

CONFERENCE PRE-PRINT

**USE OF NUCLEAR SPECTROMETRY TO MONITOR
FUSION RATE, FAST PARTICLES AND RUNAWAY
ELECTRONS IN TOKAMAK PLASMAS**

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Abstract

The article is devoted to the study of energetic particle distributions using nuclear spectrometry methods based on measurements of neutron and gamma radiation fluxes, as well as charged particles emitted from the plasma onto the wall of the tokamak chamber. The Ioffe Institute has developed the DeGaSum software package, which provides a comprehensive suite of functions for the analysis of spectrometer signals. These functions include the control of detector signal recording devices, primary signal processing including amplitude analysis using the pulse shape discrimination function, separation of piled-up pulses, reconstruction of the initial energy distributions of radiation using pre-calculated or measured detector response functions, reconstruction of plasma parameters, such as the fusion reaction rate or the energy distribution of fast ions and runaway electrons, communication with the plasma control system and the global tokamak data acquisition system that initiates signal recording, and calculation of the synthetic detector signal using the calculated energy particle distributions, plasma parameters, and spectrometer response functions. The DeGaSum software package was utilized to control diagnostic systems on the FT-2, TUMAN-3M, GLOBUS-M2, ASDEX Upgrade, JET, and EAST tokamaks. The software will form the basis for the development of gamma-ray diagnostic control systems for the ITER and BEST tokamaks. The algorithms implemented in the DeGaSum software package for the reconstruction of fast particle distributions will be used in the construction of synthetic diagnostics on these tokamaks. The program can be adapted for utilisation in the plasma control system, with a primary focus on the monitoring of the fusion reaction rate. The basis of this measurement is the observation of 17 MeV gamma quanta from D+T and D+³He reactions. Additionally, the program has the capability to control the generation of runaway electrons.

1. INTRODUCTION

As research progresses towards achieving the target plasma parameters for controlled thermonuclear fusion, the role of nuclear physics methods for plasma diagnostics and nuclear technologies is increasing. This phenomenon can be attributed to the presence of energetic particles in the plasma, which accumulate a substantial proportion of the plasma energy. Energetic particles are ions of fusion fuel, NBI injected into plasma and/or accelerated as a result of ICRF heating, fusion products such as protons and alpha particles, as well as runaway electrons (RE) in the sub-MeV and MeV range. The study of the behavior of energetic particles is facilitated by nuclear spectrometry methods, which are based on measurements of neutron and gamma-ray fluxes, as well as charged particles that escape from the plasma to the tokamak chamber wall. It is evident that a variety of particles, including neutrons, gamma-rays and charged particles, can be generated in a plasma due to nuclear reactions between various components of nuclear fuel, such as H, D, T, ³He, and also reactions involving plasma impurities,

including Be, B and C, amongst others. The presence of fast particles in plasma is attributed to the regimes that are characterized by additional heating, as well as nuclear reactions that take place in the plasma. Information pertaining to alpha particles generated in fusion reactions, and the rate of such reactions, is of particular importance. Experiments on the JET tokamak with D-³He and DT plasma have demonstrated the ability of gamma and neutron measurements to provide this important information [1, 2]. In order to ensure the safe operation of fusion facilities, it is essential to monitor the generation of runaway electron beams. This can be achieved by measuring the hard X-ray fluxes from the tokamak chamber. The present article discusses the principles of fusion plasma diagnostics based on nuclear spectrometry methods using the DeGaSum software package [3-5].

