New assessment of the fast ion energy in ASDEX Upgrade H-mode discharges

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Abstract.

Confinement scaling laws such as IPB98(y,2) are widely used to extrapolate the performance of present tokamaks to next-step devices such as ITER or DEMO. The thermal energy of the plasma (W_{th}), which is used to determine the energy confinement time for most scaling laws, is difficult to measure, due to the sizeable uncertainties in the experimental kinetic profiles. The common approach in the tokamak community is to derive W_{th} as the difference between the measured MagnetoHydroDynamic (MHD) energy and some simulation-based estimate of the fast ion energy W_{fi}. In H-mode plasmas W_{fi} can be as high as W_{th}, in presence of Neutral Beam Injection (NBI) or Radio Frequency heating, therefore an accurate assessment of W_{fi} is crucial to have a somewhat reliable H-factor, regardless of the power-scaling of a given scaling law.

In this paper we aim at evaluating the current approach to estimate W_{fi}, by comparing its predictions with a wide database of calculations using validated NBI codes. Systematic deviations and trends, as well as statistical scatter are discussed.

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We use a comprehensive database of AUG H-mode deuterium plasmas, with significant variations of plasma current, NBI power and plasma density. We neglect thereby the fast-ion losses caused by MHD modes and the synergy effect between NBI and ICRF. A new approach is proposed based on the newly developed fast NBI code RABBIT.

Keywords: Confinement, H-mode, Fast-ion energy

1. Introduction

In order to increase the confidence of our confinement predictions for future tokamak devices it is crucial to reduce all uncertainties in the determination of the parameters entering the scaling law, but even more in the estimate of the energy confinement time. Depending on the power degradation of confinement for a given scaling law, uncertainties in the determination of the heating power are more or less cancelled when it comes to confinement improvement factors (H-factors). The most widely used scaling, IPB98(y,2) [1], has a strong degradation, in fact $\tau_E^{IPB98(y,2)} \propto P^{-0.69}$. Therefore possible uncertainties in the NBI power losses play a minor role. The thermal ion energy (W_{th}), instead, enters only in the numerator. Therefore, its uncertainty propagates linearly into the H-factor. Density and temperature profiles are nowadays measured with a satisfactory accuracy for most purposes, such as transport studies. However, in this paper we show that for the specific evaluation of W_{th} even a 5-10% uncertainty can have significant consequences. This is, unfortunately, a realistic uncertainty for kinetic profiles measurements. Additionally, uncertainties in the equilibrium reconstruction also affect the volume integration of the pressure profile, with a prominent role played by diagnostics in the outermost region, where the volume elements are larger. Furthermore, the effective charge Z_{eff} is known with even less accuracy, increasing the uncertainty of the ion density profile. Due to these experimental uncertaintes the common approach is to infer W_{th} as the difference between the total stored energy W_{MHD} , and the estimated fast ion energy, typically derived on the base of simulations of the NBI fast ion population, or from the measured diamagnetic energy W_{dia} and the estimated perpendicular energy of the fast ions. In ASDEX-Upgrade we use for W_{MHD} the value reconstructed with the CLISTE equilibrium code [2], using magnetic measurements as strong constraint (within few %). A comprehensive review of the approaches used in the various devices for the definition of the confinement database can be found in [3].

The fast ion energy W_{fi} is found to be significant in NBI (and to a lesser extent RF) heated discharges, reaching values as high as W_{th} . Its uncertainties can therefore have a dramatic impact on the H-factor calculation.

To determine W_{fi} and the NBI power losses most accurately, and hence the H-factor too, the straightforward option would be to perform an individual simulation of the NBI reconstruction after each discharge. However, the relevant codes were either not accurate enough (pencil-like) or too slow (Monte Carlo) to give a reasonable estimate within minutes after a plasma discharge. Moreover, NBI codes rely on measurements which are not always immediately available, and the workflow for input preparation is not always fully reliable without some human assistance.

