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To cite this article: A. Ampollini *et al* 2020 *J. Phys.: Conf. Ser.* **1561** 012008

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Recombination effects in the ionization chambers dose delivery monitor of the TOP-IMPLART proton beam

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Abstract. The Intensity Modulated Proton Linear Accelerator for Cancer Therapy (TOP-IMPLART) is under development and construction by ENEA in collaboration with the Italian Institute of Health (ISS) and the Oncological Hospital Regina Elena-IFO with financial support of Regione Lazio.

Its peculiar time structure (few microseconds pulse width) and very high peak intensity ($\approx 10^9$ proton/pulse) demand for ad hoc dose delivery monitors (DDM). The TOP-IMPLART DDM is based on ionization gas chambers. One segmented chamber prototype uses Micro Pattern Gaseous Detector technology for the 2-dimensional simultaneous x/y readout; the charge collected from each active segment (strips with pad-like shape) is readout by a dedicated gain-adaptable electronics. Two small, highly sensitive, integral ionization chambers, using the same electronics, complement the 2D chamber for the monitor of the single pulse beam charge, down to 1 pC/pulse.

While under development and deployment of its accelerating modular cavities, the linear TOP-IMPLART beam is improved thanks also to the continuous monitoring and characterization by these devices, whose responses are periodically compared to calibrated dosimetric detectors such as real-time active microDiamond sensor, passive Alanine pellets, intrinsically stable integral Faraday Cup.

Different calibration campaigns have been recently conducted to measure the recombination and dose-rate effects on the above ionization chambers. The outcome of these measurements shows clear electron-ion recombination in the chamber active volume, largely related to the high beam intensity and its small transverse cross section. Those effects can be taken into account and used to correct the actual measurement of the DDM.

In this paper, the TOP-IMPLART project and the DDM devices are shortly presented and details of the above experimental studies are discussed.

1. Introduction

This paper focuses on the saturation effects of ionization chambers used as dose delivery monitors (DDM) for a proton linear accelerator (Linac) for cancer radiotherapy.



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Modern external radiotherapy based on accelerators, splits into two main categories: conventional radiation therapy, where Linacs are used to generate electron and derived photon beams up to 25 MeV, and particle therapy where hadron beams are produced by circular accelerators; proton therapy, with about 70 operational centers all over the world is the largest type of particle therapy.

Advantages, limitations and challenges of current proton therapy are detailed in [1]. The small emittance, high repetition frequency and high single pulse intensity of a proton beam generated by a Linac can successfully respond to some of the current technological limitations of the proton therapy [1]: better delivered dose due to smaller spot size, better collimation dynamics and respiratory control with faster electronics gating.

The Linac offers a modular scheme, that allows its operation while it is under construction, with the great advantages of continuous characterization and improvement of the beam and its components and simultaneously to its exploitation (e.g. for radiobiological, dosimetric, radiological protection studies and other irradiation purposes). Moreover the high instantaneous intensity goes in the directions of hypo-fractionation [2] and ultra-fast dose rate [3] treatments.

On the other hand, a proton Linac requires complex acceleration cavities design (especially at low energies, where proton velocities are not relativistic) and it only works for a single ion species.

2. TOP-IMPLART Linac

In this scenario, the Oncological Therapy with Proton - Intensity Modulated Proton Linear Accelerator for Radio Therapy (TOP-IMPLART) [4] is under development and construction by ENEA in collaboration with the Italian Institute of Health (ISS) and the Oncological Hospital Regina Elena-IFO with financial support of Regione Lazio, Italy.

TOP-IMPLART is an innovative machine: single pulse energy, intensity, width and repetition rate control make it similar to the electron Linacs used in conventional radiotherapy, with the advantage of the proton intrinsic conformation. It requires development of original techniques in accelerating machine, radioprotection, dosimetry, and radiobiology, which are tested, characterized and optimized during its realization and deployment.

The TOP-IMPLART project is the oldest of the three projects that are trying to introduce the proton Linac in cancer radiotherapy: LinearBeam-ERHA [5] and AVO-Light [6].

