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High Resolution Gamma Ray Spectroscopy Measurements of the Fast Ion Energy Distribution in JET ^4He plasmas

M. Nocente^{1,2}, M. Tardocchi², V.G. Kiptily³, P. Blanchard³, I. Chugunov⁴, S. Conroy⁵,
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R.C. Pereira⁶, E. Perelli Cippo¹, S. Sharapov³, A. Shevelev⁴, J. Sousa⁶,
D.B. Syme³, D. Van Eester⁷, G. Gorini^{1,2} and JET EFDA contributors*

JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK

¹*Dipartimento di Fisica “G. Occhialini”, Università degli Studi di Milano-Bicocca, Piazza della
Scienza 3, 20126, Milano, Italy*

²*Istituto di Fisica del Plasma “Piero Caldirola,” Associazione EURATOMENEA- CNR, via Cozzi 53,
20125, Milan, Italy*

³*JET-EFDA, Culham Science Centre, Abingdon OX14 3DB, United Kingdom*

⁴*A.F. Ioffe Physico-Technical Institute, 194021, St. Petersburg, Russian Federation*

⁵*Department of Physics and Astronomy, EURATOM-VR Association, Uppsala University, Uppsala, Sweden*

⁶*Instituto Superior Técnico, Centro de Fusão Nuclear, Associação EURATOM/IST, 1049-001, Lisboa, Portugal*

⁷*LPP-ERM/KMS, Association Euratom-”Belgian State”, TEC Partner, B-1000, Brussels, Belgium*

⁸*Associazione EURATOM-ENEA sulla Fusione, Consorzio RFX Padova, Italy*

** See annex of F. Romanelli et al, “Overview of JET Results”,
(23rd IAEA Fusion Energy Conference, Daejeon, Republic of Korea (2010)).*

ABSTRACT.

High resolution γ -ray measurements were carried out on the Joint European Torus (JET) in an experiment aimed at accelerating ^4He ions in the MeV range by coupling third harmonic radio frequency heating to an injected ^4He beam. For the first time, Doppler broadening of γ -ray peaks from the $^{12}\text{C}(d, p\gamma)^{13}\text{C}$ and $^9\text{Be}(\alpha, n\gamma)^{12}\text{C}$ reactions was observed and interpreted with dedicated Monte Carlo codes based on the detailed nuclear physics of the processes. Information on the confined ^4He and deuteron energy distribution was inferred and confined ^4He ions with energies as high as 6MeV were assessed. A signature of MHD activity in γ -ray traces was also detected. The reported results have a bearing on diagnostics for fast ions in the MeV range in next step fusion devices.

1. INTRODUCTION

Understanding the behaviour of fast ions is widely considered a still open problem for reliable operation of a fusion device. There has been remarkable progress in the past decade in this field of research, both on the theoretical as well as on the experimental side, as recently reviewed in [1]. Many of the predicted Magneto HydroDynamic (MHD) modes driven by fast particles have been identified and their non linear frequency evolution has been measured and theoretically explained. A certain degree of uncertainty however still remains on the effects of the interaction between these modes and fast ions which has a bearing on α particles in a fusion reactor. Fast ion redistribution and losses due to the excitation of many MHD instabilities, besides the consequent role of energetic particles on the overall transport, are largely unknown and dedicated experiments are presently carried out in several machines [1]. On the diagnostics side, most of the present knowledge derives from measurements of fast ions on middle-size machines, where instabilities are driven by particles with energies in the 100keV range, either due to Neutral Beam Injection (NBI) or generated by Radio Frequency (RF) heating. Recent progress in the detection of lost ions allowed phase space characterization of the losses [2,3], while a charge exchange recombination spectroscopy technique based on fast ion D_α emission (FIDA) [4] showed flattening of the fast ion profile correlated to the onset of energetic particle instabilities [5,6]. As the energy of the ions is increased towards the MeV range, such as that of α particles in a burning plasma, many diagnostics presently used for these studies on middle size machines show limitations and new methods need to be sought. For example, the considerably small cross sections for D_α emission in the MeV range limit the applicability of the FIDA technique [4]. On the other hand, the increased size of next step devices demands methods to diagnose confined energetic ions and complement information on losses.

Gamma ray spectroscopy is one of the proposed techniques for the observation of ions in the MeV range in next step fusion devices and a number of studies have been made on the JET tokamak, the only present machine that can confine ions in that energy range [7]. In recent years, the upgrade of the JET γ -ray spectrometers with the installation of a High Purity Germanium (HpGe) and a Lanthanum Bromide- Cerium ($\text{LaBr}_3(\text{Ce})$) detectors [8] has greatly enhanced the quality of the observations and the information that can be derived from the data. For the first time, the Doppler

broadened peak shape produced by interaction of ^3He ions on ^{12}C impurities has been measured and interpreted in terms of the nuclear physics of the reaction and tail temperature of the energetic ions [9]. In this paper we report, for the first time, observations of Doppler broadened peak shapes from energetic ^4He ions and deuterons on JET. The measurements were carried out in an experiment aimed at accelerating ^4He ions by coupling RF heating at the third harmonic to a helium beam injected approximately at 40° to the magnetic axis in a (D) ^4He plasma [10]. The plasma current was $I_p = 2\text{MA}$ and the toroidal magnetic field at plasma centre was $B_T = 2.25\text{T}$, which placed the 51.4MHz resonance layer on the magnetic axis for both ^4He and d ions. Core Electron densities in the range $2.5\text{--}4 \times 10^{19} \text{m}^{-3}$ with average on axis electron temperatures of 3.4keV were available for applied antenna powers in the range $3\text{--}6\text{MW}$. The collected experimental data are interpreted in this paper by means of simulations with the GENESIS (Gamma Emission and Neutron Emission Simulation and Interpretation Software) Monte Carlo code that is an extended version of a previous programme [11,12] adopted for neutron emission calculations. A simplified semi-analytical model, described in section 3, is adopted for the distribution of RF heated ^4He and d ions as input for calculations. This simplification was found convenient to numerically investigate changes in the peak shapes and ratios as effect of modifications in parameters describing the energetic ion distribution, while still retaining the main features of the employed heating scheme. After a short overview of the γ emitting reactions of interest for this study in section 2, the experimental results and simulations are presented and the findings compared with information from other diagnostics. Implications of these results on observations of confined fast ions in the MeV range on next generation devices are finally discussed.

