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Abstract. The European Integrated Modelling effort (EU-IM) provides the European Transport Simulator (ETS) [1] which was designed to simulate arbitrary tokamak plasma discharges. Two new 1D Fokker-Planck solvers have recently been implemented within ETS: StixRedist [3] and FoPla [4]. To ensure the CPU time remains acceptable, the latter was parallelized with a generic and easy to implement method. In this paper, it will be shown how these modules were integrated in the ETS workflow in particular a first approach adopted to reach a consistency between wave and Fokker-Planck equation resolution. Also, the Verification and Validation efforts will be discussed. JET shots were analyzed and the ETS predictions were cross-checked against earlier validated codes external to the EU-IM effort, TRANSP [5] in particular, as well as against experimental neutron yield data. A good agreement was obtained, both when comparing the predictions with other codes for cases within their reach (minority or beam populations) and with experimental neutron yield data. Simulations illustrating the exploitation of the nonlinear collision operator when solving a set of coupled Fokker-Planck equations for cases when majority species play a key role will be also shown.

INTRODUCTION & BACKGROUND

In ITER, Neutral Beam Injection (NBI) and Ion Cyclotron Resonance Heating (ICRH) will be used to increase the temperatures beyond what is achieved by ohmic heating. To be able to predict how ITER discharges will behave it is necessary to have numerical tools capturing the dynamics sufficiently realistically. The European Integrated Modelling effort (EU-IM) provides the European Transport Simulator (ETS) [1] which was designed to simulate arbitrary tokamak plasma discharges. A first verification of ICRF full-wave codes was done in [2] but a detailed study of the Fokker-Planck codes, that describe the collisional power redistribution of the heated ions to the bulk plasma (via Coulomb collisions) was not done. Two 1D Fokker-Planck solvers for arbitrary distributions functions have recently been implemented within ETS: StixRedist [3] and FoPla [4]. To ensure the CPU time remains acceptable, the latter was parallelized. We discuss the integration and verification/validation of these modules in the heating and current drive (H&CD) ETS workflow in high power JET-ILW discharges, drawing special attention to the importance of the nonlinear collision operator when solving a set of coupled Fokker-Planck equations for cases when majority species play a key role.

ICRH AND ICRH-NBI SYNERGY WORKFLOW

A set of coupled problems has to be solved in order to compute simultaneous ICRH and ICRH–NBI heating. The excitation of waves by the ICRH antennas and their propagation through and absorption by the plasma – composed of various species, including fast neutral beam subpopulations - is described by the wave equation. The power exchange between charged particle populations via Coulomb collisions is captured by Fokker-Planck equation. The output of these codes constitutes the heat sources required by the transport solver. The latter evolves the kinetic profiles as a response to the ICRH and NBI power applied, and provides a new plasma target to be used in the next workflow time iteration. In order to ensure a self-consistent wave/Fokker-Planck equation computation a first approach is to represent the distribution functions (used to compute the dielectric tensor in the wave equation) coming from the Fokker-planck solver as "equivalent" Maxwellian distributions with an appropriate effective temperature. That algorithm is illustrated in figure 1.