The TOP-IMPLART is an high frequency, compact, full Linac made of three main acceleration segments:

- a 7 MeV commercial injector made by AccSys-Hitachi with a duoplasmatron proton source followed by a 3 MeV Radio Frequency Quadrupole (RFQ) and an up to 4 MeV Drift Tube Linac (DTL) operating at 425 MHz; an in-house Eizel Lens permits to control the injector output average intensity between 0 and about 200 μA , a pulse frequency up to about 100 Hz and a pulse width between 20 and 100 μs .
- eight Side Coupled Drift Tube Linac (SCDTL) structures which accelerate protons up to the first clinical energy (≈ 71 MeV); this is the most challenging and innovative segment of the whole project; the lower energy structures, have been installed, characterized and are operational since more than 1 year.
- two Coupled Cavity Linac (CCL) modules up to ≈ 150 MeV (that can be extended up to 230 MeV).

Both SCDTL and CCL operate at 3 GHz.

In 2019, the accelerator delivered a pretty stable, 35 MeV, ≈ 25 Hz¹ pulsed proton beam with pulse width in the range of 1-4 μs , peak current of 0 – 50 μA [7]; two new SCDTL modules are going to be installed and operated in the first quarter of 2020.

¹ The design pulse frequency is in the range of 10 – 100 Hz.

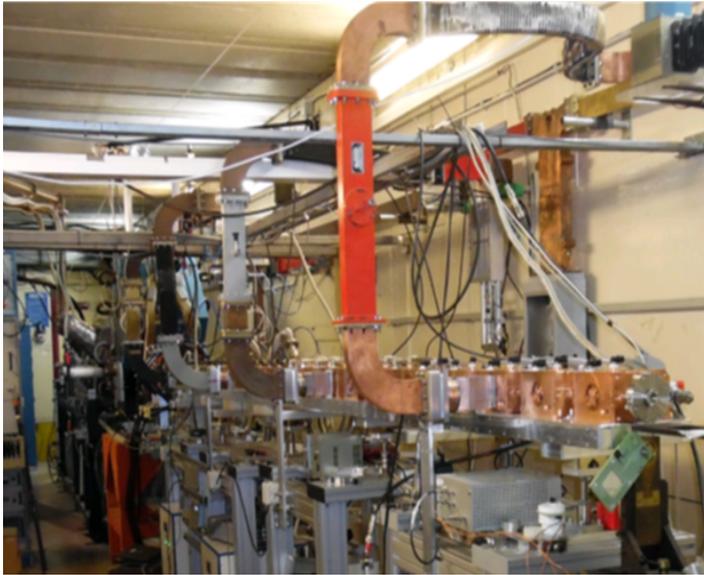


Figure 1. The TOP-IMPLART accelerator, in early 2018, before the upgrade of the radiofrequency distribution lines.

Table 1. Dose Delivery Monitor main requirements; the quoted upper limit of the DDM thickness corresponds to less than 1% contribution to the Moliere angle, for 60 MeV protons traveling the corresponding range in water.

Feature	Design Limit
Wide dynamic range	$\geq 10^4$
Good sensitivity	≤ 100 fC
Rapid response	≤ 1 ms
Good spatial resolution	$\leq 1/10$ mm
Minimal Thickness	≤ 0.62 mm (water equiv.)

3. Dose Delivery monitors

The intrinsically high conformation of the proton beam requires accurate and reliable DDM which shall measure the beam position, direction and intensity profile of each pulse, at least.

The peculiar pulsed structure of the TOP-IMPLART proton beam requires, in addition, a quick and pulse-by-pulse response of the DDM; moreover its wide range of pulse intensities need an extended dynamic range of the monitoring devices and a detailed understanding of any potential dose rate effect. The main system requirements of the dose delivery monitor are summarized in table 1.

The TOP-IMPLART DDM is based on ionization gas chambers, a consolidated approach in external radiotherapy; its current prototyping configuration consist of a 2-dimensional segmented ionization chamber (2D-IC) in Micro Pattern Gaseous Detector technology and two smaller conventional, integral ionization chambers.