2. GAMMA EMITTING REACTIONS AND CROSS SECTIONS

Gamma ray emission can occur when fast ions interact with impurities, either coming from the machine vacuum vessel or injected on purpose. On JET there are two reactions of interest for the observation of fast ^4He ions and deuterons, the $^9\text{Be}(\alpha, n\gamma)^{12}\text{C}$ and $^{12}\text{C}(d, p\gamma)^{13}\text{C}$ reactions, respectively [13]. The level scheme of the emitting nuclei is presented in figure 1. The $^9\text{Be}(\alpha, n\gamma)^{12}\text{C}$ reaction is the main candidate for α particle observations through gamma ray spectrometry on ITER [14,15] and has a positive Q value of 1.27MeV for populating ^{12}C in his first excited state, which in turn de-excites by emission of a 4.44MeV gamma ray. If the α particle energy exceeds $E_\alpha = 1.35\text{MeV}$ the second ^{12}C excited state starts to be populated and de-excites with the emission of a 3.22MeV and 4.44MeV gamma rays in cascade. The $^{12}\text{C}(d, p\gamma)^{13}\text{C}$ reaction is instead endothermic, with negative Q values of -0.37MeV , -0.96MeV and -1.13MeV for the population of the 1st, 2nd and 3rd ^{13}C excited states, respectively, yielding gamma rays of energies 3.09MeV , 3.68MeV and 3.85MeV . In the discharges analyzed in the present paper ^9Be was evaporated overnight while ^{12}C was present at a typical concentration level of about 1% due to the composition of the JET vacuum vessel.

The cross sections for the production of gamma rays observed during the measurements reported here are shown in figure 2 and were obtained by merging experimental data from several authors

in a way similar to the methods described in reference [16]. In particular, data from references [17,18] were used to obtain the total, as well as differential, cross section for production of the 4.44MeV peak from the ${}^9\text{Be}(\alpha, n\gamma){}^{12}\text{C}$ reaction up to $E_\alpha = 6$ MeV (figure 2, top). The cross section is negligible below $E_\alpha < 1$ MeV and displays a non trivial behaviour as a function of energy with major resonances at $E_\alpha = 2.0, 2.9, 4.3, 5.5$ MeV. The angular distribution of the emitted neutrons in the c.m. frame is not isotropic and shows an increased forward peaking as the energy of ${}^4\text{He}$ ions is raised, which affects the Monte Carlo simulated peak shape [17,18].

Cross section data for the ${}^9\text{Be}(\alpha, n\gamma){}^{12}\text{C}$ reaction were obtained from reference [19] and are shown in figure 2, bottom part, for laboratory energies in the range 1–4 MeV. The values are those for the production of 3.09MeV and 3.69MeV gamma rays, which are weighted by the branching ratios of figure 1. Similarly to the $\alpha + {}^9\text{Be}$ reaction, the cross section for the $d + {}^{12}\text{C}$ reaction has a complex trend as function of energy, with several resonances appearing in the MeV region.

3. FAST ION ENERGY DISTRIBUTION

For energies far from the thermal ion region, an approximate form for the anisotropic fast ${}^4\text{He}$ energy distribution f is obtained from the Fokker-Planck equation

$$\frac{\partial f}{\partial t} + S(v_p) + L(v_p) = C(f) + Q(f) \quad (1)$$

where all the quantities are expressed in terms of the velocity component perpendicular to the magnetic field v_p only. $S(v_p)$ represents the source term due to perpendicular NBI injection and is expressed as $S(v_p) = S_0 / (2\pi v_p) \times \delta(v_p - v_0)$ with v_0 indicating the NBI injection velocity and S_0 a constant. $L(v_p)$ is a loss term that absorbs ions at the same rate as $S(v_p)$, but at thermal speed. $C(f)$ and $Q(f)$ are operators representing the effect of collisions and radio frequency heating on the alpha particles respectively. Following the treatment of reference [20] they can be expressed as

$$C(f) + Q(f) = \frac{1}{v_p} \frac{\partial}{\partial v_p} \left[-\alpha v_p f + \frac{1}{2} \frac{\partial}{\partial v_p} (\beta v_p f) + \frac{1}{4} \gamma f + D_{RF} v_p \frac{\partial f}{\partial v_p} \right] \quad (2)$$

where α , β and γ are the Spitzer collision coefficients [21] and D_{RF} the radio frequency diffusion coefficient. In the steady state condition equation (1), combined with equation (2), is reduced to a 1st order ordinary differential equation for f and the solution is readily expressed in terms of one dimension velocity integrals to be evaluated numerically.

The specific form of the solution depends on the diffusion coefficient D_{RF} , which is expressed as [20,21]

$$D_{RF} = K \left| J_{n-1} \left(\frac{k_p v_p}{\omega_c} \right) + \frac{E_-}{E_+} J_{n+1} \left(\frac{k_p v_p}{\omega_c} \right) \right|^2 \quad (3)$$

For harmonics higher than the fundamental, D_{RF} has an oscillating behaviour due to the presence

of Bessel functions of the first kind $J_n(x)$ (figure 3) and contains parameters pertaining to wave propagation and absorption at the resonance that need to be known. Specifically, E_- (E_+) are the right (left) handed component of the electric field at the resonance, k_p is the perpendicular wave number and ω_c the cyclotron frequency of the resonating ion. K is a constant representing the amount of RF absorption. In this work K was varied in equation (3) until a chosen value was matched by the total absorbed power density P_{RF} . The latter was expressed as

$$P_{RF} = 2\pi n_s \int dv_p v_p \left(\frac{m v^2}{2} \right) Q(f) \quad (4)$$

where the known mass m_s and density n_s of the resonating ion appear. P_{RF} depends on K in equation (4) through the $Q(f)$ term [20]. The power density absorbed by ^4He ions can be estimated to be of the order $\approx 10^5 \text{ W/m}^3$ for the scenario under study.

Figure 3 shows the calculated ^4He ion distribution assuming $P_{RF} = 500 \text{ kW/m}^3$ and using cold plasma theory (equations (1.18) and (1.58) of [21]) to calculate the resonance parameters k_p and E_-/E_+ from measured values. ^4He ions accelerated at the third harmonic resonance develop a rather flat tail in phase space extending to high energies from the NBI injection energy up to a certain cut value E_{α}^* . The latter is determined by the appearance of the first zero in the diffusion coefficient D_{RF} (figure 3b). Correspondingly, a sharp drop is seen in the ^4He ion energy distribution and almost no particles have energies extending above E_{α}^* [21]. Figure 3 also shows the deuteron energy distribution calculated with equation (1), letting $S(v_p) = L(v_p) = 0$. As ^4He ions and deuterons have the same ion cyclotron frequency, part of the incoming wave power is damped on thermal deuterons that also develop energetic tails up to a certain energy E_d^* . The deuteron tail level is however some orders of magnitude lower compared to that of ^4He ions due to the absence of a fast ion seed provided by NBI. As E_d^* is also determined by the appearance of the first zero in the diffusion coefficient D_{RF} , the relation $E_{\alpha}^* = 2 \cdot E_d^*$ holds between the two cut energies. In fact, being k_p and ω_c the same for the two species, the cut velocity v_p^* is the same and the relation between the cut energies $E^* = 1/2 m v_p^{*2}$ is given by the mass ratios of the resonating species.

