Application of Faraday Cup and Multi-Layer Faraday Cup for UHDR Proton PBS FLASH Radiotherapy

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Jacob P. Sunnerberg[1]*, Xiaokun Teng[1]*, Andrew Friberg[1], Daniel A. Alexander[2], Wenbo Gu[1], Dimitris Mihailidis[1], Eric S. Diffenderfer[1], Boon-Keng Kevin Teo[1], Lingshu Yin[1] and Wei Zou[1]
[1]Department of Radiation Oncology, Hospital of the University of Pennsylvania, Philadelphia, PA 19104, USA,
[2]Department of Radiation Oncology and Applied Medicine, Geisel School of Medicine, Hanover, NH 03755, USA
*Indicates equal contributions

ABSTRACT

Ultra-high dose rate (UHDR) proton pencil beam scanning (PBS) FLASH radiotherapy requires beam monitoring tools capable of **resolving individual, high-intensity spots delivered in fractions of a second**.

This work characterizes the performance of a **Faraday Cup (FC)** and **Multi-Layer Faraday Cup (MLFC)** for **real-time beam current and range monitoring** under both conventional (LDR) and UHDR proton PBS delivery.

The FC resolved individual high-MU proton spots at 4 kHz sampling with charge output linear to MU ($R^2 > 0.999$). The MLFC demonstrated **stable, reproducible signal collection across multiple channels under UHDR conditions without saturation**, and Bragg curve/range measurements remained consistent between LDR and UHDR delivery.

These results support the use of FC and MLFC as reliable, high-resolution dosimetry tools for UHDR proton FLASH beam characterization and quality assurance.

INTRODUCTION

UHDR proton PBS FLASH radiotherapy delivers dose through discrete, high-intensity spots in fractions of a second — **faster than conventional dosimeters can resolve.** Faraday cups **(FC)** and Multi-Layer Faraday Cups **(MLFC)** offer fast, radiation-hard charge measurement capable **of real-time beam current and range verification.** The MLFC-128 (Pyramid Technical Consultants) uses alternating Cu/Kapton layers and a MicroHex™ filter, **validated across 100–226.7 MeV.**

Purpose: Characterize FC/MLFC performance for UHDR proton PBS FLASH beams, benchmarked against conventional (LDR) delivery.

