2017 KNS 춘계학술발표회
방사선이용 및 방호 분과

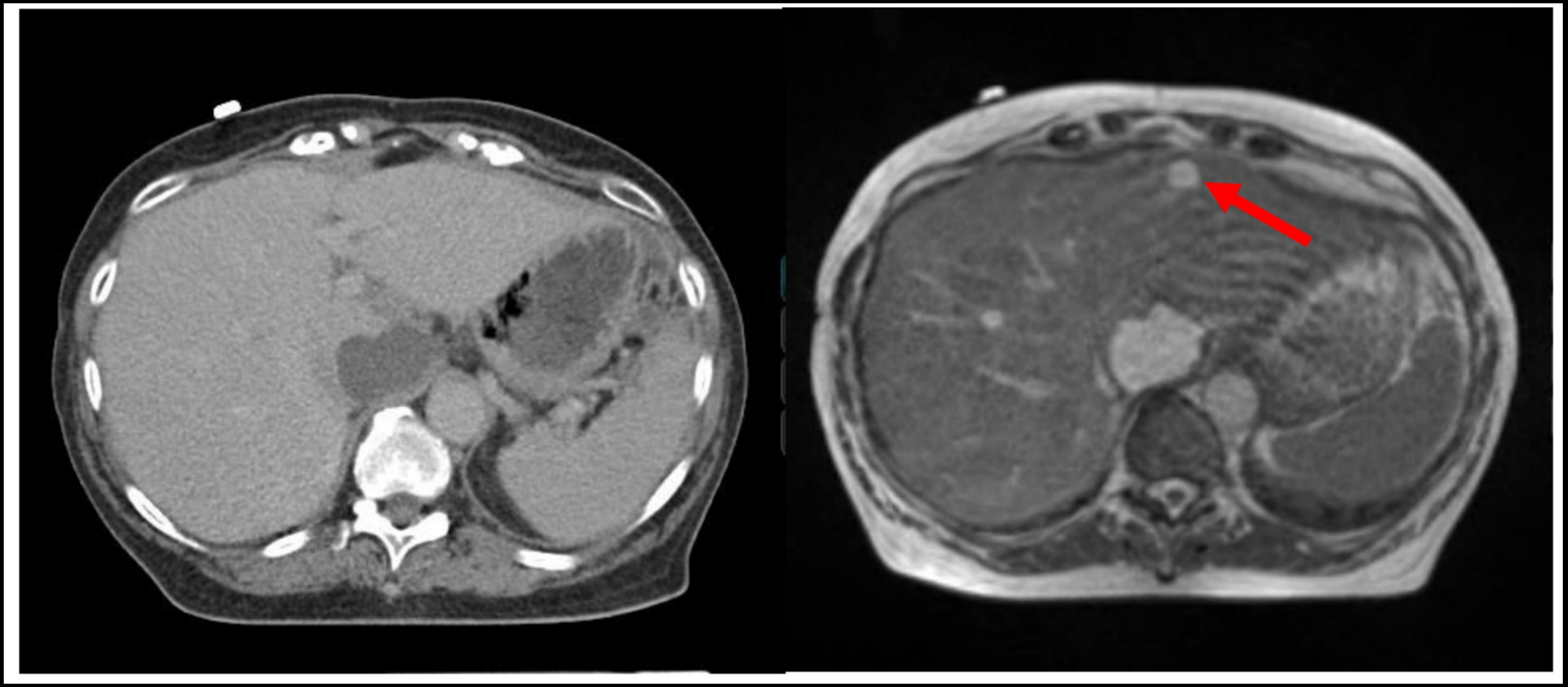
Benchmark of MCNP6 for ionization chamber simulation in the presence of a magnetic field using the Fano cavity theory: Dose comparison with EGSnrc, PENELOPE, and Geant4

서울대학교 방사선의학물리연구실
이재기

CT VS. MRI

Advantages of MRI
- High soft tissue contrast
- No radiation exposure

Target visualization (liver lesions)



