DESIGN AND REALIZATION OF A BEAM TRANSPORT LINE FOR HANDLING AND SELECTING LASER-DRIVEN ION BEAMS FOR MULTIDISCIPLINARY APPLICATIONS

F. Schillaci

IoP-ASCR, ELI-Beamlines
Prague, Czech Republic

And

INFN-LNS
Catania, Italy

francesco.schillaci@eli-beams.eu

ELIMED

MEDical application @ ELI-Beamlines

BLIN Workshop

Fyzikální ústav
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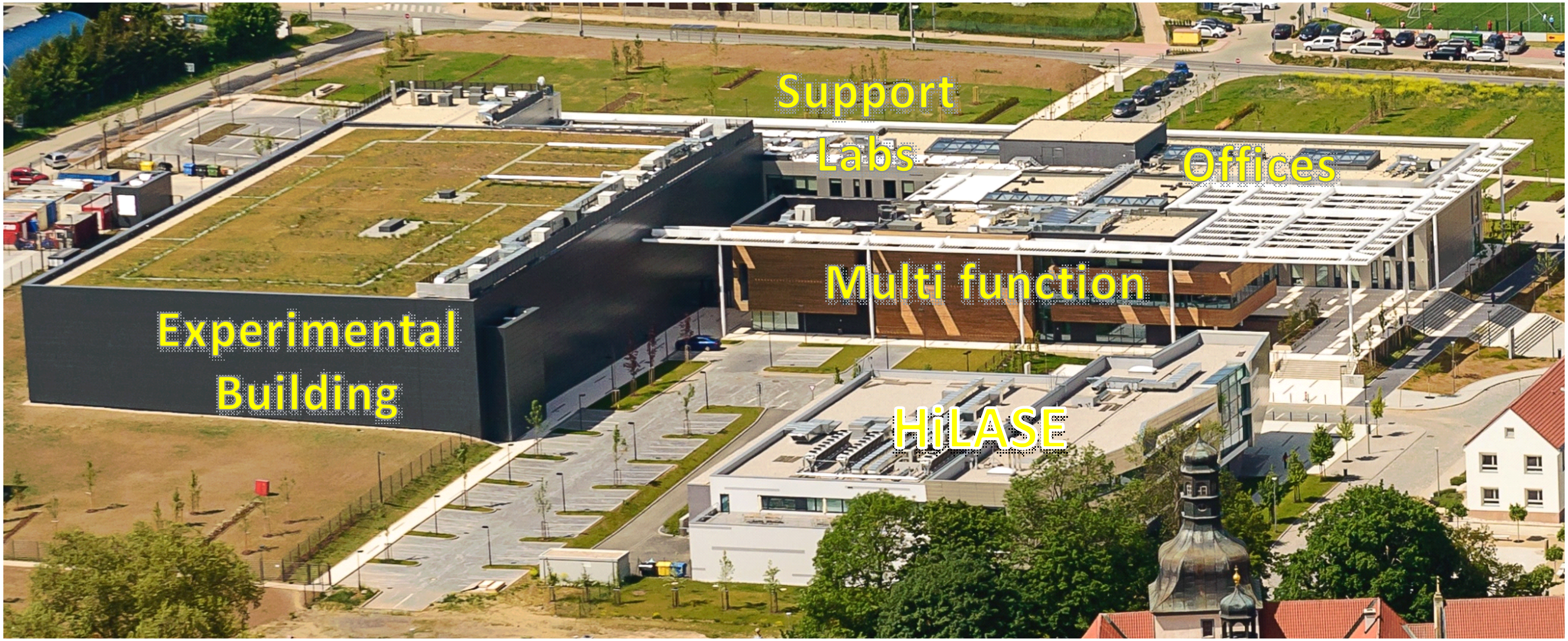
ELI-Beamlines in Czechia
Dolni Brezany



ELI-Beamlines in Czechia
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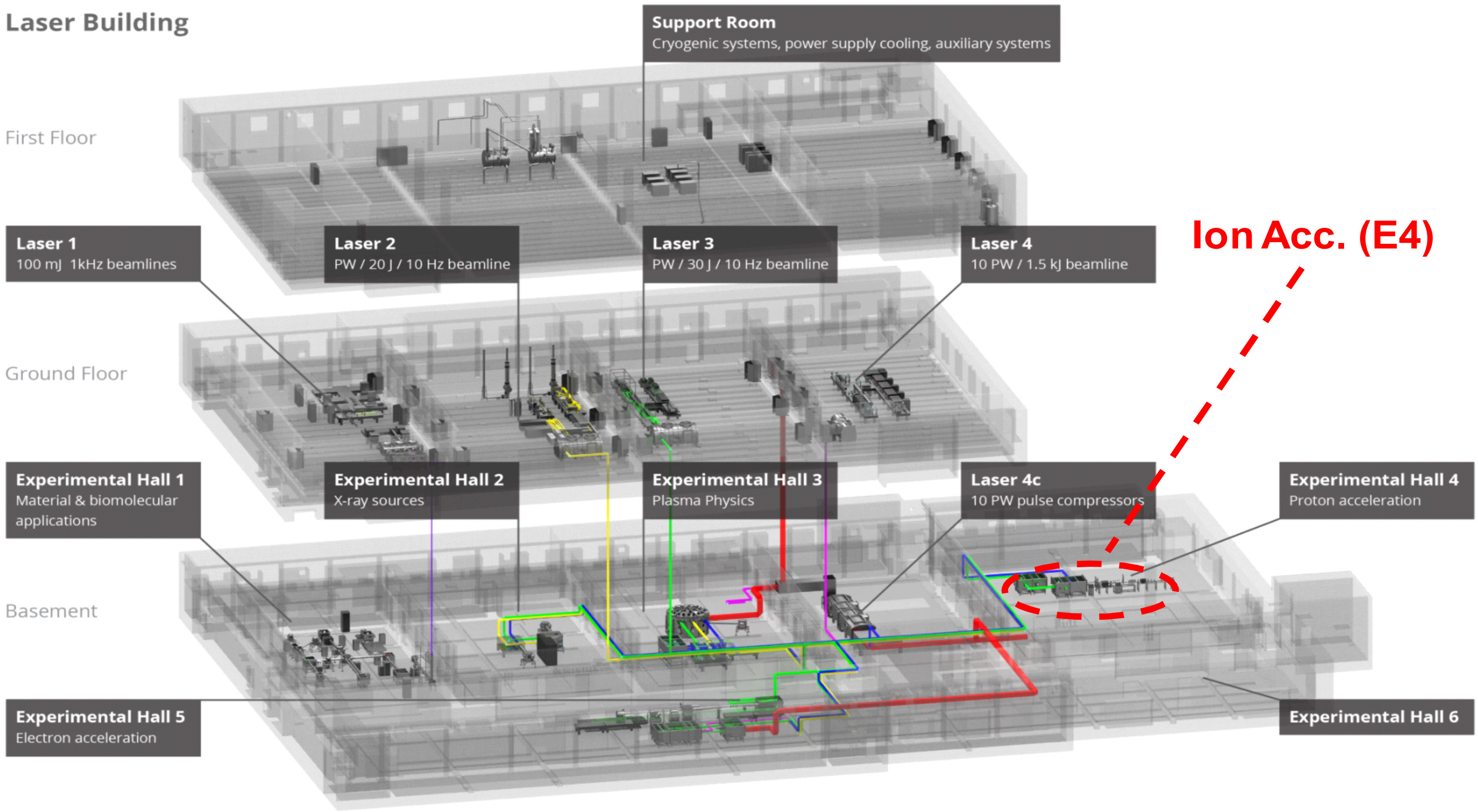

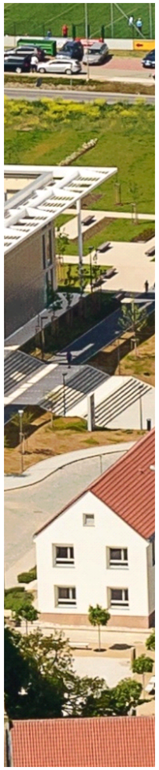

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ELIMAIA: a User Beamline

Summary of key equipment

Equipment	2018	2019-2020
Vacumm chambers	Target chamb., plasma mirr. chamb., user station	10 PW chamber
Focusing Optics (OAP)	f/1.5 (L3)	f/3 or f/4 (L4)
Targets (0.01-10 Hz)	thin foils @1Hz (0.01-10 μm)	Cryog. H @10Hz (5-100 μm)
Diagnostics (0.01-10 Hz)	TP ion spectr., TOF detectors, optical probes, Espec, X-ray cameras	Streak cameras
Ion beam transport	PMQs, energy selector, conventional elements	Second beamline (@30deg) with Ion buncher (?)
Ion beam dosimeters	Faraday cup, ionization chamber, SEM	
Sample irradiation	In-air and in-vacuum system	

What users will get

Ion Beam Features (PW)	L3 HALPS 1 PW – 30 J, 30 fsec	L4 ATON 10 PW – 2 kJ, 130 fsec
Energy range	3-60 MeV/u	3-300 MeV/u
Ion No. / laser shot	$>10^9$ (0.1 nC) in 10% BW	$>10^{10}$ (1 nC) in 10% BW
Bunch duration	1-10 ns	0.1-10 ns
Energy spread	±5%	±2.5%
Divergence	±0.5°	± 0.2°
Ion Spot Size	0.1-10 mm	0.1-10 mm
Repetition rate	1 – 10 HZ	1 shot per minute

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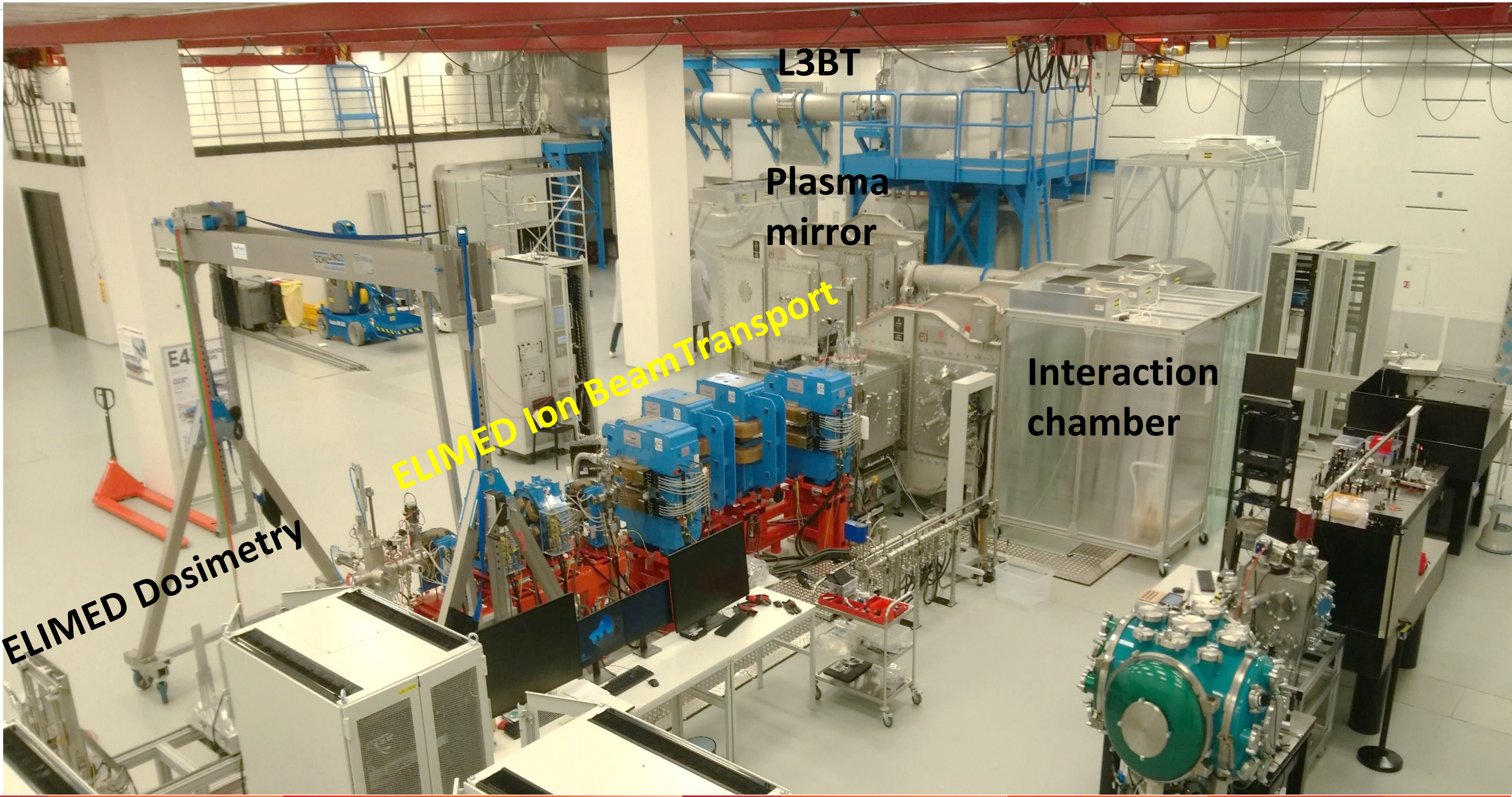

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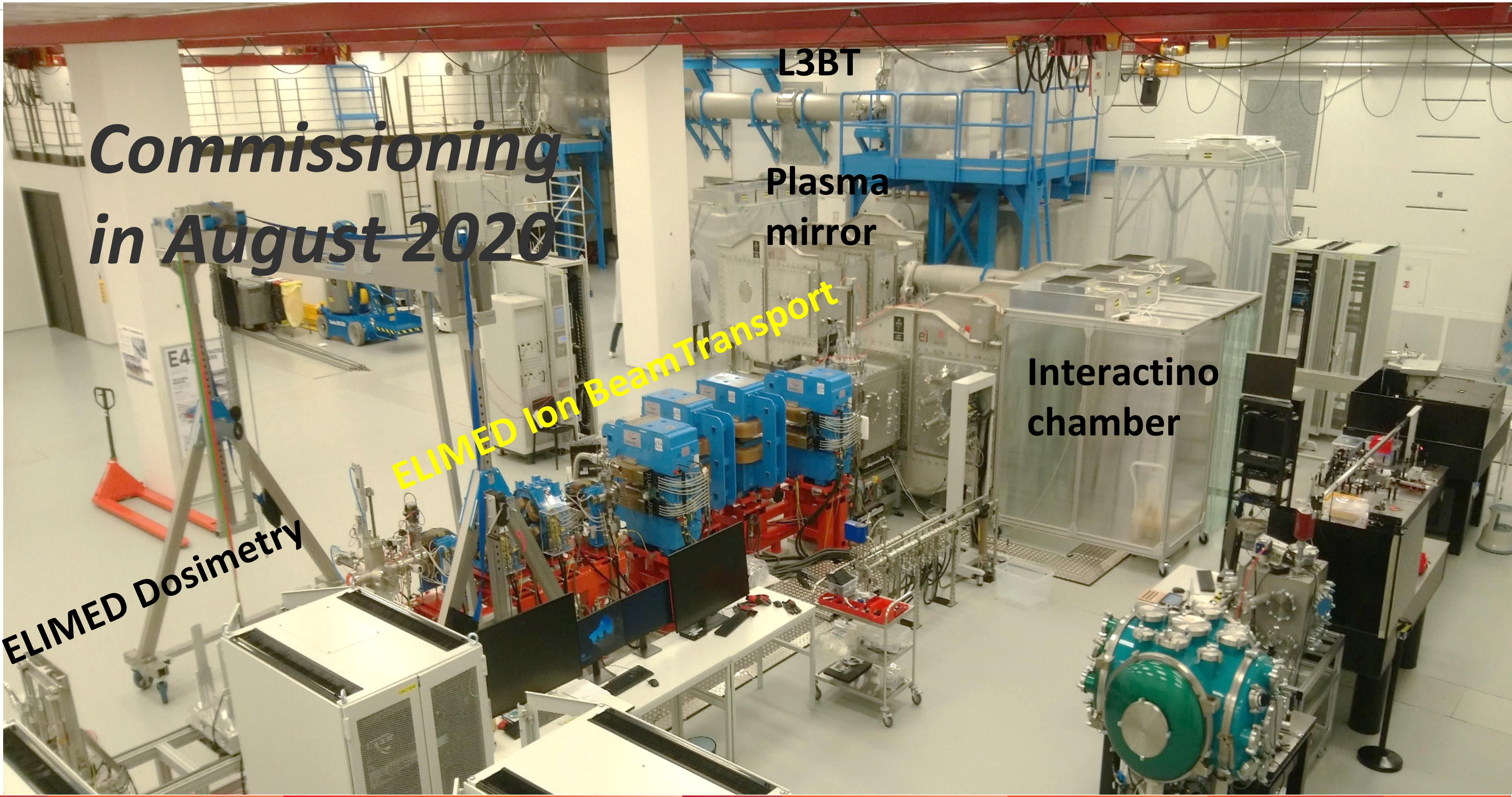

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ELIMAIA & ELIMED

Beam line elements:

1) Collection system
2) Selection system
3) Standard transport elements (quads and steerers)
4) in air dosimetry and irradiation

Beam line features:

1) Tunability (from 5 up to 60 MeV/u) with a controllable energy spread
2) Large acceptance to minimize losses
3) Flexibility to meet different User requirements