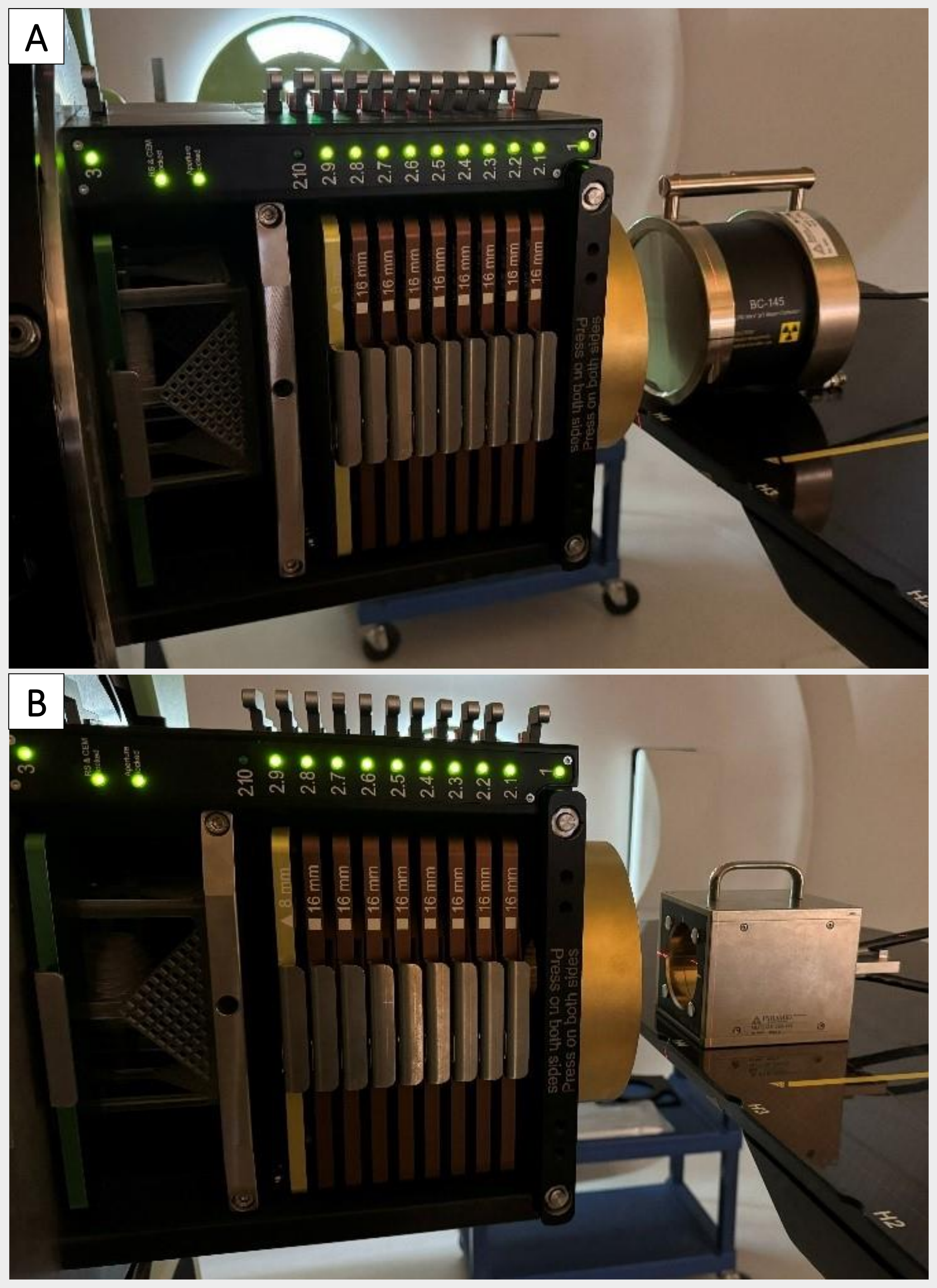

Figure 1: Experimental setup of the A) Faraday cup (FC) and B) multi-layer Faraday cup (MLFC) for UHDR proton PBS FLASH beam characterization. The scanning beam passes through energy-modifying components in a conformal FLASH nozzle before charge collection.

METHODS AND MATERIALS

FC and MLFC-128 were positioned in the proton beam path (Fig. 1). MLFC charge output was cross-validated against a reference Faraday cup (BC-75 + PTW Unidos electrometer).

Measurements were acquired under **LDR (clinical PBS) and UHDR (ConformalFLASH, ~228 MeV, ~500 nA)** delivery, sampled at **4–6 kHz** to resolve individual spots:

- Single high-MU spot current dynamics (FC)
- MLFC signal comparison, LDR vs. UHDR
- Five-spot UHDR delivery, varying MU
- FC charge linearity vs. MU

TOPAS Monte Carlo modeling supported MLFC energy calibration (**agreement within 5%** of reference FC).

RESULTS

The FC **successfully resolved individual proton spots** delivered at high MU with **4 kHz** temporal resolution, capturing fine intra-spot current dynamics throughout delivery (Figure 2). FC charge output **scaled linearly** with delivered MU, **R > 0.999**, confirming excellent charge-output linearity across the tested MU range.

The MLFC produced **stable, reproducible channel signals under both LDR and UHDR** delivery conditions, with **no evidence of signal saturation** observed even at the high instantaneous beam currents characteristic of UHDR delivery. Range measurements derived from the MLFC **Bragg curve remained consistent between LDR and UHDR** delivery, indicating that **beam range verification is preserved regardless of dose rate**.

When five spots of varying MU were delivered under UHDR conditions, the MLFC captured **real-time variation in spot current intensity across the delivery sequence while maintaining consistent range measurements throughout** (Figure 4). Together, these results demonstrate that both the FC and MLFC can reliably characterize proton beam current and range across the full range of dose rates relevant to FLASH radiotherapy.