2. EXPERIMENTAL EQUIPMENT

The use of highly efficient scintillation detectors employing heavy inorganic scintillators is a critical component in the design of gamma and HXR spectrometry systems for the diagnosis of fusion plasma in tokamaks. In the past, NaI(Tl) and BGO spectrometers were the mainstay of the field; however, over the last decade, LaBr₃(Ce) has become the scintillator of choice in gamma-ray diagnostic systems. This is due to its high light output (165% of NaI(Tl)) and fast decay time (~20 ns), which allows spectra to be measured at high counting rates (up to $\sim 3 \times 10^6$ 1/s) with a high energy resolution of ~3%. However, the high light yield of LaBr₃(Ce) also has a disadvantage: in plasma physics experiments, gamma-ray spectra are measured over a wide energy range (up to ~20 MeV). The presence of high-energy gamma-rays in the crystal results in a powerful flash of light, which depletes the bi-alkali layer of the photocathode with electrons. This, in turn, reduces the photoelectron emission coefficient. This results in distortion of the detector pulse shape and nonlinearity of the photomultiplier tube (PMT) gain. Another problem with spectrometric measurements using scintillation detectors is the sensitivity of traditional PMTs to the action of a magnetic field, which manifests itself in the loss of PMT gain stability during plasma discharge. This issue has been identified as a problem for both scintillation gamma spectrometers and compact neutron spectrometers that utilize organic scintillators, including NE-213, BC-501A, and stilbene. The resolution to this issue can be found in the utilization of semiconductor SiPM (Silicon Photomultiplier) photodetectors, which demonstrate insensitivity to the effects of magnetic fields. In recent years, there has been a notable advancement in this field, with SiPMs being used in plasma facilities for both gamma-ray detection [6] and neutron spectrometry [7]. The most promising for utilization in plasma experiments are SiPMs with minimal silicon cell sizes (10-20 μm) and short recovery times after photon detection, which, in an ideal scenario, should not exceed the scintillation decay time.

The Ioffe Institute has many years of experience in developing spectrometric equipment for gamma-ray diagnostics of tokamak plasmas. The experience gained has shown that neutron and gamma-ray spectrometers must be calibrated, characterized and tested across the full energy and load ranges, and under the conditions expected in thermonuclear experiments, before they can be installed on tokamaks. The energy range for gamma spectrometers is at least 0.1–20 MeV, and for neutron spectrometers it is 0.1–15 MeV. The count rate in spectrometric mode is at least 10^6 s^{-1} for both types of diagnostics. In order to ensure the successful measurement of the gamma spectrum in conditions of high neutron flux, it is essential that gamma spectrometers are protected by neutron attenuators. Lithium hydride is considered the optimum material for use in such attenuators, due to its high coefficient of absorption and scattering of neutrons, whilst simultaneously being relatively transparent to high-energy gamma-rays.

The data acquisition (DAQ) systems in contemporary neutron or gamma-ray spectrometers are based on the use of high-rate digitizers that record signals at high sampling rates. In order to record the signal from a LaBr₃(Ce) detector, it is necessary to use a sampling rate of at least 200 MHz. In contrast, organic scintillators utilized in compact neutron spectrometers necessitate a recording frequency of at least 500 MHz. The detector signal can be processed on an FPGA in real time, or alternatively, the oscillogram can be recorded in memory for post-processing. The second option is preferable, given that during plasma radiation measurements, spectrometers frequently operate in high counting rate mode, thereby recording a substantial proportion of piled up pulses. The digital processing of the oscillogram facilitates a comprehensive analysis of the signal, including the separation of piled up pulses and the accounting of unresolved events. The realization of the algorithms was accomplished through the development of the DGaSum program package.

3. DEGASUM SOFTWARE PACKAGE

The Ioffe Institute has developed the DeGaSum (Deconvolution of Gamma Spectrum) software package [3-5], which provides a complete cycle of work with detector signals, namely:

- The control of detector signal recording devices;
- Primary signal processing, which includes pulse-height analysis using pulse-shape discrimination procedure, the separation of piled-up pulses, the use of n-gamma separation procedure in the case of neutron detector signal processing, the creation of time-amplitude array taking into account unresolved events, and the plotting amplitude spectra for any time interval of discharge;
- Reconstruction of energy distributions of radiation using pre-calculated or measured detector response functions;
- Reconstruction of plasma parameters, such as fusion reaction rates and fast ion/runaway electron energy distributions, using general plasma parameter data provided by other diagnostic systems or calculated using plasma physics codes;
- Communication with the plasma control system and the tokamak's global data acquisition system, which initiates signal recording;
- The calculation of the synthetic detector signal using the calculated distributions of energetic particles, plasma parameters, and spectrometer response functions.

