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Monte Carlo-Based Shielding and Safety Assessment of a 7 MeV FLASH Electron Beam Facility

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ABSTRACT

This study presents a comprehensive Monte Carlo modeling approach for FLASH electron beam dose distribution analysis using GAMOS simulation methods to evaluate radiation safety considerations for ultra-high dose rate (UHDR) applications. A detailed geometric model of the FLASHLAB 7 MeV electron beam system was developed using innovative dual-geometry approach utilizing GAMOS parallel geometry functionality to overcome computational limitations with overlapping geometries. A standard solid water phantom was modeled and positioned at 5 cm air gap for dose normalization. The simulation employed a dual-geometry approach utilizing GAMOS parallel geometry functionality to separate physics interactions from dose scoring, overcoming computational limitations with overlapping geometry limitations. Comprehensive Monte Carlo modeling demonstrates that GAMOS-based Monte Carlo approach can systematically model FLASH electron beam dose distributions for comprehensive radiation safety evaluation of ultra-high dose rate therapy systems. The systematic dose attenuation patterns, spanning 10 orders of magnitude from central axis to periphery, **provide quantitative data essential for occupational exposure assessment** and regulatory compliance evaluation. The minimal secondary scattering observed beyond the primary beam field **demonstrates the comprehensive modeling capabilities** of the graphite collimation system for high-energy electron containment in clinical environments. **Future validation studies incorporating experimental measurements** will support regulatory approval and clinical translation of ultra-high dose rate electron beam systems

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METHODS AND MATERIALS

- **Geometric Model**: GAMOS Monte Carlo simulation with detailed FLASHLAB linac components including 0.1 mm aluminum beam window, stainless steel collimator (30 mm inner radius), graphite collimation elements, and current transformer structures
- **Dual-Geometry Approach**: Parallel geometry implementation separating physics interactions (mass geometry) from dose scoring (voxelized geometry) to overcome GAMOS overlapping geometry limitations
- **Water Phantom**: 300×300×50 mm³ phantom positioned at 5 cm air gap for dose normalization consistent with clinical workflow conditions
- **Voxelized Scoring**: 2.5×2.5×2.5 mm³ voxels in 600×600×260 array covering 3000×3000×1300 mm³ post-phantom region (Z = 200-1500 mm)
- **Scoring Blueprint**: Strategic front/back box configuration with left/right side boxes to provide comprehensive spatial coverage while avoiding computational conflicts
- **Beam Parameters**: 7.0 MeV electrons with 0.07 MeV energy spread, and 0.7 mm gaussian beam profile.

Figures

FLASHLAB Oriatron linac dimensions

- Electron Flash Linac for Translational Research in Radiobiology
- Average dose rate: > 300 Gy/s (10 cm field diameter)

Designation	Length (mm)	Width (mm)	Height (mm)	Weight (kg)
Radiation Head	1245	720	1210	485
Cooling Unit	1100	780	1700	250
Power Supply & Electronics Cabinet	900	600	1800	250
User Interface: PC & Safety Control Box	Desktop PC & Console			

Figure 1: FLASHLAB linac dimensions table reflecting typical dose rates and list physical dimensions.