3.1. 2D segmented Ionization Chamber

The 2D-IC prototype [8] measures the single beam pulse intensity profiles simultaneously along x (horizontal) and y (vertical) axes with spatial resolution of about 0.3 mm on a 80×80 mm² active area (figure 2); the readout plane produced in Micro Pattern Gaseous Detector technology by CERN has been designed to maximize the uniformity of the electrostatic field by rhomboidal

pad-like copper strips that cover large part of the readout kapton foil (as shown in the upper left pictures of figure 2); through holes connect the apparently isolated pads to strips on the opposite side of the kapton foil; a ground guard surrounds the readout sensitive area. The cathode-anode gap is 2 mm and the operating bias voltage is 250 V; the chamber is currently operated in air. The total thickness of the chamber is equivalent to 0.17 mm of water.

The 2D-IC dynamic range, larger than 10^4 , is obtained by a dedicated electronics, that readout the 96 strips of the chamber (only the central $40 \times 40 \text{ mm}^2$ active area is currently equipped with electronics). Each channel is based on trans-impedance amplifier and integrating capacitor that automatically adapts the gain on each segment (channel) according to the amount of collected charge, which is proportional to the intensity of the beam [9]. The capacitors voltages are multiplexed at 1 MHz into a single ADC channel.

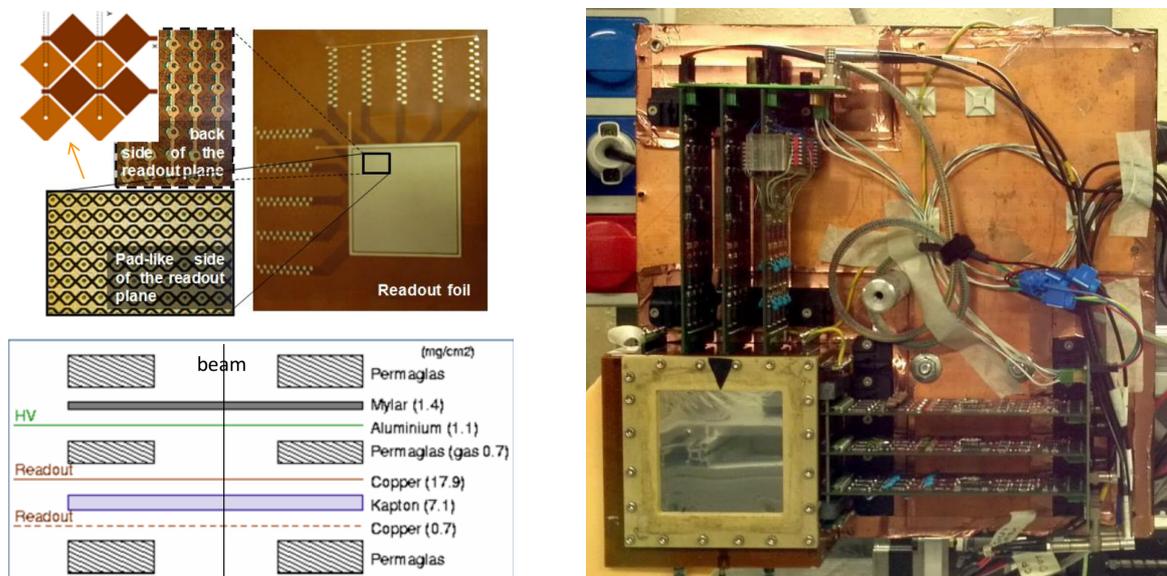


Figure 2. The 2D-IC chamber prototype. Left: pictures of its internal structure and a simplified drawing showing the peculiar pad-like strips pattern of the readout foil (above) and the cross section of the chamber (below). Right: picture of the assembled chamber with the dedicated discrete readout electronics of $48 \times$ and $48 \times y$ strips; a grounded cover (not shown) shields the whole electronics.

