Use of MC in Accelerator Head Simulation and Modeling for Electron Beams

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University of California San Francisco

Part I: Accelerator Head Simulation and Modeling for Electron Beams

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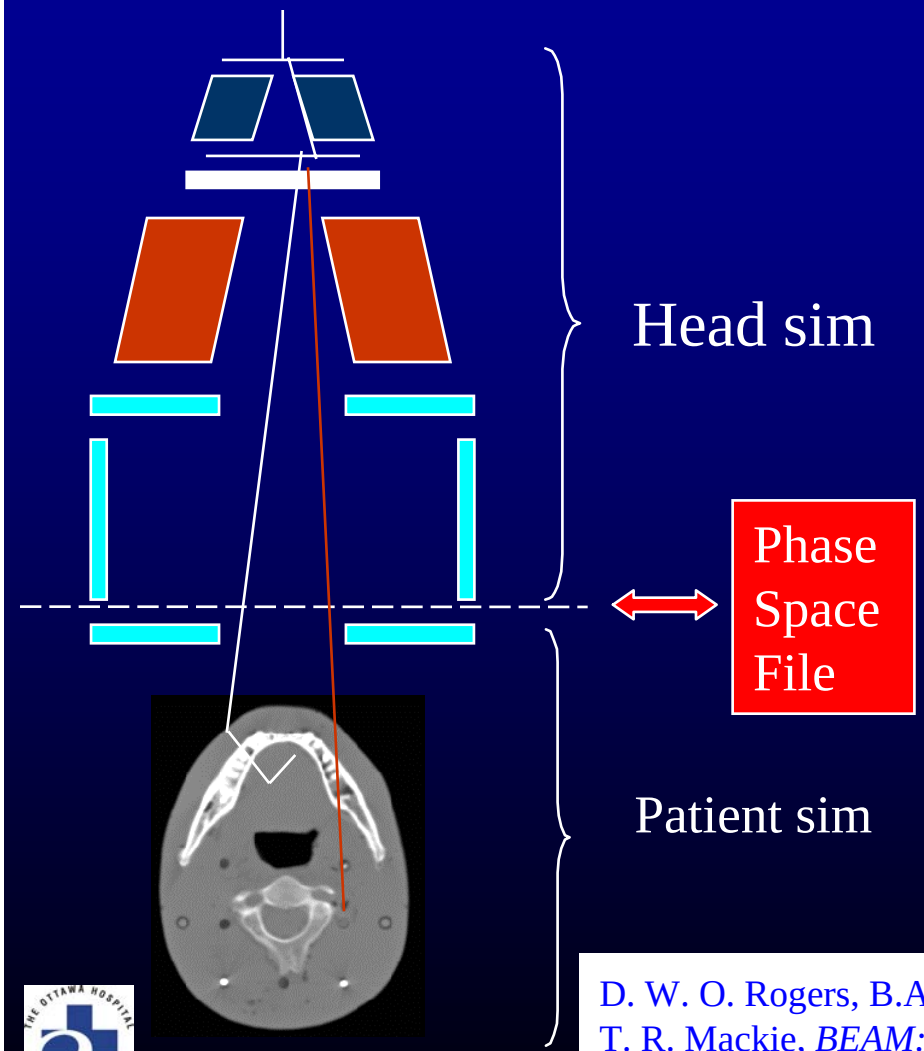
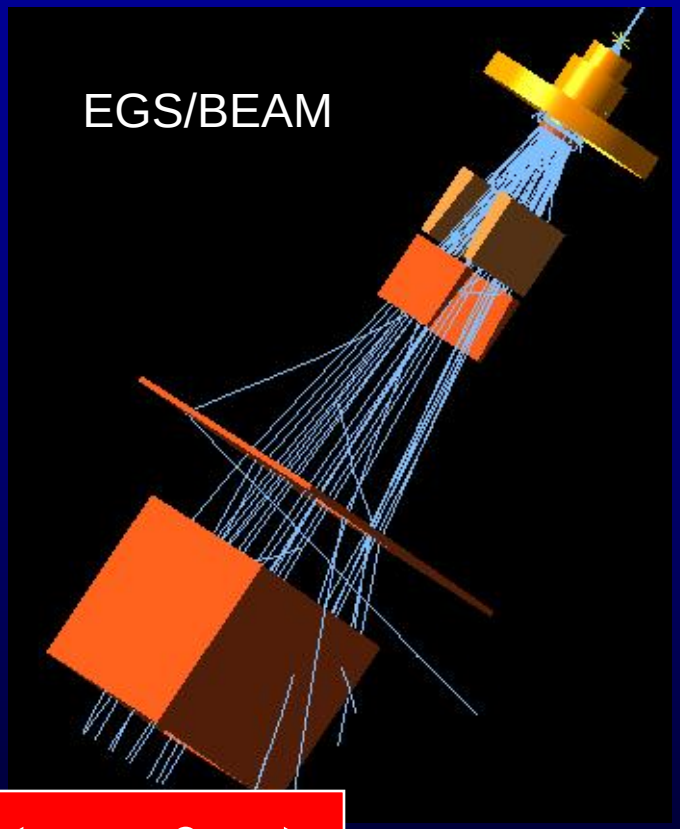
Outline

- **Phase space simulation of the linear accelerator treatment head for electron beams**
  - MC codes available for accelerator simulation and their capabilities
  - Sensitivity analysis: Source and geometry details and their impact on simulation results
  - Example of phase-space simulation on a radiotherapy accelerator
- **Beam modeling for electron beams**
  - Beam modeling objective and terminology
  - Measurement versus treatment head simulation for beam modeling
  - Example of a simple electron beam model
- **Simulation of applicators, cutouts, and MLC's for electron beams (Joanna Cygler)**

Treatment head simulation





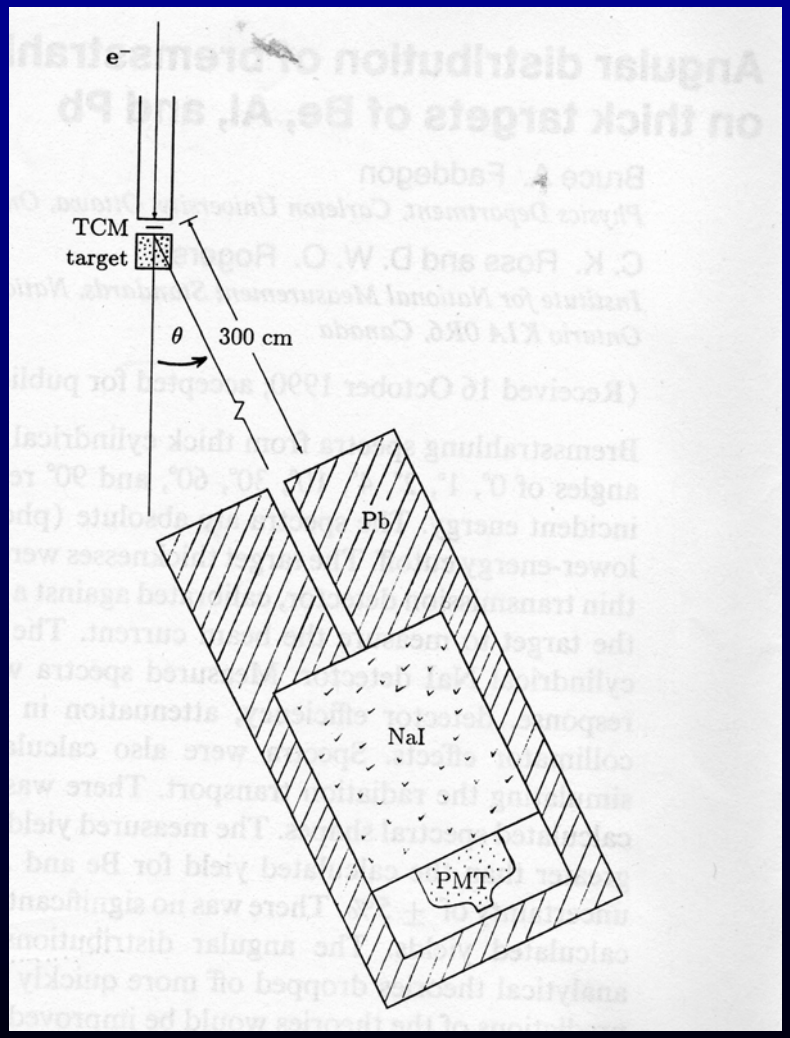
$\Phi(E,x,\theta,L)$

D. W. O. Rogers, B.A. Faddegon, G. X. Ding, C.-M. Ma, J. We, and T. R. Mackie, *BEAM: A Monte Carlo code to simulate radiotherapy treatment units*. Med. Phys. 22(5):503 (1995)

Treatment head simulation codes

- EGS/BEAM
- Geant
- MCNP
- Penelope

Thick-target bremsstrahlung measurement at 10-30 MV

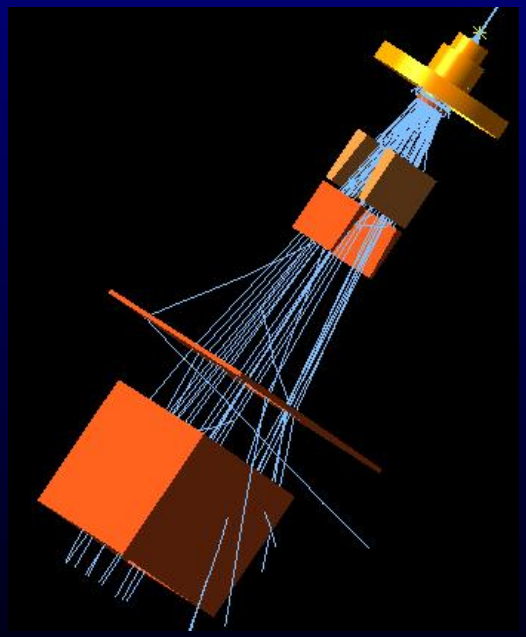


- Faddegon, Ross, and Rogers, Med Phys 18:727-739 (1991)
- Bremsstrahlung yield: photons per unit solid angle per unit energy interval
- Correct for pile-up, bkg, detector response, detector efficiency, and collimator effect

Monte Carlo benchmark: 15 MeV electrons on Be/Al/Pb

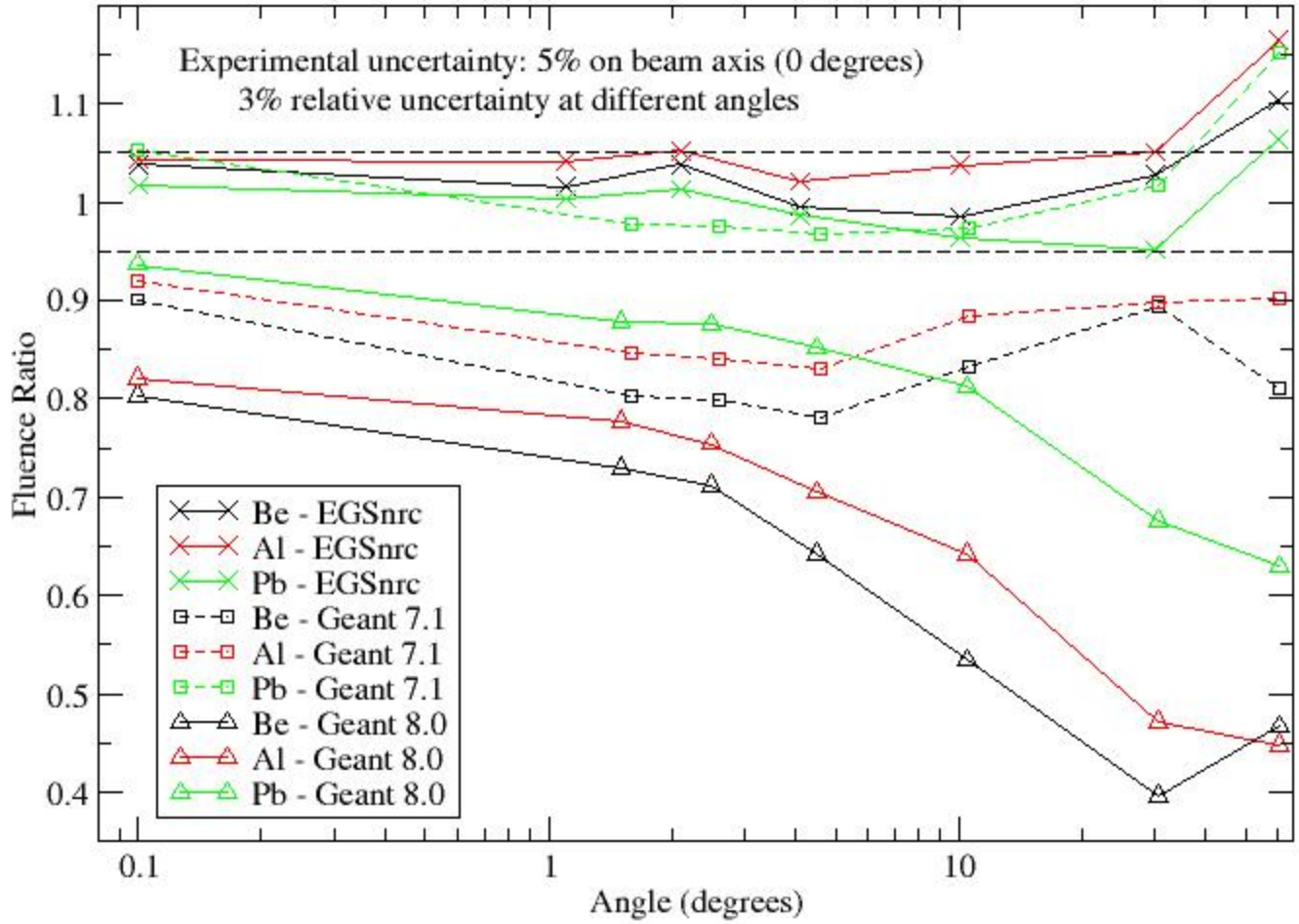
- Geant4
- New geometry and scoring developed by T. Aso
- Installation and support by J. Perl
- Bremsstrahlung splitting by E. Poon

- EGSnrc with BEAM user code from NRCC
- Revised scoring



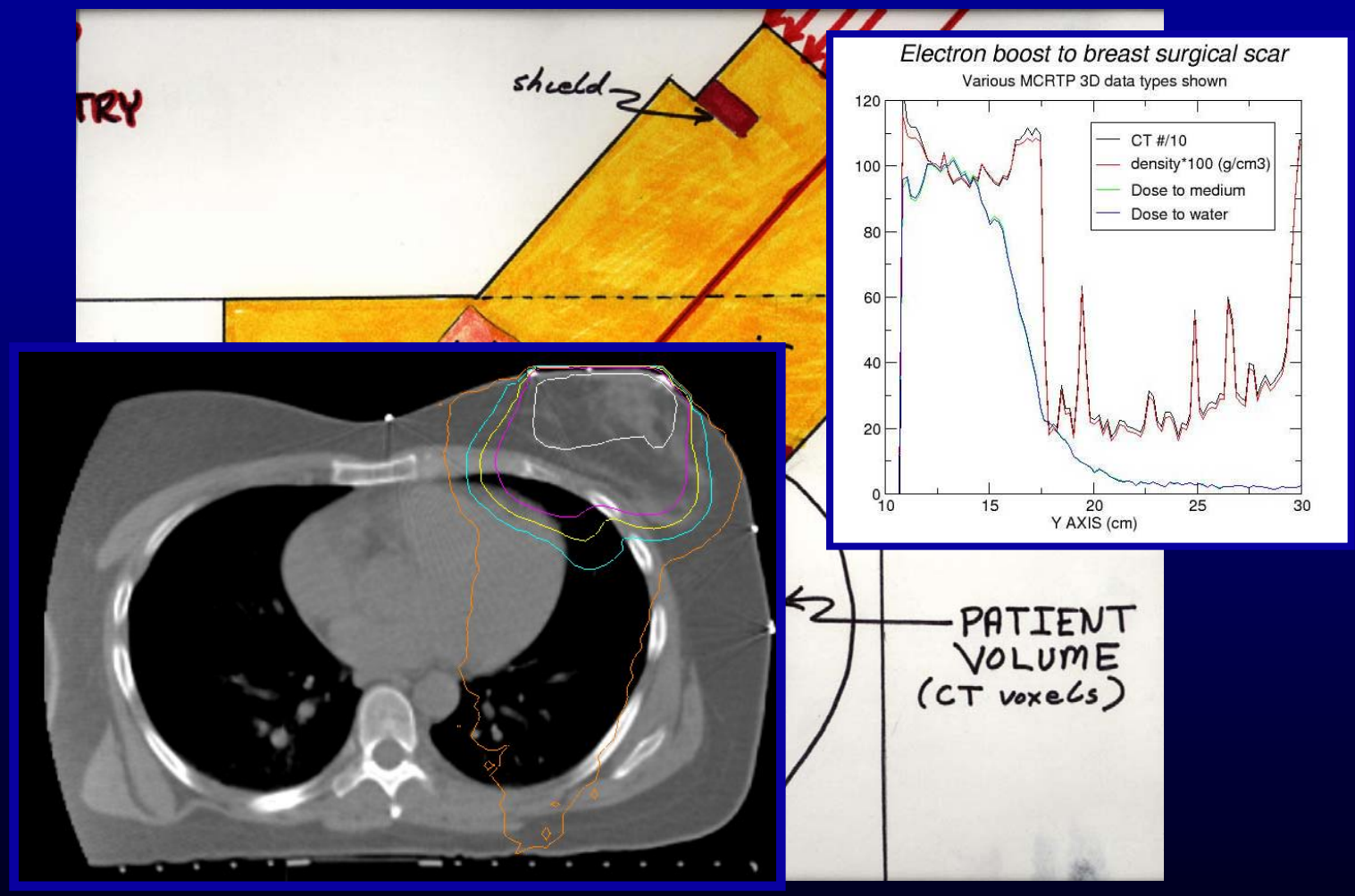
Bremsstrahlung Fluence Ratio, MC/measurement

