Joint ICTP-IAEA Workshop on Monte Carlo Radiation Transport and Associated Data Needs for Medical Applications
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Lecture 27

EGSnrc transport in a magnetic field

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Acknowledgment

This talk is based almost entirely on the work of Victor Malkov, a doctoral student in my group at Carleton until 2017. Now at Mayo Clinic, MN

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EGSnrc transport in magnetic fields

- Bielajew did this for EGS4 in the 1980s
  - EGS4 and the magnetic field transport required short steps
- these have been ported to EGSnrc by Ernesto

  ⇒but the macros are not optimized

- EGSnrc takes longer steps and uses a single scattering mode to cross boundaries

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magnetic transport

- standard starting point for change in direction due to magnetic field

$$\Delta \vec{u}_B(t) = \frac{qc^2}{v_o E} \int_0^t dt' \vec{v}(t') \times \vec{B}$$

- define

$$\boxed{\delta_u = |\Delta \vec{u}|}$$

- for little energy loss, constant magnetic field B and a small change in direction, a 1st order approximation is

$$\Delta \vec{u}_{B1} = \frac{qtc^2}{v_o E} \left(\vec{v}(0) \times \vec{B} \right)$$

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1^{st} order approximation: 1-PI

- converting time variable to pathlength, s

$$t = \frac{s}{v_o}\left(\frac{1}{2} + \frac{v_o}{2v_f}\right) = \frac{s}{v_o}\eta \Rightarrow \frac{s}{v_o}$$

gives

$$\Delta\vec{u}_{B1} = \frac{qtc^2}{v_o E}\left(\vec{v}(0) \times \vec{B}\right) = \frac{qs\eta}{\beta_o^2 E}\left(\vec{v}(0) \times \vec{B}\right)$$

where $\beta^2 = v^2/c^2$

This equation is what is often used.

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3-point integration: 3-PI

- accuracy can be improved by doing a 3 point integration of general eqn and making same substitutions for t

$$\Delta\vec{u}_{B3} = \frac{qs\eta}{\beta_o^2 E}\frac{1}{6}\left(\vec{v}(0)\times\vec{B} + 4\vec{v}\left(\frac{t}{2}\right)\times\vec{B} + \vec{v}(t)\times\vec{B}\right)$$

- change in position is given by

$$\Delta\vec{x}_B = \frac{s}{2}\left(\frac{1}{2} + \frac{v_o}{2v_f}\right)\Delta\vec{u}_B = \frac{s\eta}{2}\Delta\vec{u}_B$$

- max step size from δ_u restriction (none for B=0)

$$s(B,\delta_u,E_o) = \frac{\delta_u\beta^2 E_o}{|q\vec{v}(0)\times\vec{B}|}$$

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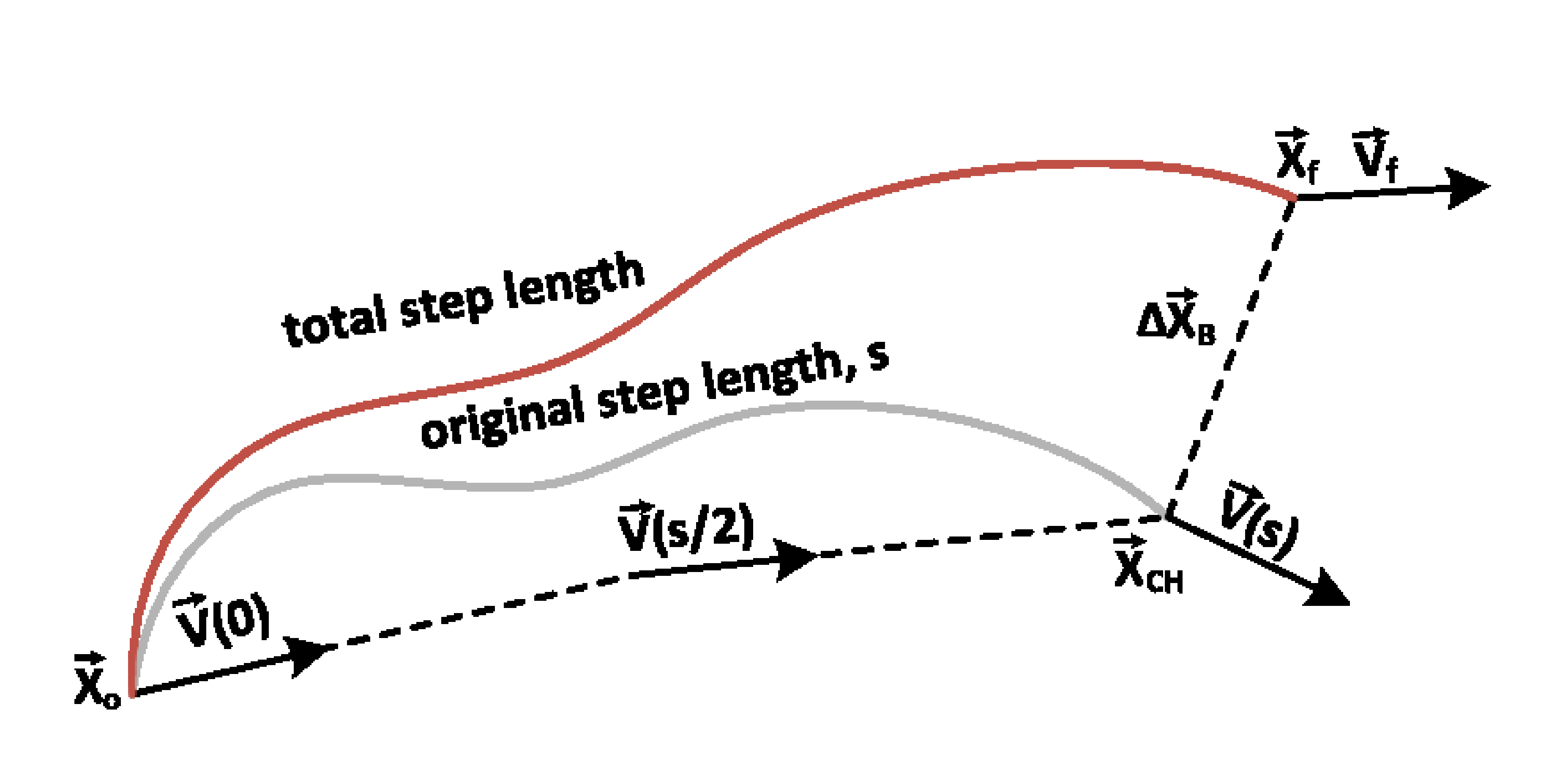
effect of magnetic field



EGSnrc transport is more complex, but this illustrates additional magnetic effects

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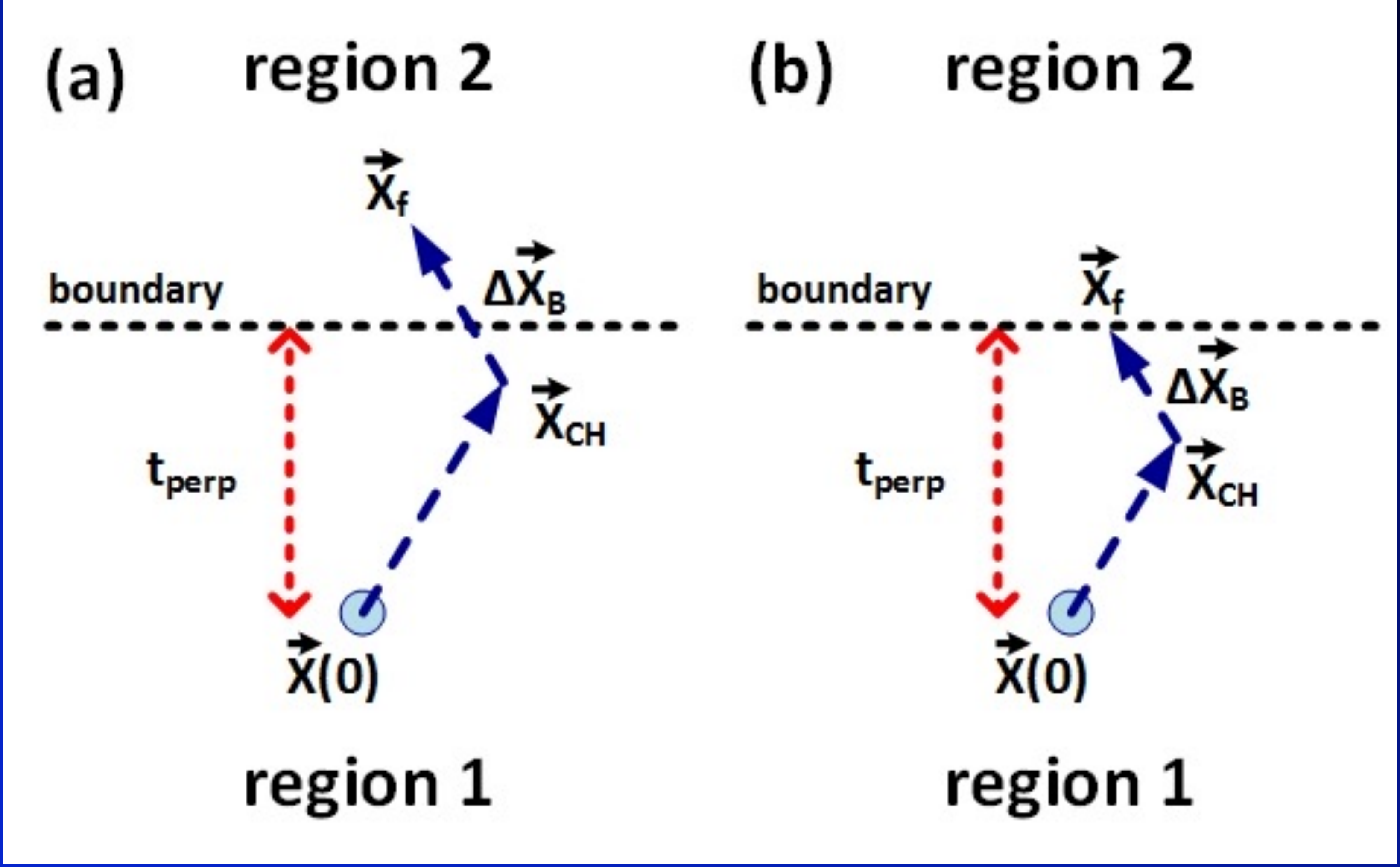
t_{perp} no longer prevents crossing boundary



$$t_{perp} = t_{CH,max} + |\Delta \vec{x}_B|$$

single scattering mode: SS

- if a particle < skin depth from any boundary
  - code goes into single scattering mode
    - default EGSnrc transports in straight lines to interaction and then scatters, or to boundary where it stops, resamples and continues to next interaction.
- with a mag field there are several issues or approaches