Fig. 1 shows a block diagram of the monitoring of plasma parameters related to the presence of energetic particles by a spectrometric system controlled by the DeGaSum package.

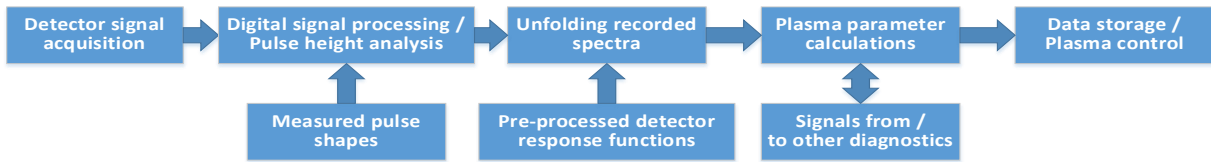


FIG. 1. Block diagram of plasma parameter monitoring using the DeGaSum package

The DeGaSum package programs are written in the C++ programming language. It is possible to compile the programs for both the Linux and Windows operating systems (XP and above). The package incorporates the executable file `degasGui.exe`, which provides a graphical user interface, the executable file `DGS-Cli.exe`, which provides a command line interface, and a set of shared libraries that facilitate interaction with various ADCs and data acquisition systems.

3.1. Signal acquisition

The primary function of the DeGaSum software package is to control the digital signal acquisition devices of spectrometers, which utilize digitizers that record signal waveforms with a high sampling rate. The signal can be recorded in its entirety to a hard drive or SSD, or in a so-called "segmented" mode, in which only those parts of the oscillogram containing information about recorded events with an amplitude exceeding a preset threshold value are saved to the computer drive. In the case of measurement modes with a relatively small number of piled up pulses, the oscillograms can be processed in real time, or, in the case of the detector high load, in offline mode.

The initiation of signal recording by the spectrometer can be executed manually (via software start) or by an external signal from the synchronization system. Data can be recorded on either a local computer hard drive or a network drive. Depending on the configuration of the data acquisition system on a specific tokamak, data can be transmitted to a remote, centralized tokamak database. The DeGaSum program has been successfully used to control the signal recording devices of gamma-ray spectrometers in experiments conducted at the JET (UK) [1] and ASDEX Upgrade (Germany) [8] tokamaks. At the TUMAN-3M and GLOBUS-M2 (Russia), DeGaSum is used to control HXR spectrometers, neutron organic scintillation spectrometers, ^{10}B and ^3He neutron counters, a U-235 fission chamber, and a Si detector that collects proton fluxes from the DD fusion reaction on the tokamak chamber wall. At the EAST tokamak (China), DeGaSum is utilized for the control of three scintillation gamma-ray spectrometers, analogous to those that are to be installed at ITER and BEST.

In order to enable primary signal processing with amplitude spectrum construction, the program `degasGui`, which is equipped with a graphical interface, incorporates a range of algorithms designed to perform pulse height analysis. These include pulse shape fitting, pulse maximum finding, signal deconvolution, and pulse area integration [9]. In the context of signal processing from scintillation detectors, the deployment of fitting and deconvolution algorithms facilitates the separation of piled up pulses and the accounting of unresolved events [5,9]. In order to undertake this process, it is first necessary to describe the pulse shape mathematically, or alternatively, to obtain the shape by averaging a large number of pulses. As demonstrated in Fig. 2, the pulse of a

LaBr₃(Ce) detector with a SiPM photodetector was recorded at a sampling rate of 500 MHz and described mathematically. The employment of a trapezoidal filter is recommended in instances where the processing of signals from HPGe detectors is required.

