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Multi-machine analysis of EU experiments using the EUROfusion Integrated Modelling (EU-IM) framework

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Multi-tokamak analysis and modelling is performed within the EUROfusion Integrated Modelling framework (EU-IM) [1], backbone to the ITER Integrated Modelling and Analysis Suite (IMAS) [2], both offering unique capabilities by providing device agnostic integrated simulation *workflows*, encompassing interchangeable physics modules spanning from (fast) simplified to high-fidelity physics models, as required by the target physics applications.

The equilibrium reconstruction and MHD stability chain IMAS *workflows*, as well as the European Transport Simulator, ETS, recently released on the EUROfusion Gateway (part of Marconi-Fusion HPC, CINECA, Bologna), have been applied to analyses of JET discharges, their functionality tested on other tokamaks and are being prepared for full exploitation on a wide variety of devices, as WEST, JET, MST, JT-60SA, ITER, DEMO.

1. Multi-machine equilibrium reconstruction workflow in IMAS

The reconstruction of tokamak plasma equilibrium is the critical starting point for experimental data interpretation and all subsequent modelling applications. An arbitrary device Kepler workflow, that can seamlessly use any tokamak data in IMAS format and performs equilibrium reconstructions over a whole pulse, has recently been released and tested on JET and MST data. The IMAS workflow, embedding equilibrium reconstruction codes (such as EQUAL[3], NICE[4]) using the same data ontology and access method, facilitates cross-code verification and validation using as many available input experimental

[*]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)
[**]See author list of "J. Harrison et.al. 2019 Nucl. Fusion accepted (https://doi.org/10.1088/1741-4326/ab121c) "
[‡]See author list of "S. Coda et al 2019 Nucl. Fusion accepted (https://doi.org/10.1088/1741-4326/ab25cb)"
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data e.g. magnetic field or flux measurements, density, temperature and polarimetry diagnostics. A first application on dedicated JET plasma discharges, e.g. shot #84600, using magnetic diagnostics and Motional Stark Effect (MSE) measurements, showed good quantitative agreement between the codes using only magnetics, whereas inclusion of MSE engendered a substantial improvement of the core plasma profiles [5]. The workflow was recently proven to be functional for multi-machine exploitation, after testing it, with magnetics only, with TCV (Figure 1, left) and MAST data mapped into IMAS. For WEST, where raw data are natively in IMAS format, including interferopolarimetry as a constraint for NICE equilibrium reconstruction (Figure 1 right), improves the safety factor profile and good agreement is found between the inverted density profile against interferometry measurements.

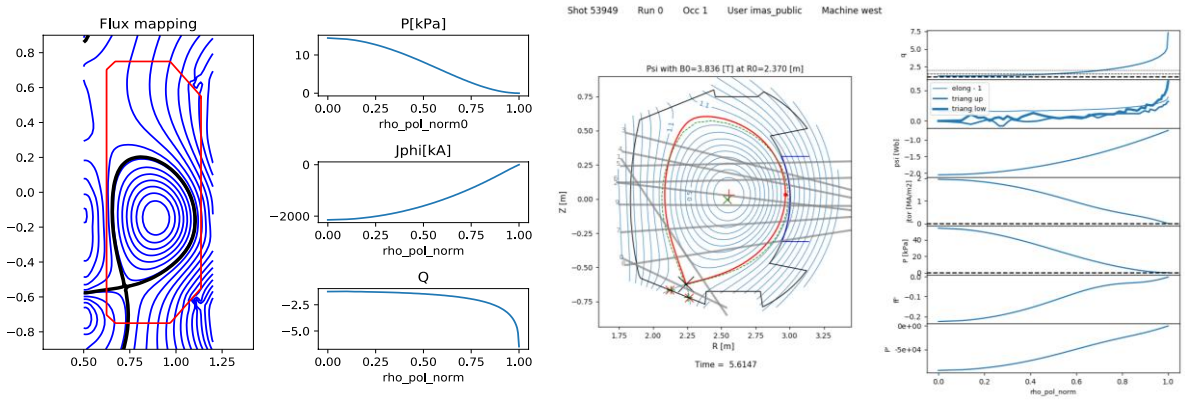


Figure 1 Left: IMAS equilibrium reconstruction workflow output for TCV #51262/4, using EQUAL code with magnetics only. Pressure, current and safety factor profiles. Right: WEST IMAS Plasma Reconstruction Chain output for #53949 using NICE with interferopolarimetry (lines of sight shown in gray, separatrix in red) .

