# Fano Test for Therapeutic Carbon and Helium Beams in Magnetic Fields Using Geant4/GATE

Jing Syuen Wong[1], Kilian-Simon Baumann[2,3,4], Armin Lühr[5], Hugo Palmans[6,7], Björn Poppe[1], Hermann Fuchs[6,8], Hui Khee Looe[1]

[1]University Clinic for Medical Radiation Physics, Medical Campus Pius Hospital, Carl von Ossietzky University, Oldenburg, Germany
[2]University Hospital Giessen-Marburg, Department for Radiotherapy, Marburg, Germany
[3]University of Applied Sciences, Institute of Medical Physics and Radiation Protection, Giessen, Germany
[4]Marburg Ion-Beam Therapy Center, Marburg, Germany
[5]Department of Physics, TU Dortmund University, Dortmund, Germany
[6]MedAustron Iontherapy Centre, Wiener Neustadt, Austria
[7]National Physical Laboratory, United Kingdom
[8]Division of Medical Physics, Department of Radiation Oncology, Medical University of Vienna, Vienna, Austria

# Introduction to DosiMagic

- **Dosi**metry in **mag**net**ic** fields for MR-guided ion therapy
- DFG-funded project G:(GEPRIS)545018522
- Goal: extend dosimetry in particle therapy towards magnetic field environments

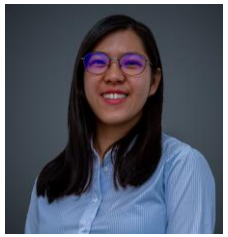
PD. Dr.
Hui Khee Looe
(Oldenburg)

Prof. Dr.
Kilian-Simon Baumann
(Marburg, Giessen)

Jun.-Prof. Dr.
Armin Lühr
(Dortmund)

Ap.Prof.
Hermann Fuchs, PhD
(Vienna)

Dr. ir. PhD
Hugo Palmans
(Wiener Neustadt, UK)



Jing Syuen Wong

Fynn Joris Güldenhaupt




Contact: jing.syuen.wong@uni-oldenburg.de

# Introduction

- Ion therapy: offers excellent Bragg-peak characteristics
- MR-guided ion therapy: changes of dosimeter behaviour in magnetic fields

**Fano´s Theorem**

"In a medium of given composition exposed to a uniform flux of primary radiation (such as X-rays or neutrons), the flux of secondary radiation is also uniform and *independent of the density of the medium* as well as of the density variations from point to point"

*U. Fano 1954*


Contact: jing.syuen.wong@uni-oldenburg.de

# Motivation

– Blum *et al* 2023 https://doi.org/10.1088/1361-6560/ad311a

  – Fano cavity test for proton beams in magnetic fields

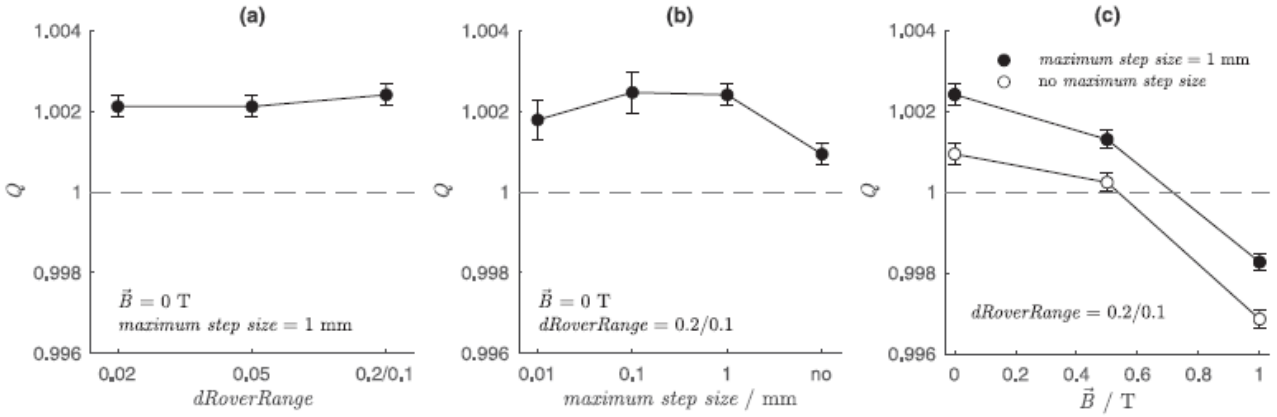



**Figure 4.** Results of the Fano cavity test given by $Q$-values. (a) changing of *dRoverRange*, (b) changing of the *maximum step size* (c) with magnetic field of $\vec{B}$ = 0.5 T and $\vec{B}$ = 1 T.

