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[1]P. Huynh, [2,3]E.A. Lerche, [2]D. Van Eester, [7]R. Bilato, [4]J. Varje, [5]T. Johnson, [6]O. Sauter, [6]L. Villard, [8]J. Ferreira JET contributors* and the EUROfusion-IM contributors**

EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK

[1]CEA, IRFM, F-13108 Saint-Paul-lez-Durance, France - [2]LPP-ERM/KMS, EUROfusion Consortium Member - Trilateral Euregio Cluster, Brussels, Belgium - [3]CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK - [4]Aalto University, AALTO, Finland - [5]KTH, Royal Institute of Technology, Stockholm, Sweden - [6]Ecole Polytechnique Fédérale de Lausanne (EPFL), Swiss Plasma Center (SPC), CH-1015 Lausanne, Switzerland - [7]MPI for Plasma Physics, 85748 Garching, Germany, [8]IST, Lisbon, Portugal

**See the author list of "Overview of the JET preparation for Deuterium-Tritium Operation" by E. Joffrin et al., to be published in Nuclear Fusion Special issue: overview and summary reports from the 27th Fusion Energy Conference (Ahmedabad, India, 22-27 October 2018)*

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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 .

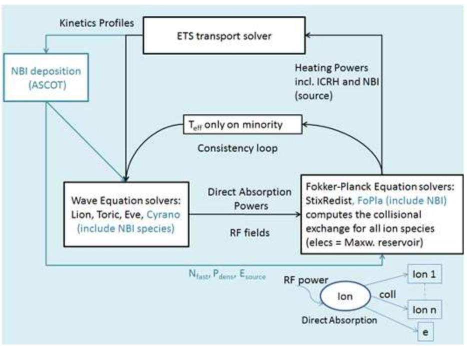
ICRH and ICRH-NBI synergy workflow

A set of coupled problems:

1) The RF wave solver provides the RF electric fields and the RF power absorbed by the various species in the plasma, including fast neutral beam subpopulations;

2) The Fokker-Planck solvers describe the power exchange between the RF accelerated ion populations and the bulk plasma via Coulomb collisions, providing a heat source (per species) to the transport solver;

3) The transport solver 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 iteration.



Note: As a first approach, the distributions coming from the Fokker-Planck solver are represented as "equivalent" Maxwellian distributions with an appropriate Teff in the wave solvers (same approach as in TRANSP[5])

Parallelization of FoPla

The parallelization is based on solving the Fokker-Planck equation at each radial grid independently, and distributing the task over several cores using a cyclic distribution method. The method has multiple advantages: it is generic , easy to implement , compatible with future developments, and has quite good performance.

cores	1	8	24	30	40	48
time	24h	3.44h	1.33h	1.21h	46 mn	47.6 mn
Speed-up	1	7	18	19.9	31.3	30.5

Scalability of FoPla obtained on a large velocity grid and using the full feature of the module

Conclusion and Perspectives

- Good agreement 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.

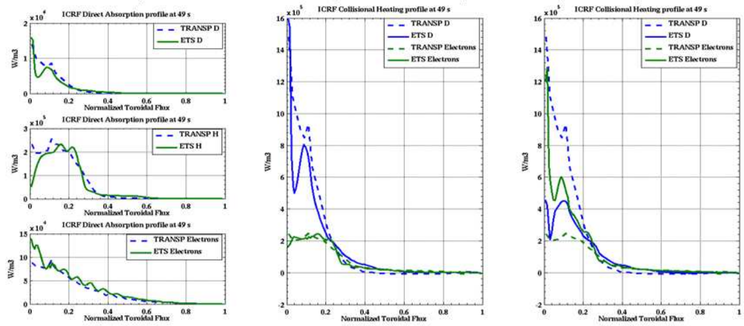
- Using a 1D parallelized Fokker-Planck solver to account for beam populations enables to have fast simulations.

- Improve the self-consistency between RF-fields and fast ion distribution by using the numerical distribution functions given by the FP codes (instead of "equivalent" Maxwellians) in the wave solvers.

- Assess 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.

Benchmarking and Verification of ICRH modelling (no NBI)

JET pulse 92436 at t=49s with ETS (CYRANO/StixReDist) and TRANSP (TORIC/FPP)



(Left) Direct ICRH power absorption profiles per species and (Middle) collisional power redistribution computed for H minority ICRF heating similar method use as in TRANSP. (Right) Full StixRedist calculation with non-linear H, D and self-collisions.

1) Good agreement with TRANSP when similar algorithms are used (middle plot): 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.

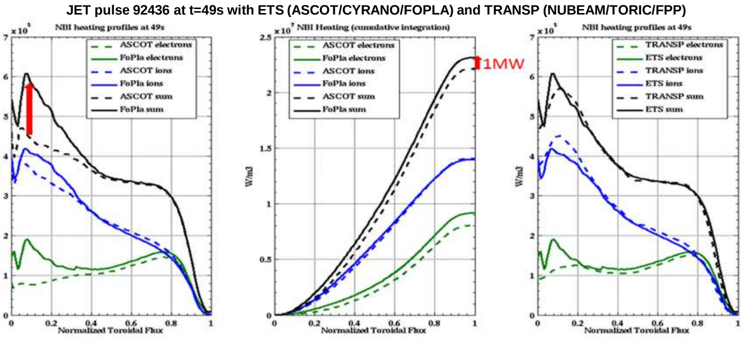
2) When the D majority Coulomb collisional redistribution is accounted for (right plot), a part of the RF power originally absorbed by the D ions now ends up in the electron channel, leading to more balanced core electron/deuterium heating.

3) Because the D majority is accelerated by 2nd harmonic ICRH ($\omega=2\omega_c$) in this case, a small fraction of the D ions carrying a significant part of the wave power is accelerated to high energies.

Note: 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.

Benchmarking and Verification of ICRH/NBI synergy modelling

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



(Left) Comparison between ETS(ASCOT) without synergy and ETS(ASCOT/CYRANO/FOPLA) with synergy. (Middle) Cumulative integrals. (Right) Comparison between ETS and TRANSP

1) 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.

2) 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.

Neutron yield

	ETS collisional power computed for H only (n/m^3/s)	ETS full collisional power computed (n/m^3/s)	Experiment Data (n/m^3/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**

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.

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[5] TRANSP group in Princeton Plasma Physics Laboratory, TRANSP Hompage http://w3.pppl.gov/transp/

JET CHALMERS Aalto University CCFE CEA ERM-KMS IST ipfn IFPiLM IPP KTH VTT

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