EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–PR(01)30

V G Kiptily et al

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Gamma-Rays:
Measurements and Analysis at JET

V.G. Kiptily[1], O.N. Jarvis[1], L. Bertalot[2], S.W. Conroy[3],
S. Popovichev[1], M.J. Mantsinen[4]
and contributors to the EFDA-JET workprogramme

[1] Euratom/UKAEA Fusion Assoc., Culham Science Centre, Abingdon, Oxon. OX14 3DB UK
[2] Ass. Euratom/ENEA/CNR sulla Fusione, Centro Ricerche Energia ENEA-Frascati 00044 Frascati, Rome
[3] INF, Uppsala University, Euratom-VR Association, Box 535, 75 121 Uppsala, Sweden
[4] Helsinki University of Technology, Association Euratom-Tekes, P.O.Box 2200, FIN-02015 HUT, Finland

This work has been conducted under the European Fusion Development Agreement and is partly funded by Euratom and the UK Department of Trade and Industry

1. INTRODUCTION

Optimisation of auxiliary plasma heating by means of Ion Cyclotron Radio-Frequency (ICRF) and Neutral Beam Injection (NBI) as envisaged for the future fusion reactors is one of the main priorities in present research at today's tokamaks. Therefore, investigation of the production of fast ions during heating and of the subsequent fast ion behaviour in magnetically confined plasmas, together with an evaluation of the resulting bulk ion heating efficiency, are of essential importance for fusion reactor development.

Gamma-ray diagnostics, based on the measurement of the gamma-ray emission from nuclear reactions between fast ions and the main plasma impurities, is a valuable technique for studying the fast particle energy distributions. Gamma-ray spectrometry provides information on the energy distribution, and the measurement of emission profiles supplies information on the spatial distribution of the reaction sites.

Since 1987, the γ-ray emission from JET plasmas has been systematically monitored and used successfully in the analysis of heating effects during ICRF and NBI heating in the JET tokamak. The classical character of the fast ion slowing down behaviour has been demonstrated and estimates have been obtained of the fast particle confinement time [1]. The study of sawtooth crashes has demonstrated dramatic spatial redistribution of fast particles and other effects [2].

In recent JET experiments to study the ITER-relevant ICRH scenarios (^{3}He)D and (^{3}He)^{4}He, γ-ray measurements provided information on the fast ion population, with the effective temperature of the energetic tail ions being deduced with the help of a γ-ray spectrum simulation code, GAMMOD. In this paper, the main γ-ray results are presented and the capabilities of gamma diagnostics are discussed in the light of the ITER-project programme.

2. EXPERIMENTS AND RESULTS

Gamma-ray energy spectra are recorded with a calibrated bismuth germanate (BGO) scintillation detector (75 mm x 75 mm). This detector is located in a well-shielded bunker and views the plasma tangentially. The detector line-of-sight lies in a horizontal plane about 30cm below the typical plasma axis. The γ-rays are recorded in the energy range 1-28 MeV with an energy resolution of about 4% for the 10-MeV g-line.

Gamma-ray emission profiles have been obtained using the JET neutron profile monitor [3]. This monitor consists of two cameras, a vertical camera with 9 line-of-sights and a horizontal camera with 10 line-of-sights. Due to finite collimation, the poloidal viewing extent of each channel at the centre of the plasma is about 10cm. The radiation detectors are NE213 liquid scintillators. Separation between γ and neutron events is possible by exploiting the differing pulse shape characteristics exhibited by the detectors for the two forms of radiation. The 19 Pulse Shape Discrimination (PSD) electronics modules were set up so as to restrict the detection of gamma rays to the energy range from 1.8 to 6 MeV.