In order to investigate the fractions of RF power absorbed by the different species, simulations were performed with the TOMCAT wave code for single pass absorption [22]. The ^4He ion and deuteron distribution were represented as Maxwellians at temperatures $T_{\alpha} \gg T_i$ and T_i respectively and a scan was made in ^4He temperature and beam density. Figure 4 shows the power fraction absorbed by different species for a case with $T_{\alpha} = 50 \text{ keV}$ and a beam density equal to 6% of the electron density. The incoming wave is mainly damped on the ^4He beam ions and electrons, with only about 1% of the power coupled to deuterons. The simulations show quantitative changes depending on the exact value of T_{α} and the beam fraction. However in all cases only a fraction around 1% of the power is coupled to deuterons and can be considered independent of the simplistic representation of the ^4He ion energy distribution as a Maxwellian at $T_{\alpha} \gg T_i$. Thus one can expect P_{RF} to be of the order $\approx 10^3 \text{ W/m}^3$ for deuterons at resonance. In figure 3 the value $P_{RF} = 5 \times 10^3 \text{ W/m}^3$ was used to calculate the deuteron distribution.

Figure 5 shows variations of the ${}^4\text{He}$ ion distribution by changes of $\pm 10\%$ in P_{RF} and k_p around the values predicted by cold wave theory. A small variation in k_p strongly affects the energy distribution, as it directly acts on the cut energy E^* , while P_{RF} mainly acts on the level of the plateau, without significant influence on E^* . Similar trends are seen in the deuteron energy distribution.

4. EXPERIMENTAL RESULTS AND MODELLING

The measured gamma-ray emission spectrum in the region $E_\gamma > 3\text{MeV}$ for JET Pulse No's: 79168 to 79171 is shown in figure 6 in the time window 12 to 17s. The spectrum was collected with a HpGe detector, time integrated during RF heating and summed over these similar 4 discharges to improve statistics. The resolution of the measurement in this energy region is about 1keV, which allows one to appreciate broadening of the peak shapes besides identifying signatures of de-excitation from different states of the same emitting nucleus. The most intense peak appears at $E_\gamma = 3.09\text{MeV}$ that corresponds to de-excitation of the first ${}^{13}\text{C}^*$ excited level produced by the $d+{}^{12}\text{C}$ reaction. The 3.68MeV and 3.85MeV peaks from deexcitation of the second and third ${}^{13}\text{C}^*$ states (the latter barely emerging from the background) are also seen and qualitatively indicate deuteron energies greater than 1.13MeV. ${}^4\text{He}$ ions with energies in excess of 1MeV are manifested by the appearance of the $E_\gamma = 4.44\text{MeV}$ peak. This is in turn mirrored in the single escape peak at $E_\gamma = 3.93\text{MeV}$ which depends on the detector response function and does not correspond to a new reaction occurring in the plasma. No clear evidence of the 3.22MeV peak from de-excitation of the second ${}^{12}\text{C}^*$ excited state is seen in the data.

Besides qualitatively indicating that ions exceeding a certain energy were produced in the analyzed discharges, quantitative information can be derived from the measured spectrum by comparison with modelling. From the experimental data shown in figure 6 one can derive the peak ratio r between counts due to de-excitation of the first and second ${}^{13}\text{C}^*$ levels, yielding $r = 6.5 \pm 0.6$ after correcting for the difference in detector intrinsic efficiency at the two peaks and background subtraction. The peak ratio is related to the ratio of the reactivities Y_γ through the relation [16]

$$r = \frac{Y_{\gamma 1}}{Y_{\gamma 2}} = \frac{\int d^3\vec{v} \sigma_{\gamma 1} v f(\vec{v})}{\int d^3\vec{v} \sigma_{\gamma 2} v f(\vec{v})} \quad (5)$$

where $\sigma_{\gamma i}$ represents the cross section for populating the i -th ${}^{13}\text{C}^*$ level. The advantage of distinguishing several excited states of the same emitting nucleus is that the calculated peak ratio is independent of the densities of the reactant (d and ${}^{12}\text{C}$ for the present reaction) and of the effective emission volume, that both simplify in the ratio expressed by equation (5).

The expected peak ratio was evaluated with equation (5) and is compared to the measured value in figure 7. The fast deuteron distribution was varied by independently changing the P_{RF} and k_p parameters and resulted in the calculated curves shown in the figure. The wave polarization was set to the constant value obtained by applying cold plasma theory as it did not significantly affect the distribution. The horizontal shadowed bar represents the experimental value r with its uncertainty.

The calculated curves are rather independent of P_{RF} but for very low power densities, say $P_{\text{RF}} < 1\text{kW/m}^3$. Here a sharp rise is seen that is due to the rapidly decreasing cross section for populating the second $^{13}\text{C}^*$ state.

From the results of figure 7, k_p must lie in the range 44 m^{-1} to 47 m^{-1} that corresponds to $E_d^* = 3.0 \pm 0.2\text{MeV}$. This interval is consistent with the estimated P_{RF} in the range $10^3 - 10^4\text{ W/m}^3$ and reproduces the absolute number of counts measured under the $E_\gamma = 3.09\text{MeV}$ and $E_\gamma = 3.68\text{MeV}$ peaks assuming ^{12}C concentrations of a few percent. Lower k_p values are, for instance, ruled out, as the number of counts under $E_\gamma = 3.68\text{ MeV}$ peak would be underestimated by 1 to 2 orders of magnitude. As the electron density varied between $2.3 \times 10^{19}\text{ m}^{-3}$ and $3.6 \times 10^{19}\text{ m}^{-3}$ in the time window 12 to 17s, which changed k_p in time, the value $k_p = 44 - 47\text{ m}^{-1}$ must be regarded as effective, i.e. inferred by time integrating γ -ray spectra for statistical reasons. Temporal changes in k_p could be resolved in future measurements with better statistics (see discussion). From the relation $E_{\alpha^*} = 2 \cdot E_d^*$ one can also derive the cut energy of ^4He ions to be $E_{\alpha^*} = 6.0 \pm 0.4\text{MeV}$.

We now move to the analysis of the detailed $E_\gamma = 4.44\text{MeV}$ peak shape from the $^9\text{Be}(\alpha, n\gamma)^{12}\text{C}$ reaction. Data collected with the HpGe detector for the sum of four discharges during RF heating are presented in figure 8. The error bars are those associated to the Poisson statistics of the measurement. The energy calibration is linearly extrapolated from known calibration source peaks at lower energy, with an estimated error of $\approx 3\text{keV}$ in the region of the $\alpha + ^9\text{Be}$ peak. Two features are clearly displayed by the data. The first one is that the $\alpha + ^9\text{Be}$ peak is Doppler broadened, as it was found for gamma ray peaks from reactions between radio frequency heated ^3He ions and ^{12}C in reference [9]. The second is that the centroid of the peak is around 4470keV , i.e. $\approx 30\text{keV}$ upward shifted with respect to the expected value of 4439keV .

