Published by IOP Publishing for Sissa Medialab

Received: *November 23, 2021*
Accepted: *July 21, 2022*
Published: *October 13, 2022*

12th International Conference on Position Sensitive Detectors
12–17 September, 2021
Birmingham, U.K.

Position sensitive detectors in proton therapy: online monitoring of the beam position

R. Schaefer,* O. Actis, S. Koenig, M. Eichin and D.C. Weber

Center for Proton Therapy, Paul-Scherrer-Institute, 5232 Villigen, Switzerland

E-mail: robert.schaefer@psi.ch

Abstract: Spot-scanning is a highly dynamic treatment method in proton therapy, tailored to each tumor shape individually. By superimposing many single spots in all three spatial axes, a prescribed dose is applied to the tumor volume. To minimize dose inhomogeneity across this volume, tight constraints on the beam position accuracy apply: for a dose inhomogeneity below 1%, a longitudinal beam position accuracy of the order of 1 mm is necessary, whereas in the lateral plane, the accuracy needs to be roughly one order of magnitude better. Longitudinal position control is achieved through selecting the beam energy; laterally, this is achieved by two sweeper magnets, allowing position changes within milliseconds. Such dynamics and accuracy constraints require an online measurement of the beam position to enable and maintain high treatment quality assurance. Gantry 2 at the Center for Proton Therapy at PSI operates a plane parallel strip ionization chamber for this purpose as the final beamline element before the patient. The foil-based detector design is optimized for an in-situ placement in the beam axis and keeps beam disturbance at a minimum. A strip pitch of 2 mm allows to reconstruct the Gaussian shape beam profile with the desired accuracy. These beam profiles are analyzed (and verified) during a treatment on a spot-by-spot basis, before the next spot is applied, introducing a dead time after every spot. Applying 50,000 spots in a treatment introduces the challenge to data acquisition and — processing in terms of keeping treatment times reasonable. Data pileup and long dead times are mitigated by optimized front-end electronics and early-stage data processing, without compromising data quality and the accuracy of the measured beam position.

Keywords: Beam-line instrumentation (beam position and profile monitors, beam-intensity monitors, bunch length monitors); Gaseous detectors; Instrumentation for particle-beam therapy; Control and monitor systems online

*Corresponding author.

https://doi.org/10.1088/1748-0221/17/10/C10017

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1 Introduction

One of the main advantages of treating tumors with proton beams are the Bragg-peak characteristics, allowing precise longitudinal confinement of the prescribed dose to the tumor. Laterally, this is achieved by using narrow pencil beams to scan the tumor volume.

The Center for Proton therapy (PSI) operates the Gantry 2 [1], where tumor irradiations through spot-scanning are carried out with pencil proton beams between 70 MeV and 230 MeV. Initially, the superconducting COMET cyclotron [2] delivers proton beams with an energy of 250 MeV, which is then moderated to the given energy range through carbon-based degrader wedges a few meters downstream of the cyclotron. Lateral beam position control is achieved by two sweeper magnets directly on the Gantry. These magnets are driven by fast power supplies allowing scanning speeds of up to 2 cm/ms in an active scanning area of $12 \times 20\,\mathrm{cm}^2$.

In proton therapy the spatial dose inhomogeneity across the tumor should be as low as possible and can be directly related to the beam delivery position accuracy. At the CPT, we aim for an spatial dose distribution inhomogeneity of <1%, requiring accuracy constraints on the sub-millimeter-level for the lateral beam position, and millimeter-level accuracy for the longitudinal position. Proper quality assurance for the patient can only be carried out by measuring and verifying the beam positions on a spot-by-spot basis at such accuracy levels. To do so laterally, a foil based planar ionization chamber with strip pattern electrodes is permanently installed in the beam axis for online position measurements.

2 Online and in-situ beam position measurement with a strip chamber

2.1 Strip chamber design

An in-situ detector requires special design constraints: the detector's material budget has to be minimized to mitigate beam scattering. In order to minimize maintenance work, high-robustness during quasi-continuous irradiation is another key design feature, since a detector breakdown and a following cease of position measurement requires a full stop for patient treatments. If (urgent) maintenance work is expected on such a detector it has to be easily accessible. Therefore, the strip chamber is located in the Gantry 2 nozzle, as the last beam line element before the patient, cf. figure 1.

