Explorative energy deposition studies in the superconducting dipole magnet of the carbon ion gantry for CNAO

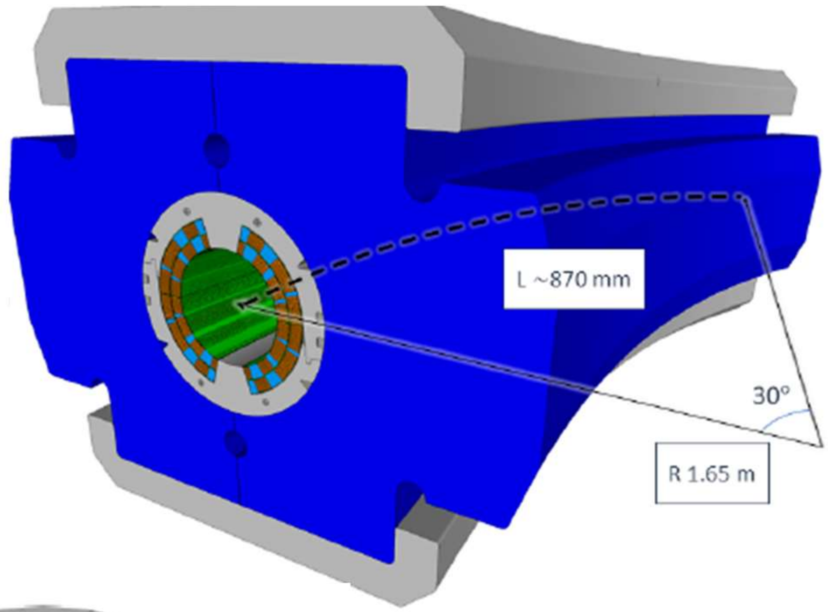
G. Tosetti – A. Mereghetti – M. G. Pullia

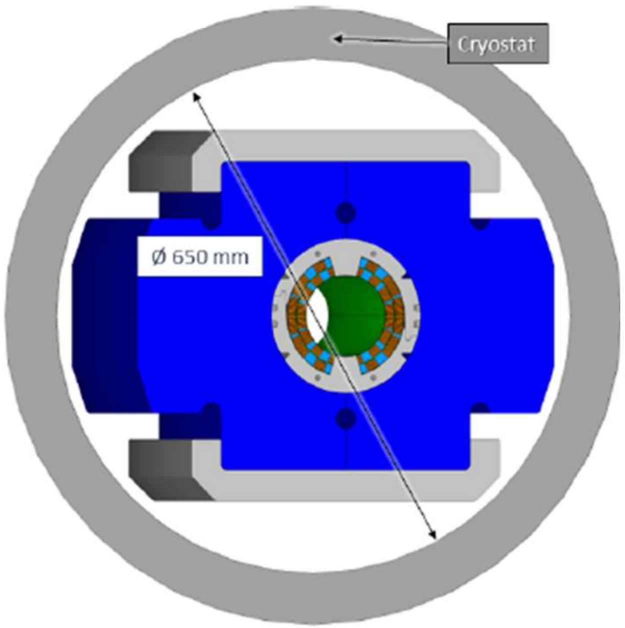
❑ Introduction and overview of Gantry design

❑ Energy deposition:

- in homogeneous material
- in straight and curved magnet geometry

❑ Conclusions and Outlooks





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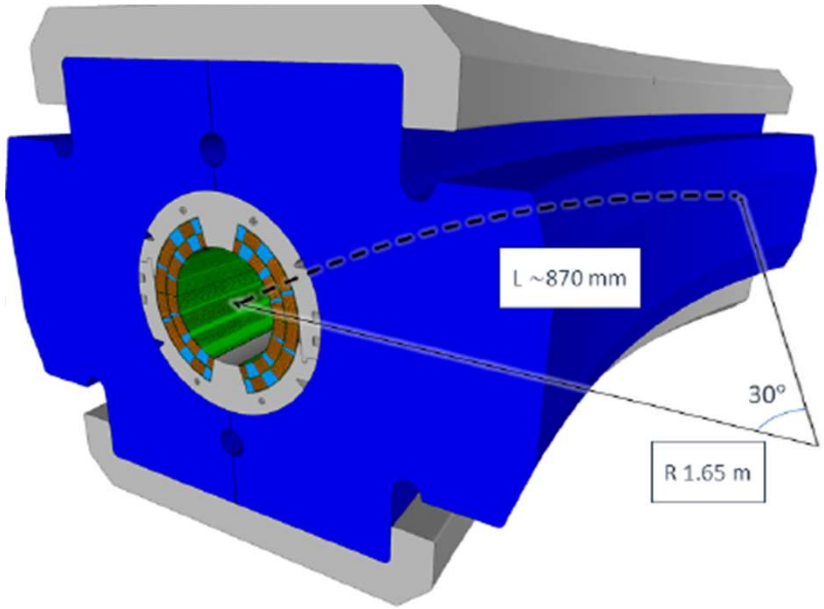

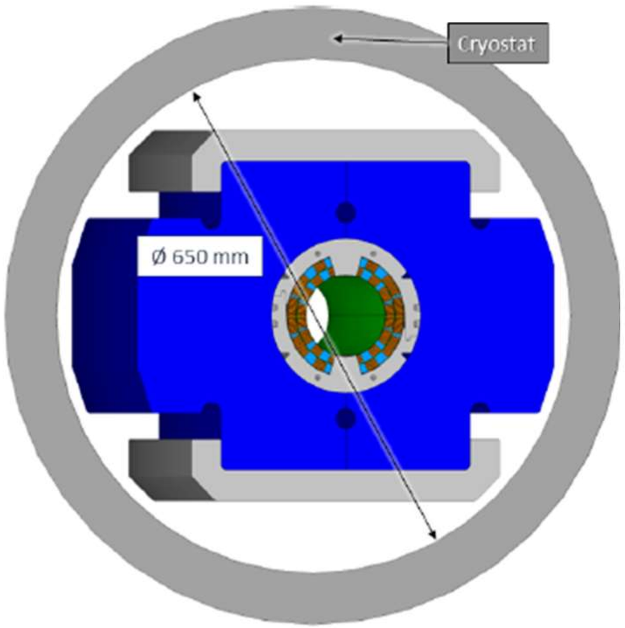

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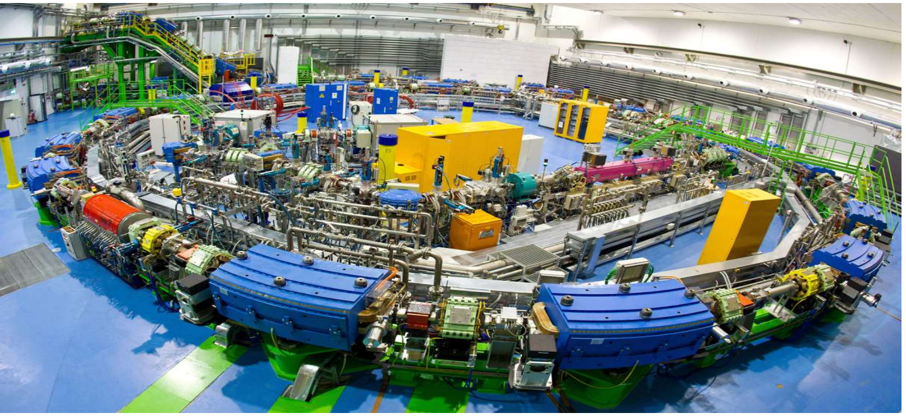

Introduction: CNAO

The National Center for Oncological Hadrontheray (CNAO) is a hadrontherapy center located in Pavia, Italy. In the center, proton and carbon-ion beams are used to treat radio-resistant tumors. Beams are accelerated by a synchrotron.

- **HITRIplus** and **EuroSIG** projects: a **Carbon–ion gantry** is being designed for CNAO, based on **superconducting magnet** technology.

