MCMA 2017

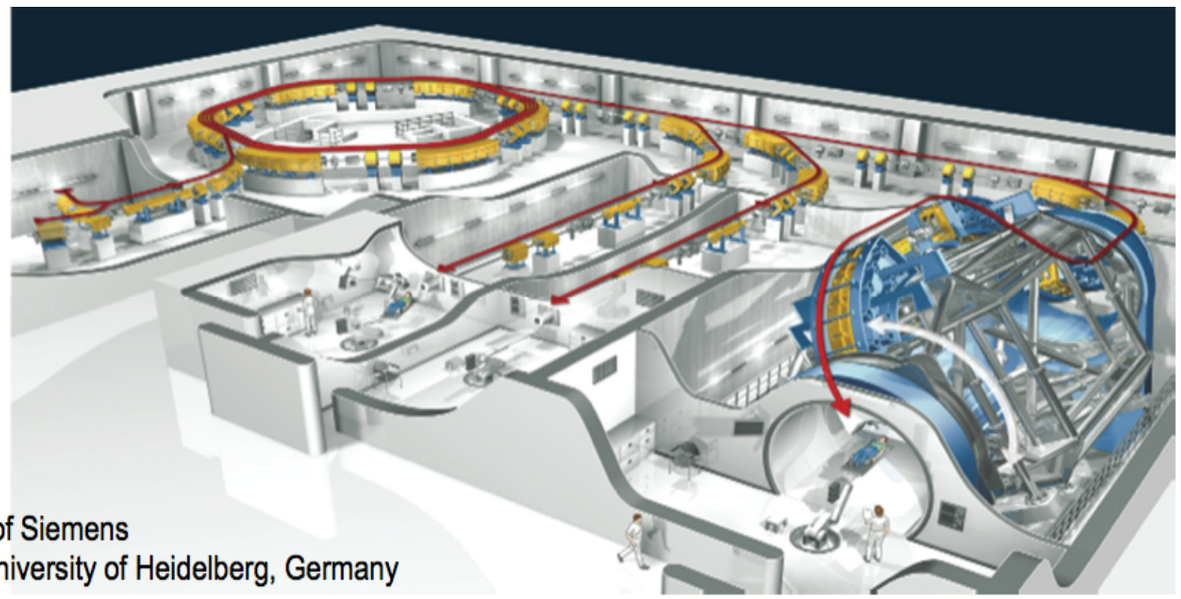
Napoli, Italy
17th October 2017

Geant4-based Monte Carlo simulations of a transport beam line for multidisciplinary applications of laser-driven proton beams

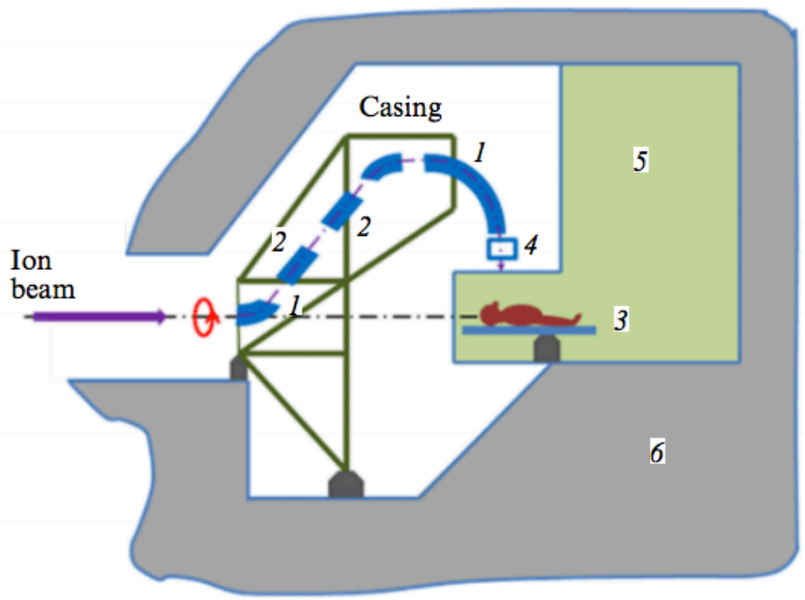
Giuliana Milluzzo

On behalf of the ELIMED collaboration
INFN - Laboratori Nazionali del Sud, Catania, Italy
Università degli Studi di Catania

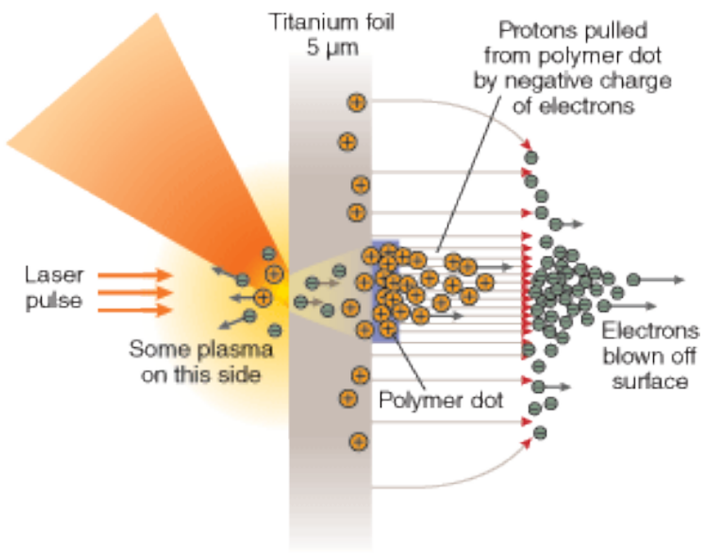
Conventional RF accelerators vs laser-driven for hadrontherapy

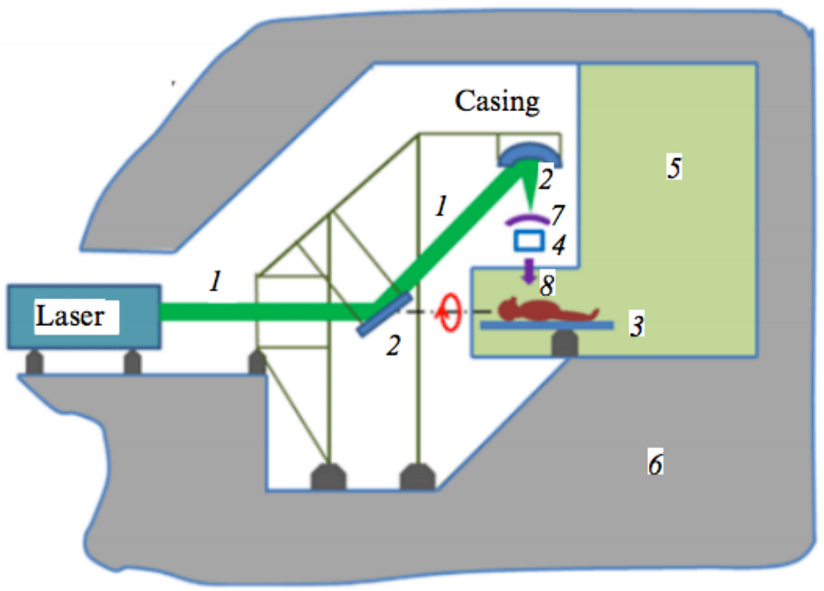


Courtesy of Siemens
And the University of Heidelberg, Germany



- An intense laser field (> 10^{18} W/cm^2) blows off electrons from a target surface
- Fast electrons penetrate the foil and ionize atoms along their path → a strong electric field is created (≈ TV/m)

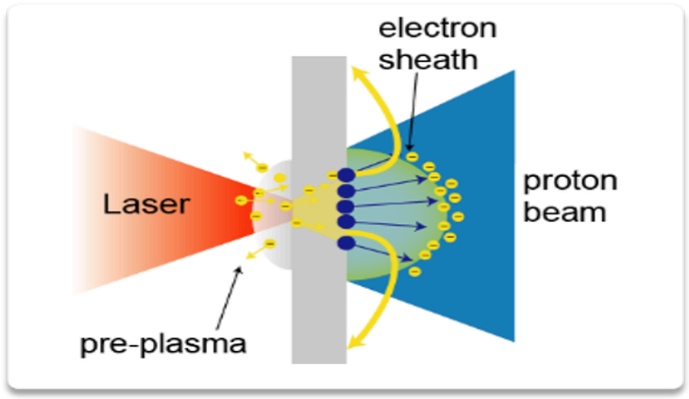


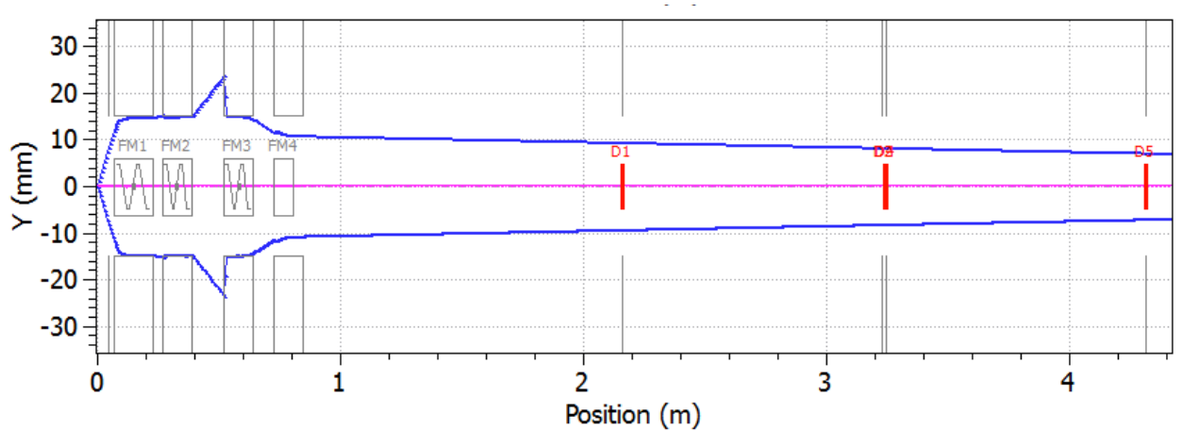


In a few microns multi-Mev protons and ions are accelerated

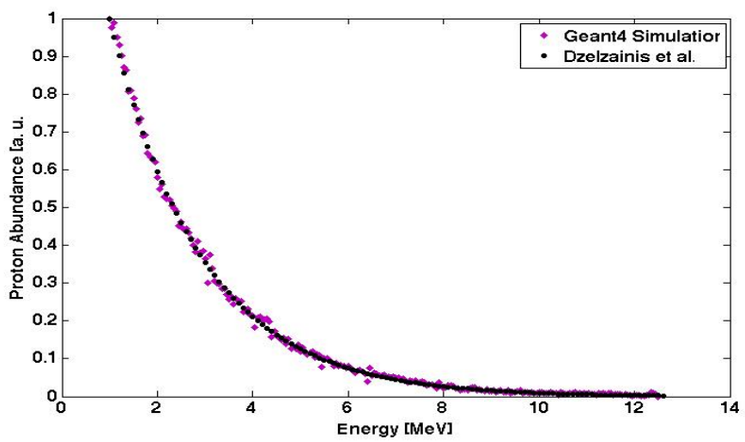
Laser-driven beams peculiarities

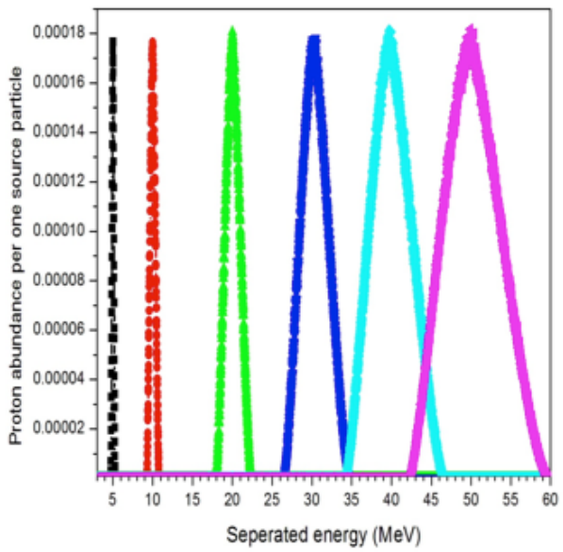
- **Wide angular distributions**





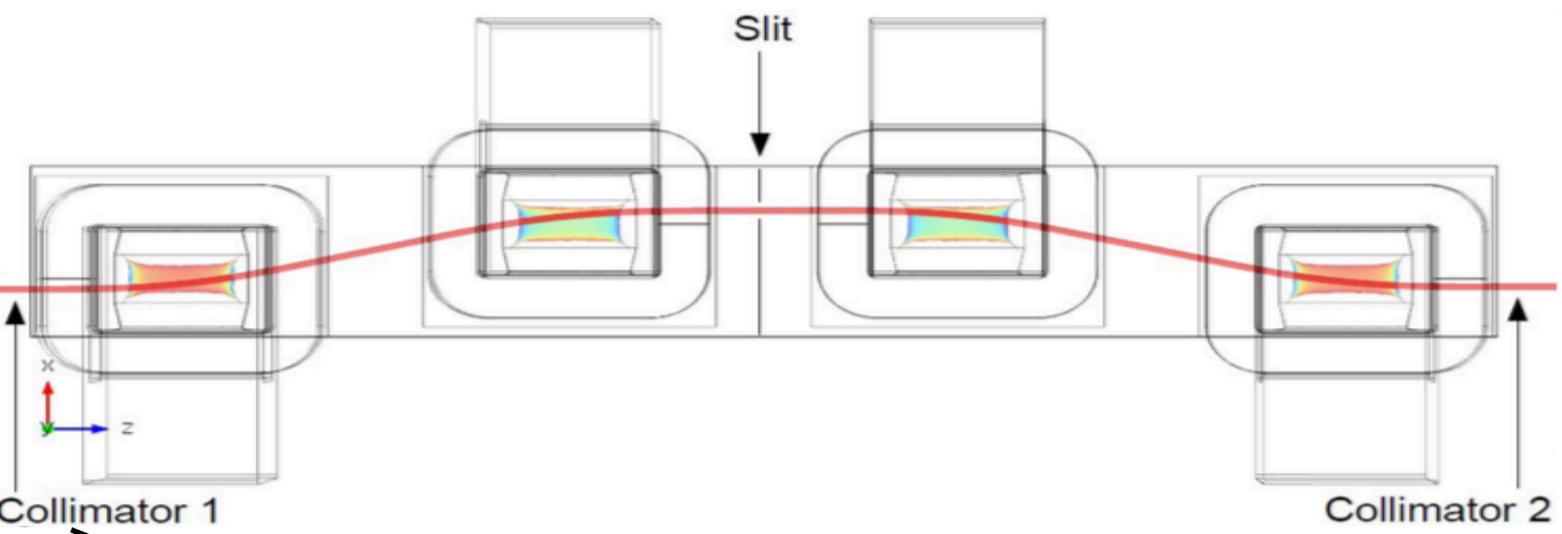
- **Large energy spread**

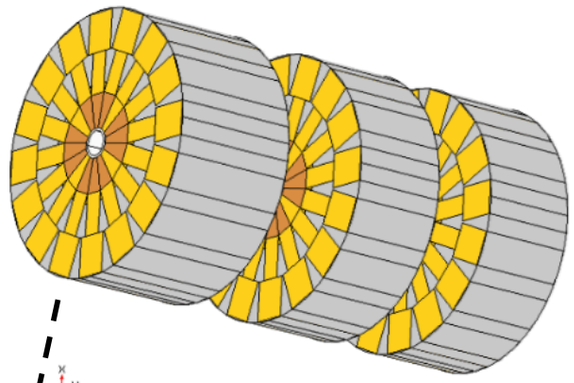


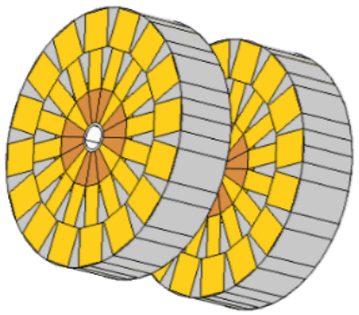


- **Extremely high dose rate per pulse 10^7 -10^9 Gy/min (vs 10-50 Gy/min)**

New paradigms for beam dosimetry







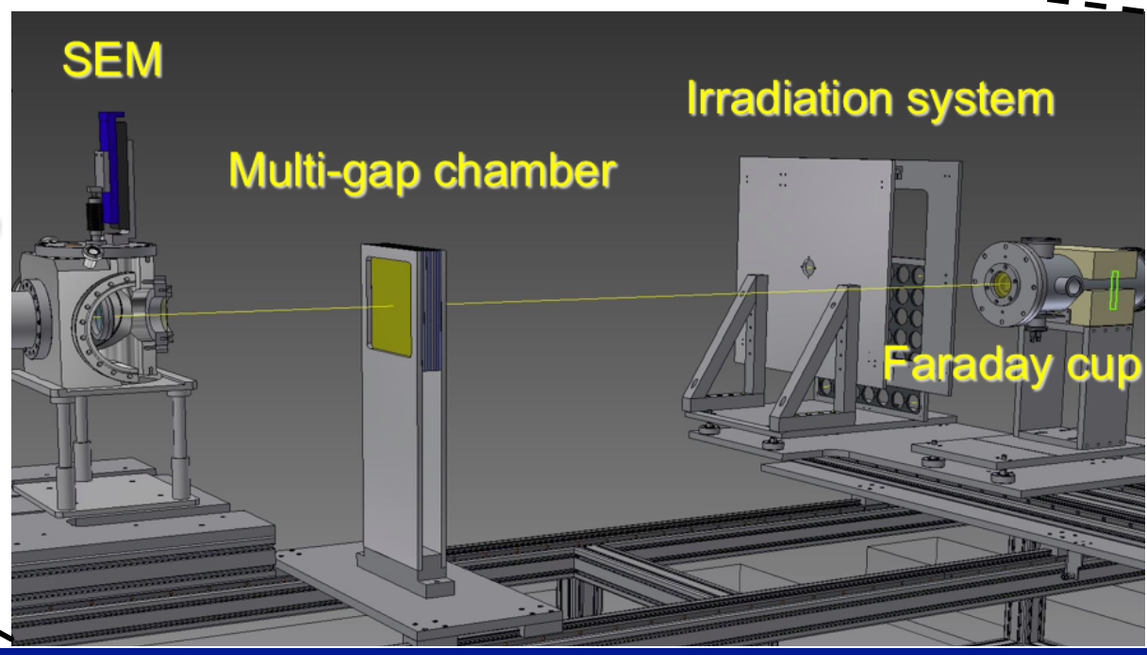
INFN LNS

eli beamlines

Collection and diagnostics

Selection, transport and diagnostics

Dosimetry and sample irradiation

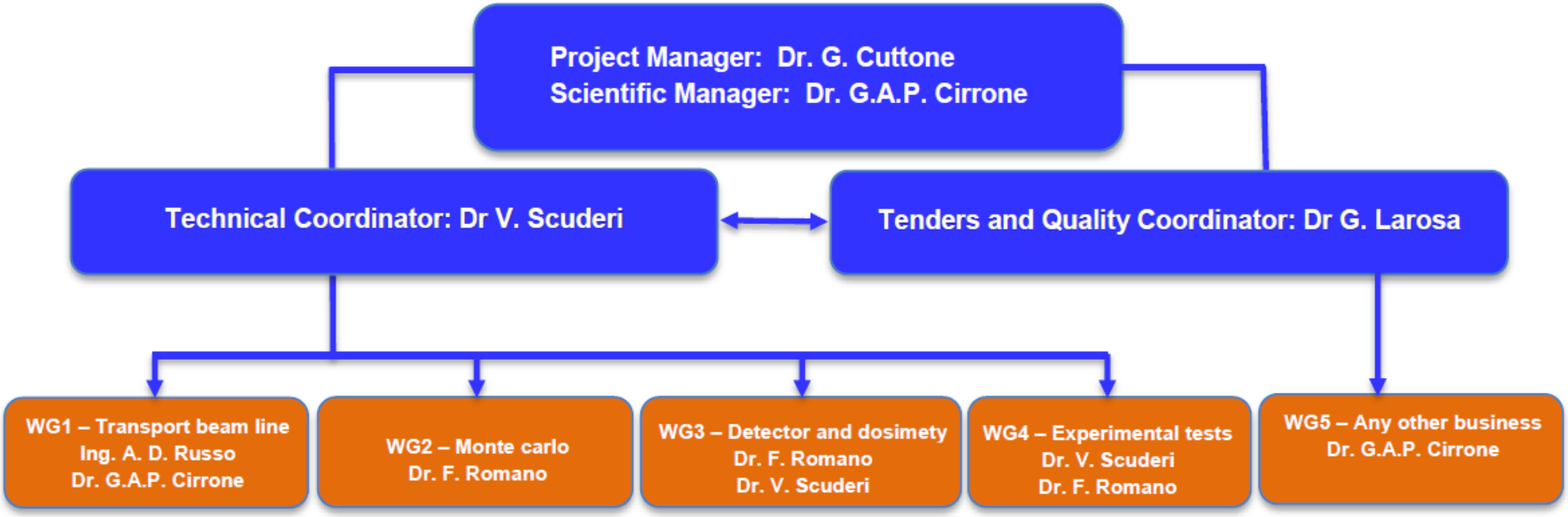


Front. Oncol. (in press)
NIM A, Vol. 829 (2016)
JINST, Vol. 11 (2016)
JINST, Vol. 10 (2015)

Graphics by L. Allegra

G. Milluzzo- INFN-LNS (Italy) - gmilluzzo@lns.infn.it

ELIMED WPs



G.A.P. Cirrone, G. Cuttone, M. Costa, G. Gallo, L. Calabretta, D. Rifuggiato, M. Maggione, G. De Luca, N. Salamone, S. Pulvirenti, N. Amato, N. Maugeri, A. Seminara, S, Cavallaro, C. Viglianisi, D. Rizzo, L. Allegra, P. Reina, E. Zappalà, G. Messina, S. Salamone.

F. Romano, G.A.P. Cirrone, G. Milluzzo, L. Pandola, A. Attili, J. Pipek

F. Romano, G. Milluzzo, R. Leanza, G. Petringa, G.A.P. Cirrone, N. Amato, N. Randazzo, G. Larosa, A. Amico.

Everyone is involved (directly or indirectly)

G.A.P. Cirrone, V. Marchese, L. Pandola, G. Petringa, R. Leanza, F. Romano, G. Larosa

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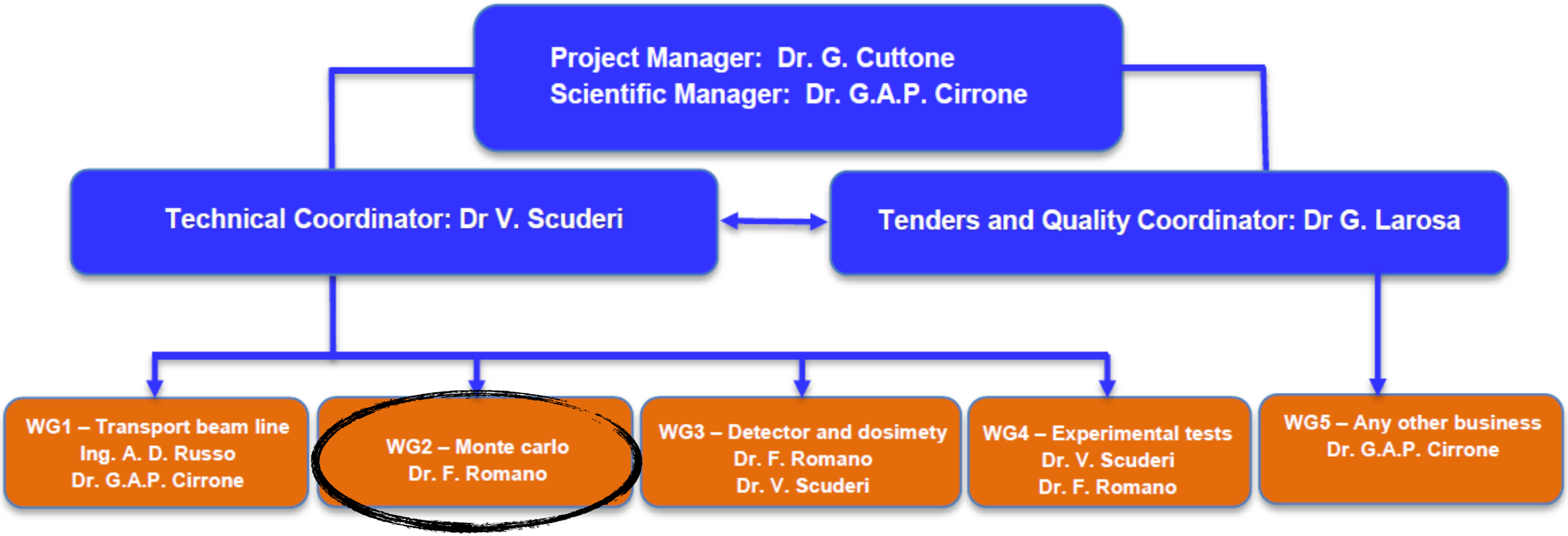

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The ELIMED application

J. Pipek, F. Romano, G. Milluzzo et al.,, Journal of Instrumentation, Volume 12, March 2017

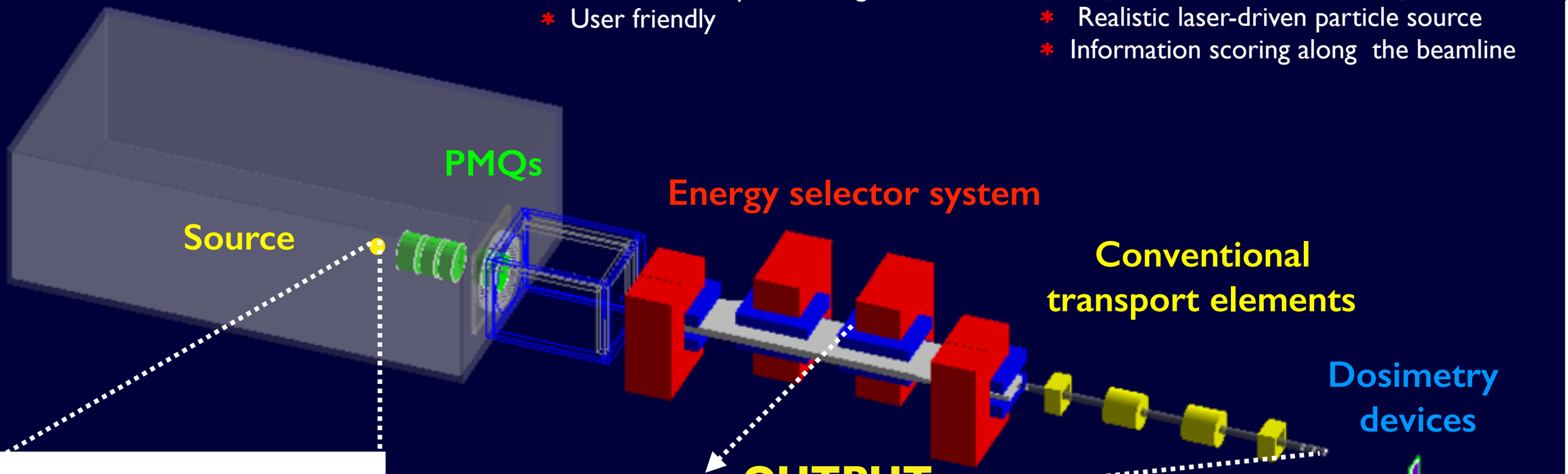
Geant 4

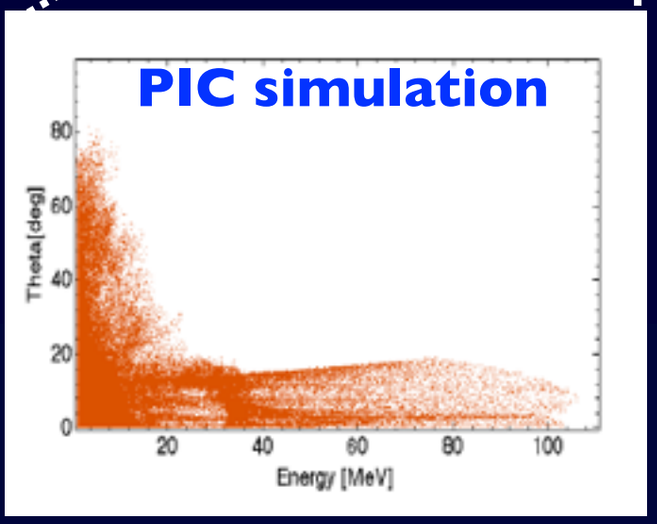
Requirements from ELI

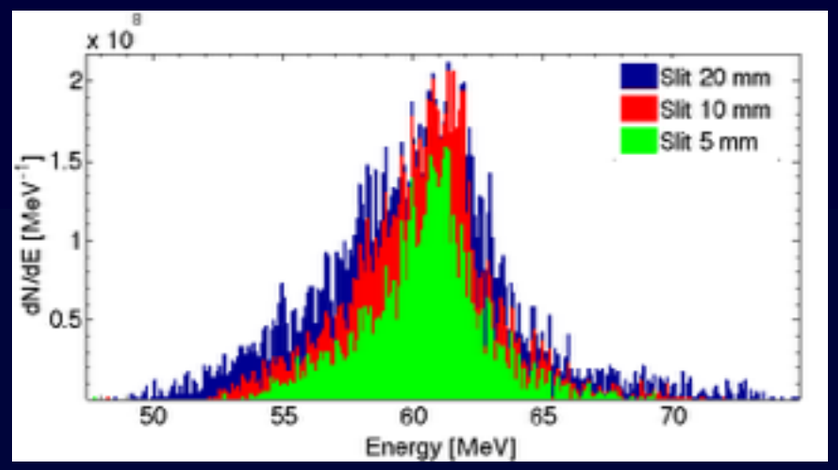
* Easily modify geometrical configurations
* Accurate transport in magnetic fields
* User friendly