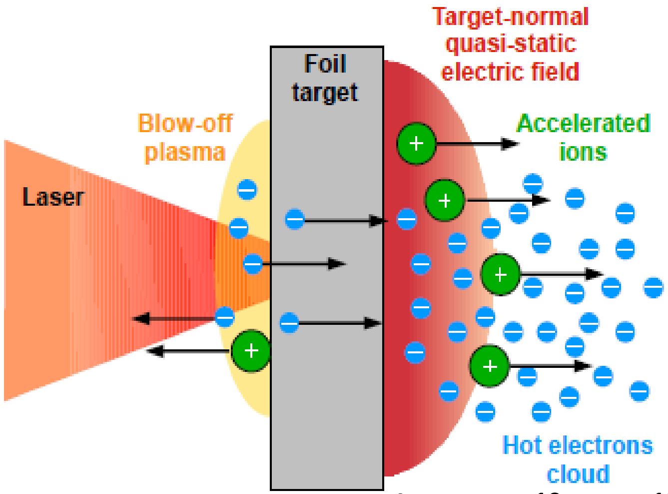
Acceleration & Collection

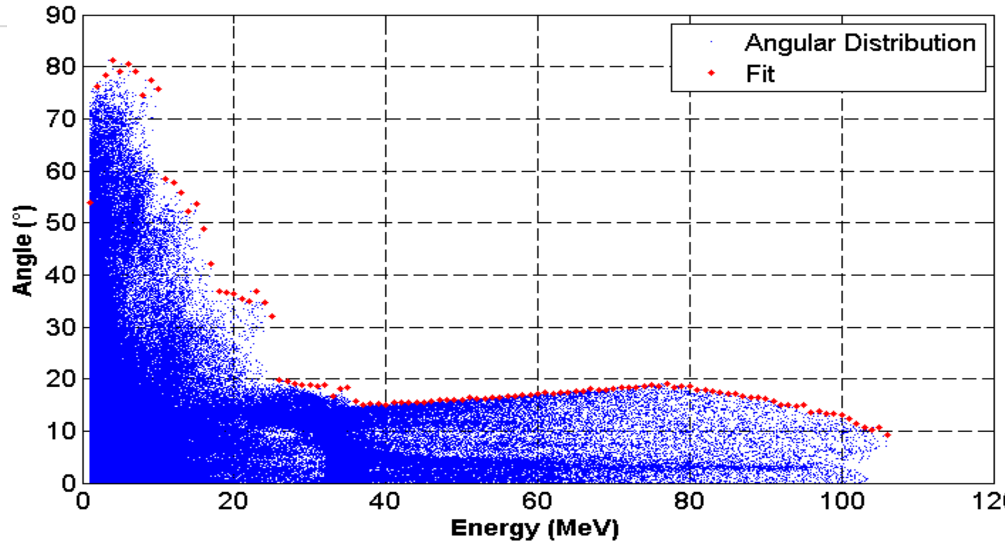
Selection, Transport & Diagnostics

Dosimetry & Sample Irradiation

ELI Multidisciplinary Applications of laser-Ion Acceleration

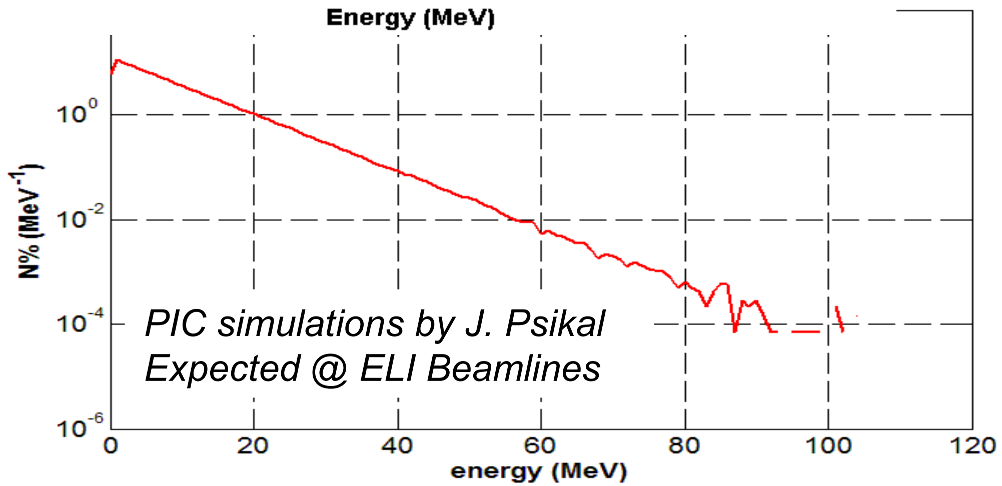
Laser-driven ion *beams*

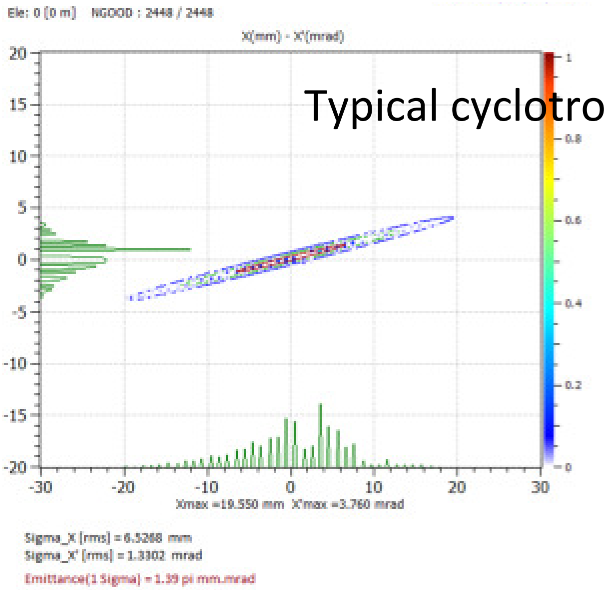




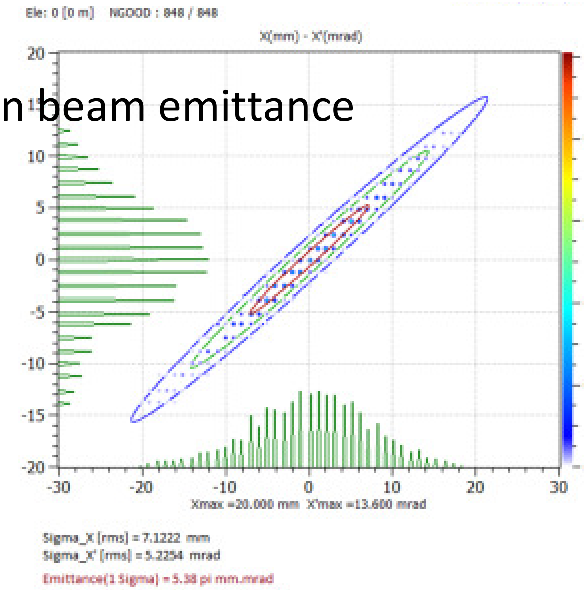
- Large proton number: **$10^{10} \div 10^{13}$**
- Short bunch duration: **few psec**
- High Beam Current: **kA**
- *<u>!Low Emittance!</u>*: **5×10^{-3} π mm mrad**

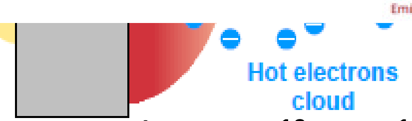
- Wide Angular Aperture: **10 – 20°**
- High Energy Spread: **ΔE/E >> 10%**
- Low shot-to-shot reproducibilty
- High dose-rate per bunch: ~10^9 Gy/sec

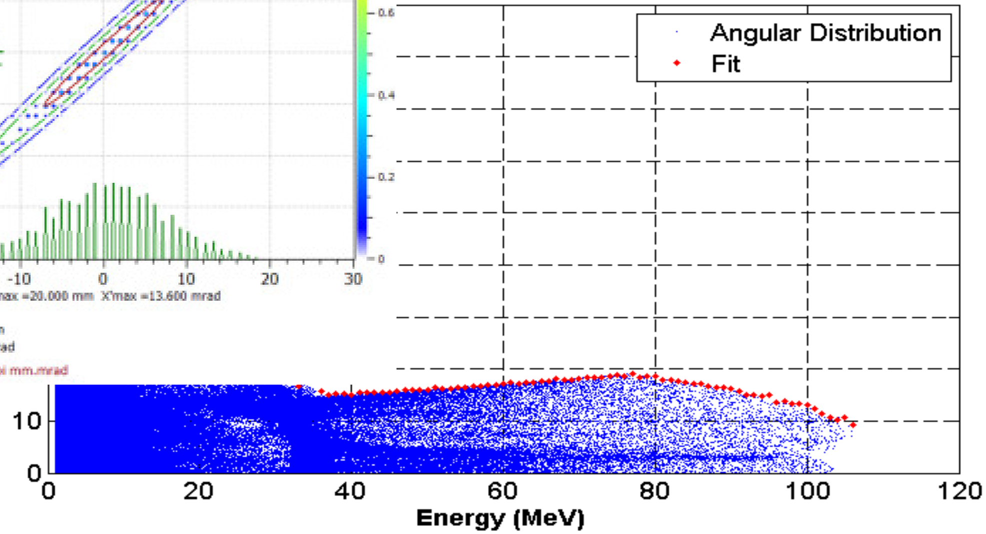




Typical cyclotron beam emittance

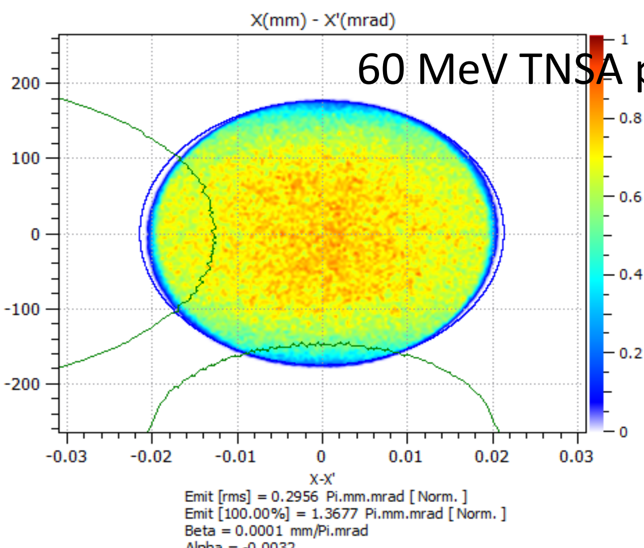


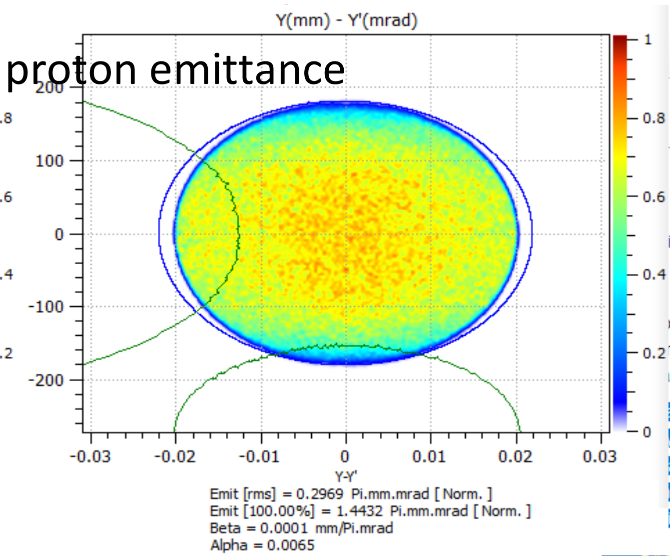




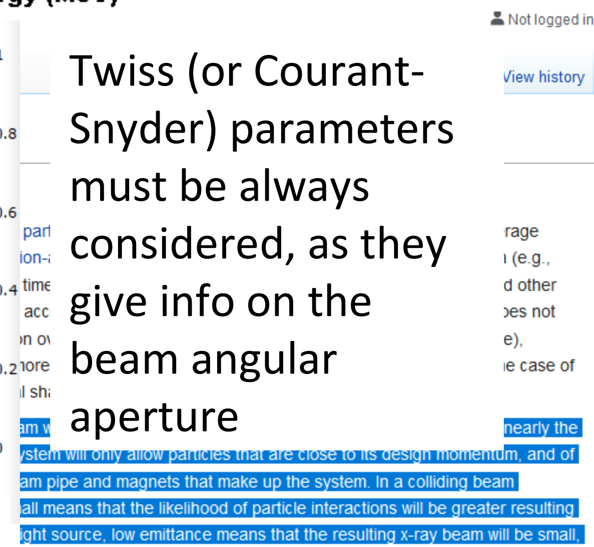
- Large proton number: $10^{10} \div 10^{13}$

60 MeV TNSA proton emittance





Twiss (or Courant-Snyder) parameters must be always considered, as they give info on the beam angular aperture



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Acceleration & Collection | Selection, Transport & Diagnostics | Dosimetry & Sample Irradiation

ELI Multidisciplinary **A**pplications of laser-**I**on **A**cceleration

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- Beam transport simulations
- High resolution Thomson Parabola

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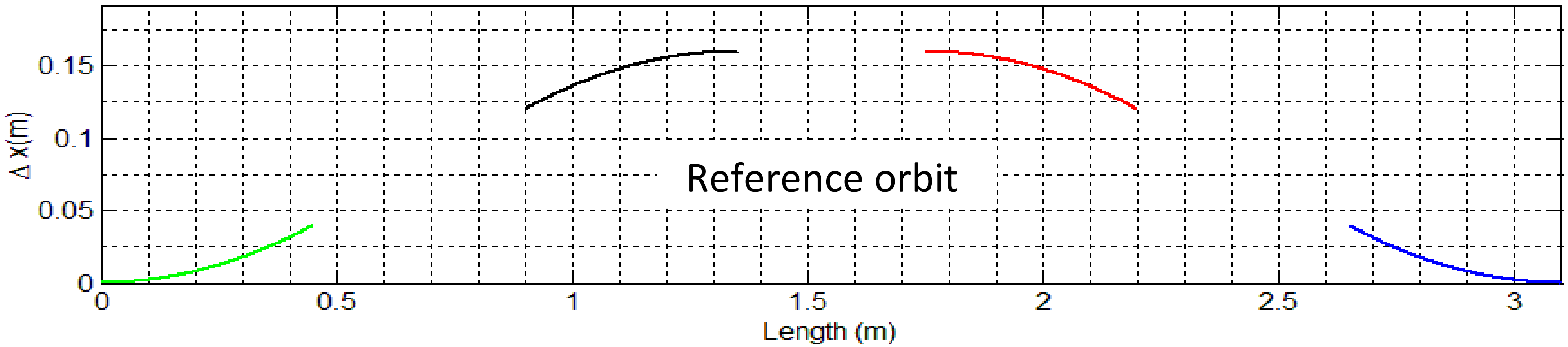
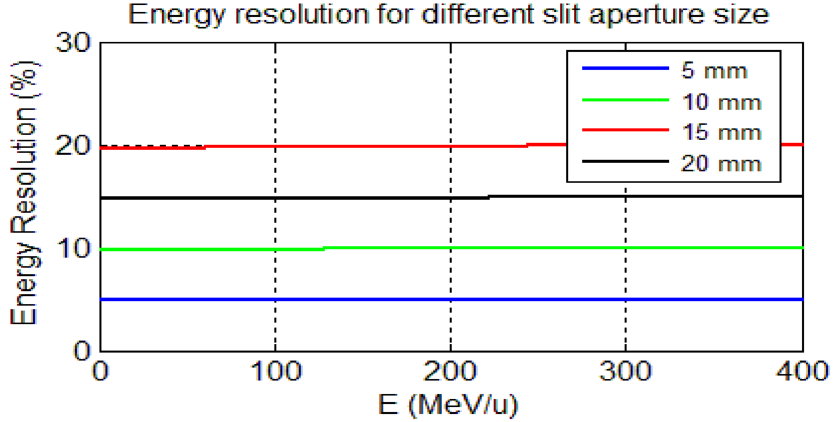
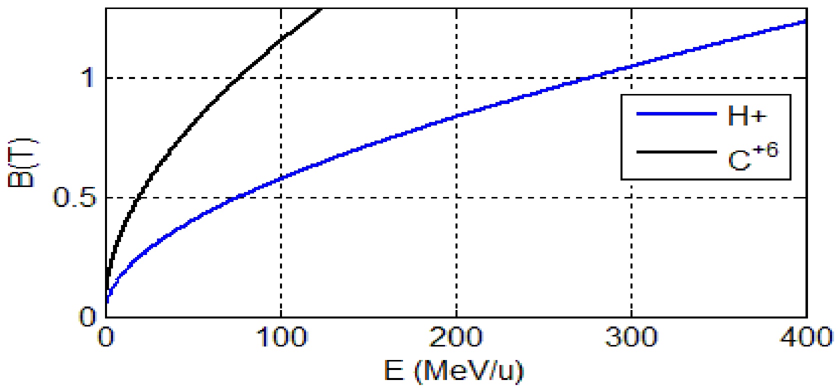
Energy selector
Reference orbit and layout

ESS Features







- Magnetic chicane based on a bunch compressor scheme

Path length: 3,168m

Two collimators φ = 30 mm, selection slit s x 20 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 $M_{12}=0$

