DEVELOPMENT OF VHEE SCATTERING SYSTEMS FOR FLASH RADIOTHERAPY

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Abstract

Very High Energy Electrons (VHEE) are an emerging modality for FLASH radiotherapy, offering deep penetration and magnetic beam control in potentially compact systems. However, achieving transversely uniform dose distributions at ultra-high dose rates remains challenging, as current magnet technology cannot provide sufficiently fast beam scanning. Conventional dual-scattering systems can produce uniform beams but introduce significant bremsstrahlung photon contamination in the VHEE regime, requiring impractically long beamlines to mitigate.

This work investigates replacing the first scatterer with a quadrupole lattice to magnetically enlarge the beam prior to flattening. Simulations using RF-Track and TOPAS show that the optimised quadrupole–scatterer system achieves a uniform beam with uniform radius ≈ 75 mm while reducing photon contamination by 94.5% compared to the conventional approach. These results demonstrate that magnetic beam expansion in addition to a Gaussian scattering foil is a promising solution for FLASH-compatible VHEE delivery, improving dose uniformity while minimising secondary particle production.

INTRODUCTION

Radiotherapy (RT) would benefit approximately half of cancer-patients in approximately half of cancer treatments [1]. While photon therapy dominates clinical practice, its depth-dose profile leads to unavoidable irradiation of healthy tissue [2]. In contrast, hadron therapy provides superior dose conformality through the Bragg peak, but requires large and costly accelerator systems [3].

Very High Energy Electrons (VHEE, 50 MeV to 250 MeV) offer a potential alternative, combining deep penetration with magnetic steerability in more compact systems [4]. VHEE beams are promising for FLASH radiotherapy, where ultra-high dose rates (UHDR) ($\gtrsim 40\,\mathrm{Gy/s}$) reduce normal tissue toxicity while maintaining tumour control [5, 6]. The potential benefits of the FLASH effect could simplify radiotherapy by reducing the need for complex gantry systems and multi-angle irradiation.

In VHEE therapy, achieving transversely uniform dose distributions at these dose rates remains a key challenge. Conventional pencil beam scanning [3] is impractical at UHDR due to limitations in magnet speed [7], motivating alternative beam-shaping approaches.

In the previously studied solution by Robertson *et al*, with dual-scattering system, a first scatterer (S1) broadens the beam and a second, shaped scatterer (S2) flattens the transverse profile by preferentially scattering the central component of the beam with higher intensity [8]. This is the clinical method currently used for low-energy electrons [9]. While effective at producing uniform beams, this approach introduces significant bremsstrahlung photon contamination in the VHEE regime. Reducing this contamination requires increased drift space, leading to beamline lengths incompatible with clinical constraints [10].

To address these limitations, this work investigates replacing the first scatterer with magnetic beam expansion using a quadrupole lattice. By magnifying the beam prior to flattening, the total mass thickness of scattering material can be reduced, thereby minimising secondary photon production while maintaining dose uniformity. The proposed quadrupole–scatterer system is studied using RF-Track and TOPAS simulations, and its performance is compared with a conventional dual-scattering configuration. This paper also touches upon the optimisation of the quadrupole settings to improve the efficiency of the CLEAR dual-scattering foil.

THEORY

Scattering Effects

The Gaussian approximation to Moliere's fundamental theory of multiple Coulomb scattering describes the scattering effect of charged particles in matter [11]. In the VHEE regime, the electrons interact with the scatterers and produce photons mainly from bremsstrahlung [12]. These photons may constitute a large proportion to the measured dose downstream, and do not necessarily have a transversely uniform dose distribution even if the electron beam is flattened; this is due to the differences in scattering mechanisms.

Beam Conformality

Super-Gaussian Fit A super-Gaussian fit is used to parameterise the flattened transverse beam profiles:

$$f(x) = A\exp\left[-\left(\frac{(x-\mu)^2}{2\sigma^2}\right)^P\right], \qquad (1)$$

where A is the amplitude, μ the mean of the particle distribution in x, and σ the standard deviation. The parameter

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P characterises the flatness of the distribution, with $P = 1$ corresponding to a Gaussian profile and larger P indicating a beam with more significant uniform component. Super-Gaussian functions are also useful for fitting to a variety of secondary photon profiles.

To quantify beam size, the uniform radius r_{90} is used, defined as the radius at which the fit to the profile falls to 90% of its maximum. This provides a consistent measure of beam size for varying P, where σ becomes less representative of a certain proportion of the beam.

METHOD

Software

RF-Track [13] was used to simulate the transport of a 3×10^6 particle beam through the quadrupole lattice and perform beam magnification. Its output was then exported to TOPAS [14] for detailed Monte Carlo simulation of beam–matter interactions.