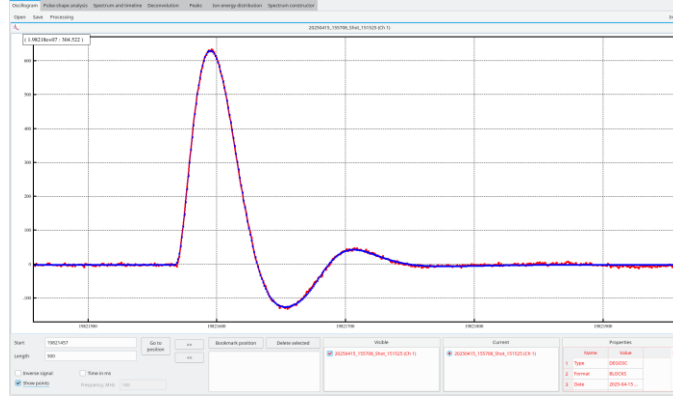


FIG. 2. Fitting the pulse shape of a LaBr₃(Ce) detector with a SiPM using the DeGaSum program

During the process of digital signal processing, DeGaSum calculates the deviations of measured pulses from a given shape and subsequently classifies events as either resolved or unresolved. The correct operation of the program can be visually monitored based on a selected signal fragment. In instances where the signal comprises events exhibiting disparate pulse shapes, such as in scenarios where neutron and gamma events are recorded by neutron scintillation spectrometers, the program employs a pulse shape discrimination technique [10]. Subsequent to primary signal processing and pulse height analysis, DeGaSum generates a data array in time-amplitude format, accounting for the number of unresolved events. This array can be utilized to plot the amplitude distribution of events with a specific pulse shape for any selected time interval of signal recording, corrected by the number of unresolved events.

Subsequent to the execution of pulse shape analysis and amplitude analysis with the formation of a time-amplitude array, the amplitude distributions are displayed in two windows. The first shows the amplitude spectrum for the selected measurement time, while the second shows the time dependence of the number of recorded events for the selected energy range. Therefore, the program is able to function as a multichannel analyzer. The capacity to construct spectra for any designated time interval is a possibility. Conversely, it is possible to display the measurement of signal intensity over time in any energy distribution interval. The data is displayed for resolved events, corrected by unresolved ones. A graphic interface from DeGaSum is used to calibrate the energy of spectra. Two approaches are available for calibration: the first, linear calibration, involves the use of two points, and the second, non-linear calibration, employs second- and third-order polynomials with multiple points for fitting. Calibration involves implementing a procedure that uses an approximation of the peak shape to identify the channel number of the peak maximum. Procedures are also available for subtracting one spectrum from another (background subtraction) and for summing multiple spectra. It is possible to perform spectrum correction based on the analysis of reference pulse amplitudes when using a light-emitting diode to periodically illuminate the detector's PMT. Additionally, the program facilitates the construction of spectra in multi-detector operations in coincidence mode and time-of-flight measurements.

3.2. Reconstruction of the initial radiation spectra and runaway electron distribution function

Plasma diagnostics using nuclear spectrometry involves not only recording neutron or gamma radiation spectra, but also reconstructing the distributions of the initial radiation emitted from the tokamak plasma. However, neutron and gamma spectrometers have a complex response to monoenergetic radiation, making the analysis of their instrumental spectra difficult. Spectrum reconstruction algorithms have been implemented in the DeGaSum program to reconstruct the distributions of the initial radiation. The ML-EM method [11] was used to reconstruct the gamma and neutron radiation spectra recorded during hot plasma experiments. The spectrum $y(\varepsilon)$, as measured by the detector, can be represented as follows:

$$y(\varepsilon) = \int_0^{\infty} x(\varepsilon')h(\varepsilon, \varepsilon')d\varepsilon' + n(\varepsilon),$$

where x represents the initial spectrum of gamma rays or neutrons, h is the detector response function, n represents noise and ε represents the energy of gamma rays or neutrons. The application of deconvolution methods to gamma-ray and neutron spectrum analysis using the DeGaSum program is detailed in [3, 5, 10]. Reconstructing the initial radiation distribution requires detailed knowledge of detector response functions. These functions can be calculated using a Monte Carlo code (e.g. MCNP, GEANT4 or OpenMC) or measured experimentally. The latter approach was employed during the calibration of compact neutron spectrometers based on the BC-501A liquid scintillator at the Ioffe cyclotron [10]. When reconstructing the distributions of gamma radiation emitted by the tokamak plasma, the response functions are typically calculated using the MCNP code in the energy range of 0.1–30 MeV, with an energy bin size of 0.1 MeV.