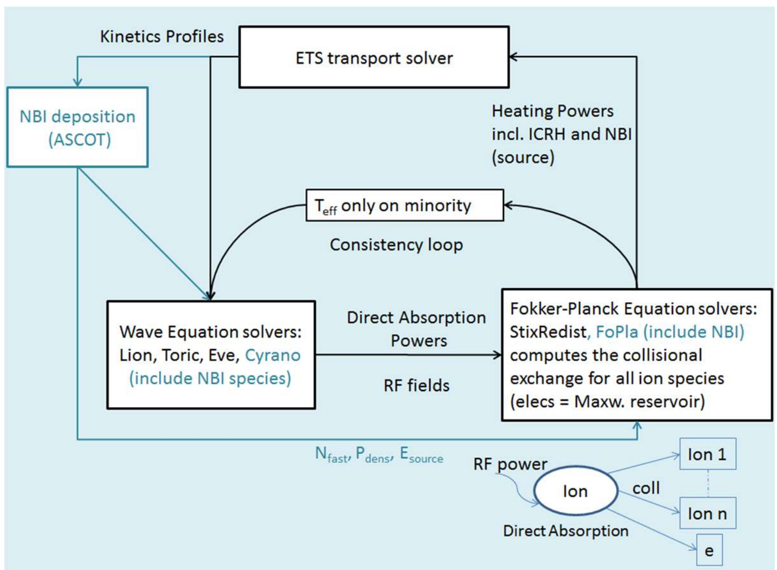


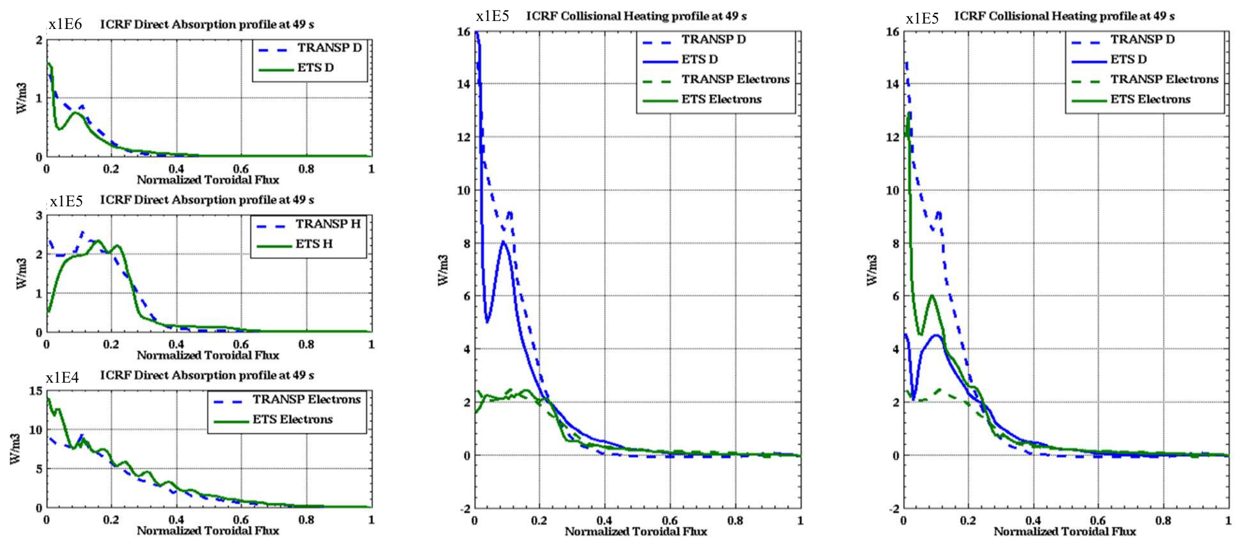
FIGURE 1: Sketch of ICRH-NBI Synergy Modelling in ETS

Since such computations are time consuming and in order to reduce the execution time to a more acceptable level, the FoPla code was parallelized. The method is based on solving the Fokker-Planck equation at each radial grid independently, and distributing the task over several cores using a cyclic distribution algorithm. It has multiple advantages: it is generic, easy to implement, compatible with future developments and has quite good performance (speed-up of ~32 when using 40 cores).

BENCHMARKING AND VERIFICATION OF ICRH AND ICRH/NBI SYNERGY MODELLING

The studied case is the JET baseline shot 92436 which has the highest fusion performance. Interpretative simulations were done in the flat-top phase (49s). In that region, 5.5 MW of ICRH and 27.5 MW of NBI are injected in the plasma. The plasma current is around 3 MA, the electron density at the centre is around 7.5 10^{19} m^{-3} and the magnetic field B_o is equal to 2.88T. The plasma composition contains Deuterium, 1.7% of Hydrogen (KS3B) and 0.07% of Nickel. The ICRF frequency antennas are equal to 42.5MHz thus it is a first harmonic heating on H minority and second harmonic heating on D majority.

A good agreement is obtained with TRANSP when similar algorithms are used (subfigures 2(a) and (b)): The Fokker-Planck equation is not solved for the majority D ions so the RF power absorbed (~50%) stays in the bulk D heating channel. When majority populations are modelled, self-collisions cannot be neglected and the nonlinear collision operator needs to be adopted. An iterative scheme (stopping when the self-collisions are small) is used for solving this nonlinearity. In subfigure 2 c), the D majority Coulomb collisional redistribution is accounted for. A part of the RF power originally absorbed by the D ions now ends up in the electron channel, leading to more balanced core electron/deuterium heating because the D majority is accelerated by 2nd harmonic ICRH ($\omega=2\omega_c$) in this case. A small fraction of the D ions carries a significant part of the wave power and is accelerated to high energies.