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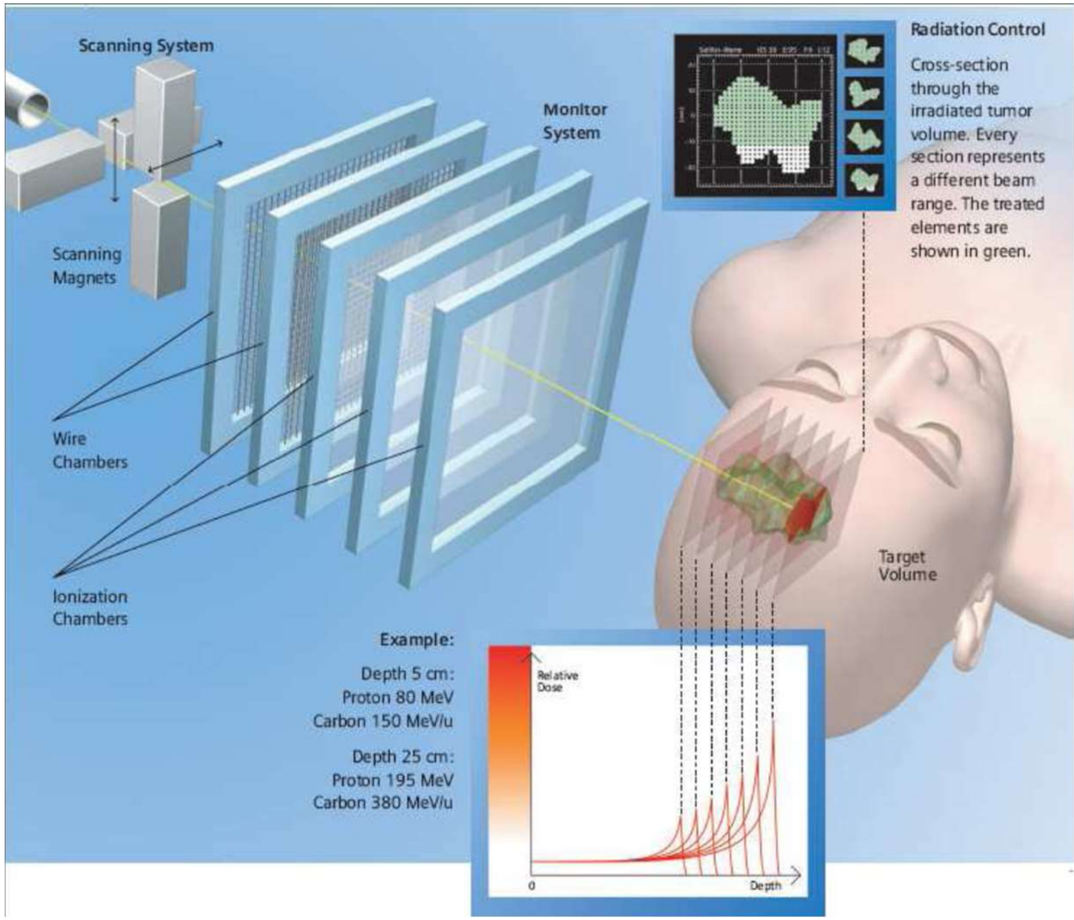
Introduction: hadrontherapy

Hadrontherapy is an advanced cancer treatment method.
It achieves precisely the targeting and killing of tumor cells while minimizing damage to surrounding healthy tissues, thanks to a range of particle energy.

C-ions		Protons	
62 MeV	228 MeV	115 MeV/u	400 MeV/u
30 mm	320 mm	30 mm	270 mm

Range of particle in water (extreme beam energies treatment available at CNAO)



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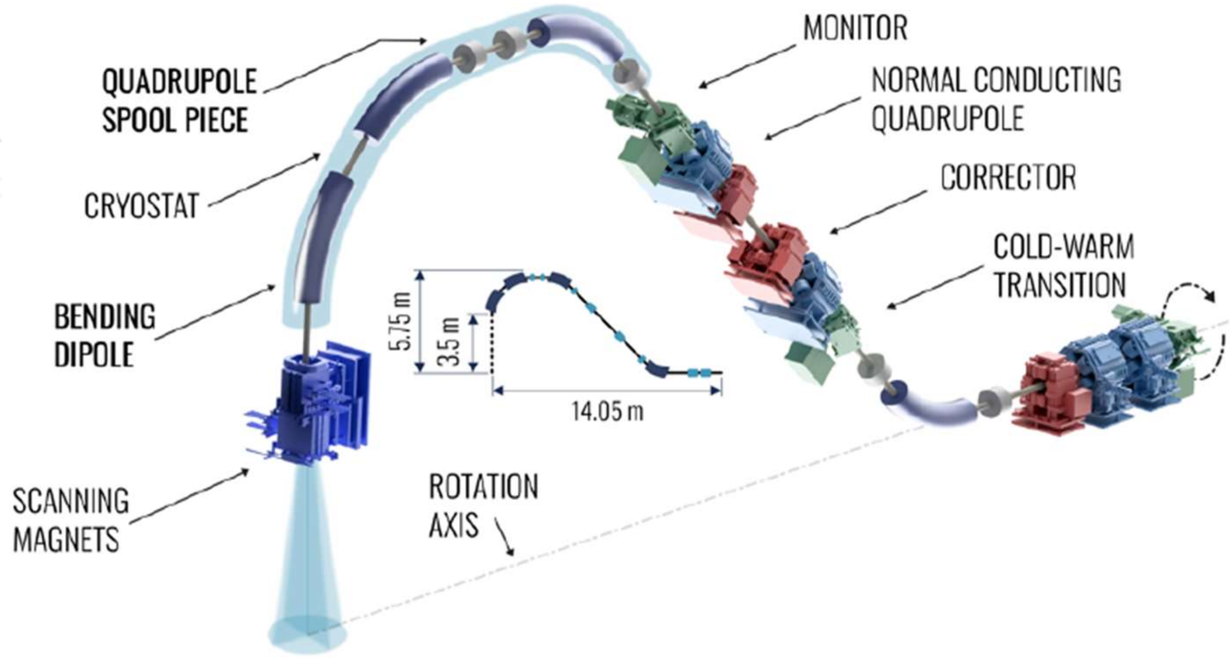
Introduction: overview of the gantry design

The **conceptual design** features scanning magnets positioned downstream of the final bending section, with superconducting dipole magnets generating a 4 T magnetic field.



Some technical aspects are still under study, as the optimal indirect cooling scheme and the configuration of the beam pipe.

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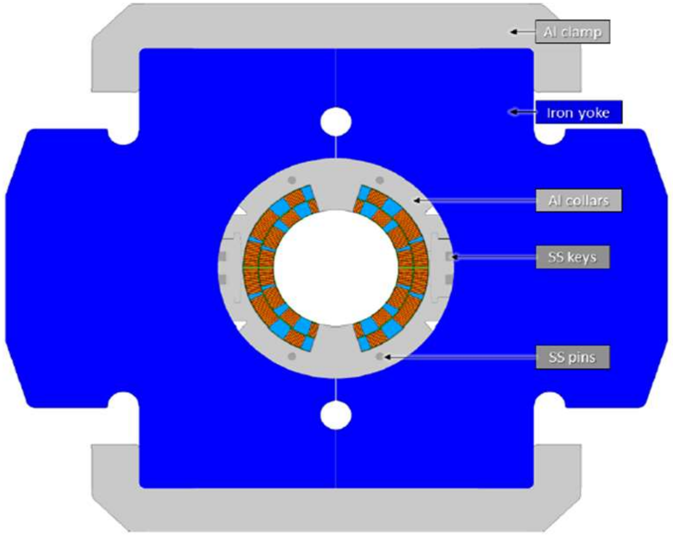
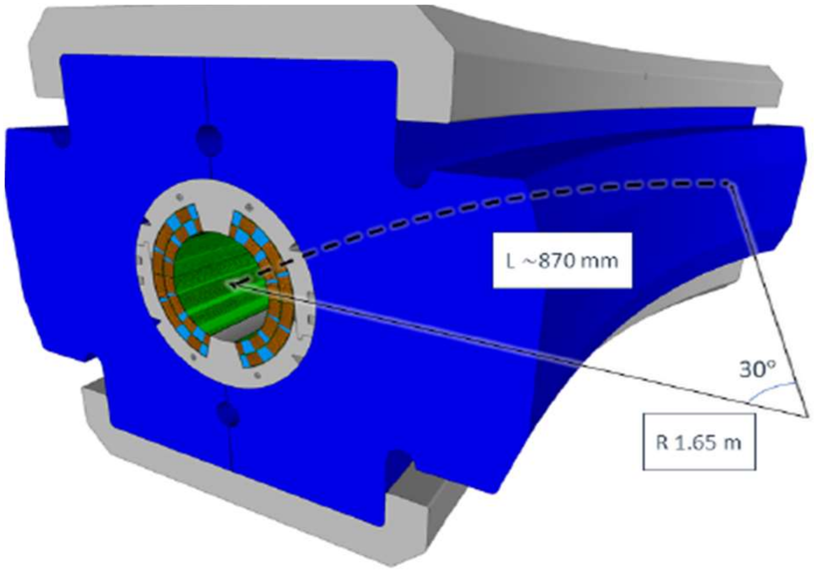
Introduction: overview of the SIG demonstrator design



