



AAPM 2025
JULY 27-30 | WASHINGTON, DC
67TH ANNUAL MEETING & EXHIBITION
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Treatment Planning System for UHDR Mobetron: Refinement and Validation of Phase Space Data Input

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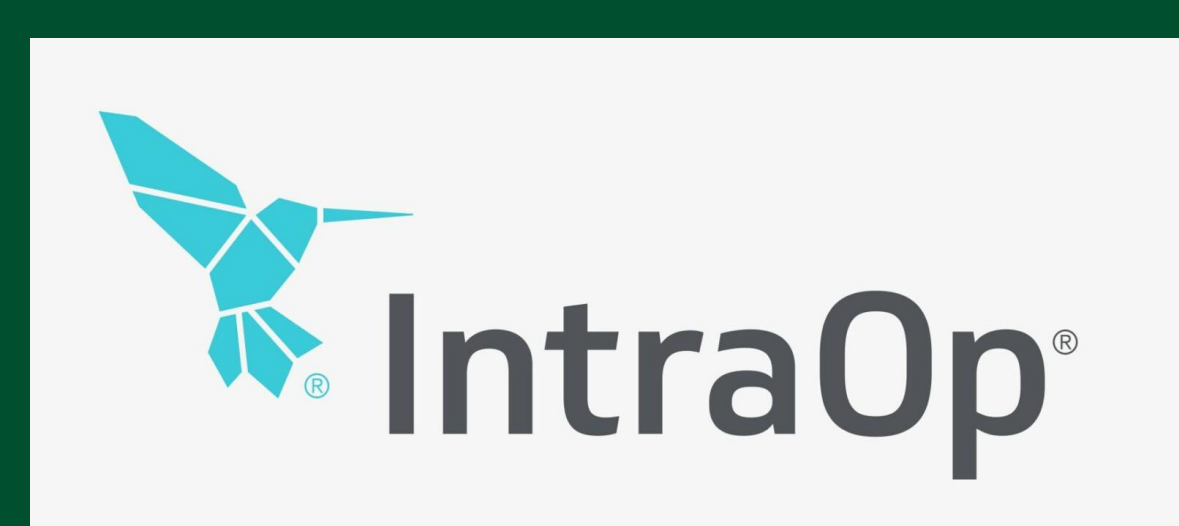


ABSTRACT

This study presents a comprehensive Monte Carlo simulation and phase space (PHSP) analysis for FLASH electron beam dose distribution modeling using GAMOS Monte Carlo methods to evaluate beam characteristics for ultra-high dose rate (UHDR) applications. **Phase space files enable significant computational efficiency improvements by allowing beam characterization simulations to be separated from dose calculation simulations, reducing overall computation time for treatment planning applications.** A geometric model of the IntraOp Mobetron was developed based on technical specifications. **A critical backscatter contamination issue was identified when using PHSP data recorded at the applicator exit with short source-to-surface distance (SSD = 2 cm).** The PHSP recording plane was systematically evaluated at two positions: applicator exit and LINAC exit. **Phase space analysis revealed significant backscatter contamination at the applicator exit, evidenced by distorted PDD curves, broadened beam profiles, and altered energy/angular distributions. Moving the PHSP plane to the LINAC exit eliminated backscatter contamination, resulting in accurate beam modeling with proper depth-dose characteristics and beam quality metrics. Energy spectrum analysis showed clean forward-directed electron beam characteristics at the LINAC exit compared to contaminated spectra at the applicator exit.** This work demonstrates that PHSP plane positioning is critical for accurate FLASH electron beam modeling, with LINAC exit positioning providing superior beam characterization suitable for UHDR therapy treatment planning validation.