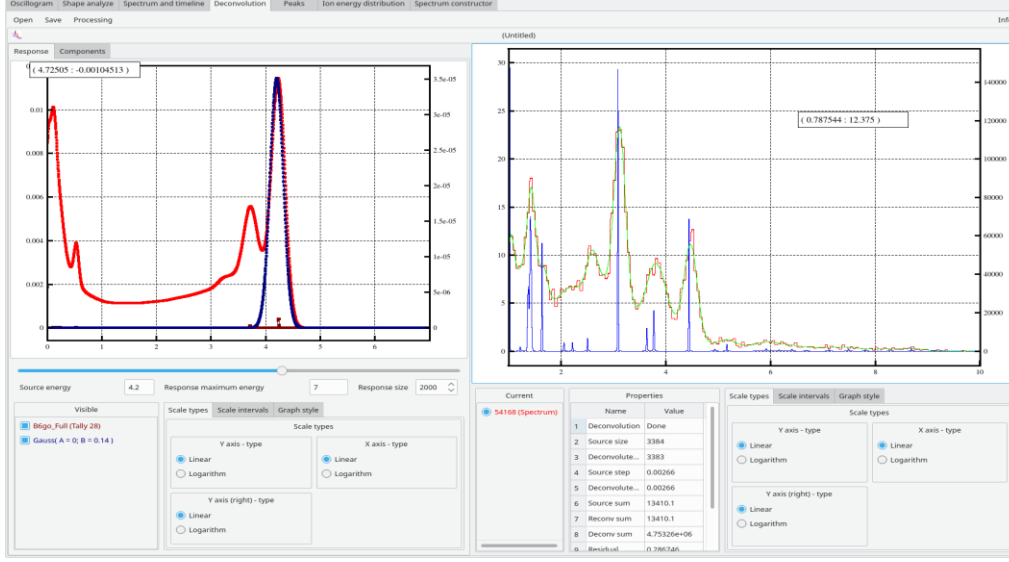


FIG. 3. Reconstruction of the gamma-ray spectrum from the tokamak plasma using the DeGaSum program. On the left is an example of a detector response function with Gaussian blurring for monoenergetic radiation, and on the right is the gamma-ray spectrum recorded in the JET discharge (red line) and the reconstructed gamma distribution. The green line shows the result of convolving the reconstructed spectrum with the detector response functions

Fig. 3 shows the gamma-ray spectrum recorded by a BGO spectrometer during a JET discharge involving helium plasma with a deuterium minority, as well as the injection of a ^4He beam with ICRF heating at the $3\omega_{c4\text{He}}$ resonance frequency of ^4He . Due to the BGO detector's low energy resolution ($\sim 12\%$), the spectrum is difficult to analyze. Only two peaks can be identified: the 4.44 MeV peak, which corresponds to gamma radiation emitted in the $^9\text{Be}(\alpha, n\gamma)^{12}\text{C}$ reaction; and the 3.09 MeV peak from the $^{12}\text{C}(d, p\gamma)^{13}\text{C}$ reaction. After deconvoluting the measured spectrum using the DeGaSum program, the 3.68 and 3.85 MeV peaks from the $^{12}\text{C}(d, p\gamma)^{13}\text{C}$ reaction could be observed and their relative intensities measured. This information, in turn, enabled the energy distributions of d and α particles to be reconstructed based on the application of the Stix formalism for calculating the distributions of ions accelerated during the $3\omega_{c4\text{He}}$ ICRH [4].

