Development of Gamma-ray Diagnostics for ITER.

I.N. Chugunov 1), A.E. Shevelev 1), D.B. Gin 1), V.G. Kiptily 2), G. Gorini 3), M. Tardocchi 3), D.N. Doinikov 1), V.O. Naidenov 1), E.M. Khilkevitch 1)

1) Ioffe Physical-Technical Institute of the Russian Academy of Sciences, St.-Petersburg, 194021, Russian Federation
2) EURATOM / CCFE Fusion Association, Abingdon, OX14 3DB, United Kingdom
3) Associazione EURATOM-ENEA sulla Fusione, IFP Milano, Italy

e-mail contact of main author: Chugunov.cycla@mail.ioffe.ru

Abstract. 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 α-particles and other ions (H, D, T, ^{3}He), to obtain its relative densities and also to perform tomographic radial profile reconstruction of the gamma-emission sources. Vertical ports absence in ITER makes much more complicated to develop the implementation of tomographic neutron and gamma-ray reconstruction systems. At the moment it is suggested to use divertor port for vertical viewpoint implementation. Strong magnetic field (order of 2T) in 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. Since developed in Ioffe Institute high speed technique of detector pulse height analysis allows tracing of changing in the photomultiplier gain, these tests demonstrated feasibility of using the micro-channel photomultiplier based detectors for gamma spectrometric measurements in the divertor port zone.

1. Introduction

The investigation of fast ions, especially alpha-particles, behavior is of crucial importance for large tokamaks. Particularly, this problem is important for international thermonuclear reactor ITER. Since gamma-ray spectroscopy based on detection of nuclear levels de-excitation gamma quanta resulted from reaction in plasma with ions in MeV energy range, this diagnostics makes possible to fulfill the specified task. 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, ^{3}He), to obtain its relative densities and also to perform tomographic radial profile reconstruction of the gamma-emission sources. Gamma-ray spectra time dependence analysis allows obtaining dynamics of the mentioned parameters during the discharge.

Principles of gamma-ray diagnostic technique were described elsewhere [1-3]. Three types of nuclear reactions may be noted for diagnostics are: reactions between fuel nuclei (H, D, T, ^{3}He), interaction between fast charged particles (p, d, t, α, ^{3}He) and plasma impurities (^{9}Be, ^{12}C) and reactions with specially doped impurities (^{10}B, ^{11}B, ^{7}Li).

There are three sources of fast particles that can give rise to a gamma-ray emission from fusion plasmas. Firstly, fusion reactions between the plasma fuel ions produce fusion products such as fast tritons, protons, ^{3}He and ^{4}He ions with energies in the MeV-range. Secondly, ICRF heating of H, D, T, ^{4}He and ^{3}He-minority ions accelerates these ions to energies in the MeV-range . Thirdly, NBI heating introduces D, T, H, ^{4}He and/or ^{3}He ions.

The reaction ^{9}Be(α,nγ)^{12}C is the main for the fusion-born alpha-particle measurements, the significance of which was investigated in detail [4]. 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 exceeding 2 MeV.

Alpha-particles birth profile can be reconstructed basing on the tomographic measurements of 16.7 gammas from the reaction $D(t,\gamma)^5He$, which is the second branch of main thermonuclear DT reaction (γ/n branch ratio is $\sim 1.2*10^{-4}$ [5]).

Nuclear reaction gamma-ray diagnosis is one of the important techniques used on the JET tokamak for studying fast ions [2]. The intense gamma-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 gamma-ray emission spatial 2D-profiles are measured with the JET neutron/gamma profile monitor. Together, these provide information on the spatial distribution of fast ions and fast ion tail-temperature. For example, in the experiments with NBI and ICRF ^{4}He heating it was simultaneously reconstructed both gamma-ray emission profiles: corresponding to heated ^{4}He and fast D ions [6].

2. Gamma-ray diagnostics in ITER: possible solutions

In ITER the gamma-ray diagnostics could perform the same functions as on JET. The primary application of the diagnostics is time-resolved spatial measurements of gamma-rays to derive

(i) alpha-particle birth profile by means of reaction $D(t,\gamma)^5He$;
(ii) profile of fast confined alpha-particles - $^9Be(\alpha,n\gamma)^{12}C$;
(iii) fast ion confinement effects during ICRF or/and NBI heating;
(iv) bremsstrahlung hard x-ray profile for runaways.

