# First Comprehensive Pulse-Width-Specific Phase Space Characterization for FLASH Radiotherapy Treatment Planning: Universal Beam Model Development and Validation for the Mobetron

**Rafael Carballeira**[1], David J. Gladstone[1,2], Kevin J. Willy[1], Philip Von-Voigts Rhetz[4], Rongxiao Zhang[1,3]
Thayer School of Engineering, Dartmouth College, Hanover, NH[1]
Dartmouth Cancer Center, Lebanon, NH[2]
School of Medicine, University of Missouri, Columbia, MO[3]
IntraOP Medical Corporation, Sunnyvale, CA[4]

## Purpose and Methods

**Purpose:** FLASH radiotherapy (>40 Gy/s) demonstrates normal tissue sparing while maintaining tumor control, but pulse width variations systematically alter electron beam energy through waveguide loading effects, creating treatment planning system (TPS) challenges. This work establishes pulse-width-specific phase space characterization across the Mobetron UHDR's clinical range and proposes a universal beam model for implementation.

**Methods:** Using experimentally characterized regression relationships between pulse width and beam penetration, we developed an iterative optimization process for phase space parameter refinement. Starting with a 6cm diameter aperture, we systematically adjusted mean energy and energy spread by minimizing discrepancies between computation and measurements for R50 (fall-off region), surface dose and build-up gradient (build-up region), and integrated dose accuracy. Convergence required R50 and FWHM matching within 0.5mm.