The analysis of hard X-ray spectra arising from the deceleration of fast electrons on plasma ions, plasma impurities and materials of the first wall of the tokamak chamber is more complex case. To reconstruct the electron distribution in the plasma in this case, knowledge of the bremsstrahlung generation functions in the tokamak chamber is required in addition to the detector response functions. These functions can be calculated using the MCNP or GEANT4 code. The spectrum of bremsstrahlung $y(\varepsilon)$, caused by accelerated electrons and measured by the detector, can be represented as follows: [4–5].

$$y(\varepsilon) = \int_0^\infty d\varepsilon' h_d(\varepsilon, \varepsilon') \int_0^\infty d\varepsilon'' h_e(\varepsilon', \varepsilon'') f(\varepsilon'') + n(\varepsilon)$$

where f is the electron distribution function and h_e is the HXR generation function (i.e. the function describing the energy dependence of the probability density of bremsstrahlung emission in the direction of the detector during the passage of an accelerated electron with a given energy through the plasma volume visible to the detector), h_d is the detector's response function calculated by any Monte Carlo code; $n(\varepsilon)$ is noise and ε is the electron energy.

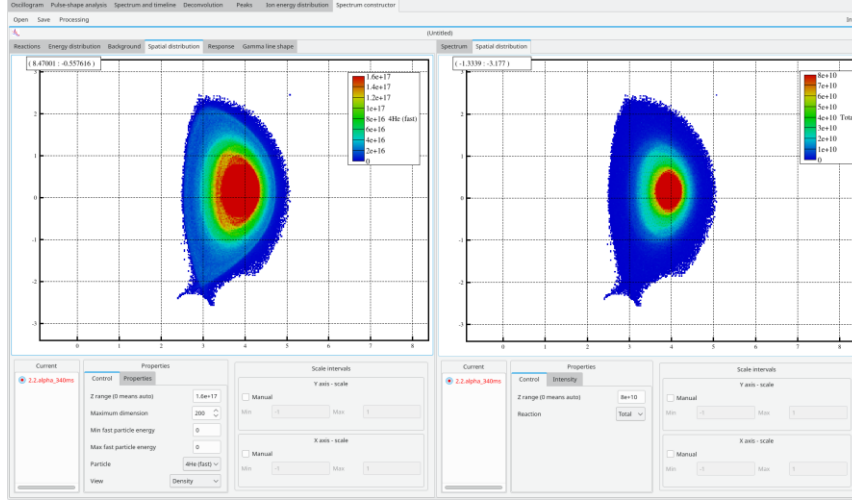


FIG. 5. Modelling of the gamma-ray source profile in the DeGaSum program. Left: Distribution of alpha particles expected to be generated in the BEST tokamak. Right: Profile of the 3.85 MeV gamma-ray source from the $^{10}\text{B}(\alpha, \gamma)^{13}\text{C}$ reaction

The program enables two-dimensional profiles of model distributions of fast particles to be built and the profiles of gamma radiation generated by them to be calculated. Fig. 5 shows an example of such a construction for the BEST tokamak discharge scenario with $Q \sim 1$.