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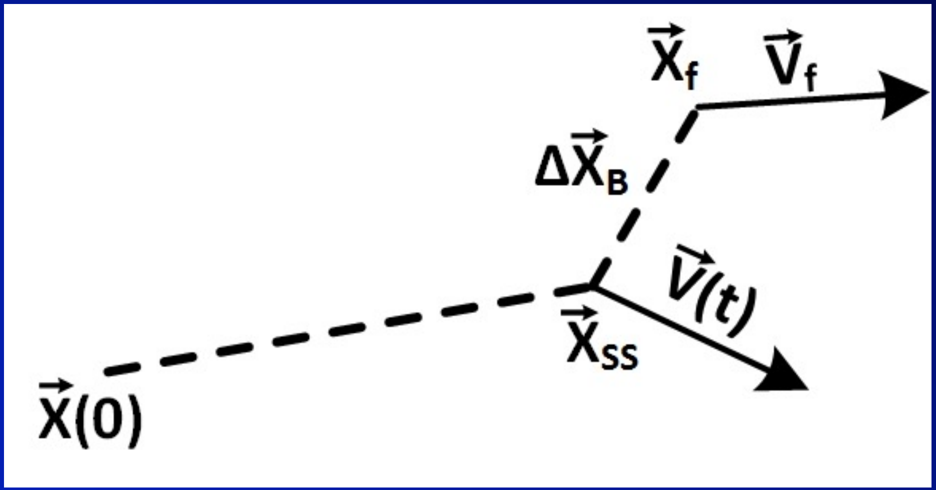
single scatter transport options

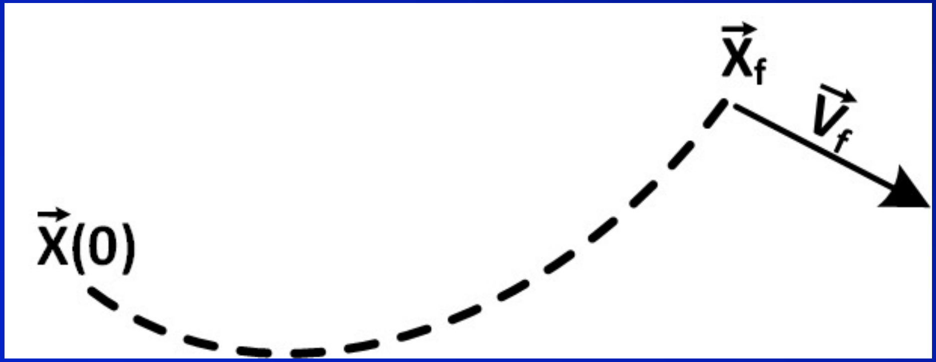
SS-1st



1st O calc as in CH step.

But leads to significant breakdowns

SS-analytic



analytic sol'n for transport in vacuum. Always used

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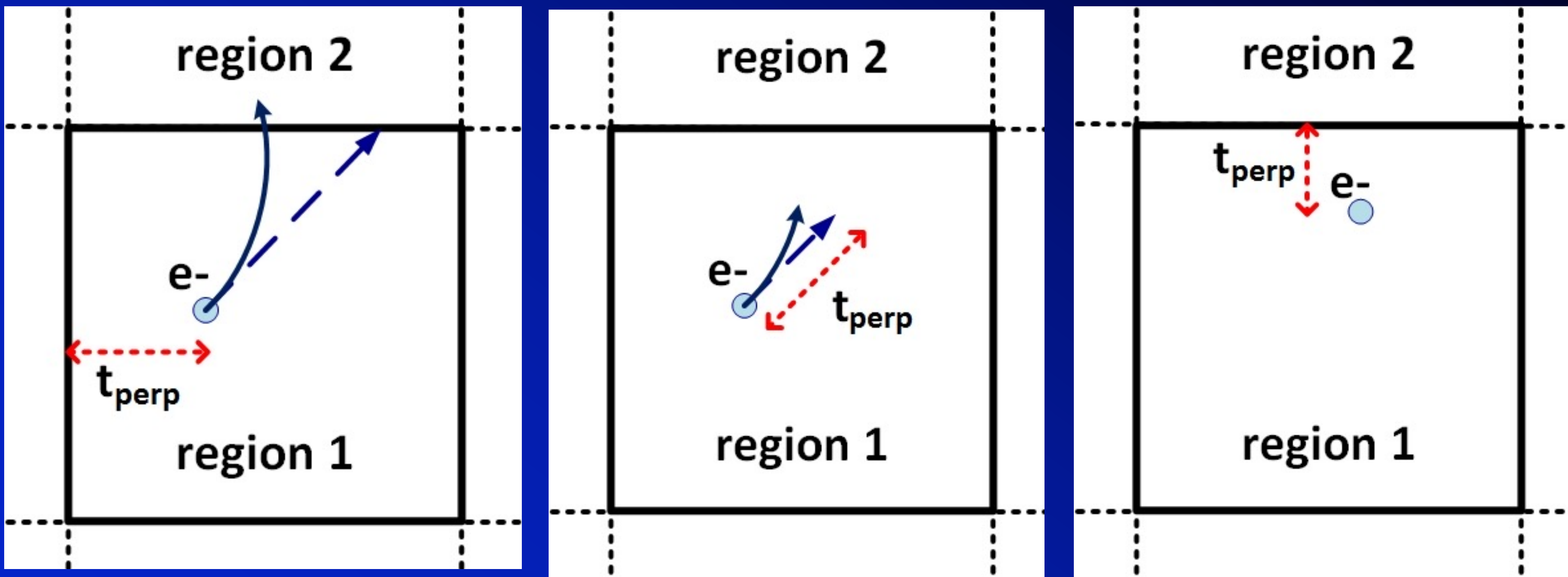
boundary crossing algorithm: BCA$_{perp}$



SS mode: step to boundary could go to wrong region

so shorten it to t_{perp}

below some limit (default 10 nm) just ignore B

guaranteed to work(slower)

Fano test with magnetic field

- the Fano test of a Monte Carlo code is a rigorous test of its ability to simulate ion chamber response accurately
  - ion chamber response is the most difficult simulation to do
- Bouchard et al (PMB 60(2015)6639) have proposed a version valid in a magnetic field
  - with a uniform B, the electron source needs to be isotropic and uniform per unit mass
  - geometry is 2 semi-infinite slabs separated by a gas of same material or ion chamber volume

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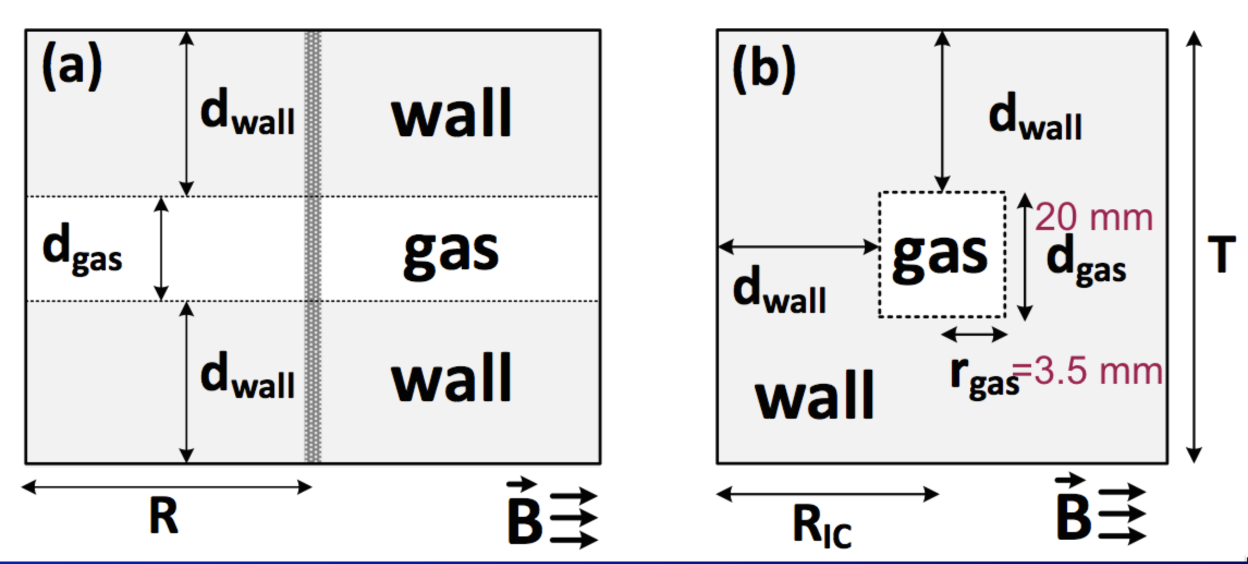
Fano test (continued)

