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Fusion Alpha-Particle Diagnostics for DT Experiments on the Joint European Torus

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ABSTRACT.

JET equipped with ITER-like wall (a beryllium wall and a tungsten divertor) can provide auxiliary heating with power up to 35MW, producing a significant population of α-particles in DT operation. The direct measurements of alphas are very difficult and α-particle studies require a significant development of dedicated diagnostics. JET now has an excellent set of confined and lost fast particle diagnostics for measuring the α-particle source and its evolution in space and time, α-particle energy distribution, and α-particle losses. This paper describes how the above mentioned JET diagnostic systems could be used for α-particle measurements, and what options exist for keeping the essential α-particle diagnostics functioning well in the presence of intense DT neutron flux. Also, α-particle diagnostics for ITER are discussed.

1. INTRODUCTION

The nuclear fusion reaction between deuterium and tritium, $D(T,n)^4He$ is a main source of energy in future thermonuclear reactors. Charged fusion products of this reaction, α-particles (^4He-ions), which are born with an average energy of 3.5 MeV and transfer the energy to the thermal plasma during their slowing down, will provide the power for the self-sustained *DT*-plasma burn. Adequate confinement of α-particles is essential to provide efficient heating of the bulk plasma and steady burning of a reactor plasma. Therefore investigation of α-particles behaviour will be a priority task for the planned deuterium- tritium experiments on JET in order to understand the main mechanisms of their slowing down, redistribution and losses and to develop optimal plasma scenarios.

Today's JET machine has been equipped with a beryllium wall, a tungsten divertor (ITER-like wall) and enhanced auxiliary heating systems, including NBI with power up to 35MW. Therefore possible future deuterium-tritium experiments on JET are expected to produce significant population of α-particles at plasma parameters approaching as closely as possible the ITER values, so the experiments will give great opportunities to study fusion alphas. The confinement of fast particles produced in fusion reactions is of crucial importance for future fusion devices like ITER and DEMO.

What do we want to measure in the next deuterium-tritium experiments on JET? First of all these are the deuterium-tritium fusion reaction rate and spatial α-particle source profile. Measurement of the slowing down, redistribution and losses of α-particles is another high priority task for optimisation of the plasma scenarios and assessments of MHD effects on the DT plasma performance.

The first full scale DT-experiment on JET in 1997 (DTE1) has shown that direct measurements of alphas are very difficult. Alpha-particle studies require a significant development of dedicated diagnostics. Since DTE1, JET has been gradually building up dedicated fast ion diagnostics, which have been tested step-by-step in a variety of plasma scenarios such as ICRH accelerated ^{4}He-ions and fusion born α-particles in Trace Tritium Experiments (TTE) in 2003. JET has now excellent set of confined and lost α-particle diagnostics, which comprise of γ-ray spectrometry for measuring energy distribution of fast ions; 2D neutron/γ-ray camera for tomographic reconstruction of the α-particle source and the temporal evolution of its spatial profile; a fast ion loss detector (Scintillator

Probe) with energy and pitch-angle resolutions and a set of Faraday Cups with poloidal, radial, and energy resolution for measuring lost alphas. For operating all these diagnostics at the high DT neutron fluxes expected in future high-power DT campaign, specific improvements are proposed for some of the diagnostic tools.

This paper describes how the above mentioned JET diagnostic systems could be used for α-particle measurements, and what options exist for keeping the essential α-particle diagnostics functioning well in the presence of intense DT neutron flux. It is organized as follows. The fusion α-particle source measurements on JET are described in section 2. The confined α-particle diagnostics are presented in section 3. Section 4 is devoted to the escaped α-particle measurements.

2. FUSION ALPHA-PARTICLE SOURCE MEASUREMENTS

There are two major fusion reactions that produce energetic α-particles,

$$D + T \quad {}^{4}He(3.5MeV) + n(14.1MeV)$$

and

$$D + {}^{3}He \quad {}^{4}He(3.7MeV) + p(14.7MeV)$$

For the first one, which is reactor relevant, 14MeV neutron measurement is a main tool for the DT fusion power and α-particle source profile measurements. Measurements of the neutron source profile (which is identical to the alpha-particle source) provide the principal technique for studying fast fuel ion distributions, which are produced non-symmetrically on flux surfaces by NBI and ICRH. This is very important in reactors and plasmas influenced by magneto-hydrodynamic (MHD) instabilities.

