G4-ELIMED

Geant4 example for laser-driven proton beamline simulation

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Outlook

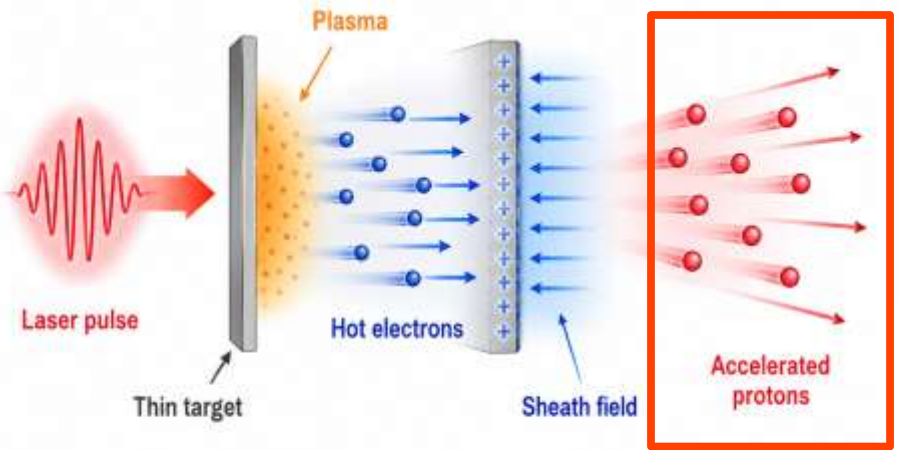
- **Laser-driven proton beams**
- ELIMED beamline

- **G4-ELIMED application**

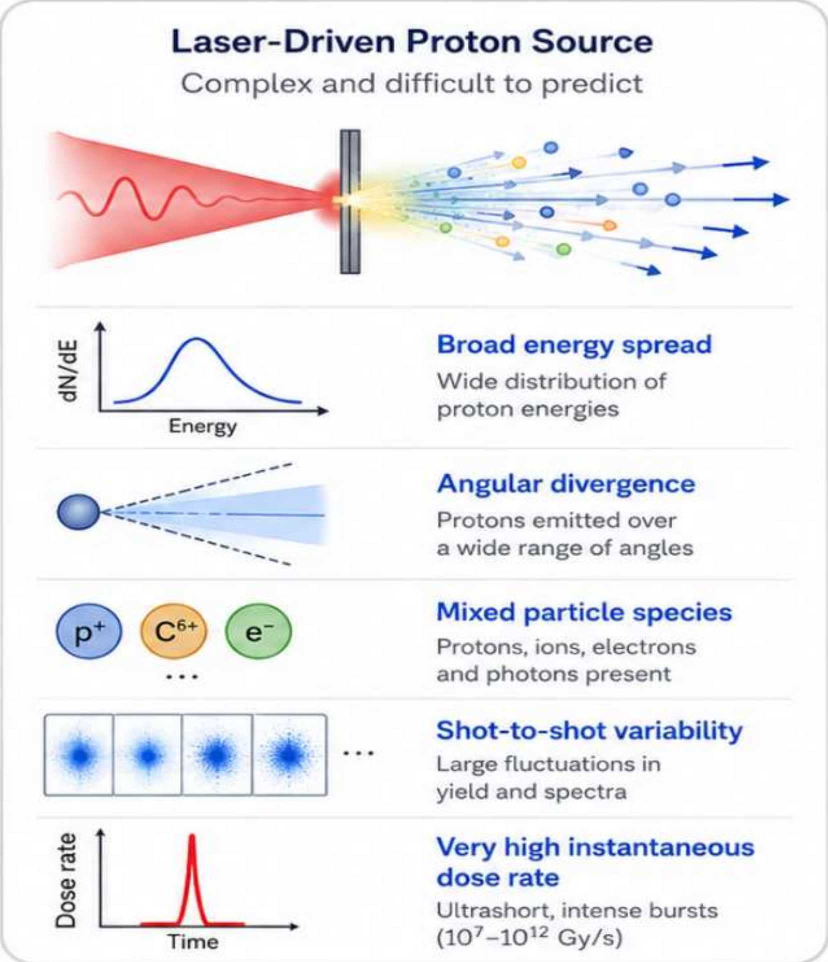
- **ELIMED & Geant4**

- source
- Magnets and field maps
- Beamline exit and dosimetry section
- Virtual planes and scoring
    - G4-ELIMED macros as example

Laser–target interaction



Geant4 input source



What is the problem?

Simulation is essential to understand, optimize and safely laser- driven proton sources.

This proton beam has broad energy spread, and large angular divergence….

so it is not ready for irradiation.