Recent γ-ray measurements demonstrated the first direct evidence for ICRF-induced pinch of ^{3}*He*-minority ions based on profile data [4]. Toroidally asymmetric ICRF waves were used in this experiment. Depending on the toroidal direction in which the launched wave propagates (co-current or counter-current for $+90^{O}$ or -90^{O} phasing), the resulting spatial pinch of the trapped ions is either inwards (shot # 54239) or outwards (shot # 54243). Figure.1 (left) shows the effect of different spatial distributions of the g-radiation due to nuclear reactions between fast ^{3}*He*-ions and carbon, which is the main impurity in JET. The disparity is due to the differing character of the fast ^{3}He ion orbits for two ICRF phasings, as predicted by theory [4].

The γ-ray spectra recorded by the BGO-spectrometer permit an assessment of the energy distribution of the ^{3}He-ions because the reaction excitation function exhibits a threshold nature. A dedicated code for γ-ray spectrum modelling, GAMMOD, has been used to deduce an effective temperature of the fast ions-tail. The program is based on basic reaction cross-section data for 16 nuclear reactions, includes 88 γ-ray transitions in the final nuclei and applies calculated response functions for the gamma spectrometer. Experimental data for the time-averaged plasma temperature, the applied NBI power, fuel and impurity densities are used as input parameters. A Maxwellian energy distribution is chosen to describe the line-of-sight averaged ICRF-driven ions' tail. Energy distributions of the fusion products have been approximated by the classical distribution function for steady-state plasmas. The analysis of recorded gamma-ray spectra using GAMMOD gives the effective tail temperatures, the fast ion particle concentrations and the contribution to the neutron yield made by the fast particles.

Experimental and modelled γ-ray spectra are compared in Fig.1 (right) for discharge # 54239, with $+90^{O}$-phasing. Spectrum analysis indicates that the γ-radiation is mainly produced by the nuclear reaction $^{12}C(^{3}He,p\gamma)^{14}N$ and the effective temperature of the ICRF accelerated ^{3}He ions is $<T_{eff}>=650 \pm 150$ keV. In the case of discharge # 54243 with the opposite phasing (-90^{O}) $<T_{eff}>$ is roughly the same, but the total g-radiation intensity is halved.

In a special JET experiment [4], during third harmonic heating of ^{4}*He* plasma in the presence of ^{4}*He*-beams (120 keV and/or 70 keV), γ-radiation due to reaction $^{9}Be(a,ng)^{12}C$ was observed for the first time. This reaction has been proposed previously as a dedicated diagnostic for fusion alpha-particles [5,6]. Gamma-ray spectrum analysis shows the acceleration of ^{4}*He* ions up to energies in excess 2 MeV. An example of measured and calculated spectra is presented in Fig.2 (left) for discharge # 54172. Observation of strong γ-ray emission from $^{12}C(d,pg)^{13}C$ shows that some ICRF power was also absorbed at the third harmonic *D*-resonance. It is possible that the *D*-tail is enhanced by knock-on collisions between thermal deuterium and fast ^{4}*He* ions[4]. The results of the spectrum modelling are $<T_{eff}>_{4He}=550 \pm 150$ keV and $<T_{eff}>_{D}=300 \pm 100$ keV. This calculation is based on an assumption that ratio of impurity concentrations Be/C is in the range from 0.15 to 0.5.

Gamma-ray modelling facilitates the interpretation of the neutron yield produced by the fast particles during low neutron yield discharges. In ^{4}*He*-discharges, as in shot #54172, the fast ^{4}*He*-

ion component is about 10 times stronger than the *D*-component; nevertheless, the accelerated deuterons provide more than 90% of the *d-d* neutron yield.

In the deuterium-tritium JET campaign, DTE1, the γ-ray emission due to the reaction $^{12}C(p,p'g)^{12}C$ indicates the presence of ICRF-accelerated protons with energy exceeding 5 MeV. For tritium discharge # 41759 the effective tail temperature of ICRF-driven *H*-ions is estimated to be in the range 0.4 to 0.6 MeV. This allows the identification of the threshold reaction $T(p,n)^3He$ as the source of 40% excess neutron emission [7]. Since there is no indication of gamma rays due the reaction $^{12}C(d,pg)^{13}C$ in the measured γ-spectrum (Fig.2, right), the surprisingly high neutron yield in this discharge cannot be due to the second-harmonic-accelerated *D*-ions.

