RIPTIDE: A PROTON-RECOIL TRACK IMAGING DETECTOR FOR FAST NEUTRONS

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INTRODUCTION

Neutron detectors are an essential tool for the development of many research fields, as nuclear, particle and astroparticle physics as well as radiotherapy and radiation protection. Not ionizing directly, neutrons are detected via nuclear interactions producing charged particles or electromagnetic radiation. Consequently, the detection efficiency depends on the probability of neutron interaction in the detector and on the escape probability of the reaction products. Fast neutron detection is often based on the neutron-proton elastic scattering reaction: the ionization caused by recoil protons in a hydrogenous material constitutes the basic information for the design and development of neutron detectors. Although experimental techniques have continuously improved, proton-recoil track imaging remains still at the frontier of neutron detection systems, due to the high photon sensitivity required [1].

THE RIPTIDE PROJECT

RIPTIDE is a Recoil Proton Track Imaging (RPTI) detector for fast neutrons aiming at measuring with good efficiency all kinematic properties (energy and momentum) of incoming neutrons retrieving their trajectory from both single n-p scattering (when the primary vertex of neutron trajectory is known e.g. point-like target in fixed-target experiments) and double or multiple n-p scattering (general case) in the detector active volume. In RPTI framework the basic tool for momentum reconstruction is the two-body kinematics where the neutron energy E_n is related to the proton recoil angle and energy (ϑ_p, $\mathrm{E_p}$) by the formula:

$$E_\mathrm{n} = \mathrm{E_p}/\cos^2\vartheta_\mathrm{p} \qquad (1)$$

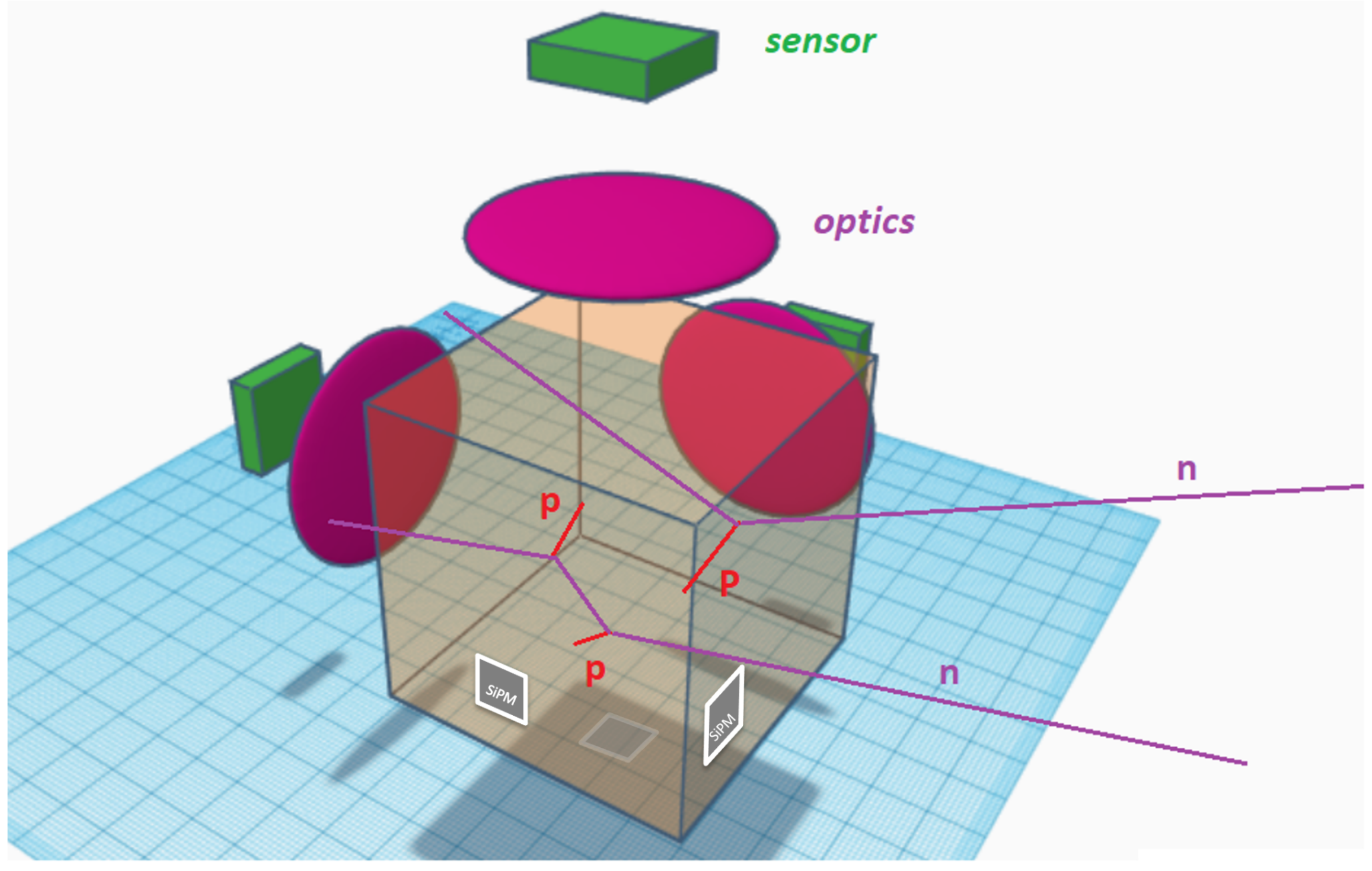

Figure 1 RIPTIDE working principle.

The RIPTIDE detector concept consists of a cubic (216 cm^3) plastic scintillator (BC-408/EJ-200) surrounded by two (or more) optical lens systems focusing the scintillation light produced by recoil protons into CMOS cameras (Fig. 1). For long enough paths, the light production is greater at the end of the range (i.e. Bragg peak) allowing to identify the track direction while the track length is linked to the proton energy. In order to measure the kinematics, we need to perform a full 3D tracking using images by CMOS cameras following promising proof-of-principle experiments [2, 3]. The detector will also be equipped with non-imaging sensors (such as commercial SiPMs) to have a fast signal acting as a trigger for the data acquisition.

PROTOTYPE CONSTRUCTION AND TESTS

The construction of the first setup began in early 2024. An optical bench inside a custom black box was designed to host the scintillator, the optical system and the camera in the darkest environment achievable. We started using an astronomy imaging camera with a continuous acquisition coupled with a SiPM or PMT to select only interesting frames (Fig. 2). After camera calibration, with this setup we were able to see integrated signals from both α and γ radioactive sources placed on the distal face of the scintillator (Fig. 4). Moreover, we are on track to test a microchannel plate (MCP) to enhance light collection to detect even minimum ionizing particles such as cosmic muons.

