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# A quantitative comparison between confined fast ion data and models from radio frequency heating experiments with the three ion scenarios at JET

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## Introduction

An effective way to generate fast ions in a fusion plasma is by means of Ion Cyclotron Resonance Heating (ICRH). The most adopted scenario is the so called minority heating, where a minority species at a few percent level is added to the main bulk plasma and is accelerated by ICRH. A typical example is the heating of <sup>3</sup>He ions in a bulk deuterium plasma, which has also been used to study the excitation of fast ion instabilities and their transport [1]. A new ICRH scenario for plasma heating and fast ion studies has been theoretically proposed and experimentally demonstrated at the JET and Alcator C-mod tokamaks [2]. It is based on optimizing the polarization of the wave at the resonance in the vicinity of the ion-ion hybrid layer. This can be accomplished in a 3 ion species plasma, where two bulk species determine the propagation properties of the wave and a third species, which is added at the per mille level, efficiently absorbs the power in the vicinity of the ion-ion hybrid layer. In this paper we present a first quantitative analysis of the data obtained in a recent experiment on 3 ion ICRH heating in a D-(<sup>3</sup>He)-H plasma at JET, where H and D, in the ratio of approximately 70:30, were the two bulk species required by the scenario and <sup>3</sup>He was the species to accelerate ( $X[{}^3\text{He}] \approx 0.2 - 0.3\%$ ).

## JET D – (<sup>3</sup>He) – H acceleration experiment

Figure 1 shows the time traces of some relevant quantities from the D – (<sup>3</sup>He) – H 3 ion scenario experiments performed at JET, with particular reference to discharge #90753.

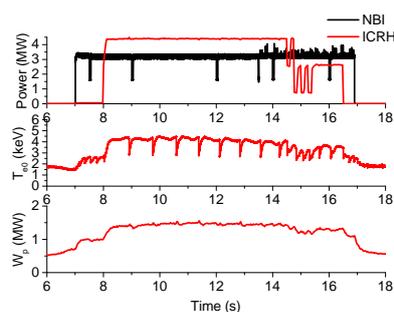


Figure 1: Time traces for the D – ( $^3\text{He}$ ) – H experiment at JET for discharge #90753. From top to bottom: ICRH and NBI power; core electron temperature  $T_{e0}$ ; plasma energy  $W_p$

The plasma was preheated by means of Neutral Beam Injection (NBI), followed by the application of ICRH in the 3 ion scheme. The power delivered by the radio-frequency (RF) wave is effectively absorbed by the plasma, as testified by the increase of the stored energy as a function of time in response to the application of ICRH. A first indirect evidence of the production of fast  $^3\text{He}$  ions in the plasma comes from the time trace of the core electron temperature  $T_{e0}$ . As the NBI power is applied, sawteeth manifest themselves in the time trace of  $T_{e0}$  with a characteristic period of  $\approx 0.2$  s. As ICRH is turned on, the sawteeth period increases up to a  $\approx 0.8$  s. This qualitatively indicates the production of MeV range  $^3\text{He}$  ions, which have a stabilizing effect on the sawtooth period.

The most direct evidence of effective  $^3\text{He}$  acceleration to MeV energies and their confinement in the 3 ion scheme is provided by gamma-ray spectroscopy, in particular from the observation of the gamma-ray lines born from the  $^{11}\text{B}^*$  and  $^{11}\text{C}^*$  excited nuclei produced in the  $^3\text{He} + ^9\text{Be} \rightarrow ^{11}\text{B}^* + \text{p}$  and  $^3\text{He} + ^9\text{Be} \rightarrow ^{11}\text{C}^* + \text{n}$  reactions, which are spontaneous processes occurring in the plasma between fast  $^3\text{He}$  ions and  $^9\text{Be}$  impurities.

Figure 2 shows the gamma-ray spectrum measured by a  $\text{LaBr}_3(\text{Ce})$  detector observing the plasma along a vertical line of sight. A large number of peaks appears, which results from the production of  $^{11}\text{B}^*$  and  $^{11}\text{C}^*$  in a variety of excited states.

### Quantitative modeling

Modeling of the gamma-ray emission from the plasma and the detector response function can be adopted to infer quantitative information on the  $^3\text{He}$  distribution function at MeV energies produced in the D – ( $^3\text{He}$ ) – H scenario. This is done by identifying the individual lines that contribute to the spectrum of figure 2, where the aim is to infer the relative population of the excited states of  $^{11}\text{B}^*$  and  $^{11}\text{C}^*$  as a function of  $\langle E_{3\text{He}} \rangle$ . Here we focus in particular on two specific lines at  $E_\gamma = 7.28$  MeV and  $E_\gamma = 7.98$  MeV, which are born from the de-excitation