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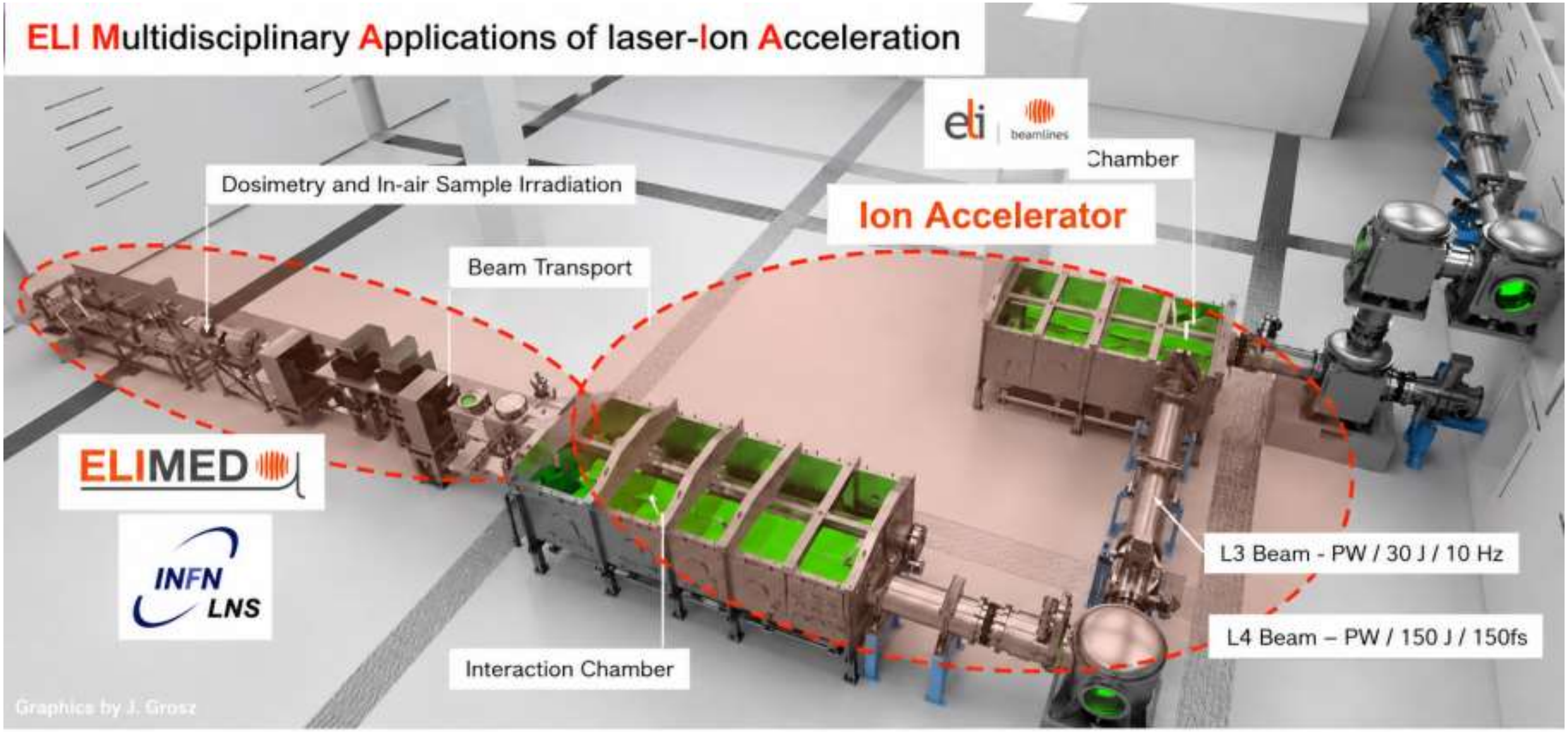
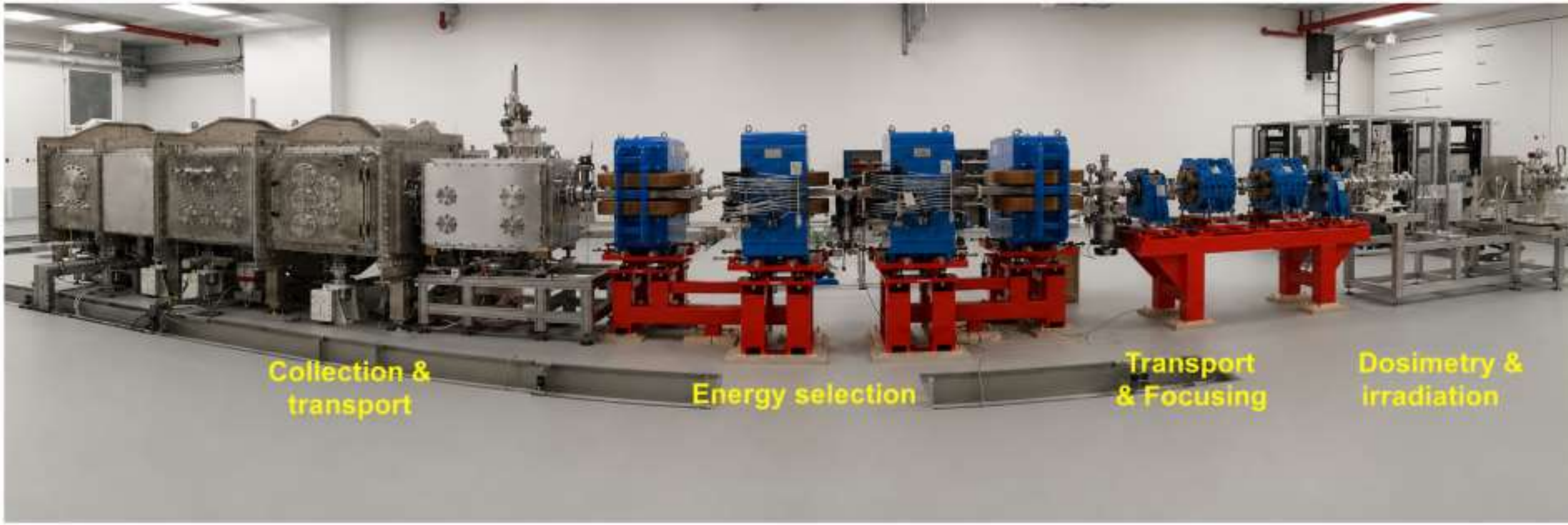
The ELIMAIA beamline



Margarone et al., Quantum Beam Sci. 2, 8 (2018), Fig. 3. Graphics: J. Grosz.

The main sections of the **ELIMAIA** beamline (Ion Accelerator and ELI **MEDical applications** consist of different subsystems: **(I) acceleration, collection; (ii) selection, transport; (iii) dosimetry and sample irradiation.**

ELIMED beamline



Cirrone et al., Frontiers in Physics 8, 564907 (2020)

- ELIMED
  - PMQs: Beam collection
  - ESS: Energy selection
  - Conventional magnets: Beam transport
  - Dosimetry
  - Sample irradiation

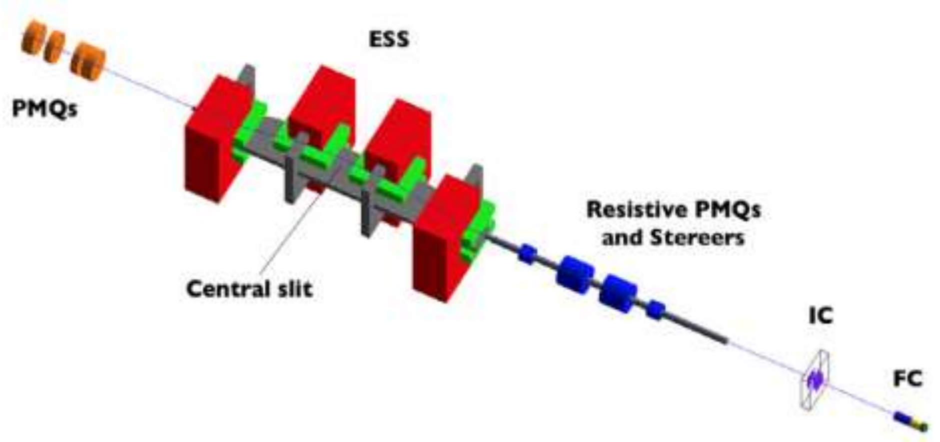
G4-ELIMED application

What is it?

A Geant4-based application to simulate the ELIMED beam transport and dosimetry line: source, geometry, field maps, physics, and scoring.