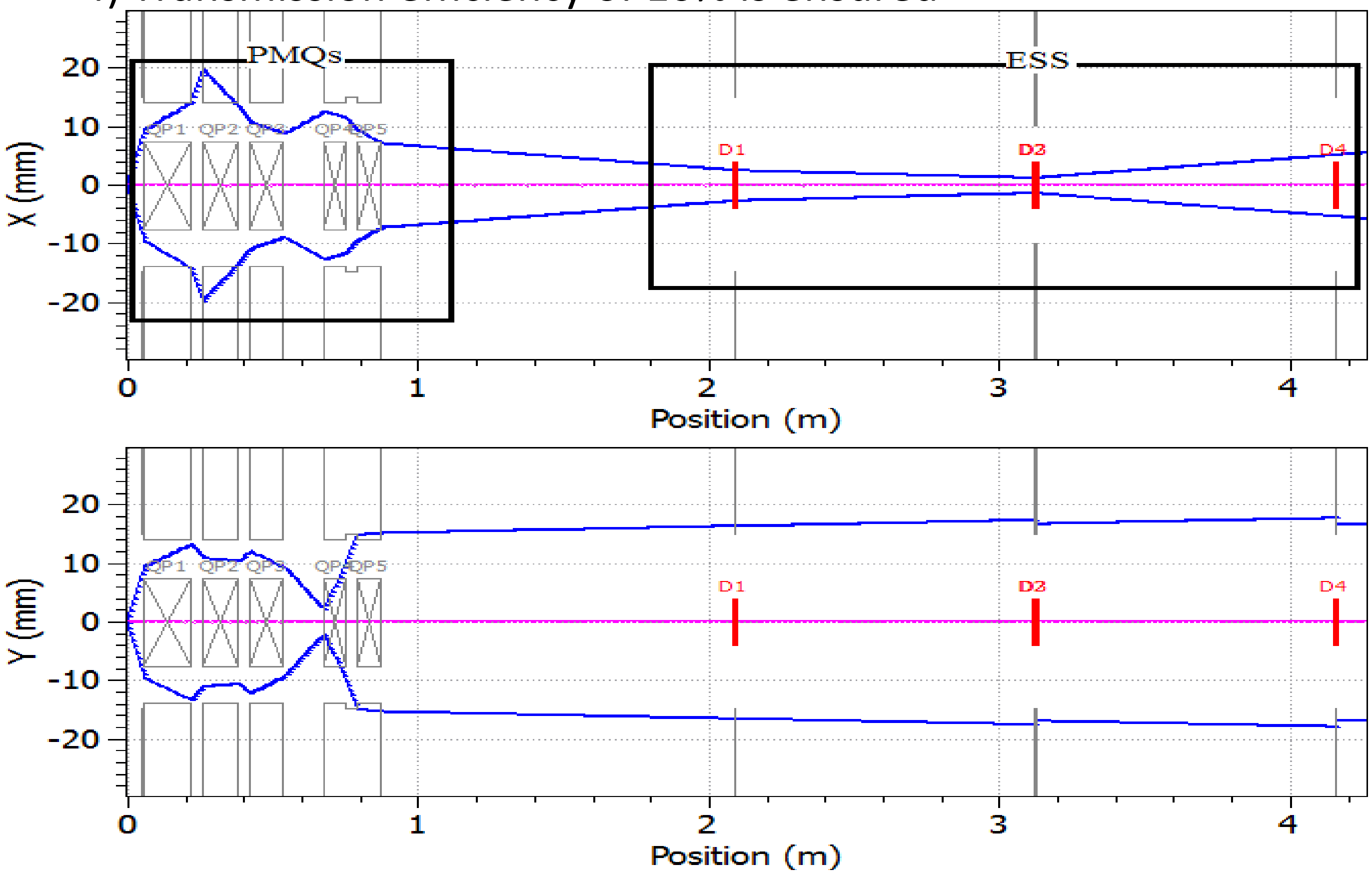
2) Parallel beam on the transverse plane $M_{44}=0$

3) Fixed beam dimensions at the selection plane (20x20mm)

4) Transmission efficiency of 10% is ensured

4 conditions require 4 quads

Originally they were 2x160 and 2x120
One of the longest was cut in 2 to match condition for all energies as cost effective solution



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

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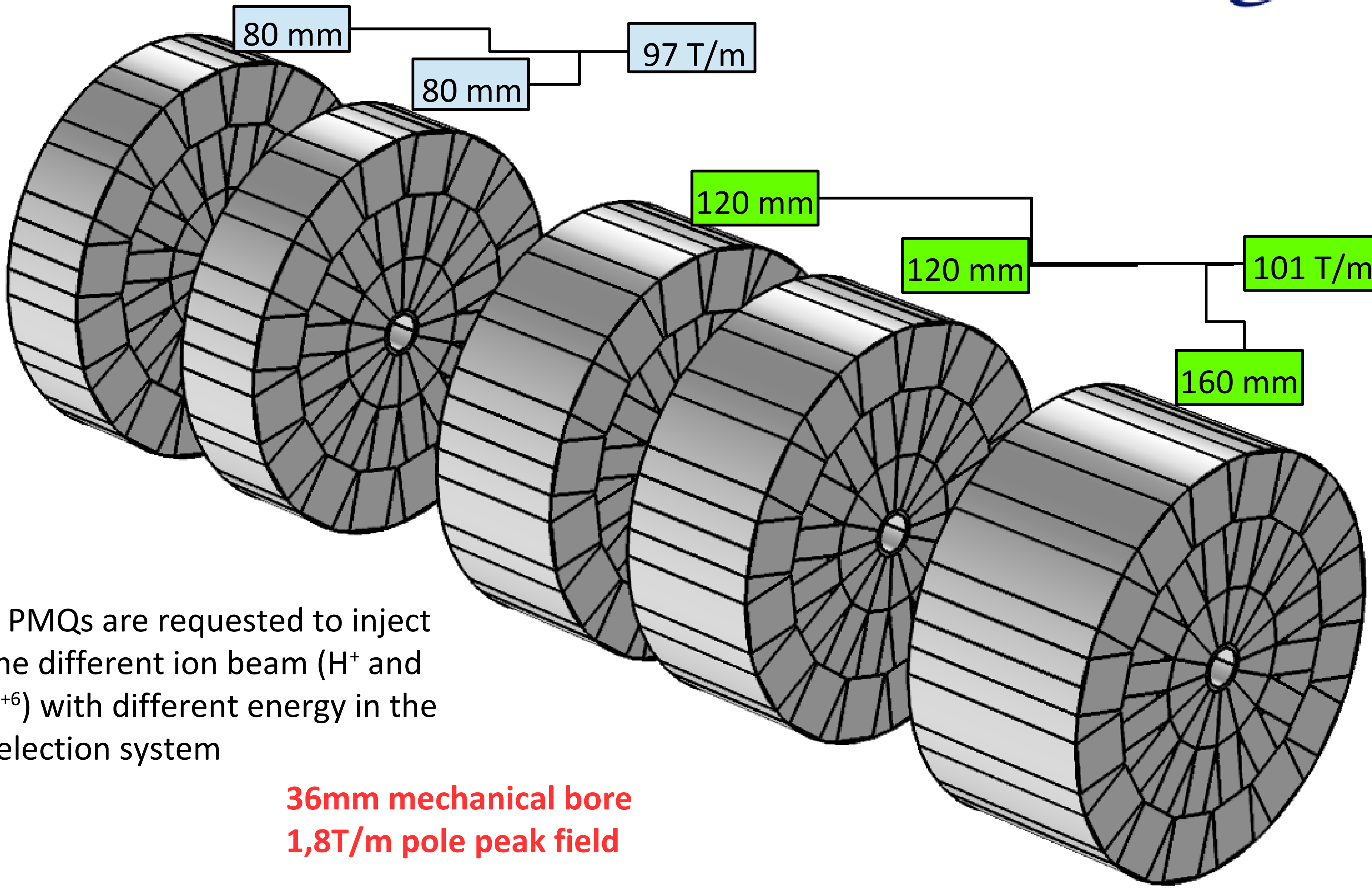
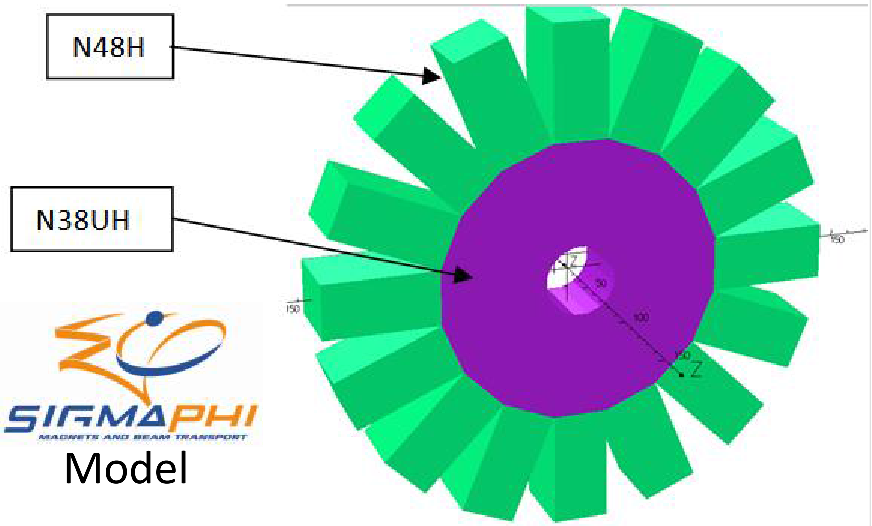
Collection systems

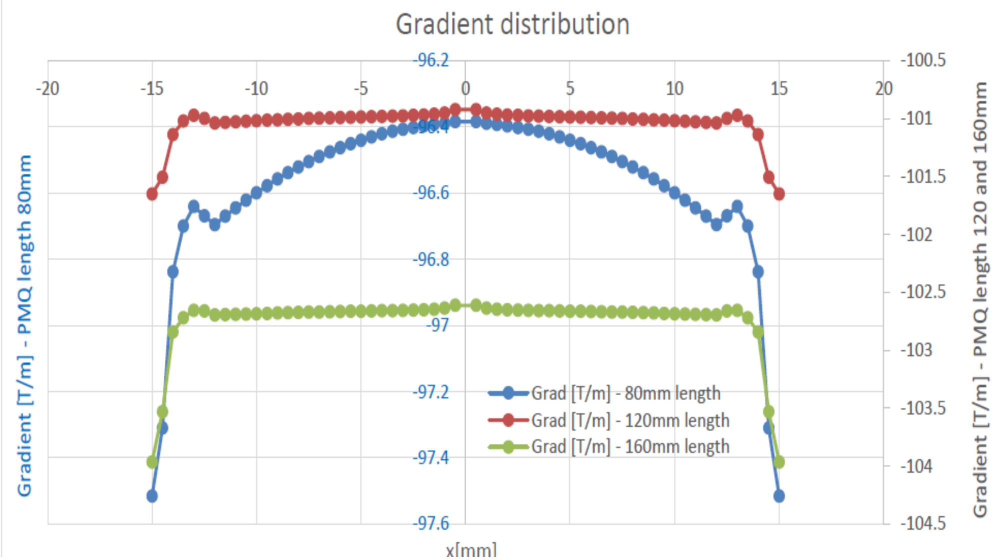


5 PMQs are requested to inject the different ion beam (H^+ and C^{+6}) with different energy in the selection system

36mm mechanical bore
1,8T/m pole peak field

Permanent Magnet Quads Final Design





36 mm magnetic bore

(3 mm shield + 30 mm for the beam – <u>same as INFN design</u>)

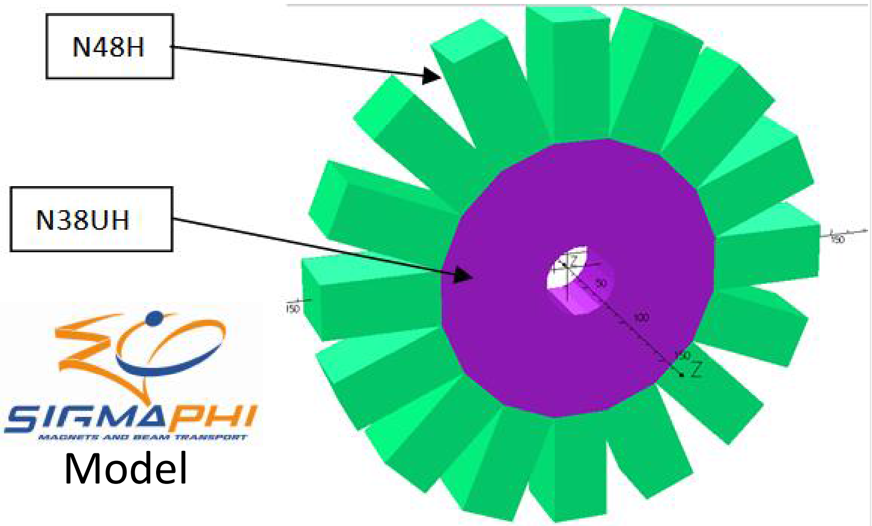
Inner Halbach trapezoidal

(149 mm outer diameter, NdFeB N38UH – 27 mm bigger than INFN design)

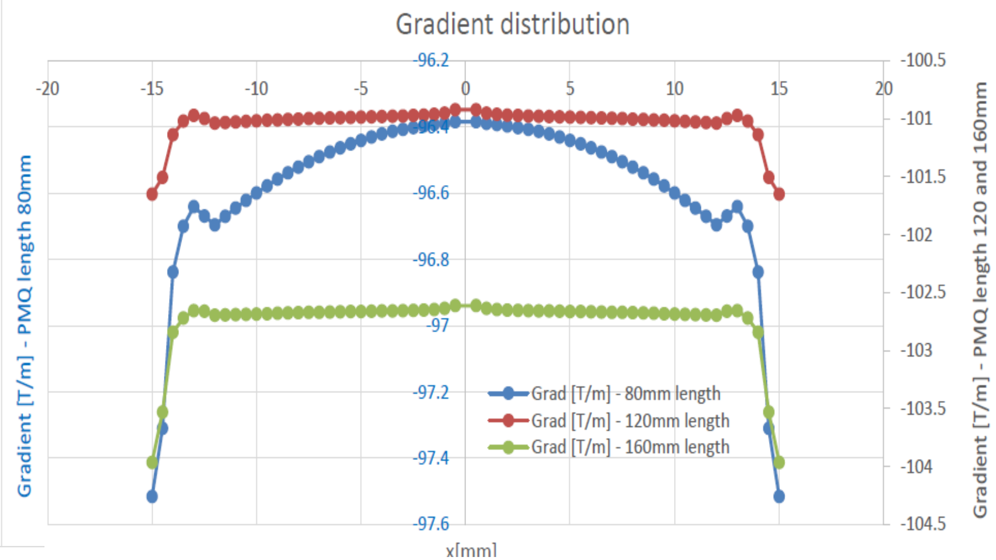
External array with rectangular blocks

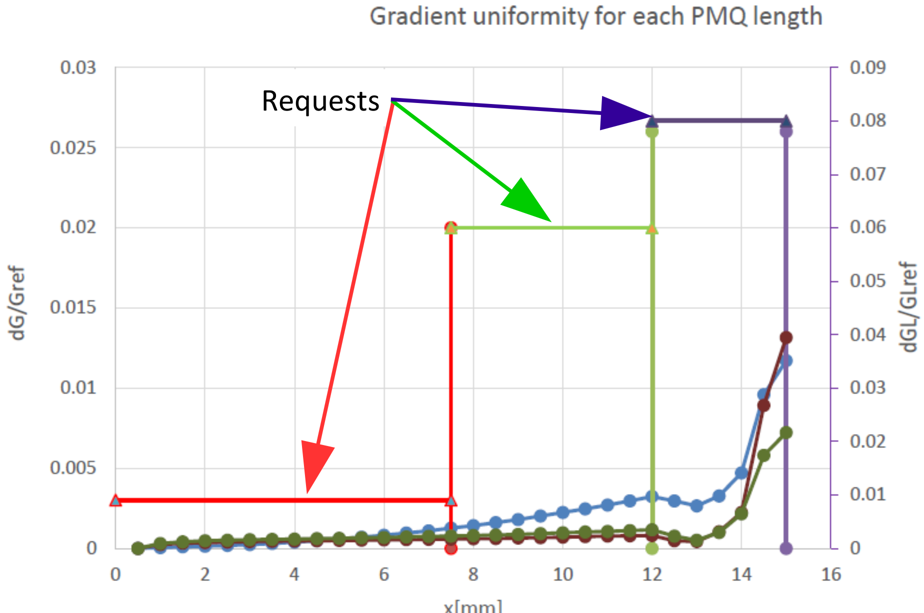
*(266 mm NdFeB N48H – <u>56 mm **smaller** than INFN design</u>)*