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METHODS AND MATERIALS

PHSP Recording Positions: Two phase space recording planes were systematically compared:

Applicator Exit

LINAC Exit: At LINAC head exit before applicator (upstream position)

Short SSD Configuration: 2 cm source-to-surface distance used for clinical beam characterization

Backscatter Analysis: Comprehensive evaluation of energy spectrum, angular distribution, and z-direction momentum components to identify contamination sources

Beam Quality Metrics: PDD analysis including R50, D90, D20 calculations and profile analysis (FWHM, penumbra, flatness) for treatment planning validation

Geometric Model Validation

Beam Characterization: Phase space files analyzed for energy spectrum, angular distribution, spatial characteristics, and gamma contamination assessment

Statistical Analysis: Quantitative assessment of energy homogeneity, directional quality, beam FWHM, scattering angles, and contamination metrics for treatment planning validation

Backscatter Detection: Z-direction momentum analysis and energy spectrum evaluation to quantify backscatter contamination levels



Figure 1: Standard IntraOp Mobetron

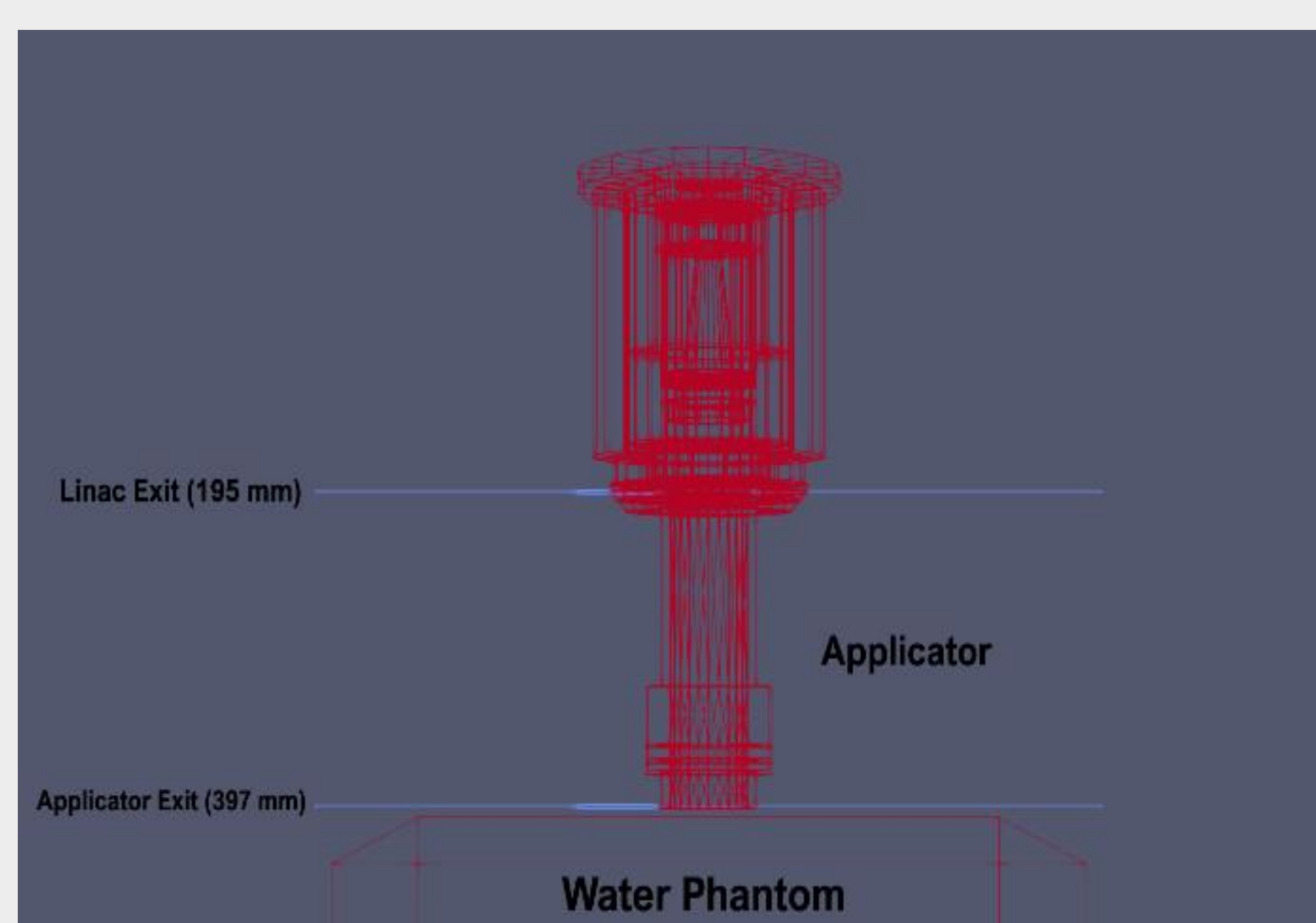


Figure 2: Labeled visualization of GAMOS simulation

RESULTS

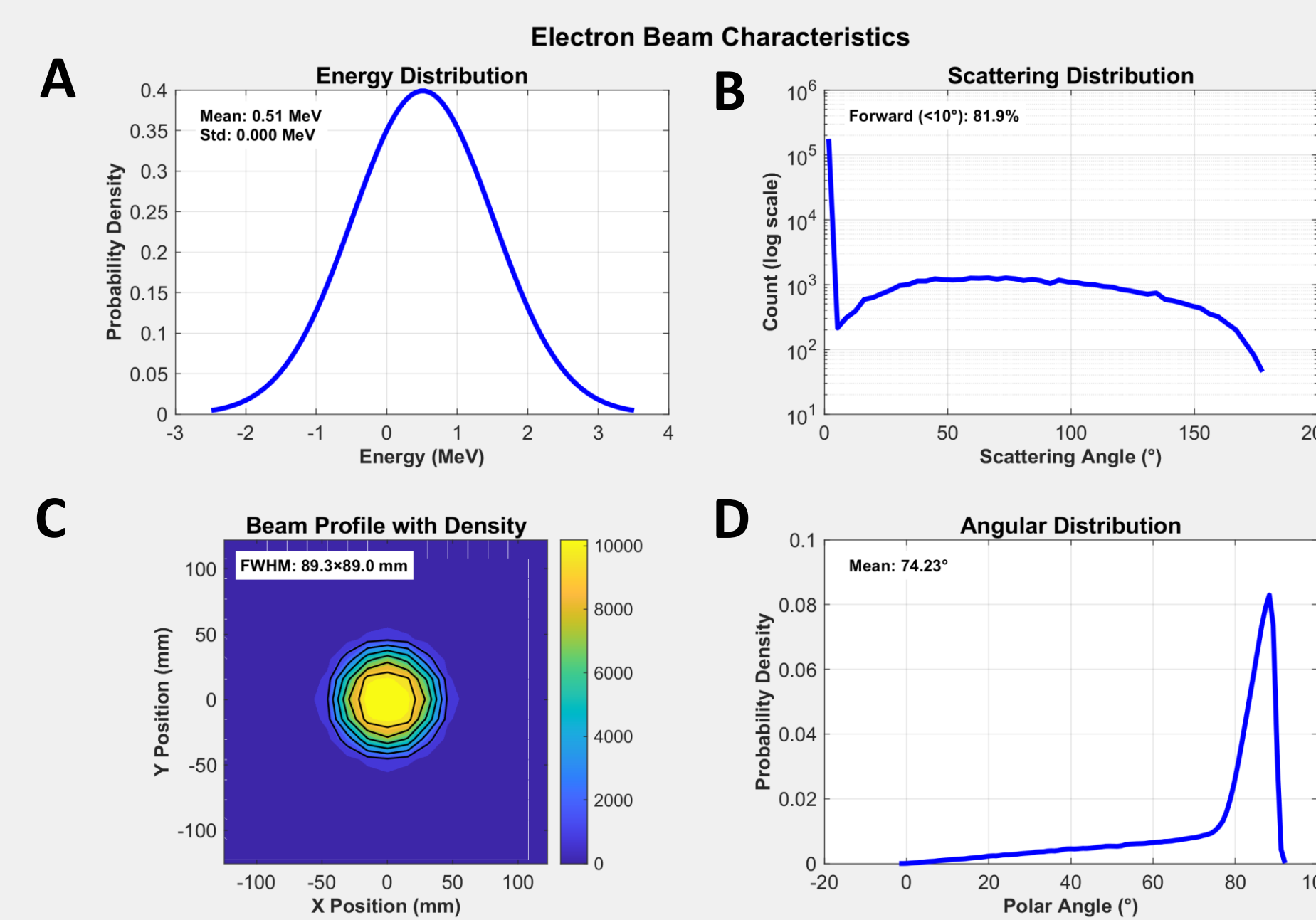


Figure 3: Electron multiple parameter analysis of A) the average deviation from the nominal energy, B) scattering distribution, C) beam XY profile, and D) the angular distribution.