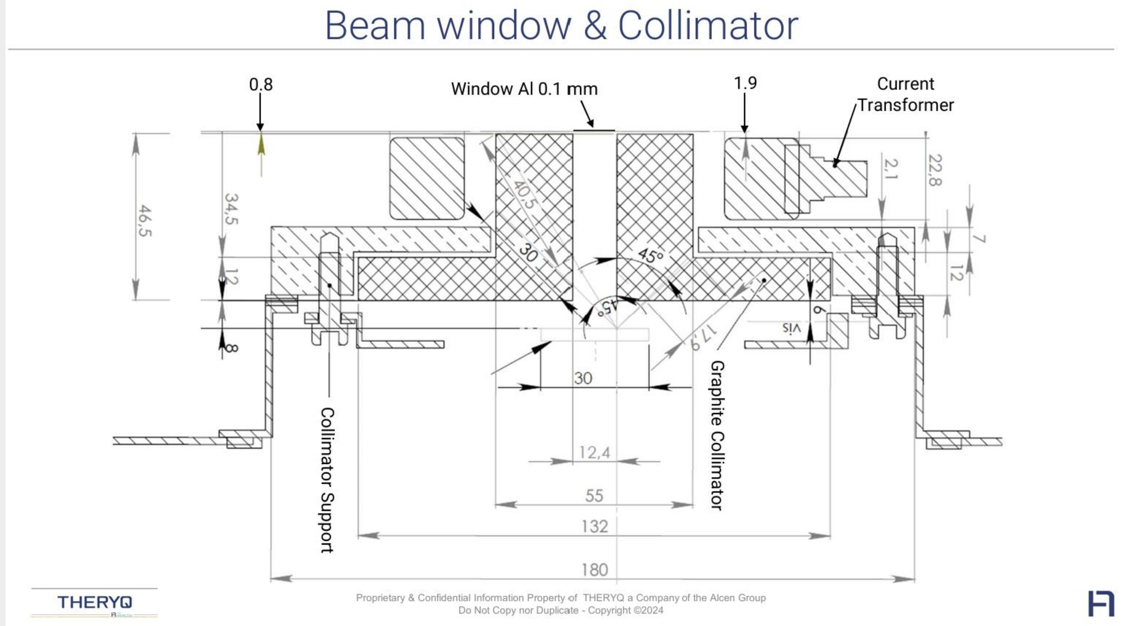

Figure 2: Official FLASHLAB collimator drawing, showing material layers and angles used in the GAMOS geometry.

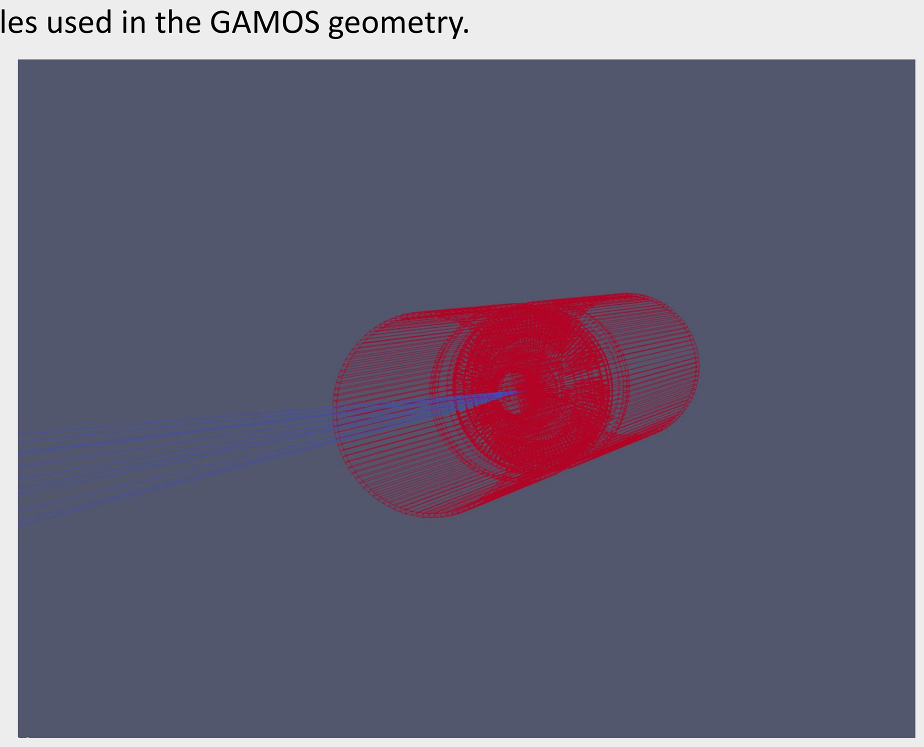

Figure 3: GAMOS geometric visualization of the FLASHLAB electron beam system showing the detailed linac components (aluminum beam window, stainless steel collimator assembly, graphite collimation elements)

