Use of nuclear spectrometry to monitor fusion rate, fast particles and runaway electrons in tokamak plasmas

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Abstract

- Modern neutron and gamma spectrometry systems are based on the use of highly efficient, fast scintillation detectors and semiconductor spectrometers equipped with modern data acquisition (DAQ) systems.
- The DeGaSum software package has been developed to control recording devices and perform in-depth analysis of spectrometer signals.
- DeGaSum enables the reconstruction of fast ion and electron distributions from measured gamma and neutron radiation.
- The program can be used in a plasma discharge control system.

Background

Sources of energetic particles in plasma:

- fusion products p(3 MeV, 15 MeV), T(1 MeV), ^{3}He(0.8 MeV), α (3.5 MeV)
- ICRF-driven ions: H, D, T, ^{3}He, ^{4}He
- Fast particles NB injected into the plasma
- "Knock-on" ions

Gamma-ray and neutron measurements provide information on fast particle distributions, alpha particles generated in fusion reactions, and the fusion rate.

Runaway electron diagnostics based on the HXR measurements is critical for machine protection

Methods and Challenges

Experimental equipment

Scintillation and semiconductor detectors are used in the nuclear spectrometry.

Figure 1 – HPGe detector combined with electrical cooler

- Energy resolution ~2 keV (on 1332 keV)
- Efficiency 70-80% vs. Ø76×76 mm NaI(Tl)
- Acceptable neutron fluence 10^{11}–10^{12} n/cm^2
- Electrically powered, completely maintenance free cooler

Challenges:

- High magnetic field → PMT gain instability
- High counting rate → significant portion of piled up pulses
- Wide energy range → Photomultiplier's gain nonlinearity