Installation essentials

- **Geant4** (10.3.p02 version)
- **Operating system** (**GNU/Linux** distributions (Fedora 25 & 26, CentOS 7 and Ubuntu 16.04) and **macOS** versions (El Capitan and Yosemite))
- **CMake**
- **C++ compiler**
- **ELIMED source code**
- **ELIMED data package**
- **External field maps**

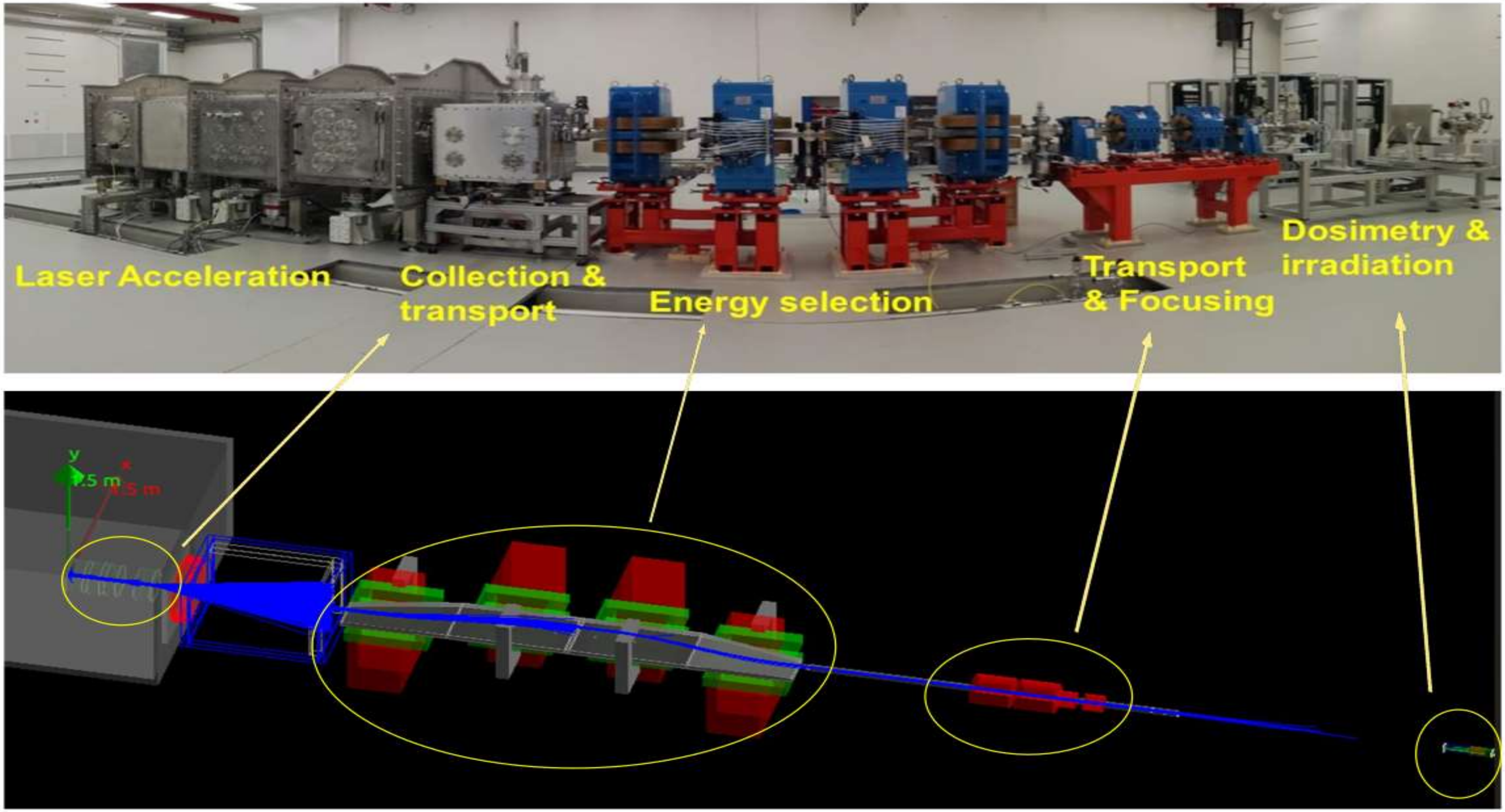


ELIMED data package

```
├── conf
│   ├── conventional
│   │   ├── conventional_2016.json
│   │   ├── conventional_2017.json
│   │   └── README.txt
│   ├── pmq
│   │   ├── pmq_2016.json
│   │   ├── pmq_2017.json
│   │   └── README.txt
│   └── README.txt
├── field-maps
│   ├── conventional
│   │   ├── Conventional-quad.table
│   │   ├── Conventional-quad-2016.table
│   │   ├── Conventional-steerer.table
│   │   ├── Conventional-steerer-2016.table
│   │   └── README.txt
│   ├── ess
│   │   ├── ESS-full.table
│   │   └── README.txt
│   ├── fc
│   │   ├── FaradayCup.table
│   │   └── README.txt
│   ├── pmq
│   │   ├── PMQ_120.table
│   │   ├── PMQ_120-2016.table
│   │   ├── PMQ_160.table
│   │   ├── PMQ_160-2016.table
│   │   ├── PMQ_80.table
│   │   ├── PMQ_80-2016.table
│   │   └── README.txt
│   └── README.txt
├── README.txt
└── source
    ├── energy
    │   ├── korea_cdf.csv
    │   └── README.txt
    ├── energy_angle
    │   ├── pic2d-angle_bins.csv
    │   ├── pic2d-energy_bins.csv
    │   └── README.txt
    ├── particle_list
    │   ├── pic3d-carbons.csv
    │   ├── pic3d-protons.csv
    │   ├── pic3d-sample.csv
    │   └── README.txt
    └── README.txt
```

The properly unpacked data tree

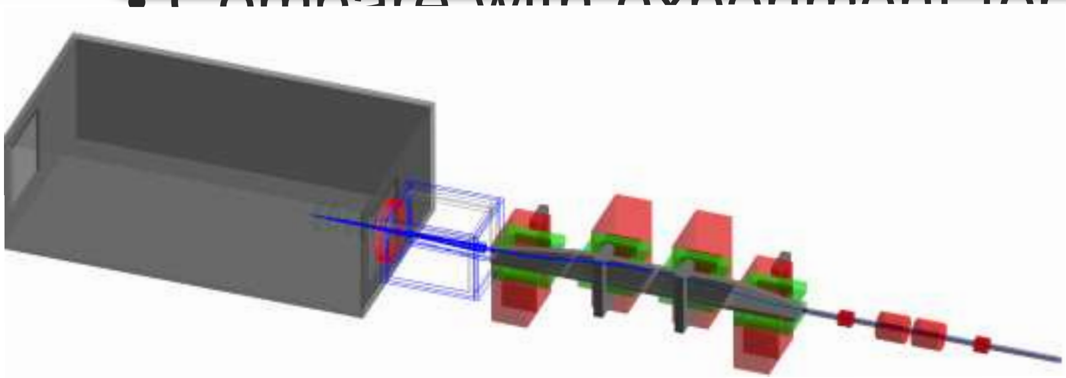
ELIMED & Geant4



ELIMED & Geant4

What do we want from simulation?