For the fusion alpha-particle measurements the 2-D gamma cameras will be used with gamma-ray detectors protected against harsh neutron emission. The gamma cameras will be integrated with radiation shielding of the radial (RNC) and vertical (VNC) neutron cameras, and 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.

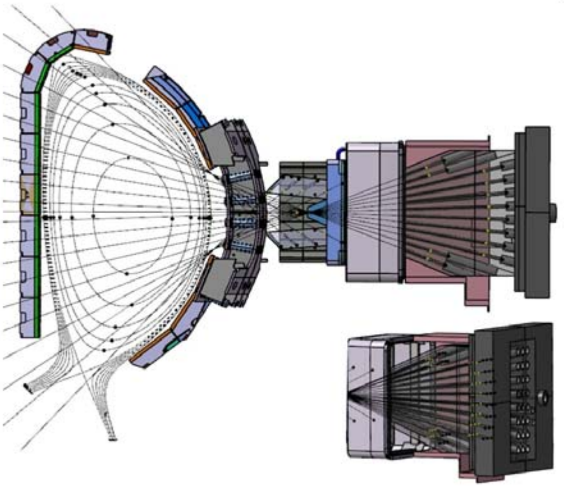

FIG.1. Radial Neutron Camera with an additional oblique view onto the outside of the portplug [7]

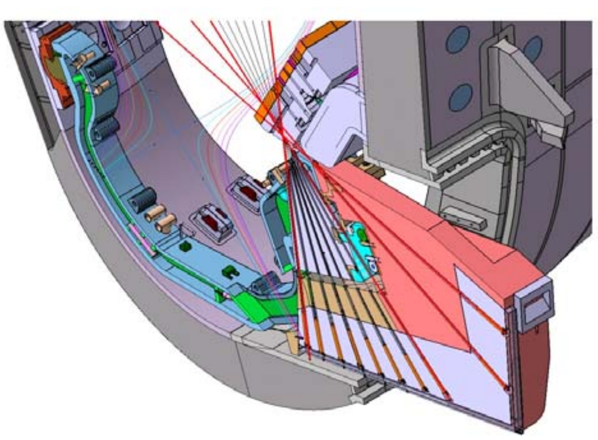

FIG.2. Vertical Neutron Camera mounted adjacent to a port at the lower level [7]

The radial neutron camera is designed by the EU team. The current ITER RNC layout consists of two sub-systems [7] based on fan-shaped arrays of cylindrical collimators in order to provide full plasma coverage (fig.1):

(a) an ex-port system with three sets of 12 lines of sight (LOS) embedded in a shielding block. Each set lies on a different poloidal plane: the central one (on-axis) passes through the torus axis while the other two (off-axis) are tilted toroidally of ±2° with respect to the central one.

(b) an in-port system composed by nine LOS distributed in three removable cassette systems.

It is proposed to use ten off-axis LOS in the ex-port RNC for gamma-ray measurements. The gamma-ray detector modules could be integrated to the flight tubes individually or behind the neutron detector modules. In order to protect the gamma-ray detectors from intensive neutron radiation the collimators in front of the gamma-ray detectors must be plugged by special neutron attenuators (see bellow).

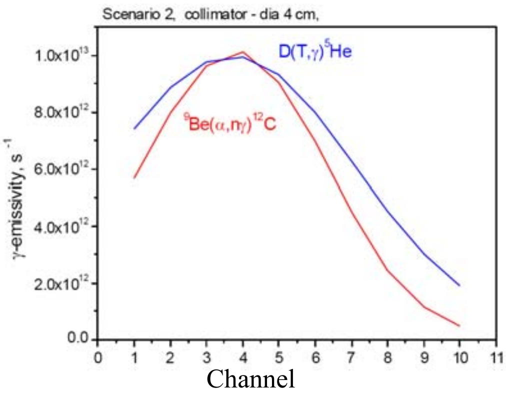

FIG.3. Calculated radial profiles of 4.44-MeV and 17-MeV gamma-ray emissions [8]

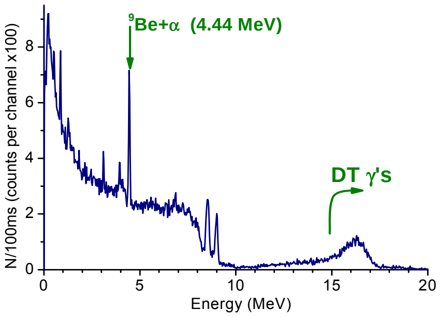

FIG.4. Gamma-ray spectrum, which could be measured from ITER DT plasmas (500 MW). MCNP calculations.