2. Modelling of JET hybrid scenarios with H minority ICRF and beam heating, using the European Transport Simulator H&CD workflow

Analysis of JET mixed isotope scenarios, was enabled by self-consistent simulation of multi-species plasmas with the ETS [6, 7], recently enhanced to meet the requirements for D-T predictive modelling, deployed and validated on JET L-mode H and D plasmas [8].

A major challenge for predictive scenario modelling is a description as realistic as possible of advanced heating schemes, relevant to ITER operation, e.g. where ion cyclotron resonance heating (ICRH) is used in conjunction with neutral beam injection (NBI), in order to heat the plasma to fusion relevant temperatures. Modelling such interaction requires solving iteratively in a self-consistent loop, the wave and the Fokker-Planck (FP) equation, for all the plasma species simultaneously, thus accounting for the power absorbed by the various populations in different plasma regions. Experimentally relevant scenarios typically involve various heated populations, some of which have large concentrations and distributions deviating significantly from Maxwellians, whereas FP solvers often implicitly assume a minority population while the majority ions are in thermal equilibrium. To bridge this gap, dedicated 1-d (fast) FP

solvers were developed and implemented in the ETS: StixReDist [9] and the freshly developed parallelized code, FoPla [10], which allows for modelling NBI as well as the synergy between ICRH and NBI [11]. Besides, improved self-consistency is obtained by using the numerical distribution functions given by the FP codes in the wave solvers, as in the coupling presented in [12] between the full-wave EVE [13] and Monte Carlo orbit following SPOT [14] augmented by the wave-particle interaction library RFOF [15], all implemented in EU-IM. The above solvers have been applied to model minority heated hybrid scenarios relevant for the upcoming JET D-T campaign. Specifically, self-consistently accounting for the RF acceleration of both the D-thermal and the D-NBI, engenders higher core electron heating, in closer agreement with the experimental neutron yield [11,12].

Modelling of JET baseline reference discharge #92436 was achieved by simultaneously solving the FP equation, with FoPla, for the five RF heated ions: H minority, D majority and the three subpopulations of the D beam (with at birth 1, 1/2, 1/3 of the maximum beam source energy). Figure 2 shows the very different impact of the direct fundamental ICRH heating versus indirect harmonic heating, on the energy density of the five populations.

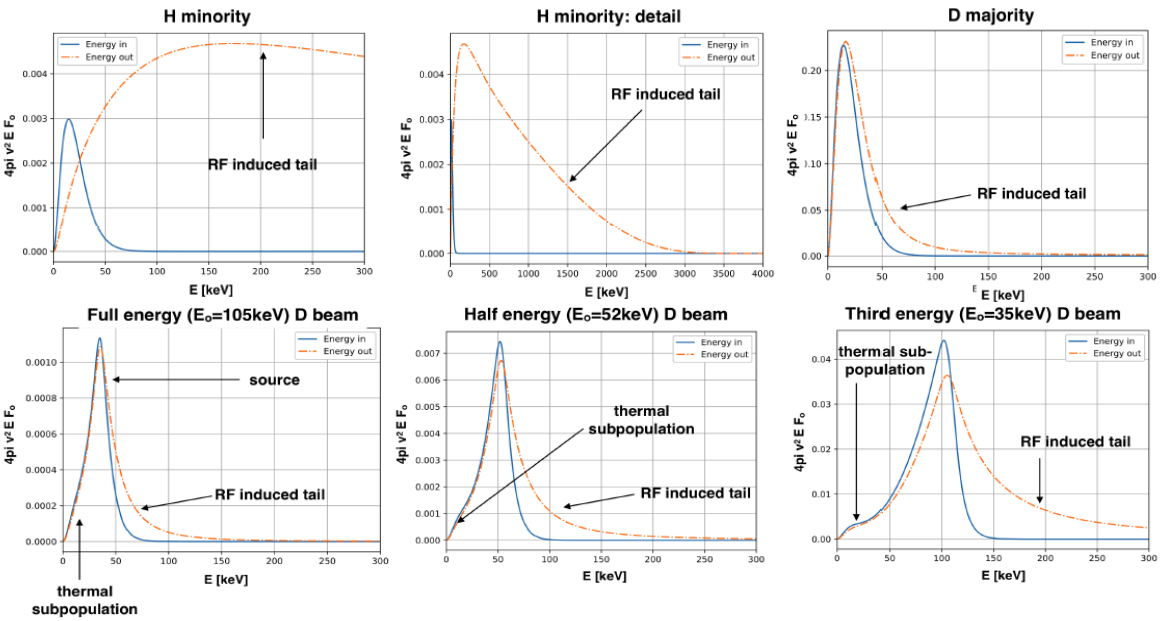
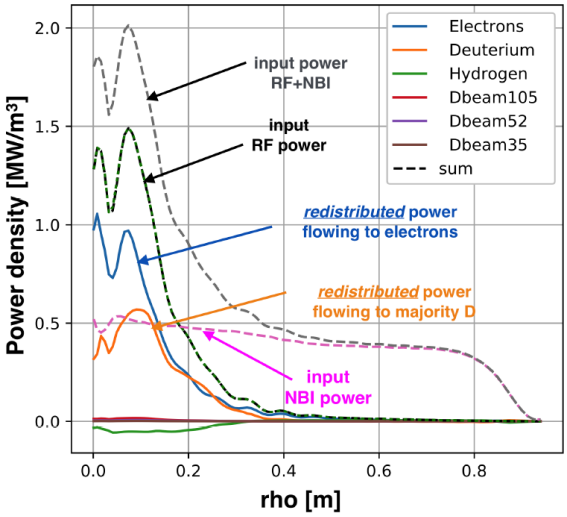