MC with target chamber out to 10 degrees, no target chamber 30 and 60 degrees



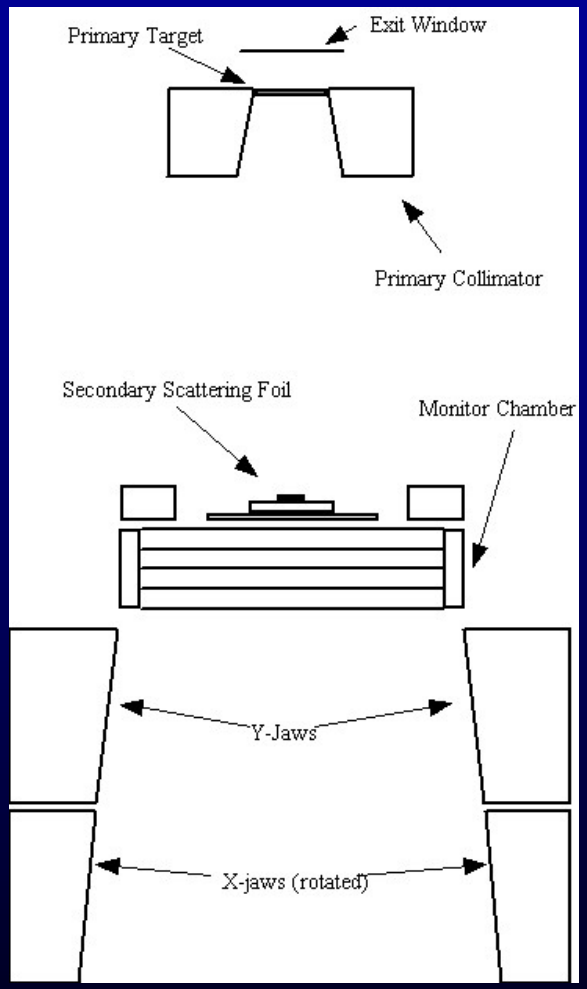
fluenceratio

Dose calculation: EGS/MCRTP



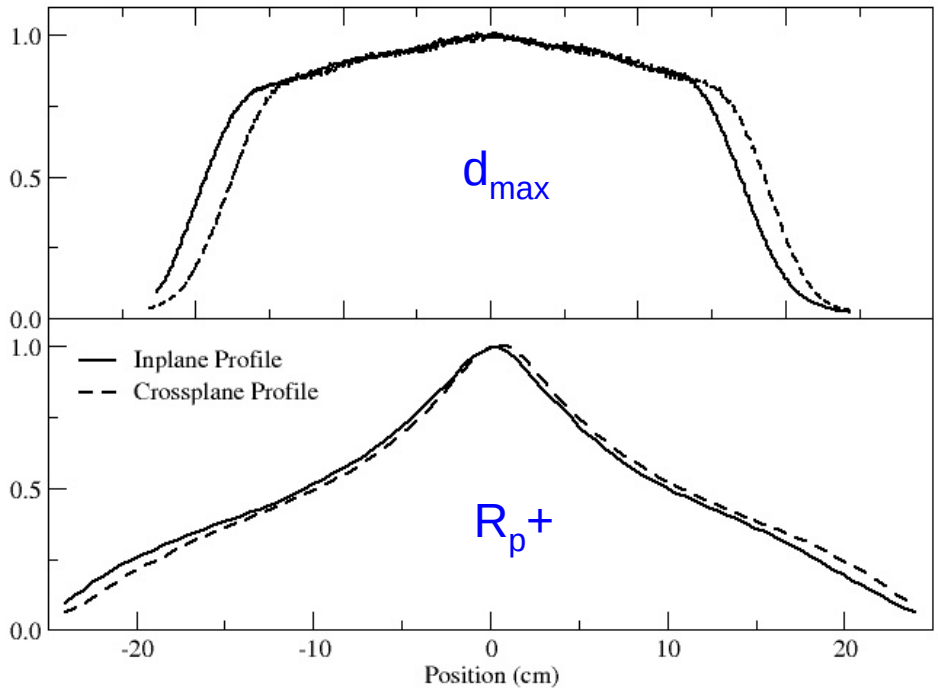
J. Coleman, Joy, C. Park, J.E. Villarreal–Barajas, P. Petti, B. Faddegon, *"A Comparison of Monte Carlo and Fermi-Eyges-Hogstrom Estimates of Heart and Lung Dose from Breast Electron Boost Treatment,"* Int. J. Onc. Biol. Phys., Volume 61(2):621-628, 2005

Primus Treatment Head



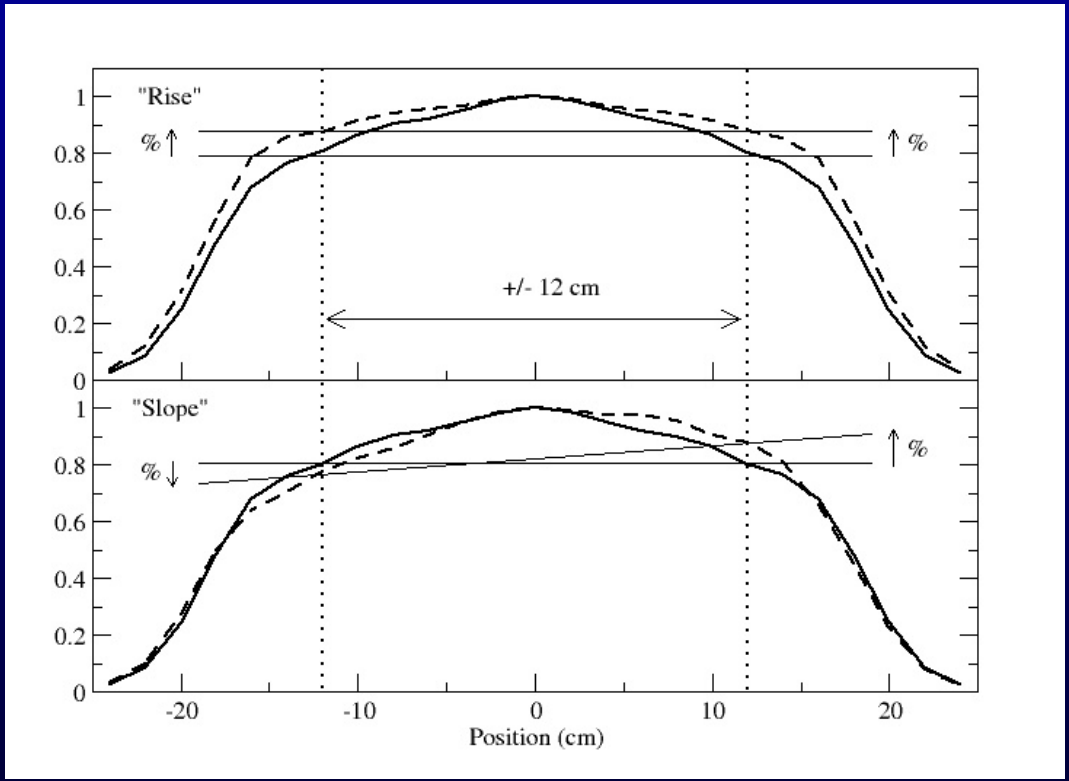
E. Schreiber, B.A. Faddegon, "*Sensitivity of large-field electron beams to variations in a Monte Carlo accelerator model,*" Phys. Med. Biol. 50 (2005) 769-778;

Measured asymmetry:
Primus 21 MeV, 40x40 cm, 100 cm SSD



E. Schreiber, B.A. Faddegon, "*Sensitivity of large-field electron beams to variations in a Monte Carlo accelerator model,*" Phys. Med. Biol. 50 (2005) 769-778;

Definitions for sensitivity analysis



Symmetry, integrate profile from isocenter to 50% dose and compare LHS (U) to RHS (V):

$$(U-V)/(U+V)$$

Flatness, limited to 60% of field size:

$$(D_{max}-D_{min})/(D_{max}+D_{min})$$

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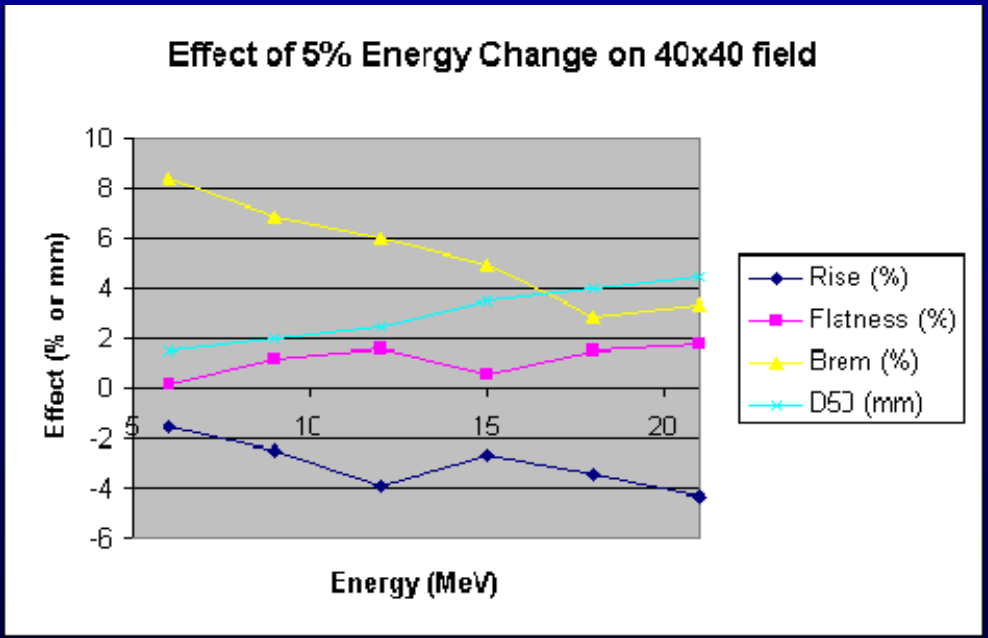
Energy change



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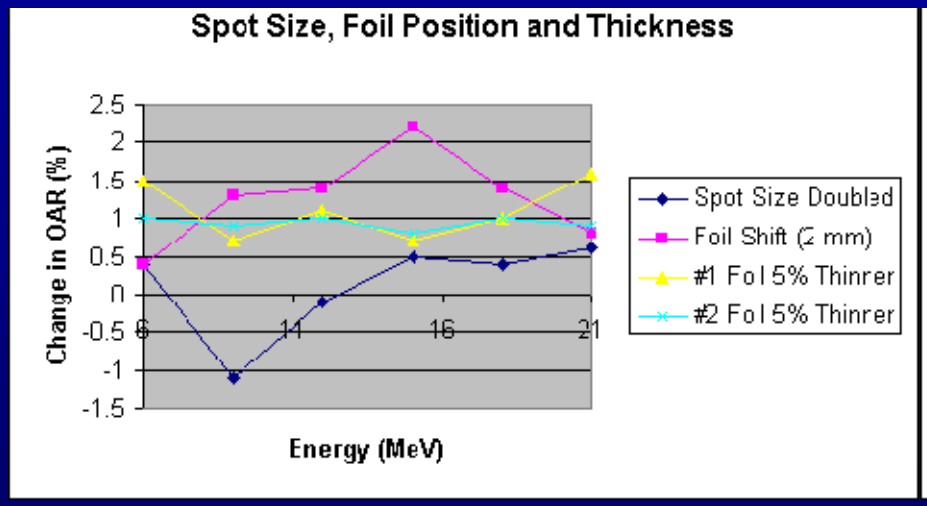
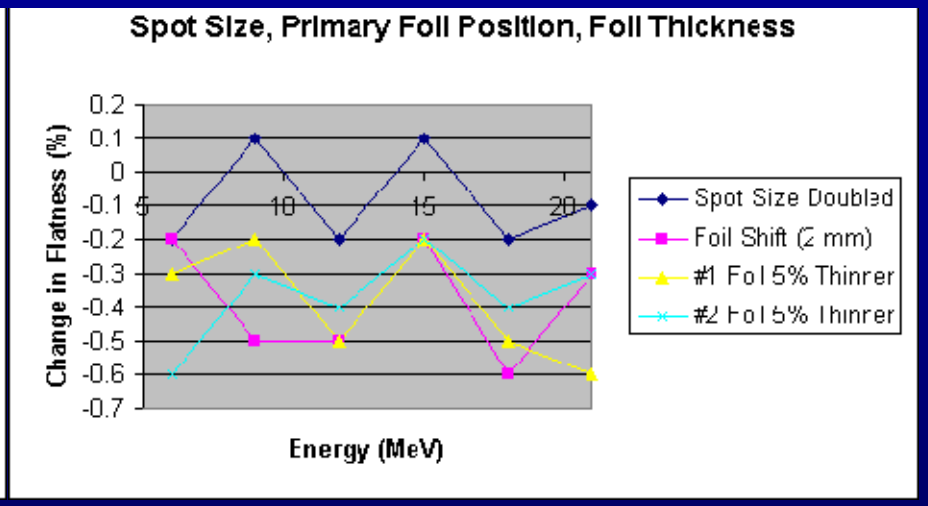
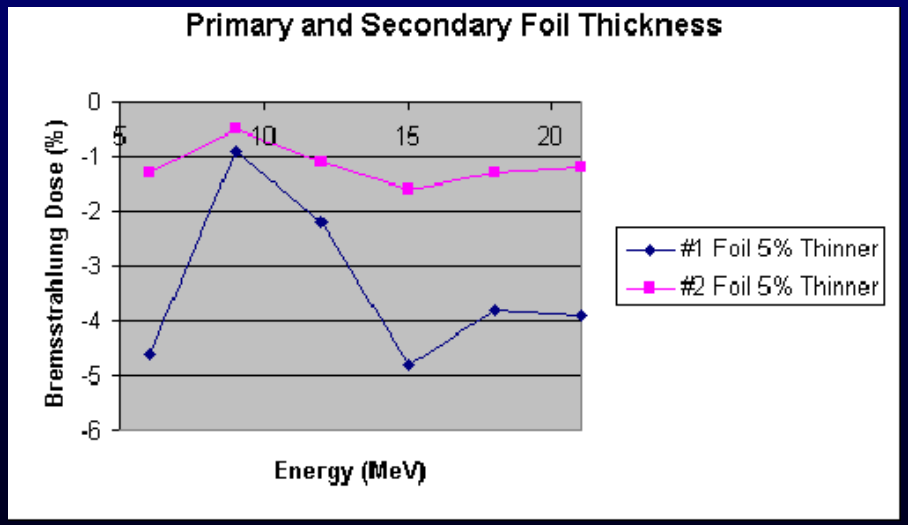
More symmetric effects







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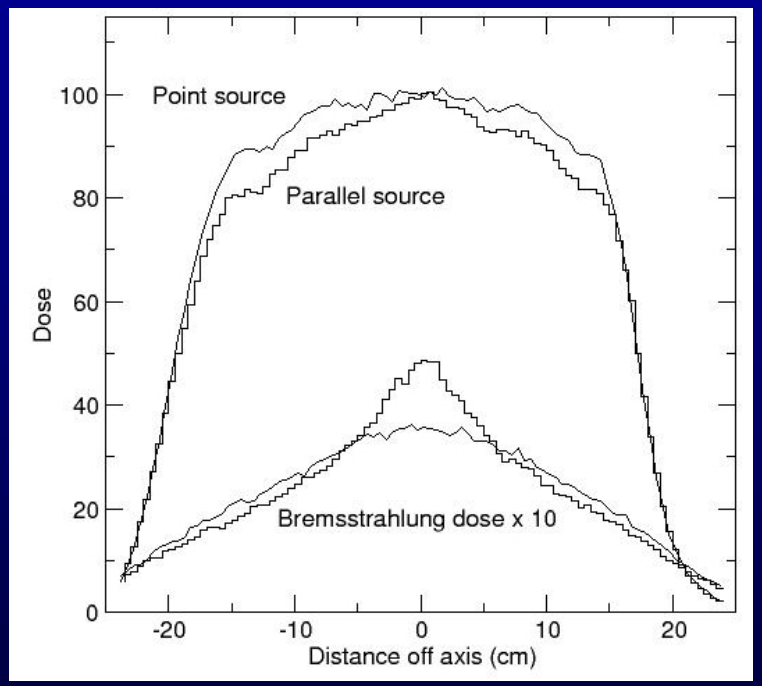
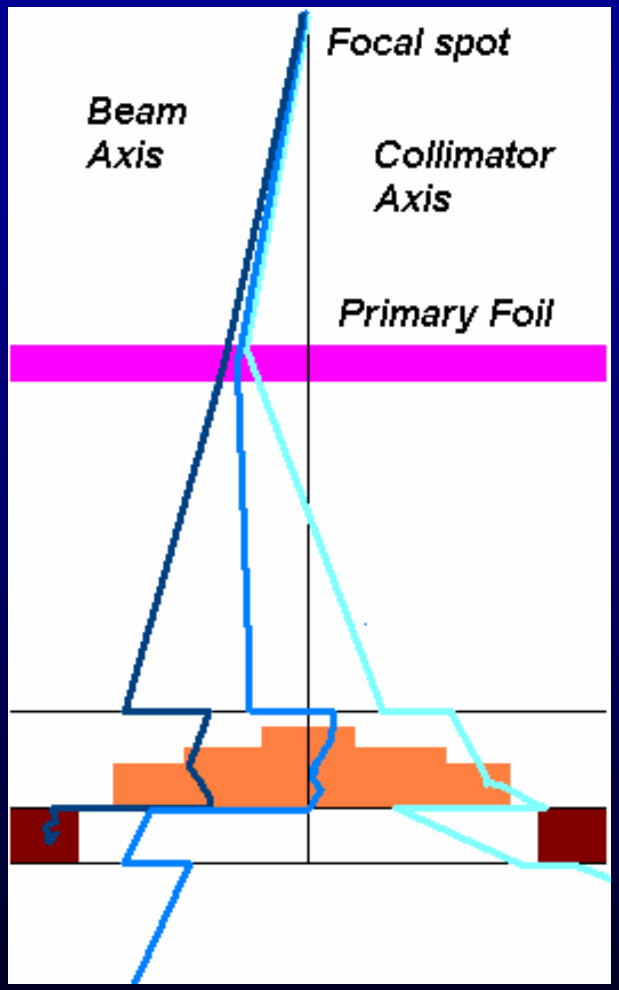
Point source with 5° angle



