DOSIMETRY OF PULSED BEAMS IN PROTON THERAPY

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Abstract

In the proton therapy system ProteusONE™ by Ion Beam Applications, the superconducting synchro-cyclotron provides intense proton pulses of 230 MeV in 10μs and with a repetition rate of 1 kHz. In these conditions, the large gap (few mm's) air-filled ionization chambers at the exit of the proton gantry suffer from recombination losses. Since these ionization chambers are crucial to control the dose delivered to the patient, these recombination losses have to quantified pulse-by-pulse. The concept of an "asymmetrical ionization chamber" has been introduced at the exit of the gantry to be able to do this.

INTRODUCTION

In order to reduce the cost of proton therapy systems, Ion Beam Applications has developed in recent years the ProteusONE™ system, which consists of a compact superconducting synchro-cyclotron (S2C2) [1] and a compact, iso-centric rotating gantry [2], which rotates 220 degrees around the patient. A layout of this gantry is shown in Figure 1. The S2C2 delivers a pulsed proton beam at 230 MeV with a repetition rate of 1kHz and a pulse duration of 10 μs. The concept of pulsed beam is ideally suited for Pencil Beam Scanning (PBS), a technique by which the tumor volume is scanned with a fixed size (typically 3 mm) proton beam with varying energy and intensity per irradiated voxel. The proton charge in each pulse in PBS treatments has to be measured with high precision.

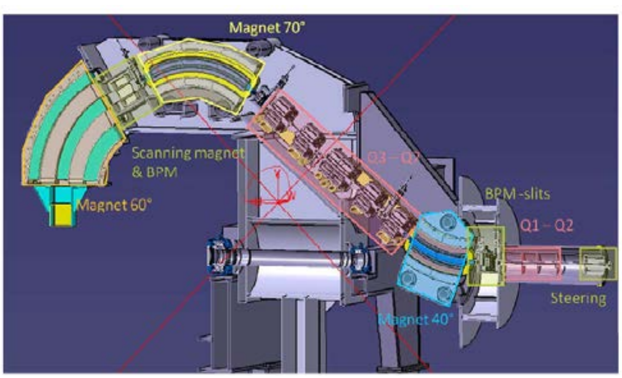


Figure 1 : Layout of the ProteusONE™ compact gantry. The ionization chambers are located at the exit of gantry, after the 60° magnet.

Air-filled ionization chambers (IC's) are used at the exit of the rotating gantry, with a typical surface area of 200x300 mm^2 and gap sizes of a few mm. This large surface area is needed to cover the full irradiation area. The charge collection times in these IC's is typically a few hundred μs, much more than the proton pulse of 10 μs. Recombination losses of the created electron-ion pairs in the air-filled IC's cannot be avoided with the pulse intensities needed to irradiate a tumor volume, which can go as high as 10 pC/pulse. To ensure an accurate measurement of the pulse intensity in PBS, these recombination losses have to be quantified on a pulse-by-pulse base. The concept of an "asymmetric ionization chamber" (AIC) has been introduced at the gantry exit to enable this.

THE ASYMMETRIC IONIZATION CHAMBER (AIC)

A schematic layout of the asymmetric ionization chamber (AIC) is shown in Figure 2. It consists of two ionization chambers with different gap sizes, d_1 and d_2. One such ionization chamber is in itself divided in two parts : the grounding foil is placed in between two high voltage foils and the detector signal is read from this grounding foil. For recombination calculations, only a distance d_1 has to be considered, the gain of ICi (i=1,2) in Figure 2 is given by :

$$G_i = \frac{2d_i S\rho}{W}$$

where S is the stopping power of protons for a given energy, ρ is the density of air in the IC and W is the ionization potential of air. The measured charge in ICi ($Q_{det,i}$) is given by :

$$Q_{det,i} = G_i Q_{IN} \varepsilon_i$$

where Q_{IN} is the incident proton charge, which is the quantity of interest and ε_i is the efficiency of ICi, which is determined by recombination losses in the air-filled IC. The ratio of the two measured charges ($Q_{det,}$) is given by

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

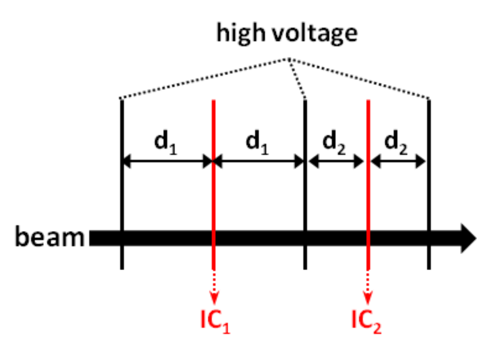


Figure 2 : Schematic layout of the asymmetric ionization chamber. It consists of two ionization chambers with different gap sizes (d1 and d2).

