*31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, O-1.06 (2004)*

Gamma-Ray Measurements of Fusion Alpha Particles in JET Trace Tritium Experiments

V.G. Kiptily,[1] Yu.F. Baranov,[1] R. Barnsley,[1] L.Bertalot,[2] V. Goloborod'ko,[4,5] N.C. Hawkes,[1] A. Murari,[3] S. Popovichev,[1] S.E. Sharapov,[1] D. Stork,[1] V. Yavorskij [4,5]
and JET-EFDA contributors [6]

[1] *Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxon, OX14 3DB, UK*
[2] *Associazione Euratom/ENEA/CNR sulla Fusione, Frascati, Rome, Italy*
[3] *Consorzio RFX - Associazione Euratom-Enea sulla Fusione, I-35127 Padova, Italy*
[4] *Euratom/OEAW Association, Institute for Theoretical Physics, University of Innsbruck, Austria*
[5] *Institute for Nuclear Research, Kiev, Ukraine*
[6] *Annex of J. Paméla et al, Fusion Energy 2002, Proc 19th IAEA Fus Energy Conf, Lyon 2002*

This paper presents the details of γ-ray measurements of fusion-born α particles, which were carried out in JET 'trace tritium' discharges, i.e. in majority deuterium plasma after seeding with a small population of tritium Neutral Beam Injection (NBI) fast ions [1]. The γ-ray emission from the nuclear reaction $^{9}Be(\alpha,n\gamma)^{12}C$ is used to measure changes in the density of the fast α particles with energy E_α>1.7 MeV in the post-NBI period. This important diagnostic nuclear reaction has already been applied to detect the presence of the fast α-particles in JET experiments, where ion-cyclotron-resonance heating of ^{4}He-beam ions was used to accelerate ^{4}He to the MeV range [2]. In this paper we demonstrate how a nuclear diagnostic based on the γ-ray spectrometry of the interaction between α's and *Be* impurity in plasmas is used in JET [3] and how it could be used in future magnetic fusion machines to obtain essential information on the slowing down and confinement of the fast α particles.

In the presented JET experiments γ-ray energy spectra are measured with a calibrated bismuth germanate (*BGO*) scintillation detector with diameter of 75 mm and a height of 75 mm. The detector is located in a well-shielded bunker and views the plasma quasi-tangentially. In order to reduce neutron and γ-ray background, the front collimator is filled with polythene to a depth of 0.5 m. Behind the detector there is an additional 1.5-m long dump of polythene and steel. The detector line of sight lies in a horizontal plane about 30 cm below the plasma magnetic axis. During these experiments the γ rays were continuously recorded with integration time 250 ms over the energy range 1-28 MeV, with an energy resolution of about 4% at 10 MeV.

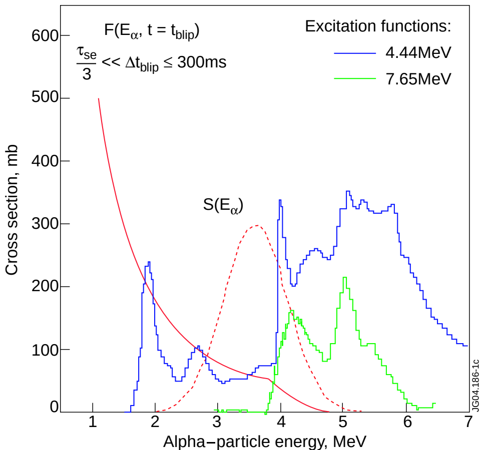

Fig.1. Excitation functions of ^{12}C levels populated in the reaction $^{9}Be(\alpha,n\gamma)^{12}C$. The α-source distribution, $S(E_\alpha)$, was calculated for the 105-keV T-beam injected in D-plasma; $F(E_\alpha,t)$ - steady-state α-particle energy distribution (a.u.).

Diagnostic capabilities of the nuclear reaction $^{9}Be(\alpha,n\gamma)^{12}C$, the significance of which for the fusion α particles has already been reported in [4], are determined by the specific reaction cross-section. The excitation functions of the first two levels of the final nucleus, ^{12}C, populated in this reaction, are shown in Fig.1. Energy thresholds in the cross sections provide the energy selectivity for the α-particle measurements. The first energy level, 4.44 MeV, is excited by α particles with energies exceeding 1.7 MeV, and de-excited emitting 4.44-MeV γ rays. The second one, 7.65 MeV, is populated by α's with energies in excess of 4 MeV, and de-excited emitting 3.21-MeV γ rays.

