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** See annex of F. Romanelli et al, “Overview of JET Results”, (Proc. 22nd IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).*

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Burning plasmas of future Deuterium-Tritium experiments such as ITER rely on self heating by fusion 3.5MeV confined particles. Diagnosing with time and space resolution the α particles is essential for the achievement and control of burning plasma conditions. In this contribution it is presented the first high resolution observation of the gamma ray spectrum in JET discharges with ^{4}He beams accelerated by ICRH at the 3^d harmonic resonance.

Gamma ray spectroscopy measures the γ-ray emission spectrum caused by reactions of fast particles with fuel ions or with impurities (carbon and beryllium) [1]. The γ-ray spectrum depends on the specific nuclear reaction, the energy of the interacting particles and on the nuclear levels of the formed final nucleus. At JET, in order to perform high energy resolution spectroscopy, γ-ray diagnostics have been recently upgraded with two new collimated spectrometers, namely a HPGe semiconductor and a $LaBr_3$ scintillator [2] (see Fig.1). The two spectrometers share with a NaI scintillator the same vertical Line Of Sight (LOS), at ~23m from the plasma centre with an aperture at the midplane similar to the TOFOR neutron spectrometer one [3]. The HPGe detector features a very high energy resolution (2.4keV a 1.33MeV) combined with good efficiency, while the $LaBr_3$ scintillator has the highest efficiency due to the large crystal size, a resolution matching the kinematical peak broadening and a high count rate capability. The most detailed γ-ray spectroscopy diagnostic information on fast ions is in the line shapes of the γ-ray peaks, which are Doppler Broadened by the kinematics of the reaction [4]. A Monte Carlo code has been developed to simulate for a specified viewing angle the γ-ray emission spectrum from the plasma. The first application of the code was for D(^{3}He) JET plasmas with ICRH tuned at ω_{3He}. For ^{3}He energies above 1.3MeV two γ-rays are emitted of energies 1635 and 2313keV from the reaction ^{12}C(^{3}He,pγ)^{14}N. The code uses experimental differential cross section data from different sources, in the assumption of no correlation among the p and γ-emission [5]. A typical measured spectrum is shown in Fig.2 for the 1635keV peak together with a simulation which assume a ^{3}He Maxwellian distribution with pitch angles equal to 90^o±5, which is taken as representative of a simplified ^{3}He distribution of population created by ICRH. The agreement found between the simulation and data of both gamma ray peaks is good (χ^2~1) for T^{3}He equal to 380keV.

The data set for ICRH accelerated 4He beam experiments consists of a total of eight discharges (Pulse No's:79167 to 79175) with main plasma parameters with B = 2.25T, $n_e = 3\text{-}4\times10^{19}\,m^{-3}$, $n_d = 0.16n_e$, $n_{4He} = 0.39n_e$ and T_e = 3-4keV. ICRH, which was set at 3−4 = 51.4MHz, delivered a power in the range 3−5.5MW while the NB power of either 1MW or 2MW were used, corresponding to the injection of a single or dual 110keV ^{4}He PINI. The measured spectrum recorded with the HPGe detector is shown in Fig.3 for a sum of four discharges and shows clear evidence of G-ray peaks from both the ^{9}Be(α,nγ)^{12}C and ^{12}C(d,pγ)^{13}C reactions. Several other peaks have been identified and ascribed to the reaction involving fast D, namely ^{9}Be(d,nγ)^{10}B, ^{9}Be(d,pγ)^{10}Be and ^{12}C(d,γ)^{14}N. If we consider the reaction ^{9}Be(α,nγ)^{12}C, the presence of the peak at 4439keV, which is due to population of the first level of the final nucleus ^{12}C, indicate acceleration of ^{4}He to energies in excess of 1.5MeV. The peaks at 3089, 3684 and 3853keV of the reaction ^{12}C(d,pγ)^{13}C corresponds to different excited levels of the final nucleus 13C and indicate acceleration of D ions in excess of 1.3MeV, according to thresholds in the cross section for populating the levels and in agreement with earlier observations [6]. D ions, which resonate at the same frequency of 4He, absorbed some ICRH power. The ratio of the 3089keV and 4438keV peak intensities for the HPGe discharges which were heated with only single PINIs is in the range 1.5–2.6 with a statistical uncertainty of about 10%. This can be compared with a double PINI discharge (Pulse No: 79174) where data collected with the LaBr scintillator show a peak ratio, corrected for the detector efficiency, of 5, which indicate higher power deposition on D for the double PINI case, in agreement with neutron spectroscopy observation [3].