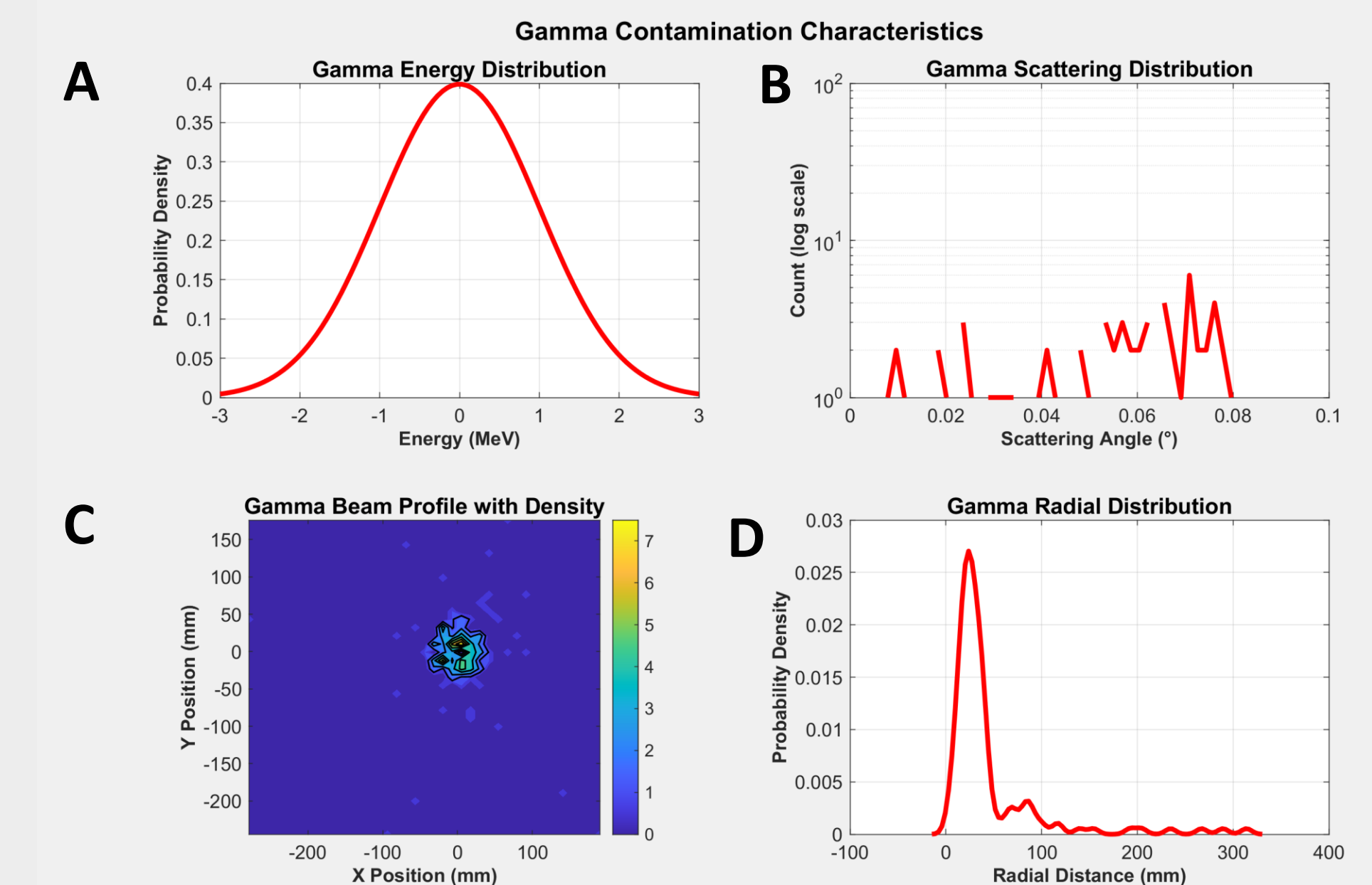


Figure 4: Gamma multiple parameter analysis of A) the deviation from nominal energy, B) scattering distribution, C) beam profile, and D) radial distribution.

