An advanced simulation and reconstruction framework for a novel in-beam PET scanner for pre-clinical proton Irradiation

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An advanced simulation and reconstruction framework for a novel in-beam PET scanner for pre-clinical proton irradiation

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***Abstract*- Within the project "Small animal proton Irradiator for Research in Molecular Image-guided radiation-Oncology" (SIRMIO) we have designed an in-beam PET scanner for pre-clinical application. The system is based on a novel spherical geometry, and in order to fully exploit its potential we are developing an integrated computational framework for simulation, image reconstruction and range verification. The software comprises a full Monte Carlo engine to simulate the proton treatment with related detector response, and an image reconstruction tool for simulated and experimental data. The platform is designed to integrate robust analytical reconstruction algorithms and new statistical approaches based on deep learning. The core of the framework is based on MEGAlib (The Medium Energy Gamma-ray Astronomy software library). The physical simulation is based on GEANT4. The machine learning method for the event classification is implemented with the ROOT based Toolkit for Multivariate Data Analysis (TMVA). The first prototype of the SIRMIO irradiation platform foresees a fixed beam, thus requiring the movement of the mouse for scanned beam delivery. Hence, we have extended the MEGAlib image reconstruction algorithm based on maximum-likelihood expectation-maximization (ML-EM) to correct for geometrical efficiency and attenuation taking into account the mouse motion. The goal is to be able to discriminate proton range shifts of $\sim$ 0.5 mm. Moreover, we are augmenting the image reconstruction framework with a new approach based on machine learning, which aims at using all photon events collected during irradiation (dominated by prompt gamma) to retrieve on-the-fly the range of the beam, to complement the PET information.**

1 Introduction

Positron emission tomography (PET) allows visualizing the spatial distribution of positron annihilations followings the interaction of the proton beam with biological matter: this information is closely related with the dose distribution and the range of the proton beam [1]. Moving from the human to the small animal scale, additional challenges arise due to the involved small dimensions. In order to maximize the gamma detention efficiency, important to improve the reliability of range monitoring, our solution consists in a fixed scanner in which the mouse can be moved to allow different positions and angles of irradiation.

The scanner is composed of 56 depth of interaction capable scintillator blocks of pixelated LYSO ($Lu_{1.8}Y_{0.2}SiO_5$) [2]. The detector technology is being developed at NIRS-QST [3] in collaboration with LMU. The pixel size is 1 mm, each single block is divided in 3 layers and the total thickness is 20 mm. The inner radius of the sphere is 72 mm. The expected detection efficiency is calculated to be between 8% and 12%.

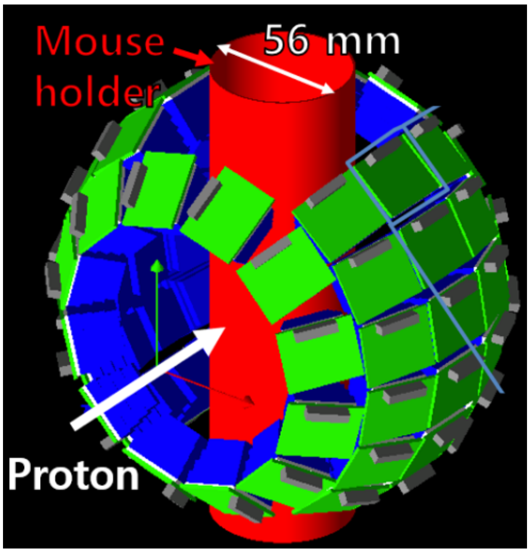

Figure 1: SIRMIO PET scanner design. The detector is composed of 56 scintillator blocks. The radius of the sphere is 72 mm. The mouse holder can be moved to place the tumor in the center of the scanner field of view.