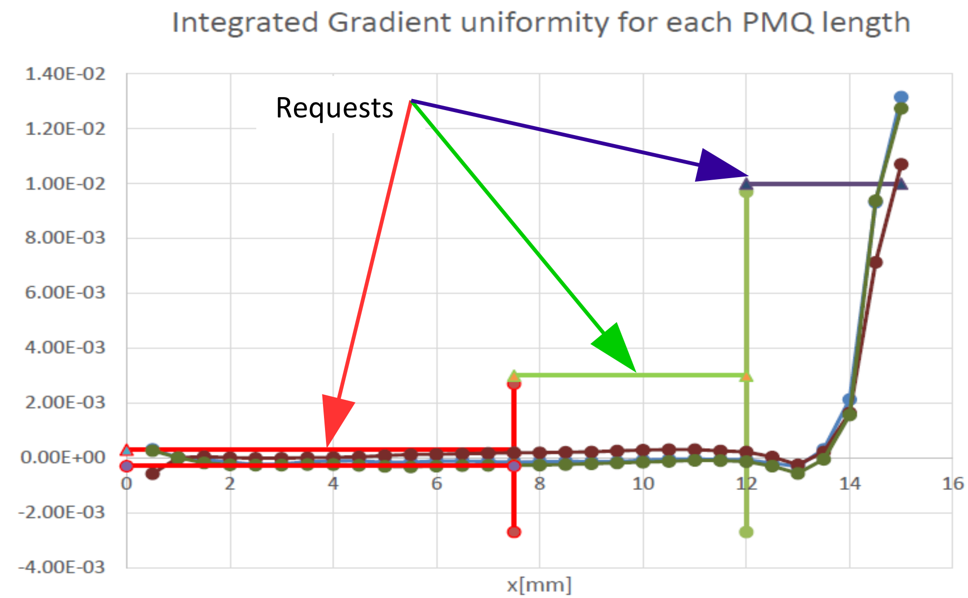
Permanent Magnet Quads Final Design



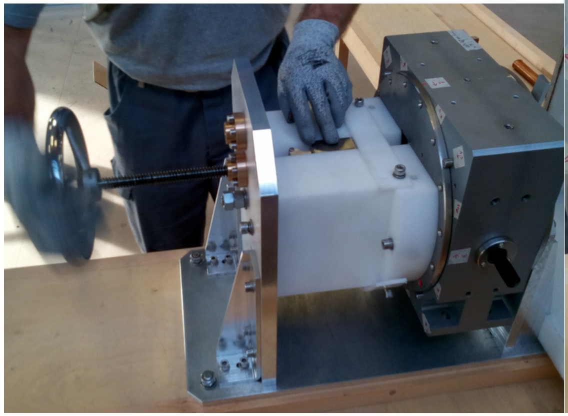
Model

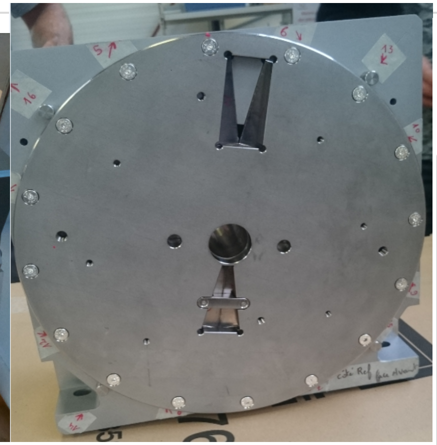




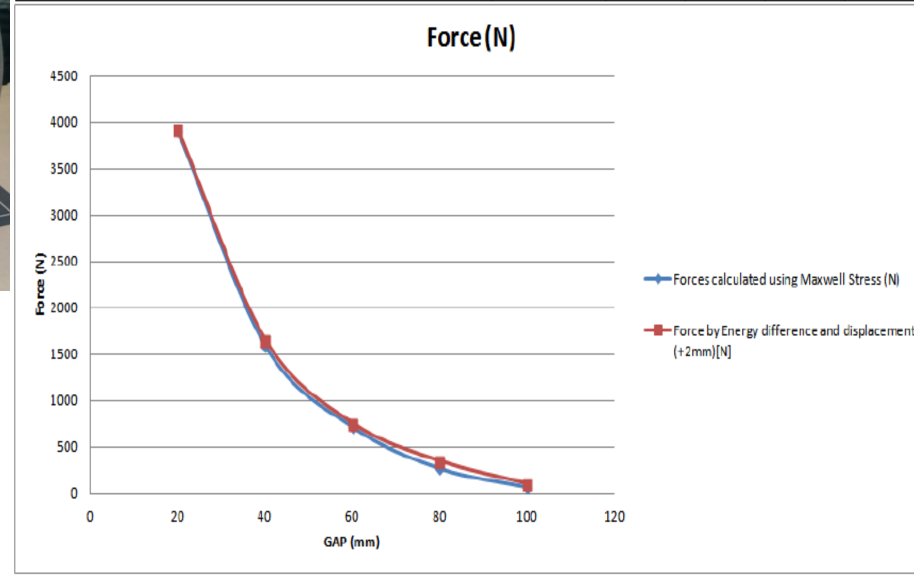


PMQs + Mechanics



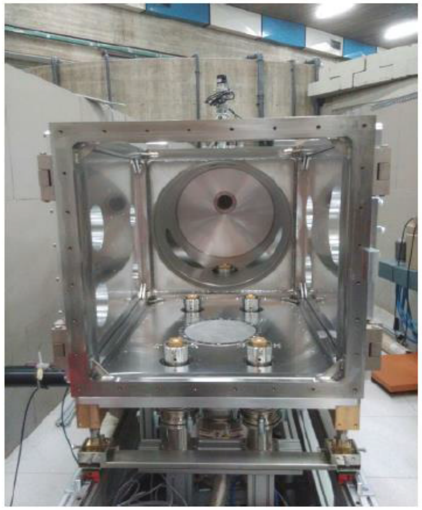


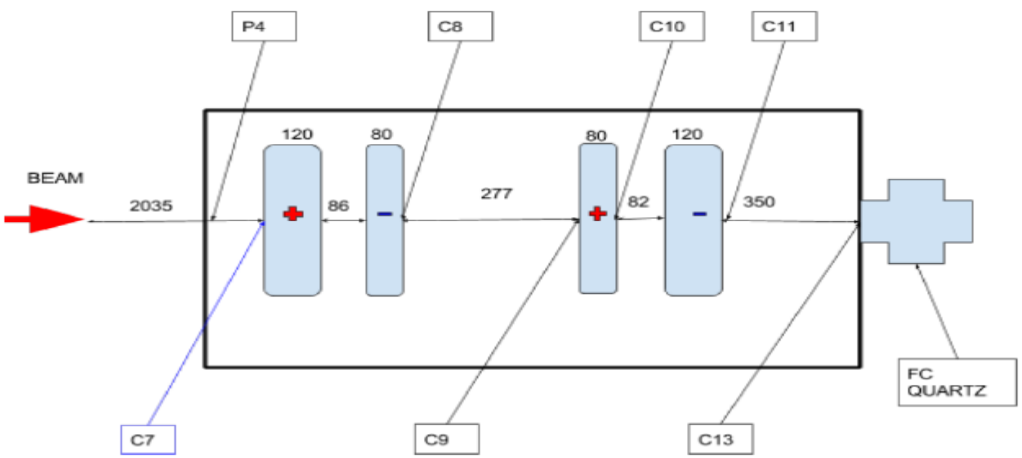
GAP between magnets	20	40	60	80	100
Forces calculated using Maxwell Stress (N)	3900	1591	716	266	64
Energy [J]	3467	3413	3389	3378	3373
Energy [J] +2mm	3460	3410	3388	3377	3373
Force by Energy difference and displacement (+2mm)[N]	3925	1660	760	350	105

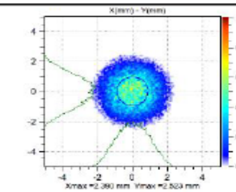
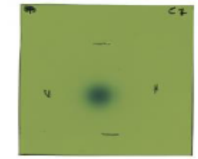
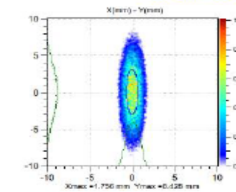
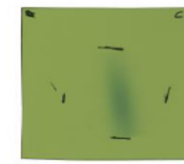
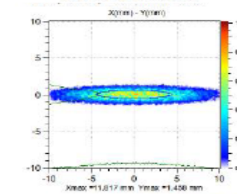
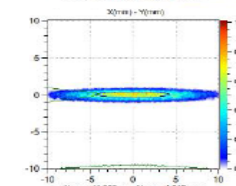
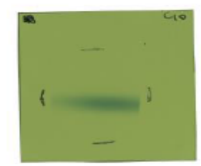
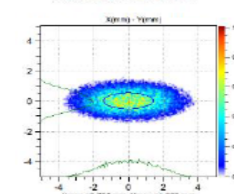
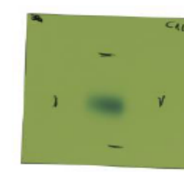
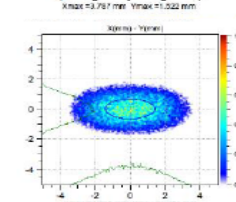


- 6 axis system
- Vacuum motors with low backlash gear (ratio 100:1)
- Absolute potentiometers for position encoding
- High precision radiation resistant switches
- High torques vacuum carriages and rails

ELIMED Collection system





Position	Simulation	GAF
C7		
C8		
C9		
C10		
C11		
C13		

OUTLINE

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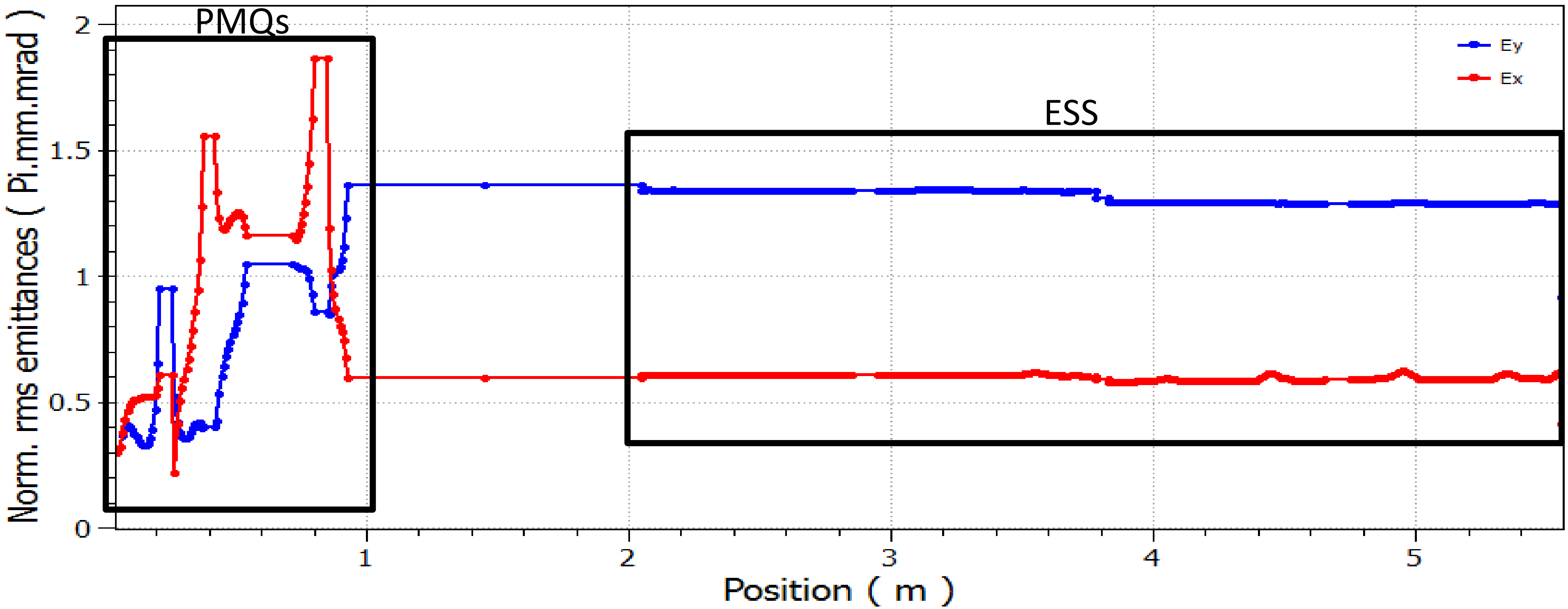
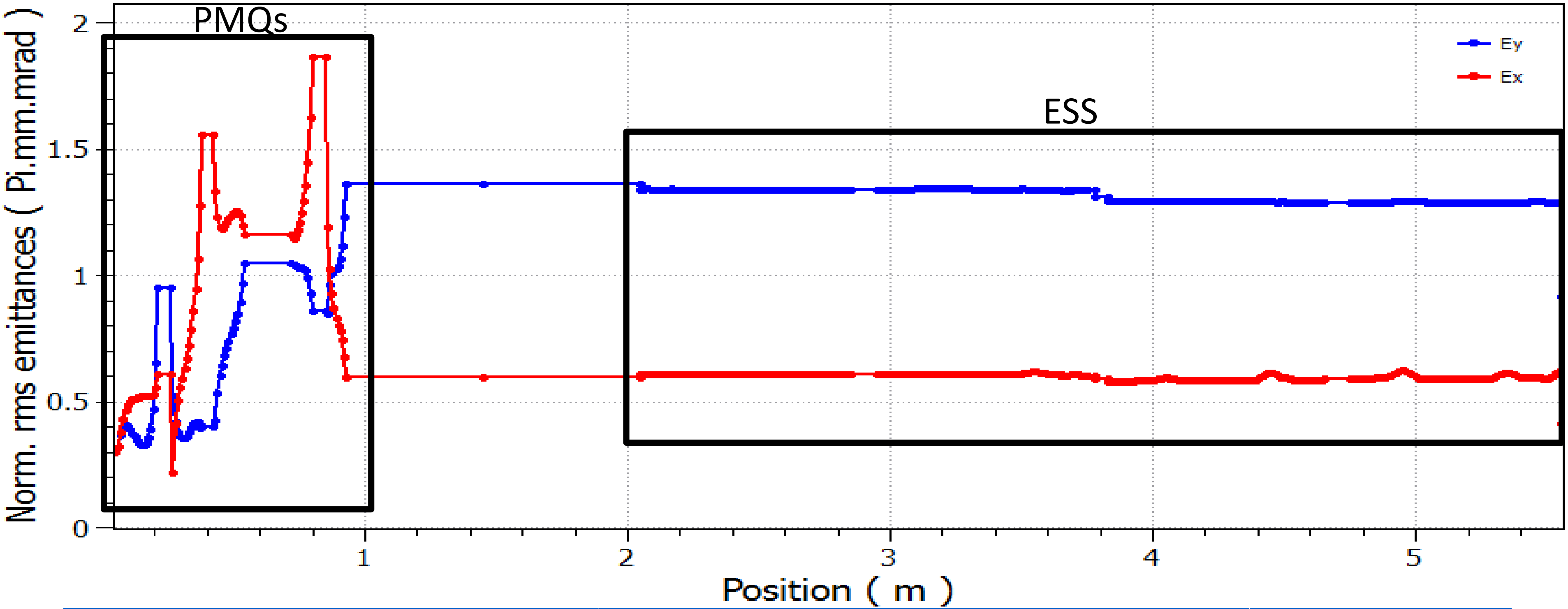
Emittance Growth and ESS acceptance



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.

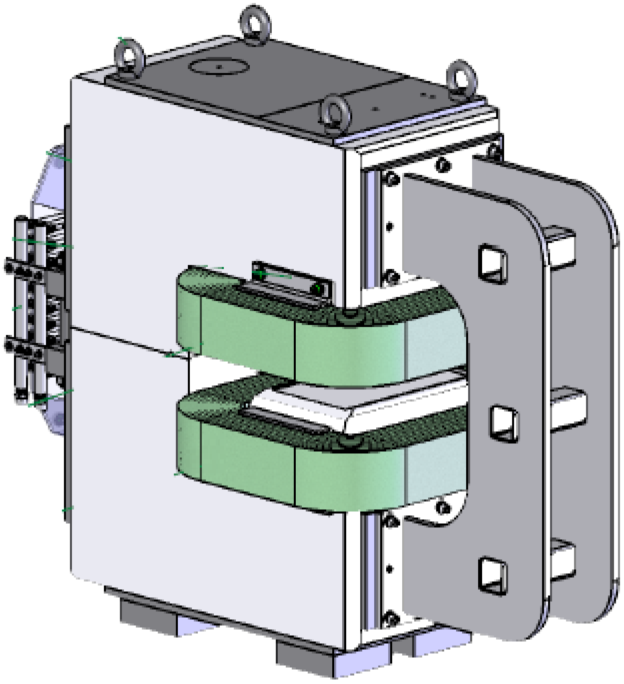
Emittance Growth and ESS acceptance



	XX`	YY`	XY
α	0.8401	0.3556	0.0002
β (mm/π mrad)	2.7094	2.4484	0.9112
Emit. Norm (mm/π mrad)	2.9506	3.9324	24.15 mm^2
Xmax	***Ymax***	***X`max***	***Y`max***
14.97 mm	14.99 mm	8.632 mrad	7.162 mrad

Energy Selector Features

n° of Dipoles	B field	Geometric length	Effective length	Gap
4	0.06 – 1.226 T	400 mm	450.23 – 448.34 mm	55 mm (shim)
Good Field region (GFR)	**Field uniformity**	**Curvature radius**	**Bending angle**	**Drift between dipoles**
100 mm	0.4 %	2.570 m	10.10°	500 mm



- Magnet efficiency: 97%
- Packing factor: 99% (1 mm lamination)
- 116x116 mm coil section (10x10 turns, 0.4 mm of insulator, 4 mm water channel)
- Max current: 300 A
- Total weight: 2.6 Tons
- < 28 kWatt in total

