On the quest to reach nuclear fusion as a future energy source

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I. INTRODUCTION

[1] The advantages of nuclear fusion are numerous. It is capable of producing large amounts of energy, its fuel is virtually unlimited as it is extracted from water and it is environmentally friendly as it produces no long-term radioactive waste. However, the goal of achieving controlled nuclear fusion as a future energy source has not yet been reached. Since the early 1950s the scientific community has been working on this field and achieved several milestones such as the design of a toroidal experimental reactor, the so-called tokamak. The main difficulty lies in the complexity of reaching positive energy balance, i.e., $\mathrm{Q} = \mathrm{E}_{\mathrm{out}}/\mathrm{E}_{\mathrm{in}} > 1$. The plasma, which is a mixture of hot ions and electrons, needs to be confined inside the reactor in order to avoid losses. Stability and confinement are major issues together with radiative losses which are physically inherent to the system. All in all, controlled nuclear fusion is a challenging physical and engineering problem with potential to solve the increasing energy demands of the world's growing population.

Magnetic confinement fusion is one of approaches to develop fusion energy and the subject of this work. It is based upon confining hot plasma using strong magnetic fields by bending the ion and electron trajectories through the Lorentz force. Typically, plasma is composed by hydrogen (H) isotopes such as deuterium (D) or tritium (T) which are heated beyond their ionization energy. Plasma heating is of fundamental importance as it is necessary for fusion reactions to occur and to maximize them. There are two main external methods to heat the plasma, i.e. through the injection of energetic neutral beam particles (NBI) or radiofrequency heating such as heating with electromagnetic waves in the ion cyclotron range of frequencies (ICRF). In some cases the applied heating mechanisms interact with each other. This is the case for example when the frequency of the ICRF wave matches the cyclotron frequency of the beam particles. This effect is known as the ICRF-NBI synergy.

In this work we study the impact of NBI and ICRF heating on the fusion performance of several hybrid discharges at the Joint European Torus (JET), UK. JET is the largest operating tokamak in the world and the only one capable of operating with the reactor relevant D-T fuel mixture. The hybrid scenario is an advanced regime expected to operate in ITER, the fusion reactor being built in France with the main goal to demonstrate the capability of producing Q = 10. Here, a brief summary of the results that have been shown in Refs [1], [2] is presented. These references study the heating performance of the recent hybrid discharges where the performance of ICRF+NBI heating is assessed together with the fusion enhancement through ICRF heating. This analysis is performed with the ICRF code PION [3] and the NBI deposition code PENCIL [4]. Our modelling takes into account the ICRF+NBI synergy by introducing the computed beam source terms from PENCIL as a source term in the velocity distribution function of PION.

II. PHYSICS OF ICRF HEATING

Heating the plasma with ICRF waves has shown to be a successful mechanism to bring plasmas at high temperatures. There are several ICRF schemes or approaches to heat the plasma. In this work minority heating is considered. Minority heating consists of introducing a small concentration of resonant ion species that is different than that of the principle ion species, i.e., D in the cases studied here. For good ICRF accessibility and absorption we choose the cyclotron frequency of the minority species that is higher than that of main ion species. The cyclotron frequency is defined as $\omega_{\mathrm{c}} = \mathrm{qZB}/(\mathrm{Am}_{\mathrm{p}})$, where ω_{c} is the cyclotron frequency, q is the electron charge, Z the atomic number, A the atomic mass and m_{p} the proton mass. Therefore, $\omega_{\mathrm{cH}} = 2\omega_{\mathrm{cD}}$, i.e., the fundamental resonance of H coincides with the 2nd D harmonic resonance. The ICRF wave launched from an external antenna have a frequency that matches the cyclotron frequency of H. When this condition occurs, the ions become accelerated by the wave field, which effectively damps the wave. In these plasmas, there are three main damping mechanisms competing for the wave energy: the fundamental H resonance, the 2nd D harmonic resonance and the direct electron damping. The ICRF+NBI synergy is taken into account through the D beams.

III. EXPERIMENTAL RESULTS

Several hybrid discharges performed to evaluate the impact of ICRH on the fusion performance were modelled. Here, we focus on the role of H concentration and the record neutron rate obtained in one of the best performing discharges.

A. Hydrogen concentration scan

A set of hybrid discharges was carried out at JET to assess the impact of the H concentration on the ICRF heating and

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[1] ‡See the author list of X. Litaudon et al. Nucl. fusion 57 (2017) 102001.

fusion performance. These discharges were prepared in the same way except for the different H concentration, see Table 1. Note that only a few percent of hydrogen is used and there is only a small difference between the hydrogen concentration between the discharges. Nevertheless, it is large enough to have an impact on the way plasma damps the ICRF wave energy and, consequently, on the plasma performance.

