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Online verification study for a VHEE-FLASH Beam

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INTRODUCTION

Very-High Energy Electrons (VHEE) in FLASH radiotherapy deliver doses within milliseconds, making real-time dose verification challenging.

This study explores the use of secondary particles generated during irradiation for **online dose verification**. Similar to PET imaging in hadron therapy, these secondary particles can help confirm treatment accuracy and reconstruct dose distributions. Previous research has shown that significant positron emission occurs in a PMMA phantom, enabling post-treatment PET verification [1].

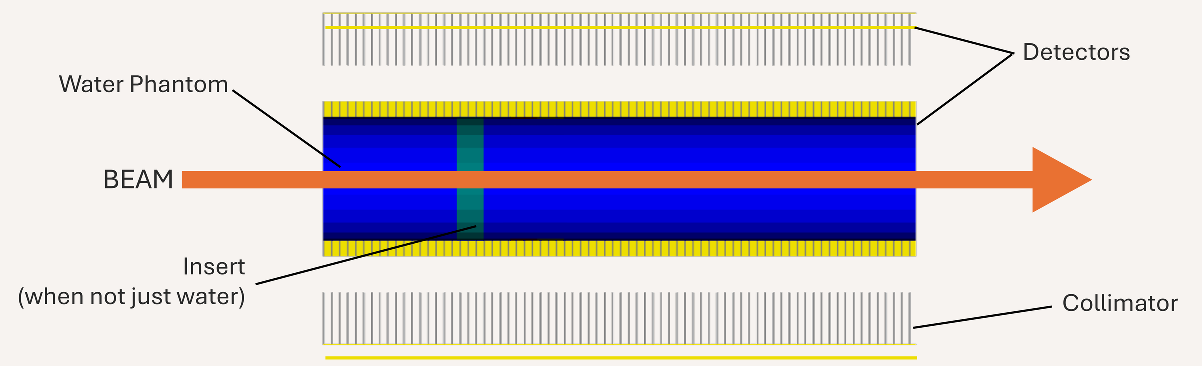
We investigate the characteristics of **prompt gamma rays (PG)** and **annihilation-process gamma rays (GAP)** produced by VHEEs, as well as the dose delivered in a water phantom.

MATERIALS & METHODS

We used **Monte Carlo simulations** with OPENTOPAS v4.0.0 (based on Geant4 v11.1.3) [2,3] to simulate a VHEE beam in a water phantom with a single pencil beam. We scored dose deposition and fluence in the phantom and at various distances in air and compared the results with simulations of an equivalent proton beam. The study comprised three steps:

- **STEP 1** **Particle Survey:** Neutrons, GAP, and PG yields were measured with four planar detectors positioned 5 cm from the phantom's surface.
- **STEP 2** **Detection Survey:** Collimators were added to enhance accuracy, and the detection surfaces were moved 10 cm from the cylindrical phantom.
- **STEP 3** **Phantom Heterogeneities Survey:** Bone and lung inserts, each 2 cm thick, were included in the water phantom.