Reinforcemente to guarantee 42 mm inner clearence in the vacuum chamber

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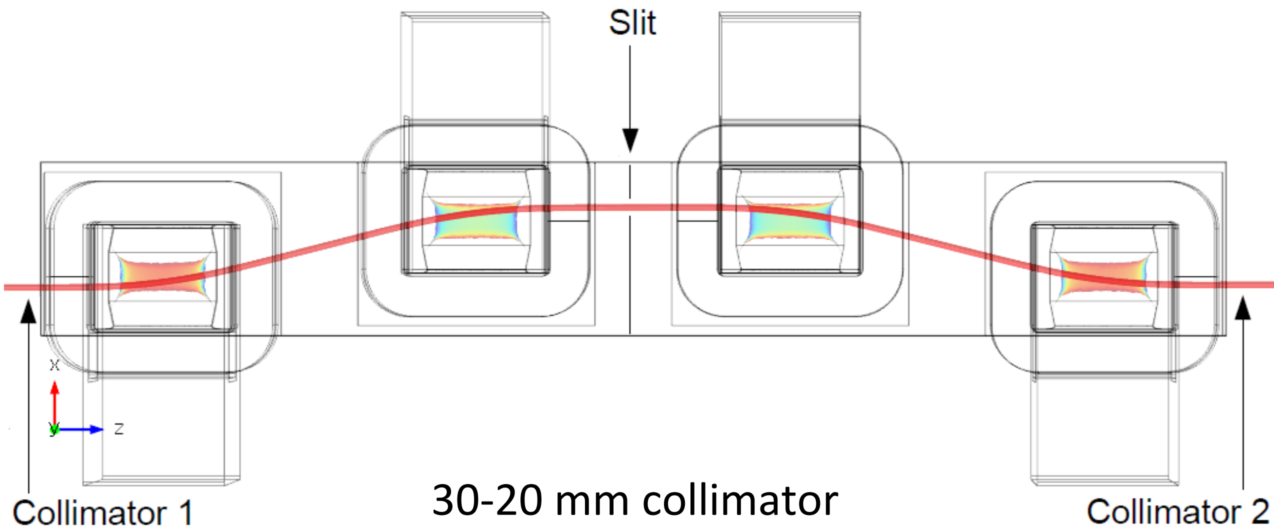
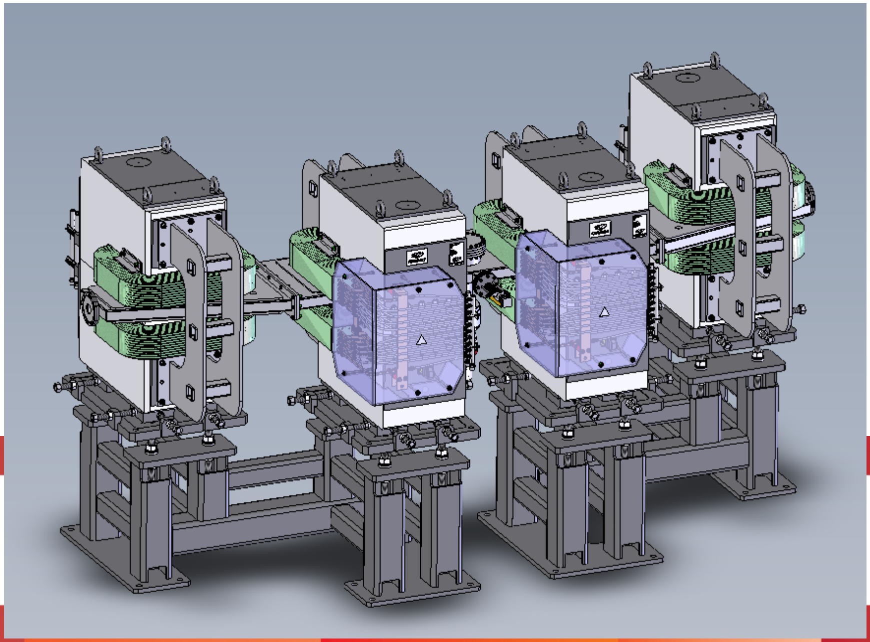
Double Dispersive Mode Magnetic Chicane





30-20 mm collimator upstream and downstream the chicane
(200 mm far from dipoles)

Variable slit aperture size (4 up to 20 mm)

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

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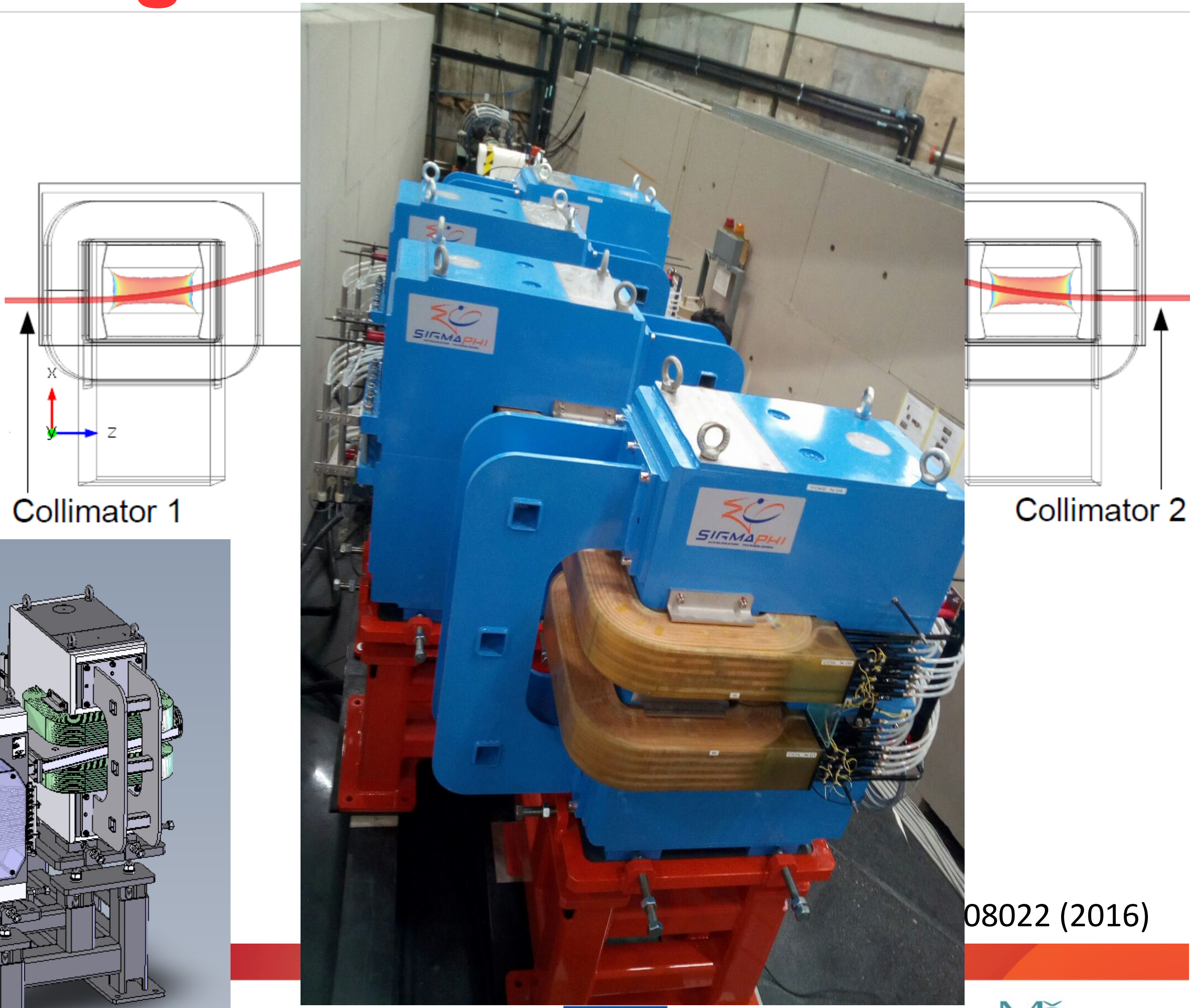
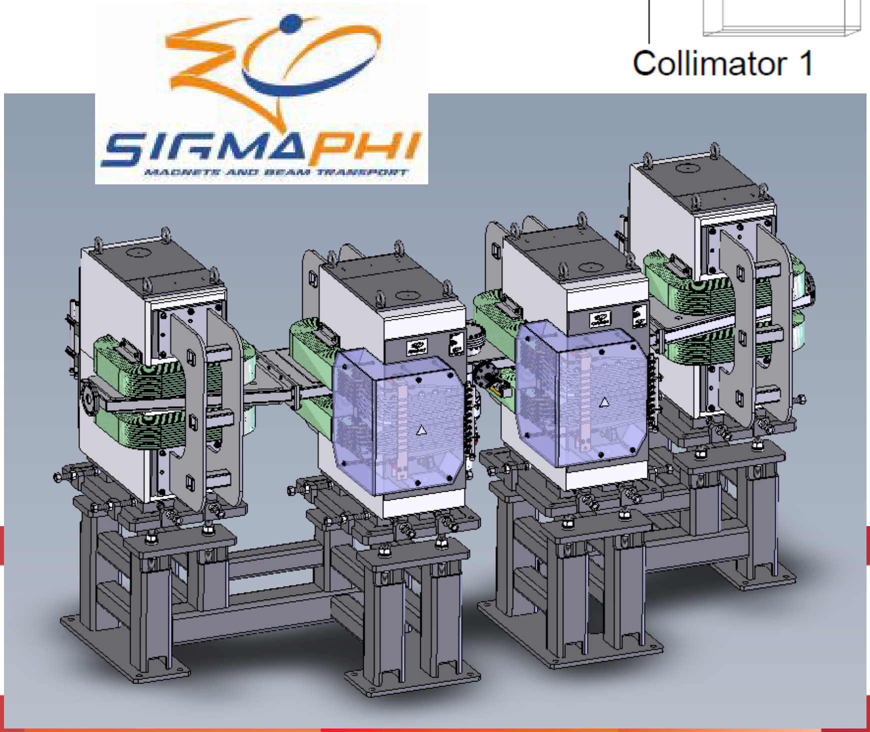
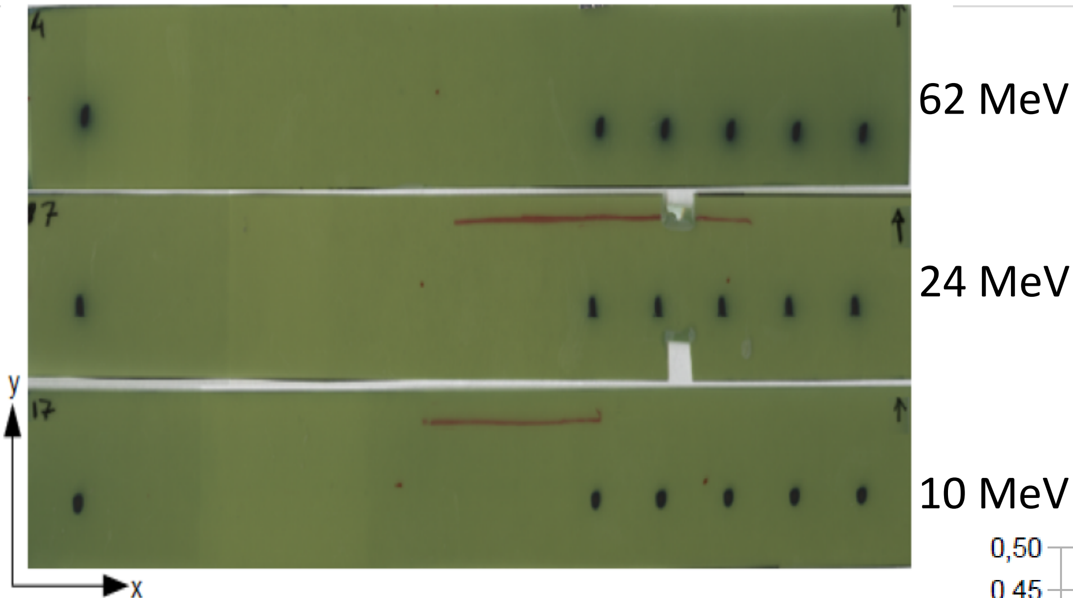




08022 (2016)

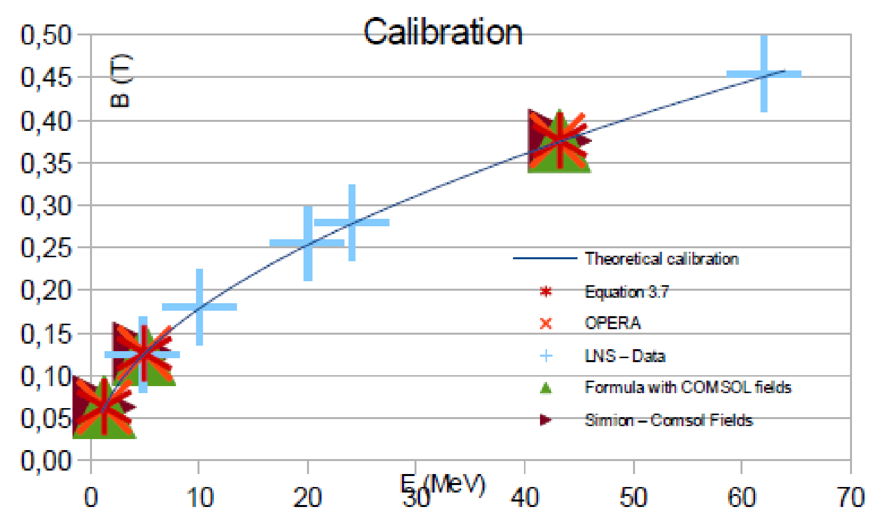
Calibration at INFN LNS



GafChromic films set up on the selection plane

B field [G]	Nominal position [mm]	Measured position [mm]	Deviation [%]
3630,3	127,5	128	0,4
4084,1	142,5	143	0,3
4537,1	160	160,5	0,3
4991,7	177,5	177	-0,3
5445,5	192,5	193,5	0,5

Data for 62 MeV Protons



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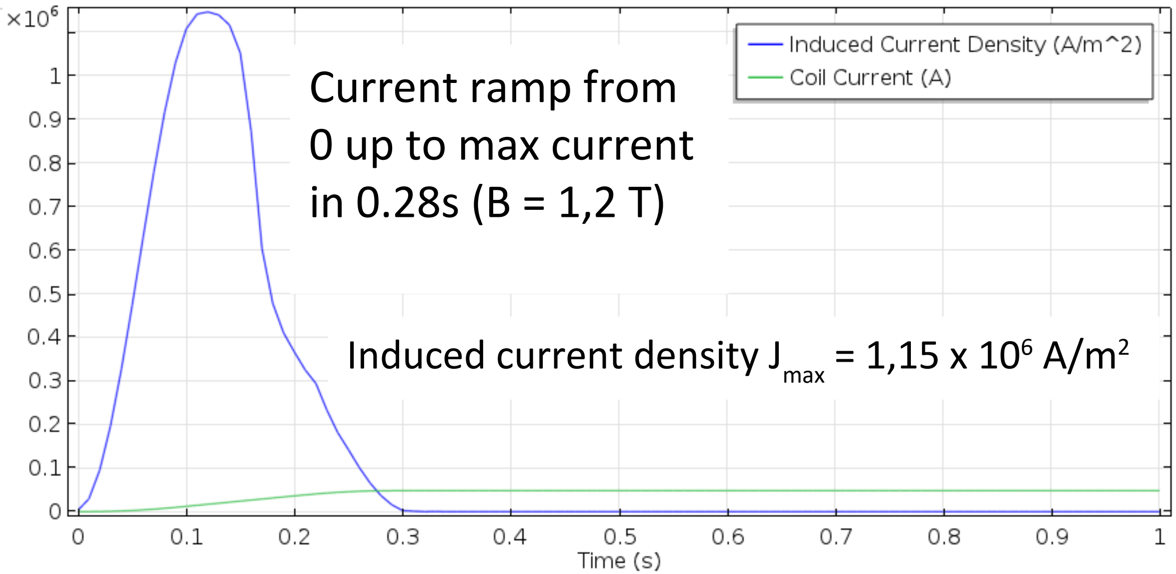
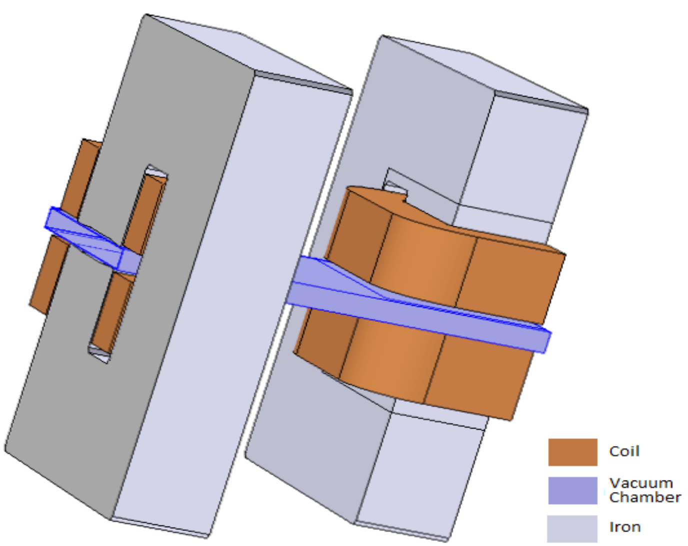
Not just a magnetic chicane...
Towards an active energy modulator

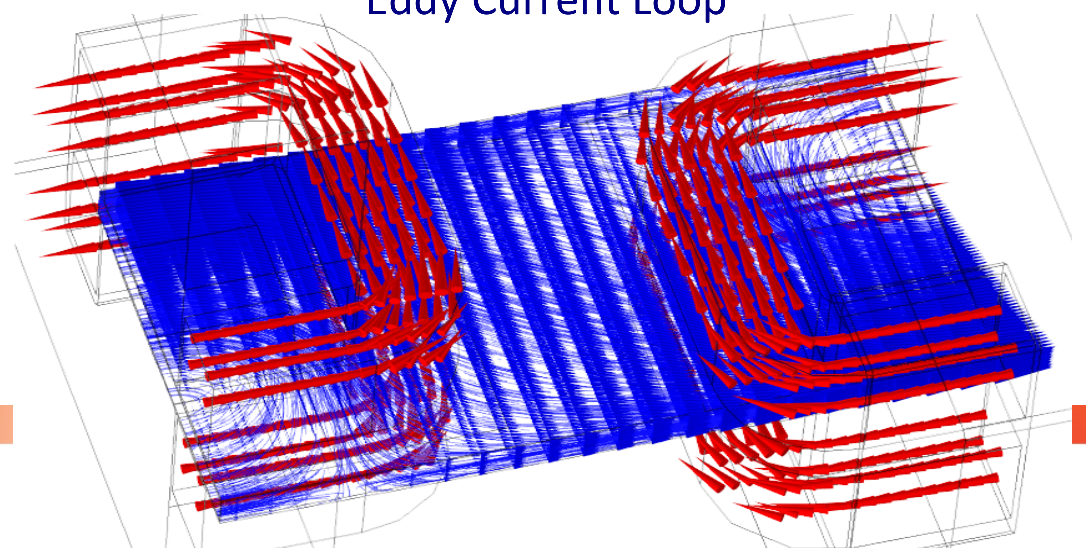


If the current is changed each second (each laser shot) the system could be used as an active energy modulator system

