FLUKA simulations of selected topics regarding proton pencil beam scanning

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Contents

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- Simulation techniques
- Lateral scattering of pencil beams
- Integral depth-dose distributions with pencil-beam scanning (PBS)
- Large-electrode MLIC/zebra
- Neutron radiation protection
- Outlook
- Conclusions

Simulations technique

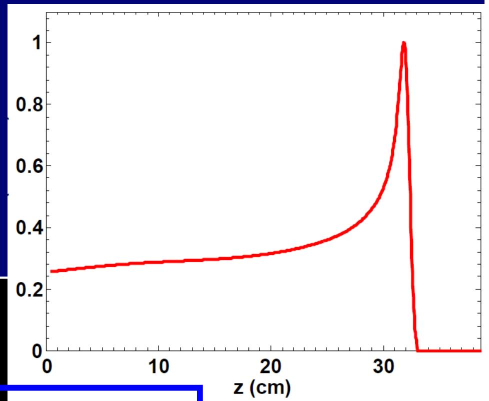
- Performed on a single workstation with 4x Intel Xeon processors, 3 GHz
- 64bit Linux Debian Lenny (with additional packages, e.g. g77, from older Etch edition)
- Most recent FLUKA and FLAIR releases
- Use combinatorial geometry
- No user routines employed and HADROTHE defaults for the projects presented today
- No variance reduction techniques
- Typically a few million primaries. Suffices for problems where primaries dominate statistics
- Mainly use USRBIN and USRYIELD estimators, post-processing in Matlab
- MCNPX 2.7 on Windows computer to cross-check some type of FLUKA simulations

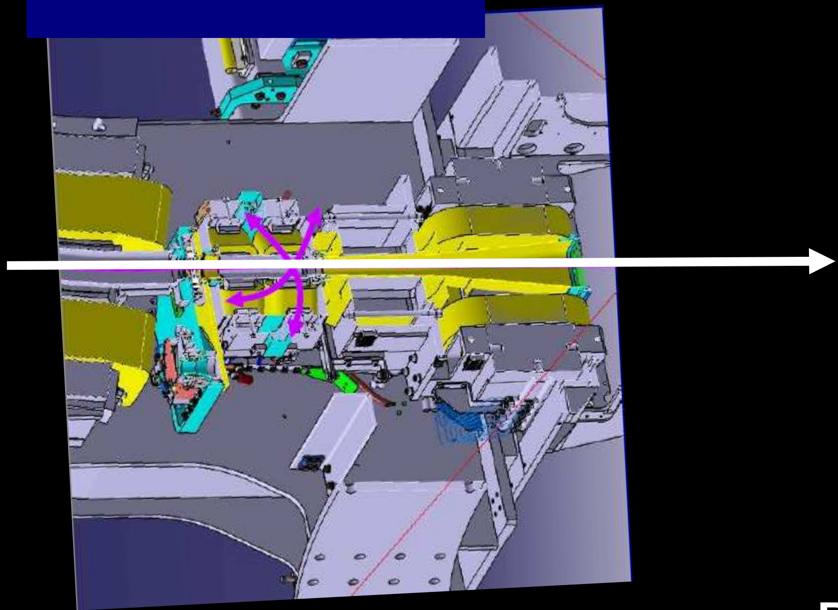
Pencil Beam Scanning

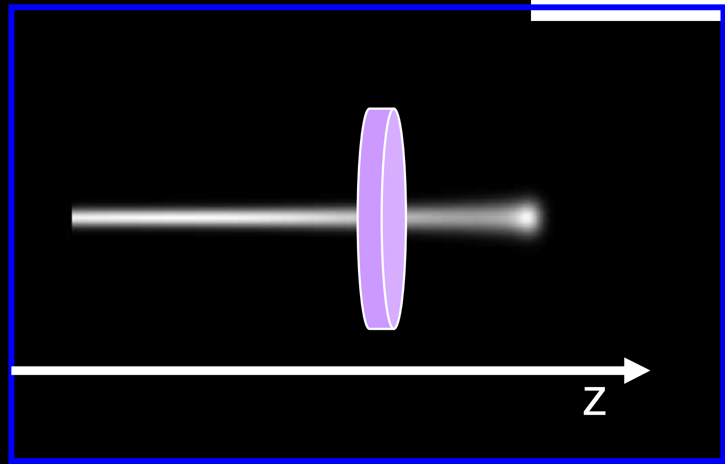
- Source: 230 MeV cyclotron with continuous energy selection
- Basic measurement: completely capture static pencil beam at depth z

Gantry mounted PBS nozzle

spot “size“ 3 mm sigma @ 230 MeV in air





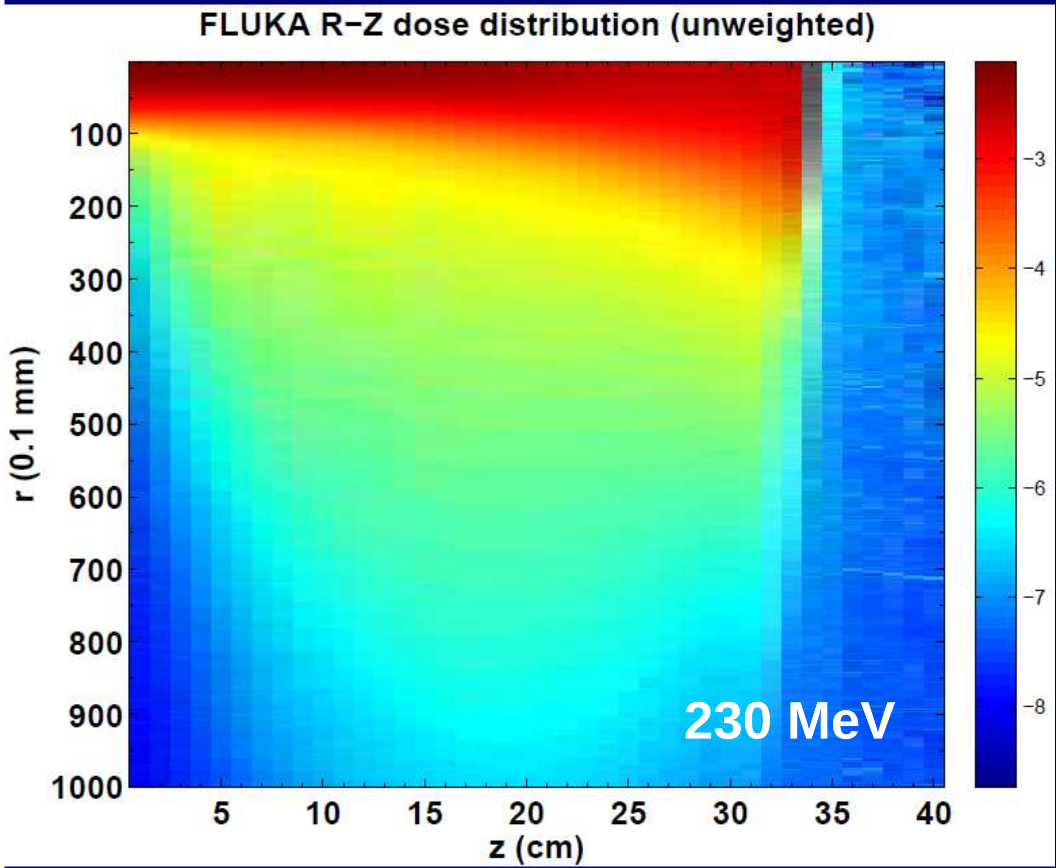


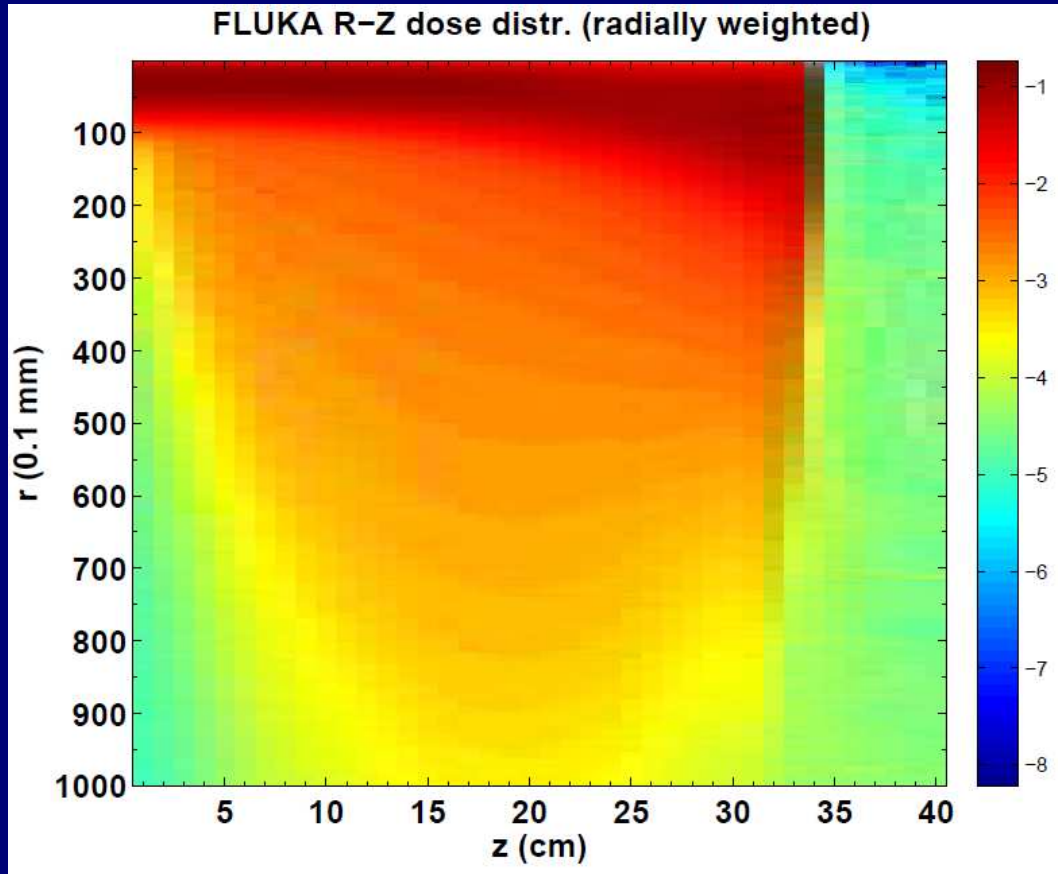
Bragg Peak ionization chamber in water tank or Multi-layer ionization chamber

