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Gamma-Diagnostics of Alpha-Particles in ^{4}He and D-T Plasmas

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ABSTRACT

This article reports on γ-ray diagnosis of ICRF-accelerated ^{4}He-ions and fusion α-particles used for the first time in the JET tokamak. This diagnostic based on the analysis of γ-rays emitted in nuclear reaction ^{9}Be(α,nγ)^{12}C. Doppler broadening effects which could be used for the fast ^{4}He-ion diagnosis with high energy resolution γ-ray detectors are discussed. Assessments of the diagnostic application of other nuclear reactions are presented. Capabilities of the γ-ray measurements in next step D-T devices are discussed.

1. INTRODUCTION

Nuclear reaction γ-ray diagnosis is one of the important techniques used in the JET tokamak for studying fast ions [1]. The intense γ-ray emission is produced in JET plasma when fast ions (ICRF-driven ions, fusion products, NBI-injected ions) react either with fuel ions or with the main plasma impurities such as carbon and beryllium. Gamma-ray energy spectra recorded with collimated spectrometers and the γ-ray emission radial profiles measured with the JET neutron/gamma profile monitor [2] provide information on the spatial distribution of fast ions, their tail temperature and, in some cases, indicate the reactions contributing to the total neutron yield [3].

In this article, the α-particle diagnostic technique based on the nuclear reaction ^9B_e(α,nγ)^{12}C between confined α-particles and the beryllium impurity typically present in plasmas is examined [4]. The γ-radiation due to the reaction ^9B_e(α,nγ)^{12}C has been observed for the first time in JET experiments with the third harmonic ICRF heating of ^{4}He beam ions in a ^{4}He plasma [5] and in D-T plasmas for a-particles. In the ^{4}He-experiment the possibility of simulating fusion-born a-particles in the non-activating plasmas has been demonstrated. The use of the reaction ^9B_e(α,nγ)^{12}C for the α-particle investigation in the D-T reactor plasmas and, in particular, the γ-ray profile measurements can provide information on the 3.5-MeV a-particle source and the spatial distribution of confined alphas with the energy above 2 MeV. Further development of this diagnostic technique is discussed, showing the feasibility of using high resolution spectrometry to provide the Doppler shape spectrum analysis to deduce information on the pitch-angle distribution of the ICRF-accelerated ^{4}He-ions. Use of the nuclear reactions ^{6,7}Li(α,γ)1^{0,11}B and ^{10}B(α,pγ)^{13}C for the ^{4}He and α-particle measurements [6, 7, 8], is also considered.

The paper is organised as follows. In section 2 we describe experimental equipment and analysis technique used in recent measurements. In section 3, results of γ-ray measurements in ^{4}He-experiments and D-T plasmas performed at JET are presented, as well as further proposals on the γ-ray measurements in D-T reactor plasma experiments are given. The use of Doppler broadening effects for fast ion diagnosis with high energy resolution detectors is presented in Section 4. Capabilities of the application of other diagnostic nuclear reactions are assessed in section 5.

2. EXPERIMENTAL EQUIPMENT AND ANALYSIS

On JET, γ-ray energy spectra are measured with a calibrated bismuth germanate (BGO) scintillation detector which is located in a well-shielded bunker and which views the plasma tangentially. For the neutron flux and the γ-ray background suppression, the collimator is filled to a depth of 500 mm with polythene. There is an additional 1000-mm long dump of polythene and lead behind the detector. The detector line-of-sight lies in a horizontal plane about 30 cm below the plasma magnetic axis. The γ-rays are recorded in the energy range 1-28 MeV, with the energy resolution of about 4% at 10 MeV. The spatial distribution of γ-ray emission sources in the plasma is measured using the JET neutron/gamma profile monitor, which is routinely used for the neutron measurements [9]. The monitor consists of two cameras, vertical and horizontal, with 9 and 10 lines-of-sight, respectively. The radiation detectors are NE213 liquid scintillators. Though the JET profile monitor was developed for neutron measurements [9], in some low-neutron discharges with ICRF-only heating the γ-ray measurements are possible by using the differences in pulse shapes that are produced by neutrons and γ-rays. The standard pulse-shape-discrimination electronic modules were set up to restrict the detection of the γ-ray emission to the energy range 1.8-6 MeV.