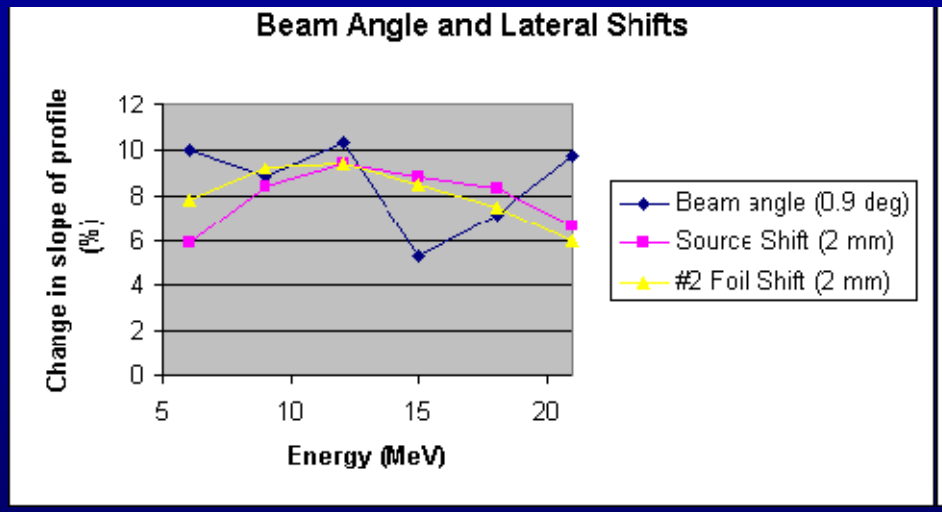
B.A. Faddegon, E. Schreiber, X. Ding, *"Monte Carlo simulation of large electron fields,"* Phys. Med. Biol. 50 (2005) 741-753

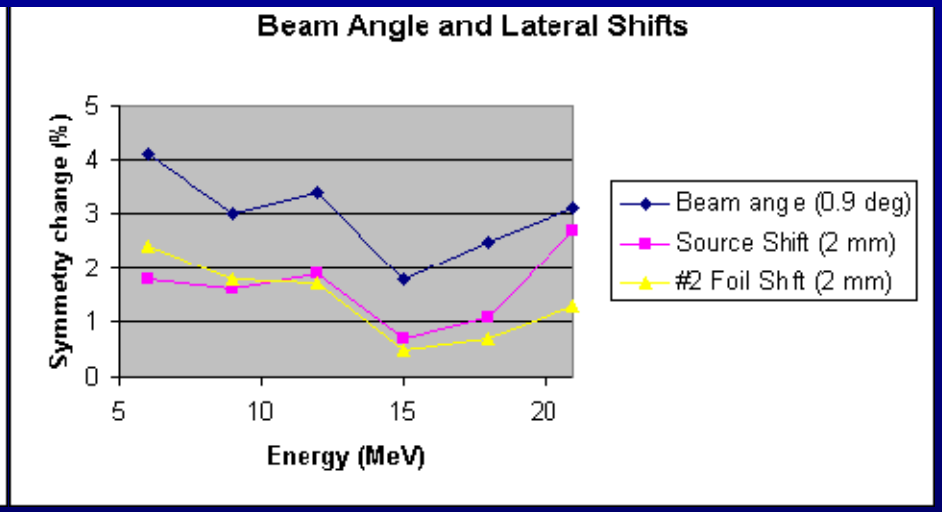
Lateral shift of component

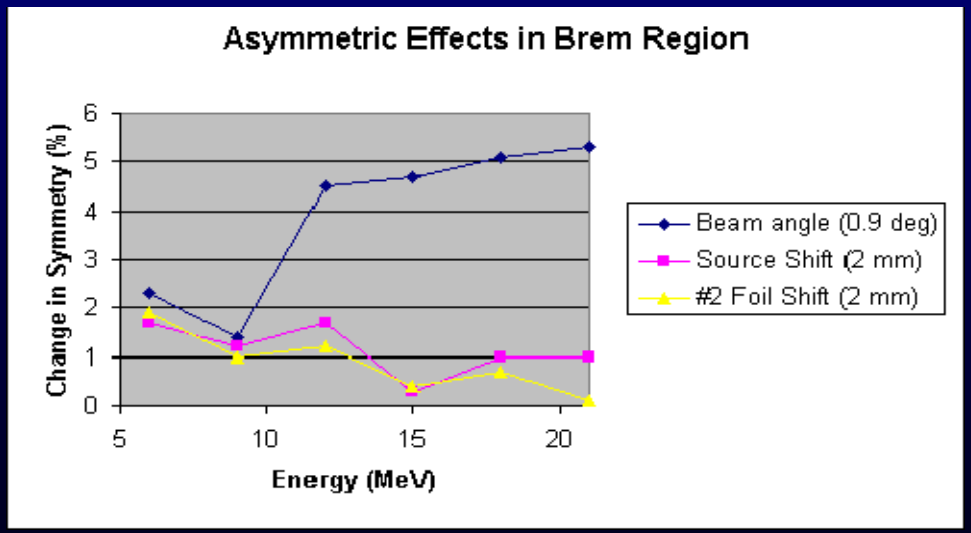


B.A. Faddegon, E. Schreiber, X. Ding, *"Monte Carlo simulation of large electron fields,"* Phys. Med. Biol. 50 (2005) 741-753

Asymmetric effects

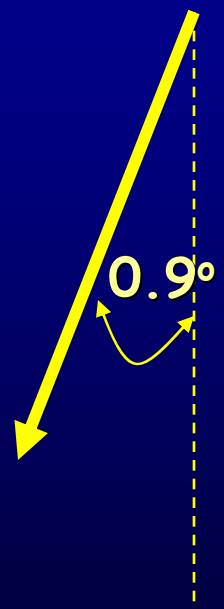


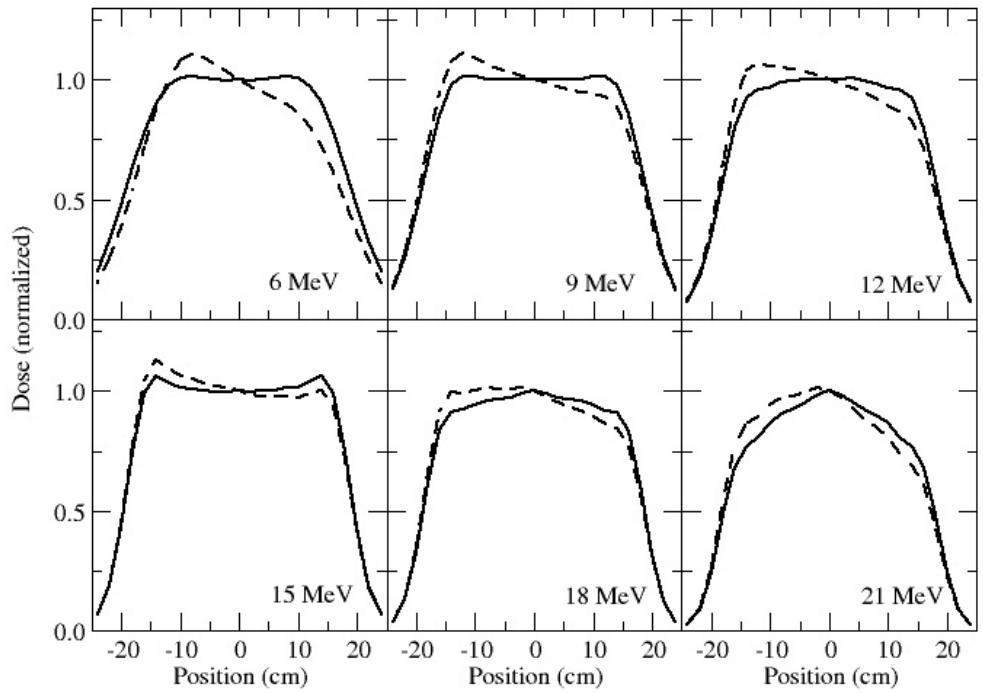




E. Schreiber, B.A. Faddegon, *"Sensitivity of large-field electron beams to variations in a Monte Carlo accelerator model,"* Phys. Med. Biol. 50 (2005) 769-778;

Beam angle of 0.9°





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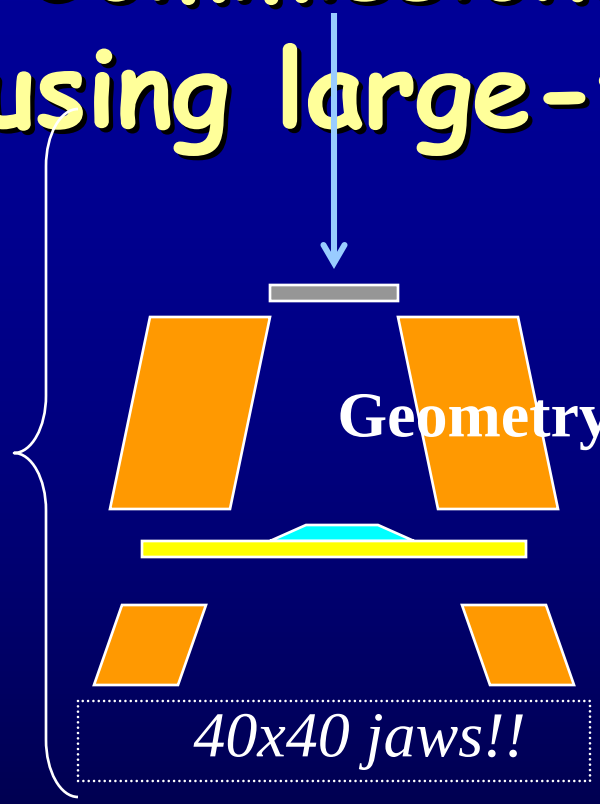
Commissioning electron beams using large-field measurements



Geometry measurements

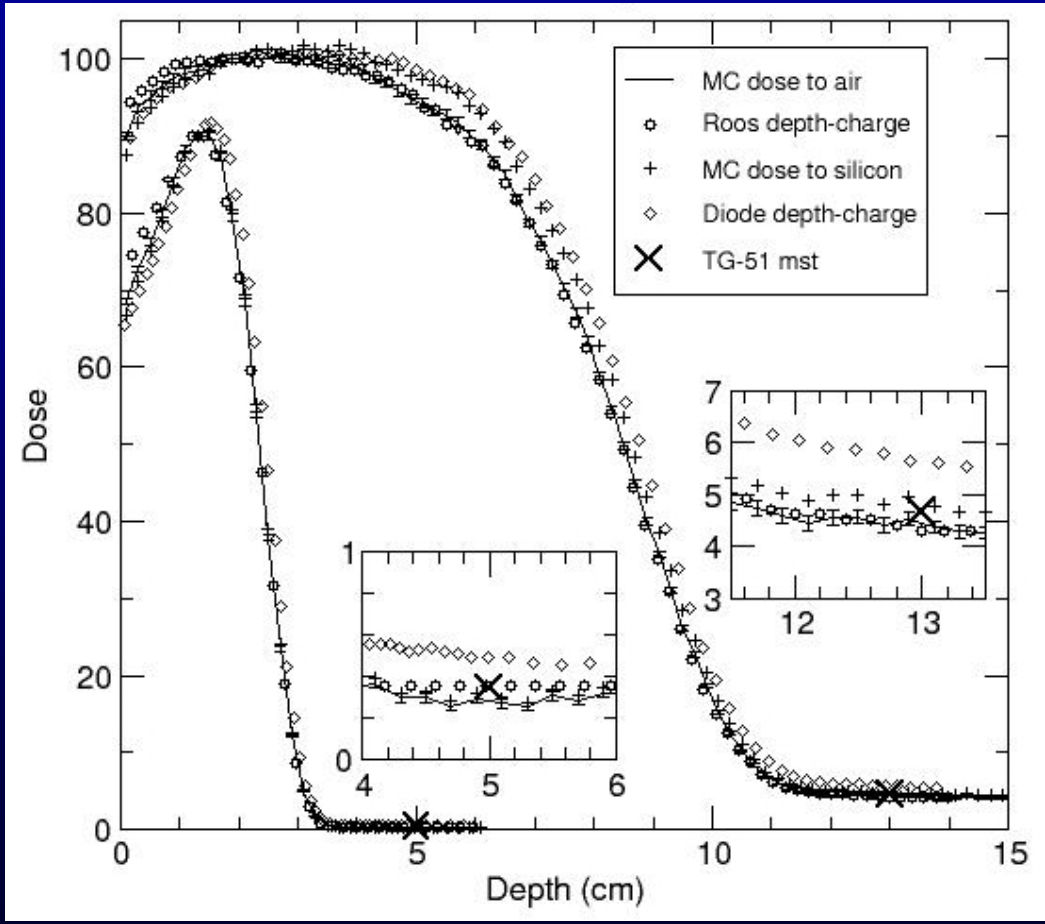
No Applicator!!

Objective: Evaluate large-field approach to beam modeling

- Treatment head simulation accuracy goal: 1%/1mm

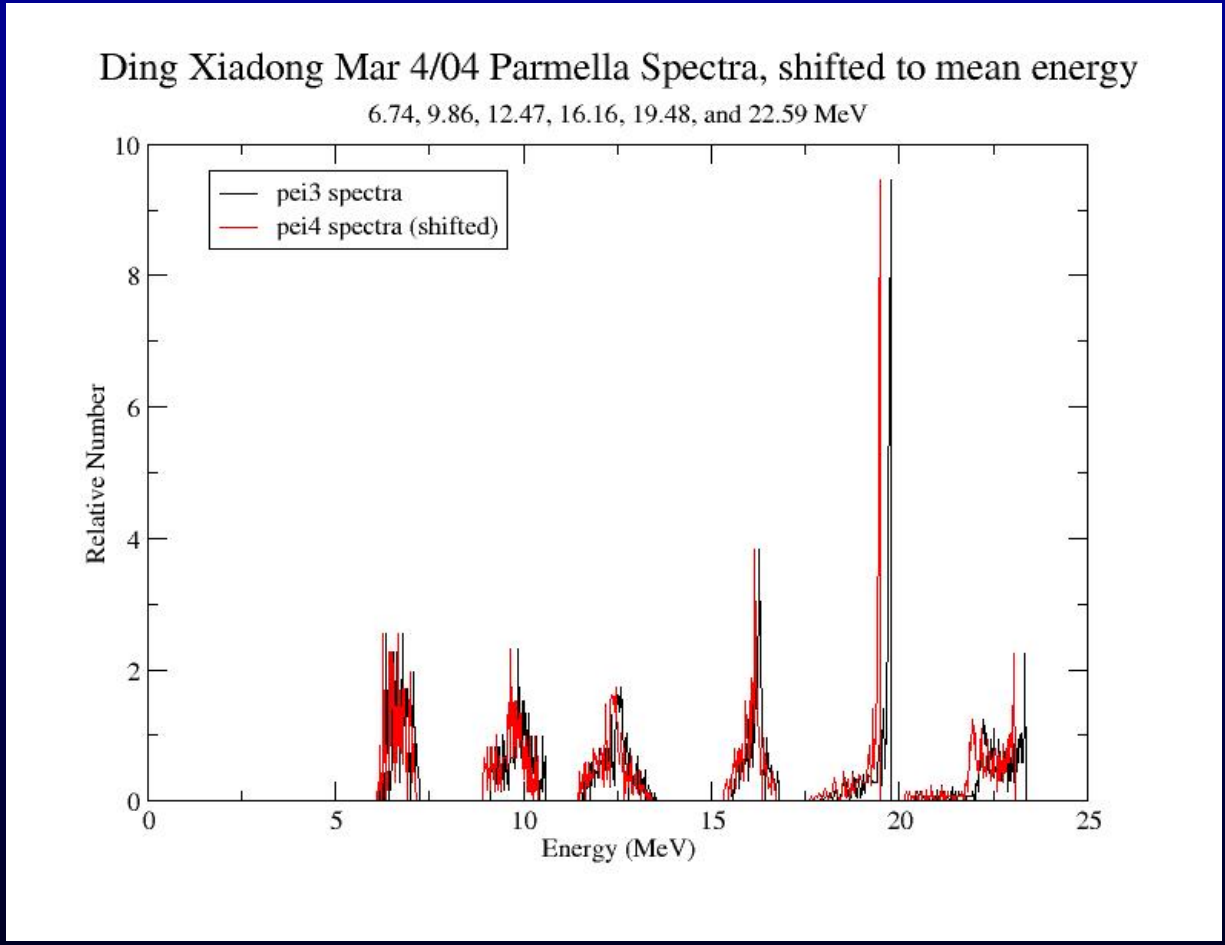
Dose measurements

Choose your detector wisely…



M Aubin, B Faddegon, J Pouliot, *"Clinical Electron Beam Verification with an a-Si Electronic Portal Imaging Device.* Submitted to Radiotherapy and Oncology, Nov, 2005