The development of superconducting magnet technology is a significant challenge. Nowadays, **INFN LASA** is assembling a **cos-theta dipole** with:

- 4 T central field
- 80 mm aperture
- curvature radius of 1.65 m
- angular sector of 30°
- Field ramp rate 0.15-0.4 T/s



Current [A]	2770
Operetional temperature[K]	5
Superconductor	Niobium-Titanium
Cable type	Rutherford
Twist pitch [mm]	66

INFN CNAO

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  - in straight and curved magnet geometry

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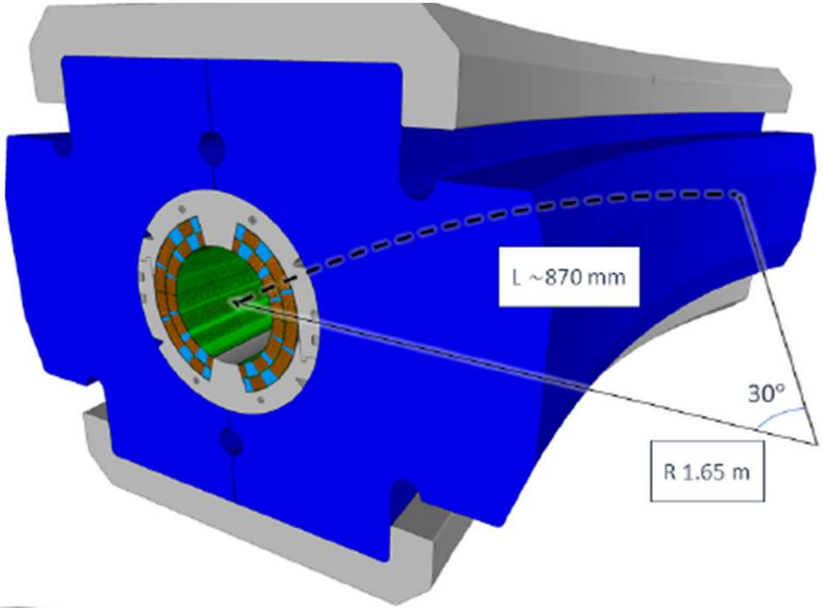
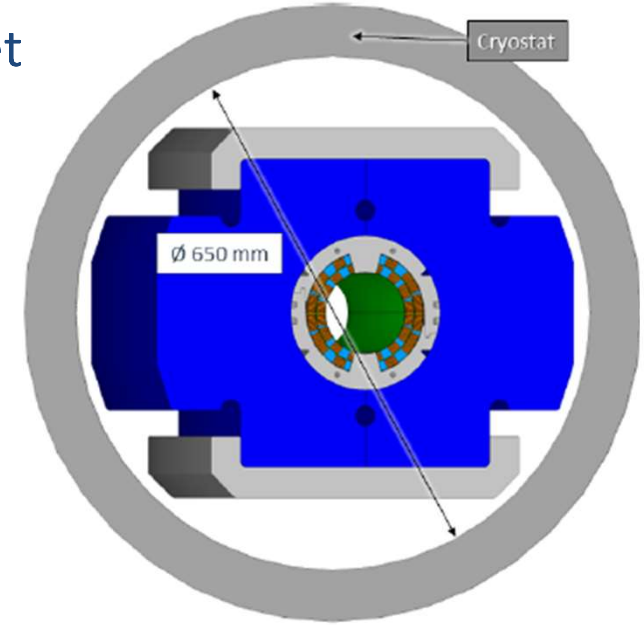




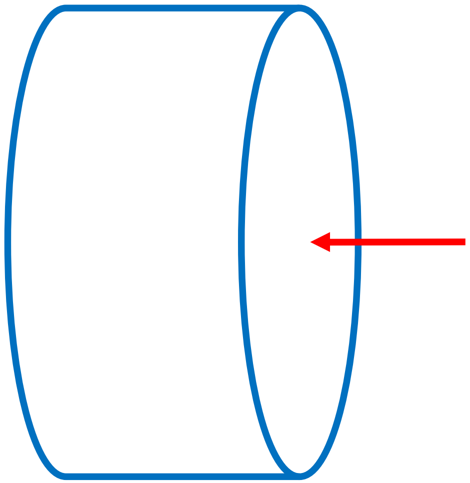
Energy deposition in homogeneous materials I

Full Beam impact on a cylindrical target made of an **homogeneus material**:

- each material composing the dipole was considered;
- with extreme beam energies treatment available at CNAO (beams of C-ions at 400 and 115 MeV/u and proton at 230 and 62 MeV).
- Monochromatic Gaussian beam.

The energy deposition is estimated by means of **Monte Carlo simulations**, using the **FLUKA** code. The thermodinamic of the quench is not considered (**adiabatic assumption**).

Aim: very **conservative assessment**



Scoring mesh characteristics:

- Cylindrical mesh;
- Longitudinal step: 50 µm ;
- Radial step: 300 µm;
- Only one azimuthal angle.

