Simulating Ionization Chambers in UHDR

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Background:

Currently, Boag's model is used to calculate the charge collection efficiency (CCE) of ionization chambers (ICs), particularly in the context of proton therapy. Ionic volume recombination, which occurs during the drift of ions in the chamber, reduces the CCE, defined as the ratio of the charge collected to the total charge initially produced.

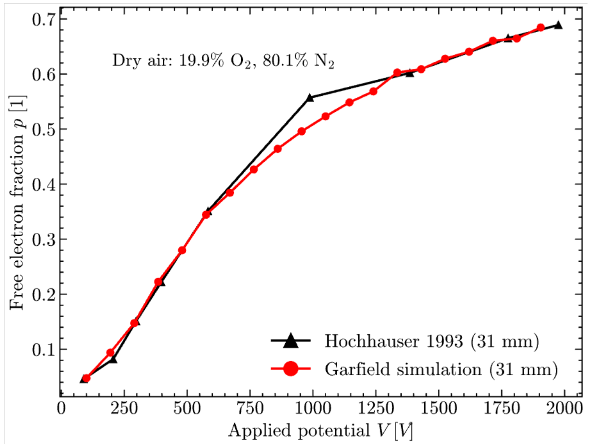
To prepare for FLASH proton therapy, these ICs must provide accurate readings under ultra-high dose rates (UHDR), where effects like space-charge screening (SCS) - not covered by Boag's theory - may impact free electron fractions (FEF) or collection time.

Method:

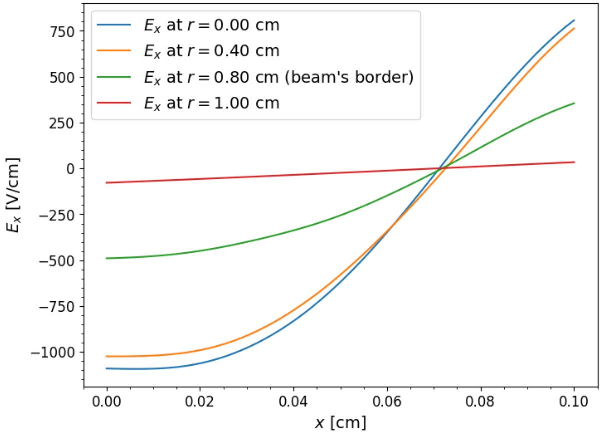
To simulate air-filled ICs, we used Garfield++ [1], an open-source software developed in collaboration with CERN, in parallel with Heed for track and ionization simulations and Magboltz [2] for electron transport. Unlike the attachment process, Garfield++ does not yet simulate recombination.

We successfully replicated Hochhäuser [3] 's experimental results of FEF as a function of electric field inside air-filled ICs.

To simulate proton pulses of the ProteusONE® synchrocyclotron, we modelled a uniform 100 pC circular beam (r=0.8 cm) of 230 MeV protons, with 10 µs pulse width, and 1 kHz



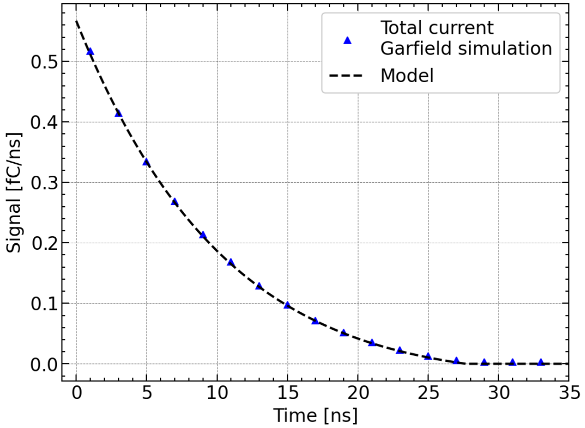
pulse frequency. The IC has a 1 mm gap and 500 V potential applied across the electrodes. By dividing a single pulse into 10 time steps, we analysed the distributions of ions and compute the SCS electric field.



This simulation also enabled us to propose and validate a measurement protocol for the FEF based on fast electronic current readings. This is possible by fitting the attachment coefficient in the equation of the electronic induced current to match the measured signal.

$$I_e(t) = \frac{w_e}{d}\, e\, n_0 \left(1 - \frac{w_e}{d} t\right) e^{-\eta w_e t}$$

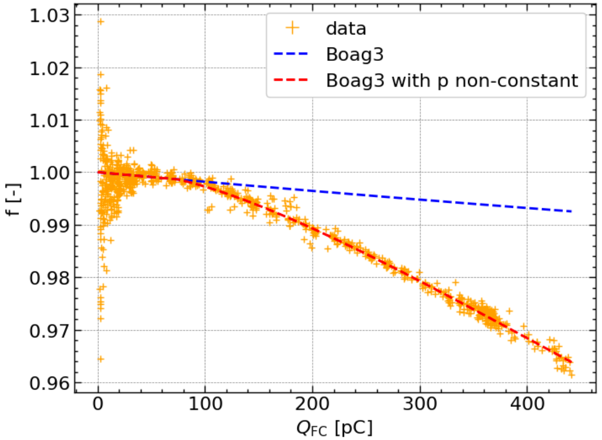
$$p = \frac{1}{\eta d}\left(1 - e^{-\eta d}\right)$$



Results:

Results shown that the magnitude of the SCS electric field can reach up to 1000 V/cm inside the chamber. This value is highly significant compared to the 5000 V/cm applied in the chamber.

Motivated by our results and the recent work of Paz-Martín [4] on the evolution of the FEF with dose per pulse, we adjusted this parameter in Boag's model as a function of the dose per pulse, leading to encouraging results.



Conclusion:

The SCS effect appears to have a significant impact on the CCE of ICs. The reduction in the electric field and its effect on the attachment coefficient, leading to a modified FEF, could be one possible explanation for the overestimation of the CCE. Additionally, this effect could extend the collection time, increasing the duration during which ions can recombine.

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[2] S. Biagi. "Magboltz: Transport of electrons in gas mixtures". In: CERN program library, https://magboltz.web.cern.ch/magboltz/ (2005)
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[4] Paz-Martín, Jose et al. "Numerical Modeling of Air-Vented Parallel Plate Ionization Chambers for Ultra-High Dose Rate Applications." (2022). Physica Medica 103 147–56

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