

GAMMA-RAY SPECTROMETRY OF HOT PLASMAS

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Gamma-ray spectrometry provides diagnostics of fast ion behavior in plasmas of large tokamaks. Information acquiring with the gamma-ray diagnostics gives possibility to identify and distinguish simultaneously presence of fast alpha-particles and other ions (H, D, T, ³He), to obtain its relative densities and also to perform tomographic radial profile reconstruction of the gamma-emission sources.

I. INTRODUCTION

Diagnosis of alpha-particles and other fast ions, which are born in nuclear reactions during ICRF and NBI heating is needed for heating scenario optimization in large fusion machines like the JET tokamak. For ITER, which is under construction this moment this problem is of a crucial importance. Gamma-ray spectrometry techniques allow studying the behavior of energetic ions, including fusion alpha-particles in fusion plasmas providing important information on spatial and energy distribution of fast particles. More than 20 years gamma-ray diagnostics is developed in the Ioffe Institute (Ref. 1). Gamma-ray diagnostic is included into the implementation list of ITER diagnostics.

Main principles of gamma-ray diagnostics, as well as some experimental results and conceptual design of the ITER gamma-ray spectrometer system are briefly represented in this paper.

II. BASICS OF THE GAMMA-RAY DIAGNOSTIC TECHNIQUE

II.A. Physical Basis

Gamma-ray spectrometry in hot plasma experiment is based on registration and analysis of radiation from nuclei excited in reactions that can take place during plasma discharge (Ref. 2). There are three types of nuclear reactions that may be noted for diagnostics: reactions between fuel nuclei (H, D, T, ³He), interaction between fast charged particles (p, d, t, α , ³He) and plasma impurities (⁹Be, ¹²C) and reactions with specially doped impurities (¹⁰B, ¹¹B, ⁷Li). The primary application of the diagnostics is the measurement of time-dependent spatial gamma-ray and neutron emissivities to derive (i) fusion reactivity and alpha-particle birth profile by means of

reactions D(t, γ)⁵He and D(t,n)⁴He; (ii) profile of fast confined alpha-particles - ⁹Be(α ,n γ)¹²C and ¹⁰B(α ,p γ)¹³C; (iii) D/T fuel ratio - D(d, γ)⁴He and D(t, γ)⁵He; (iv) degree of the fast ion confinement under ICRF or/and NBI heating; (v) profile of runaway electrons from bremsstrahlung hard x-rays.

Gamma-ray emissivity of fusion plasma is defined by a value of the reaction rate

$$R(r) = \frac{n_1(r)n_2(r)}{1 + \delta_{12}} \langle \sigma v \rangle, \quad (1)$$

where $\langle \sigma v \rangle$ is rate parameter averaged over the Maxwellian distribution of fusion particles; n_1, n_2 are the densities of reacted ions and δ_{12} is Kronecker's symbol. In the case of fast ion reactions the rate is expressed as

$$R_i(r) = \left(\frac{2}{m_i} \right)^{1/2} \int n_i(r) \sigma(E) E^{1/2} F_i(E, r) dE, \quad (2)$$

where $F_i(E, r)$ is the fast ion distribution function; $n_i(r)$ is a density of the impurity target.

A spectrometer, placed in a collimator views a plasma volume along the line of sight. The gamma-ray count rate can be written as

$$P = k(E_\gamma) \mathcal{E}(E_\gamma) \int R \Omega dV_{LOS}, \quad (3)$$

where $k(E_\gamma)$ is a gamma-ray attenuation factor in the LOS, $\mathcal{E}(E_\gamma)$ - the detector efficiency; Ω - the detector solid angle, V_{LOS} the plasma volume viewed by the spectrometer.

It should be noted, that the reaction ⁹Be(α ,n γ)¹²C is the main for the fusion-born alpha-particle measurements, the significance of which was investigated in detail (Ref. 1). It is a resonant reaction which also has thresholds. The presence of the 4.44 MeV peak in the gamma-ray spectra is evidence of the existence of alphas with energies that exceed 2 MeV. This reaction was successfully used at JET for the fast ⁴He ions and fusion alpha-particle studies (Ref. 3).

II.B. Gamma-Ray Detectors

The gamma ray detector operated in the hot plasma experiment must have reasonable energy resolution and be capable of maintaining the resolution while operating at high-count rates. In addition, the detector should have a

high enough detection efficiency to allow a statistically significant number of counts be measured in a relatively short time so that the time evolution of fusion gamma ray production may be reconstructed over the course of a single plasma pulse. Finally, the detector should be able to withstand a moderate flux of neutrons that is associated with a broad class of fusion plasmas. At the moment it is possible to choose between two classes of gamma ray detectors: scintillators or semiconductor detectors.