3.2. Integral chambers

Two small and thin integral ionization chambers (see figure 3, left) have been developed for monitoring of the single pulse beam charge, down to 1 pC/pulse [9]. The two chambers performs identically but have different mechanical supports and geometries: they operates at a bias voltage of 250 V and the small (few cm^2 area) electrodes are made of aluminized mylar (12 μm mylar, 4 μm aluminum) and are spaced by 2 mm. Their single channel front-end electronics, based on a transimpedance amplifier and integrating capacitor is derived from the 2D-IC described above, while the readout of the capacitor trans-impedance voltage is managed by a NI-cRIO modular instrumentation, integrated in the beam control system. Chamber IC_A sits at the exit of the beam pipe while IC_B can be placed along the beam line in air. They are currently used as, fast and sensitive, beam delivered charge monitor for development, testing and during the irradiation campaigns.

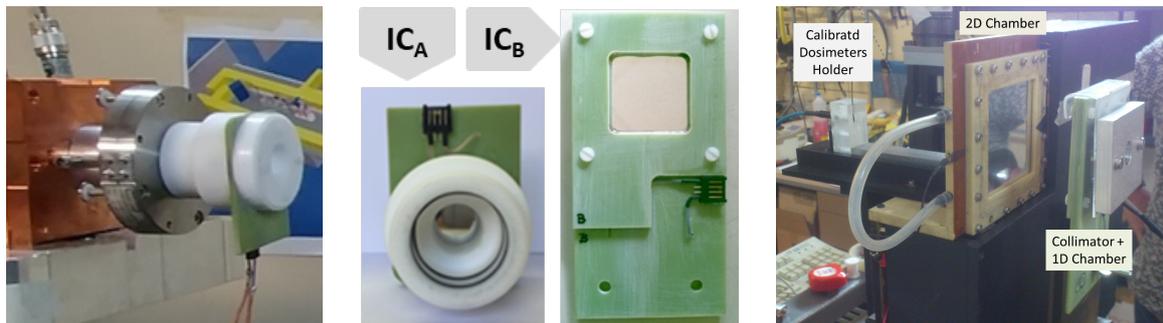


Figure 3. Left: the IC_A in place at the beam pipe exit. Middle: the two integral chambers, IC_A with its cylindrical holder acts as a plug on the beam pipe terminal and the IC_B . Right: the typical configuration during calibration and irradiation: IC_B with an aluminum collimator, in front of the 2D-IC; beyond them the holder of the calibrated dosimeters (e.g. microDiamond, alanine pallets and other devices).

4. Characterization and calibration campaigns

The DDM responses have been and are routinely compared and calibrated against commercial passive small alanine pellets (from Gamma-Service, Leipzig, Germany)², one commercial real-time active microDiamond (PTW-Freiburg mod. 60019, Germany).

In 2018 and 2019 several test and calibration campaigns have been carried on with the main purposes of characterizing and improving the proton beam and the above ionization chambers as well as of calibrating and using them for irradiation studies on biological targets. The preliminary characterization of the 35 MeV TOP-IMPLART beam, and intercalibration of the different dosimetric devices, has been reported in [7].

The DDMs are then used for characterization of the beam, as shown in figure 4, where the left plot shows the (gaussian) x and y profiles of the spread beam in air, measured by the 2D-IC at 160 cm from the beam pipe exit; as expected from the beam optics, the proton spot has an ellipsoidal cross section, larger along y than x . It is worth mentioning that the 2D-IC measures the charge accumulated along the whole strips perpendicular to the profile direction. On the right plot of figure 4 are reported the gaussian fit sigma's of the beam profiles measured at different distances from the beam pipe exit.

The characterization campaigns contributed to better understand the accelerator performances and tune them; the pulse-to-pulse stability improved significantly, allowing to explore the DDM chambers responses at different dose rates.

5. Dose Rate Effects

The delivered TOP-IMPLART dose rate can be controlled in at least three ways, acting on the main pulse parameters: intensity (or instantaneous current), width and frequency.