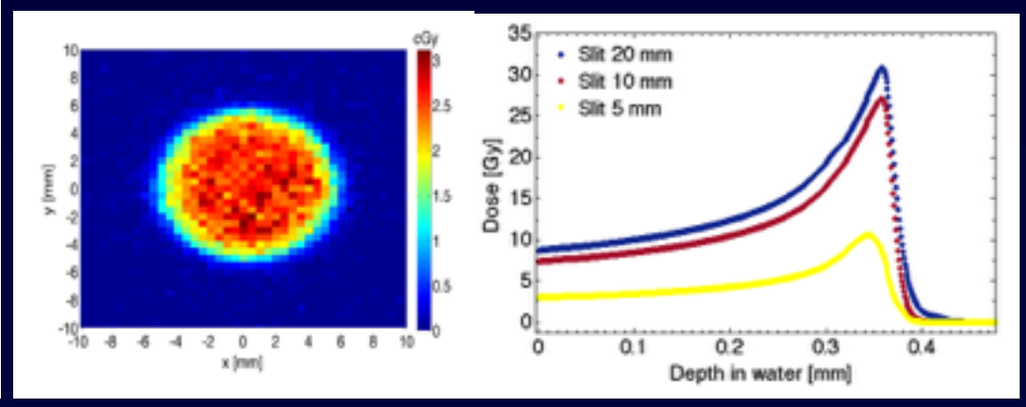
Application structure

* Component realistic model
* Magnetic and electric field implementation
* Realistic laser-driven particle source
* Information scoring along the beamline









The ELIMED application as a tool for beam optimization and feasibility studies for multi-disciplinary applications

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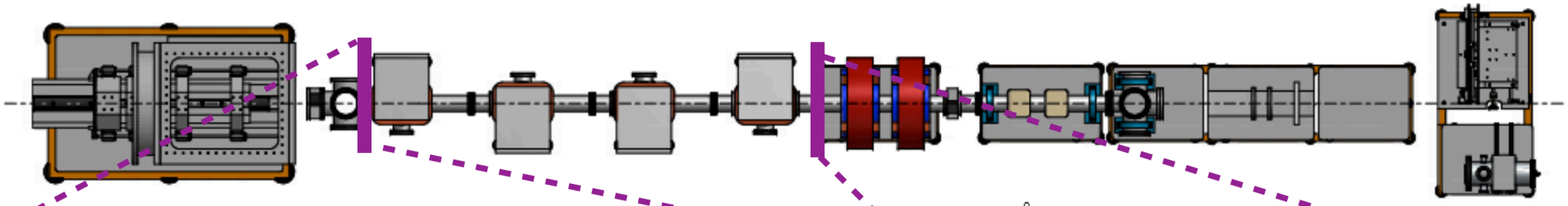
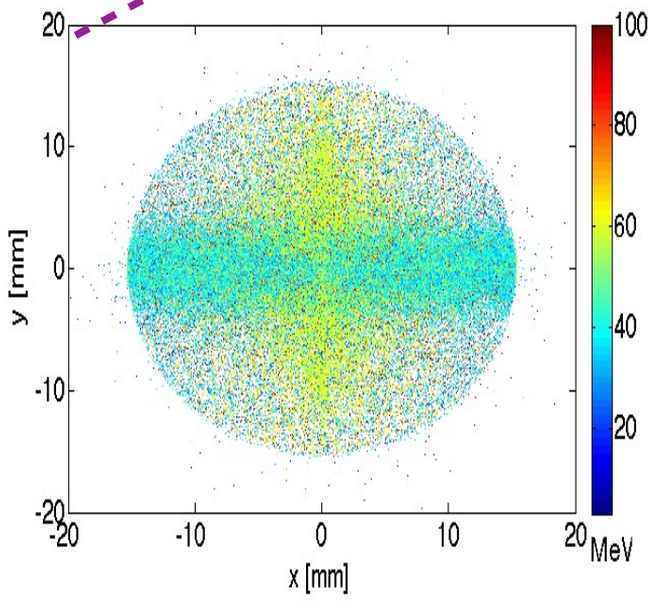
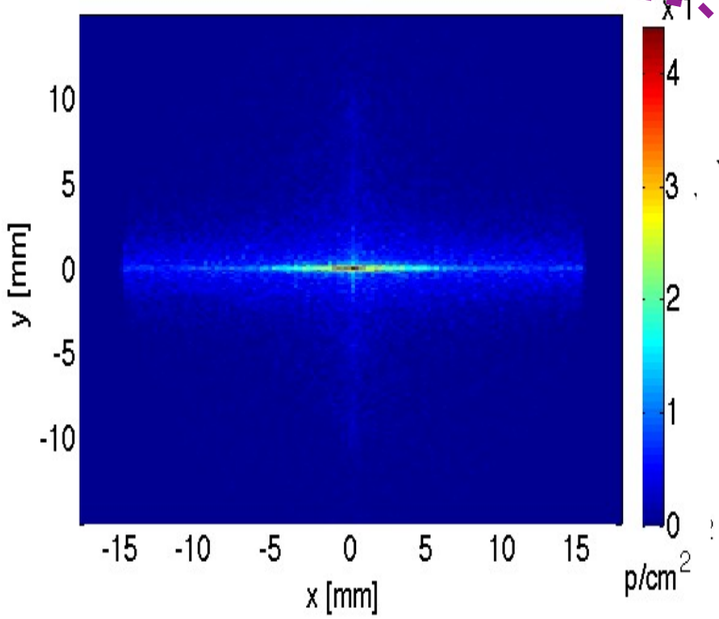
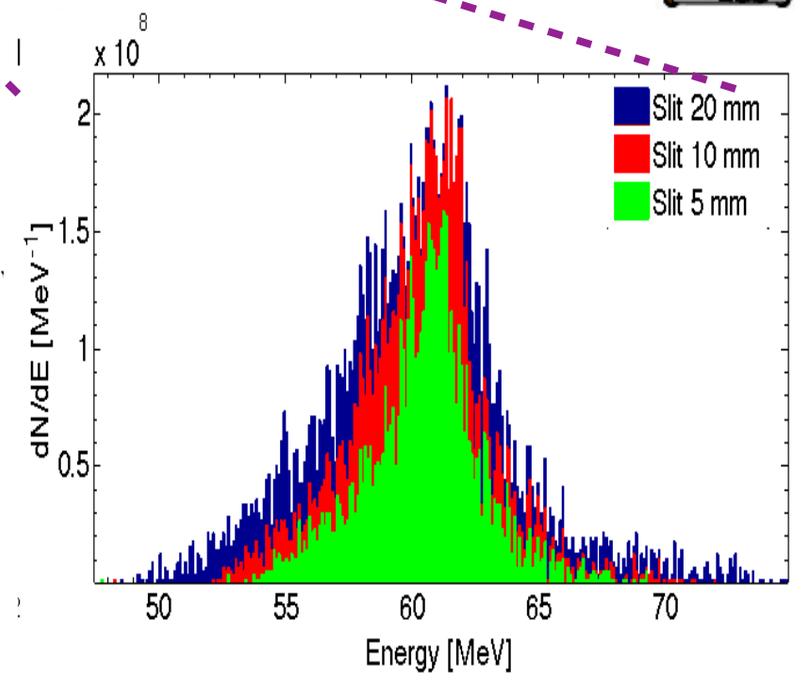


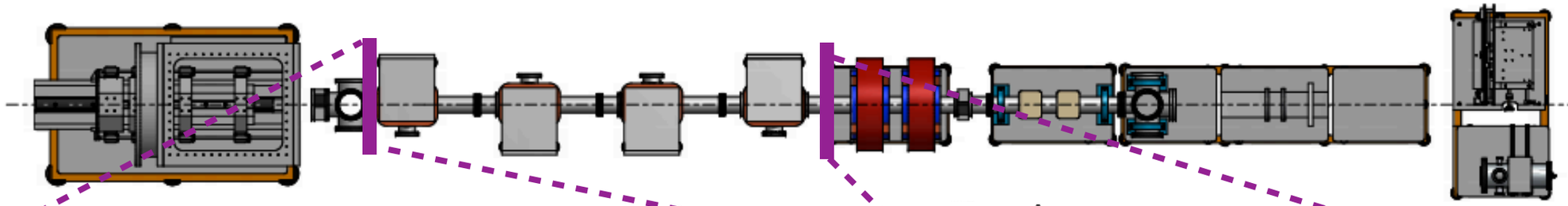
60 MeV







ΔE/E	Tr. Eff.
11%	9.9%
8%	8.0%
7%	4.9%



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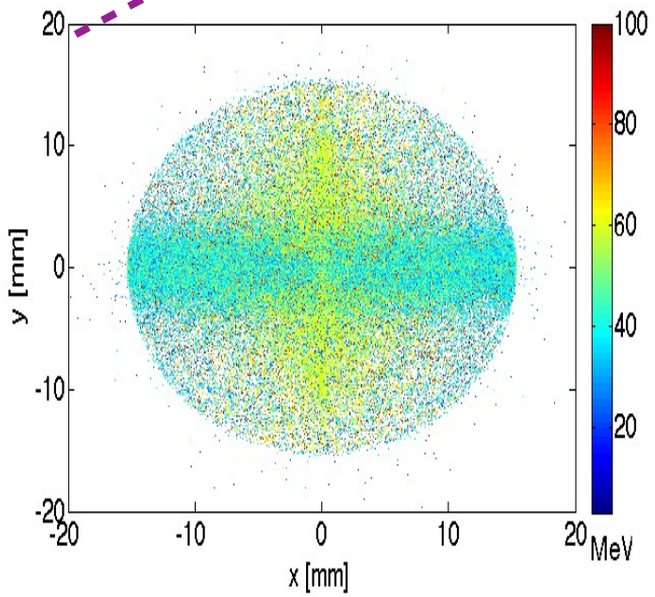

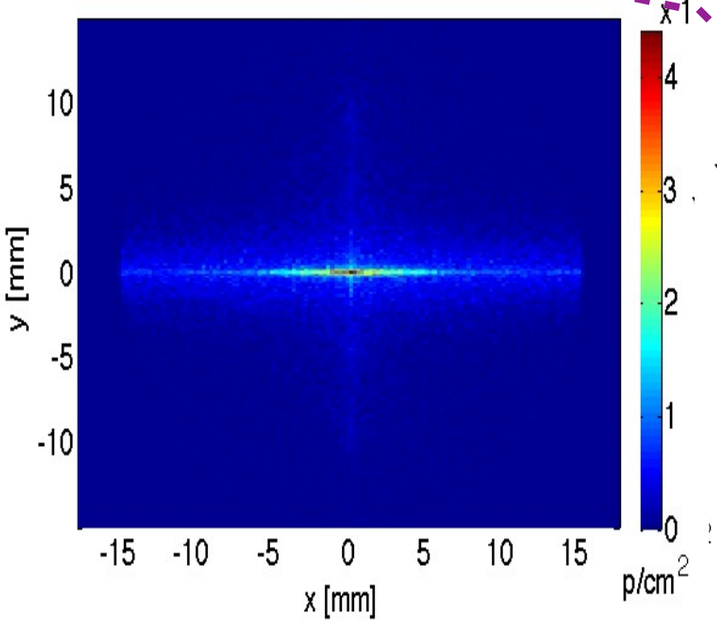

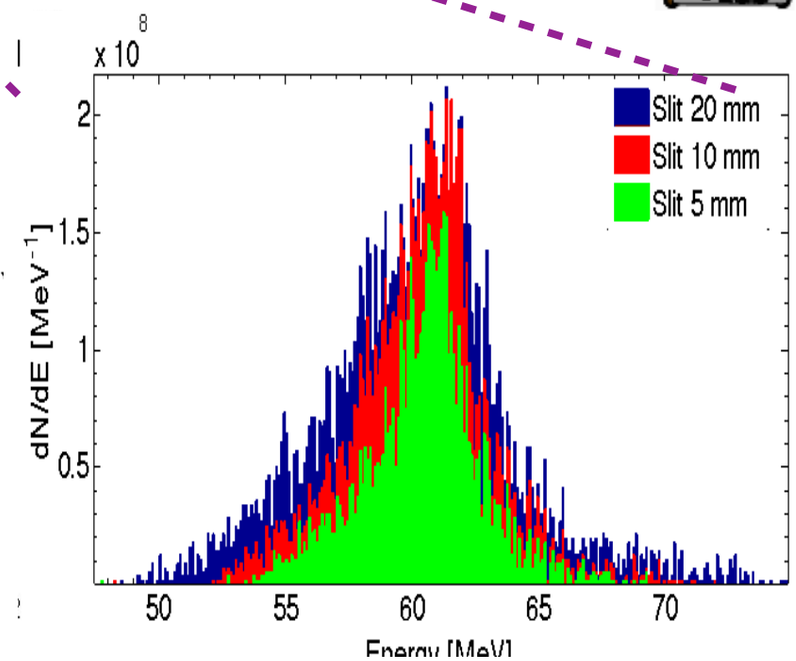

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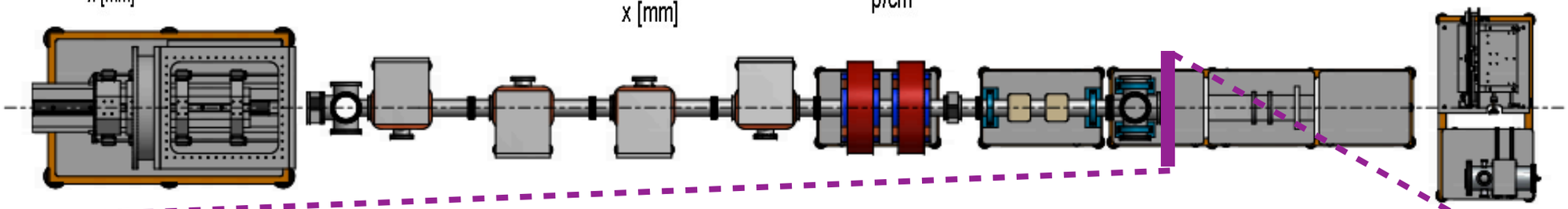
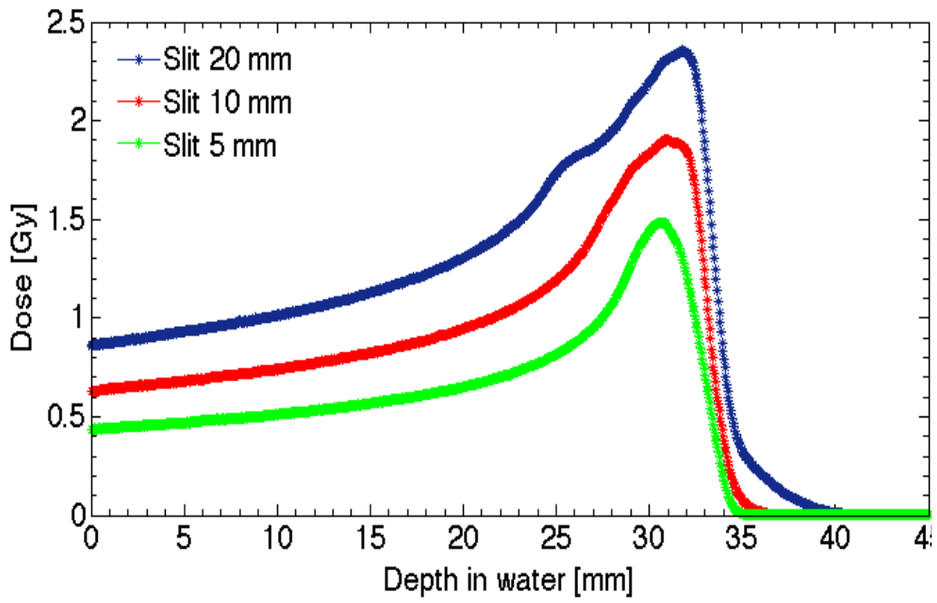
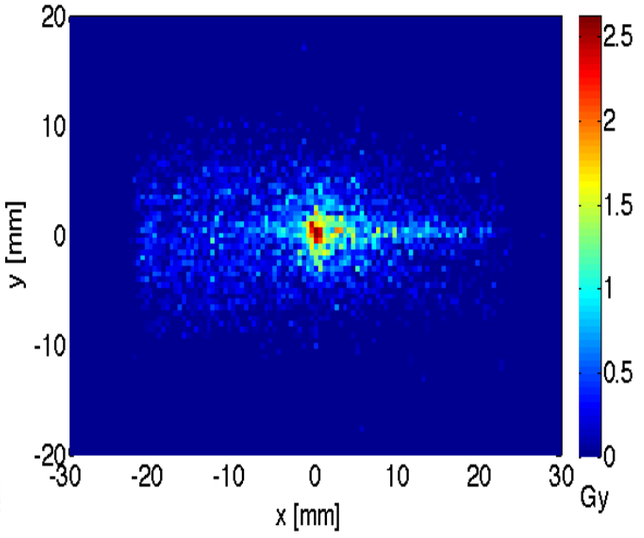
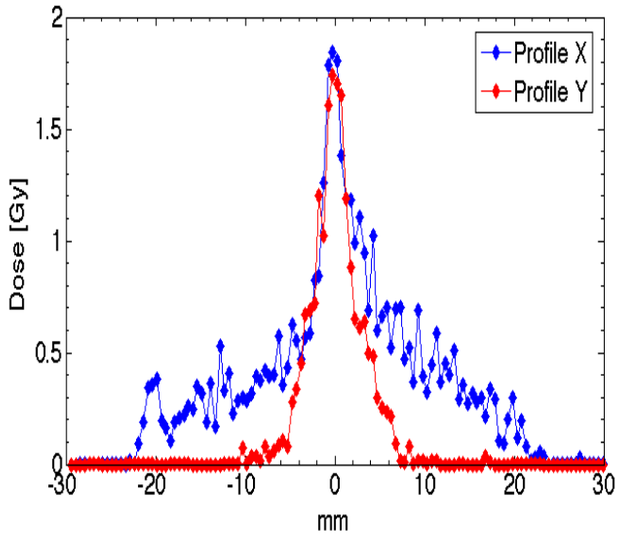
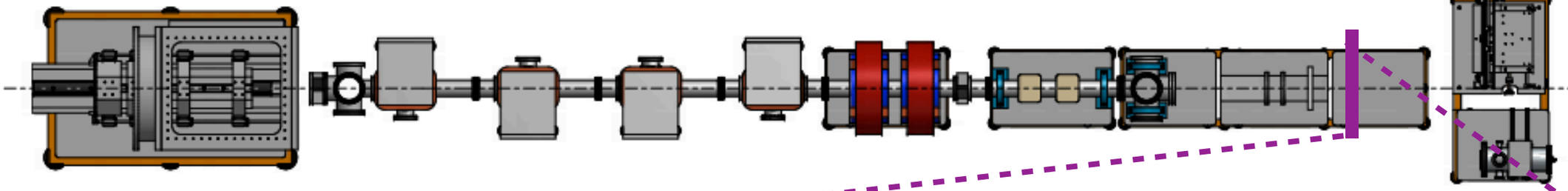




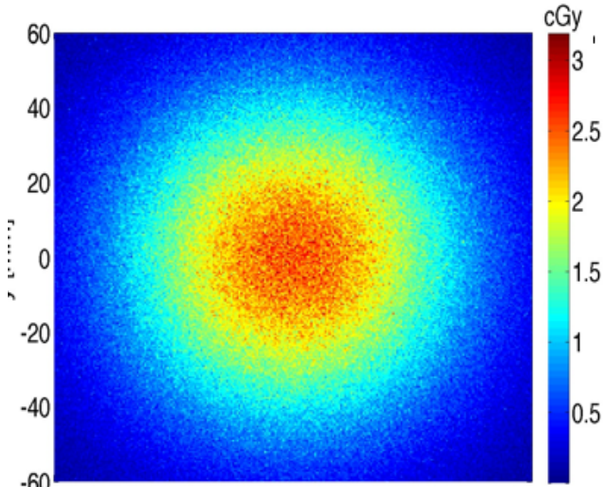


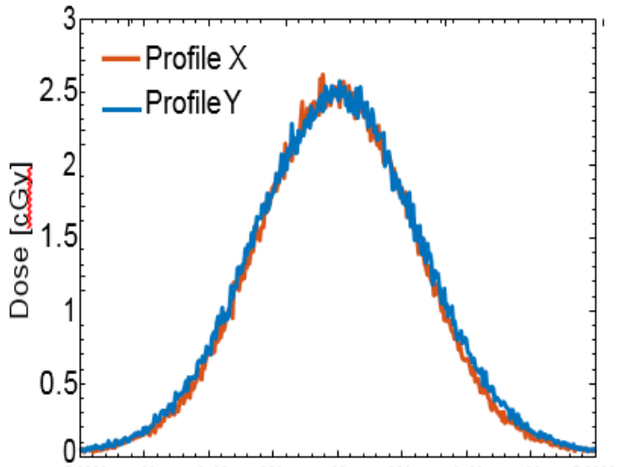


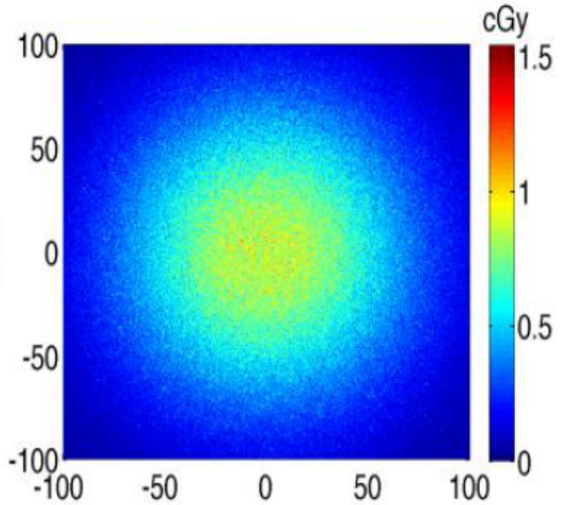


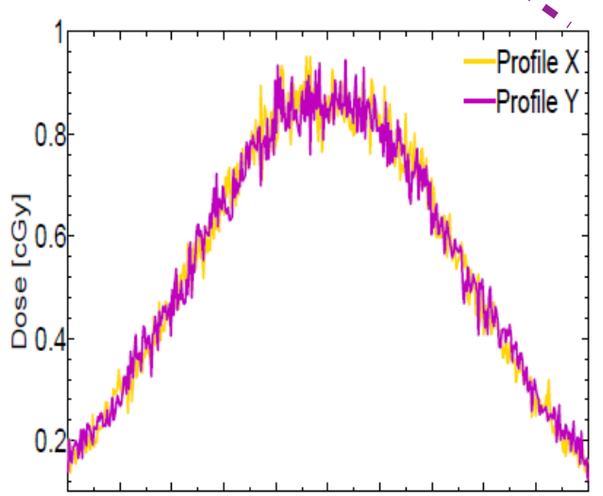
2 m air + 100 um Ta

2 m air + 300 um Ta

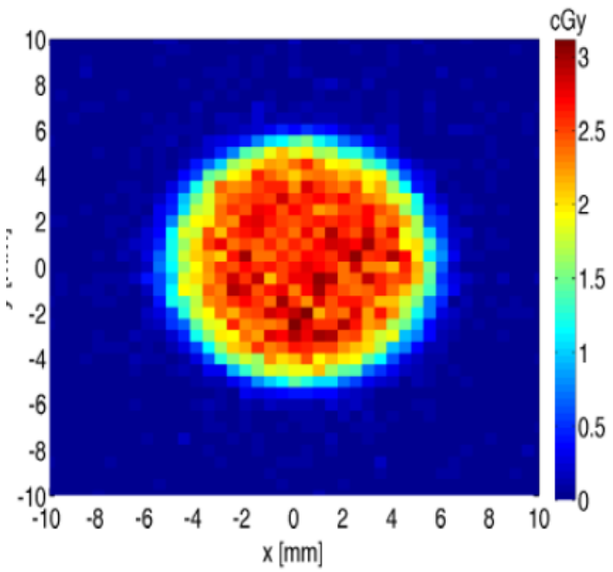


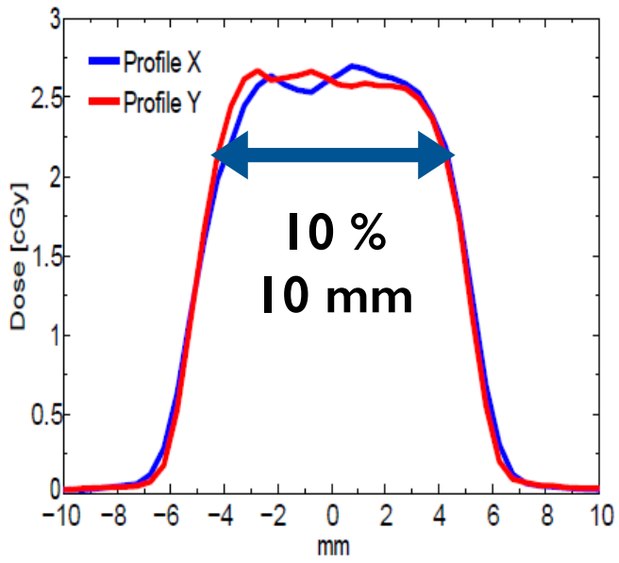




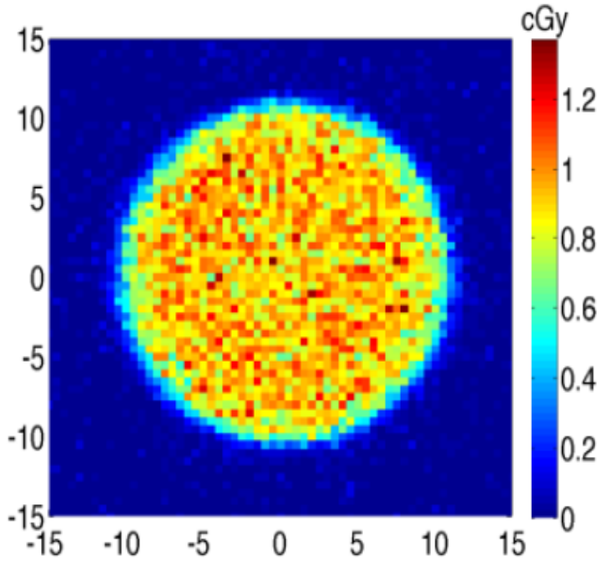


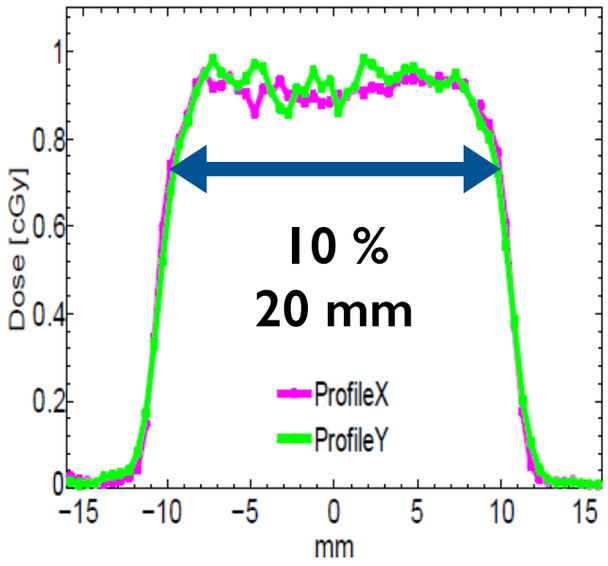
+ 10 mm collimator





+ 20 mm collimator





Towards dose delivery of clinical relevance: feasibility studies for multi-disciplinary applications

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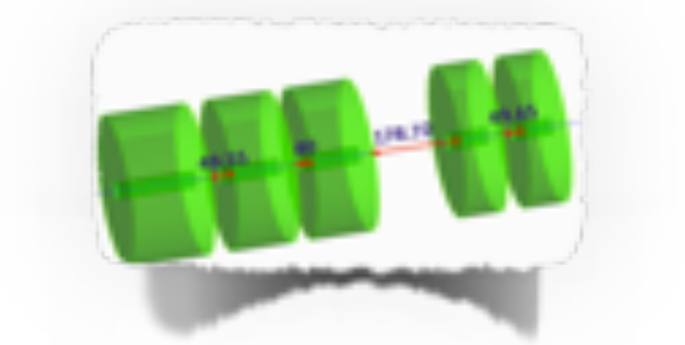
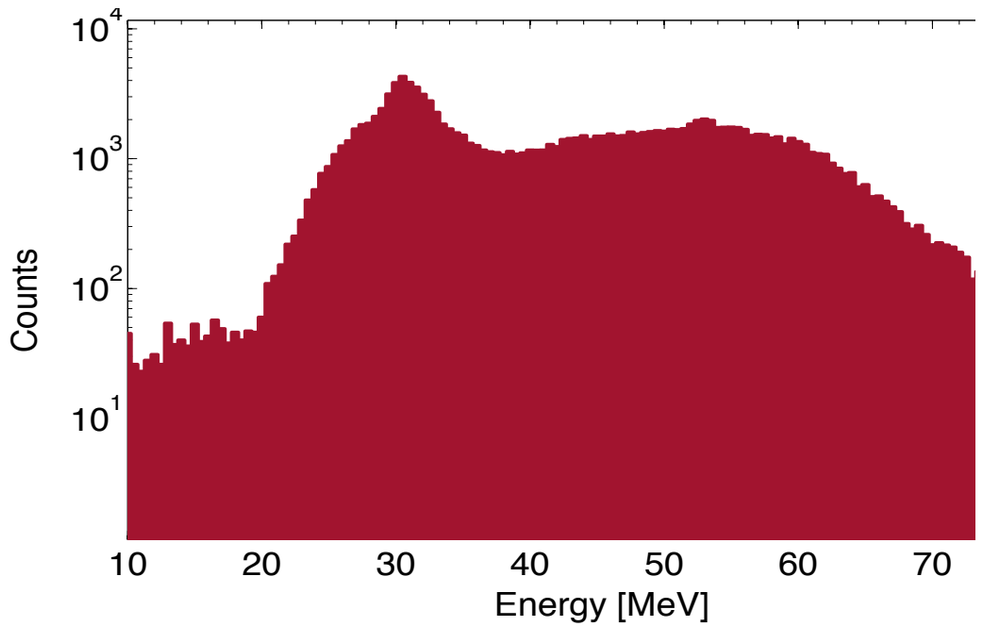
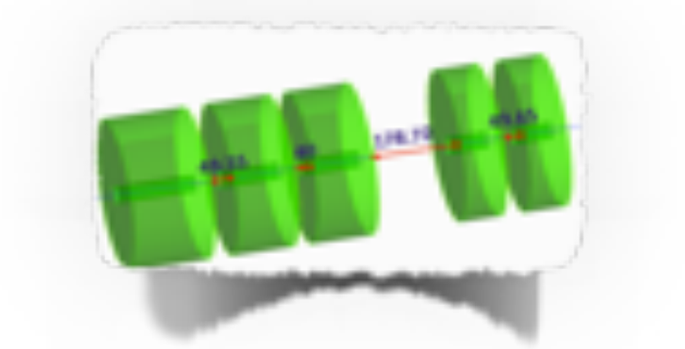
ESS as an active energy modulator?