## Monte Carlo Modeling

**Figure 1:** IntraOP Mobetron UHDR

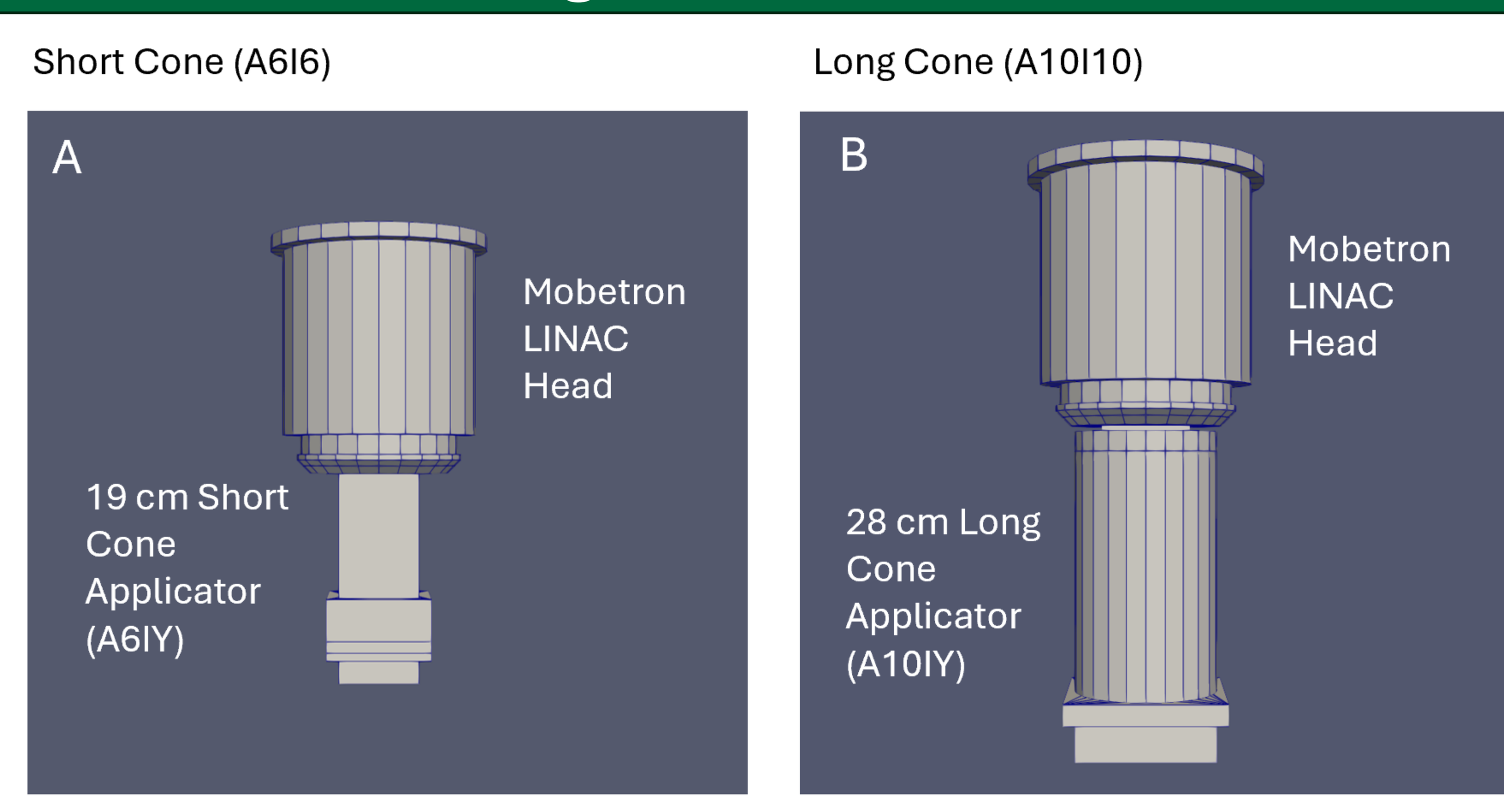



**Figure 2A-B:** Short Cone and Long Cone visualizations

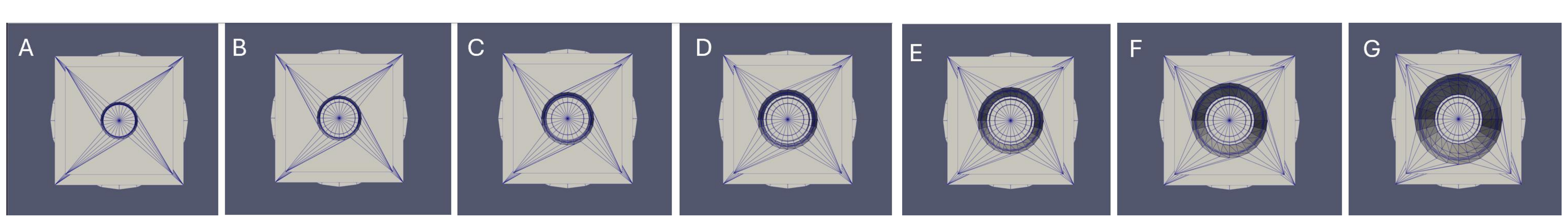



**Figure 3A-G:** A6IY configurations with aperture size, Y, following A) 2.5, B) 3, C) 3.5, D) 4, E) 4.5, F) 5, and G) 6 cm.

