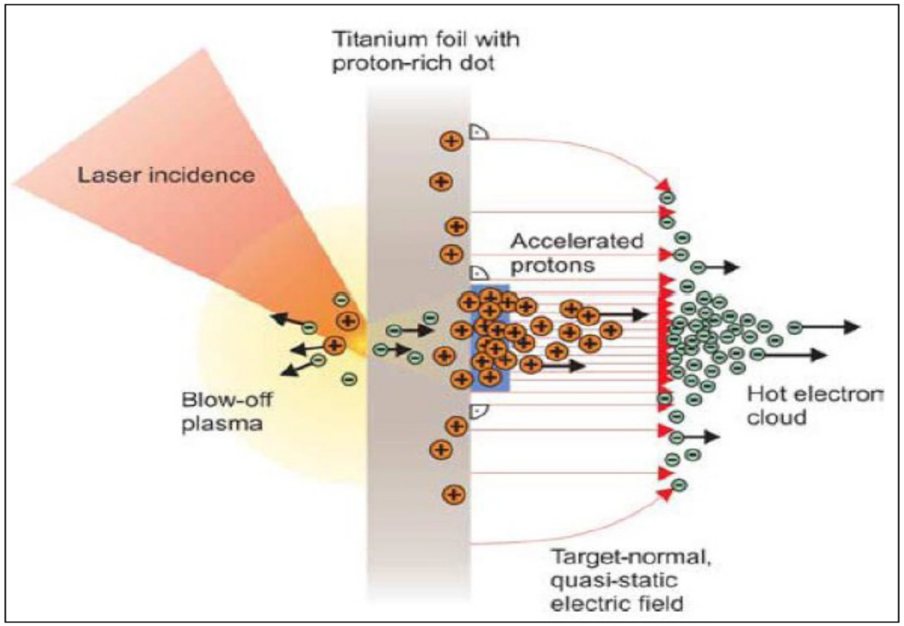
Design of the ELIMED in-vacuum transport beam-line

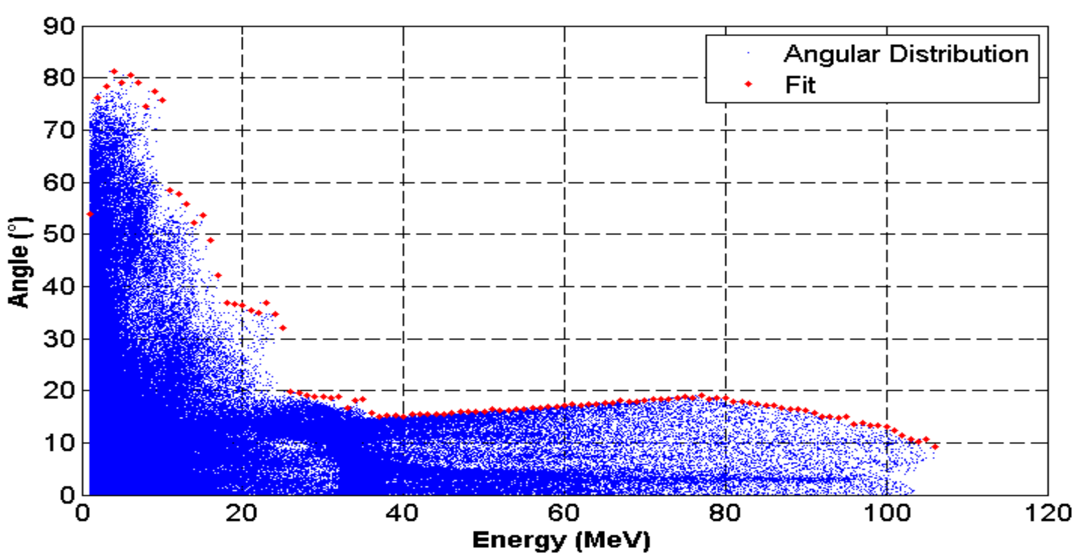
F. Schillaci

on behalf of the INFN-LNS (IT) and ELI-Beamlines (CZ) collaboration

Laser driven ions

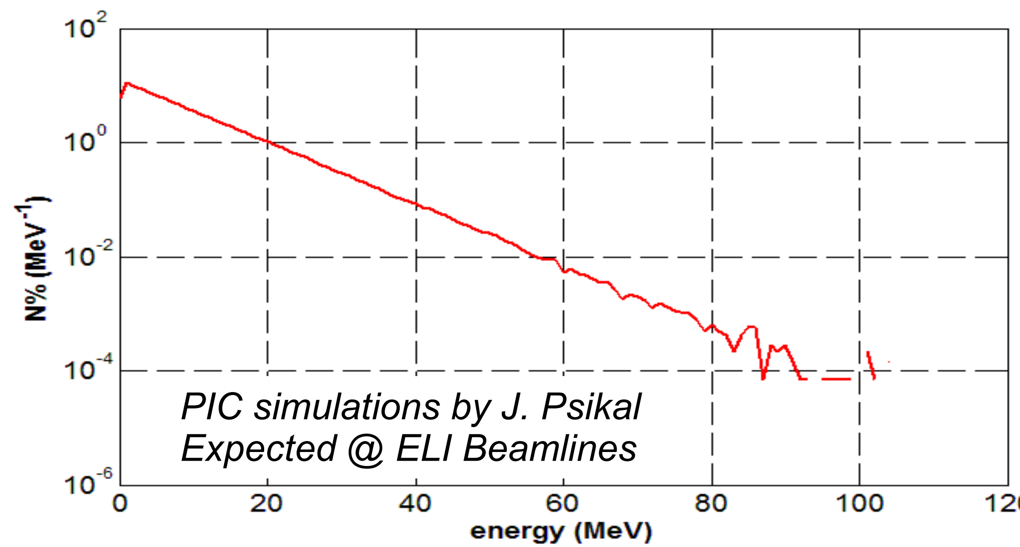
INFN LNS





TNSA regime:

- Large accelerating field (GV/m)
- High flux 10^{11} particles/bunch
- High dose-rate per bunch: ~ 10^{9} Gy/sec
  (~ 10 Gy/sec for conventional accelerators)



Challenges:

- Decreasing exponential energy distribution
  - 100% energetic spread
- Maximum energy record ~58 MeV protons
  - Big angular spread (~35°)
- Acceleration of several ion species

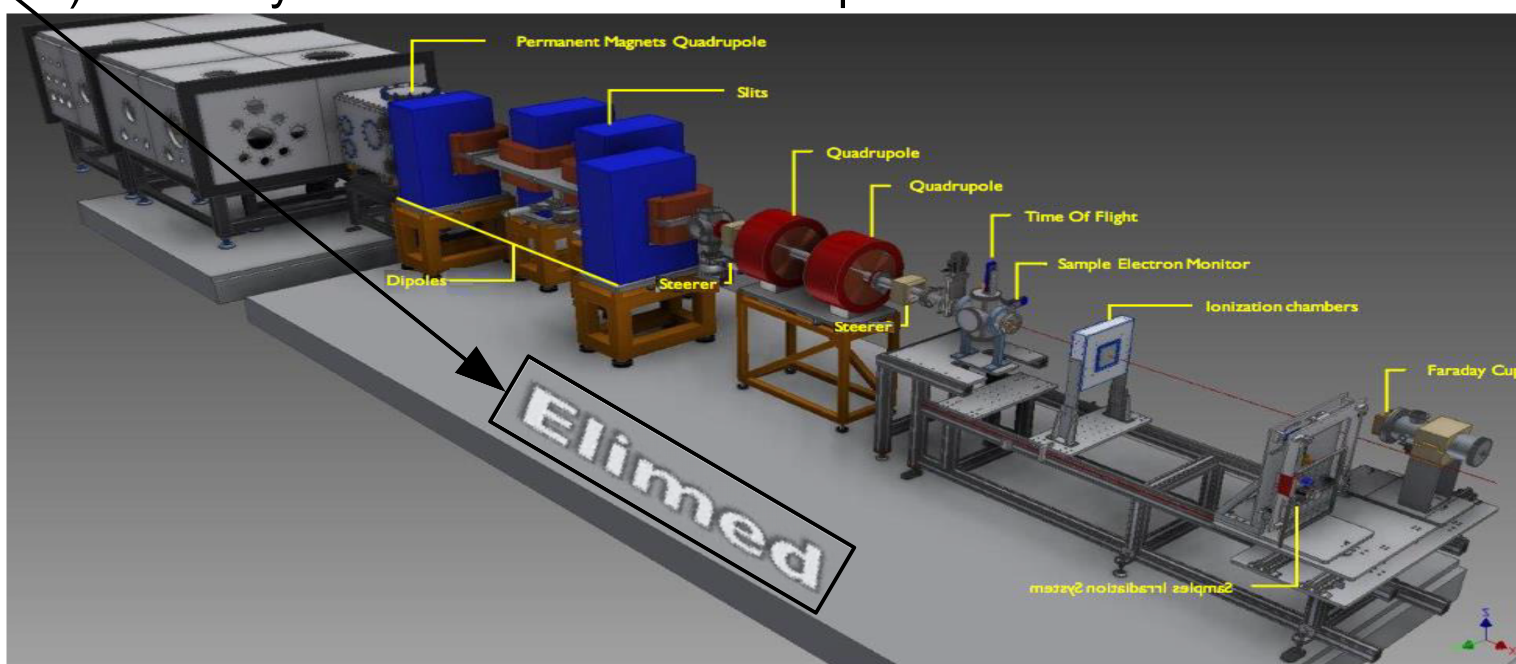
Laser driven ions

ELIMAIA & ELIMED

In-air beam line for dosimetry and radiobiology

Beam line elements:
1) Collection system
2) Selection system
3) Standard transport elements (quadrupoles and steerers)
4) in air dosimetry and irradiation

Beam line features:
1) Tunability (deliver ion beams from 5 up to 60 MeV/u) with a controllable energy spread (5% up to 20%) and 10^6-10^{11} ions/pulse
2) Large acceptance
3) Flexibility to meet different User requirements



Outline

- Design of the ELIMAIA Collection System
- Design of the ELIMAIA Selection System
- Additional transport elements
- Beam transport simulations

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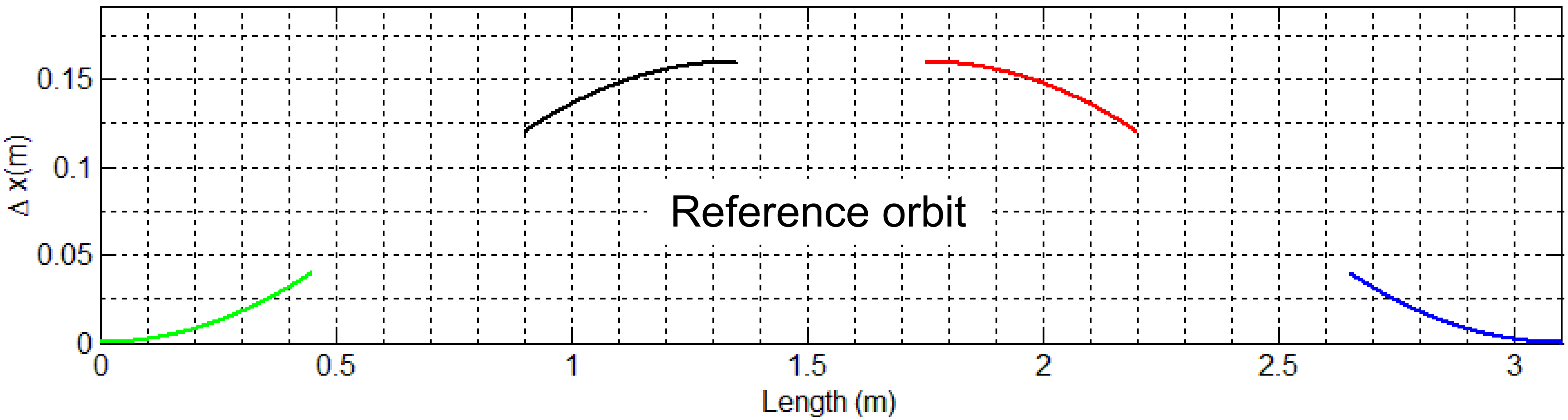
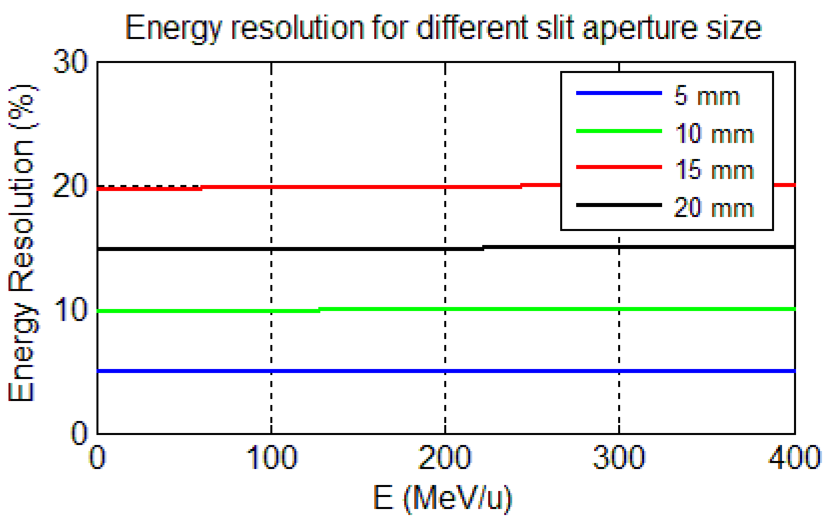
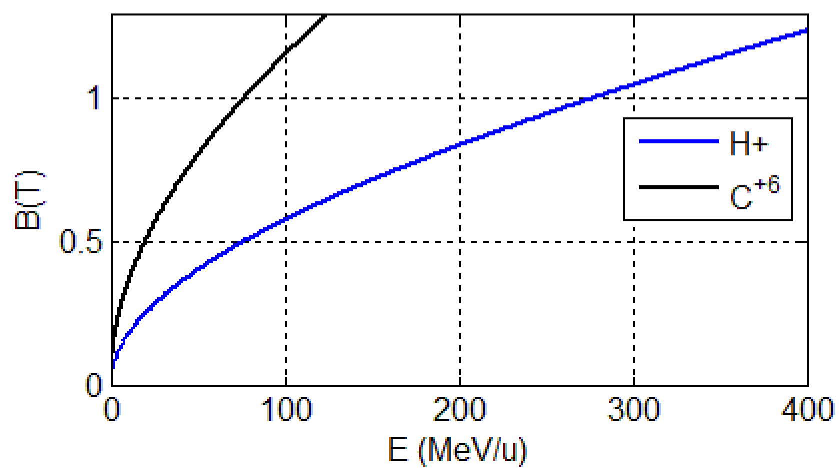
Energy selector
Reference orbit and layout

ESS Features





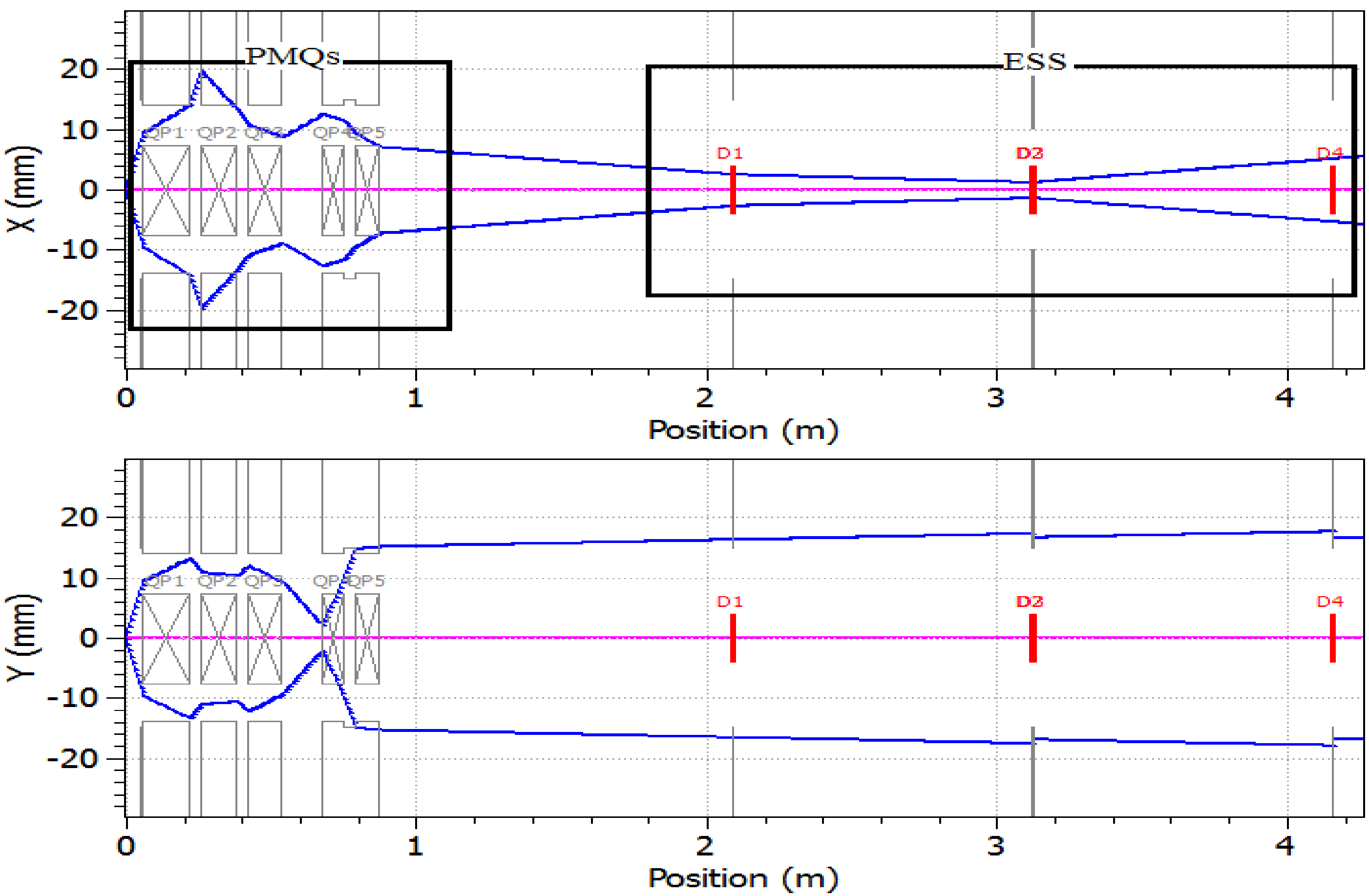


Magnetic chicane based on a bunch compressor scheme
Path length: 3,168m
Two collimators φ = 30 mm, selection slit s x 40 mm.