- force photons to deposit energy on spot
- reciprocity theorem
  - isotropic line source equivalent to isotropic sources everywhere



$$\mathrm{MC}(\text{dose in gas}) \stackrel{?}{=} I E_o$$

I is number per unit mass of initial electrons of energy E_o

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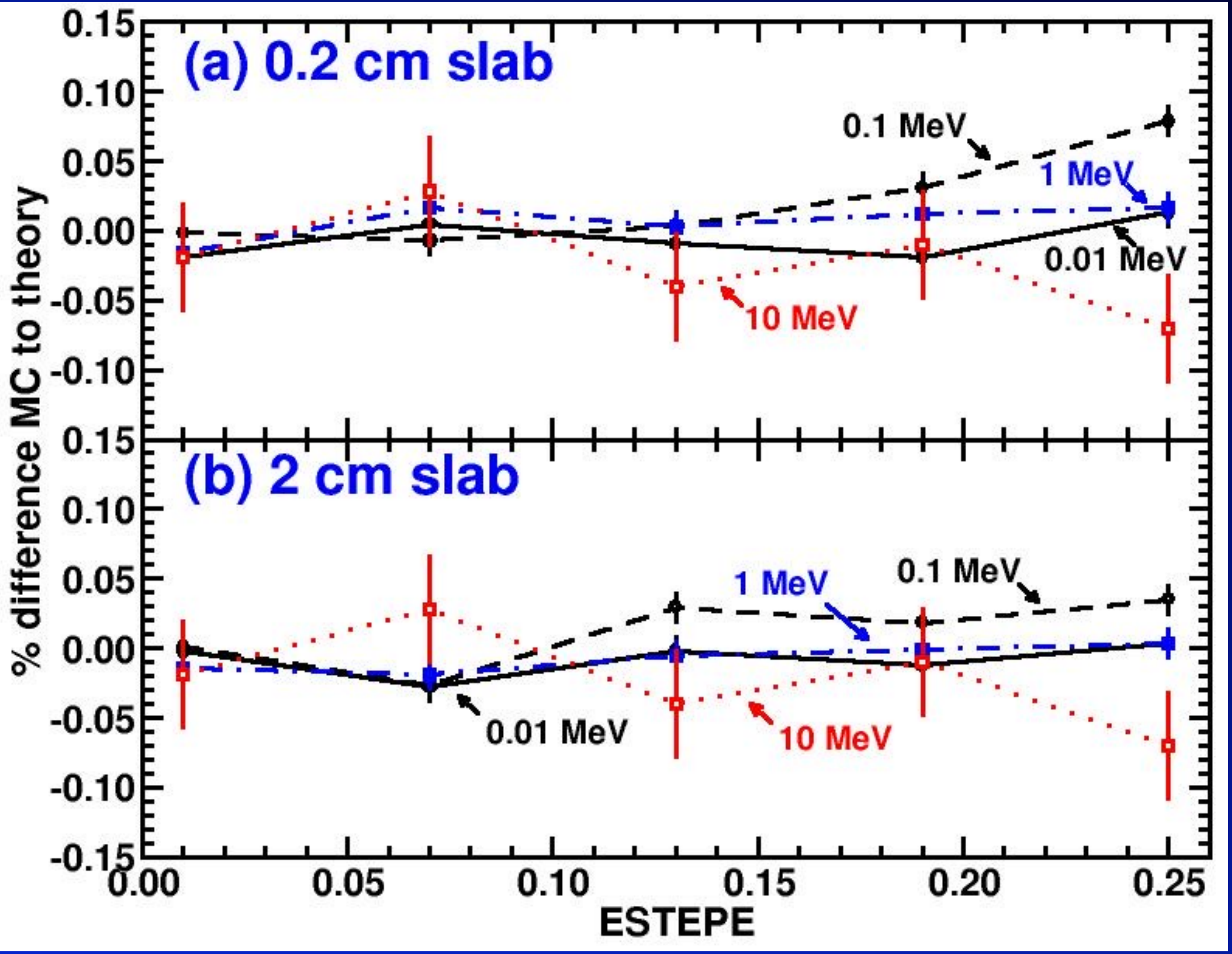
EGSnrc Fano test with no B field



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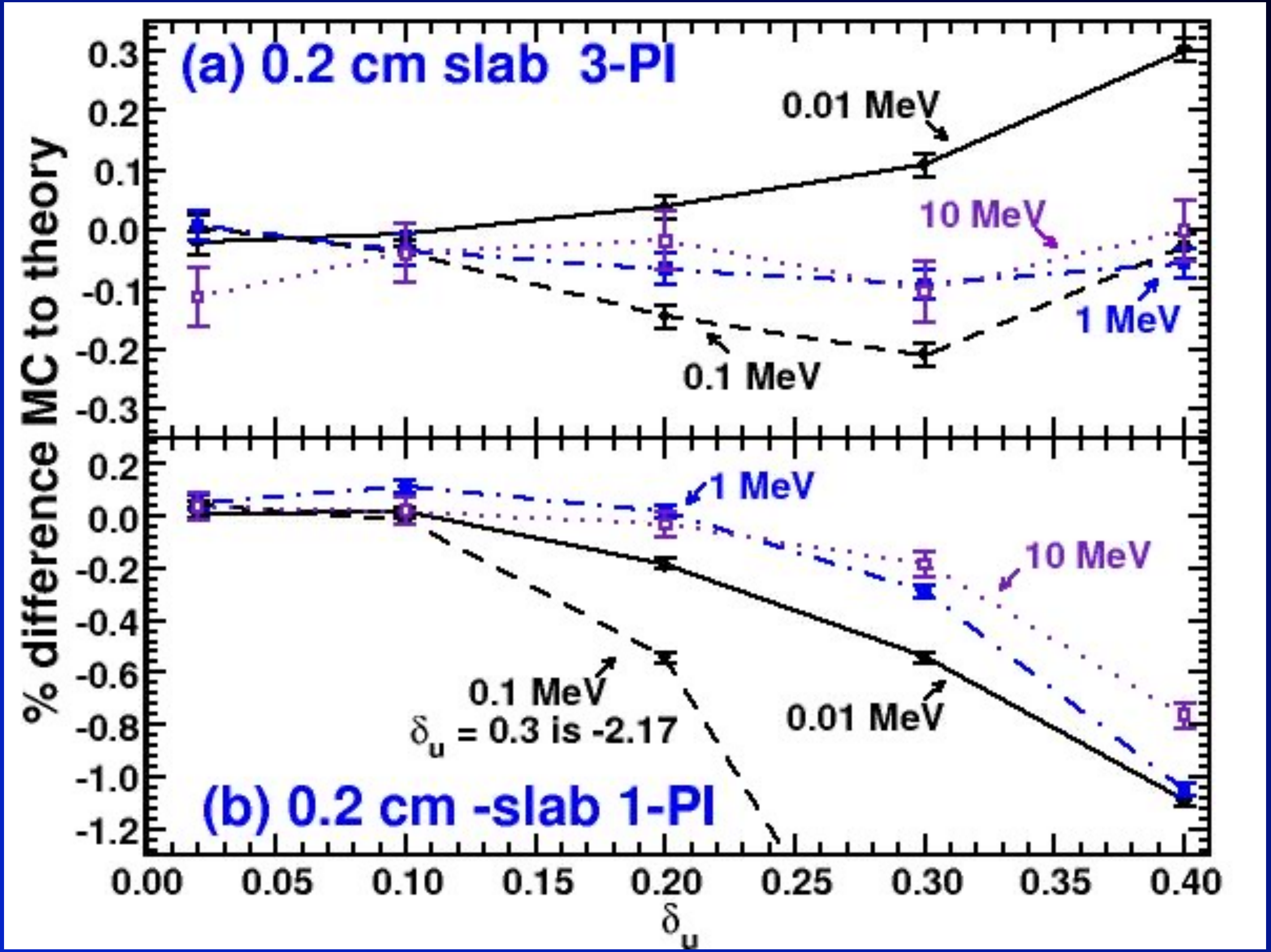
isotropic electron sources

EGSnrc Fano test 1.5 T: 2 mm gap

B || gap.