Particle-dynamics code to simulate accelerator and bending magnet



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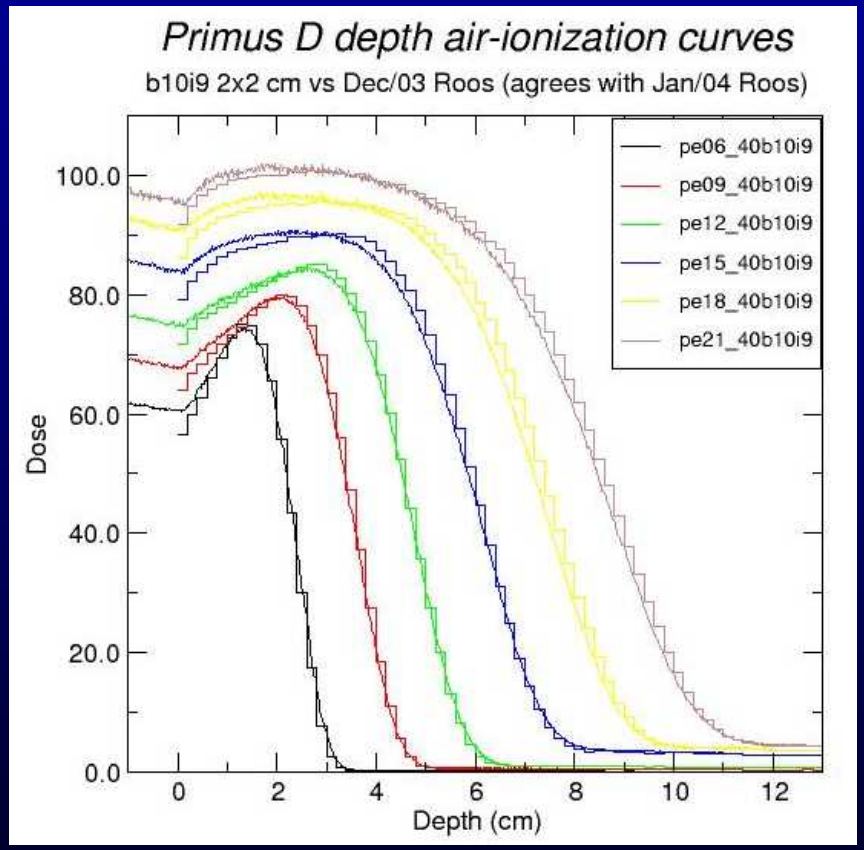
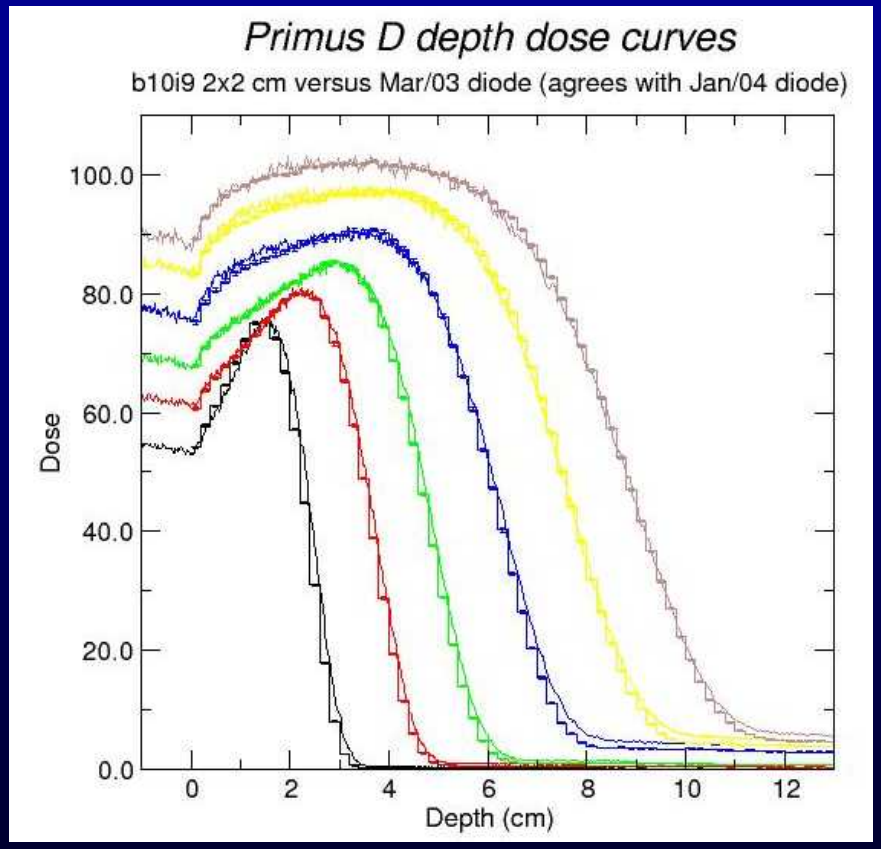
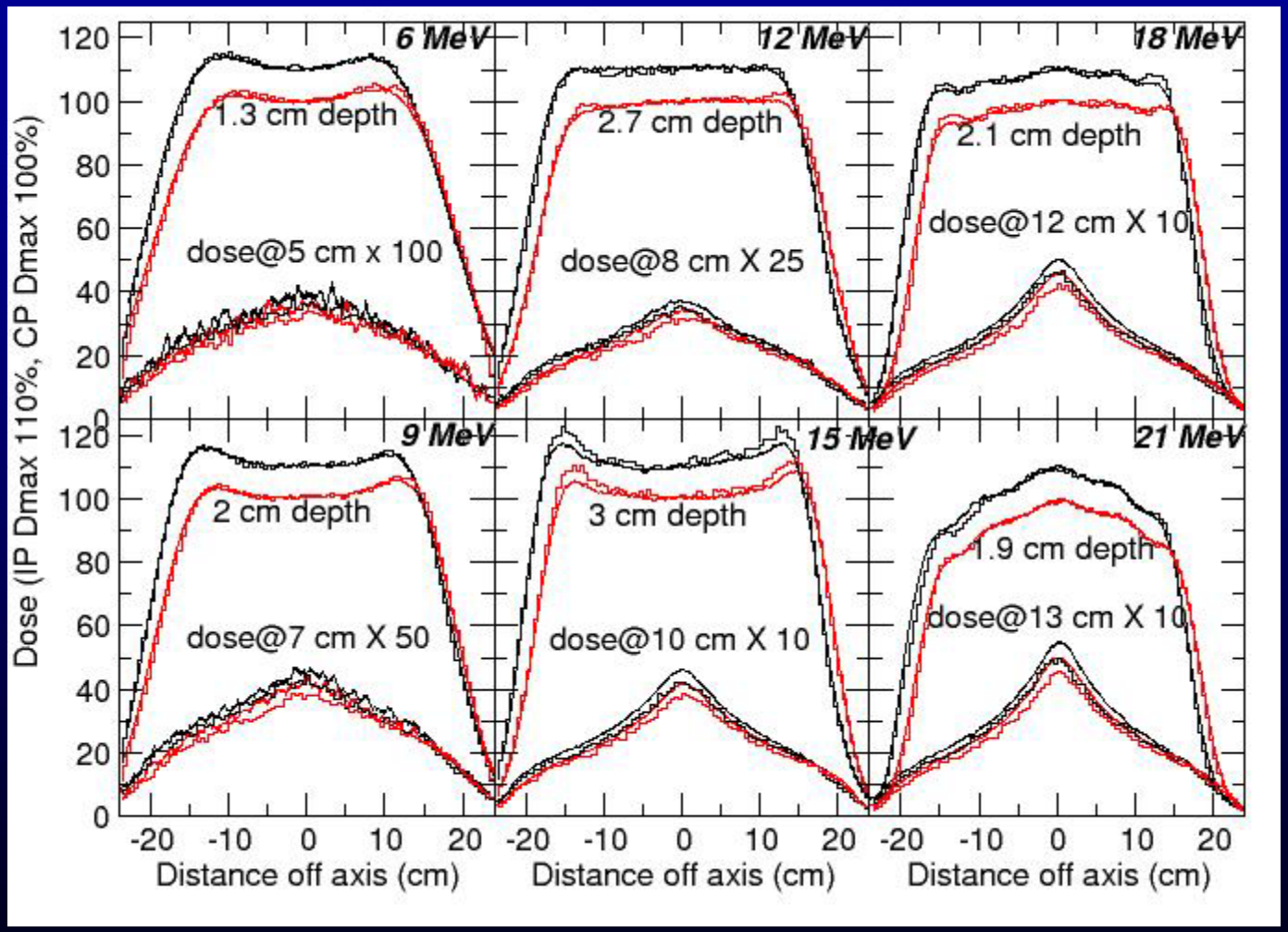
Beam penetration





B.A. Faddegon, E. Schreiber, X. Ding, *"Monte Carlo simulation of large electron fields,"* Phys. Med. Biol. 50 (2005) 741-753

Beam profiles
EGS4 (steps) vs diode and ion chamber



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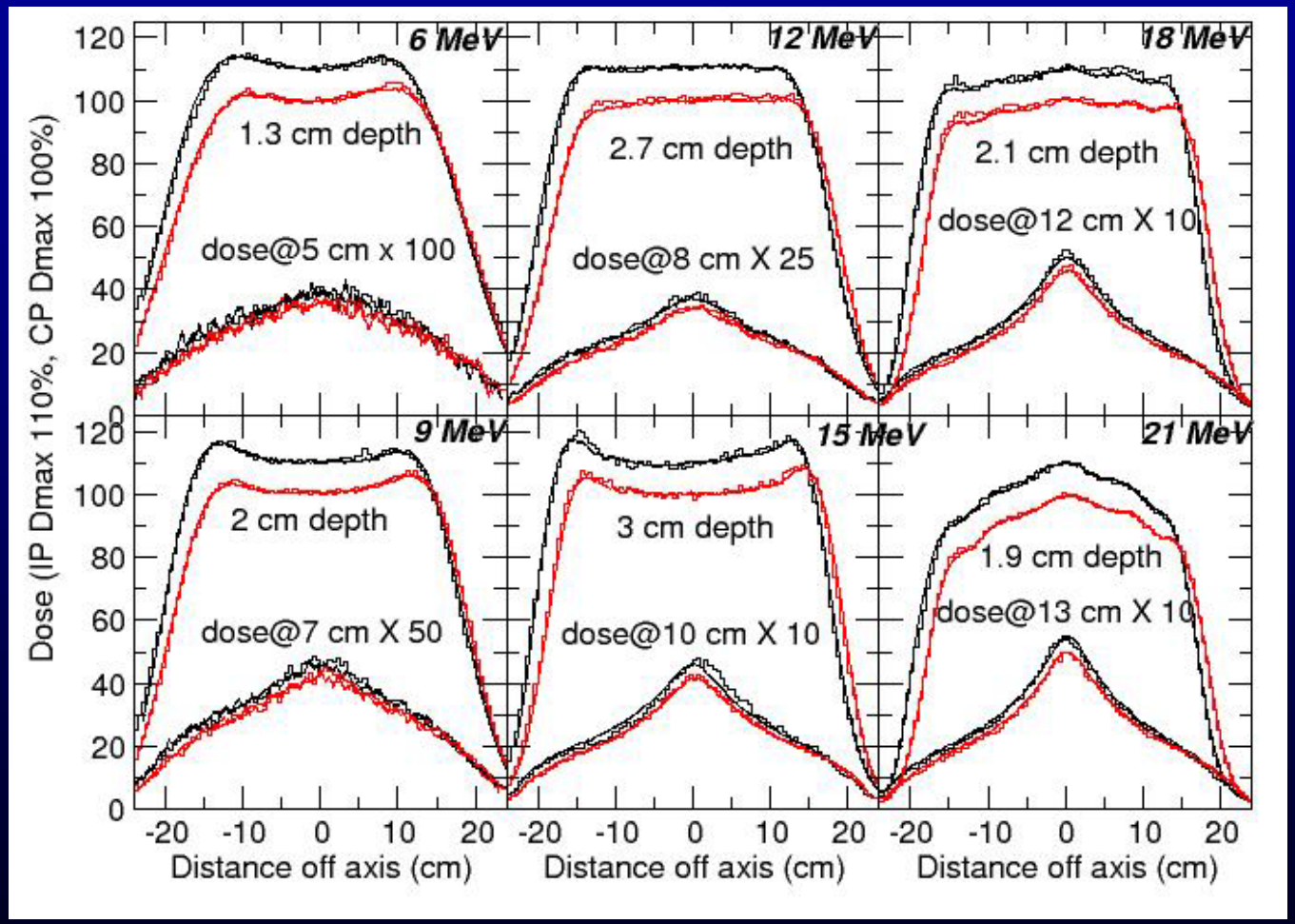
Choose your code wisely…
D_{Rp}/D_{max} correct with EGSnrc (steps)



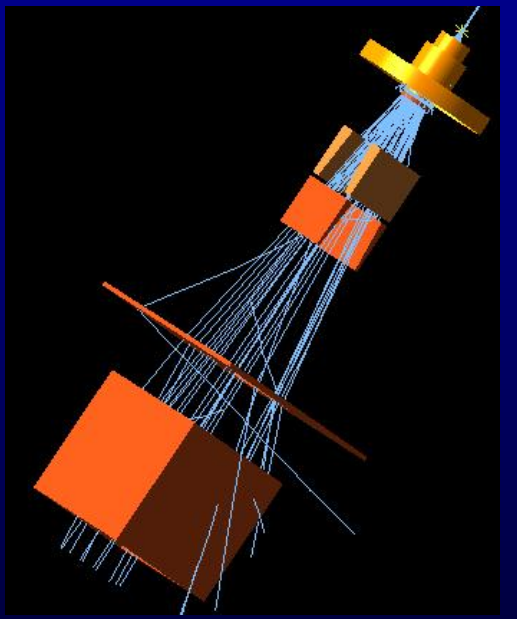
B.A. Faddegon, *"A higher accuracy electron beam model based on large field measurements,"* Med Phys 32(6):SU-FF-T-260:2010 (2005)

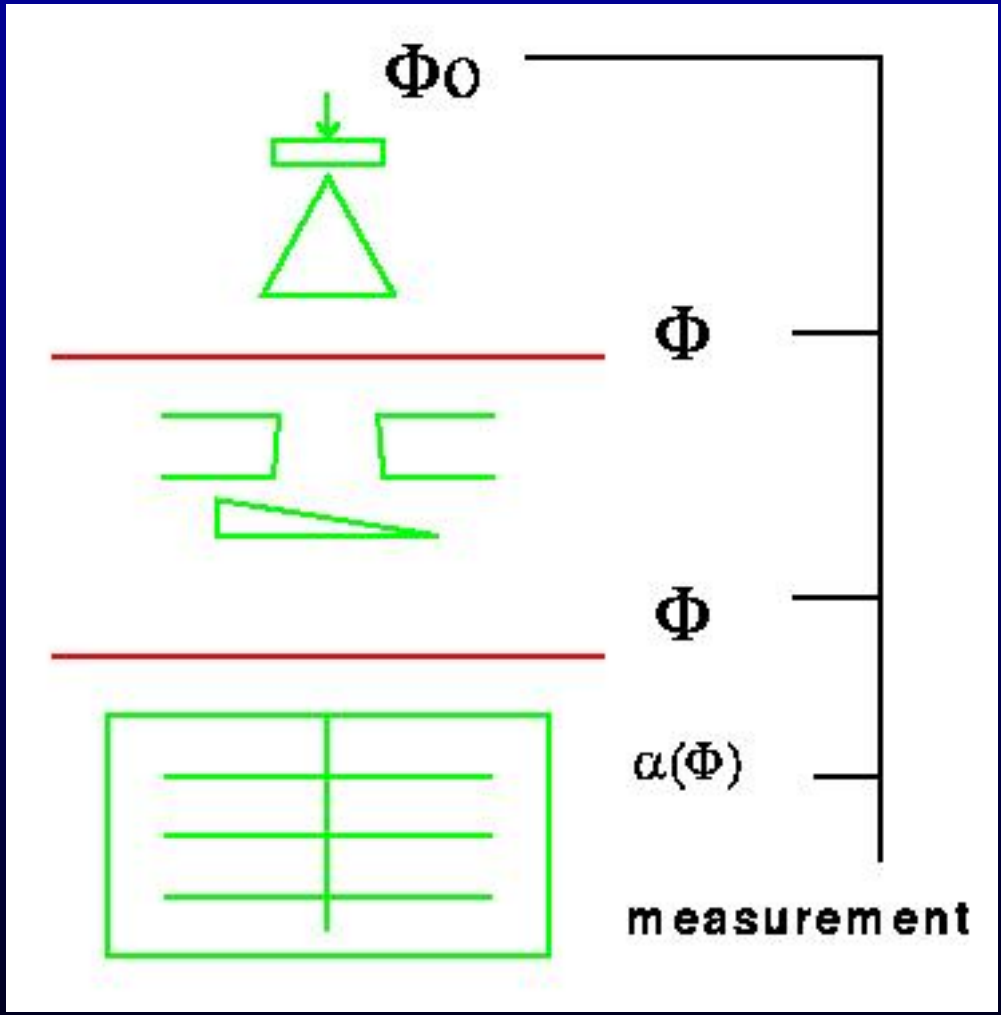
Beam modeling
Objective and terminology

- The objective of beam modeling is to accurately predict dose measured for an individual treatment unit.
- A complete beam model consists of a mathematical representation of the beam along with a procedure to reconstruct the fluence.
- The beam is generally characterized from dose measurements, that is, a comprehensive sampling of output, dose distribution and transmission.
- To commission a beam model, parameters are adjusted to match calculated dose with the measurements.
- An ideal model will apply to the full range of field sizes (up to 40 cm wide), shapes (square, circular, and irregular), and beam modifiers (inserts, surface shields).