PMQs configuration fixed for the maximum energy transport optimization (60 MeV)



ESS as an active energy modulator?



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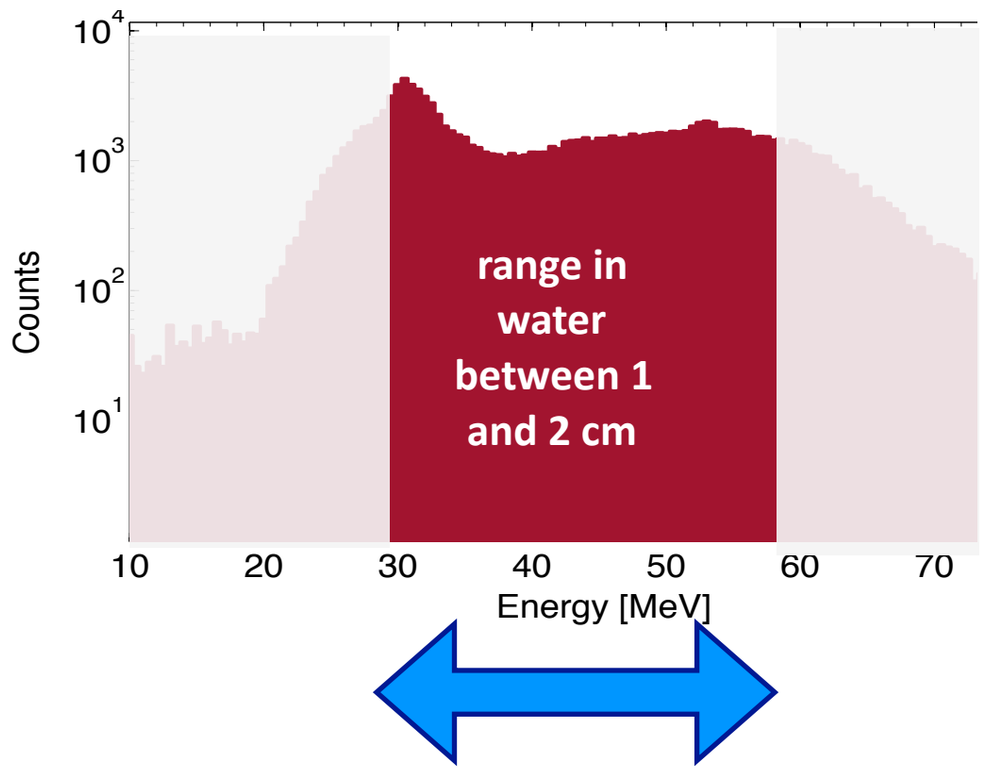

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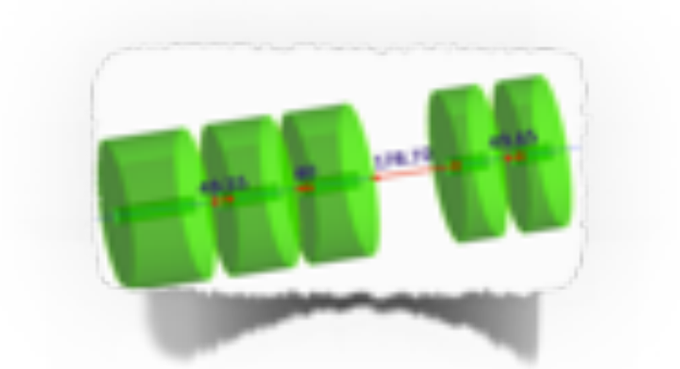
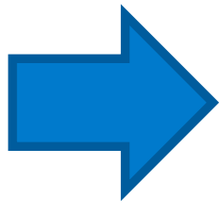
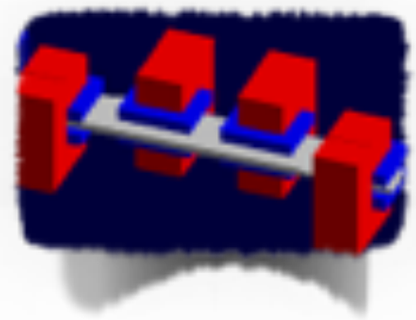
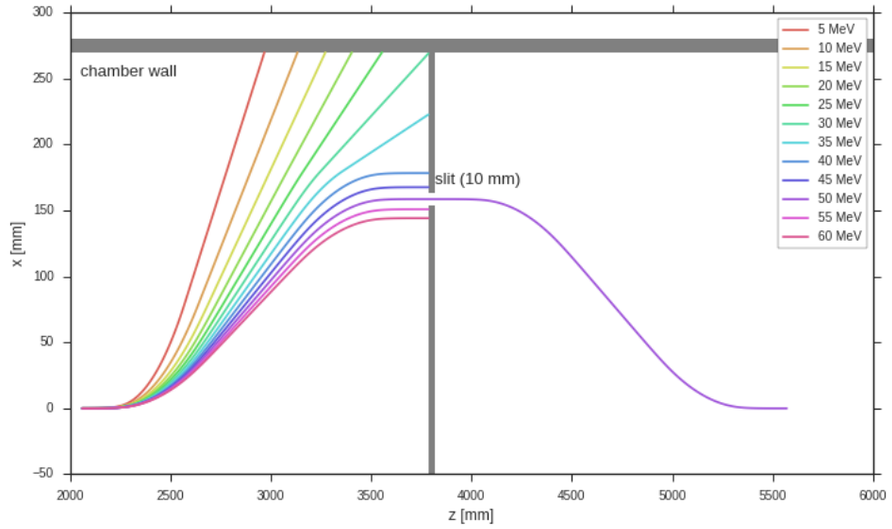


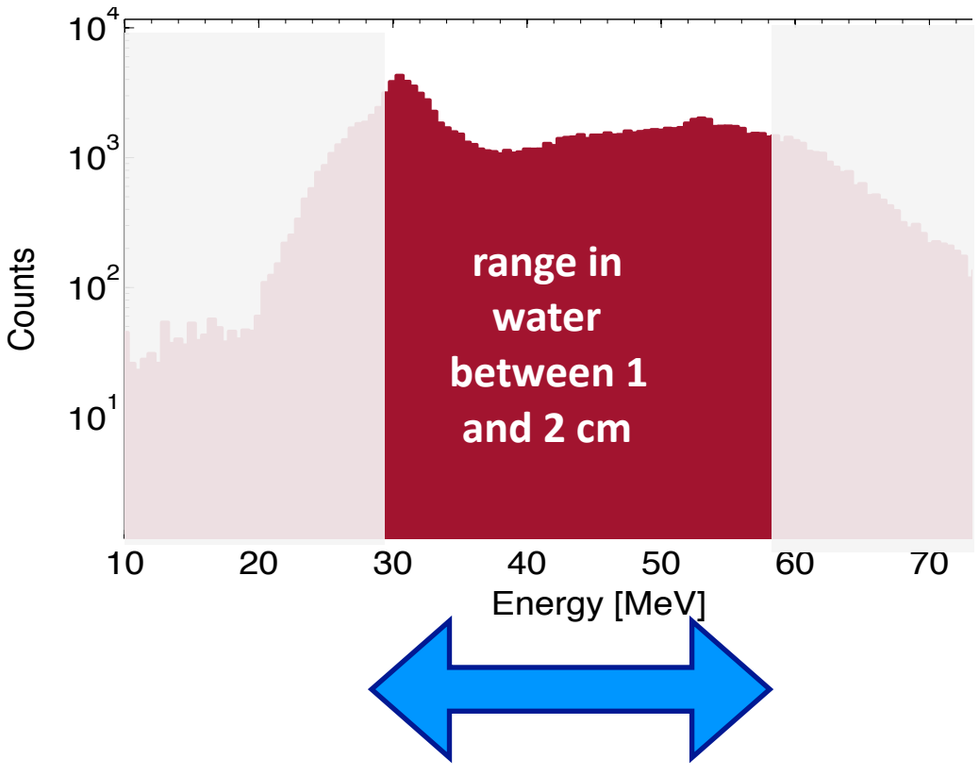




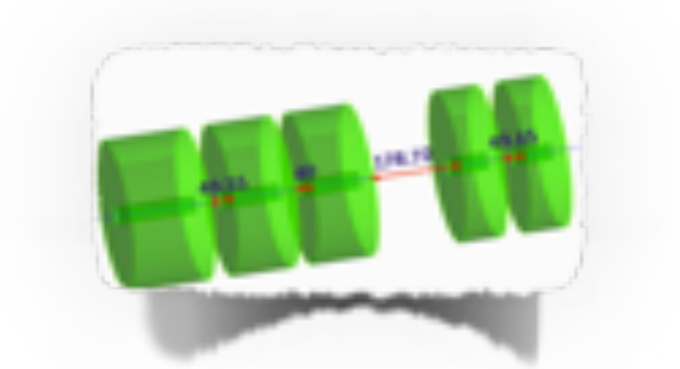
PMQs configuration fixed for the maximum energy transport optimization (60 MeV)

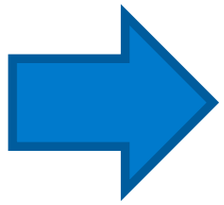
Protons in the energy selector

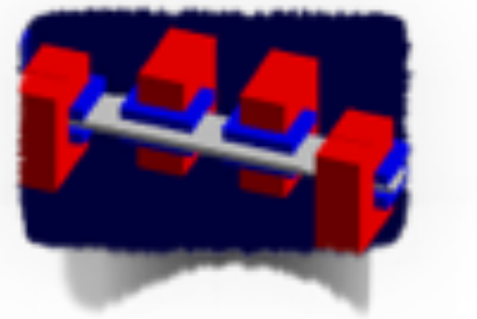




ESS as an active energy modulator?

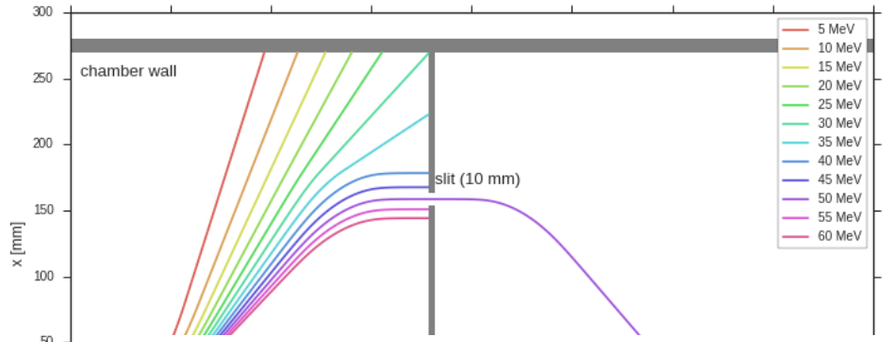


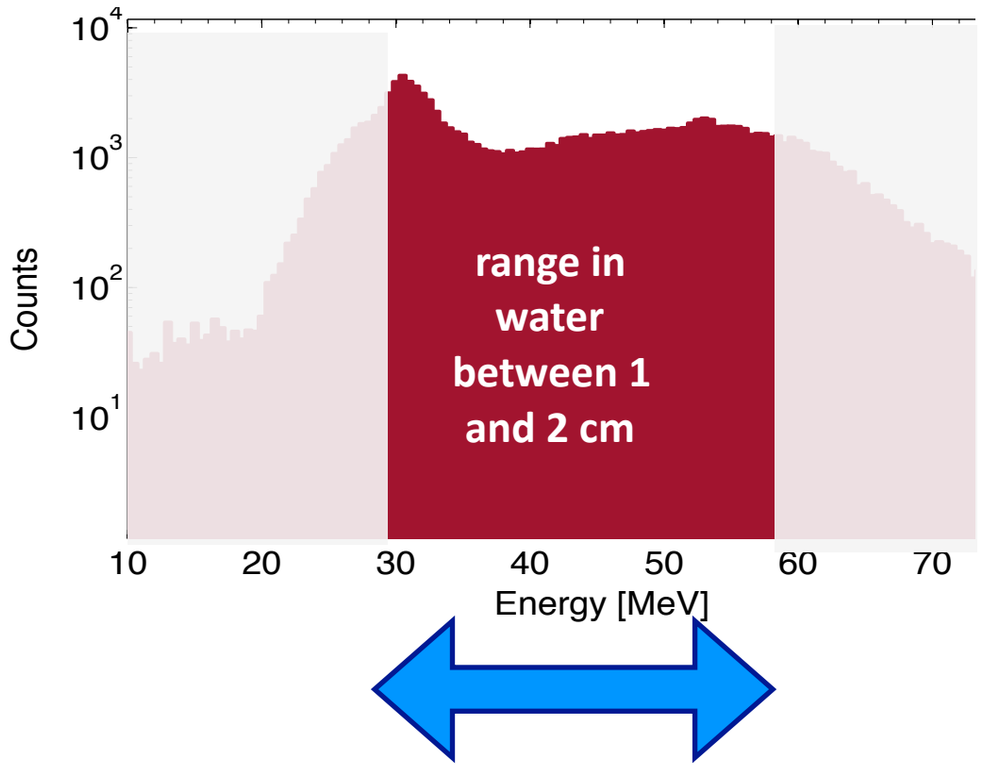


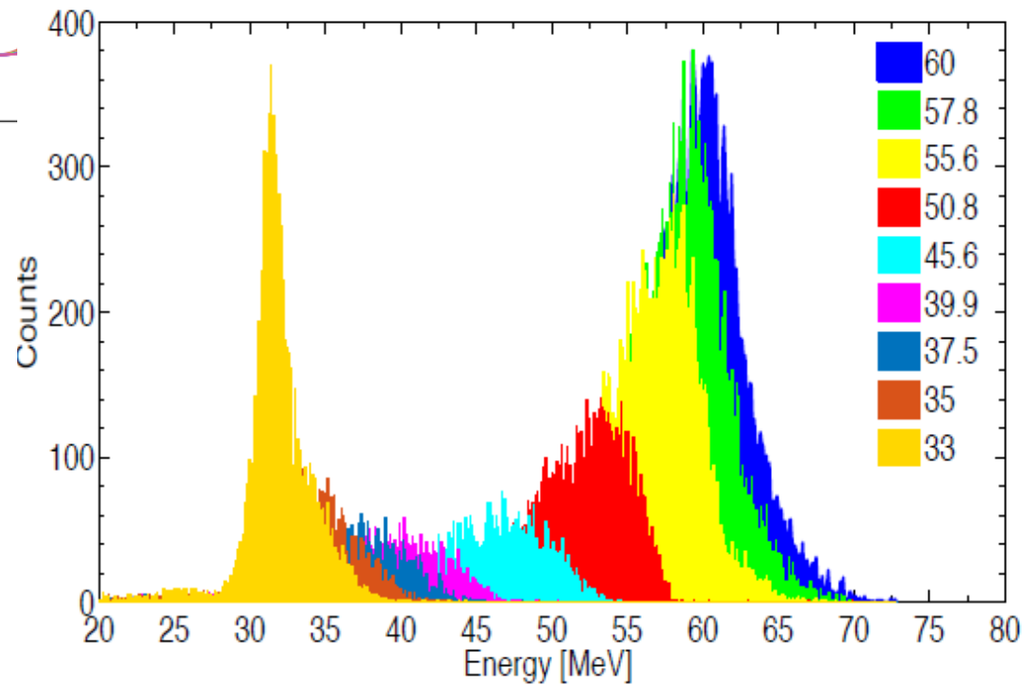


PMQs configuration fixed for the maximum energy transport optimization (60 MeV)

Protons in the energy selector







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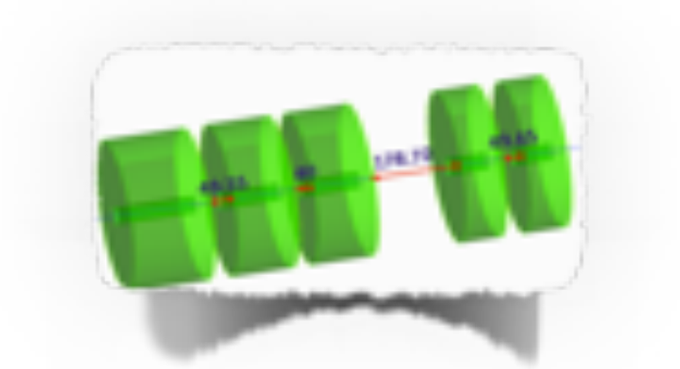

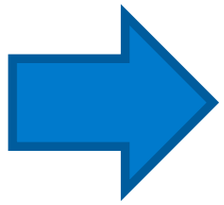

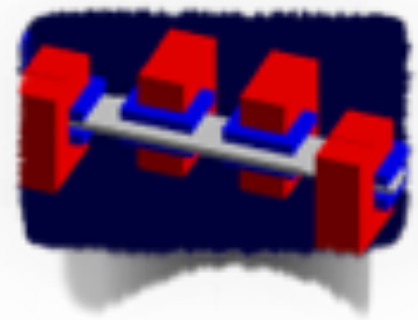

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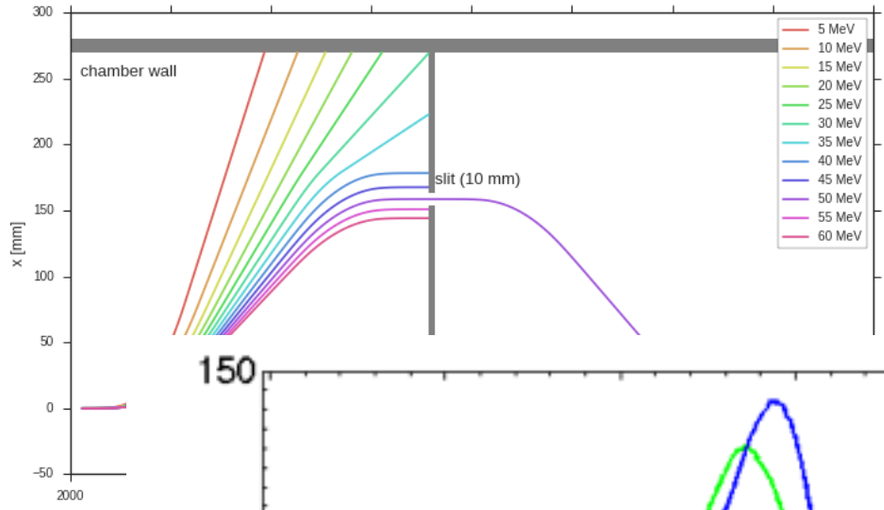
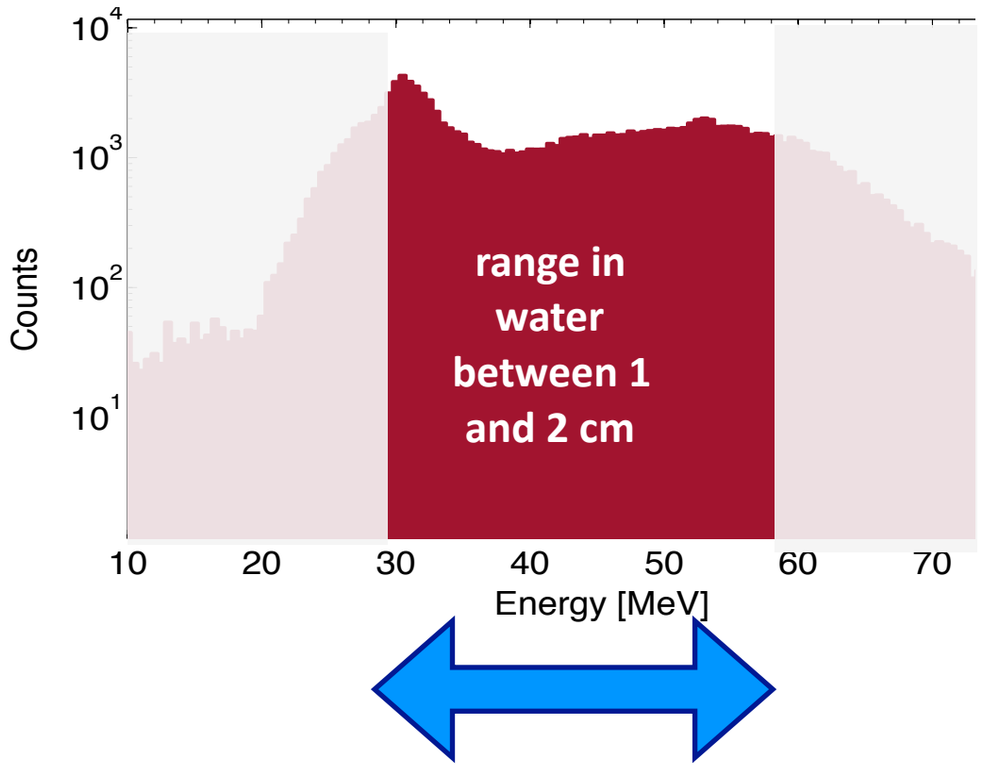
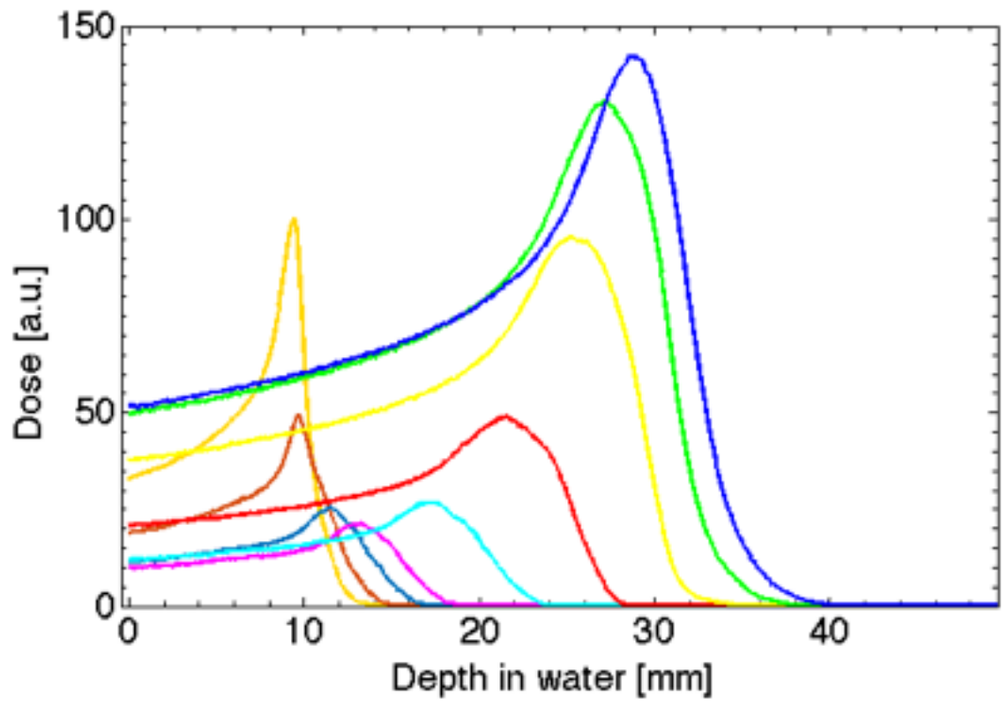
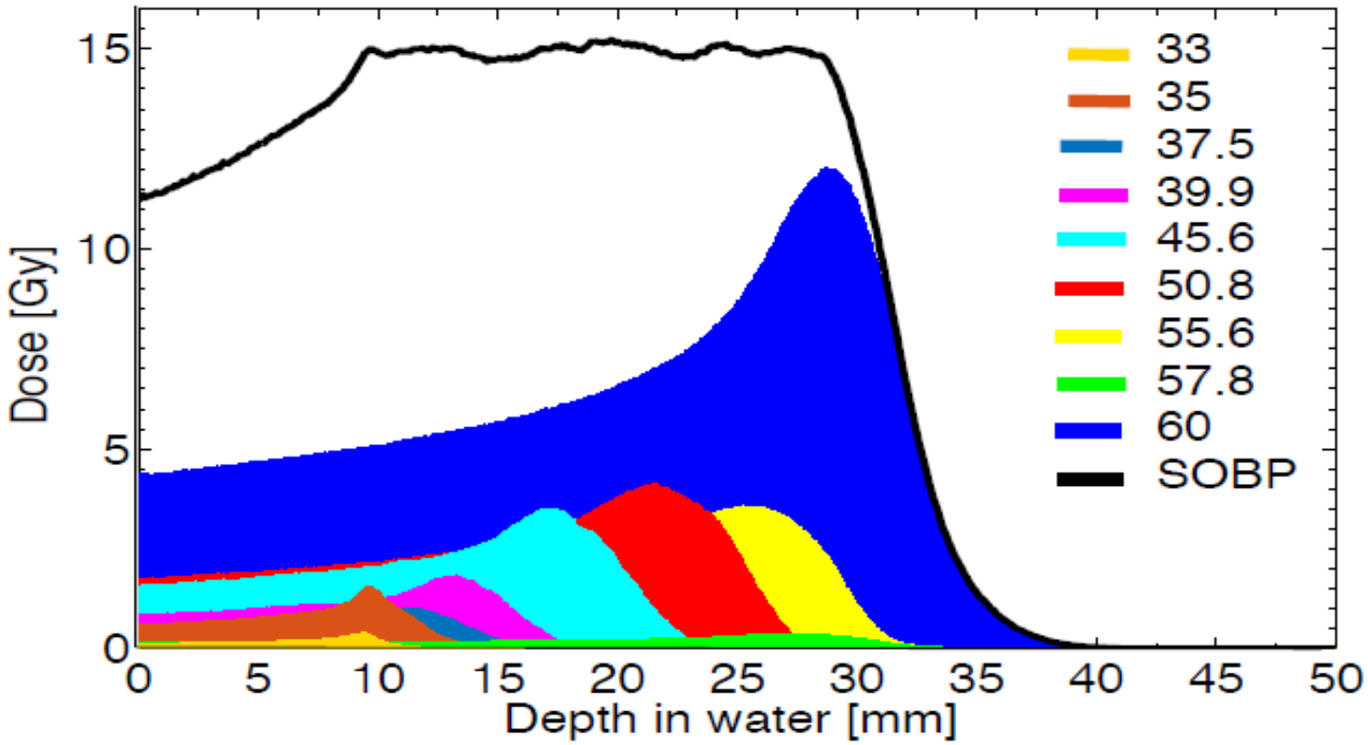




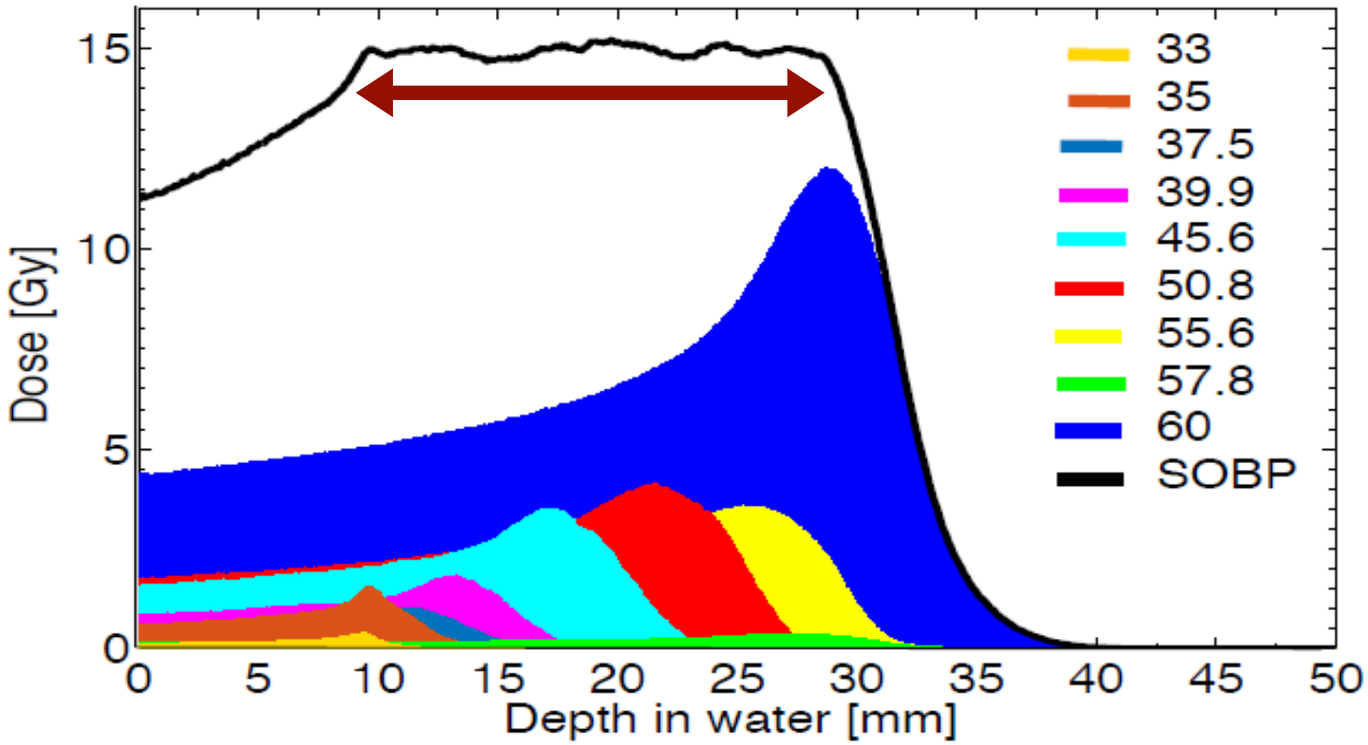


ESS as an active modulator: results



ESS as an active modulator: results

3% of dose homogeneity in 2 cm of modulation region!