There is another instrument for α-particle source profile measurements. The detection of 17MeV gammas from a weak branch of the DT fusion reaction

$$D + T \quad {}^{5}He(16.5MeV)$$

can provide the same information as 14MeV neutrons. A disadvantage of this method is a low cross-section of the branch $\sigma_\gamma/\sigma_n \sim 0.005\%$. However, efficient γ-ray detectors allow information to be obtained with required time resolution for high performance plasmas. This tool has been tested on JET in experiments with ^{3}He-minority ICRF heating of deuterium plasmas. The similar γ-rays with energy ~16MeV from a weak branch of D^{3}He fusion reaction ($\sigma_\gamma/\sigma_p \sim 0.005\%$),

$$D + \ {}^{3}He \quad {}^{5}Li + (16.39MeV)$$

were detected with an efficient scintillation detector and γ-ray energy spectra have been recorded during discharges. In both reactions peaks related to ground states are broad; widths are $\Gamma_{DT} \sim$ 0.6MeV and $\Gamma_{D3He} \sim$ 1.6MeV. There is a second peak related to the first excited state with $\Gamma \sim$ 5MeV in the D^{3}He reaction.

The JET neutron/gamma camera is a unique instrument for imaging of the noncircular plasma neutron/gamma source [1-6]. It consists of two fan-like multi-collimator detector arrays [7]. A nine-channel camera is positioned above the vertical port to view downward through the plasma, while a ten-channel assembly views horizontally from the side. The collimation can be remotely adjusted by use of two pairs of rotational steel cylinders. Each channel is equipped with a set of three different detectors: a NE213 liquid organic scintillator with digital data acquisition system, which allows pulse shape discrimination for simultaneous measurement of 2.5MeV DD neutrons, 14MeV DT neutrons, and γ-rays; a BC418 plastic scintillation detector for measurement of 14MeV D-T neutrons, which is located in front of the NE213 scintillator and is coupled to a photomultiplier tube via a light guide; and a CsI(Tl) photodiode with a diameter of 20mm and a height of 15 mm for measuring the HXR/γ-ray emission in the range between 0.2 and 6 MeV. All neutron detectors are absolutely calibrated for both DD and DT neutrons.

3. CONFINED ALPHA-PARTICLE DIAGNOSTICS

Nuclear reaction γ-ray diagnosis is one of the important techniques used on the JET tokamak for studying confined fast ions [1-6]. The intense γ-ray emission is produced in JET plasmas 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 are recorded with collimated spectrometers, while the γ-ray emission spatial 2D-profiles are measured with the JET neutron/gamma camera. Together, these provide information on the spatial distribution of fast ions and fast ion tail-temperature.

For identification of the fast ions, 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 [3] is used. This code is based on the known nuclear reaction cross-sections and it contains information on about one hundred γ-ray transitions in the final nuclei of the low-Z impurity reactions. It also includes the γ-ray response function of the BGO-spectrometer. A Maxwellian energy distribution is used to describe the line-of-sight averaged tail of ICRH-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.

On JET, the α-particle diagnostic technique is based on the nuclear reaction $^{9}Be(\alpha,n\gamma)^{12}C$ between confined α-particles and the beryllium impurity typically present in the plasma [8, 9]. The γ-radiation due to the reaction $^{9}Be(\alpha,n\gamma)^{12}C$ 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 [4,10] and in deuterium plasmas with short T-NBI blips for α-particles [11]. These experiments on JET showed that an improvement of the diagnostics is needed for the measurements in the high neutron yield DT discharges to demonstrate the capabilities of γ-ray diagnostics for burning plasma physics in future reactors.

3.1. GAMMA-RAY SPECTROMETERS

Gamma-ray energy spectra are measured on JET with five independent devices, one with a tangential, and four with vertical lines of sight, through the plasma centre. The tangential spectrometer is a calibrated bismuth germanate (BGO) scintillation detector with a diameter of 75mm and a height of 75 mm. It is located in a shielded bunker, which views the plasma quasi-tangentially. In order to reduce the neutron flux and the γ-ray background, the front collimator is filled to a depth of 500mm with polythene. Behind the scintillation detector, there is an additional 500mm long dump of polythene and a 1000mm long steel plug. The detector's line of sight lies in a horizontal plane about 30cm below the plasma magnetic axis. The γ-ray spectra are continuously recorded in all JET discharges over the energy range 1-28 MeV, with energy resolution of about 4% at 10MeV.

