22/06/2026

2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

Designing pin-type ridge filters for Bragg peak FLASH proton therapy to maximize dose-rates and robustness to beam instabilities

Christopher Mayhew[1]; Richard Amos[1]; Maria Hawkins, MD[1]; Lee Harrison-Carey[2]; Simon Dawes[1]; John Fenwick, PhD[1]
[1]University College London, [2]University College London Hospital

BACKGROUND

- FLASH irradiation at ultra-high dose rate (UHDR, ≥40 Gy s^{-1}, orders of magnitude above standard proton therapy rates) spares normal tissue at iso-effective tumour dose-levels [1].
- Bragg-peak FLASH requires single-energy SOBP delivery: conventional layer-by-layer energy selection is too slow (>80 ms per layer) for UHDR, and energy-degrading losses reduce dose rates [2].
- Pin-type ridge filters (pRFs) degrade a single beam energy into many ranges, forming an SOBP across a scanned field without energy switching.
- Scatter and nuclear interactions in pRFs and range-shifters (RS) broaden beams and deplete protons — limiting dose rate and broadening fields' distal and lateral penumbra.
- Critically, pRFs make the delivered depth-dose profile sensitive to beam errors: lateral offsets change the fraction of protons traversing each pin thickness, distorting the SOBP — a sensitivity absent in conventional delivery.

METHODS

- The UCLH ProBeam beamline was matched across the clinical energy range in TOPAS; dose-to-water scored in water phantoms and patient CTs at ≤2 mm voxel resolution [3].
- A pRF design methodology was developed accounting for the non-uniform Gaussian fluence incident on each pin stack, including contributions from neighbouring spots.
- Uniform pRFs and non-uniform pRFs (NURFs) representing phantom and clinical cases were designed and investigated in-silico.
- pRF/RS materials compared in-silico: polypropylene, Lexan, water, beryllium, aluminium, lead.
- Dose-rate metrics: average dose rate (ADR), depth-averaged ADR (DADR), V_{40} (volume fraction ≥40 Gy s^{-1}) [4].
- Robustness assessed for spot offsets (≤2 mm), spot-σ changes (±0.2 mm), pRF rotation, and beam divergence — across the square-pin baseline, spline-profiled pins, 2×2 pin blocks, and RF-after-RS placement.
- pRFs manufactured by SLA 3D printing of a polypropylene-based resin (stopping-power ratio 1.144 ± 0.004), giving low lateral scatter and minimal dose-rate loss.
- Experimental validation at UCLH with a 245 MeV beam; depth-dose profiles measured with an IBA Giraffe MLIC detector.

RIDGE-FILTER DESIGN

- A range of pencil-beam/pin-stack spacings was investigated to assess the effect on dose conformity and dose rate.
- The design accounts for the summed fluence map from neighbouring pencil beams — which varies with spot spacing — to set each pin's energy weighting correctly.

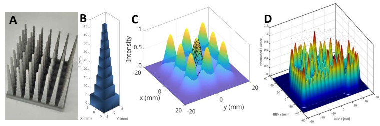

Figure 1 - A) An SLA 3D-printed polypropylene-resin uniform pRF (10 mm pin spacing) and B) an individual pin stack, designed to produce a 5 cm. C) A uniformly weighted set of pencil beams, spaced at 10 mm, with stack pin boundaries overlaid. D) A more complex set of pencil beam weighting for a glioblastoma treatment plan.

EXPERIMENTAL VALIDATION

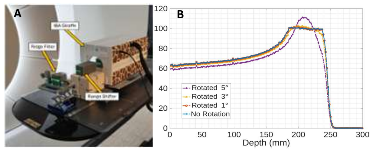

Figure 2 - A) A pRF (5 mm pin spacing) with 10 cm of RS. This produced a 5.1 cm SOBP at 1.3% max–min in a 245 MeV beam, matching design intent. B) With a 5 mm pin spacing, the IDD tolerated lateral shifts up to 2 mm (≤2.0%) but was sensitive to rotation: 1°, 3° & 5° tilts from the CAX gave 1.9%, 7.1% & 29.4% max-min variation.