– **To test the transport parameters in the presence of a magnetic field for Carbon and Helium ions**



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# Setup

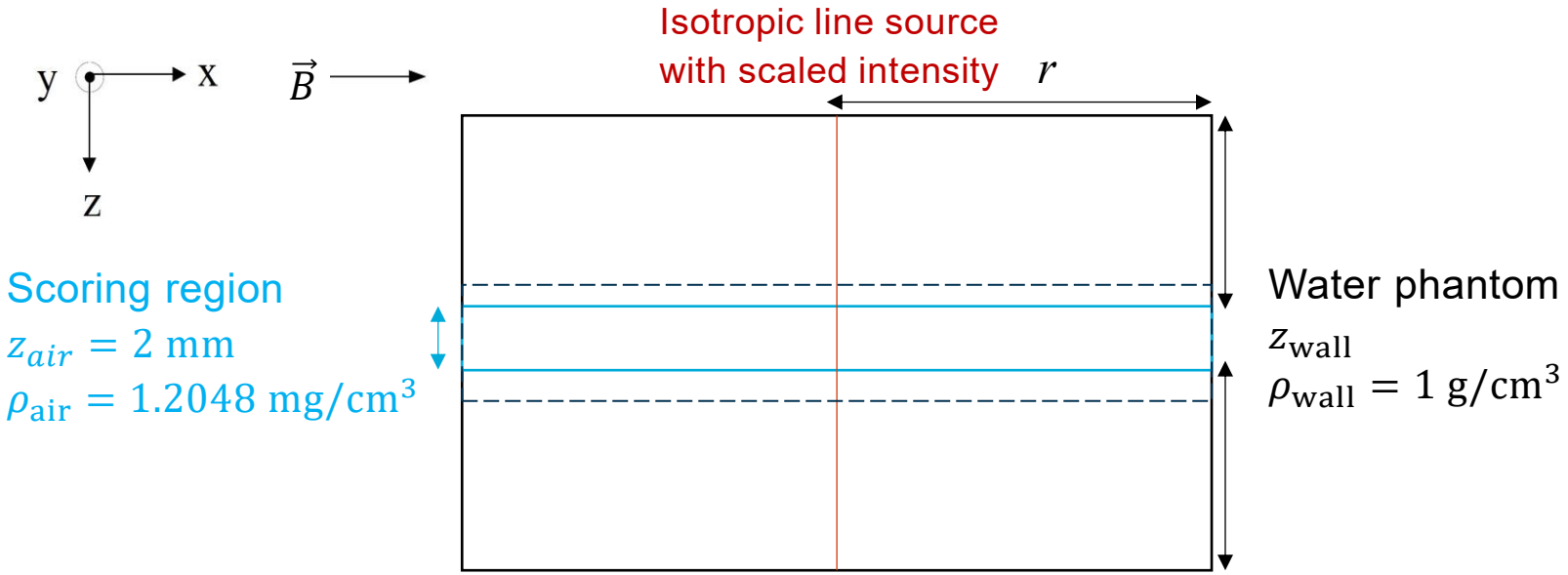



Fig. 1: Schematic drawing of the simulation's setup, not to scale.

| | Carbon | Helium |
|---|---|---|
| $z_{\mathrm{wall}}$ / cm | 62 | 186 |
| $r$ / m | 573.5 | 1736.5 |

Table 1: Dimensions of the setup for 400 MeV/u Carbon and Helium beam.





Contact: jing.syuen.wong@uni-oldenburg.de

# Evaluation

$$Q = \frac{E_{\mathrm{dep}}}{N \cdot E_0}\left(1 + \frac{2\,\rho_{\mathrm{wall}}\,z_{\mathrm{wall}}}{\rho_{\mathrm{air}}\,z_{\mathrm{air}}}\right)$$

$E_{\mathrm{dep}}$: Deposited energy in the scoring region

$N$: Number of initial particles

$E_0$: Initial energy

– Deviation between initial and deposited energy in the scoring region



Sempau and Andreo 2006
Wulff *et al* 2018

# General Settings

- GATE version 9.4. / Geant4 version 11.2.2 with density correction deactivated

- QGSP_BIC_HP_EMZ (EMstandardOpt4)
- Nuclear interactions are switched off, only electromagnetic interactions are considered

- $E_0$ = 120, 250, 400 MeV/u for Carbon and Helium ions
- $\vec{B}$ = 0, 0.5, 1 T