Collection and Selection systems matching conditions

Linearised chicane to define the PMQs set up according the (general) matching conditions:

1) Waist close to the slit on the radial direction $M_{12}=0$
2) Parallel beam on the transverse plane $M_{44}=0$
3) Transmission efficiency of 10% is ensured



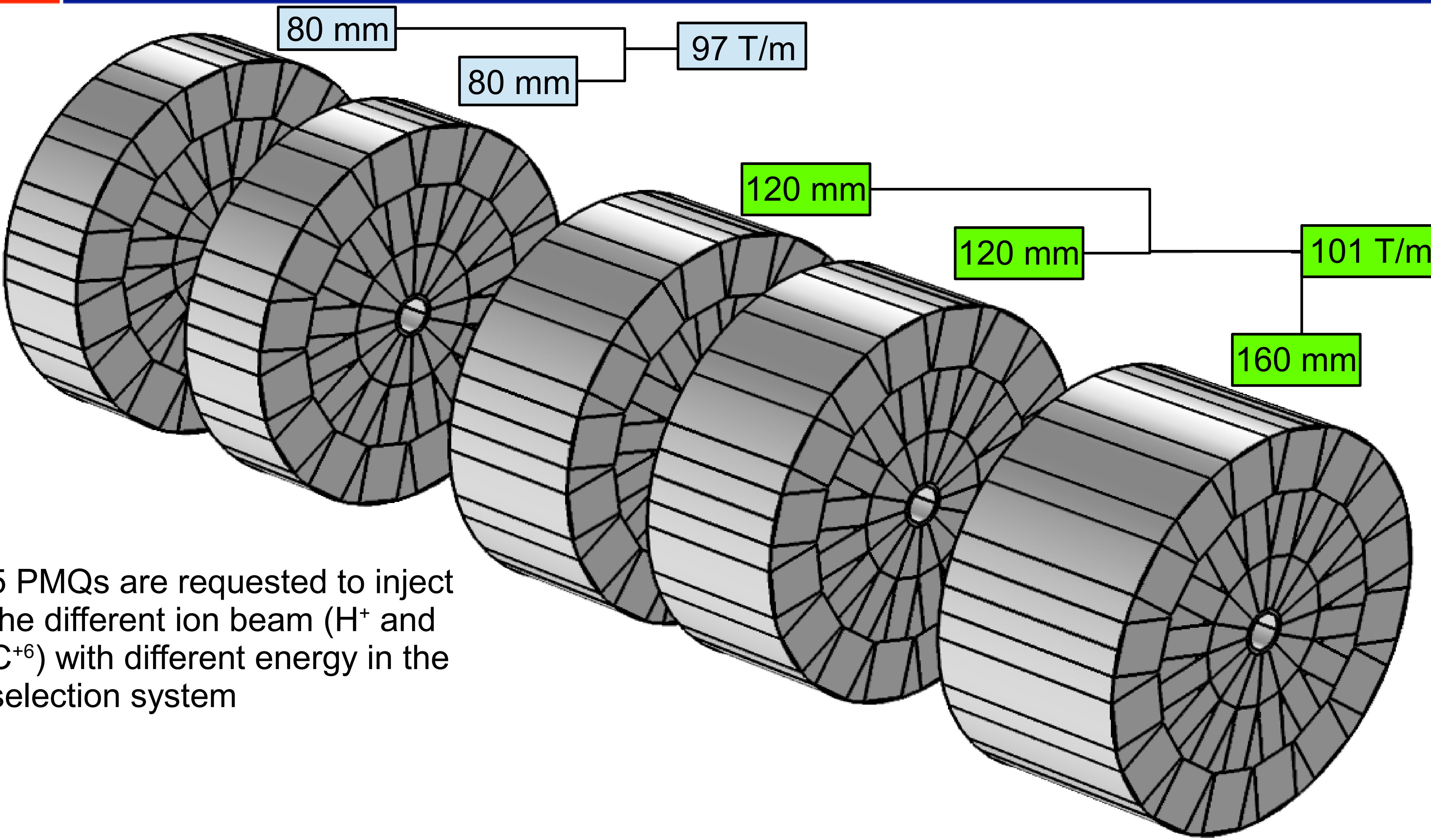
Input Beam:

- 60 MeV
- ±10° uniform angular spread
- ~40 μm diameter

Constraints:

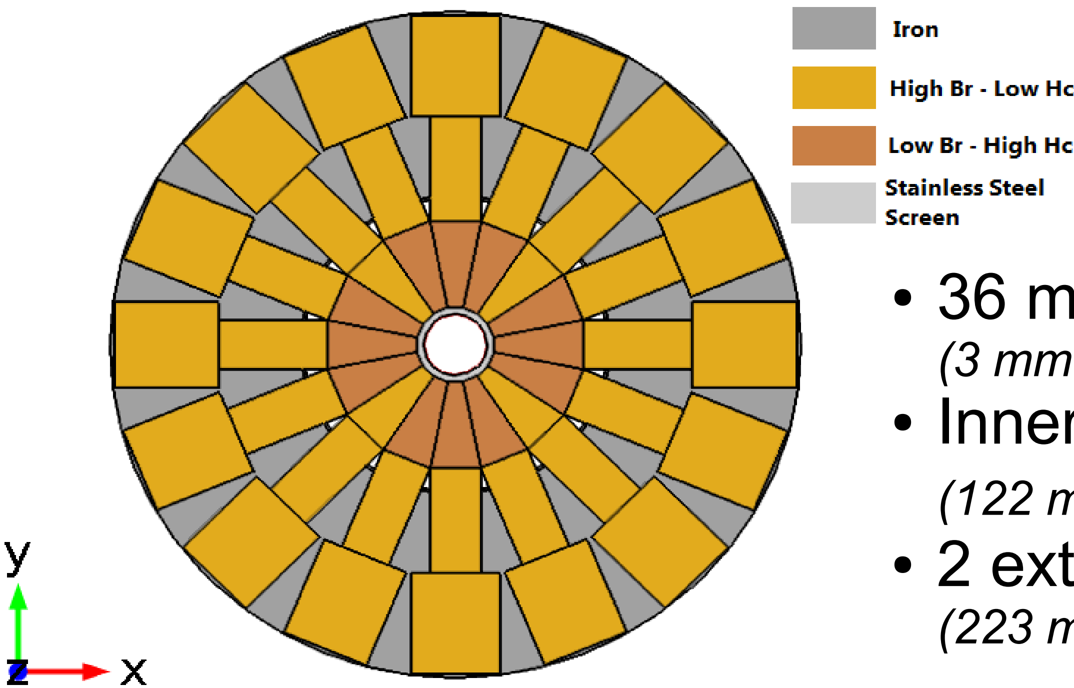
- Target-Quad1 minimum distance: 50 mm
- Minimum distance between Quads: 40 mm
- Target-ESS distance 2.05 m

Collection system



5 PMQs are requested to inject the different ion beam (H^+ and C^{+6}) with different energy in the selection system

Permanent Magnet Quads Preliminary Layout



F. Schillaci et al., JINST 10 T12001 (2015)

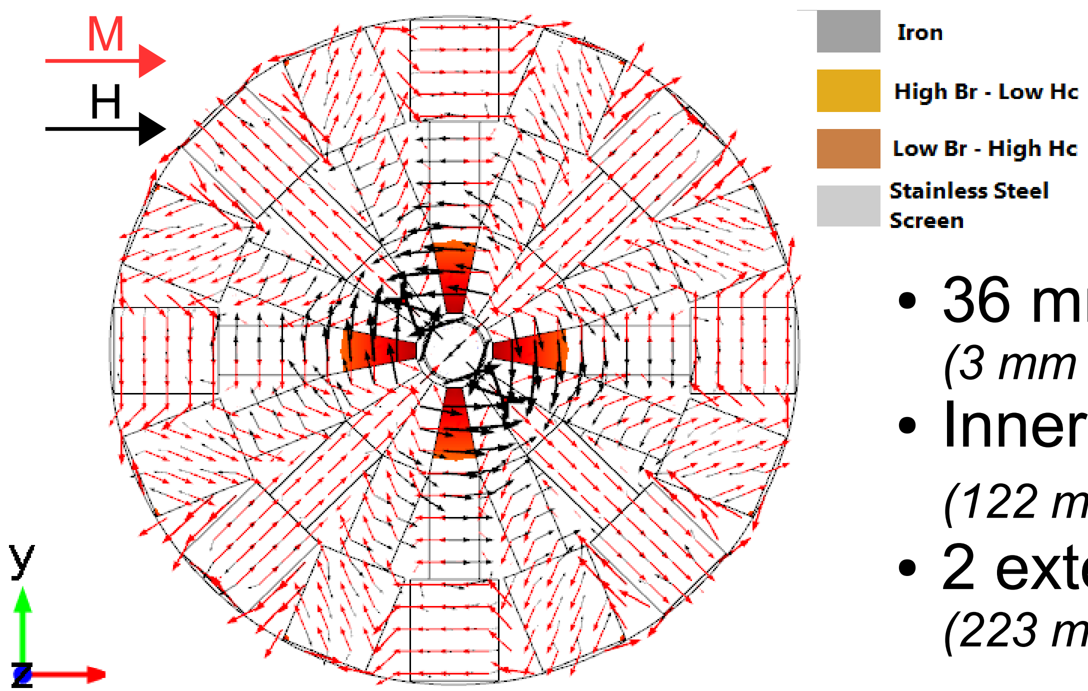
NdFeB N48H (Br = 1,39 T Hc= 1273 kA/m)

NdFeB N38UH (Br = 1,26 T Hc= 1990 kA/m)

Hybrid multiarray:

- 36 mm magnetic bore
  (3 mm shield + 30 mm for the beam)
- Inner Halbach trapezoidal
  (122 mm outer diameter, two NdFeB alloys)
- 2 external arrays with rectangular blocks
  (223 mm and 322 mm outer diameter)

Permanent Magnet Quads Preliminary Layout



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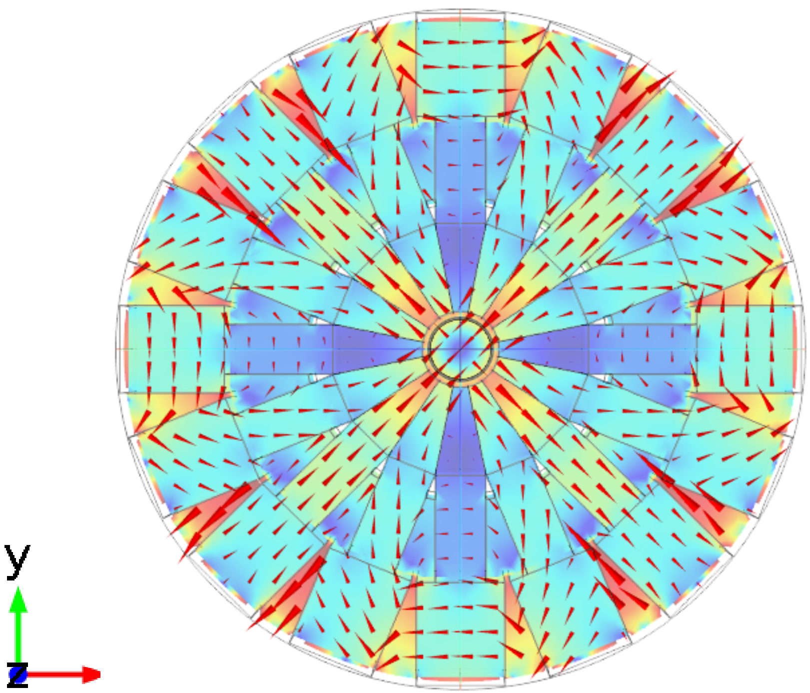

F. Schillaci et al., JINST 10 T12001 (2015)

- Iron
- High Br - Low Hc
- Low Br - High Hc
- Stainless Steel Screen

NdFeB N48H	NdFeB N38UH
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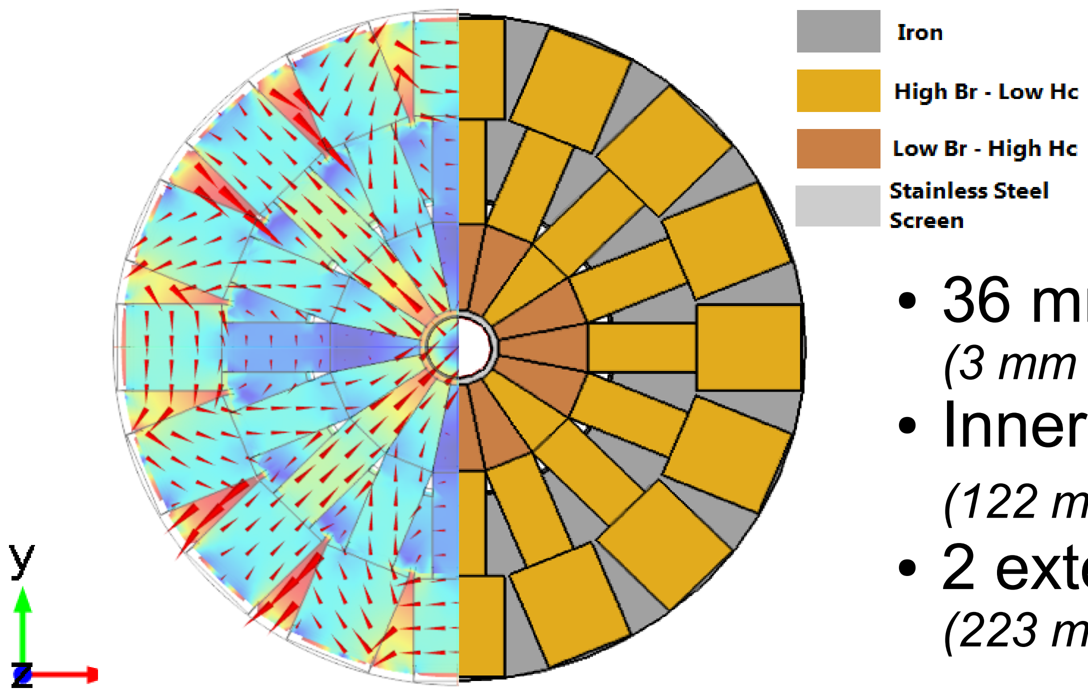

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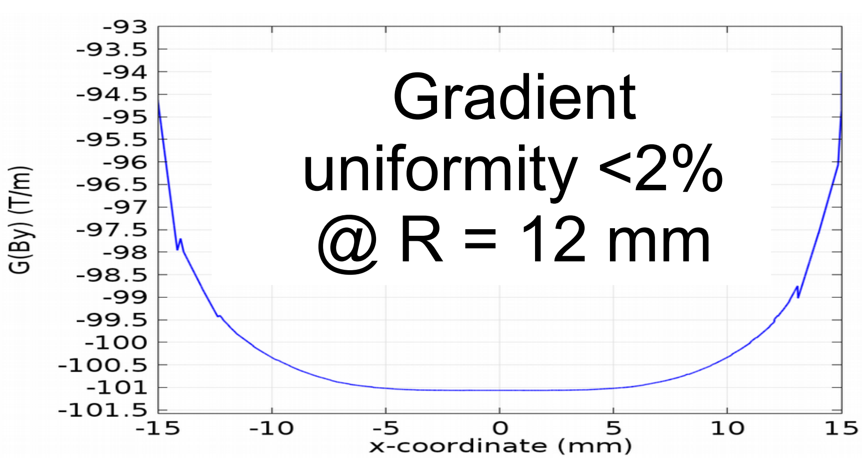

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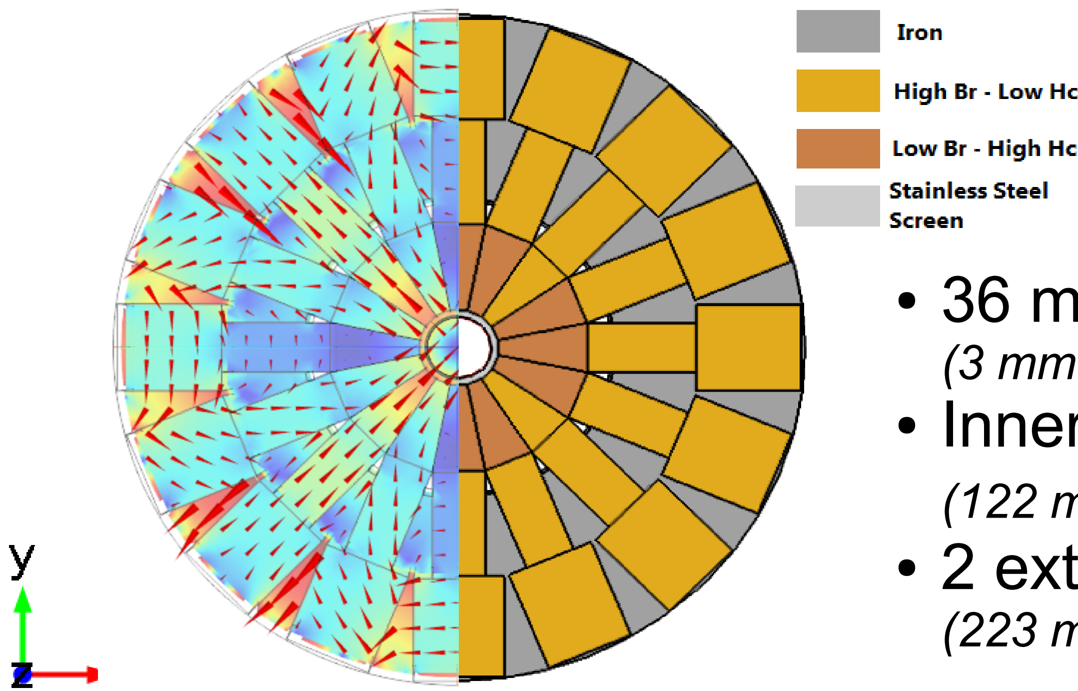

