Clinical proton pencil beam scanning gantry as a test bench for the FLASH effect

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INTRODUCTION

- FLASH effect - there is an experimental evidence, particularly with electrons, that a similar total dose delivered to the target volume with a high dose rate (> 40 Gy/s) results in the same tumor control but decreases toxicity on healthy tissues [1-3].
- At PSI there is a unique opportunity to explore this effect with protons on Gantry 1 [4] – a clinical pencil beam scanning (PBS) unit, which has been decommissioned for patient treatments. As it is equipped with a fully automated, discretized and nozzle mounted range shifter, adaption to FLASH type irradiations will allow for detailed studies of this effect in different parts of the Bragg peak curve.

AIM

- To modify Gantry 1 to achieve FLASH dose rates and demonstrate the feasibility of irradiations with FLASH rates.
- To define the monitoring and safety requirements for future FLASH experiments with protons.

MATERIALS AND METHODS

- We optimized beam optics to transport an un-degraded proton beam from the cyclotron to the isocenter.
- Dose monitoring for up to 1000 times higher dose rates was studied and suitable solutions based on ionization chambers and Faraday cup were developed.
- We characterized the beam in air for different beam widths by means of a scintillator-CCD detector and we measured depth-dose curves in water.
- Safety requirements have been defined and the existing safety system of the gantry has been adapted accordingly.

RESULTS

- New settings of beamline magnets (tune) were defined to transport a 250 MeV proton beam with minimal losses to the isocenter, and its reproducibility was verified (Fig. 1). The optimized beam optics allows 250 MeV proton beam to be transported from the cyclotron to the isocenter with a transmission of at least **75%**.
- Cyclotron beam currents of up to **800 nA (600 nA** at the isocenter**)** were used for irradiations in the FLASH mode (Fig. 2).
- For a 2 mm (1 sigma) beam we achieved a peak dose rate of **(9300 ±400) Gy/s** along the central axis of the pencil beam at 3 mm water equivalent depth and 56 cm distance from the gantry nozzle (Fig. 3).
- Different field sizes (95% homogeneity) were achieved by varying the number of range shifter plates in the gantry nozzle. As such, the maximum field size tested so far (4x4 mm^2) corresponds to a 6.3 mm (1 sigma) beam, leading to a peak dose rate of **(1000 ±40) Gy/s** at 3 mm water equivalent depth and 56 cm distance from the nozzle. The beam energy in such a configuration is 237 MeV.
- Dose monitor (ionization chamber) in the gantry nozzle has been characterized in the FLASH regime and corrections for significant recombination effects were applied. As such, the monitor allows desired total dose to be delivered with a reproducibility better than **1%** and an accuracy of **2-3%**.
- Faraday cup and a commercial large-area plane-parallel ionization chamber (PTW, Freiburg) were used to verify the delivered dose.
- With a dose rate of 1000 Gy/s we delivered to 30 mm^3 water samples different doses ranging from **2 to 40 Gy**.

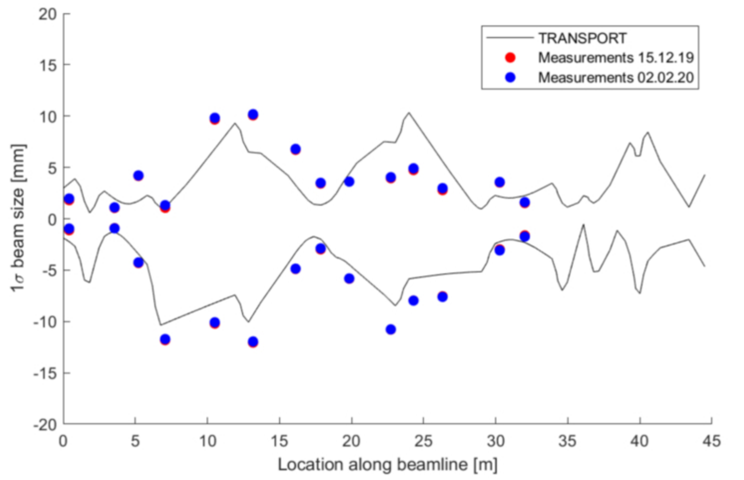

Figure 1: Beam envelope corresponding to the new beamline tune.
Continuous line – result of simulations with TRANSPORT; blue and red dots – beam profile measurements from different experimental sessions.