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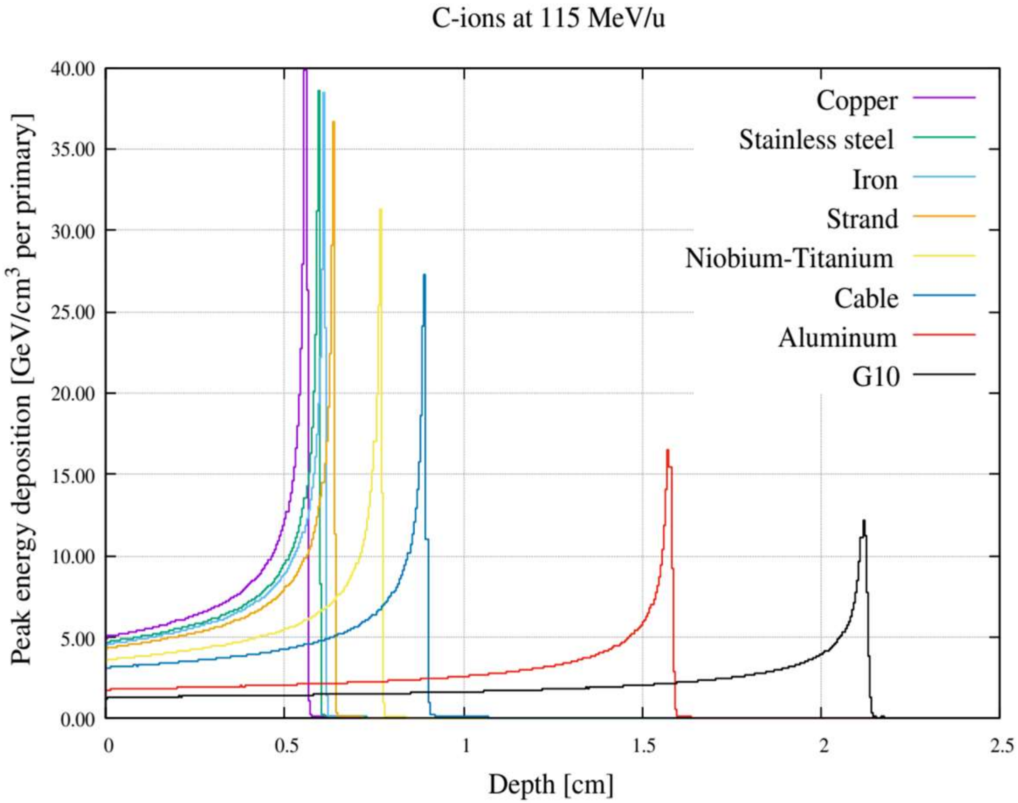
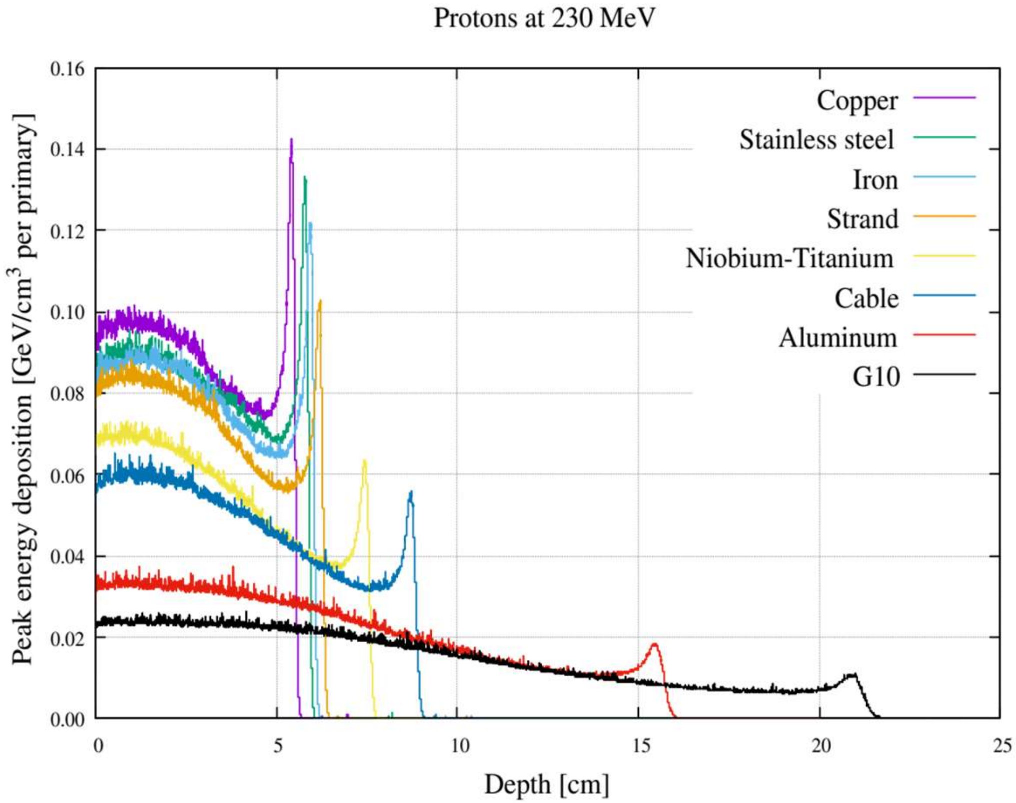
Energy deposition in homogeneous materials II





Longitudinal profiles of peak energy deposition in a thick target of homogeneous material for protons at maximum and C-ions at minimum energy.

Energy deposition in homogeneous materials III

Assuming a nominal full beam extraction

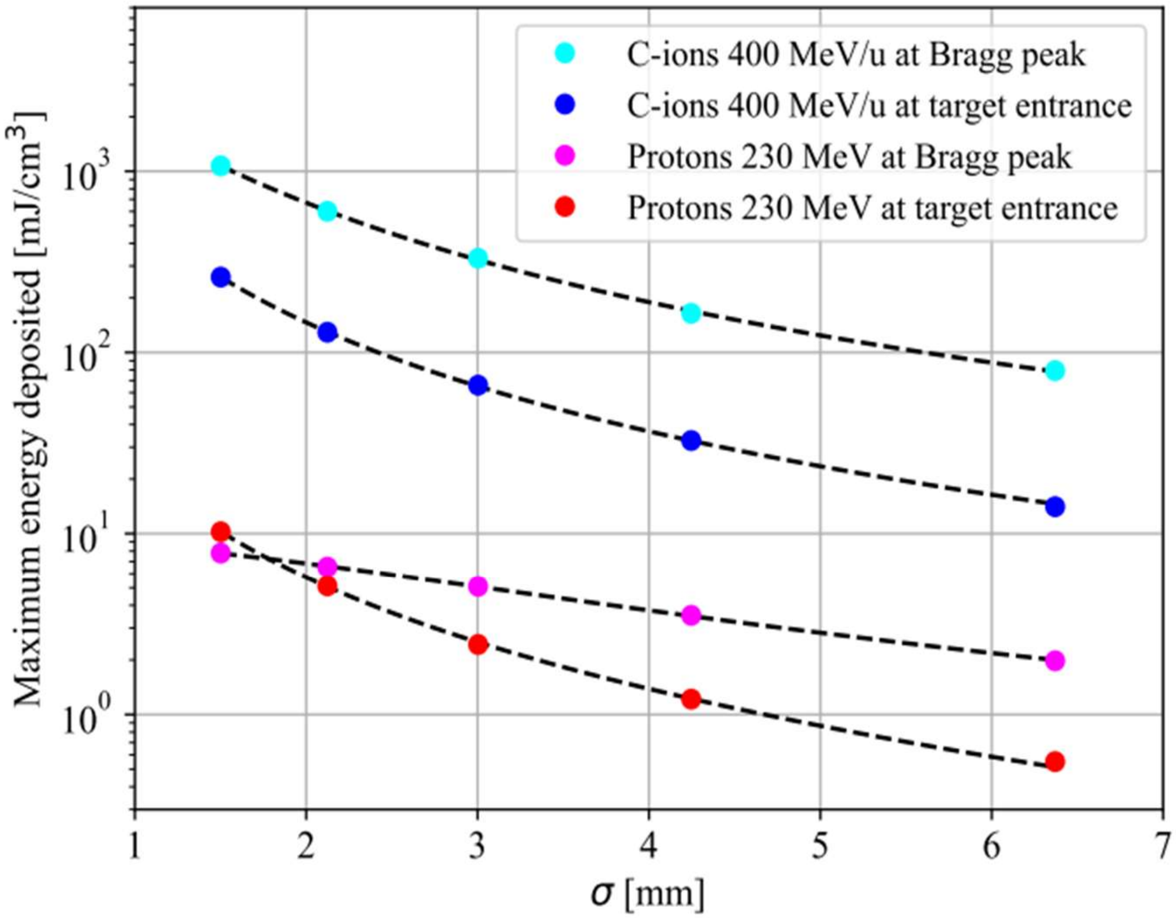
- **4 E8** C-ions extracted in 1s;
- **1 E10** protons extracted in 1s;

Material	C-ions		Protons	
	115 MeV/u	400 MeV/u	62 MeV	230 MeV
Copper	2560	685	1952	224
Strand	2368	602	1632	166
Nb-Ti	1984	480	1344	104
Cable	1768	339	1184	91

Maximum values of energy deposition before quenching, given in **mJ/cm^3**.

Considering a **conservative quench limit** of energy density (**10** mJ/cm^3 strand enthalpy at max current) is exceeded in all the simulated cases.