Contact: jing.syuen.wong@uni-oldenburg.de

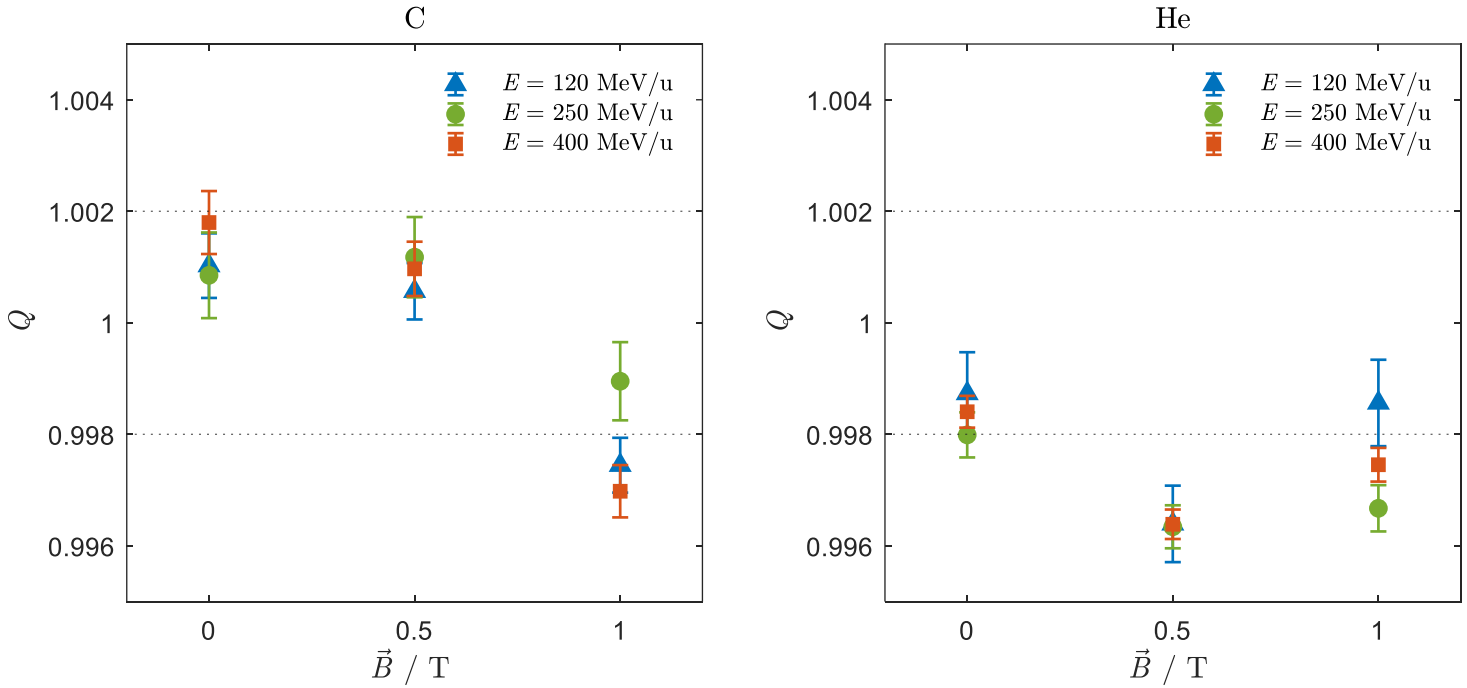
# Starting Point

- ***Production cut***: particle's range below which will not be generated
  - kept constant at 1 µm in cutbox
- ***Maximum step size:*** upper limit of step size
  - 1 mm for all particles in cutbox
- ***dRoverRange***: limits the maximum change in the particle's stopping range
  - Default: 0.2 (electrons), 0.1 (other particles)
- ***finalRange:*** 'lower limit' of the range
  - Default: 1-50 µm