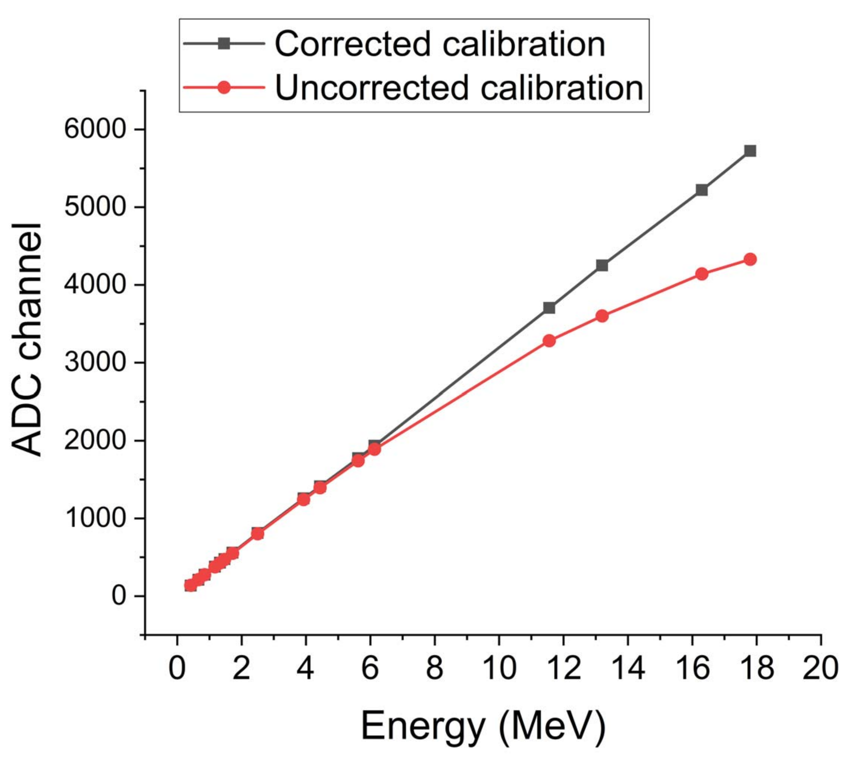


Figure 2 – Non-linearity of a LaBr$_3$(Ce)+PMT spectrometer calibration

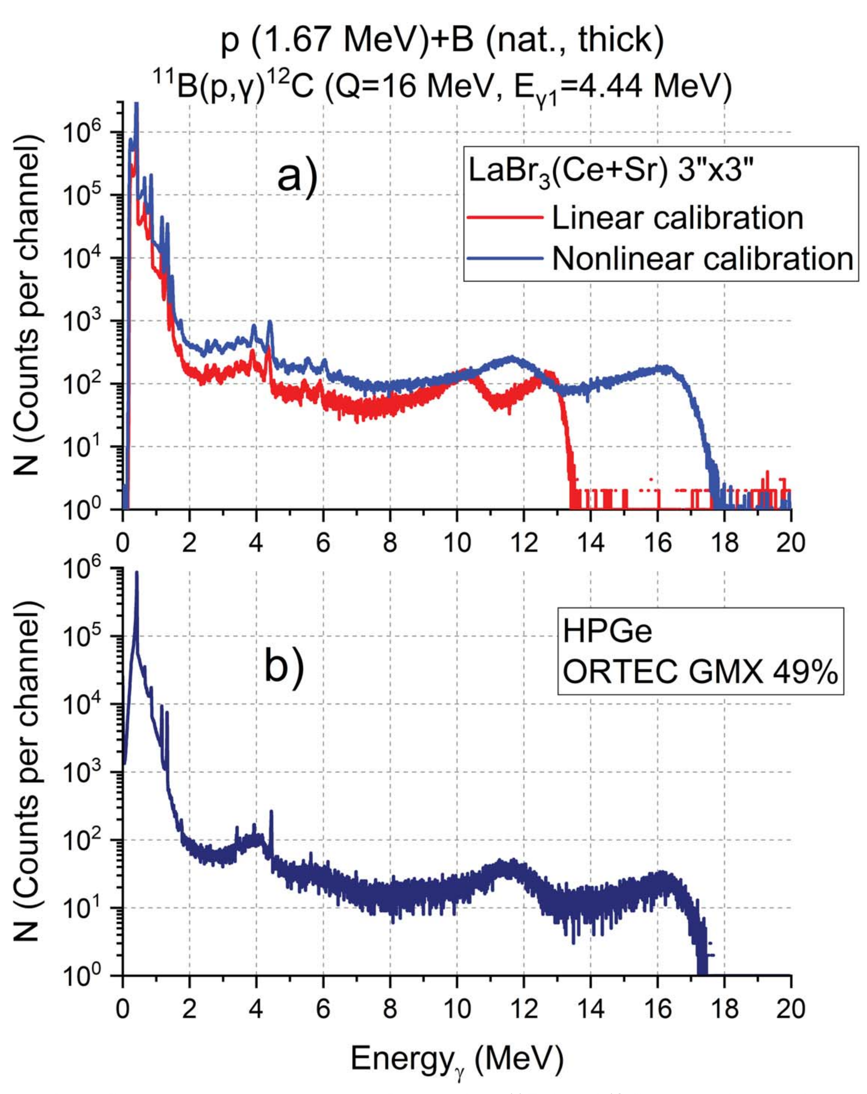


Figure 3 – Gamma-ray spectra from the ^{11}B(p,γ)^{12}C reaction: a) spectra measured by a LaBr$_3$(Ce+Sr) spectrometer with PMT using linear (red line) and non-linear (blue line) calibrations; b) spectrum measured by an HPGe spectrometer.

DeGaSum software package

Provides a complete 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 and the separation of piled-up pulses,
- 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;
- Communication with the plasma control system;
- The calculation of the synthetic detector signal

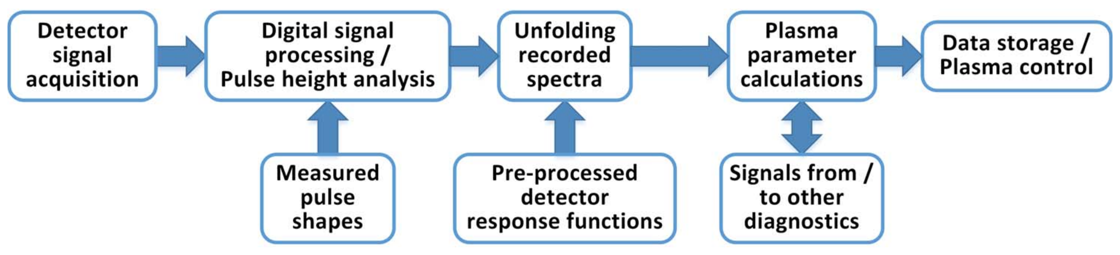


Figure 4 – Block diagram of plasma parameter monitoring using the DeGaSum package

Signal processing

DeGaSum incorporates a range of algorithms designed to perform pulse height analysis, including pulse shape fitting, pulse maximum finding, signal deconvolution, and pulse area integration.