CT image MRI

DOI: 10.15761/ICST.1000181

RADIATION IN B-FIELDS

- MR-linac
  - High-quality & real-time images during radiotherapy

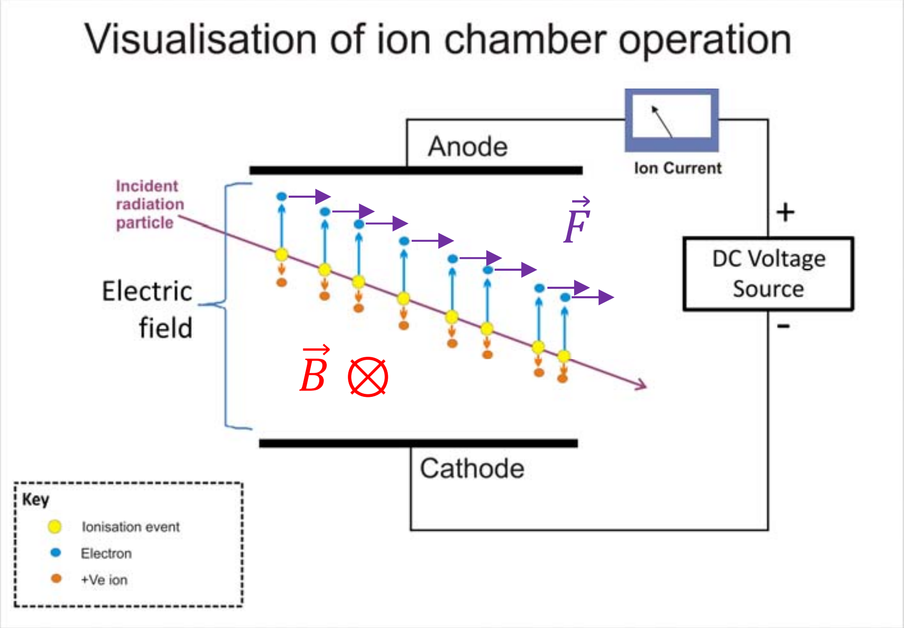
https://www.philips.co.uk/healthcare/education-resources/publications/hotspot/mr-linac

DOSIMETRY IN B-FIELDS

- The magnetic fields influence the trajectories of the secondary electrons by the Lorentz force.
- Dose distribution in water and dose response of ionization chambers are changed.

http://img.medicalexpo.com/images_me/photo-mg/68812-9169214.jpg

Phys. Med. Biol. **60** (2015) 8625



https://upload.wikimedia.org/wikipedia/commons/b/bd/Ion_chamber_operation.gif

MONTE CARLO SIMULATION

- High accuracy without B-fields
- Sophisticated algorithm
  - Condensed history & multiple scattering
  - To maximize step size maintaining accuracy (for speed-up)
- B-field simulation
  - MCNP6.1, EGSnrc, PENELOPE, and Geant4

- We need to validate the accuracy of the Monte Carlo codes in the presence of B-fields.

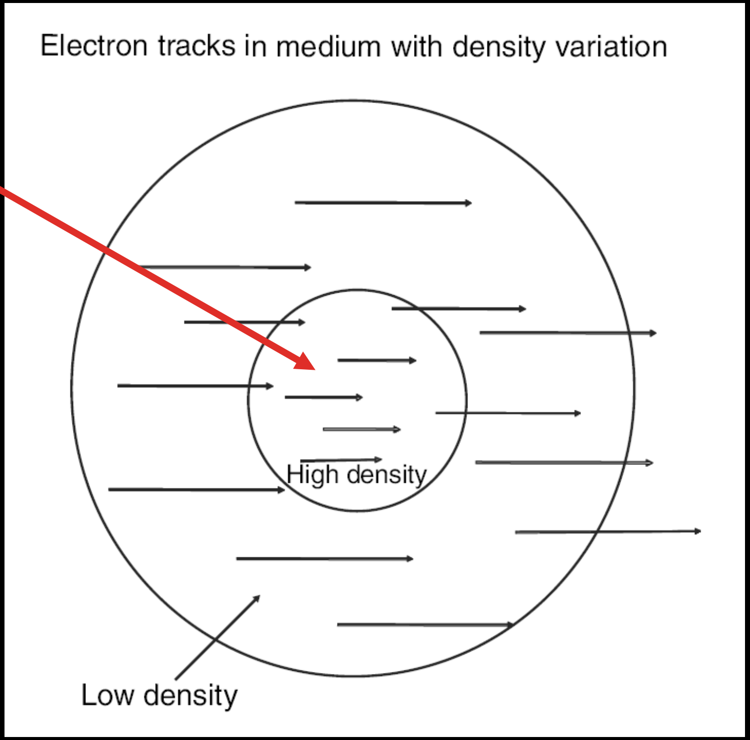
FANO CAVITY THEOREM

- *In a medium with uniform atomic properties irradiated by a source of primary particles being spatially uniform, the charged particle fluence is also uniform and independent of the mass density distribution.*

More electron tracks are started per unit volume

But, each track is shorter due to the higher stopping power

→ the electron fluence in the central region will be exactly the same as that in the outer region