Clear variations in the intensity of the 4.44-MeV γ-ray emission were observed in the post-beam-blip period of many discharges. Figure 2 shows decays of the 4.44-MeV γ-ray intensity, recorded by the spectrometer in discharges with different NBI heating power. The measured rate of 14-MeV neutrons, which are born during the *T*-beam injection, is shown as well. It is important to note that the main plasma heating (deuterium NBI) is kept constant for several seconds after the *T*-blip, ensuring steady plasma conditions. This applies to all the shots in our database. The γ-ray decays are thus measured against unchanging plasma conditions. In these experiments the duration of *T*-beam blips was $t_{blip} \leq 300$ ms.

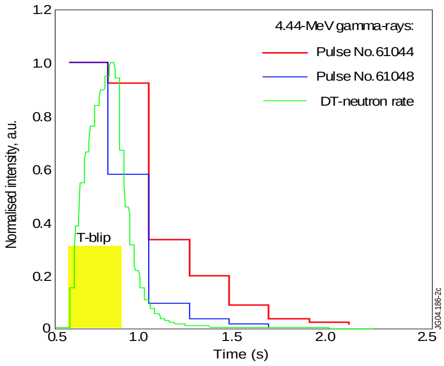

Fig.2. Comparison of evolutions of 4.44-MeV γ-ray emission. Pulse No. 61044: 2.0MA/2.25T, $P_{DNBI} \cong$ 14.5 MW, $T_e(0) \cong 5$ keV. Pulse No. 61048: 2.0MA/2.25T, $P_{DNBI} \cong 2.9$ MW, $T_e(0) \cong 3.5$ keV.

Neutrons with energy that exceeds 5 MeV could give rise to background 4.44-MeV γ rays due to the nuclear inelastic scattering $^{12}C(n,n'\gamma)^{12}C$. The main source of this background γ-ray emission is the polythene plug, which is placed in front of the detector and contains carbon as main chemical element in the compound. Extraction of the neutron background is an important part of the data processing. This factor is the main source of uncertainties in the interpretation of the present measurements.

The variation of the γ-ray intensity after the T-blip, as shown in Fig.2, can be approximated as $I_\gamma(t) \propto \exp(-t/\tau_\gamma)$. The γ rate is $R_\gamma(t) \propto n_{Be} \int F(E_\alpha,t)\sigma(E_\alpha)v_\alpha \, dE_\alpha$, where n_{Be} is the *Be* density in the plasma; $F(E_\alpha,t)$ is the slowing-down energy distribution of α's; $\sigma(E_\alpha)$ is the energy dependence of the reaction cross-section for $^9Be(\alpha,n\gamma)^{12}C$; v_α is α-particle velocity. The distribution function $F(E_\alpha,t)$, which depends also on the slowing down of the T-beam is altered by any non-classical α-losses and other processes, principally, orbit drift. The time variation of the 4.44-MeV γ-ray emission after the end of the T-beam blip was modelled. The modelling revealed that the expected rate $R_\gamma(t)$ was approximately exponential in the case $t_{blip} > \frac{1}{3}\tau_{se} \propto AZ^{-2}T_e(0)^{3/2}/n_e(0)$, where T_e and n_e are the temperature and density of electrons in the plasma centre; A, Z are the atomic and charge numbers of the fast ion. This follows from the fact that the expected distribution function $F(E_\alpha,t)$ is a result of the α-particle slowing down within the T-beam blip and it is therefore can be described by the curve for $t_{blip} >> \tau_{se}/3$ shown in Fig.1. In the case $t_{blip} < \tau_{se}$, the initial α-distribution after the blip and prior to the measurement phase is similar to the α-particle source distribution, which is presented in Fig.1. A simple exponential decay for $R_\gamma(t)$ would not then be observed, but these conditions did not apply in any of the experimental shots studied.

More than 20 discharges were analysed, comparing two parameters: τ_γ - decay time of the 4.44-MeV γ-ray intensity from the reaction $^9Be(\alpha,n\gamma)^{12}C$, and $\tau_\alpha + \tau_T$ - classical slowing-down time of the fast α particles and the beam tritons on electrons, where $\tau_{\alpha,T} = (\tau_{se}/3)\ln\left((E_i^{3/2} + E_c^{3/2})/(E_f^{3/2} + E_c^{3/2})\right)$, $E_c \propto AT_e(0)$ is the so-called 'critical energy'. Results of the comparison of measured τ_γ against calculated classical $\tau_\alpha + \tau_T$ for the plasmas are presented in Fig.3. For the calculation of τ_α, τ_T the slowing down of α-particles from 3.5 MeV to 1.7 MeV and T-beam ions from 105 keV to 40 keV are accepted as possible contributions to the effective decay-time, τ_γ. One can see from the figure that in most of the discharges with toroidal magnetic field and plasma current in the ranges 2.25-

3.2T and 2.0-3.0MA the scaling $\tau_\gamma \geq \tau_\alpha + \tau_T$ is observed. The fact that τ_γ's lies above the estimated values is explained by the broad α-particle source distribution $S(E_\alpha)$ and more complicated link between τ_γ and $\tau_\alpha + \tau_T$. The discharges displaying classical behaviour are all ELMy H-modes with monotonic *q* profiles. Modelling of the fast α-particle slowing-down was performed using the TRANSP code for some discharges. The results of these calculations are in agreement with the experimental data, within the error bars.