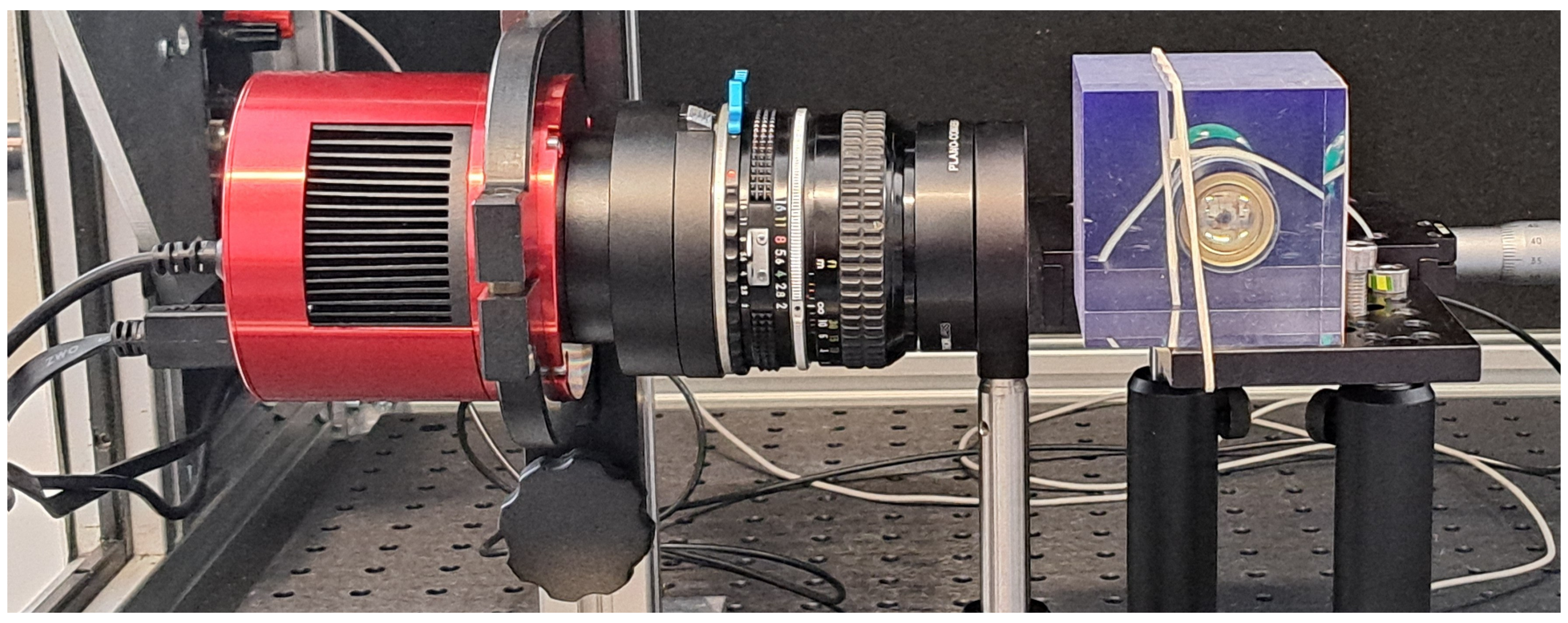

Figure 2 RIPTIDE setup with astronomy imaging camera and on-the-shelf optics.

MONTE CARLO SIMULATION AND TRACK RECONSTRUCTION

The detection concept proposed in the project has been supported through Geant4 Monte Carlo simulations with a careful choice of relevant physics lists. In particular, neutron-proton interaction has previously been tested within the framework of other experiments and it is reliable in the interesting energy range. Firstly, a few sets of mono-energetic protons ($5 < E_\mathrm{p} < 100$ MeV) were randomly originated in the centre of the detector with isotropic momentum direction. The energy deposition of protons in the plastic scintillator volume induce the production of optical photons which are then transported to the surface for the optics simulation step. This step is performed through a custom C++ propagation code simulating the response of a simple optical system made of a lens and a large surface sensor: in this way it is possible to study the performance of the setup in terms of photon collection efficiency, light refraction and aberrations. In the following, a cube-shaped fiducial volume with a side of 40 mm was considered. Lens and sensor parameters were set in a way to cover the whole fiducial volume. By considering a realistic sensor size of 20 mm, a magnification factor of 0.5 was chosen.