A pair of neutron/γ-ray collimators working in a tandem configuration has been installed for background reduction and precise characterization of the tangential γ-ray spectrometer field of view (FoV) [12, 13]. The tandem collimators provide shielding factors $C_{DD} \approx 2\times10^{-3}$ for 2.45MeV neutrons and $C_\gamma \approx 10^{-3}$ for 9MeV γ-ray.

A similar collimator system was designed for DT experiments: $C_{DT} \approx 2\text{x}10^{-3}$ for 14 MeV neutrons and $C_\gamma \approx 10^{-3}$ for 9 MeV γ-ray. This system provides necessary conditions for the operation of diagnostics in high performance DD and DT discharges. However, this is not sufficient to diagnose the confined α-particles. There is a proposal of further upgrade of shielding and neutron attenuators. It consists of the additional neutron and γ-ray shields at the entrance of the bunker and replacement of polythene attenuators in front of the detector by *LiH* attenuators. Also, the detector change is considered.

The feasibility of γ-ray measurements depends on efficiency of the neutron suppression. Also, it is important to avoid carbon-containing materials in the neutron attenuator because of inelastic scattering neutrons with energy exceeding 5 MeV, $^{12}C(n,n'\gamma)^{12}C$, leads to the unwelcome background of 4.44MeV γ rays. The best neutron attenuator is ^6LiH, but *LiH* with a natural *Li* composition could be used as well. It is compact, effective and well transparent to MeV γ-rays. It does not produce interfering γ-rays in the high-energy range. A 30cm sample of the ^6LiH-filter reduces 2.5-MeV neutron flux ~900 times and the 15MeV neutron flux ~30 times [14]. The attenuator has been tested in JET experiments with deuterium plasmas [15]. Assessments of the γ-ray background reduction in the energy range below 3MeV gave a factor of 100. A small reduction of the spectra (factor of 2) was found in the energy range above 3MeV, which is defined by γ-ray transparency of the ^6LiH-attenuator. Further tests in DT discharges will prove the full capability of ^6LiH-attenuators as an essential component of the γ-ray diagnostic system in ITER.

Another four spectrometers are viewing the plasma centre vertically through 2m collimators. Three of them, a *NaI(Tl)*, $LaBr_3(Ce)$ scintillators and Hp*Ge*-detector (a high purity *Ge*-detector) placed on a remotely controlled slider are sharing the same line of sight (LoS). Depending on the experimental task one of the detectors is moved in the working position. A second slider with polythene slabs is used for choosing optimal neutron/γ-ray attenuation. The γ-ray spectra are continuously recorded in all JET discharges over the energy range 1-20MeV. The fourth detector, $LaBr_3(Ce)$ scintillator installed at another toroidal position is permanently recording spectra viewing the plasma centre through 30cm ^6LiH attenuator. For the DT operation an additional 30cm attenuator is considered. The best detector for the DT operation is a fast high-Z heavy scintillator $LaBr_3$(Ce), known as "BriLanCe". It has short decay times of ~20ns, high photons yield and practically insensitive to neutrons. The detector crystal is coupled to a photomultiplier tube (PMT) designed to allow operations at count rates up to 2MHz. High rate capability is enabled by a dedicated pulse digitization data acquisition system based on the ATCA platform with a sampling frequency up to 400 MSPS and a nominal 14-bit resolution [16]. Their outstanding properties open a possibility to extend the counting rate limit beyond 5MHz, and at the same time to improve the energy resolution for γ-ray spectrometry in the range 2–30MeV. A test on an accelerator [17] has demonstrated that spectra can be measured in the MHz range without significant degradation of the energy resolution up to 2.6MHz (~2% at 3 MeV). Measurements at higher counting rates up to 4.4MHz showed just a modest broadening of the energy resolution (0.2% increase at 3MeV). This spectrometry system meets the requirements of α-particle diagnostics on ITER. It is considered replacing the tangential BGO detector by the scintillator. Replacement of the tangential BGO detector by a $LaBr_3(Ce)$ scintillator is being considered.