Induced sextupole due to the eddy current on the vacuum chamber can be neglected after 0.31s



Eddy Current Loop



OUTLINE

- Design of the ELIMAIA Collection System
- Design of the ELIMAIA Selection System
- Additional transport elements
- Beam transport simulations
- High resolution Thomson Parabola

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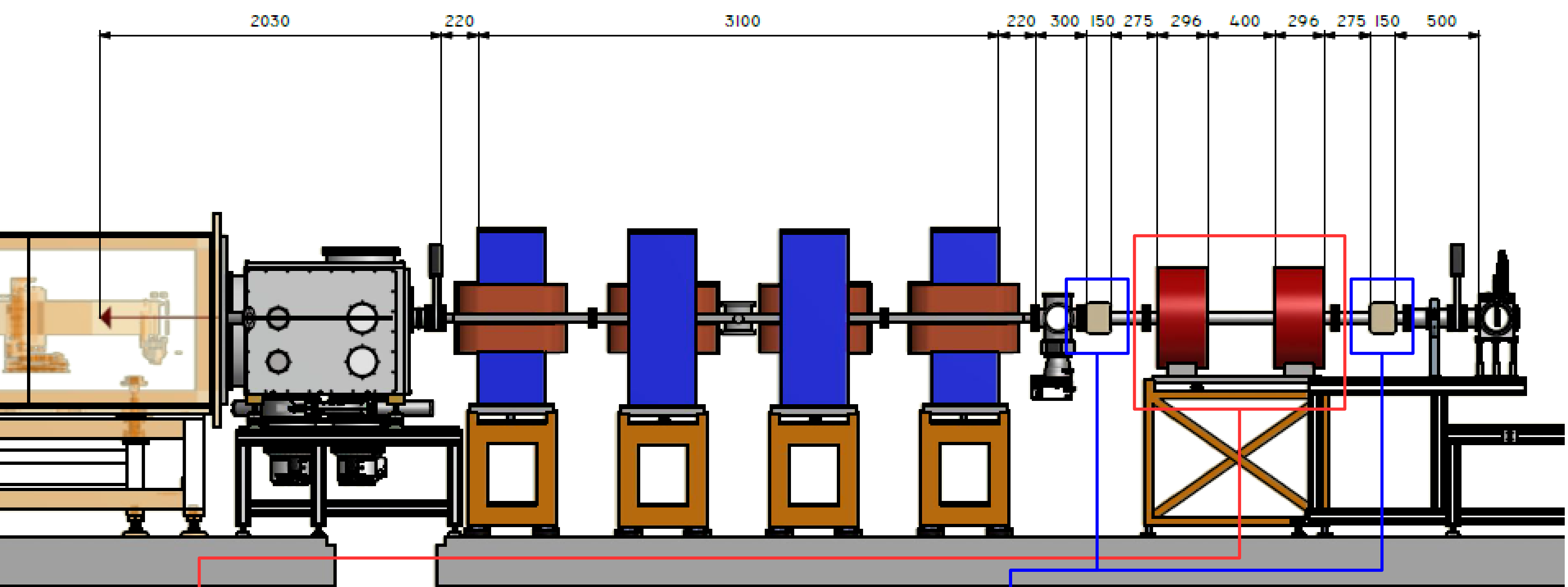
Quads and Steerers



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

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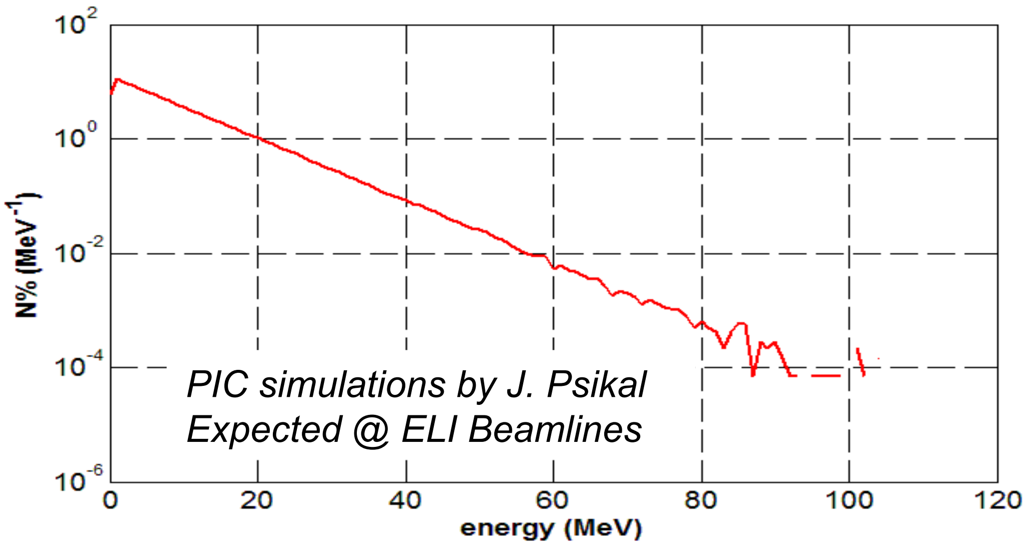
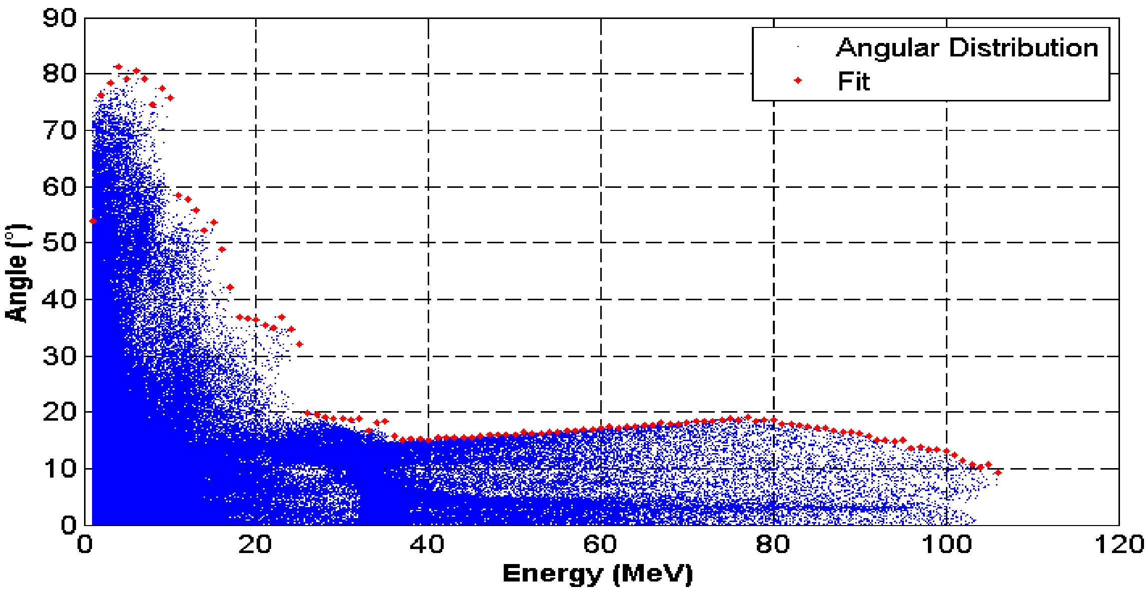
PIC simulation ELIMAIA source



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



HUGE ANGULAR APERTURE > 15°

Worst Case Scenario!

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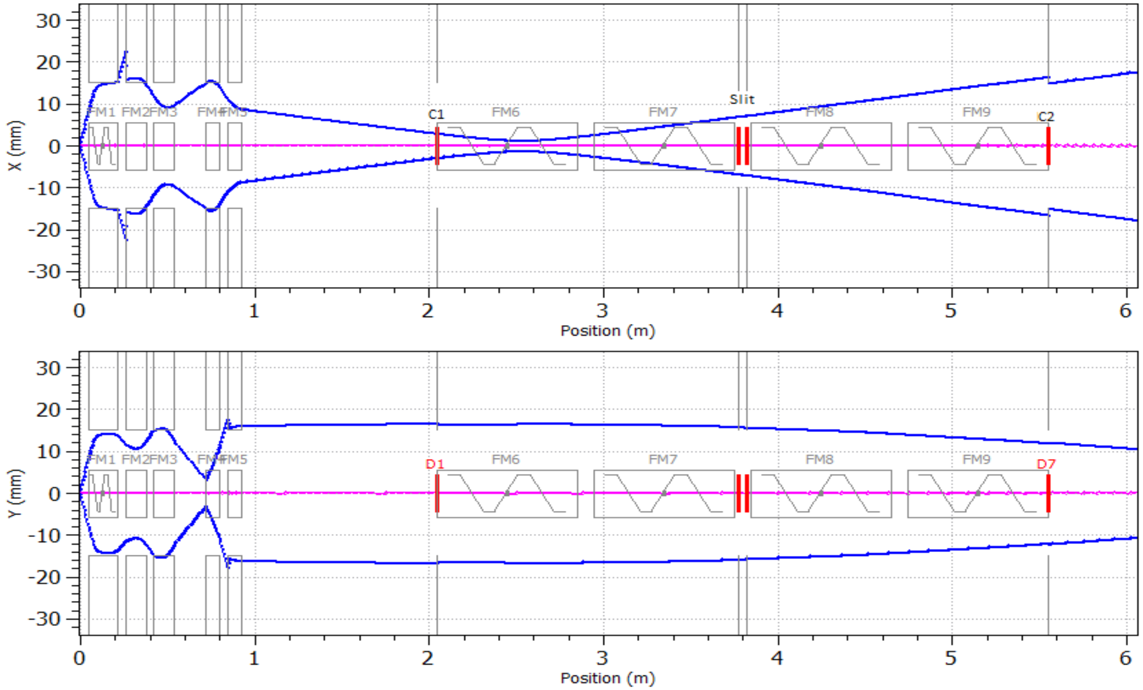
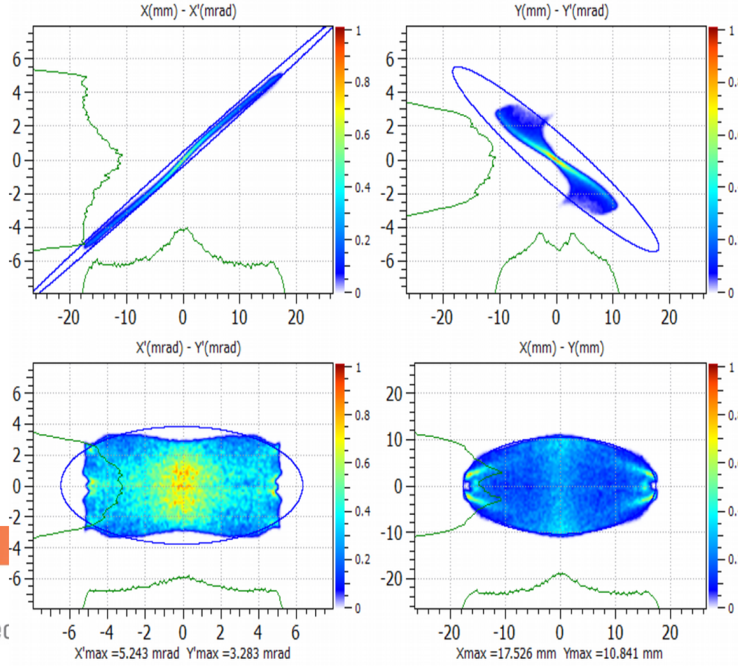
Beam transport 60 MeV protons

Example of 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%

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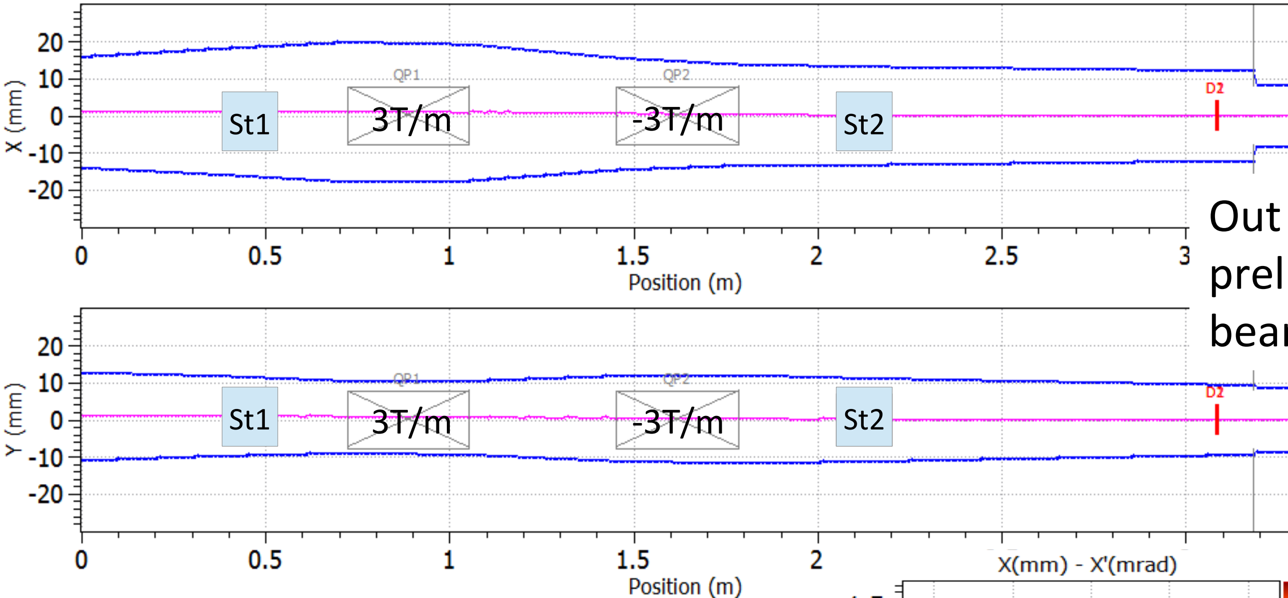
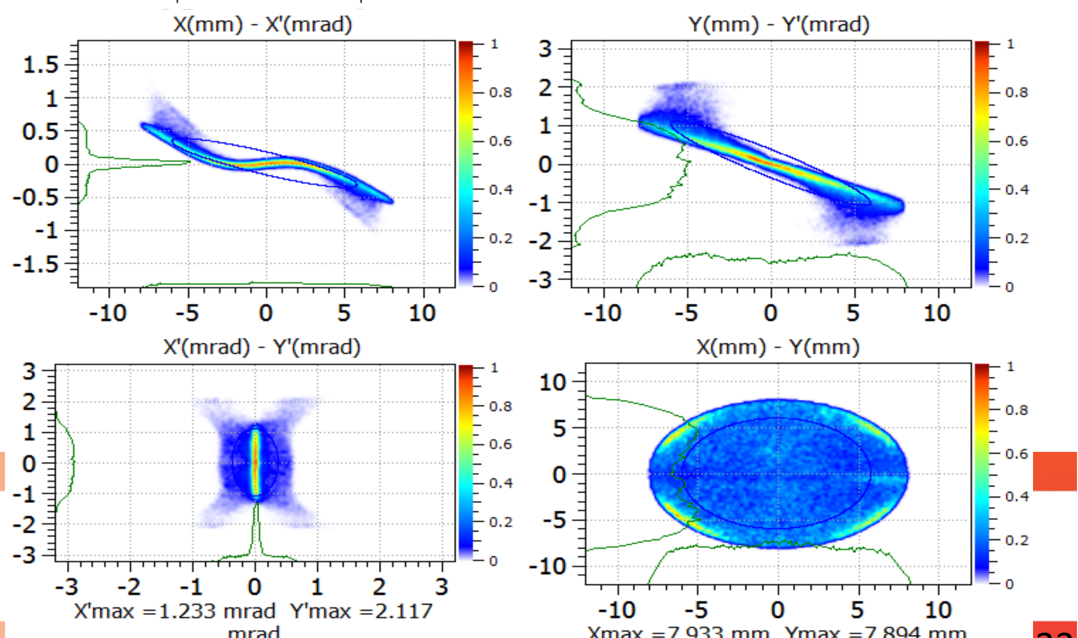
Beam transport 60 MeV protons



