Design of a new 2D amorphous Silicon-based detector for Particle Therapy

Khalil El Achi [1], Eduardo Cortina Gil [1], Alexis Warnier [2], Victor De Beco [2], Severine Rossomme [2]
[1] *Université Catholique de Louvain, Louvain-la-Neuve, Belgium,* [2] *IBA Dosimetry, Louvain-la-Neuve Belgium*

Introduction to Particle Therapy

Particle Therapy is a radiation treatment that precisely delivers accurate doses to tumors by utilizing the unique property of energy deposition of each particle as seen in Figure 1. Heavier particles, such as Protons and Carbon ions, can penetrate tissue and deliver narrow doses in an acute region [1]. Moreover, particle therapy also has radiobiological advantages compared to conventional therapy.

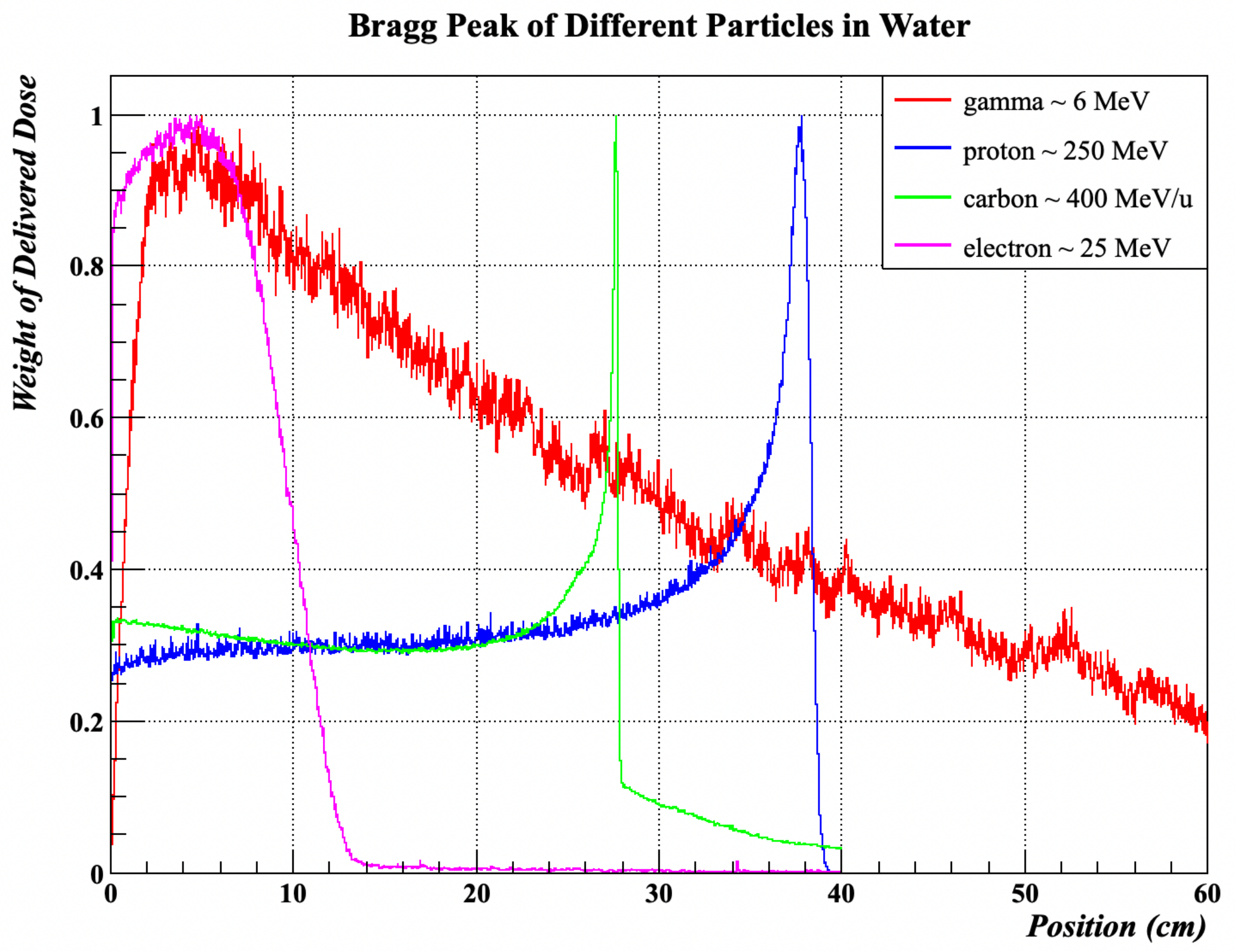

Figure 1: Energy Deposition Spectrum of different particles utilized in Particle Therapy treatments.

Proton Therapy

Proton therapy (PT) utilizes high-energy protons of about 60 ~ 250 MeV that penetrate tissue and deposit most of their energy at the end of their trajectory. The dose can be administered by superpositioning multiple Bragg Peaks with different energies and intensities to create a uniform spread-out Bragg Peak (SOBP) in Figure 2. The dose can also be delivered using Pencil Beam Scanning (PBS), which delivers the dose successively using a narrow beam (σ~3.5mm) guided via magnetic coils, as seen in Figure 3 [2]. Ultra-high dose rate (UHDR) proton therapy is a new treatment modality that is currently being studied by several groups. The treatment delivers high doses in a short period of time (higher than 40 Gy/s) and is highly effective against tumor cells while maintaining healthy cells [3]. The aim of this work is to design a semiconductor-based detector to perform proper quality assurance (QA) measurements for proton therapy, including UHDR conditions.