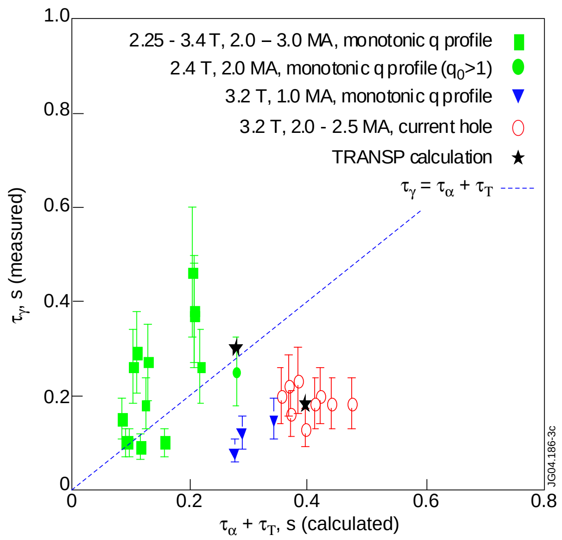

Fig.3. Measured 4.44-MeV γ-ray decay-times for plasma scenarios with: B_T=2.25–3.2 T, I_P=1.0–3.0 MA ; $\tau_\alpha + \tau_T$ – classical slowing-down time of the fast α's and the beam tritons on electrons.

There are two groups of discharges, which do not follow the classical behaviour, i.e. have $\tau_\gamma < \tau_\alpha + \tau_T$. The explanation for the fast decay of the γ-ray emission in low current plasmas is the effect of a poor α-particle confinement due to the significant orbit losses. Our modelling assessments show that a critical plasma current I_{cr} > 1.5-2MA is required to avoid significant first orbit (FO) losses of 3.5-MeV alphas in the discharges with monotonic plasma currents. Therefore, in discharges with I_p^{max} = 1MA the γ-ray decay-times are expected to be lower than $\tau_\alpha + \tau_T$. Another similar anomalous behaviour of the γ-ray emission decay was observed in discharges with current hole profiles. These discharges have strongly reversed magnetic shear in the plasma centre. Measurements based on the motional Stark effect (MSE) [5], show very small central current density in the plasma core area, the so called 'current hole'. The typical size of the current holes in the analysed discharges is around 0.35*a*, where *a* is a minor radius of the plasma. According to the confinement criteria [6], developed for α particles born in a plasma with a current hole, the effect is equivalent to an increase of the critical plasma current needed for confining α's, $I_{cr} \approx 1.5/(1-x_h^{1/2})$(MA), where $x_h = r_h / a$. For the discharges with the current hole as large as $x_h \approx 0.35$ the critical current value is equal to $I_{cr} \approx 3.7$ MA. In the case of discharges with I_p^{max} = 2 – 2.5 MA the FO losses of 3.5-MeV alphas are therefore rather significant, 20-30%. Another factor, which decreases the γ-ray decay-times, is drift of orbits during slowing down. This effect is important because the γ-ray measurements are made with strongly collimated spectrometer. These factors explain the faster observed decay-times of the γ-ray emission measured in the discharges with non-monotonic q-profiles.

In the recent JET experiments the relaxation of the distribution functions of fast ^{4}*He*-ions accelerated with 3rd harmonic ICRH of ^{4}*He*-beam have been simultaneously studied during slowing down in ^{4}*He*-plasma (2.2T/ 2MA, 51 MHz). For the measurements the 4.44-MeV gammas from the reaction ^{9}Be(α,nγ)^{12}C have been used. The *D*-minority ions, which are also accelerated due to parasitic ICRF absorption, give rise to 3.09-MeV γ-rays from the reaction ^{12}C(d,pγ)^{13}C.

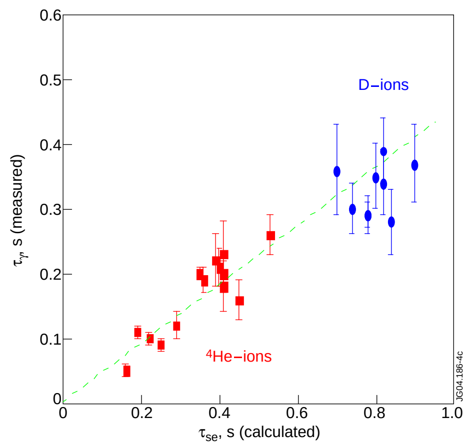

Fig.4. Measured 4.44-MeV and 3.09-MeV γ-ray decay-times for plasma scenario with: B_T=2.2 T, I_P=2.2 MA.