Therefore, a large database of 15k NBI simulations has been constructed for ASDEX Upgrade NBI-heated H-mode plasmas [4], varying the most significant plasma parameters. For this purpose the TRANSP-NUBEAM Monte Carlo code was used [5] [6]. Scaling laws were derived as regression fits of the simulation database, for NBI power loss terms and for W_{fi} , with an assessment of the residual and the scatter.

In this paper we take the comprehensive, well-balanced confinement database DB5v3.2

(extended) described in [7] to validate this approach in its entire workflow, including the approximations assumed for the profile information which is missing just after an experimental plasma discharge. It is the recent ASDEX Upgrade addition to the world-wide cross-machine H-mode confinement database. It is described in detail in Section 2.

The parametrisation law for W$_{fi}$ and the accuracy of the current assumptions in our database are discussed in Section 3.

Section 4 contains the evaluation of W$_{fi}$ from the parametrisation as compared with individual NBI simulations of the time-intervals in the present database. Such simulations are performed with the MonteCarlo orbit-following code TRANSP-NUBEAM, but also with the faster, semi-analytic RABBIT code [8], providing a valuable benchmark for the latter. Systematic deviations and trends are discussed, as well as the magnitude of the scatter of the parametrisation points around the simulated ones.

Conclusions are drawn in Section 6, suggesting a new approach for the determination of W$_{fi}$ based on the RABBIT code.

2. Experimental database of ASDEX Upgrade NBI-heated H-modes

The full database (3048 time intervals) has been simulated by the TRANSP and RABBIT code, with an automatic workflow for input preparation, job-submission, output fetching and database creation. Runs with $\bar{T}_e < 0.5$ keV or with $\bar{n}_e < 1.94\ B^2_{tor}$ were rejected, where $\bar{T}_e$ is the line-averaged electron temperature, $\bar{n}_e$ is the line averaged density

Parameter	Unit	Min	Max
$\bar{n}_e$	10^{19} m^{-3}	2.3	13.
$\bar{T}_e$	keV	0.54	4.8
I_{pl}	MA	0.4	1.4
P_{NBI}	MW	1.3	17.0

Table 1. Database coverage in terms of the most relevant plasma parameters with respect to W$_{fi}$

in $10^{19}m^{-3}$ units and B_{tor} the toroidal magnetic field in Tesla. In those discharges the Electron Cyclotron Emission (ECE) measurement of T_e was hampered by cut-off. We discarded 1568 points from the database due to ECE cut-off. Further 7 time intervals were discarded because no NBI heating was applied, therefore they are not relevant for this study. Otherwise, all TRANSP and RABBIT runs were successful.

In table 1 the main parameters ranges relevant for W$_{fi}$ are summarised. Thereby, $\bar{n}_e$ and $\bar{T}_e$ are the line-averaged electron density and temperature, respectively, while I_{pl} is the plasma current and P_{NBI} the injected NBI power.

3. TRANSP-based regression of W$_{fi}$ for NBI-heated H-modes

Until now, W$_{fi}$ has been evaluated using a parametrisation of roughly 15k TRANSP simulations, taking a standard H-mode as reference and varying the plasma electron density, electron temperature, plasma current, magnetic field, density peaking, Z_{eff} and

