

Some assumptions have been made to scale ASDEX Upgrade experiments up to ITER. The choice is, of course, not unique. The toroidal field, the equilibrium boundary and the impurities' concentration are taken from the ITER-FEAT design [1]. The parameter q95 is changed with respect to the ITER target to be the measured value in the selected

ASDEX Upgrade discharges. The plasma current is hence determined. The experimental density profile shape is kept. A factor multiplies the profile as to obtain a volume average density of a given Greenwald fraction in the ITER plasma, the reference being 85 %. Electron and ion temperature profiles are assumed to be equal in ITER due to the fast heat exchange among species. Although fusion α particles heat mainly electrons, the rapid heat exchange between ions and electrons adjusts heat transport to be carried mainly by the channel most affected by turbulence. In present day devices one can roughly assume the channel with higher central temperature to carry most of the heat flux in the core plasma. So we choose the ITER temperature profiles to be proportional to the ASDEX Upgrade profile with the highest central temperature. In fact, temperature gradient lengths for ions and electrons are usually quite close to each other in H-mode plasmas. The scaling factor for the temperature profiles is determined by $\beta_{N,th}$ being a given fraction of the value achieved in the ASDEX Upgrade discharge. The deuterium and tritium concentrations are assumed to be equal. The impurity concentration is taken from the ITER design: Be 2 %, Ar 0.12 % [8] and He 4.3 %, which is within the range considered in [8]. As a result, the volume averaged Z_{eff} is approximately 1.65 in all simulations. The radiation model from [11] i used. Finally, we assume the confinement time of the ITER discharge to be $\tau_E^{IPB98(y,2)} \times \mathrm{H}_{H98(y,2)}$, choosing $\mathrm{H}_{H98(y,2)}$ to be the measured value of the ASDEX Upgrade discharge. When evaluating the fusion gain we neglect the correction to the total power arising from charge exchange processes and orbit losses in the scaling law. Beam-target fusion is not included either.

3 Scaling of ASDEX Upgrade discharges

We have simulated ITER discharges with the ASTRA code for different scenarios, using the designed geometry, impurity concentrations and reference kinetic profiles. The equilibrium is computed self-consistently. The fusion power calculated with ASTRA agrees always obtained with the quoted value within less than 10 %. For scenario 4 (advanced with plasma current 9 MA), the reference simulation appears to have a different assumption for impurities, leading to Z_{eff}=2.17 and to higher radiation power. Otherwise, the small discrepancies are likely to be due to slightly different impurity profile shape or plasma equilibrium, for instance the total volume is not perfectly matched.

With the assumptions discussed in Section 2, ASDEX Upgrade discharges have been scaled to ITER. We have selected # 17847, a standard H-mode discharge with high density and q95 close to the value 3 foreseen for the ITER reference scenario, and # 17870, an improved H-mode with good confinement properties. The kinetic profiles, shown in Fig. 1, are fits between different diagnostics over stationary time intervals. The most relevant plasma parameters are summarised in Table 1. T is the temperature with higher

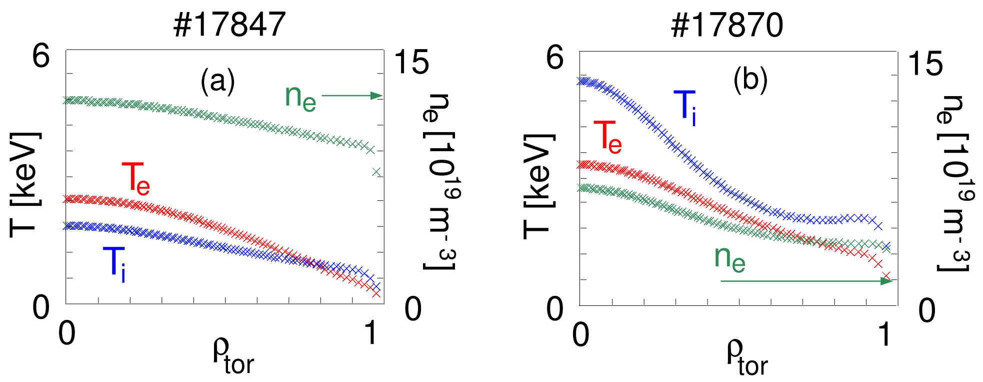

Figure 1. Measured density and temperature profiles of ASDEX Upgrade discharges. (a) #17847. (b) #17870.