Figures adapted from PTW catalog and T. Lomax, ESTRO 2009

Understanding the problem (1)

FLUKA Monte Carlo modeling performed





$$\underbrace{f(x)\,dx = \frac{1}{\sqrt{2\pi}\,x_0}\,e^{-\frac{1}{2}\left(\frac{x}{x_0}\right)^2}\,dx}$$

Radial distribution (cylindr./cartes.)

$$f(r)\,r\,dr\,d\phi = \frac{1}{2\pi\,r_0^2}\,e^{-\frac{1}{2}\left(\frac{r}{r_0}\right)^2}\,r\,dr\,d\phi$$

PDF of dose (”Radial weighting“)

Understanding the problem (2)

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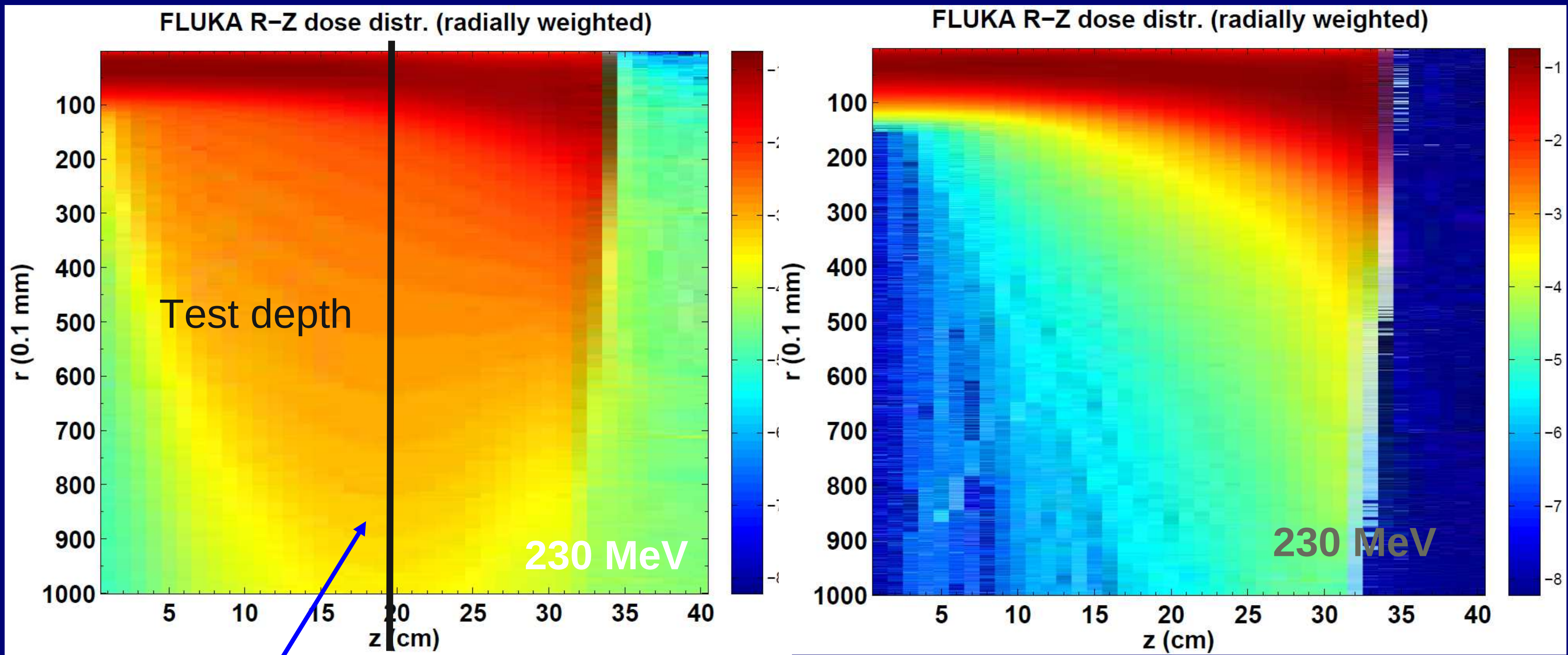
Default physics settings: | **Hadronic interactions off:**



“Low dose” enhancement at about 15 cm – 20 cm

→ Hadronic interactions direct dose to intermediate depths

Understanding the problem (3)

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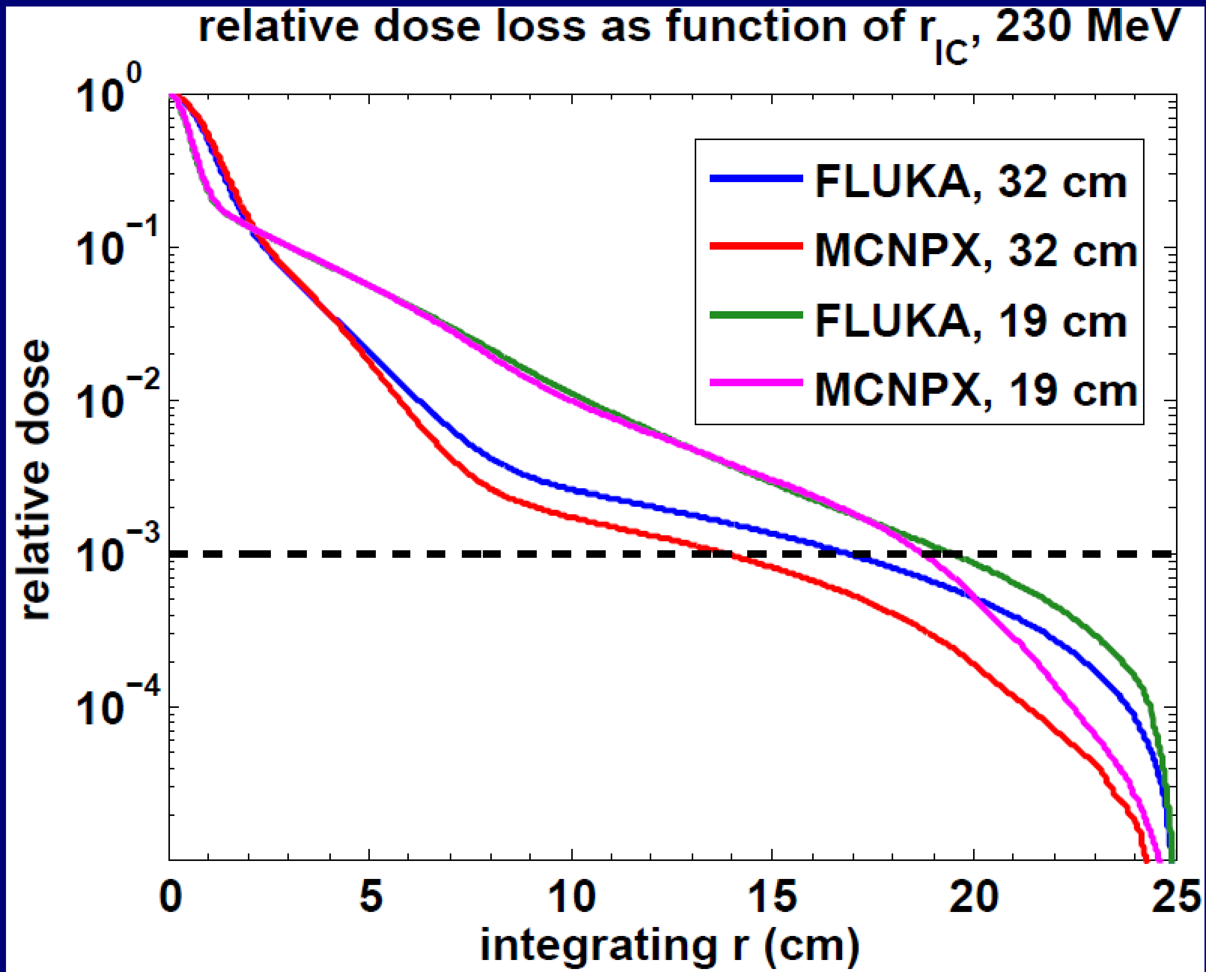
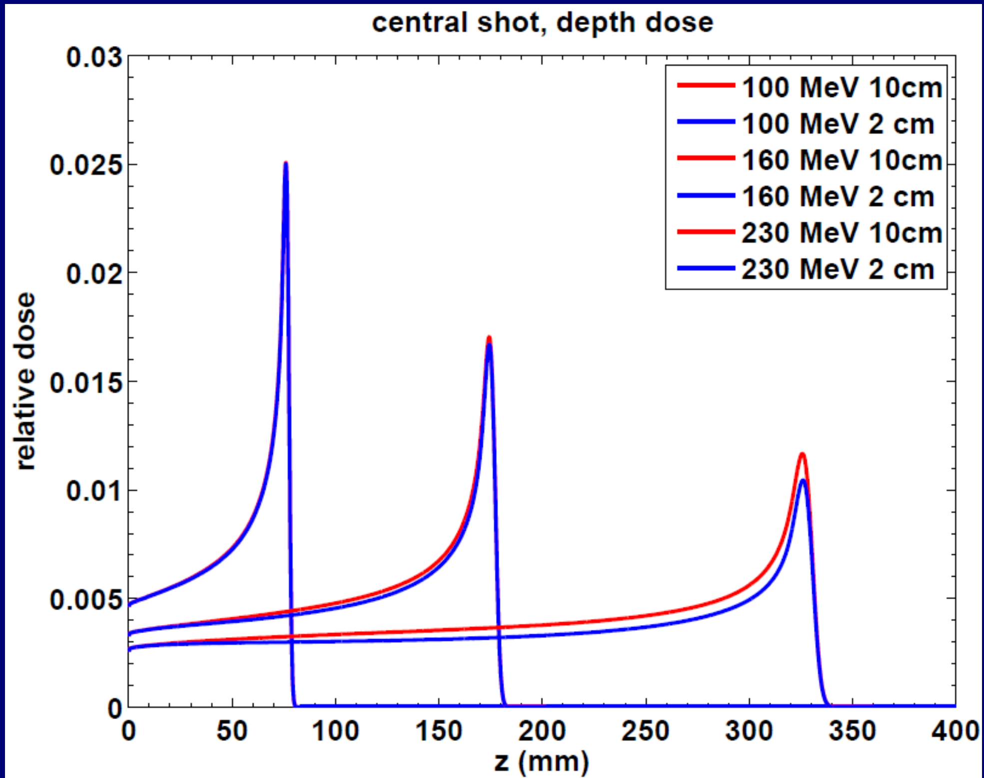


