Preparing plasma heating in ITER using integrated modelling

Tomás Bensadón*, Mervi Mantsinen*†, Thomas Jonsson‡
*Barcelona Supercomputing Center, Barcelona, Spain
†Catalan Institution for Research and Advanced Studies (ICREA), Barcelona, Spain
‡Royal Institute of Technology (KTH), Stockholm, Sweden
E-mail: tomas.bensadon@bsc.es

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I. EXTENDED ABSTRACT

Nuclear fusion takes place when two light nuclei combine to make a heavier nucleus, releasing energy in the process. Magnetic confinement fusion attempts to achieve fusion and use this energy by confining the fuel in the form of a plasma. A plasma is a fully ionized gas whose behaviour is no longer dominated by short-ranged Coulomb forces, but by long-range electric and magnetic forces. Typically, plasmas are composed by hydrogen (H), helium (He), deuterium (D) or tritium (T) ions, or a combination of these. In this abstract, we tackle magnetic confinement fusion using tokamaks. Tokamaks are toroidal devices that have axial symmetry. They use poloidal and toroidal magnetic fields to create twisted magnetic field lines along which the charged particles travel in helical trajectories. In order for the plasma to reach the necessary temperatures for fusion to take place, auxiliary heating systems are used. In this abstract we focus on heating the plasma with electromagnetic waves in the ion cyclotron range of frequencies (ICRF).

Significant advances have been made in the technological development of these magnetic confinement devices in order to progress towards the main goal of fusion research: to achieve electricity-producing fusion power stations that can provide energy reliably, safely and efficiently. The ratio of fusion power produced to the external power required to maintain the plasma in a steady state is known as the Q-factor. Fusion reactions provide energy to the plasma, which leads to self-heating and eventually to a self-sustained reaction, known as ignition. One of the long-term purposes of fusion research is to achieve this ignition (Q=infinite). However, no device so far has achieved a sustainable Q=1 plasma. The main candidate to do so is ITER (”The Way” in Latin), the largest tokamak nuclear fusion reactor, which is being built in the south of France and which is projected to start operating in 2025. The aim is for ITER to maintain Q≥5 and to reach Q=10 for a duration of 400-600s, demonstrating the feasibility of fusion power and of a ten-fold gain of plasma heating power.

The commissioning of ITER is taking place through a staged approach. The First Plasma will be followed by an upgrade of the capabilities of the tokamak and two Pre-Fusion Power Operation (PFPO I and II) phases. In the PFPO phases, the basic controls and protection systems will be demonstrated, including the auxiliary heating and diagnostics systems, in experimental hydrogen (H) and helium (He) plasmas. The Fusion Power Operation (FPO) will start and a transition to deuterium (D) and deuterium-tritium (D-T) campaigns will be made.

Most of the ICRF modelling that has been carried out so far for ITER has focused on heating scenarios relevant for the D, T and D-T plasmas in the FPO stage. There is a need to improve our understanding on the performance of ICRF in H and He plasmas in the PFPO phase of ITER, and on the heating schemes planned for this phase. In this abstract we use the ICRF heating code PION [1] integrated into the transport modelling workflow European Transport Solver (ETS) [2] to study and predict how the plasma will be heated when ICRF heating is applied to ITER PFPO plasmas. The integration into a transport modelling workflow is relevant because PION calculates the ICRF power deposition but it does not predict on its own how the heating will affect the plasma and how its parameters will evolve. A transport modelling workflow such as ETS, which has been developed inside the ITER Integrated Modelling & Analysis Suite (IMAS) [3], can calculate the evolution of the plasma discharge and provide the capabilities for self-consistent predictive simulations.

A. The Physics of ICRF

The basic mechanism by which the plasma absorbs energy from radio-frequency (RF) waves is a wave-particle resonance. In the case of ICRF waves, this resonance takes place when the Doppler shifted frequency of the wave matches an exact harmonic of the ion cyclotron frequency. This condition is described by $\omega = k_{\|} v_{\|} + l\omega_c$ [4] where l = 0, 1, 2, etc. Here, ω is the frequency of the wave, $k_{\|}$ is the wavenumber parallel to the background magnetic field, $v_{\|}$ is the parallel velocity, ω_c is the ion cyclotron frequency and l represents the harmonics of the wave. The l=0 resonance is known as Landau damping, the l=1 resonance corresponds to the fundamental and the l=2 to the second harmonic. There are several schemes or approaches to heat the plasma with ICRF; in this abstract we will consider the minority heating scheme. In minority schemes, a small amount (usually up to a few percent) of a minority ion species with a larger charge-to-mass ratio than the main ion species is added to the plasma. The ICRH frequency can then be set to target both fundamental and harmonic resonance frequencies of this minority ion species.