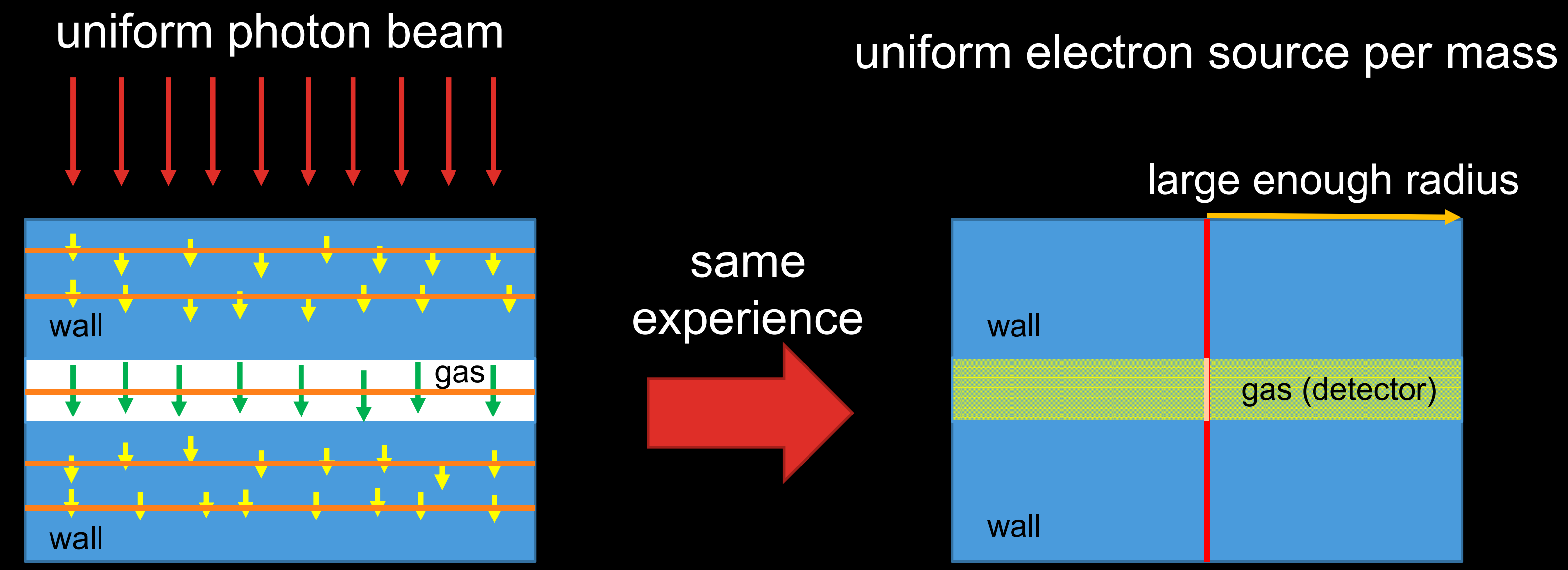
Mayles, Philip, Alan Nahum, and Jean-Claude Rosenwald, eds. *Handbook of radiotherapy physics: theory and practice*. CRC Press, 2007. p.114

FANO CAVITY TEST IN B-FIELDS

- To test the accuracy of Monte Carlo transport algorithms in the presence of magnetic fields, the Fano cavity test cannot be applied.

- Special conditions for Fano's theorem to hold in external b-fields (By H. Bouchard *et al.*, Phys. Med. Biol. 2015)
  - Condition 1: isotropic & spatially uniform sources
    - (charged particle isotropy, CPI)
  - Condition 2: spatially uniform sources & density-scaled b-field

SIMULATION GEOMETRY

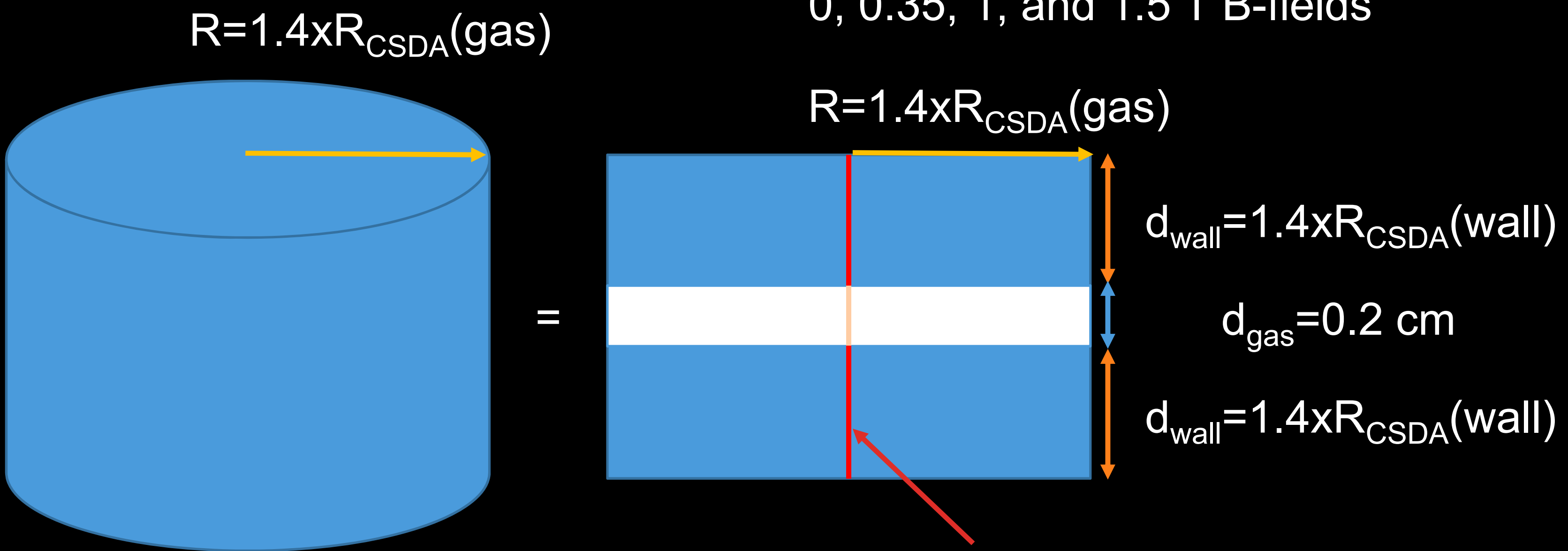


By the Fano cavity theory, every row/column has same fluence

The reciprocal problem involves a line source and a detector that covers the whole gas in the cavity