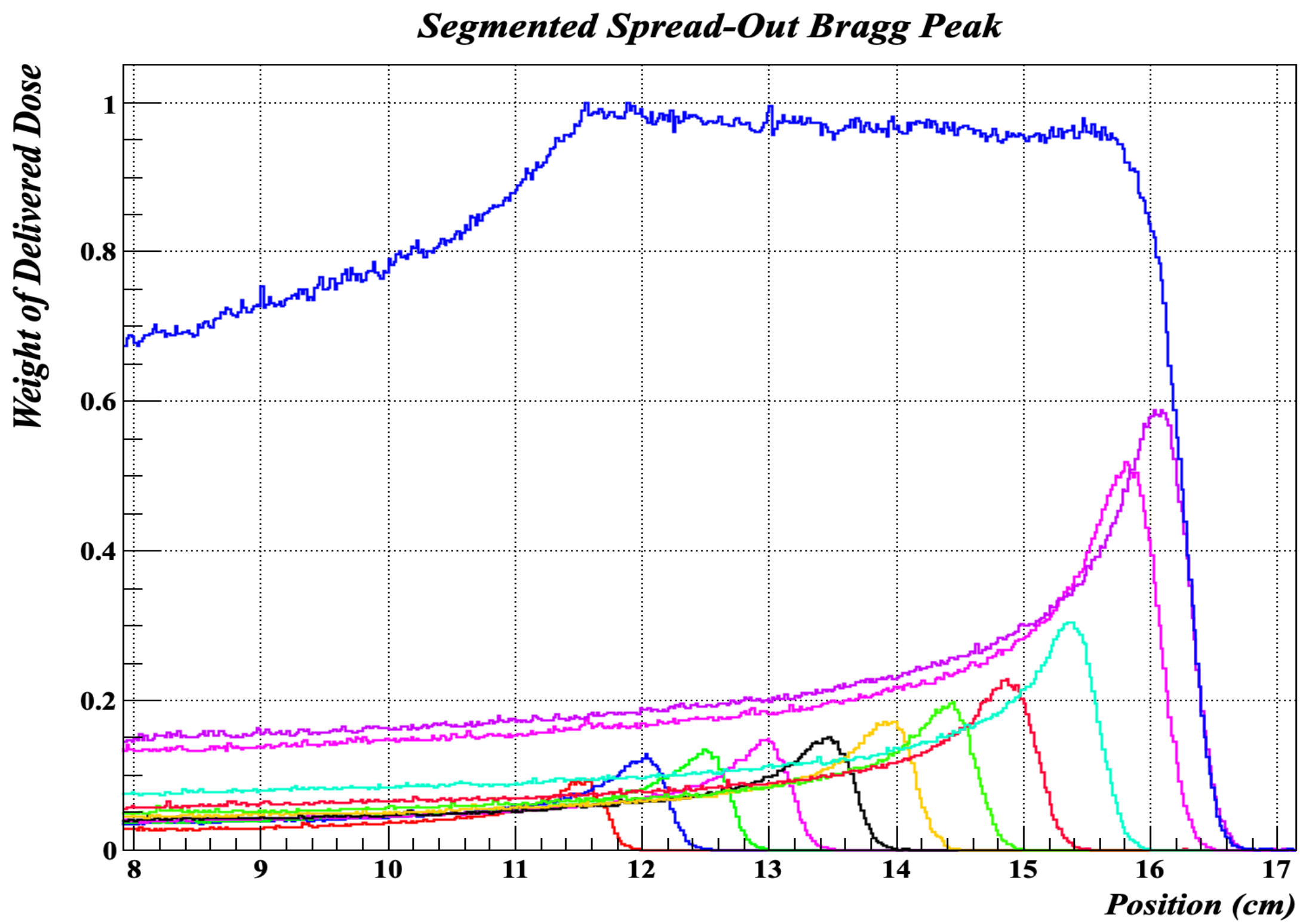

Figure 2: Superpositioned Bragg Peaks that create an SOBP to deliver a uniform dose.