The reason of this shift is clarified when simulating the expected peak shape produced by ^4He ions described by the distribution in figure 5. The simulations were performed with the GENESIS Monte Carlo code [9]. The $^{12}\text{C}^*$ energy spectrum is determined through classical kinematics by sampling the reactant energy distributions. In a second stage, the resulting gamma ray emission spectrum is evaluated along a specified line of sight. Isotropic γ -ray emission with respect to the excited nucleus direction in the laboratory frame is assumed and branching ratios are taken into account so to simulate cascade transitions when necessary [16]. The result of the simulation is presented in figure 8 (dashed line). The only parameter fitted is the normalization of the spectrum with the addition of a linear background. Quite surprisingly, the curve completely fails to describe the lower half of the peak, which is not present in the measured data. The reason for this effect may be explained by considering the orbit of RF heated ^4He ions at the resonance. The calculated trajectory of 4MeV ^4He ions projected on to the poloidal plane is shown in figure 9. The particles are generated on the magnetic axis with 90° pitch angle. The line of sight of the HpGe detector is determined by collimators designed for the JET Roof Laboratory and is the same of that of TOFOR neutron spectrometer [23,24]. The latter was evaluated in reference [25] and covers the region in major radius $2.74 - 3.02\text{m}$, with an uncertainty of about 1cm at the edges. When the line of sight

is taken into account in figure 9, it is revealed that only the upward gyro-motion of the particle is seen by the detector. This explains why the lower half of the peak, which corresponds to downward motion, is missing from the data. In order to quantitatively describe the measurements, an “ad hoc” orbit effect was introduced in the code. This was done by sampling the radial position of the ^4He ions with Gaussian probability. The centre of the radial distribution was placed at the resonance location while the FWHM was varied between 5cm and 30cm. At each particle location only the fraction of gyroradius falling inside the line of sight was considered for the calculation of the resulting γ -ray spectrum. In this way, the measured peak shape is described when the FWHM of the ^4He ion radial distribution lies in the range 10cm to 20cm (figure 8, solid line); here a reduced $\chi^2 \approx 1.5$ is found, with little variations depending on the exact value of the chosen FWHM in the interval 10 to 20cm.

Simulations of the 4.44MeV peak show changes in shape depending on the k_p parameter of the ^4He ion energy distribution. Figure 10 compares the upper half of the 4.44MeV peak with calculations. The comparison is limited to this part of the peak so to discard the orbit effect discussed above. The best fit is obtained for $k_p \approx 45 \text{ m}^{-1}$ (reduced $\chi^2 = 1.0$). The range of variation for k_p , determined by an increase of ± 1 in reduced χ^2 is $35\text{--}55 \text{ m}^{-1}$, which is rather large because of the limited statistics of the measurement. $k_p = 45 \pm 10 \text{ m}^{-1}$ is in good agreement with the interval 44 to 47 m^{-1} obtained from analysis of the $^{13}\text{C}^*$ peak ratio r and confirms the value $6.0 \pm 0.4 \text{ MeV}$ for E_{α^*} . This result shows that information on the confined ^4He energy distribution can indeed be derived from the detailed peak shape for the scenario of this experiment and independently benchmarks the information obtained from the $^{13}\text{C}^*$ peak ratio. In figure 10 k_p was varied in steps of 5 m^{-1} , but smaller variations may be appreciable in future measurements with improved statistics.

A $\text{LaBr}_3(\text{Ce})$ spectrometer was also used in the measurements. The detector, designed for high rates, has been already described in [8]. Although its resolution is not as good as that of HpGe , its enhanced detection efficiency allows for better statistics. Figure 11 shows the measured gamma emission spectrum for JET Pulse No: 79174. Besides peaks from the $d + ^{12}\text{C}$ and $\alpha + ^9\text{Be}$ reaction, a further peak at $E_\gamma = 3.37\text{MeV}$ appears. This is produced by the $^9\text{Be}(d, p\gamma)^{10}\text{Be}$ reaction and was not observed in Pulse No’s: 79168-79171. As the antenna had $\pm 90^\circ$ phasing in JET Pulse No: 79174 (to be compared with dipole phasing for Pulse No’s: 79168-79171), cold plasma theory predicts an increased k_p , which would correspond to a decreased E_d^* . Indeed, according to figure 7, an augmented k_p is compatible with an increased peak ratio r , which for this discharge equals 17 ± 8 . The large error on this value comes from background subtraction below the $E_\gamma = 3.68 \text{ MeV}$ peak and is partially due to the still not optimized detector parameters adopted in this discharge. As E_d^* is lowered, the appearance of the peak from the $^9\text{Be}(d, p\gamma)^{10}\text{Be}$ reaction can be explained only by higher P_{RF} . The temporal evolution of the $E_\gamma = 3.09\text{MeV}$ and $E_\gamma = 4.44\text{MeV}$ count rates are shown in figure 12 every 20ms between 3 and 8s. The count rate starts to rise at 4s and drops between 7.2 and 7.6s, i.e. 0.4s before the end of the RF heating phase, between 4 and 8s in this discharge. The reason is that core electron density experiences a jump from $3 \times 10^{19} \text{ m}^{-3}$ at 7s to $3.8 \times 10^{19} \text{ m}^{-3}$ at 7.2s that impedes fast ion acceleration, with a delayed drop in the γ count rate due to slowing down. Between 5.6 and 5.8s

a further sharp drop of a factor ≈ 1.6 that exceeds the statistical fluctuation of the data is observed in the $E_\gamma = 3.09\text{MeV}$ count rate. This drop corresponds to the appearance of toroidal Alfvén eigenmodes (TAE) in the magnetic traces at 5.75s and suggests redistribution of fast deuterons. A similar drop is not observed in the count rate for the $E_\gamma = 4.44\text{MeV}$ peak ($\alpha + {}^9\text{Be}$ reaction) but might be masked by the larger statistical data fluctuation. No signs of MHD activity was observed in the magnetic traces, as well as in the γ -ray count rates, for Pulse No's: 79168-79171 where the HpGe detector was used.

5. DISCUSSION

γ -ray observations can be compared to neutron measurements with the TOFOR spectrometer on JET [23,24]. The instrument measures the neutron time of flight t_n between two arrays of scintillators so that the neutron energy E_n is univocally related to t_n through $E_n = 1.04 \times 10^4 / t_n^2$ where E_n is expressed in MeV and t_n in nanoseconds. This relation implies that higher neutron energies correspond to smaller time of flights. Figure 13 shows the measured neutron spectrum for the sum of JET Pulse No's: 79168–79171 in the time window 12 to 17s that directly compares to the γ -ray spectrum of figure 6. Neutron emission is expected mainly from the $d + d \rightarrow n + {}^3\text{He}$ reaction, but there is a component from the $\alpha + {}^9\text{Be} \rightarrow n + {}^{12}\text{C}$ reaction as well. Noticeably, the highly non Maxwellian character of the energy distribution is manifested in the neutron spectrum that does not show a Gaussian peak centred at $t_n = 65\text{ns}$ ($E_n = 2.45\text{MeV}$) due to thermal emission. The GENESIS code was used to calculate the expected neutron spectrum from the $d + d \rightarrow n + {}^3\text{He}$ and $\alpha + {}^9\text{Be} \rightarrow n + {}^{12}\text{C}$ reactions using as input the distributions calculated as described in section 3 and setting k_p to the value 45 m^{-1} inferred from γ -ray measurements. As the result of equation (2) is not adequate in the thermal region, the deuteron distribution was here joined to an isotropic Maxwellian representing the bulk component with a procedure similar to that adopted in [26]. This choice, although simplistic, was found adequate to describe the data within the statistics. The same procedure was not necessary for the neutron component from the $\alpha + {}^9\text{Be}$ reaction, as neutron emission for thermal ${}^4\text{He}$ ions is negligible. The result of the simulation is shown in figure 13 and confirms the presence of ${}^4\text{He}$ ions with energies as high as 6MeV determined through γ -ray spectroscopy. It is also revealed that the $d+d$ contribution has a sharp cut off at $t_n = 42\text{ns}$ which sets $E_d^* \approx 3\text{MeV}$, consistent with γ observations. More details on neutron measurements for this experiment can be found in reference [27]. Here we just add that orbit effects do need to be taken into account also to describe neutron data, for which the empirical model illustrated in section 3 was adopted in the simulations of figure 13. A more accurate procedure was used in [27] and its developments are the subject of [28]. A similar study of the energy distribution of fast deuterons accelerated by RF at the third harmonic using neutron emission spectroscopy at JET is reported in [29] for a different experiment and confirms the results presented here. In reference [30] measurements with a Faraday cup array are reported for the experiment considered here. A signal in terms of current from ${}^4\text{He}$ ions in the energy range 2.3MeV – 5.9MeV was detected for the first time throughout all the discharges, while no evidence of ${}^4\text{He}$ ions exceeding 6MeV was seen. This is also consistent with the values stated in this paper. In this work