Semiconductor detectors (primarily germanium) offer superior energy resolution compared with scintillation detectors, but they have lower efficiency at high energy gamma-ray registration. Also, the cost of the larger volume semiconductor detectors is considerably higher than of scintillation detectors. Finally, semiconductor detectors are significantly more sensitive to performance degrading neutron damage than scintillation detectors. However, the JET experiments with fast ^4He -ions in the ^4He -plasma have shown (Ref. 4) that there is a possibility to use the specific mechanism of $^9\text{Be}(\alpha, n\gamma)^{12}\text{C}$ reaction for α -particle study, measuring the Doppler broadened line shape of the 4.44 MeV gamma-line in the spectrum with high energy resolution Ge detectors.

A number of scintillation materials, such as NaI(Tl), Bismuth germanate (BGO), CsI(Tl) are presently utilized in the measurement of gamma rays in general and fusion gamma rays in particular. These scintillators provide high efficiency of registration together with suitable energy resolution. However, comparatively long scintillation decay times of these materials (230 ns for NaI(Tl), 1 μ s for CsI(Tl)) makes them unusable for measurements in MHz count rate range. New heavy scintillators with densities from 5.3 g/cm³ to 8.3 g/cm³: LSO, LYSO, LuAP and LaBr₃(Ce) are now available for gamma-ray spectroscopy. These are rather fast crystals with a decay constant around 40 ns. The LaBr₃(Ce) - 'BrLanCe' (Saint-Gobain Crystals) is the most attractive one for fusion research. This scintillator has short decay times of 16 ns and high photons yields of 63 keV⁻¹, (NaI(Tl) scintillator - 38 keV⁻¹). Its properties open a possibility to extend the counting rate limit, and at the same time to improve the energy resolution for γ -ray spectrometry in the range 2-30 MeV.

II.C. Digital Signal Processing and Data Acquisition System

Since the intensities and the shapes gamma-ray spectra can change essentially and rapidly in the course of plasma discharge, it is important that the spectrometer characteristics, such as energy resolution and the efficiency of the spectrometer, as well as the gain of the measuring channel, must be held constant over a wide range of counting rates. The time resolution (i.e., the minimum time it takes for a spectrum with an adequate statistical significance to be acquired) is governed by the

detection efficiency and the relative counting loss. The time resolution can be improved by using fast-response high-efficiency spectrometers and high-speed electronic equipment.

A traditional approach includes spectrometric analog-to-digital converters (ADCs) in gamma-ray spectrometric systems, since they are characterized by high integral and differential linearity. However, these ADCs have significant drawbacks: the instrumental dead time and the fundamental impossibility of separating superimposed pulses. The gamma-ray detection efficiency of such systems starts substantially declining when the spectrometer counting rate increases to the level such that the percentage of superimposed pulses becomes essential. To improve the counting rate characteristics, a new data acquisition system (DAQ), exploiting new signal processing technique, has been developed in the Ioffe Institute (Ref. 5). It is based on a 2-channels 14 bit PCI transient recorder for digitizing incoming signal at a sampling rate of 25 MHz with an maximum average pulse rate of 1MHz. The module provides 2 Gbytes of on-board memory, which covers the acquisition time during the JET discharge. The recorded data is processed by a special code after the discharge. The main advantages of the developed system are PHA at high counting rates and gain stabilization that is crucial at the fast count-rate variations. It is important to note that the DAQ system allows avoidance of the pile-up effects, which distort the gamma-ray spectra, and may cause a misinterpretation of the data.

II.D. Radiation shielding

As it was discussed above, the gamma-ray spectrometry diagnostics is based on detection and subsequent analysis of gamma-ray deexcitation spectra of discrete nuclear states excited by nuclear reactions in the tokamak plasma. High efficiency detectors measure gamma-rays passing through the collimator that selects the plasma region for investigation and reduces the undesirable radiation flux. Thermonuclear neutrons are the main source of background in gamma-ray diagnostics; the average energies of neutrons in deuterium (DD) and deuterium-tritium (DT) plasmas are 2.5 and 14.0 MeV, respectively. Therefore, the radiation shielding of the spectrometer used in the gamma-ray diagnostic system must be designed so that the signal-to-background ratio is at a maximum and the total radiation flux incident on the detector does not exceed the admissible value in order to avoid uncontrolled distortion of information.

