Comparative prediction of 2nd harmonic deuterium acceleration by ICRF in ASDEX Upgrade NBI heated discharges

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1 Introduction

Radio-frequency (RF) waves in the ion-cyclotron (IC) range of frequencies are used in several tokamaks as a heating tool. The typical absorption scheme is resonant heating of a minority ion species at the fundamental frequency. If the minority is hydrogen in a deuterium plasma, then a 2nd harmonic heating of deuterium is expected, becoming more significant whenever the ion Larmor radius becomes comparable to the ICRF perpendicular wavelength. The effect is significant in case of plasmas heated with Neutral Beam Injection Deuterium (NBI-D) and it has been observed in several tokamaks [1][2]. In particular, the strong increase of the neutron rate and the increased tail of Pulse Height Spectra (PHS) measured with the Compact Neutron Spectrometer (CNS) [3] provide a clear experimental evidence that 2nd harmonic ICRF accelerates D-NBI resonant ions well beyond their injection energy [4].

In order to have a quantitative assessment of the modification of the fast ion population, the PHS must be unfolded into Neutron Emissivity Spectra (NES) [4]. The NES must be compared to simulations based on the coupling of kinetic solvers with wave codes.

In this paper we aim to compare two different unfolding methods, one based on the maximum entropy principle and one based on adaptive kernels. We take advantage of the significant effect of NBI-D acceleration by ICRF on NES and PHS to validate different predictive approaches for the synergetic effect of NBI and ICRF on the ion distribution function.

2 Comparing unfolding methods

In order to infer the energy distribution of neutrons - the above mentioned NES - the measured PHS must be unfolded with the instrumental response functions. For this purpose, the CNS has been fully characterised at the accelerator facility of the Physikalisch-Technische Bundesanstalt, so that the response matrix could be determined [5]. We compare here two unfolding methods, taking advantage of the significantly different shapes of the PHS for plasmas with NBI heating only or with NBI+ICRF, displayed in Fig. 1.

The MAXED code [6] is based on the maximum entropy principle, the DAK code [7] on deconvolution with adaptive kernels. Both methods use the same response matrix [5]. As Fig. 2 (a) shows, the solution NES is similar for both, in terms of width and shape.

Two different values of χ^2 are selected for the unfolding with MAXED: increasing its value (magenta in Fig. 2) the artifacts at low and high energy are reduced, but also the double peak feature, which is physically sound, becomes smearred. This means that both MAXED and the adaptive kernel methods agree reasonably well, but both suffer from

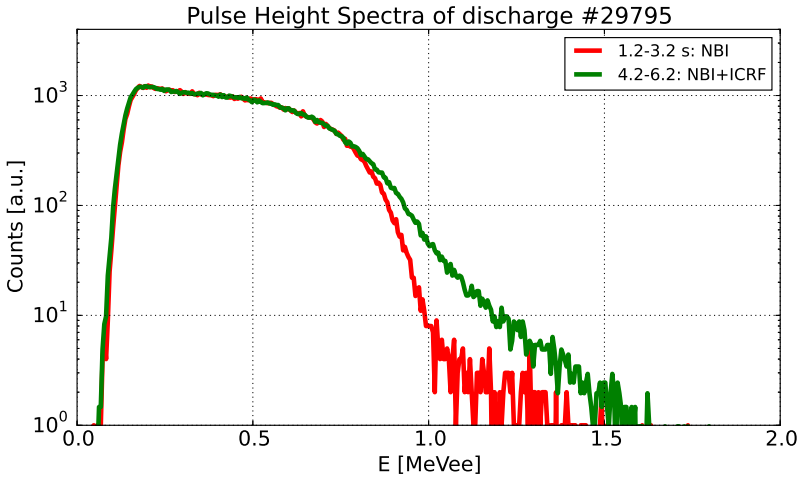

Figure 1. PHS of discharge #29795: NBI-only (red), rescaled NBI+ICRF (green).