SIMULATION GEOMETRY

0.01, 0.1, 1, and 3 MeV electron
0, 0.35, 1, and 1.5 T B-fields



monoenergetic isotropic line (thin) source
intensity probability ratio: $d_{wall} : d_{gas}/1000 : d_{wall}$
(i.e. for 1 MeV, 0.4088 : 0.0002 : 0.4088)

ρ_{wall}: carbon 1.7 g/cm^3

ρ_{gas}: 0.0017 g/cm^3

same carbon, but diff. density (1/1000)

R_{CSDA}: continuous slowing down approximation-range

FANO CAVITY ASSUMPTIONS

$$D = \Phi_0 p_{wall} p_{fluence} \left(\frac{\bar{L}}{\rho}\right)_{wall}^{cavity} \left(\frac{\bar{\mu}_{en}}{\rho}\right)_{wall}$$

- In the assumption of the Fano cavity theorem,
  - cavity material = wall material (uniform atomic properties)

  $\left(\frac{\bar{L}}{\rho}\right)_{wall}^{cavity} = 1$, and $p_{fluence} = 1$
- In the absence of photon attenuation and scatter,

  $p_{wall} = 1$
- If the Bremsstrahlung cross section is set to zero,

  $\left(\frac{\bar{\mu}_{en}}{\rho}\right)_{wall} = \left(\frac{\bar{\mu}_{tr}}{\rho}\right)_{wall}$

$$\therefore D = \Phi_0 \left(\frac{\bar{\mu}_{tr}}{\rho}\right)_{wall}$$

THEORETICAL RESULTS

- $Q = \frac{D}{\Phi_0 E_0}$
  - D: dose in the gas regions
  - Φ_0: the number of electrons per unit mass
  - E_0: the initial kinetic energy of the source electrons

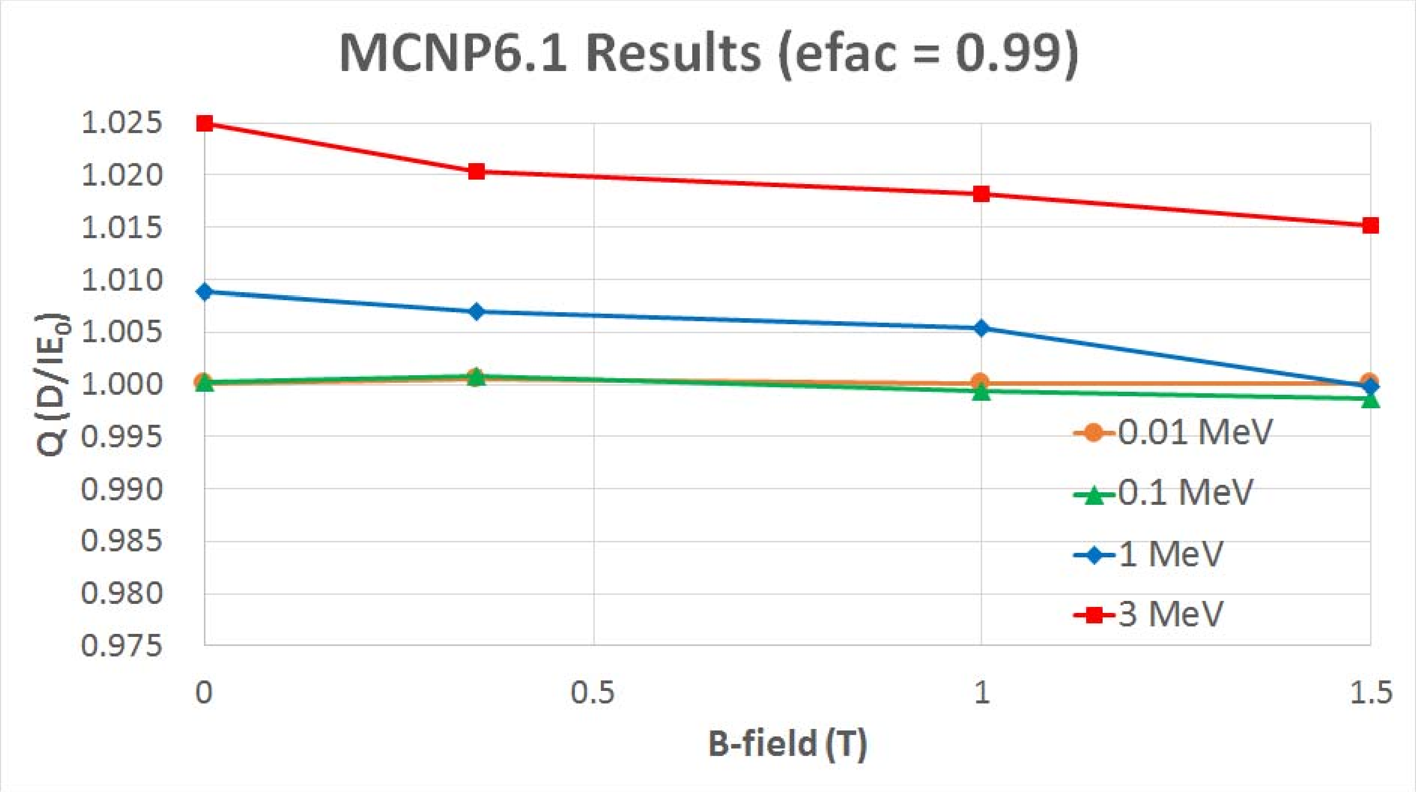
- In the ideal case, Q would be equal to 1.

