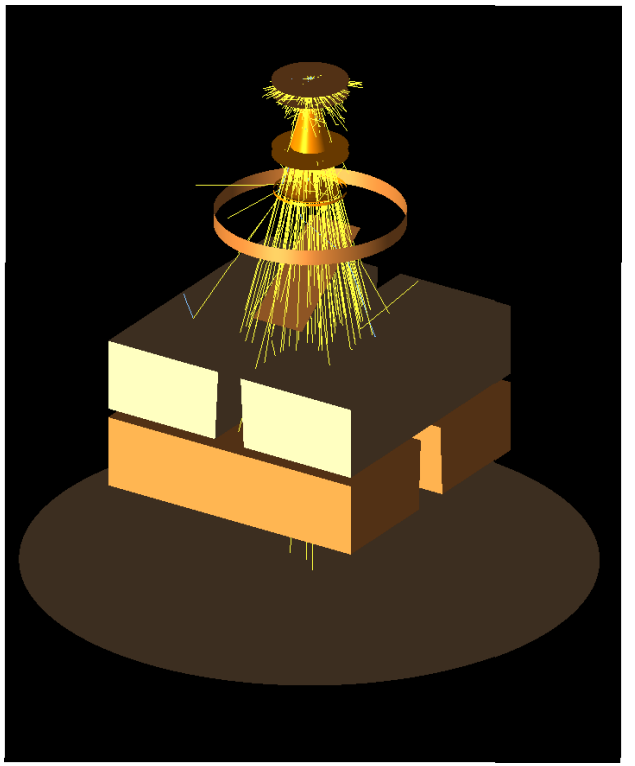
Development of an accurate Monte Carlo model of the standard Clinac 6MV beam

Alexander Egan, MS
Medical Physics Doctoral Candidate
Oregon Medical Physics Program (OSU/OHSU)

Wolfram Laub, PhD
Associate Professor
Department of Radiation Medicine
Oregon Health & Science University



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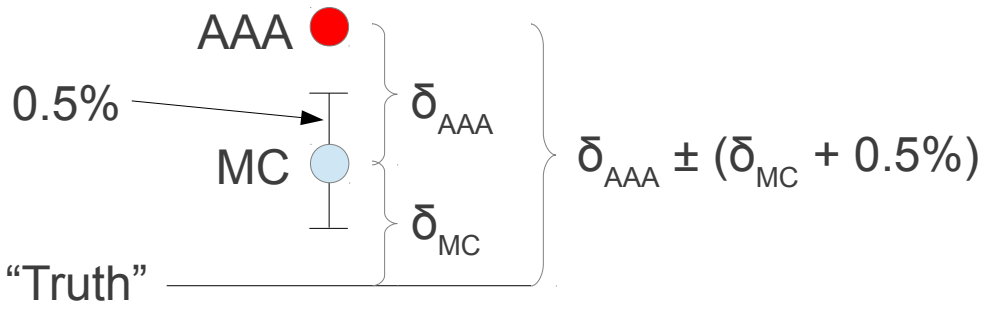
Motivation: Dosimetric evaluation of AAA in highly modulated RapidArc Plans