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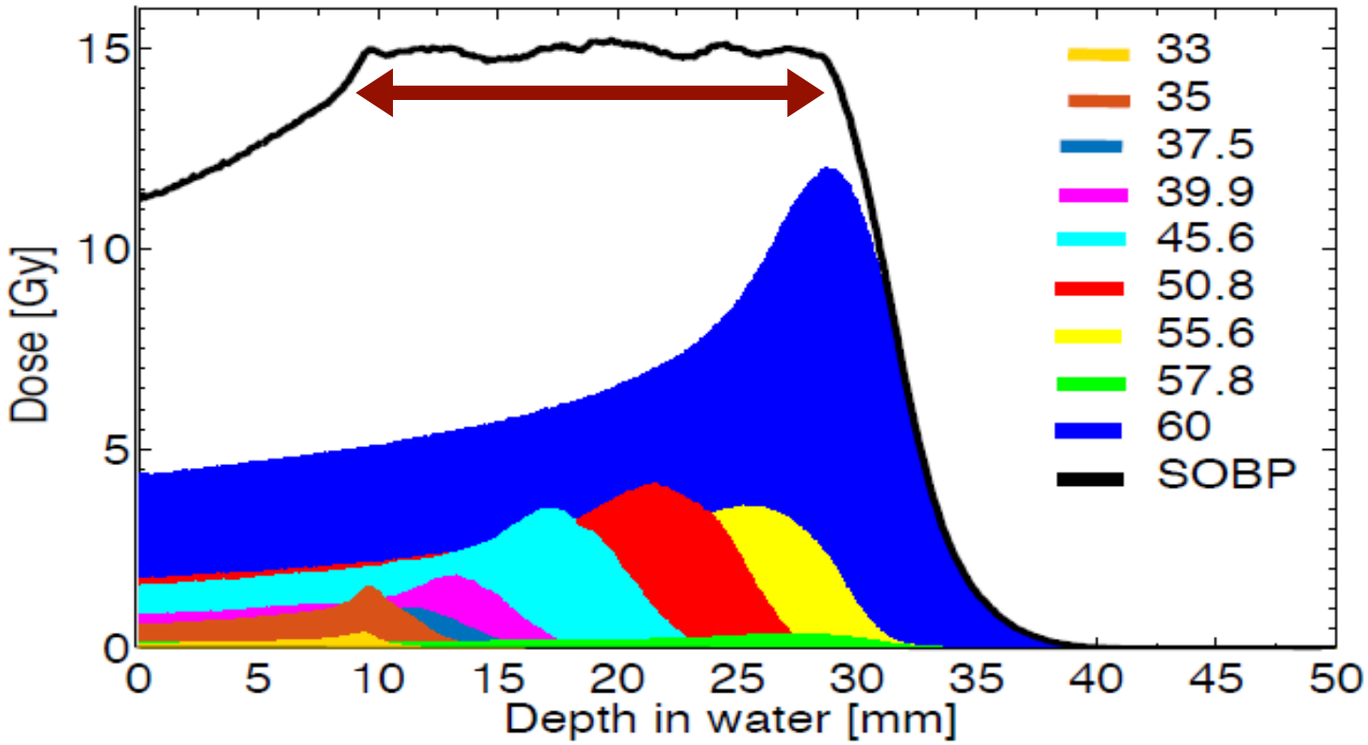

- Normalization to typical doses per session delivered in ocular melanoma proton treatments (15 Gy)
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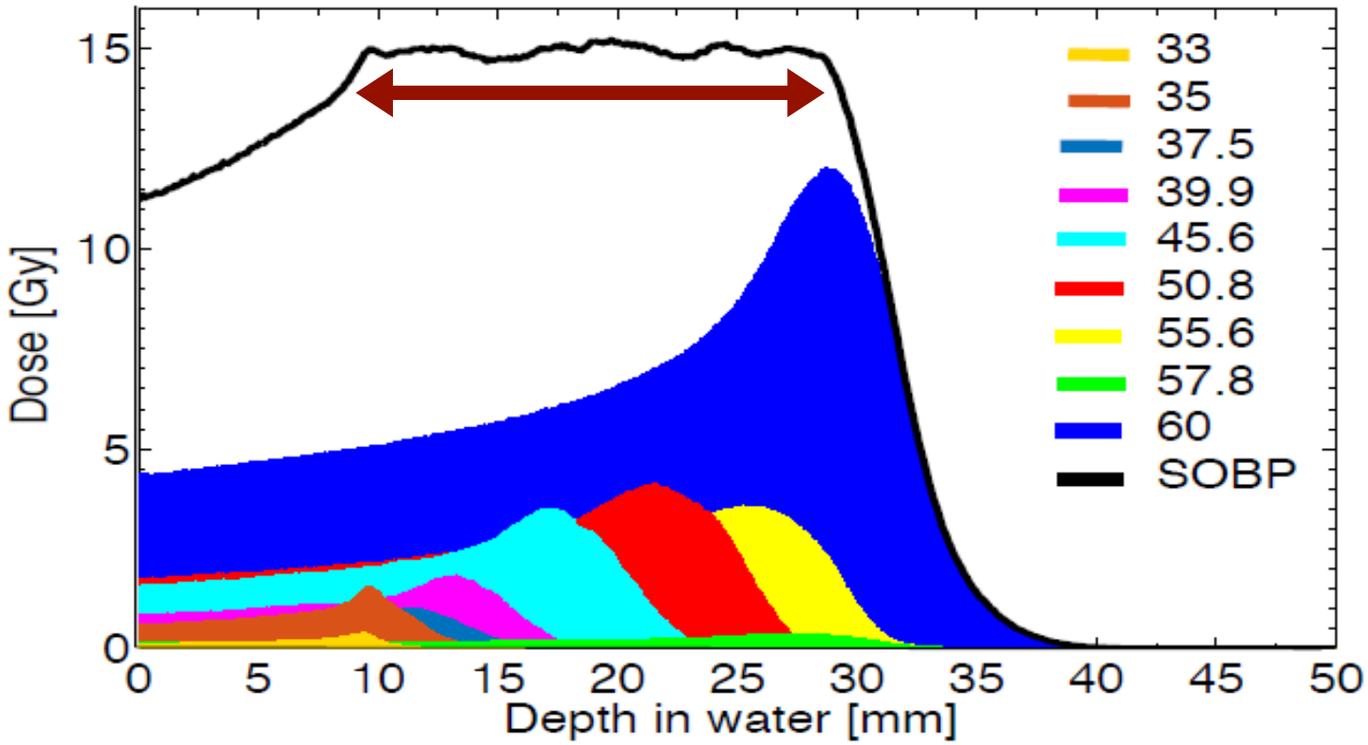


* Normalization to typical doses per session delivered in ocular melanoma proton treatments (15 Gy)
* Re-calculation of the absolute weights (in Gy) of any single peak
* Computation of number of shots per single peak to achieve the required dose

~ 1000 shots in total

* Considering **both** laser repetition rate and and ESS field frequency oh **1 Hz** ~ **16 minutes**
* Considering **laser** repetition rate of **10 Hz** and and **ESS** field frequency oh **1 Hz** ~ **2 minutes**

Conclusions and future developments

Conclusions

- ELIMED application has been designed to be a Geant4 User-oriented application
- Geant4 fits well all the requirements from ELI management:
  - Simulate **complex geometrical elements** with the possibility to **switch on/off** components ***modularity***
  - Easy methods for **changing geometrical configurations** ***interactive commands***
  - **Reliability** for particle transport in magnetic fields ***robust tracking***
  - Accurate **energy/dose depositions** predictions and **secondary particles** production -> ***well tested and validated*** physics models
  - **User-friendly** and **easy-to-use** for non experienced Users -> ***Qt interface with the possibility***
    of changing all the key parameters/elements of the beamline

Future developments

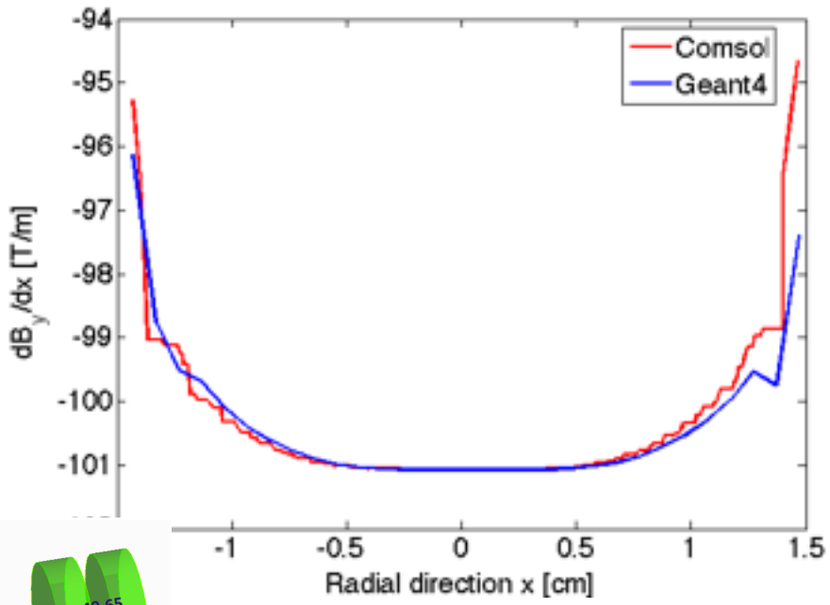
- Voxel phantom import (from DICOM)
- Calculation of LET distributions (and RBE?) in the perspective of future in-vitro/in-vivo experiments to be performed at ELI-Beamline
- Implementation of Geant4-DNA models? *spatio-temporal track correlations due to the extremely high dose rate per pulse*

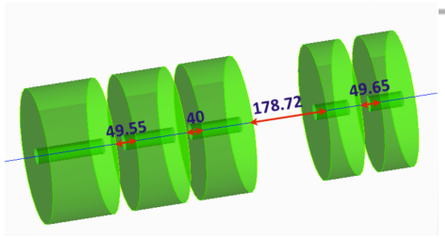
Thank you

Validation with reference code: magnetic fields& tracking

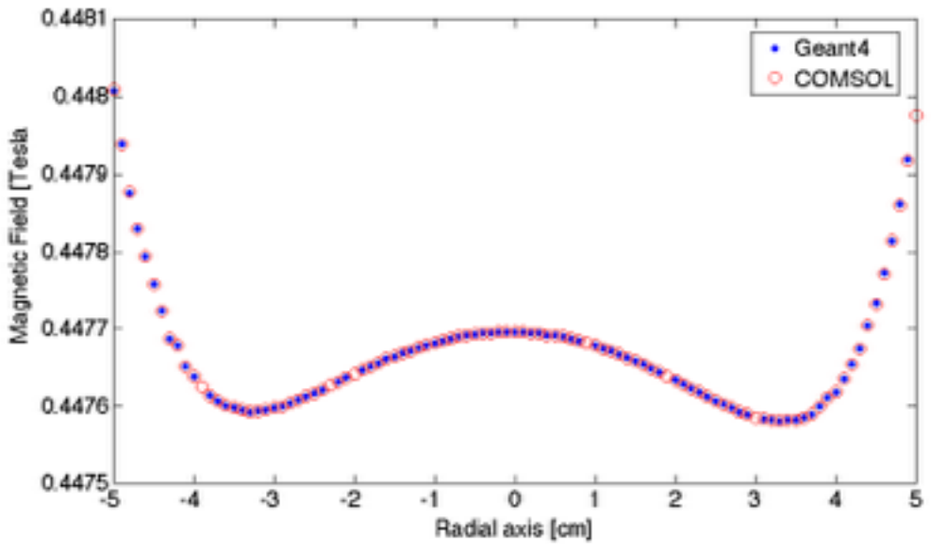
Comparison with COMSOL and SIMION software

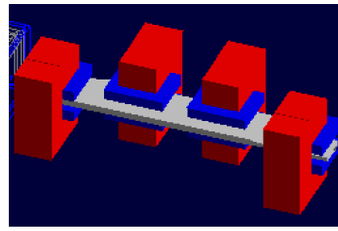
Magnetic field gradient within the 160 mm quad





Magnetic field intensity along the radial axis of the dipole





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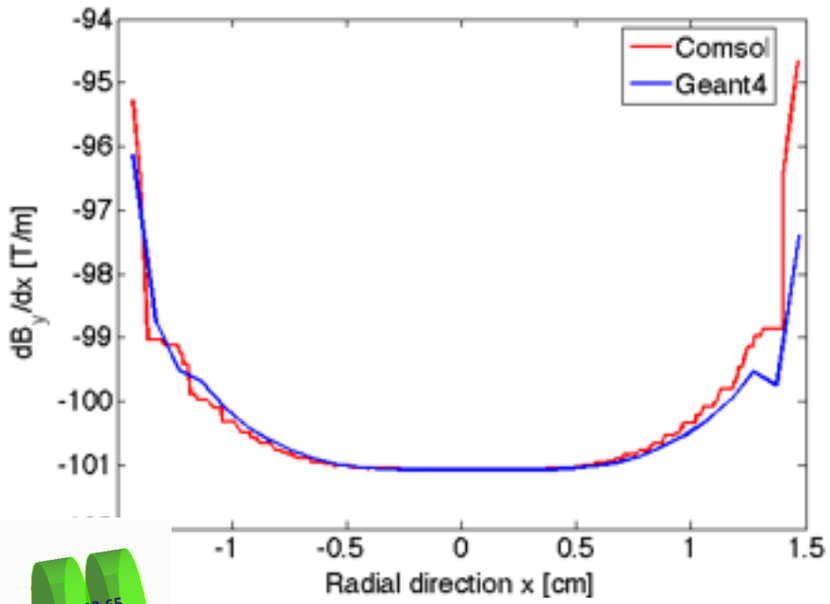

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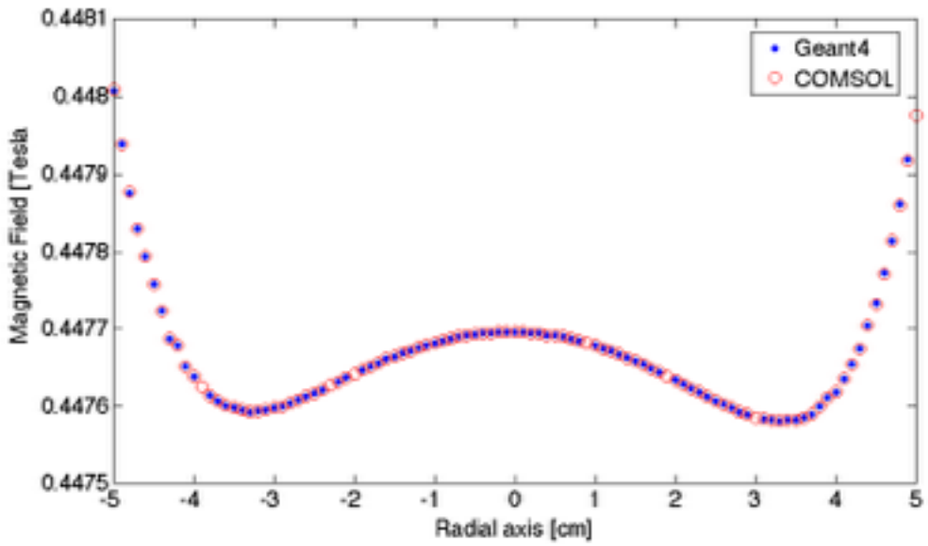
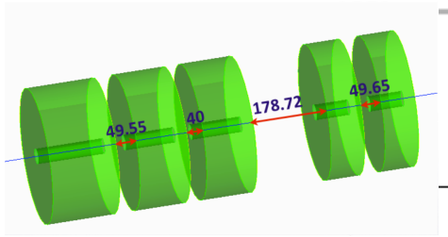
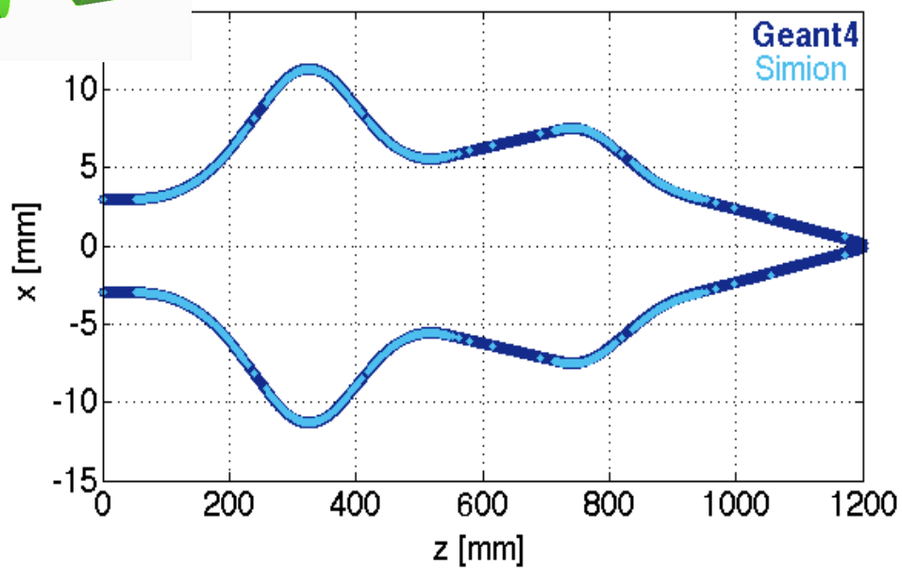
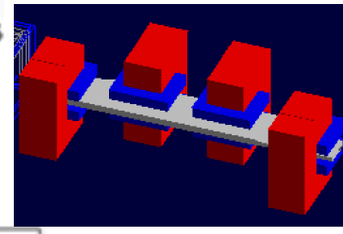


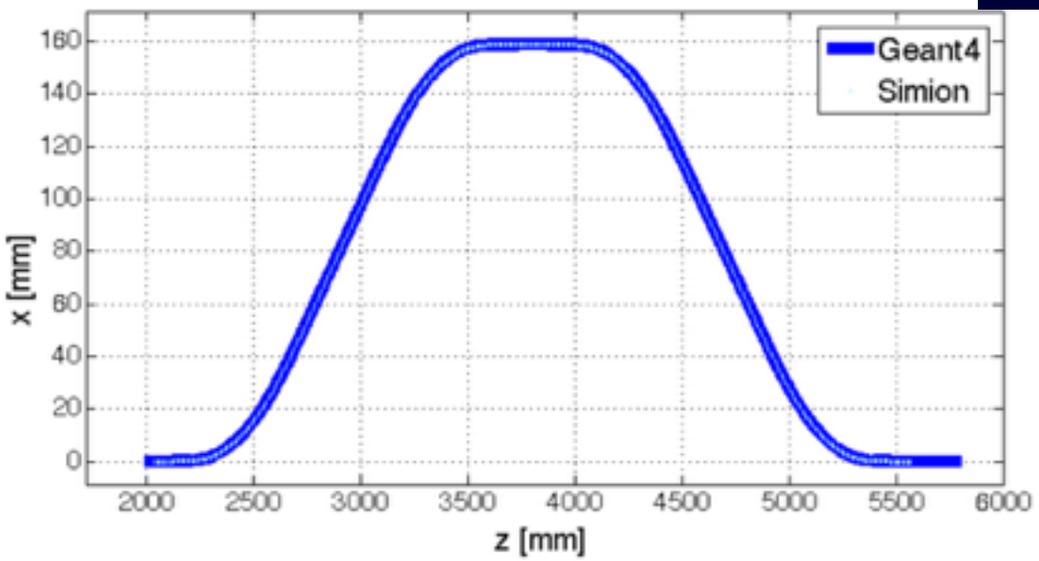


60 MeV p track within PMQ system in the x-z plane



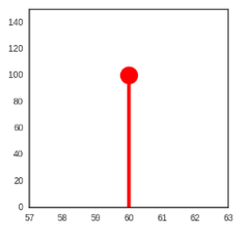


60 MeV p track within ESS system in the x-z plane



Adaptive source

Monoenergetic



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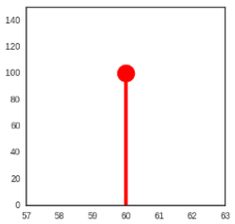
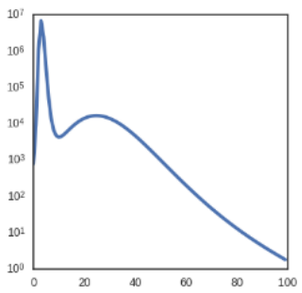


Analytic



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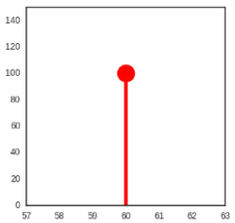

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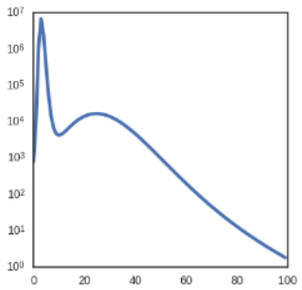
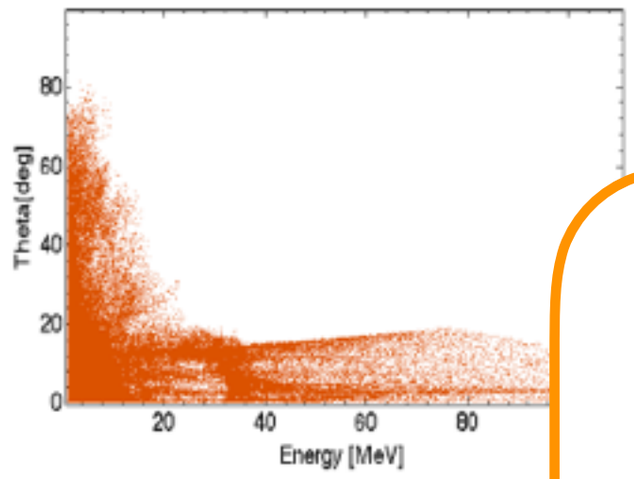
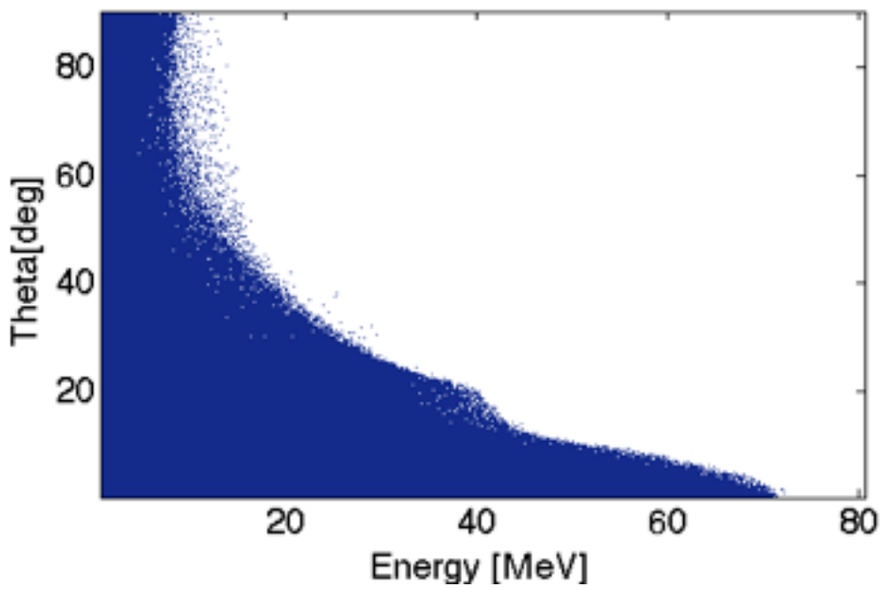


Detailed laser-driven proton and ion beam source to use as input

PIC 2D



PIC 3D



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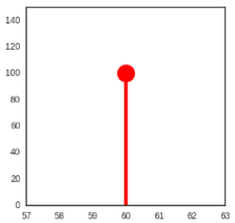

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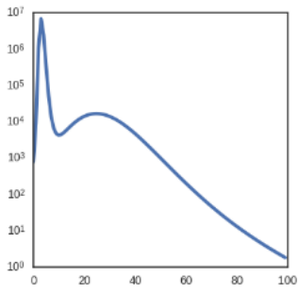

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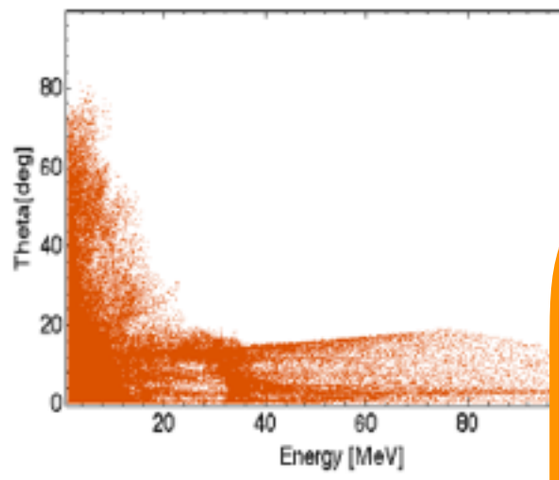

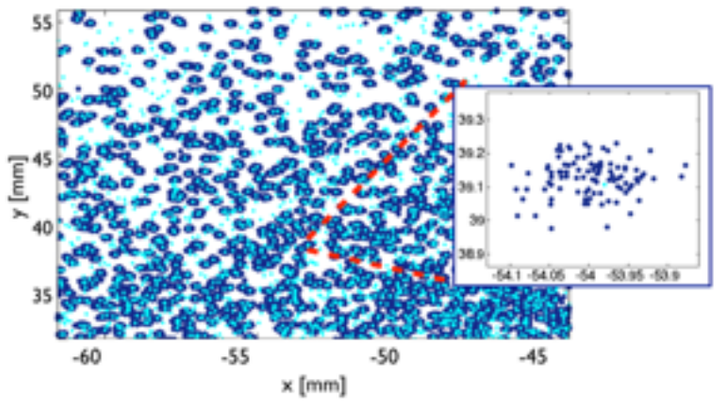

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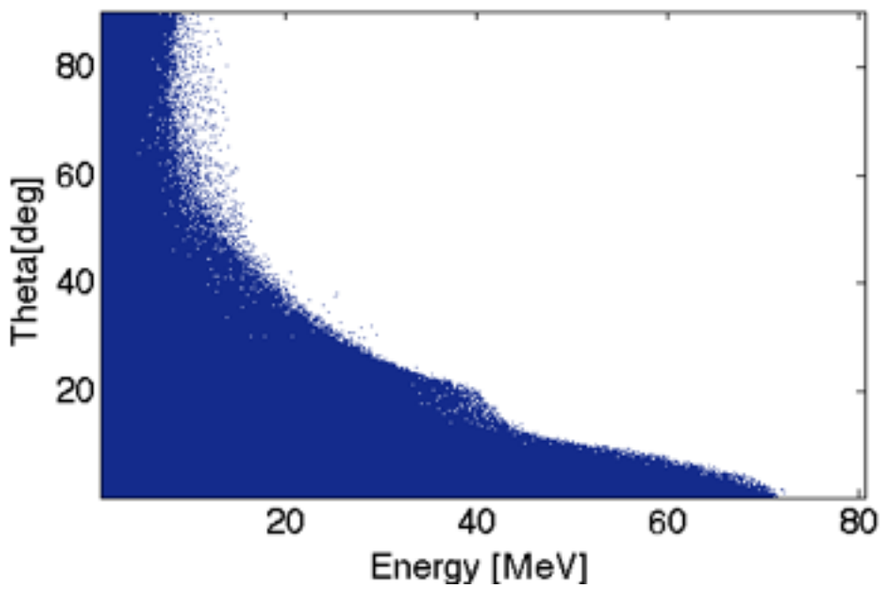