MCNP6.1

- *efac*: stopping power energy spacing
  - $E_{n-1} = E_n \times \mathrm{efac}$
  - A larger *efac* produces more points in the stopping power tables
  - 0.8 ≤ *efac* ≤ 0.99
  - default: 0.917 (=$\sqrt{\sqrt{\sqrt{0.5}}}$)

- ITS (Integrated Tiger Series)-style energy indexing algorithm was used for accurate electron dose calculation.

RESULTS (MCNP6.1)



Statistical uncertainties < symbol size

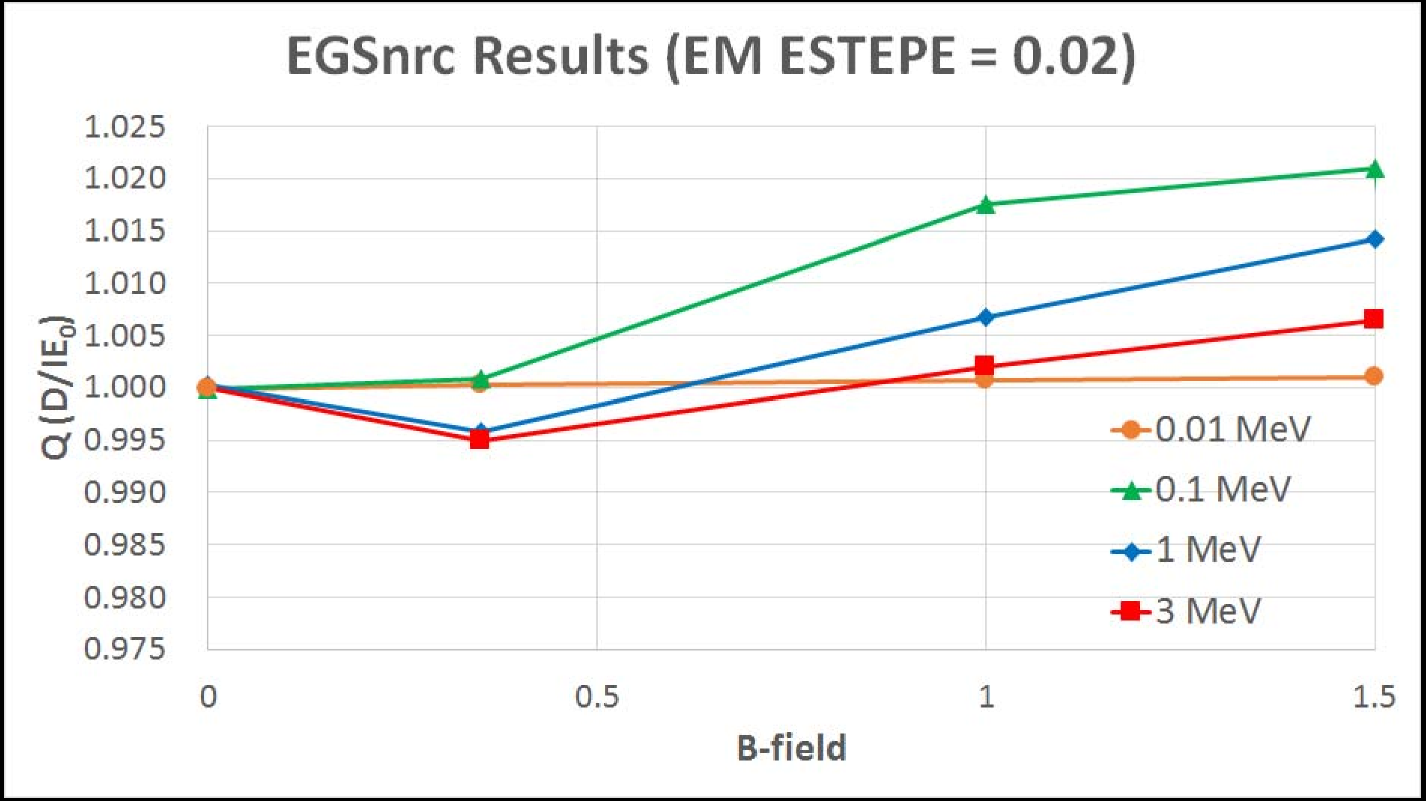
Courtesy of Jimin Lee

EGSNRC (2017)