B. Modelling and Results

Synthetic ITER discharge 110005 with ^{4}He plasma and H minority was modelled using the PION+ETS integration. The

TABLE I. Parameters from ITER PION simulations; the H concentration ([H]), magnetic field (B_0), frequency (f), ICRF power (P), electron density (n_e), ion temperature (T_i) and electron temperature (T_e)

	[H] (%)	B_0 (T)	f (MHz)	P (MW)	n_e x 10^{19} (m^{-3})	T_i (keV)	T_e (keV)
ITER	1,2.5,5,10	2.65	40	10	3.3	10.9	10.2

plasma parameters are summarised in Table I. For this ICRF frequency, magnetic field and plasma composition, there are several competing absorption mechanisms at play: the central resonance of the fundamental minority H heating, the second harmonic ^{4}He heating and direct electron damping. A typical ITER pulse will last for 400s to 600s. This particular ITER synthetic discharge has a pulse duration of 647s. However, here we are not simulating a full ITER discharge, but rather a shorter duration aimed at demonstrating the capabilities of the PION+ETS integration. The plasma was pre-heated to the electron and ion temperatures shown in Table I until t=300s, at which point ICRF heating was applied. The chosen duration for the simulation was 5s. This is longer than the slowing down time of the fast ions, which guarantees that the plasma reaches a steady state.

Table II summarises the results of the simulation. A trend can be seen in the increase of energy content and parallel energy content with the H concentration, excluding ΔW at 2.5%, which is slightly lower. It can be noted that the power absorbed by the H ions does also follow the same trend and increases with increasing H concentration, reaching its maximum at 5%. The collisional power transferred from the resonant ions to the electrons is higher than the fraction transferred to bulk ions and hence electron heating dominates over bulk ion heating for H concentrations below 5%. This is due to the formation of a high-energy tail in the resonating ions distribution function with a critical energy lower than the average energy of the fast H ions, which leads to collisional energy transfer to the background electrons.

TABLE II. Results from PION simulation with ITER discharge, including total (ΔW) and parallel ($\Delta W_{||}$) energy content of the main resonant ion, power absorbed by the main resonant ion species ($P_{abs.H}$), fraction of the power transferred from resonant ions to bulk ions (P_{ci}) and electrons (P_{ce}).

[H] (%)	ΔW (MJ)	$\Delta W_{\|\|}$ (MJ)	$P_{abs,H}$(MW)	P_{ci}(%)	P_{ce}(%)
10	4.36	1.16	7.96	65.83	43.17
5	3.16	0.63	8.02	56.11	43.89
2.5	2.83	0.41	7.52	41.62	58.38
1	2.87	0.22	6.81	21.15	78.85

We also present the RF power density absorption profile of electrons and resonant ions at [H]=5% as a function of the normalized flux surface, s, in Figure 1. Figure 1 shows that most of the RF power is absorbed by the resonant H ions, yet there is some competitive absorption from the ^{4}He ions. An off-axis absorption can also be noted, as the power density peaks at around s=0.3 in the case of H, while the ^{4}He absorption is more central at the steady state. The broadening and flattening of the electron's power absorption profile is also due to the presence of high-energy fast ions.

C. Conclusion

In this study we present results of predictive simulations at different H concentrations of an ITER synthetic discharge using the PION+ETS integration. Fundamental minority H heating was found to be a strong ICRF power absorption mechanism as compared to the competing absorption mechanisms, yielding increasing power absorption with increasing H concentration and reaching a maximum of 80.2% at [H] $\sim$ 5%. Further work is needed to exploit the full capabilities of the workflow integration and study the effect of ICRF heating on transport.

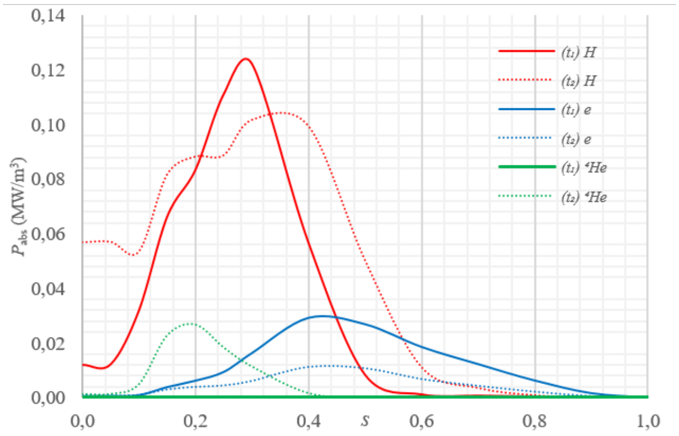

Fig. 1. RF-power density absorbed in the ITER scenario by the resonant ion species, H and ^{4}He, and the electrons as a function of the normalized flux surface, s, for the first time step t_1=300s (solid) and steady-state t_2=305s (dashed), at [H]=5%

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Tomás Bensadón graduated in Quantum Physics and Physical Chemistry (2018) from University College London (UCL), UK, where he also obtained an MSc in Particle Physics (2019). He then worked for the United Nations at the Fusion Department in the International Atomic Energy Agency (IAEA), Austria. In 2020 he joined the Fusion Group (CASE) at Barcelona Supercomputing Center (BSC) as a PhD student under the supervision of ICREA professor Mervi Mantsinen.