For the reduction of the intensive neutron fluxes that lead to additional detectors load it has been developed a ^6LiH neutron attenuator concept (Ref. 6). The attenuator is a sealed cylindrical capsule (diameter 30 mm, length 300 mm) with 1-mm-thick walls, which is used for plugging the collimator. The capsule contains lithium

hydride (${}^6\text{LiH}$) enriched to 92% in ${}^6\text{Li}$ isotope and pressed into five pellets. The attenuator prototype has been successfully tested using a neutron generator and in JET DD plasma experiments. The neutron flux attenuation by this filter was measured with a neutron generator in the modes corresponding to DD and DT neutrons. Neutrons were detected using the pulse shape discrimination technique with thresholds of >2 and >10 MeV, respectively. The measured attenuation factors for 2.8- and 14.8-MeV neutrons were 900 and 30, respectively.

Gamma-ray measurements carried out on the JET tokamak have demonstrated the efficiency of the ${}^6\text{LiH}$ neutron attenuator in experiments with the DD plasma. In these experiments the attenuation factor for the intensity of gamma-ray peaks due to inelastic neutron scattering reactions in the detectors was found to be ~ 100 . At the same time the use of the attenuator reduces the intensity of gamma-rays in the range of >3 MeV only slightly (the attenuation factor is ~ 2), which indicates the high transparency of ${}^6\text{LiH}$ to gamma-rays with energies of a few MeV.

III. GAMMA-RAY SPECTROMETRY AT JET

Effectiveness of gamma-ray diagnostic techniques was demonstrated in the largest tokamak JET (EURATOM). At the moment gamma-ray diagnostics is one of the important techniques used for confined fast ions studied on JET.

Gamma-ray energy spectra are measured on JET with three independent devices, one with a quasitangential, and two with vertical line of sight, through the plasma centre. Two of these devices are a calibrated BGO scintillation detectors with a diameter of 75mm and a height of 75mm. One of them is located in a well-shielded bunker, which views the plasma tangentially. The detector's line of sight lies in a horizontal plane about 30cm below the plasma magnetic axis. Another BGO-spectrometer is viewing the plasma vertically through the centre ($R=2.95\text{m}$). The gamma-ray spectra are continuously recorded in all JET discharges over the energy range 1-28MeV, with energy resolution of about 4% at 10MeV. The third device for the gamma-ray energy spectrum measurements is a NaI(Tl) scintillation detector with a diameter of 125 mm and a height of 125 mm, viewing the plasma vertically through the centre ($R=2.95\text{m}$).

Recently, an upgrade project of the JET gamma-ray spectrometer system has been undertaken. This project concentrates on the development of high rate, high resolution gamma-ray spectrometers to be installed at the JET. The main idea was to use large $\text{LaBr}_3(\text{Ce})$ scintillators, which are just becoming available and offer a unique combination of energy resolution and scintillation decay time (Ref. 7). Another key feature is the use of digital data processing which will allow to handle count rates exceeding 1 MHz.

Spatial profiles of the gamma-ray emission in the energy range $E_\gamma > 1$ MeV are measured in JET using the Gamma Cameras, which have ten horizontal and nine vertical collimated lines of sight. Each collimator corresponds to a poloidal-viewing extent at the centre of plasma of about 10cm. The detectors array is comprised of 19 CsI(Tl) photo-diodes ($\text{Ø}20\times 15\text{mm}$). The DAQ accommodates the gamma-ray count-rate measurement in four energy windows. This allows allocating specific gamma-ray peaks to be counted separately.

A typical example of the tomographic reconstruction of the measured line-integrated profiles recorded during 1s in a steady state phase of the plasma discharge is shown in Fig.1. It is seen clearly that the gamma-ray emission profile produced by fast D-ions (left-hand figure) differs from the profile from ${}^4\text{He}$ -ions (right-hand figure). This effect can be explained by the difference in pitch-angle distribution between ${}^4\text{He}$ beam-ions injected into the plasma quasitangentially and isotropic D-minority ions. The ability to separate gamma-rays with the Gamma Cameras from different energy bands allows the study of the fast ion behaviour in some important plasma scenarios.

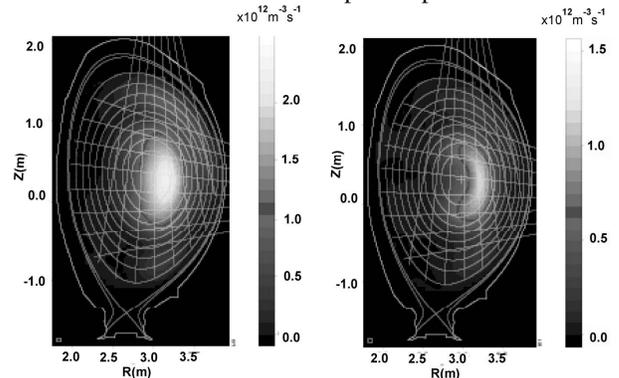


Fig. 1. Tomographic reconstructions of 4.44MeV γ -ray emission from the ${}^9\text{Be}(\alpha, \gamma){}^{12}\text{C}$ reaction (right) and 3.09MeV γ -ray emission from the ${}^{12}\text{C}(d, \gamma){}^{13}\text{C}$ reaction (left) deduced from simultaneously measured profiles (Ref. 3).