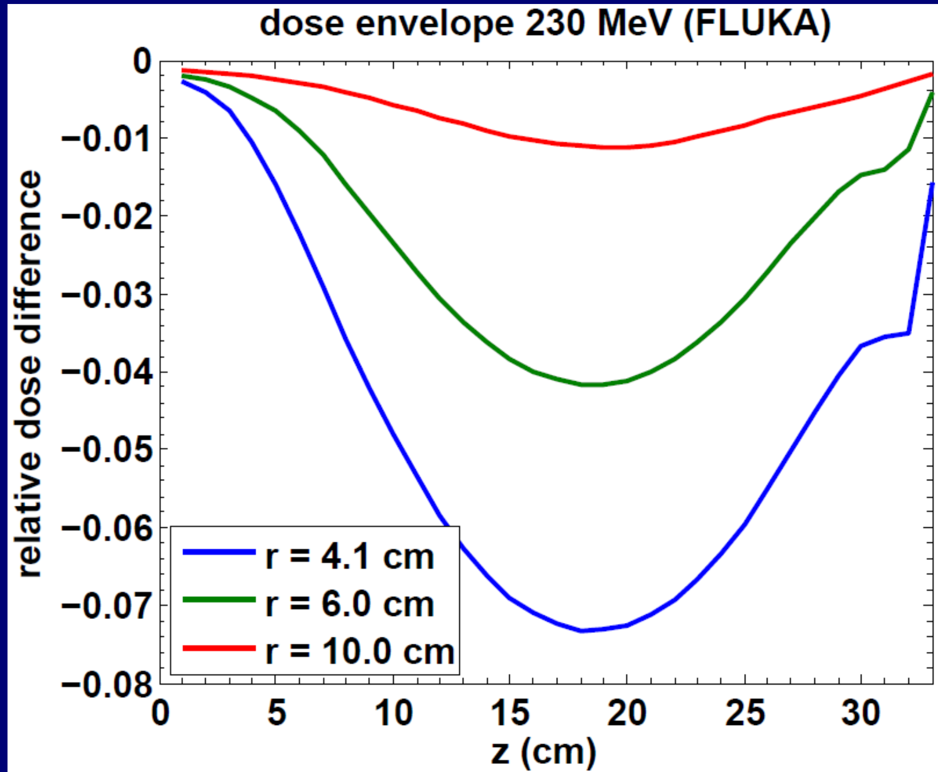
- Used 1 cm size bins in depth direction. Limited simulation to radius of 25 cm.
- Maximum relative statistical error about 0.001.
- diagram shows relative dose loss, e.g. at 10^{-3} 0.001 of the charge is not collected (i.e. geometrical collection efficiency is 0.999)

→ typically the dose is underestimated by a few percent for realistic electrode radii

Understanding the problem (4)

• measure integral depth dose curves with large electrode ionization chamber and static pencil beam on central axis



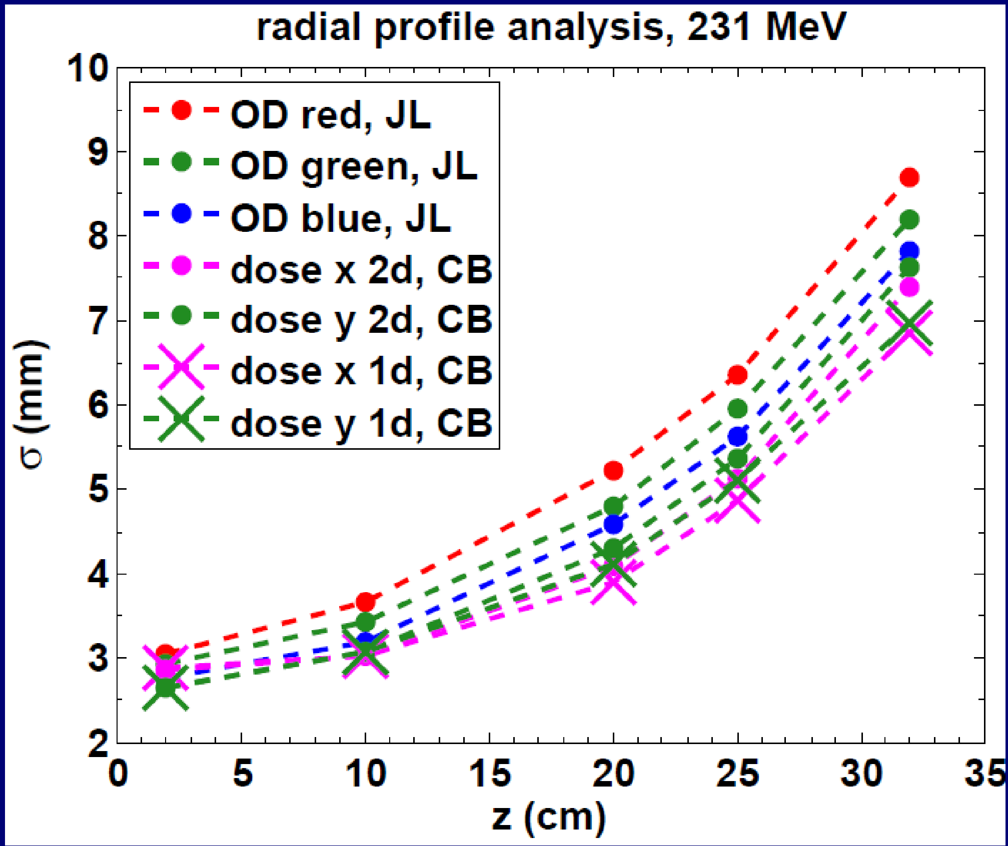


→ Shape of depth-dose distribution changes when limiting sensing radius

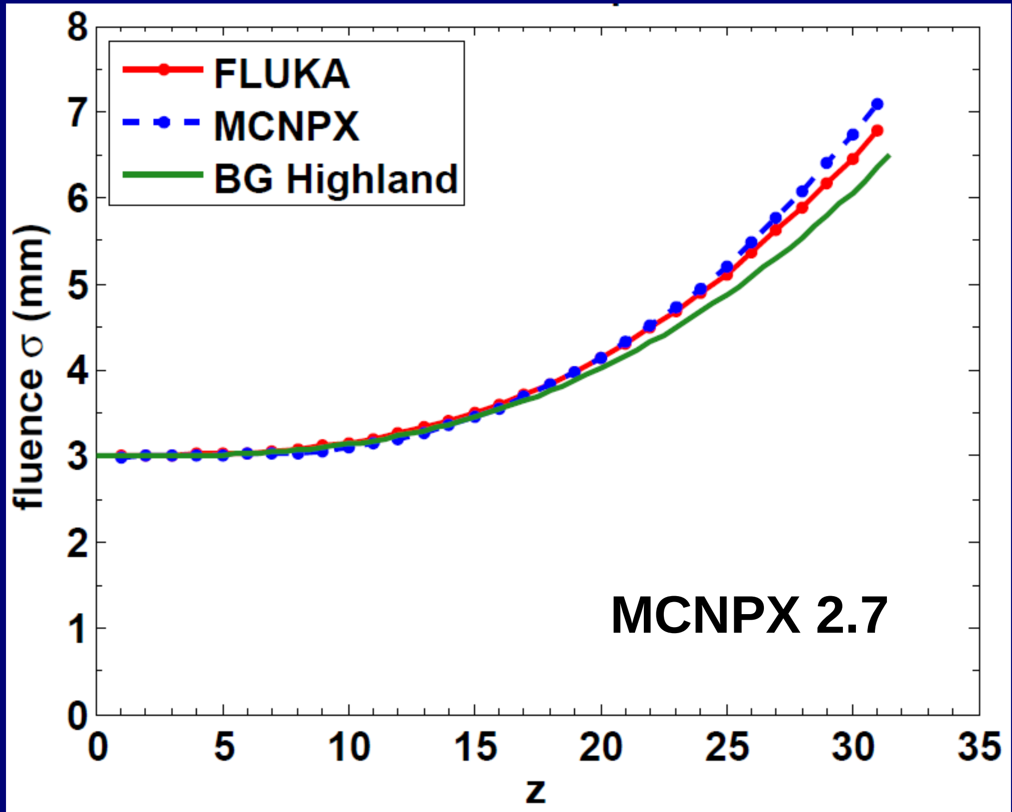
Also see G. Sawakuchi et al., An MCNPX Monte Carlo model of a discrete spot scanning proton beam therapy nozzle, Med. Phys. 37 (2010) 4960

Understanding the problem (5)

Experiment with Gafchromic EBT2 film



Simulation/Computation:



<u>Experiment:</u>
ambiguous analysis: fit of optical density (OD) or dose in 1d or 2d give different results

<u>Note ”BG Highland“:</u> analytical approach by subdividing water into 0.5 cm slabs and using Gottschalks integrable form of Highlands formula (B. Gottschalk et al., Nucl. Instr. Meth. B74 (1993) 467).