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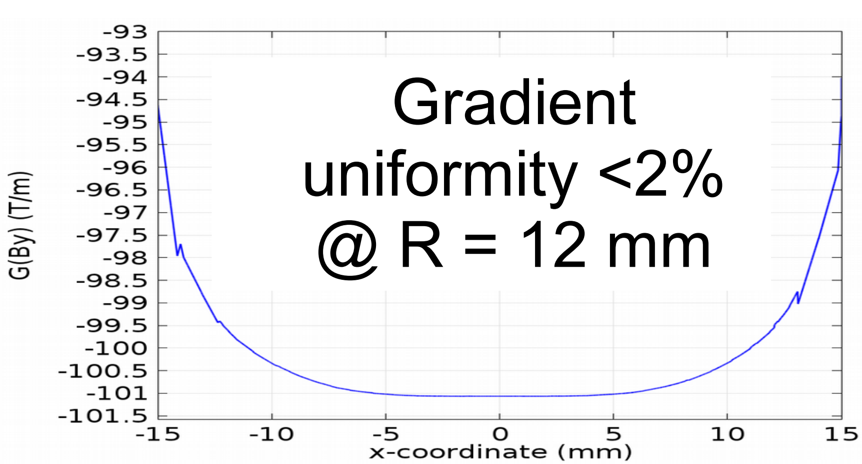
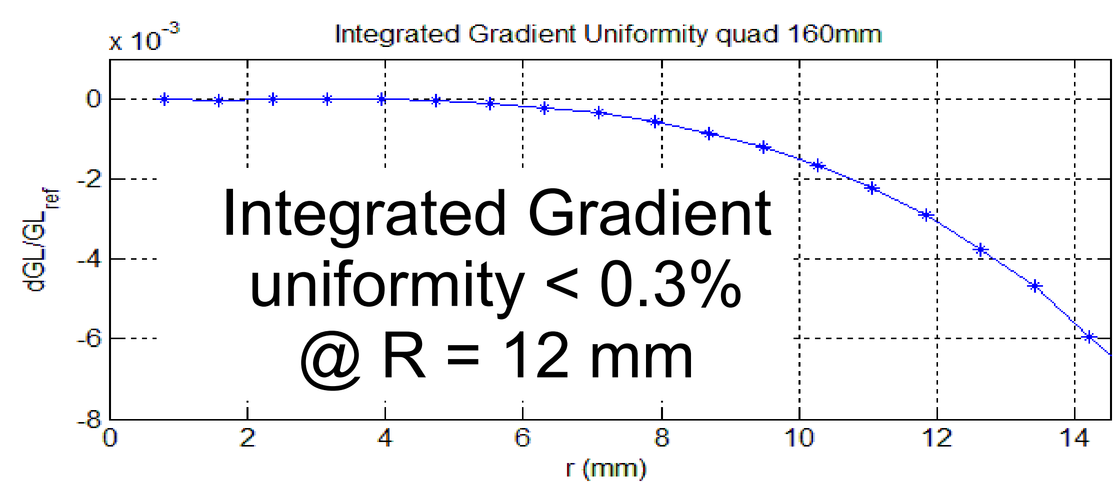
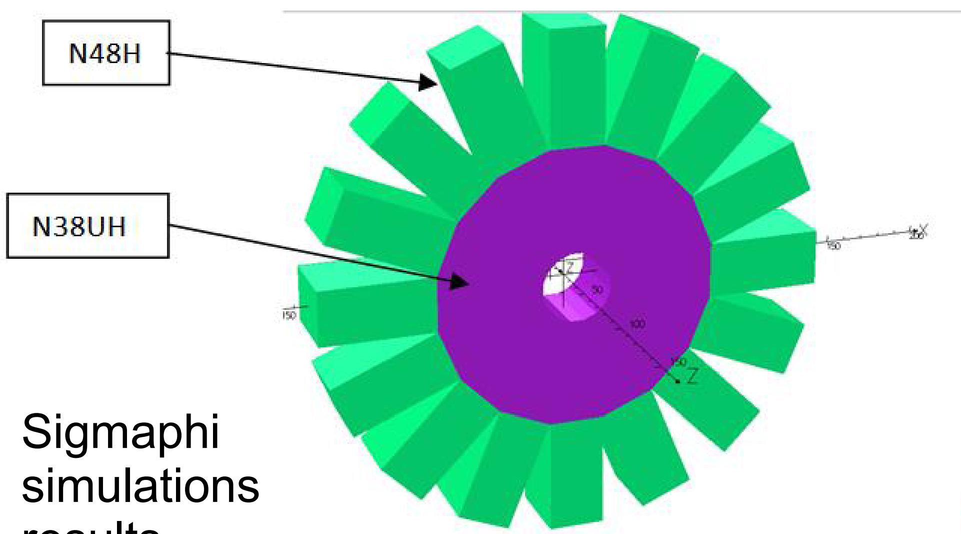
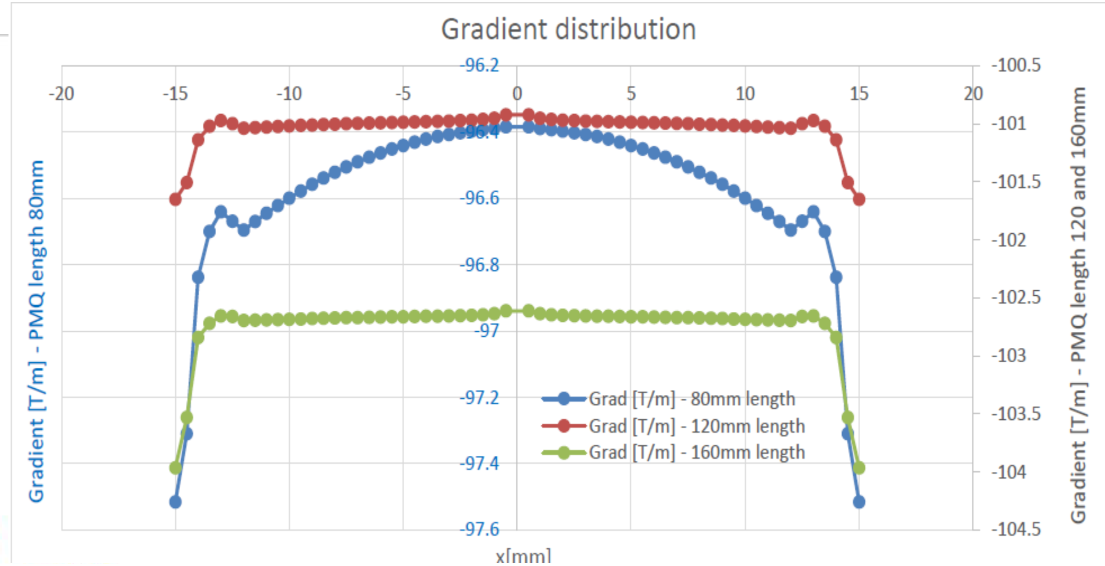




Permanent Magnet Quads Final Desing

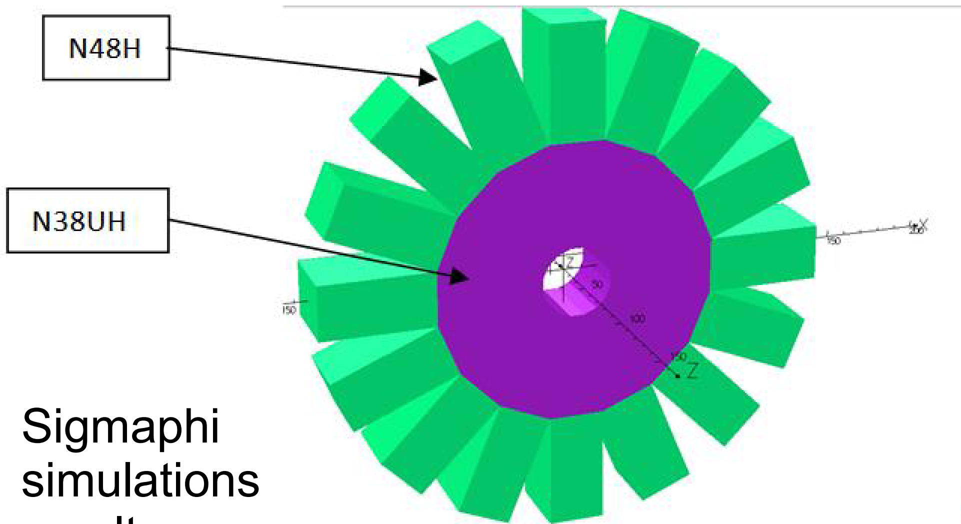


Sigmaphi simulations results



- 36 mm magnetic bore
  (3 mm shield + 30 mm for the beam – <u>same as INFN design</u>)
- Inner Halbach trapezoidal
  (149 mm outer diameter, NdFeB N38UH – 27 mm bigger than INFN design)
- External array with rectangular blocks
  *(266 mm NdFeB N48H – <u>56 mm **smaller** than INFN design</u>)*

Permanent Magnet Quads Final Desing



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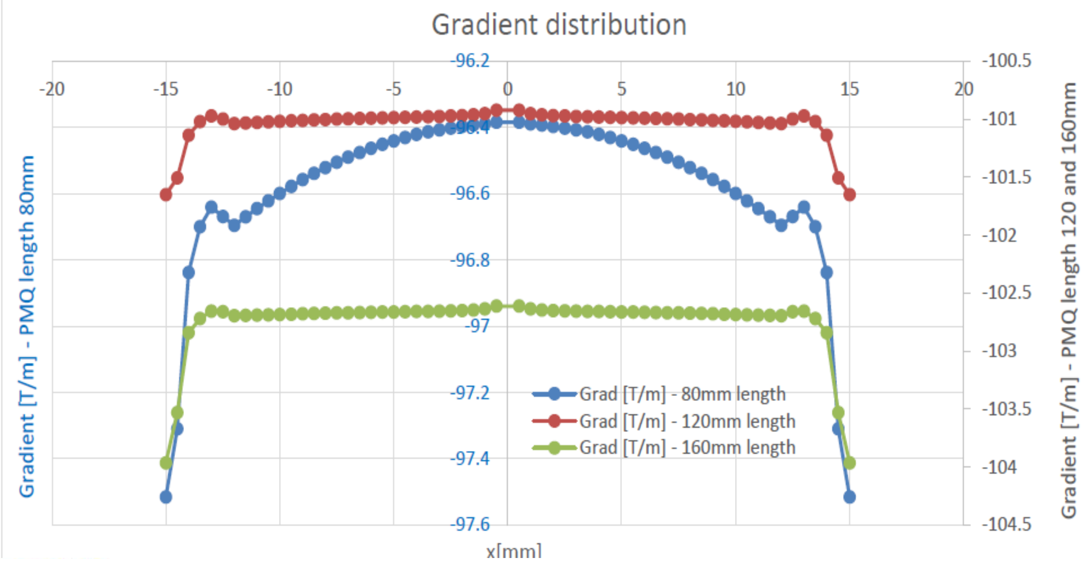

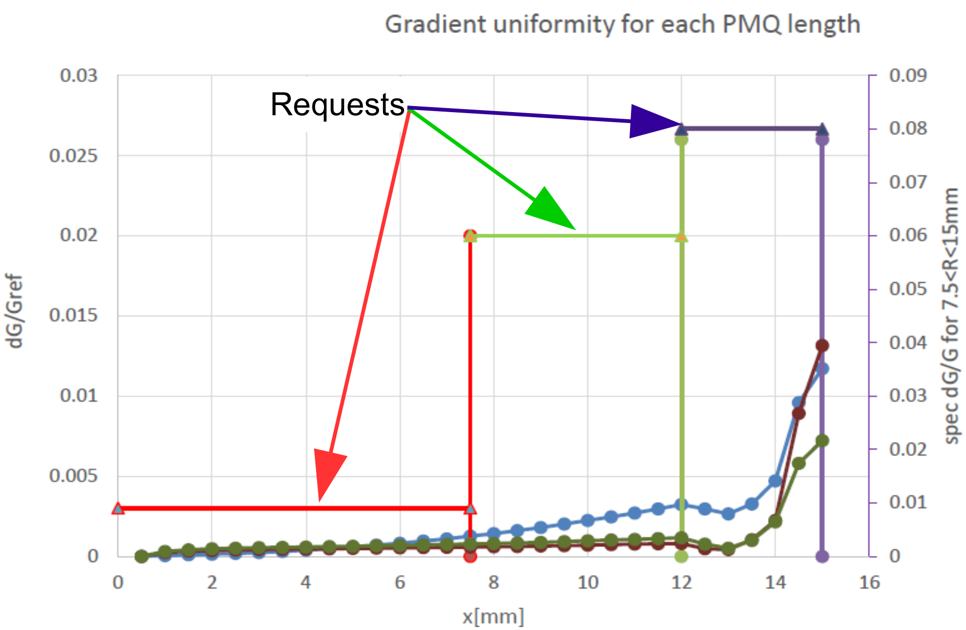

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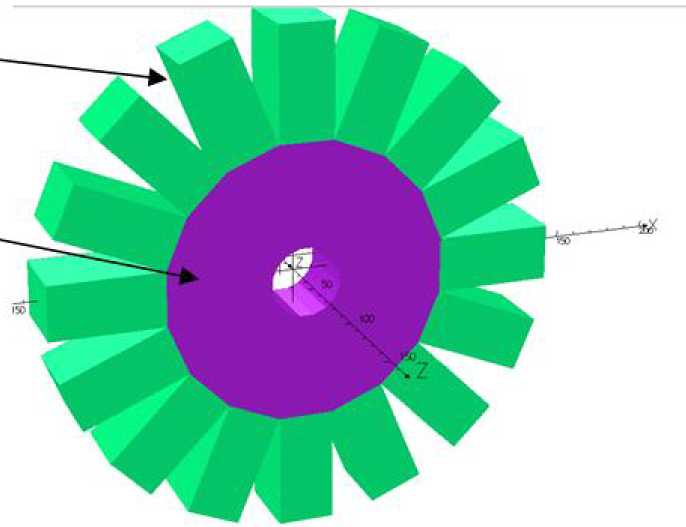

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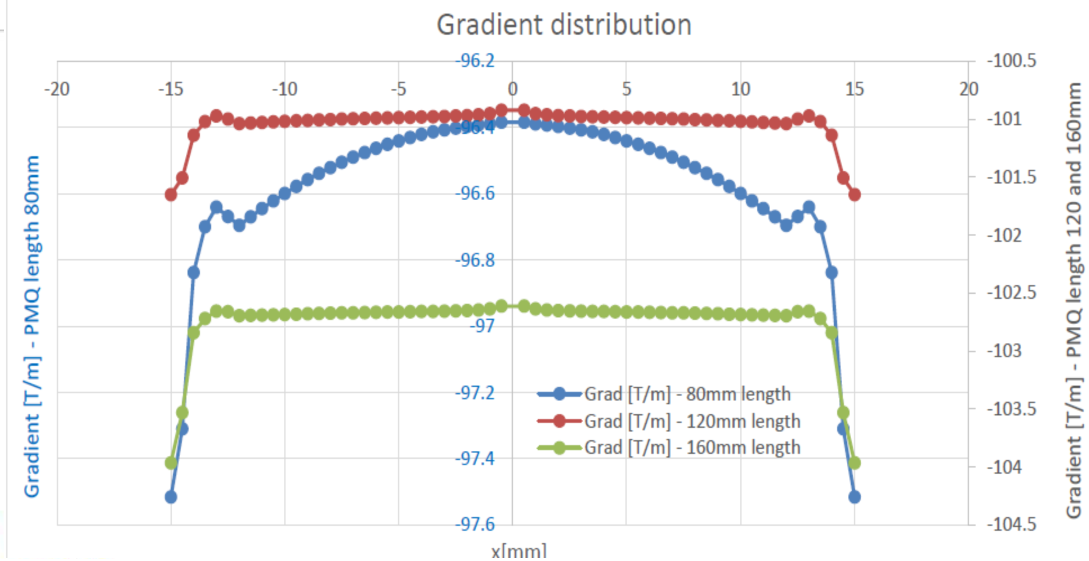
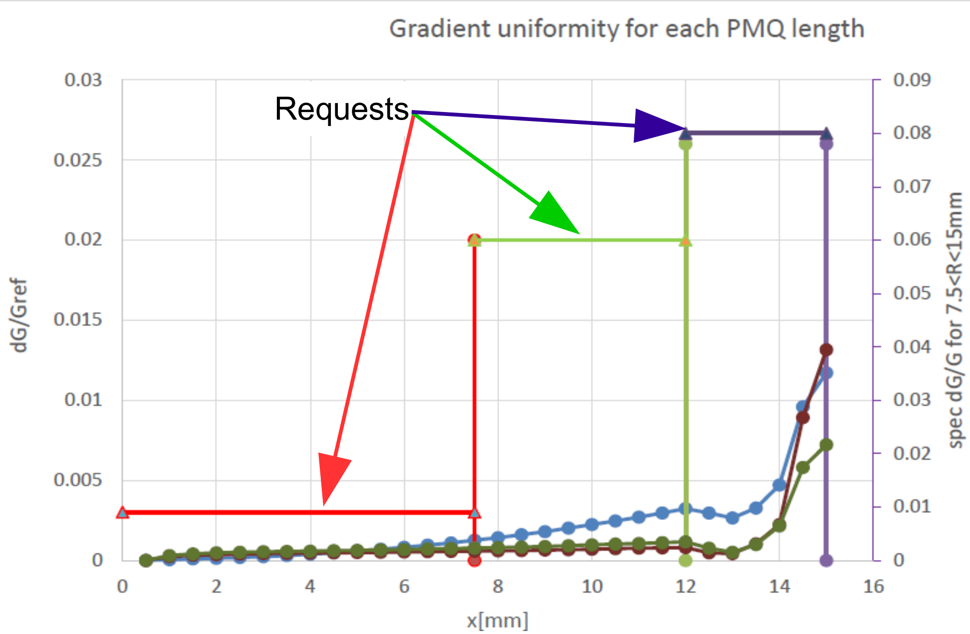
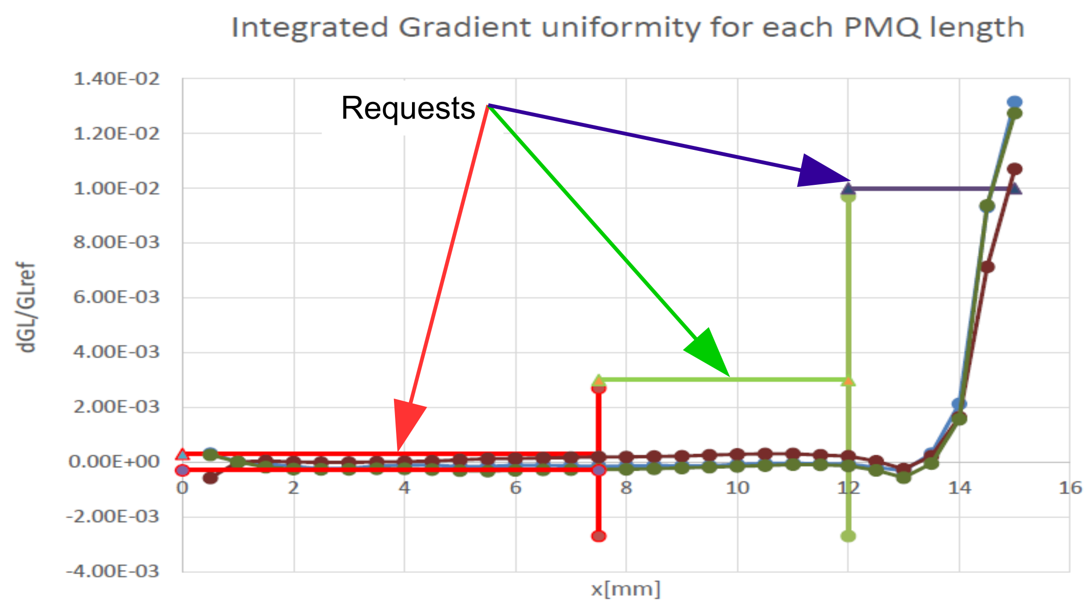
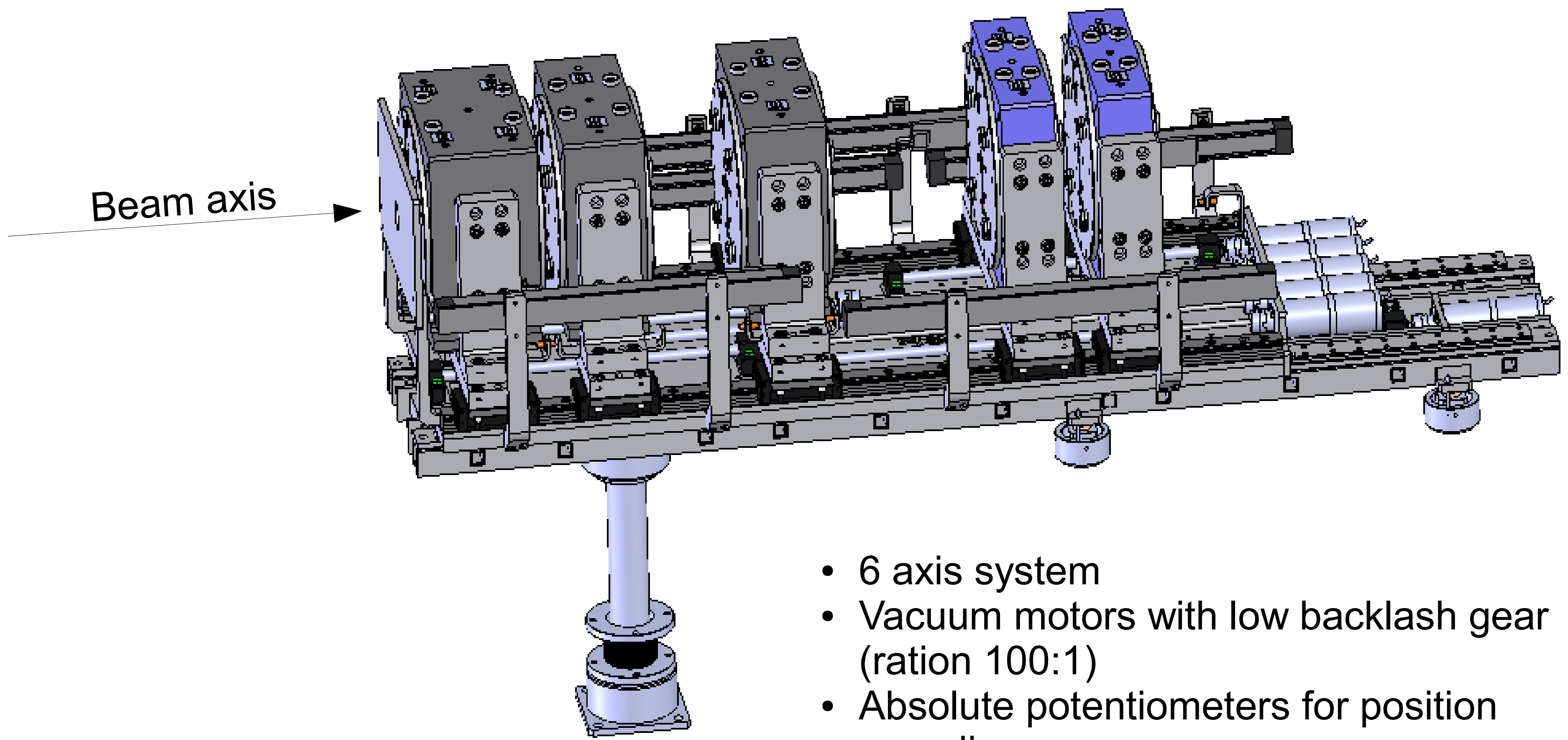






