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Gamma beam collimation and characterization system for ELI-NP-GBS

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Summary. — ELI-NP-GBS is a gamma source based on inverse Compton interaction that will provide photons with tunable average energy ranging from 0.2 to 19.5 MeV, energy bandwidth down to 0.5% and average flux of about 10^8 photons/s in ultra-short pulses. Given these challenging characteristics, dedicated devices and techniques were developed to measure and monitor the gamma beam parameters during the commissioning and the operational phase. Futhermore an adjustable collimation system was developed to fulfill the beam monochromaticity requirement. The gamma beam characterization and collimation apparatus, currently assembled and under test at INFN-Ferrara laboratories, is described in this work.

1. – Introduction

ELI-Nuclear Physics (NP), currently being built at IFIN-HH (Magurele, Romania), will host the Gamma Beam System (GBS), an intense and monochromatic gamma source based on inverse Compton interaction between a high-power laser and an electron beam accelerated by a LINAC [1]. The gamma beam will have an average energy tunable in the range 0.2-19.5 MeV, $\Delta E/E = 0.5\%$ and intensity of about 10^8 photons/s. In order to

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cover the entire energy range, the GBS will consist of two parallel beamlines, with two different interaction points (IPs), the first one for gamma energies from 0.2 to 3.5 MeV, and the second one from 3.5 to 19.5 MeV, after a further acceleration of the electron beam. In an inverse Compton interaction, the energy of the backscattered photons depends on the scattering angle, it is maximum in the backward direction and decreases as the angle increases. This makes possible to adjust the energy bandwidth by collimating the emission. An adjustable collimation system is then necessary to provide the required beam specification on the entire energy range. Also, a characterization system providing a measurement of the energy spectrum, intensity, space and time profile of the beam is essential for the commissioning and development of the source, as well as to demonstrate the performance achieved. The gamma beam time structure is composed of pulses of about 10^5 photons with a duration of 1-2 ps, with a pulse-to-pulse time separation of 16 ns. Sequences of 32 pulses are *macro-pulses* featuring a 100 Hz frequency. These ultra-short pulses prevents to easily disentangle the response to each single photon by using any traditional spectroscopic detector directly on the gamma beam. Therefore, to cope with these unprecedented gamma beam specifications, innovative devices and techniques have been developed to characterize the source. ELI-NP-GBS will be equipped with two complete collimation and characterization systems, one for each IP. Each of these collimation and characterization systems consists of six basic elements: (1) Collimation system (GCOLL); (2) Concrete shielding, 1 m-thick, to absorb the possible radiation scattered in the collimation process; (3) Compton spectrometer (CSPEC); (4) Sampling calorimeter (GCAL); (5) Nuclear Resonance Scattering Spectrometer (NRSS); (6) Beam profile imager (GPI).

2. – Collimation system

In order to obtain a monochromatic beam a collimation of the emission is necessary. Depending on the energy, the angular acceptance required for a relative bandwidth ΔE/E=0.5% is between 70 and 700 μrad, which translates in apertures ranging from about 1 to 14 mm [2]. The collimation is provided by a stack of 14 independently adjustable linear slits, arranged with a relative rotation around the beam axis, to obtain a continuously adjustable aperture. Each slit is composed of two 40 x 40 x 20 mm^3 blocks made of a 97% tungsten alloy. The slits are mounted on a stainless steel frame. The first 12 slits are mounted with a relative rotation of 45° around the beam axis; 20 cm downstream, two more slits are positioned to form a square aperture to further clear any beam halo. The collimator frame is placed inside a high-vacuum chamber, equipped with 14 rotative feed-throughs to transmit the rotation from the stepper motors mounted outside the chamber to the worm-gear that allows the aperture adjustment of each slit. Position encoding is obtained by counting the motor micro-steps (< 5 μm on aperture, homing limited), and the absolute position is measured by a multi-turn rotary encoder (accuracy better than 50 μm). The vacuum chamber is mounted on top of a positioning system with 6 degrees of freedom (SpaceFab, PI Micos, Germany) for a precise alignment of the collimation system. The system performance have been evaluated through detailed Monte Carlo simulation [3, 2], it has been assembled and currently under test at INFN-Ferrara laboratories [4].