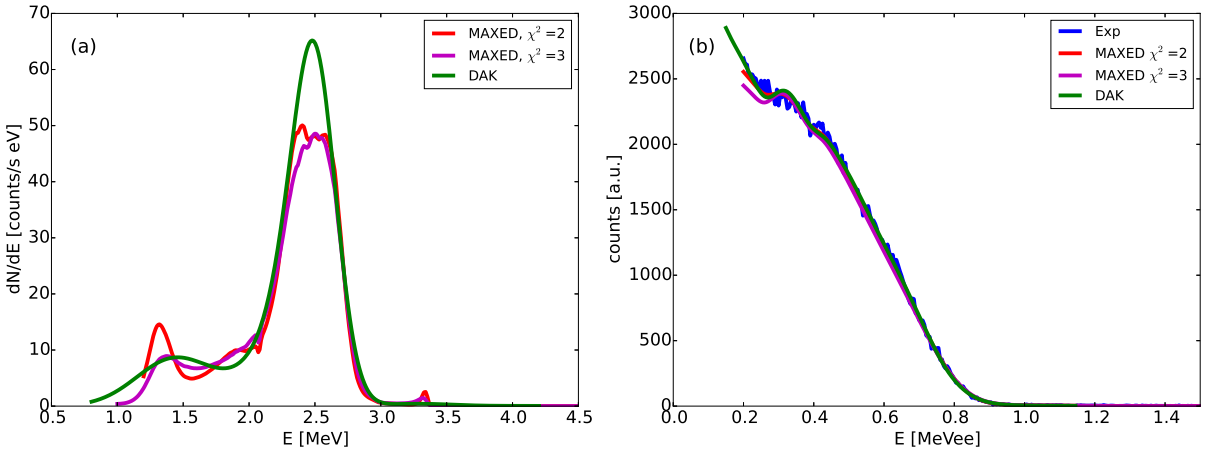

Figure 2. (a) Unfolded NES of the NBI-only phase: MAXED (red), MAXED with higher χ^2 (magenta), adaptive kernel (green) (b) Measured PHS (blue) and folded solutions MAXED (red), adaptive kernel (green).

the non-monotonic response function at low energies. Increasing the smoothness of the solution happens at the cost of a poorer accuracy matching the experimental data, as shown in Fig. 2 (b).

3 Benchmark of NES forward modelling

We have compared several approaches to the modelling of the synergy NBI-ICRF by coupling the fast ions packages to the GENESIS code [8] for the computation of NES. Since this is done for the first time for SSFPQL code [9] and the ASCOT code [10], first of all we need to benchmark these simulations to the calculation with the TRANSP code [11] in a reference case with pure NBI heating, in absence of ICRF. In this way we can verify the correct implementation of the interface and make sure the units are consistent and the velocity space coordinates are transformed properly. SSFPQL is a Focker-Planck code computing the steady-state solution of the surface-averaged kinetic equation. In our work it is used in combination with the full-wave TORIC code and to the SINBAD NBI code [9]; we call the package SST in the remainder of the paper. TRANSP makes use of

the orbit-following modules NUBEAM, while the beamlet-based BBNBI code [12] is used in this work for the ASCOT simulation. The respective predicted NES of this benchmark are illustrated in Fig. 3 (a).

All three approaches predict similar spectra concerning the shape and the boundaries for