The D and ^{4}He ion energy distributions were calculated using the Stix formalism which describes the steady-state distributions with characteristic cut-off in energy (see Fig.4). It is worthwhile noting that the Maxwellian approximation of the distribution function used for ICRH at fundamental harmonic is not valid for the 3^d harmonic. The distributions, which are calculated assuming average plasma parameters, extend up to MeV energies and depend on the electron density. Faraday cups observations indicate cut-off energies above 2.3MeV and 2MeV for the ^{4}He and D ions, respectively. The code simulating the emission spectrum was extended to the reaction ^{9}Be(α,nγ)^{12}C by including the relevant cross sections. Input to the code are the Stix ^{4}He energy distribution with a Gaussian cut in pitch angle around 900 to describe ICRH heated ^{4}He ions and a 3keV Maxwellian ^{9}Be distribution. The simulated γ spectrum was found to agree well with the data only if ^{4}He orbit effects were included by introducing suitable cuts in gyroangle. Simulations of the ICRH power deposition provide a value of R = 2.91-3.11m which fall partly outside the γ spectrometer LOS [3]. Due to their finite Larmor radius, a significant fraction of ^{4}He ions will fall outside the LOS, which result in measured ^{9}Be(α,nγ)^{12}C γ-ray spectrum which is significantly cut on the low energy side and centred around 4478keV (see Fig.5). More detailed modelling of the ^{4}He ion distribution (in progress) can be made but cannot explain the measured Doppler shifted γ-ray spectrum without including the LOS effect. The Magnetic spectrogram traces of pick up coils for the set of discharges show no strong MHD activities correlated with the acceleration of fast ^{4}He ions. Exception is the Pulse No: 79164 for a period of about 1s, which is not enough to show significant effects in the spectroscopy data within the available statistics. Possible MHD effects could cause for instance change in the position of fast ^{4}He ions (redistribution and losses) or in their velocity distribution. These changes of the ^{4}He fast population would affect the measured gamma rays spectrum of the ^{9}Be(α,nγ)^{12}C reaction in way similar to what has been observed here.

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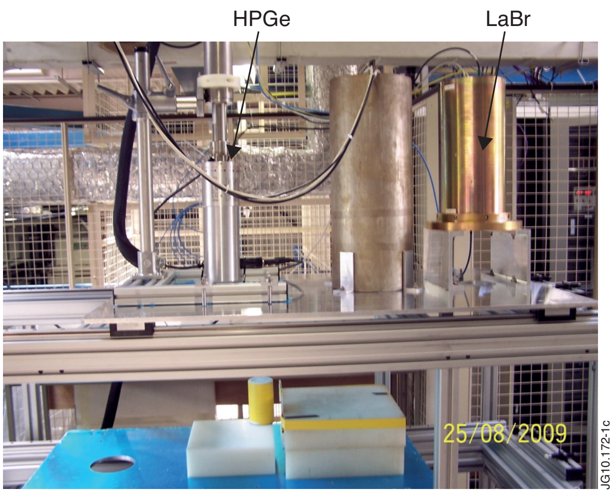

Figure 1: Picture of the HPGe and $LaBr_3$ γ-ray spectrometers installed at JET. γ-rays come from the bottom of the picture.

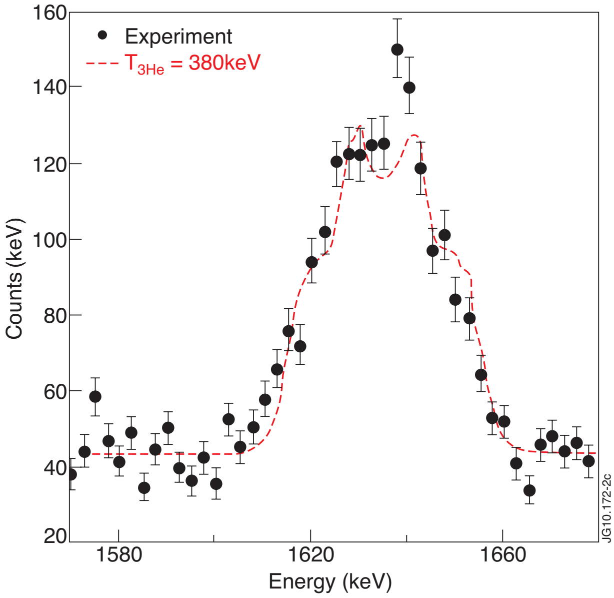

Figure 2: γ-ray energy spectrum recorded with the HPGe detector for $D(^{3}He)$ JET discharges. The peak, ascribed to the reaction $^{12}C(^{3}He,p)^{14}N$, is shown together with a simulation from which a temperature of 380keV is inferred for the fast ^{3}He population.