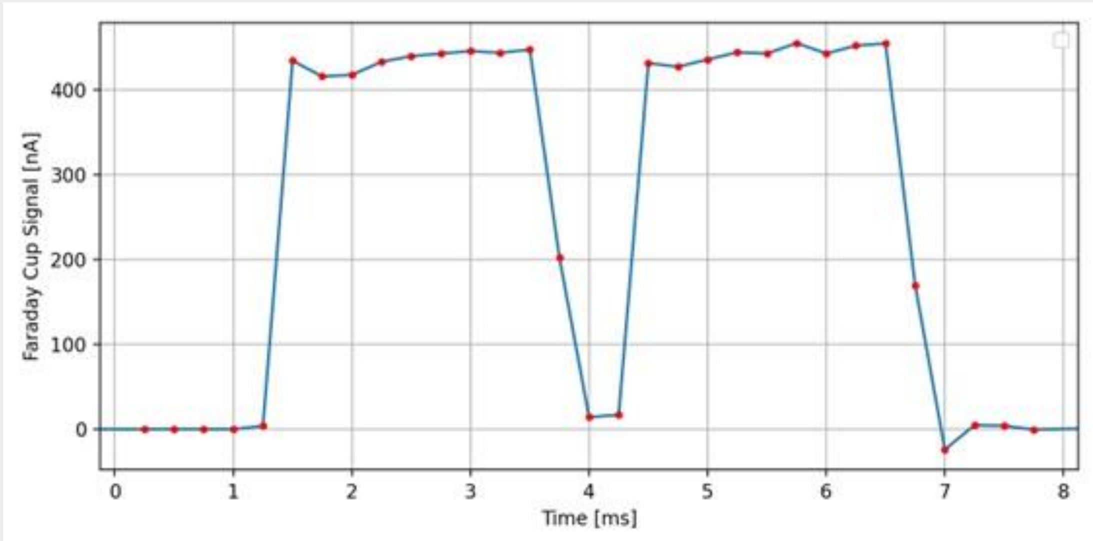

Figure 2: FC measurement of a single high-MU proton spot acquired at 4 kHz sampling rate, illustrating intra-spot beam current dynamics and temporal structure of spot delivery.

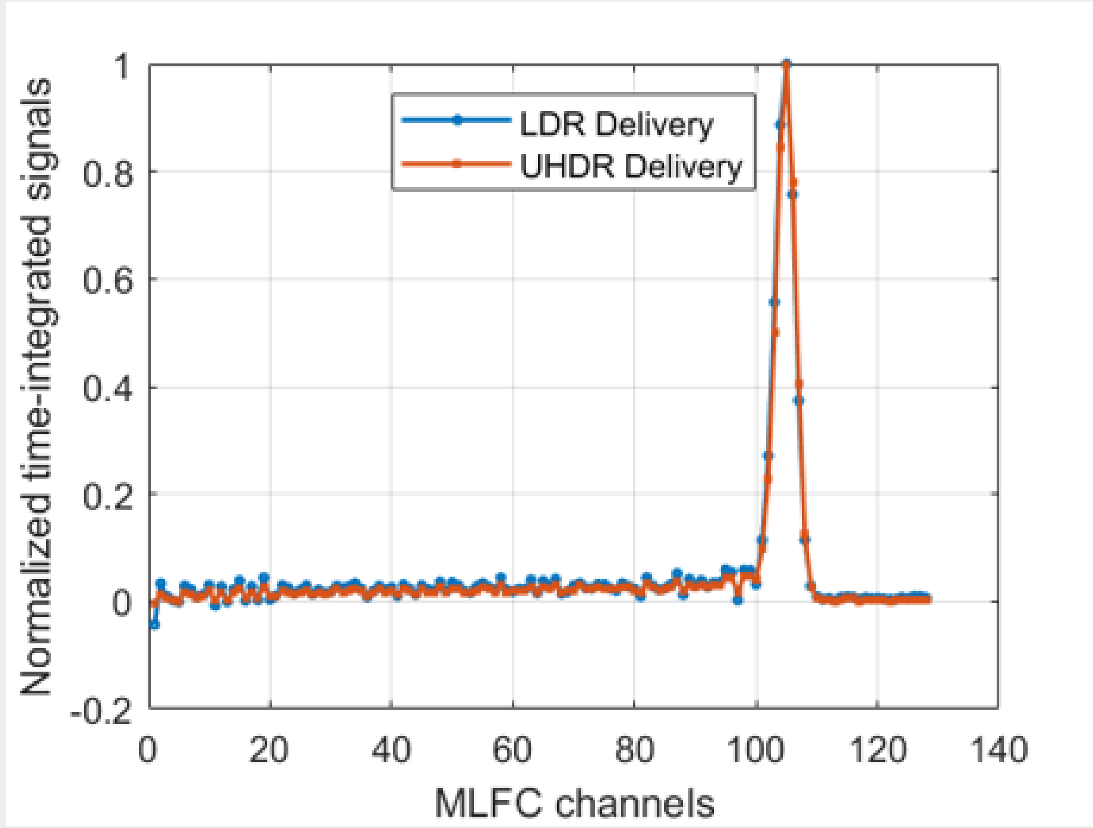

Figure 3: Overlay of time-integrated signals across MLFC channels under low dose rate (LDR) and ultra-high dose rate (UHDR) conditions, demonstrating beam range consistency independent of dose rate.

