Simultaneous neutron and gamma imaging system for real time range and dose monitoring in Hadron Therapy and nuclear security applications

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Abstract. GN-Vision is a novel dual γ-ray and neutron imaging system, which aims at imaging, simultaneously to the prompt gammas, the spatial origin of the slow and thermal neutron dose (<100 eV) generated during hadron therapy treatments. The proposed device can also be of interest for industrial applications as well as in nuclear security. The GN-Vision system has been designed following the technical developments of the iTED detector, an array of high efficiency Compton cameras intended for neutron-capture experiments, in which γ-ray energies span up to 5-6 MeV, similar to the energies encountered in hadron therapy. This manuscript presents the evolution of the i-TED detector towards the GN-Vision system and the first conceptual study of the simultaneous neutron and γ-ray imaging capability. Last, it reviews the status of the development and first results of the promising performance of this device for PG imaging in proton therapy, based on MC simulations.

1 Introduction

Hadron therapy presents clear advantages to conventional radiation therapy thanks to the maximum dose deposition at the end of the ion trajectory and its finite penetration in matter. However, it faces two important limitations related to neutron and gamma dose monitoring and ion-beam range verification, which hinder the potential benefits of this method. To solve these challenges, on-line dose and range diagnostic techniques are required.

For ion-range verification, only slit-cameras [1] have been applied for real-time Prompt γ-ray imaging (PGI) in clinical conditions [2]. Recently, the imaging of the secondary neutrons produced by the hadron-beam has been also proposed [3]. This technique is sensitive only to high energy neutrons (>20MeV), which are mainly emitted in the forward direction [4]. On the contrary, a dual neutron-gamma imaging device, such as the one proposed in this work, should be placed transversal to the beam in order to exploit Prompt γ-ray imaging.

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Several groups have also explored PGI [5] and neutron detection [6] aiming at on-line dose monitoring. However, the latter provide no information about the spatial origin of neutrons. Dual neutrongamma prototypes represent a promising approach but most of the developed devices to date [7] are only sensitive to fast neutrons (>0.5 MeV) and, thus, a thermal and epithermal neutron monitor would provide complementary information. In addition, the size of such systems can also be a limitation for clinical treatments.

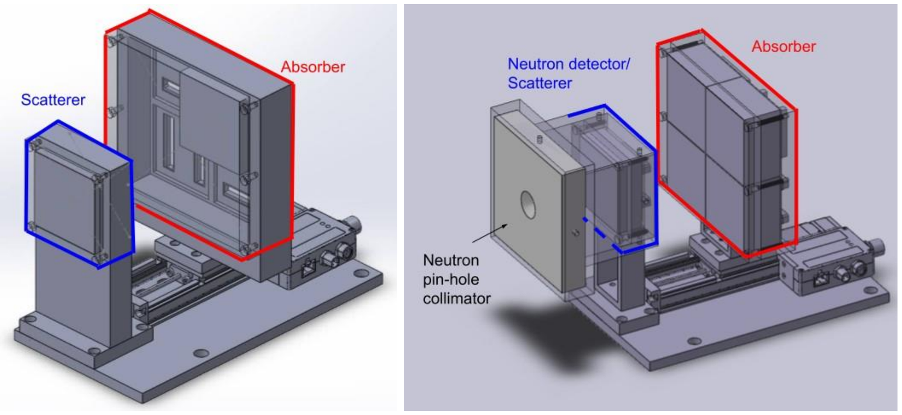

Fig. 1. Technical implementation of the i-TED Compton camera (left) and evolution towards the proposed GN-Vision device (right). The main components of both devices have been highlighted. The dimensions are indicated in Table 1.

Real-time imaging of γ-rays and neutrons is also of interest for remotely-controlled measurements in nuclear accidents [8], nuclear security applications and non-proliferation inspections [9]. In this field, the existing systems with dual γ-ray and neutron imaging capabilities consist of bulky scintillation detector arrays [10] able to image only fast neutrons. However, in many applications the radioactive material is covered by moderating material, thus leading to a thermal neutron spectrum.

The size of these devices also represents a clear disadvantage in terms of portability and applicability.

In this context, a new compact simultaneous gamma and neutron imaging device, hereafter called GN-Vision, is proposed to tackle some of the most relevant requirements in the aforementioned applications.

