Dosimetry of pulsed beams in proton therapy

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INTRODUCTION

In order to reduce the cost of proton therapy systems, Ion Beam Applications has developed in recent years the ProteusONE^{TM} system, which consists of a compact superconducting synchro-cyclotron (S2C2) [1] and a compact, rotating gantry [2]. The S2C2 delivers a pulsed proton beam at 230 MeV with a repetition rate of 1 kHz and a pulse duration of 10 μs. The larger ProteusPLUS^{TM} proton therapy system utilizes the isochronous Cyclone^{TM} 230 cyclotron and delivers a continuous beam. Both systems deliver about the same average dose rate and thus the instantaneous dose rate in the ionization chambers (IC's) at the exit of the gantry become very large in the ProteusONE^{TM} system. Recombination losses in the IC's cannot be avoided and an on-line efficiency correction has to be applied. This poster introduces an approximate formula to evaluate recombination losses by using the concept of an "asymmetrical ionization chamber".

THE ASYMMETRIC IONIZATION CHAMBER

Theoretical considerations

The detected amount of charges in an ionization chamber is given by :

$$Q_{\mathrm{det},i} = G_i Q_{IN} \varepsilon_i \quad \text{where} \quad G_i = \frac{2 d_i S \rho}{W} \qquad (1)$$

where Q_{IN} is the incident amount of proton charges, ε_i is the detection efficiency of the ionization chamber with gap size d_i, S the stopping power of protons in the gas, ρ the gas density and W the ionization potential. The detection efficiency is determined by the amount of recombination losses which occur when free electrons travel through the gas. A theoretical description of recombination losses in rectangular IC's can be found in [3]. Here we adopt the following formulation for the detection efficiency :

$$\varepsilon_i = p_i + \frac{1}{u_i} \ln\left[1 + (1 - p_i) u_i\right] \quad \text{where} \quad u_i = \frac{\mu d_i^2 r}{V} \qquad (2)$$

and r is the positive ion density in the gas, V is the applied voltage, μ is a gas constant (see [3]) and p_i is the free electron fraction (see [3,4] for details). It is clear that for two IC's with different gap sizes, sharing the same gas volume, the parameters u_1 and u_2 are related as $u_1 = (d_1^2 / d_2^2) u_2$

An asymmetric ionization chamber (AIC) is a rectangular large area IC which consists of 2 IC's in series, with slightly different gap sizes. This is schematically shown in Fig. 1. The left figure shows the detailed layout of the foils in the chamber. The typical gap size is a few mm. The ratio of detected charges from both chambers (IC_1 and IC_2) is :

$$R = \frac{Q_{\mathrm{det},1}}{Q_{\mathrm{det},2}} = \frac{d_1}{d_2}\frac{\varepsilon_1}{\varepsilon_2} = R_0 \frac{\varepsilon_1}{\varepsilon_2} \qquad (3)$$