For identification of the fast particles which exist in the plasma and produce the observed γ-ray emission, and in order to assess the effective tail temperatures of these fast ions, the γ-ray spectrum modelling code, GAMMOD, [1] has been used. This programme is based on the known nuclear reaction cross-sections and contains information on about hundred γ-ray transitions in the final nuclei of the low-Z impurity reactions, and includes the γ-ray response function calculated for the BGO spectrometer. A Maxwellian energy distribution is used to describe the line-of-sight averaged tail of ICRF-accelerated ions. The GAMMOD code analysis gives the effective tail temperatures, the fast ion concentrations and the contribution to the neutron yield from the fast particle-induced reactions.

3. GAMMA-RAY MEASUREMENTS IN JET

3.1 RECENT RESULTS ON γ-RAY OBSERVATION OF 4HE-IONS

In the JET experiment with the third harmonic ICRH heating of ^{4}He beam in ^{4}He plasma ($\omega=3\omega_{4He}$), [5] the g-radiation due to the reaction ^{9}Be(α,nγ)^{12}C has been observed for the first time. It was found that the ICRF waves accelerate the ^{4}He beam ions up to the energies in excess of 2 MeV. Heretofore, diagnostic capabilities of the reaction ^{9}Be(α,nγ)^{12}C have been investigated in detail for the fusion α-particle measurements.[4] This is of a type of resonant reaction, which has thresholds for monochromatic γ-ray emissions. Figure 1 shows the reaction excitation functions of the first two levels in the final nucleus ^{12}C. The presence of the 4.44-MeV peak in γ-ray spectra is evidence for the existence of alphas with energies that exceed 2 MeV. The 3.21-MeV γ-rays indicate that the alphas with energies in excess of 4 MeV exist in the plasma. A typical measured γ-ray spectrum is presented in Fig.2. The spectrum modelling performed by means of GAMMOD gives the effective temperature of He-ion tail $\langle T_{eff} \rangle$ ~1 MeV. It is seen from the spectral decomposition given in Fig.2 that the ^{4}He ion tail is sufficiently energetic and produces the 3.21-MeV radiation due to decay of the second excited state of the nucleus ^{12}C. These measurements also indicate surprisingly strong γ-ray emission from the reaction $^{12}C(d,p\gamma)^{13}C$. This fact means that some ICRF power was absorbed by deuterons at the third harmonic D resonance, which coincides with the third harmonic ^4He resonance. According to the GAMMOD analysis, the effective temperature of fast deuterons in the ^4He-discharges was around $\langle T_{eff} \rangle \approx 0.4$ MeV. In this discharge, the fast D component is roughly 3% of the fast ^4He ion component, but the accelerated deuterons provide rather high yield of the reaction $^{12}C(d,p\gamma)^{13}C$ due to the ratio of impurity concentrations, $^9Be/^{12}C$, which is about 1.5%. Furthermore, according to GAMMOD, around 90% of the neutron yield was from D-D fusion, and the rest of the neutron production is due to the reaction $^9Be(\alpha,n\gamma)^{12}C$.

Recently, a capability of γ-ray emission profile measurements during the study of the ICRF-induced pinch of resonating ^3He minority ions in ^4He-plasmas has been illustrated.[1] In these plasmas toroidally asymmetric ICRF waves were used to modify the orbits and the radial profile of the fast ^3He ions. In this paper we used the same technique to study the fast particle spatial distribution in the $3\omega_{4He}$-experiment. Figure 3 shows signals describing the Pulse No: 54168, where a 'monster'-sawtooth activity during t=18-19s and shorter-period sawteeth during the rest of the shot can be seen from the $T_e(0)$ time evolution. A difference in the fast particle profiles during two types of sawtooth activity in the discharge has been observed. As seen from Fig.4 with the γ-ray emission count-rate measured by the horizontal and vertical cameras, the profile averaged over time interval t=20-21 s is broader and somewhat shifted to the low field side. According to spectroscopic measurements, the radiation recorded by cameras consist of contributions from the reactions $^{12}C(d,pg)^{13}C$ and $^9Be(\alpha,n\gamma)^{12}C$. Consequently, the profiles reflect the spatial distribution of fast deuterons and fast a-particles. In spite of the fact that the concentration of deuterons is a few percent of the alphas, the larger abundance of carbon relative to Be impurity magnifies the component of the γ-radiation from ^{13}C.