• Understand each element of beamline
• Predict transport, energy selection, and beam profile
• Score dose in phantom and detector signals
• Compare with experiment for validation



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Macro file

```
# 1) pre-init
/source/type gps
# The following command explicitely define PMQs configuration
#/elimed/quadrupoles/enabled 1
/elimed/quadrupoles/loadConfigurations {data}/conf/pmq/pmq_2016.json
/elimed/quadrupoles/field80Path {data}/field-maps/pmq/PMQ_80-2016.table
/elimed/quadrupoles/field120Path {data}/field-maps/pmq/PMQ_120-2016.table
/elimed/quadrupoles/field160Path {data}/field-maps/pmq/PMQ_160-2016.table
/elimed/quadrupoles/useFieldCorrection 0
/elimed/quadrupoles/configuration proton 20
# The following command explicitely define energy selector configuration
/elimed/energySelector/fieldPath {data}/field-maps/ess/ESS-full.table
/elimed/energySelector/fieldConfiguration proton 20
# Aperture of the selection slit
/elimed/energySelector/slitWidth 20 mm
/elimed/energySelector/slitPositionX 160 mm
# Position of the two conventional PMQ
#/elimed/conventional/steerer2z 2072 mm
#/elimed/conventional/quad1z 1240.45
#/elimed/conventional/quad2z 1572.6
/elimed/selectionEnergy proton 20
```

#Beamline Configuration

```
/elimed/phantom/enabled 1
/elimed/phantom/distanceFromWindow 2 mm

/elimed/sem/enabled 1
/elimed/sem/material G4_Ta
/elimed/sem/radius 20 mm
/elimed/sem/thickness 0.015 mm

/elimed/phantom/sizeX 40 mm
/elimed/phantom/sizeY 40 mm
/elimed/phantom/sizeZ 40 mm
/elimed/phantom/material G4_WATER

#/elimed/faradayCup/enabled true
```

#Dosimetry Part and water phantom

```
# 2) post-init
/run/initialize
/gps/particle proton
#/gps/energy 60 MeV
/gps/position 0 0 0 m
#angular distribution
# the beam is travelling along the z-axis with 5 degrees dispersion
/gps/ang/rot1 -1 0 0
/gps/ang/rot2 0 1 0
/gps/ang/type beam2d
/gps/ang/sigma_x 0.75 deg
/gps/ang/sigma_y 0.75 deg
#/gps/direction 0 0 1
# energy distribution per spectra of COIL target
/gps/ene/type User
/gps/hist/type energy
/gps/hist/point 5.80000000000000 9163760225.77541
```

#Source

```
.........
# Visualisation
#
#/vis/open OGLSQt
/vis/drawVolume
/vis/viewer/set/viewpointThetaPhi 90 160
/vis/viewer/zoomTo 4.0
/vis/viewer/panTo -2500 0 mm
......
# Only protons are visualised
/vis/filtering/trajectories/create/particleFilter
/vis/filtering/trajectories/particleFilter-0/add proton

# Virtual plane to register particles just after the starting point
# Virtual plane 1 ==> just after the source
/particleWriter/addVirtualPlaneZ virtualPlane_1 1 mm
/particleWriter/write virtualPlane_1 virtual virtualPlane_1.csv proton
```

#Visualization

```
..........
# Virtual plane 10 ==> after the ESS second collimator
/particleWriter/addVirtualPlaneZ virtualPlane_10 5500 mm
/particleWriter/write virtualPlane_10 virtual virtualPlane_10.csv proton

# Virtual plane 11 ==> In air
/particleWriter/addVirtualPlaneZ virtualPlane_11 8351.8 mm
/particleWriter/write virtualPlane_11 virtual virtualPlane_11.csv proton

/elimed/phantom/createScoringMesh phantom
/score/mesh/nBin 100 100 100
/score/quantity/doseDeposit dose
/score/close

/run/beamOn 10000000

/score/dumpQuantityToFile phantom dose 3DdoseDeposition.csv
```

#Virtual plans & Scoring

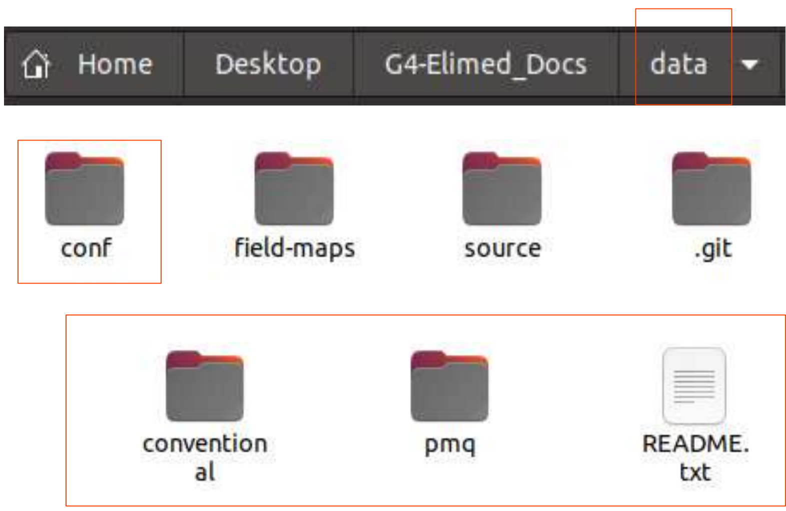
Configuration

Source → Beamline transport → Delivered beam → Sample → Biological response

positions, orientations, size

```
[
    20,
    [
        [120, -1, 60.2224],
        [80, 1, 228.2528],
        [80, 1, 798.2138],
        [120, -1, 923.9824]
    ]
],
```

Files in **JSON** format



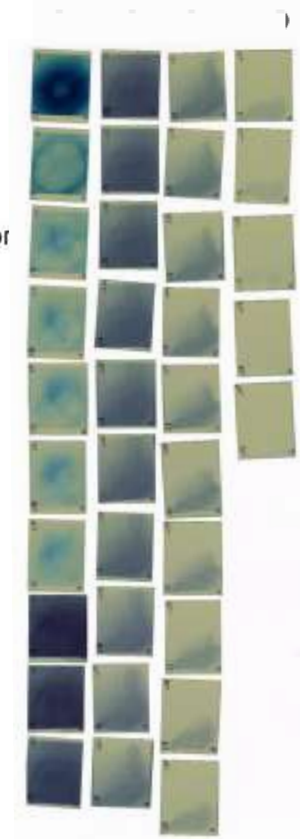
README.txt
~/Desktop/G4-Elimed_Docs/data/conf

```
Elimed data files
=================
This directory contains configuration of components, as used for the
transport of particles with different energies.

Contents
--------
- conventional : Magnet positions and field strength for the conventional part of the beamline.
- pmq : Magnet positions for the permanent magnet quadrupoles.
```