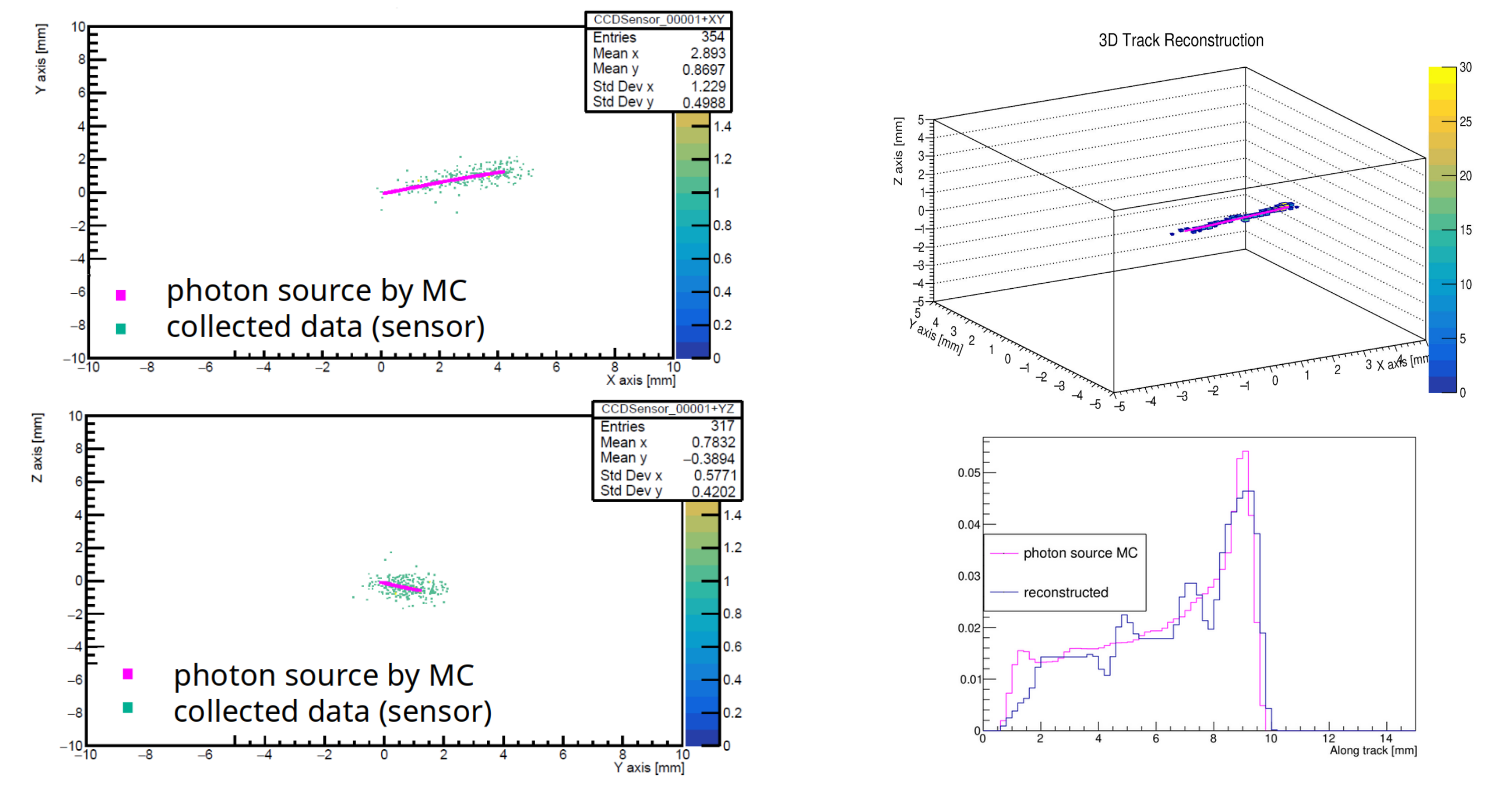

Figure 3 Data on two sensor faces, i.e. 2D projections (left). Reconstructed track of a 30 MeV proton (top right). Reconstructed vs true photon emission along the track of a 30 MeV proton (bottom right).