we have derived information on the energy distribution of ^4He ions by considering both variations in the ratio of peaks produced by different excited states of the same emitting nucleus ($^{13}\text{C}^*$ in this case) and by studying the detailed shape of the $\alpha + ^9\text{Be}$ peak at $E_\gamma = 4.44$ MeV. Although qualitative results could be derived by simple arguments based on the observed emission spectra, quantitative information were obtained only by considering the detailed nuclear physics behind the reaction in terms of differential cross section, energy levels and branching ratios of the emitting nuclei, which can be quite different depending on the emission process. Indeed, the extremely variegated properties of reactions between light nuclei and impurities (see for example [31, 32] and references therein) can sometimes produce undesirable effects, such as limiting changes of an observable even over significant modifications in the plasma parameters. An example is given by the peak ratio of the $^{12}\text{C}(^3\text{He}, p\gamma)^{14}\text{N}$ reaction, which is rather independent of the fast ^3He distribution as shown in reference [16], in clear contrast with the peak ratio from the $^{12}\text{C}(d, p\gamma)^{13}\text{C}$ reaction considered in this paper. Similar arguments hold for the peak shape that is found to depend on the detailed angular distribution of the emitting nuclei and can also show limited variations for certain reactions. These issues will be more extensively addressed in forthcoming papers. Clearly, due to the Poissonian nature of the process, the possibility to observe changes in the γ -ray emission spectrum benefits from increased statistics which sets a trade-off between time resolution and the required precision in determining the parameter of interest (for example E_γ^* in this paper).

Similarly to neutron spectroscopy [33,34], as shown with the result of figure 12, γ -ray spectroscopy can also be used to derive information on the effect of MHD modes on fast ions by studying the time dependence of the measured counting rate [34]. The energies of the interacting ions are related to the counting rate through the differential reactivity $y_\gamma = v\sigma(E)f(E)$. The latter represents the γ -ray emission intensity as a function of the fast ion energy and is the integrand appearing in equation (5). The differential reactivity for the $E_\gamma = 3.09\text{MeV}$ peak of the $^{12}\text{C}(d, \gamma)^{13}\text{C}$ reaction is shown in figure 14 for Pulse No: 79174. The curve is significantly non null only in the energy range $E_d = 0.8$ to 2.5MeV , with a peak at $E_d \approx 1.7\text{MeV}$. By inspecting figure 14, we speculate that a redistribution of fast deuterons with $E_d \approx 1.7\text{MeV}$ (i.e. around the peak in the differential reactivity curve) must have occurred in Pulse No: 79174 to justify a factor 1.6 drop as observed in the counting rate. Further insights on mode-particle interaction could be obtained by calculating resonance curves between the observed TAEs and fast ions, as done for instance in reference [35], but this goes outside the scope of the present paper. Here we note the following fact. The fast ion energies, to which γ -ray spectroscopy is sensitive, are determined by the differential reactivity of each specific reaction, which comprises the combined product of the cross section and the ion energy distribution. When resonances in the cross sections appear [31,32], the evolution of the γ -ray counting rate can be dominated by ions with energies near resonance, despite those with energies off-resonance. For example, in the case of figure 14, a change in the fast deuteron population having $E_d \approx 0.8\text{MeV}$ would hardly be manifested in the observed γ -ray counting rate. This strengthens the need to consider the detailed nuclear physics behind each reaction to derive conclusions also on the fast ion dynamics

based on the observed γ -ray emission rate. From the instrumental point of view, observations on the interaction between fast ions and instabilities through γ spectroscopy would be boosted by the capability to perform spatially resolved measurements, for example to study the effects of α particles in a DT plasma. This could be done through a tomographic system, such as the JET γ -ray camera [7], but with spectroscopy capabilities at each channel and an increased number of line of sights. Concept studies are currently undergoing in view of ITER and some solutions are reported in reference [36].

CONCLUSIONS

In this paper first high resolution measurements of Doppler broadened peak shapes from γ emitting reactions induced by energetic α particles and deuterons were reported. The data were interpreted through Monte Carlo simulations of the γ -ray emitting reactions and good agreement was found with measured data. Information on the ^4He and deuteron energy distribution was inferred and found consistent with observations from other diagnostics. In particular, the confinement of deuteron and ^4He ions with energies as high as 3 and 6MeV, respectively, was assessed. A drop in the γ -ray count rate was found in one discharge and corresponded to the appearance of TAE in the magnetic traces. The need to consider the detailed nuclear reaction data and physics of each reaction to derive quantitative information on the energetic ions from the γ -ray emission spectrum was pointed out. The methods and results reported here are of relevance for confined fast ion studies in the MeV range on next generation devices, such as α particles in ITER DT plasmas, where observations would significantly be boosted by spatially resolved measurements through a tomographic γ -ray system with spectroscopic capabilities.

ACKNOWLEDGMENTS

This work was supported by EURATOM and carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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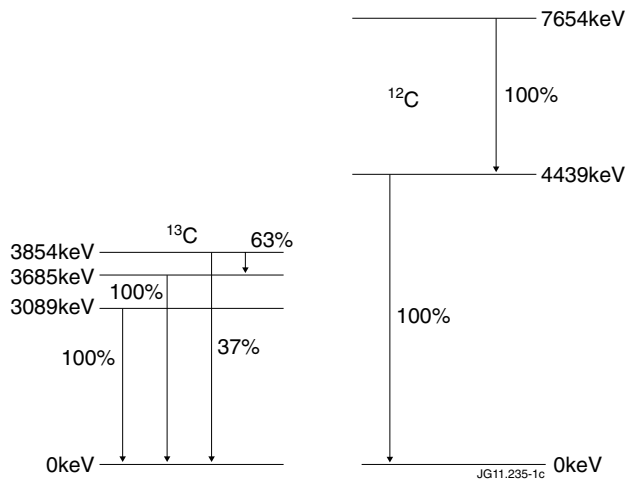


Figure 1: Level scheme of the ^{13}C and ^{12}C γ emitting nuclei produced in the $^{12}\text{C}(d, p\gamma)^{13}\text{C}$ and $^9\text{Be}(\alpha, n\gamma)^{12}\text{C}$ reactions.