Fusion alpha-particle diagnostics is based on $D(T,\gamma)^5He$ and $^9Be(\alpha,n\gamma)^{12}C$ reactions. The main idea of this technique consists of a comparison of both the 3.5 MeV alpha-particle birth profile (17-MeV gamma-rays) and profile of the confined alpha-particles slowed-down up to 1.7 MeV (4.44 MeV gamma-rays). The radial profiles of 4.44 MeV and 17 MeV gamma-ray emissions calculated on the base of the modeling with Fokker-Planck code for standard H-mode (ITER plasma scenario #2) [8] are presented in fig.3.

TABLE 1. Expected detectors loads, (LaBr3:Ce Ø7.6×15.2 cm, FEP, 100 ms)

No. of RNC Channel	No. of counts in the DT γ -peak (>15 MeV)	No. of counts in the FEP of the 4.44 MeV γ- peak
2	7290	1480
3	4410	990
4	5290	1240
5	5100	1220
6	6170	1420
7	6260	1360
8	6010	1170
9	6160	1020
10	4260	580
11	8260	880

Basing on these calculations, as well as on the 3D MCNP Monte Carlo calculations for the RNC [9], simulations of the gamma-ray spectra for the ITER scenario #2 were carried out in the Ioffe Institute. Expected gamma-ray spectrum, which could be measured by Ø7.6×15.2 cm $LaBr_3(Ce)$ detector (see bellow the information on this detector) in one of central channels, protected by ^{6}LiH neutron attenuator with 1m in length, during 100 ms of the ITER scenario #2 discharge, is shown in fig.4. 4.44 MeV gamma-ray peak, corresponding to the $^9Be(\alpha,n\gamma)^{12}C$ reaction and broad 17 MeV peak from a weak branch of DT fusion reaction are seen clearly in the spectrum. Expected detector's count rate in this regime is ~1 MHz. Estimated numbers of useful gamma events, registered by the $LaBr_3(Ce)$ detector in the full energy absorption peak (FEP) during 100 ms of the discharge, are represented in the Table 1. The statistics of the registered events in the FEP is satisfied to the ITER diagnostic requirements (100 ms time resolution with 10% accuracy). In order to improve the peak/background ratio the optimization of radiation shielding in the RNC is needed.

Because ITER does not have vertical ports it is difficult to measure the neutron and gamma-ray emission in a vertical direction, which is necessary for combination with the radial measurements for tomographic reconstructions of the neutron/alpha-particle source profile. Recently, a new concept for the vertically viewing camera was proposed [7], mounting a camera in a divertor port at the lower level. The plasma would be viewed through neutron windows in the vacuum vessel and through a slot in the triangular support that supports the Blanket Shield Modules at this level. The Blanket Modules may also have to be modified to enlarge the gap between them. This concept is currently under investigation. Neutron calculations will be carried out to evaluate the background induced on the scintillators (particularly on the activation of LaBr3:Ce), i.e. the signal-to-noise ratio, as well the nuclear heating of the ^{6}LiH attenuators.

3. Technical Approaches

In this Section we review main challenges, which we faced during the development of the Gamma-Ray Spectrometry system for ITER, and report about status of works carried out in the Ioffe Institute resolving these problems.

3.1 Neutron Attenuator

Environment of the hot plasma experiment in which gamma-ray measurements are to be carried out is a very challenging one. Neutron fluxes in the detector's installation places will reach $10^8 – 10^9$ cm^{-2}s^{-1}. For the reduction of the intensive neutron fluxes that lead to additional detectors load a ^{6}LiH neutron attenuator concept has been developed. The attenuator is a sealed cylindrical capsule with dimensions of Ø30 × 300 mm and 1-mm-thick walls, which is used for plugging the collimator (fig.5). The capsule contains lithium hydride (^{6}LiH) enriched up to 92% in ^{6}Li isotope and pressed into five pellets. The neutron attenuation factors provided by this filter were measured with a neutron generator in the modes