TABLE I. HYDROGEN CONCENTRATION FOR THREE HYBRID DISCHARGES

	92321	92322	92323
$n_H/(n_H+n_D)(\%)$	~2.0	~1.5	~3.0

ICRF power was applied with a central $\omega = \omega_{cH} = 2\omega_{cD}$ resonance. In first order, the ratio of H to D damping scales roughly as $n_H/(n_H+n_D)$, as expected. Typically, for this ICRF scenario, the hydrogen minority is the main absorber at low plasma densities and temperatures that take place during the ramp up. Once the deuterium beams are injected and the plasma gets hotter, damping by resonant D ions becomes the main damping mechanism. Channeling the power to D ions is found to be beneficial to this scheme, as the cross section from DD fusion reactions has a maximum at the MeV range, therefore giving a large margin to increase average D energy and consequently the number of DD reactions. This fact is shown in figure 1, where experimental and modelled discharges show this behavior.

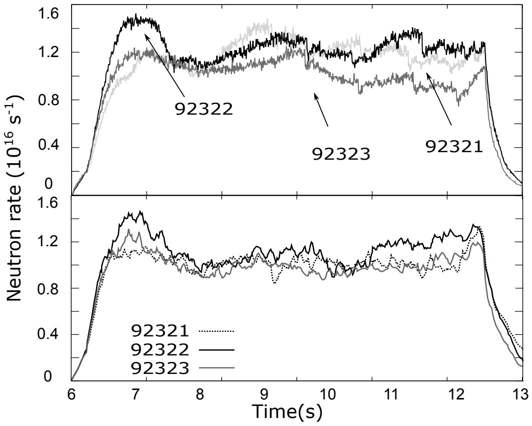

Fig. 1. Comparison of experimental neutron emission rate (top) and modelled neutron emission rate (bottom) of the H scan discharges.

The discharge with the lowest H concentration obtained, in comparison with the highest H concentration discharge, around 10-25% higher number of fusion reactions.

B. High-performing discharge

One of the main goals of the recent experiments with hybrid plasmas was to improve the fusion performance with respect to the previous neutron rate record of $2.3\text{x}10^{16}$ n/s. A total of $2.7\text{x}10^{16}$ n/s was achieved as shown in figure 2.

The modelling of this discharge showed a clear dominance of 2nd D harmonic resonance and low direct electron damping. The ICRF fusion enhancement with respect to NBI was found to be around 15% during the main heating phase.

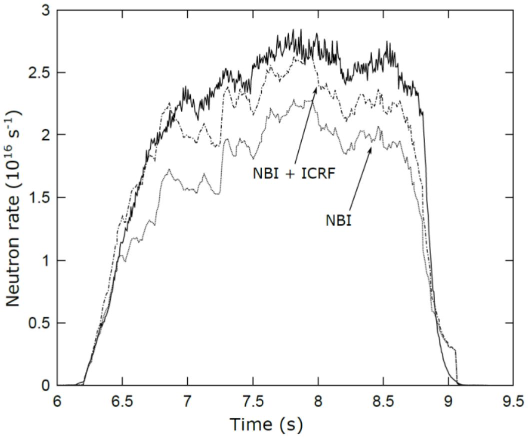

Fig. 2. Neutron production rate modelling of discharge 92398 with ICRF and without ICRF.

C. Conclusions

Many efforts are being devoted to improve the fusion performance of the hybrid and baseline scenarios on JET. Studies of impurity control together with the heating performance as the one presented here are the key to achieve a higher fusion yield. Here, we stated the main idea that channeling the wave power to D ions substantially enhances the fusion performance in this scenario. However this is not necessarily true for the DT scenario, as the cross section peaks at the keV range and, therefore, the way ICRF heats the plasma needs special attention. JET will host in 2020 the second DT campaign of its history, where many of the methods consolidated to improve the DD scenario will be applied to achieve a high performance in DT.

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Dani Gallart studied fundamental physics at Universitat de Barcelona (UB). After obtaining his degree in physics he enrolled in the nuclear engineering MSc at Universitat Politècnica de Catalunya (UPC-ETSEIB) where he obtained one of the grants from Fundació Catalunya-La Pedrera. In 2014, he joined the Fusion group at Barcelona Supercomputing Center (BSC) for his MSc thesis research under the supervision of ICREA Prof. Mervi Mantsinen. In 2015, he was awarded one of the prestigious Fundació 'la Caixa' PhD grants to continue his research at BSC. His research focuses on fast particle physics and plasma heating. He works closely with the main European fusion facilities JET and AUG under EUROfusion.