where R_0 is the ratio of the gap sizes. From Eq. (1) it is clear that the ratio of detected charges equals the ratio of the gap sizes of the two IC's, in case recombination losses are negligible. If recombination losses are non-negligible, this ratio will be lower ($R<R_0$). A theoretical description of recombination losses for pulsed radiation in air filled ionization chambers can be found in [3]. Here, the expression for the theoretical efficiency of an IC will be given as :

$$\varepsilon_i = p_i + \frac{1}{u_i}\ln[1+(1-p_i)u_i] \quad (2)$$

where p_i is the free electron fraction in ICi and depends on the applied high voltage and the gap size. More details and a parameterization of this free electron fraction can be found in [4]. The parameter u_i is given by :

$$u_i = \frac{\mu d_i^2 r}{V} \quad (3)$$

where V is the applied voltage, μ is a constant (see [3] for details) and r is the charge density of positive ions liberated per radiation pulse. The relation between the parameters u_1 and u_2 for one radiation pulse is just simply

$$u_1 = u_2\, d_1^2/d_2^2 \quad (4)$$

The principle point of the AIC is that the measured ratio of charges (R in Eq. (1)) has a direct link to the parameter u_i which appears in Eq. (2). The exact knowledge of the quantities μ and r in Eq. (3) is thus not needed. This is very important, since the charge density r depends strongly on the details of the beam spot size and intensity, which varies during proton beam treatments. The relation between the ratio of detected charges R, the parameter u_i for one specific IC (in this case u_1) and the efficiency of this IC is illustrated in Figure 3 for the case of an AIC with d_1=4.97 mm and d_2=2.92 mm.

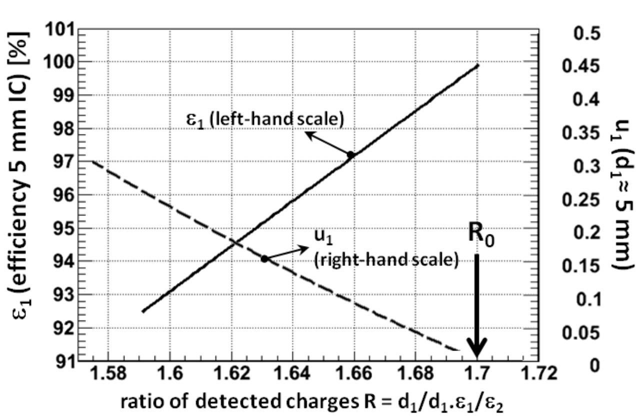


Figure 3 : relation between the ratio of detected charges in an AIC, the efficiency of a specific IC and the parameter "u" for this IC. In this case the (measured) gap sizes for the AIC are : d_1=4.97 mm and d_2=2.92 mm.

From Figure 3 it can be seen that a linear relation exists between the efficiency of the IC's and the ratio of detected charges. An approximate expression of the efficiency can thus be written as :

$$\varepsilon_i' = 1 - CF_i\left[1 - \frac{R}{R_0}\right] \quad (5)$$

where the constant CF_i is given by :

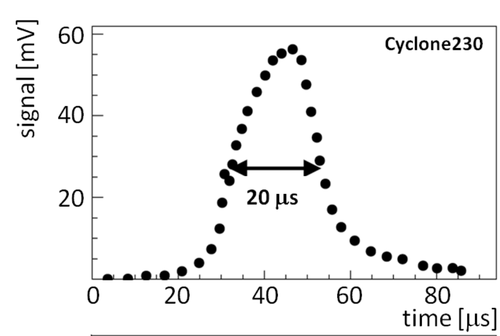
$$CF_i = \left\langle \frac{(1-\varepsilon_i)}{1-\frac{\varepsilon_1}{\varepsilon_2}} \right\rangle \quad (6)$$

The brackets indicate that the average is taken over the relevant measurement range for the AIC. This range is given by the minimum ratio which is expected for a typical treatment sequence (varying pulse intensities and energies). For example, if one considers the AIC from Figure 3 and the minimum measured ratio would be 1.6, the corresponding range of u_1-values will be 0 to 0.23. The efficiencies appearing in Eq. (6) are calculated with Eq. (2) using u-values in the range specified above. Eq. (3) provides the possibility to deduce the efficiency of the IC's from the ratio of measured charges in both IC's, comprising the AIC.

EXPERIMENTS AND RESULTS

A series of experiments was performed to check the validity of the approximate expression for the efficiencies of the IC's (Eq. (5)).