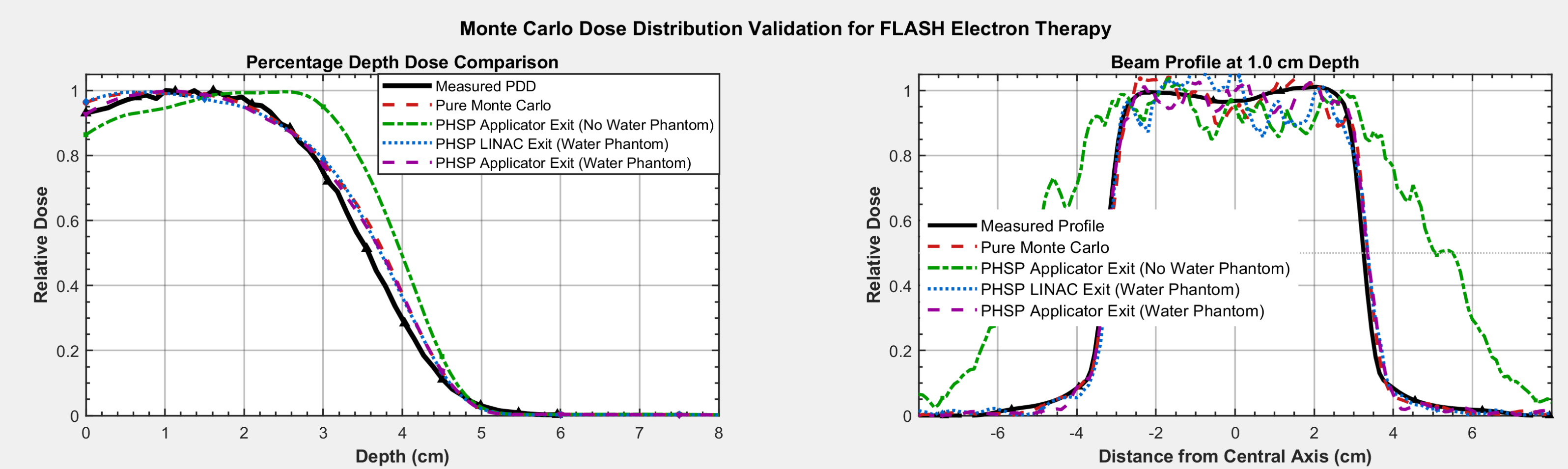


Figure 5: PDD and Profile curves showing different configurations against experimental data.