The use of Hp*Ge*-detector will be important for an experimental test of another α-particle diagnostic. Proposed two decades ago [8, 9] it is based on the Doppler shape analysis (DSA) of the 4.44MeV *γ* -ray line related to the nuclear reaction $^9Be(\alpha,n\gamma)^{12}C$ between *α*-particles and the beryllium, which is a main impurity in JET plasmas. Contrary to the radiation capture reactions, in this type of nuclear reaction the Doppler effect is the main mechanism of peak broadening. In experiments with the 3rd harmonic ICRH heating of a ^4He neutral beam ($\omega=3\omega_{4He}$) in ^4He plasmas, γ-radiation due to the reaction $^9Be(\alpha,n\gamma)^{12}C$ has been observed and DSA of 4.44MeV γ-ray line carried out for the first time [18, 19]. The use of DSA technique requires well known differential nuclear cross-sections as well as FoV and fast ion distribution modelling. A sophisticated DSA of characteristic γ-ray emission peaks from the reaction $^{12}C(^3He,p\gamma)^{13}C$ measured in D^3He plasmas with ion cyclotron resonance heating tuned to the fundamental harmonic of ^{3}He minority has been done [20].

In the DT experiments this detector can be used with a high level attenuation of the neutron flux in the LoS. To provide the same working conditions as in the case of deuterium operations the attenuation of 14-MeV neutrons should be ~10^{-4} in the high performance DT discharge. It means the LiH attenuator has to have thickness ~80cm.

3.2 GAMMA-RAY CAMERA

The imaging of fast ions with γ -ray camera has been very successfully applied so far in ICRH experiments [3-6]. The extension of these diagnostics to high fusion performance (high neutron yield) discharges requires an adequate reduction of both neutron flux and the neutron-induced gamma-ray background. To this end a set of three neutron attenuators of different shape and attenuation length have been designed, constructed and installed for the horizontal and vertical cameras [21, 22]. The radiation performance of the neutron attenuators has been modeled by neutron/photon transport calculations. The attenuators have a different design for the horizontal and vertical cameras. A quasi-crescent shaped neutron attenuator has been chosen for the horizontal camera with an attenuation factor for DD-neutrons $k_{DD} = 10^{-2}$. For the vertical camera there are two quasi-trapezoid shaped neutron attenuators, with different attenuation lengths: a short version ($k_{DD} = 10^{-2}$), to be used together with the horizontal attenuator for deuterium discharges and a long version ($k_{DD} = 10^{-4}$) to be used for high performance DD and DT discharges ($k_{DT} = 6.7\mathrm{x}10^{-2}$). All three neutron attenuators consist of a metal casing filled with pure light water as attenuating material. They have to be moved out of the detector line of sight when the camera diagnostics are used for neutron measurements. The system operates in a harsh electromagnetic environment therefore the remote steering and control are based on pneumatic components.

With a long vertical attenuator the γ-ray measurements will be possible in DT discharges with neutron rate up to $5\mathrm{x}10^{17}$ n/s. This is very important diagnostic improvement, which will be useful for the confined α-particle studies in scenarios with ICRF heating. However, the CsI-detectors used in the camera are very slow end cannot provide reliable information on the spatial re-distribution of confined α-particles due to a pile-up effect at expected high count rates. It is considered replacing them by $LaBr_3(Ce)$ detectors of the same size, which can work at several MHz count rates.

In the case of ITER, the slowed down 1-MeV beam deuterons will give rise to gammas from the $^{9}Be(d,n\gamma)^{10}B$ and $^{9}Be(d,p\gamma)^{10}Be$ reactions, whereas the fusion alphas with energies around the 2MeV resonance in the $^{9}Be(\alpha,n\gamma)^{12}C$ reaction will produce 4.44MeV gammas. Furthermore, the source of fusion α-particles can be obtained by measuring the 17MeV gammas from the $D(T,\gamma)^{5}He$ reaction. Using γ-ray spectrometers in every channel of the ITER Radial Camera, α-particle slowing down profiles could be measured with the technique successfully tested in JET Trace Tritium Experiments [11]. Simultaneous measurements of the NBI power deposition and α-particle slowing down profiles are very important for the optimisation of different plasma scenarios and understanding of the fast-ion confinement physics.

4. ESCAPED ALPHA-PARTICLE DIAGNOSTICS

JET is exceptionally well equipped for studying fast ion confinement and losses. It is capable of simultaneously measuring different species of confined fast ions, including α-particles using the γ-ray diagnostics, and equipped with lost ion diagnostics: a thin foil Faraday cup (FC) array [23] and a scintillator probe (SP) [24, 25].

