γ-ray emission from radio frequency heating experiments with the three-ion schemes at the Joint European Torus

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INTRODUCTION

In so called 'three-ion' Ion Cyclotron Resonance Heating (ICRH) experiments a third, minority species is efficiently accelerated in plasmas made by two main ions. This is achieved in the vicinity of the ion-ion hybrid layer, where the wave polarization is entirely left handed [1]. At the Joint European Torus (JET) the scheme has so far been demonstrated in H-(D_{NBI})-D, H-(3He)-D and D-(D_{NBI})-^{3}He plasmas [2], (D_{NBI}) and (^{3}He) being the minority species.

In the latter scheme, fast deuterons injected by Neutral Beam Injection (NBI) are further accelerated by ICRH up to energies in the MeV range [3]. High D+D neutron rates (between 10^{15} and 10^{16} s^{-1}) have been achieved at moderate external heating power [4]. Reversed Shear Alfven Eigenmodes (RSAEs) have also been systematically observed, which is indicative of a non monotonic q-profile induced by an non-inductive current driven by an intrinsic mechanism [4].

GAMMA-RAY EMISSION

JET is equipped with 4 γ-ray spectrometers, arranged on 2 vertical and 1 tangential lines-of-sight [5], and the Gamma-Camera Upgrade (GCU) [6], composed by two arrays of 10 and

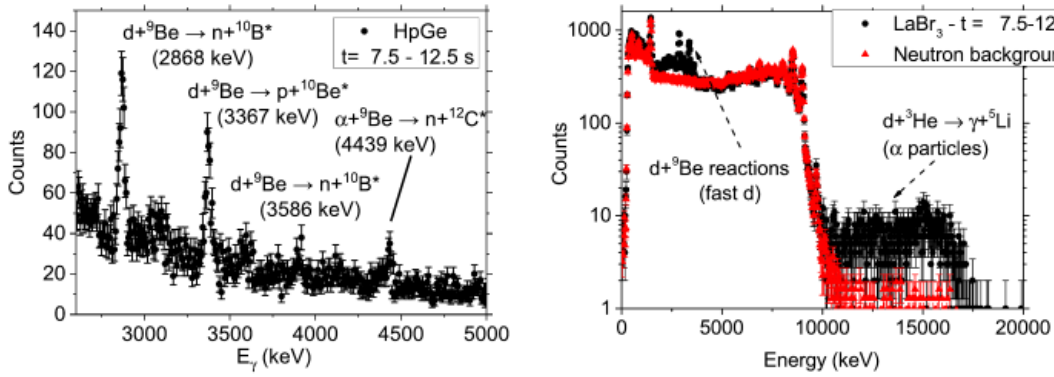

Figure 1: *γ-ray spectra recorded during JET shot #95679, in time interval 7.5-12.5 s, by (left) the high-purity Germanium spectrometer (KN6G), which has a vertical line-of-sight, and (right) the new tangential LaBr3(Ce) spectrometer (KM6T). The neutron background of KM6T (red triangles) has been calculated summing spectra recorded during the NBI only phase of all shots allocated for the D-(D_{NBI})-^{3}He experiment. Reproduced from [4] according to the author right policy of IOP.*

9 lines-of-sight that observe the plasma on the poloidal plane. These diagnostics allow us to investigate the nuclear processes that take place in the plasma during a discharge (e.g. JET shot #95679).

When only NBI heating is applied, all the spectrometers measure a signal induced by fusion born neutrons (red triangles in figures 1 and 2). When also ICRH is turned on, i.e. between 7.5 and 12.5 s, γ-ray signals are detected over the neutron background. In particular the D+^{9}Be emission (fig. 1) between 2 and 5 MeV confirms the acceleration of D_{NBI} up to energies in

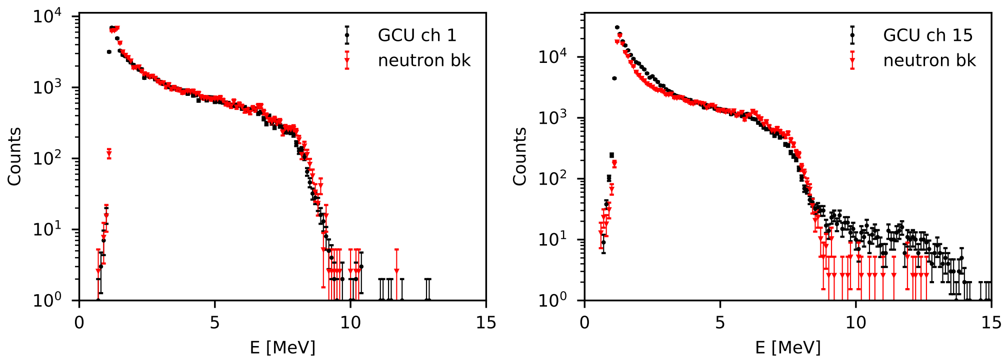

Figure 2: *γ-ray spectra recorded during JET shot #95679, in time interval 7.5-12.5 s, by (left) channel 1, whose line-of-sight observes the upper part of the poloidal plane, and (right) channel 15, whose line-of-sight observes the magnetic axis vertically, of the Gamma-Camera Upgrade. See figure 3 for a sketch of the GCU lines-of-sight. The neutron-induced background for each channel (red triangles) has been calculated as in figure 1.*