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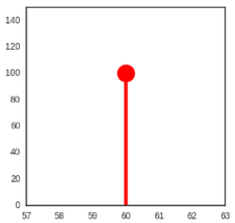

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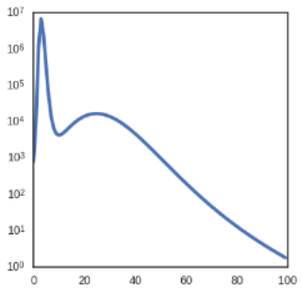

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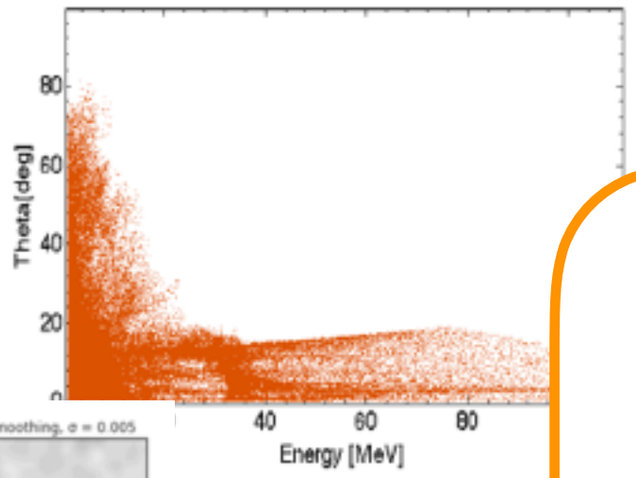

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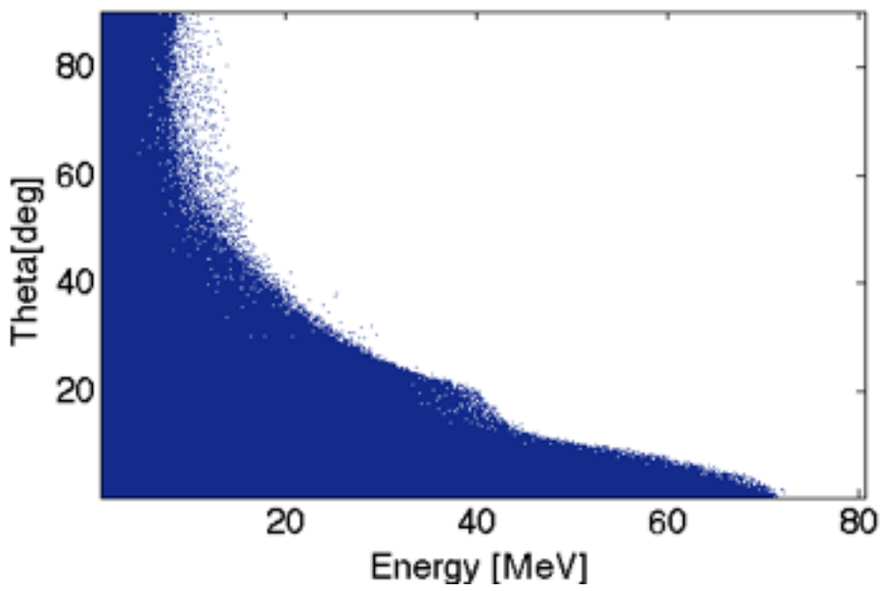
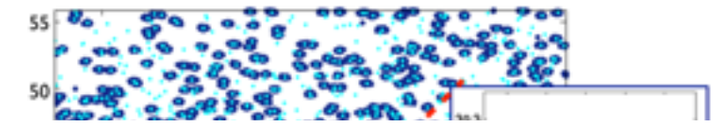
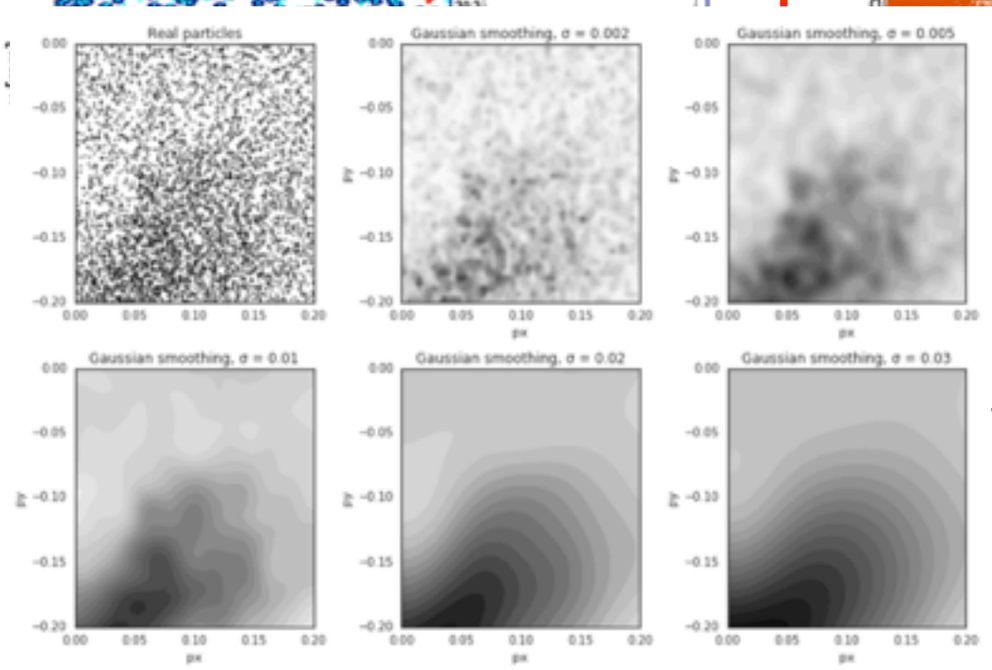
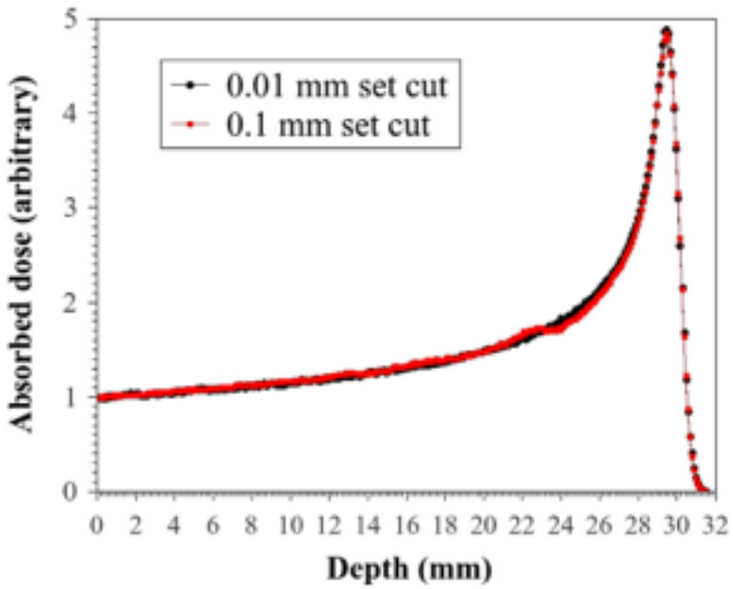




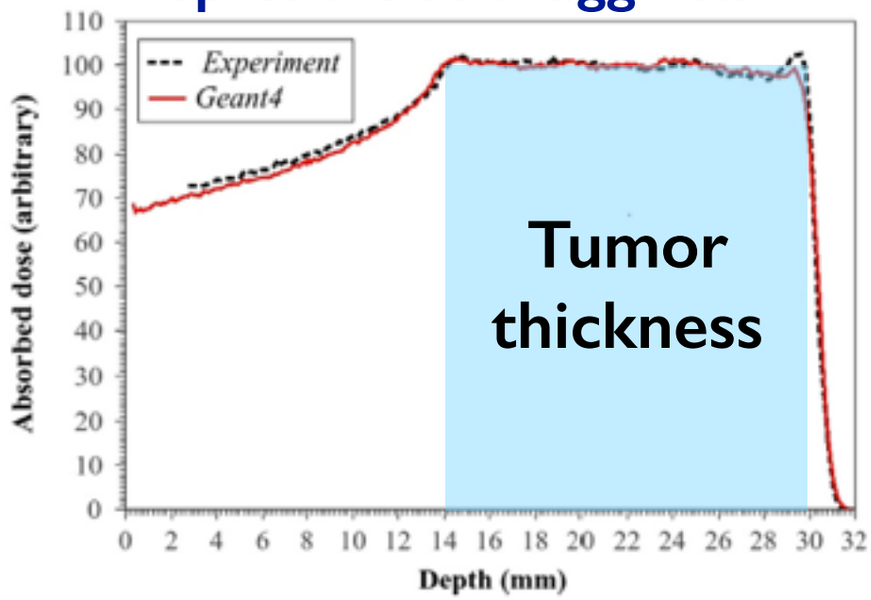


Weighting low energy conventionally accelerated proton beams for modulators



Weighting low energy conventionally accelerated proton beams for modulators

Spread Out Bragg Peak



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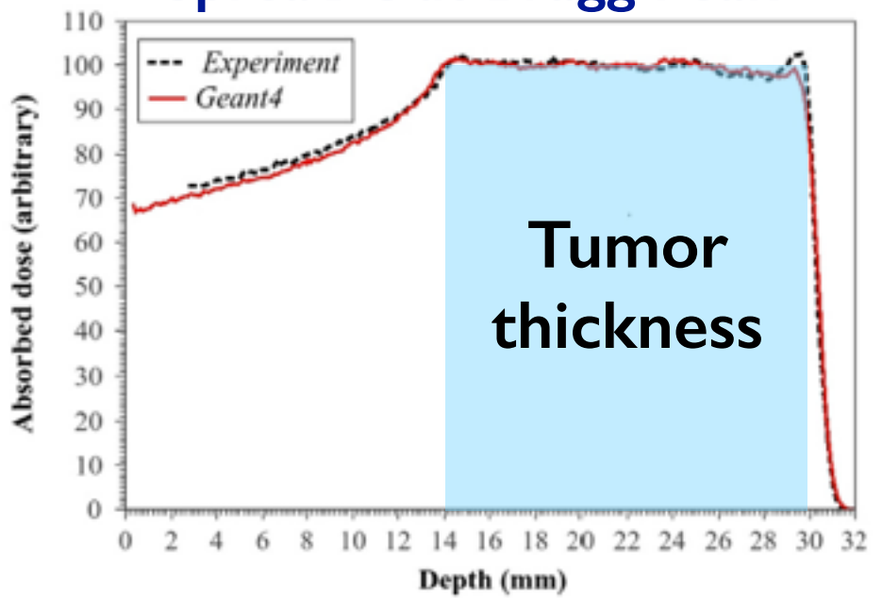

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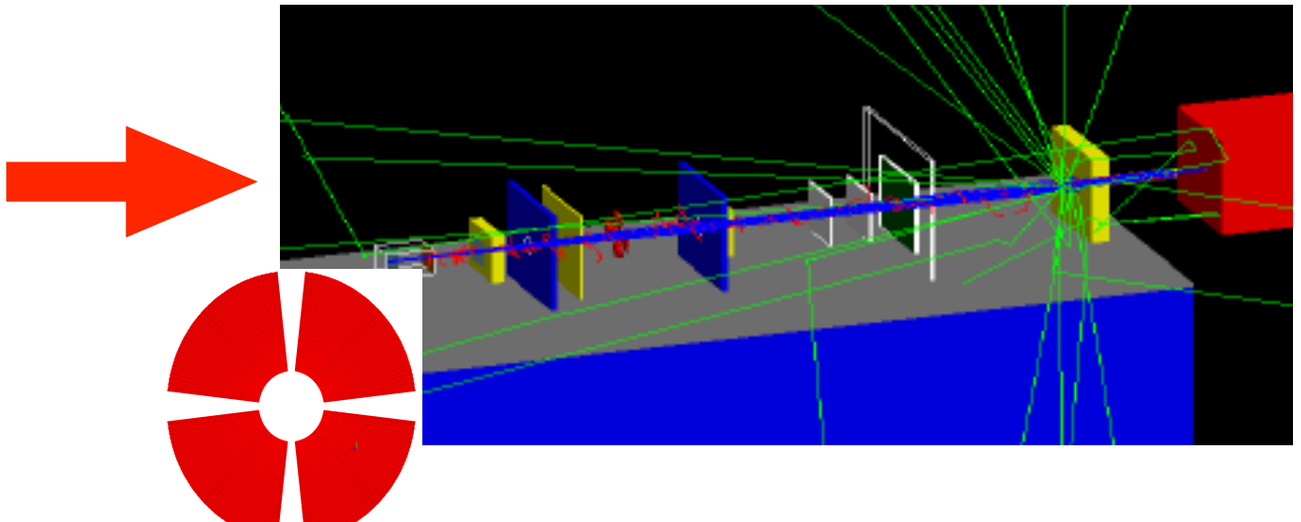

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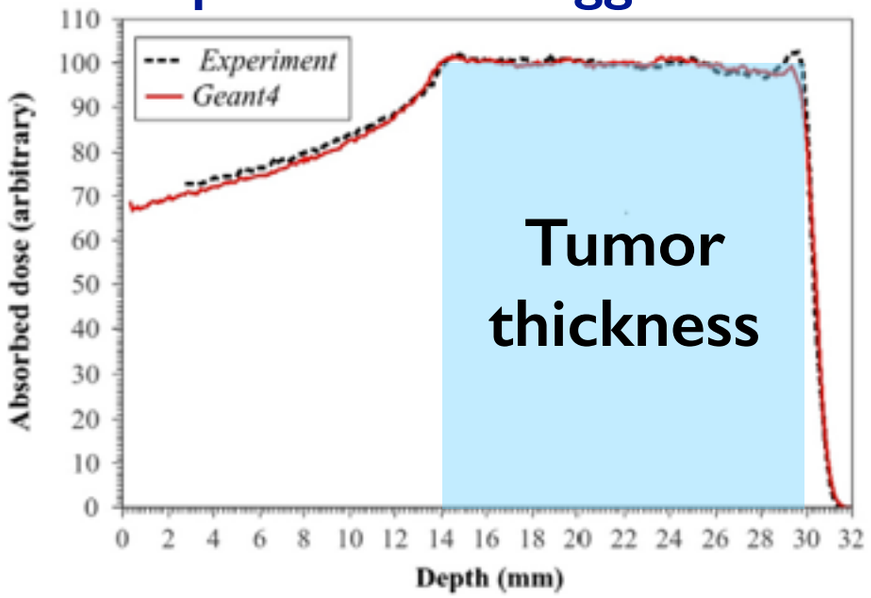
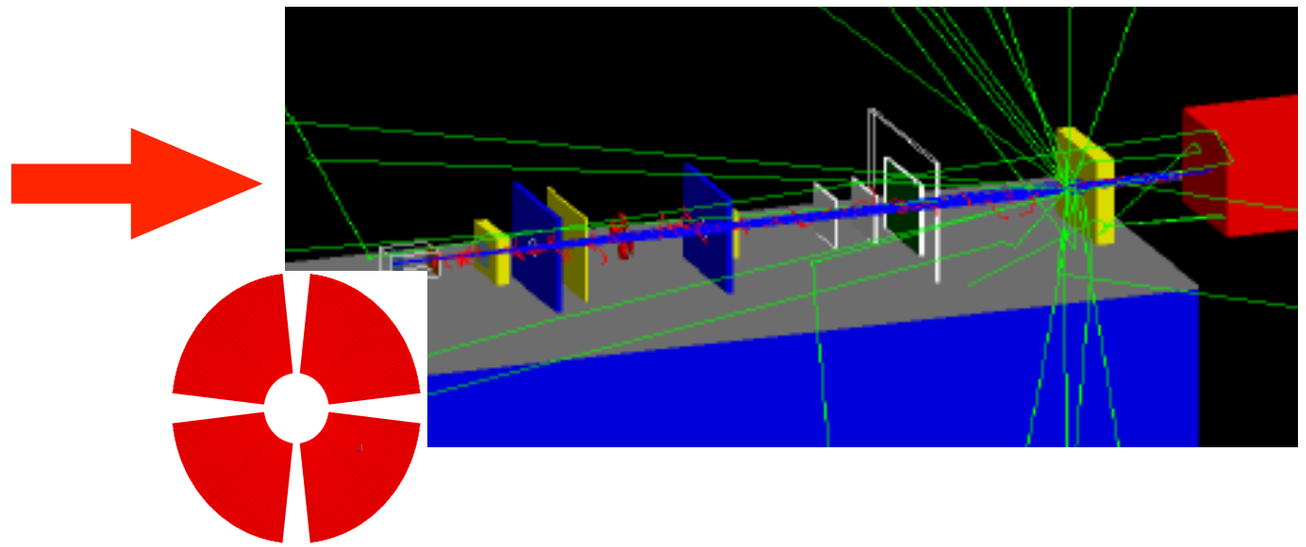
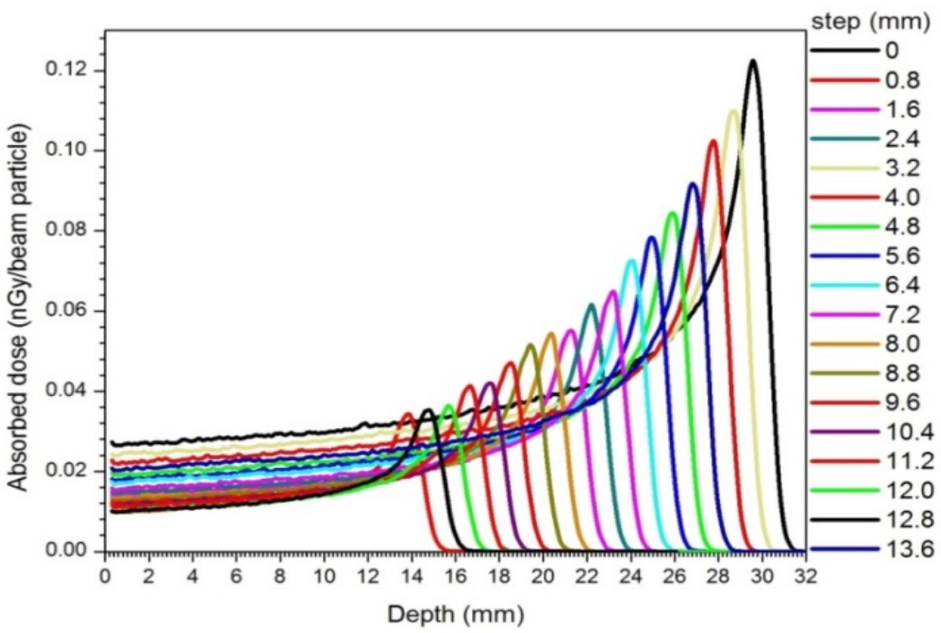


B. Jia, F. Romano, G.A.P. Cirrone, G. Cuttone, M.H. Hadizadeh, A.A. Mowlavi, L. Raffaele. NIM A (Jan 2016)

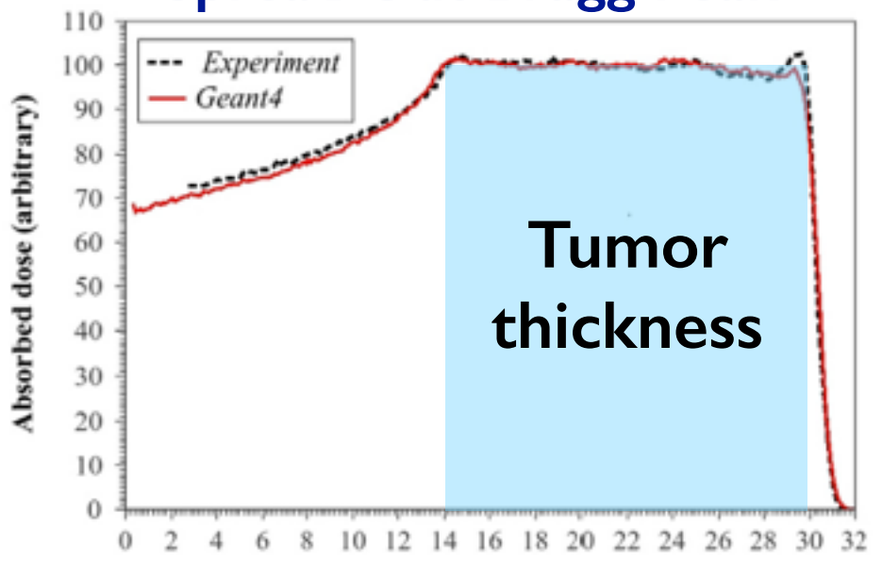


$$w_1 D_{i1} + w_2 D_{i2} + \cdots w_N D_{iN} = D_{i0} \qquad i = 1,2,\ldots,N$$

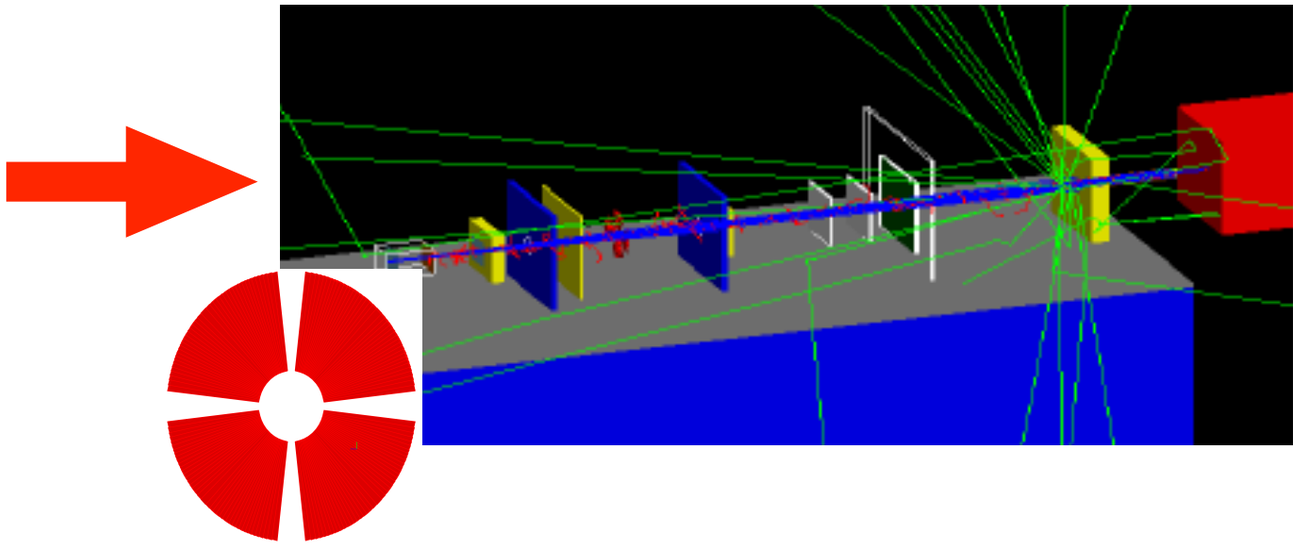


Weighting low energy conventionally accelerated proton beams for modulators

Spread Out Bragg Peak



B. Jia, F. Romano, G.A.P. Cirrone, G. Cuttone, M.H. Hadizadeh, A.A. Mowlavi, L. Raffaele. NIM A (Jan 2016)



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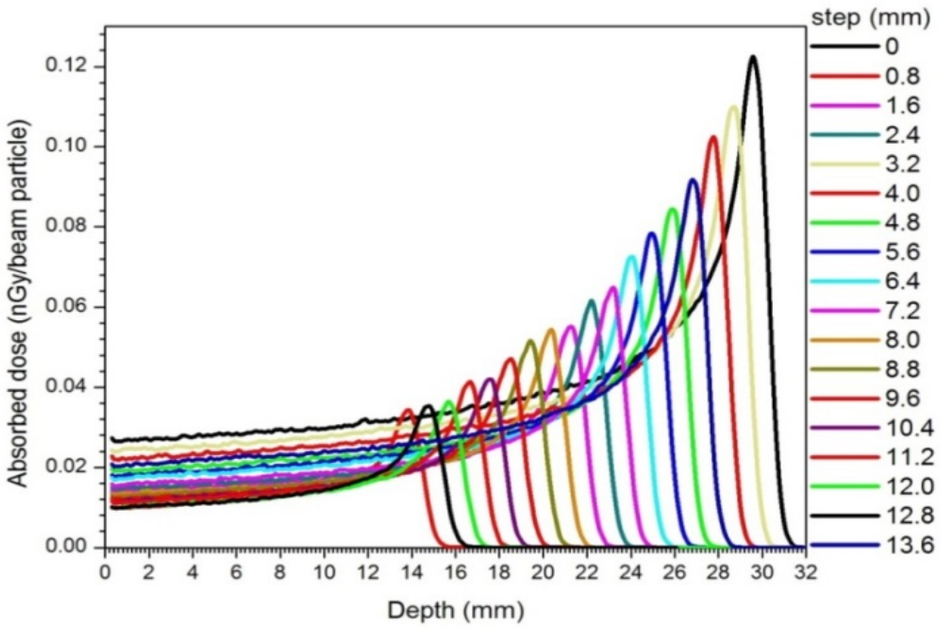
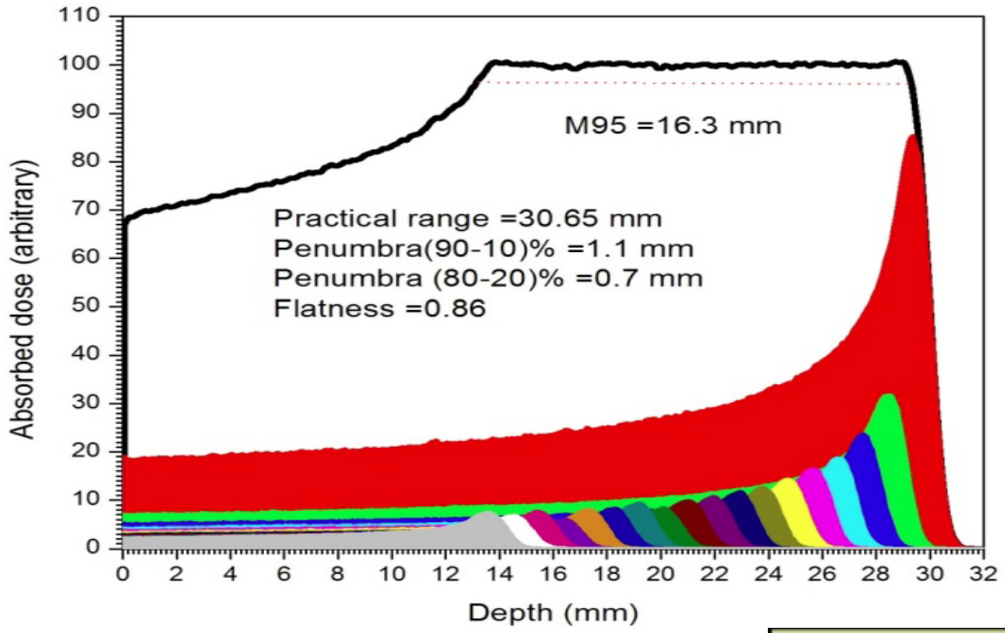
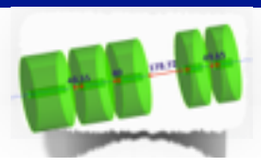