Contact: jing.syuen.wong@uni-oldenburg.de

# Energy Dependence




– No energy dependence observed for both particles

– Maximum deviation: **C 0.3 %, He 0.36 %**



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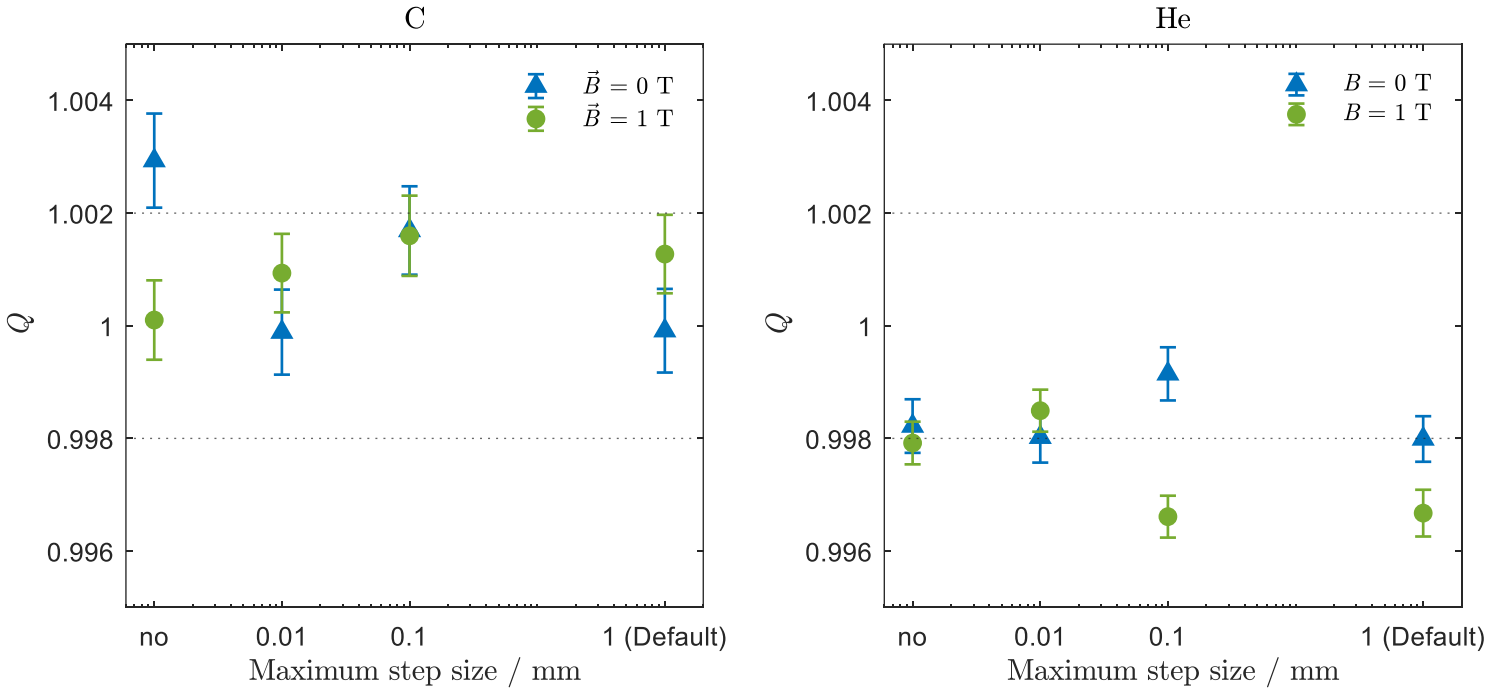
# Maximum Step Size ($E$ = 250 MeV/u)