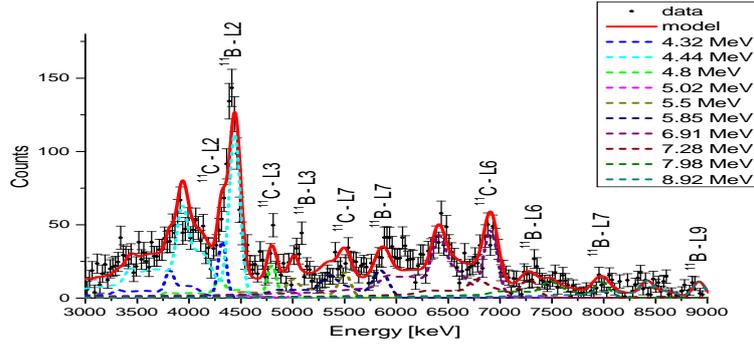


Figure 2: Gamma ray spectrum for discharge #90753 and fit to the experimental data in terms of the expected gamma-ray emissions from the different excited states of the  $^{11}\text{B}$  and  $^{11}\text{C}$  nuclei.

of  $^{11}\text{B}^*$  in its 6th and 7th excited states, respectively. After careful analysis, we find that the measured ratio of the intensities between the 7.28 MeV and 7.98 MeV lines is  $r = 1.3 \pm 0.2$ . This value can be compared with that expected from a model of the  $^3\text{He}$  distribution function and the corresponding gamma-ray emission. As the simplest approach, we can take the well known analytical, asymptotic solution of the ICRH problem proposed by Stix [3] and evaluate the expected asymptotic tail temperature  $T_{3\text{He}}$  of the  $^3\text{He}$  ions starting from measured plasma parameters and a TORIC simulation of the power density deposited in the plasma. We find that  $T_{3\text{He}} \approx 3\text{MeV}$  (for comparison, traditional  $^3\text{He}$  minority heating typically results in  $T_{3\text{He}} < 500$  keV [1]). However, at this high temperature gamma-ray modeling would predict  $r \approx 3$ , which is well above measurements.

As the discrepancy might come from the too simplistic assumptions of the Stix formulation, we have performed a full RF simulation with the SCENIC code [4], which includes both a careful computation of the wave propagation in the plasma for fundamental ICRH and detailed wave-particle interactions by means of a Monte Carlo kick operator. An illustration of the core  $^3\text{He}$  distribution determined by SCENIC for discharge #90753 is shown in figure 3 (a) and, as expected, this is more complex than the Stix description in terms of a tail temperature. Still, both Stix and the more comprehensive SCENIC simulation predict that  $^3\text{He}$  ions are found predominantly at energies of a few MeVs.

By the development of a synthetic gamma-ray diagnostic, which starts from the SCENIC simulation and carefully describes the generation of gamma-rays along the line of sight seen by the instrument, we are able to determine  $r$  and, as for the Stix model, this is predicted to be  $\approx 3$ , which is larger than the measured value. As the predominance of MeV range ions in the  $^3\text{He}$  distribution function is independently predicted by different ICRH codes, and experimentally supported by a variety of fast ion diagnostic data[2], we interpret the discrepancy between

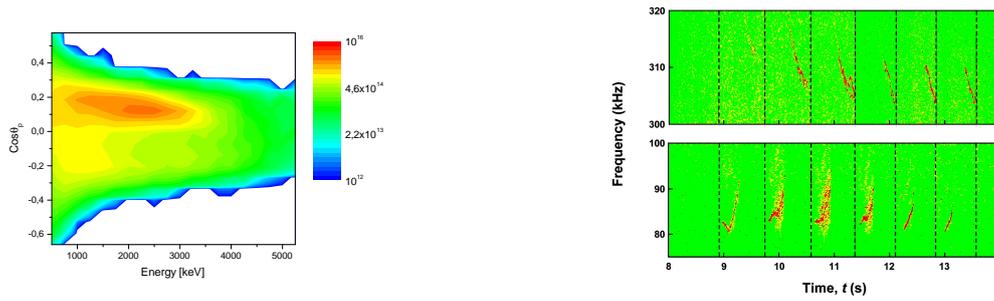


Figure 3: (a) Core  ${}^3\text{He}$  distribution function for discharge #90753 as calculated by the SCENIC code and (b) MHD activity spectrogram for discharge #90753. We observe core localised TAEs at a frequency of  $\approx 310$  kHz, as well as modes at  $\approx 80$  kHz right after the sawtooth crashes.

the modeled and measured  $r$  as due to some missing effects in the model, where a possibility is the interplay between core localized TAE modes and the  ${}^3\text{He}$  ions (see figure 3 (b)). An evaluation of the differential reactivity of the  ${}^3\text{He} + {}^9\text{Be} \rightarrow {}^{11}\text{B}^* + \text{p}$  reaction starting from the SCENIC distribution function, and when  ${}^{11}\text{B}^*$  is born in either its 6th or 7th excited state, shows that gamma-ray emission is due almost exclusively to  ${}^3\text{He}$  ions with energies between 2 and 3 MeV, which are also predicted to drive the observed core localised TAEs according to theory. Hence, we may expect a redistribution of these fast  ${}^3\text{He}$  ions from the core to the periphery, i.e. out of the line of sight of the instrument we have used. This might explain the observed discrepancy and will be investigated in future studies.

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