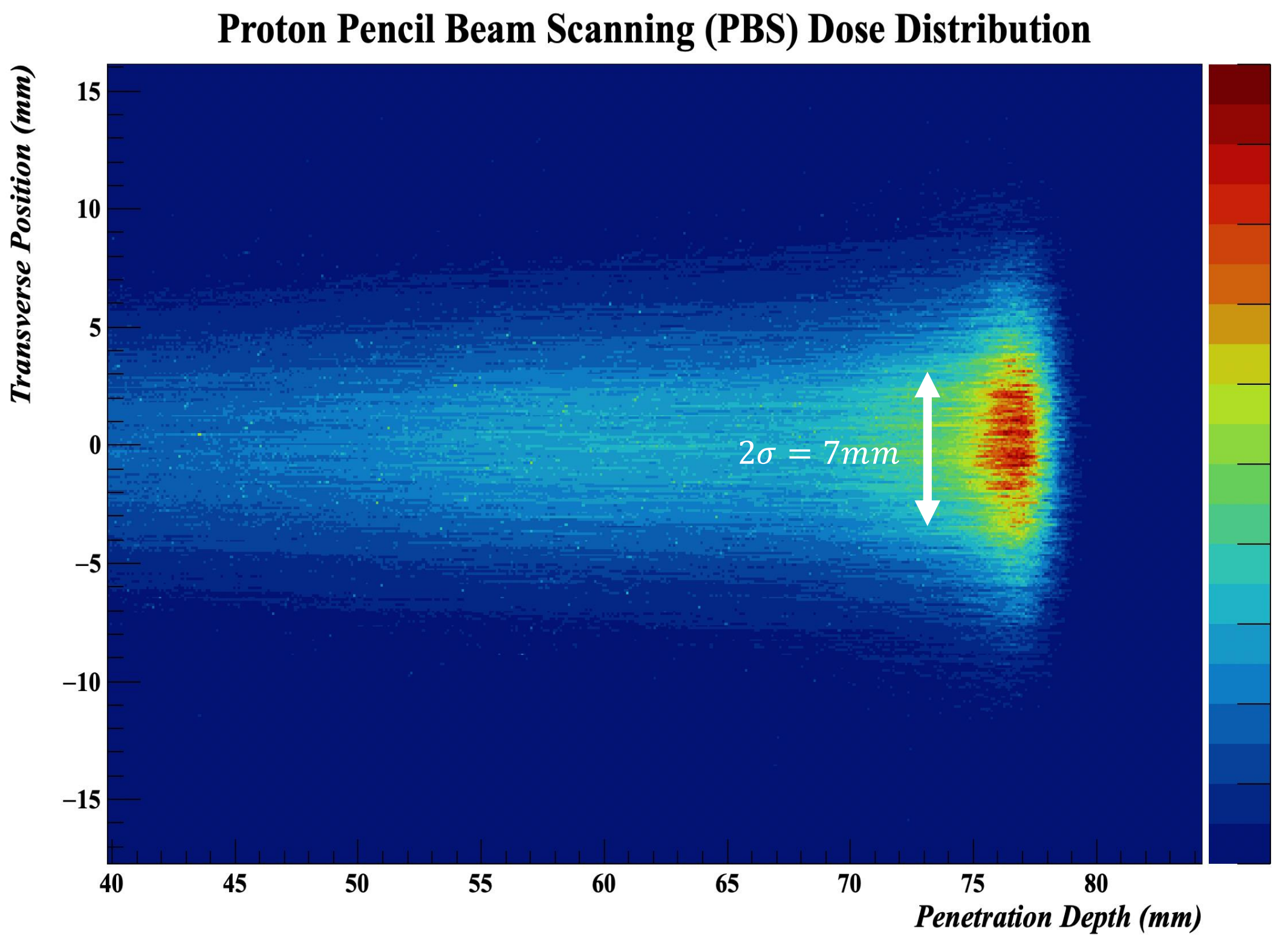

Figure 3: Dose distribution of Proton pencil beam scanning that utilizes a narrow beam to deliver the dose to an area of ~7mm

COMSOL/Garfield++ Simulation of an aSi-based Photodiode

Cross-sectional Simulation of a Single aSi Photodiode

Amongst semiconductor materials, amorphous silicon (aSi) is characterized by durable radiation hardness [4]. To properly simulate the different characteristics of a photodiode, COMSOL was used with the semiconductor module. A PN-junction is constructed by introducing highly concentrated p-doped implants $N_p = 10^{18}\ cm^{-3}$, onto a lightly n-doped a-Si substrate $N_n = 10^{15}\ cm^{-3}$. Creating an active region that can be fully expanded up to 2 µm with a reverse-bias voltage $V_{rb} \sim -5\ V$