C.-M. Ma, B.A. Faddegon, D. W. O. Rogers, and T. R. Mackie, "*Accurate characterization of Monte Carlo calculated electron beams for radiotherapy*," Med. Phys. 24(3):401 (1997)

Fluence from measurement

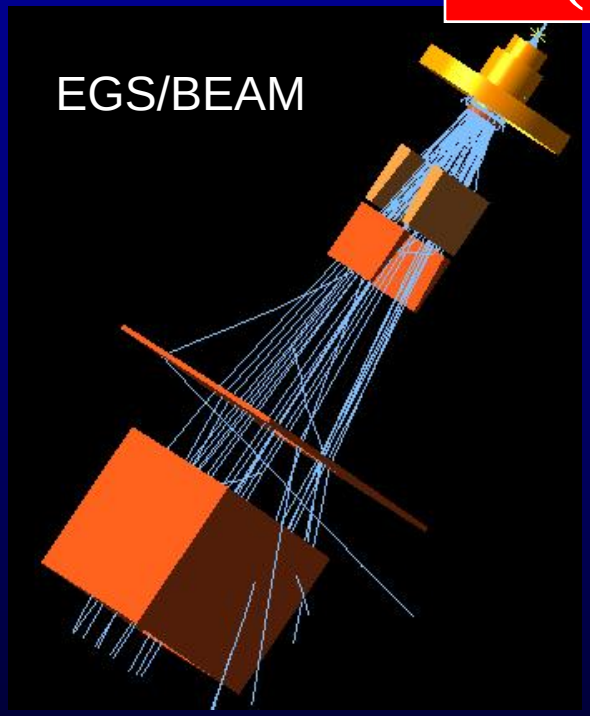


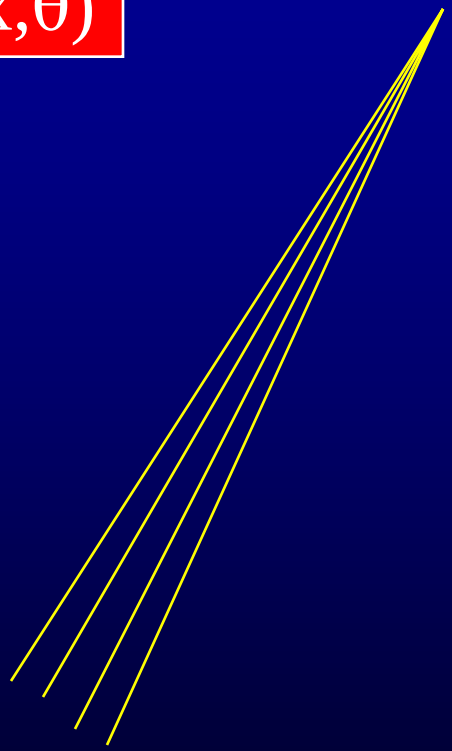


TREATMENT HEAD SIMULATION	OUTPUT AND DOSE MEASUREMENT
Accurate in fluence and dose	Fit to dose, fluence may be less accurate
Relies on measurement for source details and geometry adjustment	Could be independent of simulation
Highly detailed	Dose-sensitive detail only
Tunable - but what to adjust?	Fewer parameters, easier to tune
Full simulation takes time	No simulation, reconstruction fast
Requires accurate and detailed geometry	Source and geometry details not required

A simple beam model:
Point source with energy spectrum

$\Phi o(E,x,\theta)$



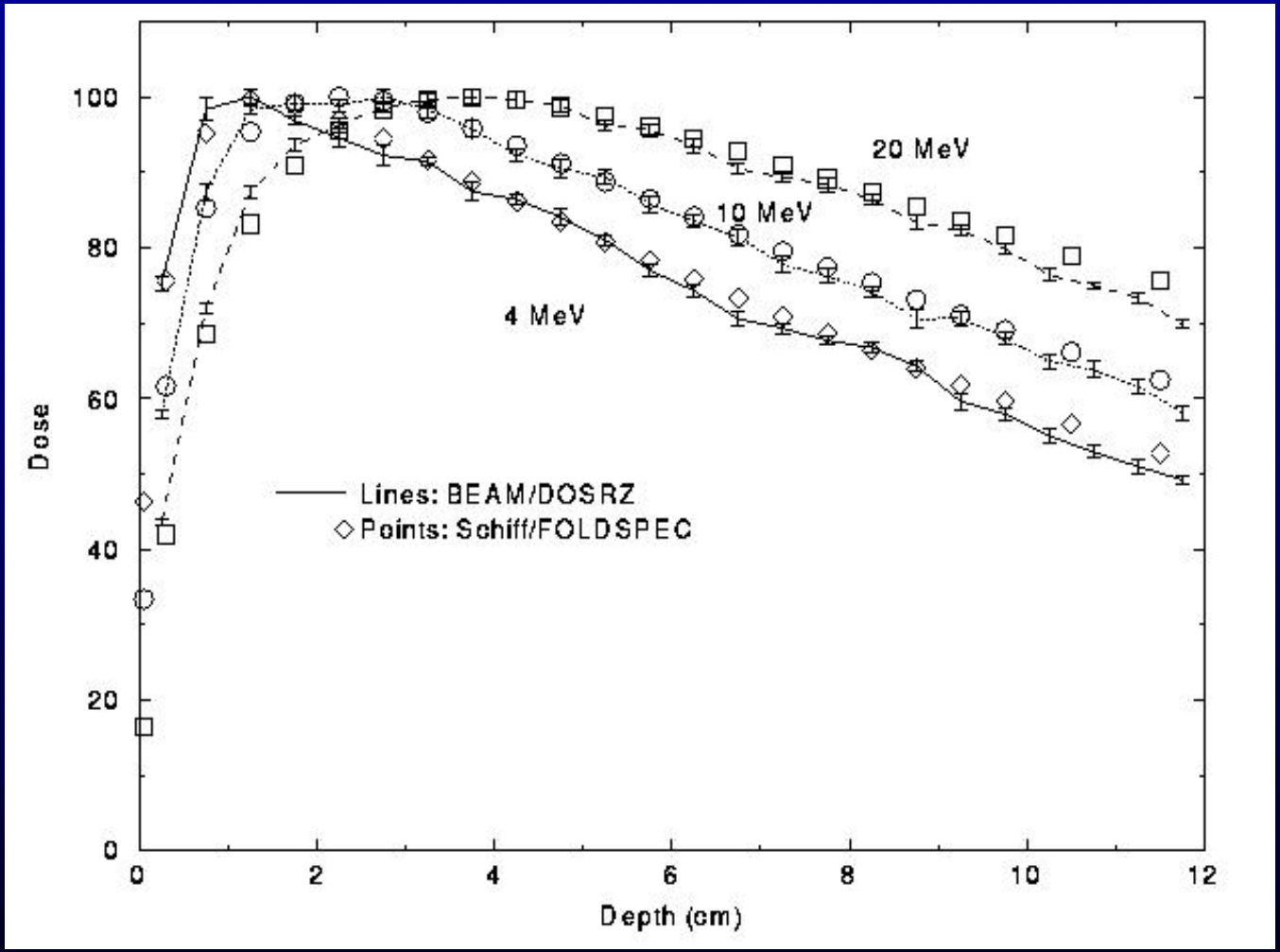


$\Phi o(E)$

$\Phi(E,x,\theta,L)$

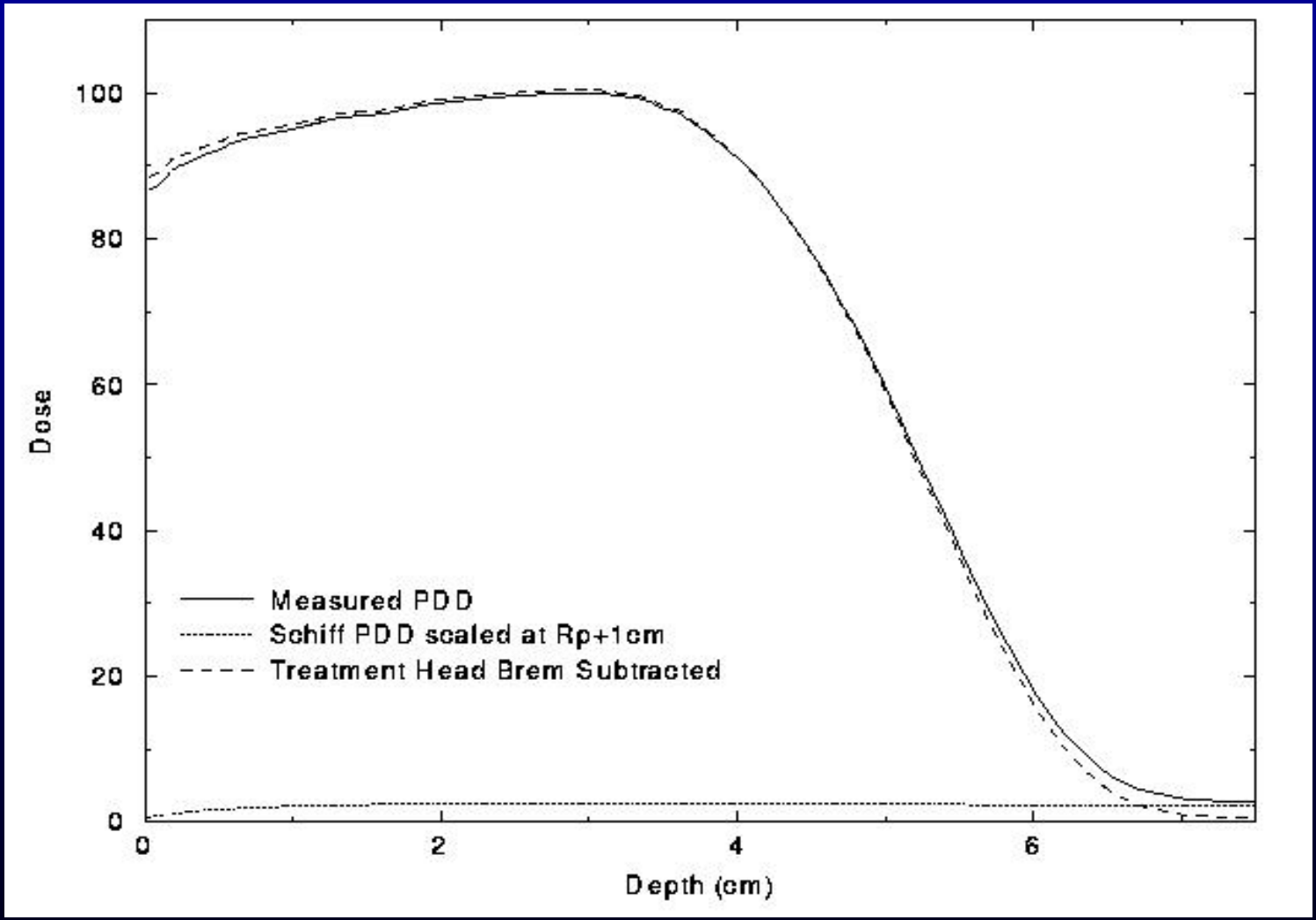
$\Phi(E,x,\theta)$

Treatment head bremsstrahlung



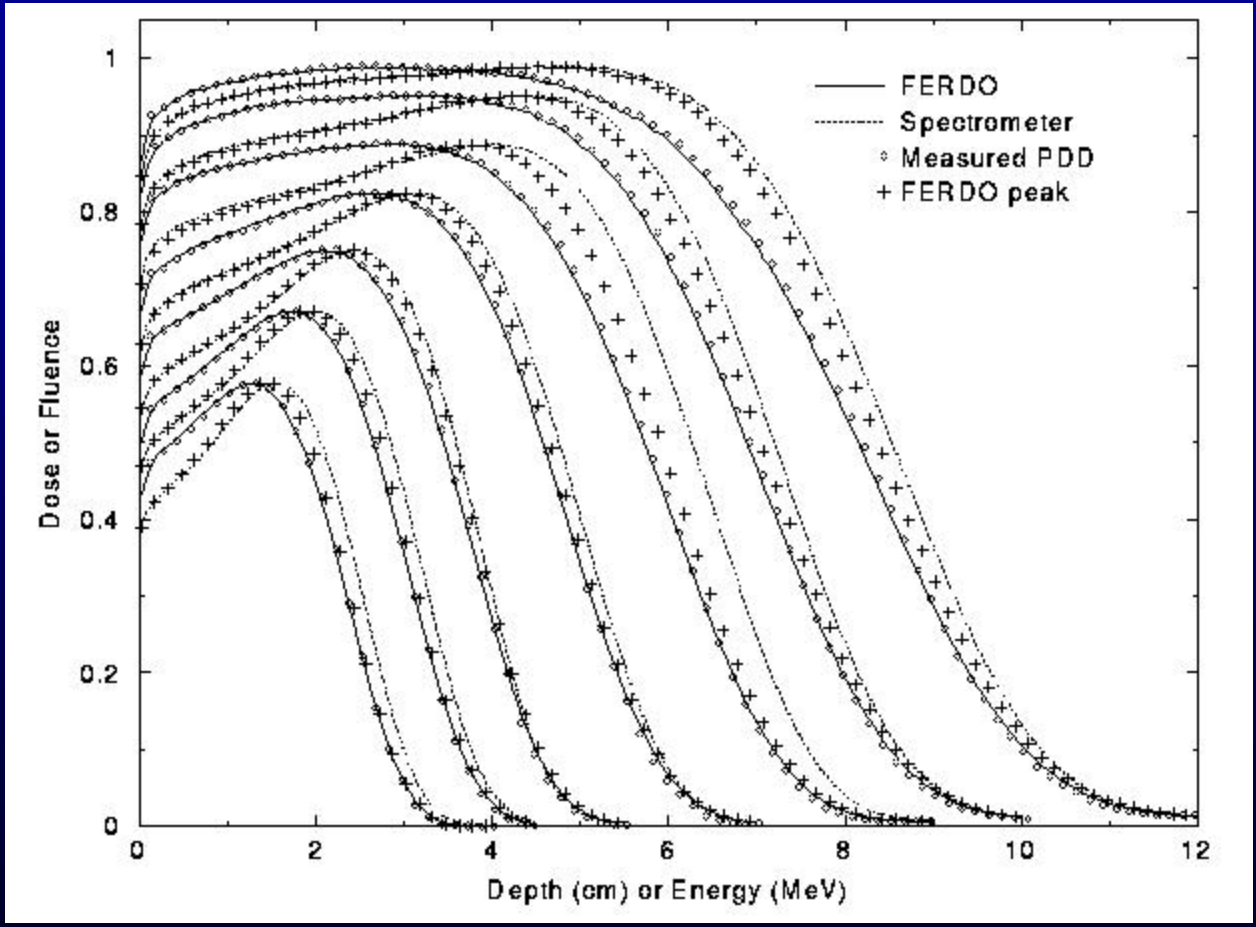
B.A. Faddegon, I. Blevis, "*Electron spectra derived from depth dose distributions,*" Med. Phys. 27(3):514-526, July, 2000;

Bremstrahlung subtraction



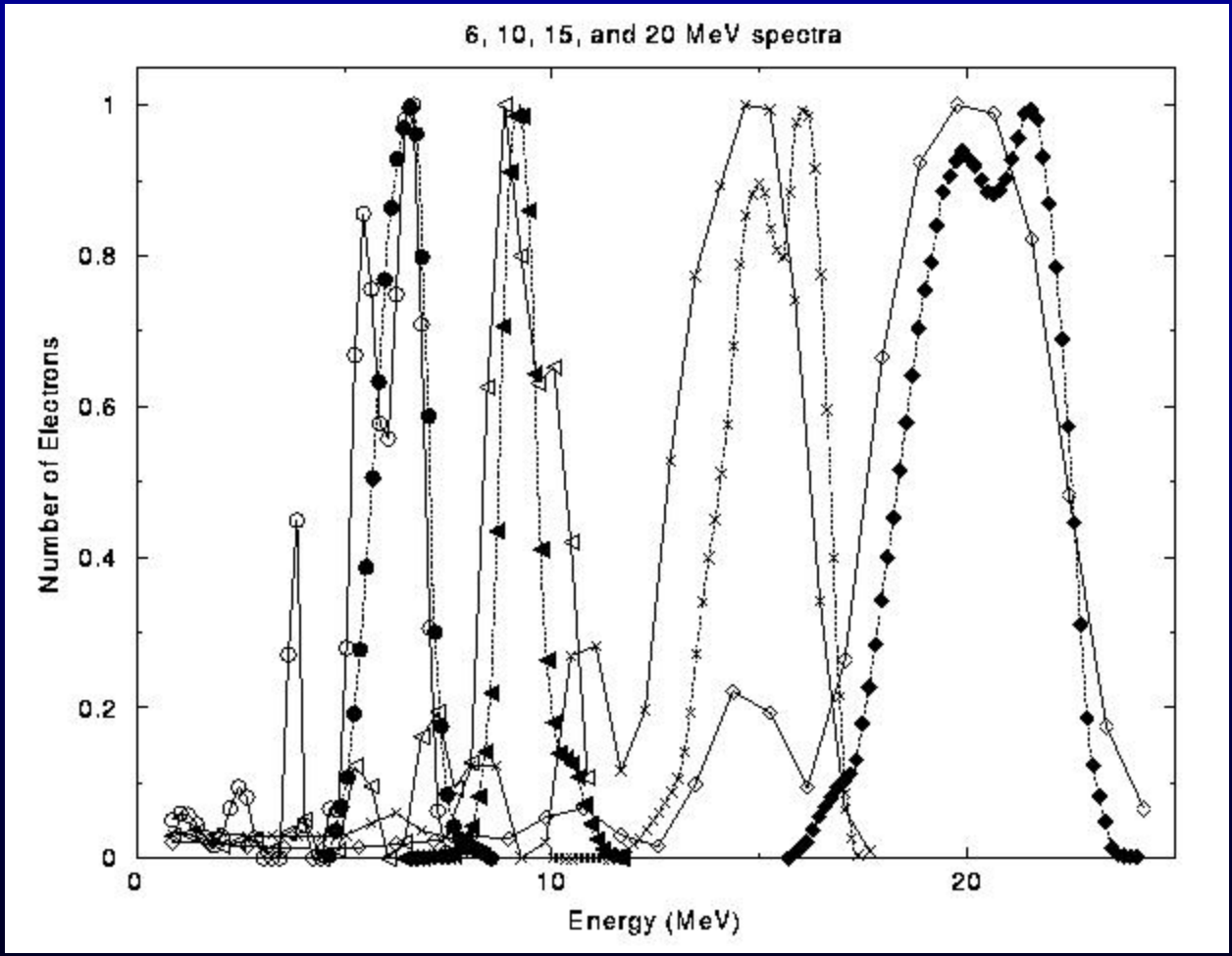
B.A. Faddegon, I. Blevis, "*Electron spectra derived from depth dose distributions,*" Med. Phys. 27(3):514-526, July, 2000;

Elekta depth dose curves:
Spectrometer vs unfolding (FERDO)



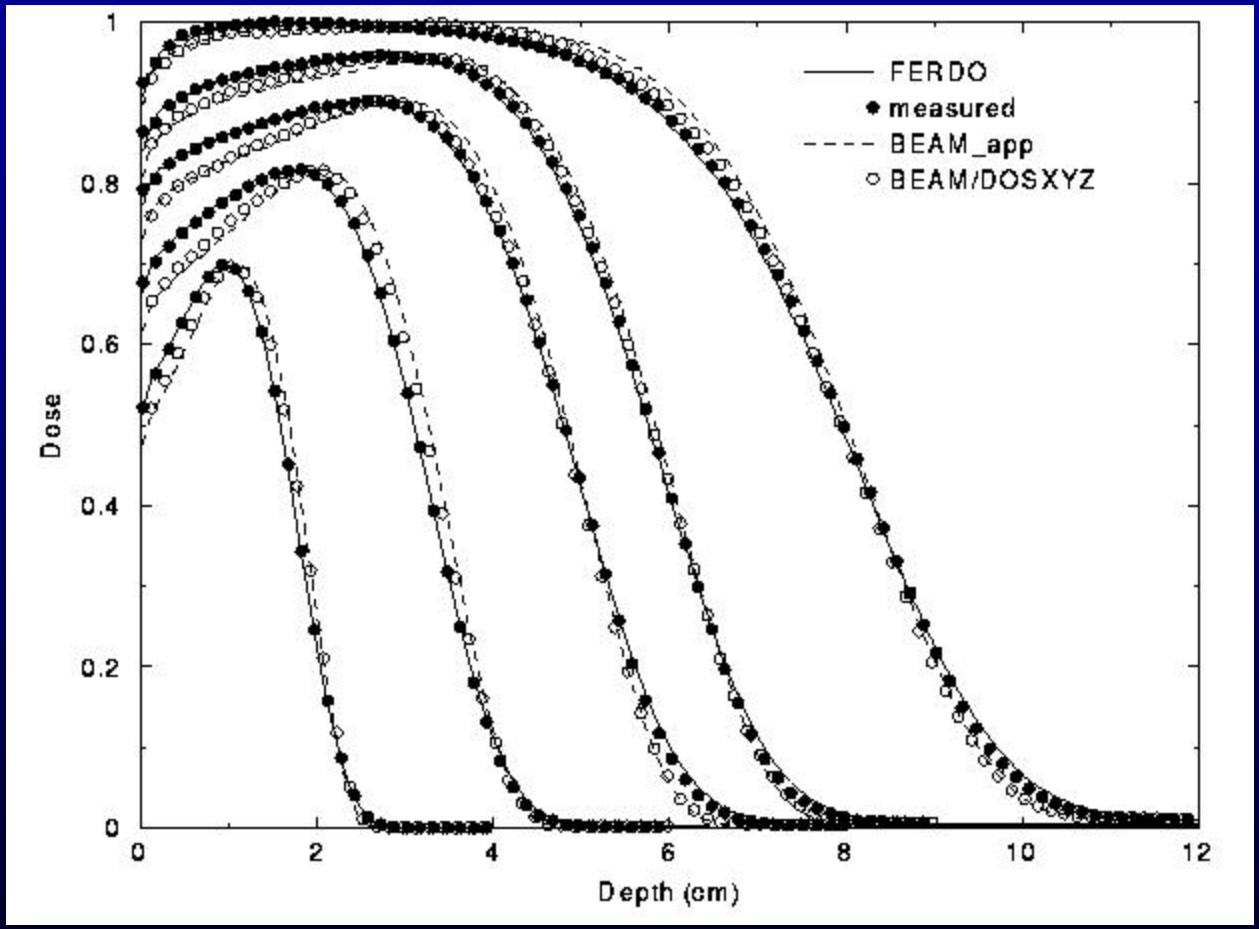
B.A. Faddegon, I. Blevis, "*Electron spectra derived from depth dose distributions,*" Med. Phys. 27(3):514-526, July, 2000;