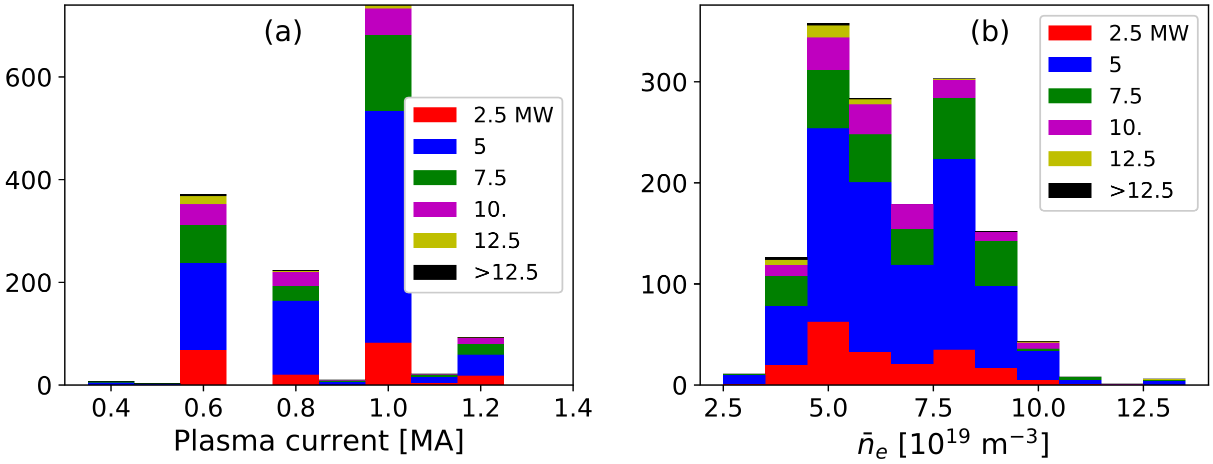

Figure 1. Distribution of plasma parameters in the database. Colours refer to the applied P_{NBI}. Occurrences of (a) plasma current (b) plasma density.

fields sign [4]. In Fig. 2, taken from reference [4], the regressions are displayed for an on-axis source (NBI #1) and an off-axis source (NBI #6). The parametrisation of W_{fi} for

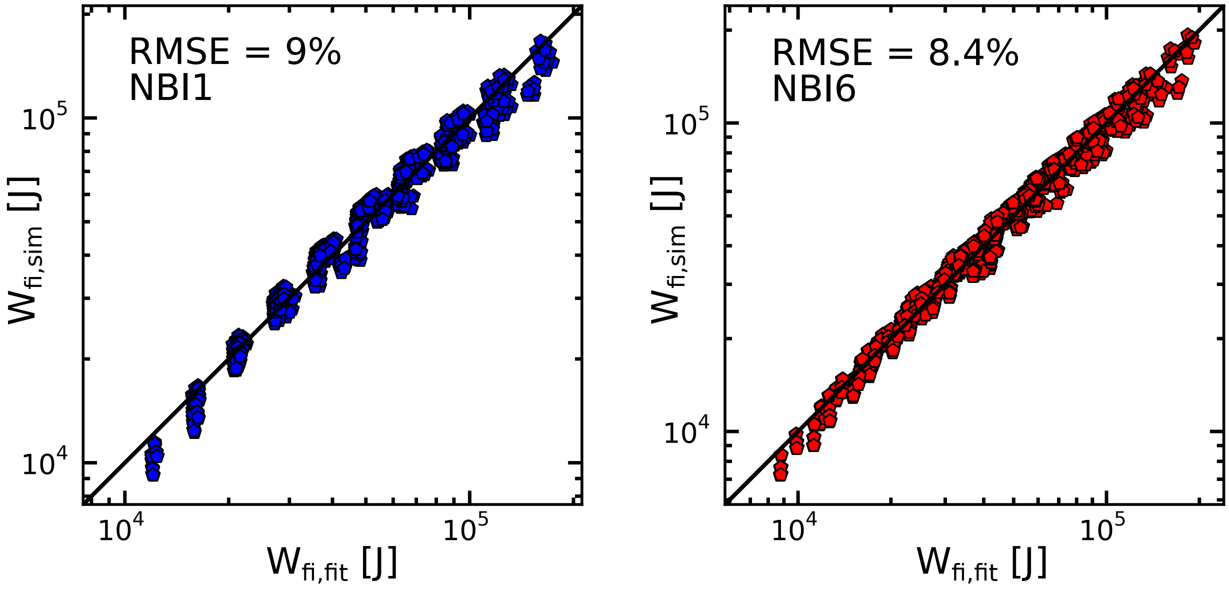

Figure 2. Regressions for W_{fi} on a TRANSP simulation database: NBI source #1 (a) and #6 (b).