G4-ELIMED & source

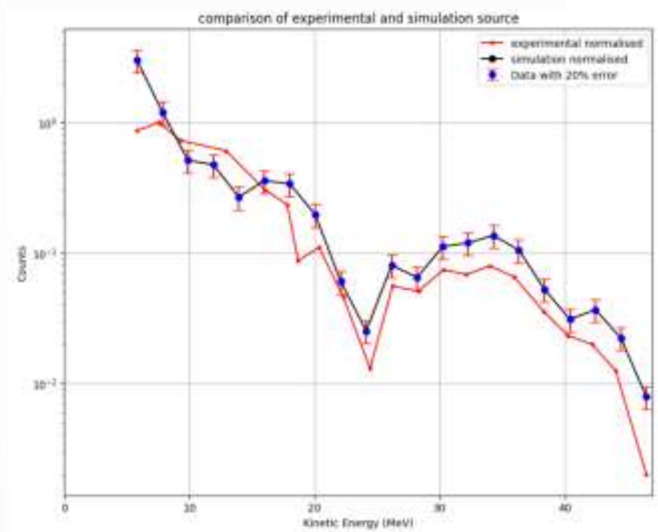
Particle type → Energy spectrum → Angular spread → Spatial distribution → Number of primaries

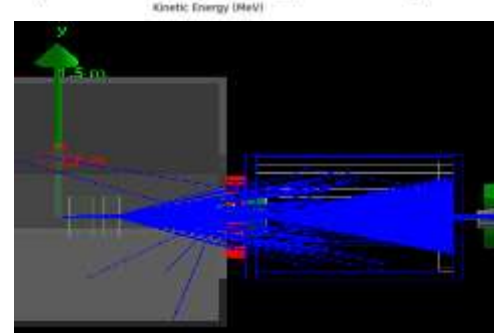
```
/run/initialize
#
/gps/particle proton
#/gps/energy 60 MeV
/gps/position 0 0 0 m

# angular distribution
# the beam is travelling along the z-axis with 5 degrees dispersion
#
/gps/ang/rot1 -1 0 0
/gps/ang/rot2 0 1 0
/gps/ang/type beam2d
/gps/ang/sigma_x 0.75 deg
/gps/ang/sigma_y 0.75 deg
#/gps/direction 0 0 1


# energy distribution per spectra of COIL target
/gps/ene/type User
/gps/hist/type energy
/gps/hist/point 5.80000000000000 9163760225.77541
/gps/hist/point 7.53000000000000 10582709319.8599
/gps/hist/point 9.30000000000000 7688253531.38630
/gps/hist/point 12.9000000000000 6433579793.78550
/gps/hist/point 15.9800000000000 3256758720.73992
/gps/hist/point 17.8000000000000 2475437701.77001
/gps/hist/point 18.6800000000000 923917340.498676
/gps/hist/point 20.3500000000000 1168827593.72114
/gps/hist/point 22.2800000000000 487741968.502704
```



Radiochromic films (RCF)

Energy distribution at source





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Magnets and field maps

Roles of beamline magnets

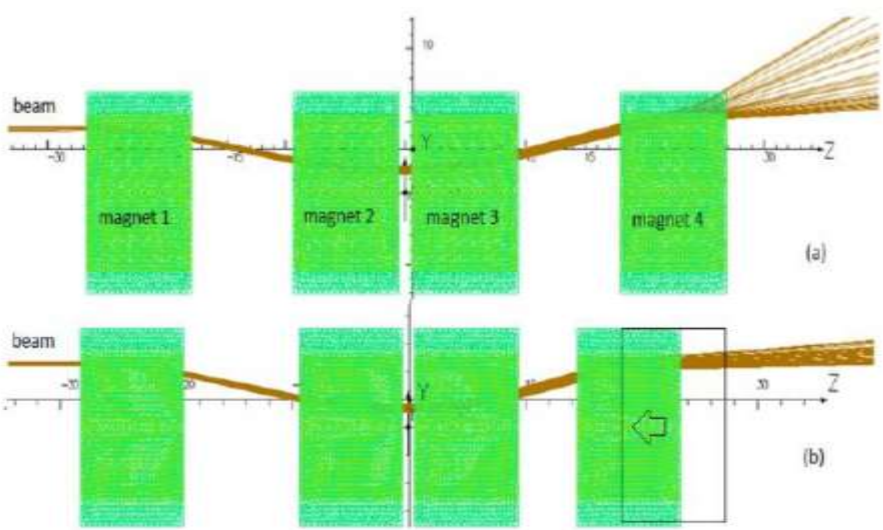
PMQs: collect and focus the divergent beam

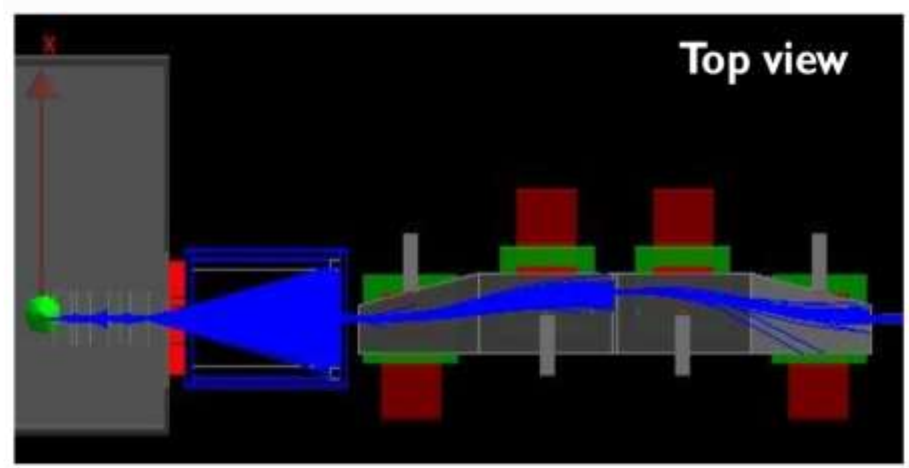
ESS dipoles + slit: select the desired energy

Steerers / quadrupoles: correct direction and shape the final transport

Field calculation or measurement → **Field map file** → **Import into G4-ELIMED**

A field map is just a table of magnetic (or electric) field values in space. Geant4 reads the map and uses it to bend and focus charged particles while they travel through the component.