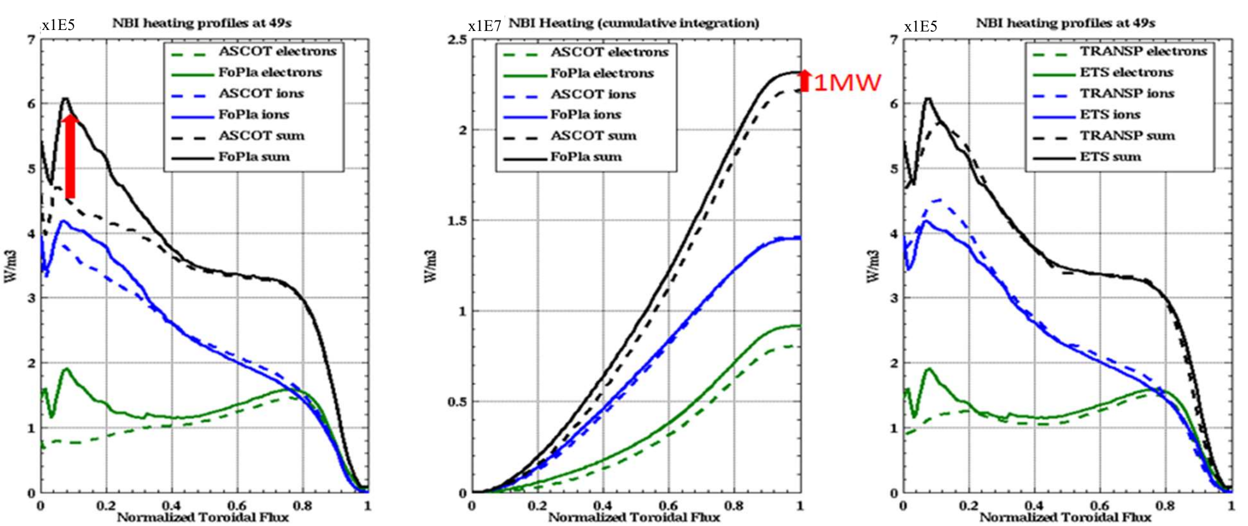


a) Direct ICRH power absorption profiles per species

b) Collisional power redistribution computed for H minority ICRF heating similar method use as in TRANSP

c) Full StixRedist calculation with non-linear H, D and self-collisions

FIGURE 2: JET pulse 92436 at t=49s with ETS (CYRANO/StixReDist) and TRANSP (TORIC/FPP) **without NBI**



a) Comparison between ETS (ASCOT) without synergy and ETS (ASCOT/CYRANO/FOPLA) with synergy

b) Cumulative integrals.

c) Comparison between ETS and TRANSP

FIGURE 3: JET pulse 92436 at t=49s with ETS (ASCOT/CYRANO/FOPLA) and TRANSP (NUBEAM/TORIC/FPP)

Figure 3 takes into account the ICRH-NBI synergy. About 1MW (20%) of the total ICRH power applied is absorbed by the D-beam ions and is partially redistributed to the electrons and bulk ions in the plasma centre. We obtained a good agreement between ETS and TRANSP, but ETS predicts somewhat higher core electron heating by self-consistently accounting for the RF acceleration of both the D-thermal and the D-NBI. That result is compatible with the experimental neutron yield shown in the next paragraph.

FUSION POWER

Table 1 shows that when the D majority tail formation is taken into account, a higher D-D neutron rate is obtained, leading to a closer agreement with the experiment data.

TABLE 1: Neutron Yield

Reaction	ETS Collisional Power Computed For H Only (n/m3/s)	ETS Full collisional Power Computed (n/m3/s)	Experiment Data (n/m3/s)
D-D	**0.120E+17**	**0.160E+17**	
D-Beam	0.107E+17	0.106E+17	
Beam-Beam	0.447E+15	0.439E+15	
Total	0.232E+17	0.270E+17	**0.26E+17**

CONCLUSION AND PERSPECTIVES

A good agreement was obtained between ETS and TRANSP on ICRH and NBI/ICRH synergy when similar algorithms are used. When all ions are considered in the ETS Fokker-Planck module, somewhat higher collisional electron heating is obtained. That result is compatible with the experimental neutron yield. Besides, using a 1D parallelized Fokker-Planck solver to account for beam populations enables to have fast simulations. For instance, getting simulation like the one shown in figure 3 roughly takes 4.5 hours. Some optimizations can be done in FoPla in order to reduce even more the computation time. The next step would be to assess the impact of the complete features of the Fokker-Planck solvers (StixRedist and FoPla) on collisional heating and neutron yield with predictive ETS simulation including temperature transport. On the other hand, the self-consistency between RF-fields and fast ion distribution can be improved by using the numerical distribution functions given by the FP codes (instead of "equivalent" Maxwellians) in the wave solvers.

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