Feasibility Study of GaToroid Gantries for Carbon Ions

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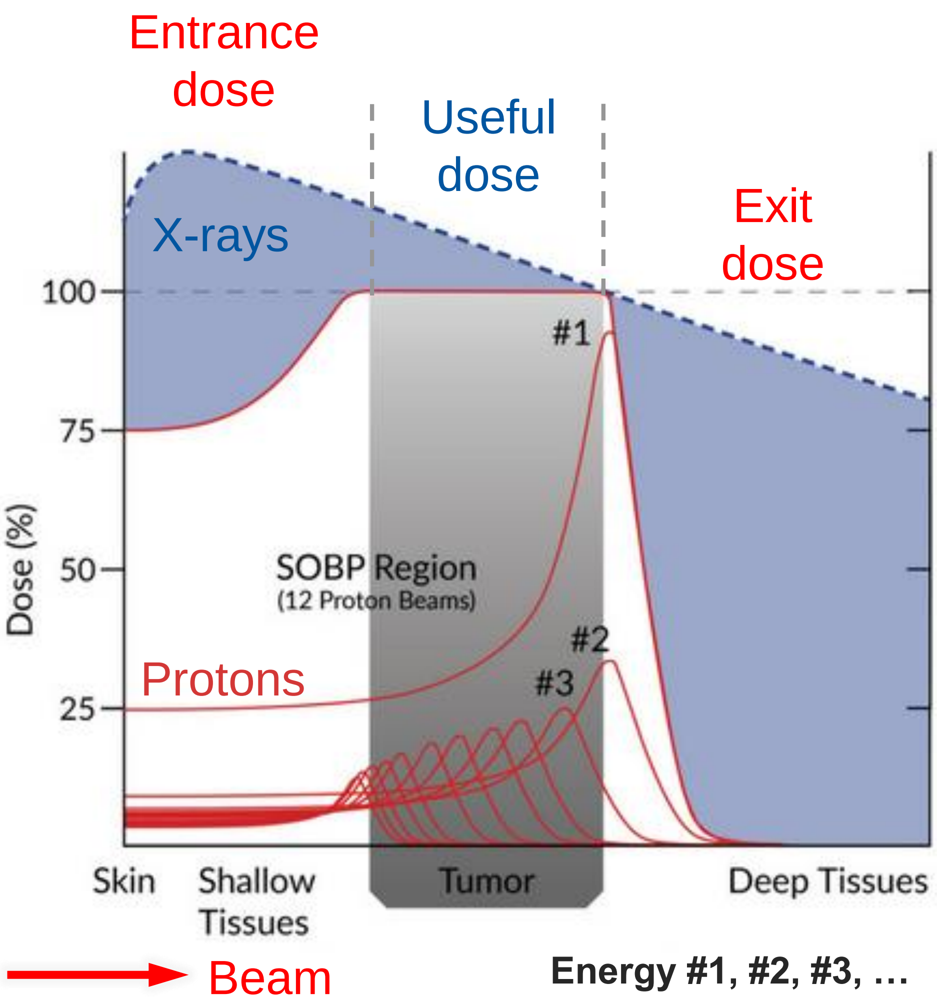
MT27, 27th International Conference on Magnet Technology