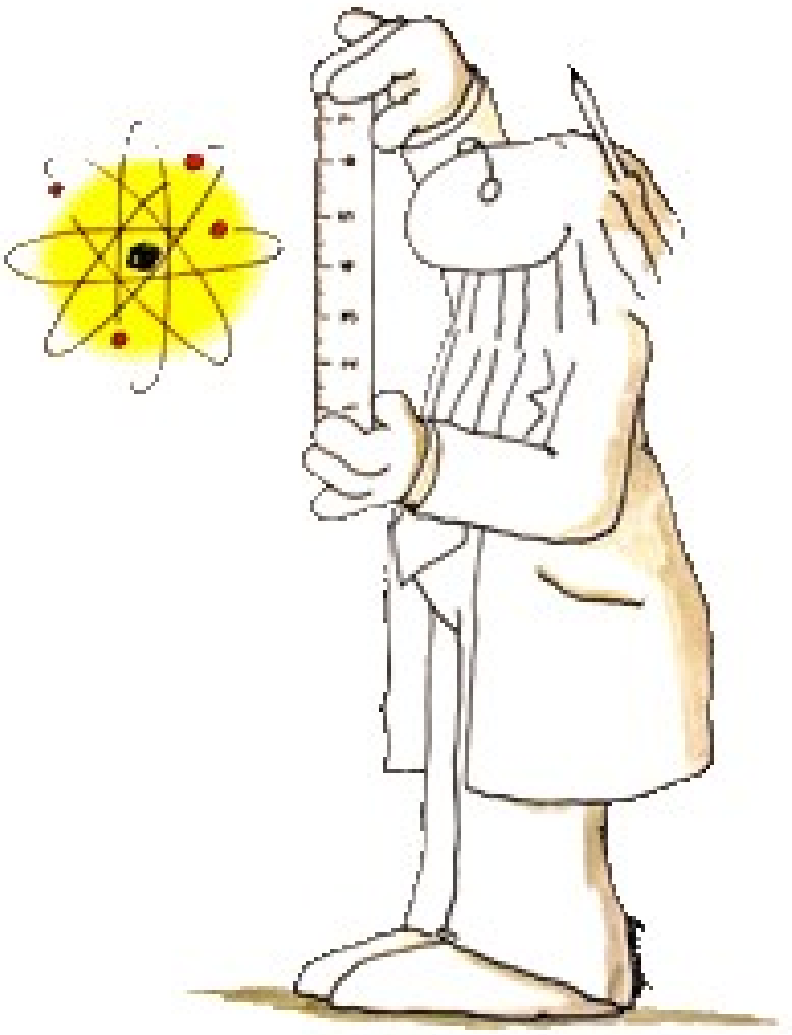
- Needed a highly accurate MC model of the 6X beam used in our TPS.
- At the very least, the model must match the data set used to configure the TPS.
- Seeking a maximum statistical uncertainty of 0.5%



and the smallest MC/measurement deviation possible.