FIG.5. Photograph of the neutron attenuator

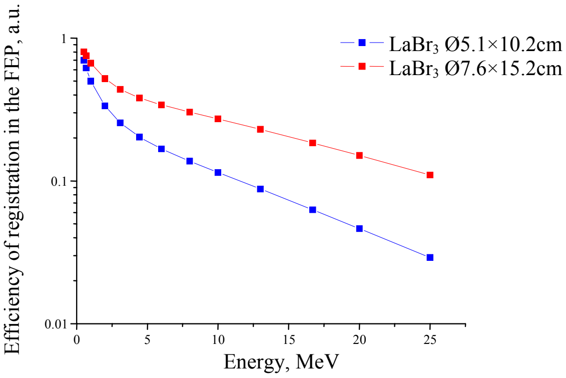

FIG.6. Energy dependences of $LaBr_3(Ce)$ detectors (dimensions Ø7.6×15.2 cm and Ø5.1×10.2 cm) efficiencies (for full energy absorption peak)

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 [10].

Gamma-ray measurements carried out on the JET tokamak have demonstrated the efficiency of the ^{6}LiH neutron attenuator in experiments with the DD plasma [11]. 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}LiH to gamma-rays with energies of a few MeV. It is planned to test the neutron attenuator in DT plasma experiment.

3.2 Fast Gamma-Ray Spectrometry

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.

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), 1μs for CsI(Tl)) makes them unusable for measurements in MHz count rate range. New heavy scintillators with densities from 5.3 g/cm^3 to 8.3 g/cm^3: LSO, LYSO, LuAP and $LaBr_3$(Ce) are now available for gamma-ray spectroscopy. The $LaBr_3$(Ce) - “BriLanCe” (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 gamma-ray spectrometry in the range of 2-30 MeV. Efficiencies of registration of high energy gamma-rays in the full energy absorption peak for $LaBr_3$(Ce) crystals with dimensions Ø3x6” (Ø7.6×15.2 cm) and Ø2x4” (Ø5.1×10.2 cm) were calculated using MCNP code(see fig.6).

Recently, two spectrometers based on new heavy scintillator $LaBr_3$(Ce) have been manufactured in the framework of project, which has been undertaken for modernization of JET gamma-ray spectrometer system[12]. This scintillator allows getting the high efficiency for the detection of energetic gammas and counting rate in the MHz range with perfect energy resolution. These detectors can be considered as a prototype of detector unit for Radial gamma-ray camera of ITER.

Achieved parameters of the $LaBr_3$:Ce spectrometers are:

- Crystals dimensions: 7.6 cm in diameter and 15.2 cm in length;
- Energy resolution 3.3 % for 662 keV gamma-rays;
- Scintillation decay time – 16 ns;
- Full energy absorption efficiency for 4.44 MeV gamma-rays : 38%.

Light output characteristics of new fast crystals allow getting the count-rate level, which is not possible to achieve using standard DAQs with conventional spectrometric ADCs. For the high count data processing it was proposed to use contemporary fast digitizers coupled with working in real time digital signal processing (DSP) nodes. This technique is capable of proceeding with amplitude analysis and separating superimposed pulses where it is needed, thus allowing avoiding loosing data within extreme high count-rate regions. In Ioffe Institute it was developed dedicated data acquisition and processing system suitable for high count rate gamma- measurements. First model of this system was tested on Ioffe cyclotron beam and on JET with NaI(Tl) and BGO scintillation detectors [13,14].

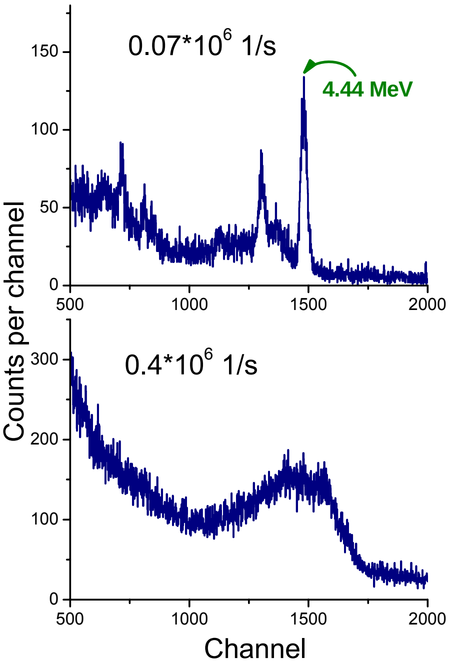

FIG.7. Spectra recorded by $LaBr_3(Ce)$ detector with conventional DAQ in experiments on cyclotron beam at different reaction rate