Energy deposition in homogeneous materials IV



Fit:

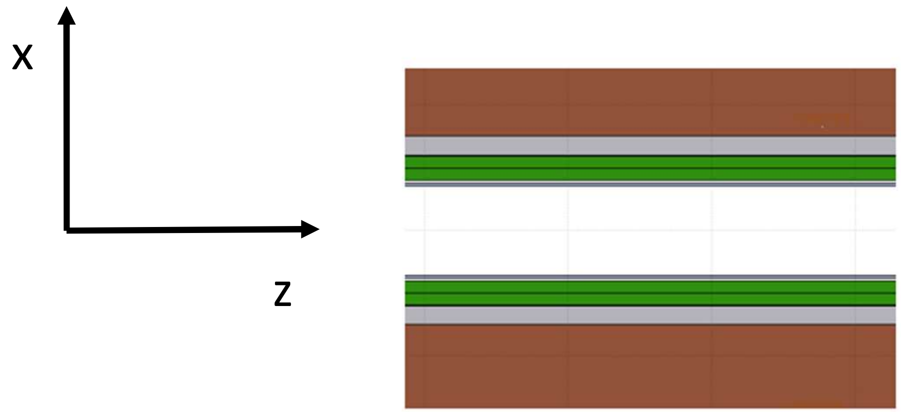
$$\text{Max energy deposition} = \frac{A}{\pi\sigma^2 - b} + c$$

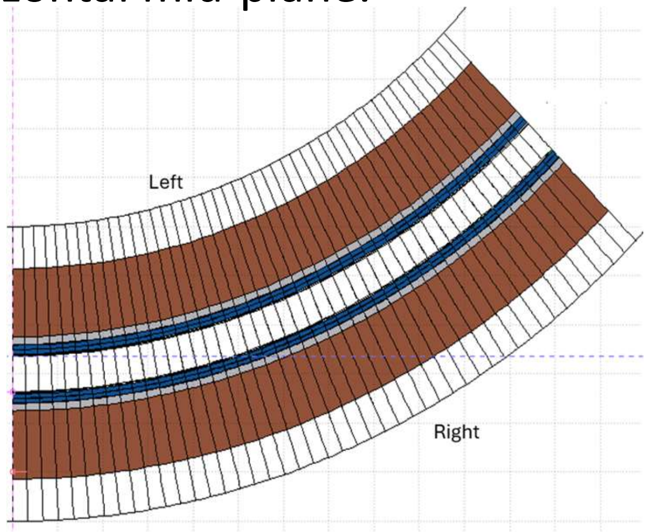
Beam sizes as of gantry optics presently considered in the context of the HITRIplus project:

$\sigma_{min} = 0.55$ mm
$\sigma_{max} = 2.56$ mm

Energy deposition in magnet geometry I

The beam hits the dipole at different angles on the horizontal mid-plane.
Two geometries are implemented: **straight** and curved.





Simulation of **C-ions beam at 115 MeV/u**, carried **without magnetic field**.
Cases with the **vacuum chamber** (2 mm of Stainless Steel).

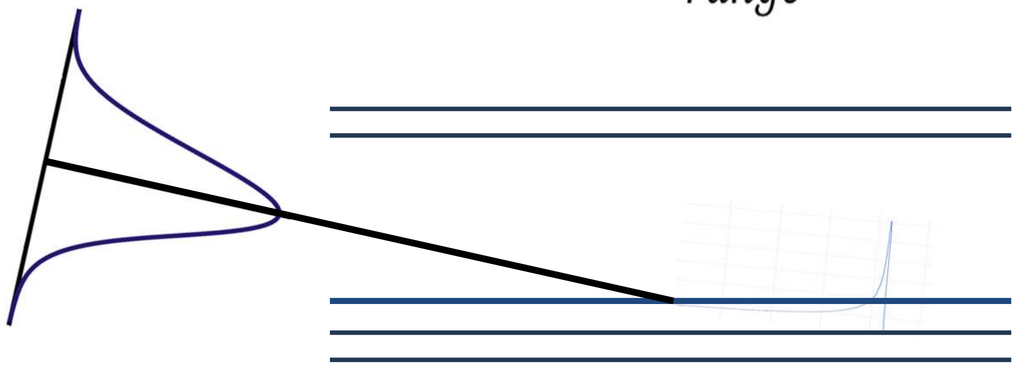
Aim: endep dependency on impact angle

Scoring mesh characteristics:

- Longitudinal: 50 µm;
- Radial: 230 µm;
- Azimuthal: bear mid thick edge (480 µm).

Energy deposition in magnet geometry II

$$\text{Cutoff angle} = \sin(\theta) = \frac{thickness}{range}$$



Angle at which **the primary particles** are **fully stopped** inside a single layer of each composing magnet material with a given thickness.

Material	Thickness	C-ions		Protons	
	mm	115 MeV/u	400 MeV/u	62 MeV	230 MeV
Strand	9.1	-	176	-	141
Stainless steel	2	340	42	318	33

Angles are expressed in **mrad**.

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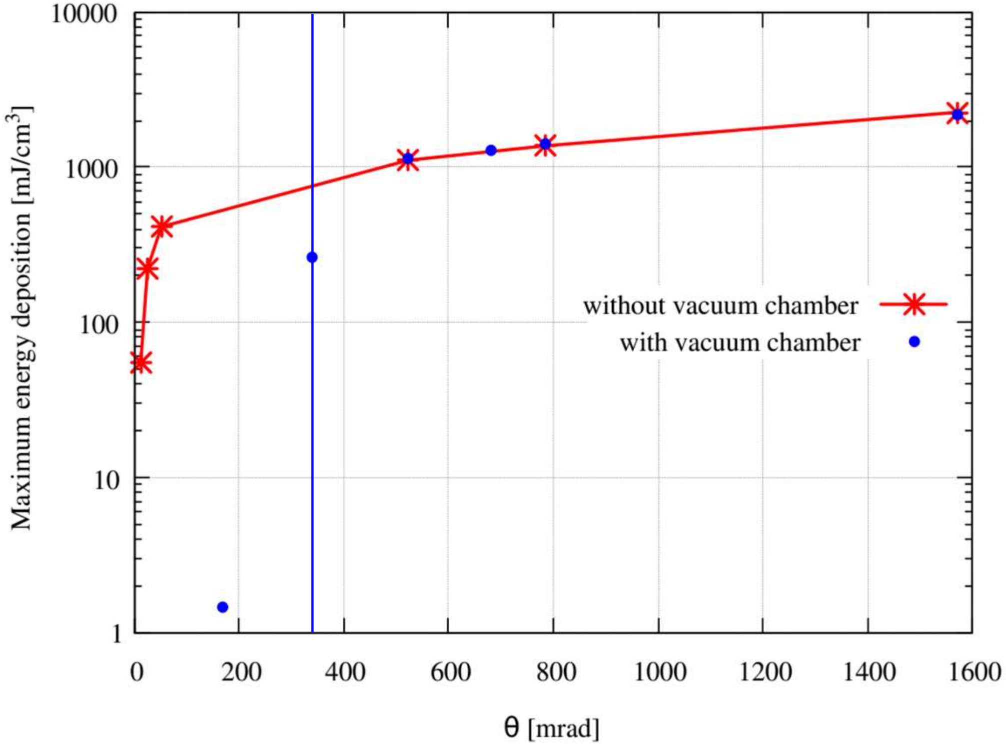
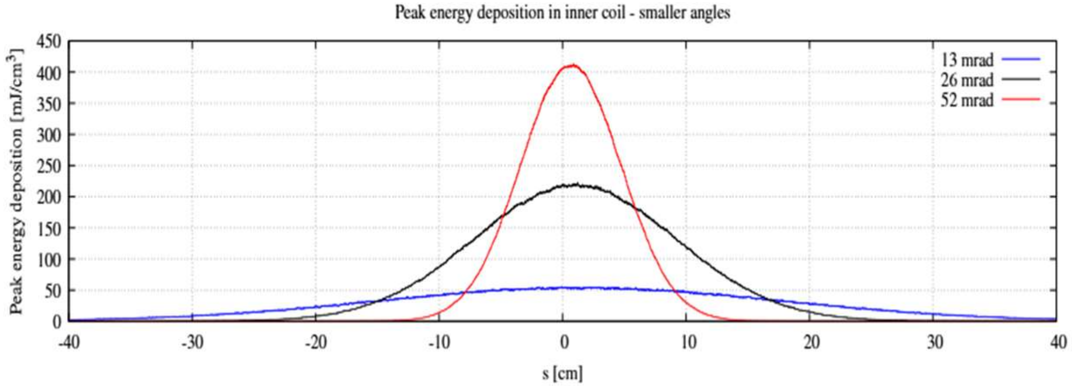
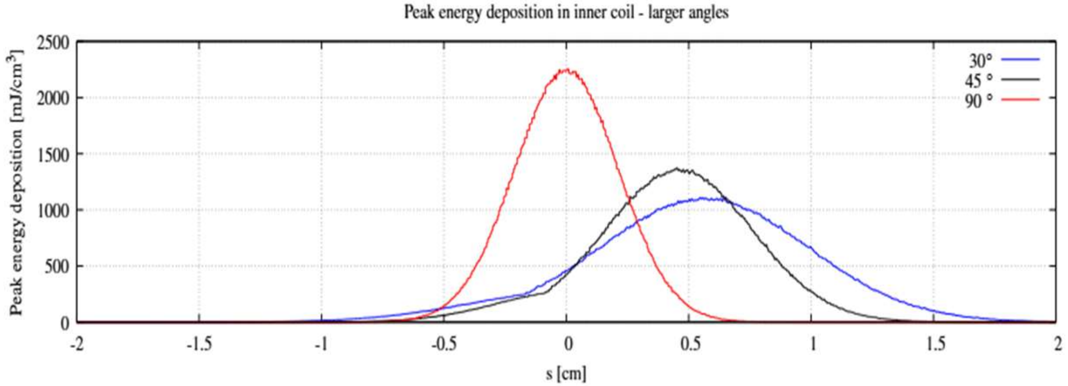
Energy deposition in magnet geometry: straight magnet