A peak at 3.09 MeV in recorded spectra reflects the presence in the plasma of fast *D*-ions with energies exceeding 0.8 MeV. The γ-ray decay-time for both ions was measured during notches in the ICRH power when the accelerated ion source was strongly reduced. The γ-ray spectra with 100-ms integration time were recorded by means of a NaI-detector, which observes the plasma core through the vertical collimator. Figure 4 presents the measured γ-ray decay-times vs. τ_{se} (as evaluated at t = t_{notch}). The data derived from discharges with monotonic q-profiles. It is seen that the correlation $\tau_\gamma \sim 0.5\tau_{se}$ is observed, which could be explained by tail-like distribution function and $T_e(0)$ decreasing during the notch. An effect of the A/Z^2-factor for the classical slowing-down time is confirmed in these experiments. Furthermore, taking into account the tail-like $F(E_{He}, t)$ function, it is found that ^4He-ions accelerated up to 5 MeV are confined.

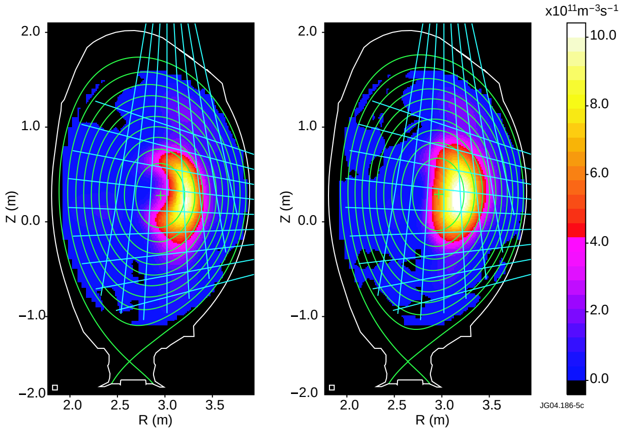

Fig.5. Gamma-ray images of α particles with E_α> 1.7 MeV in 2.2T/2.0MA JET plasmas: left– with monotonic q-profile: right – with strongly reversed magnetic shear.

The first γ-ray images of fast ^4He and *D*-ions are measured with a 2-D multicollimator spectrometer array, called Gamma Camera, distinguishing the *D* and ^4He-ion species in the discharge. The reconstruction of γ-ray emission profiles gives tomographic images of the fast-ion population in poloidal cross-section of JET. For the first time this technique provided images of the slowed down ^4He particles in monotonic and non-monotonic q-profile plasmas. In latter case the γ-ray image is a direct confirmation of the orbit topology that is predicted for the discharges with strongly reversed shear [6].

To summarise, the time-dependent γ-ray spectra from the nuclear reaction between the fusion α's and *Be*-impurities, $^9Be(\alpha,n\gamma)^{12}C$, were measured for the first time in D-T plasmas. The time evolution of the MeV α-particle density was obtained, and a correlation between the decay-time of the γ-ray emission and the classical slowing-down time in different plasma scenarios was established. The majority of the results are consistent with classical behaviour of particles, however in discharges with low plasma current and in discharges with current hole the γ-ray emission was found to decay on a much shorter time-scale. This is attributed to orbit losses and orbit drifts, which determine the α-particle behaviour. This interpretation is consistent with theoretical predictions. Further confirmation of classical behaviour of fast ^4He and *D*-ions in monotonic q-profile plasmas obtained in the recent ^4He-accelaration experiments. The γ-ray images of ^4He-ion orbits obtained for the first time are consistent with theoretical predictions. It is important to note that application of this γ-ray technique with dedicated multi-channel devices could provide the time- and spatial-resolved fusion α-particle measurements in next-step fusion machines, such as ITER.

This work has been conducted under the European Fusion Development Agreement and was funded partly by the United Kingdom Engineering and Physical Sciences Research Council and by EURATOM.

[1] V. G. Kiptily *et al*., submitted to Phys. Rev. Letters
[2] M. J. Mantsinen *et al*., Phys. Rev. Lett. **88**, 105002 (2002).
[3] V. G. Kiptily *et al*., Nucl. Fusion **42**, 999 (2002).
[4] V. G. Kiptily, Fusion Technol. **18**, 583 (1990).
[5] N.C. Hawkes *et al*., Phys. Rev. Lett. **87**, 115001 (2001)
[6] V. Yavorskij *et al*., Nuclear Fusion **44**, L5-L9 (2004).