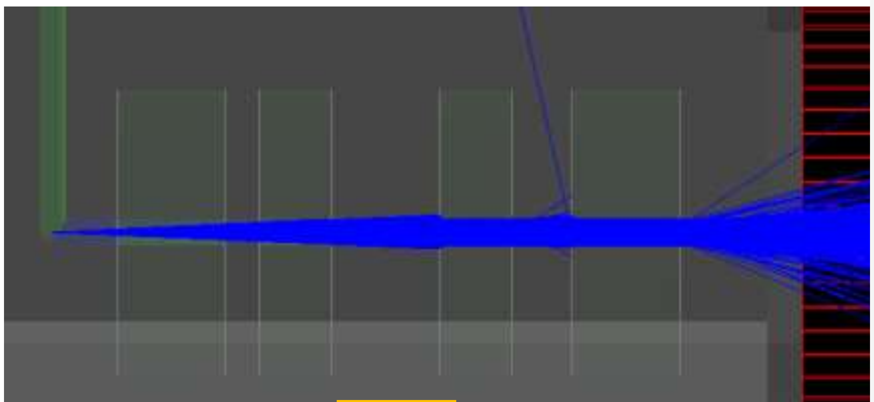




Permanent Magnet Quadrupoles (PMQs)

PMQ_120.table

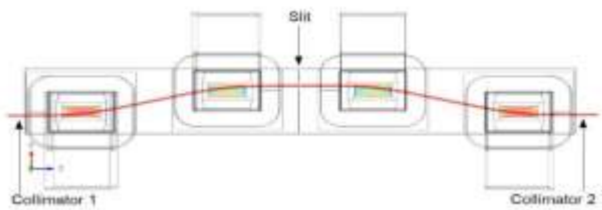
```
31 31 121 2
1 X [MM]
2 Y [MM]
3 Z [MM]
4 BX [TESLA]
5 BY [TESLA]
6 BZ [TESLA]
0
-15.000000 -15.000000 -60.000000 1.151120 1.152770 -0.721658
-15.000000 -15.000000 -59.000000 1.136110 1.131110 -0.704351
-15.000000 -15.000000 -58.000000 1.124520 1.121810 -0.650456
-15.000000 -15.000000 -57.000000 1.102270 1.110460 -0.600467
-15.000000 -15.000000 -56.000000 1.102480 1.112410 -0.537095
-15.000000 -15.000000 -55.000000 1.124290 1.124080 -0.486962
-15.000000 -15.000000 -54.000000 1.131750 1.129120 -0.434013
-15.000000 -15.000000 -53.000000 1.130260 1.133190 -0.395754
-15.000000 -15.000000 -52.000000 1.132110 1.142600 -0.362020
-15.000000 -15.000000 -51.000000 1.145590 1.133330 -0.318931
-15.000000 -15.000000 -50.000000 1.154310 1.146660 -0.293113
-15.000000 -15.000000 -49.000000 1.164560 1.157920 -0.268272
-15.000000 -15.000000 -48.000000 1.174900 1.169280 -0.243430
-15.000000 -15.000000 -47.000000 1.179190 1.170800 -0.220501
```

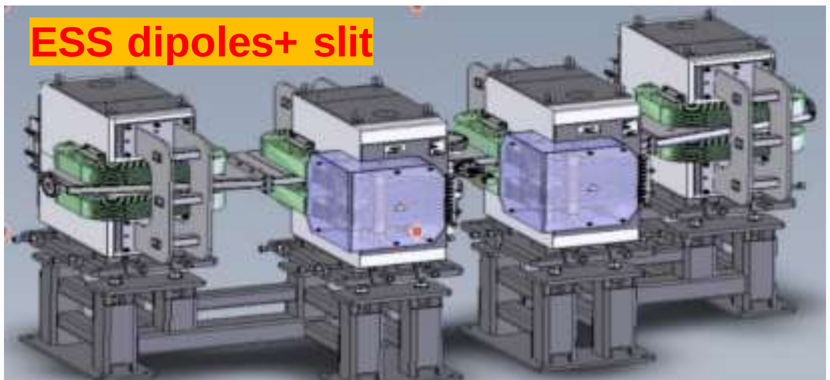


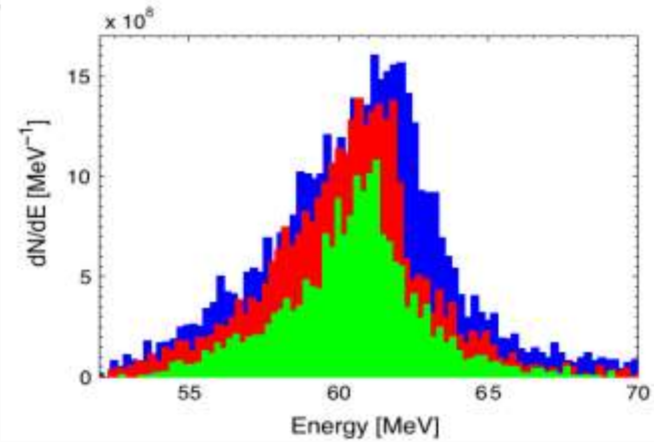
PMQs

Field maps for the permanent magnet quadrupoles (The files are exported from **Opera software**.)