C-ions beam at 115 MeV/u

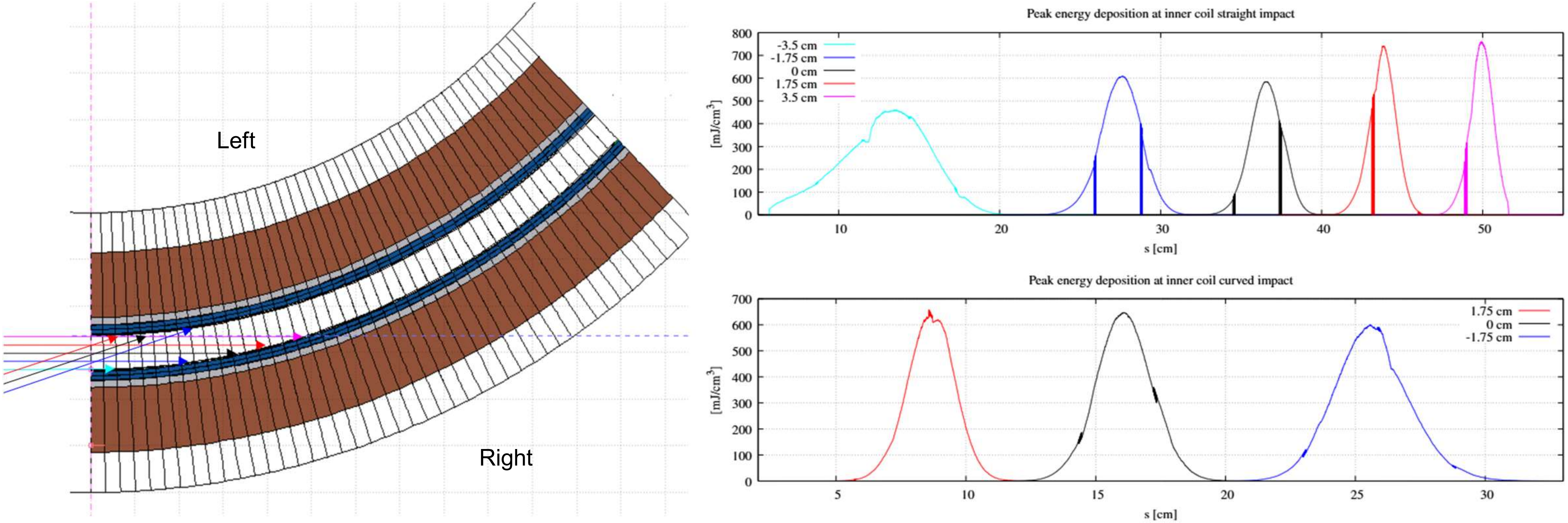






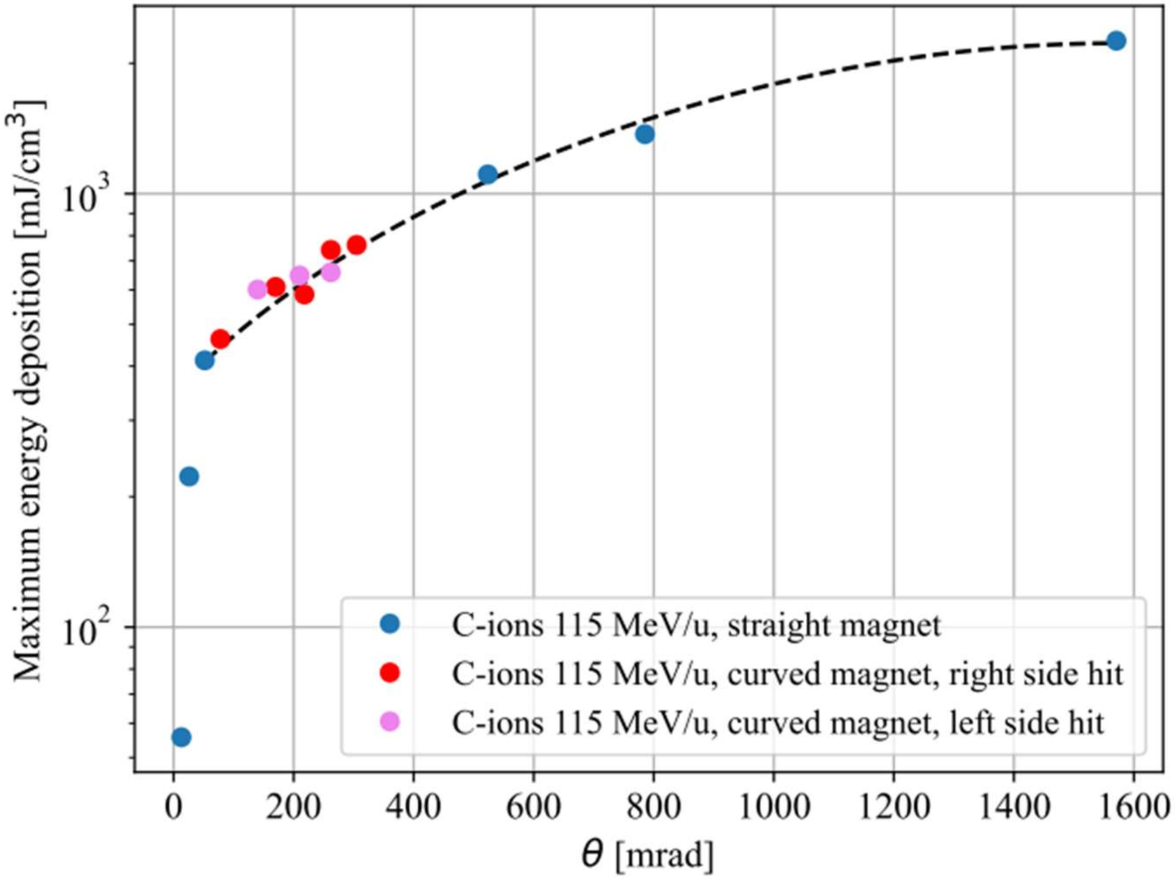
The quench occurs at higher impact angles or probably does not occur when the pipe is considered.

Energy deposition in magnet geometry: curved magnet



The beam impacts on the left and right side are separately evaluated (cases without the vacuum chamber).

Energy deposition in magnet geometry: comparison



Fit:

$$\text{Max energy deposition} = \frac{A}{\frac{\pi\sigma^2}{\sin\theta} - b} + c$$

Simulation results for the curved geometry are consistent with those obtained for the straight geometry.