GEOMETRY OF THE TOPAS SIMULATION

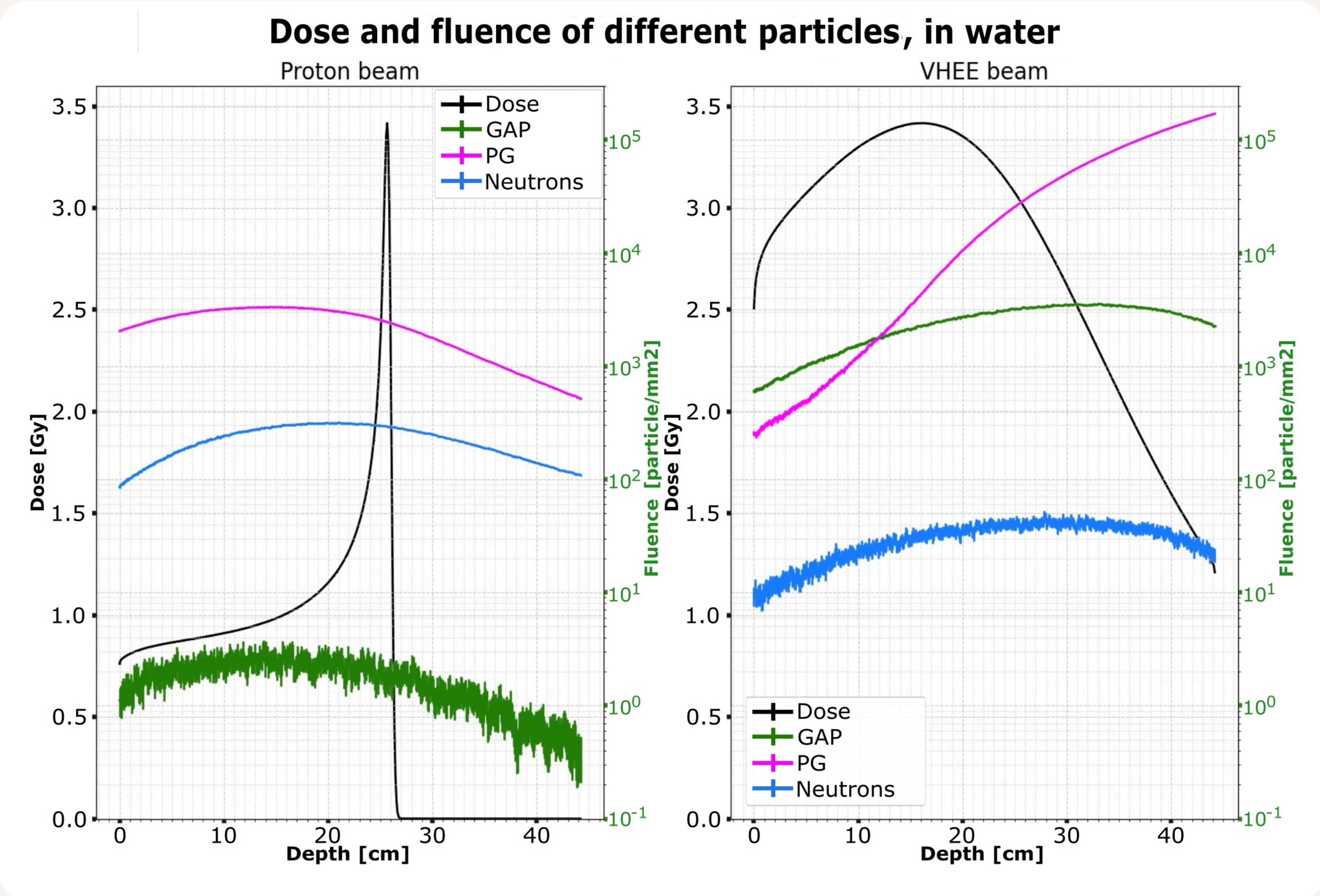


CONCLUSION

- This work highlights the use of **online verification** to monitor Very High Energy Electron (VHEE) beams **through secondary particle emissions.**
- The **VHEE beam produces higher PG and GAP** outputs with fewer neutrons than a proton beam. **Prompt gammas** are promising for online verification, providing the **lowest uncertainty.**
- **Lateral gamma-fluence profiles align** with the dose distribution of a pencil beam, unlike longitudinal profiles.
- **Heterogeneities induce visible profile deformations**, suggesting the feasibility of photon-based online verification for VHEE-FLASH.
- A more detailed feasibility study is needed, along with more realistic Monte Carlo simulations and conditions.