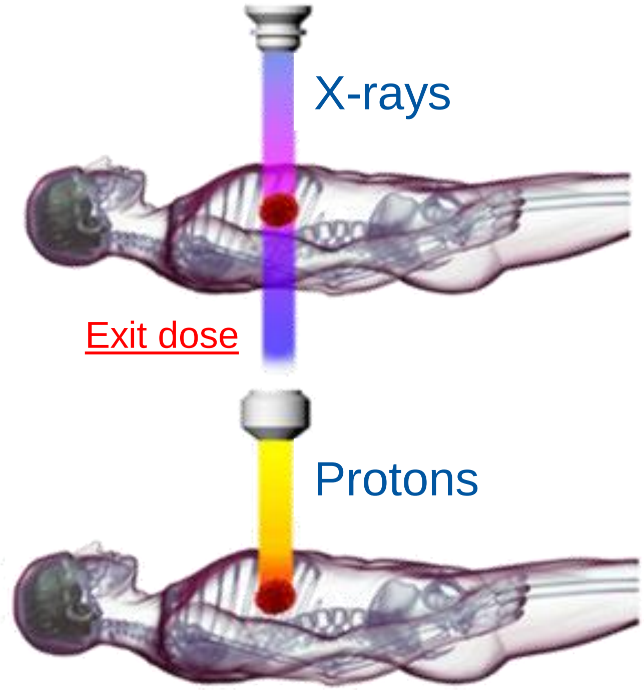
18/11/2021

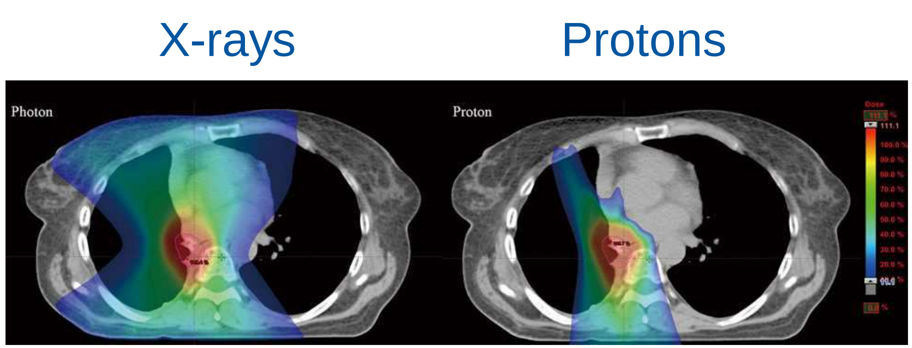
Outline

- Hadron therapy and gantries
- GaToroid concept
- GaToroid for Carbon Ions
  - Coil optimization
  - *Baseline* and *Compact* versions
  - Conductor and Protection
- Conclusions