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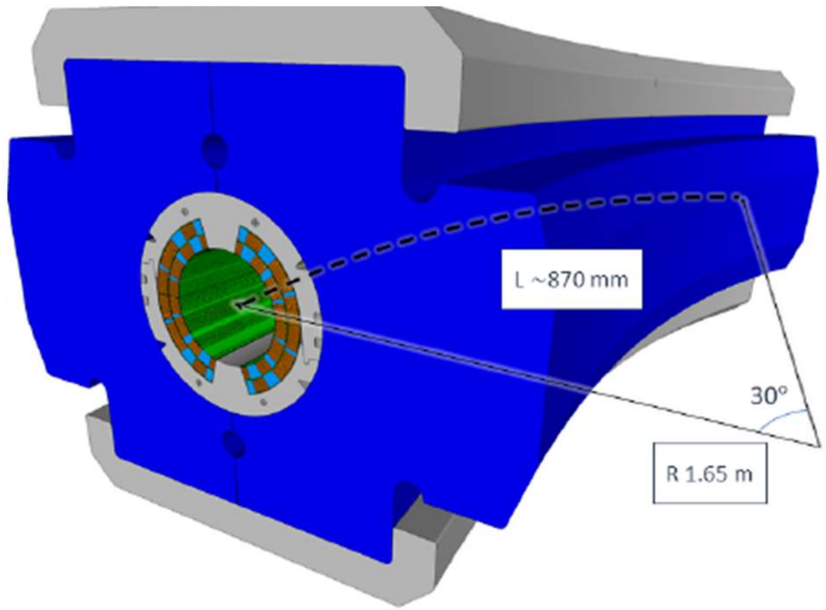

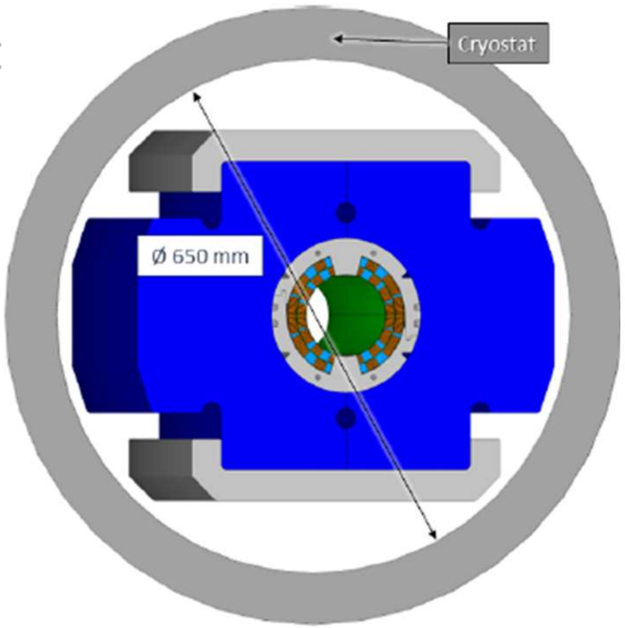

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Conclusions and Outlooks I

- Motivations for the studies

  - Can CNAO beams losses induce quenching?
  - Should mitigation be considered (protection devices or reduce the beam intensity)?

- Montecarlo simulation with FLUKA

  - not based on operational beam losses at CNAO.
  - Adiabatic assumption.
  - no magnetic field.

- Homogeneous material

  - The particles at minimum energy present the most concerning results.
  - Spot size is comparable to the beam sizes of the gantry optics studies.
  - The spot size is a ruling factor.

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Conclusions and Outlooks II

- Considering the SIG magnet cross section
  - The inclusion of a vacuum chamber has led to a significant improvement in the results.
  - Impact angle is a ruling factor.

- Outlooks
  - Studies on more realistic upstream line impact condition.
  - Technical design of a vacuum chamber.
  - Simulation of the entire gantry geometry.

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EuroSIG
European Superconducting Ion Gantry

CNAO
Centro Nazionale di Adroterapia Oncologica

HITRI plus
Heavy Ion Therapy Research Integration

RADSUM 2025

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MILANO 1863

Thanks for your attention!

Explorative energy deposition studies in the superconducting dipole magnet of the carbon ion gantry for CNAO BACKUP

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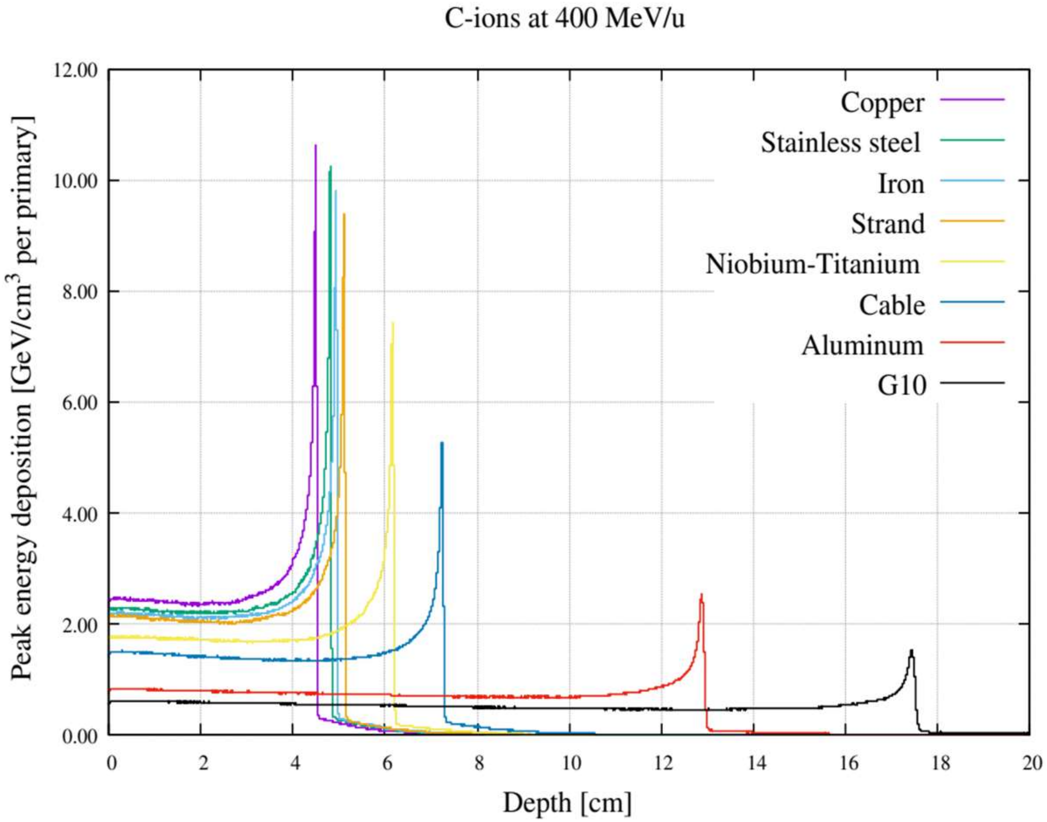
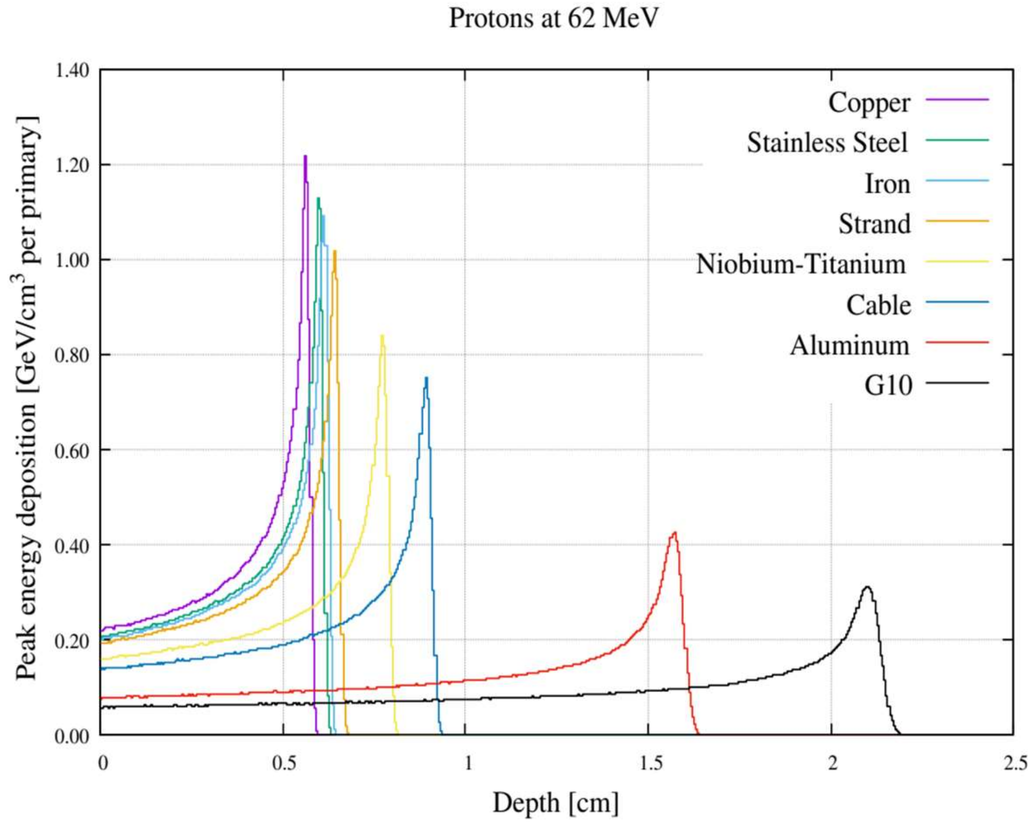
Energy deposition in magnet geometry : Backup