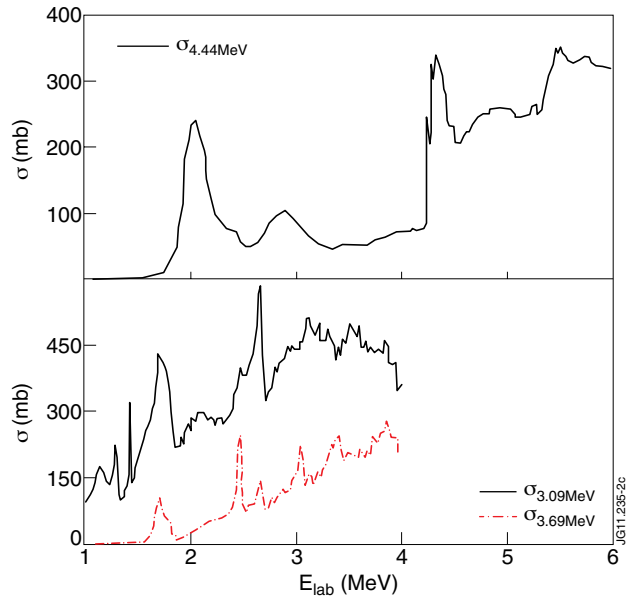


Figure 2: Cross section for the production of γ -rays at energies $E_\gamma = 4.44\text{MeV}$ (top, $^9\text{Be}(\alpha, n\gamma)^{12}\text{C}$ reaction), $E_\gamma = 3.09\text{MeV}$ and 3.69MeV (bottom, $^{12}\text{C}(d, p\gamma)^{13}\text{C}$ reaction) as a function of the light ion energy in the laboratory frame. The values shown are weighted by the branching ratios of figure 1.

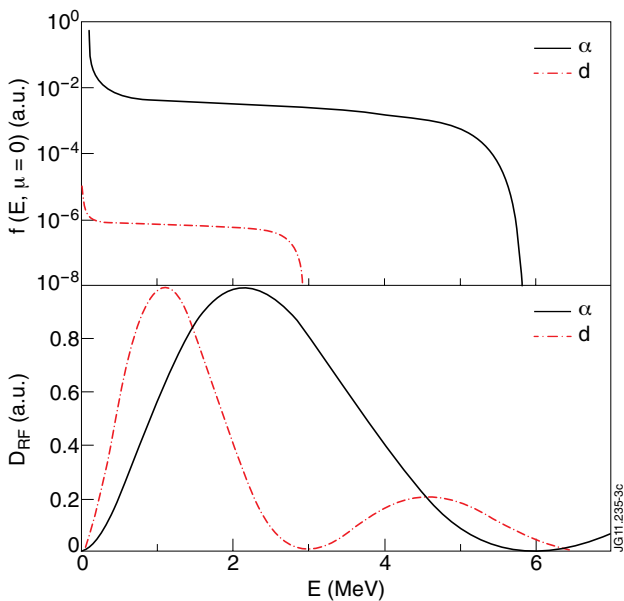


Figure 3: Calculated perpendicular ($\mu=0$) energy distribution for deuterons and ^4He ions accelerated at the third harmonic as described in the text (top) and corresponding RF diffusion coefficient D_{RF} (bottom). Coupled power densities $P_{RF} = 5 \times 10^5 \text{W/m}^3$ and $5 \times 10^3 \text{W/m}^3$ are assumed for ^4He ions and deuterons respectively.

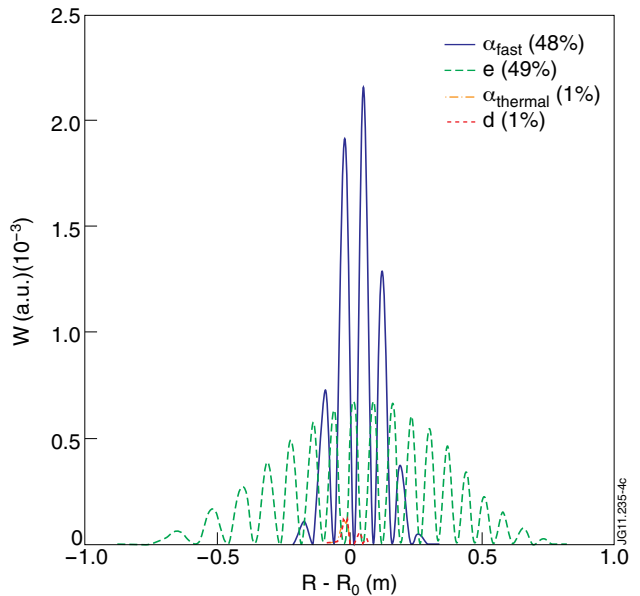


Figure 4: Single pass wave absorption simulated with the TOMCAT code for a $(D)^4\text{He}$ plasma with ^4He neutral beam injection. The beam was represented in the code as a $T_\alpha = 50\text{keV}$ Maxwellian with 6% concentration. The power fractions absorbed by the different species are written in parentheses.

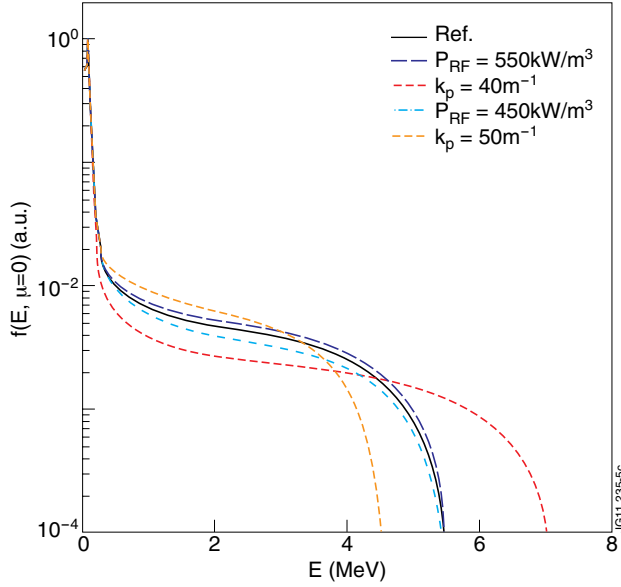


Figure 5: Changes in the ^4He ion perpendicular energy distribution by variations of the coupled power density P_{RF} and perpendicular wave number k_p of $\pm 10\%$ around reference values.