3.2 GAMMA-RAY OBSERVATION OF FUSION α-PARTICLES

Analysis of results obtained during JET Deuterium-Tritium Experiment (DTE1) has shown that, in spite of high flux of the 14-MeV neutrons, the BGO-spectrometer installed at JET can be used without radiation shield modifications for γ-ray diagnosis of some special discharge scenarios with neutron rate below 10^{17} s^{-1}, for example, high power ICRF heating of a hydrogen minority ion species in tritium plasmas.[3] Here, we report the first observation of the 4.44-MeV g-radiation due to the reaction $^9Be(\alpha,n\gamma)^{12}C$ and 17-MeV γ-rays from $D(t,\gamma)^5He$ in JET DTE1 experiments. Figure 5 shows the spectra recorded in deuterium Pulse No: 43057 with ICRF heating of tritium minority ($\omega \approx \omega_{cT}$). The main challenge in these measurements is to separate 4.44-MeV γ-rays from the $^9Be(\alpha,n\gamma)^{12}C$ and a background 4.44-MeV inelastic neutron scattering, $^{12}C(n,n_1\gamma)^{12}C$, which take place due to using a polyethylene neutron attenuator in the collimator. The background contribution from the reaction $^{12}C(n,n_1\gamma)^{12}C$ was deduced by means of analysis of the neutron capture reaction H(n, γ)D, which take place in the neutron attenuator. Figure 6 shows the change of the relative rate of the $^9Be(\alpha,n\gamma)^{12}C$ reaction with increasing of 14-MeV neutron rate, which is identical to the fusion α-particle birth rate. The growth of the 4.44-gamma-ray intensity indicates the rise of the α-particle density in the energy range above 2 MeV due to slowing down of the confined fusion-born α-particles.

The γ-ray diagnostics based on the reaction $^{9}Be(\alpha,n\gamma)^{12}C$ could provide crucial information on behaviour of the fusion a-particles in next step D-T plasmas. The main idea of the technique consists of a comparison of profiles both the 3.5-MeV α-particle birth profile and profile of the confined α-particles slowed-down up to 2 MeV. This experiment can be performed with dedicated γ-ray profile camera, which is similar to the neutron/gamma camera operated now at JET. For time-resolved profile measurements, efficient γ-ray spectrometers and neutron attenuators, in each channel of the cameras, are needed. General requirements to the spectrometers are the high efficiency and peak-to-background ratio. It could be a spectrometer like GAMMACELL[11] based on the high radiation resistant Ba_2F-scintillators which allows measurements of γ-rays in energy range 1-30 MeV. The feasibility of the measurements also depends on the quality of neutron suppression of the collimators. A simple neutron filter without a carbon content is water, but this attenuator will be activated by 14-MeV neutrons, and 6.13-MeV γ-ray background will be unwelcome. A more convenient neutron filter is based on ^{6}LiH. It is compact, effective and transparent for γ-rays, and it does not produce interfering γ-rays in the high energy range. A 30-cm sample of the ^{6}LiH-filter reduces 2.4-MeV neutron flux to ~900 times and the 15-MeV neutron flux to ~30 times [12]. Gamma-ray cameras with such neutron filters seem to be a best candidate for measuring of γ-ray spectra in the presence of high neutron fluxes typical for DT-reactor plasmas.

4. CAPABILITIES OF HIGH ENERGY RESOLUTION γ-SPECTROSCOPY

The specific nuclear reaction mechanism of $^{9}Be(\alpha,n\gamma)^{12}C$ and the possibility of measuring the distortion of the 4.44-MeV γ-line in spectrum by the Doppler effect, using high energy resolution detectors, opens new capabilities of γ-diagnostics for the fast α-particle study in ^{4}He or other low-activated plasmas. An in-beam study of this reaction has demonstrated that the Doppler shape of the γ-line depends on the α-particle energy and parameters of the n-γ angular correlation, which are also energy dependent. The energy of γ-rays, ε_r, radiated by the moving nucleus can be expressed as

$$\varepsilon_\gamma \approx \varepsilon_\gamma^0 (1 + \frac{V_{13}}{c} \cos \theta_\alpha - \frac{V_{12}}{c} \cos \phi_n)$$

where ε_γ^0 is energy of the γ-ray transition in the final nucleus which is equal to 4.438 MeV in this particular case, V_{13} is a velocity of compound nucleus due to the reaction $^{9}Be\ \alpha \rightarrow {}^{13}C$, V_{12} is the final nucleus velocity in centre-of-mass system after neutron decay reaction $^{13}C \rightarrow {}^{12}C + n, \theta_\alpha$ is an angle between the α-particle velocity vector $\vec{\upsilon_\alpha}$ and the axis of collimated detector, θ_n is the angle between the vector $\vec{\upsilon_\alpha}$ and the velocity vector of escaped neutron, $\vec{\upsilon_\alpha}$. The velocity of the target,

^{9}Be, can be neglected in this analysis.