harder test than B⊥gap

note different scales



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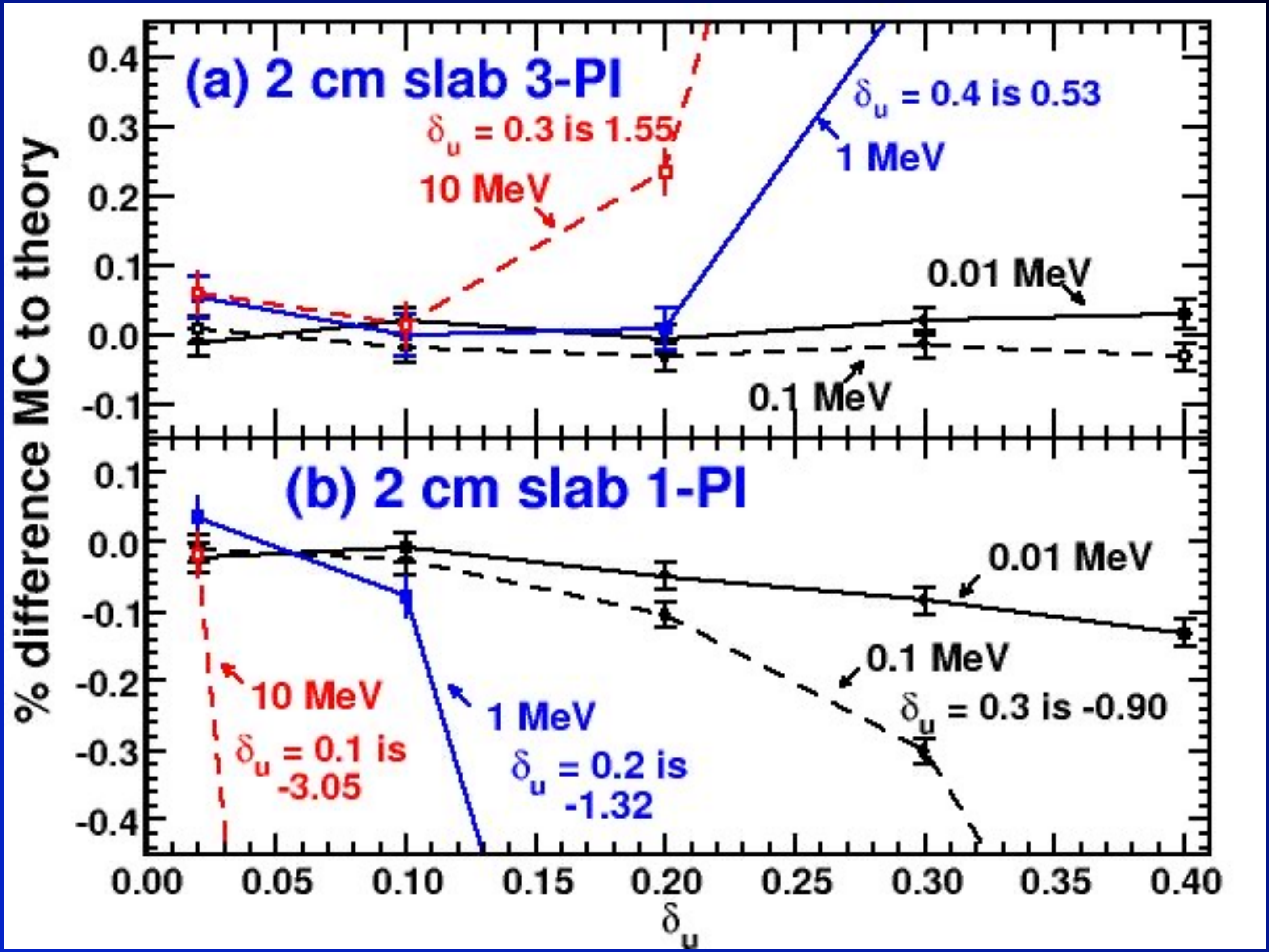
EGSnrc Fano test 1.5 T: 2 cm gap

B || gap.

harder test than B⊥gap

scales same



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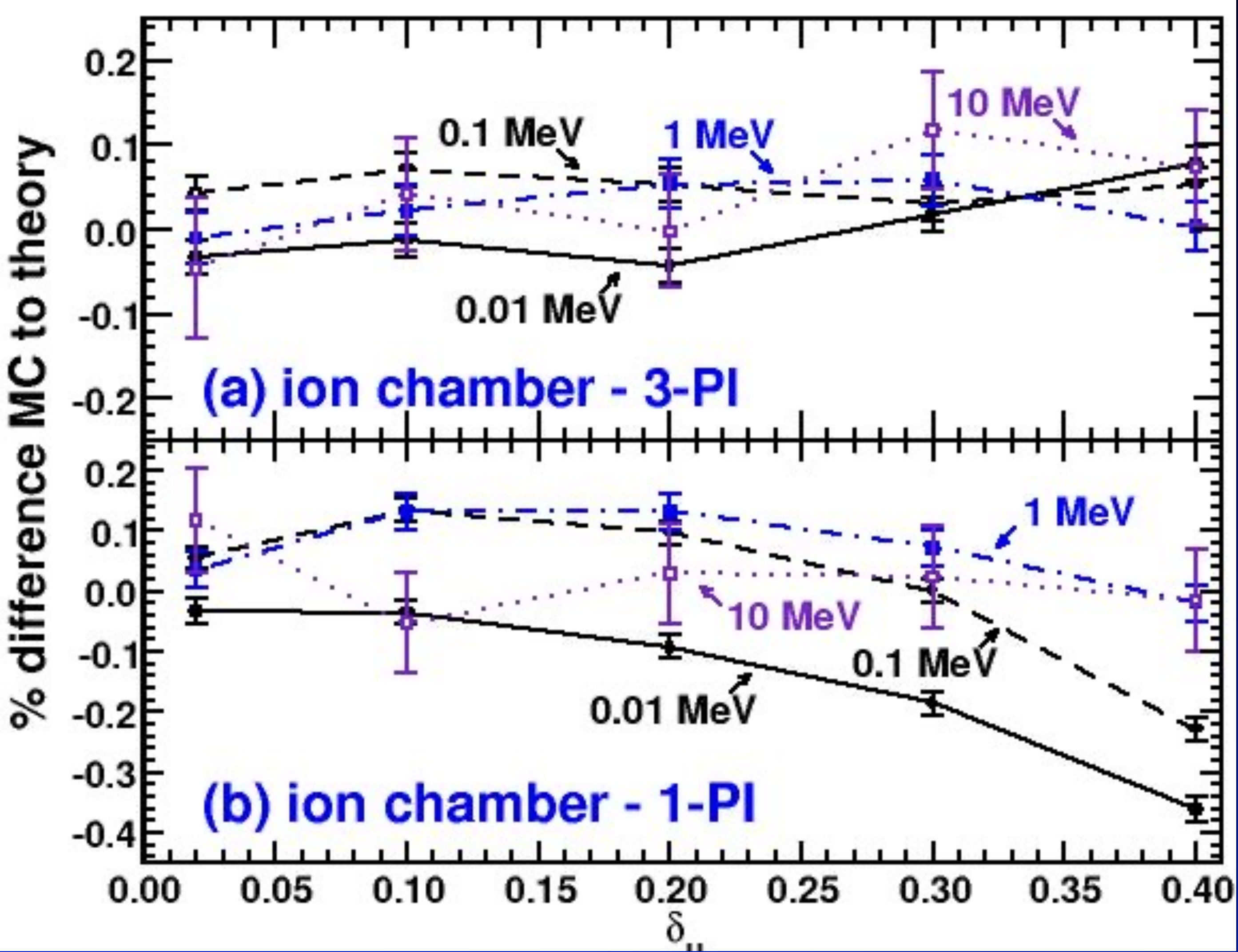
EGSnrc Fano test 1.5 T: ion chamber