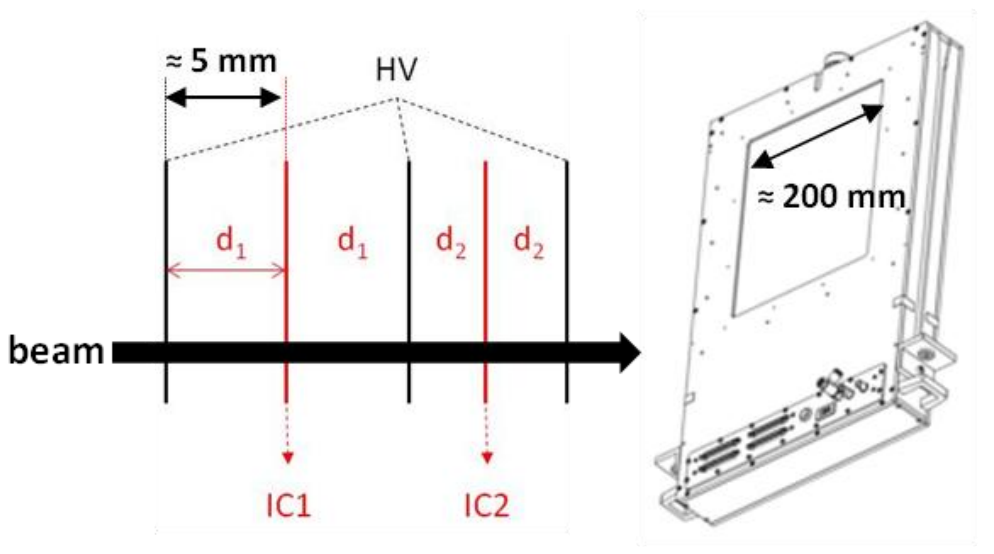

Figure 1 : drawing of the rectangular AIC and the foil configuration with typical dimensions.

Fig. 2 shows the relation between the (theoretical) efficiency for the IC with gap size d_1 (Eq. (2)), the expected ratio of detected charges from the AIC ($d_1 \approx 5$ mm, $d_2 \approx 3$ mm) and the value of u_1. From this figure it can be seen that there is <u>a linear relation between the efficiency of the IC and the ratio of detected charges</u>.

We can re-write an "approximate" formula for the efficiency of IC_i in the AIC as follows :

$$\varepsilon_i^{'} = 1 - CF_i\left[1 - \frac{R}{R_0}\right] \quad \text{where} \quad CF_i = < \frac{1 - \varepsilon_i}{1 - \varepsilon_1 / \varepsilon_2} > \qquad (4)$$

The value of CF_i is averaged over the relevant range of u-values. With this approximation, we do not need to know the exact value of the parameter "u" to evaluate the efficiency. We simply use the detected ratio of charges in an AIC to calculate the efficiency of each IC in the AIC.

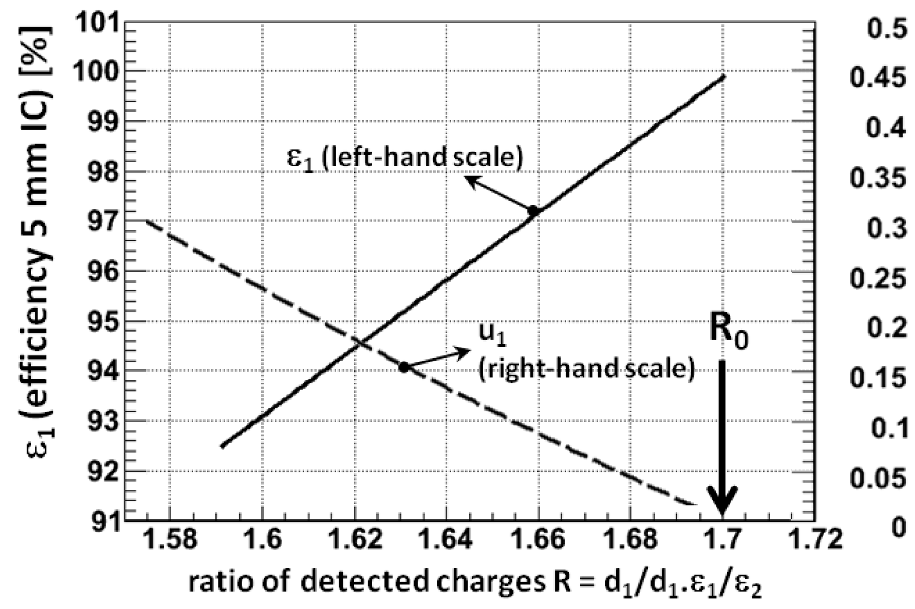

Figure 2 : Relation between the theoretical efficiency of the IC with gap size d_1 (≈ 5 mm) in the AIC, the ratio of detected charges and the parameter u_1.