As an illustration of the Doppler effect scale, Fig.7 presents typical spectra of the 4.44-MeV γ-rays recorded with 0.4% energy resolution high-purity Ge-detector (HPGe), which was placed at 0^o angle respect to the α-particle mono-energetic beam. In the plasma experiment, velocities of the recoil nuclei are between 2% and 4% of the speed of light is equivalent to ~ 90 keV.

In an ICRF heated plasma, the α-particle distribution function $F(E_\alpha,\theta_\alpha)$of accelerated ^{4}He fast ions is anisotropic and γ-ray spectrum can be expressed by

$$S(\varepsilon_\gamma) \propto \iint F(E_\alpha, \theta_\alpha)\, \sigma(E_\alpha)\, \upsilon_\alpha\, R(\varepsilon_\gamma, E_\alpha, \theta_\alpha) \sin\theta_\alpha d\theta_\alpha dE_\alpha$$

where $\sigma(E_\alpha)$ is a reaction cross section, and $R(\varepsilon_\gamma, E_\alpha, \theta_\alpha)$is complex response function which contains the elementary γ-line shape functions, depending on E_α and θ_α. Doppler shape analysis of the 4.44-MeV γ-line can provide information on both tail temperature and pitch angle distribution of the fast α-particles. It is necessary to note that the γ-line energy profiles have to be recorded by at least two spectrometers, whose lines-of-sight are in perpendicular planes. In particularly, the spectrum measured with a detector observing plasma in the tangential direction relative to toroidal magnetic field, is sensitive to both the parallel, υ_α^{II} , and the perpendicular, $\upsilon_\alpha^{\perp}$, components of the α-particle velocity. The value of υ_α^{II} is responsible for the energy shift of the γ-line, while component $\upsilon_\alpha^{\perp}$ provides its broadening. The measurement of γ-rays in the vertical direction, which is perpendicular to equatorial plane, of the Doppler shape of the γ-line provides only information on value of $\upsilon_\alpha^{\perp}$ and is not sensitive to the value of υ_α^{II} .

5. OTHER NUCLEAR REACTIONS FOR THE α -DIAGNOSTICS

Another nuclear reaction which could be useful for the α-particle measurements is $^{10}B(\alpha,p\gamma)^{13}C$. The strong population of the first three levels in ^{13}C, 3.09 MeV, 3.68 MeV and 3.85 MeV, gives a possibility to use this reaction for the study of the fast α-particle distribution function. The cross sections of the reaction are roughly three times lower than in the case of reaction with ^{9}Be, however the reaction $^{10}B(\alpha,p\gamma)^{13}C$ has the capability for tail measurements due to the different population features of the ^{13}C levels. It is necessary to note that this reaction is especially useful in the high resolution measurements in the ^{4}He plasma with ICRF heating. In-beam investigation of the reaction $^{10}B(\alpha,p\gamma)^{13}C$ has found that all three γ-lines have unique energy dependent Doppler shapes due to differences of p-γ angular correlation functions.[8] For example, Fig.8 shows Doppler shapes of the 3.85-MeV γ-line recorded at three different value of the α-particle beam energy.

Resonance capture reactions are another type of nuclear reactions, which can be used for the α-particle investigation in ^{4}He plasmas. The cross section for the resonant reaction as a function of the reaction energy is given by the Breit-Wigner formula:

$$\sigma(E) \propto \pi\lambda^2 \frac{\Gamma_\alpha\Gamma_\gamma}{(E - E_R)^2 + \Gamma^2 / 4} ,$$

where $\lambda = h / (2\mu E)^{1/2}$ is the reduced de Broglie wavelength, μ is the reduced mass of the reactants in amu, E_R is the resonance energy in the centre-of-mass system, Γ_α is the partial width for the reemission of α-particle (elastic scattering) and Γ_γ is the partial width for the γ-emission. $\Gamma = \Gamma_\alpha + \Gamma_\gamma + ...$ (all other possible decay channels) is the total width of the resonant state. The total cross section of any capture reaction, in general, consists of narrow resonances superposed on a continuum which is a smoothly rising function of energy due to direct capture reactions. At low energies, the cross section of direct capture reactions is determined by the Coulomb barrier penetration factor and can be express as:

$$\sigma (E) \propto \frac{1}{E} \exp [-(E_G / E)^{1/2}]$$

with the Gamow energy E_G given by : $E_G + 0.979\mu\, Z_1^2 Z_2^2$ (MeV), where Z_1, Z_2 are the atomic numbers of the reacting nuclei.