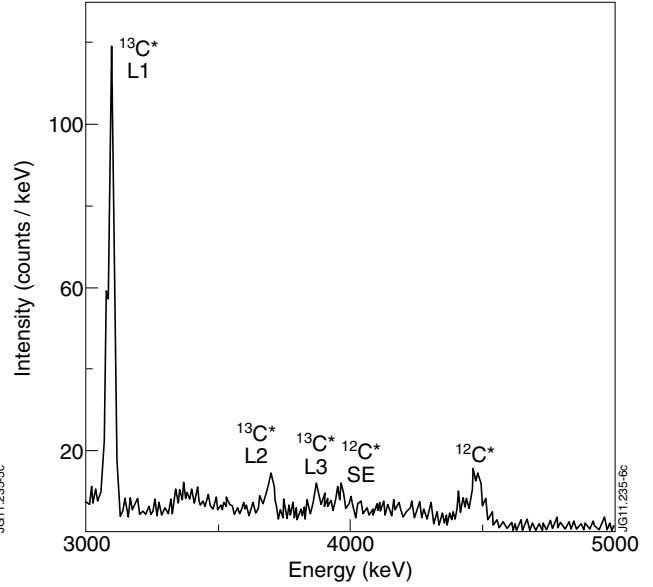


Figure 6: γ -ray emission spectrum recorded with a HpGe detector for the sum of JET Pulse No: 79168-79171 in the time window 12-17s. Labels indicate peaks from different excited states of $^{13}\text{C}^*$ (L1-L3) and $^{12}\text{C}^*$, the latter also with its Single Escape (SE) peak.

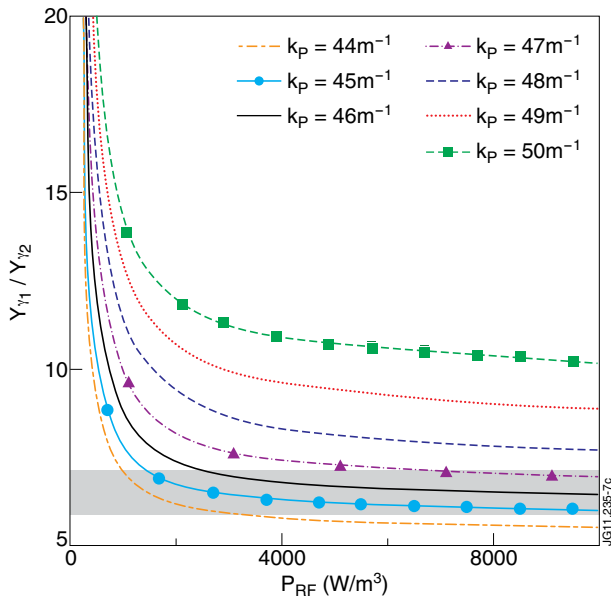


Figure 7: Calculated peak ratio $r = Y_{\gamma_1} / Y_{\gamma_2}$ between the first and second level of $^{13}\text{C}^*$ as a function of the perpendicular wave number k_p and coupled power density P_{RF} of the deuteron energy distribution. The shadowed bar represents the measured value with its uncertainty.

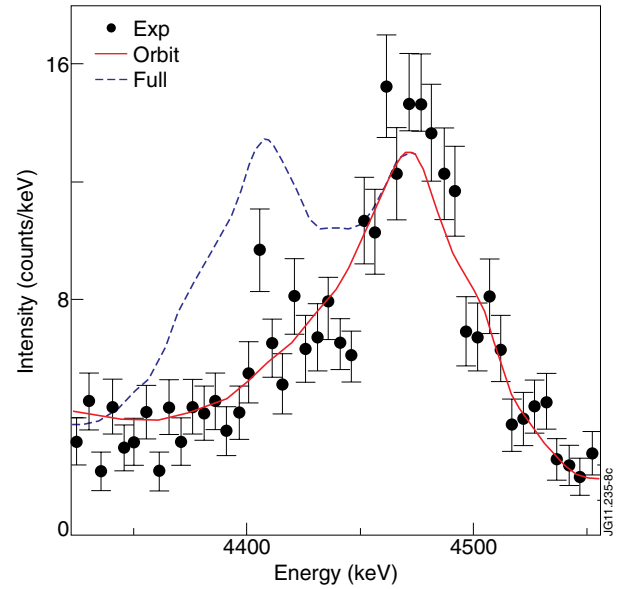


Figure 8: Doppler broadened $E_\gamma = 4.44\text{MeV}$ peak from the $^9\text{Be}(\alpha, n\gamma)^{12}\text{C}$ reaction as measured with the HpGe detector for the sum of JET Pulse No's: 79168-79171 in the time window 12-17s. The curves are the result of Monte Carlo simulations with the GENESIS code with (solid line) and without (dashed line) correlation between the gyro-radius of ^4He ions and the width of the line of sight.

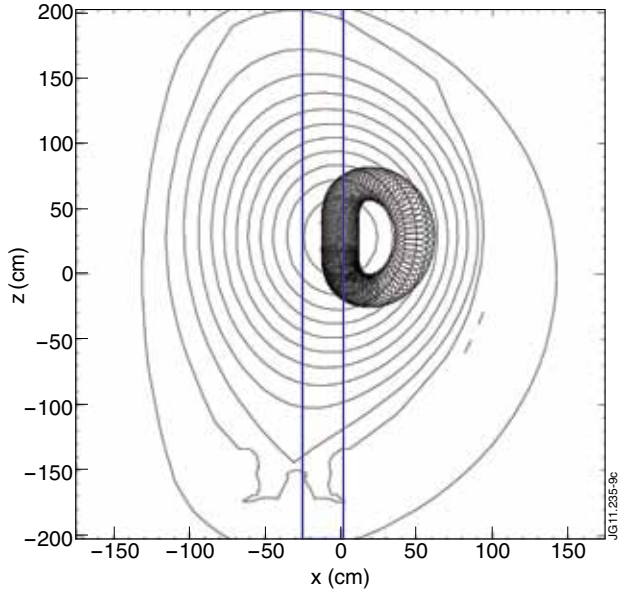


Figure 9: Orbit of a $4\text{MeV } ^4\text{He}$ ion projected onto the poloidal plane. The particle is originated on the magnetic axis ($z = 0\text{ cm}$, $x = 0\text{ cm}$) with pitch angle of 90° . The rectangle represents the detector line of sight.

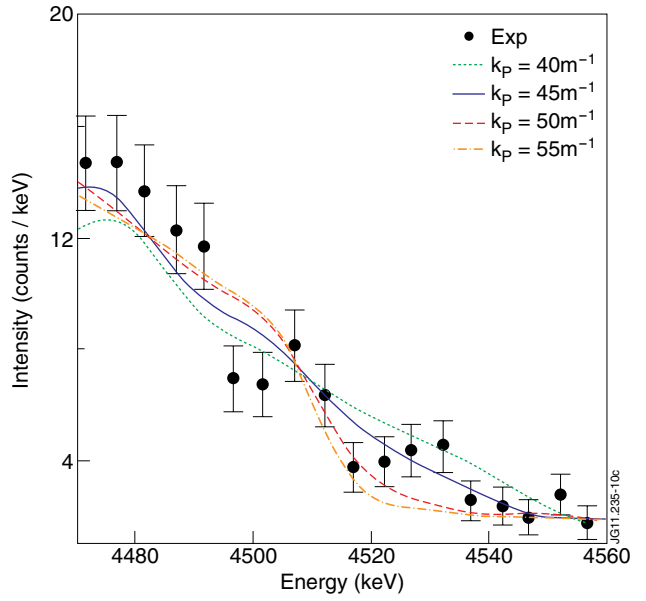


Figure 10: Upper half of the $E_\gamma = 4.44\text{MeV}$ peak from the $^9\text{Be}(\alpha, n)^{12}\text{C}$ reaction and simulations with the GENESIS Monte Carlo code for several values of the perpendicular wave number k_\perp .