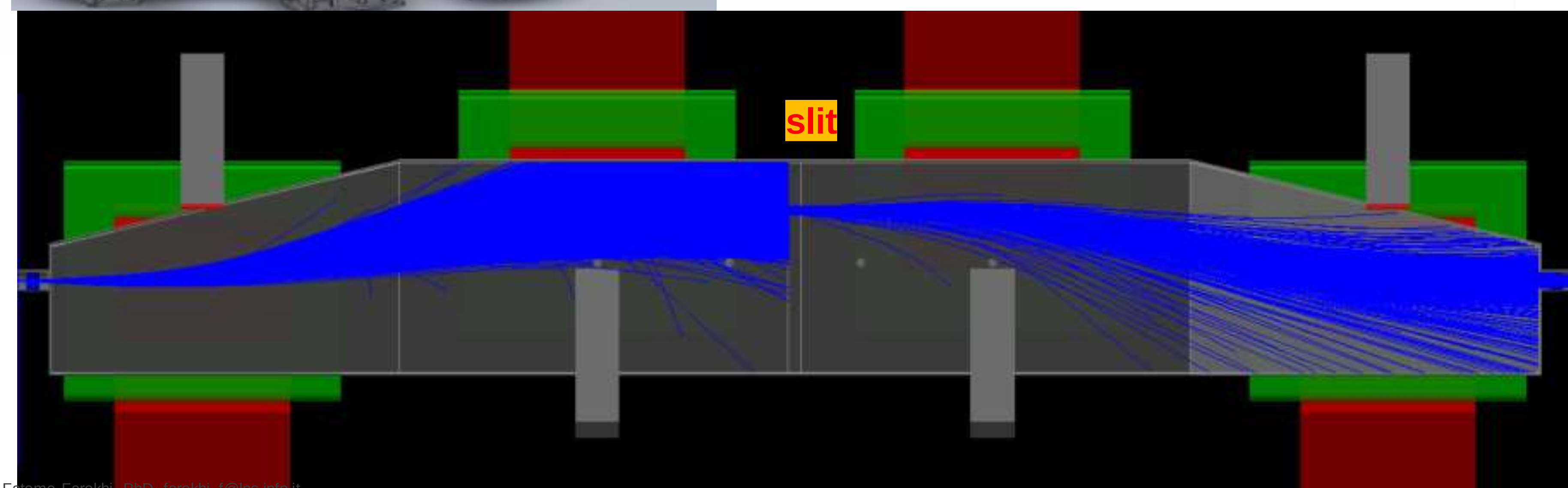
Energy Selection System







Energy spectrum for **60 MeV proton** configuration downstream the ESS with a **20 mm (blue)**, 10 mm (red) and 5 mm (green) slit aperture.

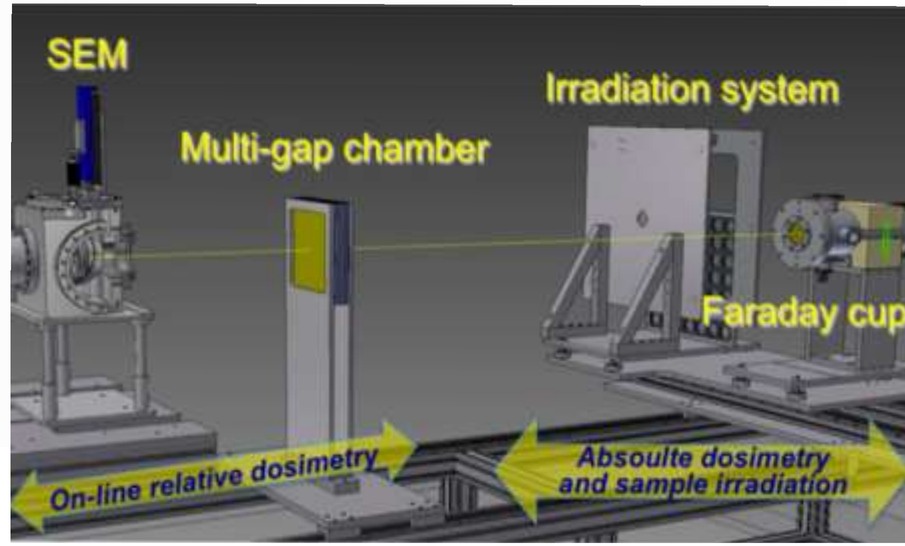


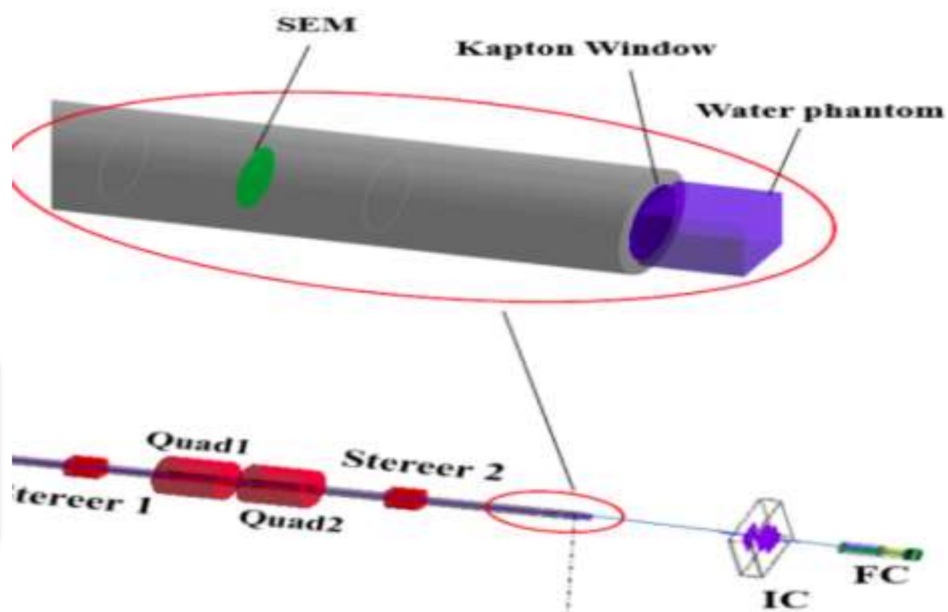
Beamline exit and dosimetry section

what dose and beam quality actually reaches the irradiation point?

Dosimetry part

- **SEM** (secondary emission monitor)
- M**ulti-gap ionization chamber** (online relative dosimetry)
- **Faraday cup**
- **Kapton Window**
- **Water phantom**





- **scoring the dose in water,**
- **estimating the beam profile, and**
- **comparing these quantities with experimental measurements.**

Scoring in G4-ELIMED

Hands-on Task 4

The goal of scoring is to extract useful information from the simulation, either as **dose/quantity maps** or as **detailed particle-by-particle data.**

Command-based scoring

Aggregated quantities Scoring mesh
Dose, energy deposit, track length

&

Particle Writer

Particle snapshots
Filters and conditions
Beam profiles and phase space

Command-based scoring for **maps and integral quantities**.
Particle Writer for **beam diagnostics, phase-space files, and detailed offline analysis**.

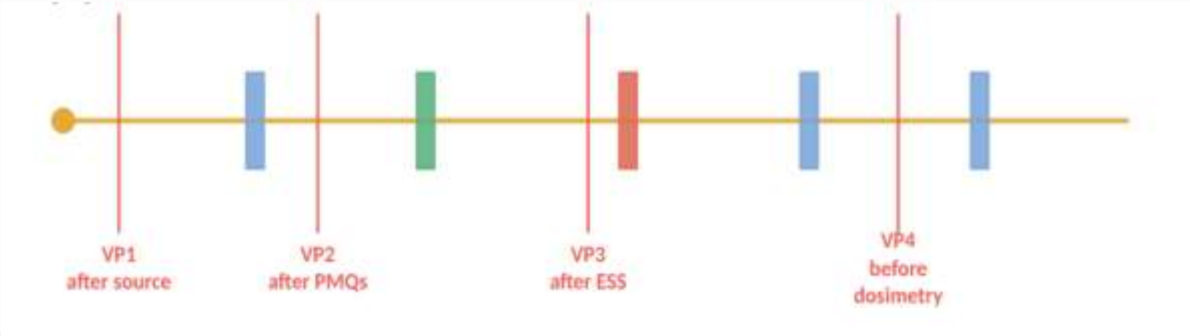
What we learn

- Transmission after each section
- Beam size and divergence
- Energy selection and losses