– Fluctuating trend for different maximum step sizes

– $Q$ of He is lower than C

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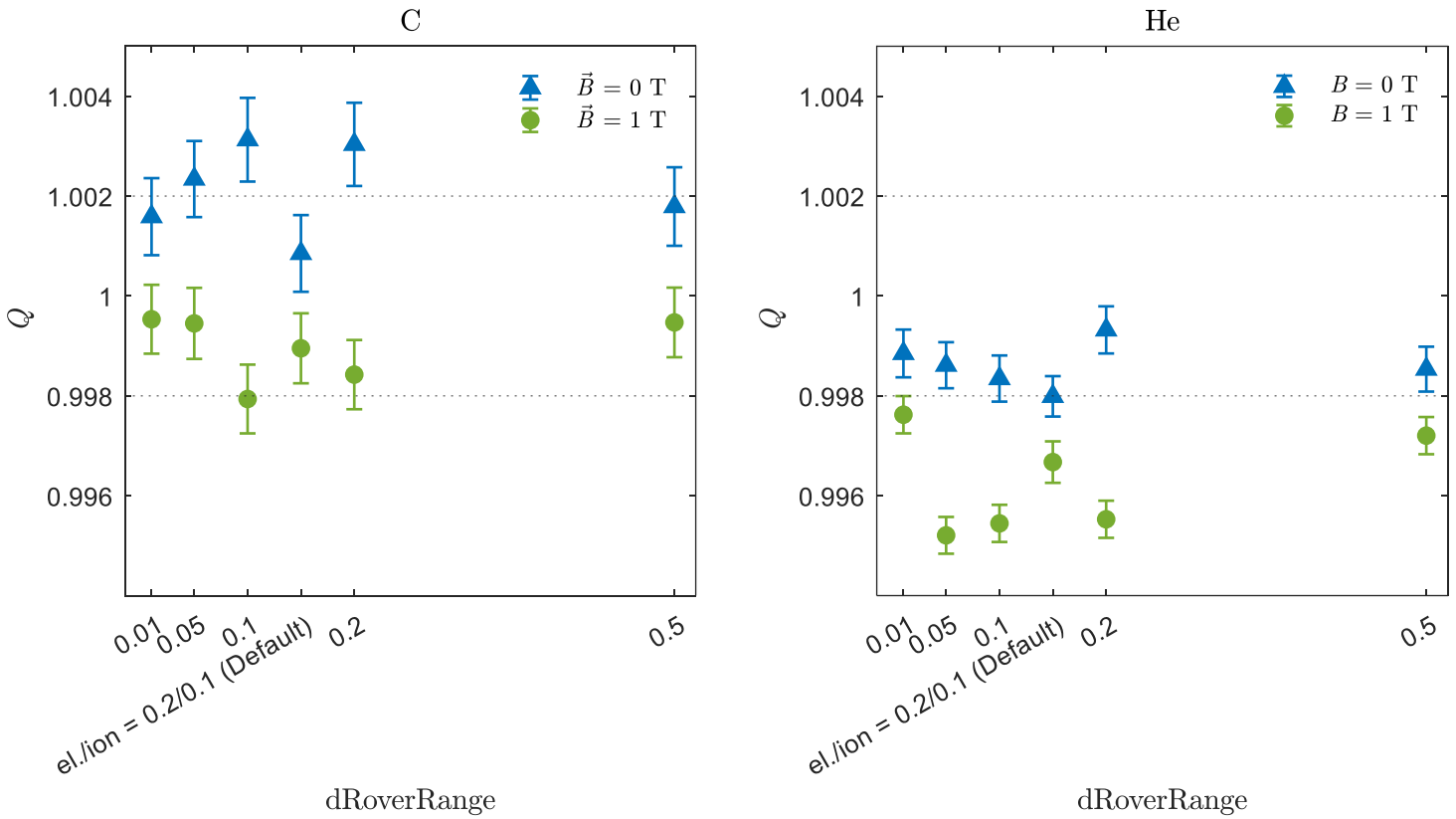
# dRover Range ($E$ = 250 MeV/u)




