Designing an ultra-thin parallel-plate ionization chamber for ultra-high dose rate applications

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Introduction

Ultra-high pulse dose rate (UHPDR) radiotherapy has been recently proposed as a new treatment delivery technique. This modality, using instantaneous dose rates exceeding 10^6 Gy s^{-1} and average dose rate greater than 40 Gy s^{-1}, has shown advantages over conventional radiotherapy due to the normal tissue sparing effect, achieving similar tumor control probabilities in pre-clinical studies[1].

Air vented parallel plate ionization chambers (PPIC) are considered the gold standard for the determination of the absorbed dose to water under reference condition in low energy electron beams. However, in the UHPDR regime, the commercially available PPIC exhibit severe problems of saturation due to ion-ion recombination during the drift of the charge inside the sensitive volume[2].

Materials and methods

When a PPIC is irradiated under UHPDR conditions, the electric field inside the chamber is modified during the collection of the charge due to the imbalance between positive and negative charge carriers in the volume. In this regime, the theory of general recombination developed by Boag fail to describe the actual behavior of the PPIC.

For this reason, a detailed computational model of a PPIC[3] has been developed with the aim of finding the optimal design parameters to obtain a linear response varying dose per pulse up to the UHPDR regime. In this model, the coupled partial differential equations describing the charge carrier transport inside the PPIC are solved along the (z) coordinate perpendicular to the electrode planes:

$$
\begin{aligned}
\frac{\partial n_+(z,t)}{\partial t} &= I(z,t) - \alpha\, n_+(z,t)\, n_-(z,t) - \frac{\partial}{\partial z}\left[E(z,t)\, \mu_+\, n_+(z,t)\right], \\
\frac{\partial n_-(z,t)}{\partial t} &= \gamma\, n_e(z,t) - \alpha\, n_+(z,t)\, n_-(z,t) + \frac{\partial}{\partial z}\left[E(z,t)\, \mu_-\, n_-(z,t)\right], \\
\frac{\partial n_e(z,t)}{\partial t} &= I(z,t) - \gamma\, n_e(z,t) + \frac{\partial}{\partial z}\left[v_e(z,t)\, n_e(z,t)\right],
\end{aligned}
\tag{1}
$$

with the Poisson equation

$$
\frac{\partial E(z,t)}{\partial z} = \frac{e}{\epsilon}\left[n_+(z,t) - n_-(z,t) - n_e(z,t)\right], \tag{2}
$$

and the boundary condition

$$
\int_0^d E(z,t)\, dz = V \quad \forall t \tag{3}
$$

Symbol	Units	Definition
n_+, n_-, n_e	m^{-3}	Positive ions, negative ions and electron densities, respectively
I	m^{-3} s^{-1}	Charge liberated per unit of time that escapes initial recombination
α	m^3 s^{-1}	Volume recombination coefficient between positive and negative ions
μ_+, μ_-	m ^{2} V^{-1} s^{-1}	Mobility of positive and negative ions, respectively
E	V m^{-1}	Electric field across the PPIC
γ	s^{-1}	Electron attachment coefficient
v_e	m s^{-1}	Electron velocity
V	V	Bias voltage applied to the PPIC
d	m	Distance between electrodes of the PPIC
e	C	Elementary charge
ϵ	C V^{-1} m^{-1}	Air permittivity

Table 1: Definition of the symbols used in the equations 1, 2 and 3 that models the PPIC behavior.

In order to test the results of the numerical simulation, two ultra-thin parallel plate ionization chamber (UTPPIC) were assembled at the University of Santiago of Compostela. The prototypes were build using electrodes made of 18 µm thick of Cu-Ni-Au deposited on a 1 mm thick FR4 disk of 30 mm radius. The high voltage and guard ring have 10 mm external radius. A clearance of 0.25 mm between the collection electrode of 5 mm radius and the guard ring was provided. In order to achieve a 0.25 mm distance between electrodes, a lase-machined Mylar spacer with a lateral slit for air renovation was used. The housing of the UTPPIC was made of Rexolite® and a triaxial cable with a PTW-M type connector was supplied for the connection to the electrometer. The distance between electrodes of this two prototypes was verified through a X-ray image performed with a MicroCT (Bruker Skyscan 1272), yielding 0.27 mm and 0.22 mm distance between electrodes.

Figure 1: Image of the first UTPPIC prototype with 0.27 mm distance between electrodes.