The 1-PI passes here but failed 2 cm slab version



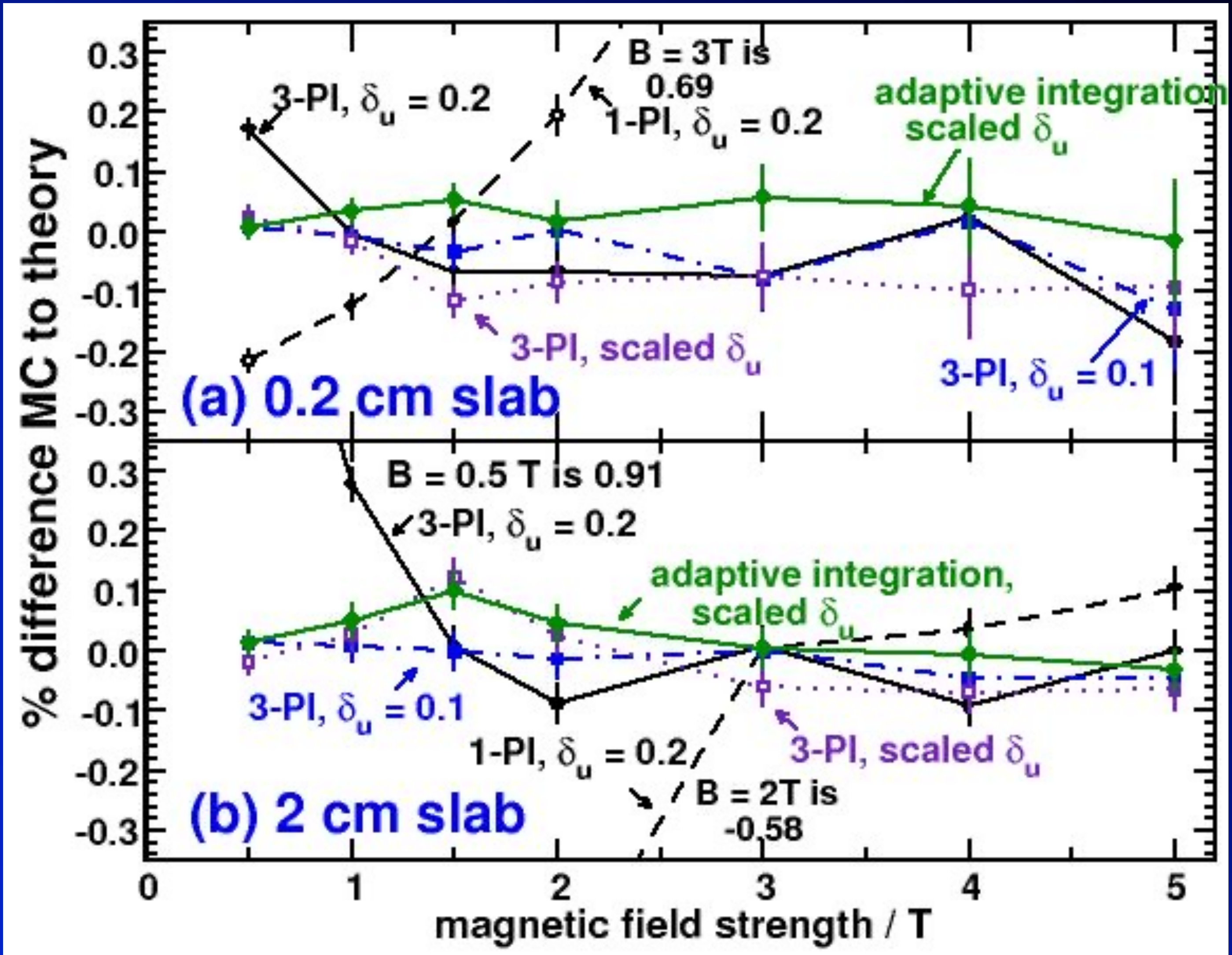
Fano slab gap test vs B: 1 MeV e-

adaptive integration

-uses 1-PI for short steps

scaled δ_u

varies with B relative to B_{ref} value



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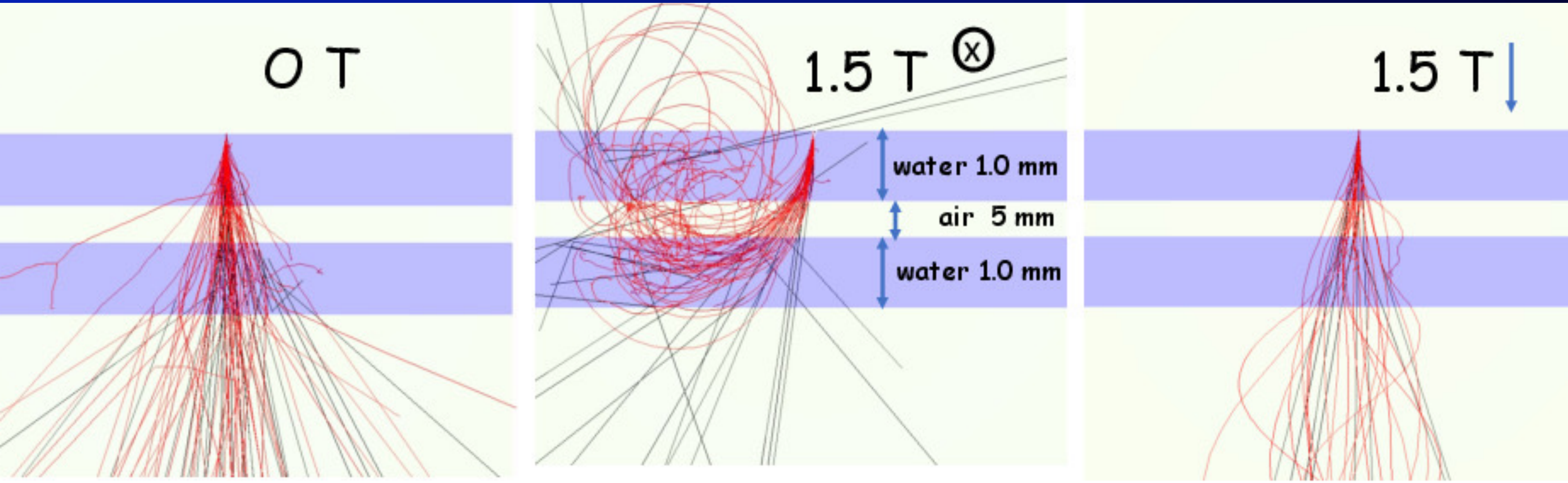
B field effects on electrons

pencil beams of 10 MeV e-



electron return effect

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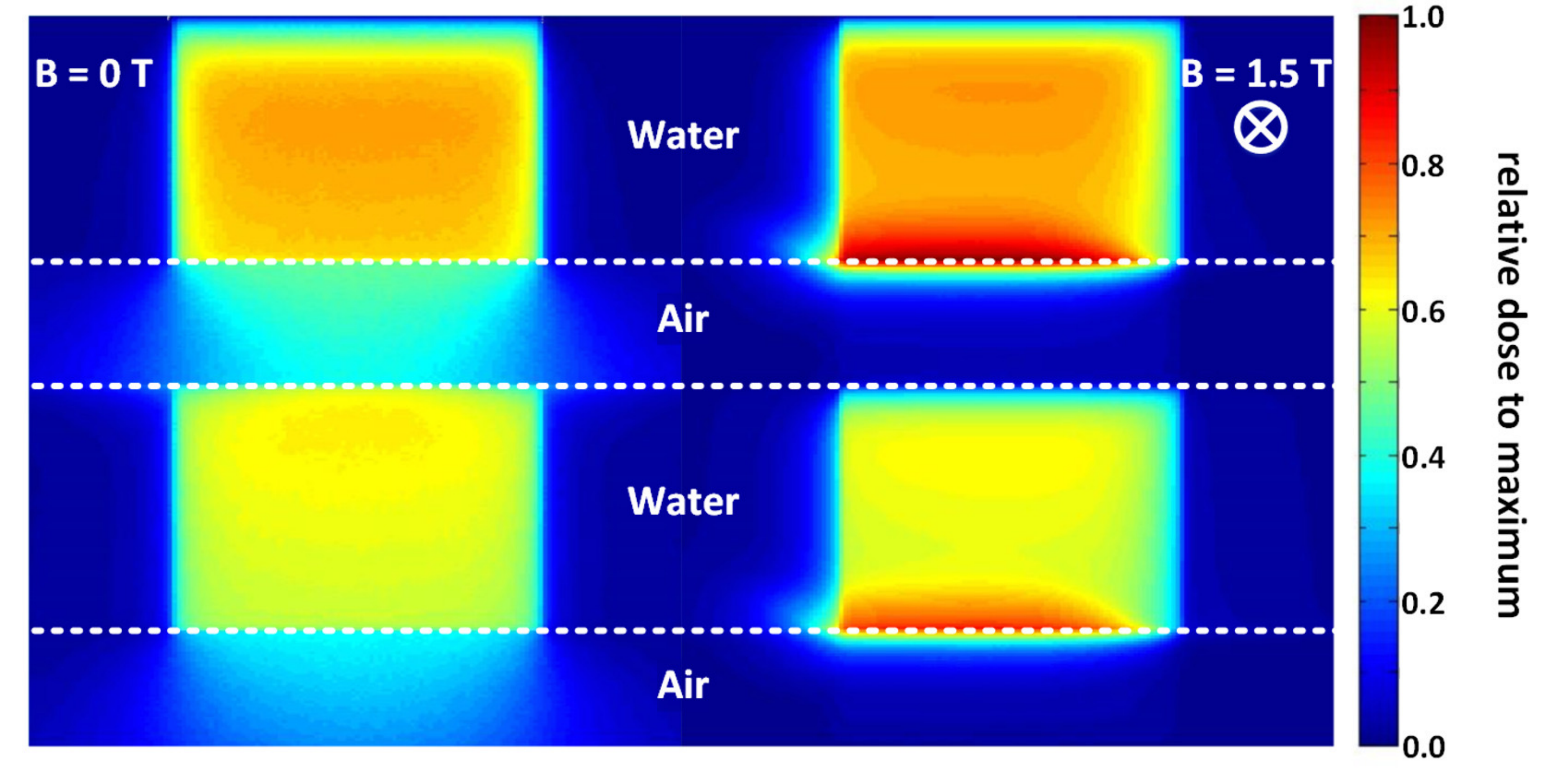
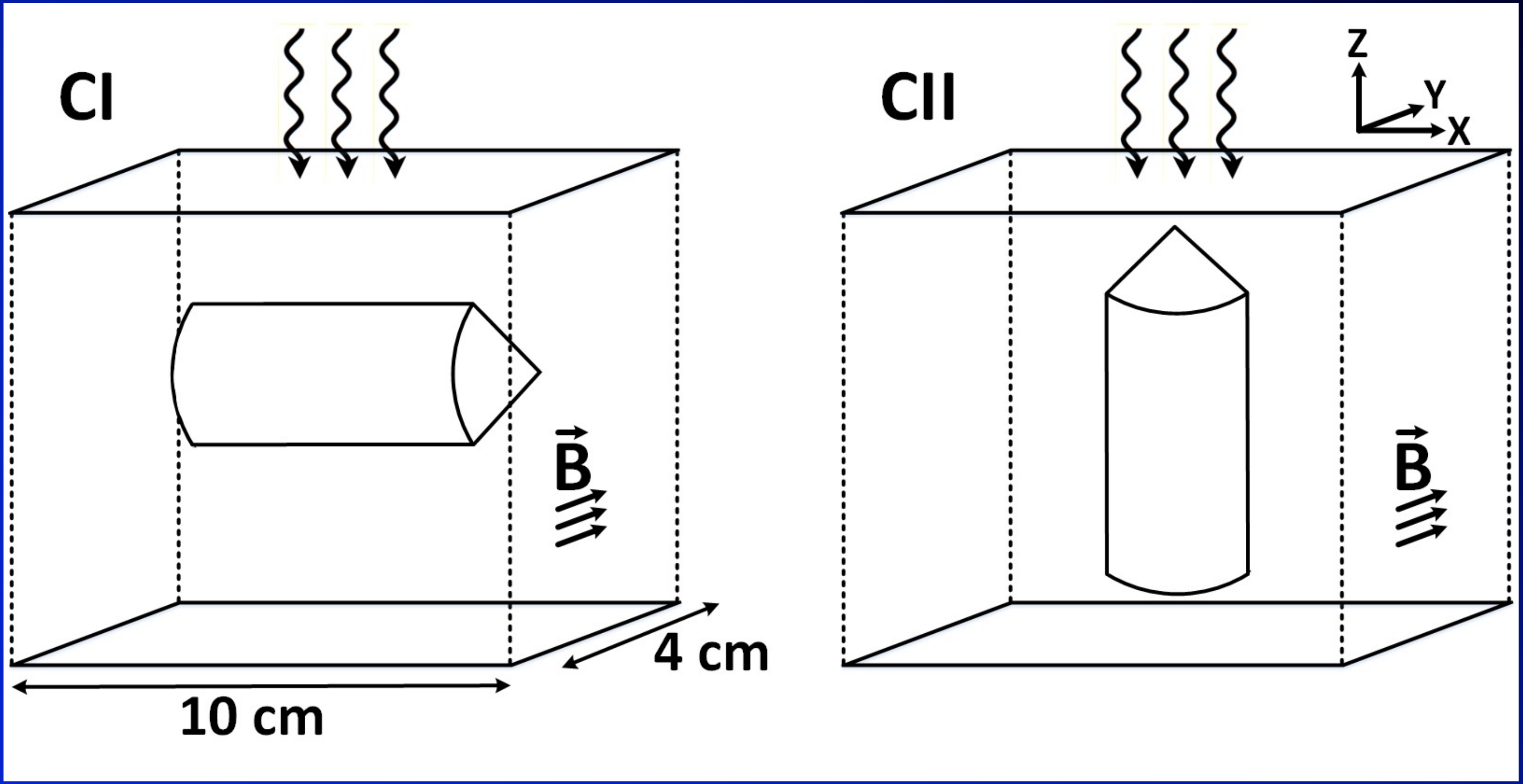
Magnetic field effects: Electron Return Effect (ERE)