In a dedicated irradiation sessions, IC_A , 2D-IC and microDiamond responses have been compared; the latter is expected to be independent (in the explored range) from dose rate, as confirmed by preliminary measurements of microDiamond and alanine pellets³. Figure 5 summarizes the obtained results: the y -axis represents the normalization factor of IC_A and 2D-IC relative to the microDiamond while the x -axis contains the instantaneous current derived from the microDiamond response. The dose rate has been controlled mainly by pulse intensity variation, keeping the pulse width at 4 μ s and the frequency at 20 Hz; some measurements have

² The alanine pellet, ≈ 4.8 mm diameter, ≈ 3 mm height, consists of a mixture, by weight, of 96% alanine and 4% of binder material. The exposed alanine is readout offline by a Bruker ELEXSYS spectrometer [10].

³ To a very large extend the alanine pellets are not influenced by dose rate variations.

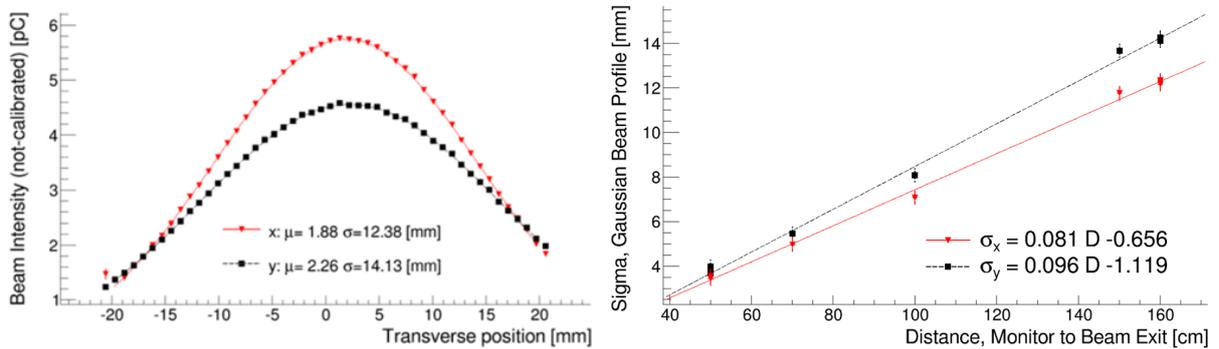


Figure 4. 2D-IC chamber response; left: x/y beam profiles measured at 160 cm^2 from beam pipe exit, with Gaussian fits and relative parameters. Right: the widths measured by the 2D-IC profiles gaussian fits (sigma) at different distances from the beam pipe exit.

been performed with pulse frequency of 10 Hz and/or smaller pulse width (2.5 and 3 μs). The results show a clear dependence of the two chamber responses from the dose rate; the 2D-IC chamber (sitting at 160 cm from the beam pipe exit) measured points are pretty well reproduced by a quadratic function with fluctuations around such curve within few percent maximum; the 2D-IC response does not depend on the way the dose rate is changed.

On the other hand, the IC_A intercepts the beam right after the exit from the vacuum pipe, where the beam spot diameter is about 1 mm; it clearly shows much larger fluctuations (approximately $\pm 15\%$) and its response seems to be affected by the way the dose rate is obtained (e.g. acting on the beam pulse length, intensity, or frequency).