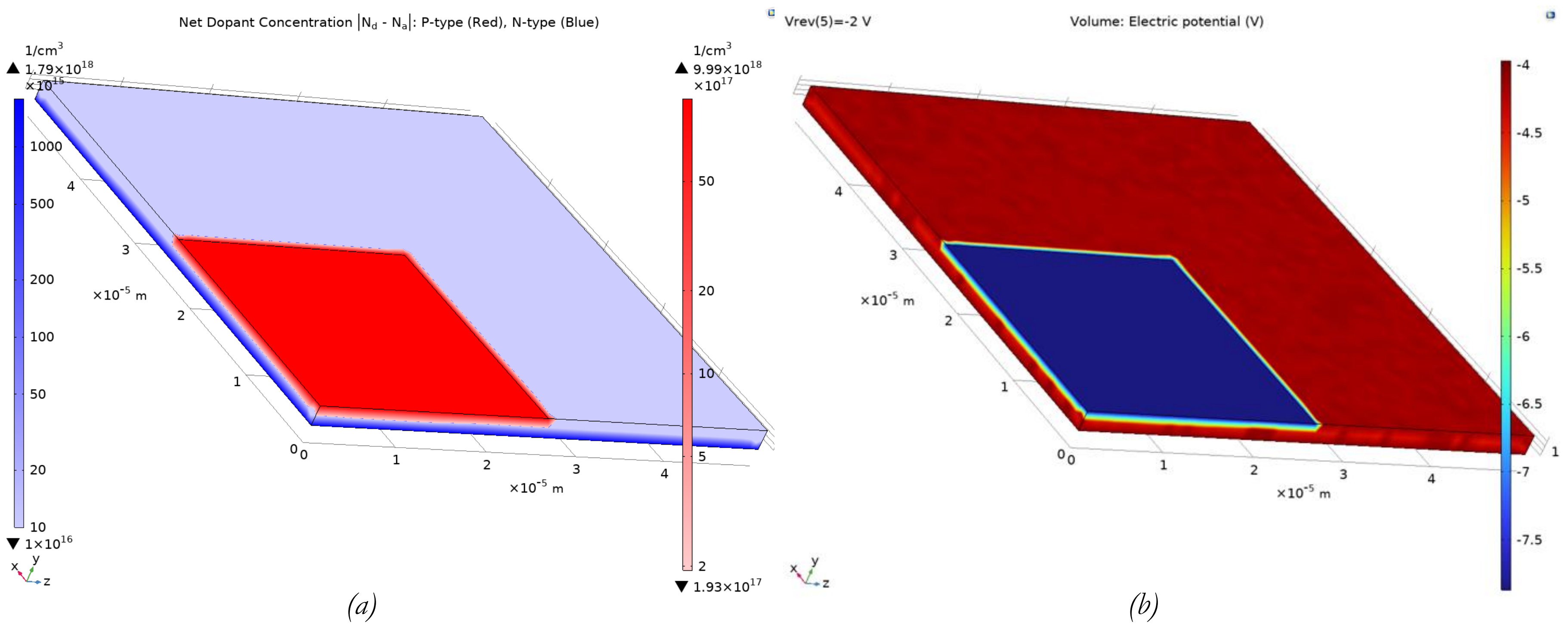

Figure 4: (a) Schematic representation of the doping concentrations across a cross-section of the photodiode. *(b)* Electric Potential map across the junction showing a high negative potential around the implant at $V_{rb} = -2\ V$.

Garfield++ Interface for Charge and Signal Generation

Using the class, Garfield::ComponentComsol(), in Garfield++ [5], allows the input of the field maps and mesh file to simulate more accurately the drift lines of electron/hole pairs and, subsequently, the charge and signal generated on the readout electrode of the photodiode. The electric potential map and the electric field can now be read correctly, as seen in Figure 5.