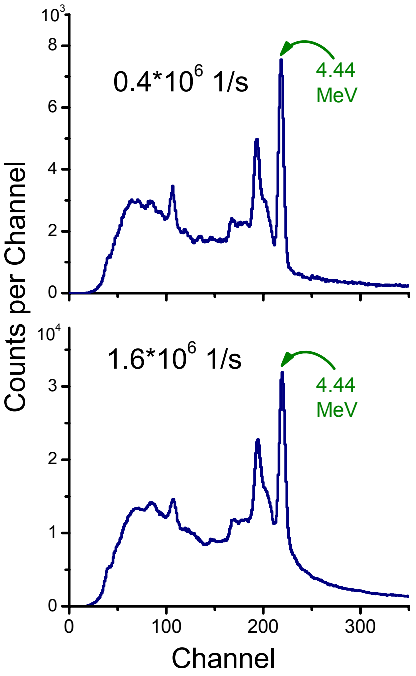

FIG.8. Spectra recorded by $LaBr_3(Ce)$ detector with new DAQ in experiments on cyclotron beam at different reaction rate

One of the big size $LaBr_3$:Ce detectors with new DAQ realized in the ATCA standard recently was tested in experiments on ion beams in the Ioffe Institute (Saint-Petersburg, RF) and in the National Institute of Physics and Nuclear Engineering IFIN-HH (Bucharest, Romania). Nuclear reactions $^{9}Be(\alpha, n\gamma)^{12}C$ and $^{27}Al(p,n\gamma)^{27}Si$ providing high gamma and neutron yields were used in these tests. These experiments have shown that the gamma-ray spectrometric system keeps its functionality at detector's loadings up to 2 MHz during continuous gamma irradiation and up to 5 MHz in the pulse regime of cyclotron operation. The figures 7-8 demonstrate advantages of the up-to-date DAQ use: the $LaBr_3(Ce)$ with conventional ADC lost its energy resolution at count rate of several hundred kHz (fig.7, bottom), while the detector with new DSP DAQ keeps its capability at the count rate of 1.6 MHz (fig.8, bottom). Analysis of the experimental data obtained in the Ioffe Institute and in the IFIN-HH is in progress now.

3.3 Detectors for the Vertical Gamma Camera

Strong magnetic field (order of 2T) in 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 (MCP-PMT) instead. In order to compare performance of these approaches it was manufactured prototypes of two gamma-ray spectrometers: one based on the conventional and another on micro-channel photomultiplier. In these tests the detector with Ø3×3 cm $LaBr_3(Ce)$ crystal and Ø1.8 cm MCP-PMT has shown acceptable for gamma-ray spectroscopic measurements energy resolution of 15% (for 662 keV line). 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. For magnetic field generation it was used Ioffe cyclotron magnet with maximum possible field value of 1.75 T. The test bench manufactured allowed changing the angle between field direction and detector axis in the range of $\pm 20^0$ with accuracy not worse than 0.2^0. For the specified angle range it has been found change in detector amplification gain by a factor of 2.5 (fig.9). At the same time no energy resolution dependence on this angle range was observed (fig.10) . Since developed in the Ioffe Institute high speed technique allows tracing of changing in the photomultiplier gain, these tests demonstrated feasibility of using the micro-channel photomultiplier based detectors for gamma spectrometric measurements in the divertor port zone.