– No direct dependence on dRover Range, but clear magnetic field dependence

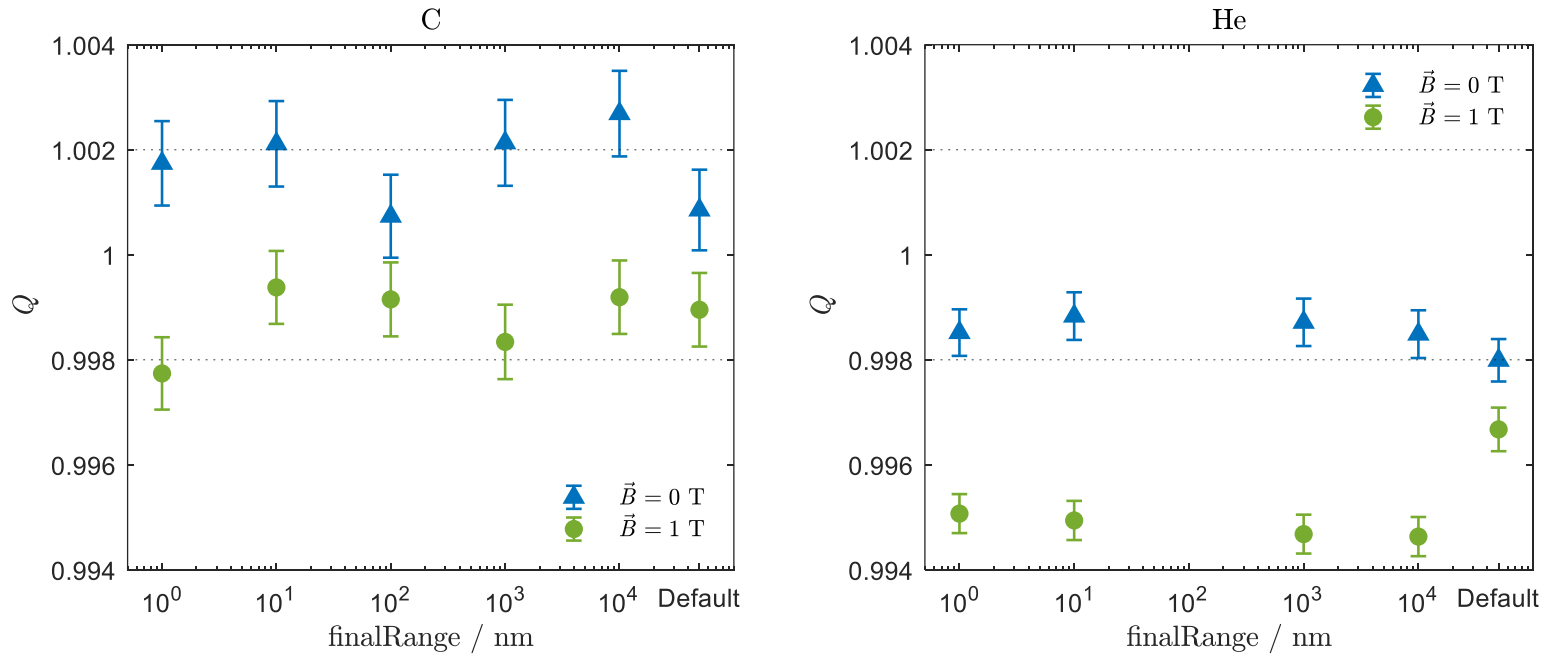
– $Q$ of He is lower than C





Contact: jing.syuen.wong@uni-oldenburg.de

# finalRange ($E$ = 250 MeV/u)




- $Q$ is insensitive to final range, but sensitive to magnetic fields
- $Q$ of He is lower than C





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# Conclusion

- No clear trend was observed by changing the investigated EM transport parameters
- Fano test passed within **0.3 % for Carbon** and **0.36 % for Helium**.
  - Original settings: 1 mm *maximum step size* in cutbox, default *dRoverRange* and *final range*
- Energy deposition for Helium seems to be underestimated




Contact: jing.syuen.wong@uni-oldenburg.de

# Future Work

- Fano test in FLUKA

- Investigation of the detectors' dose response in the presence of magnetic fields for carbon and helium ions
  - MC Simulations and measurements




Contact: jing.syuen.wong@uni-oldenburg.de

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DosiMagic

# Thank you.

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# General Settings

– Carbon

| Layer | Source Length Scaling Factor | Density Scaling Factor | Intensity Scaling Factor (= source length s. f. × density s. f.) |
|---|---|---|---|
| Wall | 62 | 830.0133 | 51460.8246 |
| Slab | 0.2 | 1 | 0.2 |

– Helium

| Layer | Source Length Scaling Factor | Density Scaling Factor | Intensity Scaling Factor (= source length s. f. × density s. f.) |
|---|---|---|---|
| Wall | 186 | 830.0133 | 154382.4738 |
| Slab | 0.2 | 1 | 0.2 |




Contact: jing.syuen.wong@uni-oldenburg.de

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# Transport Parameters Settings

– Default dRover Range and final range

```
Step function for e+-                          (0.2, 0.01 mm)
Step function for muons/hadrons                (0.1, 0.05 mm)
Step function for light ions                   (0.1, 0.02 mm)
Step function for general ions                 (0.1, 0.001 mm)
Lowest e+e- kinetic energy                     100 eV
Lowest muon/hadron kinetic energy              1 keV
```

– Production cut settings

```
Index : 0     used in the geometry : Yes
 Material : Air
 Range cuts        :  gamma  10000 km     e-  10 m      e+  10000 km  proton 10000 km
 Energy thresholds :  gamma  9.57183 GeV    e-  2.40269 MeV    e+  9.57183 GeV proton 1 PeV
 Region(s) which use this couple :
    DefaultRegionForTheWorld

Index : 1     used in the geometry : Yes
 Material : Water
 Range cuts        :  gamma  10000 km     e-  1 mm      e+  10000 km  proton 10000 km
 Energy thresholds :  gamma  9.57183 GeV    e-  351.324 keV    e+  9.57183 GeV proton 1 PeV
 Region(s) which use this couple :
    phantom

Index : 2     used in the geometry : Yes
 Material : Water
 Range cuts        :  gamma  10000 km     e-  1 um      e+  10000 km  proton 10000 km
 Energy thresholds :  gamma  9.57183 GeV    e-  250 eV      e+  9.57183 GeV proton 1 PeV
 Region(s) which use this couple :
    cutbox

Index : 3     used in the geometry : Yes
 Material : LD_Water
 Range cuts        :  gamma  10000 km     e-  1 um      e+  10000 km  proton 10000 km
 Energy thresholds :  gamma  9.57183 GeV    e-  250 eV      e+  9.57183 GeV proton 1 PeV
 Region(s) which use this couple :
    aircyl
```