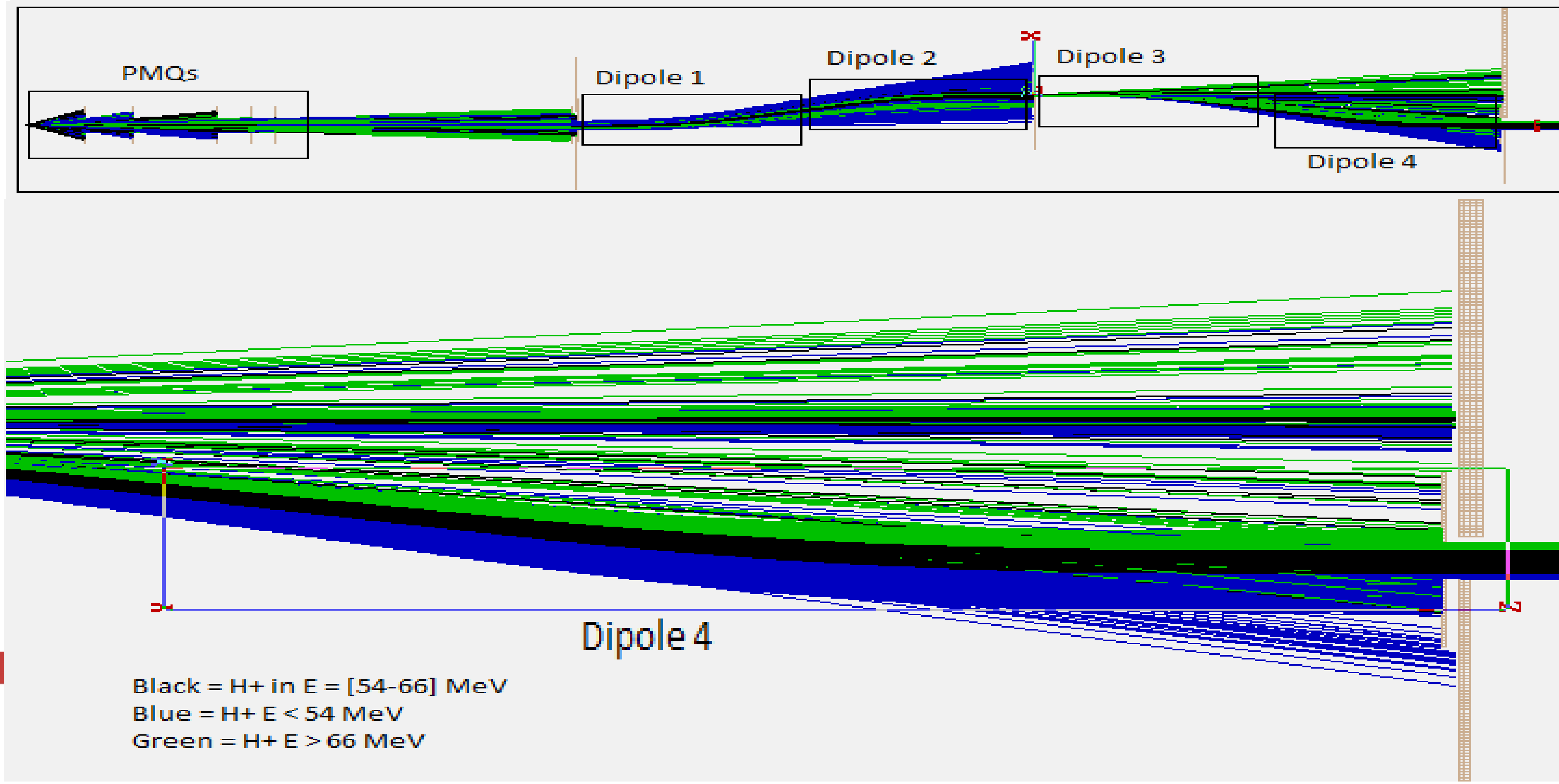
Out of PMQs+ESS used in input for preliminary simulation of last beam-line section



Beam transport
TNSA-like protons

Angular divergence = 5° (FWHM)

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



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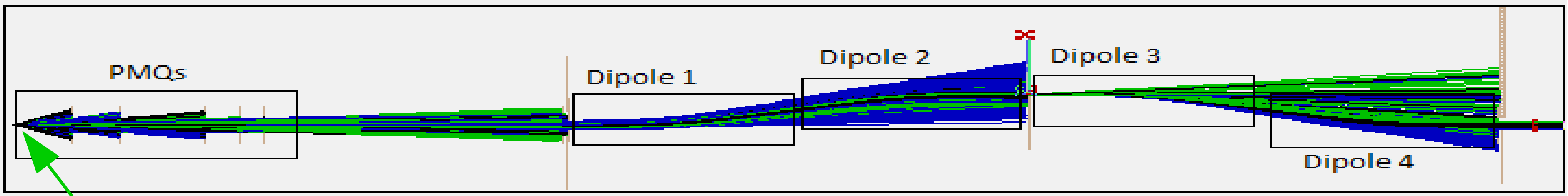

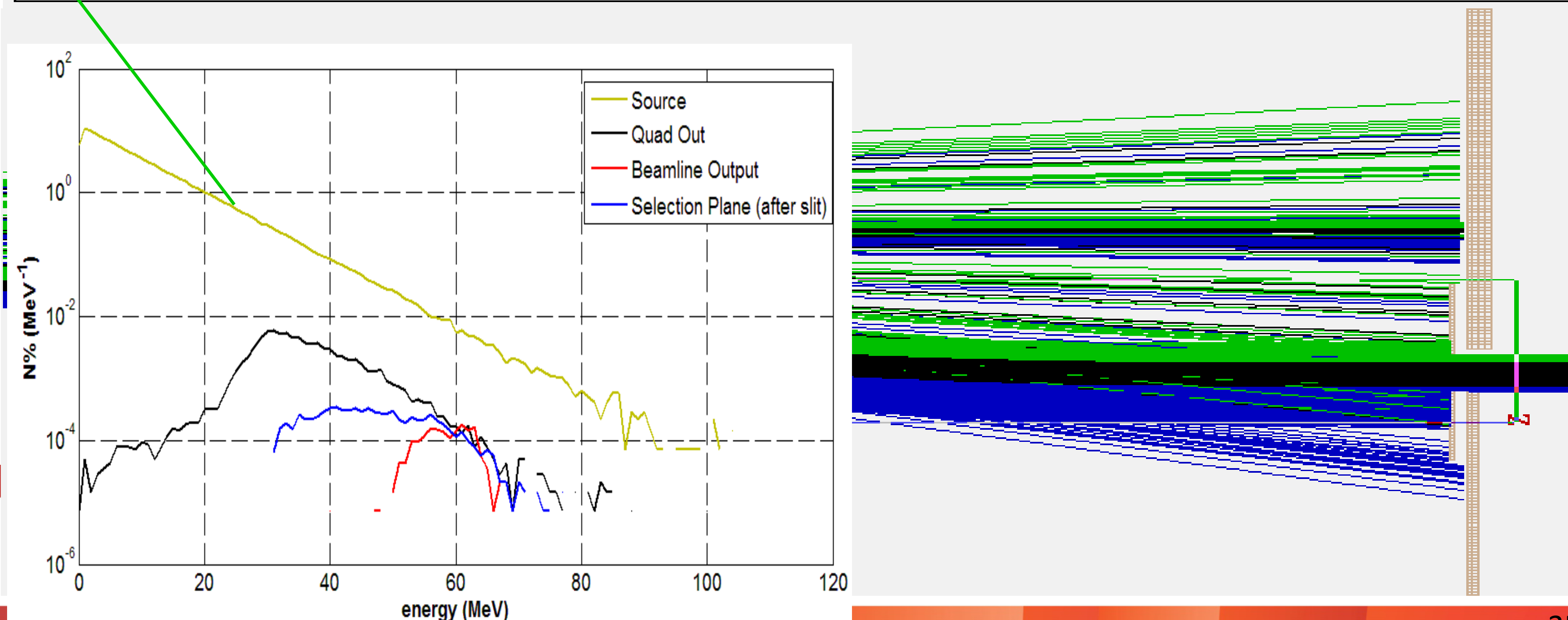

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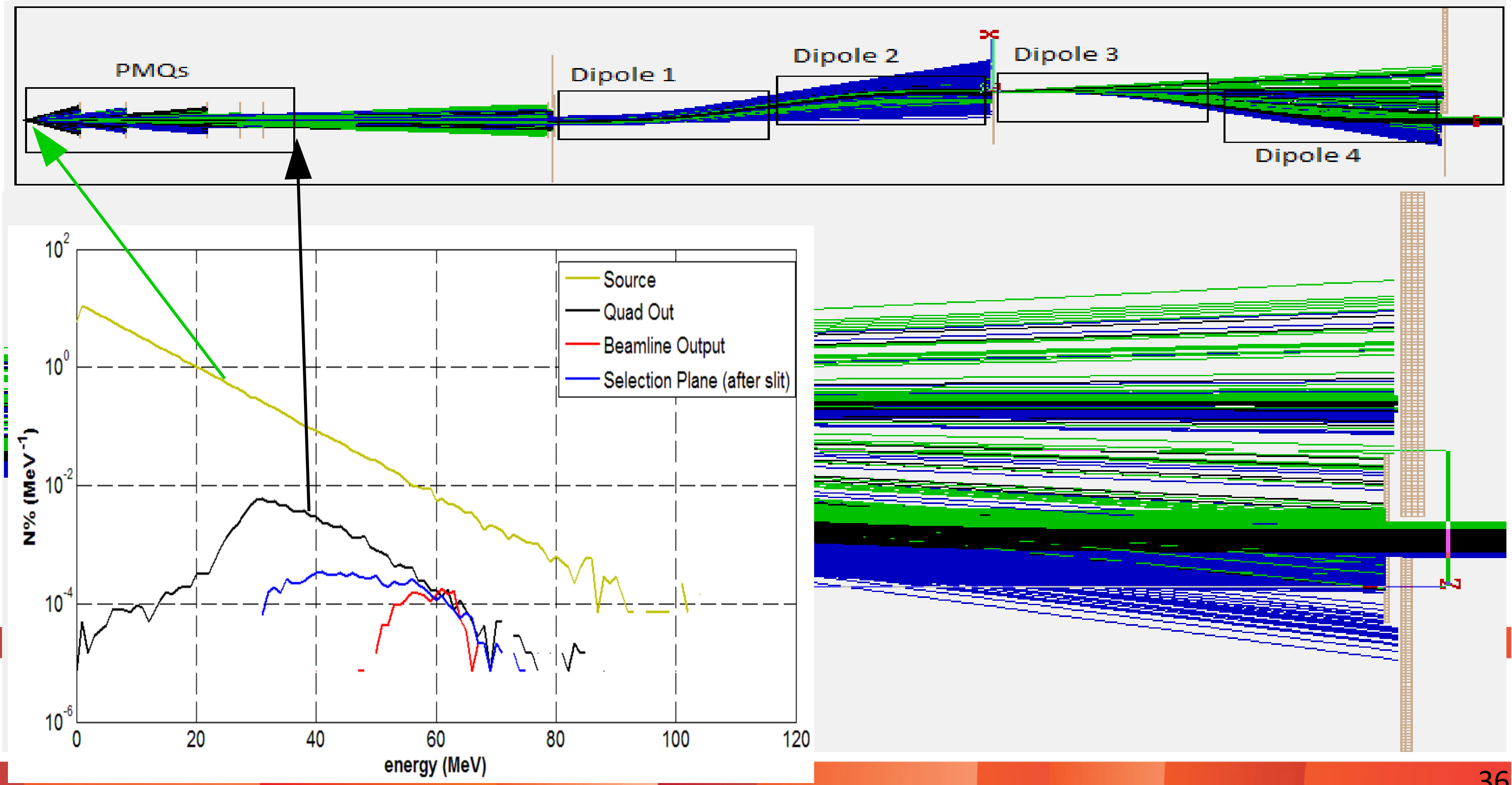

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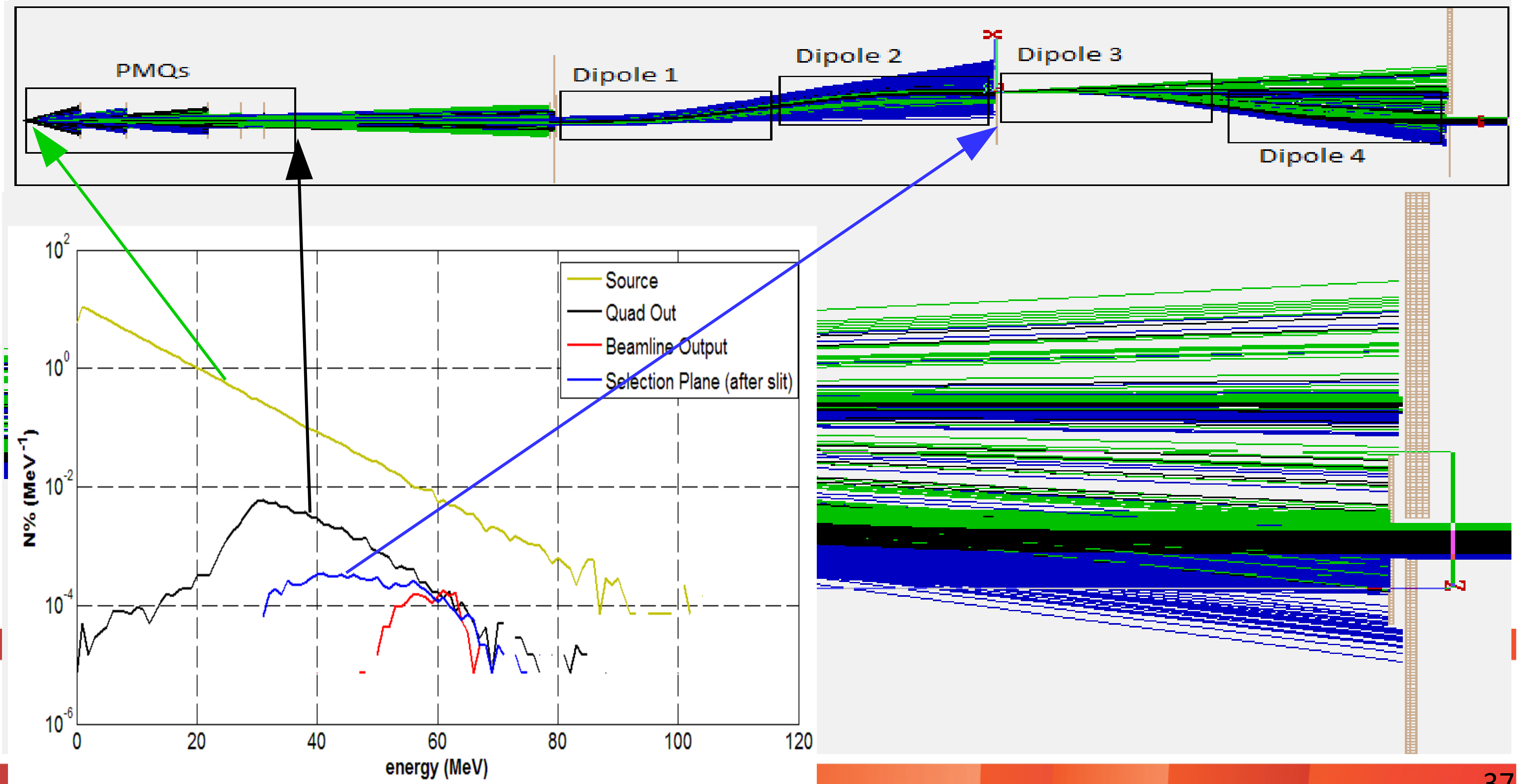

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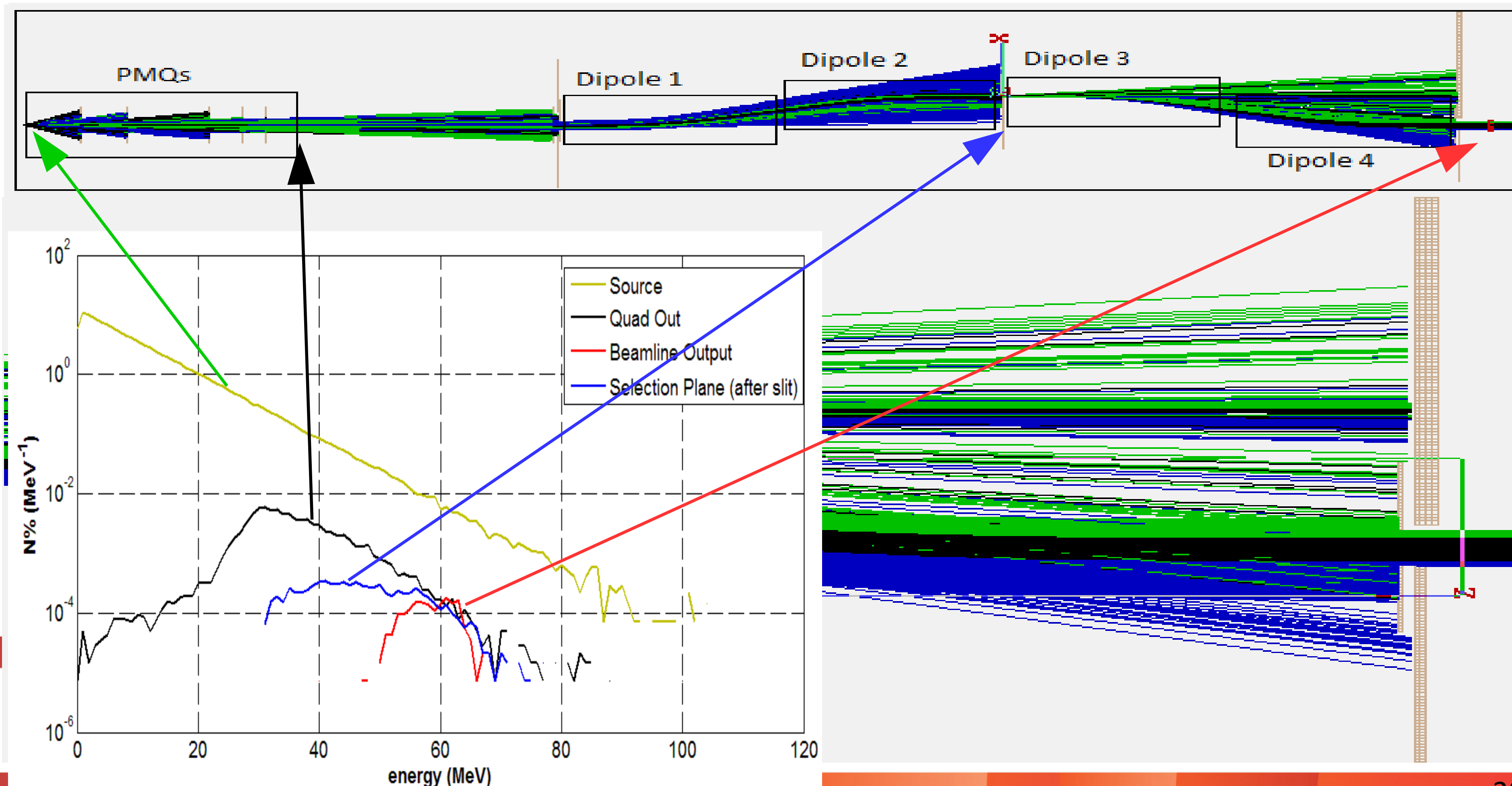