- ESTEPE: Max. fractional energy loss per step
  - 0.01 ≤ ESTEPE ≤ 0.25
  - default: 0.25

- EM ESTEPE: coefficient b/w gyration radius (r_g) and path-length to the next interaction (s).
  - $s = \delta \cdot \frac{E_0 \gamma_0 \beta^2}{q(\vec{v}_0 \times \vec{B}_0)} = \delta \cdot r_g$
  - 0.02 ≤ EM ESTEPE ≤ 0.40
  - default: 0.02

RESULTS (EGSNRC)



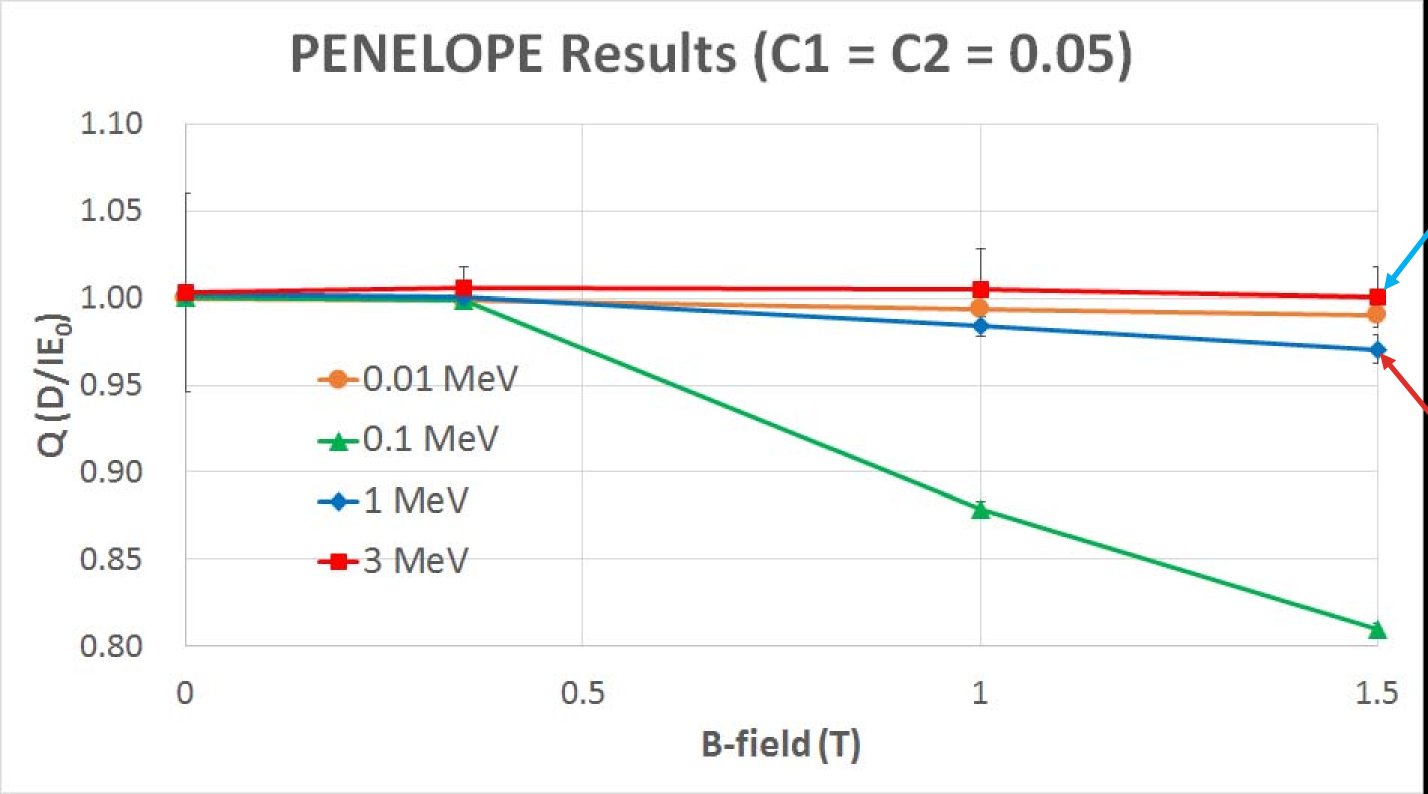
Statistical uncertainties < 0.03%

PENELOPE 2014

- C_1, C_2: determine cutoff angle that separates hard from soft elastic interactions
  - C_1: mean free path b/w hard elastic events
  - C_2: max. average fractional energy loss in a single step
  - $C_1 = 0.05$, $C_2 = 0.05$
  - $0 \leq C_1, C_2 \leq 0.2$
  - default: $C_1 = C_2 = 0.1$

- W_{CC}, W_{CR}: cutoff energies for the production of hard inelastic and bremsstrahlung events
  - $W_{CC} = 10$ eV, $W_{CR} = 10$ eV
    - Soft events ($W \leq 10$ eV), and hard events ($W > 10$ eV)
  - $0 \leq W_{CC}, W_{CR} \leq$ no upper limit

RESULTS (PENELOPE)



1% diff.