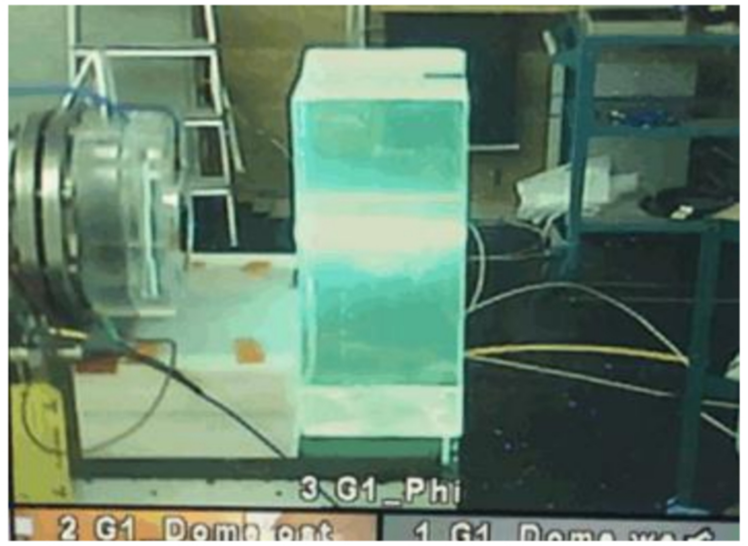

Figure 2: Live image from a video camera of a 525 nA proton beam traversing a scintillating block. The length of the pulse was 10 ms.

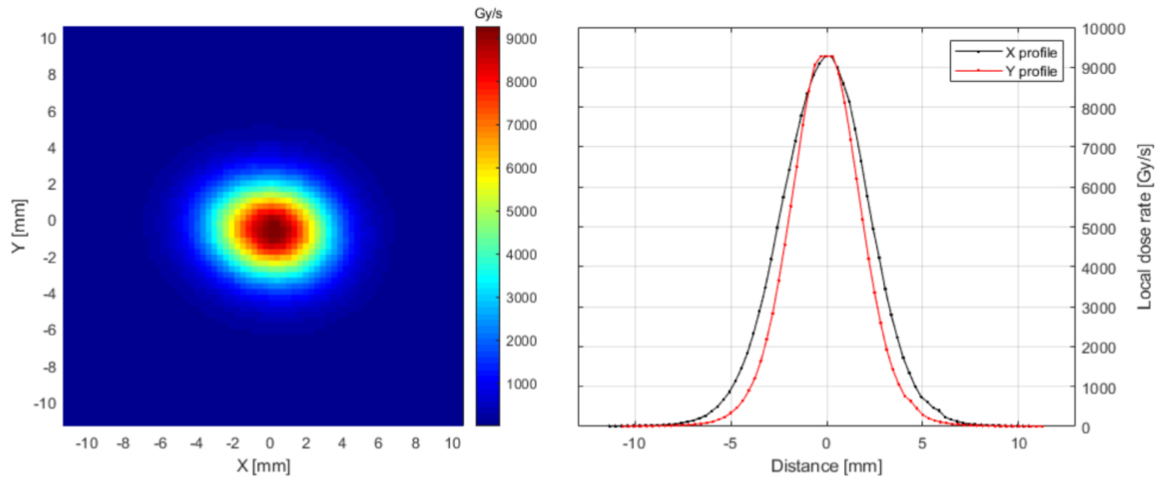

Figure 3: Characterization of a beam spot in air corresponding to a 150 ms irradiation with a cyclotron beam current of 800 nA.
Left: Beam spot of 2.27 mm/1.80 mm (X/Y – 1 sigma) in air recorded with a CCD camera at a distance of 56 cm from the gantry nozzle.
Right: Corresponding dose rate distribution in water at 3 mm water equivalent depth. The maximum dose rate was determined from the measured delivered protons by means of a Faraday cup and delivery time, and was found to be 9300 ± 400 Gy/s.

CONCLUSIONS

- A previously clinical PBS proton gantry has been successfully modified into a test bench for FLASH irradiations with protons.
- In addition to transmission irradiation, it will also allow conformal (Bragg peak) PBS irradiations to be conducted in FLASH mode.
- First experiments with cell lines are ongoing.

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