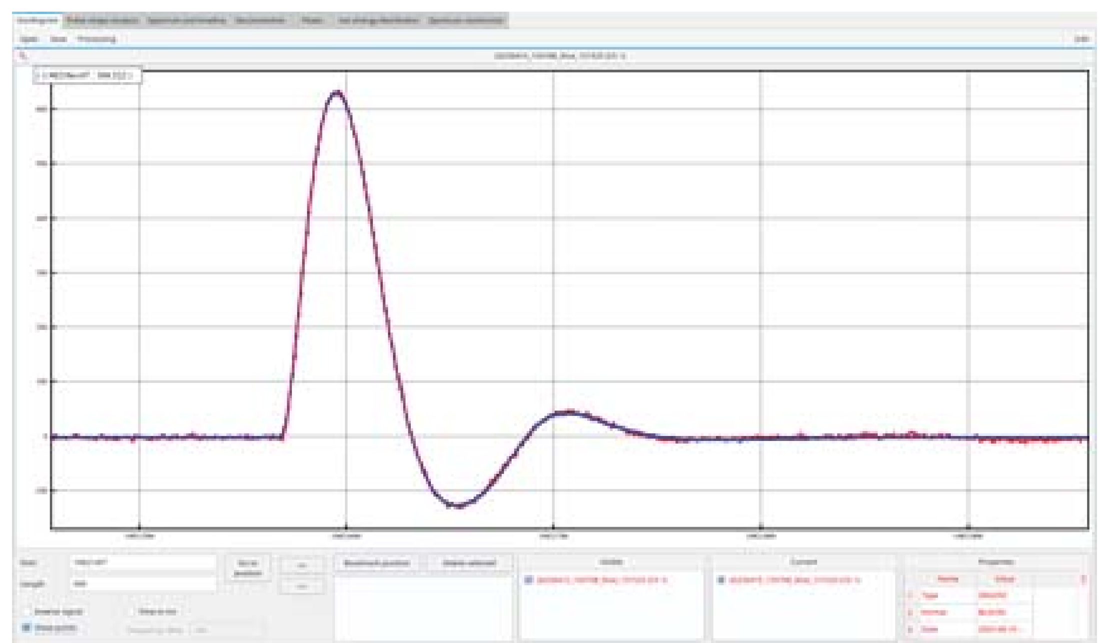


Figure 5 – Fitting the pulse shape of a LaBr$_3$(Ce) detector with a SiPM using the DeGaSum program

Reconstruction of initial gamma-ray spectrum:

The spectrum y(ε), as measured by the detector, can be represented as follows:

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

x is the original gamma spectrum, *h* is the detector's response function, *n* is noise, and *ε* – gamma-ray *energy.*