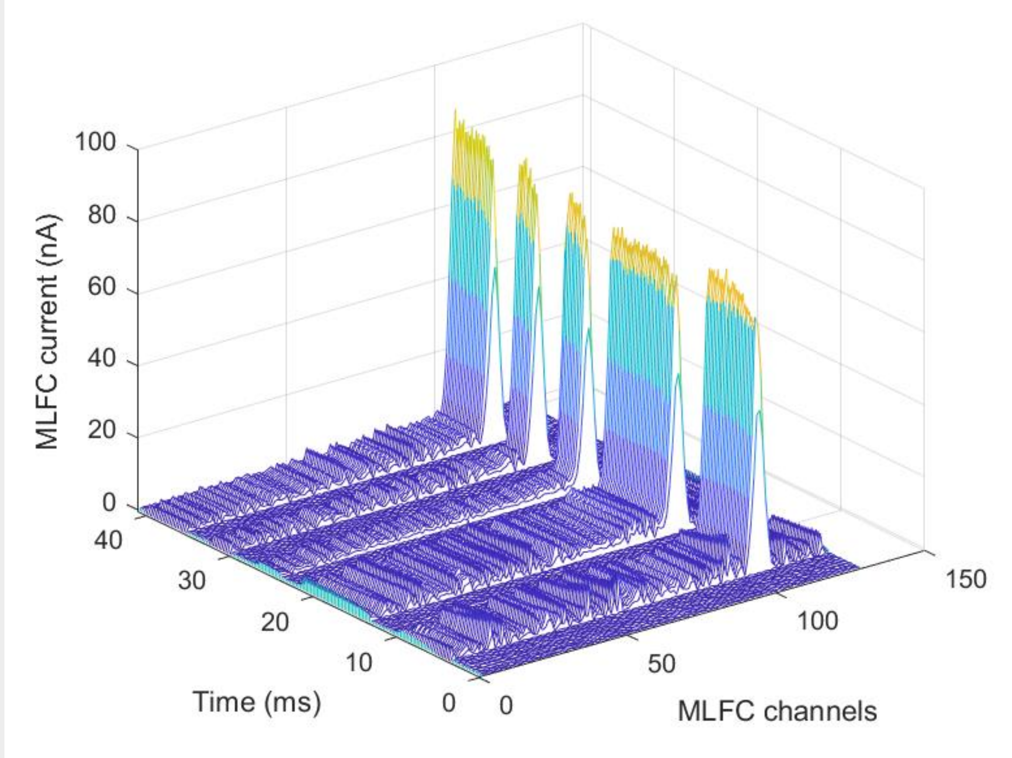

Figure 4: UHDR delivery of five spots of different MUs were collected by the MLFC showing real-time instantaneous spot current intensity variations and range consistencies.

DISCUSSION

These results demonstrate that the **Faraday Cup and Multi-Layer Faraday Cup are high-fidelity dosimetry tools** for monitoring UHDR proton PBS FLASH beams. They address a critical gap in current practice: most **standard detectors cannot resolve individual spot dynamics** at the sub-millisecond timescales of UHDR delivery. The FC's ability to **resolve intra-spot current fluctuations at 4 kHz**, combined with its **excellent charge linearity ($R^2 > 0.999$)**, makes it well suited for fine-grained beam current verification during FLASH commissioning and delivery.

The MLFC's performance is equally encouraging. The **absence of signal saturation**, together **with consistent range measurements between LDR and UHDR,** suggests that its layered Cu/Kapton design and MicroHex™ filtering **are robust to the characteristic high instantaneous currents** of FLASH delivery. This robustness is reinforced by **MLFC output agreement within 5%** against a reference Faraday cup and by Monte Carlo–validated energy response **across 100–226.7 MeV,** supporting confidence in both charge and range accuracy.

Taken together, these findings support integrating the FC and MLFC into **UHDR PBS FLASH commissioning and routine QA workflows**, where fast, spot-resolved beam current and range verification are essential — but not yet standard practice.

CONCLUSIONS

FC and MLFC **reliably characterize** proton PBS beam current and range under both conventional and UHDR FLASH delivery. The FC delivers **high-resolution (4 kHz)** beam current monitoring with **excellent linearity ($R^2 > 0.999$)**; the MLFC delivers **stable, non-saturating, reproducible** range and charge measurements, consistent across dose rates.

This work is among the **first demonstrations** of simultaneous spot-resolved beam current and range verification under UHDR proton FLASH conditions — establishing FC and MLFC as **strong candidates for future FLASH commissioning and QA.**

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Jacob Sunnerberg, PhD
Chief Medical Physics Resident
Department of Radiation Oncology
Hospital of the University of Pennsylvania
Jacob.Sunnerberg@PennMedicine.UPenn.edu