Prototype Detector System for AI-assisted Online Dose Monitoring in VHEE Radiation Therapy

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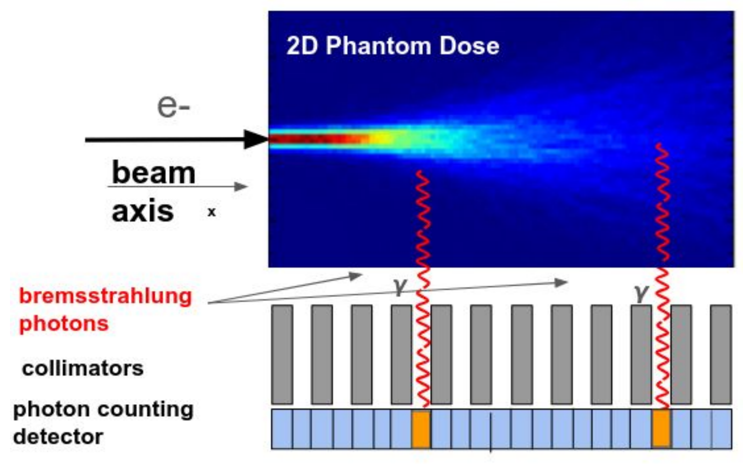
Introduction

- **FLASH RT** delivers ultra-high dose rates (>40 Gy/s within <200 ms) to reduce normal tissue toxicity while preserving tumor control .
- **VHEE beams (50–250 MeV)** offer deep penetration, favorable dose distributions, and reduced sensitivity to tissue heterogeneities, making them well-suited for deep-seated tumors and improved organ-at-risk sparing .

Methods

- **Concept:** Using secondary particles from VHEE irradiation—specifically bremsstrahlung photons generated by electromagnetic showers.
- **Design:** A collimator selects photons emitted at 90° to the beam axis, enabling spatial sampling of the bremsstrahlung radiation; the detected bremsstrahlung profile is correlated with the absorbed dose (see Figure 1).
- **Simulation:** Monte Carlo simulations in a PMMA phantom guided the system design.
- **Radionuclide Signatures**: Production of 11C and 15O due to photonuclear interactions. These **β+ emitters** could be used for offline dose verification.
- **Experimental Testing:** Validation performed at the Beam Test Facility (BTF) of Laboratori Nazionali di Frascati (Figures 2 and 3), INFN, confirmed bremsstrahlung detection. Experiments conducted at the CNR-INO facility in Pisa (Figures 7, 8 and 9) confirmed the radionuclide production.
- **Deep Learning:** A dedicated pipeline was developed to reconstruct the dose distribution from the bremsstrahlung radiation profile, The model used was a Continuous Normalizing Flow trained in a Flow-Matching regime (see Figures 4b and 5b).