each NBI source is of the form

$$W_{fi} = c_{jNBI} * \tau_{sd,jNBI} * P_{jNBI}$$

where units are SI, jNBI is the label of the respective NBI source, and τ_{sd} the corresponding slowing down time, defined according to ref [9] as

$$\tau_{sd} = 7.376\ 10^{13} \bar{T}_e^{1.5} / \bar{n}_e\ *\ ln[1 + (E_{NBI}/W_{crit})^{1.5}]/3$$

where $W_{crit} = 0.01865 * \bar{T}_e$, following reference [9] for deuterium. Here, τ_{sd} is in seconds, $\bar{T}_e$ in eV, E_{NBI} and W_{crit} in keV, $\bar{n}_e$ in m^{-3}.

As Fig. 2 shows, there is a significant scatter around the fit, with deviations as high as 30%. Depending on whether W$_{fi}$ is a small or large fraction of W$_{MHD}$, this can have a weak or strong impact on the evaluation of thermal confinement. Moreover, it has to be pointed out that the regression has been done with $\bar{T}_e$ from TRANSP, i.e. from the input T_e profile. Such profile information is usually not immediately available after a shot, therefore we rather use an estimate:

$$\bar{T}_{e,TOT} = \frac{0.207\ W_{MHD}}{Vol\ \bar{n}_{e,exp}} \tag{1}$$

Units here are eV for T_e, J for W$_{MHD}$, m^3 for the volume, m^{-3} for n_e.

Equation 1 is derived from a (non-unique) set of assumptions:

$$< T_i > \ \approx \ < T_e >$$

$$W_{th} \approx 0.83\ W_{MHD}$$

$$\bar{n}_e\ \bar{T}_e \approx 1.2\ < n_e >< T_e > \tag{2}$$

Solving for the line-averaged density and temperature:

$$\bar{n}_e\ \bar{T}_e \approx 1.2\ \ < n_e >< T_e > \approx 0.207\ \frac{W_{MHD}}{Vol}$$

The set of assumptions 2 is realistic, but it contains several uncertainties, as all 3 quantities can deviate significantly from the values assumed. The pressure profile peaking is (overall) underestimated and it spans a wide range of values; the ratio T_i/T_e can reach down to 0.5 or up to 2 (for conventional scenarios) depending on the heating applied and on the plasma density; the fast ion energy fraction varies significantly, roughly proportionally to $P_{NBI}\ T_e/n_e$, as shown later in Fig. 6 (a). The discrepancy between $\bar{T}_e$ from W$_{MHD}$ and $\bar{n}_e$, compared to $\bar{T}_e$ from equation 1 is highlighted in Fig. 3, showing systematically higher values being fed into the TRANSP simulations with respect to our simplified assumption 1, in average by a factor 1.5. This leads to different values for the slowing-down time and hence to different W$_{fi}$, as we discuss in the next section.

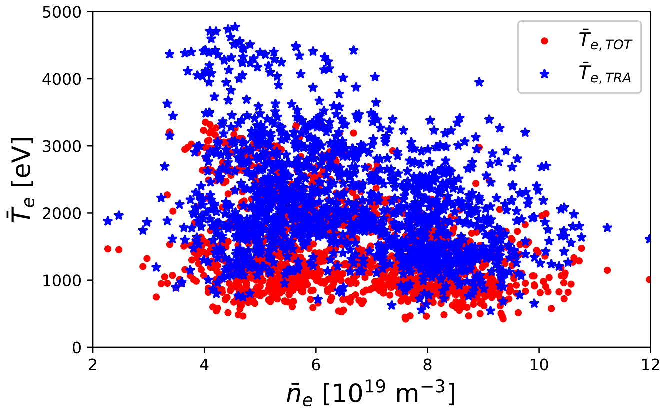

Figure 3. Line averaged T$_e$: according to assumption 1 (red) and taking the line-average of the experimental T$_e$ profile (blue).

