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Extrapolation of ASDEX Upgrade H-mode discharges to ITER

G. Tardini, L. D. Horton, O. J. W. F. Kardaun, C. F. Maggi, A. G. Peeters[1], G. V. Pereverzev, A. C. C. Sips, J. Stober, and the ASDEX Upgrade Team

MPI für Plasmaphysik, Euratom Association, Boltzmannstr. 2, 85748 Garching, Germany

[1] Centre for Fusion, Space and Astrophysics, University of Warwick (UK)

1 Introduction

Various scaling laws predict the thermal confinement and fusion performance of ITER ELMy H-mode discharges. Besides the well established IPB98(y,2) scaling law [1], which has a strong power degradation, other scalings have been proposed with a weaker β dependence, such as the scaling proposed in equation (9) of [2] ('Cordey' scaling) and the electro-static Gyrobohm [3] scaling laws, in order to explain experimental observations in several tokamaks [4][5][6].

Theory based models have the advantage of being intrinsically dimensionless and can be used as predictive tools as long as they do not have free parameters to be adjusted to the device. Although there is a general agreement about the instabilities dominating core transport, they yield somewhat different predictions for the core, but more importantly they are strongly sensitive to the values of the kinetic profiles on the pedestal top, which are predicted with large uncertainties [7].

In order to predict the fusion performance in ITER, in this work we extrapolate ASDEX Upgrade discharges using the information contained in the scaling laws and adding some features from present experiments, in particular the shape of the kinetic profiles, the confinement improvement factor for each scaling law (H-factor), the thermal contribution to the normalised pressure ($\beta_{N,th}$) and the safety factor (q_{95}). A large profile database of 92 well diagnosed H-mode discharges has been setup, including only stationary time intervals. The scaled profiles have been then used for ASTRA simulations with ITER geometry, in order to predict the fusion power (P_{fus}), the radiated power (P_{rad}) and the auxiliary power (P_{aux}) needed to sustain the prescribed $\beta_{N,th}$ at the given H-factor. P_{fus} is a direct output of the profile normalisation. The scaling laws predict confinement and therefore the fusion gain $Q = P_{fus}/P_{aux}$. The effect of different levels of tungsten concentrations is investigated here. 0D figures of merit discussed in [8] are validated against the present database.

2 Fusion power

Several assumptions for the profiles extrapolation have been made [9][10]. The ITER geometry is taken from the ITER-FEAT design, as well as the toroidal magnetic field [1]. The parameter q_{95} is assumed to be the same as in the AUG discharge, thus determining the plasma current. We retain the shape of the AUG kinetic profiles, with multiplying factors in order to obtain $n_e/n_{GW} = 0.85$ and $\beta_{N,th}$ as in the AUG discharge. We set $T_e = T_i$ in ITER, taking the shape of the AUG profile with higher central temperature. The deuterium and tritium concentrations are assumed to be equal. The impurity content was taken in agreement with the central values discussed in [11] for Be, Ar and He.

Additionally, the tungsten concentration has been scanned from zero to the maximum tolerable value for ITER of $n_W = 10^{-4} n_e$ proposed in [12]. This affects both P_{rad}, which has to be compensated by increasing P_{aux}, and the fusion fuel dilution, which affects P_{fus}. In Fig. 1 we show P_{fus} and P_{rad} in the case without tungsten (black diamonds) compared to the worst case with peaked tungsten density profiles and a volume average concentration $< n_W/n_e >= 10^{-4}$ (red stars). P_{rad} is calculated in ASTRA as the sum of the bremsstrahlung, the synchrotron radiation and the line radiations due to Ar, Be and W. Fig. 1 (a) shows P_{fus} as a function of $\beta^2_{N,th}/q^2_{95}$. As expected the effect of

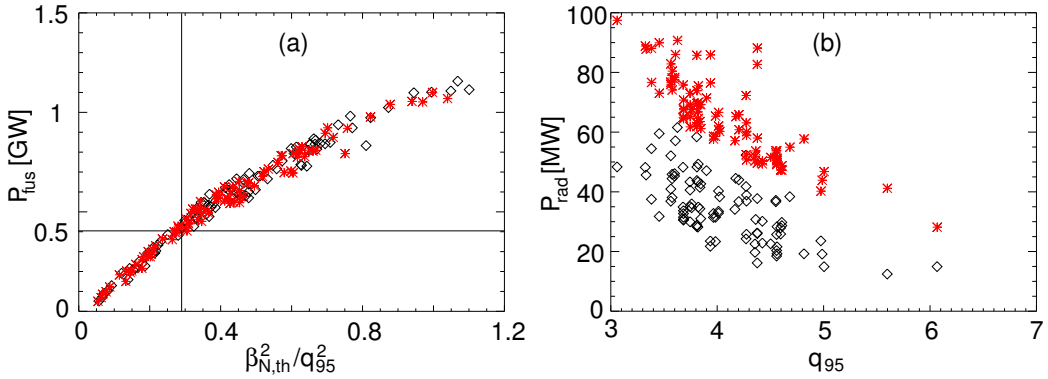

Figure 1. (a) P_{fus} in an ITER-sized device as a function of $\beta^2_{N,th}/q^2_{95}$ without tungsten (black diamonds) or with $< n_W/n_E >= 10^{-4}$ and peaked n_W profile (red stars). The lines mark the ITER operation point. (b) P_{rad} versus q_{95} with different tungsten content in an ITER-sized device. Colors as in (a).