Contact: jing.syuen.wong@uni-oldenburg.de

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Universität
Oldenburg

# Production Cut Settings

## Default:

```
Index : 0     used in the geometry : Yes
 Material : Air
 Range cuts        :  gamma  1 mm     e-  1 mm     e+  1 mm  proton 1 mm
 Energy thresholds :  gamma  250 eV     e-  329.118 eV     e+  325.038 eV  proton 100 keV
 Region(s) which use this couple :
    DefaultRegionForTheWorld

Index : 1     used in the geometry : Yes
 Material : Water
 Range cuts        :  gamma  1 mm     e-  1 mm     e+  1 mm  proton 1 mm
 Energy thresholds :  gamma  2.93538 keV    e-  351.324 keV    e+  341.643 keV proton 100 keV
 Region(s) which use this couple :
    phantom

Index : 2     used in the geometry : Yes
 Material : Water
 Range cuts        :  gamma  1 mm     e-  1 mm     e+  1 mm  proton 1 mm
 Energy thresholds :  gamma  2.93538 keV    e-  351.324 keV    e+  341.643 keV proton 100 keV
 Region(s) which use this couple :
    cutbox

Index : 3     used in the geometry : Yes
 Material : LD_Water
 Range cuts        :  gamma  1 mm     e-  1 mm     e+  1 mm  proton 1 mm
 Energy thresholds :  gamma  250 eV     e-  332.683 eV     e+  328.754 eV  proton 100 keV
 Region(s) which use this couple :
    aircyl
```

## Our settings:

```
Index : 0     used in the geometry : Yes
 Material : Air
 Range cuts        :  gamma  10000 km     e-  10 m      e+  10000 km  proton 10000 km
 Energy thresholds :  gamma  9.57183 GeV    e-  2.40269 MeV    e+  9.57183 GeV proton 1 PeV
 Region(s) which use this couple :
    DefaultRegionForTheWorld

Index : 1     used in the geometry : Yes
 Material : Water
 Range cuts        :  gamma  10000 km     e-  1 mm     e+  10000 km  proton 10000 km
 Energy thresholds :  gamma  9.57183 GeV    e-  351.324 keV    e+  9.57183 GeV proton 1 PeV
 Region(s) which use this couple :
    phantom

Index : 2     used in the geometry : Yes
 Material : Water
 Range cuts        :  gamma  10000 km     e-  1 um     e+  10000 km  proton 10000 km
 Energy thresholds :  gamma  9.57183 GeV    e-  250 eV     e+  9.57183 GeV proton 1 PeV
 Region(s) which use this couple :
    cutbox

Index : 3     used in the geometry : Yes
 Material : LD_Water
 Range cuts        :  gamma  10000 km     e-  1 um     e+  10000 km  proton 10000 km
 Energy thresholds :  gamma  9.57183 GeV    e-  250 eV     e+  9.57183 GeV proton 1 PeV
 Region(s) which use this couple :
    aircyl
```


Contact: jing.syuen.wong@uni-oldenburg.de

Carl von Ossietzky
Universität
Oldenburg

# Physics Settings

## Generic ions & Alpha:

```
msc:  for GenericIon  SubType= 10
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            UrbanMsc : Emin=    0 eV  Emax=  100 TeV
         StepLim=Minimal Rfact=0.2 Gfact=2.5 Sfact=0.6 DispFlag:1 Skin=3 Llim=1 mm

ionIoni:  for GenericIon  XStype:3  SubType=2
      dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
      Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
      StepFunction=(0.1, 0.001 mm), integ: 3, fluct: 1, linLossLim= 0.02
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
    LindhardSorensen : Emin=    0 eV  Emax=  100 TeV  deltaVI

nuclearStopping:  for GenericIon applyCuts:1  SubType=8 BuildTable=0
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
   ICRU49NucStopping : Emin=    0 eV  Emax=    1 MeV
```

```
msc:  for alpha  SubType= 10
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            UrbanMsc : Emin=    0 eV  Emax=  100 TeV
         StepLim=Minimal Rfact=0.2 Gfact=2.5 Sfact=0.6 DispFlag:1 Skin=3 Llim=1 mm

ionIoni:  for alpha  XStype:3  SubType=2
      dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
      Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
      StepFunction=(0.1, 0.02 mm), integ: 3, fluct: 1, linLossLim= 0.02
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            BraggIon : Emin=    0 eV  Emax=7.9452 MeV  deltaVI
         BetheBloch : Emin=7.9452 MeV Emax=  100 TeV  deltaVI

nuclearStopping:  for alpha applyCuts:1  SubType=8 BuildTable=0
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
   ICRU49NucStopping : Emin=    0 eV  Emax=    1 MeV
```