RESULTS

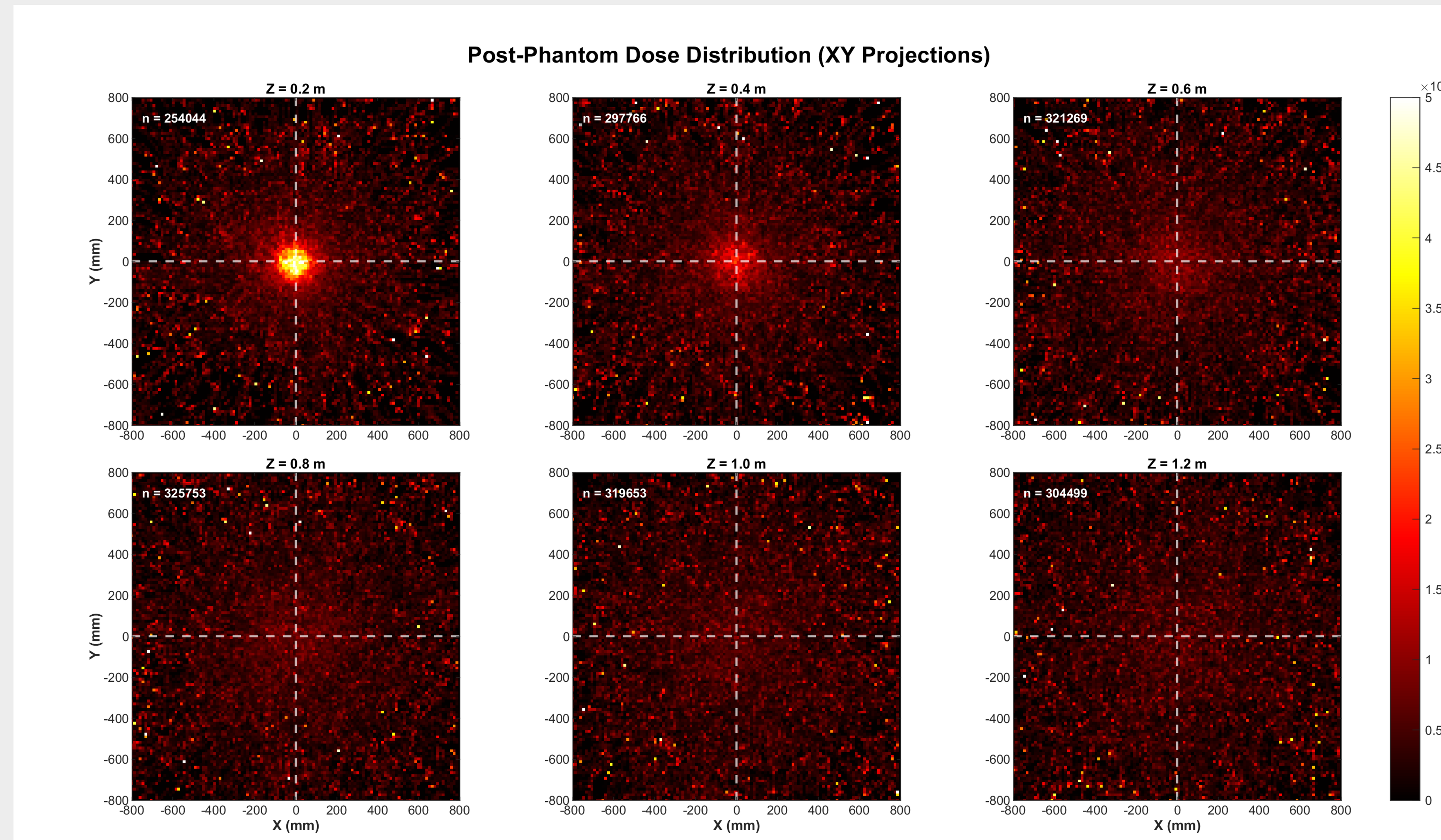

Figure 4: Post-phantom dose distribution normalized to phantom dmax, showing scatter radiation levels of 0.001% of treatment dose. Systematic dose attenuation with distance demonstrates effective phantom absorption and minimal radiation exposure beyond the primary treatment field, confirming excellent beam containment after phantom interaction.