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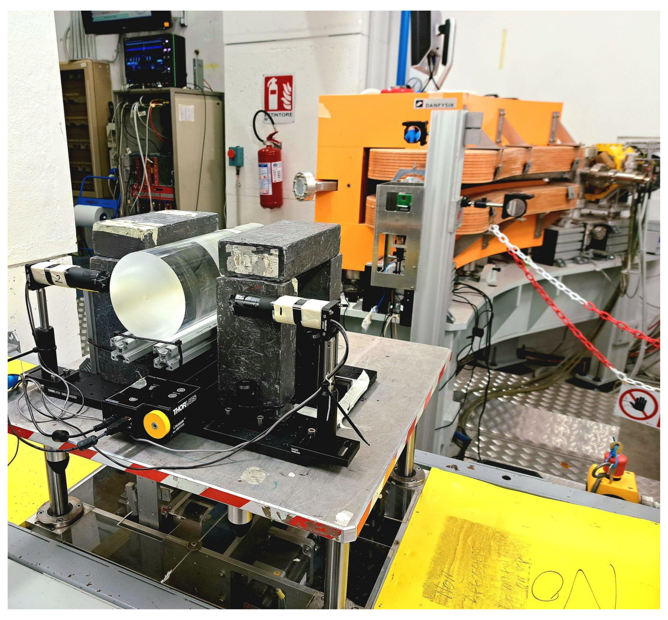
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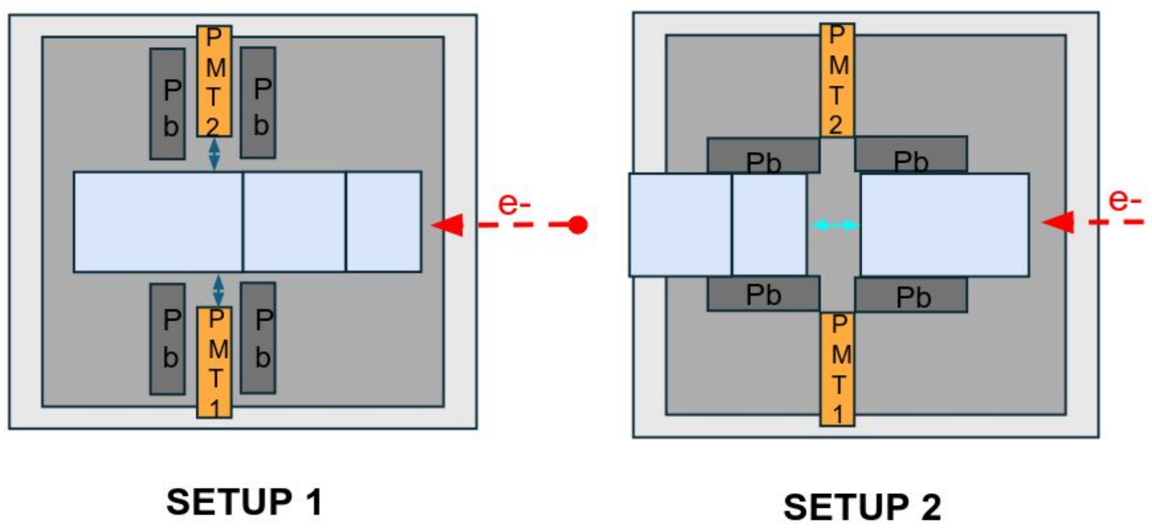

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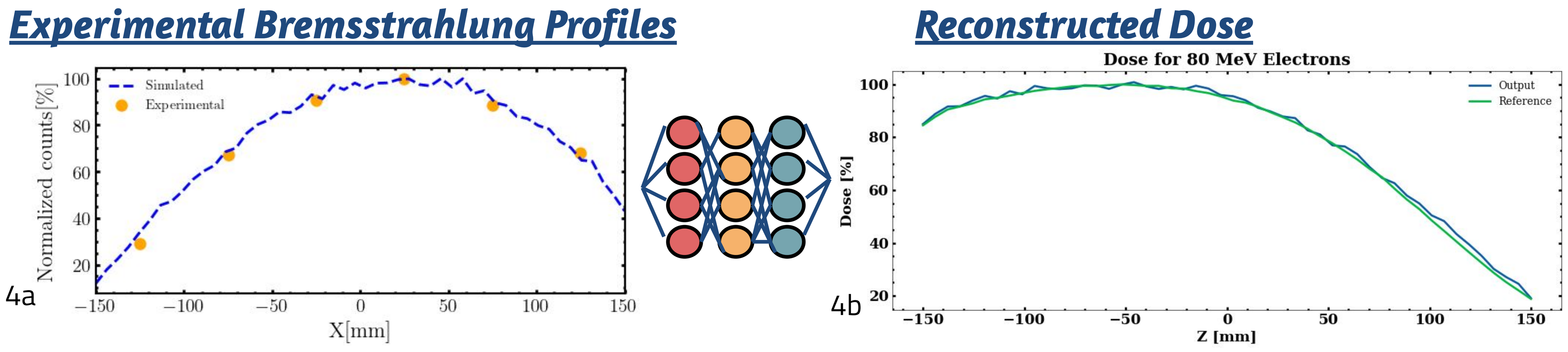
Experimental Bremsstrahlung Profiles