fuel dilution due to tungsten is negligible. However, in Fig. 1 (b) the clear increase of P_{rad} with tungsten is observed, by an amount comparable to the total auxiliary heating capability of ITER, 73 MW. Any increase of P_{rad} beyond the ITER baseline estimate has to be compensated by increasing P_{aux}. It has to be noted, however, that Ar is foreseen in ITER as a radiator, so its concentration can be reduced in case of high P_{rad} due to tungsten. In the following sections we neglect the tungsten contribution.

The relation between P_{fus} and $\beta^2_{N,th}/q^2_{95}$ is close to linear over a wide range including the ITER operating point. Since the profile shape information plays a role only for P_{fus}, from the linear relation of Fig. 1 (a) one can conclude that a 0D scaling is a good approximation of the fusion performance, provided the 0D scaling is chosen consistently with the assumptions made.

3 Fusion gain

In Fig. 2 we illustrate the range of the H-factors and of $\beta_{N,th}$ in our database. The parameter q_{95} ranges between 3 and 5, except two discharges featuring $q_{95} = 5.5$ and 6. The H-factors of the scaling laws [1][2][3] measured on AUG are kept as confinement improvement factors for ITER. As a result, one obtains the required P_{aux} as $P_{aux} \approx P_{heat} - P_{\alpha} - P_{Ohm}$. In Fig. 3 the ITER P_{aux} is plotted according to the three scaling laws. The two horizontal lines mark P=0 and P=73 MW. Negative auxiliary power means ignition, power larger than 73 MW means that such a $\beta_{N,th}$ value is not accessible

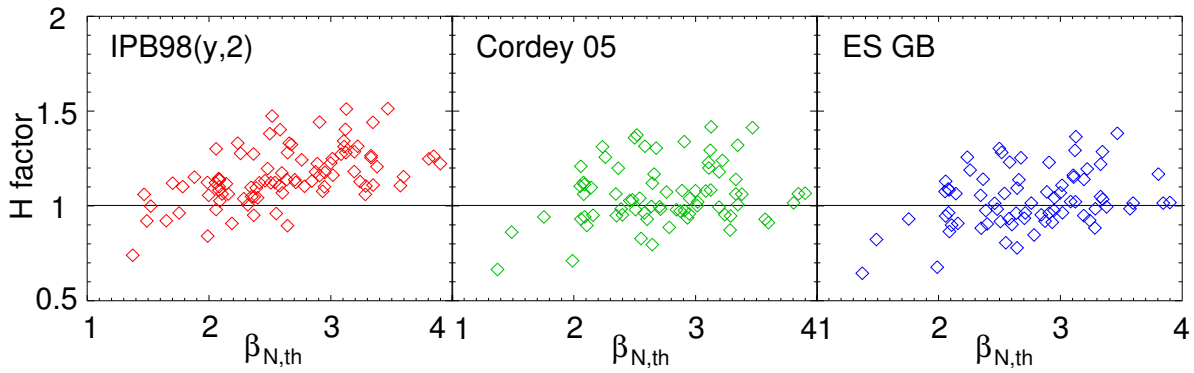

Figure 2. H-factors as a function of $\beta_{N,th}$ for the IPB98(y,2) (red) Cordey 05 (green) and electrostatic Gyrobohm (blue) scaling laws. The line marks H=1.

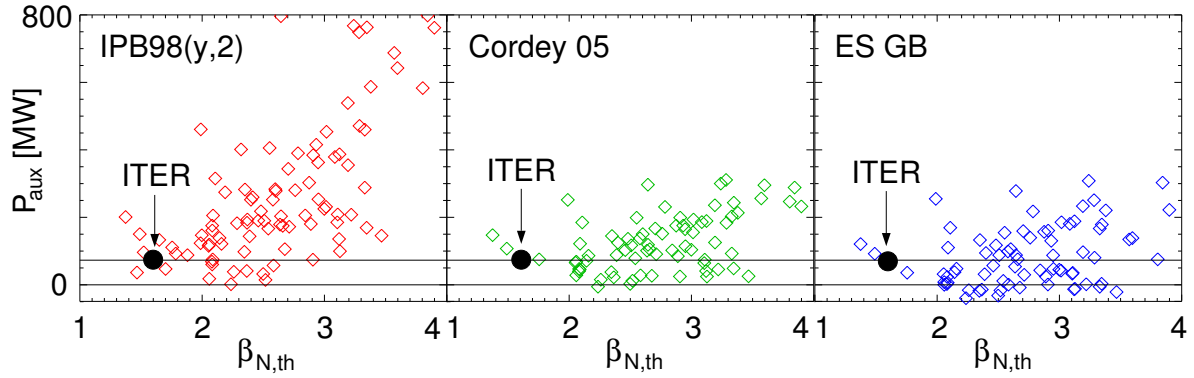

Figure 3. Needed P_{aux} versus $\beta_{N,th}$ for the IPB98(y,2) (red) Cordey 05 (green) and electrostatic Gyrobohm (blue) scaling laws. The lines marks P_{aux}=0 (ignition) and P_{aux}=73 MW (ITER's scheduled P_{aux}).

