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The Nuclear Resonance Scattering Calibration Technique for the EuroGammaS Gamma Characterisation System at ELI-NP-GBS

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ABSTRACT: A Gamma Beam System (GBS), designed by the EuroGammaS collaboration, will be implemented for the ELI-NP facility in Magurele, Romania. The facility will deliver an intense gamma beam, obtained by collimating the radiation emerging from inverse Compton interaction. Gamma beam energy range will span from 0.2 up to 19.5 MeV with unprecedented performances in terms of brilliance, photon flux and energy bandwidth. For the characterization of the gamma beam during the commissioning, a full detection system has been designed to measure energy spectrum, beam intensity, space and time profiles. The gamma-beam characterisation system consists of four elements: a Compton spectrometer (CSPEC), to measure and monitor the photon energy spectrum, in particular the energy bandwidth; a sampling calorimeter (GCAL), for a fast combined measurement of the beam average energy and its intensity; a nuclear resonant scattering spectrometer (NRSS), for absolute beam energy calibration and inter-calibration of the other detector elements; and finally a beam profile imager (GPI) to be used for alignment and diagnostics purposes. In this paper, a general overview of the ELI-NP gamma characterisation system will be given and the NRSS system will be in particular discussed.

KEYWORDS: Beam-line instrumentation, Gamma Detectors

Contents

1 Introduction

ELI-NP-GBS, that will be implemented in Magurele, Romania, will deliver an intense gamma beam, obtained by collimating the radiation emerging from an inverse Compton interaction. Gamma-ray beams will be produced using a 10 PW laser in collision with a high brightness electron beam provided by a warm linac. Unprecedented performances in terms of brilliance, photon flux and energy bandwidth in an energy range from 0.2 to 19.5 MeV will be obtained [1, 2].

Up to $2.6{\cdot}10^5$ photons in FWHM bandwidth ($<$0.5%) per one laser shot electron beam interaction are expected to be provided by the ELI-NP gamma beam system. The 100 Hz laser pulses will be recirculated 32 times using a multi-pass recirculating system. The 32 bunches will be separated by a 16 ns time interval.

As a result of the inverse Compton interaction, the maximum energy of the gamma beam is tunable by adjusting the electron energy, while the bandwidth depends on the collimation aperture. In fact, the radiation emitted is not intrinsically monochromatic, but the energy is related to the emission angle: it is maximum along the laser backscattering direction and decreases as the emission angle increase. Therefore, the required energy bandwidth can be obtained by collimation of the gamma beam [3] .

For the gamma beam characterisation a detection system has been designed by the EuroGammaS consortium to provide a measurement of the energy spectrum, intensity, space and time profiles, a precise energy calibration of the gamma beam and the monitoring of the beam operation.

In the following, after a general overview of the Gamma Beam Characterisation system, the Nuclear Resonant Scattering System (NRSS) that will be used for the absolute gamma beam energy calibration will be described.

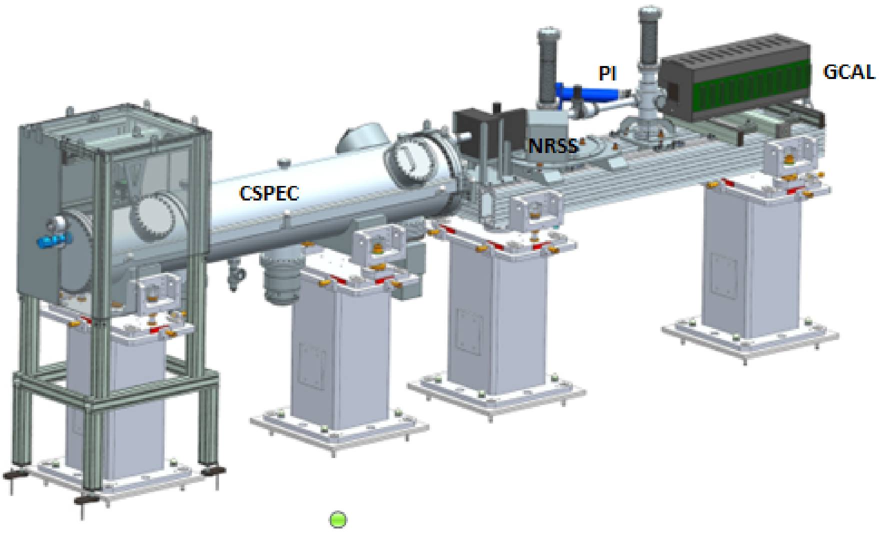

Figure 1. A 3D model of the Gamma Beam Characterisation system.

2 The Gamma Beam Characterisation System

The Gamma Beam characterisation system (see Figure 1) is composed by the following elements: a Compton spectrometer (CSPEC), a sampling calorimeter (GCAL), a nuclear resonant scattering spectrometer (NRSS) and a beam profile imager (GPI).