IV. GAMMA-RAY DIAGNOSTICS IN ITER

In ITER the gamma-ray diagnostics could perform the same functions as on JET. The main difference is a severe neutron/gamma background that requires the development of a special design of the system to maximize the signal-to-background noise ratio. For the fusion alpha-particle measurements the 2-D gamma cameras could be used, however, the gamma-ray detectors should be protected against harsh neutron emission with special neutron attenuators. That is why the results of the LiH-attenuator test on JET are very important for the development of the gamma-ray system in ITER. The Gamma Cameras could be integrated inside the radiation shielding of the radial and vertical neutron cameras, and,

which have the same type of the fan-shaped viewing geometry. It would be appropriate to have a separate line-of-sight for each gamma-ray detector module with two adjustable collimators and intermediate flight tube, which would allow gamma-ray measurements over the wide dynamic range of ITER operation. The collimators could be individually rotatable to set an appropriate collimation and neutron/gamma suppression depending on experimental priorities.

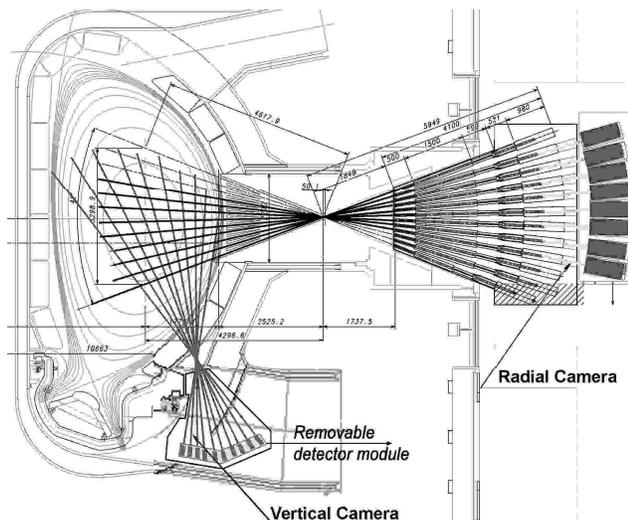


Fig.2. Possible arrangement of the gamma-ray spectrometer system in the channels of Radial and Vertical Neutron Cameras in ITER.

The absence of vertical ports on ITER makes it much more complicated to develop the implementation of tomographic neutron and gamma-ray reconstruction systems. At the moment it is suggested to use a divertor port for vertical viewpoint implementation.

Strong magnetic field (order of 2T) in the divertor port makes it hardly possible to use conventional multi-dynode photomultipliers as light detectors in vertical neutron and gamma detection systems, so it is suggested to use micro-channel plate photomultipliers instead. It has been carried out investigations of magnetic field impact on the performance of the gamma-spectrometer with the micro-channel photomultiplier used as a light detector. Recent tests of micro-channel plates (MCP-PMT) gave encouraging results. $\text{LaBr}_3(\text{Ce})$ detector with MCP-PMT has shown capability for spectrometric measurements in the 1.8T magnetic field (see Fig.3). The Ioffe cyclotron magnet was used in the tests as a source of magnetic field. In spite of worse energy resolution in comparison with conventional PMTs (by a factor of 2 approximately) MCP-PMTs give a chance to arrange the tomographic measurements in ITER.

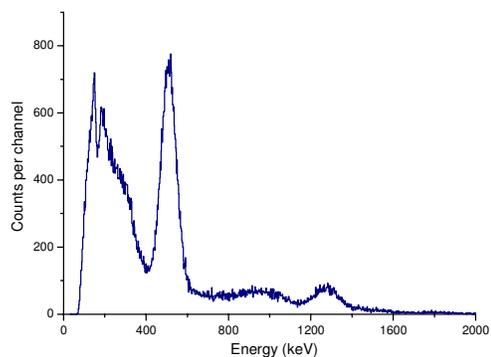


Fig.3. Spectrum of radioactive source ^{22}Na (511 and 1275 keV gamma-lines) measured by $\text{LaBr}_3(\text{Ce})$ detector with MCP-PMT in the magnetic field of 1.8T.

V. CONCLUSIONS

After 20 years of studies the gamma-ray spectrometry provides an effective tool for studies of fast ions behavior in the hot tokamak plasmas. This method is unique nowadays, which can get information about density and energy distribution of alpha-particles in the thermonuclear tokamak plasmas. Systematic studies of fast ions behavior at JET together with important technological and methodical developments of Ioffe Institute make a basis for realization of the gamma-ray spectrometric diagnostics in ITER.

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