- pRFs were tested in a Varian Probeam beamline, using a 245 MeV beam at standard dose rates.
- Spatial offsets and rotational misalignments were purposefully introduced to assess the effect of potential setup errors and machine output variabilities.

REFERENCES

1. Favaudon V, et al. Sci Transl Med. 2014;6(245):245ra93.
2. van de Water S, et al. Acta Oncol. 2019;58(10):1463–9.
3. Perl J, et al. Med Phys. 2012;39(11):6818–37.
4. Folkerts MM, et al. Med Phys. 2020;47(12):6396–404.

pRF-RS SYSTEM MATERIALS

- Lateral beam spread was assessed for pRF-RS degraded beams across the clinical energy range. For 250 MeV degraded to 150 MeV, beryllium produced the narrowest beam (σ = 8.5 mm at Bragg-peak depth), polypropylene 9.8 mm, aluminum 13.2 mm, lead ~30 mm. Polypropylene gave the highest fluence transmission, and therefore the highest deliverable dose rate. Range straggling (R_{10}–R_{80} ≈ 6.8 mm) was essentially material-independent (ΔR_{10}–R_{80}<0.4 mm, except lead +1.2 mm).

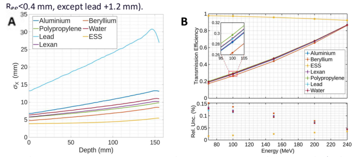

Figure 3 - A) Lateral spread measured by σ width by material for a 150 MeV beam degraded from 250 MeV. B) RS/ESS fluence transmission efficiency vs energy, as a percentage of proton fluence at the nozzle. * ESS = Energy Selection System

LATERAL FIELD UNIFORMITY

- RS-induced lateral broadening raised the maximum spot spacing maintaining PVDR < 1.02 from ~10 mm (ESS beam) to 16–20 mm (pRF/RS beam, energy-dependent), reducing the number of spots required per energy layer.

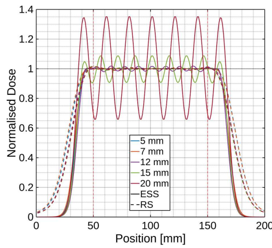

Figure 4 – Field profiles at Bragg-peak depth (100 MeV) for spot spacings of 5–20 mm. RS-broadened beams keep the peak-to-valley dose ratio below 1.02 for spacings up to 16–20 mm (energy-dependent), versus ~10 mm for ESS beams — allowing fewer spots per layer with no loss of uniformity.

DOSE-RATE

- Polypropylene produced the highest ADR of all materials tested, with gains of 10–68% over aluminium, beryllium, and lead at a 215 nA nozzle current. Field size was the primary determinant of FLASH coverage: V_{40} fell from 88.5% (4×4 cm^2) to 8.9% (10×10 cm^2) at 10 mm spot spacing. Deeper SOBPs gave modestly higher ADR due to reduced RS thickness.

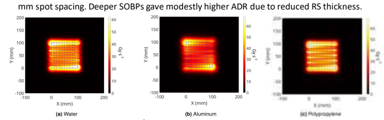

Figure 5 – Average dose-rate maps for 10×10 cm^2 fields delivering 8 Gy at 215 nA. Field size dominates FLASH coverage: the volume receiving ≥40 Gy s^{-1} falls from 88.5% (4×4 cm^2) to 8.9% (10×10 cm^2) at 10 mm spacing, while deeper SOBPs give modestly higher ADR. Polypropylene (c) sustains the highest dose rate.

Configuration	N Spots	PP ADR (Gy s^{-1}) / V_{40} (%)	Water ADR (Gy s^{-1}) / V_{40} (%)	Al ADR (Gy s^{-1}) / V_{40} (%)
Field size [10 mm spacing, 5–10 cm SOBP]				
4 × 4 cm^2	25	54.4 / 90	53.2 / 89	50.2 / 86
5 × 5 cm^2	36	49.1 / 76	48.0 / 72	45.4 / 65
6 × 6 cm^2	49	42.4 / 51	41.5 / 47	39.3 / 38
10 × 10 cm^2	121	28.6 / 11	28.0 / 9	26.7 / 7
Spot spacing [5x5 cm^2, 10–15 cm SOBP]				
5 mm	121	51.7 / 84	50.8 / 82	47.0 / 71
7 mm	64	54.2 / 83	53.4 / 82	48.7 / 73
10 mm	36	52.2 / 84	51.5 / 83	47.7 / 71
12 mm	25	52.7 / 88	51.4 / 87	45.9 / 73

Table 1 – Mean ADR (Gy s^{-1}) and FLASH coverage V_{40} (% volume ≥ 40 Gy s^{-1}) for polypropylene (PP), water and aluminium (Al) pRF-RS systems.