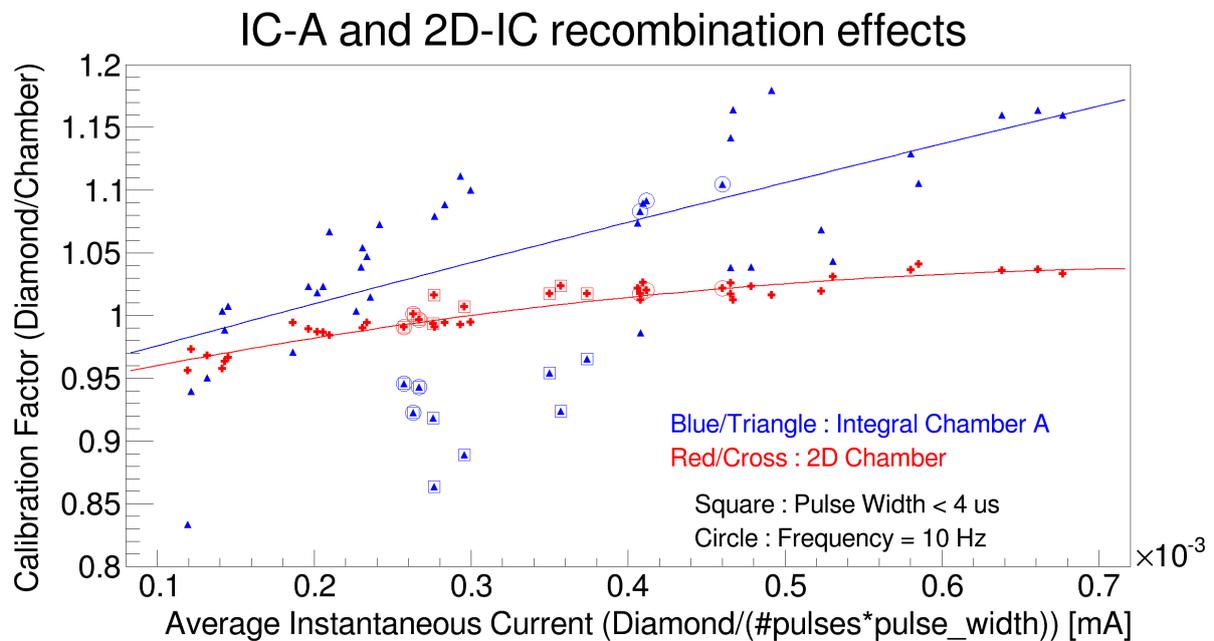


Figure 5. Evidence of recombination effects in IC_A and 2D-IC; dose rate variation induced by current, width, frequency of the pulses; the typical therapeutic dose rate of 1 Gy/min corresponds to about 0.2 mA on the x -axis.

The different behavior of the two ionization chambers most likely depends on the much more localized beam passing the IC_A which causes larger recombination effects and therefore more sensibility of this chamber to small variation of the beam spot parameters: the much larger fluctuation in IC_A is probably related to the fact that variations of the pulse parameters affect, to different extend, the spot characteristics at the IC_A level; in fact, in the current implementation, pulse width and frequency variation may influence the beam stability more than the changes in pulse intensity, and this seems to reflect on correspondingly large fluctuation of the IC_A response for the points marked with open squared and circles in figure 5.

The recombination effects have been further investigated on the integral chamber IC_B comparing its response to a custom designed Faraday Cup (FC) which is dose rate independent: the beam passing the IC_B is completely intercepted by the FC sitting right after the ionization chamber (see figure 6). The FC is a block of aluminum, with an internal cylindrical cavity (30 mm diameter) and a thick conical base (> 10 mm); it is sensitive to beam current larger than $\approx 5\mu A$, and its amplified current is readout by one dedicated single channel of the same electronics than the DDMs, mentioned above.

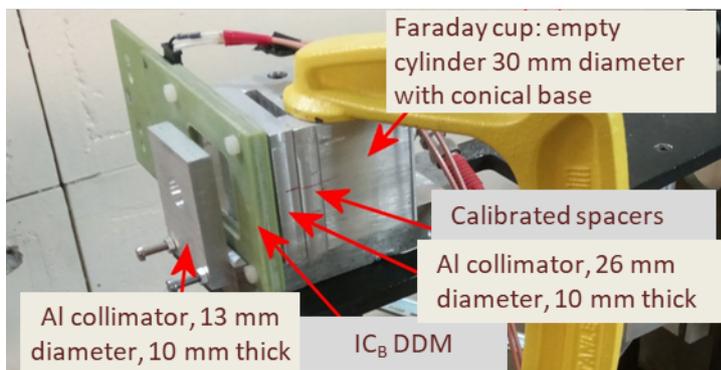


Figure 6. IC_B and FC assembly for recombination studies in the integral chamber.