3. – Compton Spectrometer

The aim of the Compton spectrometer is to reconstruct the energy distribution of the gamma beam by using a non-destructive method, which consists in measuring energy and position of electrons recoiling at small angles from Compton interactions of the beam on a thin micro-metric mylar target. By also detecting in coincidence the scattered photon, whose position and energy can be predicted from the electron measurement, the background from pair production, Compton photons and other scattered radiation can be strongly suppressed. A high purity germanium detector (HPGe) will be used to precisely measure the electron energy, while a double sided silicon strip detector placed in front of the HPGe allows to measure the scattering angle. This two detectors will be located inside a cylindrical vacuum chamber at approximatively 2 m from the target holder. The Compton scattered photon is detected by BaF_2 crystals, whose fast response in coincidence with the HPGe signal will provide the trigger. The photon detector is located outside vacuum, and can collect the scattered photons passing through a low-absorption carbon window. Monte Carlo (MC) simulations have shown how this coincidence will be very effective in suppressing the background signal in HPGe. The expected performances of this detector indicate its capability to reconstruct the peak energy with 0.1% uncertainty [5].

4. – Sampling calorimeter

The sampling calorimeter (GCAL) was developed for a fast combined measurement of the beam average energy and its intensity. It is a sampling device composed of 22 identical layers. Each layer consists of a block of 30 mm-thick passive absorber made of Polyethylene, followed by a thin sensitive layer. The sensors are 320 μm-thick silicon strip detectors, segmented in 128 strips (80 μm pitch, 20 μm width) for a total active area of 10.32×80.00 mm^2. These sensors provide the necessary efficiency and response linearity, as well as the required radiation hardness (up to 100 kGy), to survive to the extremely high photon flux and space density of the expected ELI-NP gamma beam [6]. Each silicon layer is made of seven adjacent silicon sensors. Such a design allows covering a large active area while keeping the detector capacitance low enough (around 300 pF) to achieve a fast response and an efficient charge collection (bias voltage 600 V). The fast response time allows us to disentangle the signal due to different pulses within a macro-pulse. The average beam energy can be reconstructed by comparing the measured energy deposition profile against the simulated ones. Once the photon energy is determined, the beam intensity can also be inferred from the measured total energy release. In the case of ELI-NP, this approach takes advantage of the narrow bandwidth of the beam energy and of the high number of impinging photons, which suppresses the fluctuations of the shower profile. Preliminary tests and detailed Monte Carlo simulations indicate that the statistical accuracy on the average beam energy and on the number of photons per pulse is expected to be better than one per mill after few seconds of operation [7].

5. – Nuclear Resonance Scattering System

The nuclear resonant scattering system (NRSS) will be used to perform an absolute energy calibration of the CSPEC and GCAL subsystems. The underlying idea is to use a gamma counter detector to check (during an energy scan) whenever the beam overlaps one nuclear resonance level of a properly chosen target material. The position of these levels is well documented in the literature and their widths (typically $\leq$ eV) is smaller than the beam energy bandwidth. During the beam energy scan, an emission of photons of the same energy of the beam will be generated over the whole solid angle when the resonant condition is reached. Different targets are mounted on a movable holder in vacuum. The resonant gammas will be detected by an array of scintillators placed outside vacuum at 135° with respect to the beam line. This angle was selected to avoid most of background due to Compton scattering in the target. The scintillating crystals are made of barium fluoride (BaF_2), characterized by a very fast emission component ($\leq$ 1 ns decay time), except the central one which is a LYSO, slower but with higher energy resolution. This design makes possible for the system to operate in two modes. The main is a *Fast Counting* (FC) mode, where only the BaF_2 crystals are read as counters of resonant photons. The fast response of the crystals permits to resolve the challenging time structure of the beam. In *Energy Spectrum* (ES) mode a redundant energy measurement can be performed using the central LYSO crystal with the surrounding BaF_2 crystals acting as an anti-Compton shield [8, 9].

6. – Gamma Beam Profile Imager

The Gamma Profile Imager (GPI) is devoted to the measurement of the transverse spatial distribution of the gamma beam. The beam image is obtained acquiring the scintillation light emitted by a thin crystal through a CCD-camera. A thin LYSO scintillator target (thickness 0.1-0.5 mm) is crossed by the gamma beam at 45° in vacuum. A mechanical actuator is used to place the selected target on/off the beam. The light emitted by the scintillator is acquired outside vacuum, through a quartz view-port, by using a mirror, a CCD camera and lens system (85mm/f1.4) installed in a dark-box to avoid contamination of environmental light.

A prototype was assembled and tested, allowing to characterize the light emission and imaging system response, as well as to evaluate the signal and spatial resolution expected at ELI-NP-GBS [4, 10].

7. – Conclusions

The combination of the measurements performed by the devices described will make possible to fully characterize the gamma beam energy distribution and intensity with the accuracy required. The entire low-energy beamline is currently being assembled and tested at INFN Ferrara laboratories.

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