4. Validation of the parametrisation-based $\mathbf{W}_{fi}$ with individual NBI simulations

The time intervals of the database have been simulated with TRANSP and RABBIT. It has to be noted that in the modelling no other fast-ion loss mechanisms have been considered beyond pure orbit and collision effects (corresponding to neoclassical transport of fast ions). It is known that such losses can be indeed significant, in particular in presence of MHD activity and in general at high P_{NBI} [10][11]. However, it is not trivial to find a general scaling law for such effects, nor a fully predictive modelling with orbit-followng codes with a unique setting of parameters, unless one can use sophiticatedd diagnostics for the kind and magnitude of the MHD instabilities [12]. This might lead to an overestimate of the fast-ion content, especially at high P_{NBI} and low n_e.

A further option would be to use TRANSP/NUBEAM for each individual discharge, applying a fast-ion diffusion coefficient adjusted to match the measured neutron rate. This method appears promising, but has several drawbacks. The computing time, already quite demanding, is dramatically increased by adding a fast-ion diffusion coefficient. To match the neutron rate in an automatised feedback loop, moreover, several simulations per discharge would be needed, till the neutron rate is matched with sufficient accuracy. This would lead to exploding CPU times, even at highest possible parallelisation. There are, however, also experimental limitations which make this approach not viable. The neutron-rate measurement in ASDEX-Upgrade has, unfortunately, no uniform calibration over several past campaigns [13], making the backward application to older discharges impossible. Efforts for a clean, reproducible, absolute calibration are in progress [14]. An additional strong limitation for this method is also the experimental uncertainty of the Z_{eff} measurement. As beam-target D-D fusion dominates the neutron rate [13], and we measure n_e and not n_D experimentally, even a 10-20 % uncertainty in Z_{eff} can affect the neutron rate by an amount which is largely significant to invalidate the estimate of W$_{fi}$.

The Z_{eff} profile plays almost no role in this study, neither in the parametrisation-based approach, nor in the enw one proposed in this paper. That's because we do not reconstruct W$_{th}$ directly, but we rather compute W$_{fi}$. In fact, the exact Z_{eff} value has a negliglible impact on the NBI deposition, and a marginal effect on the slowing-down process. This holds unless Z_{eff} takes unrealistically high values such as Z_{eff} ¿ 3, which have never been observed in ASDEX Upgrade H-modes, even less since the completion of the tungsten wall. Since Z_{eff} measurements are not always accurate (or even not available, in particular for older discharges), we set Z_{eff} = 1.6 for the TRANSP and RABBIT simulations in this work. This is a rule-of-thumb value, moderately underestimated for the old carbon-wall discharges and slightly overestimated for discharges with a tungsten wall.

Note that for TRANSP and RABBIT the effect of anisotropic velocity distribution was retained, using the formula

$$W_{th} = W_{MHD} - 0.75 * W_{fi,\perp} - 1.5 * W_{fi,\|} \tag{3}$$

which can be derived considering the definitions of total stored energy and W$_{MHD}$ as energy corresponding to the Grad-Shafranov equilibrium pressure [3]. We will refer to the quantity $0.75 * W_{fi,\perp} + 1.5 * W_{fi,\parallel}$ as W$_{fi,aniso}$ in the following, while W$_{iso}$ is just the toal fast ion energy, $W_{fi,\perp} + W_{fi,\parallel}$. The effect of considering the anistropic velocity distributin of fast ions is summarised in Fig. 4 for TRANSP (blue) and RABBIT (green).