Longitudinal profiles of peak energy deposition in a thick target of homogeneous material for protons minimum and C-ions at maximum energy

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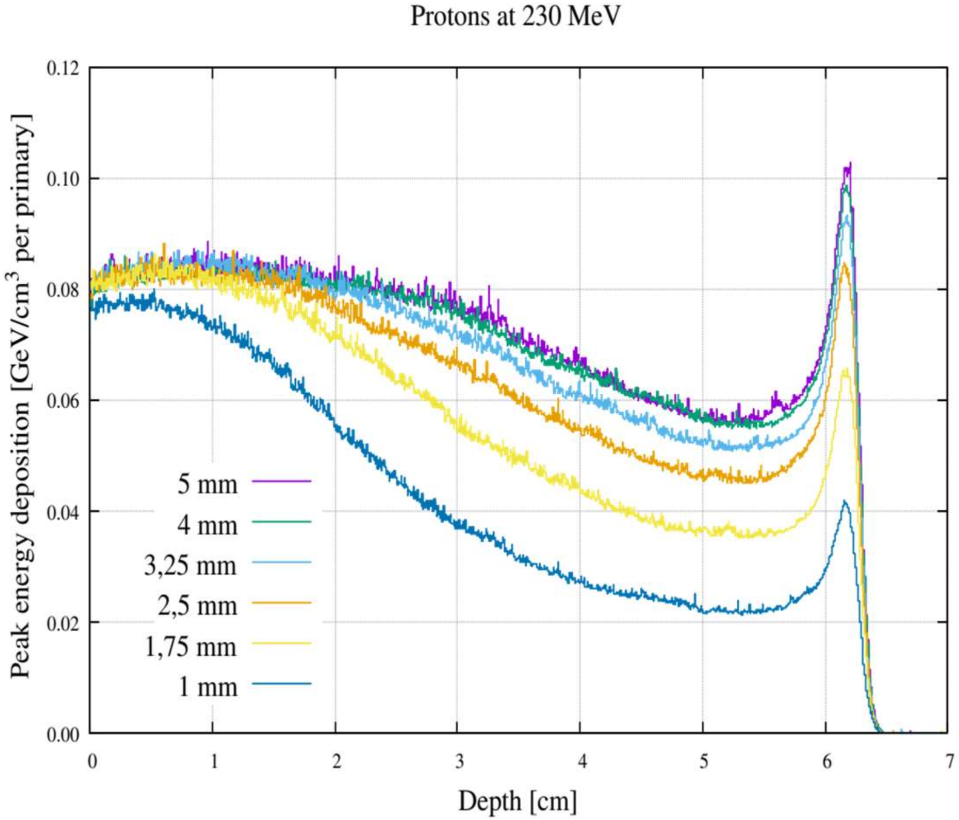
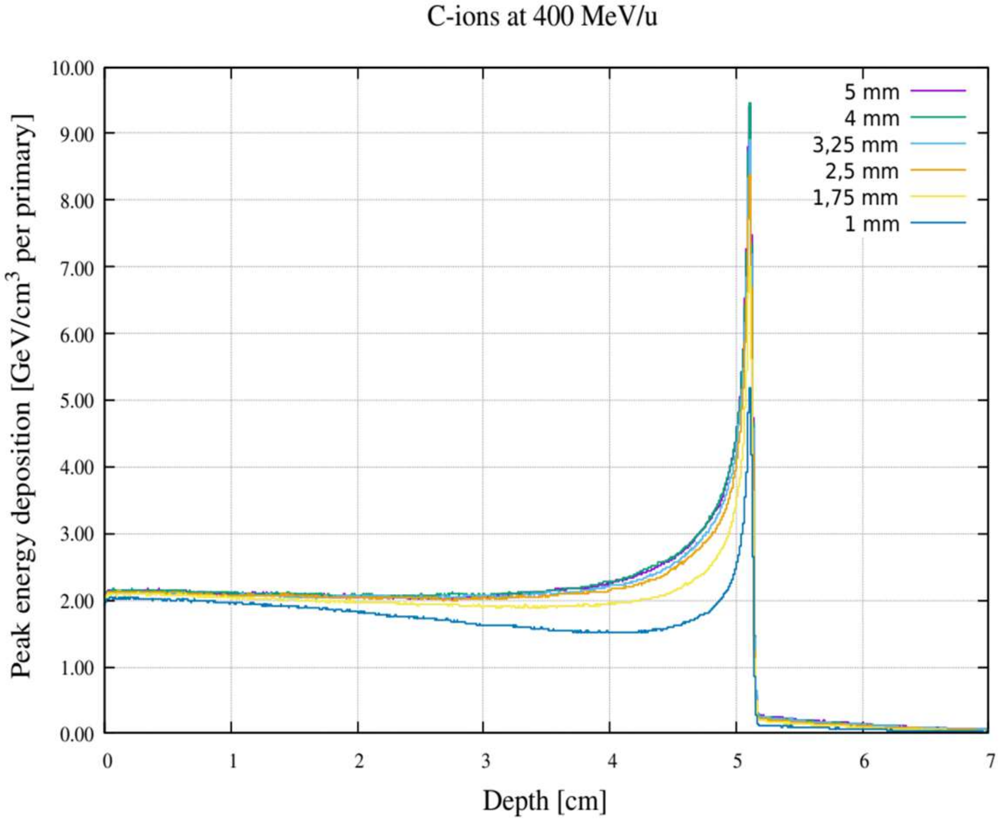
Energy deposition in magnet geometry : Backup

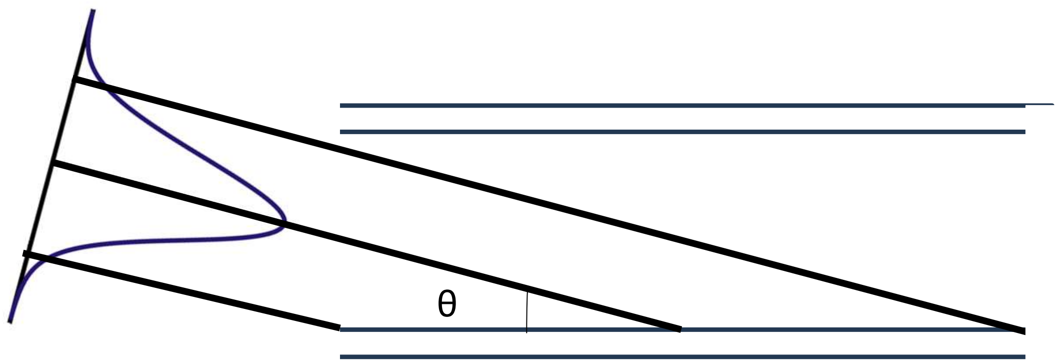




Longitudinal profiles of peak energy deposition in a thick target of homogeneous material for protons and C-ions at minimum energy, with different σ on the x and y axis but same area

Energy deposition in magnet geometry: Backup

$$\text{Full illumination angle} = \sin(\theta) = \frac{2n\sigma}{length}$$



Angle such that the entire beam hits the magnet illuminating the entire length.

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