The Faraday Cup array detects the current of fast ions at multiple poloidal locations, with a dynamic range from 10 nA/cm^2 to 10 mA/cm^2 at a temporal resolution of 1ms. The detectable range of α-particle energies is about 1–5MeV. The energy resolution for 3.5MeV α-particles is estimated to be about 15%–50%. The array consists of nine detectors spread over five poloidal locations (Z) between 22 cm and 80 cm below the midplane. Radially, the detectors are equally spaced on three locations between 25 and 85 mm behind the adjacent poloidal limiter. Each detector consists of at least four 75 25 mm^2 Ni foils (2.5 μm in eight of the detectors and 1.0μm in the ninth), which are separated by insulating mica foils. Depending on its energy, a particle can pass through a certain number of foils before it is stopped in one foil, thus causing a current signal. The detection of the temporal evolution of the current signals in all foils in the radially and poloidally distributed detectors will allow mapping particle energies at different locations.

The Faraday Cups are resistant to neutron and γ-ray radiations. At the n/γ flux $\sim 10^{13}$ cm^{-2} s^{-1} the predicted background foil currents are $I_n \sim 0.1$ nA/cm^2 and $I_\gamma \sim 0.01$ nA/cm^2 that is much less than current produced due to α-particle losses $I_\alpha \sim 100$ nA/cm^2.

The Scintillator Probe, which is located about 28 cm below the mid-plane of the JET torus outside the plasma, detects lost ions and provides information on the lost ion pitch angle $\theta = \arccos(v_{\|}/v)$ with 5% resolution in the range 35°–85° and gyro-radius between 3cm and 14cm with 15% resolution. The underlying principle of scintillator measurements is the emission of light by a scintillating material after a particle strikes this material. Selection criteria for the particles that hit the scintillator are introduced by using a set of collimators within the magnetic field of JET. An optical arrangement within the scintillator probe is used to transfer the light emitted by the scintillator through a coherent fibre bundle towards a charge-coupled device (CCD) camera and a photomultiplier (PMT) 4×4 array. The 128x256 pixel CCD camera used in SP can provide 20-kHz snapshots of the light intensity on the pitch-angle – gyro-radius grid calculated with the EfipDesign code [26]. A fast 20μm scintillator with decay time 0.5μs is installed in SP, which is radiation resistant. An electrically-heated hose for restoration of the fibre optic bundle degradation will be used.

Fusion alpha-particle [5, 27, 28] and ^{4}He-ion [29] losses have been measured with FC and SP in JET experiments with ^{3}He-minority heating of deuterium plasmas and the 3rd harmonic ICRH ($\omega=3\omega_{4He}$) acceleration of ^{4}He-beam ions in ^{4}He plasmas. The 4.44MeV γ-radiation due to the reaction $^9Be(\alpha,n\gamma)^{12}C$ was observed that means α-particles/^{4}He-ions had energies in excess of 2MeV. Also the measured 17MeV γ-rays of the D(^{3}He,γ)^{5}Li reaction indicate the rate of the D(^{3}He,p)^{4}He fusion reaction, which produces α-particles at 3.6MeV and protons at 15MeV and in most of the discharges this rate was rather high. It was found that the fusion α-particles more frequently escape from the plasma during Alfvén cascade and tornado mode activity. There are two possible reasons for the observed effect of the loss dependence on the Alfvénic activity. First, ICRH-accelerated ^{3}He ions with tail temperature of few hundred keV, which are the source for D(^{3}He,p)^{4}He fusion reaction, may be so strongly re-distributed by a resonant interaction with the Alfvénic modes, that the re-distribution of ^{3}He affects the profiles of α-particles born in D(^{3}He,p)^{4}He fusion reactions. Second, the perturbed magnetic field associated with the Alfvénic modes, may directly affect the fusion-born α-particles in the region of the phase-space close to the boundary between confined and unconfined particles.

There is another γ-ray technique proposed to measure escaped α-particles [9], which is ITER relevant. It is based on the same nuclear reaction $^9Be(\alpha,n\gamma)^{12}C$ as for confined particle diagnosing. In this case, escaped α-particles with energies in excess of 2MeV, interacting with beryllium wall or a specially installed target, give rise to 4.44MeV γ-radiation. Measurements of the radiation provide the rate of fast α-particle losses. It is important that the detector FoV do not intersect the plasma core, which is a source of 4.44MeV γ-emission produced by confined α-particles. This lost α-particle diagnostic could be tested on JET during the DT experiments. A thick beryllium target with 500-600cm^2 surface installed in FoV of a gamma-camera detector could provide the required intensity of the 4.44MeV γ-radiation for α-particle loss monitoring in DT experiments.

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