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Novel applications and future perspectives of a fast diamond gamma ray detector

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ABSTRACT

For the first time, a diamond sensor was operated for the characterisation of a high average-intensity gamma-ray beam. Data was collected for gamma beam energies between 2 and 7 MeV, at the HIγS facility of TUNL. The nanosecond-fast resolution of diamond detectors is exploited to distinguish bunches of gamma rays 16.8 ns apart. It allows a precise direct determination of the time-structure of the gamma beam. The strong potential of such a detector for precise absolute flux, position and polarisation measurements is exposed. It is thus shown that diamond detectors are a decisive and unique tool for the detailed characterisation of upcoming gamma sources, such as ELI-NP and HIγS-2.

1. Introduction

ELI-NP [1] (Extreme Light Infrastructure – Nuclear Physics) is a new physics centre being built in Magurele, Romania. Its aim is to probe the limits of nuclear research using highly energetic photons. The main infrastructure consists of a linear accelerator generating 32 electron bunches 16.8 ns apart every 10 ms with energies ranging from 80 to 720 MeV.

A pulsed laser beam is shone onto the electrons at a precise interaction point to generate photons of energies between 0.2 and 20 MeV through inverse Compton scattering. The excellent electron beam energy spread of 0.05% and emittance of 0.5 μm results in an excellent on-axis spectral purity. The expected flux will be of approximately 3×10^{10} photons per second and the spectral density an unprecedented 5000 photons/(s.eV).

A complex optical system [2] has been developed to recirculate the laser beam 32 times. The interaction point of the laser beam with its corresponding electron beam needs to be spatially constant. Furthermore, the crossing of this precise point by both beams needs to happen simultaneously for an interaction to take place.

This is a completely new design of optical recirculation, where alignment and synchronicity are governed by complex algorithms. The time structure of the resulting photon beam is shown in Fig. 1. The 32 pulses need to be monitored individually to verify that they fulfil the desired specifications. For this purpose, a diamond detector was selected. Its principal appeal is its short double pulse resolution of a few nanoseconds [3]. This is the ability to resolve two successive pulses and is given by the full width at half maximum of one pulse. It is dependent on the drift time and thus the thickness of the detector, and the bias voltage applied to it. This feature will allow the measurement of fluxes relative to one another in real time, which will in turn help monitor and eventually adjust the Compton interaction system.

Finally, the ideal detector will monitor the beam continuously without destroying it for the users. This can be achieved with the described detector by placing it slightly off the beam-axis as only the centre of the beam will be used for nuclear experiments. Indeed, the central photons will be selected with a collimator of radius of aperture 1 mm. This is done to increase the monochromaticity of the beam.

In Section 2, a first experiment demonstrating the fast response of the detector is described. In Section 3, a technique is presented showing how this detector can be used to determine the global shape of the beam, and in turn have an insight on the polarisation of the laser beam during the optical circulation. This will be crucial as the recirculator is an enclosed isolated system.

2. Experiment

The HIγS facility located at Duke University [4] is currently the most brilliant facility for nuclear physics based on gamma rays. Photons in the range 2–7 MeV were used in the experiment described below. They are produced by Compton backscattering off electrons. The incoming light comes from a laser obtained by synchrotron radiation in a Free Electron Laser (FEL).

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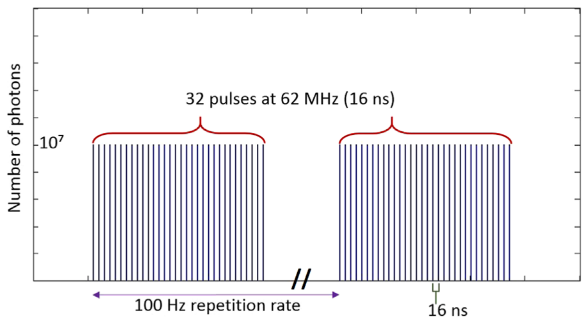

Fig. 1. Time structure of the pulsed photon beam at ELI-NP.

A single-crystal diamond detector from CIVIDEC Instrumentation [5] was installed in the beam. It has a transverse size of 5×5 mm^2 and a thickness of 500 μm. A gold–platinum–titanium metallisation is applied to the diamond effective area to form an electrode that reads the drift signal. The incoming photons can react in two different ways inside the diamond: Compton scattering or electron–positron pair production. A bias voltage of 400 V is applied to the detector making the charged particles drift towards the electrode. The signal is amplified by a CIVIDEC C2 Broadband Amplifier [5], which has 2 GHz analogue bandwidth, 46 dB gain and an equivalent input current noise of less than 400 pA. It is then read out by a USB WaveCatcher [6], that registers 1024 points at a sampling frequency of 3.2 GHz.

Data was taken with the production of three photon bunches separated by 16.8 ns. The great time resolution of the diamond sensor is exploited to clearly distinguish two successive photons interacting in the detector. One example of such an event is shown in Fig. 2.

