Monte Carlo Simulation of Air-Filled Parallel Plate Ionization Chamber in Ultra-high Dose Rate

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Background

Air-filled Parallel Plate Ionization Chamber (PPIC) are recommended by TRS-398 [1] for reference dosimetry for conventional radio and particle therapy. However, the high, even ultra-high dose rates (UHDR) required for the FLASH effect cause losses in the charge collection efficiency (CCE) that can no longer be accurately corrected with conventional models such as Boag's.

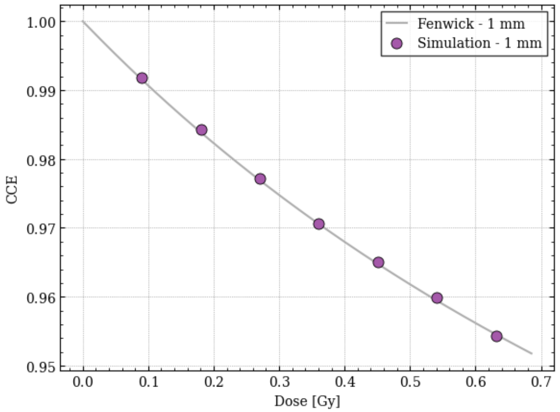
Method

We based our Monte Carlo simulation on Garfield++ [2-3], an open access project maintained mainly by Heinrich Schindler and contributors at CERN. Garfield++ is an object-oriented C++ toolkit dedicated to the study of charged particle transport and interactions in gases and semiconductors. In addition, it can provide the simulation of primary radiation beam.

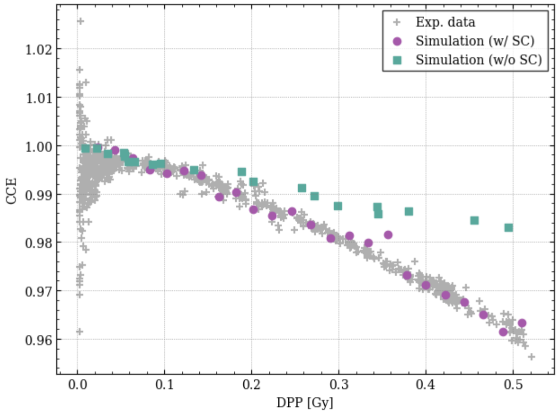
We implemented to this software two key physical processes occurring in PPIC at UHDR. Ion-ion volume recombination, which reduces the charge collection efficiency and space charge effects, which distort the applied electric field inside the chamber. Recombination probabilities are computed on a three-dimentional mesh populated using particle in cell methods. To make the simulation self-consistent in Garfield++, we implemented a Poisson solver using the Successive Over-Relaxation (SOR) method to compute the electric field created by the free charges.

Results

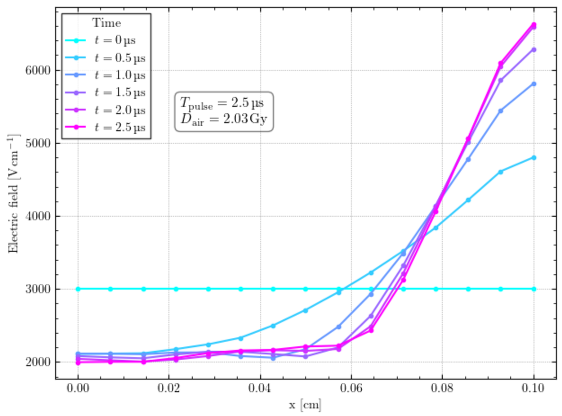
The recombination model without space charge was first validated against Fenwick's analytical model [4] for an instantaneous pulse. Fenwick derived a charge collection efficiency (CCE) based on a realistic negative-ion distribution, instead of an approximation like Boag.



In a second step, the simulation including space charge was compared with experimental measurements obtained using a 230 MeV pulsed proton beam delivered by an IBA S2C2 synchrocyclotron. The beam featured 10 µs pulses at a 1 kHz repetition rate, with doses reaching up to 0.5 Gy per pulse. The investigated PPIC has a 1 mm gap and was operated at 500 V.



Finally, to further illustrate the impact of space charge in the UHDR regime, we computed the temporal evolution of the electric field in the chamber during a squared 2.5 µs pulse.



Conclusion and Outlooks

We succesfuly implemented ion-ion volume recombination and space charge electric field calculations within the Garfield++ toolkit. The software can now accurately simulate the behaviour of an air-filled PPIC under UHDR conditions. Our results also confirm that space-charge effects cannot be neglected in the UHDR regime. Looking ahead, we aim to confront the simulation with a wider range of experimental data and study the uncertainties associated with the model.

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[1] International Atomic Energy Agency. "Absorbed Dose Determination in External Beam Radiotherapy". Rev. 1. Technical Reports Series.
[2] Heinrich Schindler et al. "Garfield++". https://garfieldpp.web.cern.ch
[3] Stephen Biagi. "Magboltz: Transport of electrons in gas mixtures". https://magboltz.web.cern.ch
[4] John D Fenwick and Sudhir Kumar 2023 Phys.Med.Biol. 68 015016

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