for the given H-factor. The most optimistic prediction is obtained with the Gyrobohm scaling, with 13 % of the discharges igniting and 60 % within ITER's P_{aux}. The Cordey scaling predicts similar results, with slightly smaller fusion efficiency. The most pessimistic scaling is the IPB98(y,2), in particular at high $\beta_{N,th}$ due to its strong power degradation. Nevertheless, high $\beta_{N,th}$ values up to 2.5 are predicted to be accessible in ITER, provided the H-factor is high enough. Ignition is practically excluded according to the Cordey and IPB98(y,2) scaling.

The quantity $G = P_{fus}/(5P_{heat})$ is often used in the literature as a figure of merit of the fusion efficiency. In fact, $G \propto n^2 < \sigma v > \tau_E / (nT)$ can be simplified to $G \propto nT\tau_E$ because in the relevant temperature range one can approximate $< \sigma v > \propto T^2$, as discussed in [13]. Introducing the usual definition $Q = P_{fus}/P_{aux}$ one can relate the two quantities: $G = Q/(Q+5)$. In particular, $G = 0$ means $P_{fus} = 0$, whereas $G = 1$ means ignition. As pointed out in [8], however, finite power degradation in the scaling laws makes some care necessary when choosing the correct scaling of G with respect to H, $\beta_{N,th}$ and q_{95}. Our approach assumes constant B, geometry, ion mass and n_e/n_{GW}. The correct G scaling, derived in [8], reads:

$$G = C H^{\frac{1}{1+\alpha_p}} \beta_{N,th}^{2-\frac{1}{1+\alpha_p}} q_{95}^{-1-\frac{\alpha_p+\alpha_I+\alpha_n}{1+\alpha_p}} \quad (1)$$

where α's are the scaling law's exponents for power (α_p), current (α_I) and density (α_n) dependence. The coefficient C for each scaling law is determined at a given ITER reference scenario. Fig. 4 shows the good agreement between the $Q/(Q+5)$ of the ASTRA

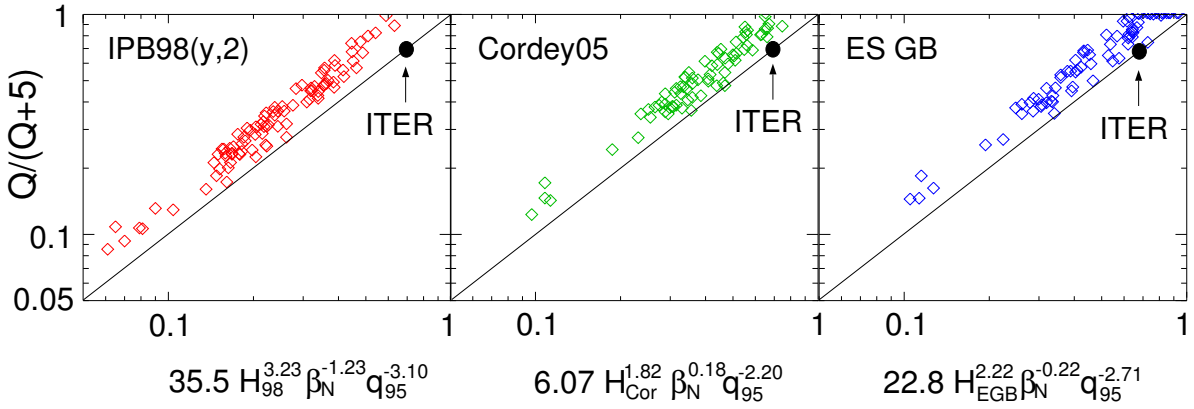

Figure 4. G from ASTRA simulations as a function of the 0D figure of merit for G at constant n_e/n_{GW}.

simulations of the scaled discharges and the 0D scaling for G given by equation 1. It can be shown that taking, for instance, the 0D G-scaling assuming constant absolute density, i.e. equation 1 without α_n (and therefore different C), the data alignment becomes significantly worse. For the usual scaling $G \propto H\beta_{N,th}/q_{95}^2$ no alignment at all is observed. The parameter $H\beta_{N,th}/q_{95}^2$ might be considered a compromise between good fusion gain and high fusion power in a reactor, but it cannot be used as an indicator for the triple product (or ignition), unless $\alpha_I = 1$ and $\alpha_p = 0$, which is not the case in any of the scaling laws considered here. Finally, Fig. 4 shows that, with a slightly better tuned coefficient C, the 0D scaling would be accurate enough to predict the figure of merit of ignition.

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