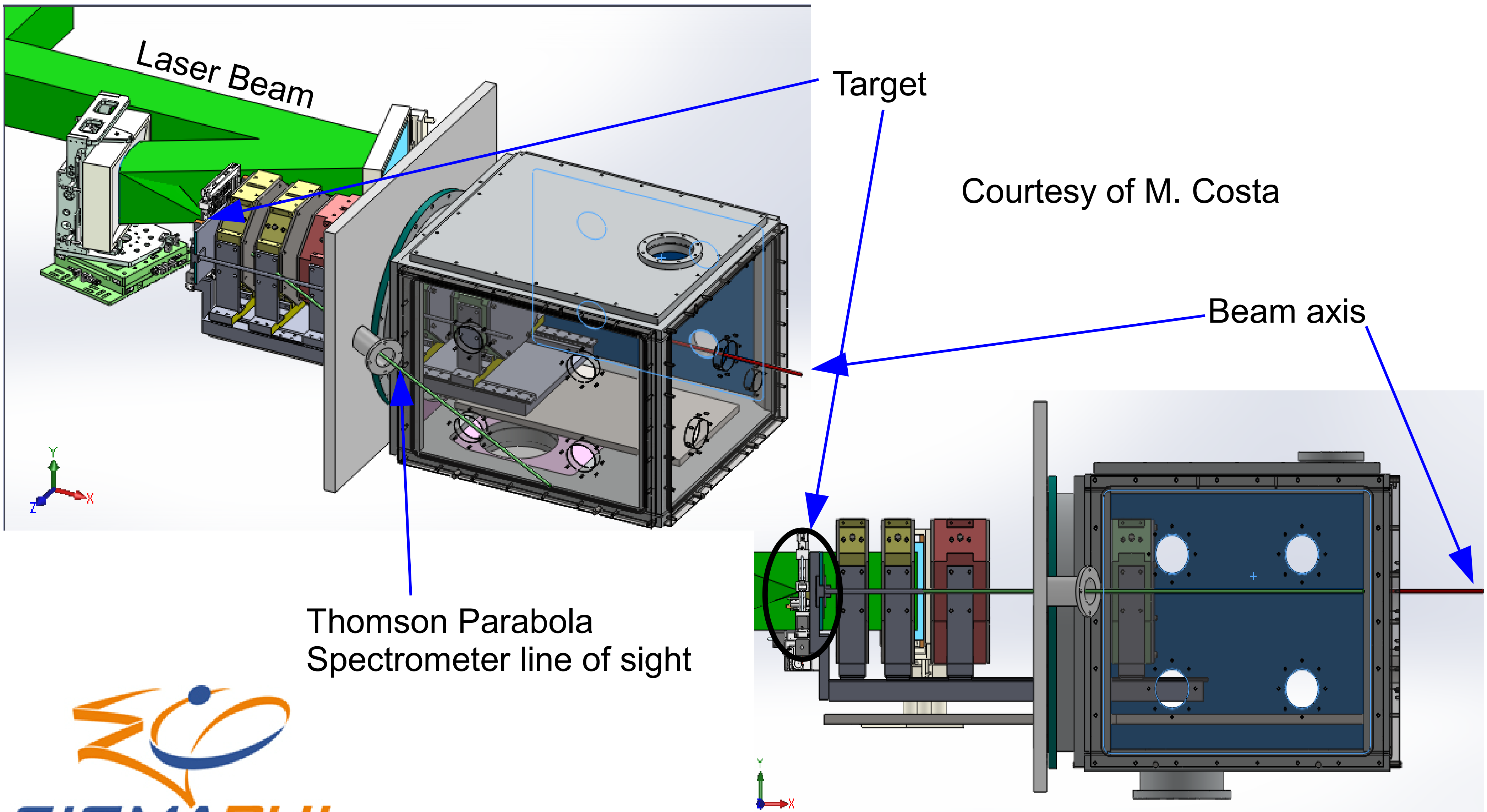
PMQs + Mechanics



- 6 axis system
- Vacuum motors with low backlash gear (ration 100:1)
- Absolute potentiometers for position encoding
- High precision radiation resistant switches
- High torques vacuum carriages and rails

In charge for realization

PMQs + Mechanics



SIGMAPHI ACCELERATOR TECHNOLOGIES

In charge for realization

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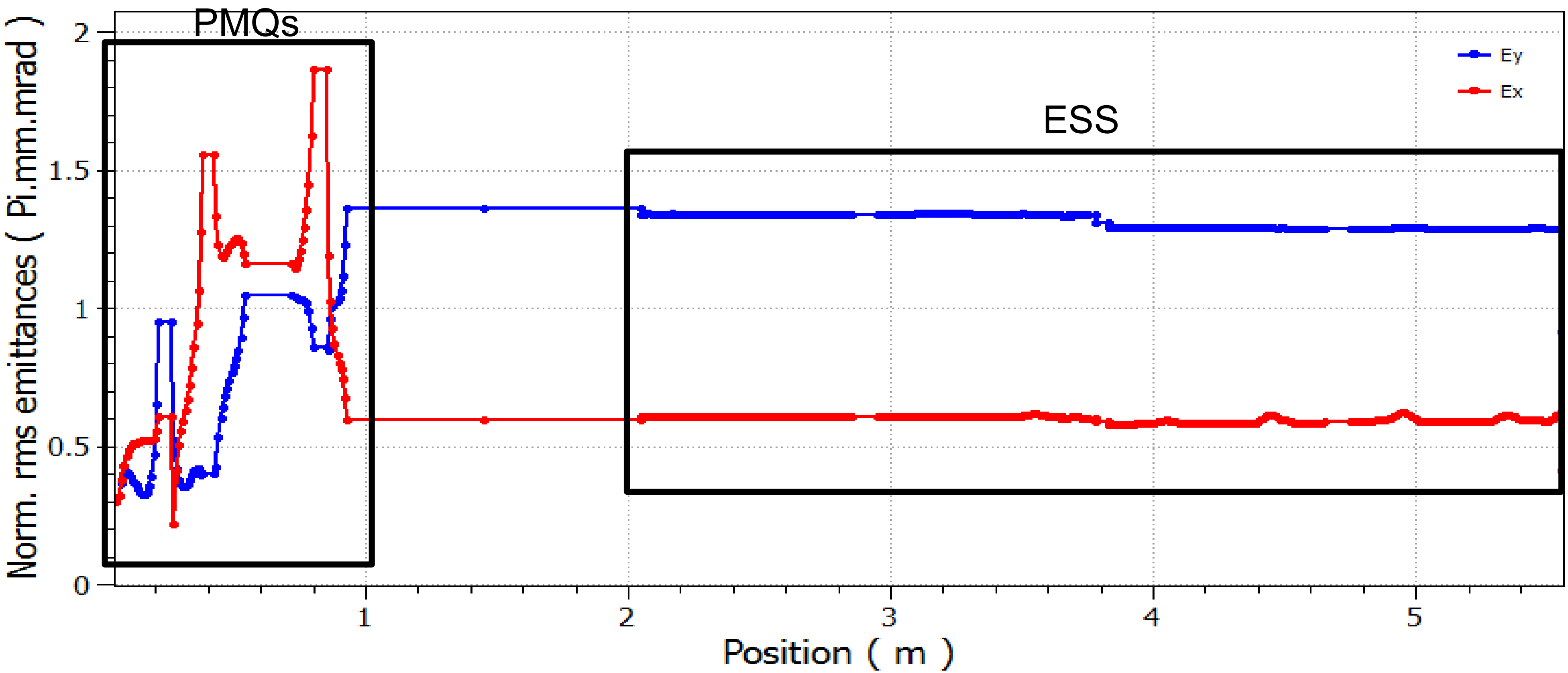
Emittance Growth and ESS acceptance

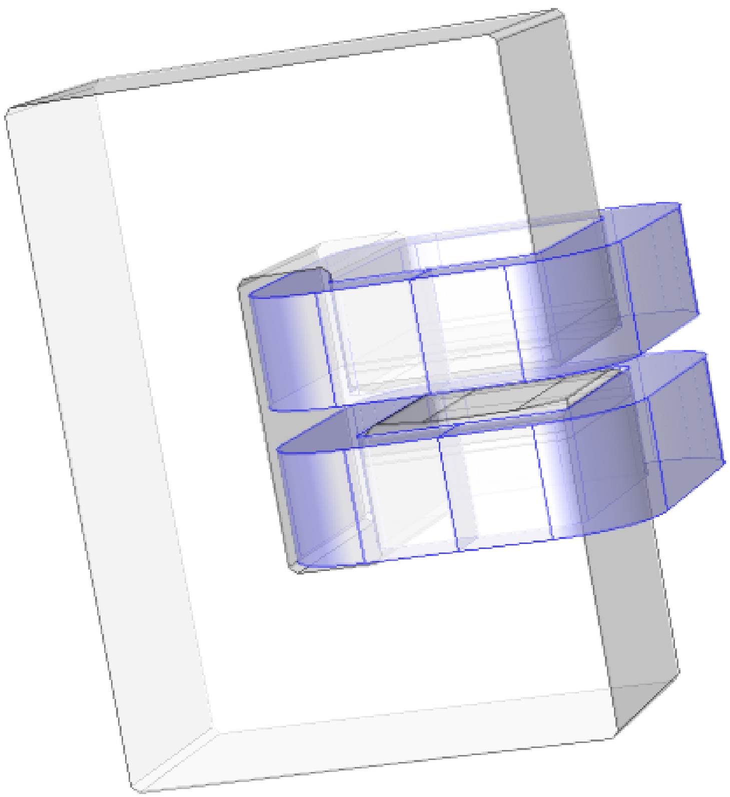


Emittance growth limited to the PMQs system and due to filamentations in the PMQs

The highest variations in the emittance are within the first section of the beam-line, namely within the PMQs. The ESS is design to accept the beam transmitted by the collection system.

Energy Selector Features

n° of Dipoles	B field	Geometric length	Effective length	Gap
4	0,085 – 1,2 T	400 mm	450 mm	59 mm
Good Field region (GFR)	**Field uniformity**	**Curvature radius**	**Bending angle**	**Drift between dipoles**
100 mm	< 0,5 %	2,570 m	10,10° (176,3 mrad)	500 mm

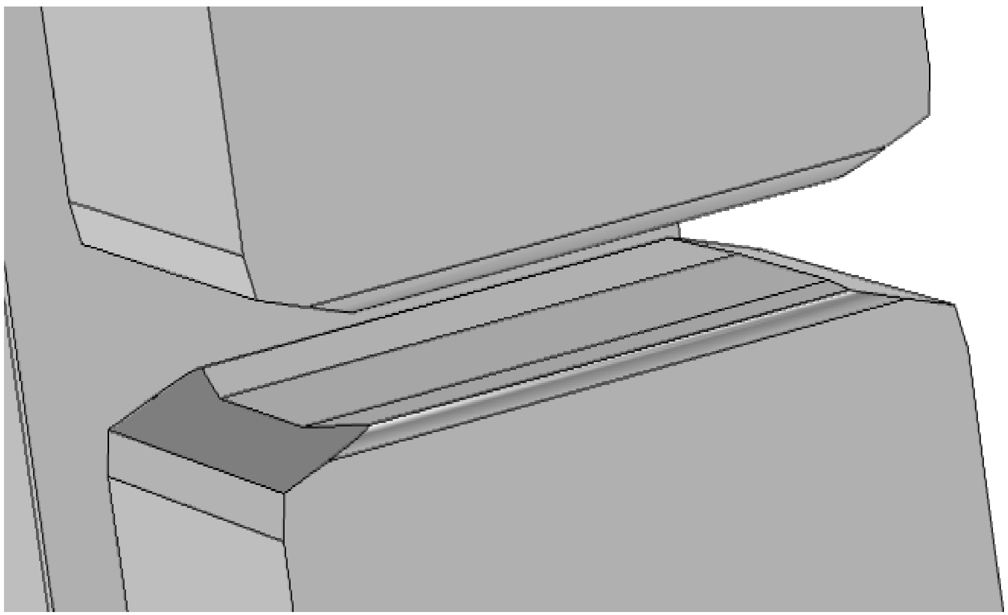


- Magnet efficiency 98%
- Packing factor 98%
- 115.5x168 coil section (11x16turns, 0,5 mm of insulator, 6 mm water channel)
- Max current ~200 A/turn
- Total weight ~3 Tons
- 40 kWatt in total

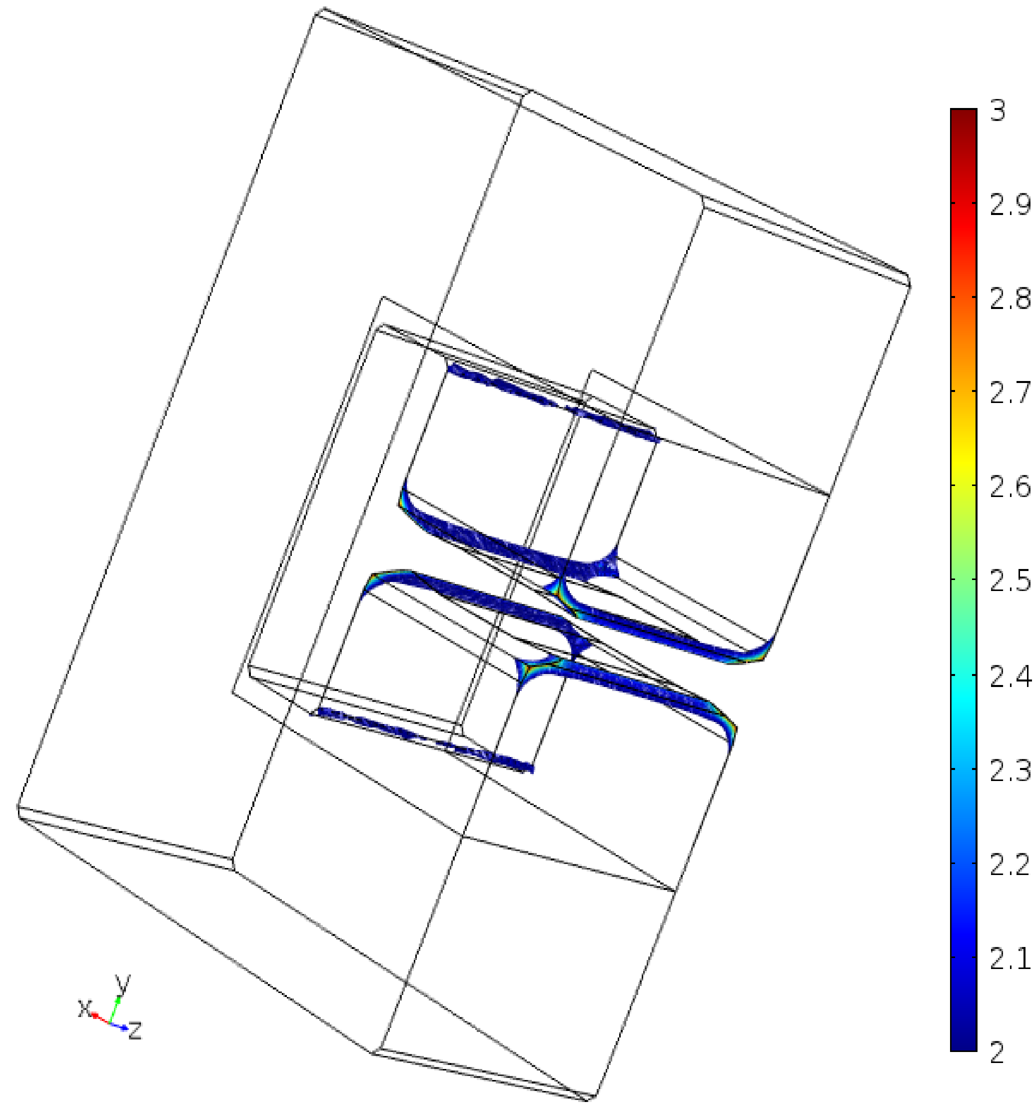
F. Schillaci et al., JINST 11 P08022 (2016)

Dipole design

Pole shape



Iron Saturation

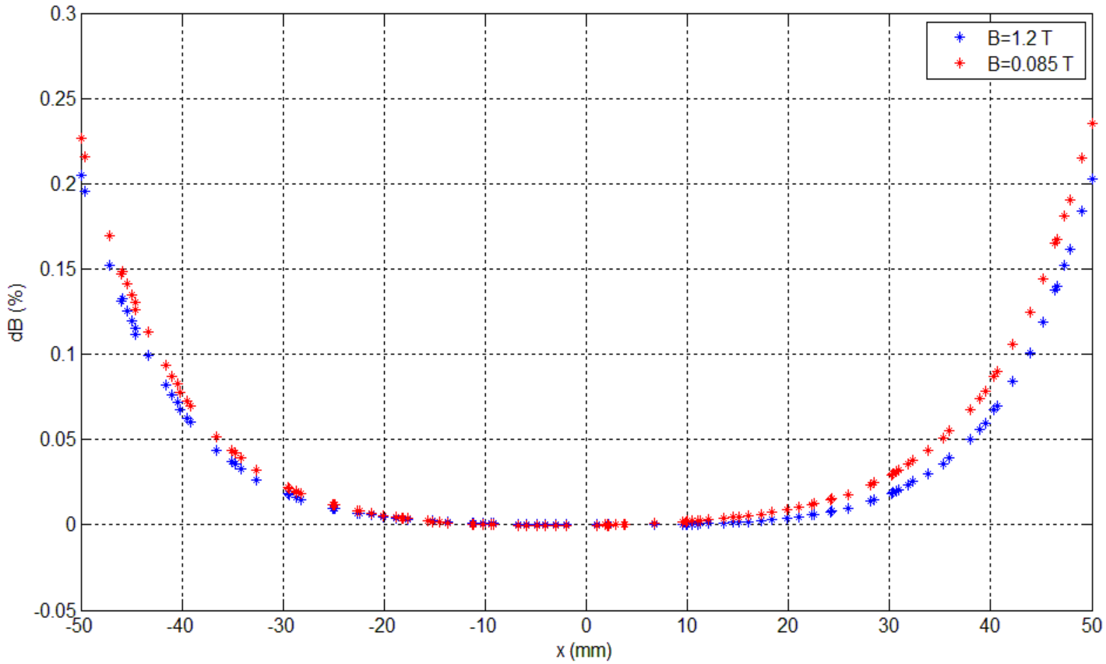


- Lateral shimming for increasing field uniformity (< 0.5% for all fields)