Hadron Therapy





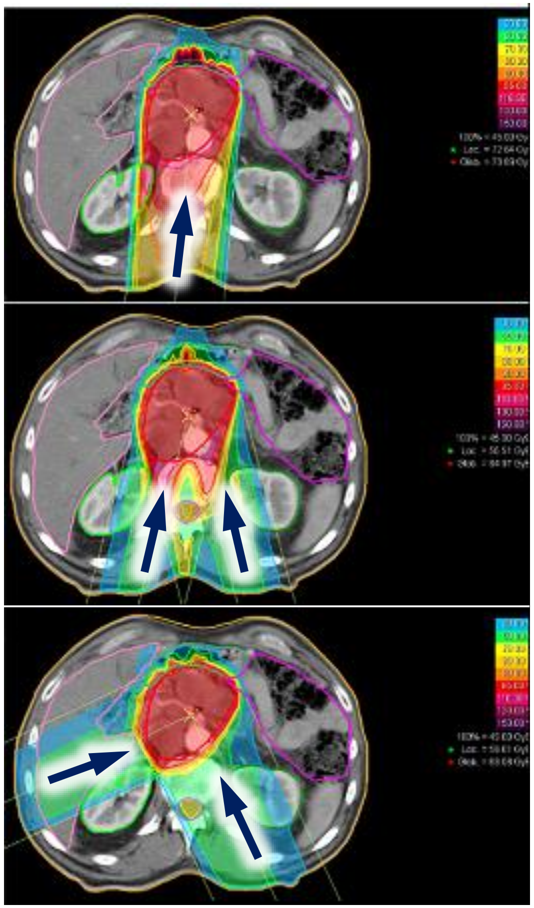


SOBP: Spread Out Bragg Peak

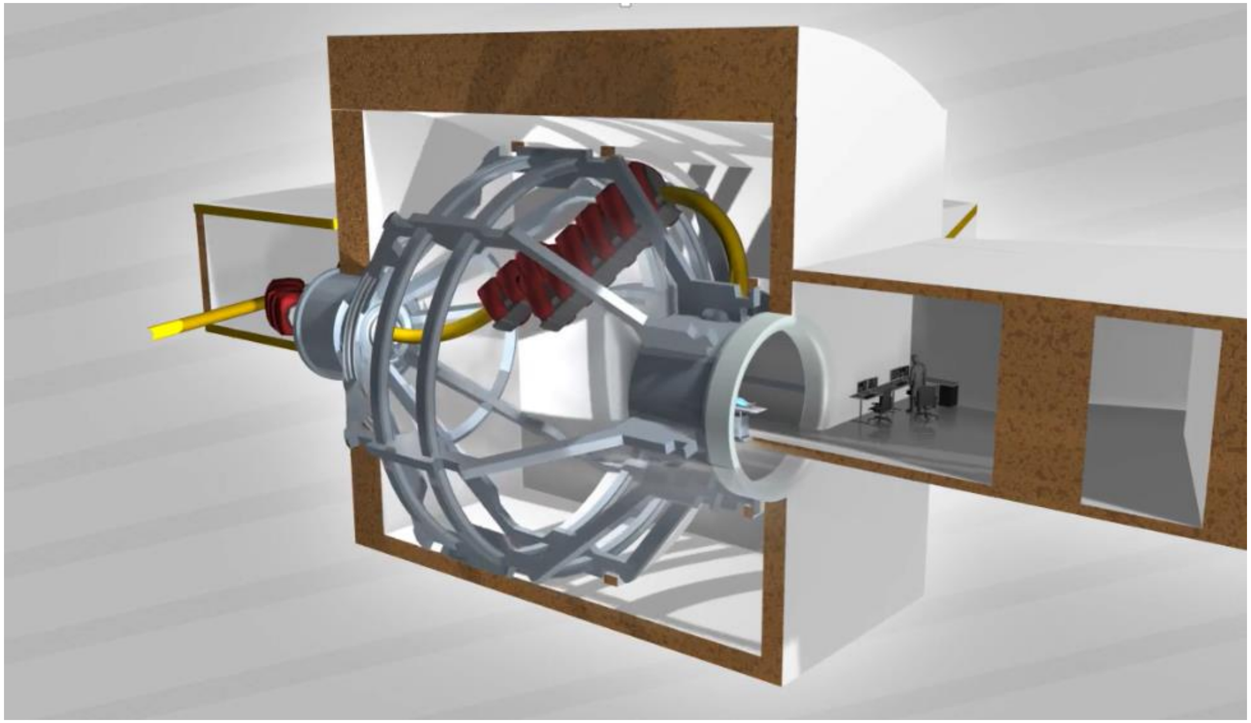
Translational Lung Cancer Research, 6(2), 2017

Gantries

Transfer lines able to irradiate from multiple directions



PLoS ONE 11(10): e0164473, 2016



- <u>Proton Gantries</u>: radius 4…5 m - weight 100…200 tons
- <u>C-Ions Gantries</u>: radius 6…7 m - weight 350…670 tons

P-ARTIS System, “The Next Generation Adaptive Proton Therapy”, June 2016
https://www.youtube.com/watch?v=oO-EiDssSAw

Challenges of Gantries

Limited magnetic field requires high radii of curvature
→ **massive machines**

→ Superconducting magnets

Current and field adjusted as a function of beam energy
→ **inductance and losses**