AUG #	q95	β_N	$\beta_{N,th}$	$\mathrm{H}_{H98(y,2)}$	n_e	$\frac{T(0)}{<T>}$	$\frac{n_e(0)}{<n_e>}$	$\frac{\bar{n}_e}{n_{GW}}$	$\rho^\star$	$\nu^\star$
17847	3.06	2.10	1.98	0.95	10.5	1.98	1.21	0.73	2.0 10^{-3}	3.6
17870	3.80	2.63	1.96	1.32	5.09	2.17	1.66	0.40	2.5 10^{-3}	0.39

Table 1: Experimental plasma parameters of the ASDEX Upgrade discharges # 17847 and #17870

value on-axis. Greenwald density fractions of 70 % and 85 % are input for the standard H-mode, 50 % and 70 % for the improved H-mode. The value of $\beta_{N,th}$ is varied to be 80 %, 100 % and 120 % of the ASDEX Upgrade measured value, respectively. In Table 2 the simulation results are presented. The Greenwald fraction and the ratio $\beta_{N,th}/\beta_{N,th}^{AUG}$ are varied in the first and second column, respectively. The resulting fusion power, fusion gain, stored energy, bootstrap fraction and loop voltage are presented. It should be noted that the volume averaged density is used, so the scaling factor for the density profile is higher.

The $\beta_{N,th}$ dependence is the most striking: as $\beta_{N,th}$ increases, Q is strongly reduced, although the fusion power grows. This is due to the strong power degradation of the IPB98(y,2) scaling. In fact, the increase of the kinetic profiles demands additional power more than linearly: $P_{fus} + P_{aux} \approx \left(W_{kin}/\tau_E^P\right)^{3.23}$, where $\tau_E^P := \tau_E^{IPB98(y,2)} P^{0.69}$ has no power dependence. In particular, working at given $\beta_{N,th}$ the positive scaling of the plasma current is cancelled, since $W_{kin} \propto \beta_{th} \propto \beta_{N,th} I_{pl}$. Within this approach, relying on the IPB98(y,2) scaling law, one cannot improve both P_{fus} and Q, but only look for the best compromise.

Quantitatively, the scaling of the standard H-mode is compatible with previous predictions, with Q between 5 and 10. The fusion power is usually higher than in the reference. The bootstrap current ranges between 10 % and 25 % of the total plasma current, similarly to present day devices.

Scaled	$\frac{\bar{n}_e}{n_{GW}}$	$\frac{\beta_{N,th}}{\beta_{N,th}^{AUG}}$	P_{fus} [MW]	P_{aux} [MW]	Q	W_{kin} [MJ]	$< T >$ [keV]	$< n_e >$ [10^{19} m^{-3}]	$\frac{I_{bs}}{I_{pl}}$	V$_{loop}$ [V]
17847	0.85	0.80	407	21.2	19.2	306	8.07	9.34	0.169	0.195
17847	0.85	1.00	635	84.6	7.51	382	10.1	9.33	0.209	0.120
17847	0.85	1.20	864	208.	4.16	459	12.1	9.32	0.250	0.075
17847	0.70	0.80	405	49.4	8.20	304	9.74	7.67	0.163	0.153
17847	0.70	1.00	601	158.	3.79	385	12.3	7.70	0.211	0.100
17847	0.70	1.20	780	346.	2.26	461	14.7	7.69	0.253	0.065
17870	0.70	0.80	180	0	∞	203	9.55	5.22	0.169	0.080
17870	0.70	1.00	269	10.9	24.8	254	11.9	5.21	0.212	0.059
17870	0.70	1.20	356	45.3	7.87	304	14.3	5.21	0.255	0.039
17870	0.50	0.80	162	15.2	10.7	201	13.3	3.71	0.166	0.069
17870	0.50	1.00	221	54.2	4.07	252	16.6	3.71	0.208	0.040
17870	0.50	1.20	272	123.	2.21	302	19.9	3.71	0.251	0.024

Table 2: Fusion performance of the ITER-scaled discharges # 17847 and #17870 for different Greenwald fractions (first column) and $\beta_{N,th}$. (second column). V_{loop} is computed neglecting beam current drive.

The improved H-mode has better performance. This is due mainly to the good confinement, as H$_{H98(y,2)} \approx 1.3$. It is worth noting that the IPB98(y,2) scaling was constructed on a database of standard H-mode discharges. Further simulations of scaled improved H-mode discharges with different H$_{H98(y,2)}$ are expected to clarify the extent of the improved performance of ITER hybrid scenarios and the need of refined scaling laws.

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