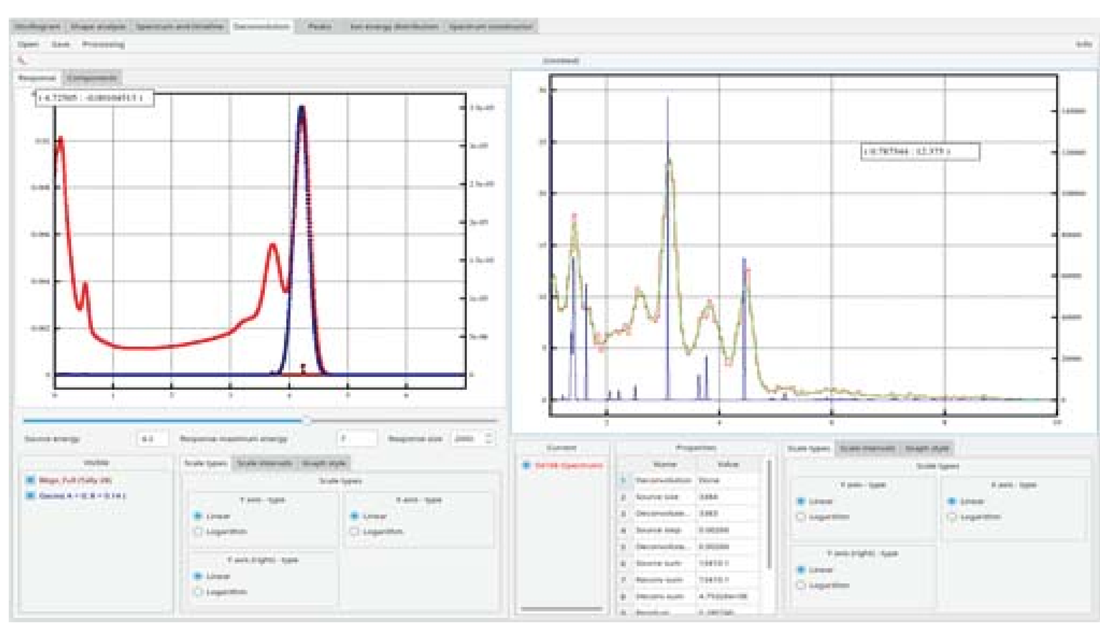


Figure 6 – Reconstruction of the gamma-ray spectrum from the tokamak plasma using DeGaSum. Left: an example of a detector response function. Right: the gamma spectrum recorded in the JET discharge (red line) and the reconstructed gamma distribution. The green line shows the result of convolving the reconstructed spectrum with the detector response functions

Bremsstrahlung spectrum y(ε) can be represented as follows:

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

where *f* is the electron distribution function and h_e is the HXR generation function, h_d is the detector's response function calculated by any Monte Carlo code; *n(ε)* is noise and ε is the electron energy.

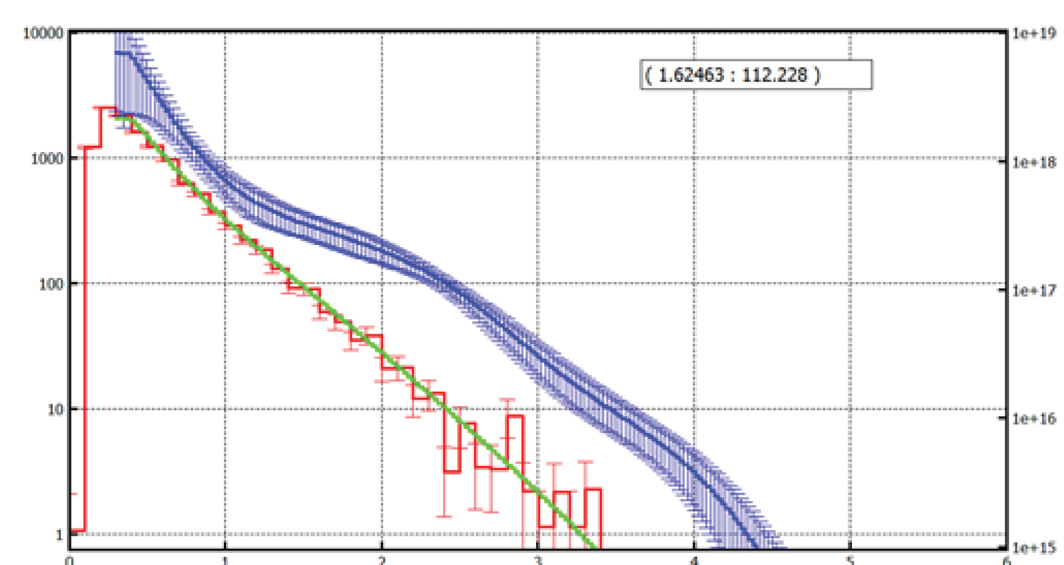
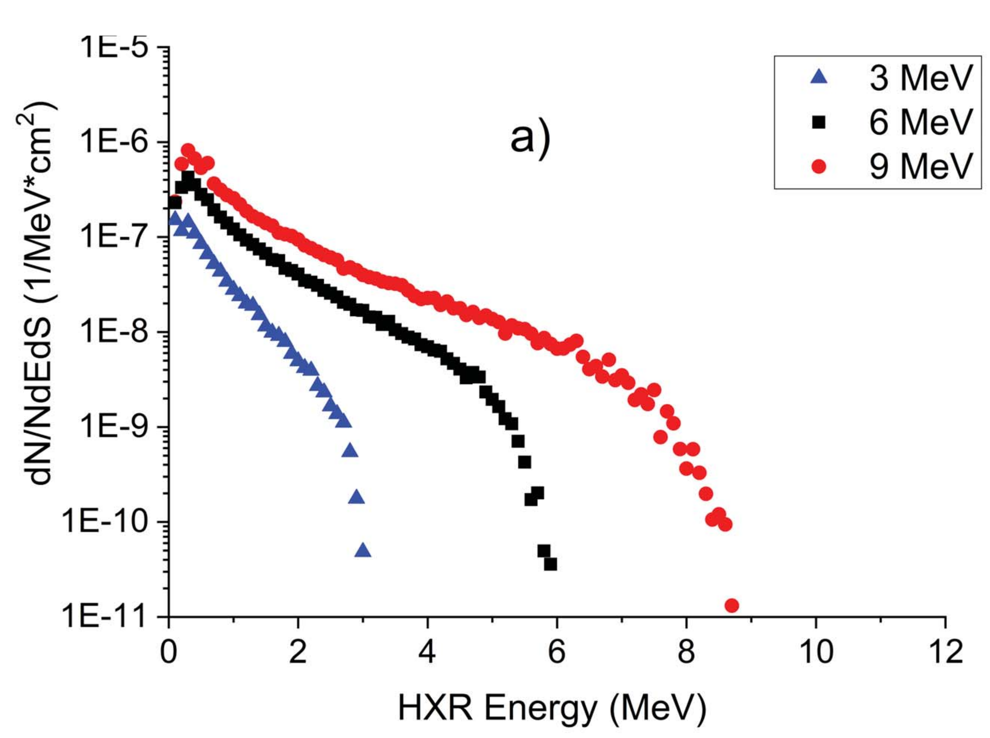