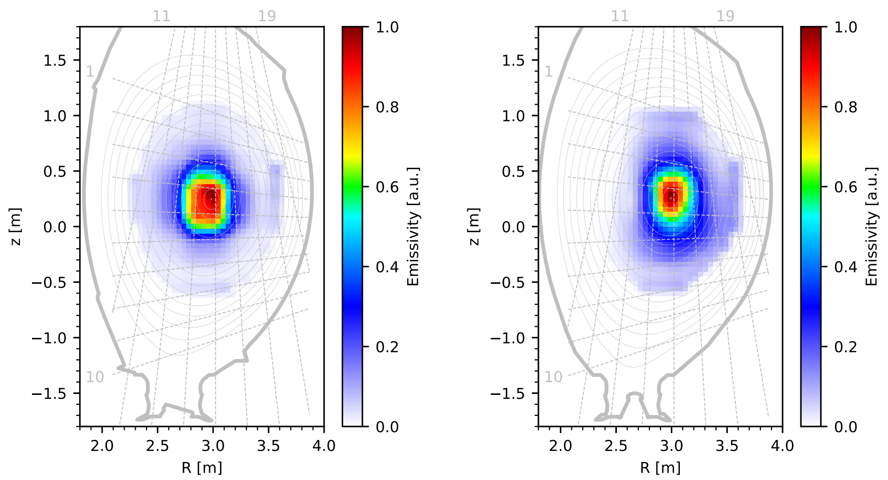

Figure 3: *Spatial profiles of the source of (right) α-particles born in D+^{3}He fusion reactions (left) neutrons born in D+D fusion reactions (the latter can be compared with figure 1 in [4] for a benchmark of the tomography code here presented). Both reconstructions have been performed during time interval 8.-12. s of JET shot #95679. GCU lines-of-sight and their numbering are shown in grey.*

excess of 0.5 MeV [4]. The simultaneous detection of the 16.4 MeV gamma-rays produced in a minor branch of the D+^{3}He reaction [4, 6] and the 4.4 MeV gamma-rays emitted in α+^{9}Be, proves the generation of fusion born alpha particles.

Figure 2 shows the spectra recorded by the peripheral ch 1 and the central ch 15 of the GCU. The camera was able to detect the D+^{3}He 16.4 MeV gamma-rays as well, giving us spatial information about the distribution of this emission, which can be used to perform a tomographic reconstruction of the source of the α-particles born in the D+^{3}He fusion reactions.

NEUTRONS AND α-PARTICLES SOURCES

Figure 3 shows the tomographic reconstruction of the neutron profile measured by the neutron-camera and the 16.4 MeV gamma-ray profile derived from the spectra shown in figure 2 [7, 8].

The two reconstructions, which were independently performed, show respectively the D-D neutron and α-particles sources, proving that the ICRF energy deposition happened in a narrow region of $\approx$ 20 cm around the magnetic axis, as expected.

The two plots also represent the spatial distribution of the reaction site for D+D and D+^{3}He, which take place between a fast D and a thermal ion. We can reasonably suppose that the distribution of thermal D and ^{3}He are similar, thus we can check that the two tomographies are consistent with one another. In fact the two slightly differ in the region spanned by ch 6 and 14, where the experimental data were corrupted and the profile was interpolated from the closest channels.

SYNTHETIC ANALYSIS

The line shape of the emission spectrum can be modelled with GENESIS code. In figure 4 the sum of KN6G measurement of 2.87 MeV γ-rays in JET discharges #95677, #95679, #95680 and #95683 is compared with two synthetic diagnostics generated assuming the energy distribution of fast deuterons as simulated by TRANSP and two pitch-angle distribution centered at $\lambda \approx 0$ and $\lambda \approx 0.4$ [4]. It confirms that, differently from traditional ICRF scheme, the D-(D_{NBI})-^{3}He three-ion ICRF heating scenario generates co-passing fast D ions with $\lambda \approx 0.3$ - 0.5. This particles are candidates for driving the non-inductive current that induces the non monotonic q-profile. This suggests the necessity to study in more detail the relationship between fast deuterons and the excitation of RSAEs.

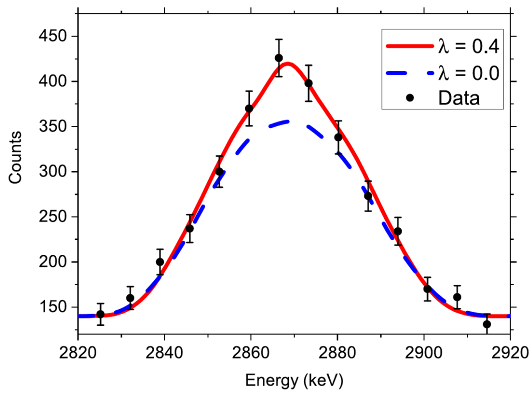

Figure 4: *(black points) Sum over JET shots #95677, #95679, #95680 and #95683 of the measured emission of E_γ = 2.87 MeV peak emitted by D+^{9}Be reactions. Line shape computed with GENESIS using deuterons energy distribution calculated with TRANSP and setting pitch-angle to $\lambda \approx 0$ (dashed blue) and $\lambda \approx 0.4$ (solid red). Reproduced from [4] according to IOP author right policy.*

CONCLUSIONS

The acceleration of D_{NBI} to energies in the MeV-range and the generation of fusion born α-particles from D+^{3}He has been confirmed by the spectral analysis of the plasma γ-ray emission. The spatial distribution of D+^{3}He born α-particles source has been reconstructed using the profile of the 16.4 MeV emission measured by the GCU. This distribution is in good agreement with the tomography of the neutron-camera profile. Synthetic modelling of the 2.87 MeV emission has been carried out and the results confirms the generation of co-passing deuterium ions, which are candidates to drive non-inductive current. Further studies on this topic will be conducted in the future.

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