EXPERIMENTS AND RESULTS

Measurements were performed with pulsed proton beams in order to check the validity of Eq. (4).

Pulsed proton beams

The measured time profile of the proton bunch from the S2C2 is shown in Fig. 3, illustrating that the bunch is effectively shorter than the collection times of ions in the IC's (typically some hundred μs).

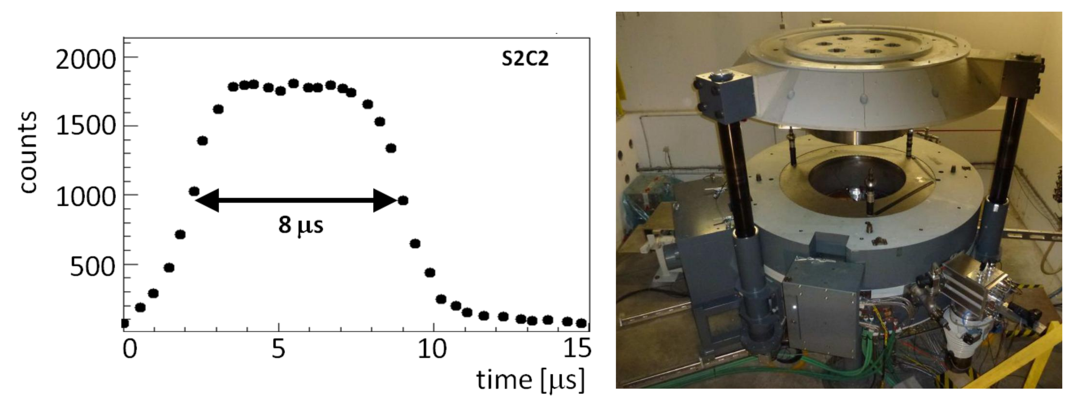

Figure 3 : Time profile of the proton pulse from the S2C2.

Nitrogen (N_2) filled AIC

With the AIC filled with the non-electronegative gas N_2, recombination losses are limited. An experiment with an AIC with gap sizes d_1=4.98 mm and d_2=4.05 mm (R_0=1.23) was performed, where the pulse intensity was gradually increased and two different spot sizes were used (σ=2 and 6 mm). Different high voltages were applied as well. As can be seen from Fig. 4, the ratio of detected charges is exactly R_0=1.23 in most cases, which shows that the N_2 filled IC's are 100% efficient in these cases ($\varepsilon_1 = \varepsilon_2$=100% in Eq. (3))