The arrival times of the signal candidates are computed relatively to an external reference clock given by the signal originating from a Beam Position Monitor placed in the HIγS storage ring. This is necessary to get an idea of the beam structure as an event-by-event analysis is not sufficient. Indeed, the limiting factors are the low rate of approximately 10 photons per event combined with the low efficiency and small geometric acceptance of the detector. Summing over 30,000 events allows identifying the three populations, as seen in Fig. 3. There are much less photons produced in the third bunch, probably due to an unequal distribution of the electrons inside the storage ring. Nonetheless, this confirms the capacity of the detector to differentiate photon populations 16.8 ns apart.

The deposited charge is calculated by integrating the detector current pulse from the first zero-crossing before the peak to the first one after. The charges collected at 2, 3 and 7 MeV present a flat response independent of the energy. A calibration needs to be performed to determine the absorption coefficients at these energies to get absolute values of the charge. This is nonetheless a good first step towards the confirmation of the GEANT4 simulation, given in Fig. 4. The simulation looks at the average energy deposition induced by photons inside a 500 μm layer of diamond. This gives a roughly flat response between 1 and 10 MeV, where the dominant process is the scattering of electrons from their carbon atoms by Compton interaction. Pair production only becomes prominent above 10 MeV, this is consistent with what is found in literature [7,8].

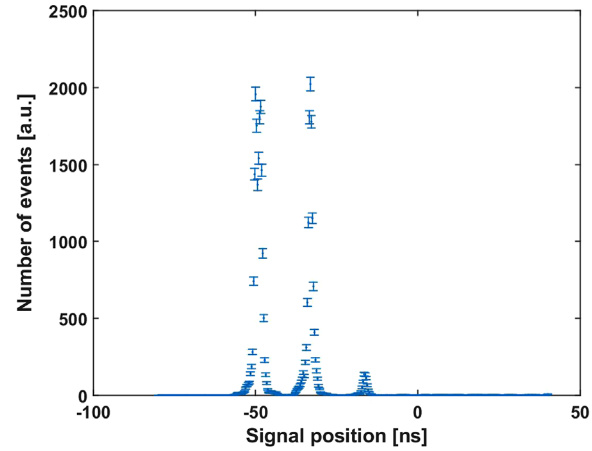

Fig. 3. Arrival time distribution of 30,000 events. The three γ-bunches separated by 16.8 are distinguished. The third population presents a significant under-filling.

3. Polarisation simulations

For an unpolarised beam of electrons, the polarisation of the beam of photons after the Compton scattering is given by the polarisation of the interacting laser. The photon beam shape is also directly affected, measuring the shape of the beam thus gives an implicit measurement of the polarisation of the photons. This is otherwise difficult to measure for the recirculator used at ELI-NP described in Section 1, which is an enclosed isolated system. The laser polarisation is described by the Stokes parameters, S_1, S_2 and S_3, which give, respectively, the linear, diagonal and circular polarisation [9].

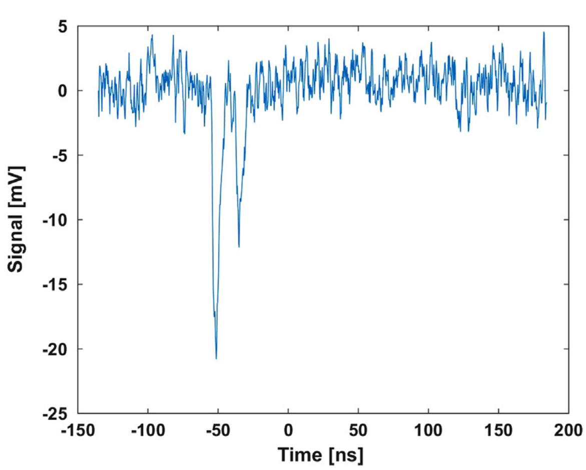

Fig. 2. An event with two candidates separated by approximately 16 ns showing the excellent separation of two consecutive peaks.

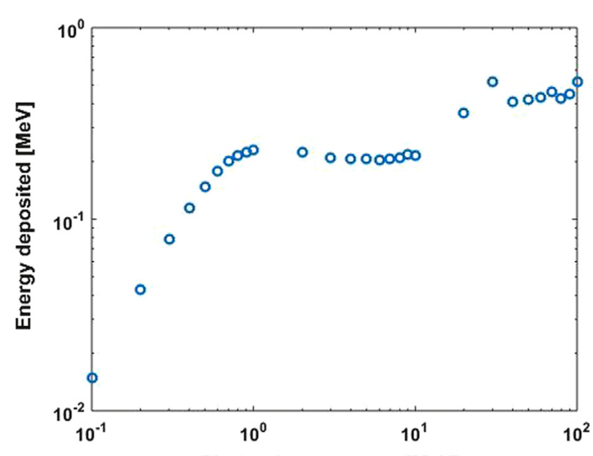

Fig. 4. GEANT4 simulation of energy deposition inside the diamond detector as a function of photon energy.

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