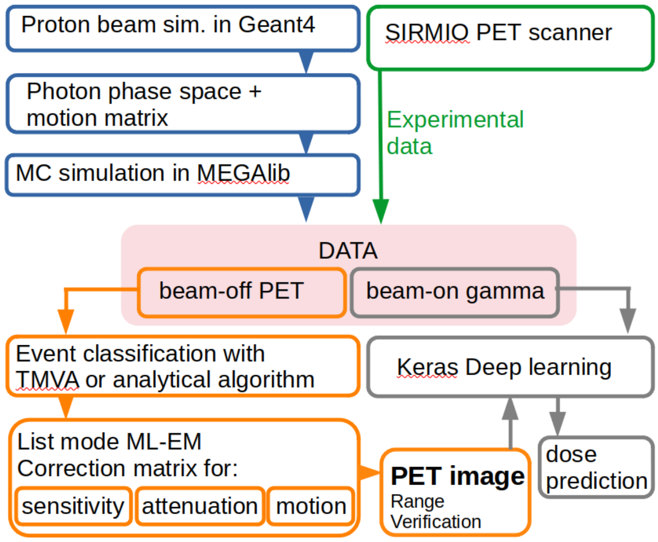

Figure 2: Framework architecture. Beam-on data are collected during the irradiation and beam-off data are collected in between the pauses of the irradiation (needed to accommodate the translation and rotation of the animal) or after it.

2 Materials and Methods

This work presents the computational framework being developed for the imaging workflow (see fig. 2).

2.1- Monte Carlo simulation

The proton beam simulation is done with a Geant4 code which can import the computed tomography anatomy of the mouse. The treatment plan is composed of many beams with different positions and energies at different times. All the spots are processed in a single Geant4 simulation and the resulting photons leaving the target are stored in a phase space. A motion matrix is created to transform this phase space to consider the movement of the mouse (from the mouse reference system to the scanner one). The new phase space is used in a MEGAlib [4] simulation modeling the detection in the PET scanner (see fig. 1). The ROOT-integrated machine-learning environment is used for accurate classification of various event types. The energy window to consider a valid PET event is set from 410 to 580 keV. No time window is used since the Neural Network (NN) is trained to process only the position and the energy of the hits. An analytical method to discriminate PET events is also included.

2.2- Image reconstruction

We have extended the MLEM list-mode image reconstruction available in MEGAlib to account for the correction of the mouse translation and rotation, photon attenuation and detector geometrical efficiency. Each line of response is stored in a i event. The final image is represented by a matrix λ_j^l where j represent a image voxel and the algorithm works over l iterations:

$$\lambda_j^{(l)} = \lambda_j^{(l-1)} \sum_i \frac{M_j(t)G_j(t)A_i s_{ij}}{\sum_j s_{ij}\lambda_j^{(l-1)}} \qquad (1)$$

s_{ij} is the system matrix of the reconstruction algorithm at the motion compensated state. $G_j(t)$, $M_j(t)$, A_i are, respectively, the efficiency, motion and attenuation correction matrix. Efficiency and motion are detector dependent, therefore function of time. The sensitivity matrix is done

2.3- Deep learning for events reconstruction and in-beam photons detection

A ROOT-integrated machine-learning environment is used for accurate classification of various event types. The accuracy (i.e. the ability of the neural network to recognise a PET event based on hits analysis) is between 99 and 70 depending on the numbers of the hits.

During the 79irradiation we expect not to be able to detect the PET signal because of the high rate of gammas created by the interaction of protons with matter. The current implementation uses a NN trained with the distribution of all the photons detected during the irradiation time as input and the range of the Bragg peak (BP) as a output. The training is so far made with a fixed PMMA phantom geometry and different monoenergetic proton beams (from 25 MeV up to 50). The NN archi-

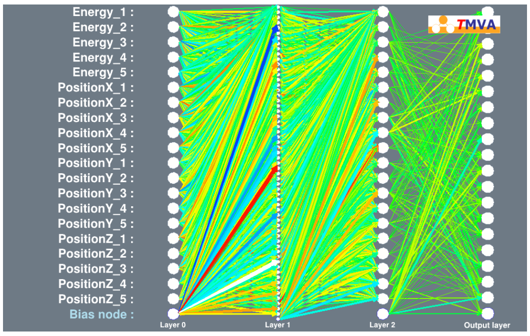

Figure 3: Orange and green lines are the PET image profile corresponding to the red and blue Bragg peak for energies separated by 0.5 MeV. The reference frame is set with the center of the scanner as central point.

tecture is implemented in Keras, the python deep learning library. A similar method in which also the dose distribution is included as output of the training data-set is under development.