- Rogowski longitudinal shape to reduce effective length variation from the lowest to the highest field (448 mm – 451 mm)

Dipole design

Pole shape



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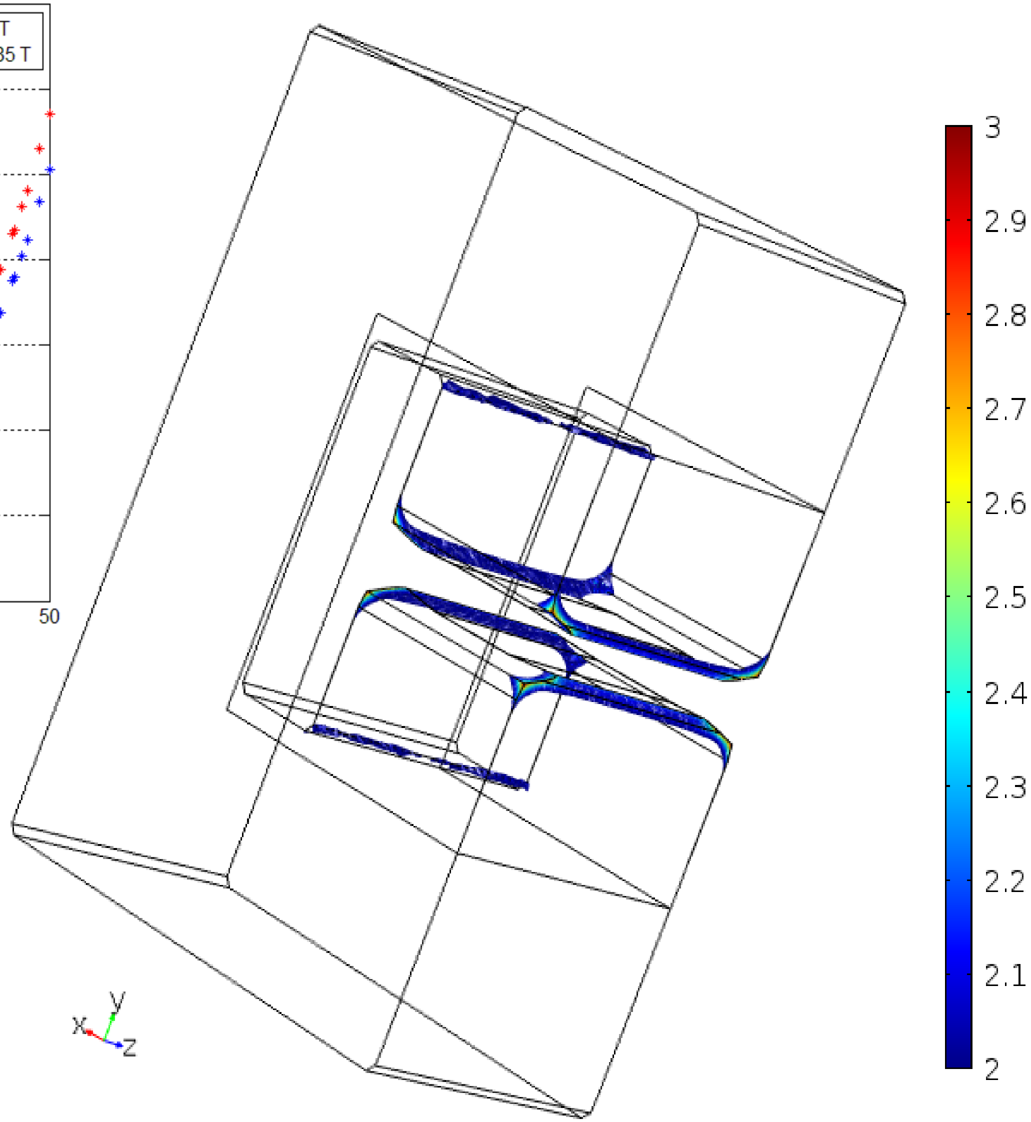

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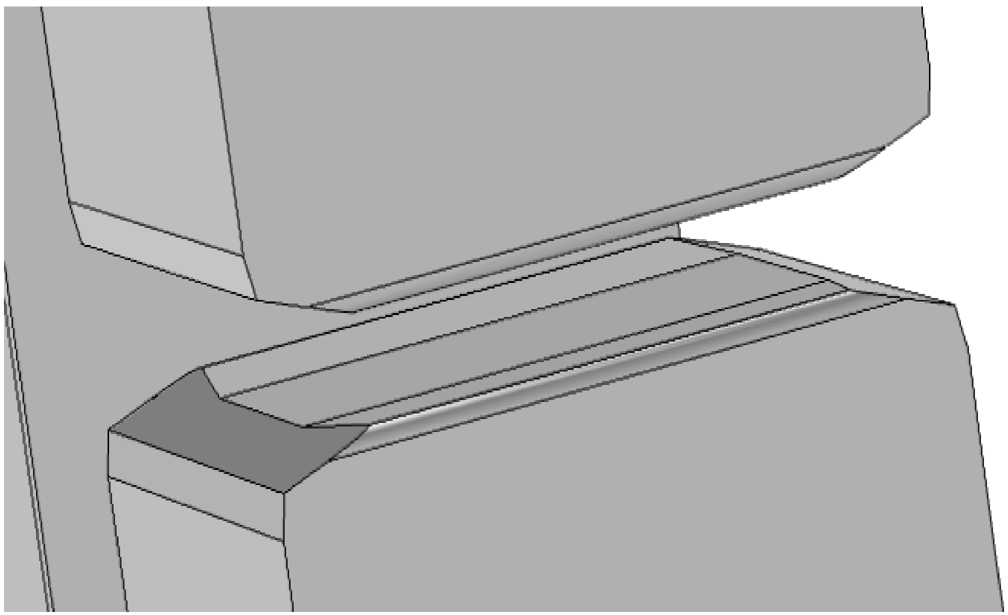

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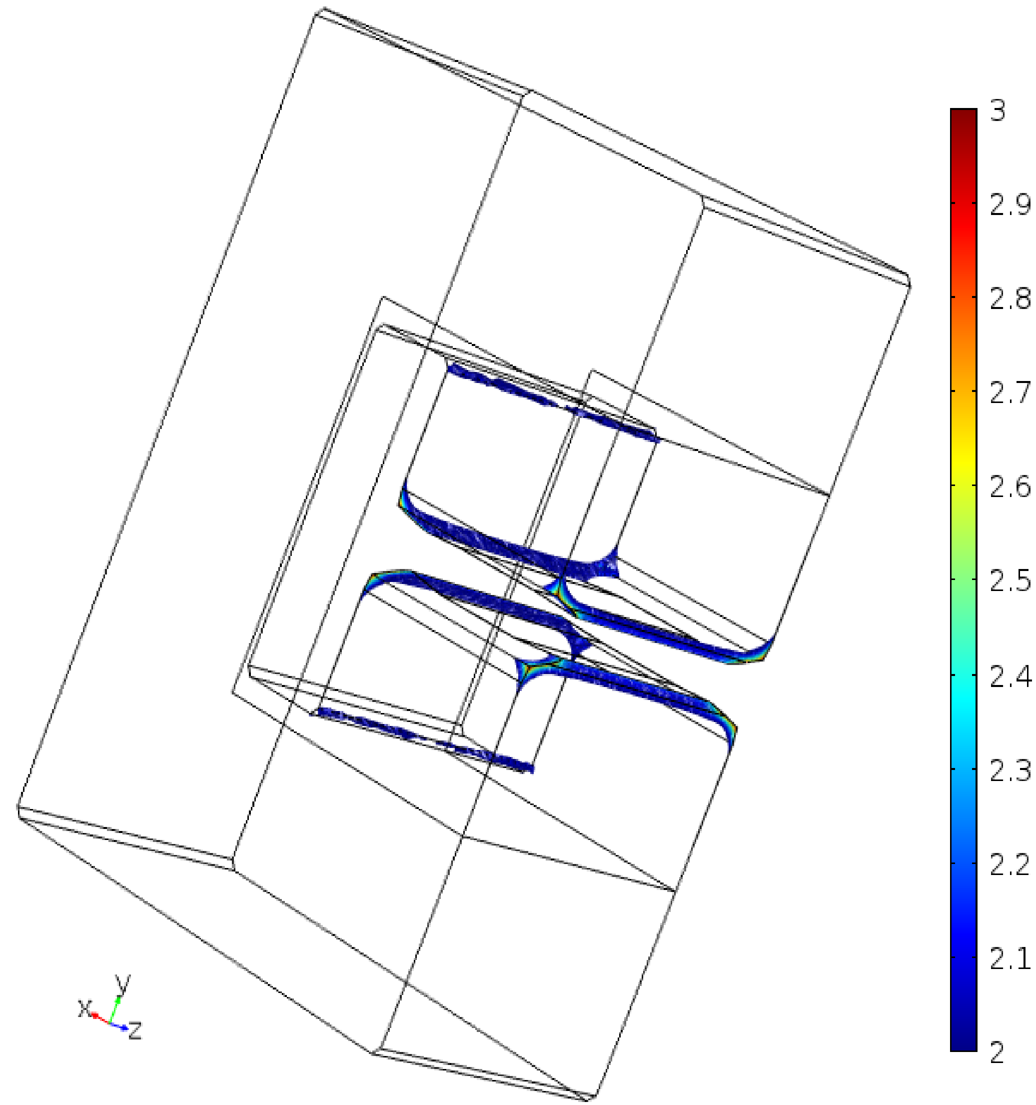

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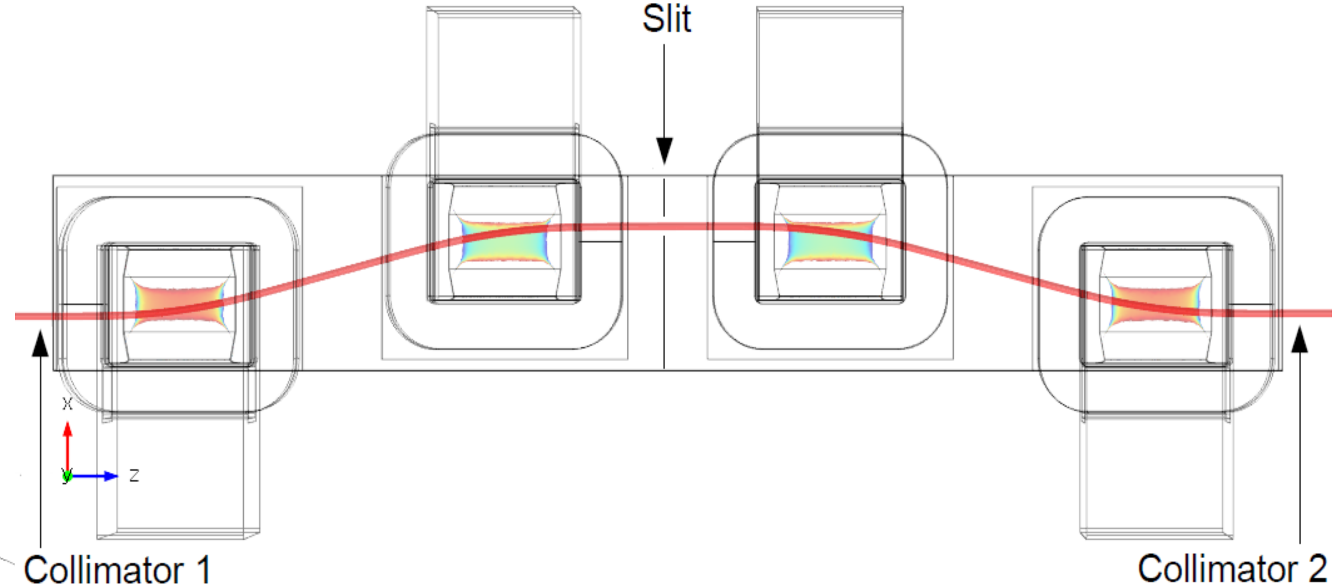
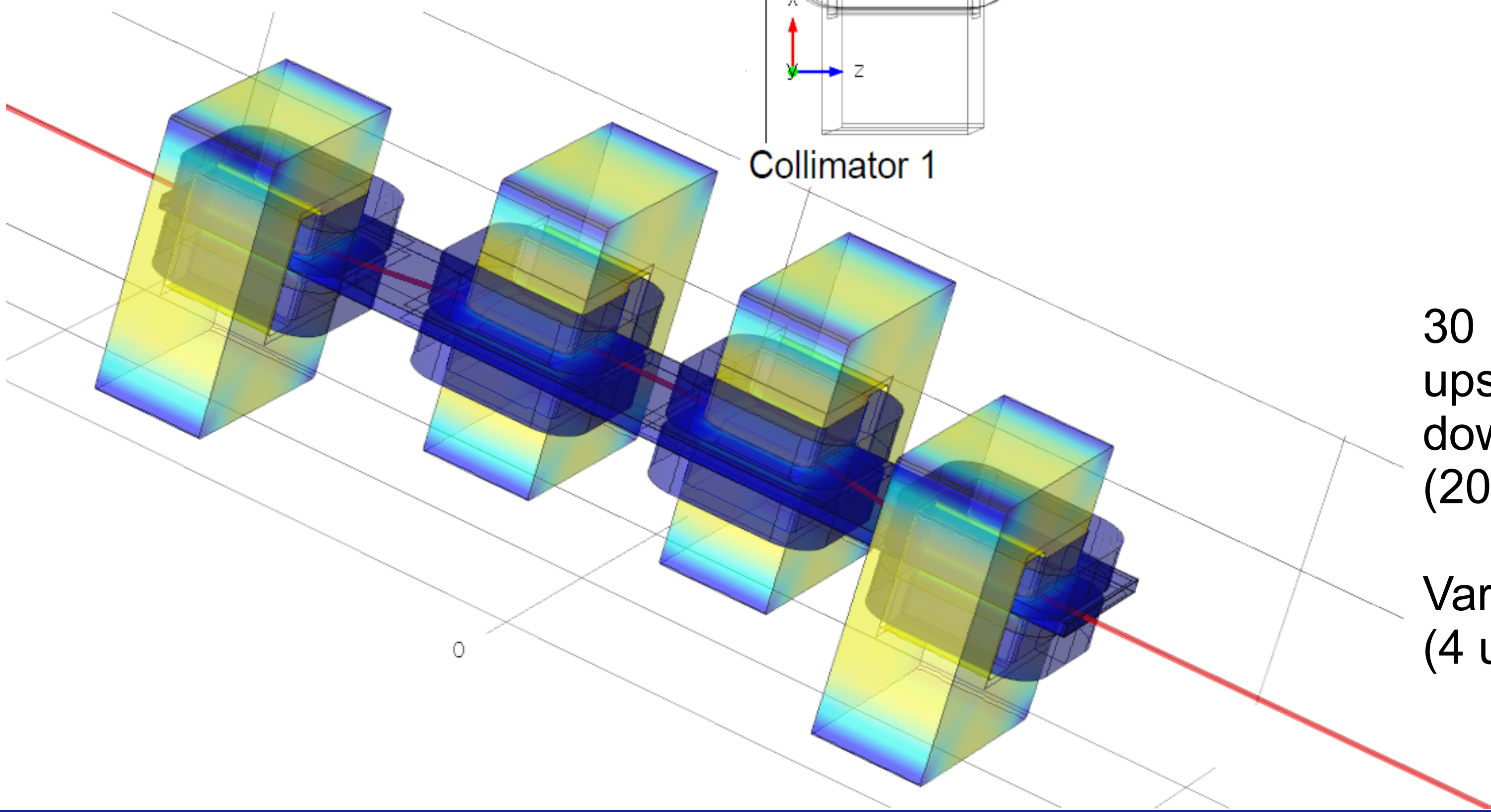
Doble Dispersive Mode Magnetic Chicane

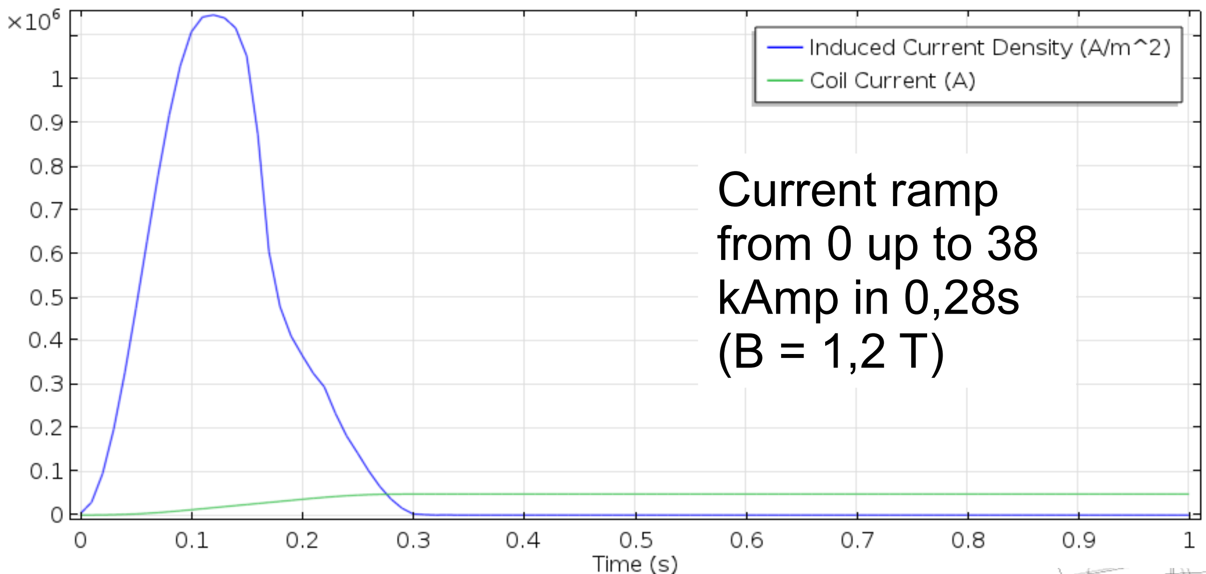




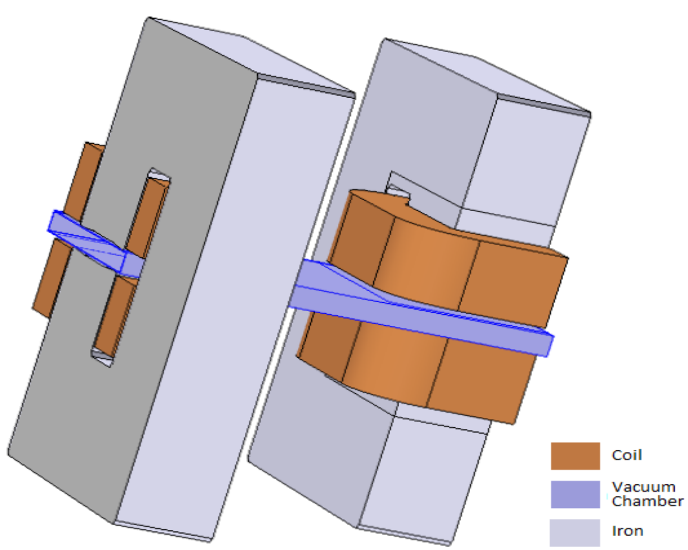
30 mm collimator upstream and downstream the chicane (200 mm far from dipoles)