## Protons:

```
msc:  for proton  SubType= 10
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
        WentzelVIUni : Emin=    0 eV  Emax=  100 TeV Nbins=240 100 eV  - 100 TeV
          StepLim=Minimal Rfact=0.2 Gfact=2.5 Sfact=0.6 DispFlag:1 Skin=3 Llim=1 mm

hIoni:  for proton  XStype:3  SubType=2
      dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
      Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 1
      StepFunction=(0.1, 0.05 mm), integ: 3, fluct: 1, linLossLim= 0.01
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            Bragg : Emin=    0 eV  Emax=    2 MeV  deltaVI
         BetheBloch : Emin=    2 MeV Emax=  100 TeV  deltaVI

hBrems:  for proton  XStype:1  SubType=3
      dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
      Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 0
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
            hBrem : Emin=    0 eV  Emax=  100 TeV  ModifiedMephi

hPairProd:  for proton  XStype:1  SubType=4
      dE/dx and range tables from 100 eV  to 100 TeV in 240 bins
      Lambda tables from threshold to 100 TeV, 20 bins/decade, spline: 0
      Sampling table 17x1001; from 7.50618 GeV to 100 TeV
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
          hPairProd : Emin=    0 eV  Emax=  100 TeV  ModifiedMephi

CoulombScat:  for proton XStype:1 applyCuts:1  SubType=1 BuildTable=1
      Lambda table from threshold  to 100 TeV, 20 bins/decade, spline: 0
      ThetaMin(p) < Theta(degree) < 180; pLimit(GeV^1)= 0.139531
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
  eCoulombScattering : Emin=    0 eV  Emax=  100 TeV

nuclearStopping:  for proton applyCuts:1  SubType=8 BuildTable=0
      ===== EM models for the G4Region  DefaultRegionForTheWorld ======
   ICRU49NucStopping : Emin=    0 eV  Emax=    1 MeV
```


Contact: jing.syuen.wong@uni-oldenburg.de

Carl von Ossietzky
Universität
Oldenburg

# Settings for Hadron Processes

## Generic ions & Alpha:

```
                    Hadronic Processes for GenericIon

Process: ionElastic
      Model:          NNDiffuseElastic: 0 eV /n ---> 100 TeV/n
   Cr_sctns:  Glauber-Gribov Nucl-nucl: 0 eV  ---> 25.6 PeV


Process: ionInelastic
      Model:  Binary Light Ion Cascade: 0 eV /n ---> 6 GeV/n
      Model:                      FTFP: 3 GeV/n ---> 100 TeV/n
   Cr_sctns:  Glauber-Gribov Nucl-nucl: 0 eV  ---> 25.6 PeV
```

```
                    Hadronic Processes for alpha

Process: hadElastic
      Model:              hElasticLHEP: 0 eV /n ---> 100 TeV/n
   Cr_sctns:  Glauber-Gribov Nucl-nucl: 0 eV  ---> 25.6 PeV


Process: alphaInelastic
      Model:  Binary Light Ion Cascade: 0 eV /n ---> 6 GeV/n
      Model:                      FTFP: 3 GeV/n ---> 100 TeV/n
   Cr_sctns:  Glauber-Gribov Nucl-nucl: 0 eV  ---> 25.6 PeV
```

## Protons:

```
Process: hadElastic
      Model:             hElasticCHIPS: 0 eV  ---> 100 TeV
   Cr_sctns:  BarashenkovGlauberGribov: 0 eV  ---> 100 TeV


Process: protonInelastic
      Model:                      QGSP: 12 GeV ---> 100 TeV
      Model:                      FTFP: 3 GeV ---> 25 GeV
      Model:            Binary Cascade: 0 eV  ---> 6 GeV
   Cr_sctns:  BarashenkovGlauberGribov: 0 eV  ---> 100 TeV
```


Contact: jing.syuen.wong@uni-oldenburg.de