photons on water phantom with air gap



ion chamber simulations



after Meijsing et al PMB 54(2009) 2993

NE2571 models were detailed.

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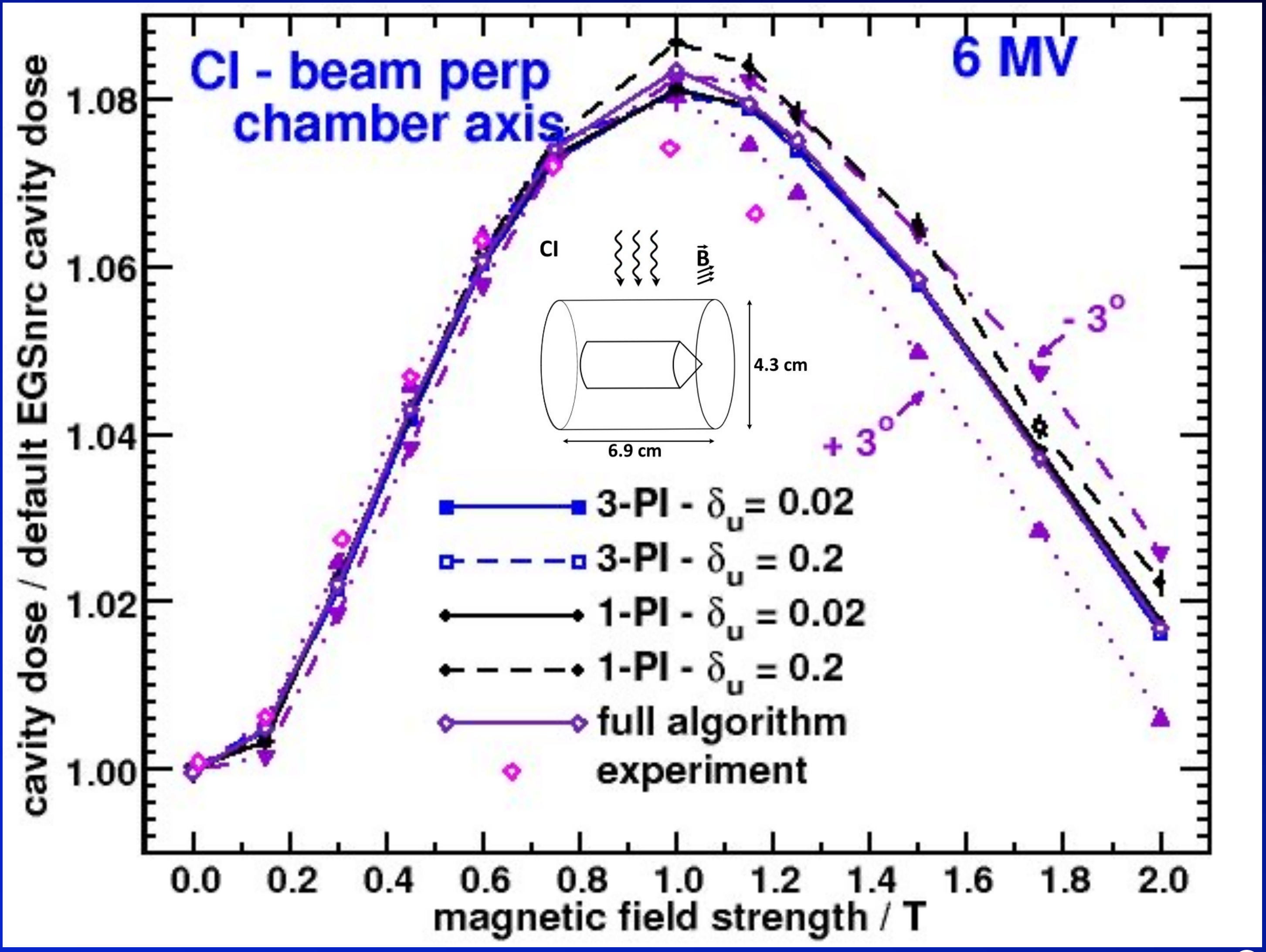
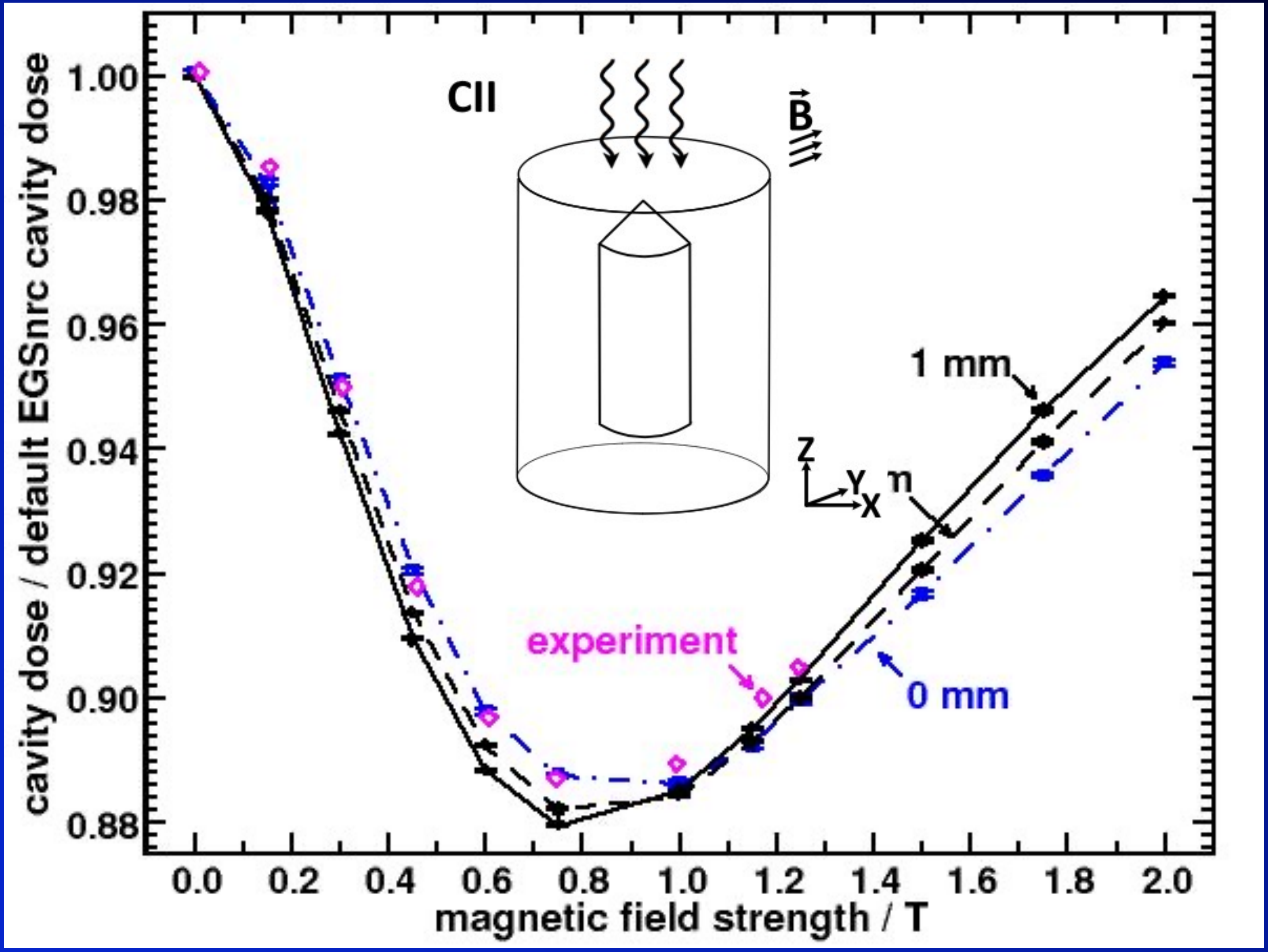
C I geometry: beam & B ⊥ chamber axis



