A 3D RANGE MODULATOR FOR ULTRA-SHORT PROTON FLASH IRRADIATION

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In the pursuit of optimal parameters for FLASH irradiation through experimental studies, both the **dose** and the **time** should be **adjustable** over a wide range and determined with **minimal uncertainties**.

In the case of protons and ions, the above conditions can be fulfilled with the use of a **static range modulator**, which creates a flat depth-dose profile and can accommodate ultra-short beam durations, regardless of their time structure. Unlike the commonly applied shoot-through irradiation, bigger and more samples can be positioned within an extended volume with uniform properties.

Such a modulator was designed and tested, with the aim to match the respective functionality of a rotating wheel that has been used for in-vivo and in-vitro FLASH investigations at HZB^{1,2}.

The modulator has the form of a **ridge filter** expanded to an **additional dimension**, with a hexagonal-pyramid pattern. The manufacturing was done with a **3D printer** using VeroWhite, a material similar to PMMA.

The design was configured to an **incoming proton beam** of ≥ 1 mm rms size, in order to create a flat dose range of 5 mm in water at the target (19 cm downstream) and a 6 mm uniform field after collimation.

The usual procedure of adding single Bragg peaks at different energies was used to calculate the weighting factors for each of the 8 modulation steps. The spacing between two adjacent cells is 2 mm and the shortest edge in the pyramid is 0.3 mm.

The distal and lateral dose distributions of both the static and the rotating modulator were measured using a Markus® Chamber in a water phantom, and a radioluminescent screen mounted in front of CCD camera, respectively.

Results

The static modulator created very **flat dose distributions** as designed, with negligible differences to the reference rotating wheel. The spread-out Bragg peak has a flatness of $\pm 1.5\%$ and shows a 0.4 mm difference in range, which can be easily compensated with an adjustable range shifter. The planning target volume has a diameter of 6 mm, as planned.

The positioning **tolerances** of the modulator were evaluated as being relatively **relaxed**, with offsets of 2 cm and an angle of 5 degrees not compromising the desired performance.

Conclusions

The developed static modulator allows systematic proton FLASH studies on small organs using various timing schemes disentangled from temporal and spatial incoherencies, which may complicate or falsify the interpretation of the FLASH effect.

With this component, further irradiation campaigns can be conducted at the HZB cyclotron, using a quasi-DC (20 MHz) proton beam of 1-10 ns long microbunches with a total duration down to 1 ms. Using an available pulsed beam kicker, alternative timing structures can be delivered as well, with dose rates up to 1 kGy/s.

1. G Kourkafas et al., "FLASH proton irradiation setup with a modulator wheel for a single mouse eye", doi:10.1002/mp.14730
2. V Ehrhardt et al., "Flash irradiation with protons of human colon organoids – a new approach to study normal tissue sparing", this conference, EPD061 / #19