Figure 7 – Reconstruction f_{RE} distribution by DeGaSum: Red line – measured HXR spectrum; Blue line – reconstructed Re distribution; Green line – convolution of REDF with detectors response and HXR generation functions



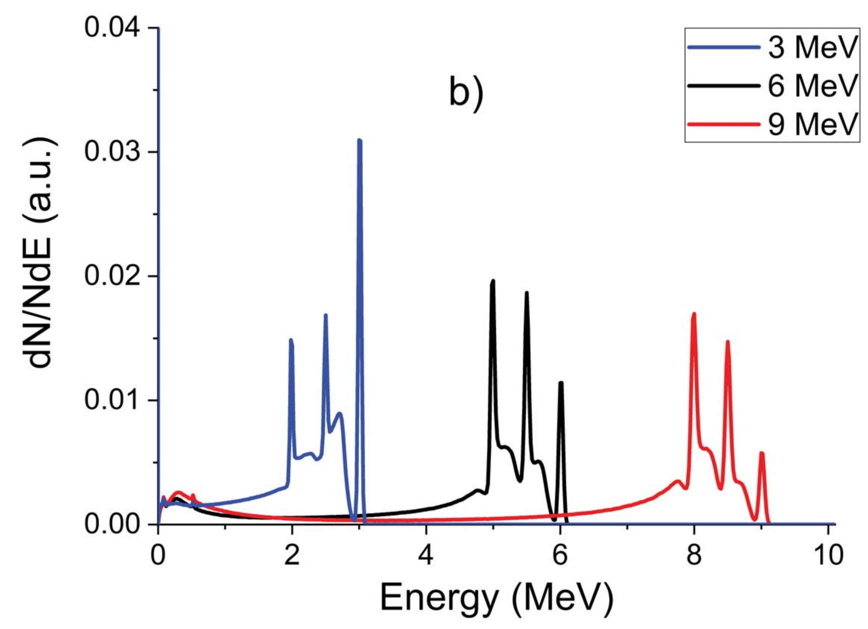


Figure 8 – a) Examples of the HXR generation functions; b) LaBr$_3$ detector's response functions