The first detector CSPEC, designed to measure and monitor the photon energy spectrum and in particular the energy bandwidth, is based on sampling Compton interactions of single photons in a micro-metric target, by accurately measuring the energy and position of the resulting electrons, by using a high resolution HPGe, and photons off beam. A minimal interference with the beam operation is expected, making it an ideal tool for beam energy monitoring and energy spectrum shape determination.
A complementary approach is implemented in GCAL [4, 5], for a fast combined measurement of beam average energy and intensity. The technique consists in performing a measurement of the total beam energy by absorbing the gamma pulses in a longitudinally segmented calorimeter relying on the high intensity and monochromaticity of the gamma beam. The longitudinal profile of the energy released by photons in a low-Z and light absorber has a rather strong dependence on the incident photon energy in the range of interest, while the profile fluctuations are suppressed by the high number of photons. Once the gamma average energy is obtained from the longitudinal profile, the beam intensity is also measured at the same time from the total energy release. Due to high statistics and fast detectors, the measurement can be performed for every single pulse allowing to check beam energy and intensity and their variation within a macro-pulse during the machine commissioning and tuning. The combination of the measurement performed by the CSPEC and the GCAL will allow a fully characterization of the gamma beam energy distribution and intensity with the precision needed to demonstrate the achievement of the required parameters.

However, an absolute energy calibration system must be included into the characterisation system. This is the task accomplished by the NRSS. Selecting appropriate nuclear levels, the detection of resonant scattering condition during a fine beam energy scan attests the beam energy very precisely for a number of values, providing accurate reference energies for calibrating the other subsystems.

Finally, the spatial profile of the beam is obtained by the GPI by using the interaction of the gamma beam with a thin scintillator screen optically coupled with lens to a CCD.

3 Nuclear Resonant Scattering Method

In order to perform an absolute energy calibration of the CSPEC and the GCAL devices, the Nuclear Resonant Scattering method [6] will be used. The idea is to detect the resonant gamma decays of properly selected and well known nuclear levels when the produced gamma beam will have energy and band-width overlapping the selected nuclear level. If E_r is the energy of the selected nuclear level, by varying the γ-beam energy, a re-emission of gamma particles will be generated at the resonant condition. The calibration correspondence is then achieved at γ-beam energy $E{=}E_r$, with an uncertainty mainly determined by the step-size in the beam energy scan.

The cross-section for resonance scattering, in the case where the direct gamma transitions to the ground state is the only de-excitation mode and the Doppler broadening is negligible, is given by [6, 7]:

$$\sigma^0(E) = \pi^2 \frac{2J_1+1}{2(2J_0+1)} \frac{\Gamma^2}{(E-E_r)^2+\frac{1}{4}\Gamma^2}, \tag{3.1}$$

where J_1 and J_0 are the total angular momenta of the excited state and the ground state, respectively, E_r is the resonance energy, is the corresponding reduced wave-lenght, and Γ is the natural width of the level.

The previous expression should be modified if other de-excitation processes are possible (e.g. particle emission or γ-transitions to other excited state, see [6]). If the selected natural width is smaller then the band-width, the resonant condition (maximum rate) will be reached by the beam band-width overlapping completely the resonance. The counting rate can be calculated by using the integrated cross-section:

$$\sigma_{int} = \int \sigma(E)dE = \sigma^0_{max}\Gamma\pi/2, \tag{3.2}$$

In the above expression, σ^0_{max} refers to cross-section value at $E = E_r$ deduced by eq. 3.1. Concerning the rate calculation, eq. 3.2 can be used if the Doppler width broadening is smaller than the beam band-width.

4 The NRSS Set-up

The detector set-up has been designed in order to work both as a Fast Counter (FC) and as an Energy Spectrometer (ES).

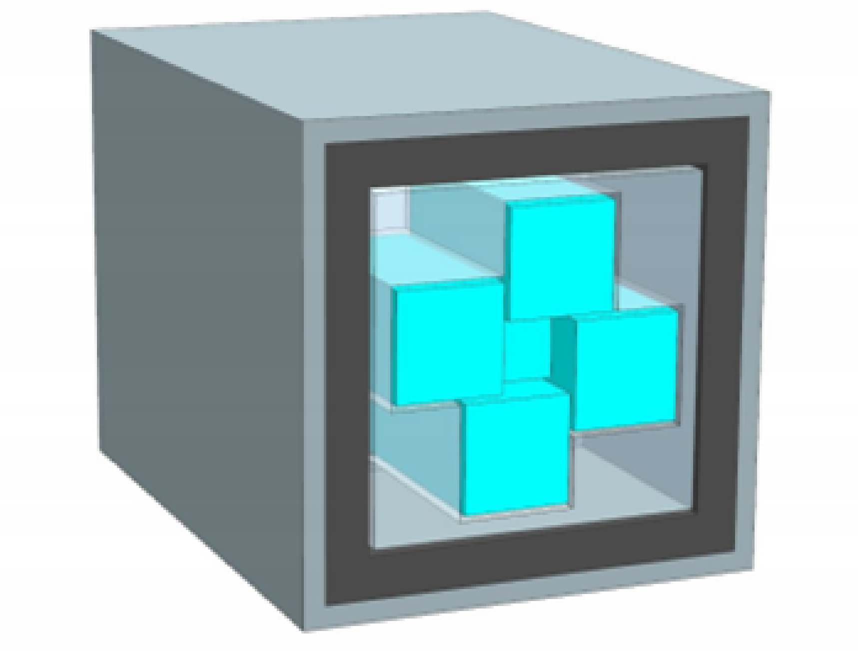

Figure 2. NRSS detector: a central LYSO type crystal, surrounded by an ensemble of four BaF_2 scintillators.