C I I geometry: beam || axis & both ⊥ B air gap effects



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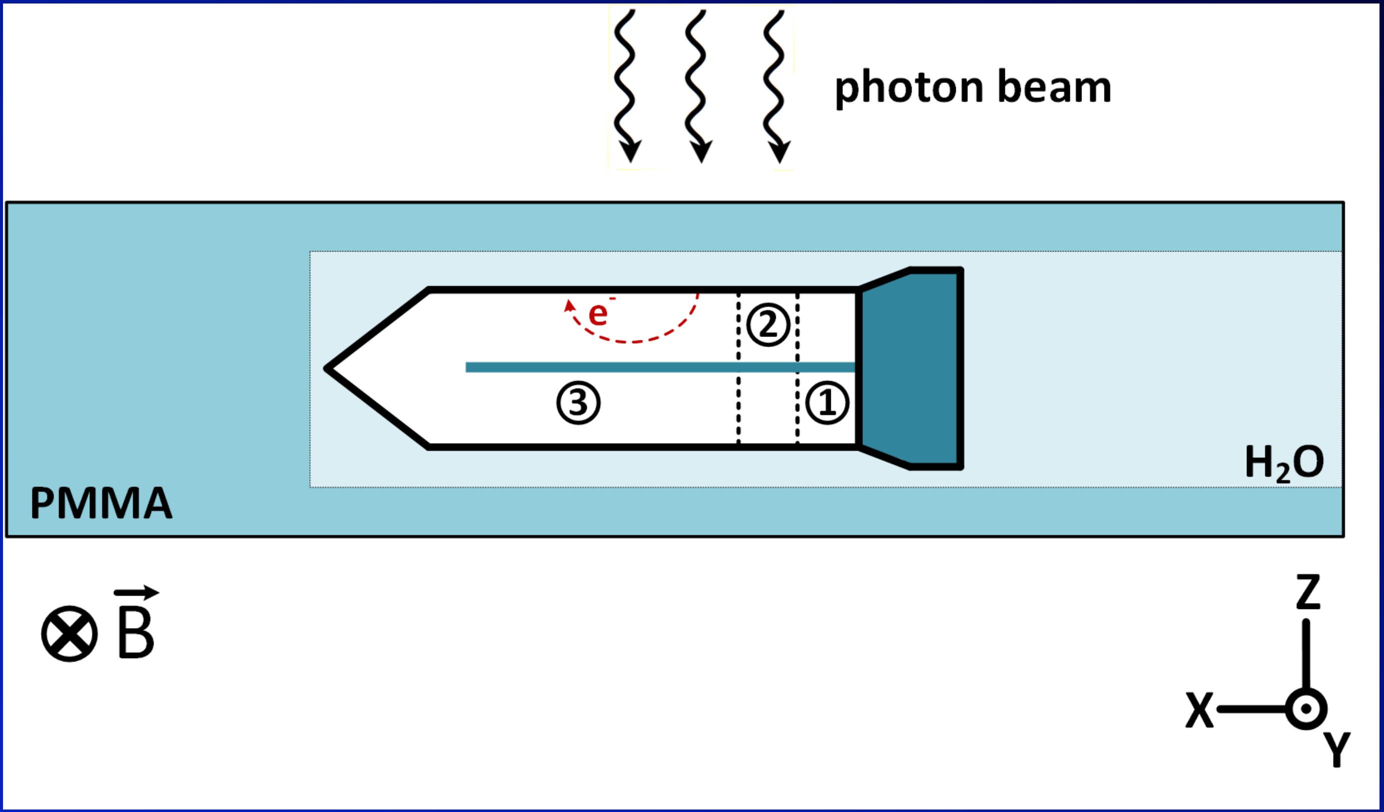
Complications in a B-field



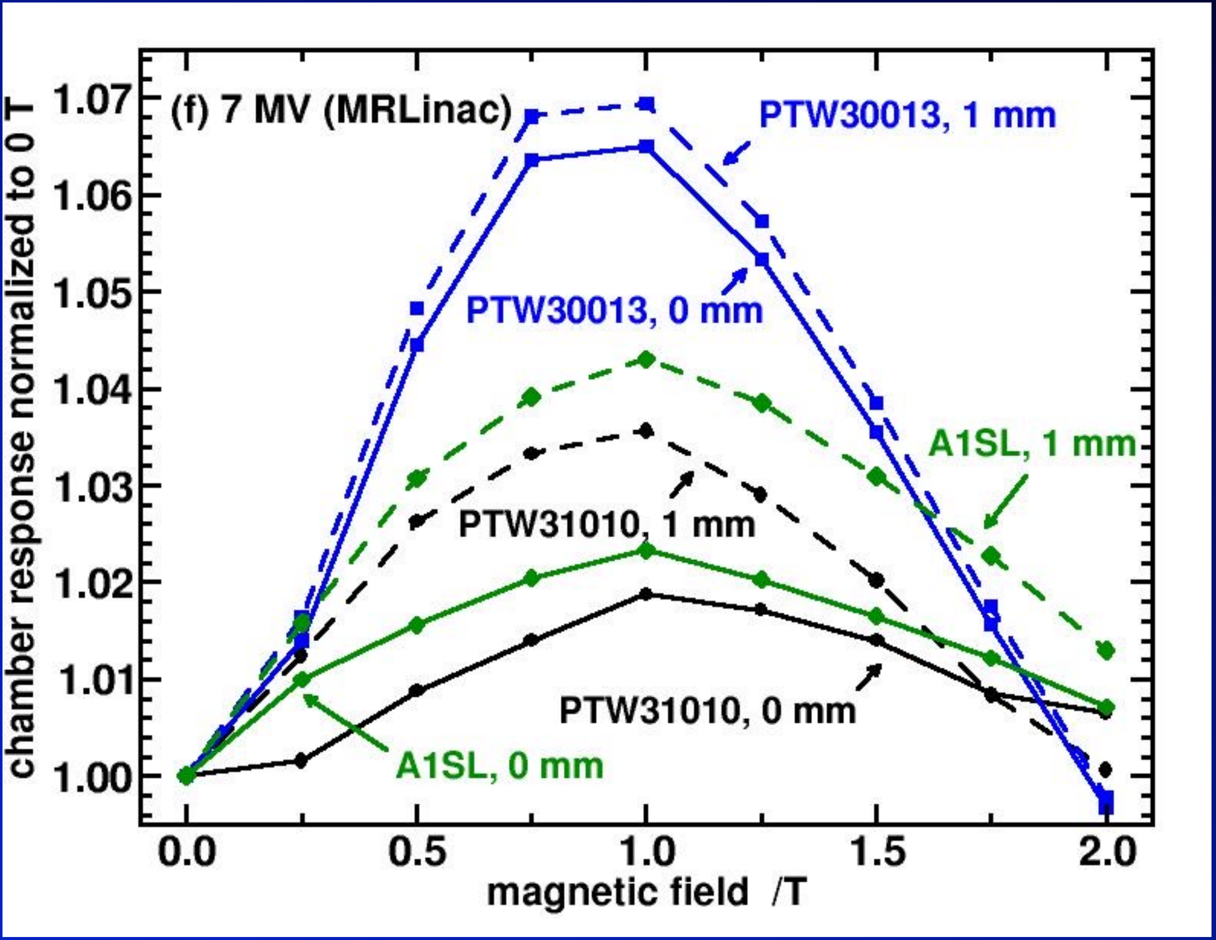
Ion chambers have dead regions near stem
due to E-field distortions

Volume uncertain.