Static pencil beam in water

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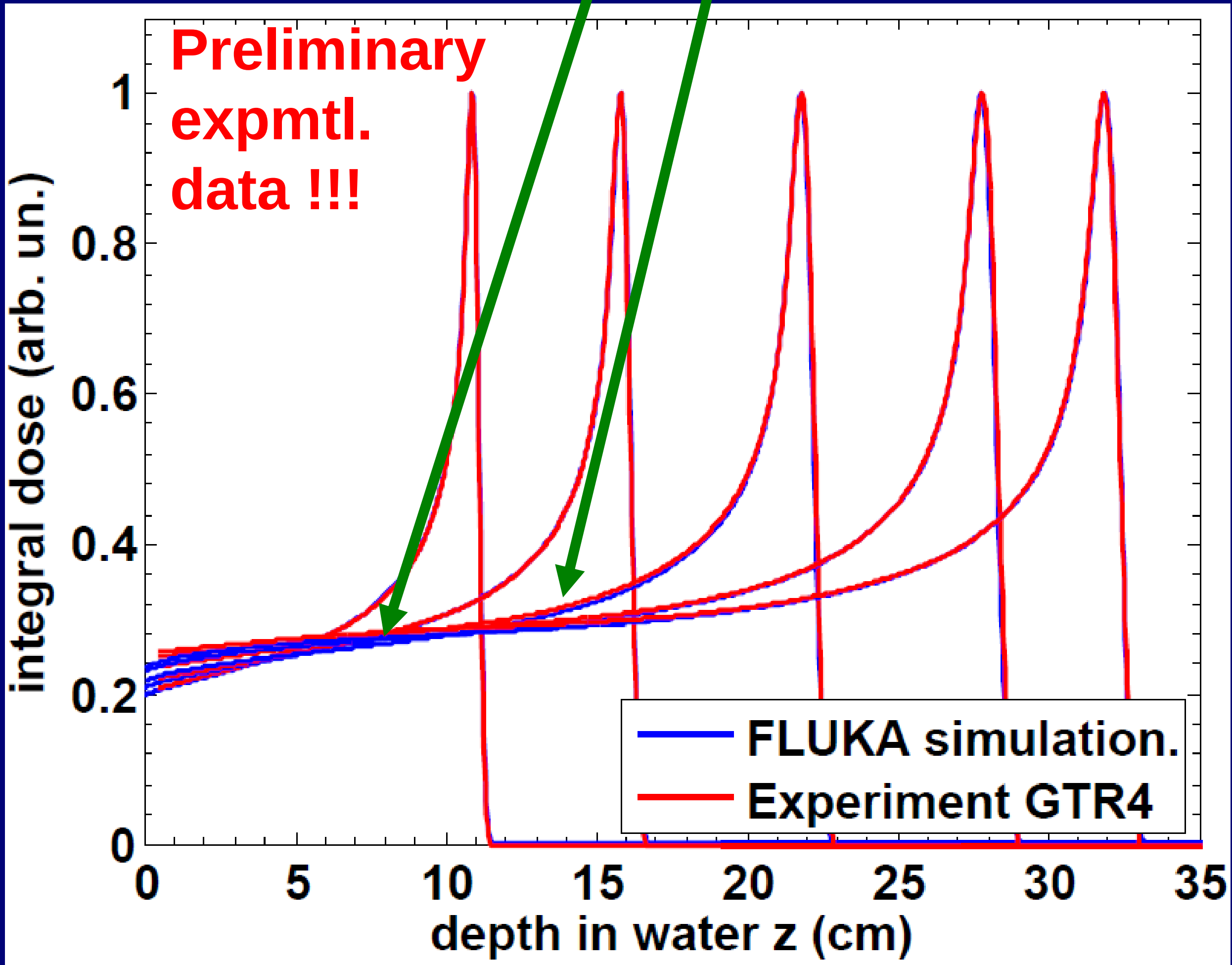
- Very good match between simulation and experiment (4.1 cm radius BPC).
- Slight deviations: simulation underestimates the dose in plateau region for intermediate and highest energies. Magnitude of deviation is about 1% (relative to BP height)



Simulation:

- I_{H2O} = 75 eV
- virtual source-axis distance: 0.6 m (preliminary)
- assumed 5 mrad (fwhm) angular divergence of source
- energy dispersion tuned to fit distal fall-off of Bragg peak
- statistical error per depth bin typically below 1%, maximum 1.5%

MLIC/zebra (1)

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MLIC Electro-mechanical properties:

- Multi-layer ionization chamber (commercial name “zebra”)
- 120 mm physical diameter collecting cross-section
- 180 layers spaced 0.8 mm apart (2 mm pitch).
- State-of-the-art printed circuit board material
- Electronic readout: two possibilities for adjustment of charge collection:
    - bias voltage
    - charge collection quantum (CCQ).

MLIC Testing

- Acquire depth dose distribution with zebra detector
- Repeat measurements with depth scans in water phantom using the same settings

Radiological detector test

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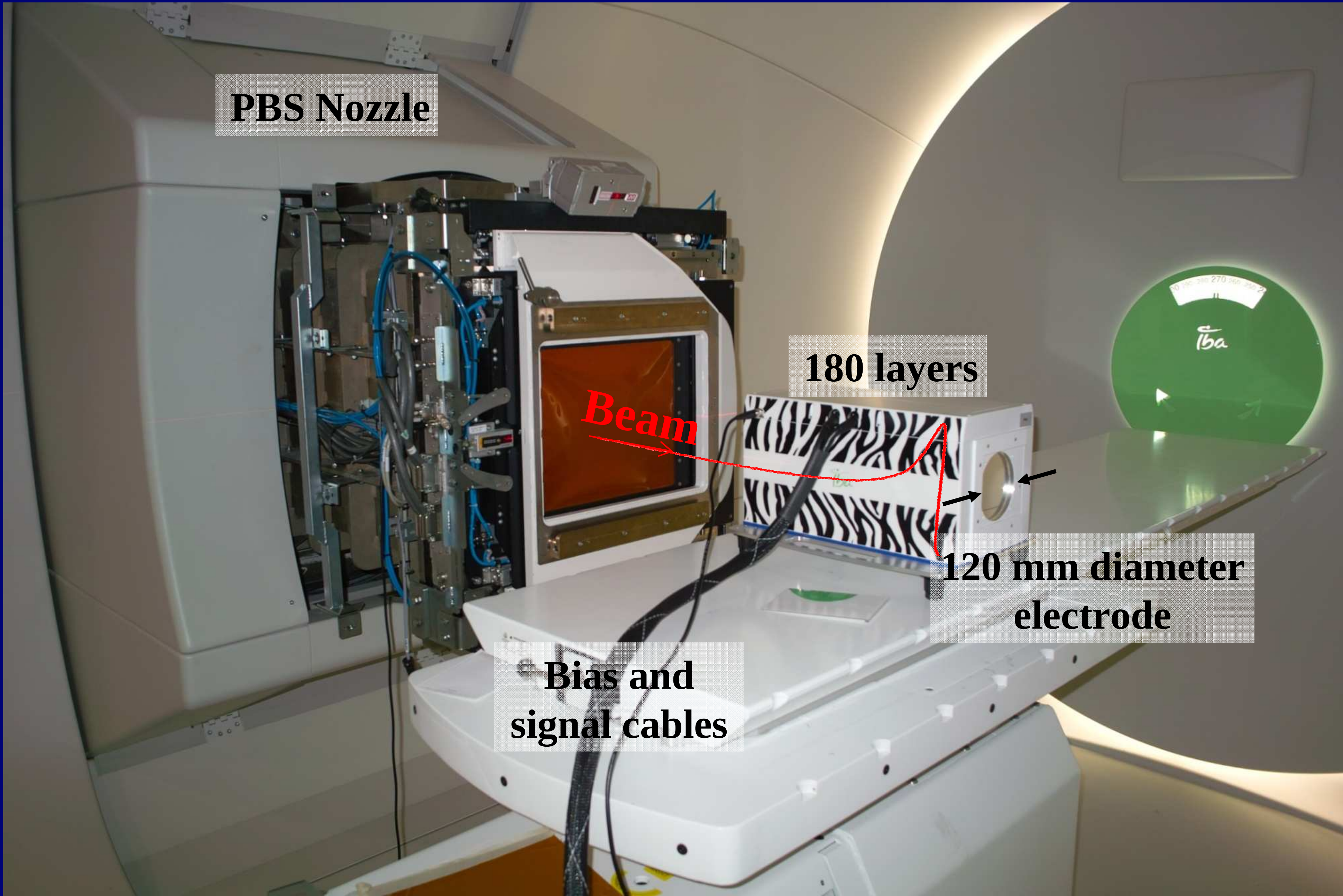
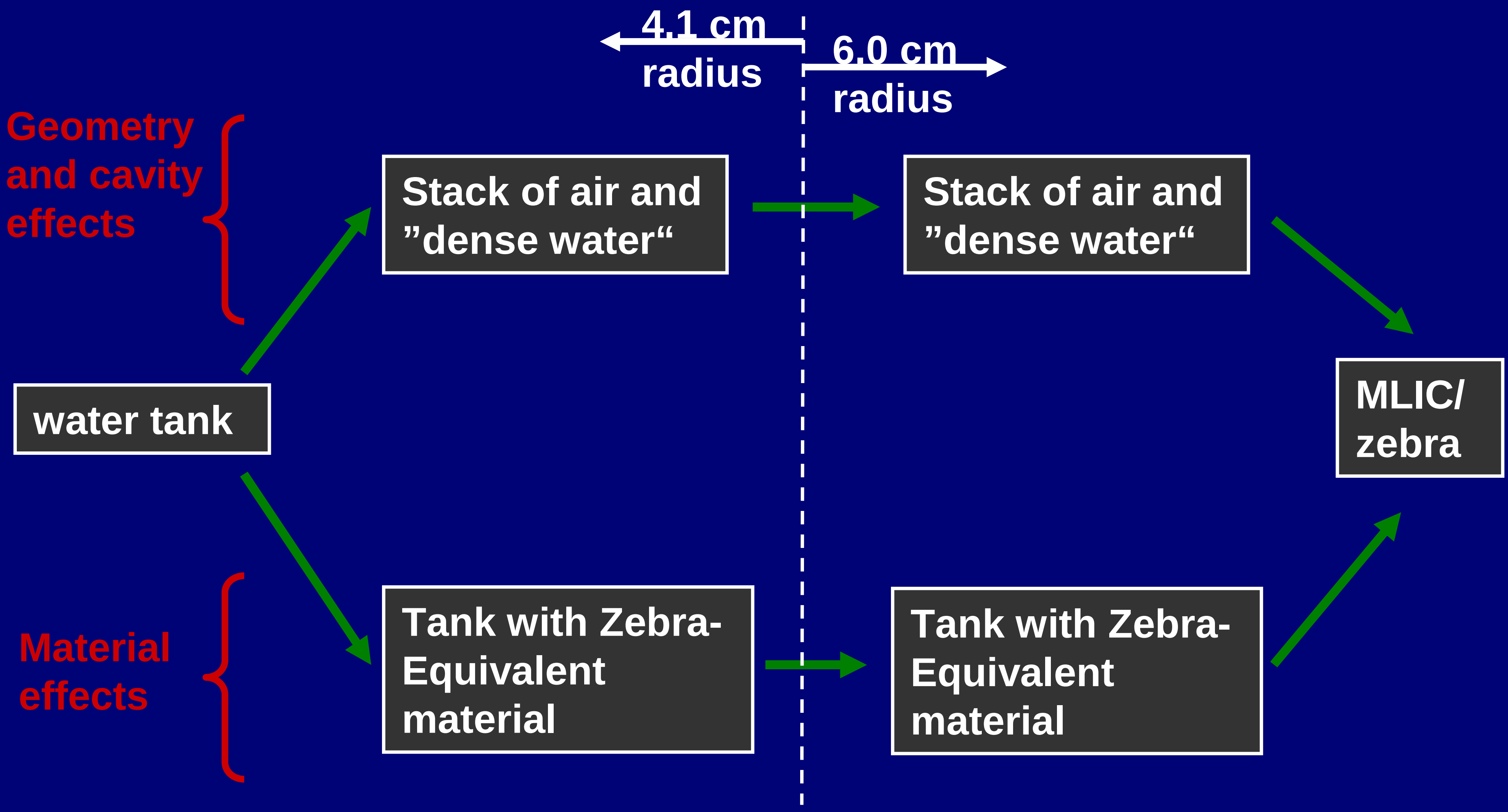