Reconstructed Dose



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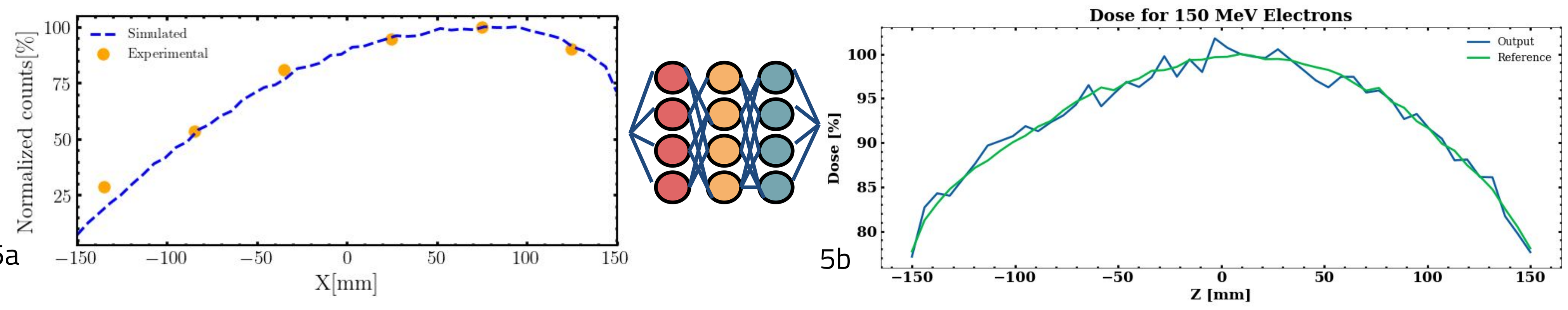

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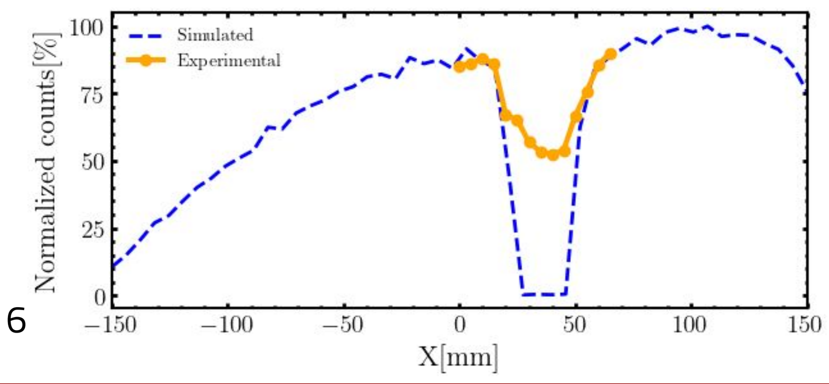

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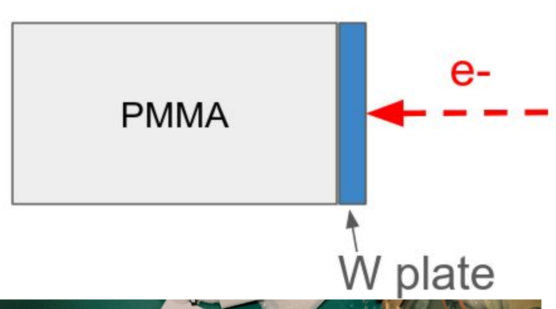
From top to bottom:

- Bremsstrahlung radiation profile acquired of the **150 MeV** scan and deep learning **reconstructed dose**
- Bremsstrahlung radiation profile acquired of the **80 MeV** scan and deep learning **reconstructed dose**
- Bremsstrahlung radiation profile acquired during the **gap scan**



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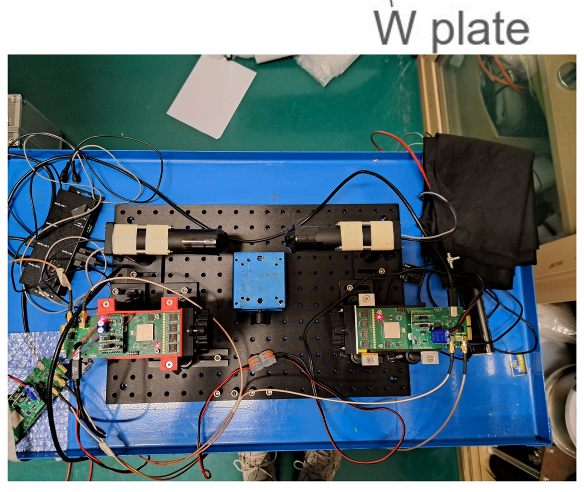
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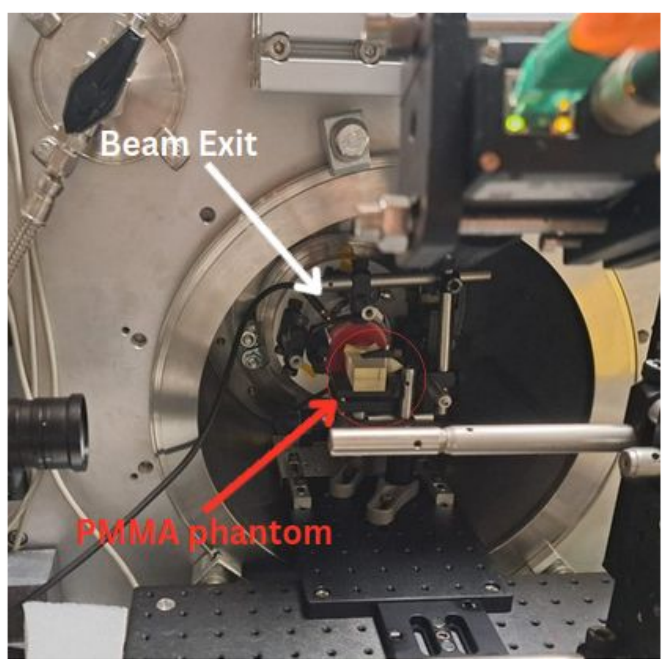