The simultaneous responses of the IC_B and FC have been initially acquired at fixed proton beam parameters, but along different longitudinal distances of the devices assembly from the pipe exit window (and therefore for different beam cross sections). The left plots of figure 7 report the pulse-by-pulse outputs of both devices versus the pulse number; different bunches of pulses correspond to different positions of the IC_B -FC assembly: while the FC (lower plot) shows constant response at different position (until the collimator starts intercepting part of the beam) as expected, the IC_B (upper plot) has a remarkable trend to increase its response (to constant beam intensity of $\approx 0.95 \cdot 10^9$ proton/pulse) due to the fact that at higher distances, the beam cross section is larger and therefore the recombination effects smaller.

Moreover, the responses of the two devices have been compared varying the pulse intensity (and therefore the dose rate) at fixed positions (beam cross section); some of the results are summarized by the right plots in figure 7, where, the IC_B and FC outputs are linearly correlated but the correlation coefficients depend on the position of the device assembly respect to the beam pipe exit window (and therefore the beam transverse size), suggesting that the recombination effects are mainly determined by volume than columnar/initial recombination [11].

Assuming the response of the FC proportional to the beam charge passing through the ionization chamber (corrected for the collimator geometrical effect), the angular coefficients of the linear fits of the left plots in figure 7 are essentially the ratio Q_c/Q between the collected charge Q_c and the produced charge Q in IC_B . This ratio is reported in figure 8 versus the chamber position along the beam path in air (and therefore the beam transverse size). The

points are fitted by an adapted Boag formula⁴ [12] where the ion density ρ in the chamber is parametrized by $\rho \sim b/(x + c)^2$ which accounts for the variation of the transverse size of the beam with x ; the free b parameter somehow includes potential charge screening effects at high intensity.