2 The GN-Vision concept and its evolution from i-TED

The system consists of a compact and portable device capable of measuring and simultaneously imaging both thermal and slow-neutrons and γ-rays with high efficiency. Simultaneous gamma and neutron imaging systems should fulfill several aspects [11]: being sensitive and able to discriminate the two particles, featuring position sensitivity to determine the interaction positions and exploit either electronic or passive collimation techniques to carry out imaging of the incoming particles or radiation.

The GN-Vision device has been developed as a a modification of the i-TED Compton camera developed for neutron capture time-of-flight experiments [12–14]. The technical implementation of i-TED, displayed in the left panel of Fig. 1 has been modified in such a way that the capability to image γ-rays is complemented in the same device with the imaging of neutrons. The first prototype of the proposed GN-Vision is displayed in the right panel of Fig. 1.

The proposed dual imaging device follows the next working principle:

- The Compton imaging technique [15] is applied to image γ-rays with energies between 100 keV and several MeV using two position-sensitive detection planes that are named as Scatterer and Absorber in Fig. 1.

Table 1. Summary of the main components and imaging techniques used in i-TED detector and its evolution GN-Vision.

	i-TED	GN-Vision
First plane	$LaCl_3$ 50×50 × 15 mm^3	CLYC-6 50×50 × 10 mm^3
Second plane	4 $LaCl_3$ crystals 50×50 × 25 mm^3	4 $LaCl_3$ crystals of 50×50 × 25 mm^3
γ-ray imaging	Compton (active)	Compton (active)
Neutron imaging	-	Pinhole camera (passive)

- In GN-Vision, unlike in the early i-TED detector, the first detection plane is capable of discriminating γ-rays and neutrons and fully absorbing the latter for energies below 1 keV.
- A passive neutron collimation system (see pin-hole collimator in Fig. 1) coupled to the neutron detecting plane enables the imaging of neutrons with energies below 100 eV using a similar concept as pin-hole γ-ray cameras [16].

The main features and components of GN-Vision are compared to the previous i-TED in Table 1. For the imaging of γ-rays, the GN-Vision operates, exactly as in the i-TED concept, as a Compton camera consisting of two position sensitive detection planes [12, 15]. The reader is referred to Refs. [13, 14, 17] for more details on the development, characterization and performance of the i-TED detector. In order to achieve the imaging of neutrons, the $LaCl_3$ crystal of the first detection layer of i-TED is replaced by a Cs_2LiYCl_6:Ce scintillation crystal enriched with ^{6}Li at 95%(CLYC-6), able of discriminating γ-rays, fast and thermal neutrons by Pulse Shape Discrimination (PSD) [18]. The use of a CLYC-6 scintillator as Scatterer detector ensures also sufficient energy resolution for Compton imaging in GN-Vision. As shown in Fig. 1, a neutron absorbing pin-hole collimator made of ^{6}Li-enriched Li-Polyethylene (6LiPE) is attached to the first plane to enable the reconstruction of 2D neutron-images. On the other hand, the 6LiPE material does not interfere with γ-rays above ∼100keV, thereby enabling the simultaneous neutron-gamma vision within the same device. The first design study of this collimator by means of MC simulations is discussed in Sec. 3. More details on the technical implementation of GN-Vision are given in Ref. [19].

3 Monte Carlo conceptual design of GN-Vision

The first conceptual design of the GN-Vision system has been carried out by means of MC simulations using the GEANT4 toolkit (v10.6) [20] including the G4NeutronHP package [21] for the accurate simulation of neutron interactions. This study aimed at demonstrating and optimizing the neutron vision concept while retaining the high γ-ray imaging efficiency and resolution of the Compton camera. The geometry model implemented in Geant4 is shown in Fig. 2. In this figure, we indicate the critical parameters in the design of the neutron collimator: diameter (D), thickness (T) and focal distance (F).

The first study of the neutron imaging capability consisted on simulating three isotropic point-like neutron sources of energies ranging from thermal energies (25 meV) to 1 keV located at 20 cm from the collimator and separated from each other by 5 cm (see Fig. 2). The simple geometry of Fig. 2 served to optimize the aforementioned design parameters of the pin-hole collimator for various neutron energies below 1 keV. A more detailed description of these simulations is given in Ref. [19].