Gamma-ray synthetic diagnostics

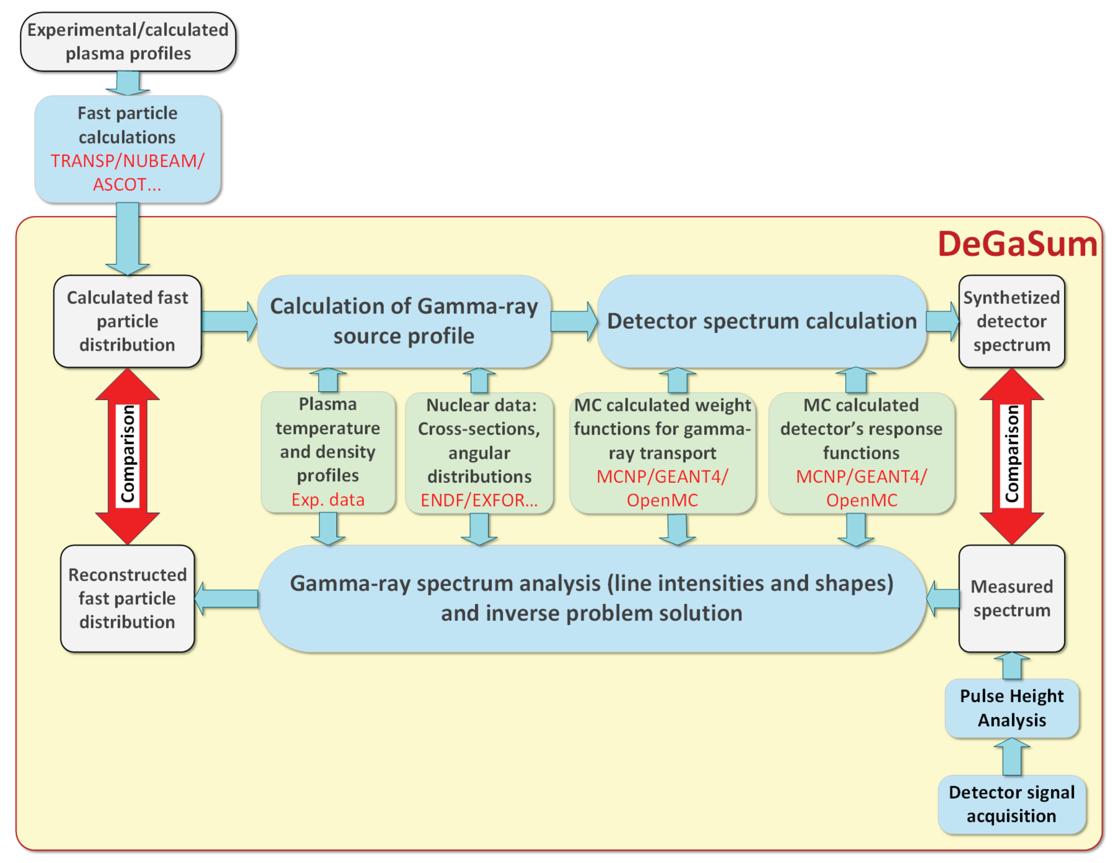


Figure 9 – Diagram of the synthetic gamma-ray diagnostics implementation using DeGaSum

Gamma-ray source:

$$I = \int d^3r\, n_f(\boldsymbol{r}) n_b(\boldsymbol{r}) \int d^3v\, \sigma_{fb}(v) f_f(\boldsymbol{r},\boldsymbol{v}),$$

n_f – fast f-ion concentration, n_b – concentration of the impurity *b*; $\sigma_{fb}(b)$ – partial cross-section of the gamma-ray transition, $f_f(v)$ – fast ion velocity distribution function