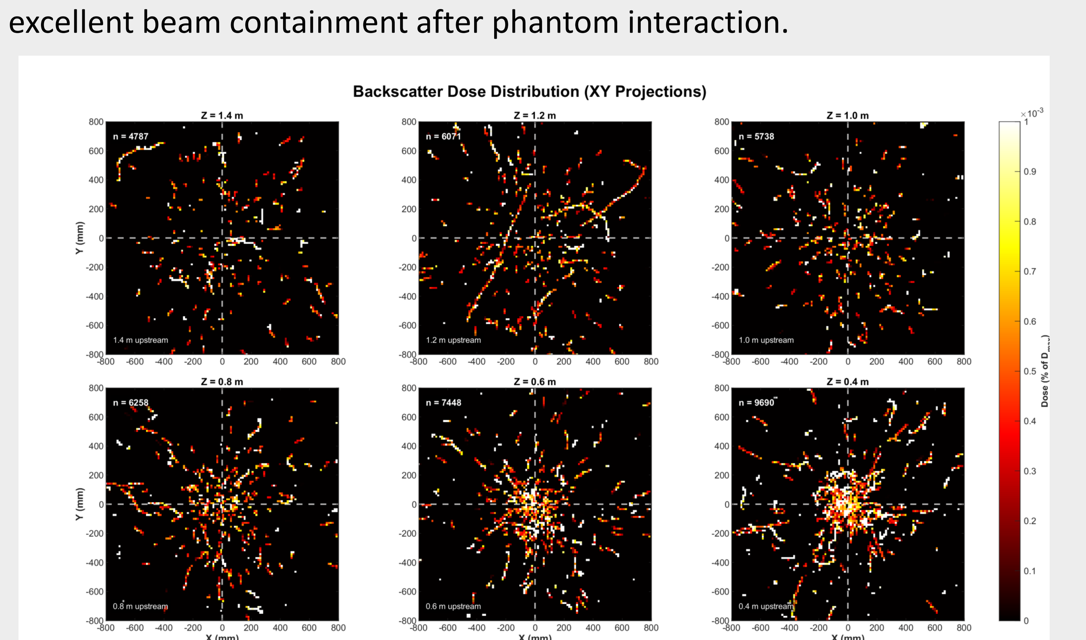

Figure 5: Backscatter dose distribution heat maps at seven Z-planes (-1400 to -250 mm upstream) demonstrating scattered radiation patterns from linac components and phantom interactions. Higher dose levels (0.001% of dmax) compared to post-phantom region reflect unattenuated scatter from accelerator head components, confirming expected upstream radiation characteristics.

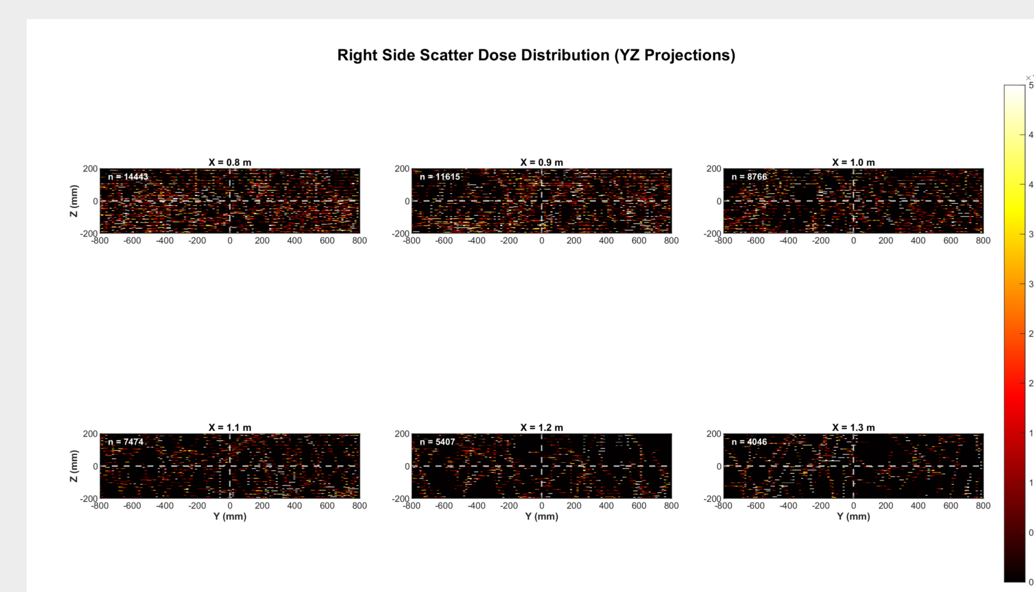

Figure 6: Right side scatter dose distribution heat maps showing lateral radiation patterns in the YZ plane at different X positions (800-1400 mm from linac centerline). Dose levels demonstrate lateral beam containment with minimal side scatter beyond the primary treatment area.