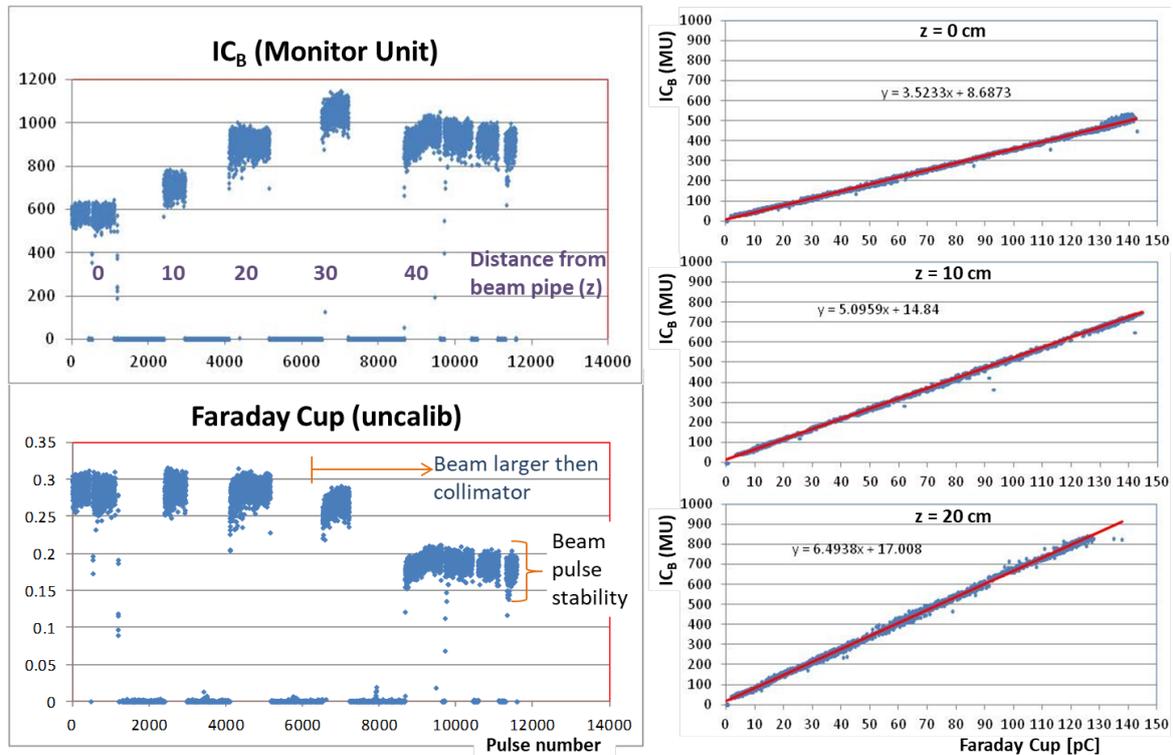


Figure 7. IC_B and FC responses. Left: the two devices pulse-by-pulse responses at different distance from the beam pipe exit. Right: the response correlations for different dose rate (pulse intensities) and at different distances; in red the linear fits.

6. Conclusions

The above results cannot be considered conclusive, however the reasonable agreement of the fit in figure 8 is a good hint toward a main role of the volume recombination effects in the IC_A and IC_B chambers, with likely contribution from charge screening at high beam intensities.

The 2D-IC is affected by the same recombination processes occurring in the integral ionization chambers; however at more than 100 cm from the beam pipe exit, where the 2D-IC sits, the transverse beam charge distributions are wide enough to make the charge density effects noticeable only at very high dose rate.

The intrinsic modularity of the TOP-IMPLART Linac permits to test the performances of the accelerator and its components simultaneously to the facility implementation. Many aspects that can be critical at lower energies (and would require specific setup at higher energies) can be carefully investigated and characterized in a sort of natural way, very in advance respect

⁴ The Boag function describes the ionization chamber volume recombination effects in rapid pulsed beam, with pulses much shorter than the ions transit time in the chamber gap as in the TOP-IMPLART beam (pulse width $\approx 4 \mu\text{s}$ versus transit time of $\approx 1 \text{ms}$).

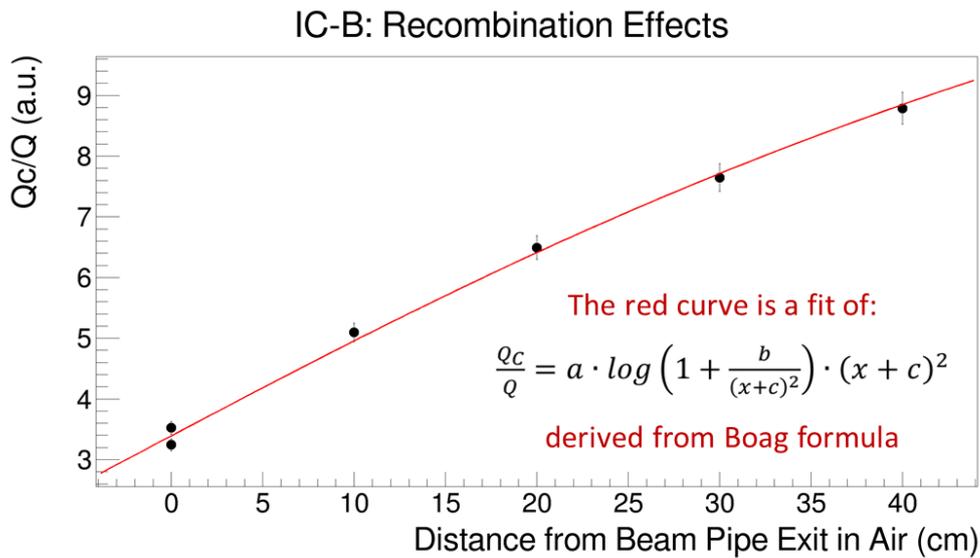


Figure 8. Recombination effects in the integral chamber IC_B : ratio of the collected Q_c and produced Q charges in the chamber versus the beam pipe exit window distance in air (and therefore the beam transverse size). The fitting curve is described in the text, $\chi_r^2 = 1.64$.

to accelerator completion; among them, the study of the effects of dose rate on the delivery monitors is one of the priority of the TOP-IMPLART developments.

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