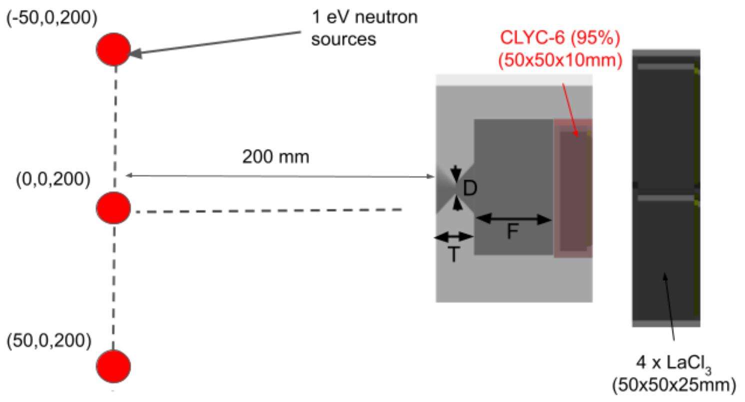

Fig. 2. Sketch of the geometry model of GN-Vision implemented in Geant4 for the conceptual demonstration of the neutron imaging capability.

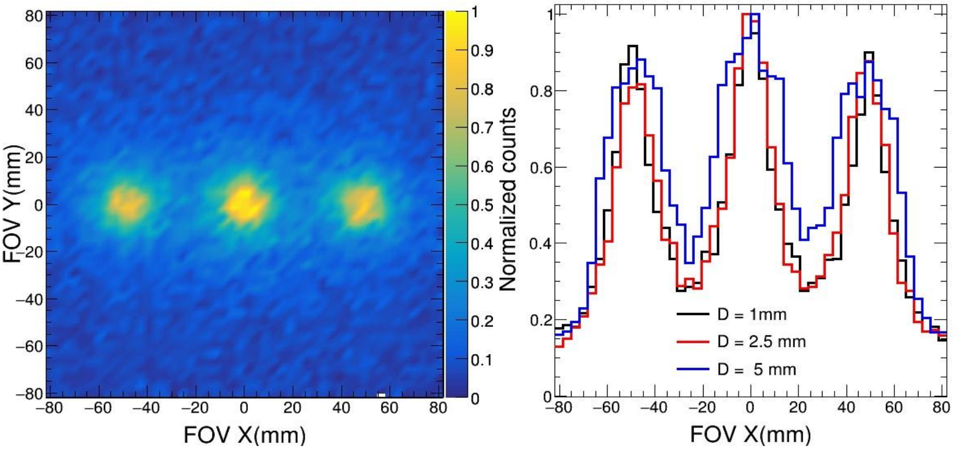

Fig. 3. Reconstructed neutron images (left) for three isotropic point-like sources of 1 eV neutrons shown in the sketch of Fig. 2 and projections (right) along the X-axis of the images obtained with different values of the collimator aperture (D) for a fixed thickness of T = 20 mm and a focal distance F = 40 mm.

The left panel of Fig. 3 shows the first results of the neutron images obtained from the simulations of the GN-Vision concept corresponding to an neutron energy of 1 eV. The balance between efficiency and resolution in the neutron images is extremely dependent on the aperture (D) of the pin-hole collimator, as it is illustrated in the 1D projections of the images shown in the right panel of Fig. 3. The full study of the neutron collimator design and its impact in the γ-ray Compton images can be found in Ref. [19].

4 Perspectives for Prompt Gamma Imaging

Moving a step forward towards the medical applications of the GN-Vision, the prospects of the predecessor i-TED detector for range verification in proton therapy via Prompt Gamma (PG) imaging has been recently studied by means of MC calculations [22]. In this work, a pencil-beam of 120 MeV protons was impinging on a water phantom with a size of 10×10×20 cm.