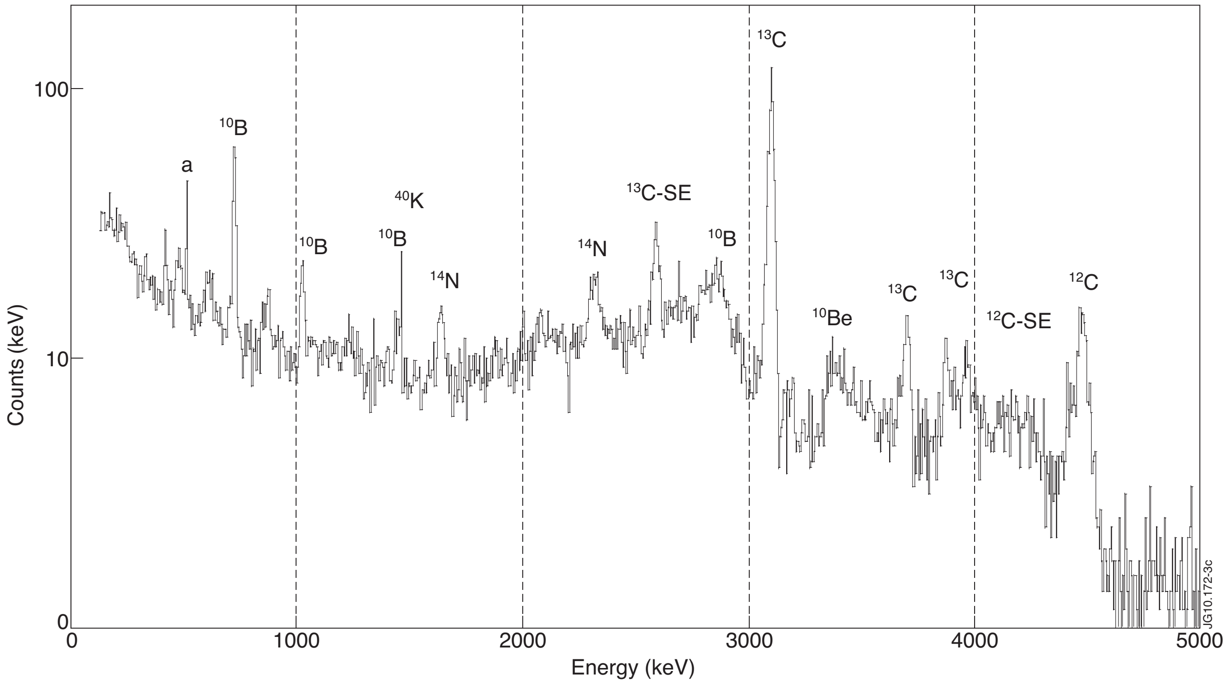

Figure 3: γ-ray energy spectrum recorded with the HPGe detector for a selection of four discharges (Pulse No's: 79168 to 79171). The peaks have been identified and labelled with the corresponding excited final nuclei. Calibration peaks are indicated with label a (511keV) and 40K.

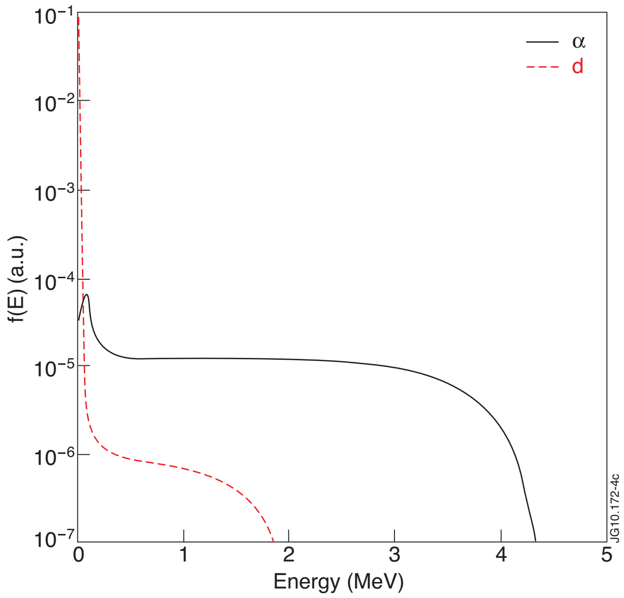

Figure 4: On the left, d (dashed line) and ^{4}He (solid line) distribution function calculated using the Stix theory and for $n_e = 2.6\times10^{19}\ m^{-3}$.

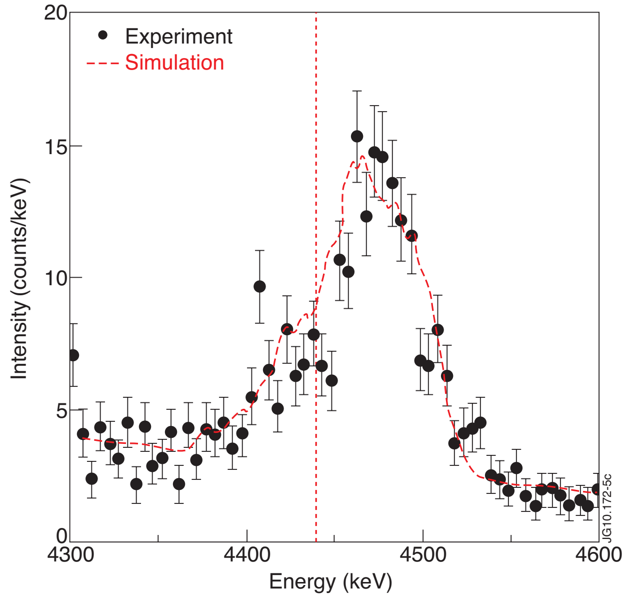

Figure 5: On the right γ-ray energy spectrum of Fig.3 shown together with a simulation which include LOS effects. The data are shifted towards higher energy relative to the reference 4439keV mean value (dashed line).