Elekta spectra:
Spectrometer (dotted) vs unfolding (solid)



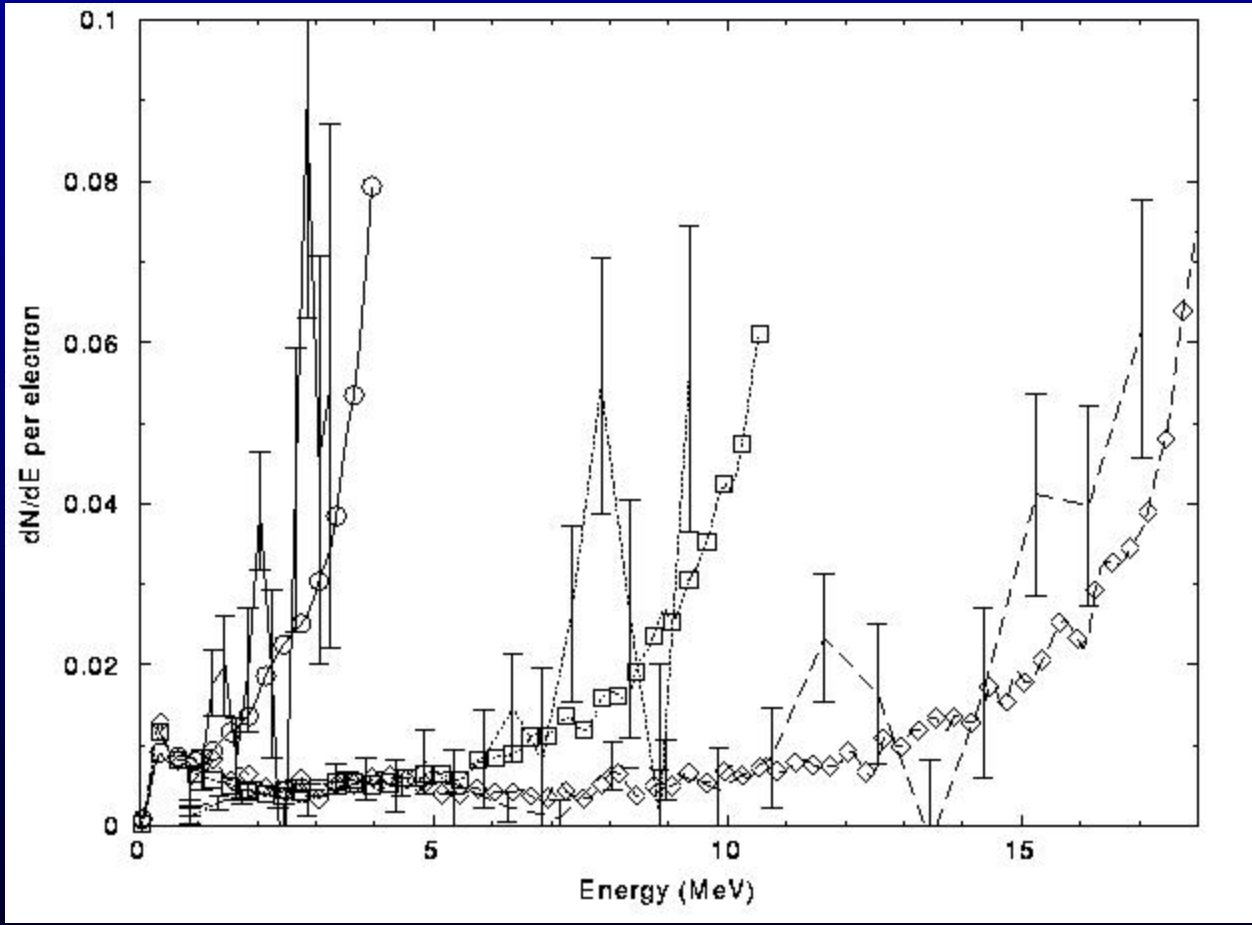
B.A. Faddegon, I. Blevis, "*Electron spectra derived from depth dose distributions,*" Med. Phys. 27(3):514-526, July, 2000;

Elekta depth dose curves:
MC vs unfolding (FERDO)



B.A. Faddegon, I. Blevis, "*Electron spectra derived from depth dose distributions,*" Med. Phys. 27(3):514-526, July, 2000;

Elekta spectra:
MC (error bars) vs unfolding (symbols)



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Part I: Conclusions

- MC is an accurate method for detailed modeling of electron beams used in radiotherapy
- MC codes are under continuous development and will improve in speed and accuracy with time
- Treatment head simulation is greatly facilitated by knowledge of the sensitivity of output and dose distributions to source and geometry parameters
- Treatment head simulation is difficult and time consuming
- Simplified beam models have the advantage of ease of commissioning with potential for high accuracy and detail in the dose-critical fluence details.

Part II: Simulation of Applicators, Cutouts and Relative Output Factors for Electron Beams

Joanna E.Cygler, Ph.D., FCCPM

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University of California San Francisco

Part II: Outline

- Simulation details of electron applicators and cutouts
- Angular and spectral distribution of electrons for various field sizes
- Analysis of MC simulated PDD
- Comparison of MC calculated and measured PDD
- Typical simulation times
- Electron beam MLC
- Conclusions

List of typical linac head components in electron mode

- Exit window
- Primary scattering foil (unless scanned beam)
- Primary collimator
- Secondary scattering foil (unless scanned beam)
- Monitor chamber
- Mirror (may be retracted)
- Secondary collimators (jaws, MLC)
- Reticule or cross-hairs (may be removed)
- Applicator
- Inserts or cut-outs

Input information needed

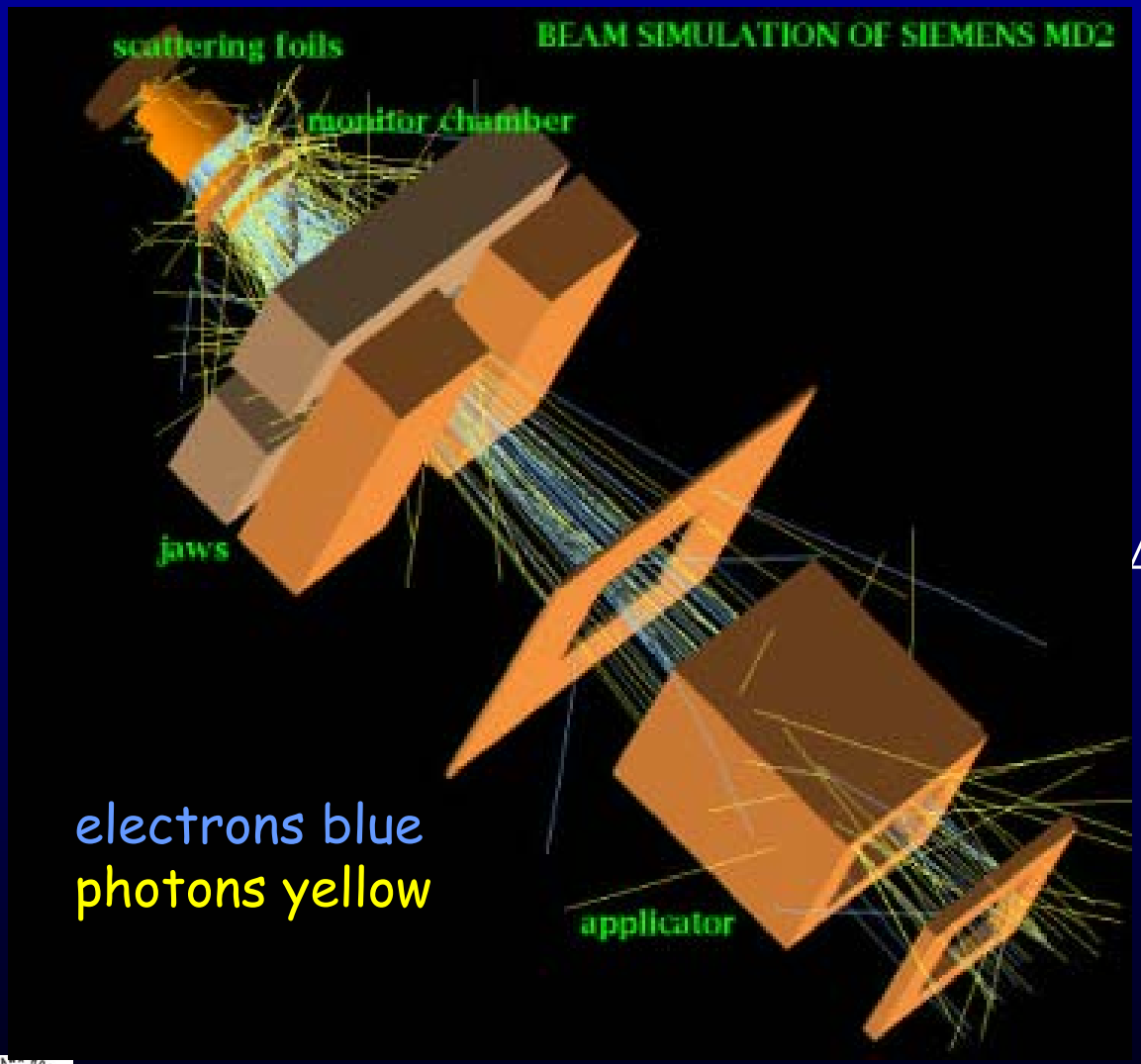
Treatment unit specifications:

- Geometrical description of the machine head components
- For each applicator scraper layer:
  - Thickness
  - Position
  - Shape (perimeter *and edge*)
  - Composition
- For inserts:
  - Thickness
  - Shape
  - Composition

Simulation steps

- The accelerator head is composed of a series of component modules, CMs, which represent exit window, primary collimator, scattering foil, monitor chamber, *x* and *y* jaws, applicator, and so on.
- A mono-energetic electron pencil beam is incident on the exit window

Siemens MD2-BEAM simulation



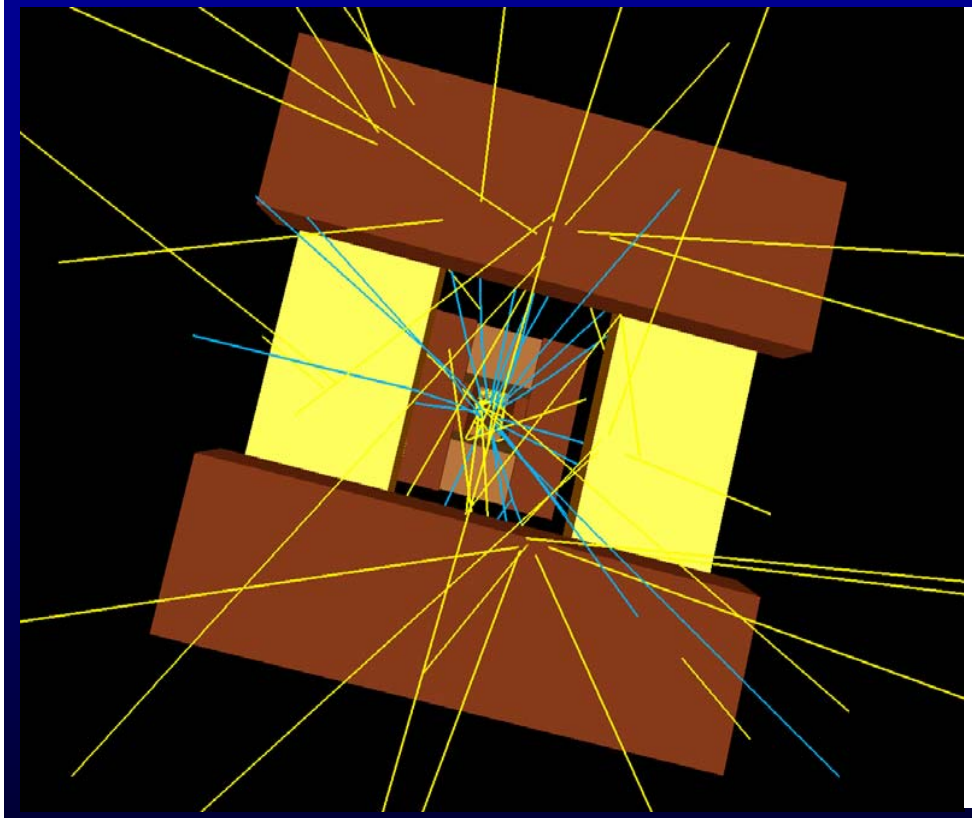
electrons blue
photons yellow

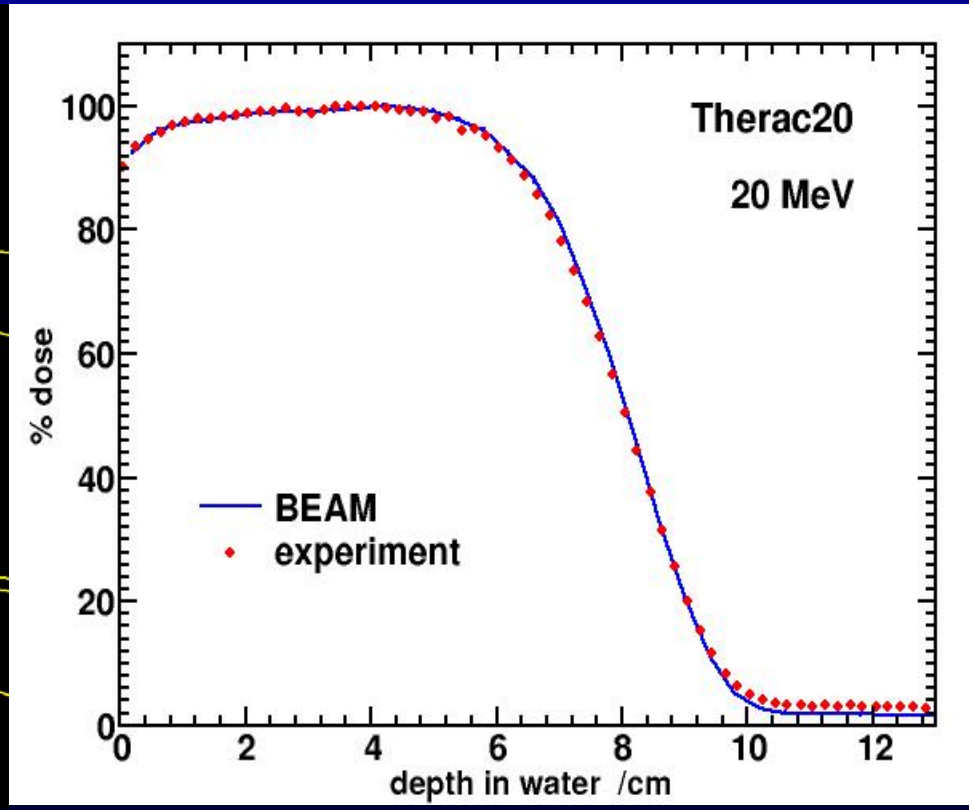
Incident energy is adjusted to match R_{50}