The γ-ray energy spectrum is proportional to the product of the reaction cross-section and the α-particle energy distribution. A narrow resonance in the cross-section gives rise to a narrow γ-ray peak in the spectrum, whose intensity is proportional to the density of α-particles with the energy corresponding to E_R. If the plasma contains target nuclei with which the α-particles undergo a series of resonances, the intensities of different γ-ray peaks give densities of the α-particles at the corresponding resonance energies. An analysis of nuclear reactions shows that from the diagnostic point of view the useful resonances of α-particles with low Z-elements are ^{6}Li+α and ^{7}Li+α resonances.[6,7] The feasibility of this diagnostic in the ^{4}He-plasma experiment depends on the ICRF heating efficiency to produce the fast α-particle density in plasmas and the Li concentration, which would be sufficient for the γ-ray measurements. For the conditions in Pulse No: 54168 and ^{6,7}Li concentrations adopted to 1%, the rates of the reactions are calculated and listed in the Table. Only a few of the examined resonances could be used for diagnostics because of low reaction rates. It should be noted that the narrow resonances populated in reactions^{6,7} Li(α,γ)^{10,11}B are useful for Doppler shape analysis. An asymmetric shape of the recorded γ-line indicates the anisotropic velocity distribution and can provide information on the $\upsilon_\alpha^{II} / \upsilon_\alpha^{\perp}$ ratio.

6. SUMMARY AND CONCLUSIONS

In this paper, the α-particle diagnostic based on the nuclear reaction ^{9}Be(α,nγ)^{12}C which has been successfully tested on JET is described. The γ-radiation due to the reaction ^{9}Be(α,nγ)^{12}C has been observed in JET experiments with the third harmonic heating of ^{4}He beam ions and in D-T experiments. The ^{4}He-experiment demonstrated the possibility of simulating of fusion-born α-particles in the non-activated plasma. In the D-T plasmas, the γ-ray profile measurement may provide information on the 3.5-MeV α-particle source and the spatial distribution of the confined alphas with energy above 2 MeV. A multicollimator γ-ray spectrometer array with the neutron attenuators are required to obtain the fusion α-particle profiles in D-T reactor plasmas. Capabilities of the Doppler shape analysis, using high resolution spectrometry, which can provide information on the pitch-angle distribution of the ICRF-accelerated ^{4}He-ions, have been illustrated. The application of the other nuclear reactions, ^{6,7}Li(α,γ)^{10,11}B, ^{10}B(α,pγ)^{13}C, for a-particle measurements has been discussed.

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Reaction	ER (Lab), MeV	ε_γ, MeV	Γ, KeV	Reaction Rate, $cm^{-3}\ s^{-1}$
$^{6}Li(\alpha,\gamma)^{10}B$	0.500	4.04	0.0084	4
	1.175	3.02	0.0017	14
	2.435	5.92	6	4
	2.605	6.02	0.048	6
$^{7}Li(\alpha,\gamma)^{11}B$	0.401	8.92	0.0044	1
	0.814	4.74	0.0018	22
	0.953	4.83, 9.27	4	110
	2.500	10.3	430	320

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Table 1: Parameters of resonances in the reactions $^{6,7}Li(\alpha,\gamma)^{10,11}B$.

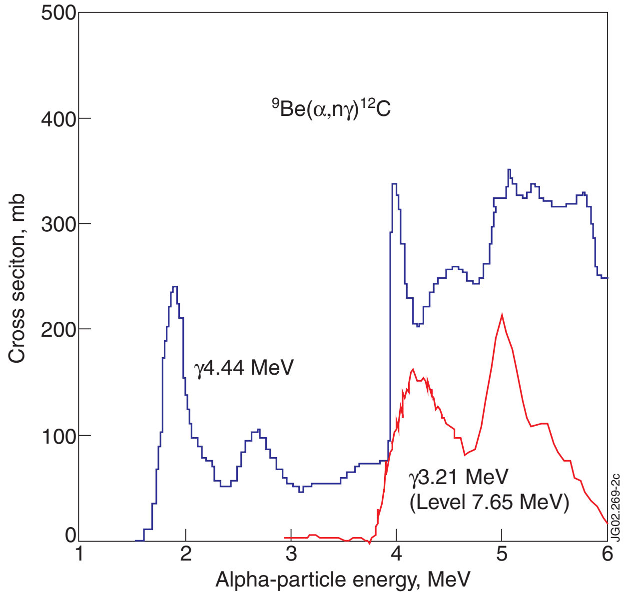


Figure 1: Excitation functions of the first two ^{12}C levels in the reaction $^{9}Be(\alpha,n\gamma)^{12}C$.