TOPAS (based on GEANT4 [15]) was used to model scattering in the foils, secondary particle production, and dose deposition in a water phantom. It was also used to evaluate particle composition, transverse intensity profiles, and depth-dose distributions.

Beam Flattening

Dual-Scattering System A dual-scattering system similar to an example described in Ref. [10] was first simulated in TOPAS using a Gaussian beam with a 1 mm radius. The phantom of dimension 300 mm × 300 mm × 300 mm was positioned at 2500 mm (relative to the start of the TOPAS simulation, i.e., the end of the accelerated beam), corresponding to a configuration where photon contamination significantly affects the dose distribution, as reported in Ref. [10].

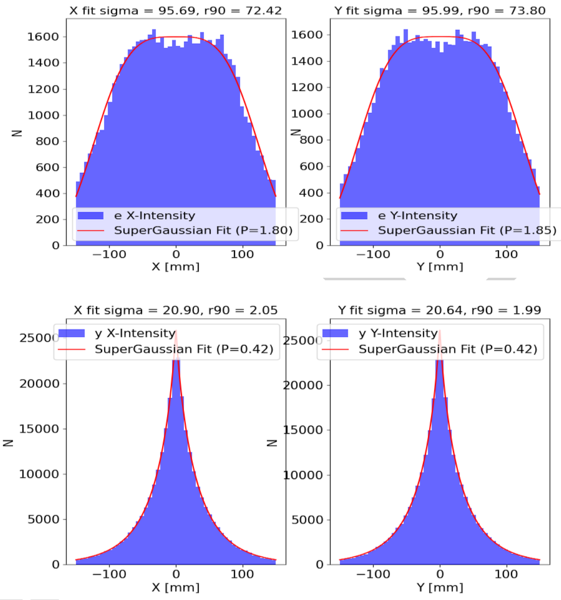

Figure 1: Beam intensity profiles in x and y for the electrons (top) and photons (bottom) after passing through the optimised dual-scattering system.

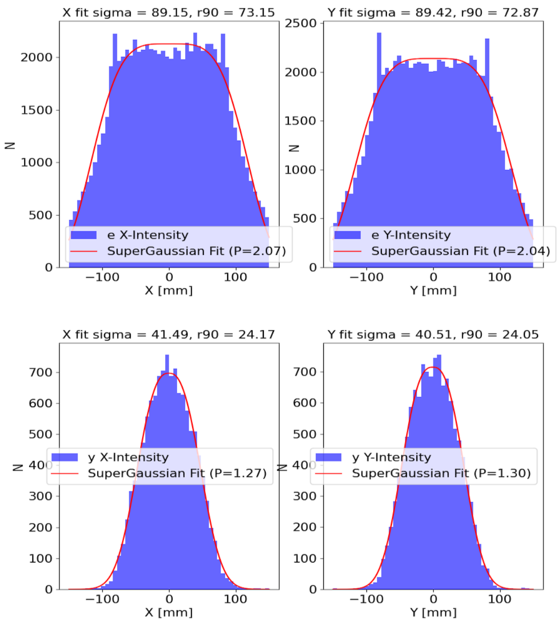

Figure 2: Beam intensity profiles in x and y for electrons (top) and photons (bottom) after passing through the optimised quadrupole-scatterer setup after removal of S1.

The first scatterer (S1) consisted of a 0.95 mm-thick tantalum layer used to broaden the beam to approximately $r_{90} \approx 75$ mm. The second scatterer (S2) was modeled with a Gaussian thickness profile and its parameters were optimised to achieve a flat transverse beam distribution. The optimisation targeted a uniform profile with $r_{90} \approx 75$ mm while maintaining electron transmission above 30%.

With this configuration, the achieved uniform beam size r_{90} was 73.3 mm. The electron and photon beam profiles for this setup are shown in Fig. 1. While the electron beam was successfully flattened, the photon distribution remained highly non-uniform, and constituted of 80.3% of all particles arriving at the water phantom. The dominating photon population with the unflattened photon distribution was expected to negatively affect the transverse uniformity of dose distributions calculated in water, particularly at significant depths.

Quadrupole-Scatterer System The goal of this section was to reduce the thickness of S1 by magnifying the beam size via quadrupoles, aiming for a similar uniform radius to that retrieved by the dual-scattering system described above.

A Nelder–Mead optimiser was firstly used to determine quadrupole strengths that achieved the target beam size while preserving beam symmetry. The optimisation targeted a 70 mm × 70 mm Gaussian beam at the beamline exit (with S2 removed), while penalising asymmetry in phase-space.