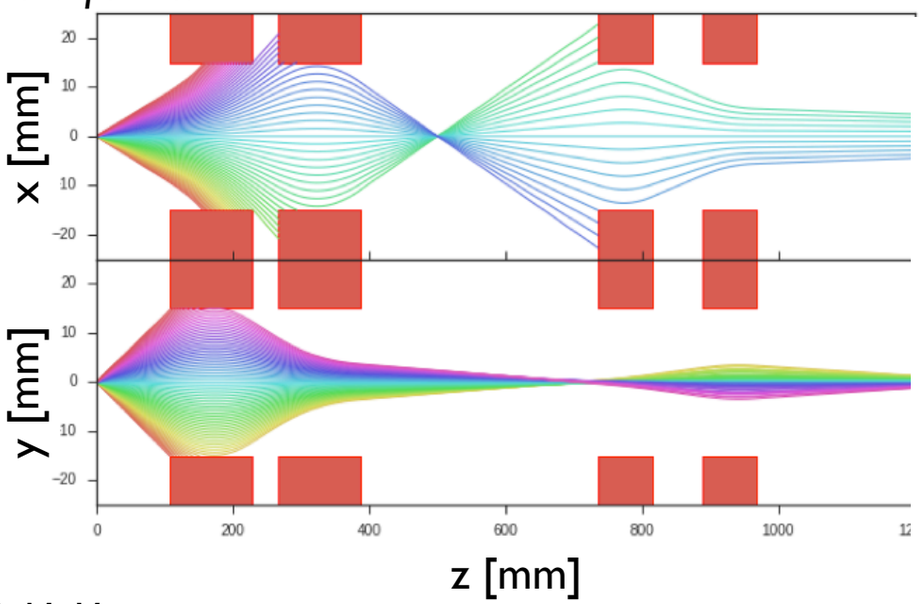


In vacuum transport- focusing and energy selection

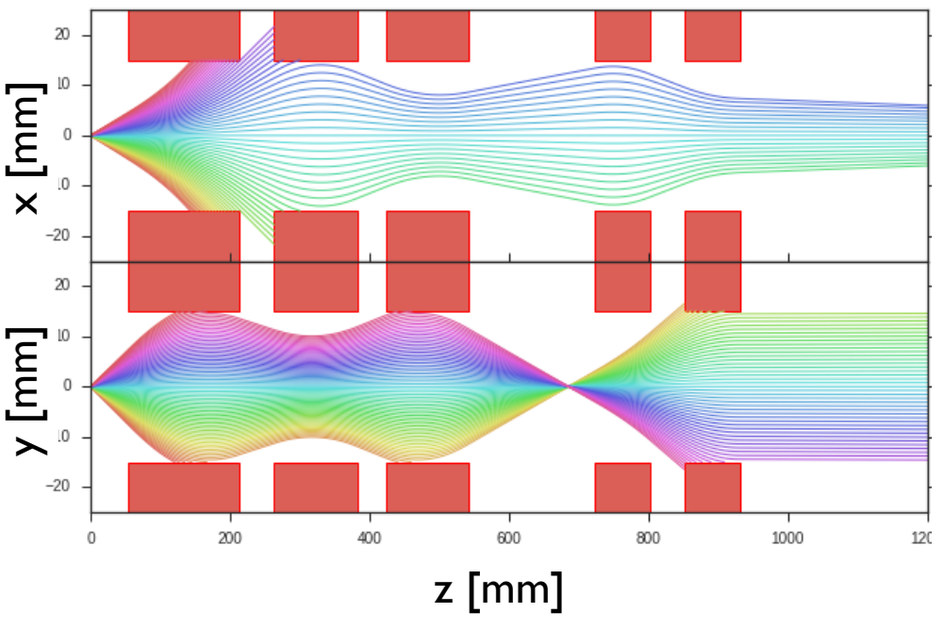
PMQs



30 MeV proton



60 MeV proton



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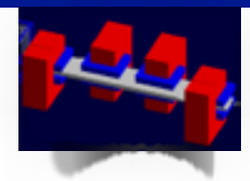
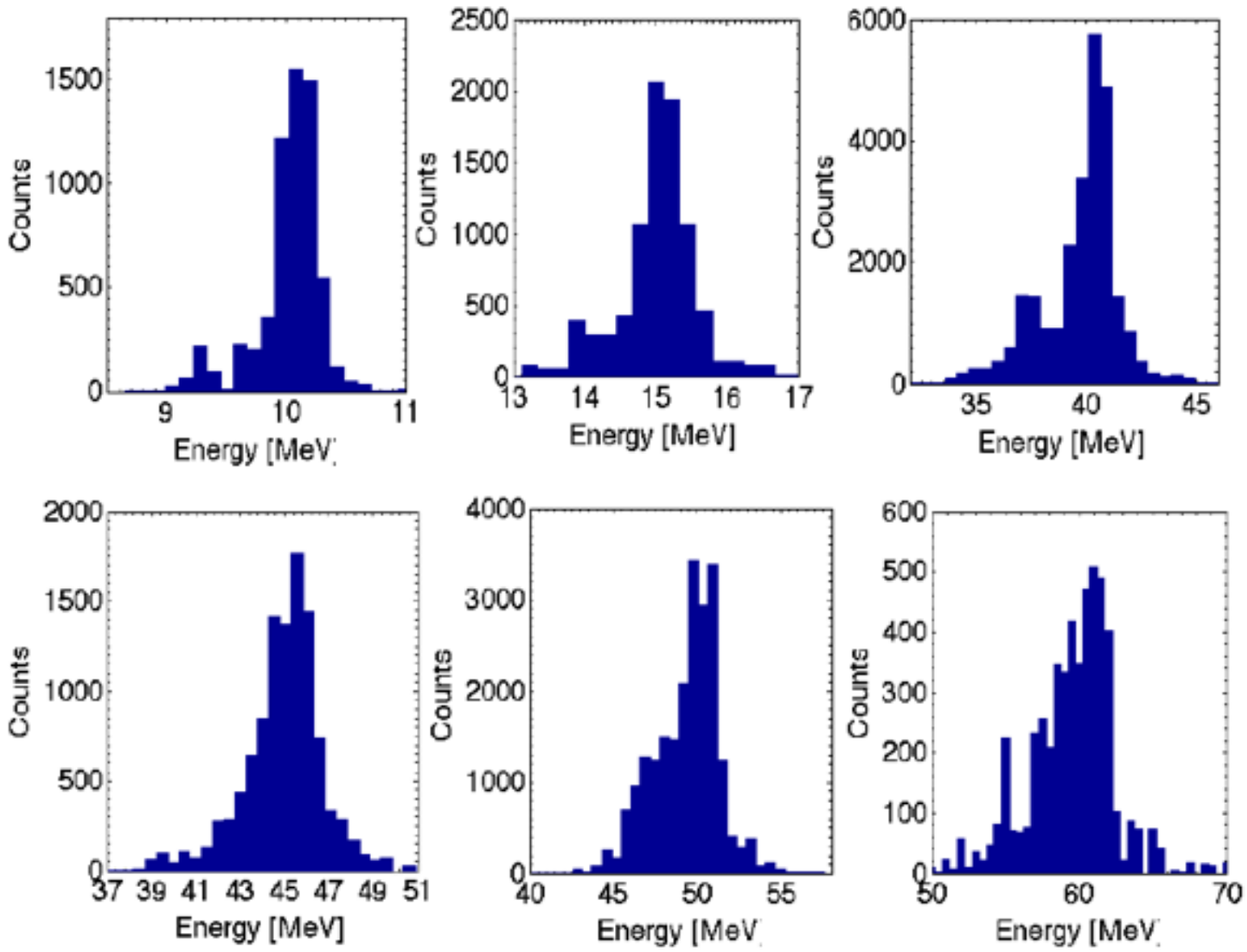




ELIMED Monte Carlo WP

ELIMED (*LNS-INFN*)
@ ELI-Beamlines

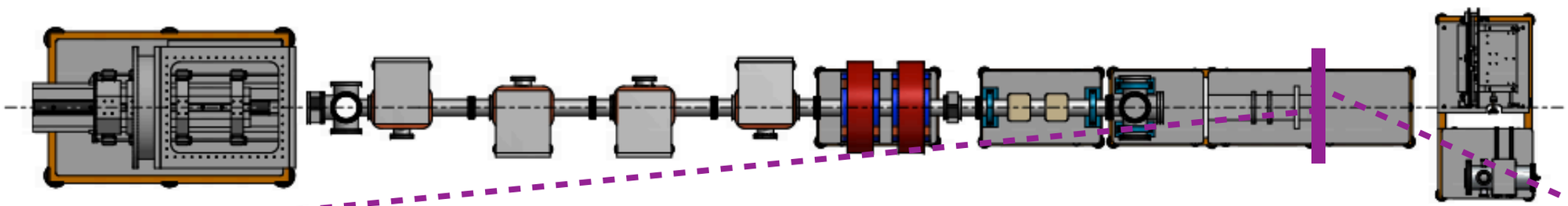
WP1 (*LNS-INFN*)
Ion Beam Transport

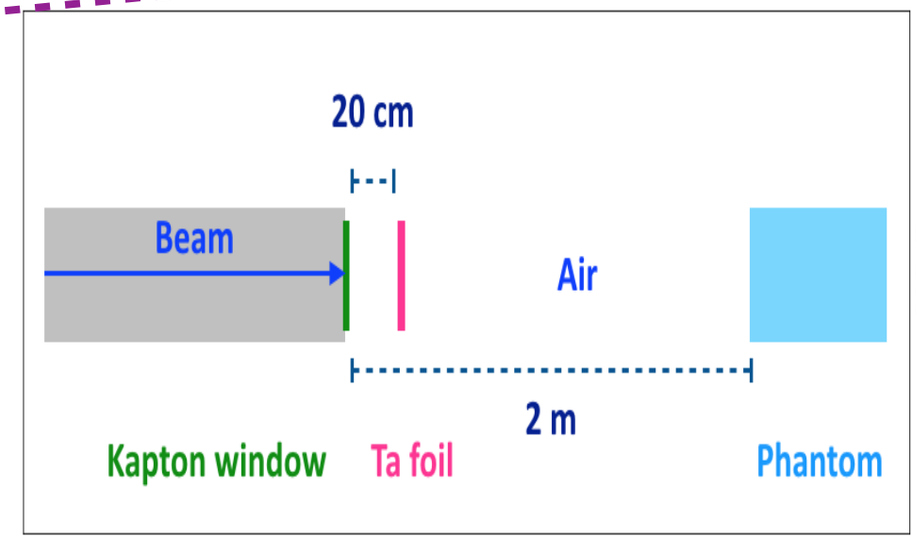
WP2 (*LNS-INFN*)
Monte Carlo Simulations

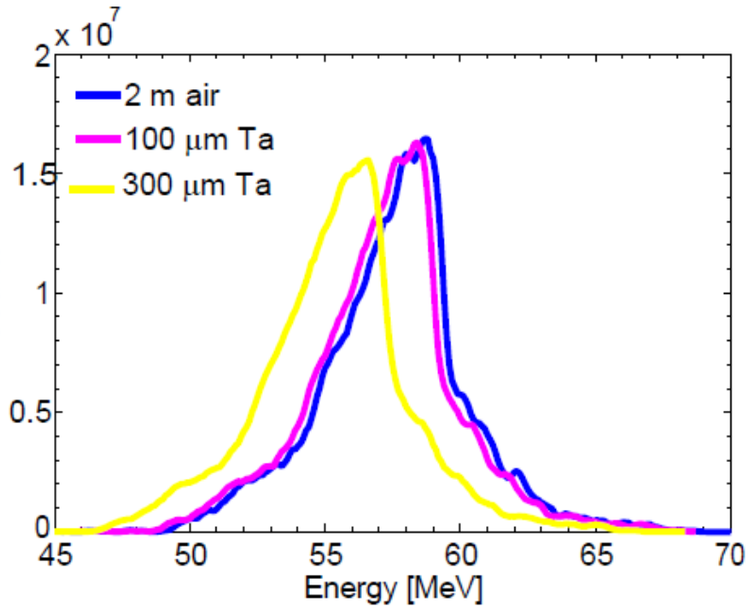
WP3 (*LNS-INFN*)
Ion Beam Diagnostics and Dosimetry

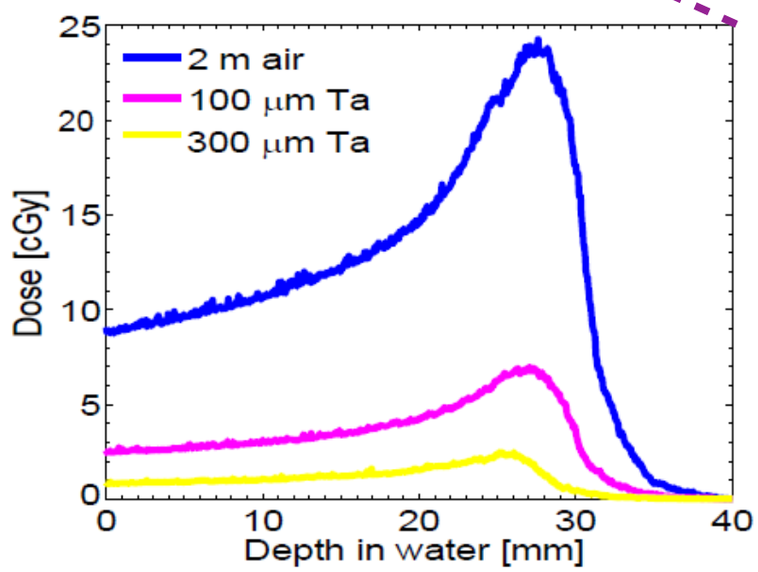
Resp.: F. Romano
J. Pipek
G. Milluzzo

Optimization of transversal profiles for applications

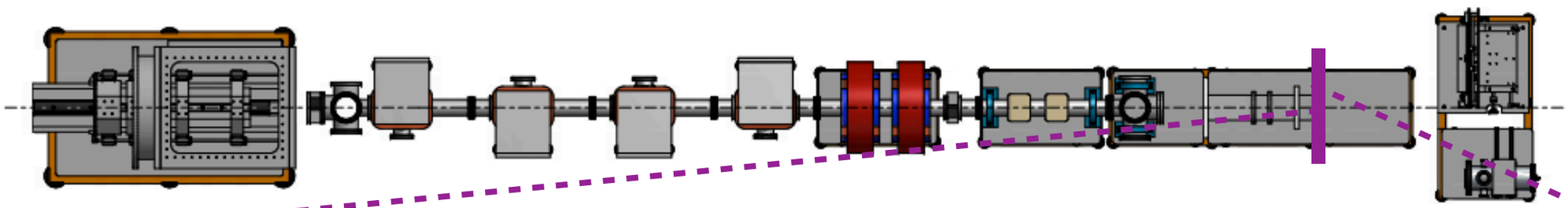


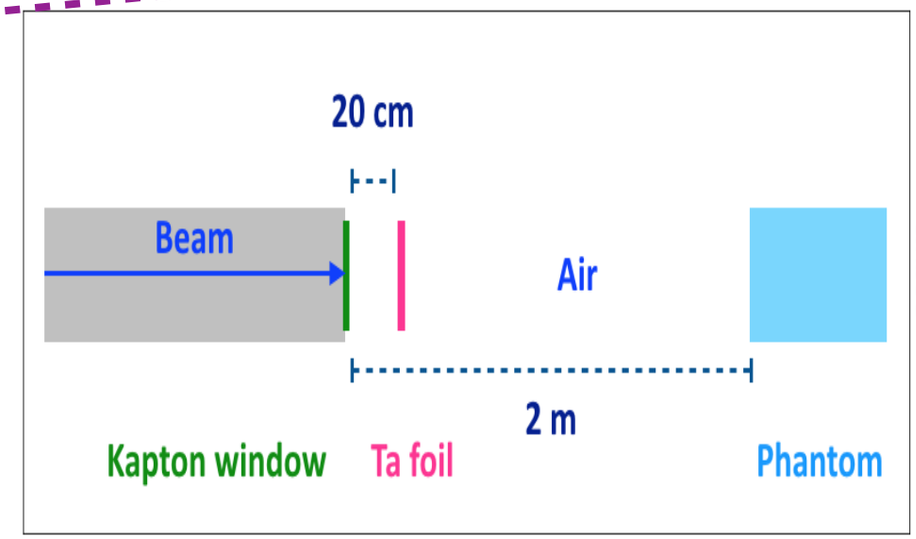


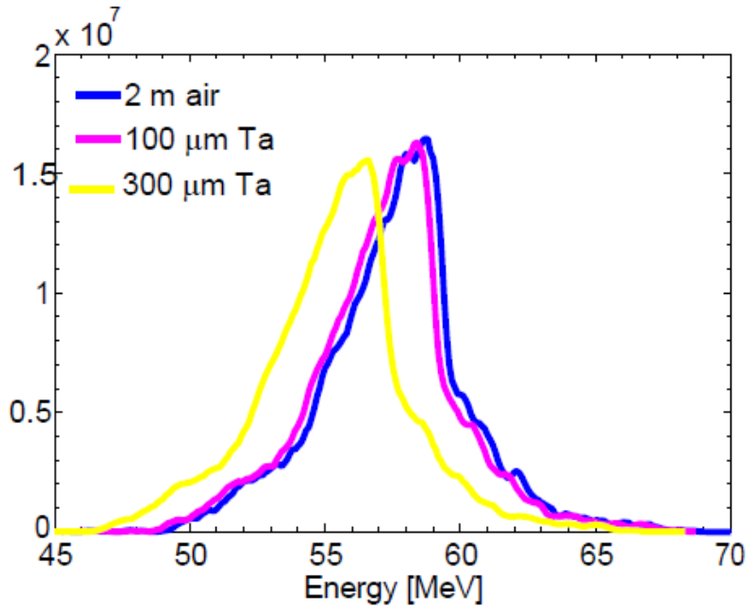


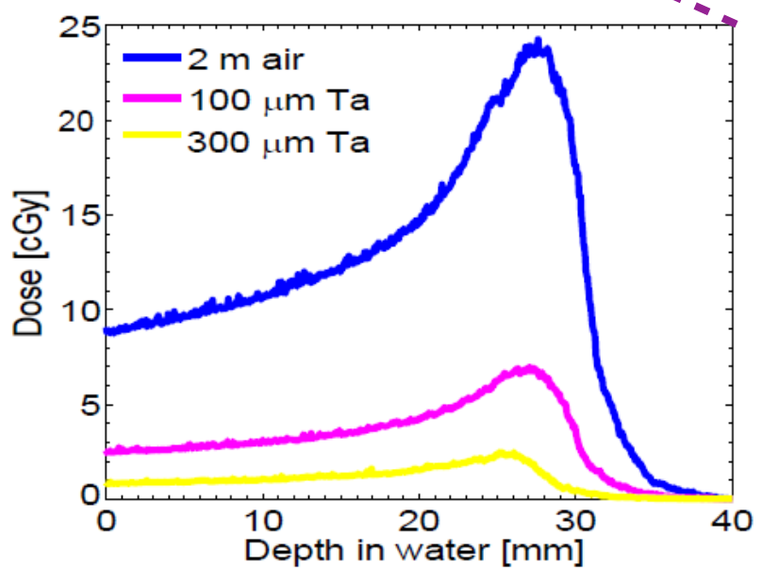


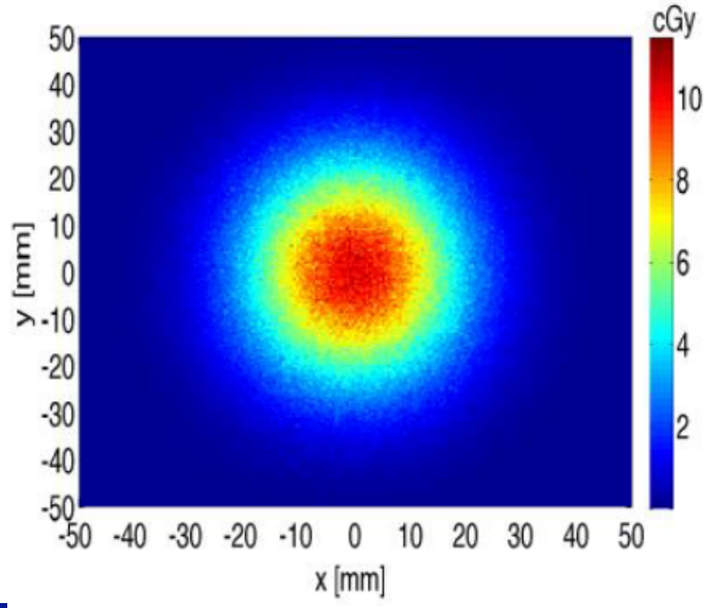
Optimization of transversal profiles for applications

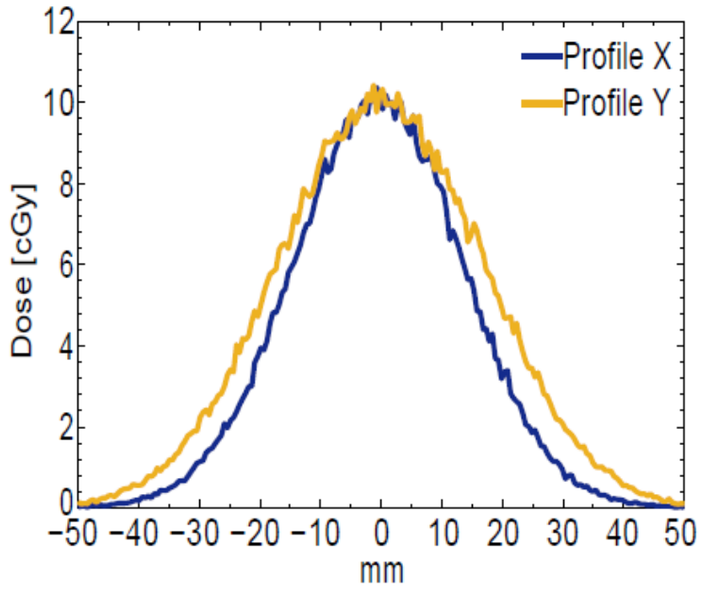












…in short

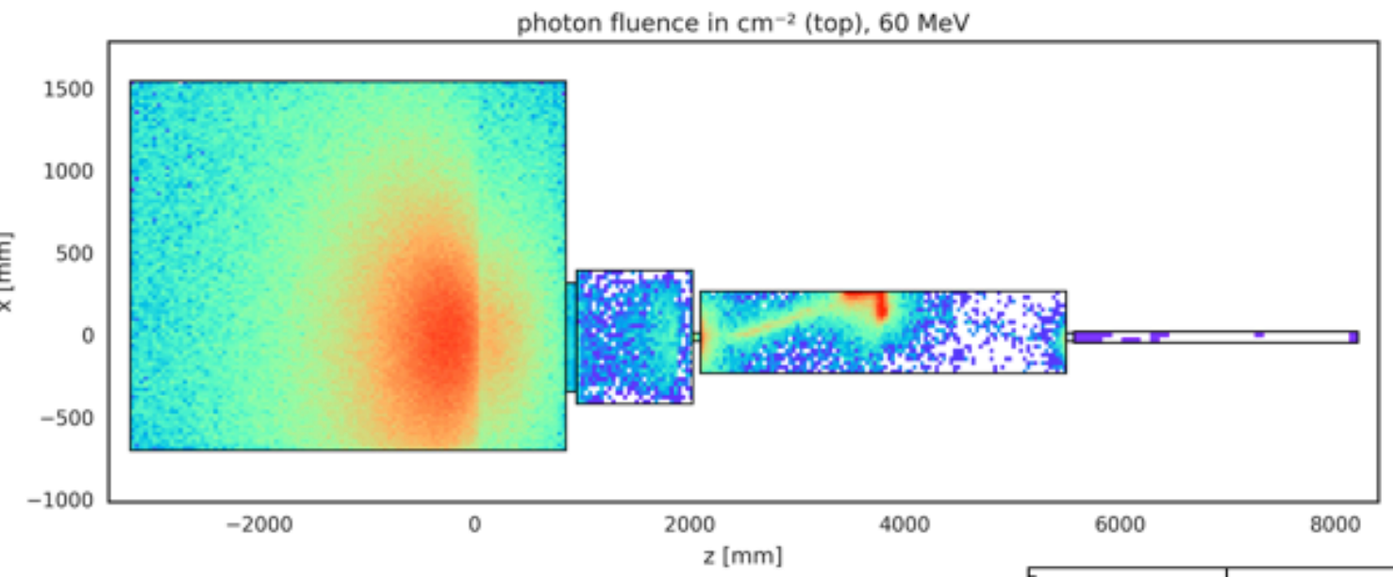
Laser-driven

Bucketful of particles!

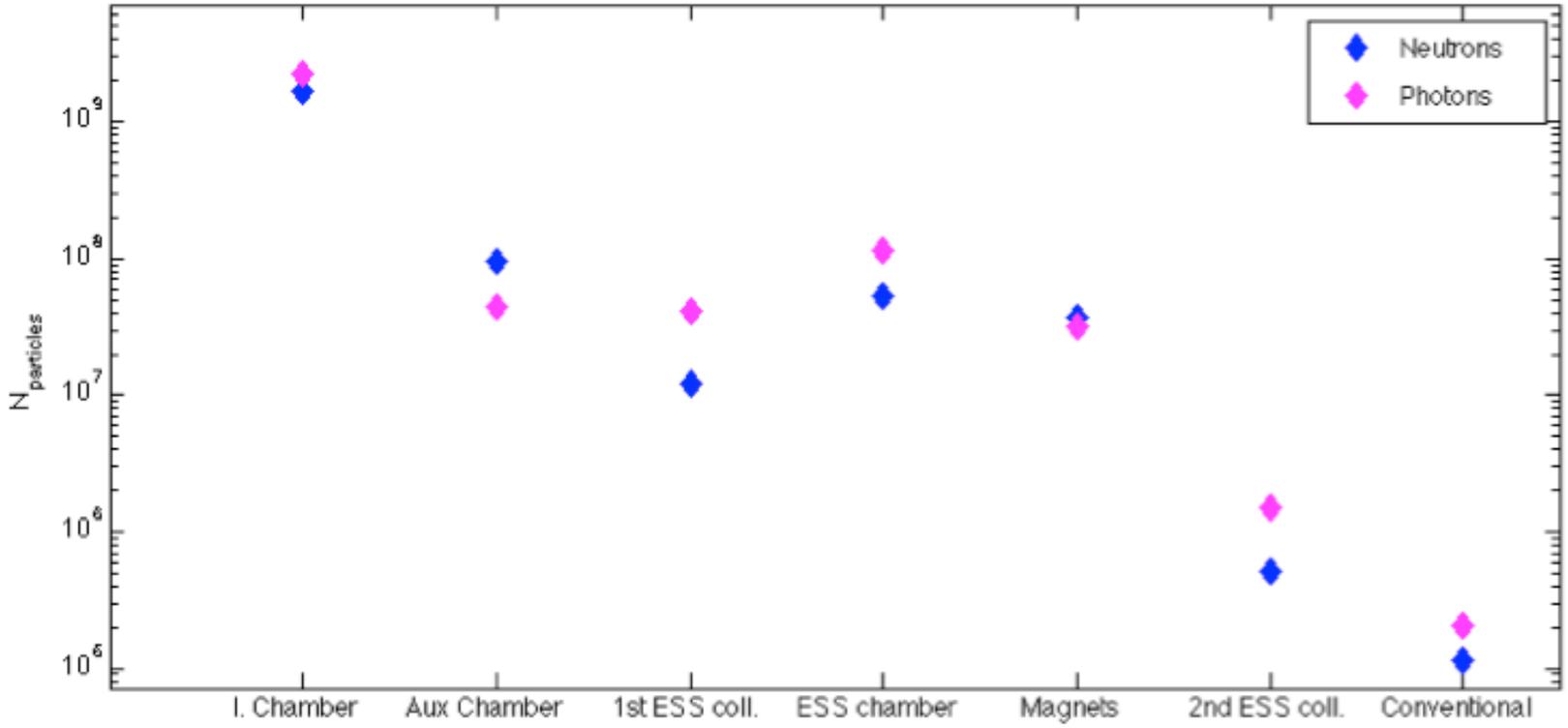
Conventional

Controlled beams

Secondary radiation: prompt radiation

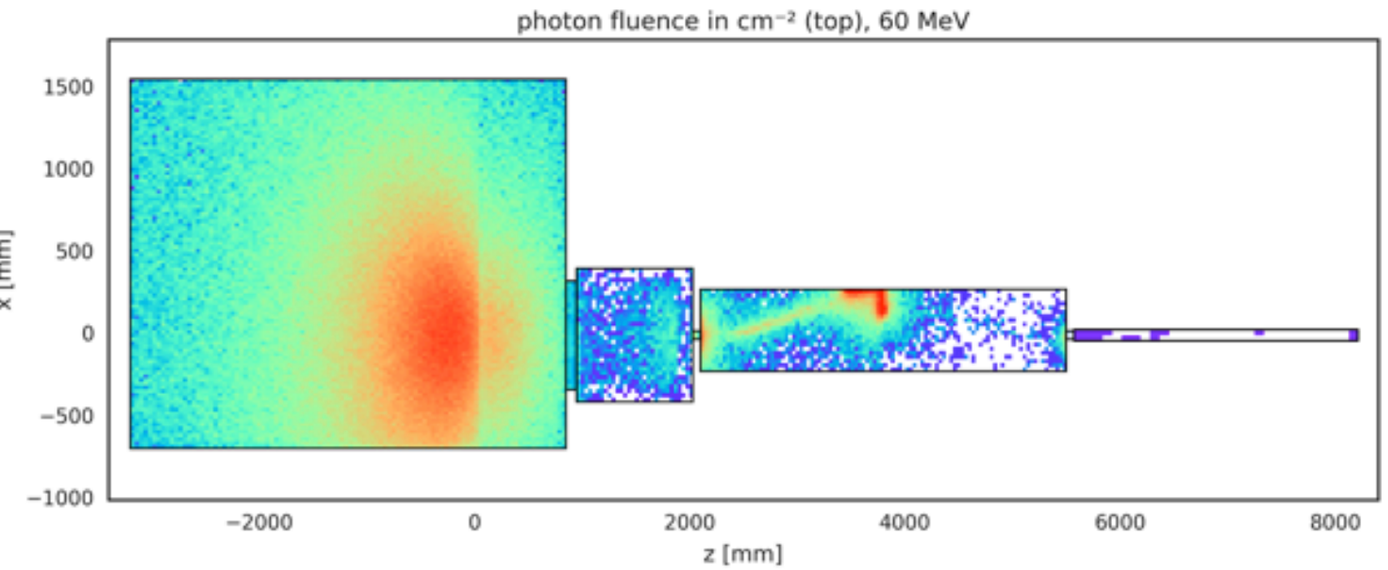


Fluence map of secondary prompt photons escaping from the beam line (top view) for 60 MeV p-configuration