In the first case (FC), it will give a prompt information about the establishment of a resonance condition, while in the second (ES) it will allow, with a slower measurement, for a later redundant identification of the level. The ES part consists of a LYSO type crystal, coupled with a super Bialkaly Photocathode, which is surrounded by an ensemble of BaF_2 scintillators which act both as counters (FC mode) and as Compton shield for the ES mode (see Figure 2).

The LYSO scintillator is a Cerium doped Lutetium based scintillation crystal with high density and a quite short decay time. The high density offer the possibility to increase, in the energy release spectrum, the probability to have a higher Full energy peak counting to Total counting ratio, which is important for the level identification.

Barium Fluoride (BaF_2) scintillation crystals have been chosen since they are characterized by a very fast scintillation emission with a decay time of 800 ps at 220 nm. They have also a much slower component signal at 310 nm. In order to select the BaF_2 fast scintillation component for FC mode, a Cs-Te photo-cathode coupled with a Quartz window will be used. This configuration allows to select from 160 up to 320 nm BaF_2 wave-lenght component, thus reducing the slow component of the signal. Signals will be processed by using a 12 bit digitizer with 1.6 GS/s sampling rate. A trigger and a time stamp provided by the main control system of the GBS will be recorded by the digitizer.

The NRSS scattering chamber has a compact geometry, see Figure 3, and is mainly composed by a multi-flange aluminum cross and a movable linear shifter that can be used to remotely change the target position.

A Geant4 [8] simulation allowed to estimate crystals shapes and dimensions and the

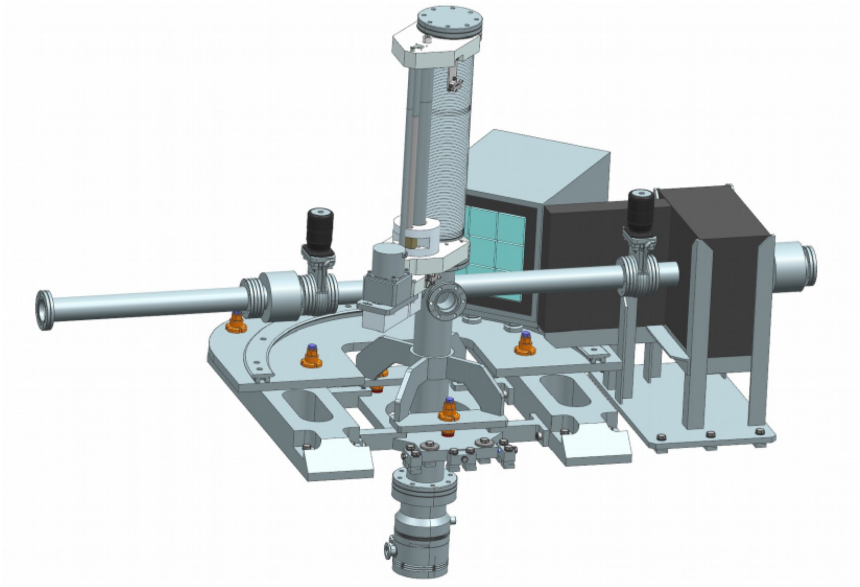

Figure 3. NRSS layout: the alluminum scattering chamber, the vertical target shifter and the detector assembly are sketched.

set-up efficiency [9]. In the chosen configuration (see Figure 2), a LYSO crystal (3x3x6 cm^3) is surrounded by four BaF_2 counters (5x5x8 cm^3). All crystals were alligned at their back side.

There are two main background radiation sources, both of them time correlated with the beam: gamma beam environmental background and target processes competing with the resonant scattering, like the Compton scattering.

The detection setup has been designed in order to measure nuclear resonance scattering from γ-beam photons at backward angles (around θ=135°) with respect to the beam direction. This angular condition is important in order to reduce the background contribution coming from the target due to Compton scattering.

The environmental background, mainly scattered photons due to the collimation of the gamma beam, has been simulated using Geant4 including the interaction with shielding, walls, floor and main elements of the beamline [9]. Lead shields will be used to suppress the background coming from diffused beam particles (see Figure 3).

Further background reduction will be obtained by time coincidence with the beam trigger.

5 Conclusions

The NRSS, which is a part of the EuroGammaS characterisation system for the gamma beams that will be delivered at ELI-NP, has been described. The system, based on the nuclear resonance scattering tecnique and mainly composed by fast counters, will provide absolute calibration for the gamma beam and inter-calibration of the other detectors of the Gamma Characterisation System.

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