RESULTS

The optimiser produced multiple viable quadrupole strength combinations capable of achieving the target beam size at the beamline exit, equivalent to that obtained using

S1. Subsequent beam flattening with S2 (following scattering foil parameter optimisation) yielded a uniform profile with $r_{90} \approx 75$ mm. A representative example is shown in Fig. 2. Crucially, removal of S1 substantially reduced photon contamination, with only 14.6 % of scored particles being photons. This represents just 5.50% of the photon number observed in the dual-scattering configuration. It also increased the electron transmission within a virtual collimator to 33.7%. The doses at 5 mm in the water phantom were simulated with both systems were simulated to verify these results. As expected, a uniform dose profile in water is observed in the quadrupole-scatterer system but not in the dual-scattering system due to the dominating effect of photon contamination (Fig. 3).

DISCUSSION

The simulations assumed an infinite beamline aperture, neglecting particle losses to the beam pipes during quadrupole defocusing. Simulations assumed an idealised beam and infinite aperture, neglecting losses and misalignment effects.

While the study employs a four-quadrupole lattice for flexibility, typical VHEE FLASH beamlines may only accommodate doublets or triplets (e.g. the CLEAR facility at CERN [16]). Future work should optimise configurations for these simpler setups, ensuring compatibility with existing infrastructure for subsequent experimental testing of the novel quadrupole-scatterer system. It should also investigate the minimum beam line possible with this method and thus determine its feasibility for a clinical setting with 1 m to 1.5 m beam line.

ONGOING WORK AT CLEAR

Studies at the CERN Linear Electron Accelerator for Research (CLEAR) are in progress to verify the validity of the simulated studies, and inform the development of future dual and quad-scattering systems and their optimisation.

Quadrupole scans were carried out using the CLEAR quad scan tool [17]; the purpose of these was to provide input to a simulated model of the end of the beamline to assist in future optimisation.

Using these results, the CLEAR beamline was simulated in RF-Track and the resultant phase-space exported into TOPAS to simulate the current dual-scattering foils, shown in Fig 4. The dual-scattering foil currently installed at CLEAR was optimised to slightly different assumed parameters; as such, a double peak is visible in the flattened profiles. Current efforts focus on writing an optimiser that tunes the currents in the 9 quadrupoles upstream of the scatterers to optimise the beam. Work on finding a robust metric as a measurement for flatness, without fitting, so that the optimiser could rapidly simulate the system, is ongoing.

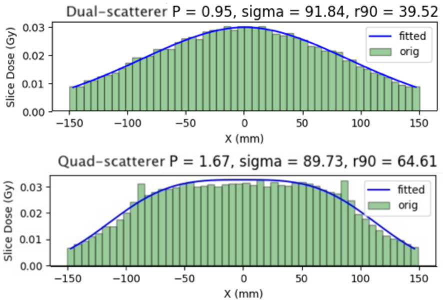

Figure 3: Comparison of the x dose distribution at 5 mm depth of a water phantom, of the dual-scattering system(top) and the quadrupole-scatterer system (bottom).

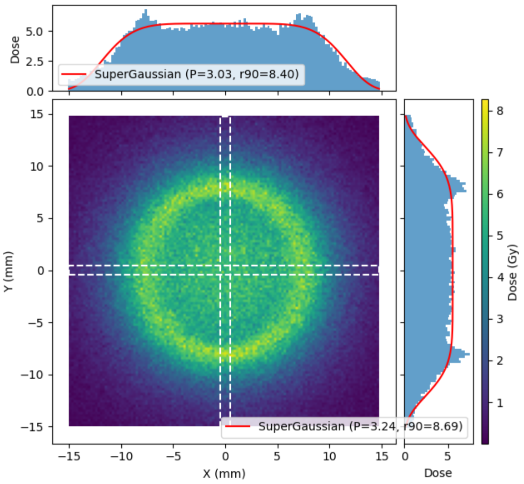

Figure 4: CLEAR beam dose profile at 5 mm in the water phantom.

Using the input from the quadrupole scan results, a dual-scattering system is expected to be designed in the second beamline at CLEAR; with a larger beam pipe diameter of 80 mm, it is expected that experimental verification of a quadrupole-scattering design in the CLEAR beamline will also be possible [18].

CONCLUSION

This study demonstrates that replacing the first scatterer in a conventional dual-scattering system with a quadrupole lattice enables magnetic beam expansion while significantly reducing bremsstrahlung photon contamination.

Simulations show that the proposed quadrupole–scatterer configuration in an arbitrary setup achieves a uniform beam with $r_{90} \approx 75$ mm, while reducing the photon fraction from 80.3% to 14.6% and increasing electron transmission to 33.7%, compared to an equivalent setup with a dual-scatter configuration. These results show the effectiveness of reducing scattering material through magnetic magnification.