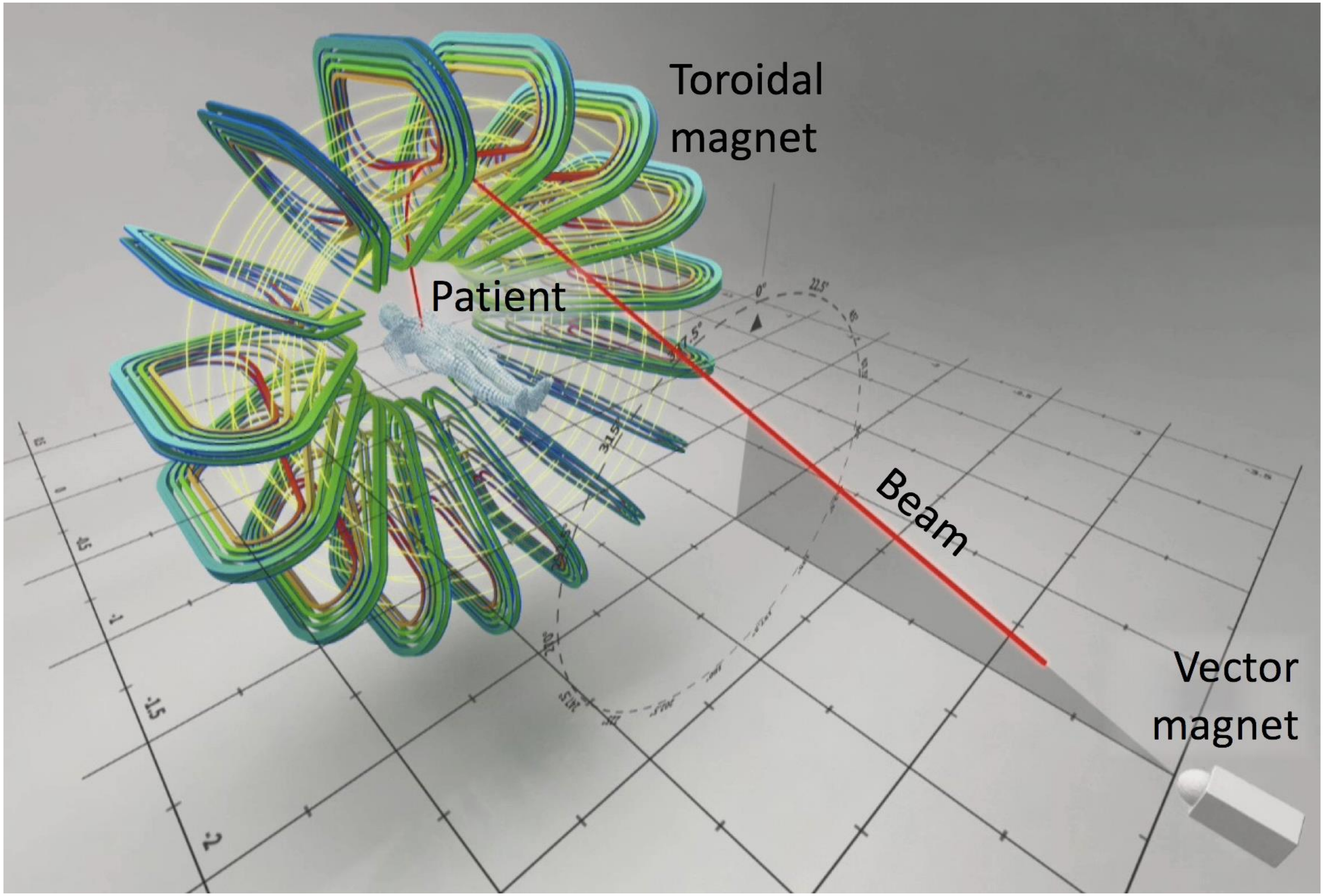
→ Large acceptance

Precise rotation
→ **complex mechanical structures**

→ Steady-state operation

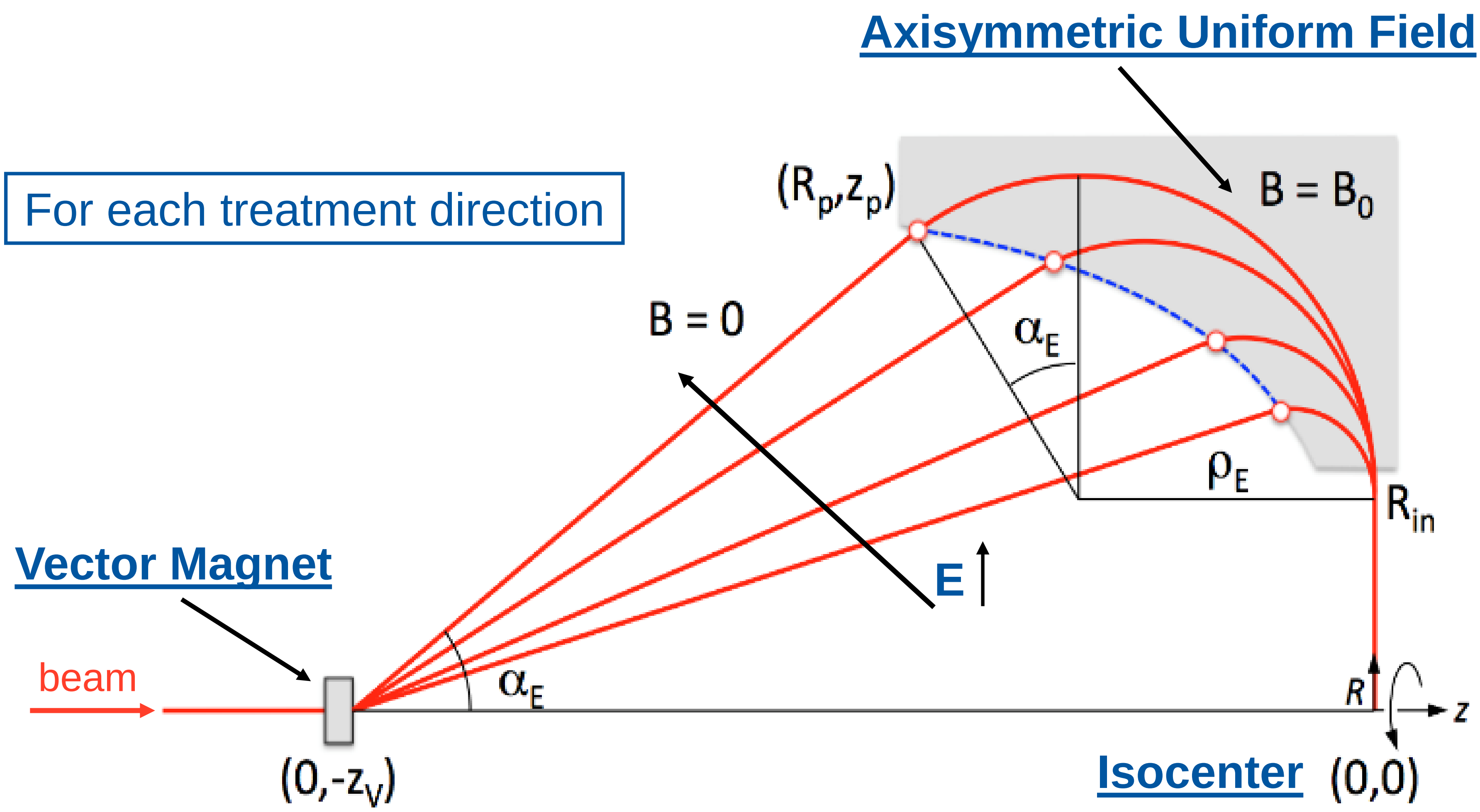
GaToroid concept

Graphics courtesy of Daniel Dominguez
(CERN Design and Visual Identity Service)



L. Bottura, *A Gantry and Apparatus for Focusing Beams of Charged Particles*, European Patent Application EP 18173426.0, May 2018, https://worldwide.espacenet.com/patent/search/family/062235811/publication/WO2019224215A1?q=WO2019%2F224215