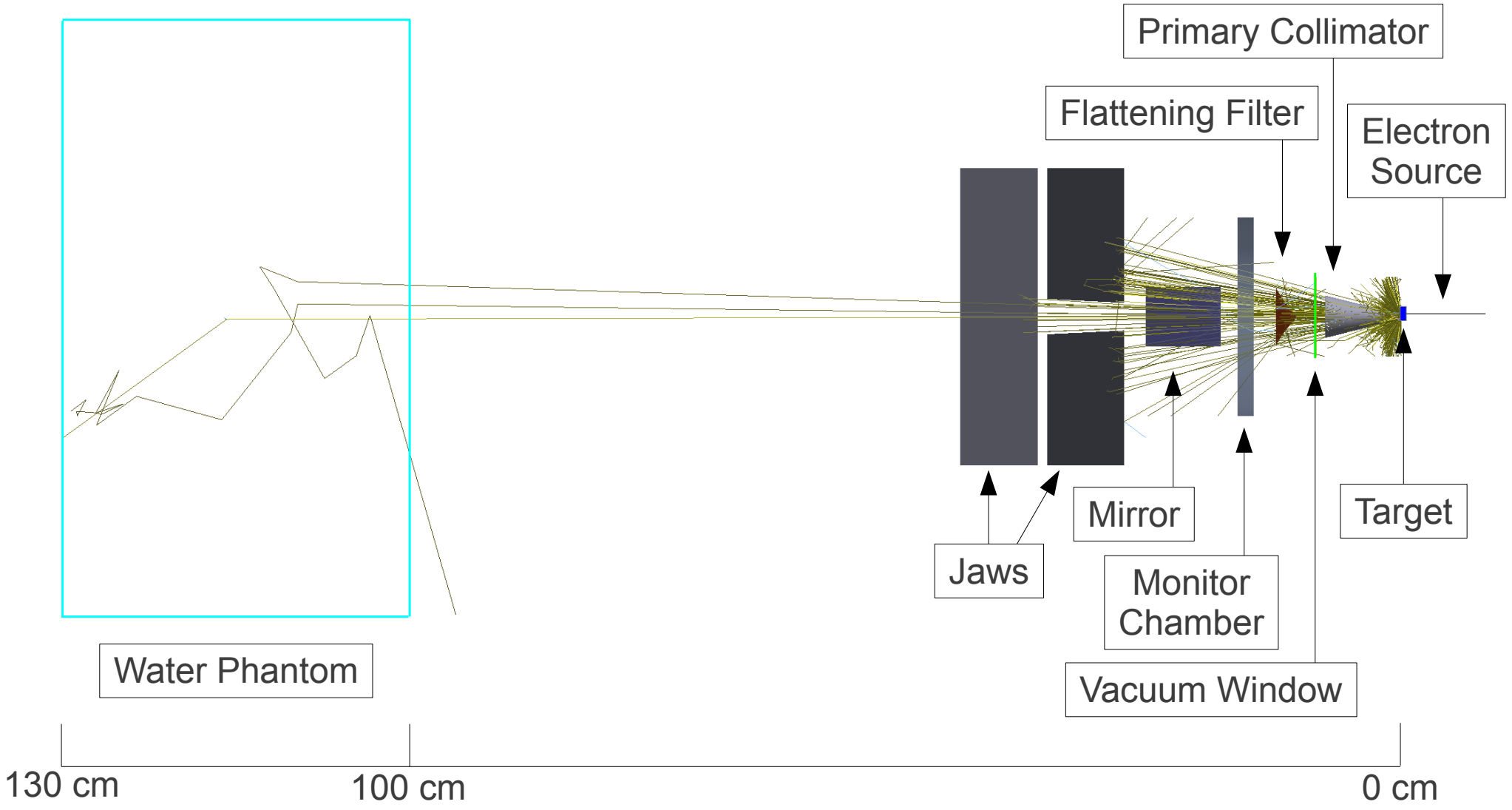
Methods & Materials

- Transport Code
  - Engine: EGSnrc
  - Treatment Head: BEAMnrc
  - Water Phantom: DOSXYZnrc
- Geometry
  - Varian Monte Carlo Data Package
    - Clinac 2100/2300, iX, DX, C/D, EX, and cX
- Data set
  - Eclipse “Golden” Beam Data
- Varied Electron Source Parameters
  - Energy (0% spread) (5.6:0.05:6.4) MeV
  - Gaussian intensity distribution FWHM (0.0:0.05:0.3) cm
  - Beam divergence (0.0:0.1:2.2)°
- Varied EGS Transport Settings
  - Total bremsstrahlung cross section (3 options)
  - Bremsstrahlung angular sampling (2 options)



Graphic copied from the BEAMnrc gui.

Monte Carlo Geometry



1000 incident electrons → 3 photons!

Electron Source Parameters

- Initially varied
  - Energy
  - Energy spread
  - Gaussian intensity distribution FWHM
- Later
  - Monoenergetic electrons
  - Added beam divergence
- Variation in matching was well behaved in each parameter.
  - Search resolution was only increased near the most optimal parameterizations.

Transport Settings

EGSnrc Transport Parameter	DOSXYZnrc Value (defaults)	BEAMnrc Value
Global ECUT	0.7 MeV	0.7 MeV
Global PCUT	0.01 MeV	0.01 MeV
Global SMAX	10^{10}	10^{10}
ESTEPE	0.25	0.25
XIMAX	0.5	0.5
Boundary crossing algorithm (BCA)	EXACT	EXACT
Skin depth for BCA	3	3
Electron-step algorithm	PRESTA-II	PRESTA-II
Spin effects	On	On
Bremsstrahlung angular sampling	Simple	Koch & Motz
Bremsstrahlung cross sections	Bethe-Heitler	NRC
Bound Compton scattering	Off	Off
Compton cross sections	Default	Default
Pair angular sampling	Simple	Simple
Pair cross sections	Bethe-Heitler	Bethe-Heitler
Photoelectron angular sampling	Off	Off
Rayleigh scattering	Off	Off
Atomic relaxations	Off	Off
Electron impact ionization	Off	Off
Photon cross sections	Storm-Israel	Storm-Israel

