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EuroGammaS gamma characterisation system for ELI-NP-GBS: The nuclear resonance scattering technique

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ABSTRACT

A Gamma Beam Characterisation System has been designed by the EuroGammaS association for the commissioning and development of the Extreme Light Infrastructure-Nuclear Physics Gamma Beam System (ELI-NP-GBS) to be installed in Magurele, Romania. The characterisation system consists of four elements: a Compton spectrometer, a sampling calorimeter, a nuclear resonant scattering spectrometer (NRSS) and a beam profile imager. In this paper, the nuclear resonant scattering spectrometer system, designed to perform an absolute energy calibration for the gamma beam, will be described.

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, with unprecedented performances in terms of brilliance, photon flux and energy bandwidth in an energy range from 0.2 to 20 MeV [1–4]. In a γ-beam macro-pulse, the pulse-to-pulse separation is expected to be 16 ns. Each macro-pulse width is 496 ns long, with a repetition rate of 100 Hz.

The Gamma Beam Characterisation system designed by the EuroGammaS consortium for the ELI-NP facility will provide a measurement of the energy spectrum, intensity, space and time profile, a precise energy calibration of the gamma beam and the monitoring of the beam operation.

In the following, after the Gamma Beam Characterisation system, the nuclear resonant scattering tecnique and the NRSS set-up will be described.

2. The gamma beam characterisation system

The Gamma Beam characterisation system (see Fig. 1) 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, to be used also as monitor during machine commissioning and development; 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.

The first detector CSPEC 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 and photons off beam. The advantage of this technique is the minimal interference with the beam operation, making it an ideal tool also for beam energy

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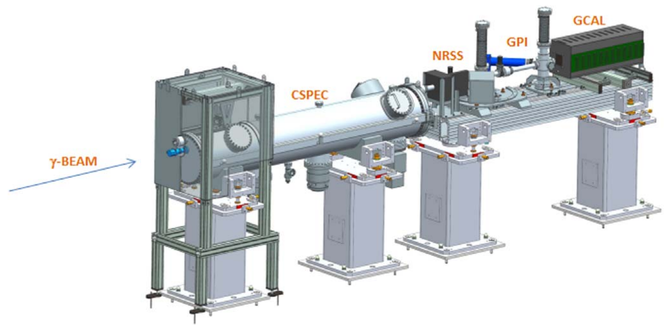

Fig. 1. A 3D model of the Gamma Beam Characterisation system.

monitoring. By acquiring a sufficiently large amount of such measurements, the shape of the energy spectrum can be precisely determined. On the other hand, the need to use detectors with very high energy resolution, such as HPGe, prevents to perform this measurement on a time scale shorter than few µs, resulting in a low rate of clean measurements.

A complementary approach is implemented in GCAL. It consists in performing a measurement of the total beam energy by absorbing the gamma pulses in a longitudinally segmented calorimeter. This approach relies 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. The advantage of this approach is that the full photon statistics can be exploited. Also, since fast detectors can be used, the measurement can be performed for every single pulse allowing it to be used during the machine commissioning and tuning to check the beam energy and intensity and their variation within a macro-pulse. The combination of the measurement performed by the Compton spectrometer and the absorption calorimeter will make possible to fully characterize 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. Using appropriate targets, 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. NRSS: theory

In order to perform an absolute energy calibration of the CSPEC and the GCAL devices, the Nuclear Resonant Scattering method [5] will be used. The idea is to detect the resonant gamma decays of properly selected nuclear levels when the produced gamma beam will have energy and band-width overlapping the selected nuclear level. The energy positions E_r of the selected levels have been previously reported with high precision in the literature. 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 [5,6]:

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

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, $\lambda\!\!\!^-$ 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 [5]). 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:

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

In the above expression, σ^0_{max} refers to cross-section value at $E = E_r$ deduced by Eq. (1). Concerning the rate calculation, Eq. (2) can be used if the Doppler width broadening is smaller than the beam band-width.

4. NRSS: detection setup

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.

The detector setup has been designed to work in two different modes:

1) Fast Counter Mode (*FC* Mode);.

2) Energy Spectrometer Mode (*ES* Mode).

The *FC* Mode allows for a fast beam energy scan, giving prompt information about the establishment of a resonance condition, while the *ES* Mode allows, with a slower measurement, for the later redundant identification of the level. The spectrometer part consist 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 (in the *FC* mode) and as Compton shield for the inner spectrometer when the ES Mode is selected.

The LYSO scintillator is a Cerium doped Lutetium based scintillation crystal that offers 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 (PtT), 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. In Fig. 2 the time response of the BaF_2 coupled with an Hamamatsu R2078 PMT is shown.

Signals will be processed by using a 12 bit digitizer at sampling rate of 1.6 GS/s. A time window of 640 ns in 1024 channels can be recorded by getting the whole macro-pulse. The digitizer dead-time has a typical value of 115 µs, in any case smaller then the distance between two subsequent macro-pulses (10 ms).

A trigger and a time stamp provided by the main control system of the GBS will be recorded by our digitizer.