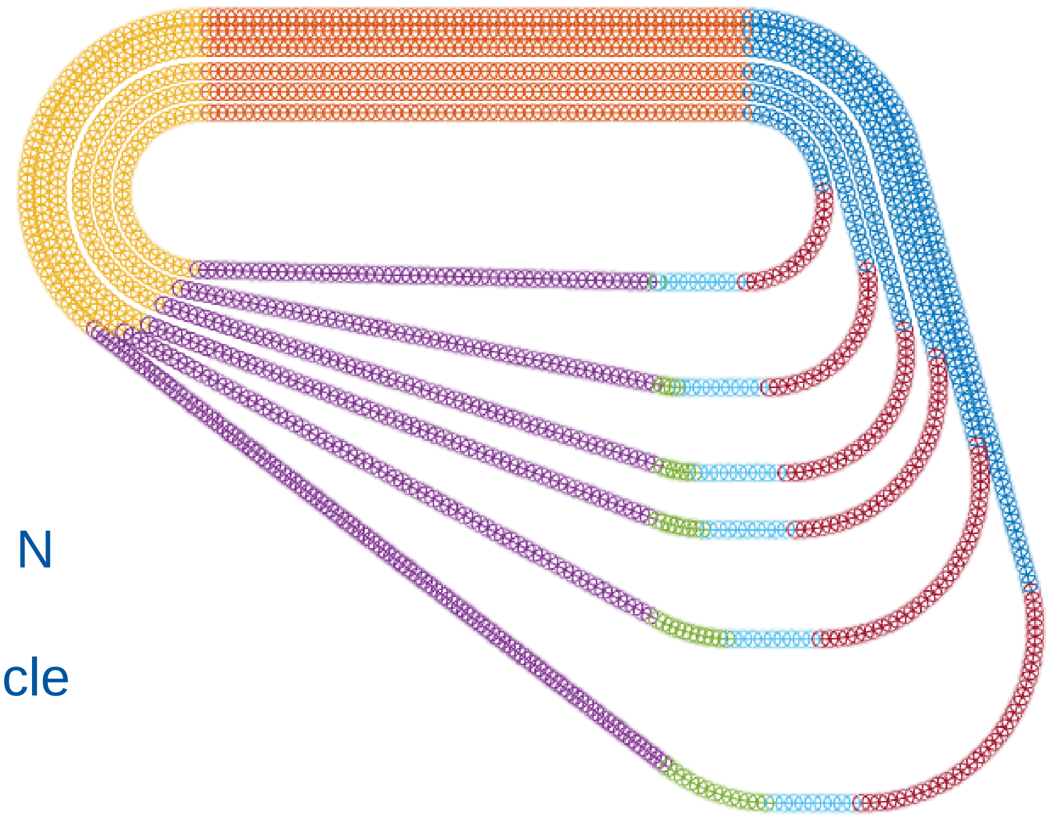
GaToroid Concept



L. Bottura, E. Felcini, G. De Rijk, B. Dutoit, “GaToroid: A Novel Toroidal Gantry for Hadron Therapy”, Nucl. Instrum. Methods Phys. Res. A, 2020

Coil Optimization

Coil geometry and current distribution need to be optimized to direct beams of different energies at the isocenter (patient)



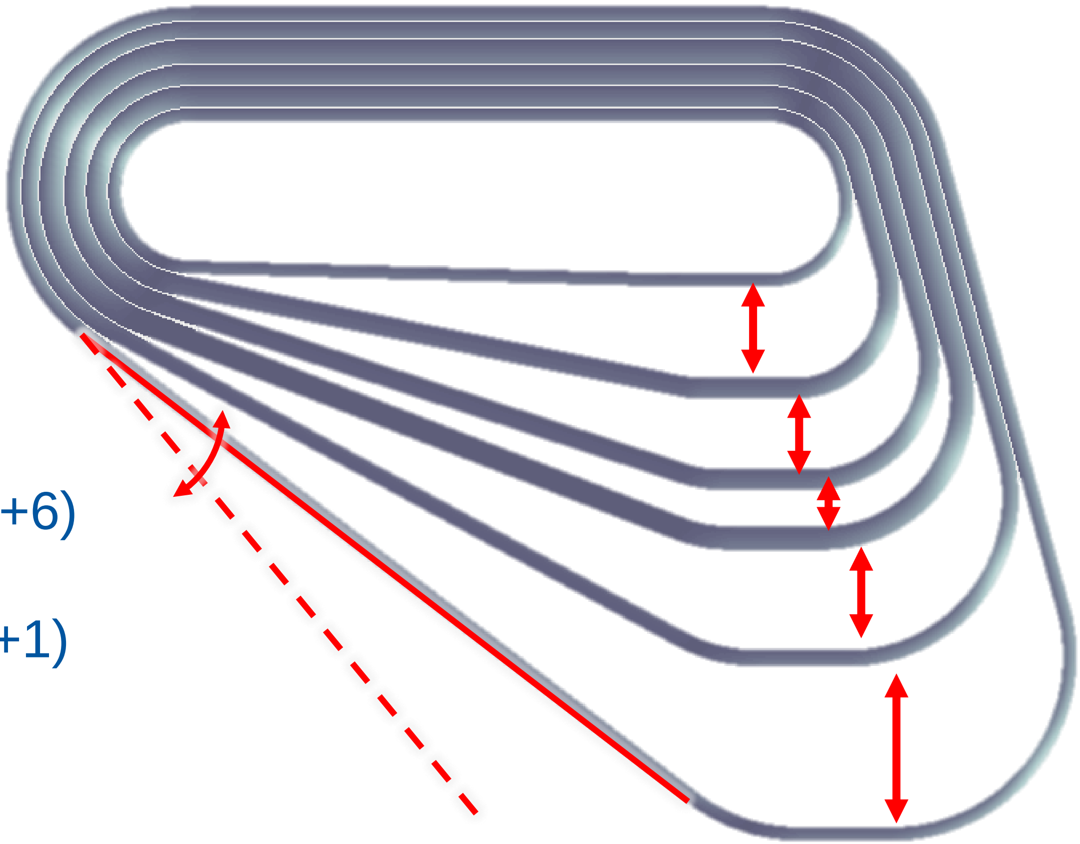
The coil can be parametrized with N variables and the optimization algorithm, integrated with 2D particle tracking, seeks for the “best” solution.

E. Felcini, L. Bottura, J. van Nugteren, G. de Rijk, G. Kirby and B. Dutoit, "Magnetic Design of a Superconducting Toroidal Gantry for Hadron Therapy," in IEEE Transactions on Applied Superconductivity, vol. 30, no. 4, pp. 1-5, June 2020, Art no. 4400405, doi: 10.1109/TASC.2020.2966174.