CONTACT

Christopher Mayhew
University College London
chris.mayhew.16@ucl.ac.uk
+44 7454 013790

ROBUSTNESS TO BEAM PERTURBATIONS

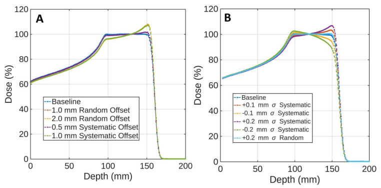

Figure 6 – A) At 10 mm spacing a 1 mm systematic spatial offset distorts the SOBP by 9.5% and B) a systematic ±0.2 mm σ change by up to 13.7%. These effects on the longitudinal dose distribution are largely absent in conventional delivery. Max–min SOBP variation (%) under each mitigation.

- At 10 mm spot spacing, a 1 mm lateral offset distorted the SOBP by a Max-Min range of 9.5%; a −0.2 mm spot-σ error produced 13.7% distortion — sensitivities absent in conventional scanned delivery. A 2° pRF rotation introduced 4.0% distortion; uncorrected beam divergence at 10×10 cm^2 produced 4.4%, reduced to 1.2% with realignment.
- Standard pin stacks were the most sensitive design: a 1 mm offset and ±5% spot-σ change produced up to 6.1% and 15.1% Max-Min distortions, respectively. Spline-profiled pins reduced these to 4.1% and 7.7%. Both 2×2 pin blocks and pRF-after-RS placement held distortion below 2% under all perturbations tested.

Perturbation	Standard Square	Spline	2×2	pRF after RS
Unperturbed	1.3	1.1	1.0	1.1
1 mm offset	6.1	4.1	1.5	1.3
Spot σ +5%	9.3	4.8	1.6	1.7
Spot σ −5%	15.1	7.7	1.5	1.5

Table 2 – Min-max distortion range across the SOBP plateau for pRF designs and their robustness to beam perturbations. 2×2 pin blocks or an pRF placed downstream of the RS all hold distortion below 2%.

- pRFs were designed to maximise robustness, dose rate and dose conformity and were then used in the NURF systems, along with the expected clinical beam outputs. Dose distributions were measured in-silico and compared to the expected base plan.
- A QA workflow is also in development to ensure accuracy and reproducibility for pRF fabrication and delivery.

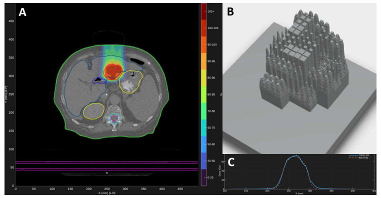

Figure 7 – A) A liver treatment plan simulated in TOPAS on a CT with a B) pRF, with the resulting dose distribution shown. C) A profile of the base plan vs TOPAS dose profile.

CONCLUSIONS AND FUTURE WORK

- The pRF pin-design methodology reproduces the intended SOBP across materials, grids and pin shapes, and was experimentally validated in a proton beamline.
- Polypropylene is the optimal pRF/RS material: it provides the highest dose rates with the 2nd narrowest beams; choice of material governs lateral spread but barely affects range straggling.
- pRF/RS broadening permits wide spot spacing (16–20 mm), reducing spots per energy layer.
- Delivered SOBPs are uniquely sensitive to mm-scale offsets, spot-σ changes and pRF rotation — robustness is restored to <2% by spline pins, 2×2 pin blocks, or RF-after-RS placement.
- The design methodology, material study and robustness analysis are integrated into a Bragg-peak FLASH treatment-planning workflow.
- A QA workflow for pin-type ridge-filters is in development.
- Further non-uniform ridge filter experimental studies are ongoing for clinical-type cases, as well as the development of adaptive pi-type ridge filters.

CANCER RESEARCH UK | RadNet City of London | UCL