Output choices

CSV • ROOT • HDF5 • HTTP • in-memory tables

Virtual planes and scoring




```
# Add virtual plane after the source
/particleWriter/addVirtualPlaneZ virtualPlane_1 1 mm
/particleWriter/write virtualPlane_1 virtual virtualPlane_1.csv proton

# Add virtual plane before PMQ1
/particleWriter/addVirtualPlaneZ virtualPlane_2 59 mm
/particleWriter/write virtualPlane_2 virtual virtualPlane_2.csv proton

# Add virtual plane before ESS first collimator
/particleWriter/addVirtualPlaneZ virtualPlane_8 2030 mm
/particleWriter/write virtualPlane_8 virtual virtualPlane_8.csv proton

# Add virtual plane in air before dosimetry
/particleWriter/addVirtualPlaneZ virtualPlane_11 8351.8 mm
/particleWriter/write virtualPlane_11 virtual virtualPlane_11.csv proton
```

- Virtual Planes (VPs): **are invisible scoring surfaces placed along the beamline.**
- VPs **record particles crossing selected positions, so let us monitor the beam at chosen positions without inserting a physical detector.**

For each crossing particle, we can save:

- **position: x, y, z**
- **direction: px, py, pz**
- **kinetic energy: Ekin**
- **particle type**
- **event / track ID**
- **time, if needed**

Virtual planes turn the beamline into a sequence of diagnostic stations. So we can check the beam step-by-step from source to irradiation point.

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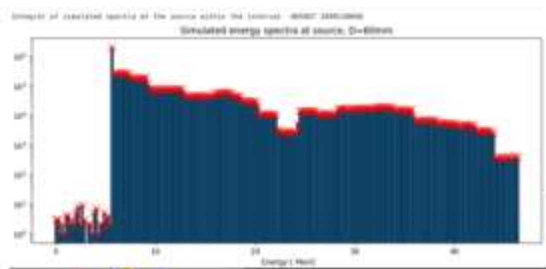
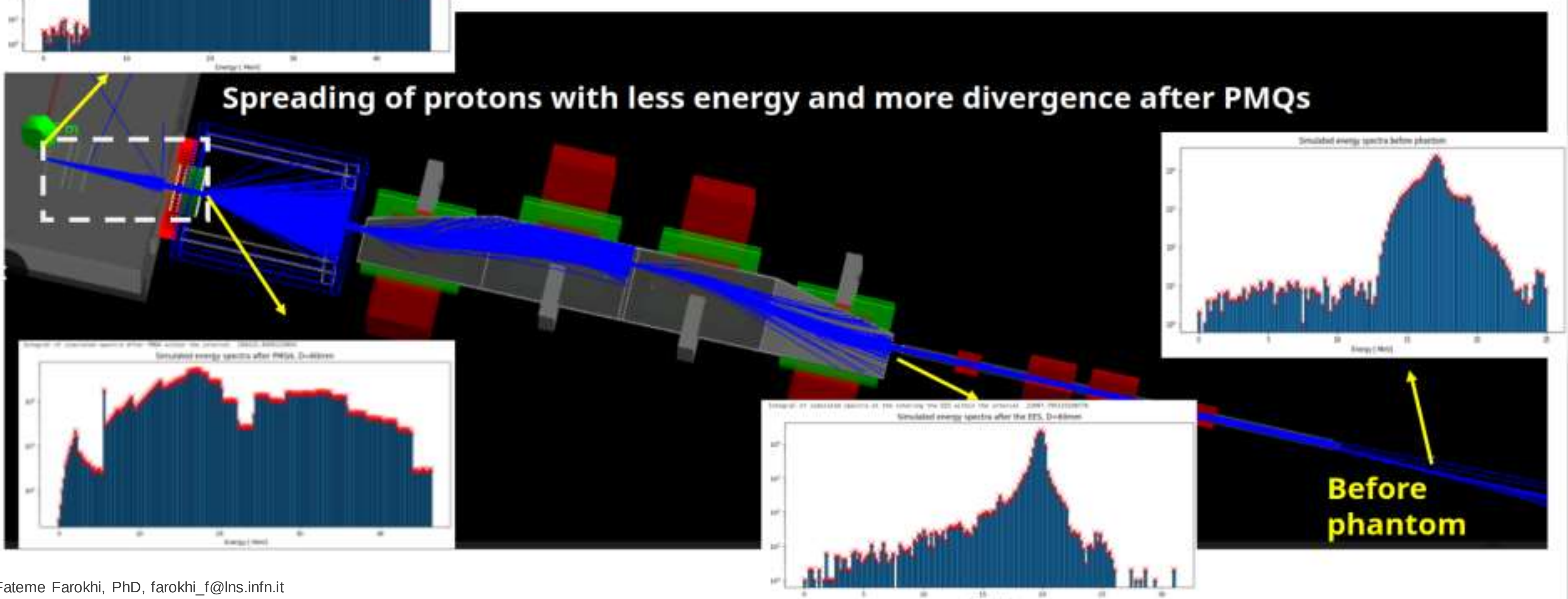
Monitoring the beam and beamline

VPs help answer:

- **How many protons survive after each beamline section?**
- **How does the beam size change?**
- **Is the beam focused correctly by the PMQs?**
- **Which energies pass through the ESS slit?**
- **Where are particles lost?**
- **What beam reaches the dosimetry section?**





G4-ELIMED example macros

Start from these examples, then modify source, beamline settings, scoring, or output.

1. `pic2d_beam_profiles.mac` — **Beam transport and profiles**

   Uses the PIC 2D source and scores protons transported through the full beamline for several selected energies.

2. `mono_bragg_peak.mac` — **Dose scoring in water phantom**

   Scores deposited energy / dose for a 60 MeV monoenergetic proton beam in a phantom after the Kapton window.

3. `tr3_fig3.mac` — **Energy selection with ESS slit**

   Shows proton trajectories with different energies through the energy selector; only the reference energy passes the slit.

4. `tr3_fig5.mac` — **PMQ focusing sensitivity**

   PMQ example: follows two protons starting at x = 3 mm through the PMQs to illustrate focusing.

5. `field_lines.mac` — **Magnetic-field debugging**

   Writes PMQ magnetic-field values along a line for different energy configurations; useful for checking field-map behavior.

Simulation can answer practical questions:

- How many particles reach the end of the beamline?
- What energy spectrum is selected?
- What is the beam profile at different sections of beamline?
- What dose is deposited in the water phantom?
- How do PMQs, the ESS slit, steerers, quadrupoles, Kapton window, monitor chamber, and Faraday cup affect the beam?
- How can simulation results be compared with experimental measurements for validation?

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Thank you!

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