Three experiments are described below. The first two experiments were conducted with a 228 MeV proton beam from the Cyclone™ 230. In order to obtain a pulsed proton beam with a pulse duration much lower than the collection time of ions in the few mm IC's (typically few



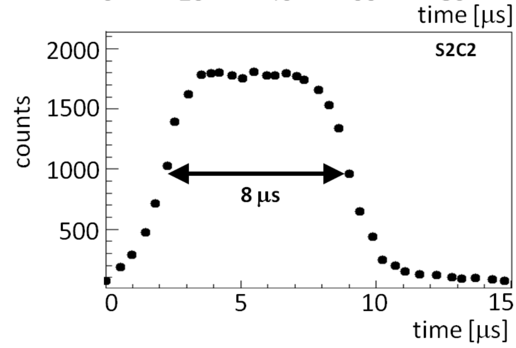


Figure 4 : measured time profile of the proton beam pulse from the Cyclone™ 230 with pulsed RF.

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100 μs), the RF of the cyclotron was pulsed and a beam pulse of about 20 μs was obtained. The last experiment was conducted with the prototype S2C2, which provides intrinsically a pulsed beam at 1 kHz and with a beam pulse duration of around 10 μs. Pulse time profiles obtained with both accelerators are shown in Figure 4.

Nitrogen Filled AIC

In the first experiment, the AIC was flushed with nitrogen (N_2) gas. Since N_2 is a non-electronegative gas, the electrons liberated during the ionization process do not get attached to ions during their drift towards the electrode (the free electron fraction in Eq. (2) is 1) and the efficiency is expected to be 100%. This hypothesis was tested as a function of applied high voltage, beam intensity and beam spot size. The gap sizes of the N_2 filled AIC were 4.98 mm and 4.05 mm. In case both IC's are 100% efficient, the ratio of detected charges should be 1.23. The results are shown in Figure 5.

Only for a 2 mm (1-σ Gaussian) beam spot and low high voltages the efficiency of N_2 filled IC's drops below 100%. Ongoing studies confirm this observation from first principles and this drop in collection efficiency is attributed to space charge effects.

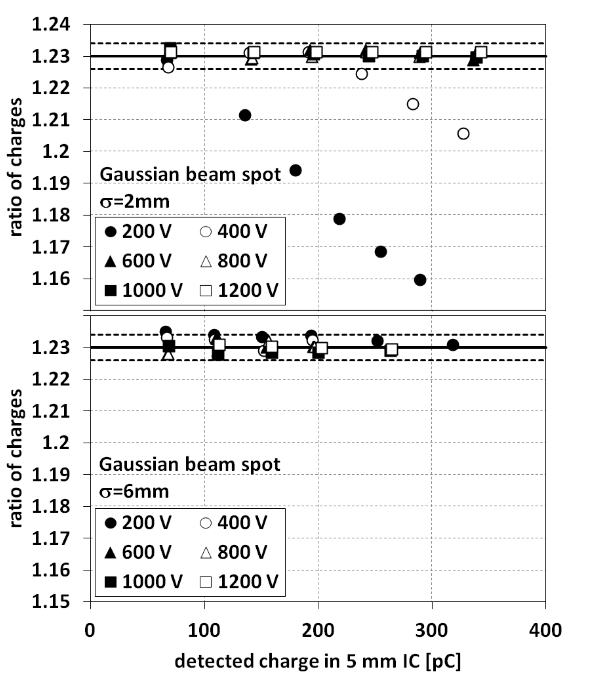

Figure 5 : the ratio of detected charges in the nitrogen filled AIC (d_1=4.98 mm, d_2=4.05 mm) as a function of increasing pulse intensity and for different voltages for a Gaussian beam spot with 1-sigma size of 2 mm (top) and 6 mm (bottom).

Air Filled AIC

In a second experiment, the efficiency of an air-filled AIC was measured as function of the incident proton bunch intensity. This was done by a stack of 2 AIC's, where the first AIC was filled with air and the second AIC was flushed with N_2. A sketch of the setup is shown in the top part of Figure 6. On both AIC's a high voltage of 1.2 kV was applied and the beam spot size was 2 mm. The N_2 filled AIC was used to determine the incoming proton pulse intensity, since this AIC is 100% efficient. The exact gap sizes of the N_2 filled AIC were d_1=4.93 mm and d_2=2.96 mm (providing a ratio R_0 of 1.67) and for the air filled AIC d_1=5.07 mm and d_2=2.96 mm (providing a ratio R_0 of 1.71). The ratio of detected charges in both the air- and N_2-filled AIC's is shown with the open symbols in the top part of Figure 6. In the N_2-filled AIC, the ratio is constant and equal to R_0, as expected from a 100% efficient IC, whereas the ratio drops in the air filled AIC with increasing pulse intensity.