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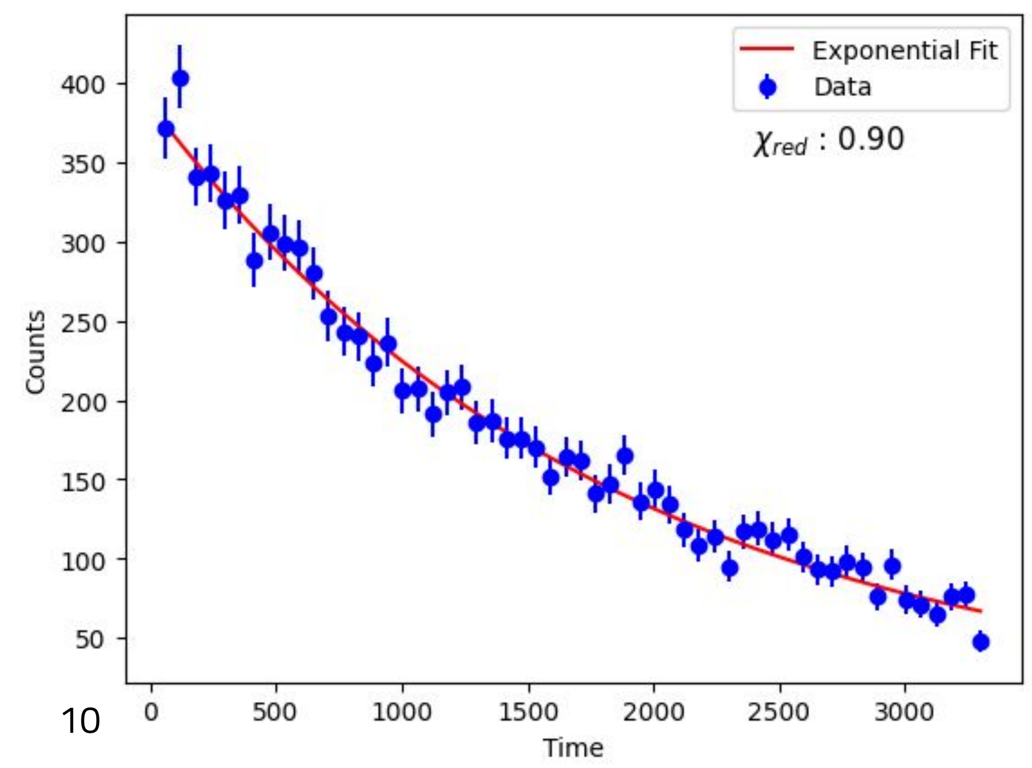
- Production of **11 C** and **15 O** due to photonuclear interactions.
- **β+ emitters**
- On the right, **fit of the observed decay**



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Results

Bremsstrahlung Radiation Profile Measurements:

- Detectors acquired radiation profiles at specific phantom positions for both 150 MeV and 80 MeV scans.
- Experimental data (orange dots) were compared to simulated profiles (blue dashed lines) in Figures 4a and 5a .
- A finer spatial scan captured additional profile details, with a clearly visible gap shown in Figure 6.

Dose Reconstruction via Deep Learning:

- A deep learning model was trained to reconstruct the dose distribution from the experimental bremsstrahlung data.
- Reconstructed dose distributions (blue) for both 150 MeV and 80 MeV scans closely follow the simulated ground truth (green), as depicted in Figures 4b and 5b.

Radionuclide Singnatures:

- The experiments confirmed the production of an element with half-life of (**20.9±0.2**), compatible with **C11**, as shown in Figure 10.

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