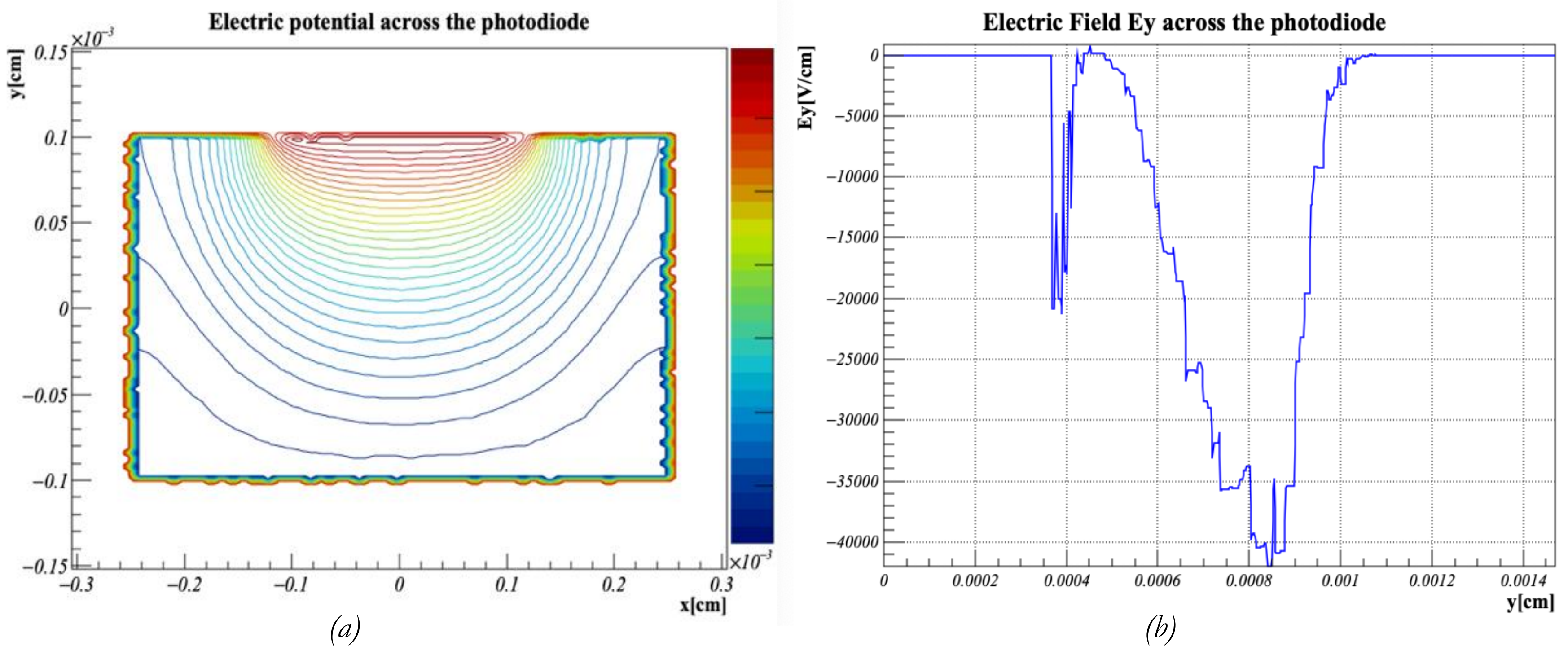

Figure 5: (a) Contour lines of the electric potential map as read by class Garfield::ViewField() from the COMSOL inputs. *(b)* The electric field E_y across the y-axis of the PN Junction, showing the creation of a depletion region.

Charge Measurements done with a Proton Beam using a Silicon-Based Diode

Monte Carlo Simulation Study using Geant4

Precise modeling of the experimental setup was done in Geant4 [5] using the FTFP_BERT_EMV physics list. Where the exact geometry of the diode and the profile of the beam were adapted to compute the perspective energy loss in the sensitive region of the diode, as seen in Figure 7. With that, the # e/h pairs and, subsequently, the measured charge. In addition, the hits position generated was used to verify the beam profile. The proton beam used at the UCL Cyclotron was closely modeled. The beam has an energy of 62 MeV with a Gaussian profile of 2cm sigma and a diameter of 8cm. The proton flux ranged from 10^5 - 10^8 protons/(s.cm^2).