The efficiency of the 3 mm and 5 mm IC in the air-filled AIC was obtained by dividing the measured charges in both IC's by their gain and by the incoming charges as detected by the N_2-filled AIC. These efficiencies are shown in the middle part of Figure 6 as a function of incident proton charge per pulse. The full lines represent

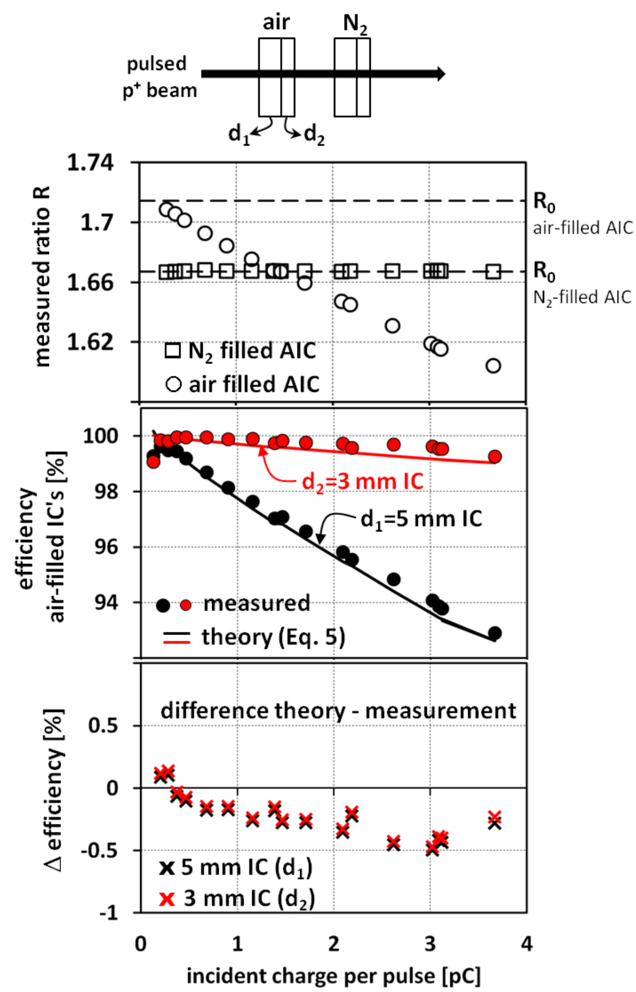

Figure 6 : (top) measured charge ratios in the air- and N_2 filled AIC. (middle) experimental efficiencies (dots) for both IC's (3 mm and 5 mm) in the air-filled AIC. The approximate efficiencies from Eq. (5) are shown with the full lines. (bottom) the difference between measured and approximated efficiencies from Eq. (5).

the approximate efficiencies obtained from Eq. (5), only utilizing the detected ratio and the constant factors CF_1=1.14 and CF_2=0.15, which were calculated with Eq. (6). The averaging in Eq. (6) was done over the range where the ratio given by Eq. (1) remains above the experimentally observed minimum ratio (R = 1.6, see top part of Figure 6).

The crosses in the bottom part of Figure 6 indicate the differences between the measured efficiencies and the approximate efficiencies of the 3 and 5 mm IC's comprising the air-filled AIC. An accuracy better than 0.5% is obtained.

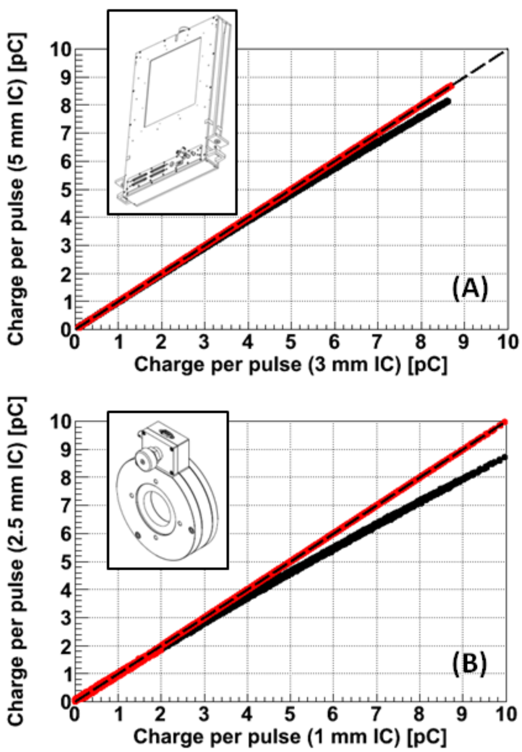

Figure 7 : Measured charge per pulse in the largest gap IC versus the measured charge per pulse in the smallest gap IC before (black) and after (red) a correction was applied for the approximate efficiency (Eq. 3).