Condensed History Settings

Bremsstrahlung Settings

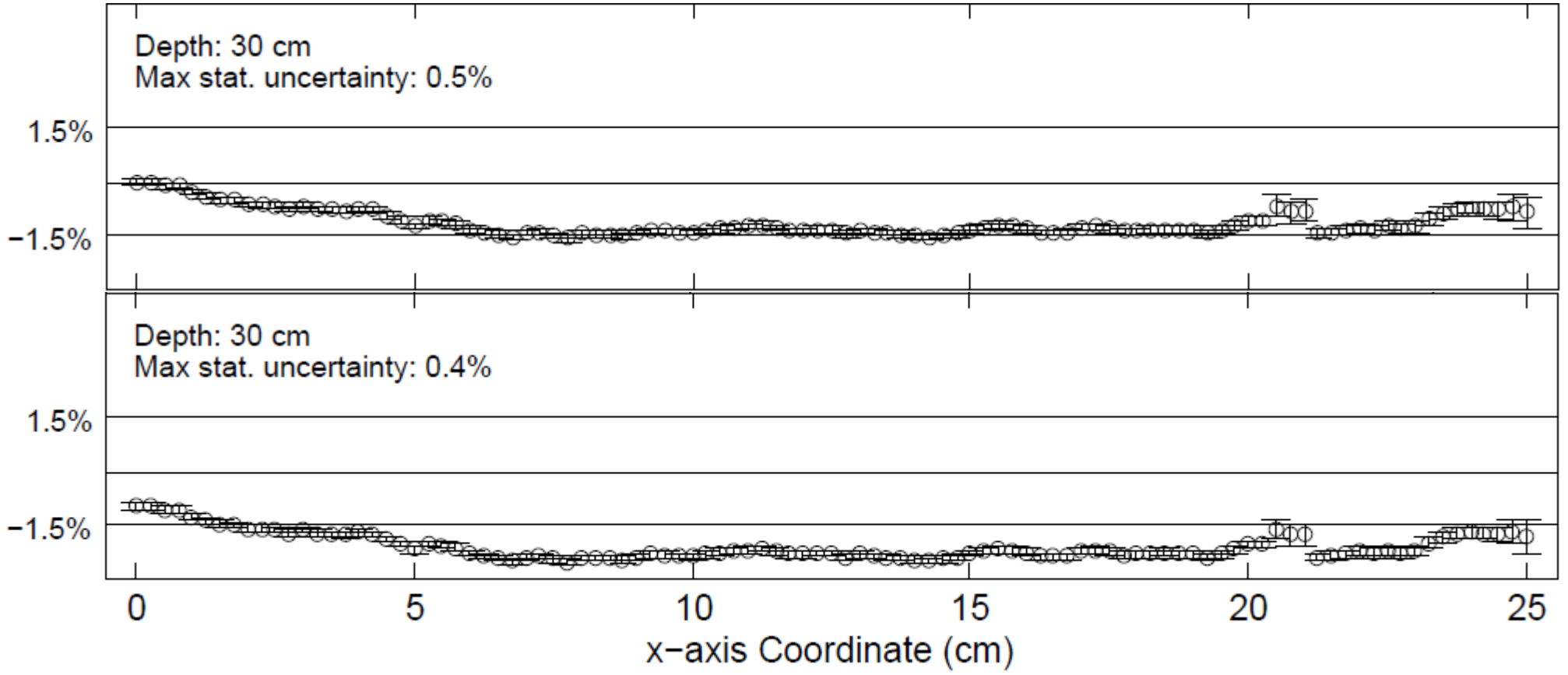
Photon Transport Settings

Low Energy Processes

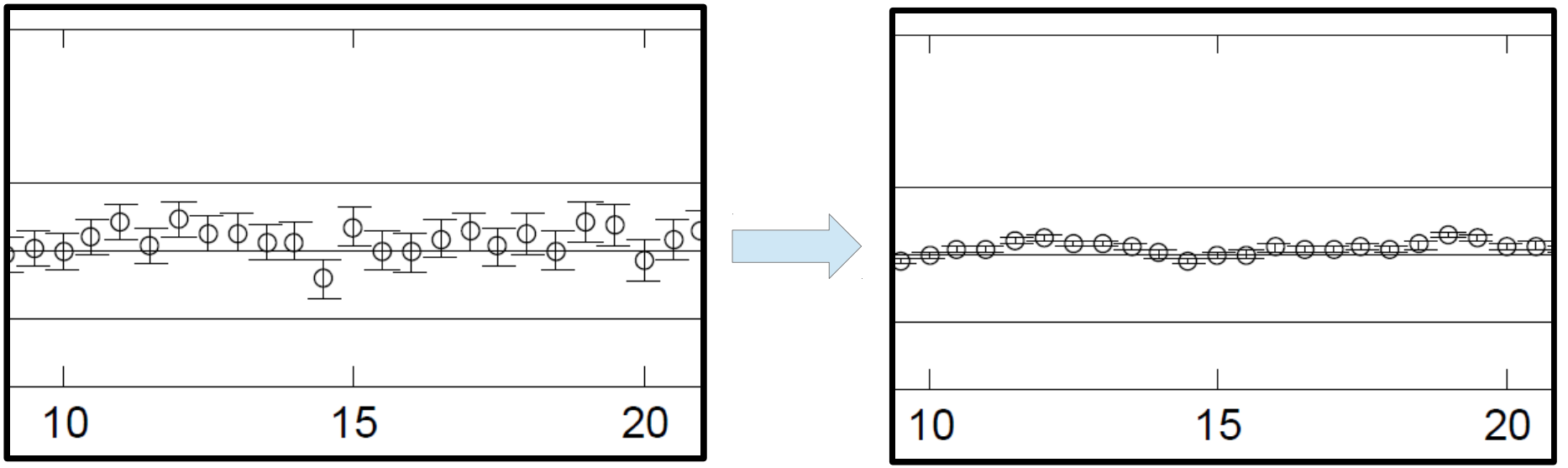
Other Charged Particle Processes

Normalization of MC Data

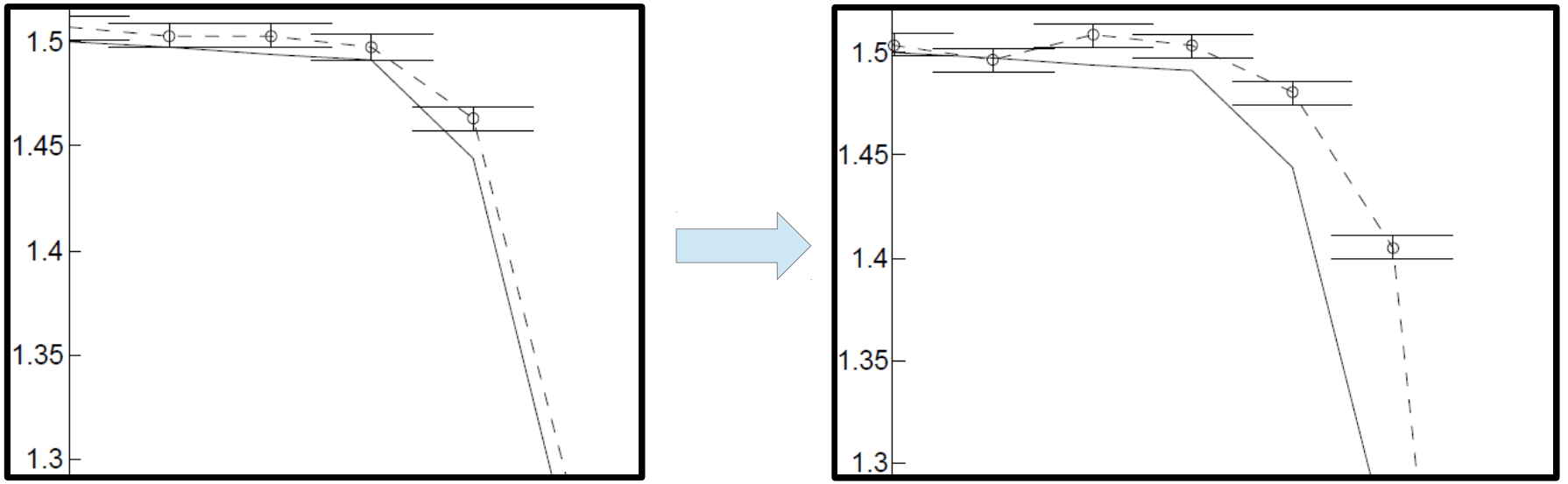
- All points normalized to a single (10 cm CAX) value.
  - Avoids hidden deviations from normalizing profiles to CAX values.



Smoothing



2nd order adaptive Savitzey-Golay filtering.



Circularly shaped averaging filter to simulate 0.6 cm diameter ion chamber measurements.

Matching Criteria

- Needed a single, well defined, uncertainty threshold.
- Deviation weighted with local dose

$$\%_{\mathrm{dev}} = \frac{\mathrm{PDD_{MC}} - \mathrm{PDD_{MC}}}{\mathrm{PDD_{MC}}}$$