MLIC/zebra (2)



Compare large electrode MLIC/zebra with 4.1 cm radius Bragg Peak Chamber!!!

MLIC/zebra (3)

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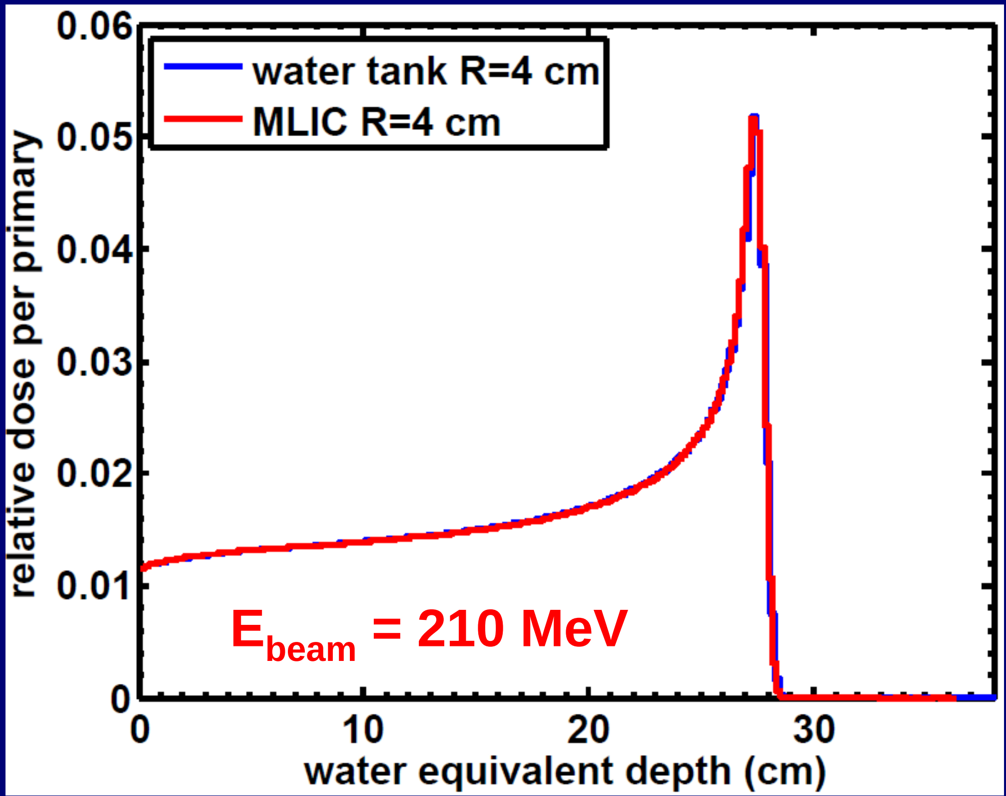
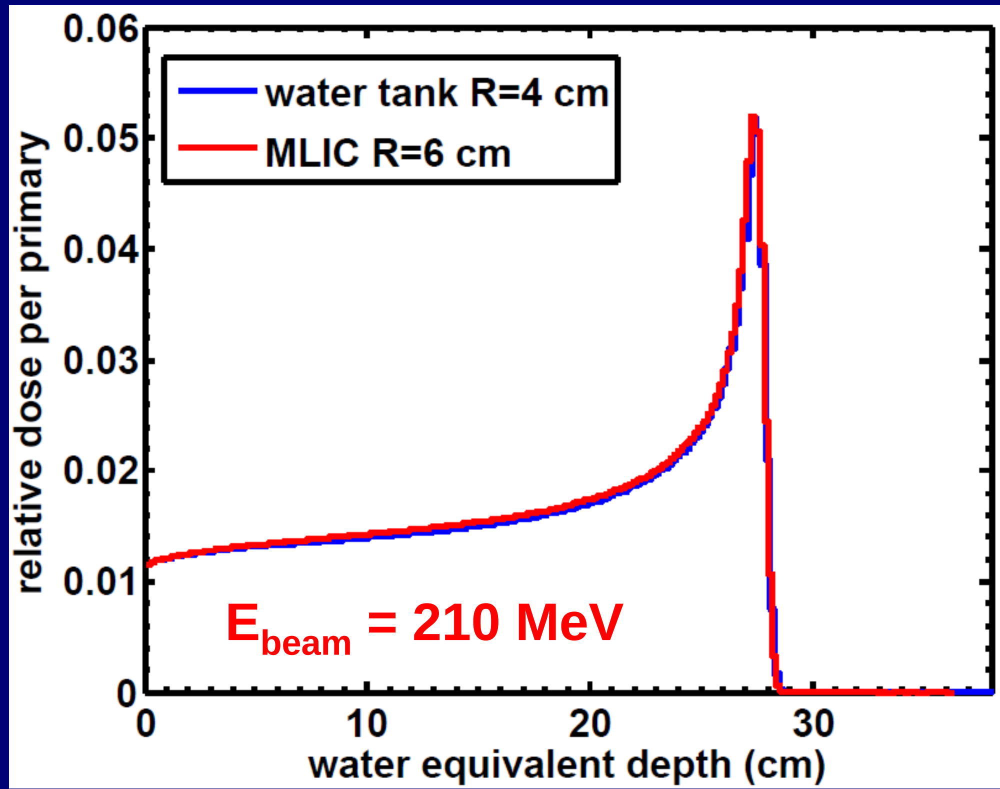
Study possible geometry and cavity effects: Model virtual detector which is stack of air and dense water. ρ(“dense H_2O”) = 1.55 g/cm^3





→ Stacked structure and contiguous water volume show no difference

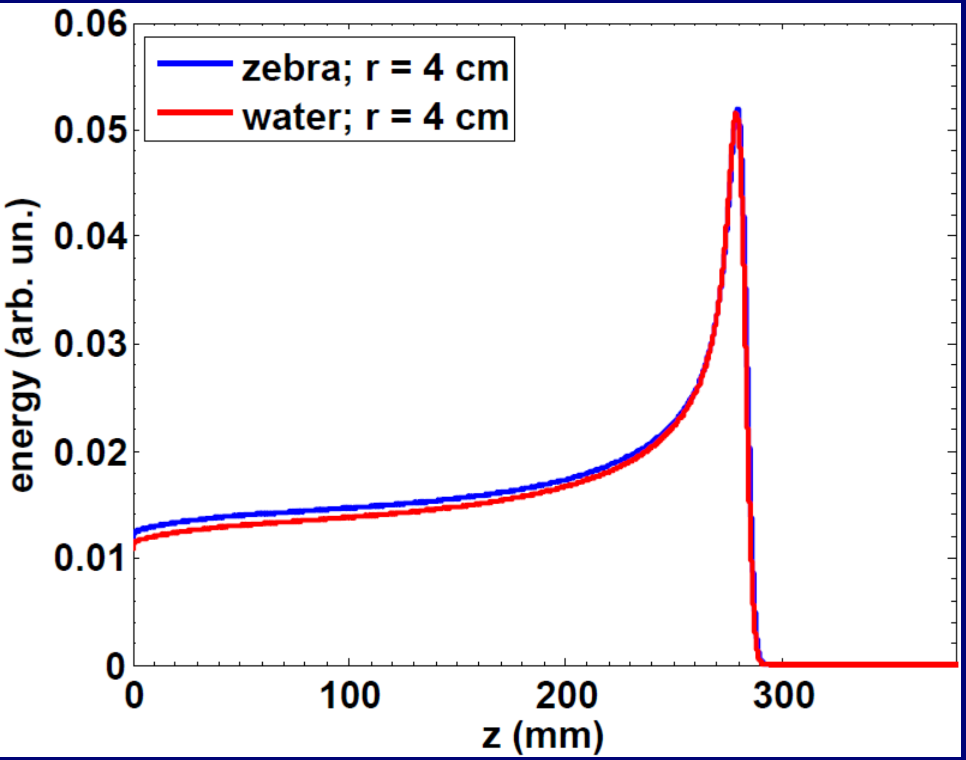
→ Increasing the electrode radius from 4 cm to 6 cm increases the geometrical collection efficiency at intermediate depths