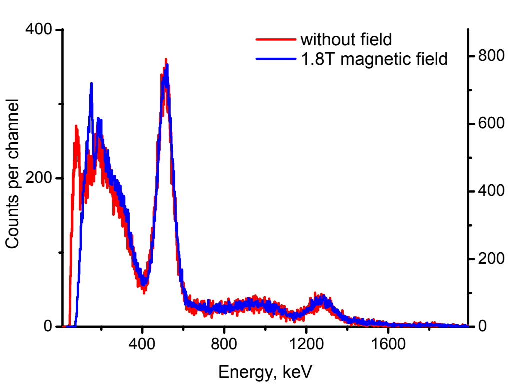

FIG.9. 22Na (511and 1275keV γ's) spectra measured with and without magnetic field

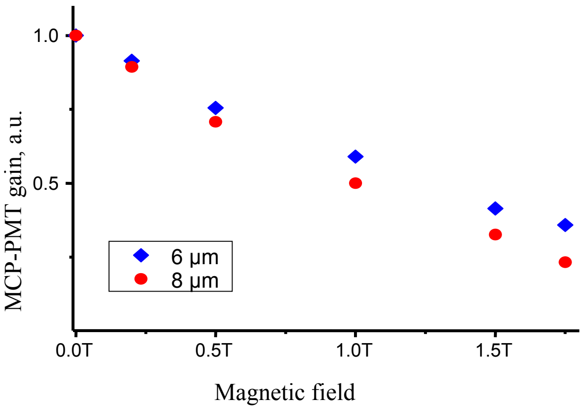

FIG.10. Dependence of the MCP-PMT gain (a.u.) from value of magnetic field (T)

Temperature tests of the gamma-ray detector with MCP-PMT were carried out by means of registration of gamma-ray spectra at different temperatures. Spectra were measured by spectrometric set-up. Positions of the detector in the thermostat dry chamber and radioactive source relative to the detector were fixed during all series of measurements.

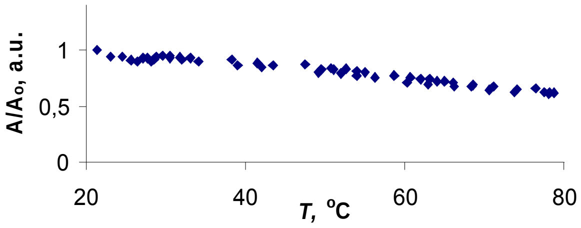

FIG. 11. Temperature dependence of the LaBr3+MCP detector's gain

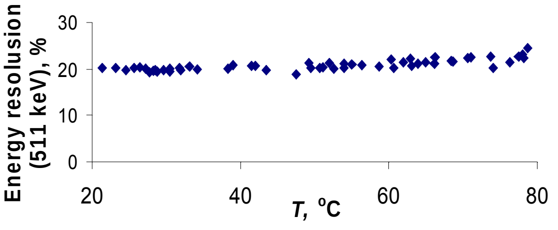

FIG.12. Temperature dependence of energy resolution of LaBr3+MCP detector

The temperature of the water heated external thermostat chamber was changed by tuning of the contact thermometer limits and the detector's temperature was measured by indications of precision centigrade temperature sensors LM35DZ. Shift of the gamma-ray line and changing of the energy resolution demonstrate the temperature influence on the detector. The detector's temperature test results are represented in the figs. 11 and 12. At the temperature increase above 75 ^{0}C an appreciable deterioration of the energy resolution is observed. The conclusion has been made, that the detector can be operable without cooling at temperatures up to 75 ^{0}C without noticeable changes of energy resolution. In the environment temperature of 160-180 ^{0}C the detector should be cooled down to the temperatures not exceeding 75 ^{0}C.

4. Conclusion

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, ^{3}He), to obtain its relative densities and also to perform tomographic radial profile reconstruction of the gamma-emission sources. Vertical ports absence in ITER makes much more complicated to develop the implementation of tomographic neutron and gamma-ray reconstruction systems. At the moment it is suggested to use divertor port for vertical viewpoint implementation, what give a chance to arrange tomographic gamma-ray measurements. But environment conditions in the divertor port is much more difficult for the detector operations than in the RNC due to high magnetic fields, high temperature and intensive neutron radiation. In order to satisfy these conditions the following prototypes of the ITER Gamma-Ray Spectrometry System's key elements have been manufactured and tested:

- LiH neutron attenuator;
- fast data acquisition system, which made it possible to extend the count rate range by an order;
- MCP-PMT detectors, capable of proceeding with measurements in conditions of up to 1.8 T magnetic field and 75 ^{0}C temperature.

This provides good basis for the development of vertical tomographic viewpoint for the Gamma-Ray diagnostics in ITER. Our future plans includes development of the Conceptual Design B13 for the Vertical Gamma Camera.

Acknowledgements

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