$$\Delta E_{incident} = 2.33 \Delta R_{50}$$

Zhang et al. Med.Phys. ***26*** *(1999) 743-750*

Tumour's eye-view and PDD



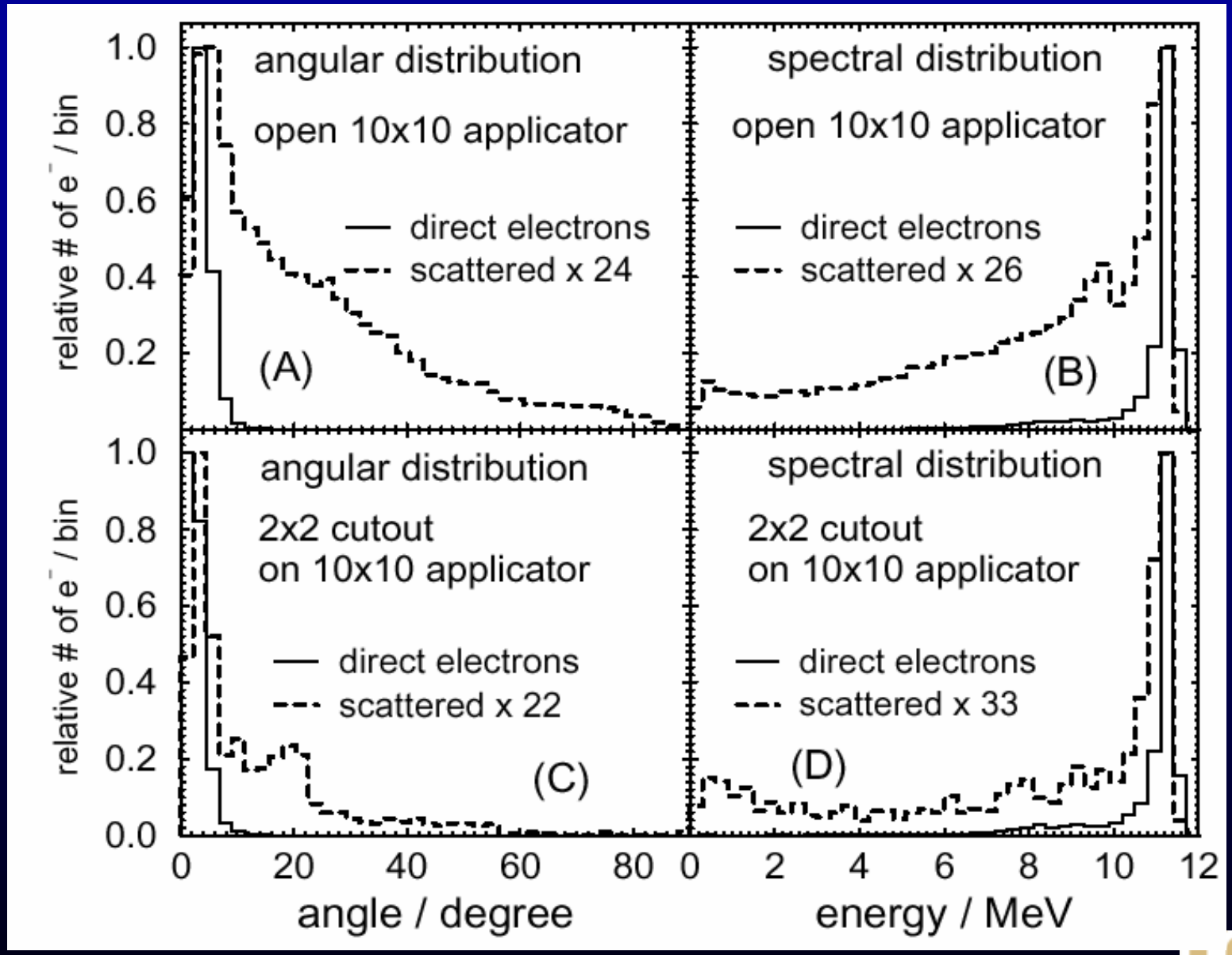


Courtesy of D.W.O. Rogers. Carleton University, Ottawa, Canada

Simulation details of electron applicators and cutouts

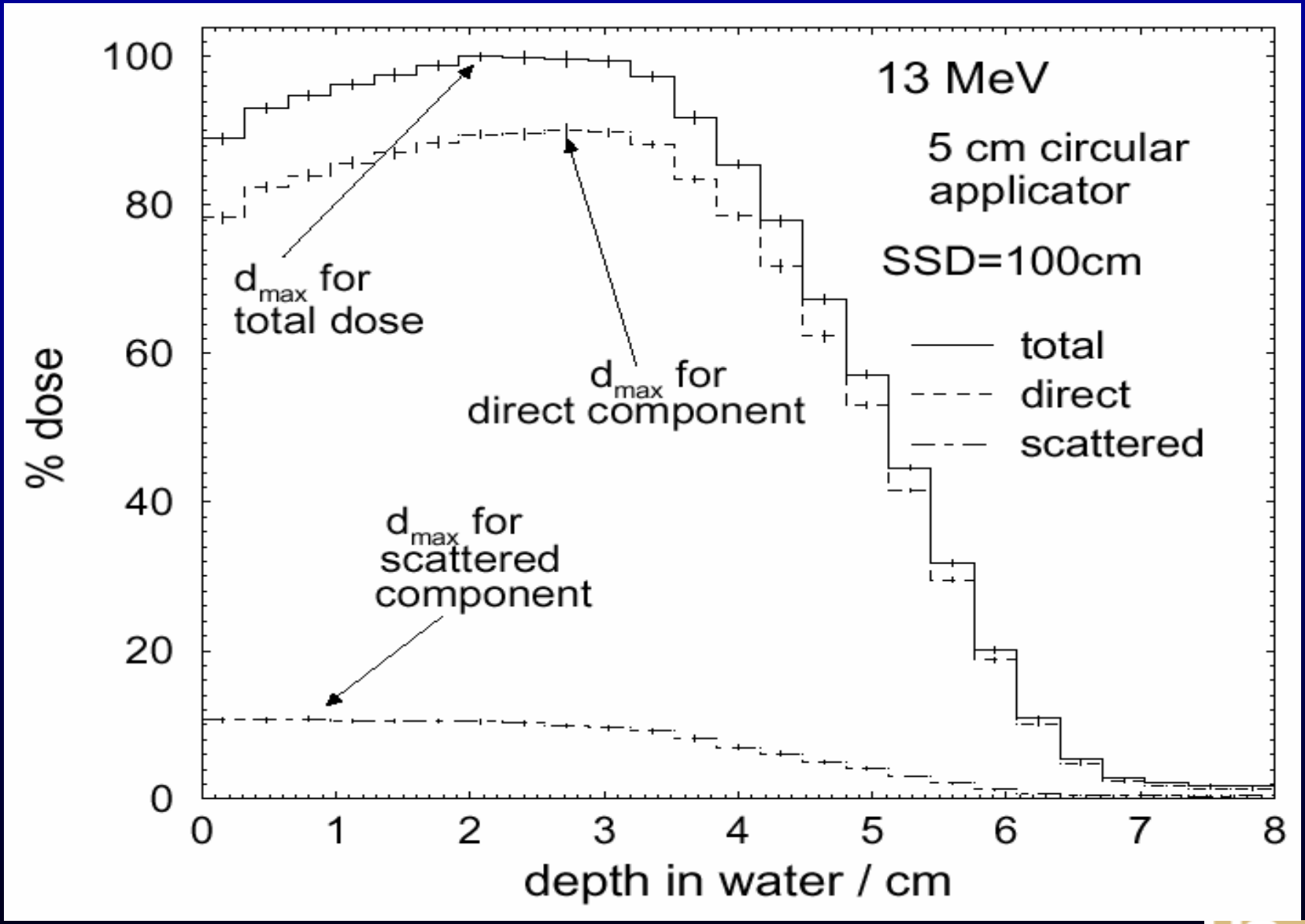
- Phase space file
  - At the end of applicator (just before the level the cutout goes in)
  - Can be used as input file for cutout simulation
  - Has to be created for each energy / applicator combination

11 MeV- angular and spectral distributions



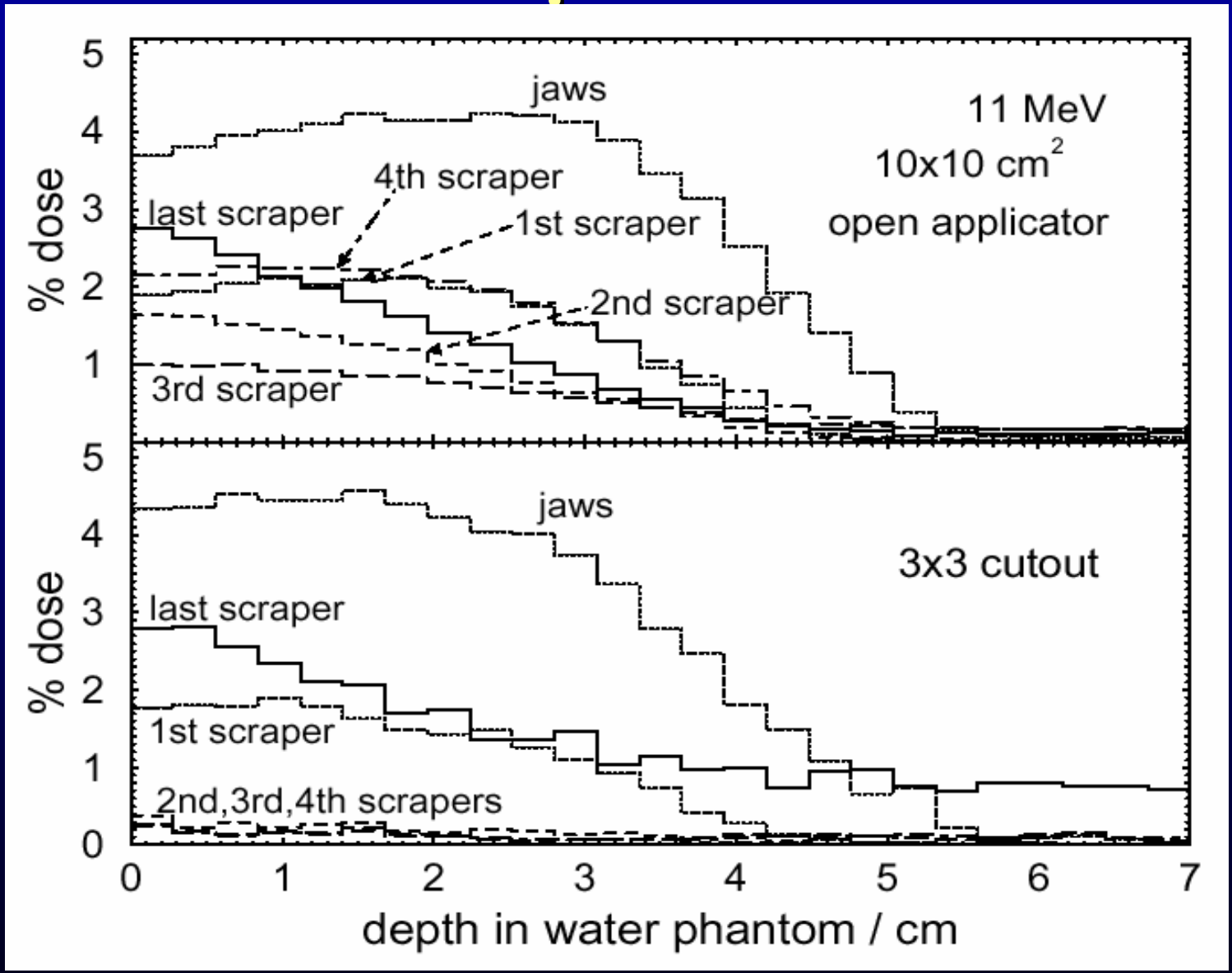
Zhang et al. Med.Phys. ***26*** *(1999) 743-750*

PDD – direct and scattered components



Zhang et al. Med.Phys. ***26*** *(1999) 743-750*

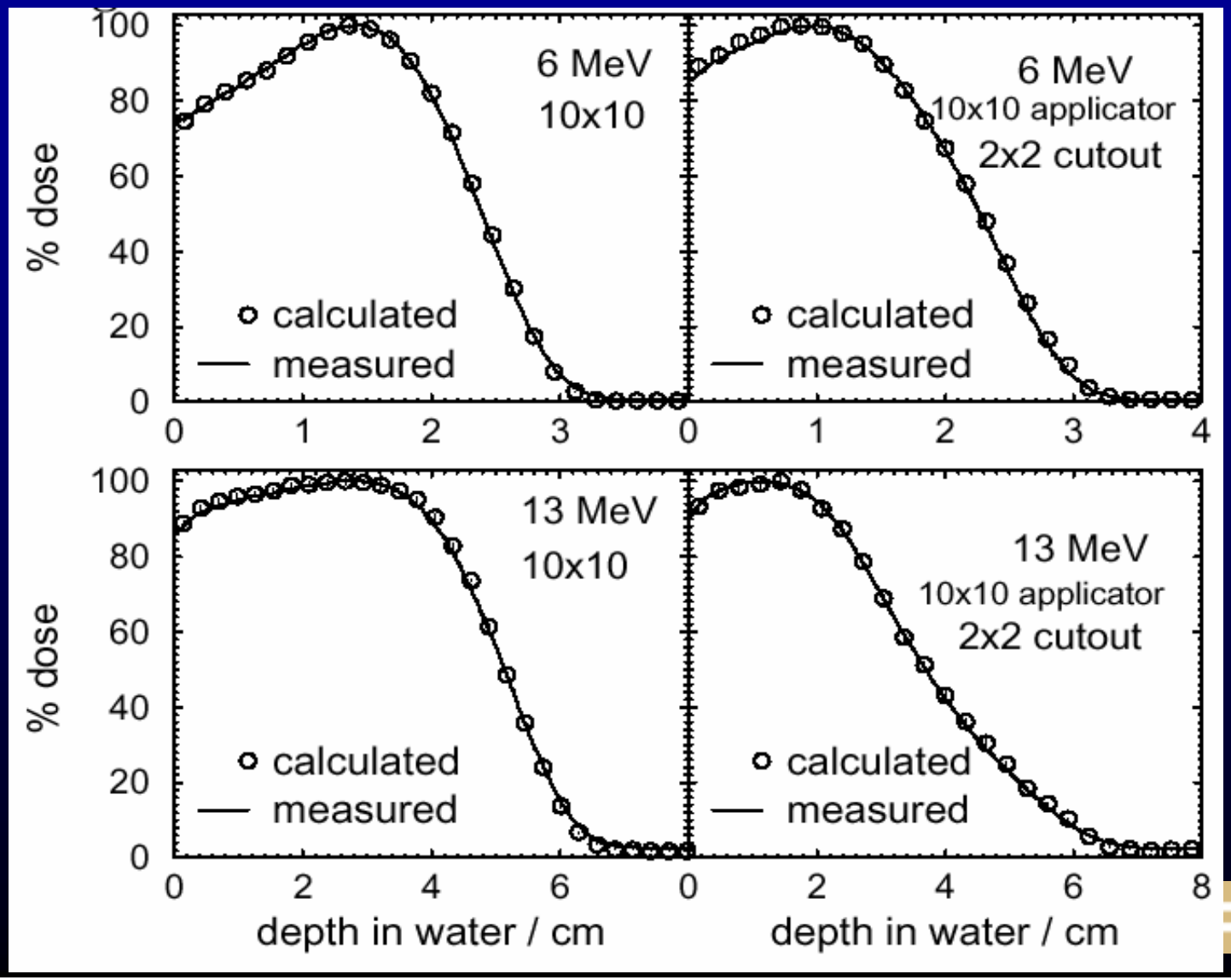
Scatter components of PDD



Zhang et al. Med.Phys. ***26*** *(1999) 743-750*

PDD-comparison of measured and calculated with BEAM code

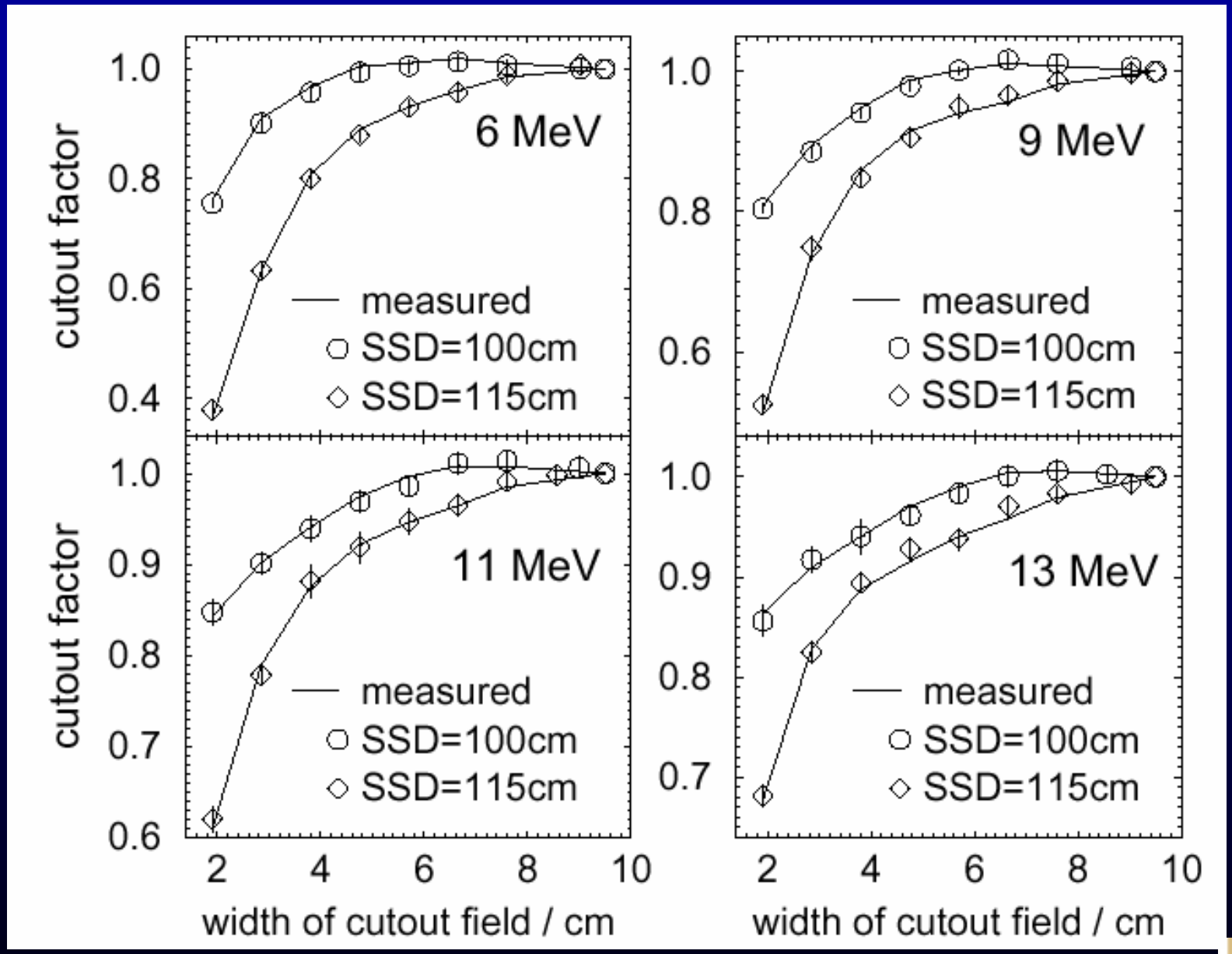
Zhang et al. Med. Phys. 25 (1998) 1711-1716