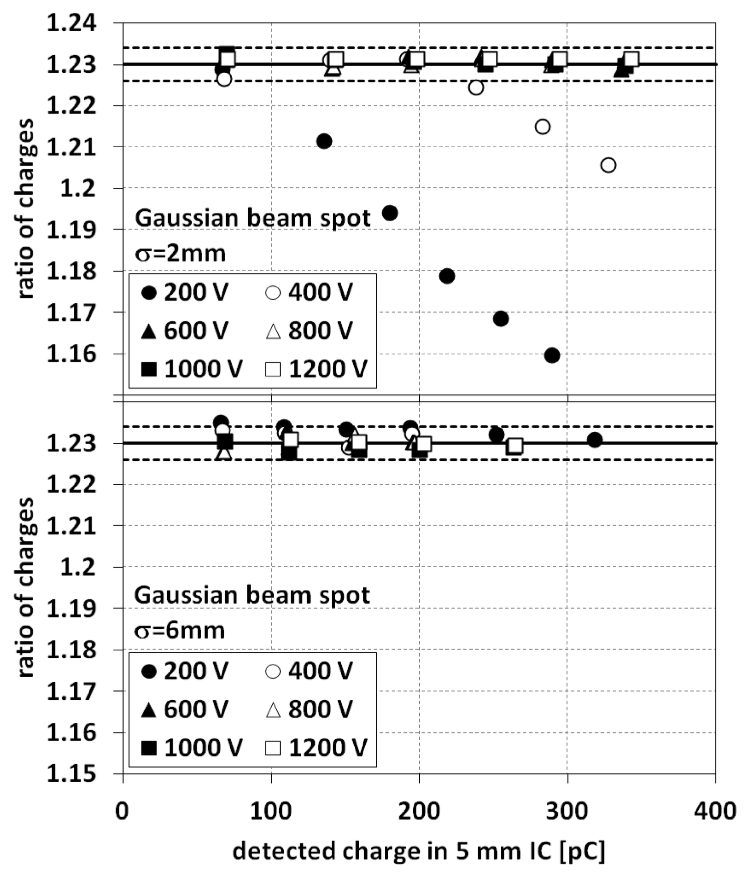

Figure 4 : The ratio of detected charges in a N_2-filled AIC for increasing pulse intensity, different spot sizes and different high voltages.

air filled AIC

By comparing the measured charges in an air-filled AIC to the measured charges in a N_2 filled AIC, which measures the same incoming beam pulse (see Fig. 5), the absolute efficiency of the air-filled AIC was determined up to 3.5 pC/pulse. The detected ratio of charges in both the air- and N_2- filled AIC's are shown in the top panel of Fig. 5. This ratio is constant in the N_2-filled AIC, showing this AIC is a good absolute measure of the incoming charge. The experimental efficiencies of the air-filled AIC are compared to the efficiencies obtained with Eq. (4) in the middle panel of Fig. 5. The difference between the theoretical and measured efficiency is shown in the bottom panel of Fig. 5. Eq. 5 predicts the efficiency accurately to 0.5%.