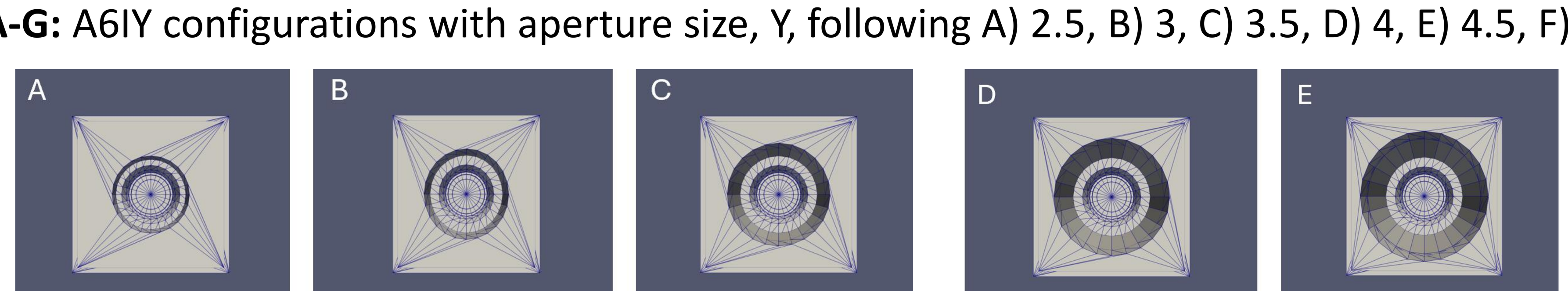
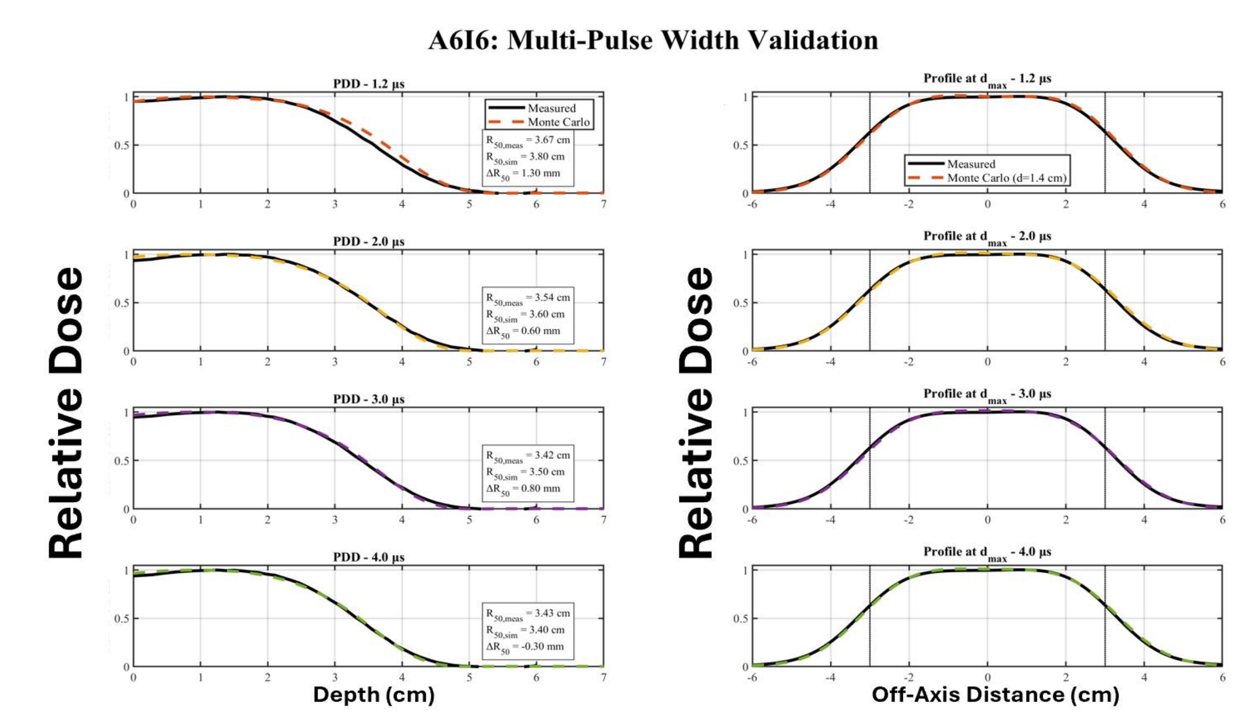