The mechanical design of the NRSS is shown in Fig. 3. The scattering chamber has a compact geometry 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. Lead shielding (dark grey blocks in Fig. 3) are included in the set-up to minimize the

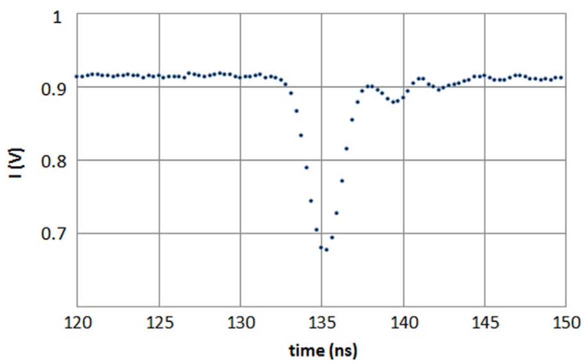

Fig. 2. BaF_2 waveform after the coupling with a Cs-Te photocathode.

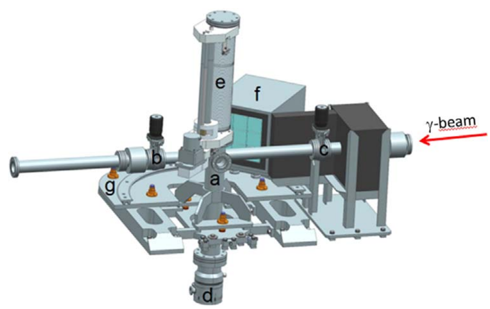

Fig. 3. NRSS layout: a) the alluminum scattering chamber (placed between the two valves b, c and connected with the vacuum pumps in d), e) the vertical target shifter and f) the detector assembly. The detector is placed on the semicircular platform g).

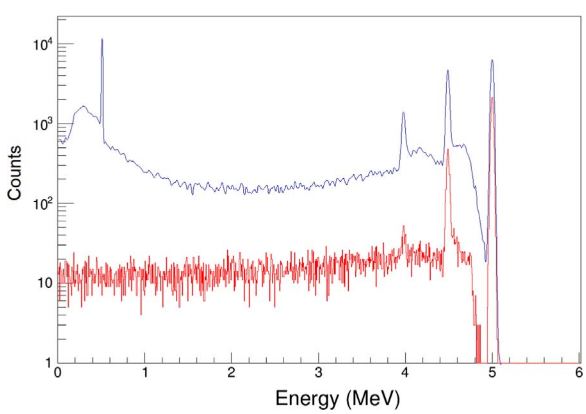

Fig. 4. Top line, the energy released by a 5 MeV photons on a LYSO crystal 3×3×6 cm^3. Bottom line, the energy released on the LYSO crystal with the surroundings four BaF_2 counters (5×5×8 cm^3) acting as Anti-Compton Shield. Spectra are not convoluted for the detector energy resolution. The NRSS detector is placed at 19 cm far from target.

detector background.

In order to optimize crystals shapes and dimensions, the efficiency of the crystals of the NRSS detector has been estimated by using Geant4 [7] simulation. We have simulated a configuration in which a LYSO crystal (3×3×6 cm^3) is surrounded by four BaF_2 counters (5×5×8 cm^3). All crystals were alligned at their back side. A total number of $5 \cdot 10^7$ gamma rays were isotropically generated with 5 MeV energy at the target point. The photons energy release was then calculated for the NRSS detector placed at 19 cm far from the target.

This allowed the estimate of the PtT for each crystal and the global efficiency for Full energy peak detection or for gamma counting above a given energy threshold. For example, for the BaF_2 counter closer to the beam-line the counting efficiency with a 3 MeV energy threshold was 0.27 %, while the Full energy peak efficiency for the LYSO crystal was 0.025 %. PtT changes from 11 % to 45 % when the BaF_2 counters are used as Anti-Compton shield for the inner spectrometer (see Fig. 4 top and bottom curve respectively).

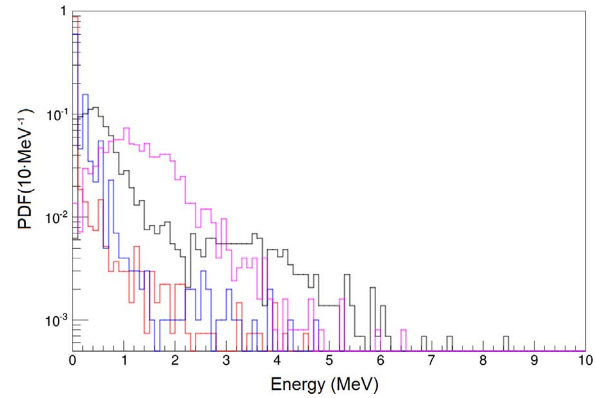

Fig. 5. Background energy distribution on the beam rightmost BaF_2 crystal in a configuration in which the NRSS detector is centered at 135° with respect to the beam direction and placed at 19 cm distance from the target. The beam environmental background when no target and no additional shield is present, simulated for 5 MeV photon energy, is shown in black. Detected counts have been normalized to the total number of beam particles. The effect of the additional shielding is shown in red. Finally the background contribution simulated for two different ^{12}C target thicknesses is shown (blue: 0.3 mm thick, pink: 3 mm thick). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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 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.

The collimated beam and the diffused particles have been followed up to the detection setup. The energy distribution of the detected background is shown for one of the NRSS BaF_2 counting detectors in Fig. 5, black curve.

To suppress the background coming from diffused beam particles lead shields will be used; the results of this simulation (see Fig. 5, red curve), show that the probability to detect background radiation above 3 MeV drops.

The contribution of the background coming from the target, due mainly to Compton scattering, has been considered in the simulation for two different target thickness (see Fig. 5 blue and pink line).

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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