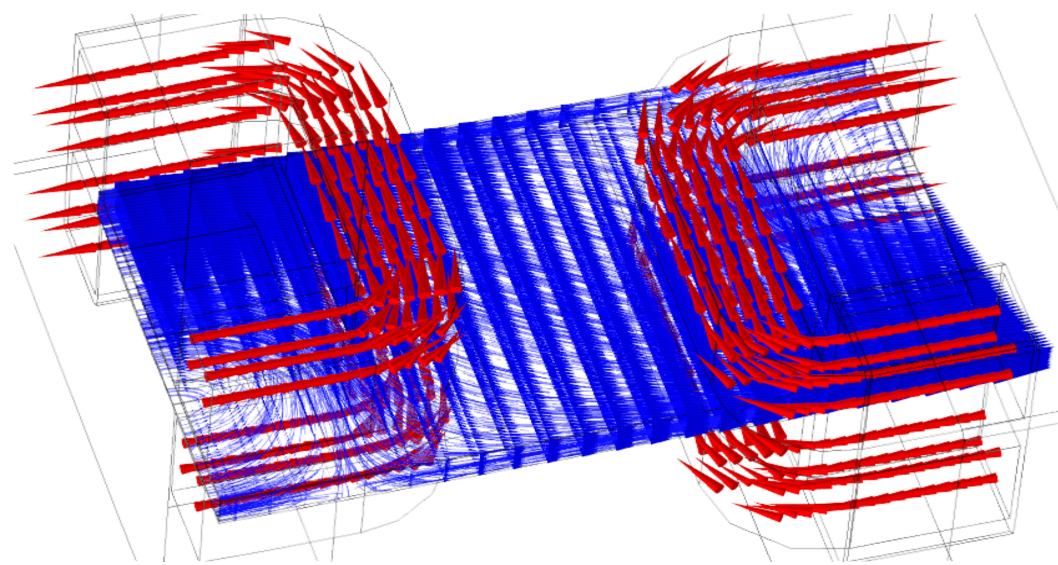
Variable slit aperture size (4 up to 20 mm)

Not just a magnetic chicane... Towards an active energy modulator



If the current is changed each second (each laser shot) the system could be used as an active energy modulator system
- Induced sextupole due to the eddy current on the vacuum chamber can be neglected after 0,31s





Eddy Current Loop

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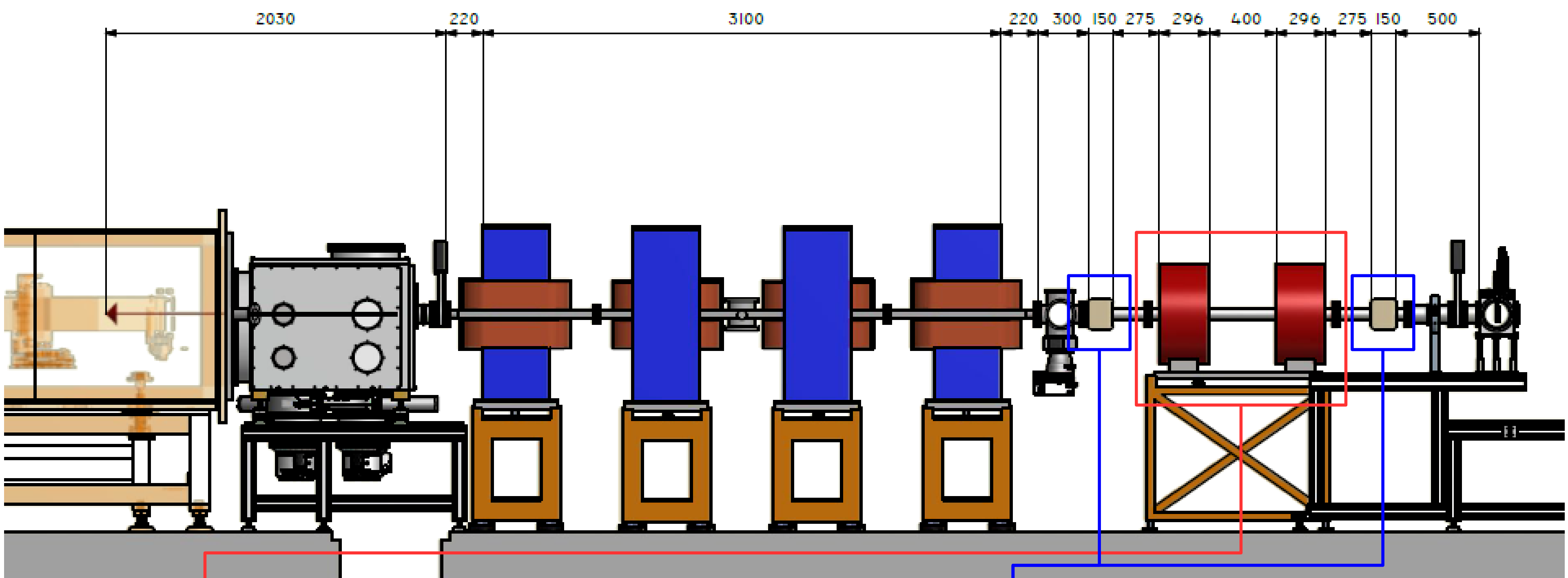
Quads and Steerers



Quads Specs:

Iron length: 296mm
Packing factor 98%
Effective length: 331.5 mm
Gradient (max): 10T/m
Bore: 70 mm
GFR: 55 mm

Correctors Specs:

xy steering magnets
B max: 300 gauss
Geometrical length: 150mm

Tender assigned and final design is work in progress →

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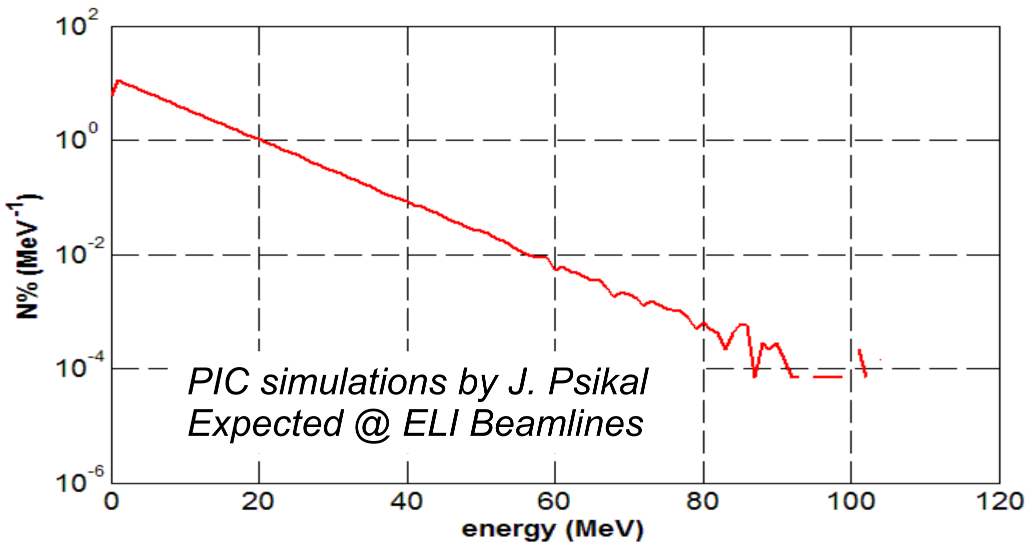
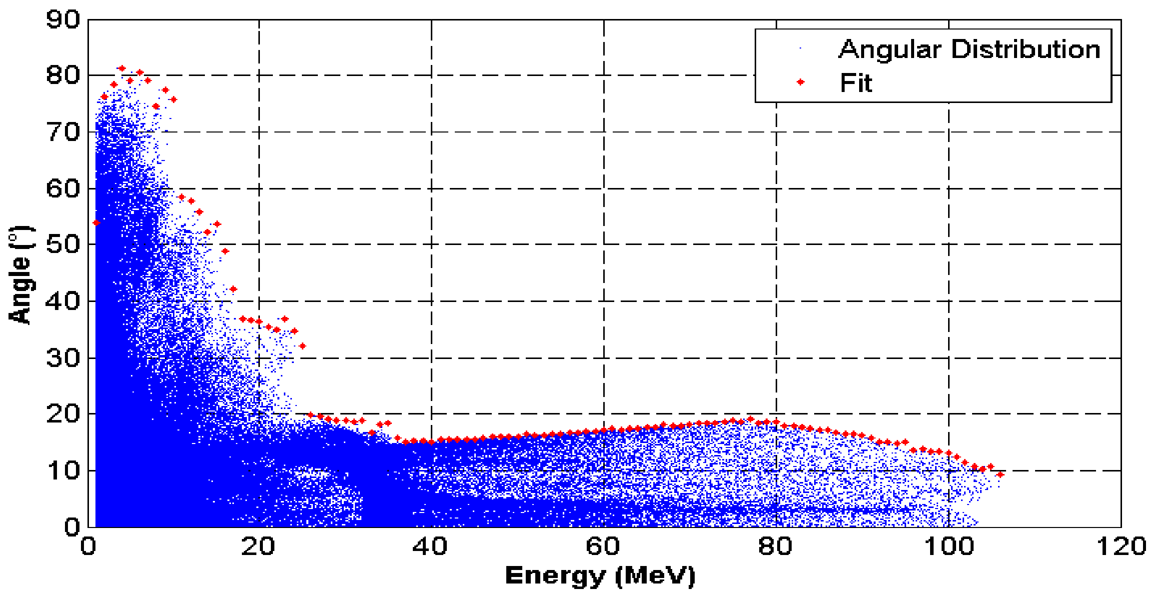
PIC simulation ELIMAIA source



Exponential energy distribution
Cut-off 105 MeV
Beam spot size ~ 40μm diameter
Uniform angular distribution (±17° @ 60 MeV)

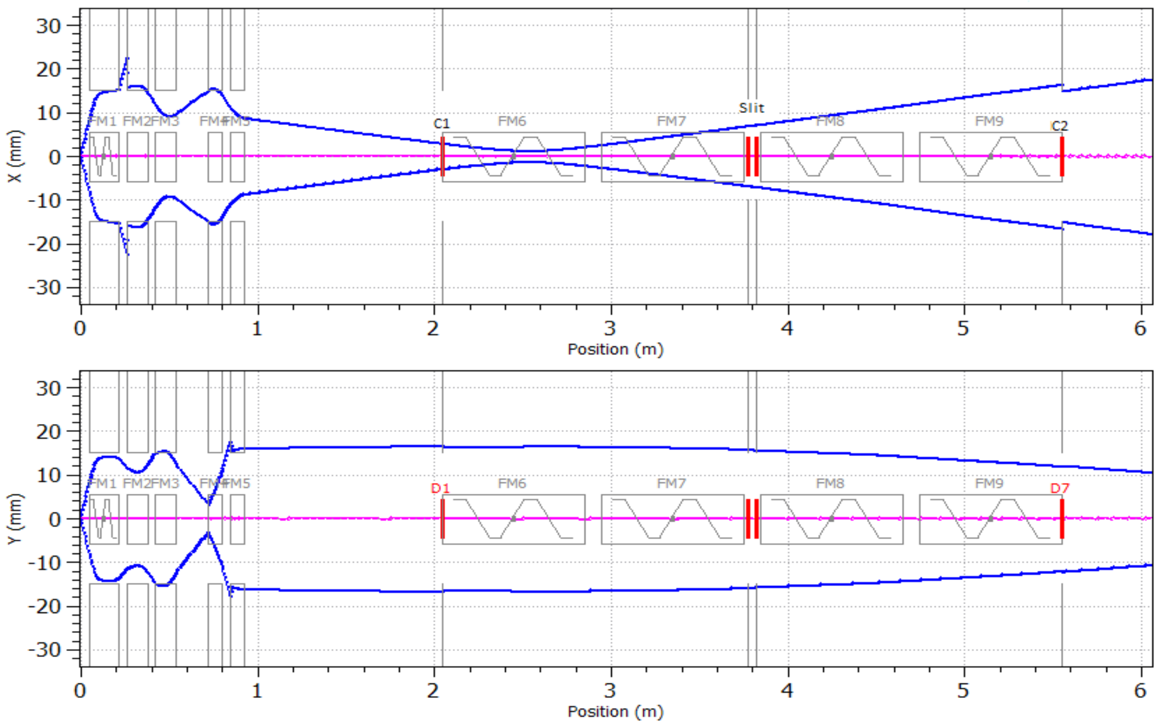


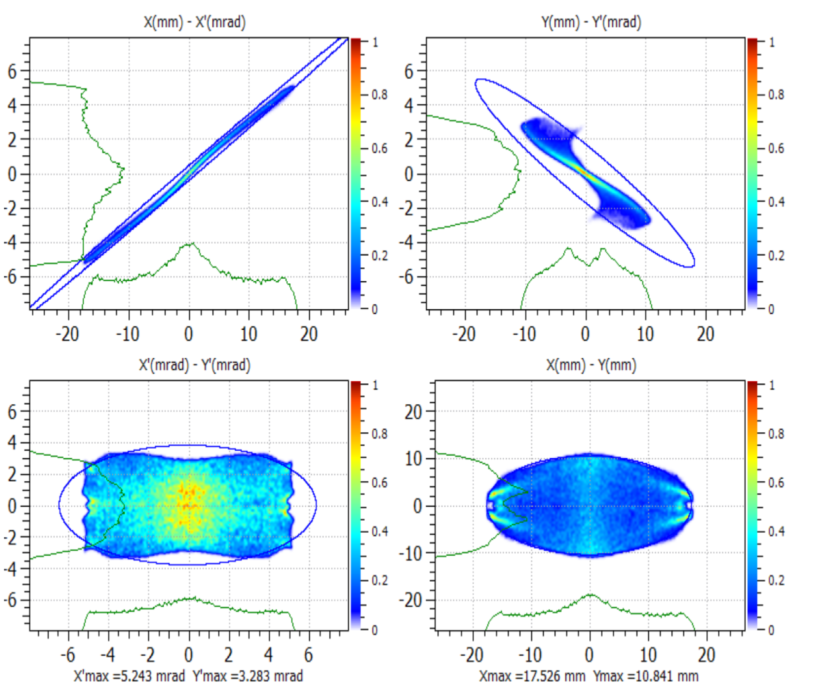
HUGE ANGULAR APERTURE > 15°

Worst Scenario!

Beam transport
60 MeV protons

Wanted output beam: Protons with central energy of 60 MeV and 20% spread

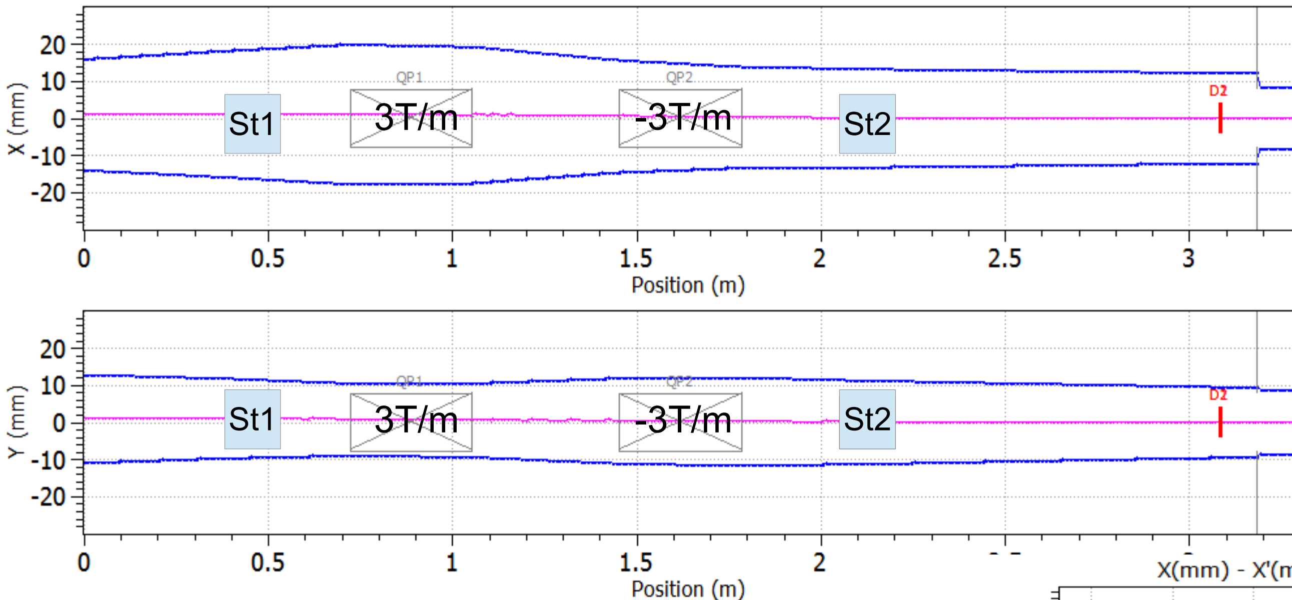




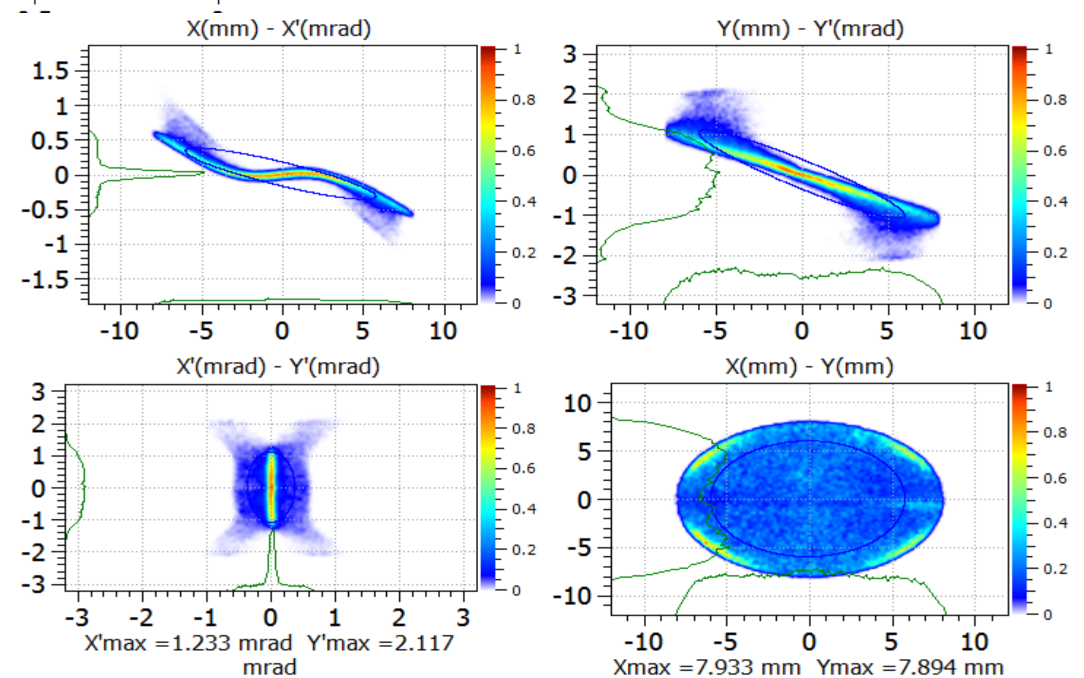
Beam envelope for reference beam 60 MeV protons and phase space plot at the ESS output