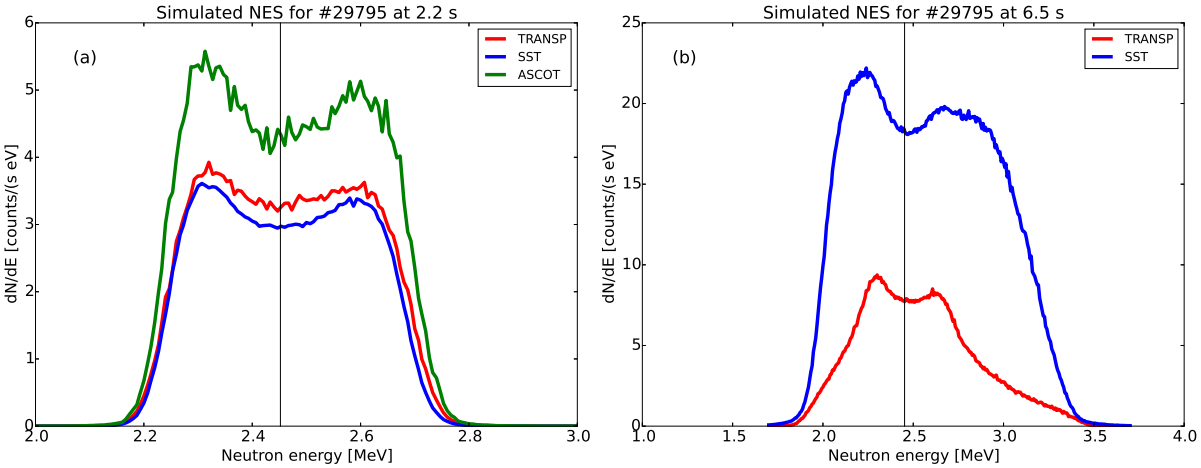

Figure 3. Predicted NES: TRANSP (red), SST (blue), ASCOT (green). (a) NBI only (b) NBI+ICRF

the neutron energy. In particular the clear double-peak structure, typical for perpendicular observation, is common to all codes. TRANSP and SST exhibit also a quantitative agreement, while ASCOT is some 20% higher.

4 Modelling of ICRF 2nd harmonic D-acceleration

After benchmarking, we compare the physics of the two different approaches of modelling NBI-D acceleration at the 2nd ICRF harmonic. The ASCOT+RFOF package is not part of this comparison yet.

Recently, a quasi-linear RF-kick operator for IRCF heating has been applied in TRANSP/NUBEAM, with the RF parameters taken from the coupled TORIC code [13]. The alternative approach is based on the SST package [9]. TRANSP, on the one hand, takes into account the finite orbit-width effects and thus it predicts fast ion losses and it describes the slowing down process more accurately. The SST suite, on the other hand, has a consistent treatment of the back-reaction of the ICRF-NBI deformed distribution function onto wave-propagation and absorption.

The modelled NES are shown in Fig. 3 (b). Qualitatively both approaches feature again the same energy range, significantly larger compared to Fig. 3 (a), and therefore the same maximum fast ion energy in the deuterium distribution function. Moreover, the double-peak typical for perpendicular observation is similarly present. However, quantitatively the SST simulation is significantly higher, by a factor ≈ 3, whereas the TRANSP code predicts a realistic increase of the NES when applying ICRF+NBI [4].

5 Conclusions

Two separate methods of unfolding are now available. This allows to test one against the other, finding possible shortcoming or increasing confidence in case they deliver similar

results. At present both highlight a limitation in the existing response matrix at low energies, due to their non-monotonic behaviour. As a consequence, NES feature artifacts in the low and high energy range. Increasing the target χ^2 reduces the artifacts, but at the cost of a poorer fit of the data, and of smearring out partly the characteristic double-peak feature typical for NBI heated discharges. Possibly the detector's estimated light output function for low energies can be improved.

The coupling of fast ions codes with the GENESIS code simulating NES is completed. The benchmark on the simpler case of NBI-only heated plasma is quantitatively successful between TRANSP and SST, while ASCOT agrees qualitatively for the spectrum shape and the energy range, but it is off by some 20%.

Concerning the NBI+ICRF phase, SST and TRANSP predict NES with similar shape and energy range, however the TORIC+SSFPQL code predicts higher neutron production by a factor 3. This can be explained by the fact that SST neglects the finite orbit-width effects, in particular the poor confinement of the most energetic ions.

It is desirable to compare also the ASCOT+RFOF simulations in case of NBI+ICRF, since this package has a similar approach to TRANSP but an independent implementation. This should enable us to confirm whether the difference between TRANSP and SST is indeed physics or some artifact due to some assumptions or implementation. The orbit-following approach seems to contain the most important ingredients, as it predicts an increase in NES, when ICRF is switched on, which is very close to the experimental one.

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Acknowlegment: 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 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.