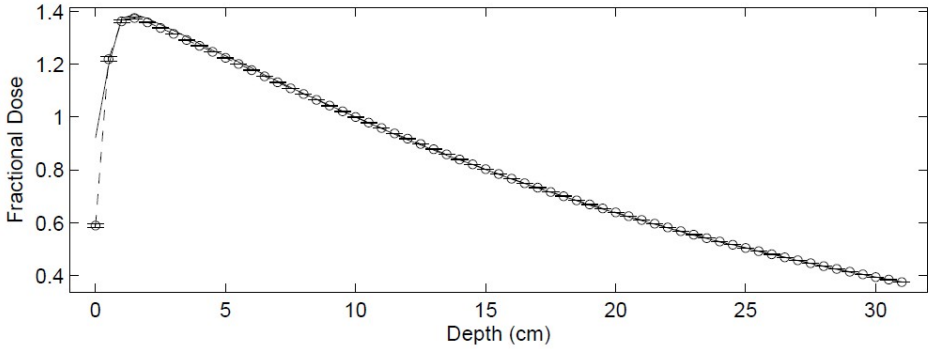
- Parameterizations were rated with a cost function

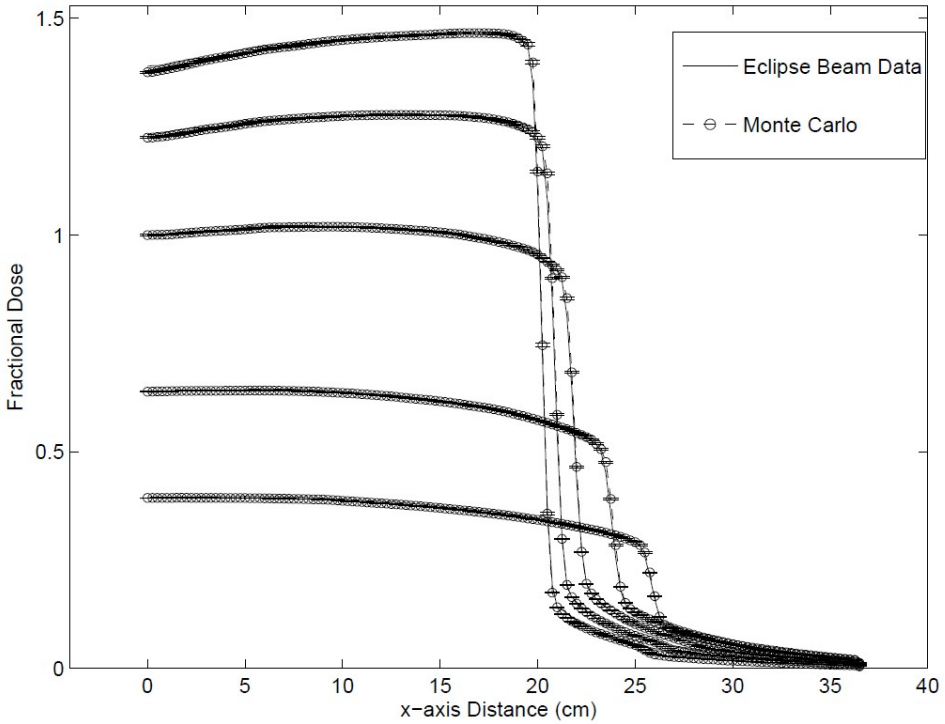
$$\mathrm{CF}(\mathrm{E_{mono}}, \mathrm{ID_{FWHM}}, \mathrm{D}) =$$