Reference beam losses ~ 80%

Quads and Steerers
60 MeV reference energy



Out of PMQs+ESS used in input for preliminary simulation of last beam-line section

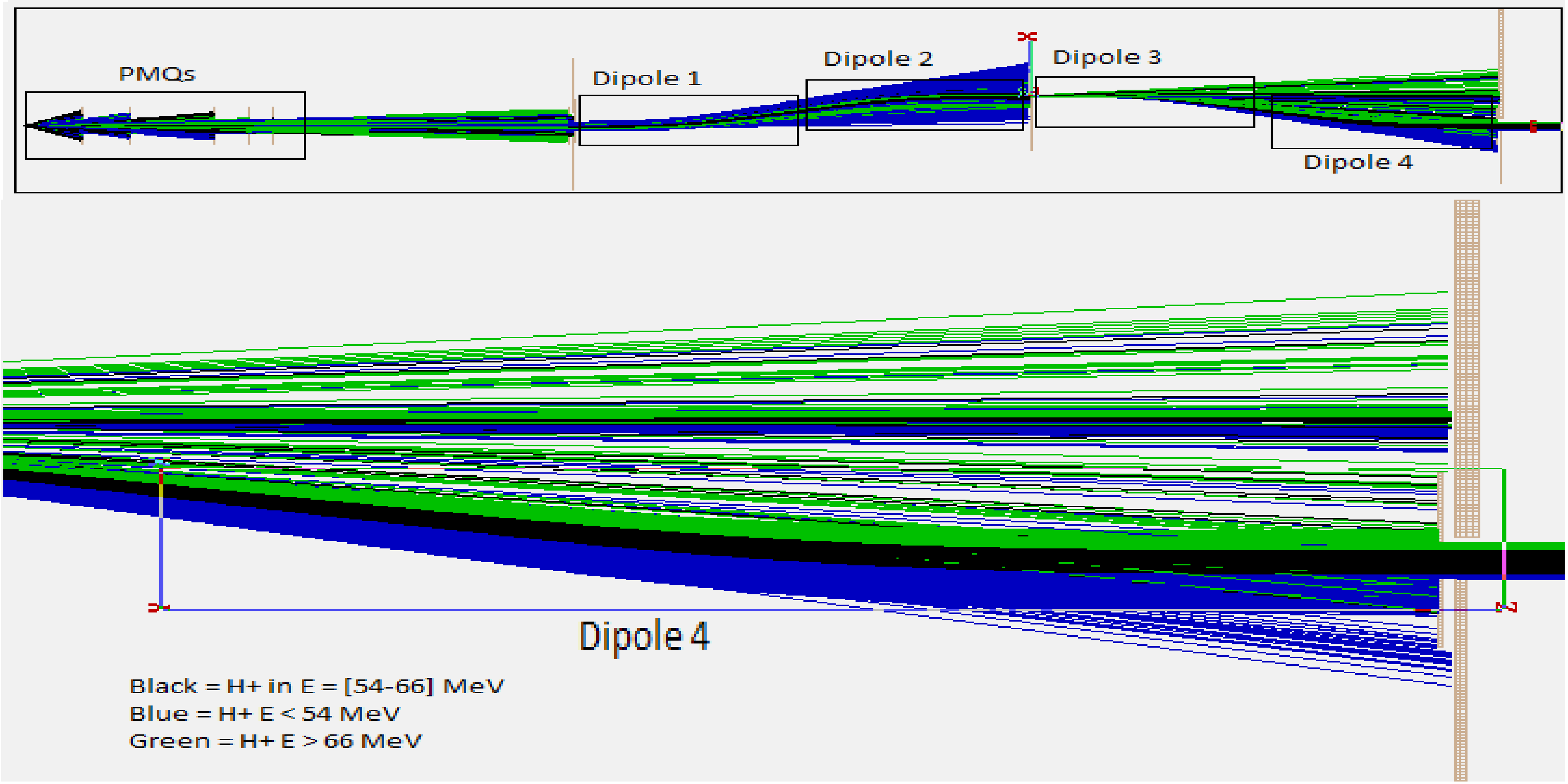


Losses are of few percent in this part of the beamline!

Beam transport TNSA-like protons

Angular divergence = 5° (FWHM)

Transmission efficiency ~12% (9,2e7 H^+/bunch)



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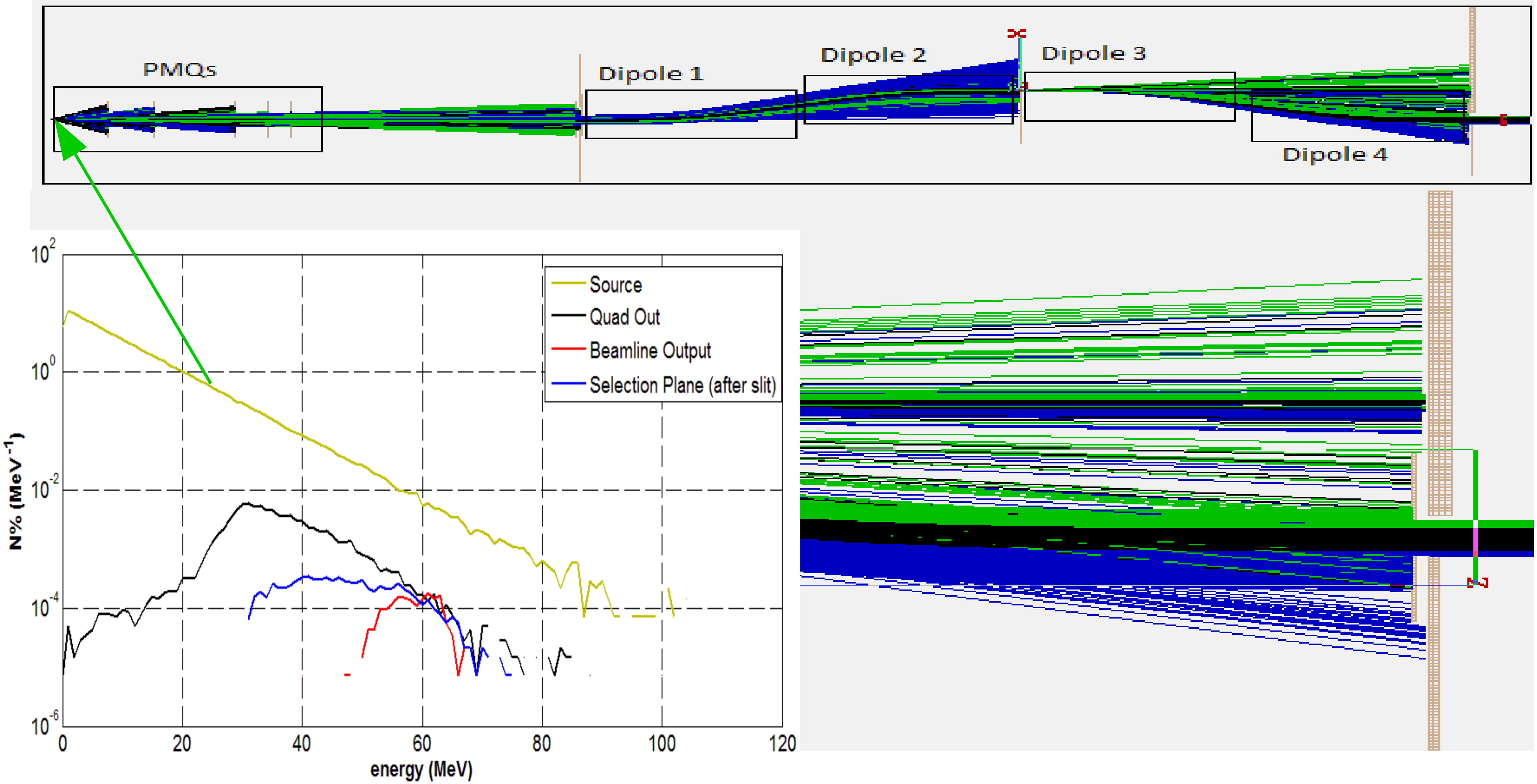

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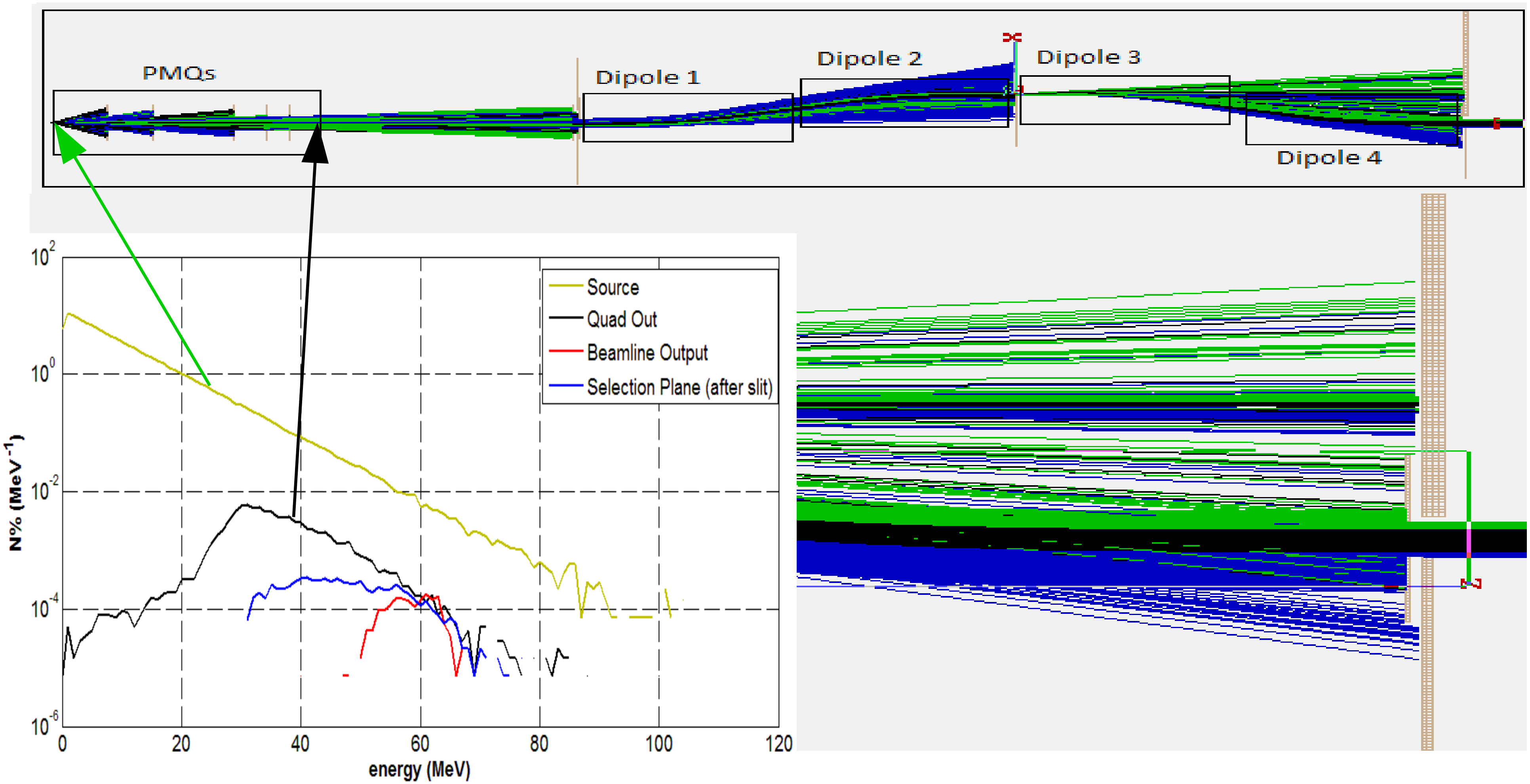
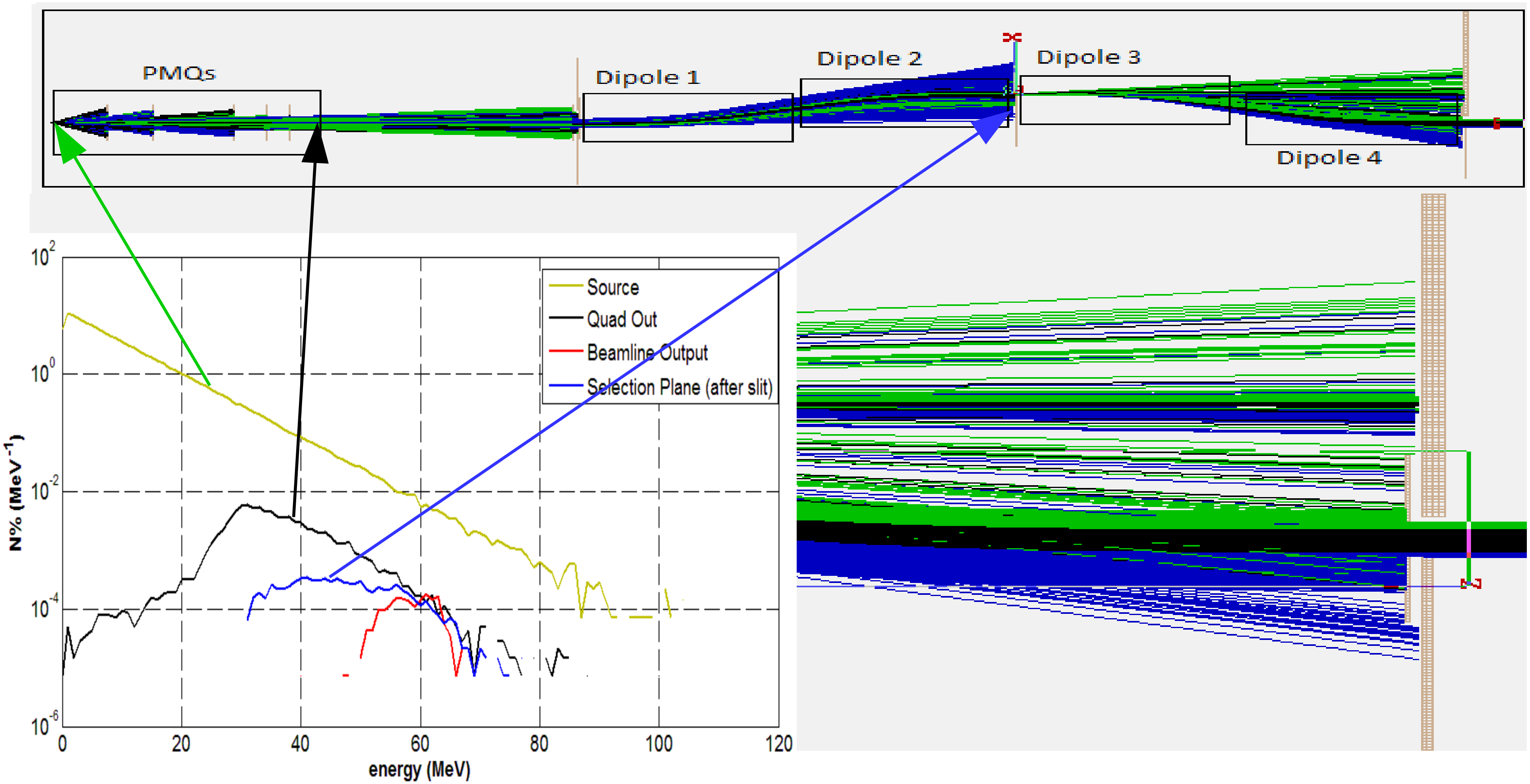


Beam transport
TNSA-like protons

Angular divergence = 5° (FWHM)

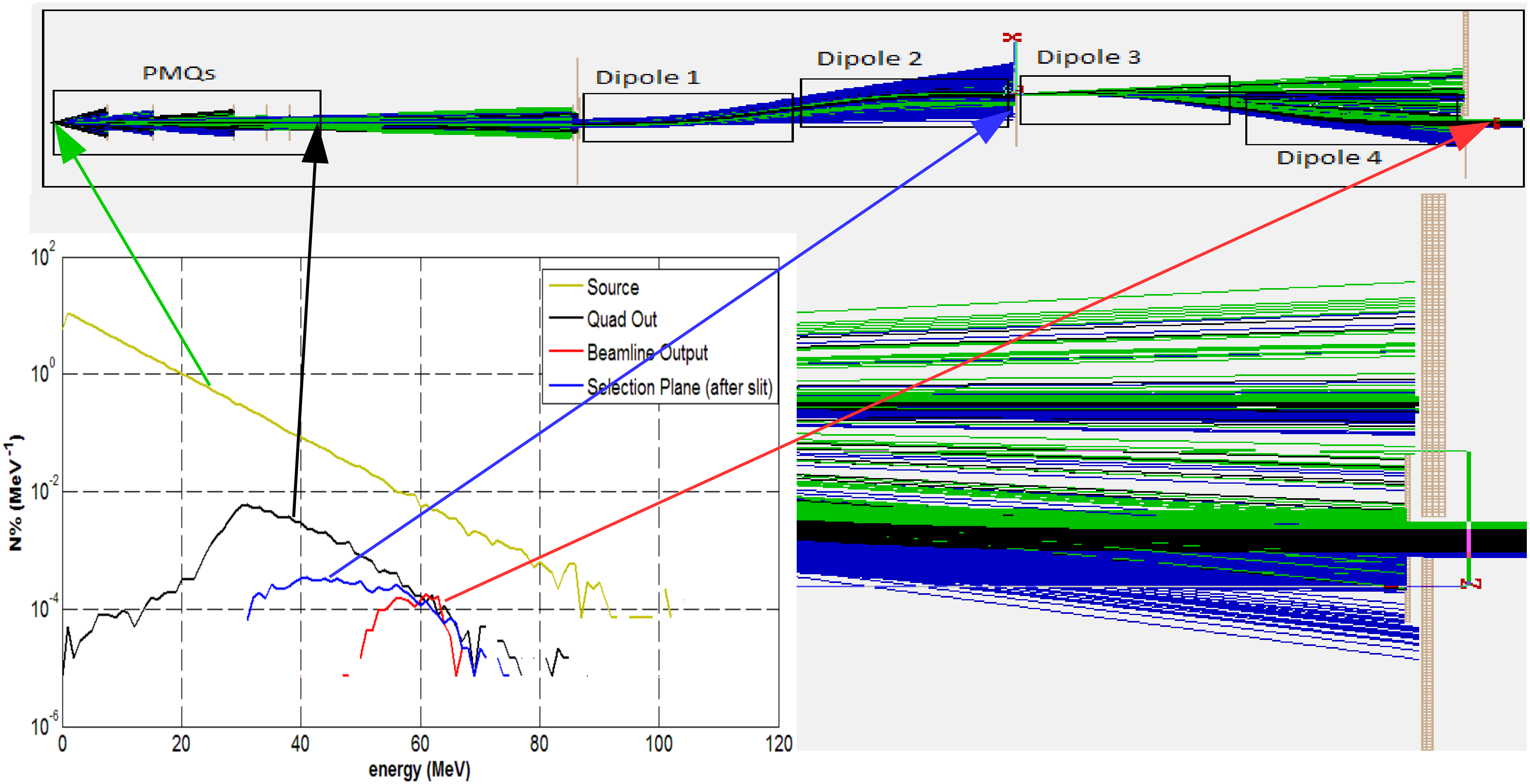
Transmission efficiency ~12% (9,2e7 H^+/bunch)