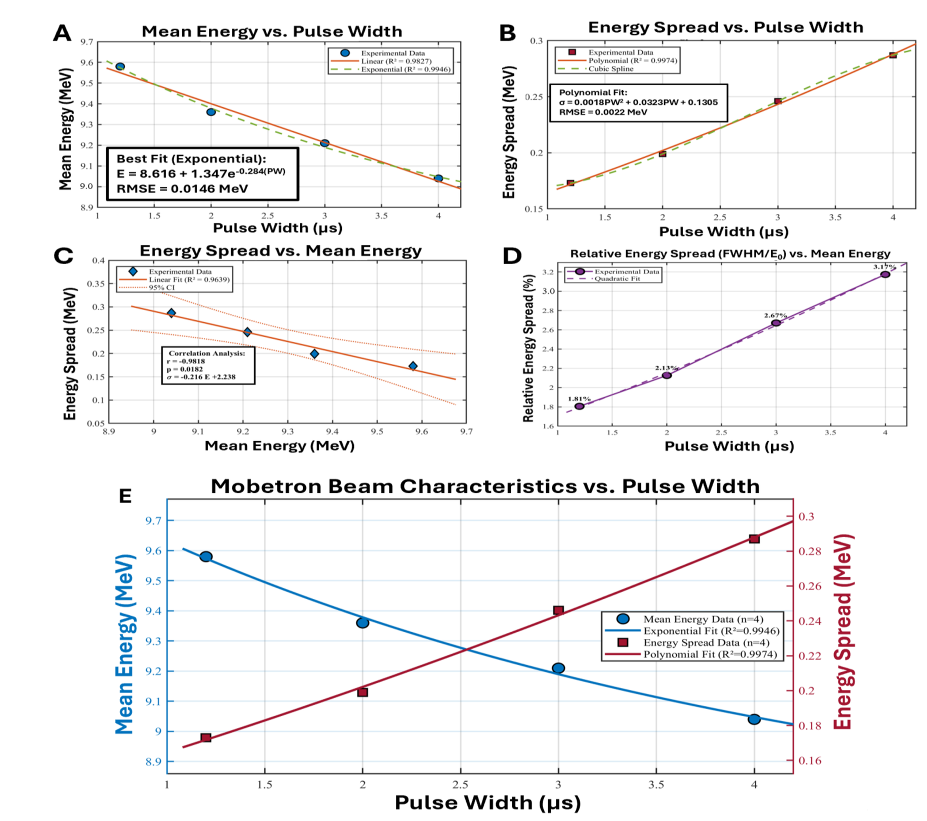
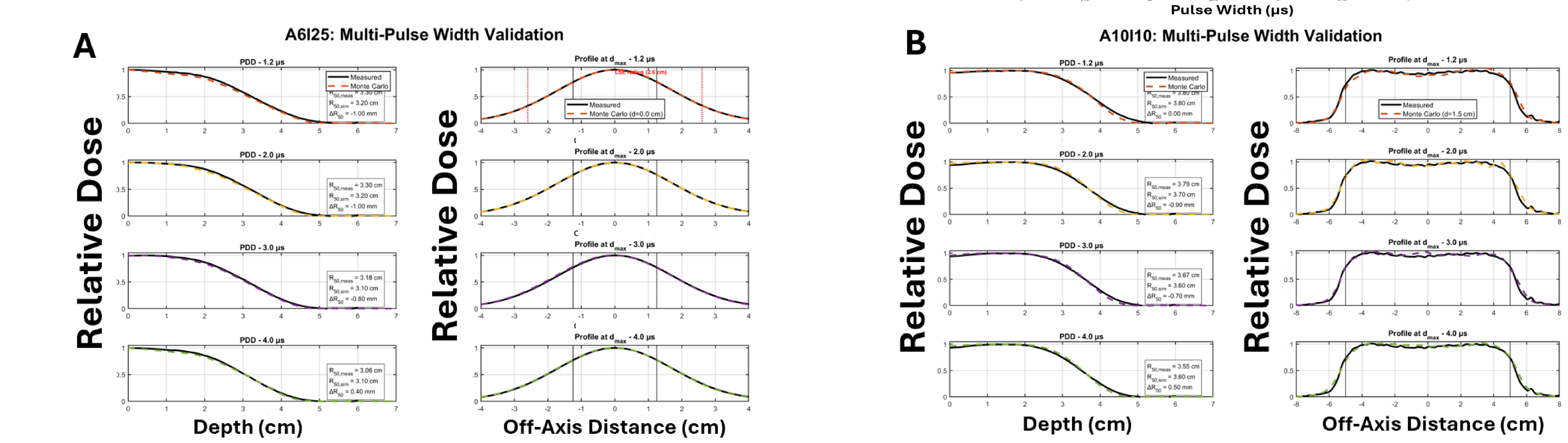