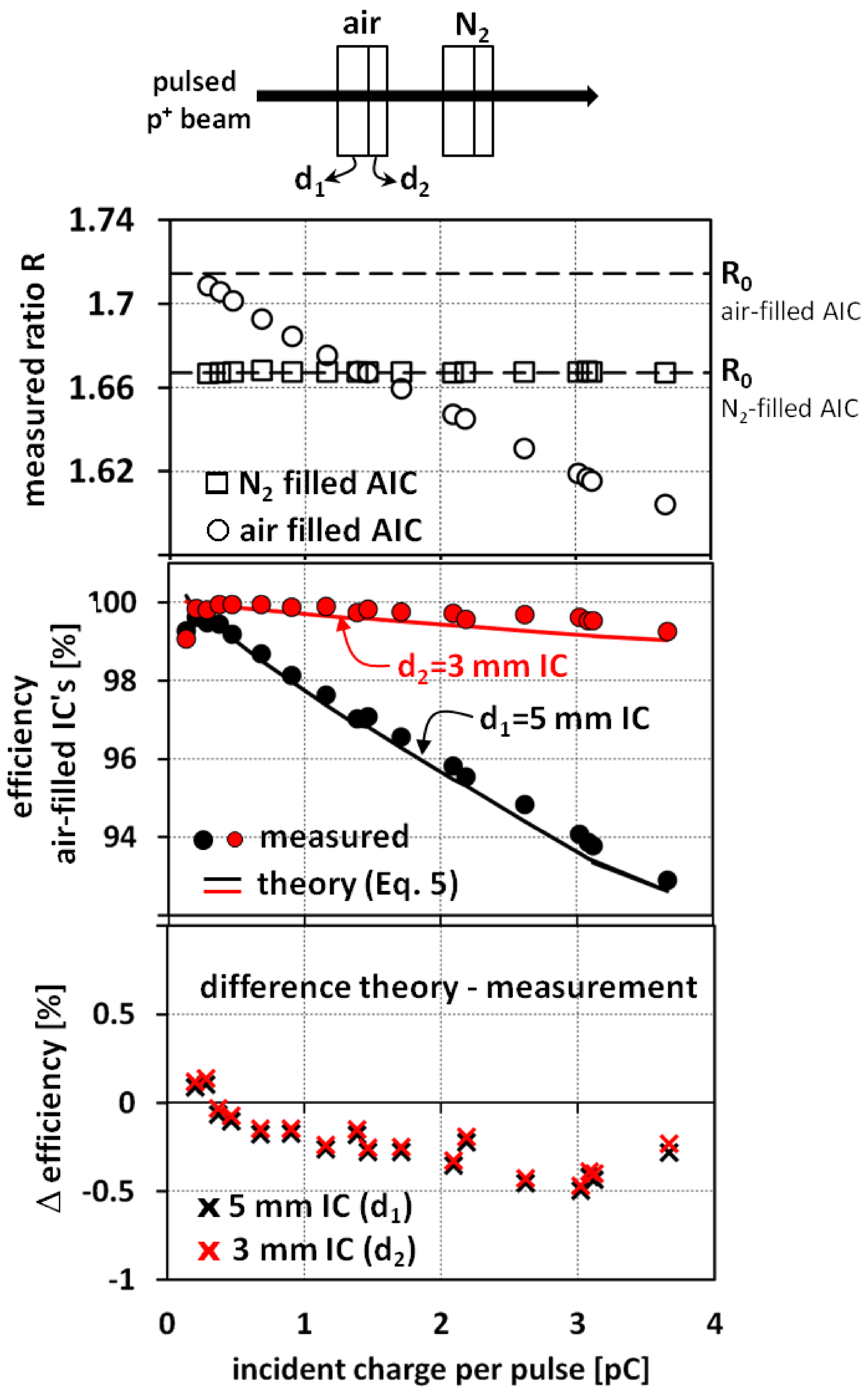

Figure 5 : (top) experimental setup and measured ratio in air-filled and N2-filled AIC's. (middle) experimental efficiency and theoretical efficiency (Eq.(4)) of the air-filled AIC. (bottom) difference between experimental and theoretical efficiency.

The same type of AIC was tested in the pulsed S2C2 beam up to 9 pC/pulse. The charge per pulse detected by the smallest gap IC is plotted versus the charge per pulse detected in the largest gap IC in Fig. 6. For the black line, no efficiency correction was applied, whereas the red line illustrates that after efficiency correction, both IC's in the AIC measure the same incident charge per pulse.

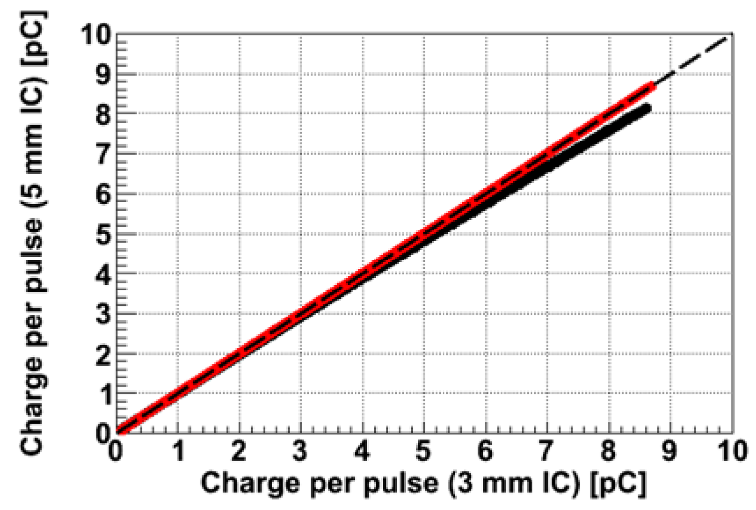

Figure 6 : Charge per pulse detected by the largest versus the smallest gap IC in the AIC. The red line shows the charge per pulse after efficiency correction with Eq. (4).

CONCLUSION

Measurements show that the recombination losses in an air-filled IC when irradiated by a pulsed proton beam can be estimated to 0.5% precision by using the concept of an asymmetrical ionization chamber.

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