Beam transport
TNSA-like protons

Angular divergence = 5° (FWHM)

Transmission efficiency ~12% (9,2e7 H^+/bunch)



Beam transport TNSA-like protons

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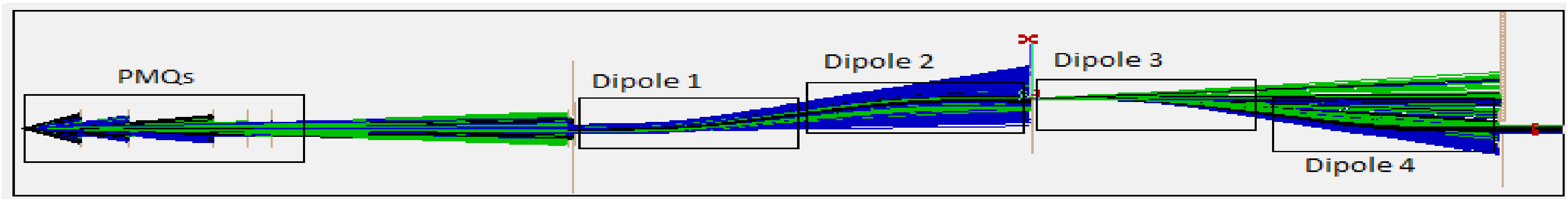
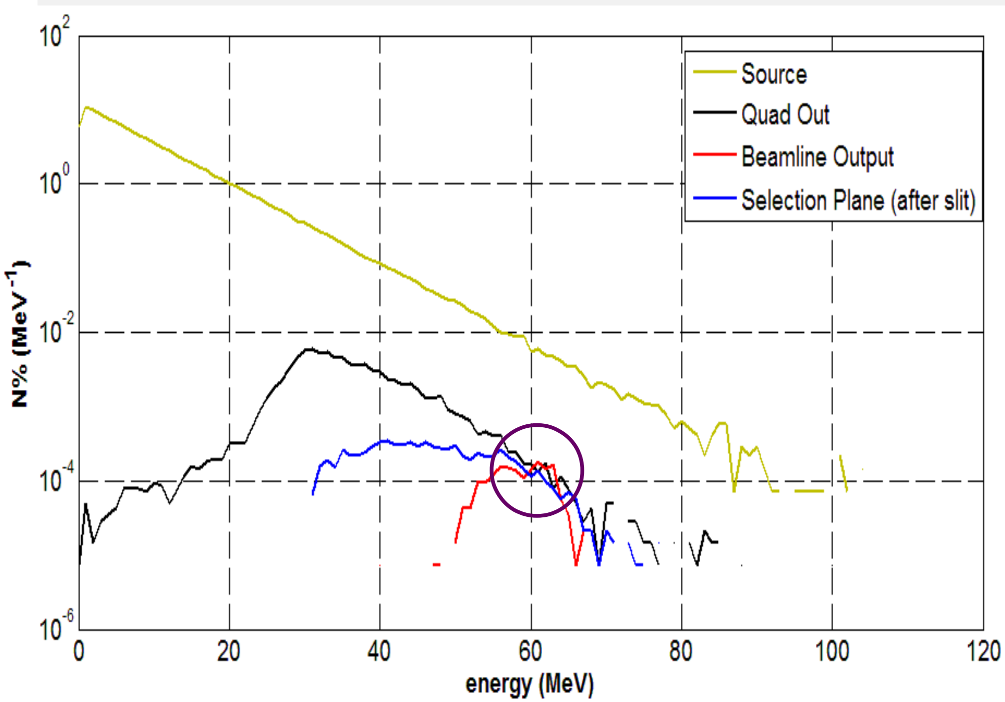
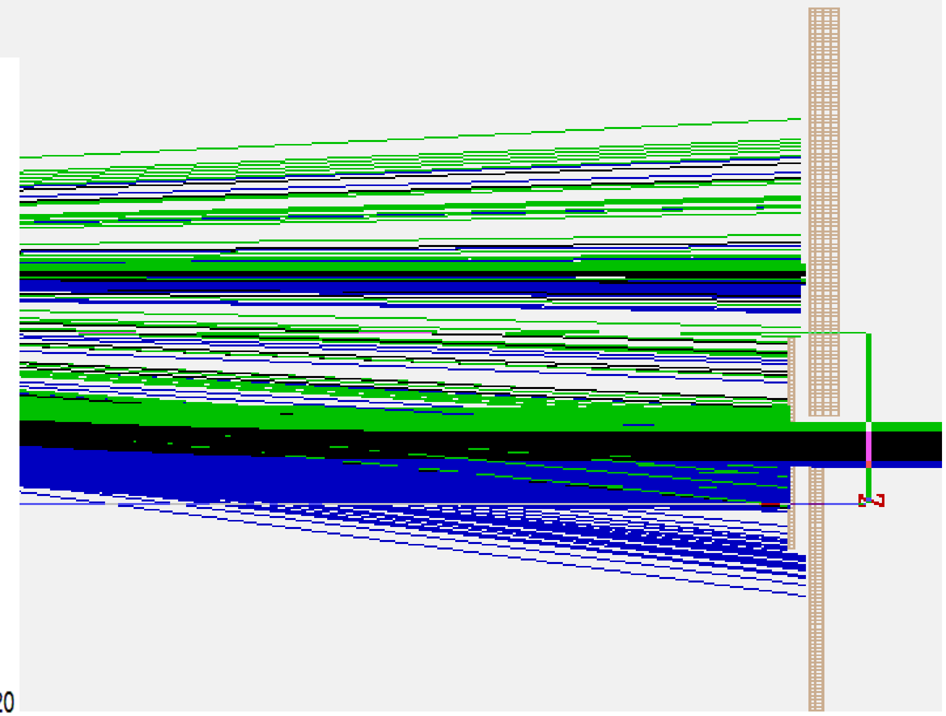




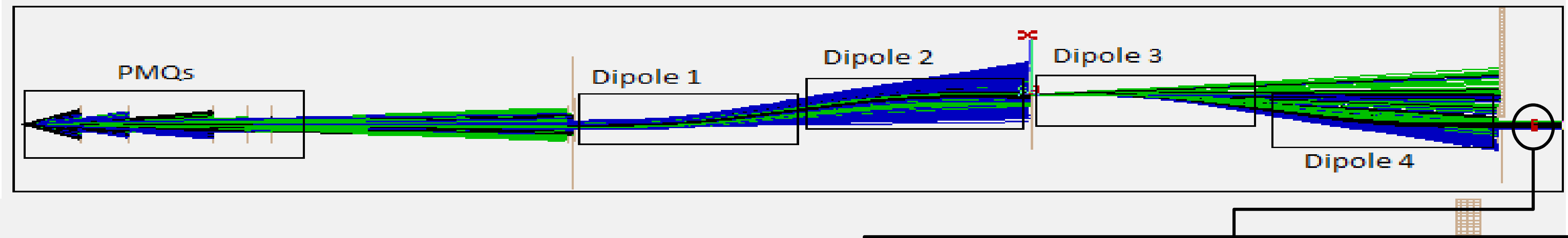


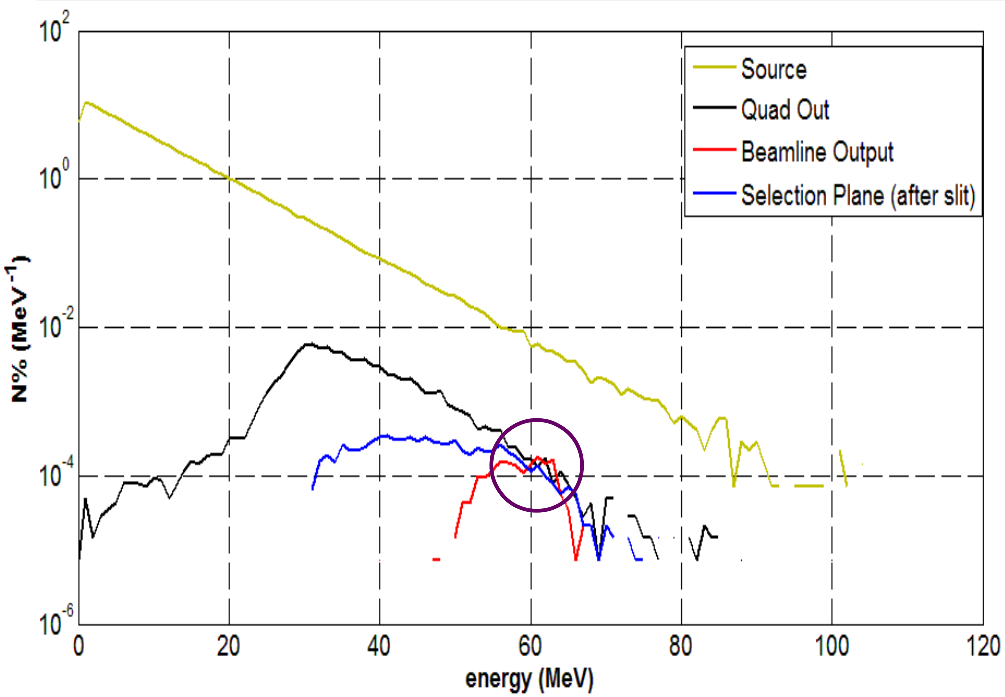
Beam transport TNSA-like protons

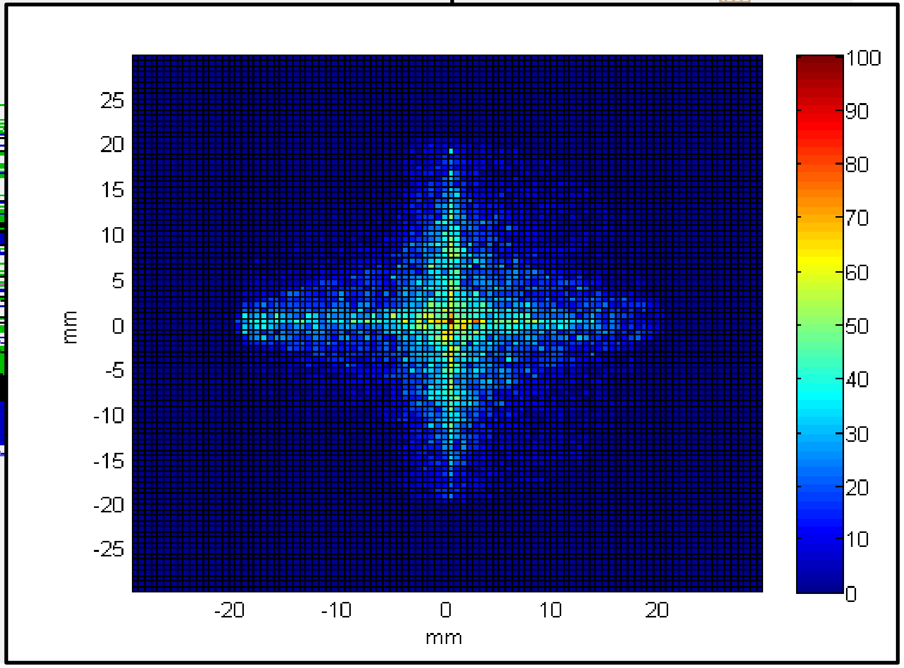
Angular divergence = 5° (FWHM)

Transmission efficiency ~12% (9,2e7 H^+/bunch)

Dose: ~0,05 Gy/bunch
Fluence: ~ $3x10^7$ H^+/cm^2







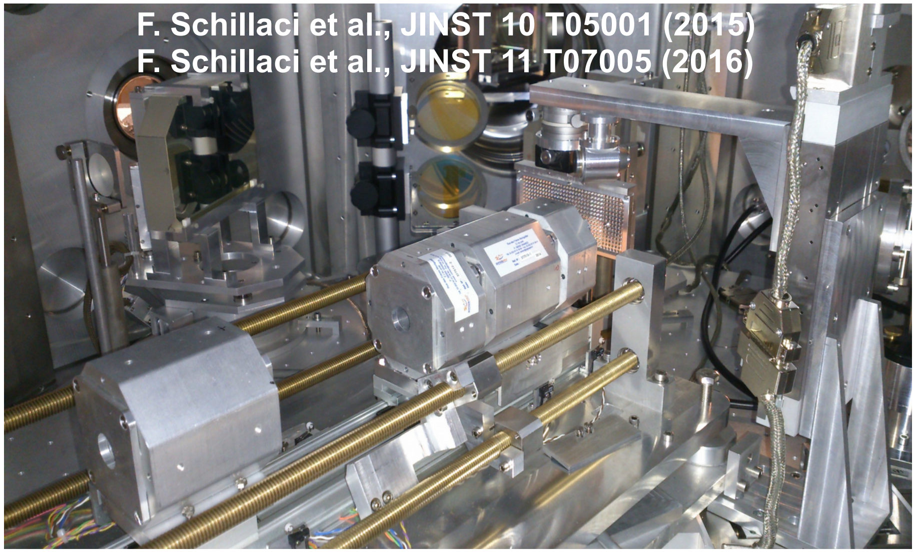
Beam transport simulations
vs
Real beam transport

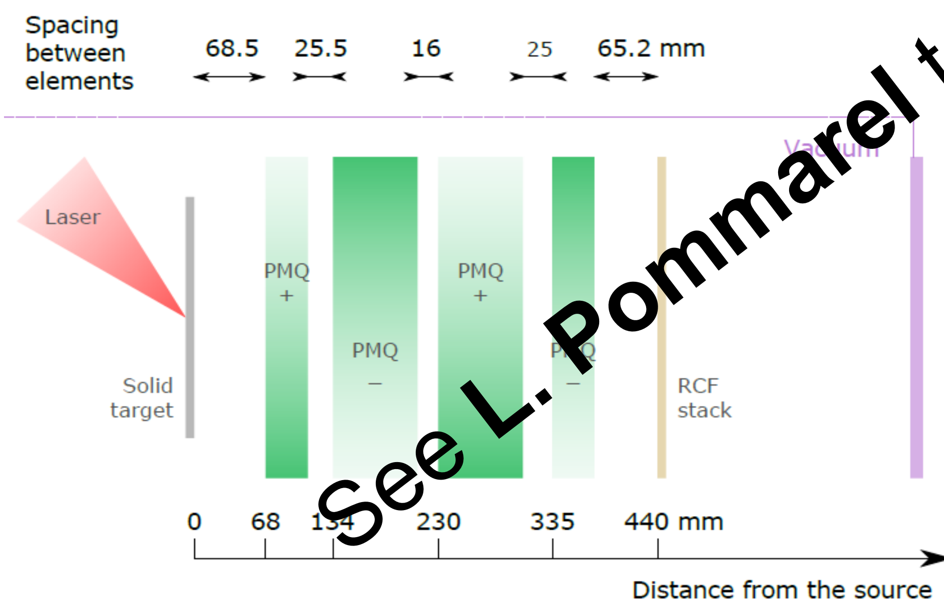
- Can be the transport codes for conventional accelerator studies used for laser-driven particles?

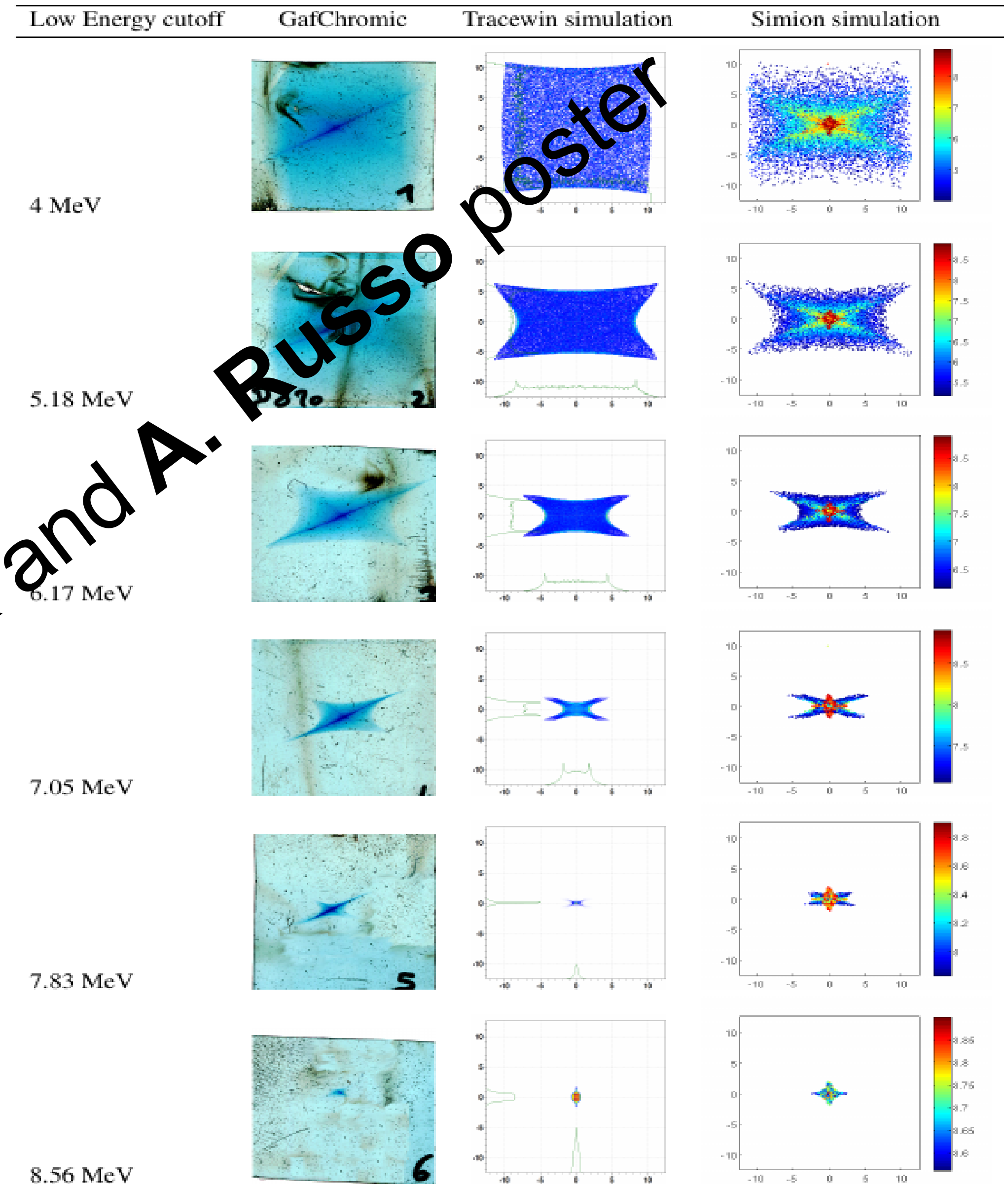
- Can we trust the results?

- Which are the limits?

Small PMQs @ LOA







See L. Pommarel talk and A. Russo poster

Conclusion

- Beam line elements have been designed considering all possible issues
  (For PMQs: demagnetization, thermal stability, secondary neutron flux and forces between magnets. Realization is in progress.
  For Dipoles: field uniformity along the reference trajectory, effective length variation and eddy currents. Final design is in progress.)
- Beam line performances are satisfactory
  (At least 10^7 particles per pulse transmitted in the wanted energy range.)
- Beam line set up have to be reviewed
  (Final design of the magnets and precise input beam features to improve optics and PMQs+ESS matching.)
- Last part of the beam line study is almost done
  (Simulations with TNSA-like beams to be carried out.)
- Beam output features to be improved
  (MC simulations for improving of the beam homogeneity with passive elements)

Grazie per l'attenzione!

INFN LNS

… and hope you'll enjoy Sicilia