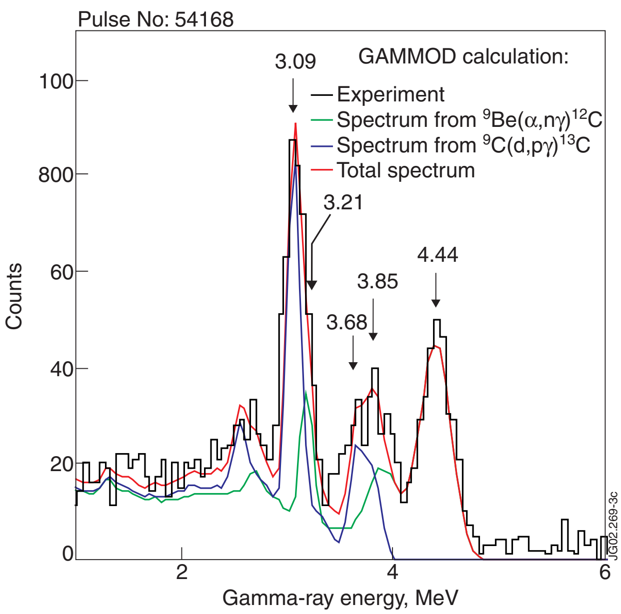


Figure 2: Experimental and calculated by means of GAMMOD γ-ray spectra for the Pulse No: 54168; γ-ray emission lines due to reactions $^{9}Be(\alpha,n\gamma)^{12}C$ and $^{12}C(d,p\gamma)^{13}C$ are clearly identified; calculation was performed with impurity concentration ratio $n_{Be}/n_C \cong$ 1.5%.

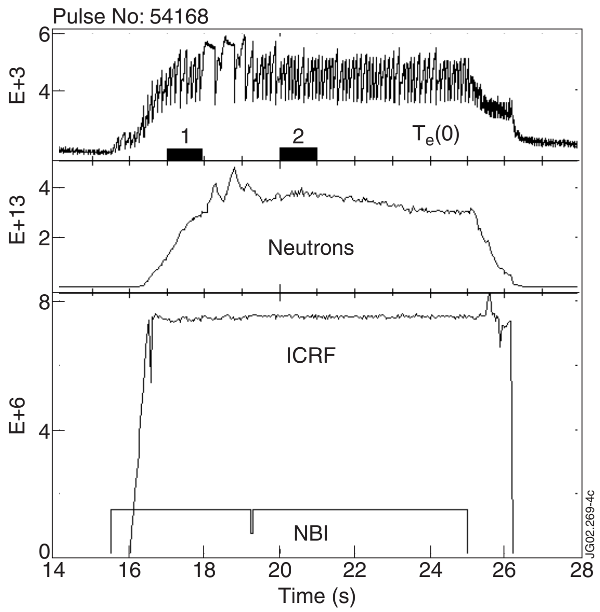


Figure 3: NBI and ICRF power (W), neutron rate (s^{-1}) and $T_e(0)$ (eV) for ^{4}He Pulse No: 54168: $n_e(0) \cong 3\ 10^{19}\ m^{-3}$, ICRF frequency f = 51 MHz (dipole phasing), $P_{ICRF} \cong 8$ MW, relative deuterium density $n_D/n_{4He} \cong 25\%$.