3 Preliminary results and outlook

The A image in figure 4 is a PET reconstruction of a Geant4 simulation of a positrons line source (50 mm length, 1 mm radius). This source moves three times during the simulation (rotations of 45o and 90o and translation of 10 mm). In the reconstruction B all the corrections are applied, so the three lines are overlapped. A is the reconstructed PET image in the laboratory reference frame and B is the reconstructed image in the object reference frame.

Figure 5 shows a comparison between 2 reconstructed PET profiles, with the underlying positron emitter distribution and the corresponding energy deposition.

The 2 beams are identical:25 MeV with an energy distribution of 2 MeV as sigma. Flux of $5x10^5$ particle/second, beam-on of 15 seconds followed by a beam-off of 10 minutes. The difference in range between the two beams (calculated with the shift method) is for the dose distribution (1.1 ± 0.1) mm, for the positron emitter distribution (1.4 ± 0.1) mm and for the PET profile (1.4 ± 0.1) mm. For the PET reconstruction are used beam-on and beam-off data.

The preliminary results of the method explained in section *2.3* show the possibility for a trained NN to predict the range of the beam based only on the gamma distribution with an estimated error of

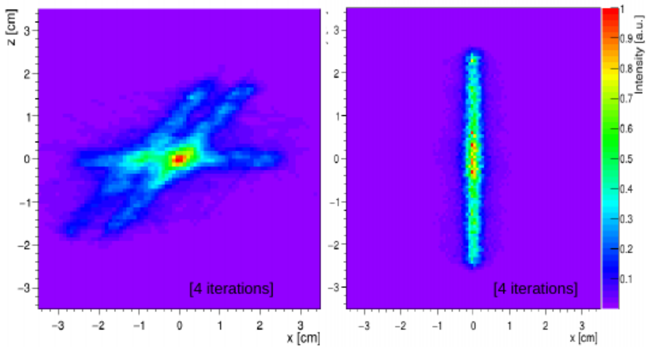

Figure 4: PET image and spatial distribution of β^+ radioisotopes for a 50 MeV proton beam in a PMMA phantom.

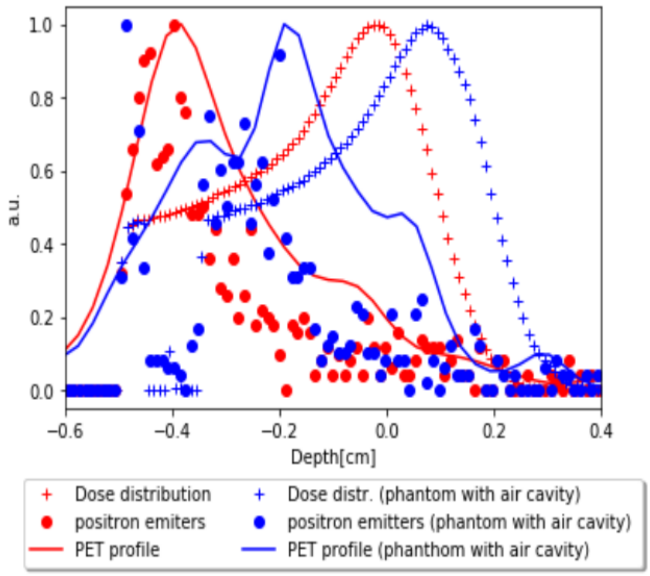

Figure 5: Orange and green lines are the PET image profile corresponding to the red and blue Bragg peak for energies separated by 0.5 MeV. The reference frame is set with the center of the scanner as central point.

1.5 mm. This method needs further development and validation. Results to be presented will include demonstration of the entire workflow for realistic mouse irradiation.

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