RESULTS

STEP 1 Particle yield along depth - proton vs VHEE

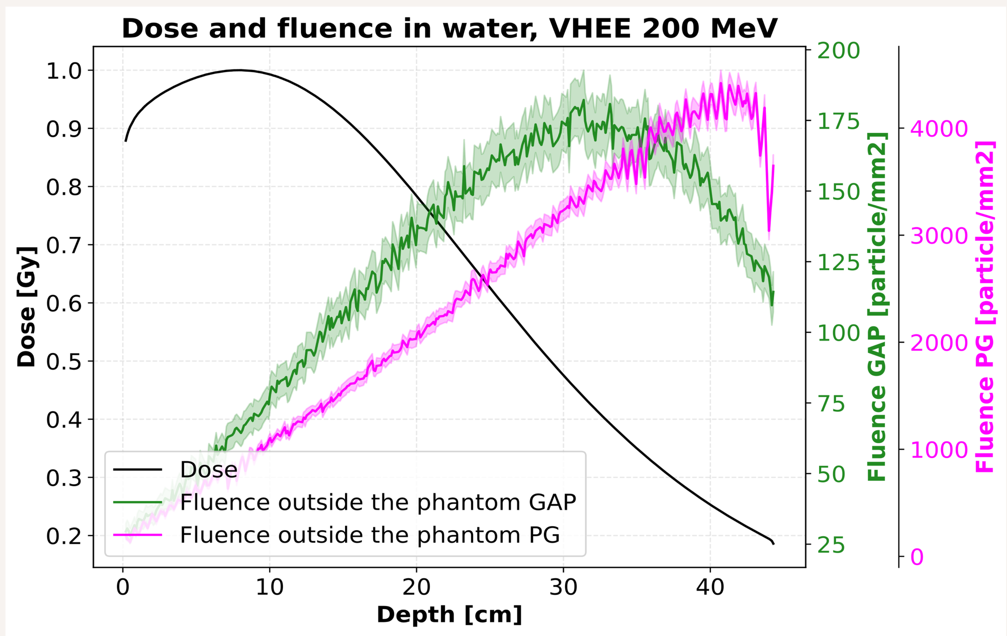


MEAN YIELD ALONG THE PHANTOM - PARTICLES/MM2

Particle	Proton	VHEE
Neutrons	222	30
GAP	1.7	2425
PG	2231	40700

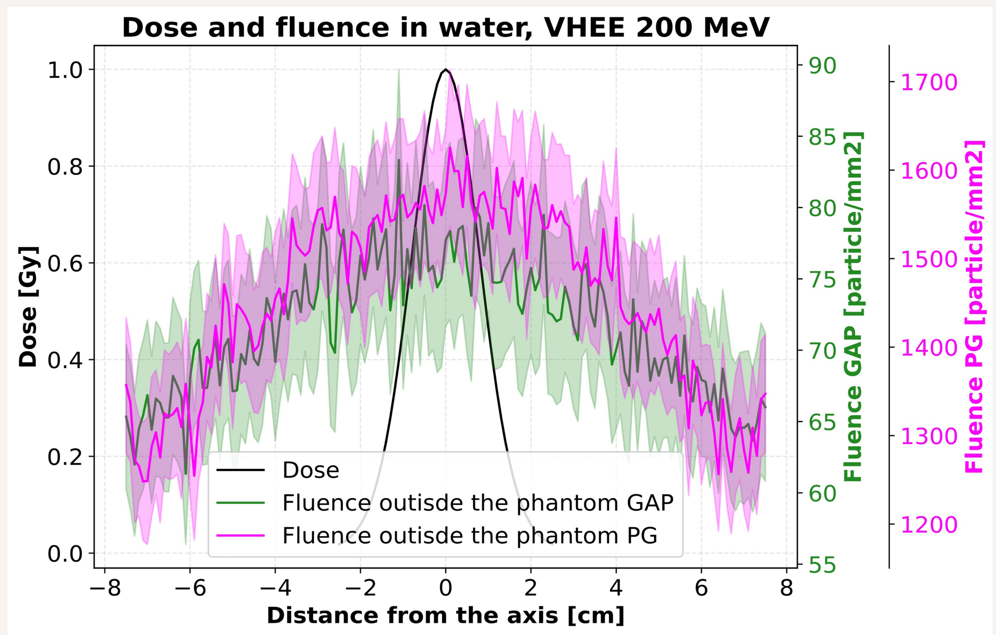
The results are normalized to the same maximum delivered dose for comparability. **VHEE produces fewer neutrons but significantly more GAP and PG than protons.** The GAP and PG have then been studied in more detail for monitoring purposes.