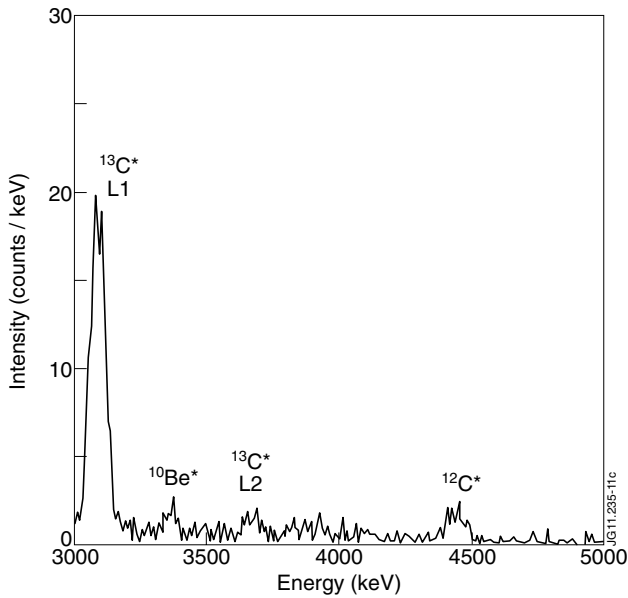


Figure 11: γ -ray emission spectrum recorded with a LaBr3(Ce) detector for JET Pulse No: 79174 in the time window 4-8 s. Shown are peaks from different excited states of $^{13}\text{C}^*$ (L1 and L2) as well as peaks from $^{12}\text{C}^*$ and $^{10}\text{Be}^*$.

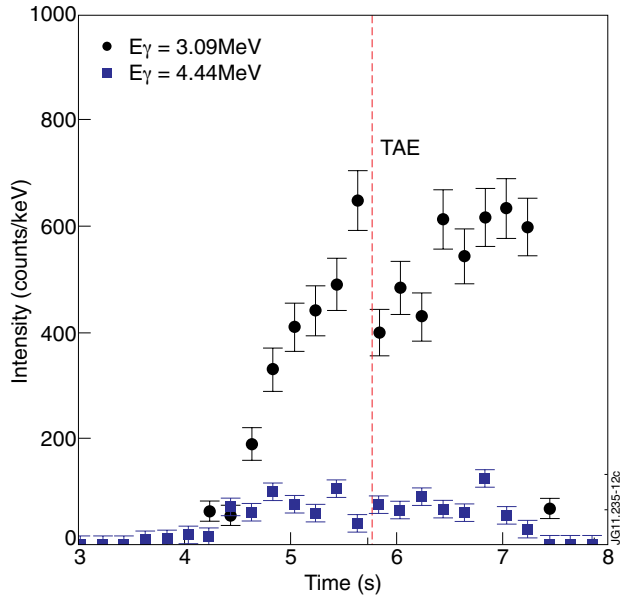


Figure 12: Count rates of the $E_\gamma = 3.09\text{MeV}$ and $E_\gamma = 4.44\text{MeV}$ peaks from the $^{12}\text{C}(d, p\gamma)^{13}\text{C}$ and $^9\text{Be}(\alpha, n\gamma)^{12}\text{C}$ reactions measured for Pulse No: 79174. The vertical dashed line represents the instant when a Toroidal Alfvén Eigenmode (TAE) was detected in the magnetic traces.

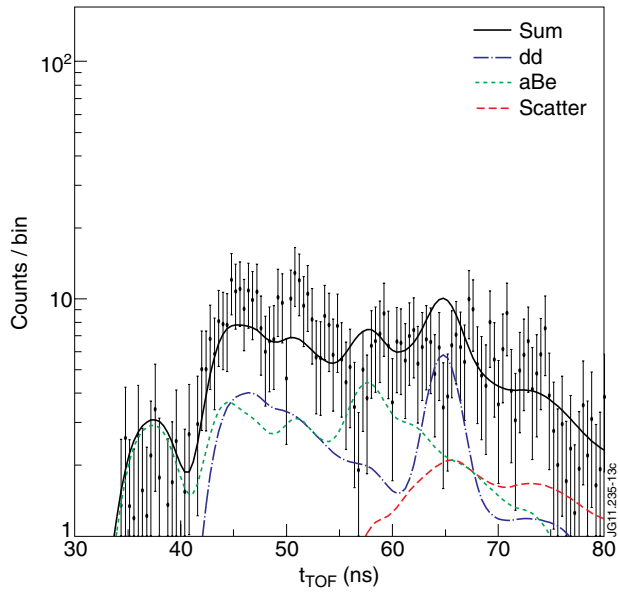


Figure 13: Neutron spectrum measured with the TOFOR spectrometer for the sum of JET Pulse No: 79168-79171 in the time interval 12 to 17s. The curves are simulations of the expected $d + d \rightarrow n + {}^3\text{He}$ (long dash) and $\alpha + {}^9\text{B} \rightarrow n + {}^{12}\text{C}$ (short dash) neutron spectra, plus a scatter component (dash-dotted) taking into account neutron diffusion from the tokamak walls.

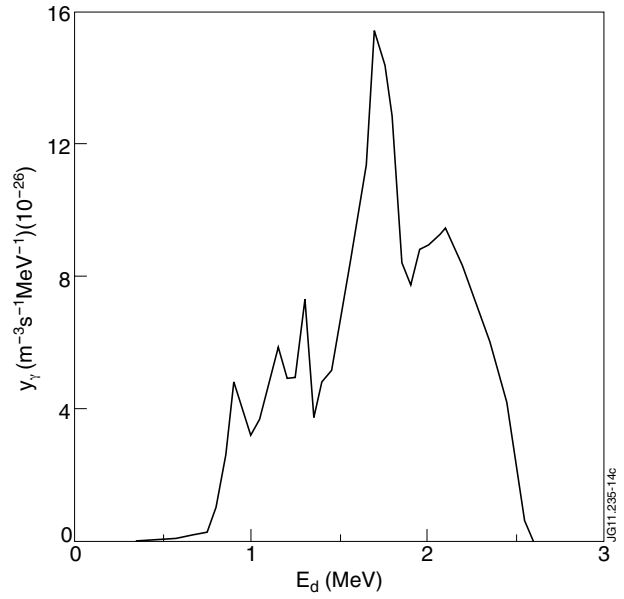


Figure 14: Differential reactivity for the production of $E_\gamma = 3.09\text{MeV}$ γ -rays from the ${}^{12}\text{C}(d, p\gamma){}^{13}\text{C}$ reaction for third harmonic RF heating and parameters described in the text.