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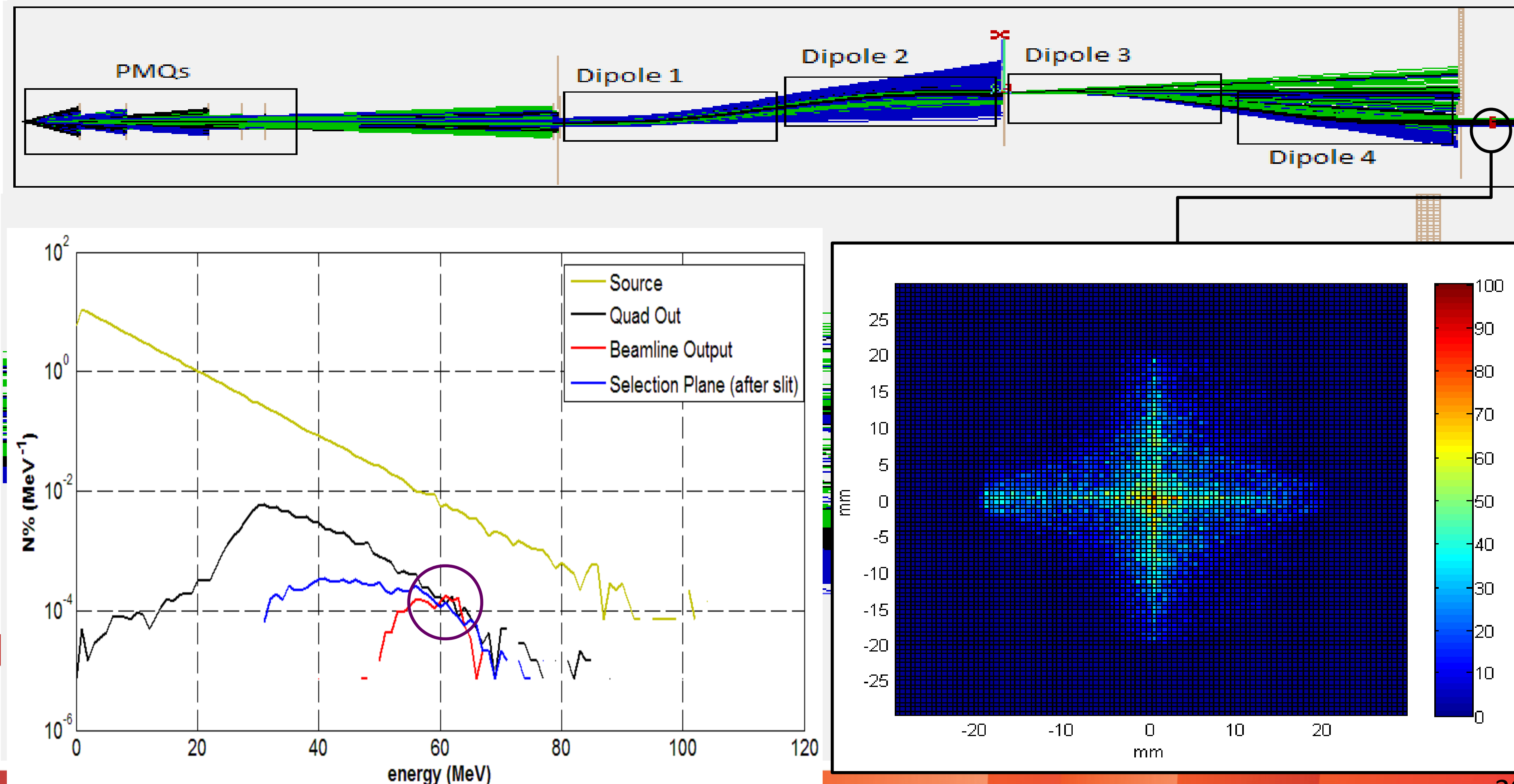

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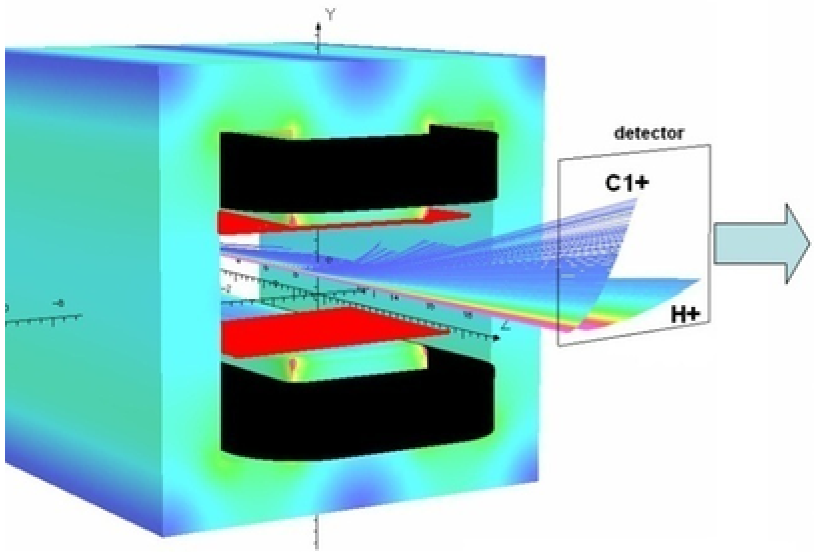
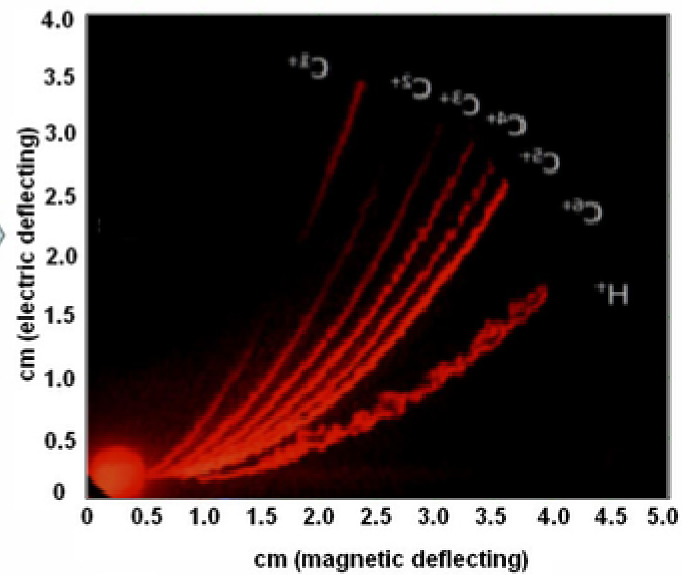
Thomson Parabola

Thomson Parabola spectrometer is a fundamental diagnostic in laser-driven accelerators as it give information on the energy and charge state of all the ion species in the accelerated bunch





Magnetic deflection and energy resolution

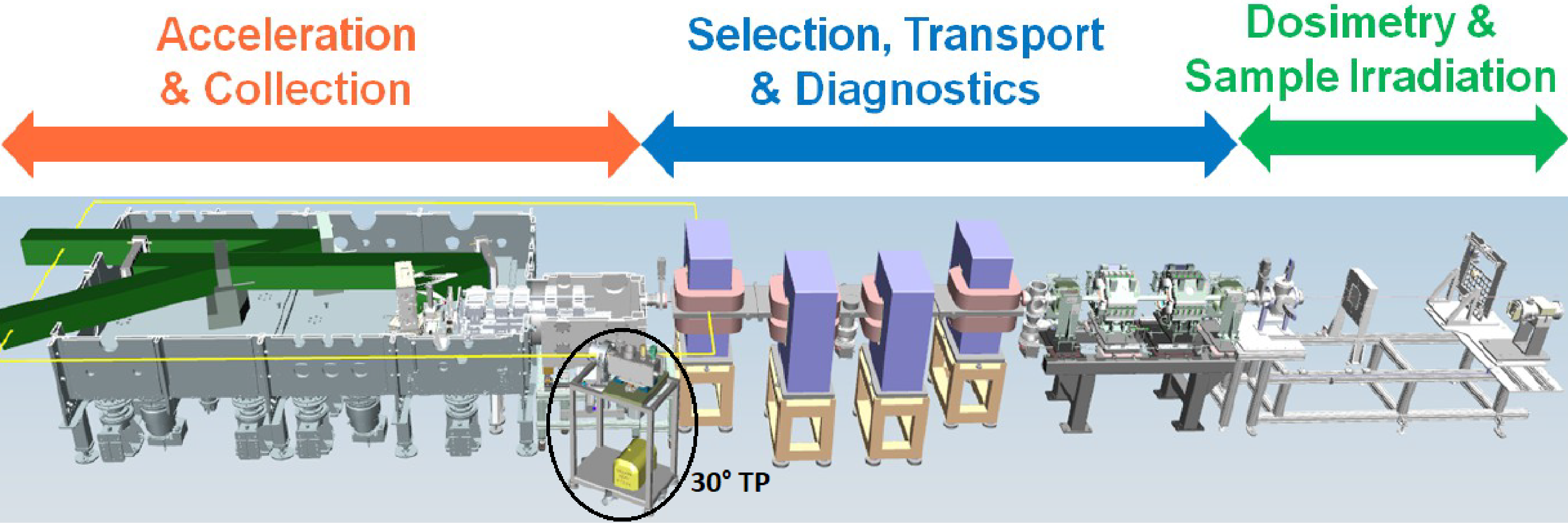
$$E_{kin}=\frac{Q^2 e^2 B^2 L_m^2 \left(D_m+\frac{L_m}{2}\right)^2}{2 m x^2}=\frac{A_m}{x^2} \qquad Res=\frac{dE_{kin}}{dx}s$$

Electric deflection and Q/A resolution

$$E_{kin}=\frac{Q e E_f L_e \left(D_e+\frac{L_e}{2}\right)}{2 y}=\frac{A_e}{y} \qquad \Delta y=\frac{A_e\left(\frac{Q_1}{A_1}\right)}{E_{kin1}}-\frac{A_e\left(\frac{Q_2}{A_2}\right)}{E_{kin2}}>s$$

Parabola equation $y=\frac{A_e}{A_m}x^2=A_{parabola}x^2$

Thomson Parabola @ ELIMAIA/ELIMED

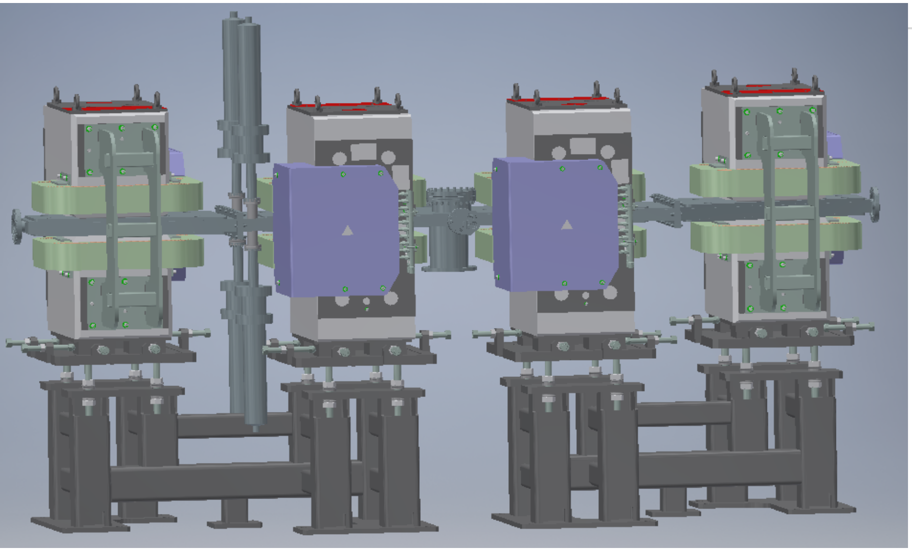


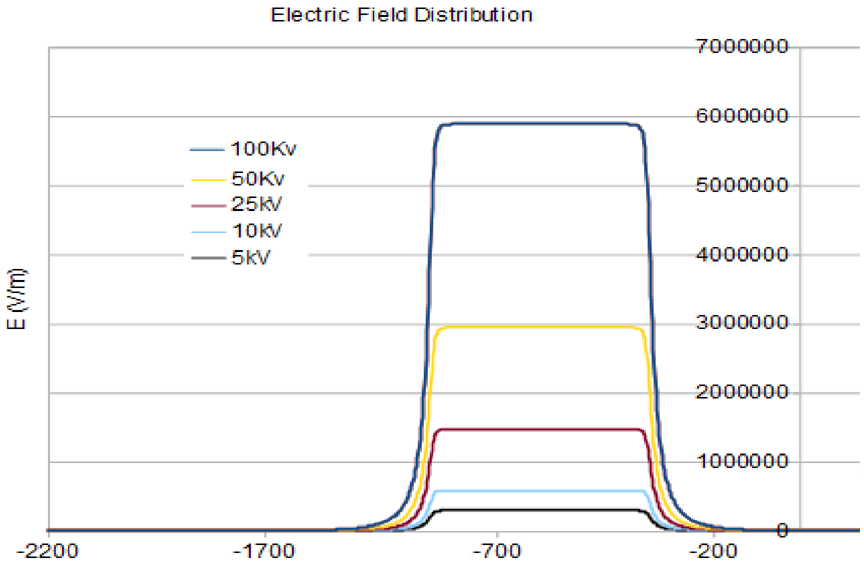
No space for an on-axis spectromete, but Dipole 1 in the chicane is independently calibrated
This Dipole can be used a magnetic deflector for a Thomson Parabola and it can resolve protons up to 300 MeV and carbons up to 75 AMeV

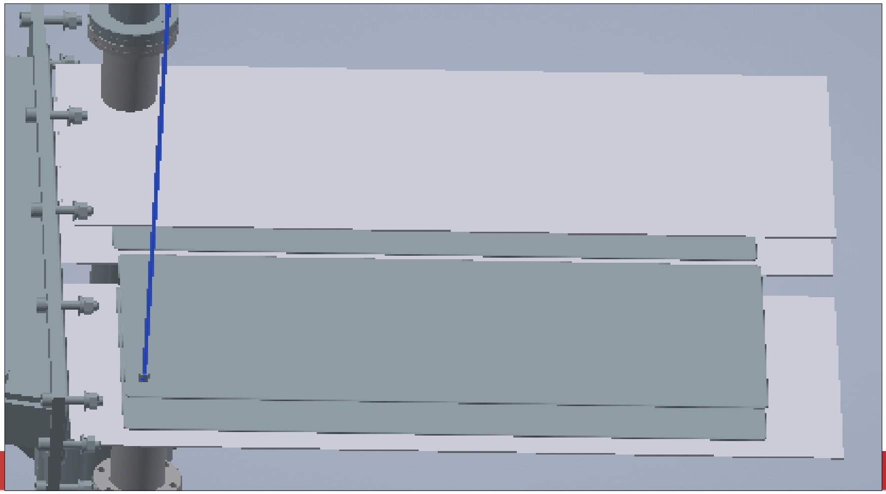
Two main problems have been faced in designing the electric deflector:

1. Inner chamber clearance cannot be less than 30 mm → huge gap and high voltage
2. Reference orbit cannot be modified → no side structures for the electrodes

Electric field analysis



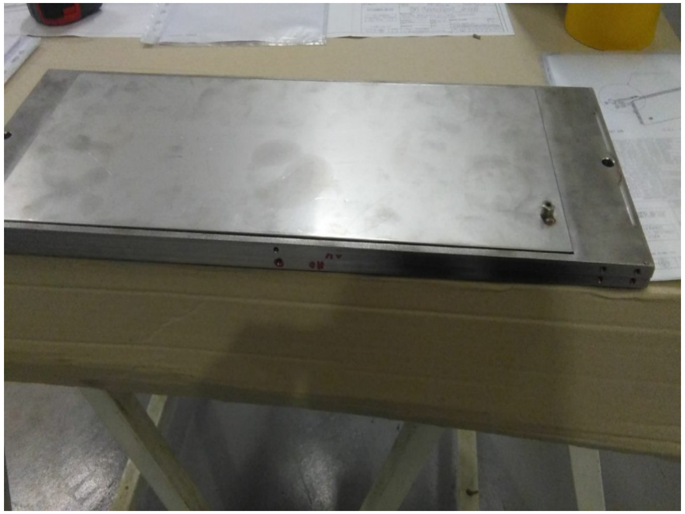




The electric field peak is $5,88 \times 10^3$ V/mm.
The electrical breakdown limit in air:
$4,36 \times 10^4$ V/mm (Paschen's Law)

Assembling mockup 1

Pneumatic expansion cushions placed between two metal structures with a groove to guide the electrode in the chamber



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 setup optimization in progress
  (Final design of the magnets and precise input beam features to improve optics and PMQs+ESS matching.)

- Beam output features to be improved
  (MC simulations for improving of the beam homogeneity with passive elements)

- Upgrades:
  (ESS in TP configuration in prototyping phase, antisimmetric ESS configuration and second beamline for sub nsec bunches)

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COMMISSIONING IS ABOUT TO START!!

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Thank you for your attention

http://www.eli-beams.eu/

INFN: G.A.P. Cirrone, F. Schillaci, V. Scuderi, F. Romano, M. Maggiore, G. Cuttone, R. Leanza, G. Milluzzo, J. Pipek

ELI-BL: D. Margarone, G. Korn, V. Scuderi, F. Schillaci, L. Giuffrida, A. Fajstavr

SigmaPhi: M. J. Leray, O. Tasset-Maye, S. Antoine, P. Jehanno

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