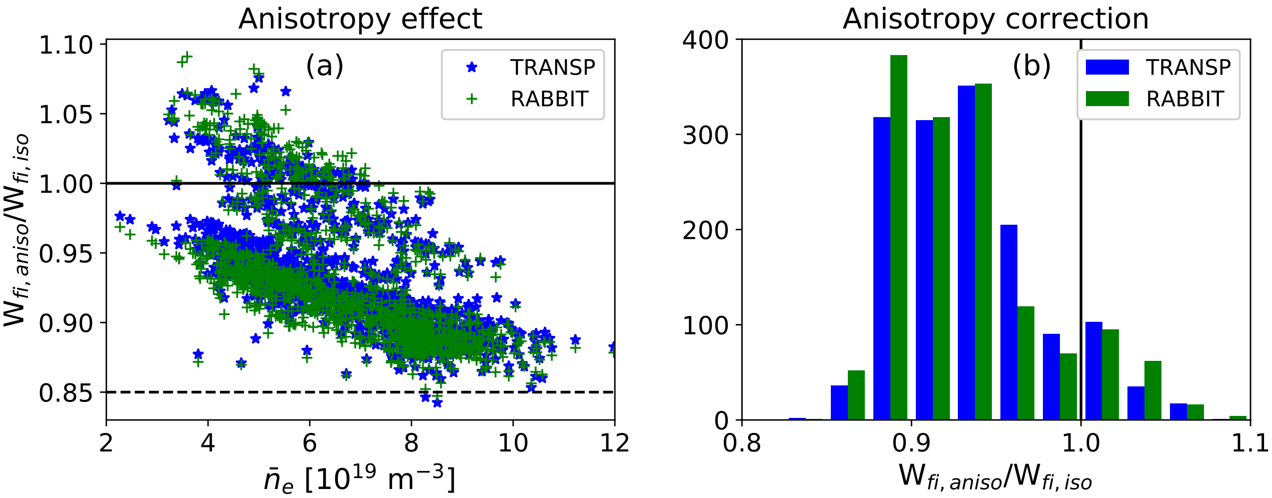

Figure 4. Ratio of the anisotropic energy W$_{fi,aniso}$ /W$_{iso}$, for TRANSP (blue) and RABBIT (green). As a function of $\bar{n}_e$ (a); histogram of occurrences of such ratio in 0.025 bin steps (b)

The code results for W$_{fi,aniso}$ is shown in Fig. 5 (a), the red circles being the reference formula-based W$_{fi}$. To quantify the deviation, both in terms of scatter and of systematic displacement, the ratios are plotted in Fig. 5 (b).

Averaged over the whole database, there is a systematic trend for the regression from [4] to underestimate W$_{fi}$. Taking the whole W$_{fi}$ both TRANSP and RABBIT are