3% diff.

Courtesy of Hochan Lee

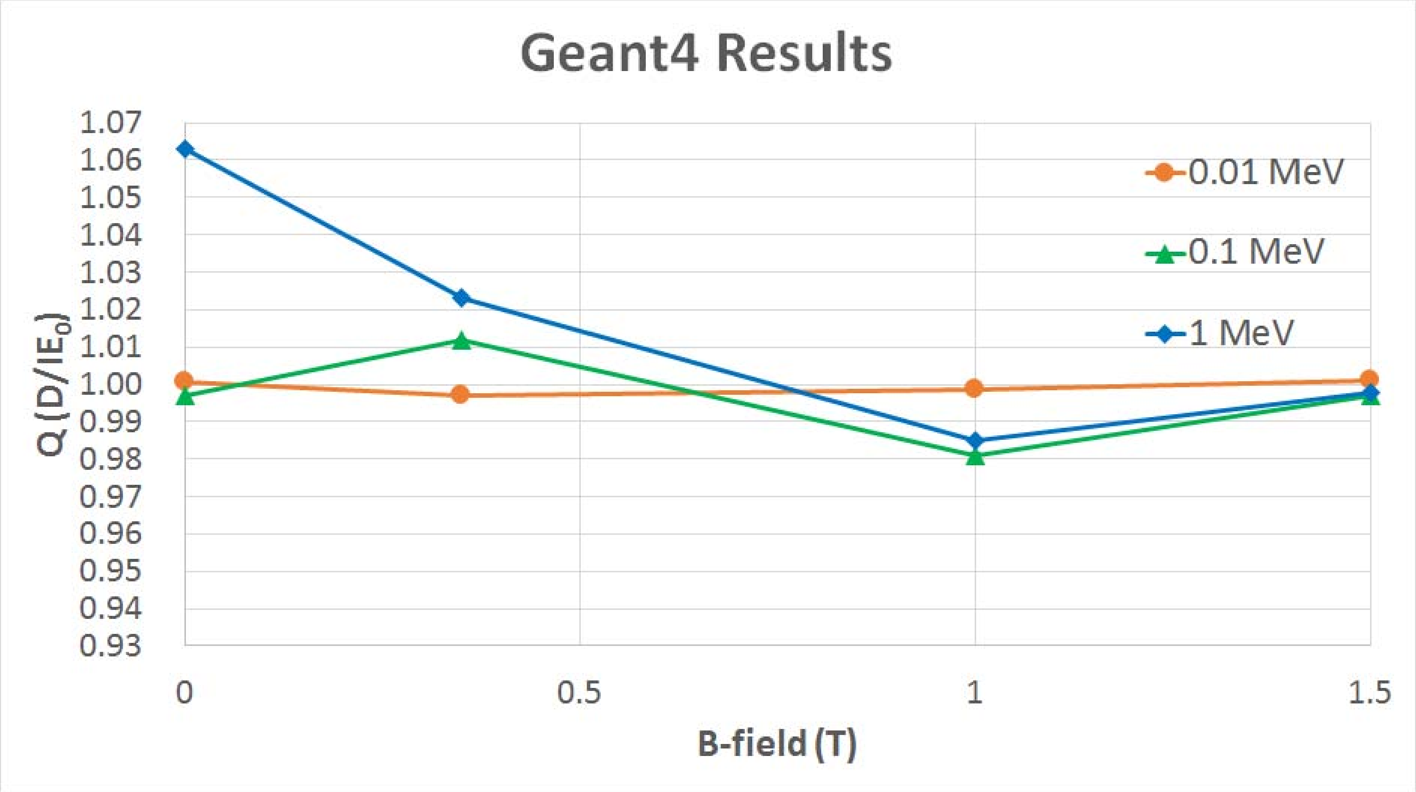
GEANT4

- dRoverRange: max. allowed ratio b/w the step-size and the range of the particle
  - dRoverRange = 0.003
  - default: 0.2

- finalRange: step limit by the ionization process
  - finalRange = 1 nm (10^{-6} mm)
  - default: 1 mm

RESULTS (GEANT4)

