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

[1]A.E. SHEVELEV, [1]E.M. KHILKEVITCH, [1]N.N. BAKHAREV, [1]O.M. SKREKEL, [2]Y. ZHANG, [2]X. WANG, [1]A.A. BOGDANOV, [1]D.N. DOINIKOV, [1,3]D.B. GIN, [1]S.V. LEBEDEV, [1]V.O. NAIDENOV, [1]A.S. NAVOLOTSKY, [1]S.YA. PETROV, [1]R.V. SOKOLOV, [1]R.YU. SHMITOV, [1]YU.V. TUBOLTSEV, [4]A.N. MOKEEV, [3]M.R. TURNYANSKIY

[1]Ioffe Institute, St Petersburg 194021, Russian Federation
[2]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei 230031, People's Republic of China
[3]ITER Organization, St. Paul-lez-Durance 13067, France
[4]Institution “Project Center ITER”, Moscow 123060, Russian Federation

E-mail: shevelev@cycla.ioffe.ru

As research progresses towards achieving the target plasma parameters for controlled fusion, the role of nuclear-physical methods of plasma diagnostic, as well as nuclear technologies, is increasing. This is due to the significant presence in the plasma of energetic particles that accumulate a significant fraction of the plasma energy. Energetic particles encompass ions injected into the plasma with NBI and/or accelerated by ICRF heating, fusion products such as protons and alpha particles, and runaway electrons (RE) in the sub-MeV and MeV range. Nuclear spectrometry, a technique based on measurements of neutron and gamma ray fluxes, as well as charged particles escaping from the plasma, is utilized to study energetic particle behaviour. The DeGaSum (Deconvolution of Gamma Spectrum) software package [1], developed at the Ioffe Institute provides a full cycle of work with spectrometer 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-g 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 (DAQ) system, which initiates signal recording;
- The calculation of the synthetic detector signal (direct problem solving) using the calculated distributions of energetic particles, plasma parameters, and spectrometer response functions.

Figure 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.

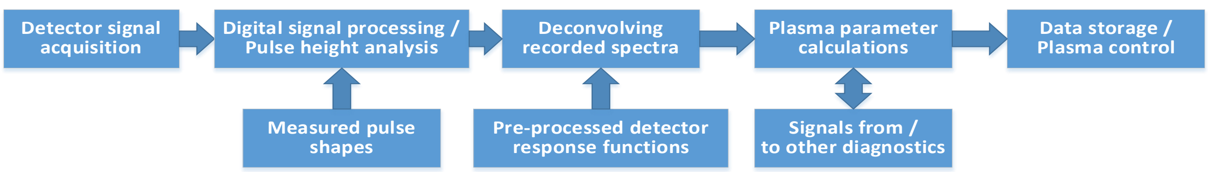

Figure 1 – Block diagram of plasma parameter monitoring using the DeGaSum package

The DeGaSum package is utilized for the following tasks:

- The fusion reaction rate in DT plasmas at the ITER and BEST tokamaks under construction can be controlled through measurements of gamma quanta born in the $T(d,\gamma)^5He$ reaction within an energy range of 15–17 MeV, where no background gamma radiation is induced by 14 MeV neutrons. In $D–^3He$ plasmas, analogous measurements in this range of gamma rays from the $^3He(d,\gamma)^5Li$ reaction may offer the sole opportunity to ascertain the fusion reaction rate. Furthermore, measurements of gamma quanta born in the $^{11}B(p,\gamma)^{12}C$ reaction with energies of 4.44, ~11.5 and ~16 MeV can be used to monitor the fusion rate in p-^{11}B plasmas;