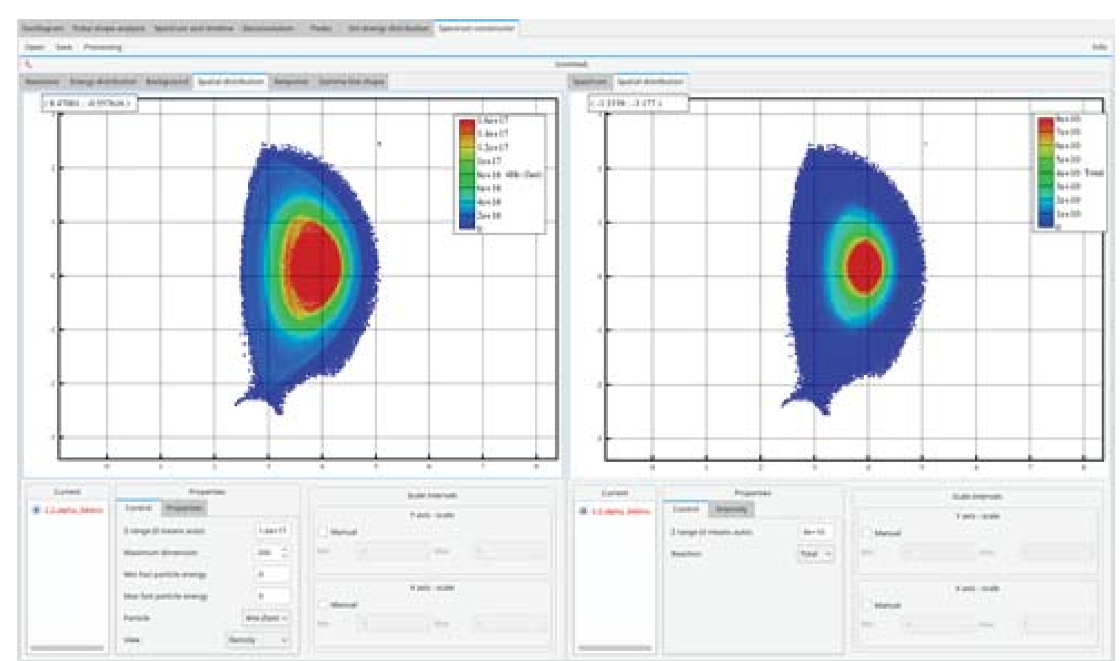


Figure 10 – Modelling of the gamma-ray source profile in DeGaSum program. Left: alpha particles distribution expected to be generated in the BEST tokamak. Right: Profile of the 3.85 MeV gamma-ray source from the ^{10}B(α,pγ)^{13}C reaction

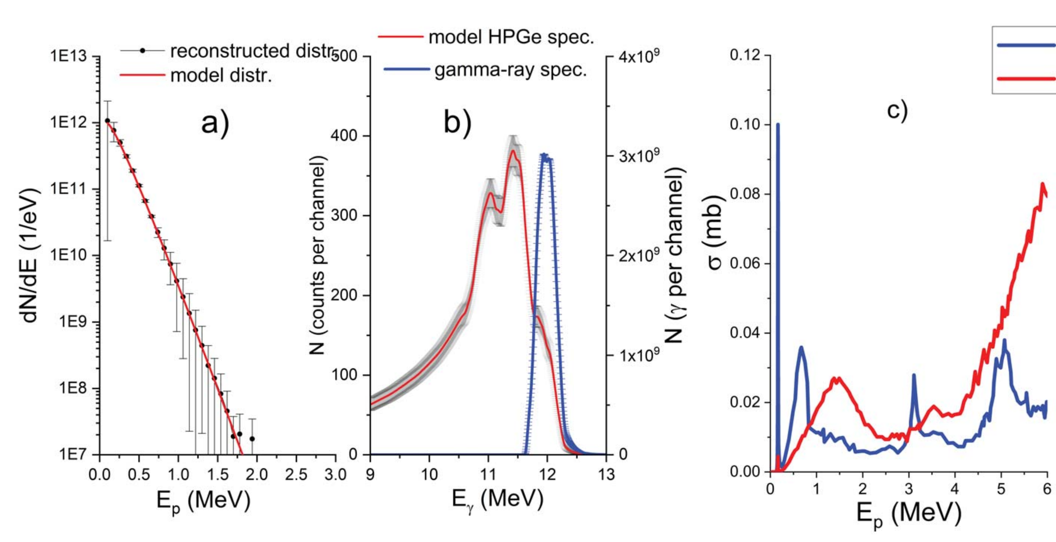


Figure. 11. Modelling of proton distribution in the ITER plasma with ICRF heating: a) Calculated proton distribution in the ITER plasma (red line), and distribution reconstructed by DeGaSum (black dots); b) Simulated gamma-ray distribution for the ^{12}C γ1 emission plasma (blue line); synthesized HPGe spectrum (black line); c) Excitation functions of the $γ_0$ and $γ_1$ transitions of the 12C, born in the ^{11}B(p,γ)^{12}C reaction.

Conclusion

- Effective diagnostics require the use of the latest fast, high-efficiency spectrometers and data acquisition systems with up-to-date software.
- The Ioffe Institute has developed the DeGaSum software package to control recording devices and primary signal processing.
- DeGaSum has been used to control diagnostic systems on FT-2, TUMAN-3M, GLOBUS-M2, ASDEX Upgrade, JET and EAST tokamaks.
- The DeGaSum software package algorithms will be used in building synthetic gamma-ray diagnostics on ITER and BEST.
- 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+^{3}He reactions. It also involves monitoring the generation of runaway electrons.

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