The experimental characterization of these two prototypes was carried out in the Physikalisch-Technische Bundesanstalt (PTB) research linac and in the ElectronFlash linear accelerator at SIT S.p.A (Aprilia, Italy).

Results

In order to determine the optimal parameters for the PPIC construction, a detailed study of the impact of the design parameters was performed. It has been found that the distance between electrodes is the parameter with the greatest impact on the charge collection efficiency. Based on the simulation, a distance between electrodes of 0.25 mm would be suitable for measurements with ion recombination losses below 1 % for doses per pulses up to 12 Gy with a pulse duration of 4.5 µs using 300 V bias voltage (Figure 2A). It has also been found that the operation limits of the UTPPIC have a dramatic dependence on the instantaneous dose rate (Figure 2B). This is due to the fact that the ion collection time of the UTPPIC is in the same range of the typical pulse duration of a clinical accelerator.

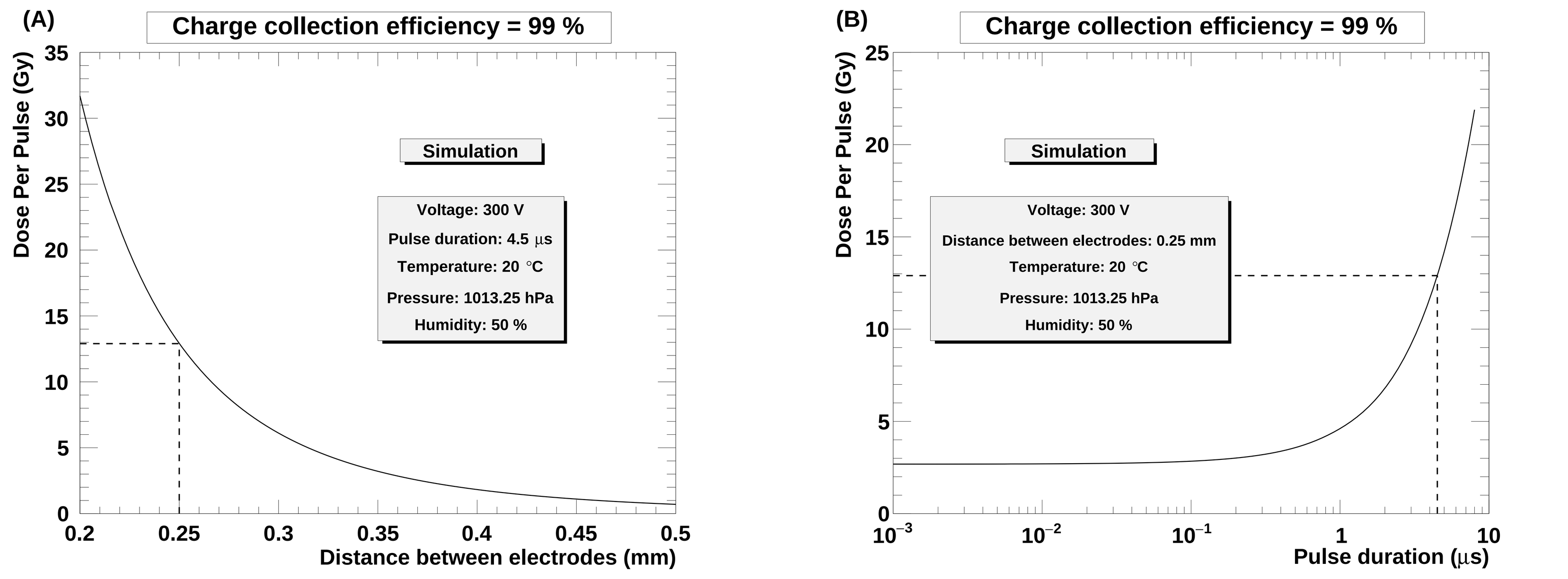

Figure 2: Results from the simulation of the PPIC. Figures show the dose per pulse that will lead to a charge collection efficiency of 99 % as a function of the distance between electrodes (A) for 4.5 µs pulse duration and as a function of the pulse duration (B) for 0.25 mm distance between electrodes. Simulations are performed for 300 V bias voltage and standard pressure, temperature and humidity conditions (1013.25 hPa, 20 °C and 50 %).