MC calculation of cutout factors

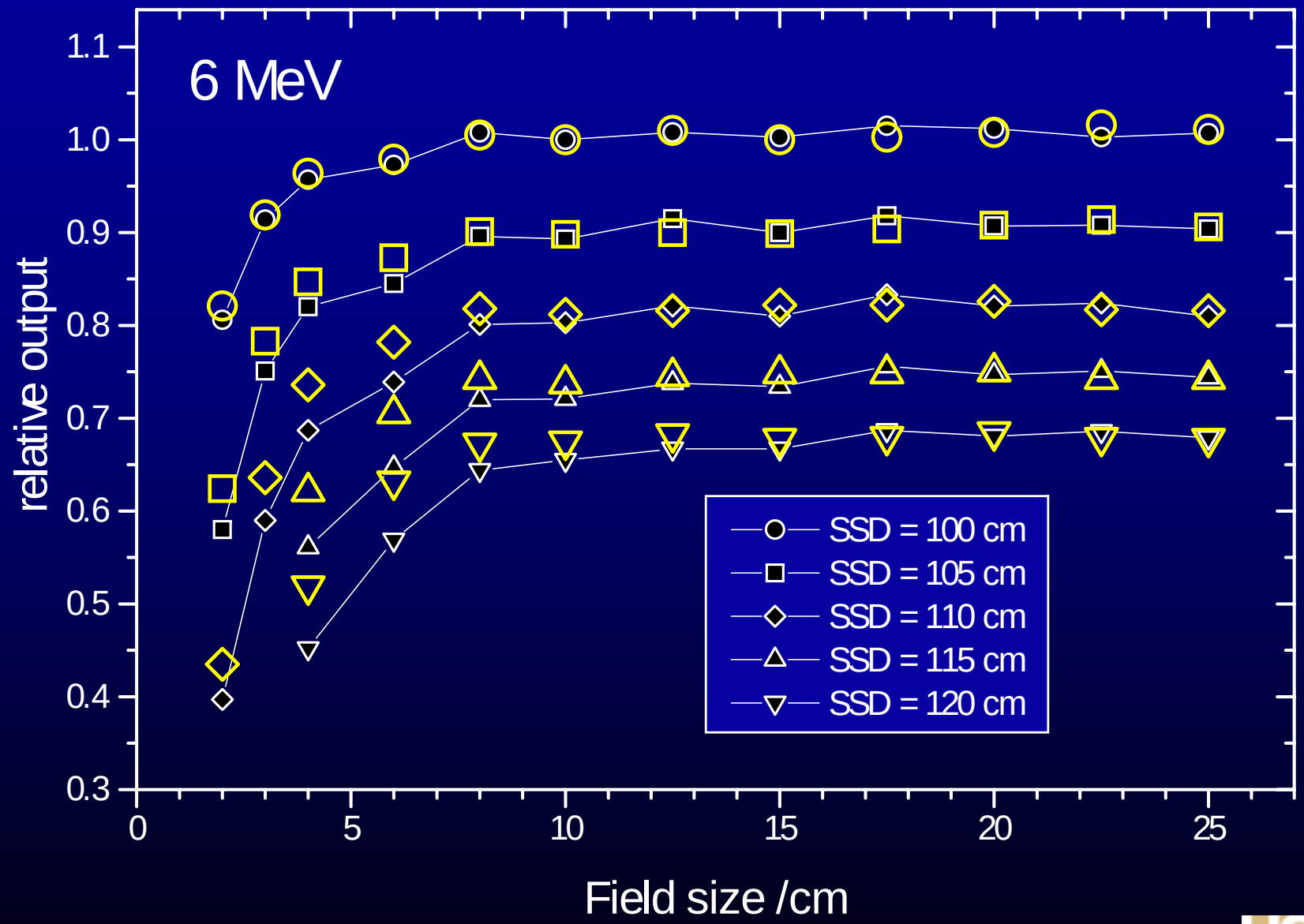
- Calculation of the cutout factors makes use of the phase space file generated at the level just above the last scraper of the applicator.
- The only variable here is the cutout size.
  - cutout factor calculations are less sensitive to the details of the upstream collimation geometry, than calculations of the applicator factors.

Cutout factors - BEAM vs. experiment



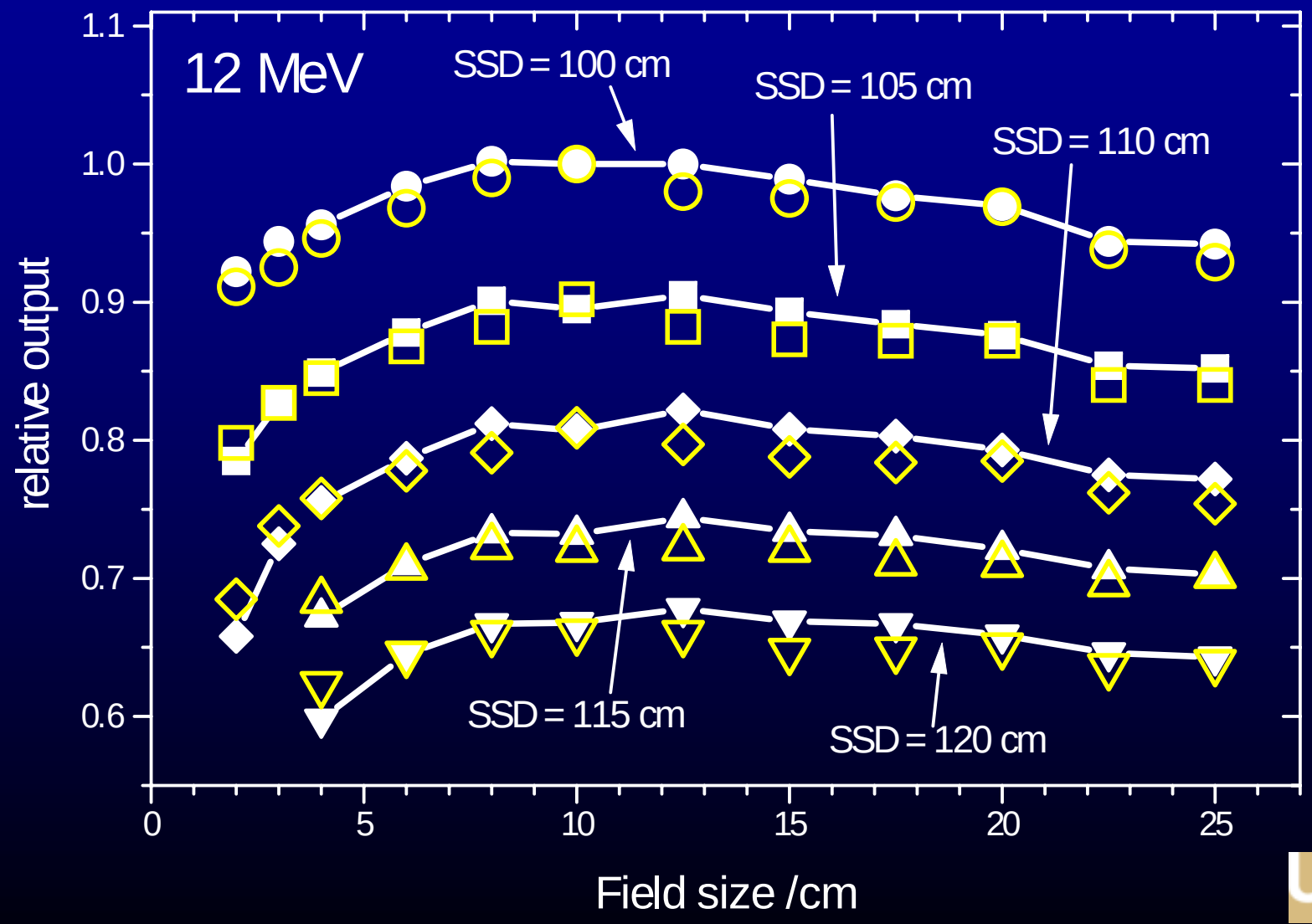
Zhang et al. Med.Phys. ***26*** *(1999) 743-750*

Cutout factors – Eclipse vs. experiment

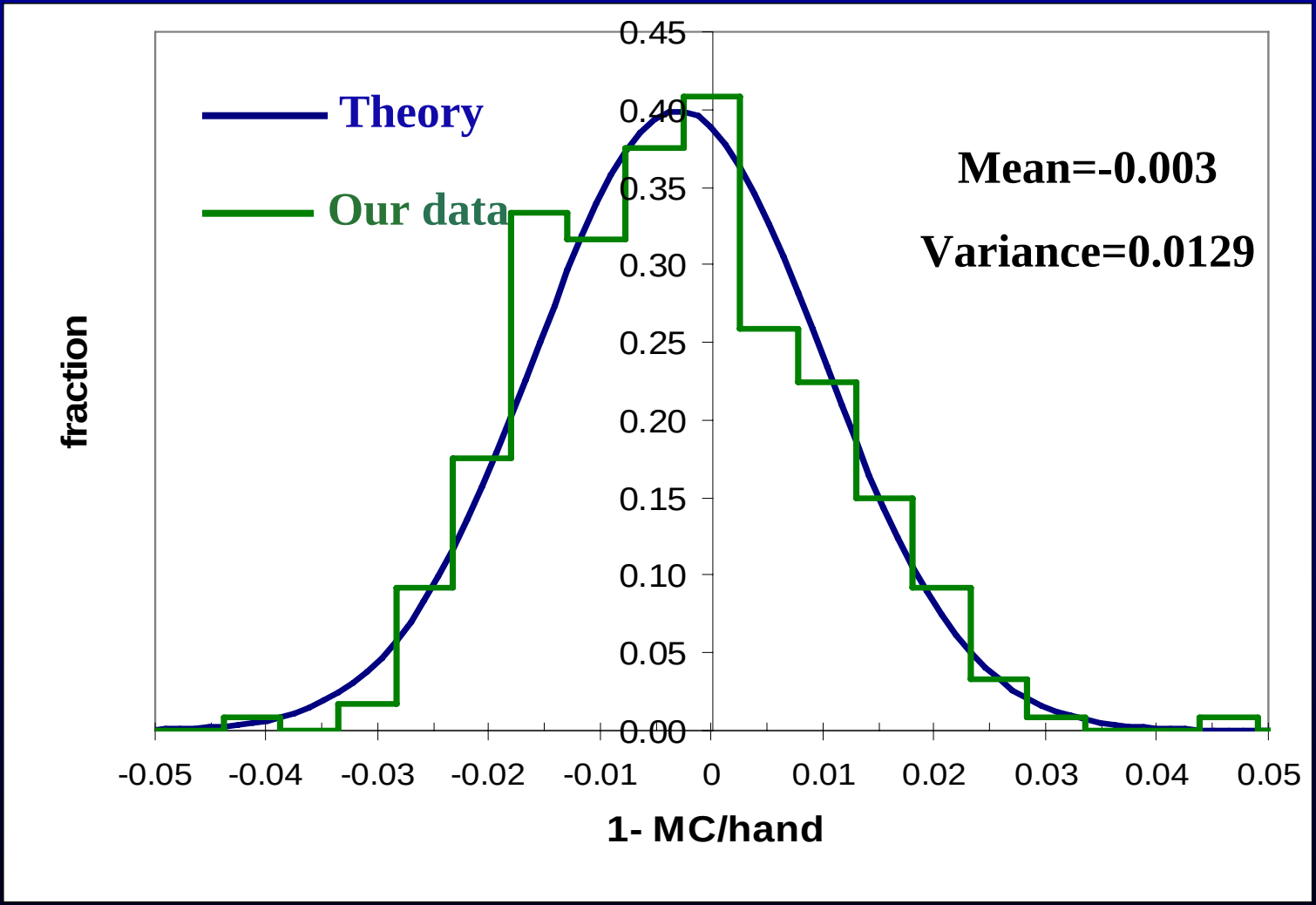


Ding et al. Phys. Med. Biol. ***51*** *(2006) 2781-2799*

Cutout factors – Eclipse vs. experiment



Overall mean and variance of MC/hand monitor unit deviation, Nucletron TPS



Cygler et al. Med. Phys. ***31*** *(2004) 142-153*

Simulation times

CPU time depends on many factors:

- complexity of the geometry
- energy of the beam
- statistical accuracy required
- selected energy cutoffs
- variance reduction techniques
- calculation voxel size

Simulation times

Single Pentium 3.0 GHz CPU, BEAM code:

- 15 minutes for the accelerator simulation
- an additional 6 minutes for each ROF

statistical uncertainty of about 1%

Simulation times – commercial systems – Nucletron TPP

- Typical calculation times on a *single CPU Pentium IV XEON, 2.2 GHz* are of the order of minutes for 1-1.5 % uncertainty (50k histories/cm^2)
  - 10x10 cm^2 field size, 4.9 mm voxel size
    - 6 MeV 4.2 min.
    - 17 MeV 8.2 min.

Simulation times – commercial systems - Eclipse

- A typical MC calculation takes about an hour on a 2 GHz CPU for a 10 × 10 cm^2 field using 100 million histories, 2 mm voxel size, and 1–2% statistical uncertainty
- It takes about 50 min of calculation time for the same voxel size using the conventional pencil beam algorithm available in the same treatment planning system.

Electron beam MLC

Energy modulated electron therapy (EMET) using Monte Carlo dose calculations is a promising technique that enhances the treatment planning and delivery of dose to superficial and moderately deep located tumors.

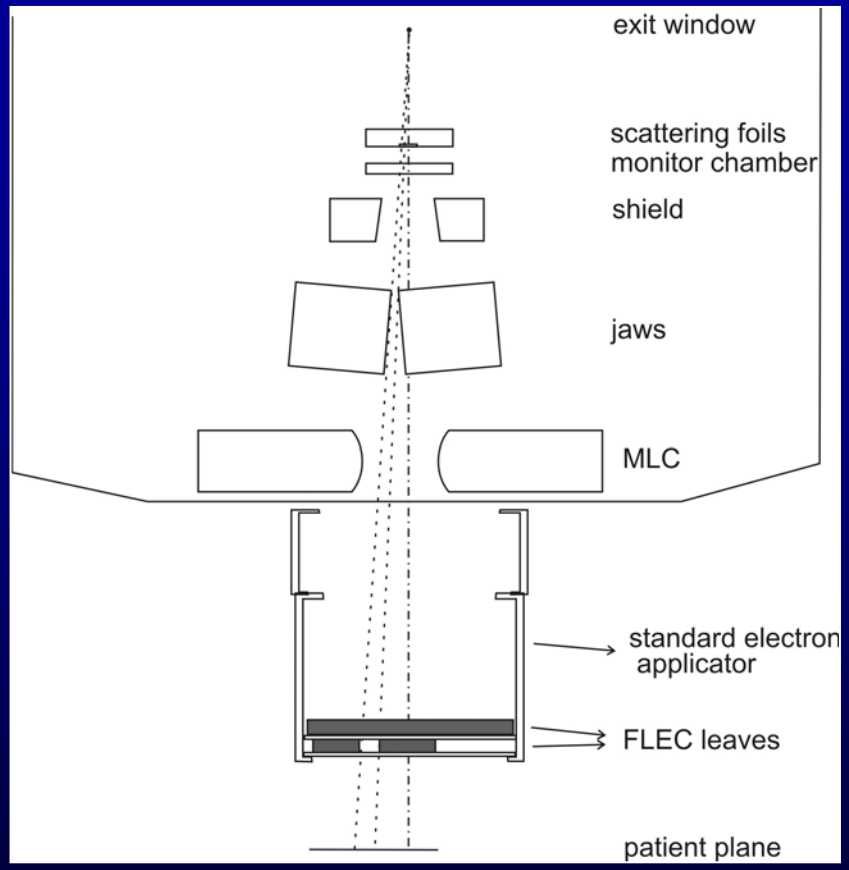
Electron beam MLC

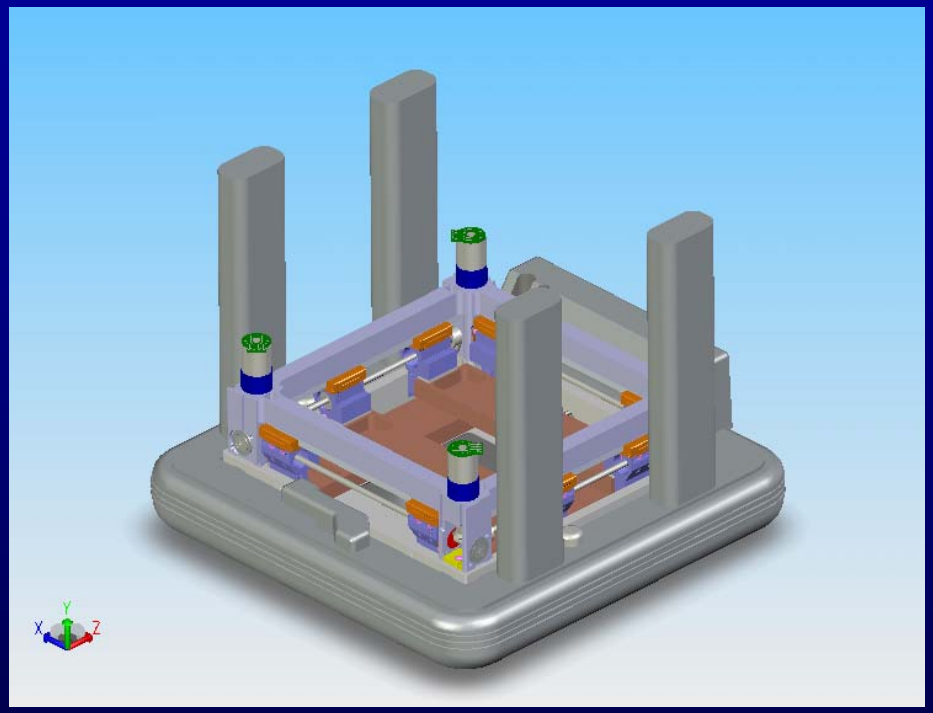
- Many leaf approach
- Few Leaf approach

MLC for electron beams

C-M Ma, et al ,Phys. Med. Biol. ***45*** *(2000) 2293–2311.*

The Few Leaf Electron Collimator





The compact design of the FLEC makes it suitable to be attached to a clinical electron applicator. FLEC can be automated and remotely controlled.

Courtesy of Jan Seuntjens, McGill University, Montreal, Canada

Part II: Conclusions

- MC is an excellent tool to model accelerator head details and beam characteristics
- Using the BEAM code or other MC code one could perform only "spot check" measurements of cutout factors and save on hours of linac commissioning.
- MC can calculate with clinically acceptable accuracy not only dose distributions but also monitor units for arbitrary shaped cut-outs and SSDs.
- New fast CPUs make the full simulation of the accelerator head clinically feasible.

Thank you