After the optics simulation, track reconstruction can be made in several ways such as Principal Component Analysis (PCA). The main idea behind using PCA for particle track imaging is to project the data points on a 1D subspace of the 3D geometrical space, thus representing the line to which the particle track belongs (Fig. 3). In particular, PCA was used to produce stereoscopic images of the charged particle tracks, starting from photons collected at the sensor, taking into account data from multiple mutually orthogonal planes. By combining this information from all planes, the complete 3D path of the particle can be reconstructed while the particle energy can be estimated by looking at the Bragg curve (Fig. 3). Other track reconstruction techniques are under study, namely the analysis of momenta or Convolutional Neural Networks.

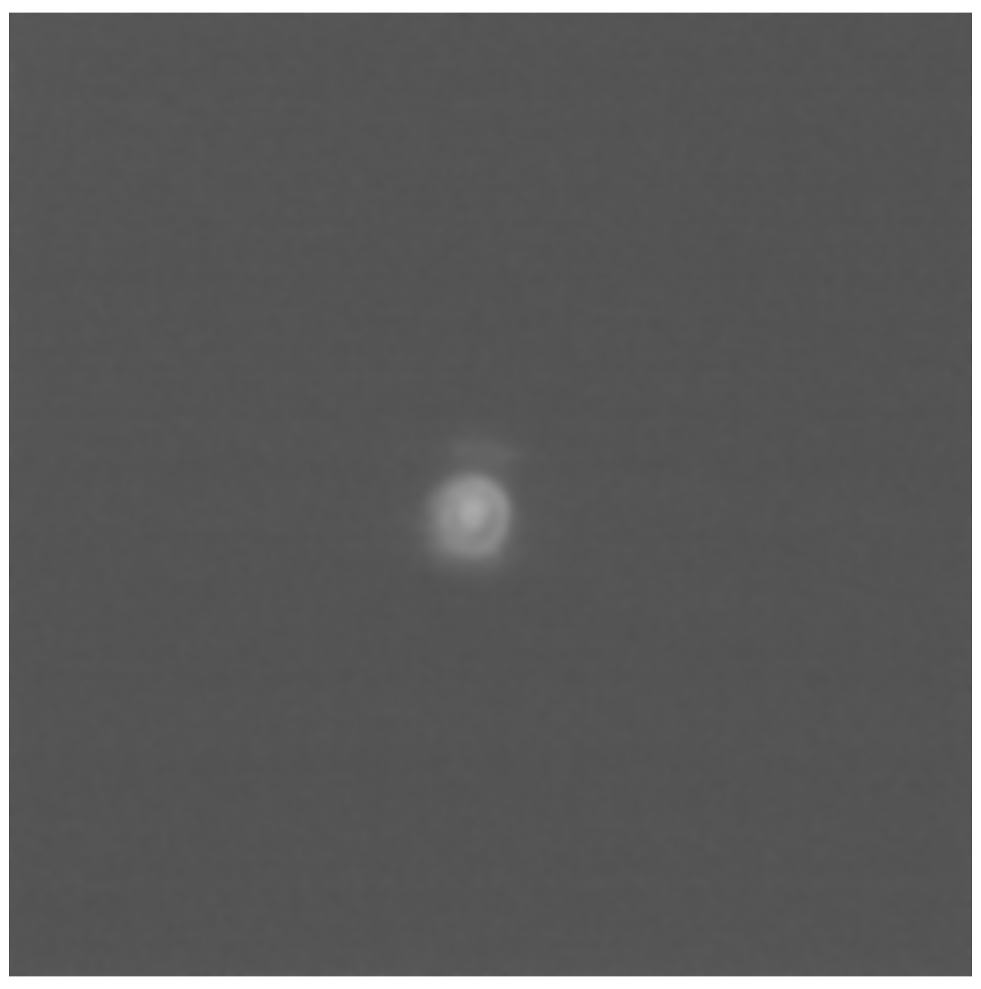

Figure 4 α source as seen by the camera with a 2 s exposure.

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