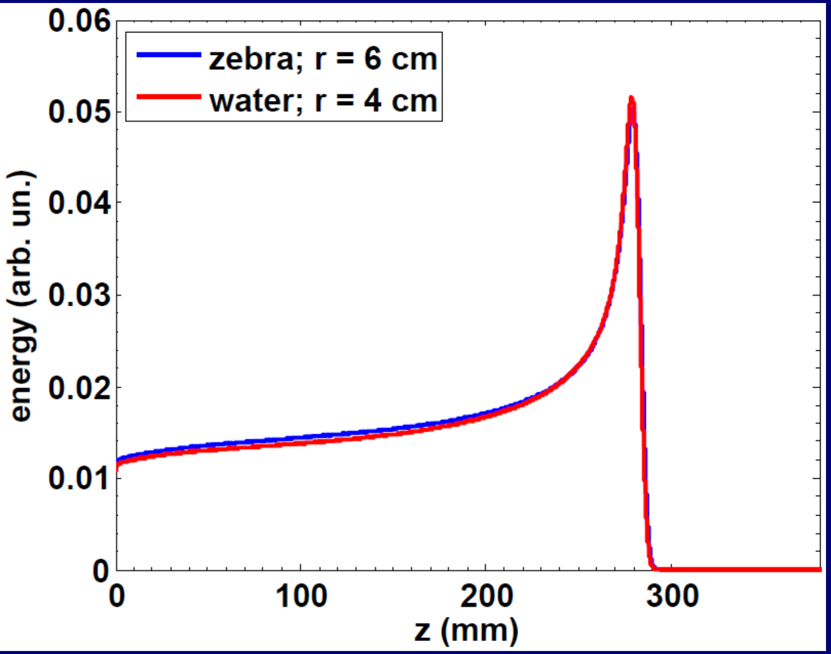
MLIC/zebra (4)

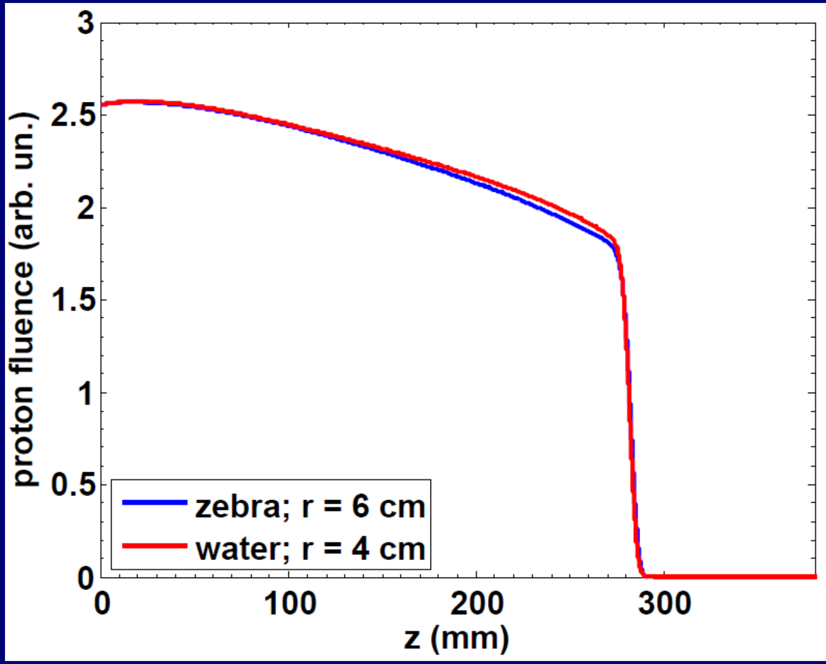
- Working with 180 MLIC layers in simulations is quite cumbersome → Establish simple MLIC model by defining zebra-equivalent (ZEQ) material
- **ZEQ** represents average material composition in zebra detector, i.e. add elemental contributions of Duraver, Polyimide and Graphite weighted by respective masses in single layer.
- Calculate mass density with mass density and thickness of each component and include WEQ factor of 1.855 mm/ch → $\rho = 1.136\ g/cm^3$

Weight fraction	Element
626.0	O
204.7	Si
17.1	B
60.3	Al
21.0	Mg
101.0	Ca
4.5	Na
4.7	Ti
1.8	F
22.0	H
960.5	C
84.5	N

MLIC/zebra (5) -ZEQ

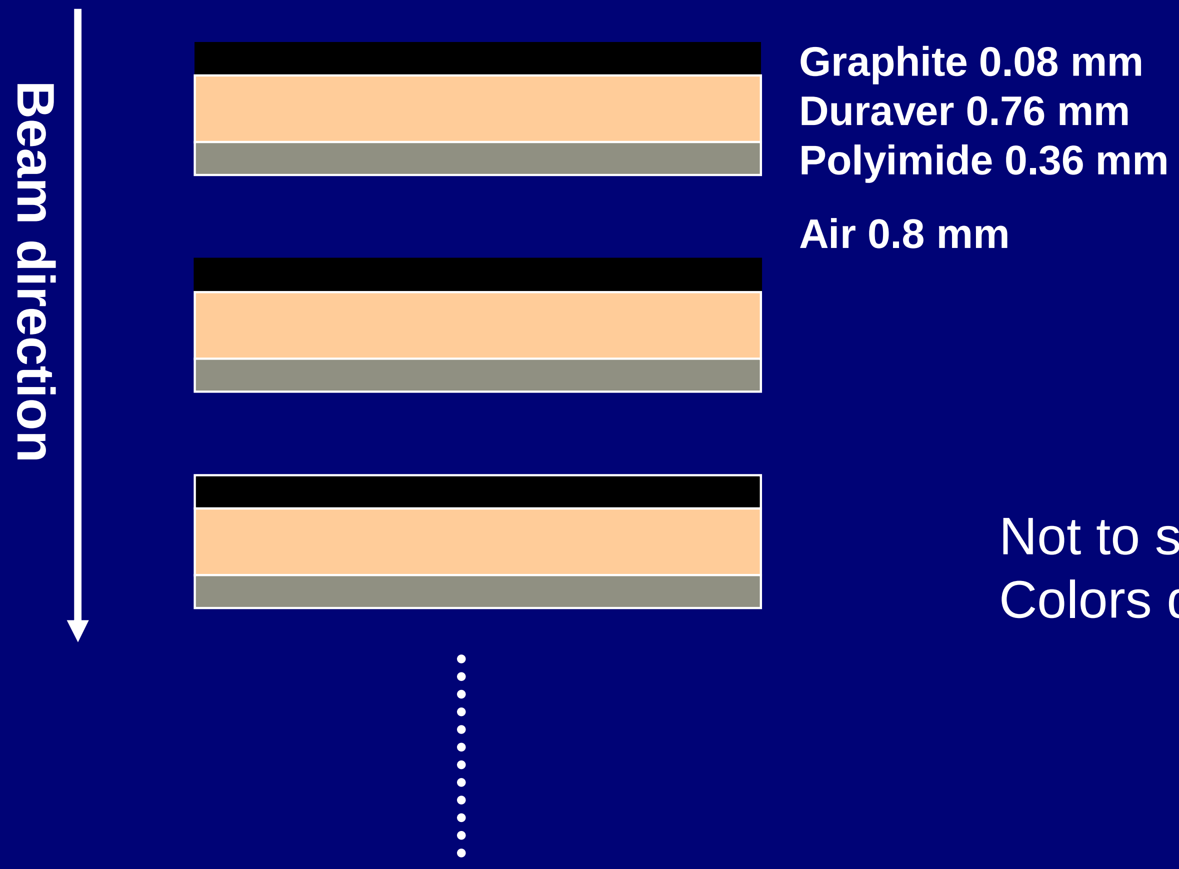






MLIC/zebra (6)

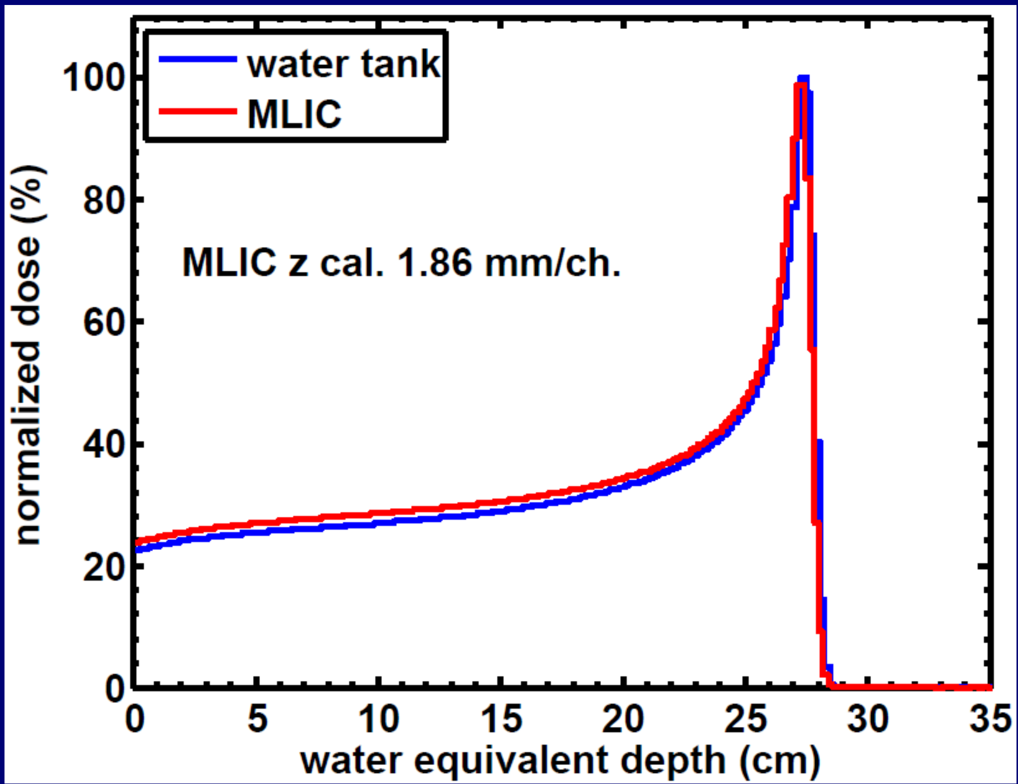
- Use simple stack of materials per layer
- Duraver = 60% polyimide + 40% E-Glass