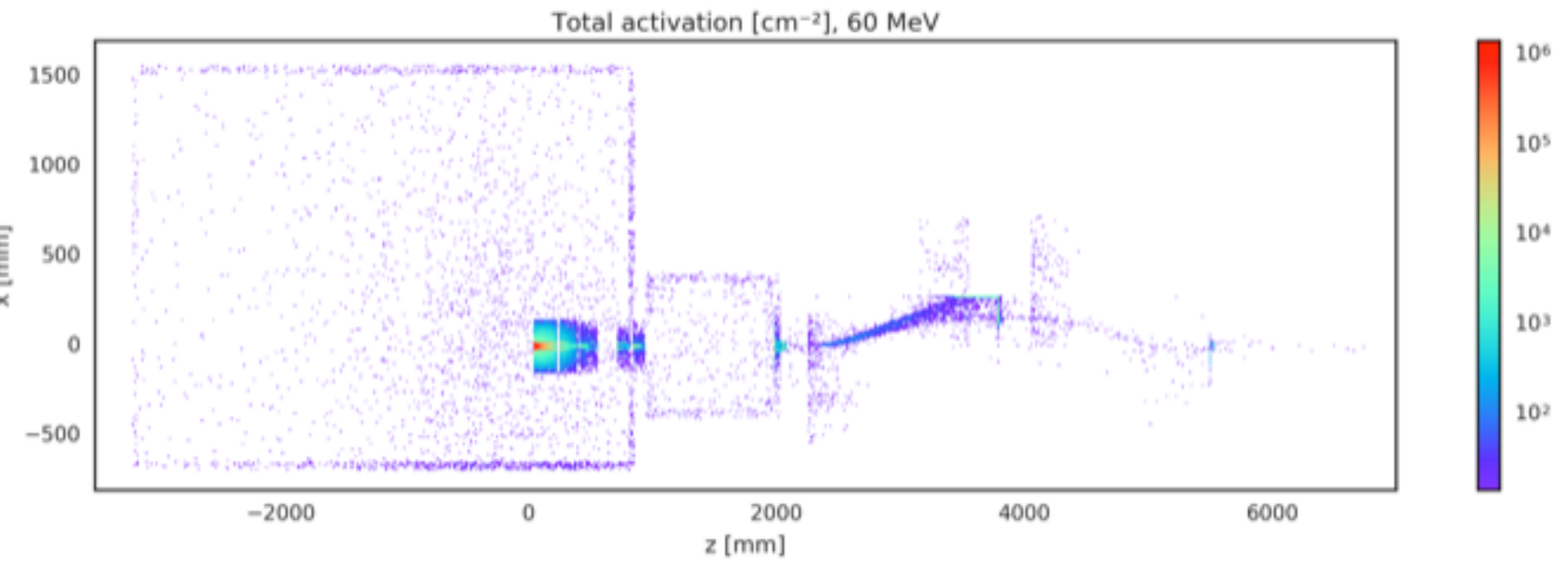


Total number of prompt neutrons and photons escaped from the different elements for 60 MeV p-configuration

Secondary radiation study

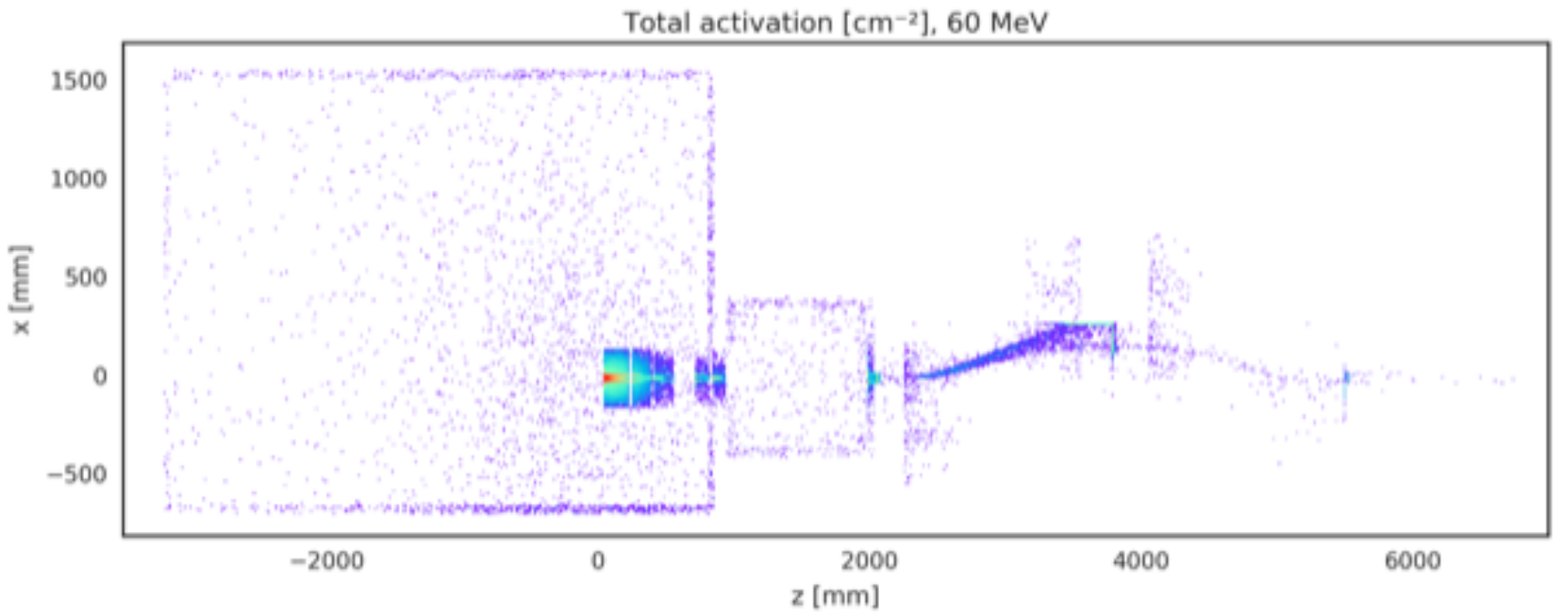


Fluence map of secondary prompt photons escaping from the beam line (top view) for 60 MeV p-configuration



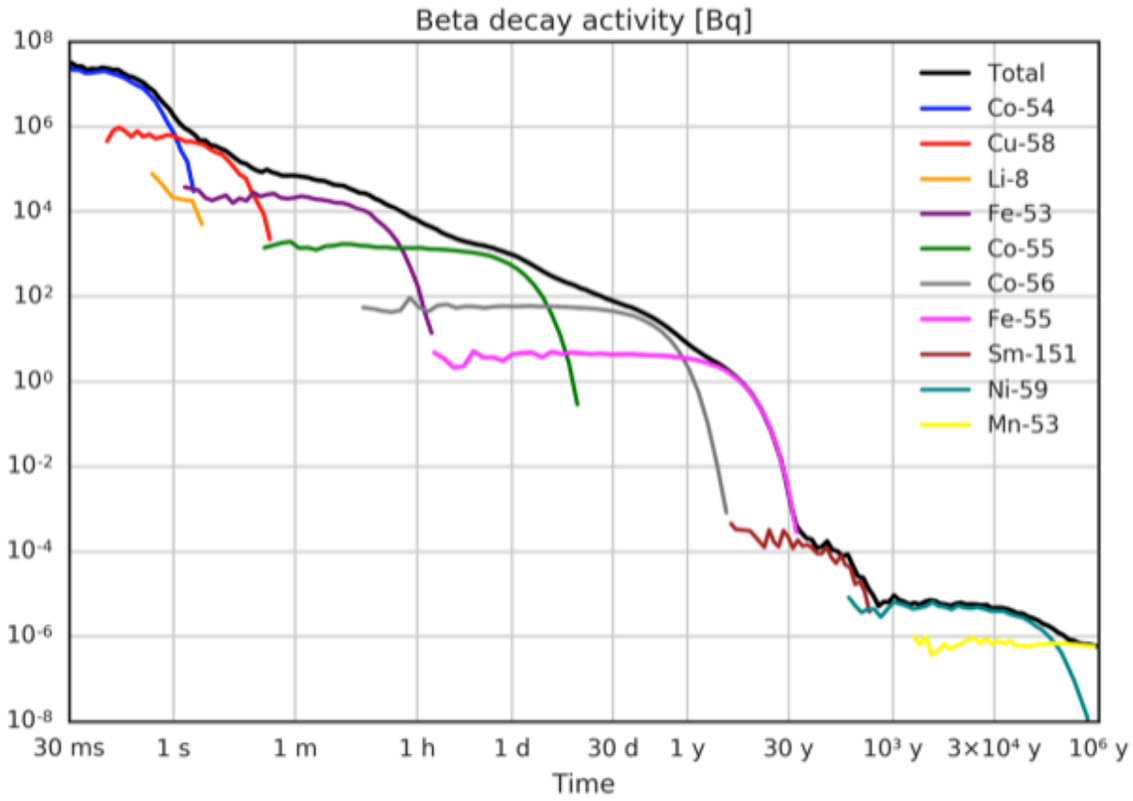
Distribution of activated nuclei projected into the horizontal plane (60-MeV proton configuration)

Activation



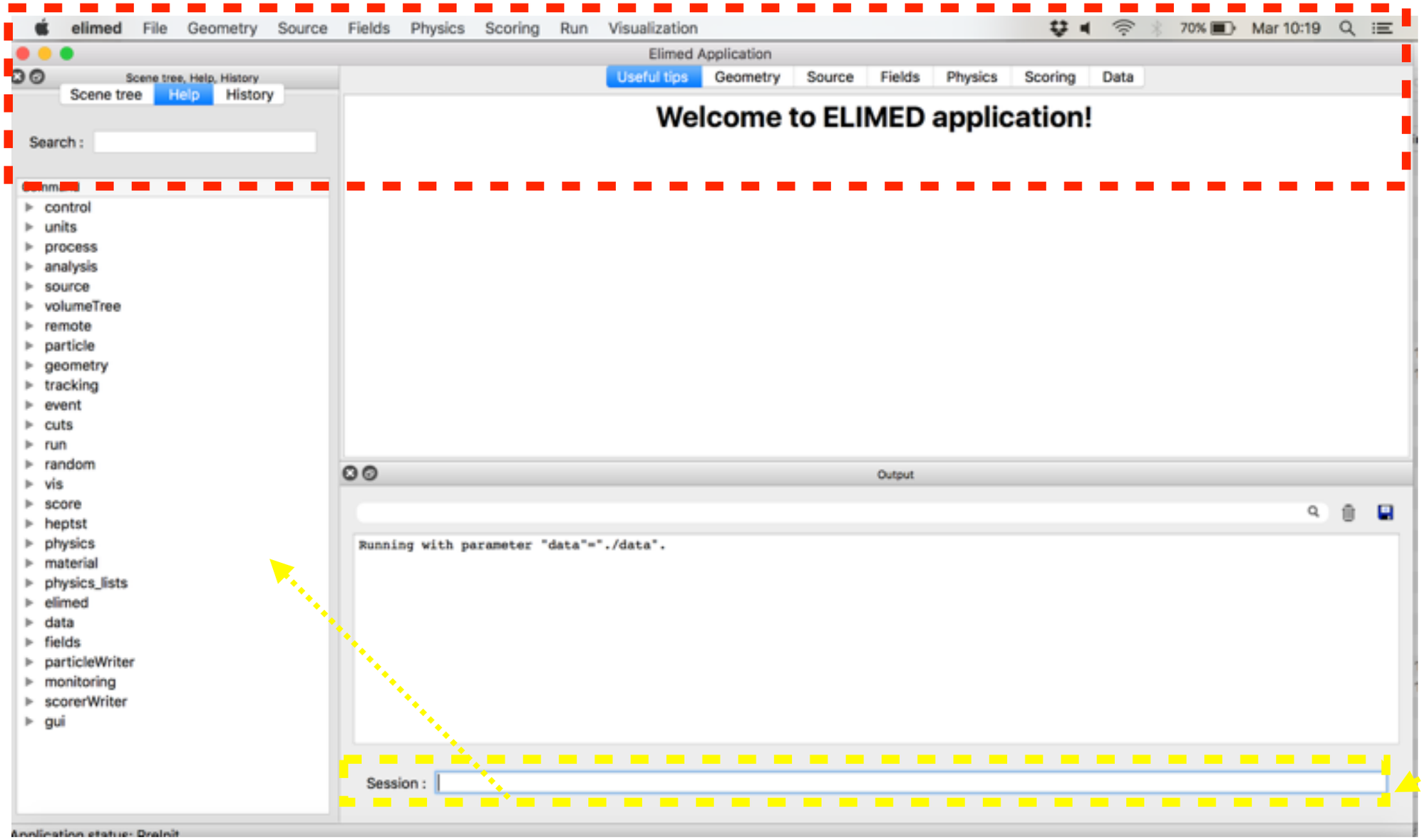
Distribution of activated nuclei projected into the horizontal plane (60-MeV proton configuration)

The total beta activity (including electron capture) of the beam-line elements as a function of time (60-MeV proton configuration).



User interface

* Qt interface for visualization and interactive simulation



* Batch mode

* Remote simulation using network performances

The ELIMED application

J. Pipek, F. Romano, G. Milluzzo et al.,, Journal of Instrumentation, Volume 12, March 2017

Geant 4

http://www.geant4.org

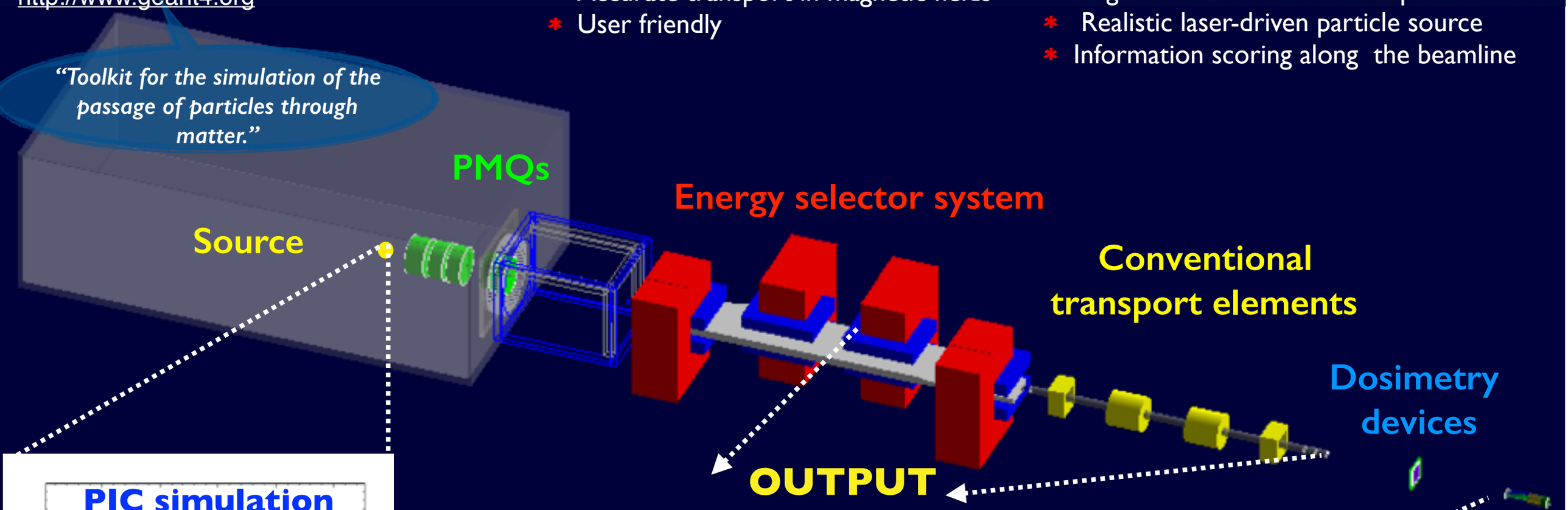
"Toolkit for the simulation of the passage of particles through matter."

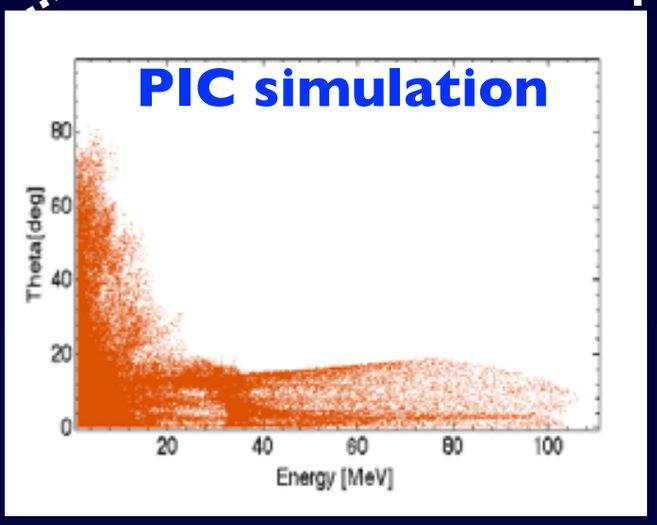
Requirements from ELI

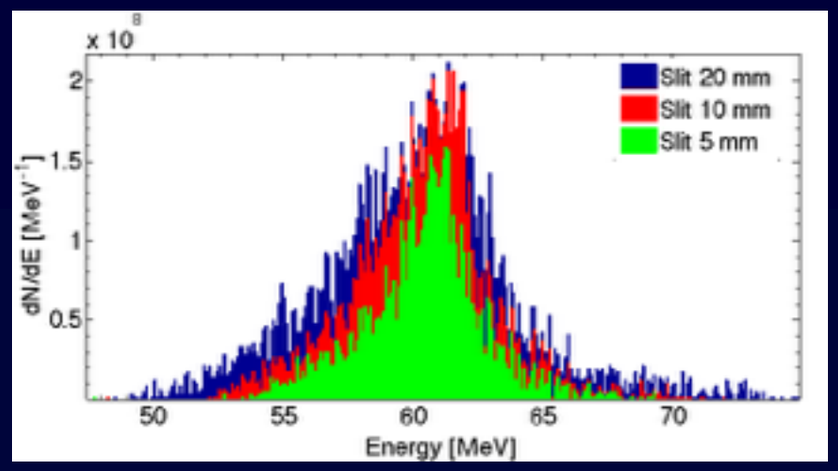
* Easily modify geometrical configurations
* Accurate transport in magnetic fields
* User friendly

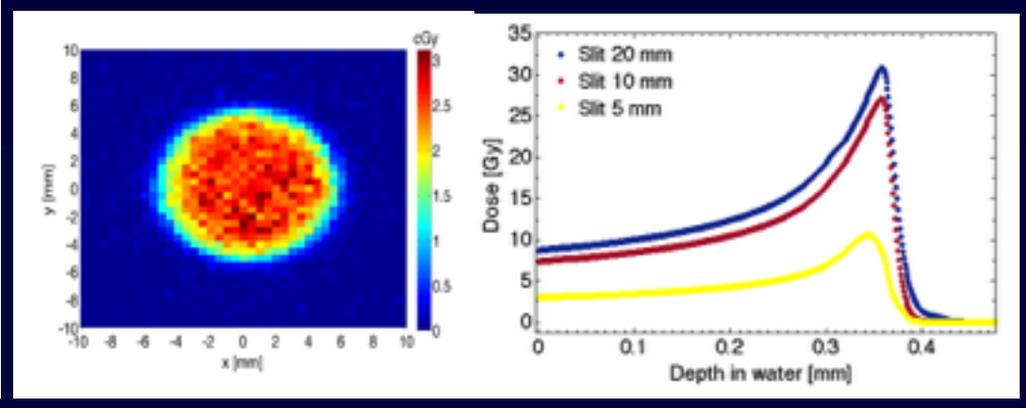
Application structure

* Component realistic model
* Magnetic and electric field implementation
* Realistic laser-driven particle source
* Information scoring along the beamline









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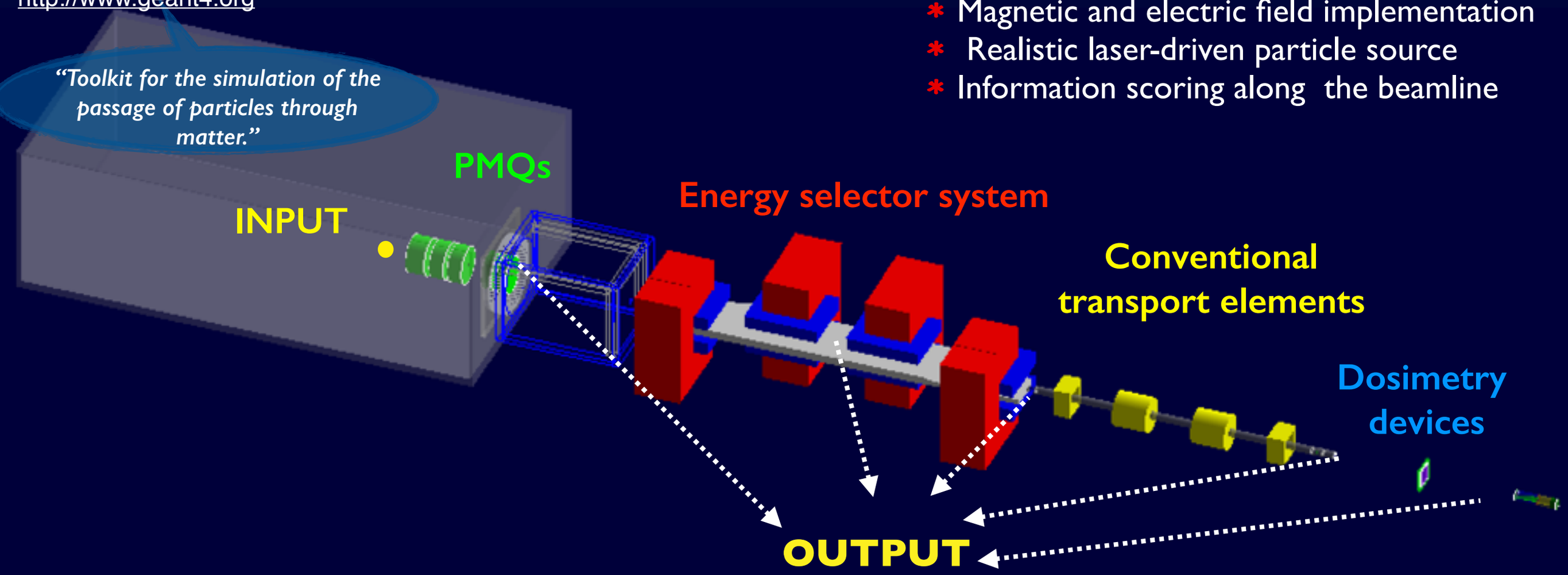

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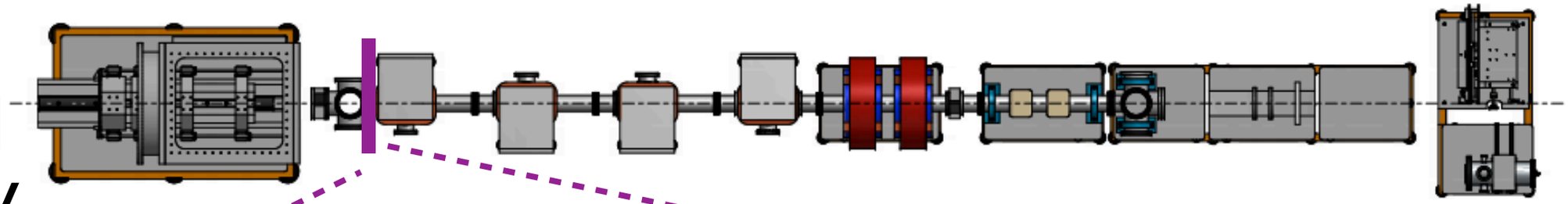
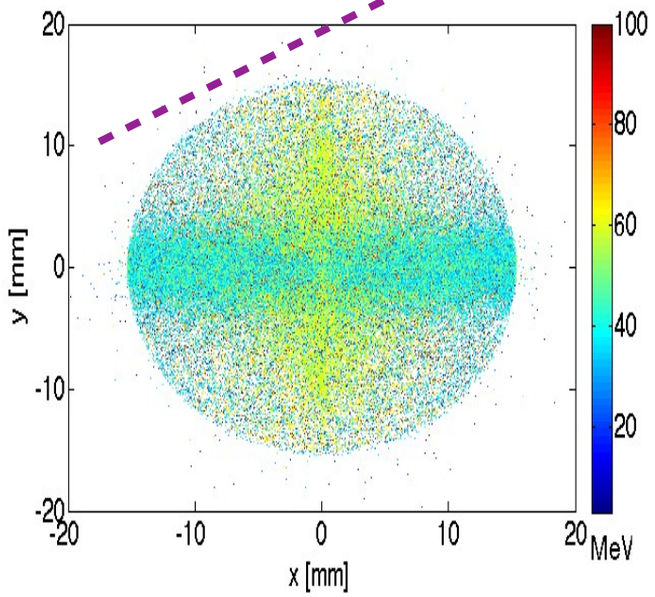
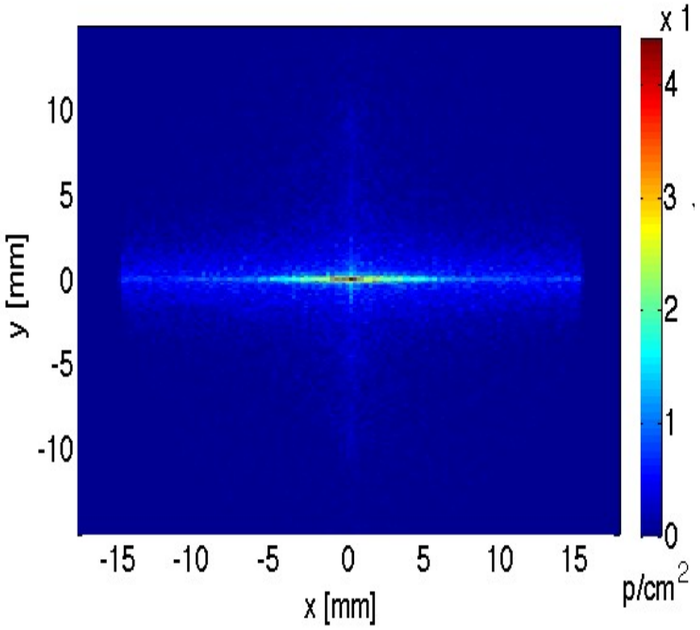
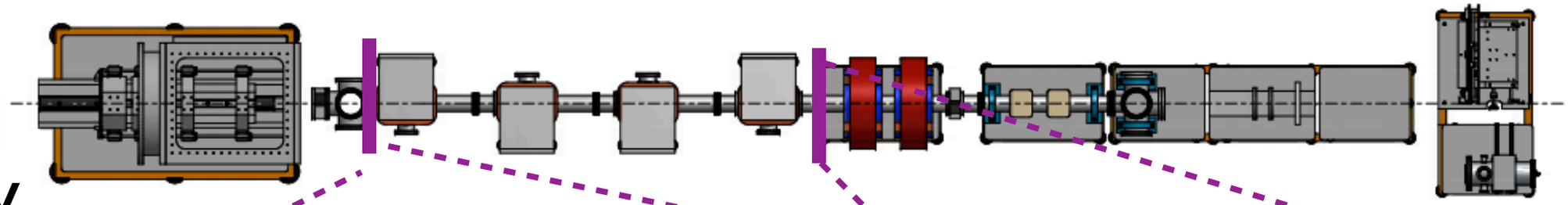
60 MeV