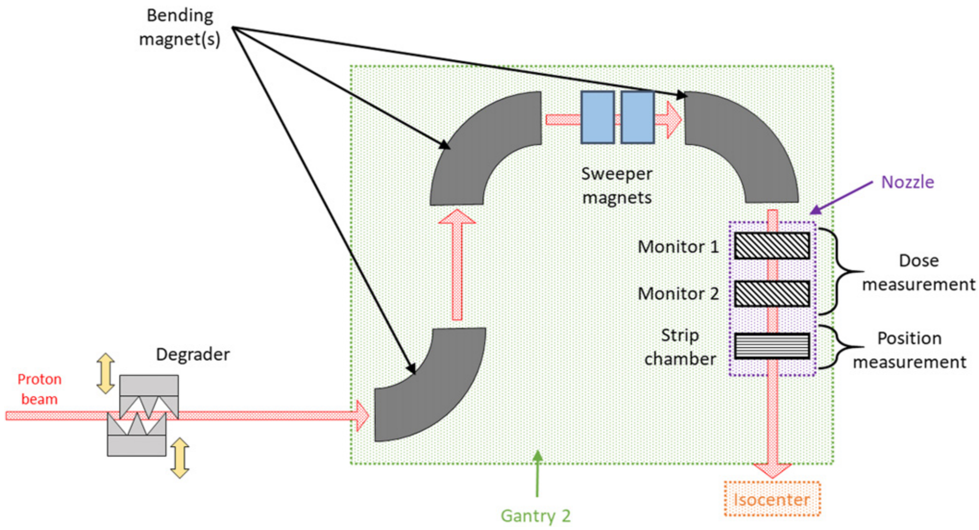

Figure 1. Schematic layout of Gantry 2 and the beam position controlling devices.

Figure 2 gives a sectional and an exploded view of the strip chamber detector. High-voltage (1.8 kV) is applied to a two-sided electrode in the center, repelling ions across a 1 cm large air gap towards 2 mm wide copper strips which segment the two axes perpendicular to the proton beam. The number of Cu strips in each direction is given by the maximum scanning range: there are 128 strips in the U-plane and 88 strips in the T-plane. The charge collection time is estimated as $t = d^2/(U \cdot \mu_{\mathrm{Air}}) = 0.4\,\mathrm{ms}$.

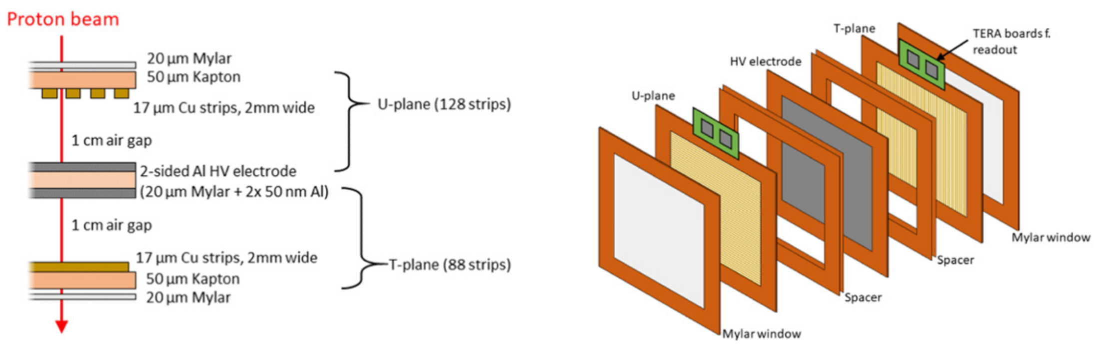

Figure 2. (Left) Sectional view of the strip chamber. The HV is generated on the central plane equipped with two Al electrodes. Each plane is segmented into 2 mm wide Cu strips, where the strip direction of the T plane is perpendicular to U. (Right) Exploded view of the strip chamber stack.

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Each plane is read out by two TERA chips [3] mounted on one TERA board, with 64 input channels per chip. The chips (TERA series 06) are only capable of an integrating readout through *charge-to-frequency-conversion*. The amount of chips used is given by the number of strips in the detector. PCB-mounted potentiometers are used to control the gain; the strip chamber is operated at its highest possible gain, requiring −100 fC to generate one ADC count (cf. figure 3, left). To mitigate radiation induced electronics damage, only the TERA boards are (in the detector housing and) close to the beam; processing electronics are placed one meter away, behind the yoke of the last bending magnet.