The 0.22 mm prototype was tested at SIT facility ranging the dose per pulse by means of the pulse duration. This UTPPIC shows a linear response up to 10 Gy per pulse for a 4 µs pulse duration (Figure 3A). The moderate over-response of the UTPPIC at higher dose per pulse can be attributed to the interaction between the electric field perturbation and the presence of electron multiplication. The 0.27 mm prototype was tested at PTB using +250 V bias voltage, showing a deviation from linearity of 1.4 % at 5.4 Gy per pulse, as predicted by the simulation (Figure 3B). Based on simulation, operating the chamber at +300 V will reduce the recombination to 0.3 %.

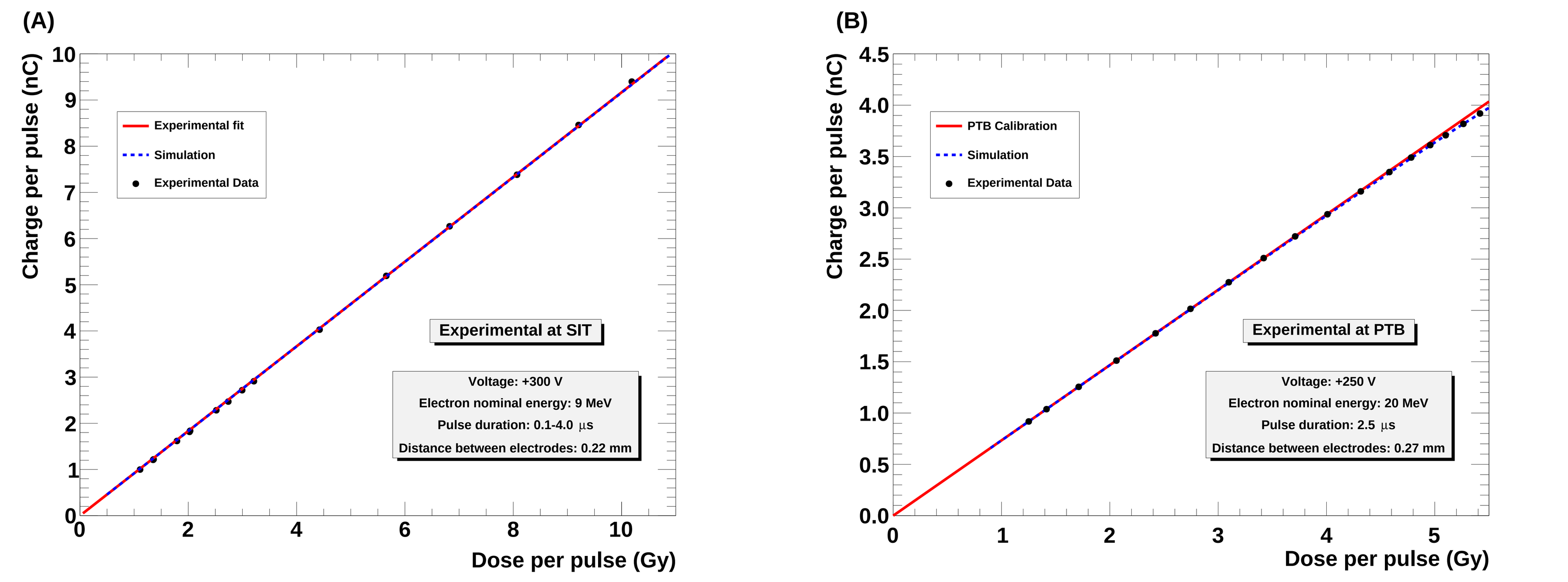

Figure 3: Experimental results of the two prototypes assembled. Figure A show the response of the 0.22 mm UTPPIC prototype tested at SIT facility using +300 V bias voltage. Figure B show the response of the 0.27 mm UTPPIC prototype tested at PTB using +250 V bias voltage.

Conclusions

- UTPPIC can be used for dosimetry in UHPDR electron beams up to high dose per pulse (10 Gy) in pulse duration of 4 µs with recombination losses lower than 1 %.
- A pronounced dependence of the detector response with the electrode distance is observed. High precision in the assembly of the detector is required for proper operation.
- As ion collection time in UTPPIC is of the same order of magnitude as the typical pulse duration of a clinical accelerator, charge collection efficiency show a dramatic dependence with the pulse duration. Due to this, the Boag-like formalism cannot be used for the determination of the charge collection efficiency as it assumes an instantaneous delivery.
- The reduction of the chamber electrode distance has its limitations. Undesired phenomena such as two-body attachment and electron multiplication are significant. A 2 % increase in the saturation current from 150 V to 400 V has been observed in X-rays. Further investigations on the impact of this effect are needed.

References

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