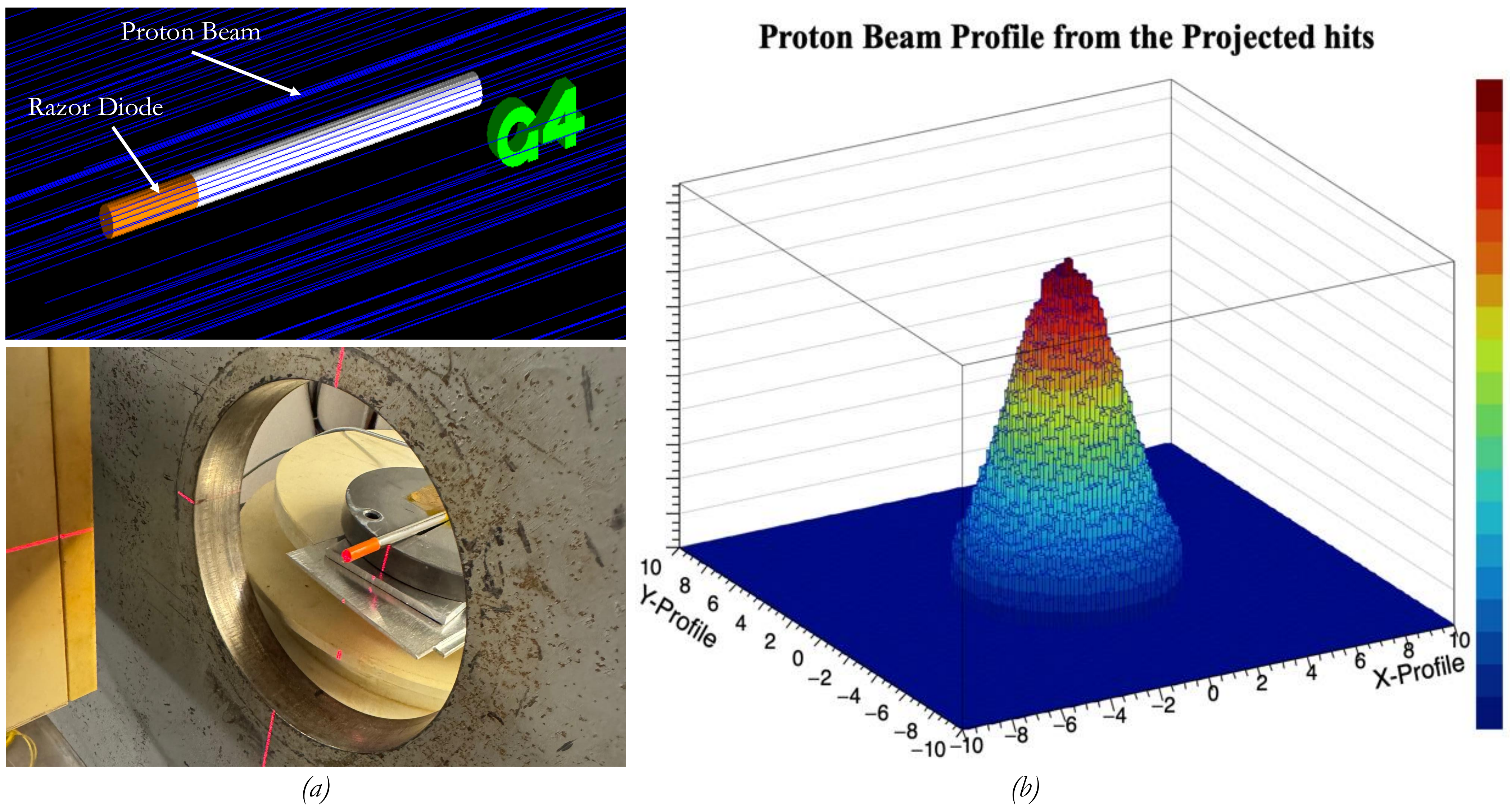

Figure 7: (a) Detector and beam construction in Geant4, along with the real picture of the diode mounted in front of the proton beam's aperture. *(b)* Proton beam profile constructed by projecting proton hits on the x-y plane.

Experimental Results at UCL - Cyclotron

To validate and calibrate the detector simulation, measurements were conducted with a Proton beam using the IBA's Razor Diode, a p-type crystalline silicon diode with an active region with a diameter of 0.6 mm and 20 µm in thickness. The measurements were performed using the Cyclotron at UCLouvain in Louvain-la-Neuve. The charge generated was measured using an electrometer with a 1 min total integration time for each beam intensity. The results are plotted in Figure 6. The results show a very close correlation with simulation estimation with an average of ~15% offset from the MPV. The measurements fall within the range of 2σ of the Landau fit estimation and show pristine charge linearity.