3. CONCLUSIONS

Experiments at JET have demonstrated the capability of the g-ray diagnostics for studies of fast ion behaviour in deuterium, hydrogen, helium and tritium plasmas. Gamma-ray spectrometry and profile measurements provide information on the energy and spatial particle distribution of the fast ions and the efficiency of ICRF heating of bulk plasma. Further development of γ-ray spectrum modelling and the extension of the nuclear reaction data-base is essential. New possibilities of γ-ray diagnostics for fast confined alpha-particle investigation have been shown in a ^4He-plasma experiment. The nuclear reaction $^9Be(a,ng)^{12}C$ could be useful not only for *DT*-plasma [8] but also in the possible *He*-phase of ITER. In this case, high-energy resolution spectrometers could provide additional information due to the possibility of measuring the Doppler-broadening of the γ-lines [6].

REFERENCES

[1]. G. J. Sadler, S. W. Conroy, O. N. Jarvis, P. van Belle, J. M. Adams, M. A. Hone, Investigation of Fast Particle Behaviour in Joint European Torus Plasmas Using Nuclear Techniques, Fusion Technology **18**, 556-572 (1990).

[2]. O. N. Jarvis, J.M. Adams, P. J. A. Howarth, et al., Gamma Ray Emission Profile Measurements from JET ICRF-Heated Discharges, Nuclear Fusion **36** (11), 1513-1530 (1996).

[3]. J. M. Adams, O. N. Jarvis, G. J. Sadler, D. B. Syme, N. Watkins, The JET Neutron Profile Monitor, Nucl. Instrum. Methods Phys. Res., **A239**, 277-290 (1993).

[4]. M.J. Mantsinen et al., ICRF heating scenarios in JET with emphasis on He plasmas for the non-activated phase of ITER, 14th Topical Conference on Radio Frequency Power in Plasmas, Oxnard, 7-9 May 2001.

[5]. V.G.Kiptily, Capabilities of Gamma Spectroscopy for Fast Alpha-particle Diagnostics, Fusion Technology **18**(4), 583-590 (1990).

[6]. V.G. Kiptily, A.V. Matjukov, A.S. Mishin et al., In-beam Study of the Reaction $^9Be(a,ng)^{12}C$ and Alpha-particle Diagnostics, Fusion Technology **22**(4), 454-460 (1992).

[7]. M.J. Mantsinen, O.N. Jarvis, V.G. Kiptily et al., First Observation of *p-T* Fusion in JET Tritium Plasmas with ICRF Heating of Protons, Nuclear Fusion (in press).

[8]. V.G. Kiptily, T. Kondoh, V.O. Naidenov et al., in: *Diagnostics for Experimental Thermonuclear Fusion Reactors 2*, edited by P.Stott, G.Gorini, E.Sindoni (Plenum Press, New York & London, 1998) pp.511-519.