Figure 2 Energy density (distribution function F_0 integrated over gyro and pitch angle, multiplied by the Jacobian in velocity space v^2 and the energy) in the core (ρ = 13cm) for the 5 solved populations (from top left to bottom right): H minority, D majority, D beams (having birth energy =105, 52, 35 keV) without ICRH (blue curves) and after RF tail has formed (orange dashed). For the fundamental cyclotron heating N=1 the whole distribution is deformed in the thermal region (top left plot, zoom in middle). For second harmonic heating the distribution is mostly deformed by the slowing down energy from the heated subpopulation which adds energy to the thermal region raising the Maxwellian to higher temperature, while a high energy tail is formed.

Figure 3 (left) shows the resulting collisional beam power redistribution per species, induced by the competition between RF heating and Coulomb collisional interaction. The interplay of the populations is highlighted: indirect electron heating dominates as electrons receive power

from the heated H minority tail. H minority becomes much more energetic than the D beam, which also gets an increased effective temperature (Figure 3, right).



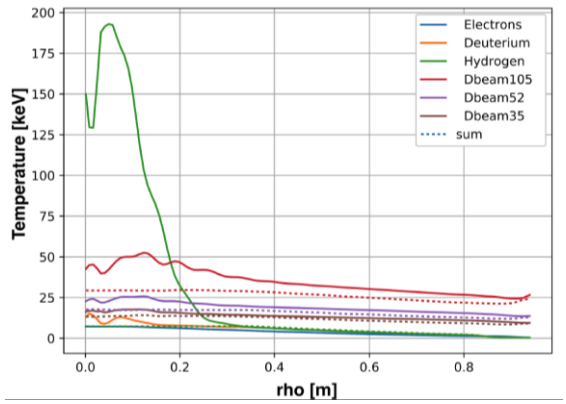


Figure 3 Left: Resulting power density profiles, per species. Right: effective temperature profiles per species $T_{eff}=2\langle E\rangle/3kN$, with $\langle E\rangle$ energy integral over velocity space, N density of the species, k Boltzmann constant.

The synergy allows reaching higher temperatures, well beyond that of the beam source, as the RF competes with a weaker Coulomb slowing down (at higher energy), hence, for the same amount of total power, particles reach higher energies than in absence of the beam.

3. Conclusions

The equilibrium reconstruction, EQSTABIL and ETS workflows have been released, their functionality in IMAS for multi-machine studies demonstrated, using JET and WEST (eventually TCV, MAST) data. Full exploitation on IMAS compliant devices is upcoming. The capability of the advanced ICRH modules embedded in the ETS to model mixed isotopes discharges with minority heating was demonstrated. Consistently to previous detailed self-consistent modelling of NBI/ICRH synergy that showed enhanced DD fusion reaction neutron rate [11], the novel results here presented on JET H minority heated hybrid discharges with the new fast 1-d Fokker-Planck EU-IM solvers show that synergy allows to reach higher temperatures and further highlight the interplay of the various particle populations and they role in the power redistribution. This predictive modelling puts forward advanced minority heated scenarios as a viable mechanism to increase fusion power in future JET DT campaign.

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