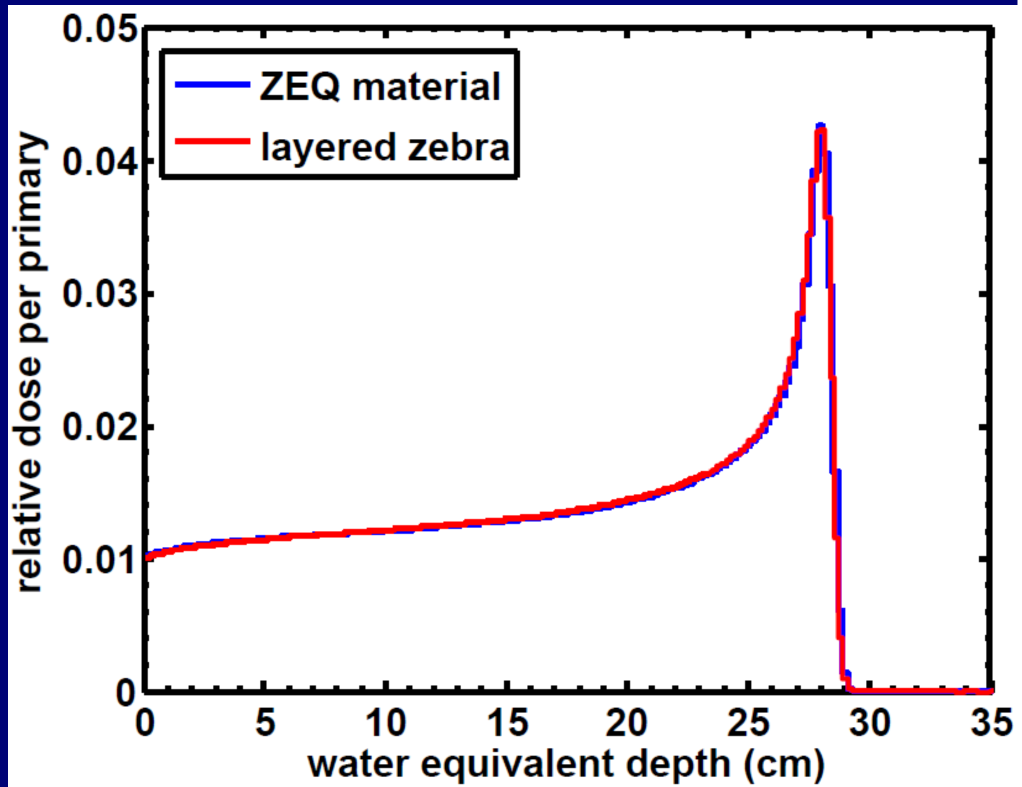
Not to scale!
Colors do not match!

MLIC/zebra (7)

Simulation



Simulation



MLIC/zebra (8)

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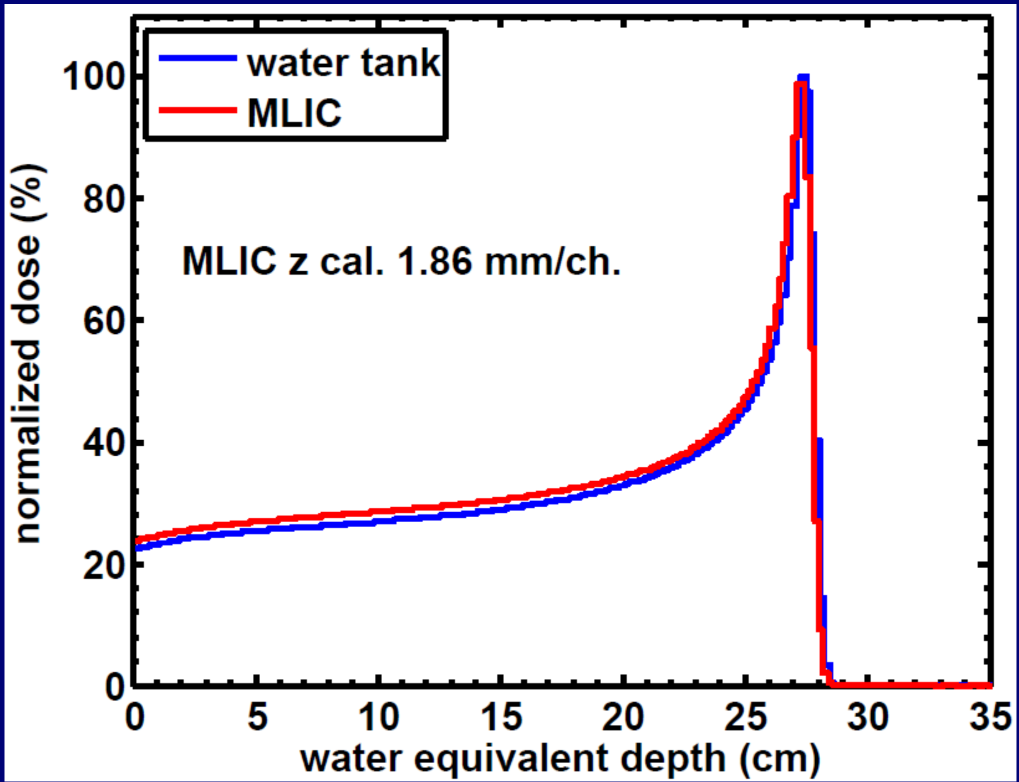
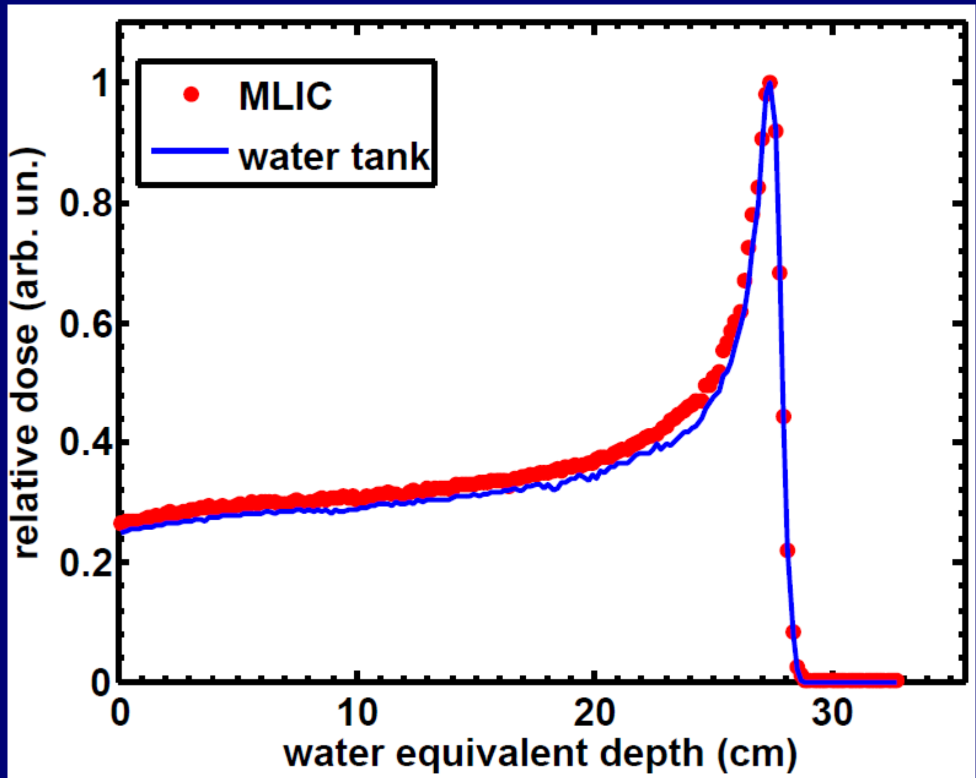
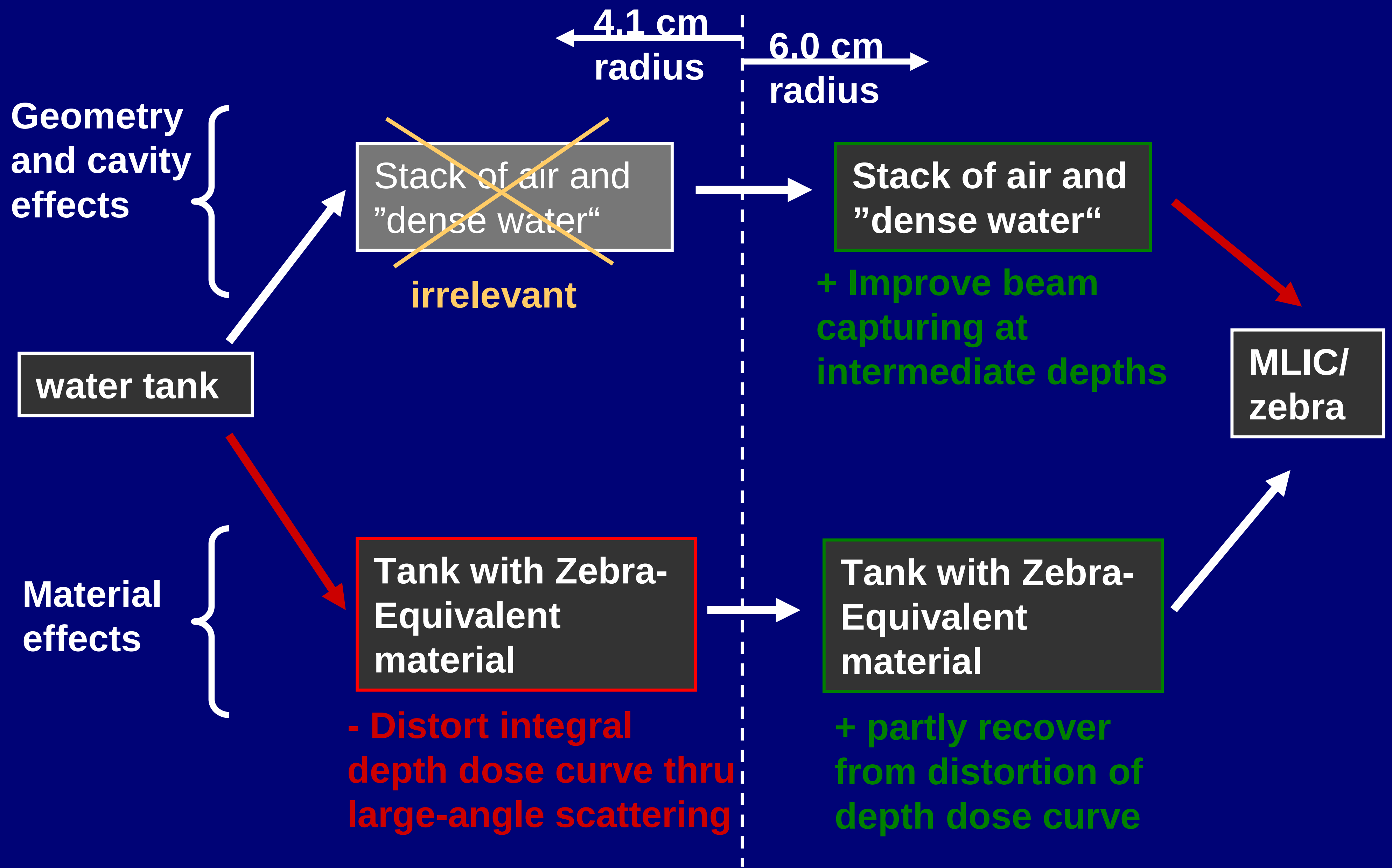
Simulation