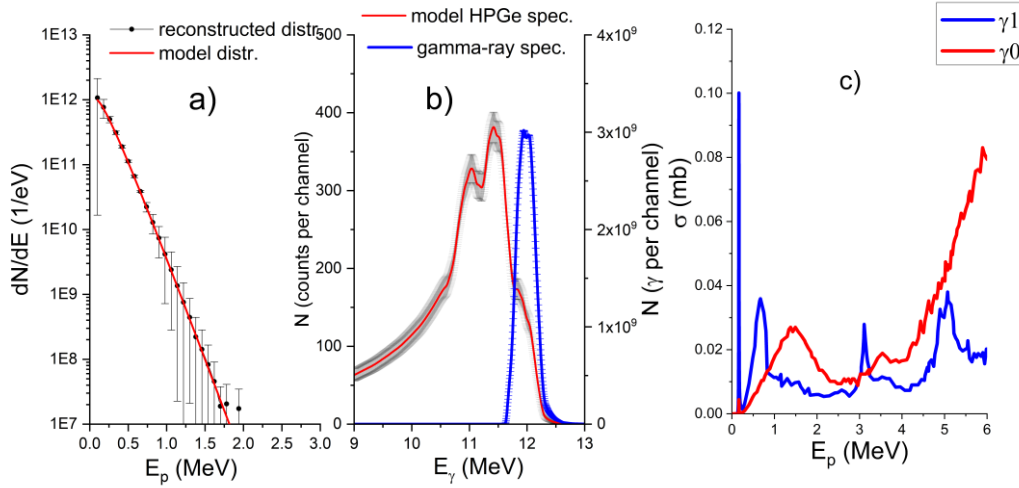


FIG. 6. Modelling of proton distribution in the ITER plasma and its reconstruction based on the model spectrum: a) Calculated proton distribution in the ITER plasma with ICRF hydrogen heating (red line), and distribution reconstructed by DeGaSum (black dots); b) Simulated gamma-ray distribution for the γ_1 emission of the ^{12}C nucleus from the ITER plasma (blue line); synthesized spectrum of the HPGe gamma detector (black line); and convolution of the reconstructed proton distribution with cross sections and detector response functions; c) Excitation functions of the γ_0 and γ_1 transitions of the ^{12}C nucleus, born in the $^{11}\text{B}(p, \gamma)^{12}\text{C}$ reaction.

Fig. 6 shows how synthetic gamma diagnostics, implemented by the DeGaSum program, can be used. The $^{11}\text{B}(p, \gamma)^{12}\text{C}$ reaction is interesting because it enables the distribution of fast protons in plasma containing boron impurities to be diagnosed, and because it allows the reaction rate of p- ^{11}B synthesis to be determined. Figure 6a shows the proton distribution calculated for the ITER scenario involving ICRF heating and a 1% hydrogen additive, in the presence of a 1% boron impurity. $P_{\text{ECRH}} = 40$ MW, $B = 2.65$ T, $I_p = 7.5$ MA, $n = 0.5 n_{\text{GW}}$, $P_{\text{ICRH}} = 10$ MW. Gamma radiation distribution from the plasma was simulated using the excitation functions of transitions to the ground (γ_0) and first excited states of the ^{12}C nucleus (Fig. 6c). Figure 6b shows the result of calculating the gamma radiation distribution during the transition to the first excited state of the ^{12}C nucleus (γ_1), with the blue line indicating this distribution. The black line shows the result of convolving this distribution with the response

function of the HPGe spectrometer: this is the expected gamma radiation spectrum for this transition that could be recorded in an ITER experiment. Reconstruction of this spectrum using the same detector response functions and gamma transition excitation function with the DeGaSum program produced the distribution of fast protons shown in Figure 6a as black dots.

4. CONCLUSION

Effective diagnostics of fusion plasma require the use of the latest fast, high-efficiency spectrometers and data acquisition systems with up-to-date software to control signal recording and digital processing. The task of adequately interpreting experimental data is also paramount, including using advanced algorithms to unfold radiation spectra to reconstruct the energetic particle distributions. The Ioffe Institute is developing new gamma-ray and neutron spectrometers, studying their characteristics over a wide energy range and taking measurements on a cyclotron beam. To control these spectrometers in thermonuclear experiments, the Ioffe Institute has developed the DeGaSum software package, which enables the entire diagnostic process to be managed, from controlling recording devices and primary signal processing to reconstructing the distributions of fast ions and electrons from the measured plasma radiation spectra. DeGaSum has been used to control diagnostic systems on FT-2, TUMAN-3M, GLOBUS-M2, ASDEX Upgrade, JET and EAST tokamaks. It will also form the basis for the development of gamma-ray diagnostic control systems on the ITER and BEST tokamaks. The DeGaSum software package algorithms for reconstructing fast particle distributions will be used in building synthetic gamma-ray diagnostics on these facilities. The program can be adapted for use in a plasma control system. This primarily involves monitoring the fusion reaction rate based on 17 MeV gamma-ray measurements from D+T and D+³He reactions. It also involves monitoring the generation of runaway electrons.

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

ACKNOWLEDGEMENTS

This work was funded in part under the State Contract No. N.4a.241.19.24.1024 dated 20.03.2024 between the State Atomic Energy Corporation Rosatom and the Institution “Project Center ITER”, and the Agreement between the Institution “Project Center ITER” and the Institute of Plasma Physics, Chinese Academy of Sciences (ASIPP).

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