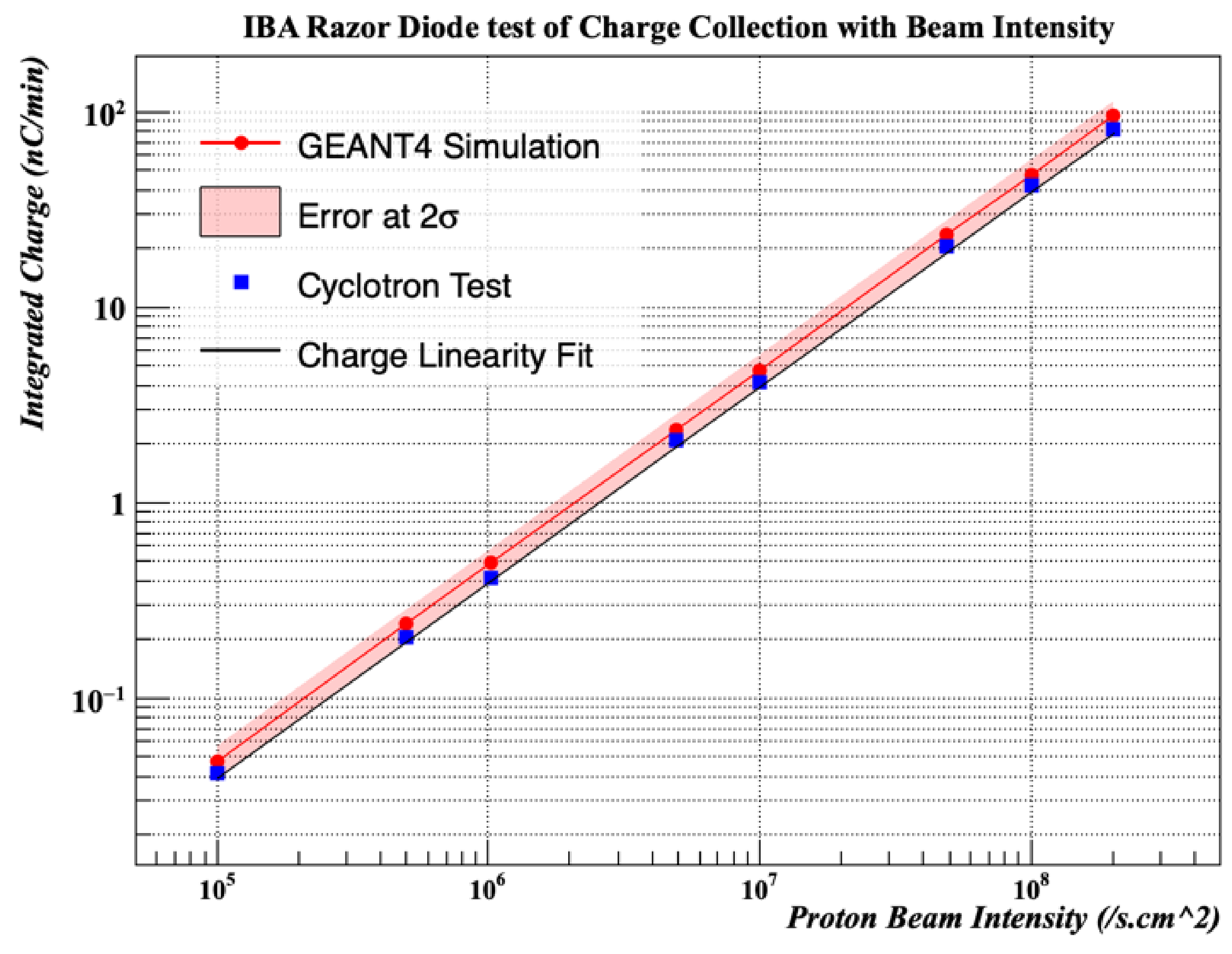

Figure 6: Results Geant4 Simulation with 2σ estimate and experimental Results of the Charge Generated integrated for 1 min for each proton beam intensity.

Conclusions and Further Work

Solid-state-based diodes offer optimal advantages when used in patient QA with proton therapy. With that, the experimental measurements done with the Razor Diode at the UCLouvain Cyclotron have confirmed the validity of the simulation estimation of the charge generation. The results fall into the 2σ range and have proper linearity. The next step would be to perform tests with proton beams in medical and flash conditions. This will be done to test for saturation effects and charge non-linearity. Along with other particles used in radiation therapy like gamma and electron beams. Nevertheless, amorphous-based silicon photodiodes will also be tested in similar experimental conditions to compare the different characteristics between the behavior of amorphous and crystalline-based silicon diodes in patient quality assurance measurements, pertaining to the difference of electron and hole mobilities and total charge generation.

References

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