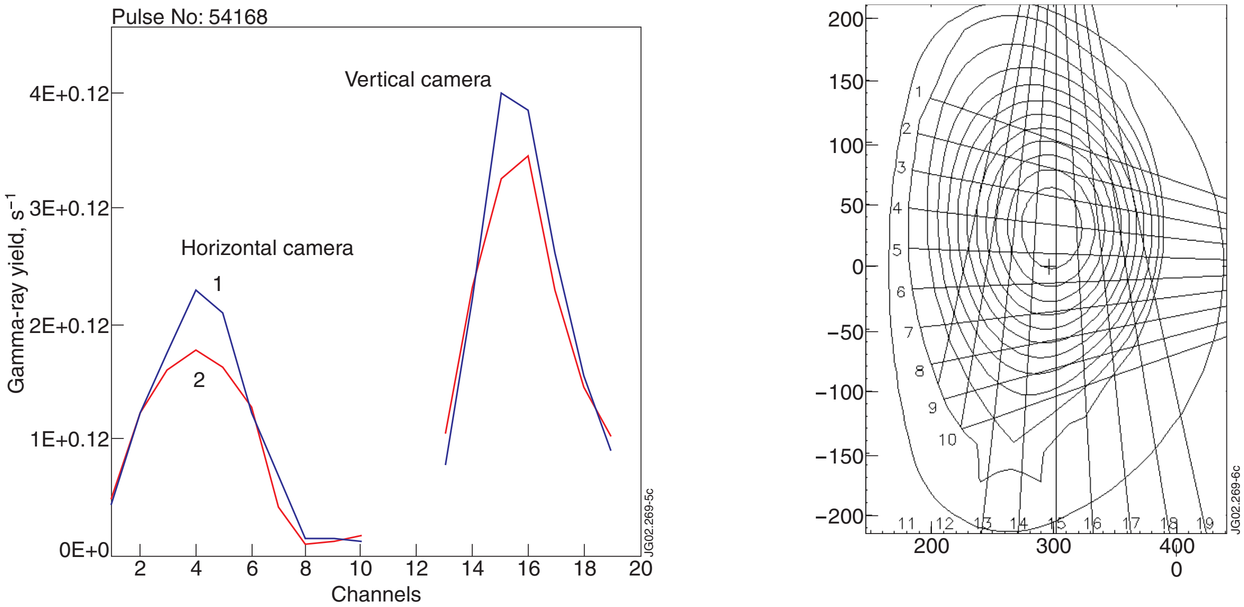


Figure 4: Left: γ-ray emission profiles recorded in Pulse No: 54168; 1- profile related to the time bin shown in Figure 3 as horizontal bar 1; 2- profile related to the time bin 2 Right: lines-of-sight of the JET neutron emission profile monitor used for the spatial γ-ray emissivity measurements.

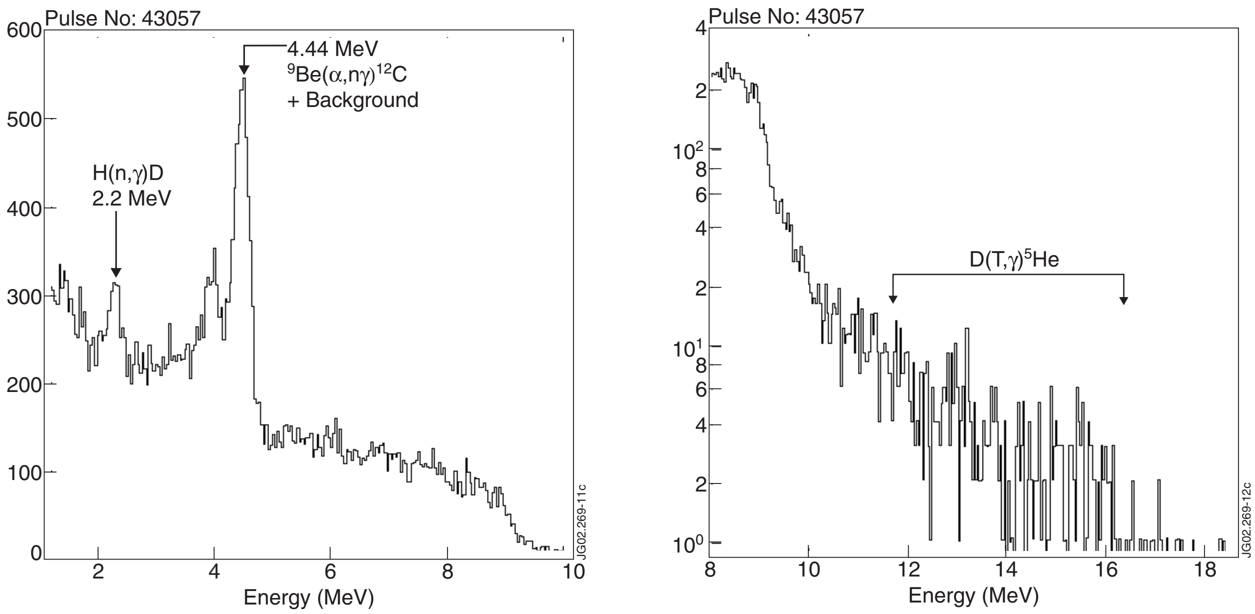
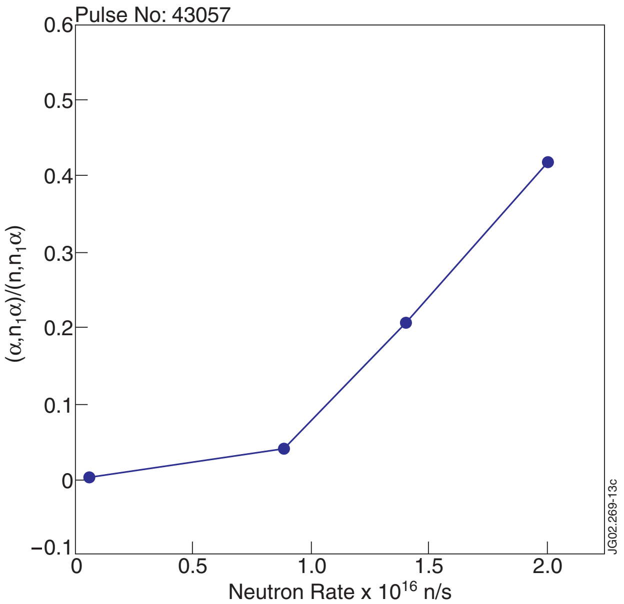