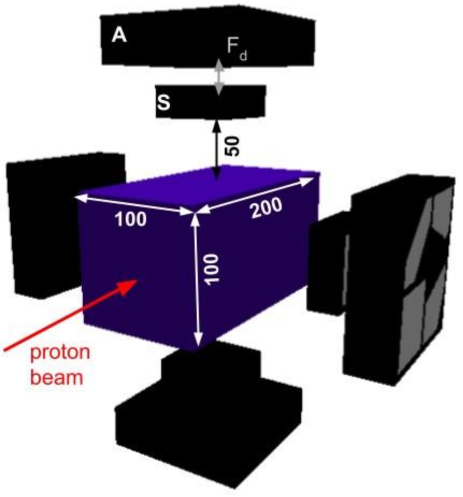

Fig. 4. Simple geometry model implemented in the GEANT4 code to study the potential application of i-TED/GN-Vision to Prompt Gamma imaging in proton therapy.

Figure 4 shows a schematic view of the simulated geometry. The phantom is surrounded by four i-TED Compton cameras at 50 mm distance from each lateral surface and at a depth of 100 mm. The Prompt gamma radiation emitted along the track of the protons, closely correlated with the proton range, was imaged using the Compton technique with these devices. All the details on these simulations can be found in Ref. [22].

To illustrate the promising results of this MC study, we show in Figure 5 the reconstructed depth profile obtained for the 4.4 MeV prompt γ-rays originated by the protons along the water phantom. The right panel of the figure shows reconstructed 2D Compton image, where one clearly appreciates the spatial distribution of the emitted PG.

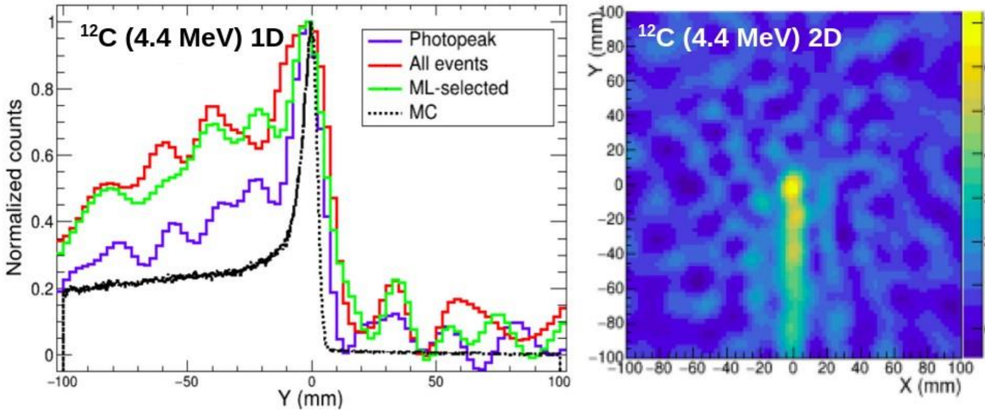

Fig. 5. Reconstructed Compton image for the 4.4 MeV prompt γ-rays (right) and 1D distribution along the proton beam axis comparing the true depth distribution (MC) with the profiles reconstructed from the Compton images (left). See text for details.

An accuracy of few mm is achieved in the reproduction of the PG emission fall-off as shown in the left panel of Fig. 5, where the reconstructed profiles are compared with the MC true distribution (black). Our inital reconstruction of the depth profile (red) has been improved thanks to a Machine Learning (ML) identification of full-energy events developed in this work [22]. As a consequence, one can recover partially the resolution and signal-to-background ratio of an ideal Camera with only full-energy events, shown by the blue line.

5 Summary and outlook

In this work we have presented the first conceptual design of the GN-Vision system, a compact simultaneous neutron-gamma imager, which may have potential applications for range and dose monitoring in HT and in nuclear security.

The GN-Vision device, designed as an evolution of the early i-TED detector, consists of two position sensitive detection layers based on CLYC-6 and $LaCl_3$ detector to enable Compton γ-ray imaging. A neutron pinhole collimator attached to the first enables the imaging of slow neutrons.

The first results of the MC design study of the system, focused in the optimization of the collimator parameters, demonstrate the capability of imaging neutrons with energies below 100 eV.

The imaging capability of GN-Vision is experimentally demonstrated with the predecessor iTED and the first MC study of its potential applicability for range verification in proton therapy shows promising perspectives. As for the neutron vision, after the conceptual proof-of-concept, the first experimental tests will be carried out in the upcoming months. The system has been recently patented [23], and further R&D will follow in the next years.

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