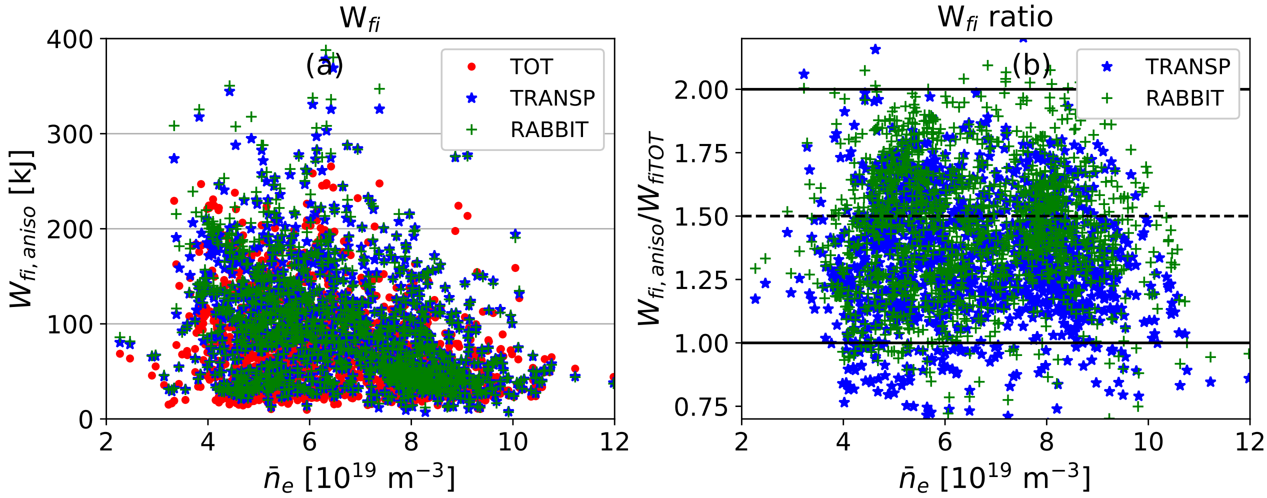

Figure 5. (a) Fast-ion energy calculated with TRANSP (blue stars) and RABBIT (green crosses) compared to the parametrisation-based formula (red circles). (b) Ratio of the code prediction and the formula, TRANSP (blue) and RABBIT (green), both systematically larger than one.

higher by a factor 1.36, retaining the anisotropy correction it is 1.28. On top there is a sizeable scatter, larger than the systematic displacement, as Fig. 5 (b) shows.

Of course the effect on the H-factor depends on the relative importance of the fast ion fraction, W$_{fi,aniso}$ /W$_{MHD}$. In Fig. 6 (a) we show this ratio over the whole database, in (b) the actual correction required to the $H_{IPB98(y,2)}$ factor is diplayed.

5. Comparison between RABBIT and TRANSP

Such a large and comprehensive database provides a good test for the accuracy of RABBIT, before considering it a candidate for the routinely evaluation of the NBI fast ion energy content. An important criterium are the failure rates: out of 3048 time intervals of the database, TRANSP failed to complete 986 discharges. In all cases, the

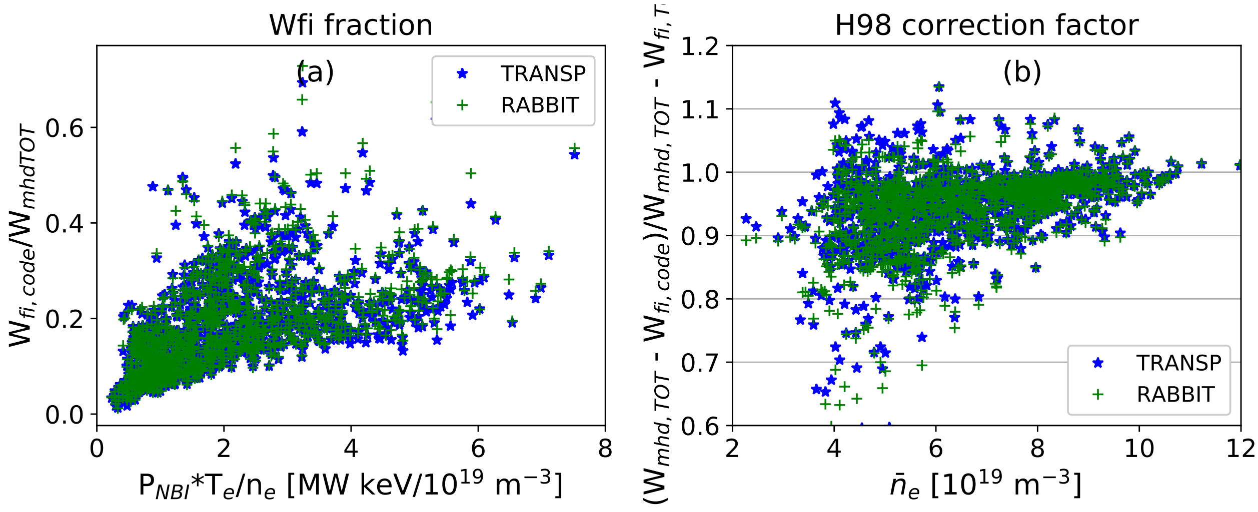

Figure 6. (a) Fast-ion energy fraction (b) Correction for $H_{IPB98(y,2)}$

input T$_e$ profile, measured with ECE, was in cut-off. RABBIT was applied only to those time intervals with successful TRANSP simulations; no RABBIT runs failed.