Malkov Med Phys
44 (2017) 4854

Complications in a B-field

beam & B-field perpendicular to chamber



Worst case effects from uncertain sensitive region

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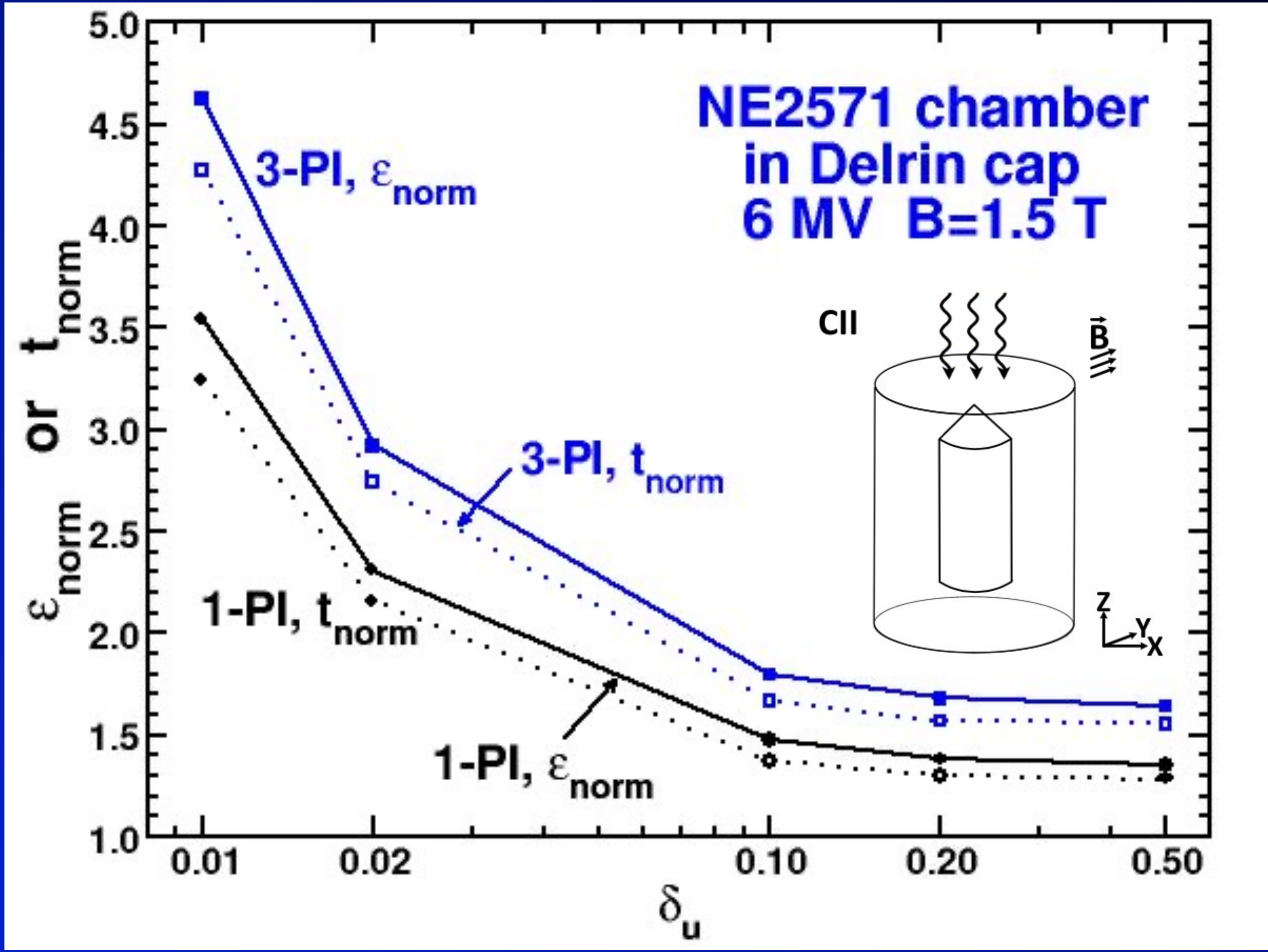
calculation efficiency: ion chamber

CII case, beam || chamber axis

$$t_{\mathrm{norm}} = \frac{t_B}{t_0}$$

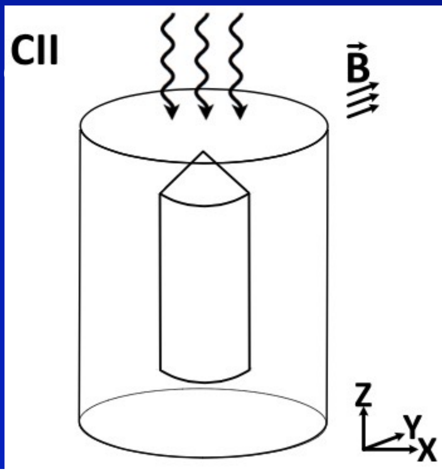
$$\epsilon_{\mathrm{norm}} = \frac{\epsilon_0}{\epsilon_B} = t_{\mathrm{norm}} \frac{s_B^2}{s_0^2}$$



smaller t_{norm} better: ε_{norm} is inverted,

higher ε better => lower ε_{norm} is better

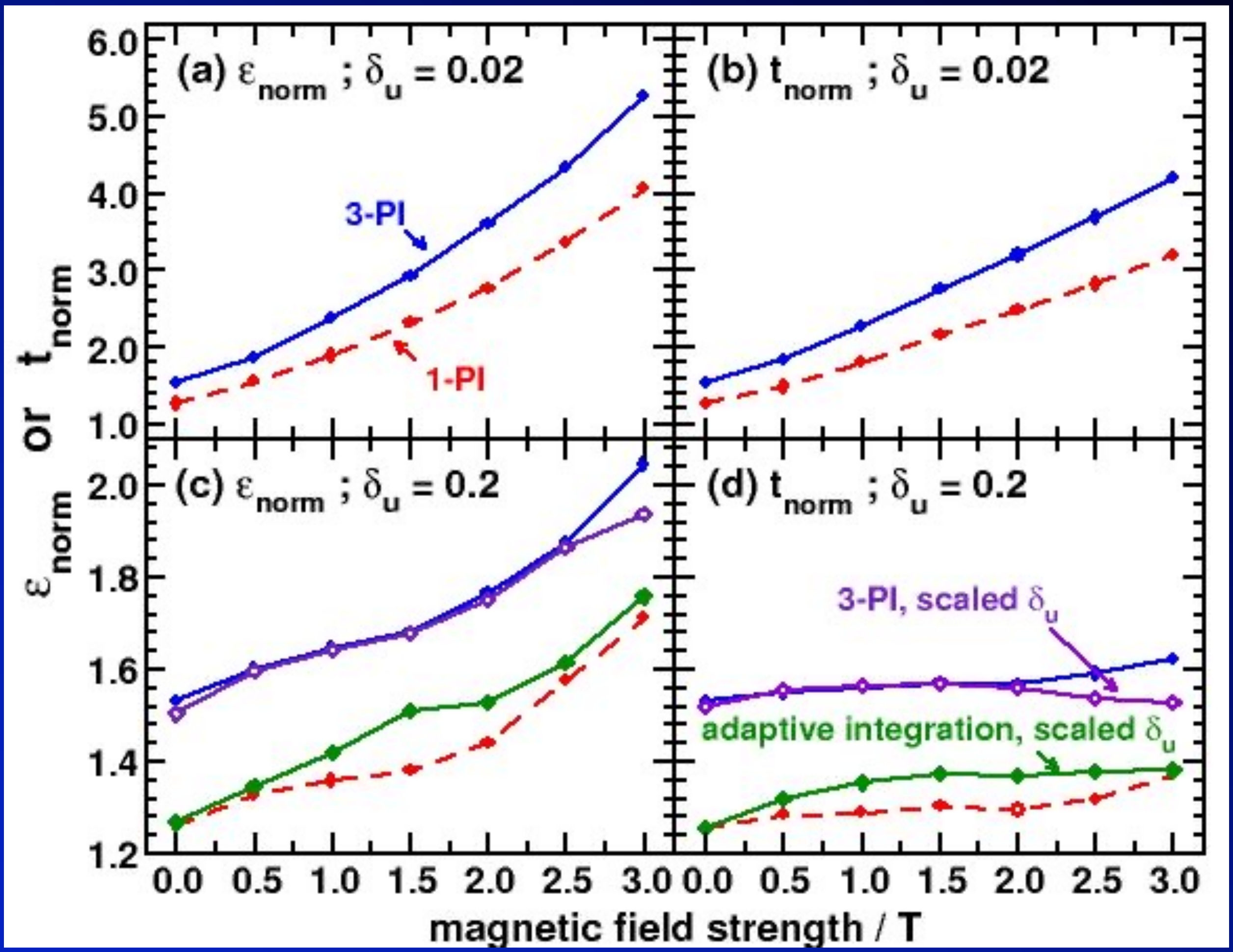
calculation efficiency: ion chamber



$$t_{\text{norm}} = \frac{t_B}{t_0}$$

$$\epsilon_{\text{norm}} = \frac{\epsilon_0}{\epsilon_B}$$

$$= t_{\text{norm}} \frac{s_B^2}{s_0^2}$$



smaller t_{norm} better: ε_{norm} is inverted,

higher ε better => lower ε_{norm} is better

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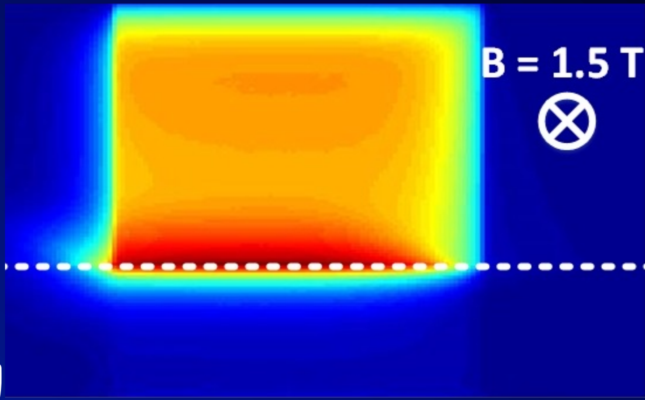
efficiency in phantom calculations

- $(30\ \text{cm})^3$ phantom, $(3\ \text{mm})^3$ voxels
- 6 MV beam with 1.5 T mag field
- 4x4 cm^2 field
- 2% stats on central axis
- on Intel Xeon 2680 2.5 GHz CPU
  - 30 min no mag field
  - 44 min 1.5 T mag field
- ion chamber calc for 2% stats
  - 6 s no mag field
  - 9 s with 1.5 T field



making it work with EGSnrc

- The EGSnrc manual (PIRS701) does not yet mention Malkov's macros, but the system appears to handle either set (EMF or EEMF).

- See section 3.14.1 in manual and use $(EGS_SOURCEDIR)EEMF_macros.mortran found on $HEN_HOUSE/src instead of $(EGS_SOURCEDIR)emf_macros.mortran when modifying SOURCES in any (except BEAMnrc) user_code.make file.

- For BEAMnrc, in sources.make use, $(EGS_SOURCEDIR)EEMF_macros_beamnrc.mortran

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Similar changes for other apps as per PIRS701

define B field in .egsinp file

```
:start MC transport parameter:
        :
        :
# B-field defined in the X , Y, Z directions
Magnetic Field = 0, 1.5, 0       # magnetic field in tesla
EM ESTEPE = 0.2                  #default 0.02
        :
        :
:stop MC transport parameter:
```

Same for electric field in V/cm,
either standalone or combined

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the end