In a last experiment, a large area (600 cm^2) air-filled AIC with gap sizes of d_1=5.07 mm and d_2=2.96 mm was tested in pulsed beam from the prototype S2C2. At the same time, a small area (60 cm^2) AIC with gap sizes d_1=2.48 mm and d_2=0.86 mm was tested. Both AIC's are shown in the insets in Figure 7. The latter AIC will be used at the exit of the S2C2 to measure the exit pulse charge from the accelerator prior to injection to the gantry. The high voltage on this AIC is 400 V. This lower voltage will lower drastically the efficiency of the largest gap IC and this AIC is thus a good candidate to test the validity of the Eq. (5).

Figure 7 shows the measured charge per pulse (measured charge divided by the gain of the IC) of the largest gap IC versus the smallest gap IC for both AIC's. The top figure shows this for the 5 mm IC versus the 3 mm IC and the bottom figure for the 2.5 and 1 mm IC. It is clear that for increasing pulse intensity, recombination losses start to become more pronounced for the largest gap sizes. When the measured charge per pulse is corrected for the efficiency of the IC by using Eq. (5), the red line is obtained and it is clear that both IC's measure the same amount of incident proton charge, illustrating the accurate estimation of the efficiency.

The top part of Figure 8 shows in detail the measured ratio of charges in the large area AIC and is illustrative of the expected performance of this AIC in the gantry. The red line in this figure was obtained from the recombination theory (Eq. (2)), where the parameter u (u_1 and u_2) was calculated for both IC's. In this case, only the beam spot size (and thus the positive ion density in the IC) was a fitting parameter. The theory reproduces nicely the ratio over the full range of pulse intensities. The fitted spot size is a factor 2.5 larger than the actual spot size. The exact reason for this is still under investigation.

The bottom part of Figure 8 shows the efficiencies of both IC's in the large area AIC. The lower black symbols are the efficiencies of the large gap IC and the red symbols are the efficiencies of the smallest gap IC. The dashed blue curves are the theoretical efficiencies calculated with Eq. 2, from which the red curve in the top figure results. Important to note is that the smallest gap IC (3 mm) provides efficiencies of >99% over the full range.

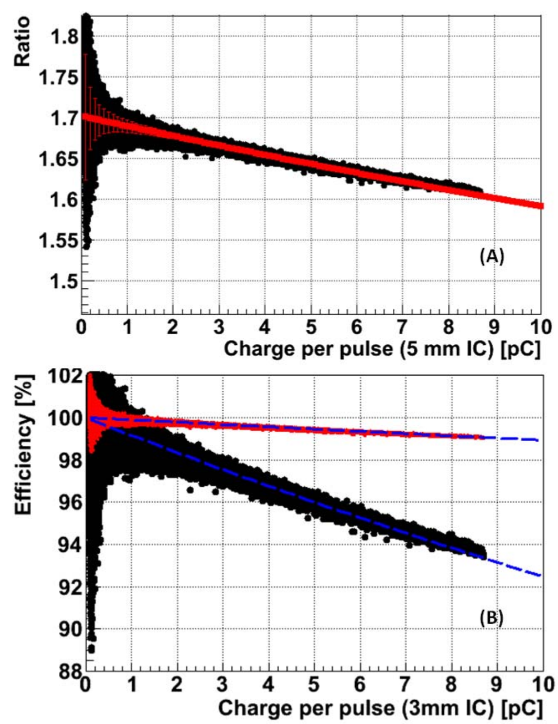

Figure 8 : (A) measured ratio in the air-filled large area AIC with S2C2 pulsed beam. The red line is the calculated ratio using the efficiencies from Eq. 2 where the beam spot size was the only fitted parameter. (B) The efficiencies (Eq. 5) from the observed ratio for both 3 mm and 5 mm IC's and the theoretical efficiencies calculated with Eq. 2 (blue dashed lines).

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CONCLUSION

Recombination losses in the large gap and large surface air-filled ionization chambers (IC's) at the exit of the gantry have to be quantified on a pulse-by-pulse base. Experiments have provided the absolute efficiencies of the air-filled IC's and these have been compared to approximated efficiencies, where only the measured ratio of charges is used as input. The experiments are well reproduced by these efficiencies and recombination losses can be corrected for up to 10 pC/pulse, the typical clinical range with the ProteusONE^{TM} system.

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