- Reactions involving plasma impurities such as ^{10}B can be used to monitor the distributions of alpha particles, the fusion products. An analysis of the 3.09, 3.68, 3.85 MeV gamma line shapes from the $^{10}B(\alpha,p\gamma)^{13}C$ reaction measured by high-precision semiconductor HPGe spectrometers can be used for this purpose;
- The distributions of injected and ICRF-accelerated particles can be monitored by measuring the intensities of gamma-ray lines from reactions with plasma impurities such as $^{11}B(d,n\gamma)^{12}C$;
- The monitoring of runaway electrons, which is a crucial task to ensure the safe operation of tokamaks, is performed by measuring bremsstrahlung fluxes with gamma-ray spectrometers. For this purpose, the measured Hard X-Ray (HXR) spectra are deconvoluted with DeGaSum using pre-calculated gamma-ray spectrometer response functions and functions of HXR generation by electrons in interaction with plasma ions, impurities, and tokamak chamber materials;
- Control of a neutron detector DAQ, including the n/g pulse shape discrimination procedure and reconstruction of neutron spectra using measured or calculated detector response functions for scintillation detectors;
- Measurements of charged fusion product fluxes on the tokamak chamber wall by particle detectors whose signal recording is also controlled by the DeGaSum software package.

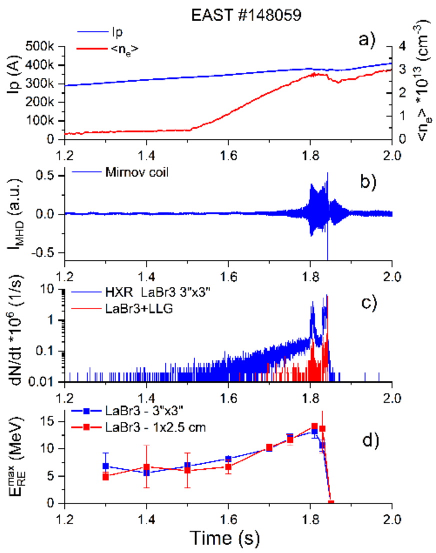

Figure 2 — EAST discharge #148059 signals: (a) plasma current (blue line), averaged electron density (red line); (b) MHD Mirnov sensor; (c) HXR count rate of $LaBr_3(Ce)$ Ø7.6×7.6 cm^2 spectrometer; (d) maximum RE energy reconstructed with DeGaSum code on the basis of measurements by Ø7.6×7.6 cm^2 and Ø1×2.5 cm^2 $LaBr_3(Ce)$ spectrometers

The DeGaSum package has been demonstrated to facilitate real-time digital signal processing of the $LaBr_3(Ce)$ gamma spectrometer at a sampling rate of 200 MHz and a count rate of up to ~10^6 s^{-1}, contingent upon the computer's performance capabilities. This facilitates the monitoring of the RE generation with a time resolution of less than 10 ms, as well as the fusion rate with a time resolution of 100 ms, which is consistent with the use of the signals by a plasma control system. DeGaSum was successfully used to control gamma-ray spectrometer signal recorders and data processing in the experiments on JET (UK) [2] and ASDEX Upgrade (Germany) [3]. At the TUMAN-3M and GLOBUS-M2 tokamaks (Russia), DeGaSum is used to control HXR spectrometers, neutron scintillation spectrometers, ^{10}B and ^{3}He neutron counters, the ^{235}U fission chamber, and measurements of escaping DD fusion proton fluxes by the Si detector. At the EAST tokamak (China), DeGaSum is used to control three gamma-ray scintillation spectrometers, similar to those to be installed at ITER [4] and BEST (see Fig. 2), and to test signal processing algorithms and synthetic gamma-ray diagnostics algorithms.

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).

REFERENCES

[1] A.E. SHEVELEV, et al., Reconstruction of distribution functions of fast ions and runaway electrons in fusion plasmas using gamma-ray spectrometry with applications to ITER, Nucl. Fusion 53 (2013) 123004.

[2] M. ILIASOVA et al., Gamma-ray measurements in D3He fusion plasma experiments on JET, NIM A 1031 (2022) 166586.

[3] A. SHEVELEV et al., Study of runaway electron dynamics at the ASDEX Upgrade tokamak during impurity injection using fast hard x-ray spectrometry, Nucl. Fusion 61 (2021) 116024.

[4] V.I. AFANASYEV, et al., Development of the NPA based diagnostic complex in ITER, JINST 17 (2022) C070019.