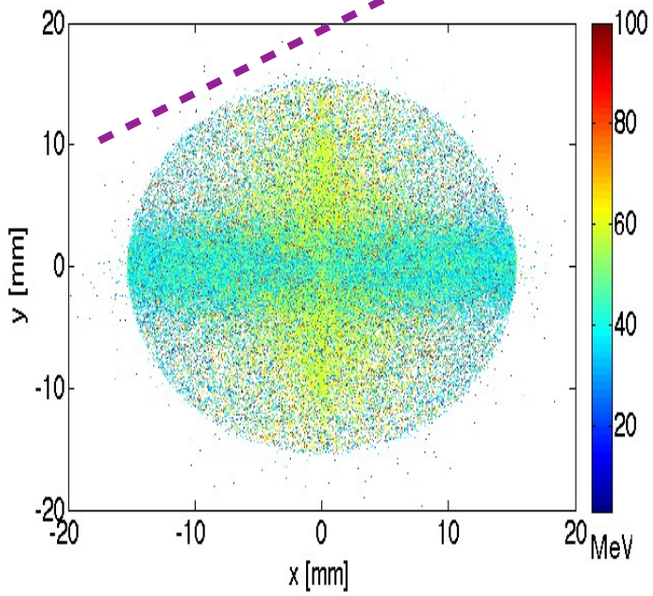


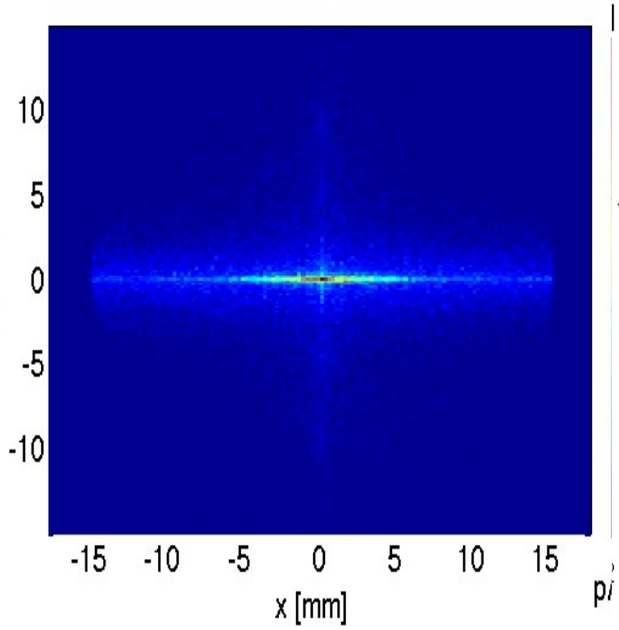

20
10
0
-10
-20
y [mm]
-20
-10
0
10
20
x [mm]
100
80
60
40
20
MeV

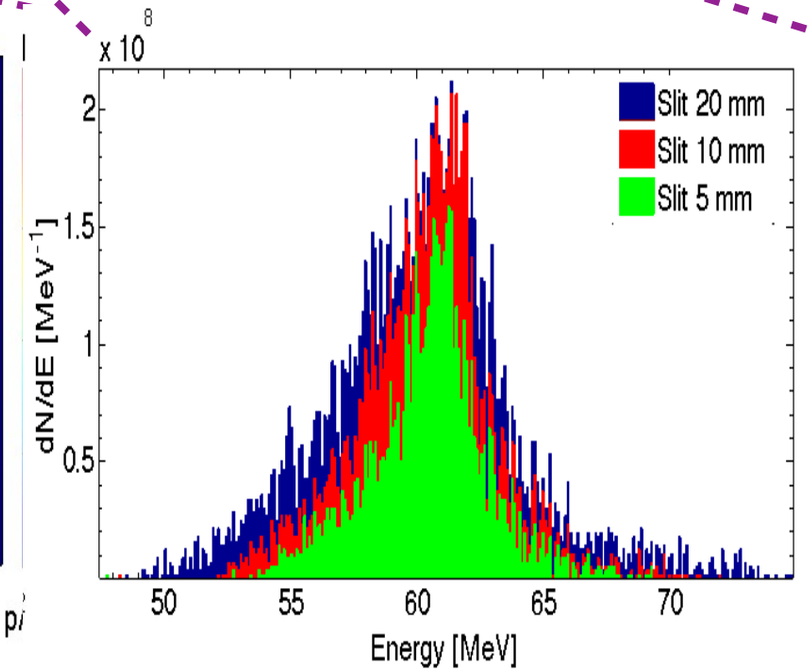

10
5
0
-5
-10
y [mm]
-15
-10
-5
0
5
10
15
x [mm]
x 1
4
3
2
1
0
p/cm^2

60 MeV

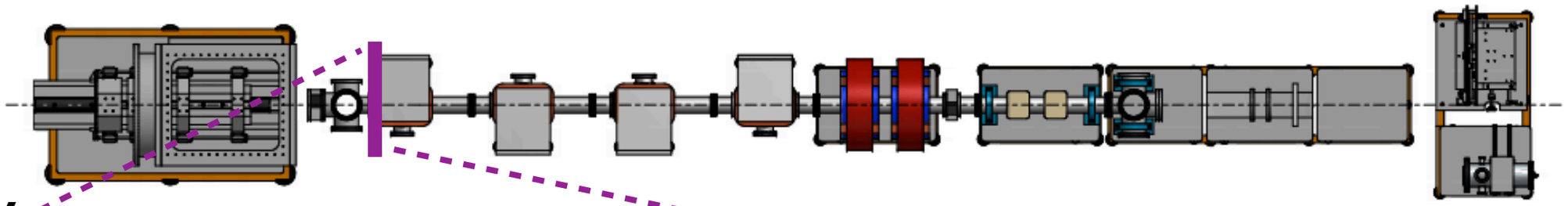




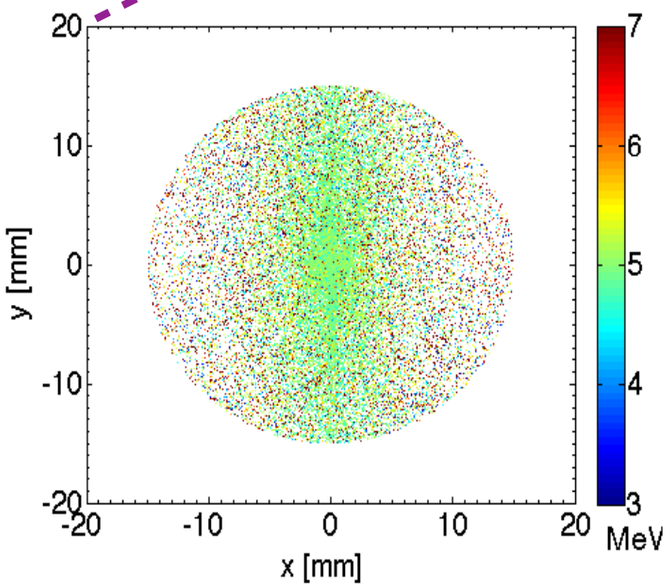


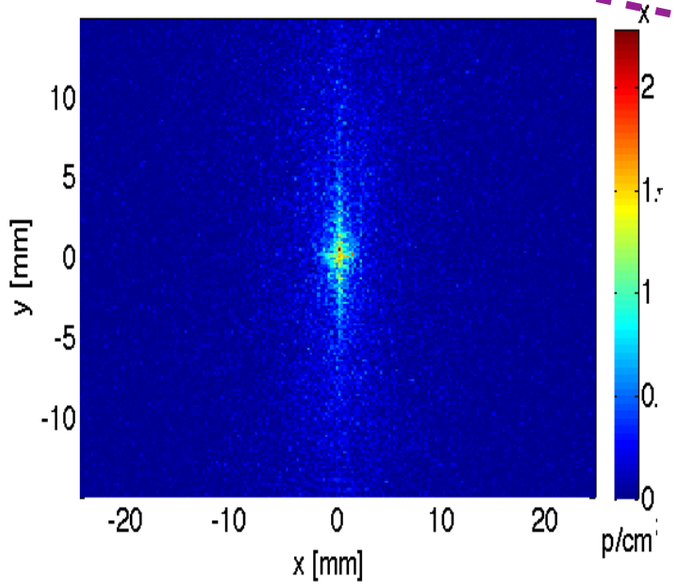


ΔE/E	Tr. Eff.
11%	9.9%
8%	8.0%
7%	4.9%

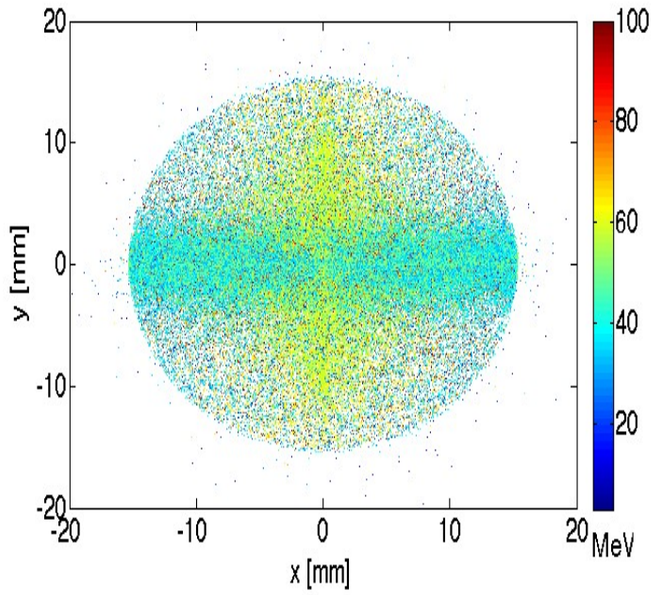


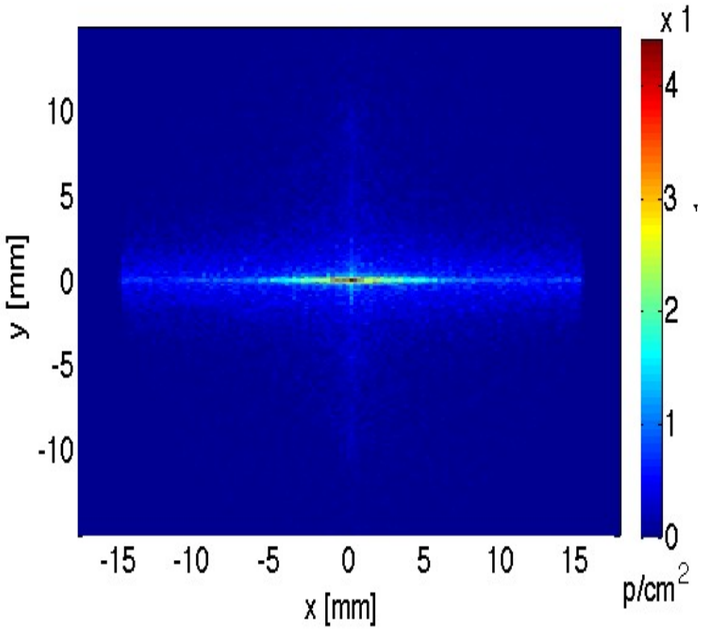
5 MeV

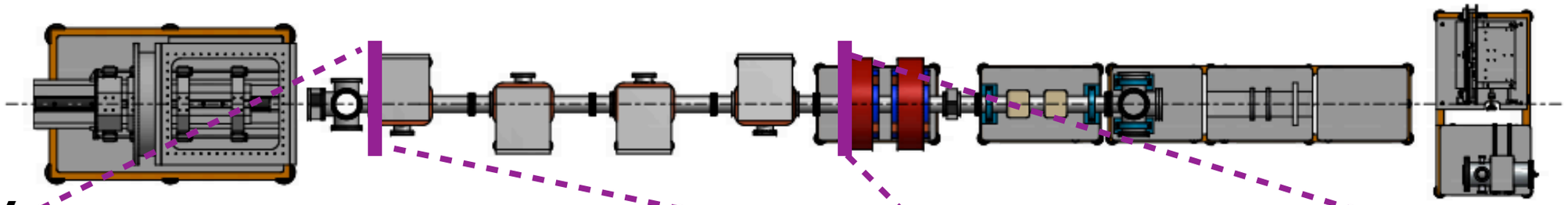




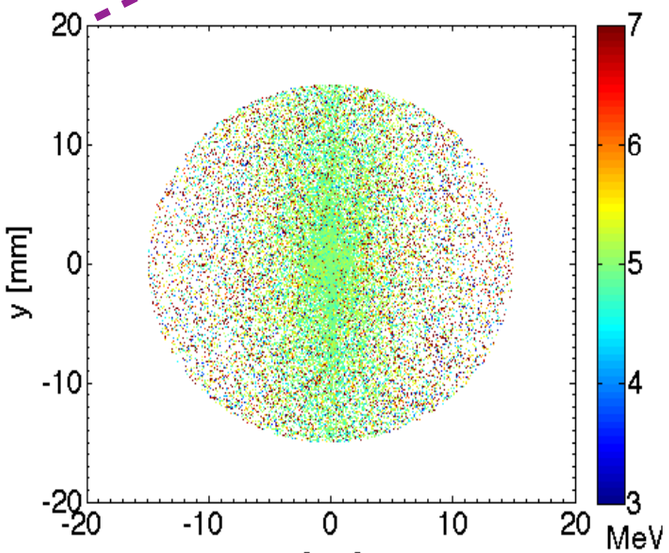
60 MeV

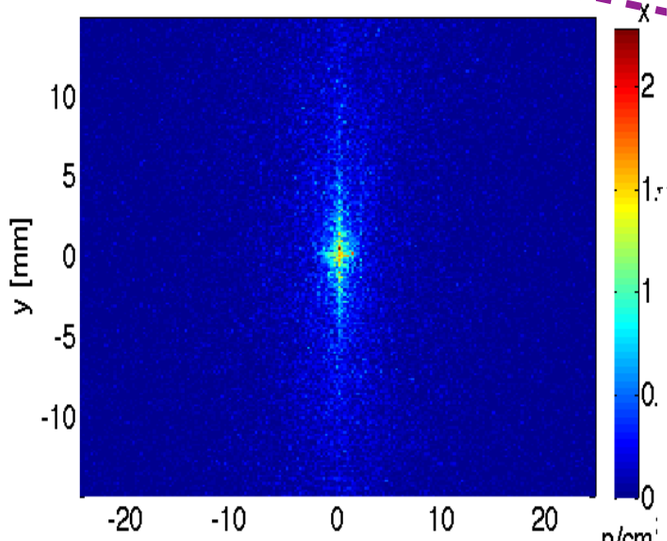


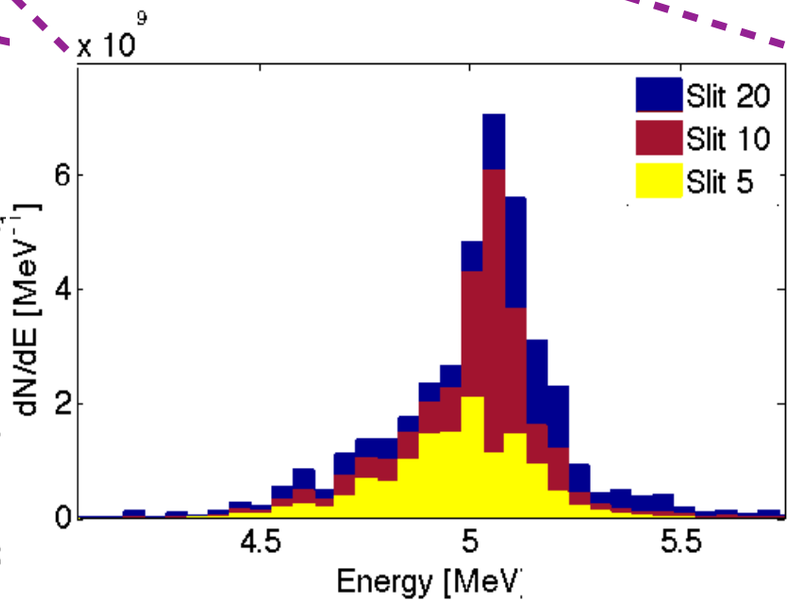




5 MeV

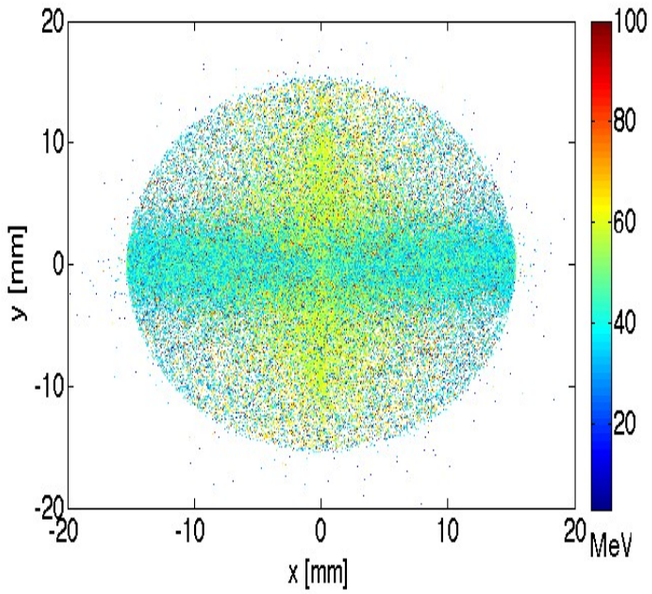


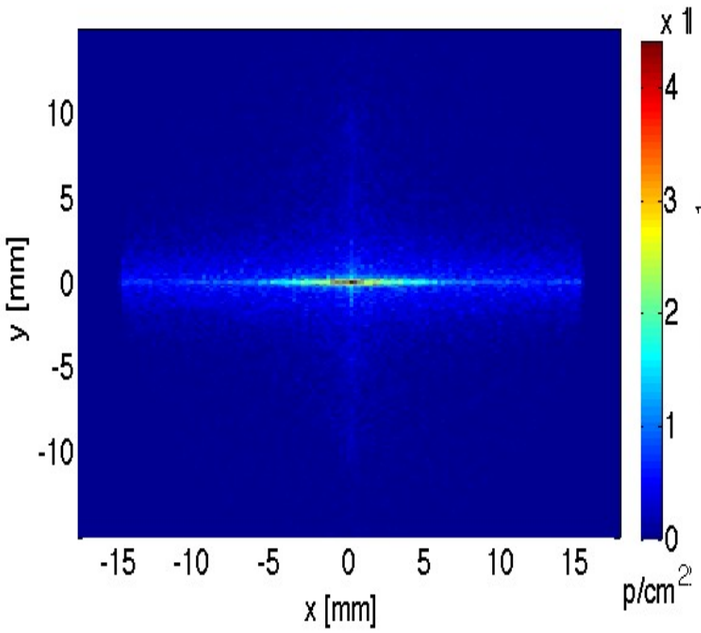


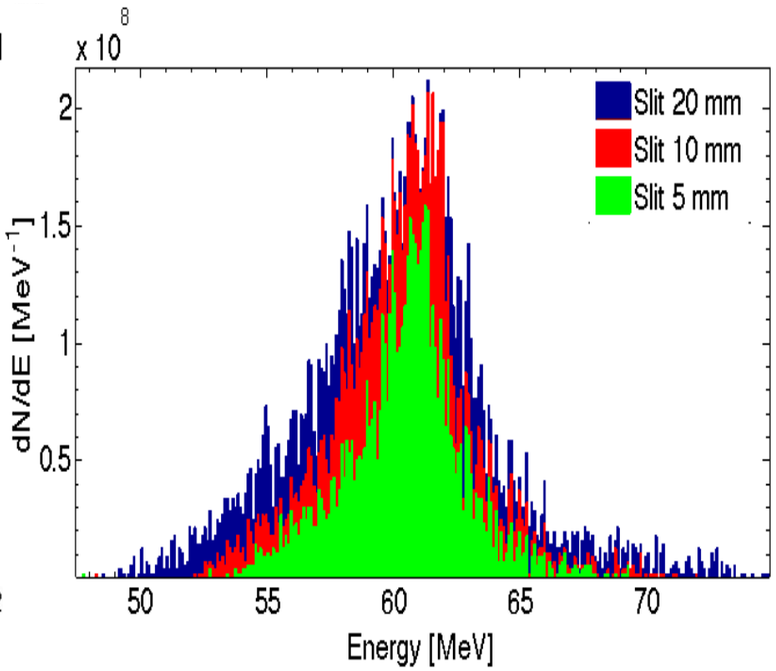


ΔE/E	Tr. Eff.
5.0%	5.9%
4.3%	4.5%
6.6%	2.1%

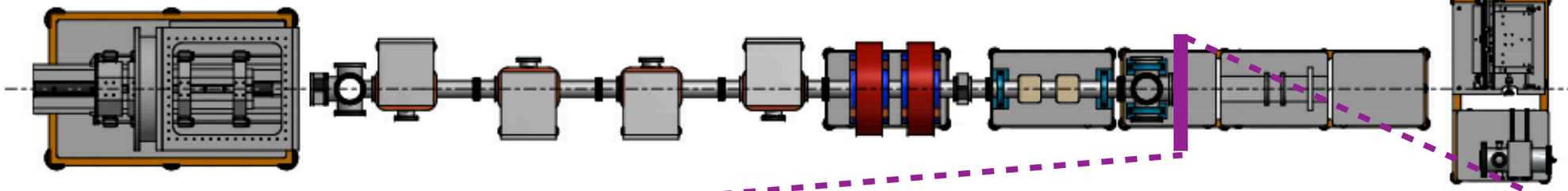
60 MeV



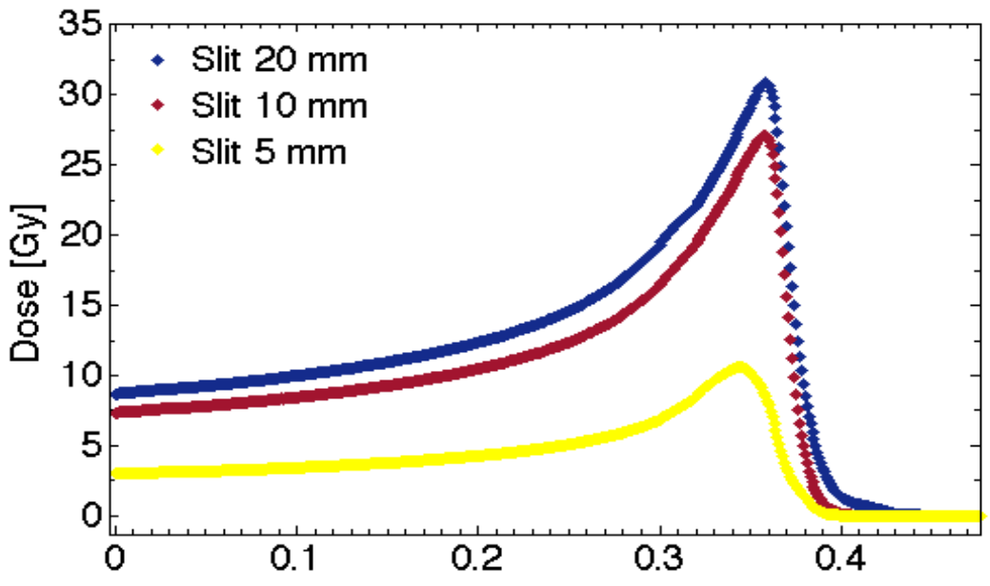


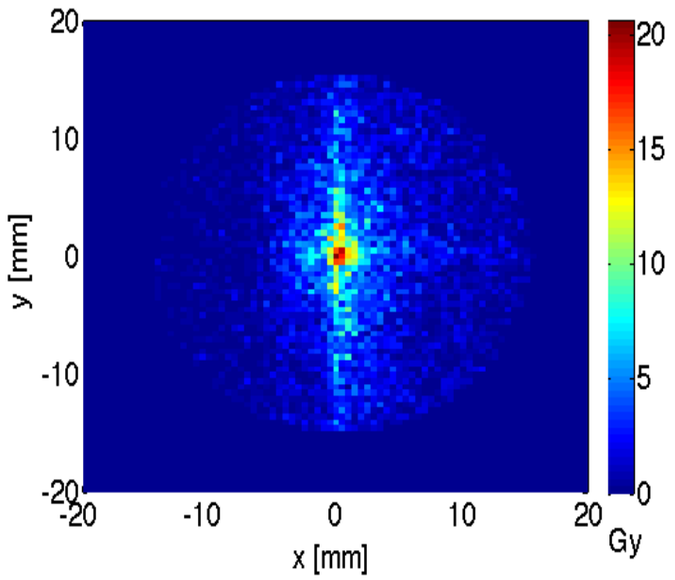


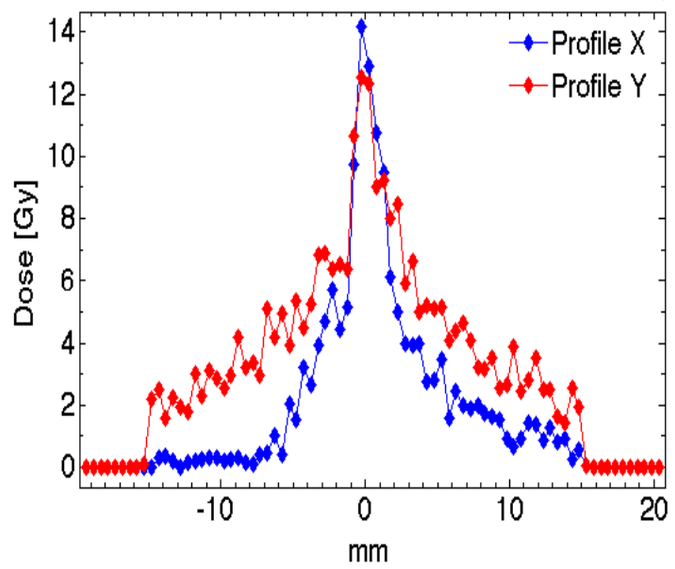
ΔE/E	Tr. Eff.
11%	9.9%
8%	8.0%
7%	4.9%



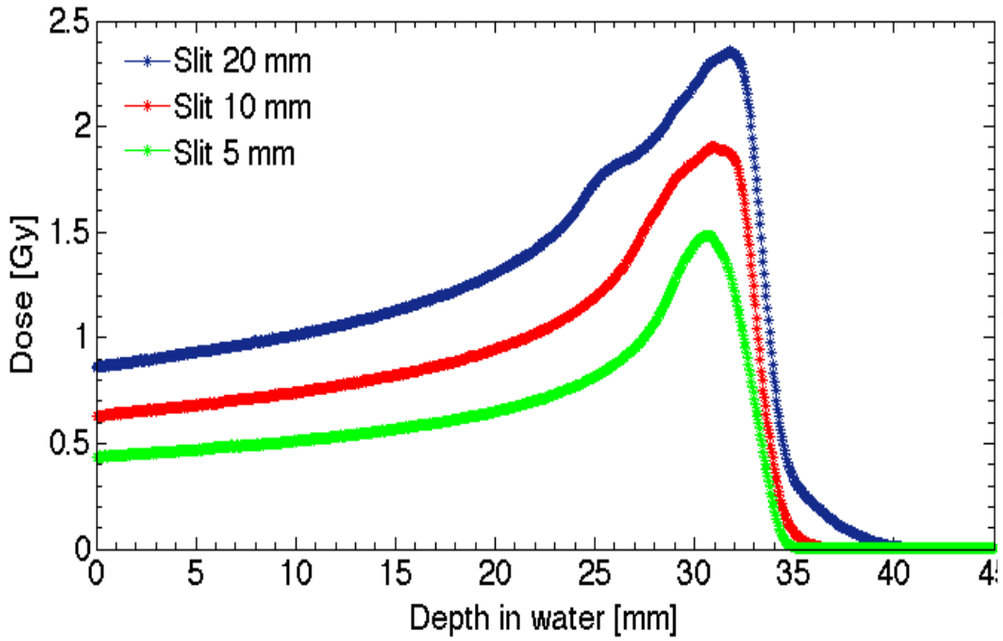
5 MeV

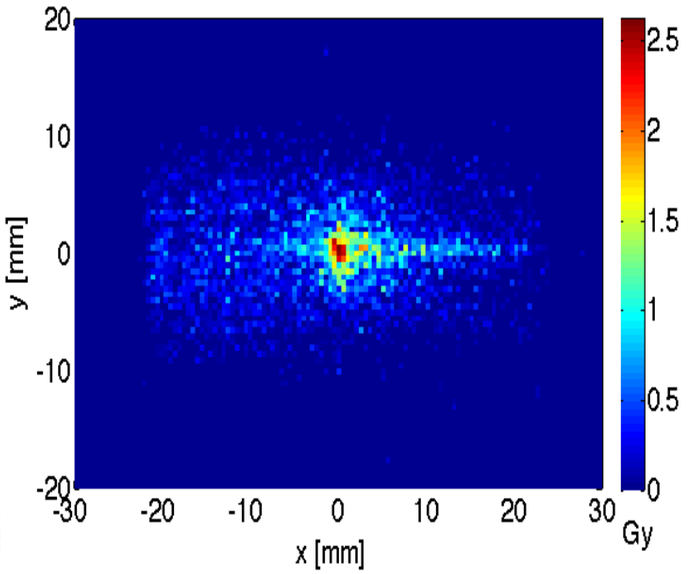

Slit 20 mm
Slit 10 mm
Slit 5 mm
Dose [Gy]
Depth in water [mm]

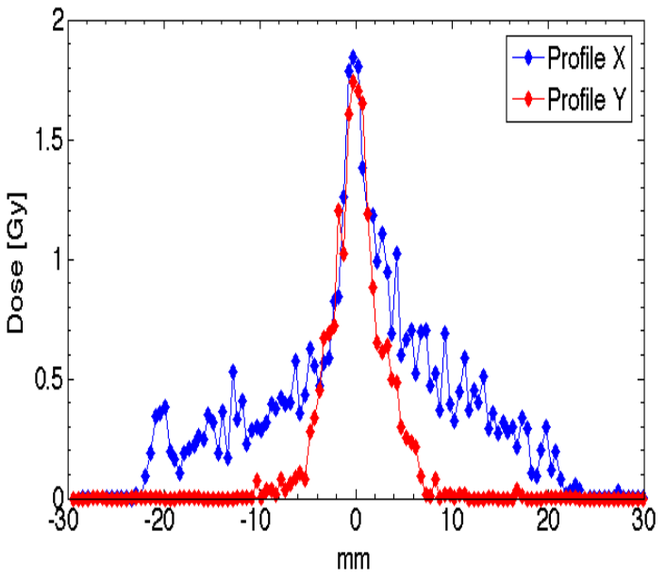

y [mm]
x [mm]
Gy


Profile X
Profile Y
Dose [Gy]
mm

60 MeV


Slit 20 mm
Slit 10 mm
Slit 5 mm
Dose [Gy]
Depth in water [mm]


y [mm]
x [mm]
Gy


Profile X
Profile Y
Dose [Gy]
mm