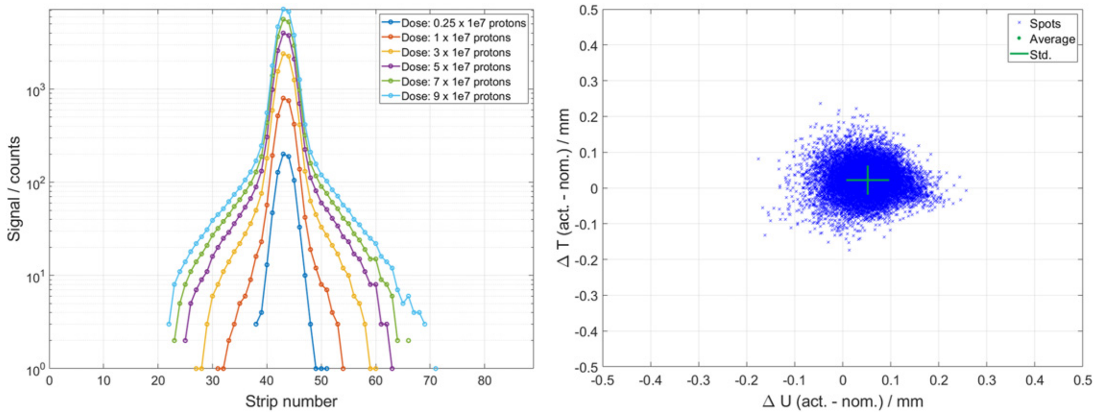

Figure 3. (Left) T-plane profiles of the nozzle strip chamber for various spot weights. (Right) Typical residuals (actual to nominal position) plot from a patient irradiation.

2.2 Data transfer and processing

The data provided by the TERA boards are spot-individual beam profiles for each plane in the form of tuples of the strip number and the counts registered, i.e. arrays of 2×88 and 2×128 values. The read-back process between the control system and the detector specific electronics (DSE) memory is sequential and takes 20 µs per value read. Thus, instead of reading back the tuples and processing these in the control system, preprocessing the beam profiles and reading back less than 10 values (beam position, beam profile spread and — area) yields lower dead times between spots and results in shorter irradiation sessions.

The raw data arrays are serially transmitted to the DSE and preprocessed in an FPGA board. The beam position is determined by defining a region-of-interest (all strips with counts above a threshold) and calculating the center-of-gravity (COG). In terms of accuracy, a Gaussian fit is only marginally better than a COG and (in our case) does not justify the additional computation time required. In addition, the position calculation is only one of several applications running on the (used to capacity) FPGA. A more sophisticated algorithm would require a larger FPGA. Samples of beam profiles are shown in figure 3, left.

The beam position is determined in the plane of the nozzle strip chamber and needs to mathematically projected to the isocenter (approx. 65 cm). Eventually, every spot is verified though its residual between the projected and planned position at the isocenter (cf. figure 3, right); the treatment is interrupted if this is greater than 1.5 mm, and subsequent spots are not applied.

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3 Results and performance

The Gantry 2 and the nozzle strip chamber were commissioned in late 2013 and patient treatment has been running since then. Throughout these years, no hands-on work was necessary on the strip chamber, only software optimizations were required for special beam delivery settings.

The strip chamber behaves linear with dose, and even spots with small weights (cf. figure 3, left) yield enough data points to be reconstructed with a COG algorithm.

A representative position residuals map from a patient irradiation is given in figure 3, right; we aim for a "cloud" centered around zero. The data point scatter (standard deviation) is a convolution of the beam delivery accuracy and the strip chamber measurement accuracy. An analysis of the patient irradiations of the last 12 months yields an average deviation $(\sigma_{\Delta U}, \sigma_{\Delta T}) = (0.06, 0.05)$ mm. This can be regarded as besting the required lateral beam position accuracy for the dose inhomogeneity limit.

4 Conclusion and outlook

The strip chamber's design and the data preprocessing feature make online quality assurance possible. Additionally, by keeping sensitive electronics away from the detector volume itself, we were able to minimize maintenance efforts. Maintaining the strip chamber's performance throughout the years is however coupled to a tight quality assurance program for the detector itself, such as continuous hardware parameter monitoring, daily interrupt functionality checks, and yearly comparisons to reference positions.

For the described application, the strip chamber performed very well, however it lacks certain essential functionality when aiming for more sophisticated treatment types. For example: FLASH [4] type treatments, where the dose rate is increased by a factor of 100 or more, requires an online gain control of the detector to avoid signal saturation or electronics damage. Or line scanning [5] type applications, where instead of spots, "lines" are applied in one direction; this would require a time resolved instead of integrating readout of the strip chamber.

The current TERA readout system is not capable of this functionality, making an upgrade necessary. The chosen successor ADAS chip [6] is a commercially available ADC chip suitable for these applications. This however doesn't affect just the detector itself but also the subsequent electronics. Since such an endeavor touches running patient operations on Gantry 2, it needs to be thoroughly planned.

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