Experiment



MLIC/zebra (9)


4.1 cm radius
6.0 cm radius
Geometry and cavity effects
Material effects
water tank
~~Stack of air and ”dense water“~~
irrelevant
Stack of air and ”dense water“
+ Improve beam capturing at intermediate depths
MLIC/ zebra
Tank with Zebra-Equivalent material
- Distort integral depth dose curve thru large-angle scattering
Tank with Zebra-Equivalent material
+ partly recover from distortion of depth dose curve

Neutron Radiation Protection (1)

Number of neutrons generated in inelastic interactions per beam particle

E_{beam} (MeV)	FLUKA		MCNPX	
			Def.	CEM
100	0.20		0.19	0.15
160	0.51		0.45	0.38
230	1.03		0.87	0.75

See also:
S. Agosteo et al., *Double differential distributions and attenuation in concrete for neutrons by 100-400 MeV protons on iron and tissue targets*, Nucl. Instr. Meth. B 114 (1996) 70 and J. V. Siebers et al., *Shielding Calculations for 230-MeV Protons Using the LAHET Code System*, Nucl. Sci. And Eng. 122 (1996) 258

Neutron Radiation Protection (2)

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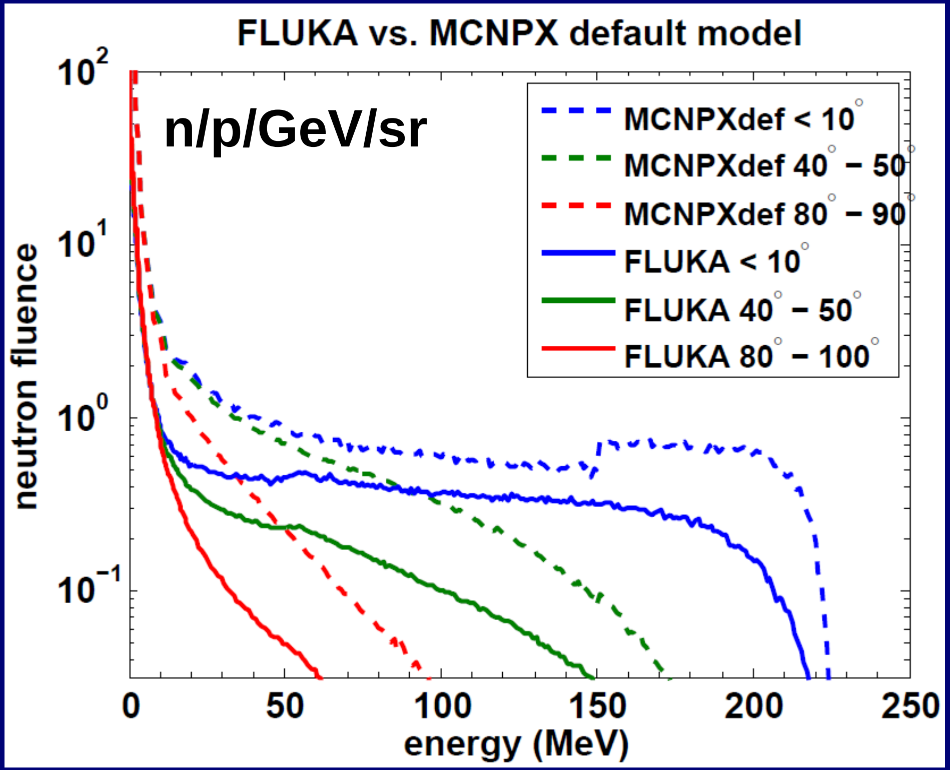
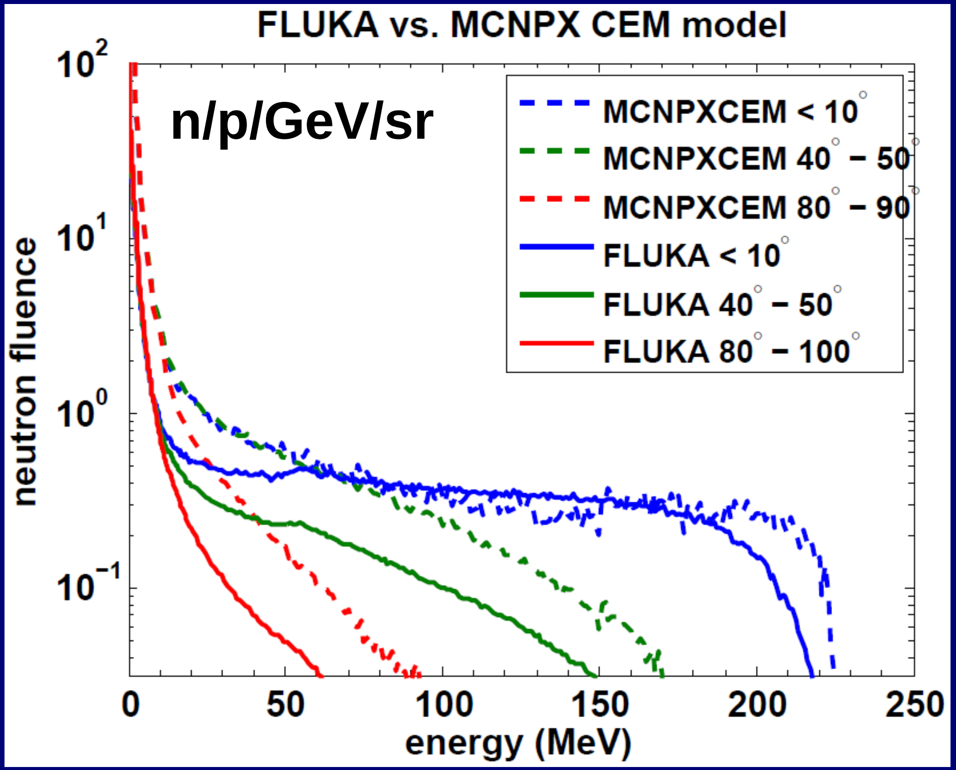
Motivation: Neutron source term for health physics calculations

Simulated Geometry: 0.5 cm radius annular beam incident on 2.5 cm radius copper cylinder (6.5 cm length)

FLUKA: USRYIELD
MCNPX: E4 + F4 (n/cm^2 averaged over concentric rings with 90 m < r < 91 m)

Graphs clipped for low fluences such to show only data points with maximum of 5% statistical error





Outlook

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- Test prototype of 6 cm radius Bragg Peak Chamber from iba dosimetry
- Establish framework of correction factors to scale MLIC/zebra acquired depth-dose distributions to equivalent measurements in water
- More elaborated source model (adapted to commissioning data)
- Build Linux cluster and set-up parallel computing of FLUKA jobs
- MC for dose verification PET (i.e. voxel geometry and activation)

Conclusions

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- When measuring depth doses for individual pencil beams (beamlets) care must be taken due to components of dose, primarily from nuclear reactions, that extend relatively far out transverse to the beam direction.
- For use in a scanning system of nominal 3 mm beam size (in air/230 MeV) a new multi-element ionization detector with capture cross-section of 12 cm has been developed, tested and simulated with FLUKA.
- FLUKA MC simulations correctly predict trend of distortion of MLIC/zebra depth dose curve compared to water.
- Main requirements on FLUKA:
  - Good condensed-history implementation of multiple Coulomb scattering
  - Good model of inelastic interactions