Figure 5: Gamma-ray spectrum measured in Pulse No: 43057: I_p=3.7 MA, B_T=3.87T, f_{RF}=23MHZ, D:T=95: 5. Left: spectrum recorded in the 1-10 MeV energy range; right: spectrum recorded in the 8-18.5 MeV energy range.



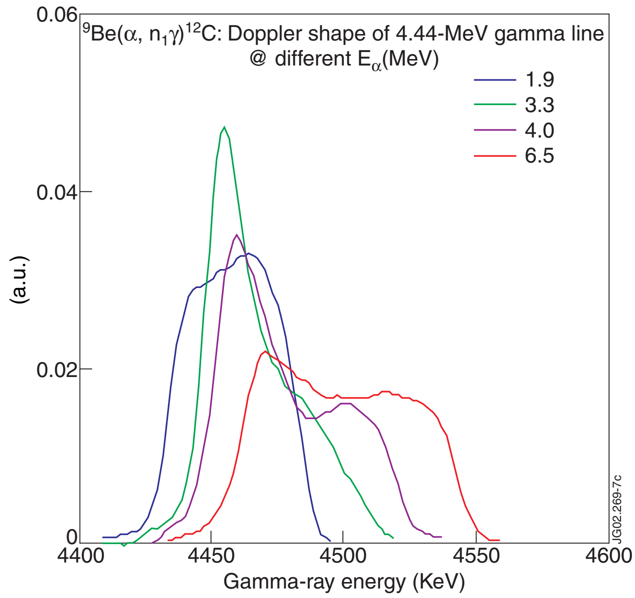


Figure 6: Ratio of 4.44-MeV γ-rays intensity from reaction $^{9}Be(\alpha,n\gamma)^{12}C$ to the intensity of γ-rays produced in the reaction $^{12}C(n,n_1\gamma)^{12}C$ versus the rate of 14-MeV neutrons.

Figure 7: Doppler shapes of the 4.44-MeV γ-line from the reaction $^{9}Be(\alpha,n\gamma)12C$ recorded by HPGe detector at forward angle during in-beam measurements at E_α=1.9, 3.3, 4.0, and 6.5 MeV.[13]

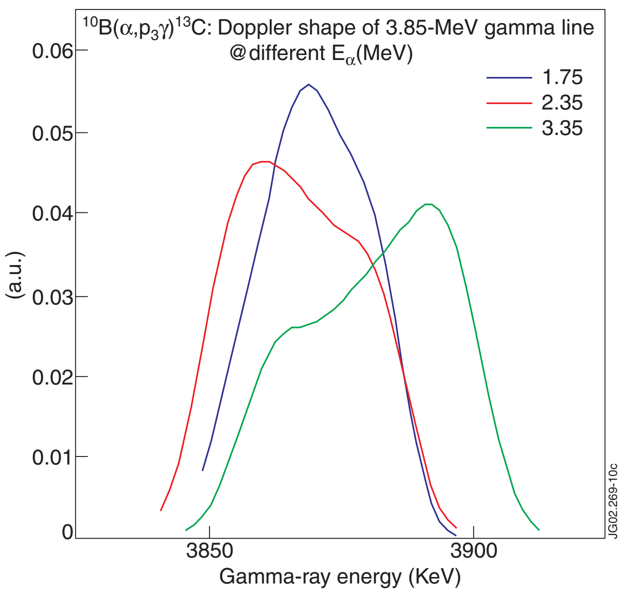


Figure 8: Doppler shapes of the 3.85-MeV γ-ray line from the reaction $^{10}B(\alpha,p\gamma)^{13}C$ recorded by HPGe detector at forward angle during in-beam measurements at E_α=1.75, 2.35, and 3.35 MeV.[8]