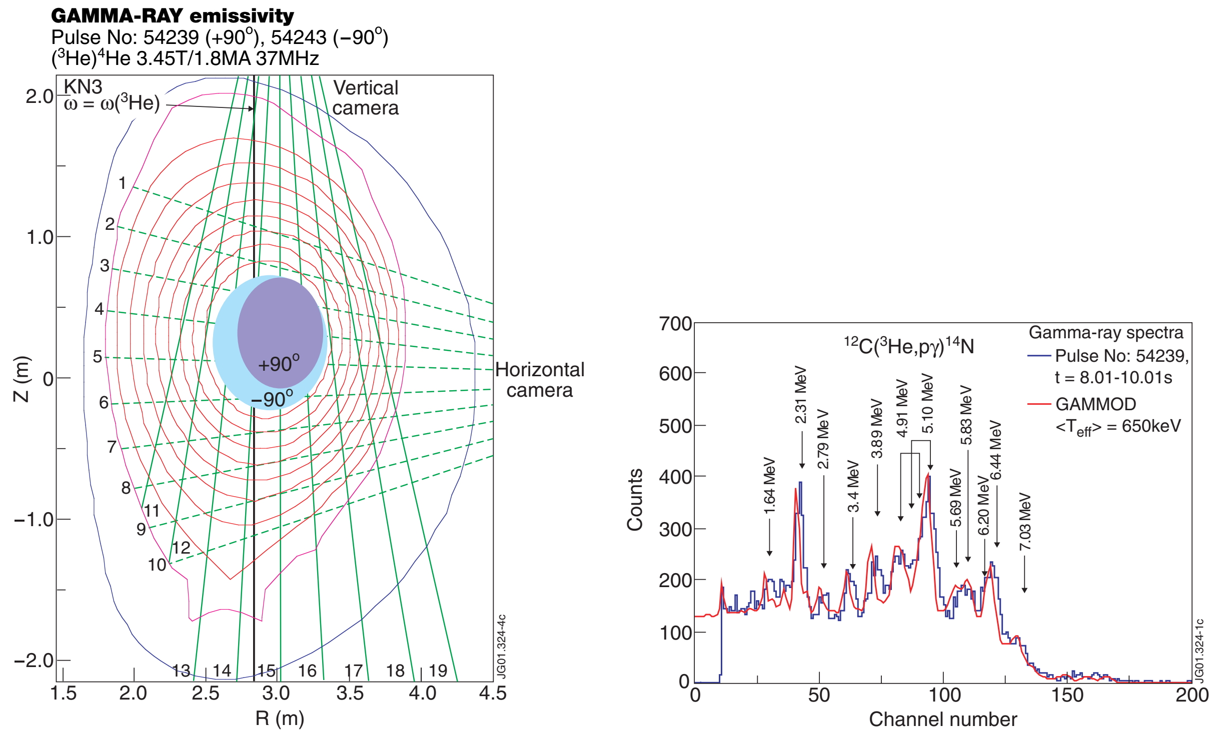

Figure.1: Left: comparison of regions radiating more than 50% of γ-rays from reaction $^{12}C(^3He,p\gamma)^{14}N$ in shots 54239 and 54243. Right: experimental and calculated spectra for shot 54239.

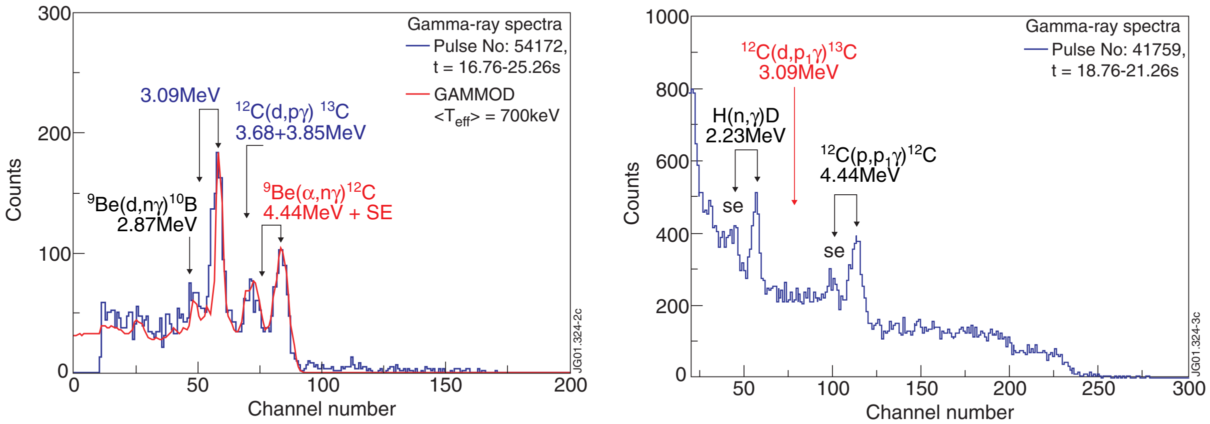

Figure.2: Left: experimental and calculated spectra for shot 54172. Right: experimental γ-ray spectrum recorded during shot 41759; se - single escaped peak.