Further work is required to assess performance under realistic beamline constraints, including finite apertures, beam offsets, and implementation with quadrupole doublets or triplets. Experimental validation at facilities such as CLEAR and evaluation of depth-dose distributions will be essential to determine clinical feasibility.

This approach represents a critical step toward compact VHEE delivery systems with minimal photon contamination, aligning with the demands of FLASH radiotherapy and expanding the toolkit for next-generation cancer treatment.

REFERENCES

[1] A. Aggarwal *et al.*, "The future of cancer care in the UK – time for a radical and sustainable National Cancer Plan", *Lancet Oncol.*, vol. 25, no. 1, e6–e17, 2024. doi:10.1016/S1470-2045(23)00511-9

[2] Z. Chen *et al.*, "Proton versus photon radiation therapy: a clinical review", *Front. Oncol.*, vol. 13, p. 1133909, 2023. doi:10.3389/fonc.2023.1133909

[3] R. Mohan and D. Grosshans, "Proton therapy – present and future", *Adv. Drug Deliv. Rev.*, vol. 109, pp. 26–44, 2017. doi:10.1016/j.addr.2016.11.006

[4] M. G. Ronga *et al.*, "Back to the future: Very High-Energy Electrons (VHEEs) and their potential application in radiation therapy", *Cancers*, vol. 13, no. 19, p. 4942, Sep. 2021. doi:10.3390/cancers13194942

[5] V. Favaudon *et al.*, "Ultrahigh dose-rate FLASH irradiation increases the differential response between normal and tumor tissue in mice", *Sci. Transl. Med.*, vol. 6, no. 245, 245ra93, 2014. doi:10.1126/scitranslmed.3008973

[6] H. C. Wanstall *et al.*, "VHEE FLASH sparing effect measured at CLEAR, CERN with DNA damage of pBR322 plasmid as a biological endpoint", *Sci. Rep.*, vol. 14, no. 1, p. 14803, Jun. 2024. doi:10.1038/s41598-024-65055-8

[7] W. Zou *et al.*, "Current delivery limitations of proton PBS for FLASH", *Radiother. Oncol.*, vol. 155, pp. 212–218, 2021. doi:10.1016/j.radonc.2020.11.002

[8] C. Robertson *et al.*, "Dual-scattering foil installation at CLEAR", in *Proc. IPAC'23*, Venice, Italy, pp. 5059–5062, Sep. 2023. doi:10.18429/JACoW-IPAC2023-THPM073

[9] K. R. Hogstrom and P. R. Almond, "Review of electron beam therapy physics", *Phys. Med. Biol.*, vol. 51, no. 13, R455–R489, 2006. doi:10.1088/0031-9155/51/13/R25

[10] C. Robertson, "Homogeneous dose delivery for very high energy electron beams", PhD thesis, University of Oxford, Oxford, UK, 2024.

[11] G. R. Lynch and O. I. Dahl, "Approximations to multiple Coulomb scattering", *Nucl. Instrum. Methods Phys. Res. B*, vol. 58, no. 1, pp. 6–10, 1991. doi:10.1016/0168-583X(91)95671-Y

[12] H. W. Koch and J. W. Motz, "Bremsstrahlung cross-section formulas and related data", *Rev. Mod. Phys.*, vol. 31, pp. 920–955, 1959. doi:10.1103/RevModPhys.31.920

[13] A. Latina, RF-Track reference manual, Nov. 2025, doi:10.5281/zenodo.17641882

[14] T. Collaboration, TOPAS user manual, `https://topas.readthedocs.io/`

[15] S. Agostinelli *et al.*, "GEANT4: a simulation toolkit", *Nucl. Instrum. Methods Phys. Res. A*, vol. 506, p. 250, Jul. 2003. doi:10.1016/S0168-9002(03)01368-8

[16] P. Korysko *et al.*, "Operational improvements and upgrades of the CLEAR user facility", in *Proc. LINAC'24*, Chicago, IL, USA, pp. 670–673, Aug. 2024. doi:10.18429/JACoW-LINAC2024-THPB017

[17] A. Petersson *et al.*, "Advanced beam tuning and beam measurements techniques in the CLEAR facility", in *Proc. IPAC'25*, Taipei, Taiwan, pp. 1216–1219, Nov. 2025. doi:10.18429/JACoW-IPAC2025-TUPM026

[18] R. Corsini *et al.*, "The future of the CLEAR facility: consolidation, ongoing upgrades and its evolution towards future electron facilities at CERN", in *Proc. IPAC'25*, Taipei, Taiwan, pp. 1220–1223, Nov. 2025. doi:10.18429/JACoW-IPAC2025-TUPM027