The two codes give similar predictions for W$_{fi,aniso}$, to a high degree of accuracy, as summarised in Fig. 7: 72% of the RABBIT estimates are within 2.5% of the TRANSP reference value, 91% are within 5%, the exact occurrence distribution is displayed in Fig. 7 (b).

6. Conclusions

The fast ion energy content of AUG H-mode plasmas has been reassessed with independent simulations with the NBI codes such as TRANSP/NUBEAM and RABBIT, in order to correct the estimate of the energy confinement time and of the H-factor.

On top of a large uncertainty in the regression fit for W$_{fi}$, with scatter as high as 50% ,

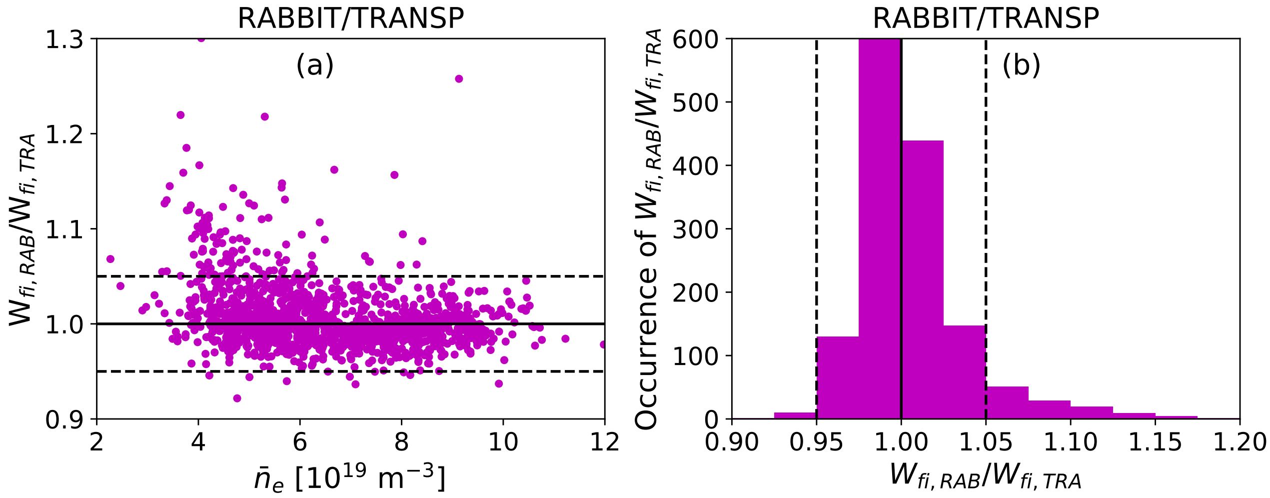

Figure 7. Fast-ion energy, ratio between TRANSP and RABBIT simulations (a) over the database (b) occurrences.

a trend for a systematic underestimate is documented. This is found to be related to the assumptions for the line averaged temperature, affecting the fast ion content through the NBI slowing down time.

The effect of the anisotropy of the fast ion velocity is taken into account, for a most accurate comparison with the measured MHD energy: the correction is significant, around 5-10% of the fast ion energy.

As a consequence, also $H_{IPB98(y,2)}$ factors need a downward correction which is usually around 5-10%, but it can be up to 30% in extreme cases with low n_e and high P_{NBI}. Note that no fast-ion losses due to MHD have been included in the simulations, therefore the actual fast-ion content can be overestimated at high P_{NBI} and low n_e.

The RABBIT and TRANSP codes yield similar predictios, with 91% of the simulations agreeing within 5%. Thereby, the present study provides an extensive benchmark of the fast Fokker-Planck solver RABBIT with respect to the established MonteCarlo orbit-following TRANSP/NUBEAM.

The approach is now to use the fast RABBIT code systematically, to process every discharge as soon as profile information is available. This is now the basis for all database and publication purposes, leaving the previous 0D calculation only as a control room tool for a quick, rough evaluation of the confinement performance.

Acknowledgement

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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