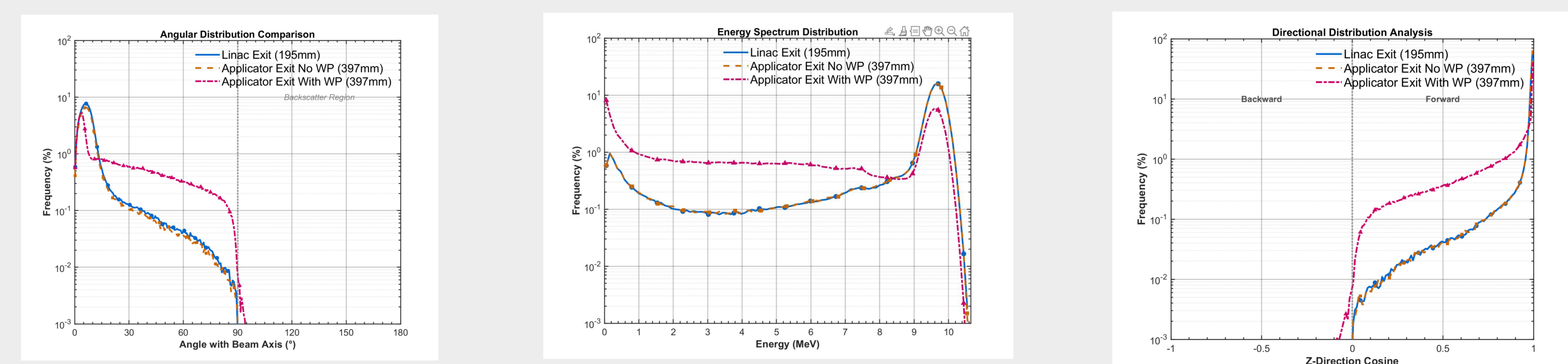


Figure 6 A-C: A) Angular Distribution, B) Energy Spectrum, and C) Z-direction cosine comparison plots (log scale)

PDD and Profile Comparison PHSP Plane at LINAC Exit Window

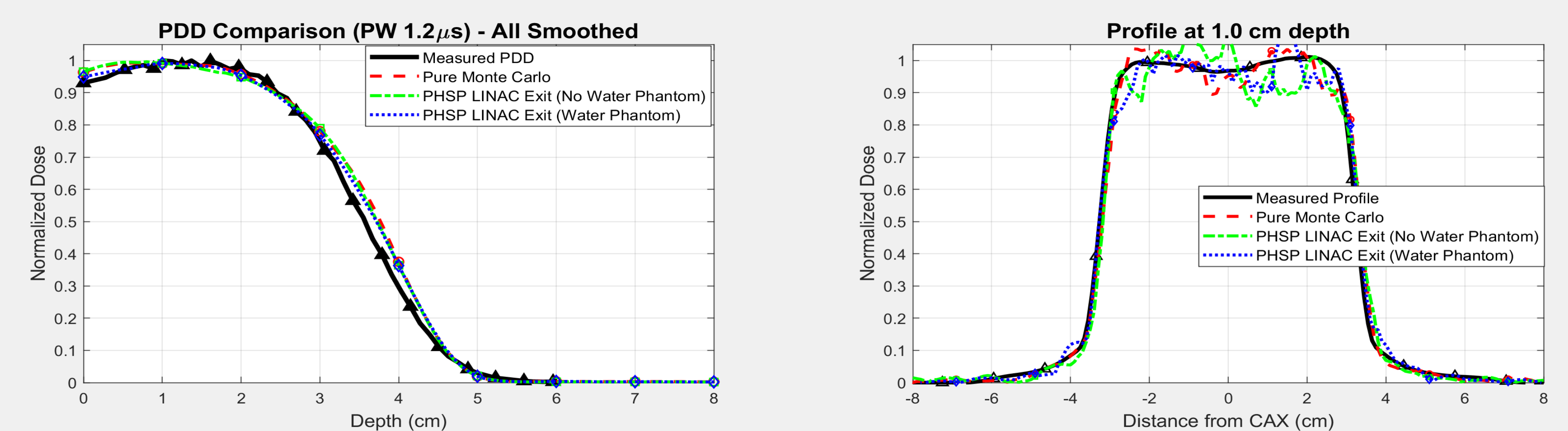


Figure 7: PDD and Profile Comparison with the PHSP plane at the Linac Exit.

CONCLUSIONS

This study demonstrates that **PHSP plane positioning is critical for accurate FLASH electron beam modeling. Significant backscatter contamination was identified when recording PHSP data at the applicator exit with short SSD (2 cm), resulting in distorted dose distributions with broadened beam profiles (53% FWHM increase) and altered energy spectra unsuitable for treatment planning.** Moving the PHSP recording plane from applicator exit to LINAC exit eliminates backscatter contamination, producing accurate PDD curves matching experimental data (R50 agreement within 3.5%), proper beam profiles, and clean forward-directed energy spectra. **Energy spectrum, angular distribution, and z-direction momentum analysis confirm that LINAC exit PHSP positioning provides essential clean beam data for treatment planning system integration.** These results establish that backscatter contamination at short SSD significantly compromises beam characterization for UHDR therapy, while the validated Monte Carlo model with proper PHSP positioning provides a robust foundation for FLASH radiotherapy treatment planning and clinical implementation.