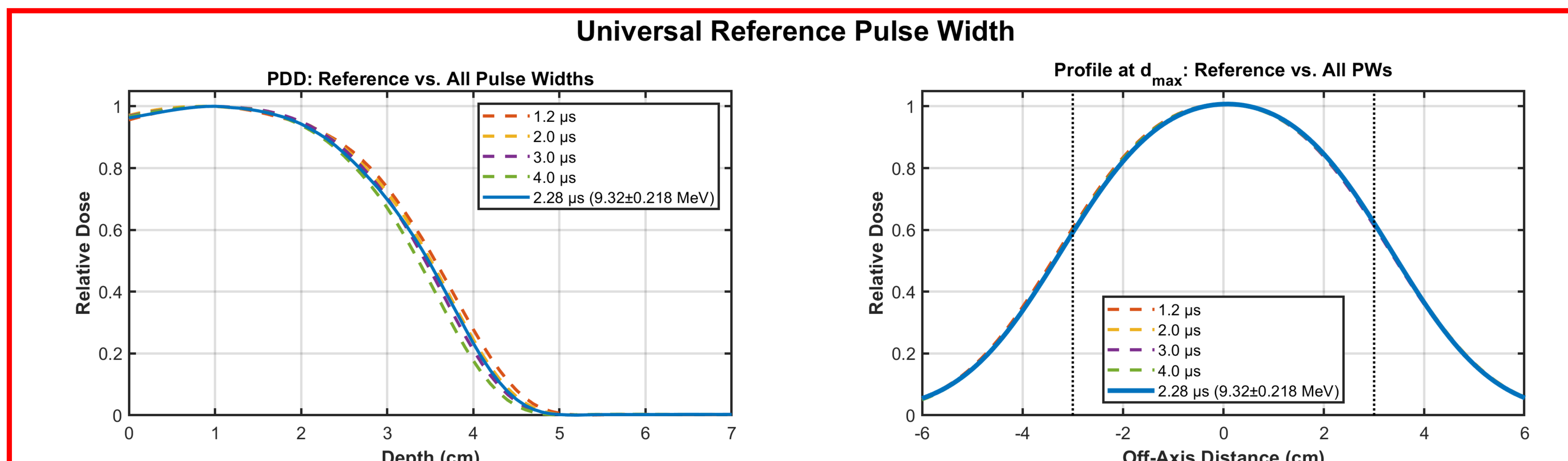

**Figure 4A-E:** A10IY configurations with aperture size, Y, following A) 6, B) 7, C) 8, D) 9, E) 10 cm.

## Results




## Conclusion

Regression analysis revealed exponential decay for mean energy ($R^2$=0.9946) and quadratic growth for energy spread ($R^2$=0.9974) with pulse width. Mean energy decreased from 9.58 MeV (1.2 µs) to 9.04 MeV (4.0 µs), while energy spread increased from 0.173 to 0.287 MeV. Strong negative correlation existed between mean energy and energy spread (r=-0.98, p=0.018), with 1.81-3.17% beam quality degradation. **Based on exponential beam loading physics, the geometric mean was selected as universal reference, corresponding to 9.32 MeV mean energy and 0.214 MeV energy spread. This establishes the first comprehensive pulse-width-specific phase space characterization for FLASH TPS development, with validated regression models enabling parameter prediction at arbitrary pulse widths. This universal beam model provides clinically acceptable accuracy while reducing computational requirements from four pulse-specific calculations to single reference configuration, facilitating practical FLASH TPS implementation.**