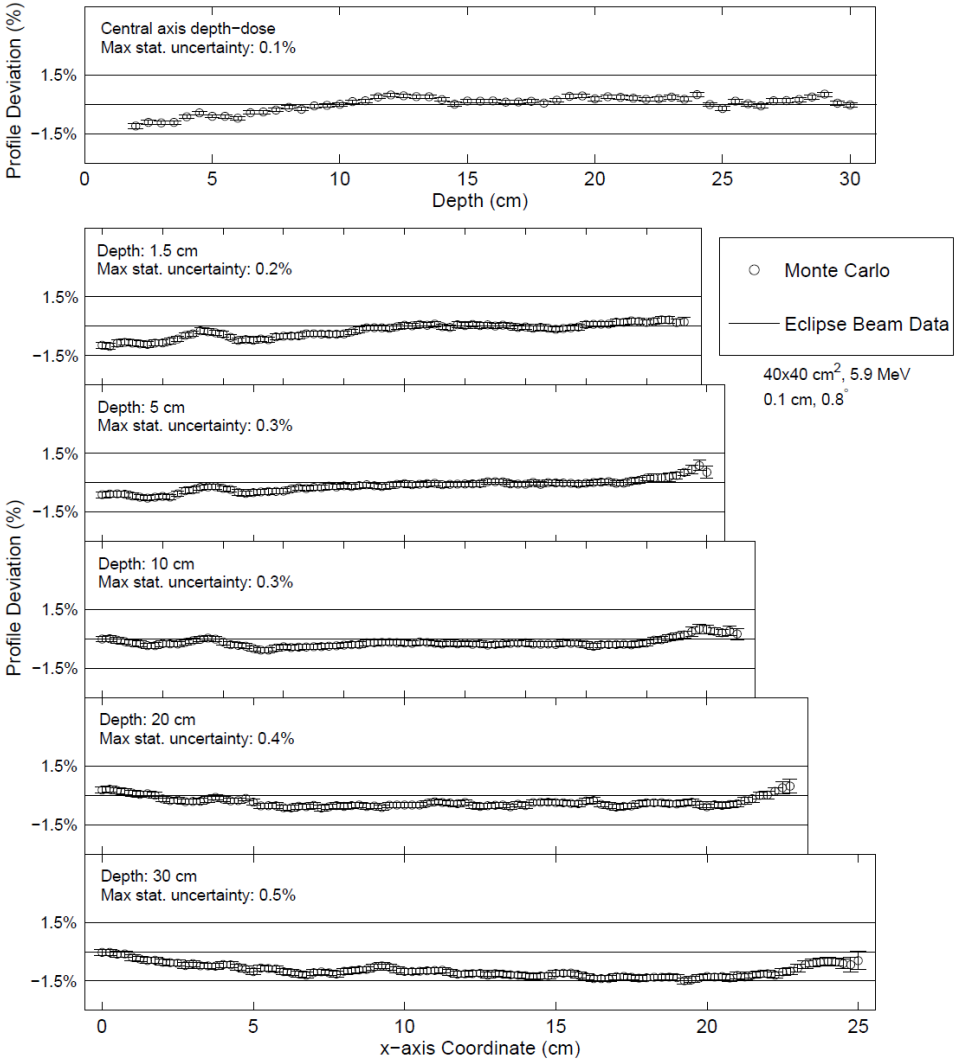
$$\frac{1}{\mathrm{N_{FS}}} \sum_{n=1}^{\mathrm{N_{FS}}} \left[w_{\mathrm{FO}} \frac{\mathrm{N_{FO,pass}}}{\mathrm{N_{FO,total}}} + \frac{w_{\mathrm{PL}}}{\mathrm{N_{prof}}} \sum_{p=1}^{\mathrm{N_{prof}}} \frac{(\mathrm{N_{PL,pass}})_{\mathrm{n,p}}}{(\mathrm{N_{PL,total}})_{\mathrm{n,p}}} + \frac{w_{\mathrm{PN}}}{\mathrm{N_{prof}}} \sum_{p=1}^{\mathrm{N_{prof}}} \frac{(\mathrm{N_{PN,pass}})_{\mathrm{n,p}}}{(\mathrm{N_{PN,total}})_{\mathrm{n,p}}} \right]$$

- Initially searched with 3×3 cm², 20×20 cm², 40×40 cm².
- Later added 10×10 cm², and 20×20 cm² field sizes for verification.

Results







- Most optimal parameterization: 5.9 MeV, 0.1 cm, and 0.8°
  - Resolution: 0.05 MeV, 0.05 cm, 0.1°

Conclusions

- Parameterization optimality was sensitive to
  - Repeated runs (i.e. statistical uncertainty)
  - Smoothing parameters
  - Normalization methods
- Statements of model accuracy should encompass MC statistical uncertainty.
  - 1.5% + 0.5% = 2.0%
- KM angular sampling improved all brem. CS combinations.
- NRC/KM brem. setting provided the most optimal matching.

Related Work

- Manuscript which describes our modeling process in full detail.
- MC recalculation of RapidArc plans for the dosimetric evaluation of AAA.
  - We have a functional recalculation tool which can input DICOM CT and RP files.
  - Next step is to validate heterogeneous MLC fields with radiochromic film.
- Voxel-wise dose calculation error prediction for patient plan quality assurance.
  - Can we trust AAA for this plan or should we use a MC dose calculation instead?
  - We have a prototype tool, but considerable development is still required.

Resources & Affiliations

- Research work is being conducted at OHSU Dept. of Radiation Medicine under the supervision of my doctoral advisor Dr. Wolfram Laub.
- High capacity computing resources are being provided by OSU College of Engineering.
- Graduate Research Assistantship funded by OSU Dept. of Nuclear Engineering and Radiation Health Physics.