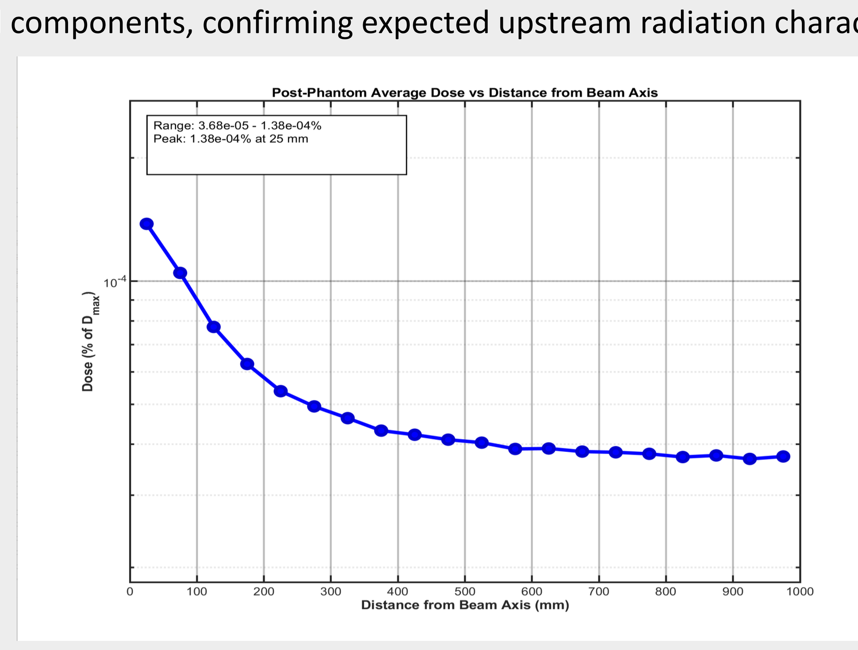

Figure 7: Post-phantom average dose versus radial distance from beam axis showing exponential dose falloff with distance. Quantitative analysis demonstrates phantom attenuation effects, providing essential data for radiation safety zone determination with doses well below 0.001% of dmax at all measured distances.

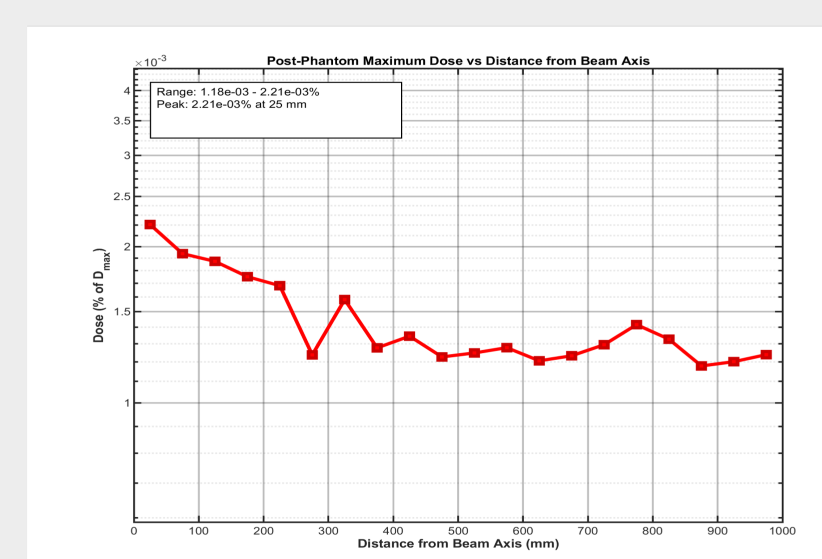

Figure 8: Post-phantom maximum dose versus radial distance from beam axis demonstrating peak exposure levels at varying distances from the beam centerline. Analysis confirms phantom effectiveness in reducing downstream scatter and provides conservative dose estimates for occupational exposure limits and safety zone establishment.

CONCLUSIONS

This study **demonstrates that a GAMOS-based Monte Carlo approach can systematically model** FLASH electron beam dose distributions **providing comprehensive radiation safety evaluation** of ultra-high dose rate therapy systems. The parallel geometry implementation successfully resolved technical limitations while delivering clinically-relevant dose mapping **across extended spatial regions spanning 10 orders of magnitude**. The systematic dose attenuation patterns **provide quantitative data essential for occupational exposure assessment and regulatory compliance evaluation**. The minimal secondary scattering observed beyond the primary beam field **validates the modeling framework's ability to capture** the effectiveness of the graphite collimation system for high-energy electron containment in clinical environments. **This modeling framework establishes the foundation for comparative** Monte Carlo predictions with ionization chamber measurements, ultimately supporting regulatory approval and clinical translation of ultra-high dose rate electron beam systems.