STEP 2 Depth profiles



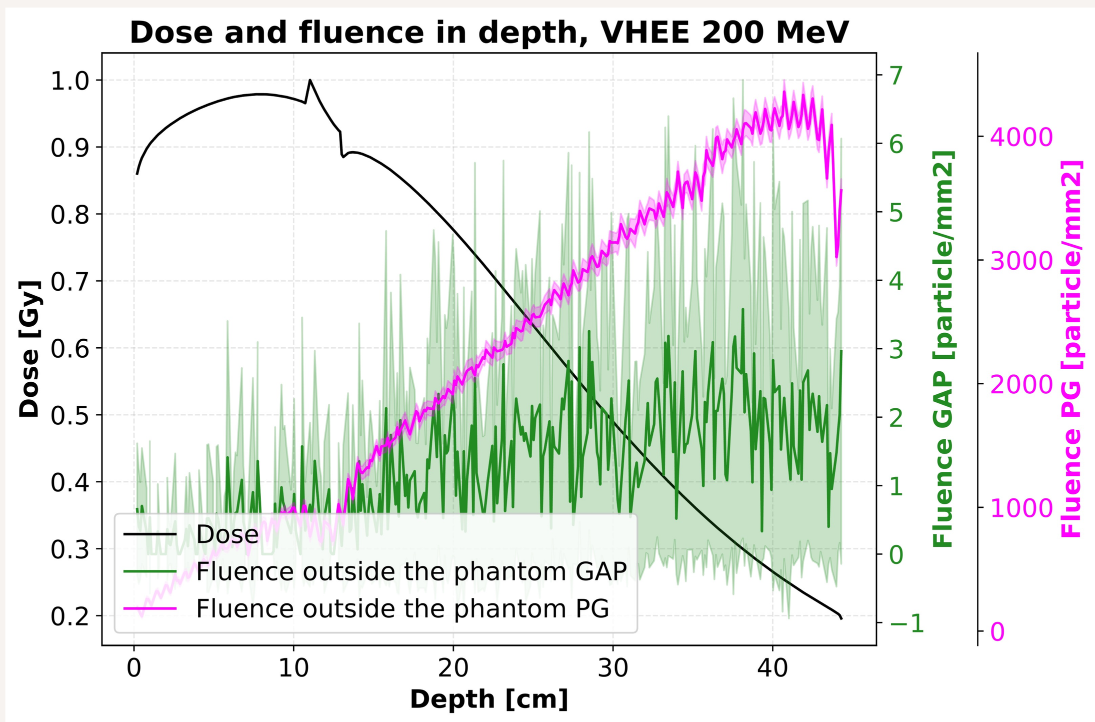
As expected, more PG than GAP are detected, and so for the same dose, the uncertainty on PG is smaller. The result is shown **along the beam axis**. **Fluence is anti-correlated with dose**, complicating direct control of depth-dose or beam parameters.

STEP 2 Lateral profiles



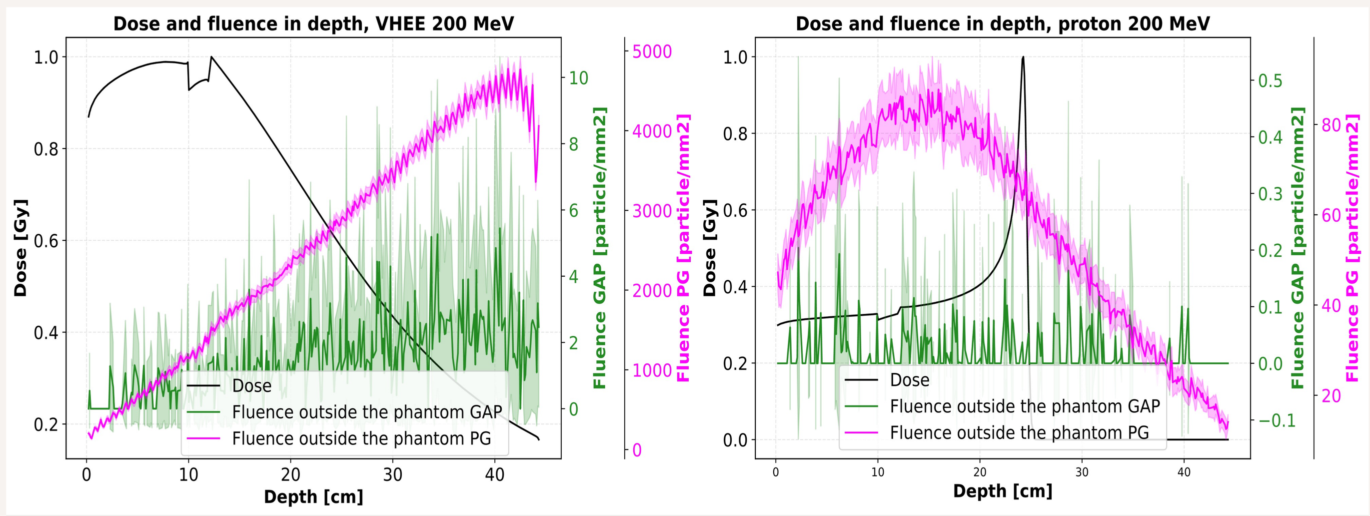
The beam dose or secondary particle fluence profiles are shown at a depth of 15 cm from the phantom entrance. **Along the lateral axis, PG and GAP fluences follow the dose profile**; PG yield dominates, reducing uncertainty.

STEP 3 Lung heterogeneity



A lung heterogeneity produces a **clear, localized change** in the PG fluence profile.

STEP 3 Bone heterogeneity



Bone heterogeneity results in **slight variations** in the fluence profile. The result from the VHEE beam is more visible than that from protons.

REFERENCES
[1] Urso Francesco et al., Nuclear Instruments and Methods in Physics Research, 2026.
[2] Faddegon Bruce et al., Physica Medica, 2020.
[3] Perl J et al., Medical Physics, 2012.

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