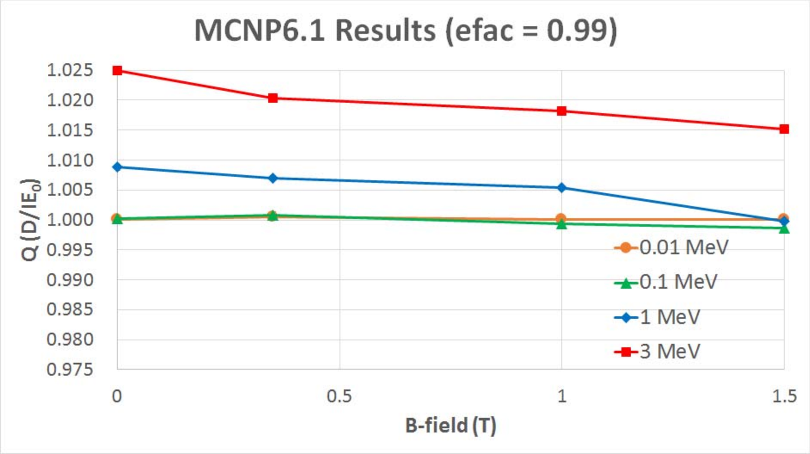
dRoverRange = 0.003, finalRange = 1 nm

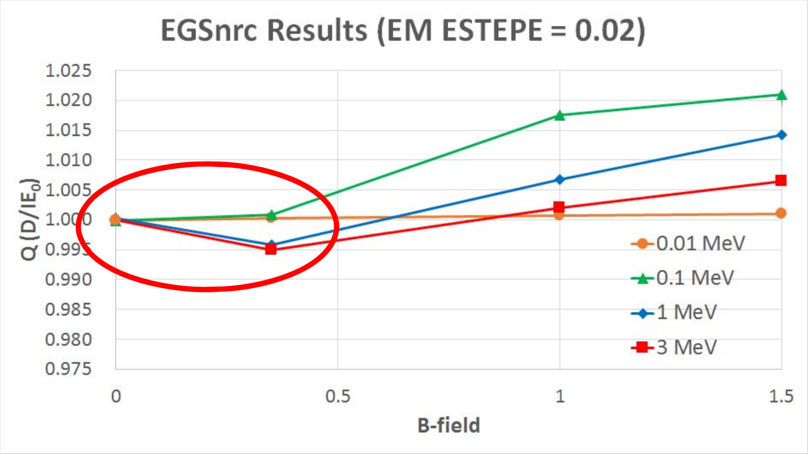


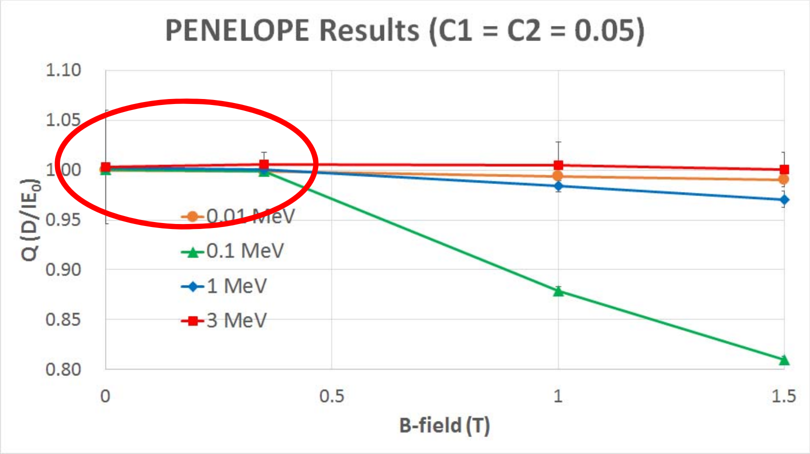
Courtesy of Dongmin Ryu

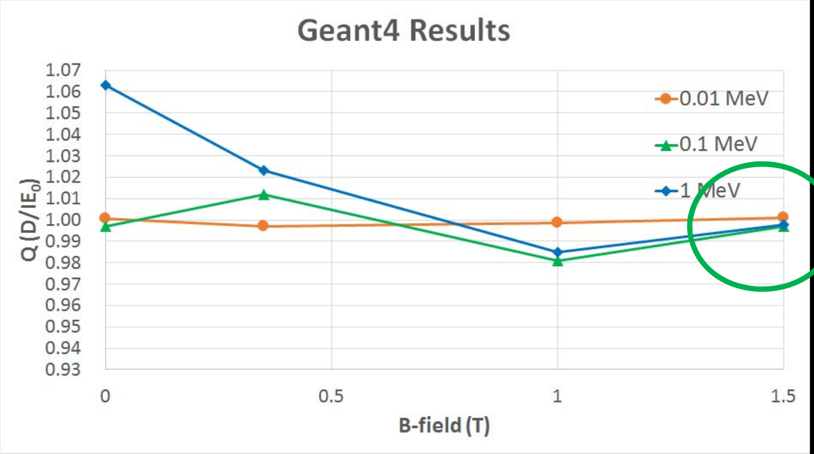
SUMMARY

Low B-fields: EGSnrc & PENELOPE are accurate.
High B-field: Geant4 is accurate.









CONCLUSION

- Radiation transport of charged particles in B-fields has been implemented in MCNP6, EGSnrc, PENELOPE, and Geant4 codes.
- In order to simulate ion-chambers for reference dosimetry in B-fields, high accuracy of MC code is needed.
- By the new Fano cavity test, each Monte Carlo code shows different accuracy.
    - MCNP6.1 shows good accuracy (< 0.2%) in low energy (kV range), but dose difference larger than 2% in 3 MeV.
    - EGSnrc shows acceptable dose differences (< 0.5%) in low B-field (≤ 0.35 T), but accuracy decreases as B-field increases.
    - PENELOPE shows the best accuracy in all results except 0.1 MeV (> 10% diff.).
    - Geant4 needs more simulation to compare the results from other codes.

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THANK YOU