Coil Optimization

In the following solutions we used 12 variables:

- Distance between grades (+5)
- Ampere-turns on each grade (+6)
- Angle of the main coil profile (+1)



The number of possible parametrization variables is limitless, but the computational time is not…

**we define a grade as each sub-coil composing the coil*

Clinical Requirements*

- Large number of treatment directions (≥ 20):

Pro (clinical-side)	Cons (engineering-side)
Treatment flexibility	System complexity (i.e. forces, stored energy, mass…)

- Large bore aperture (≥ 3 meters):

Pro (clinical-side)	Cons (engineering-side)
Non coplanar treatments	System complexity (B α 1/R) (i.e. dimension, cryo., mechanics…)

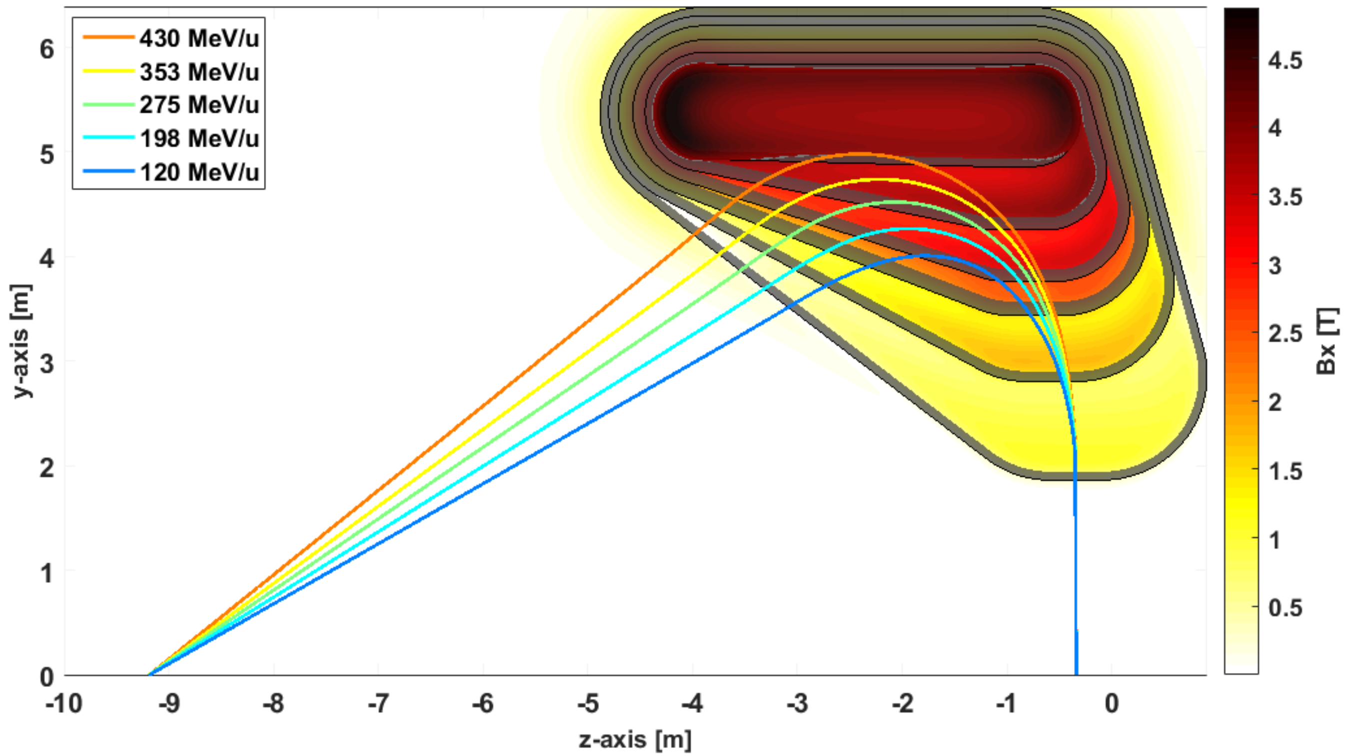
- Beams orbits perpendicular at the isocentre:

Pro (clinical-side)	Cons (engineering-side)
Easier treatment planning	More complex optimization

* resulting from extensive discussions with CNAO (IT) and MedAustron (AT)

GaToroid for C-ions

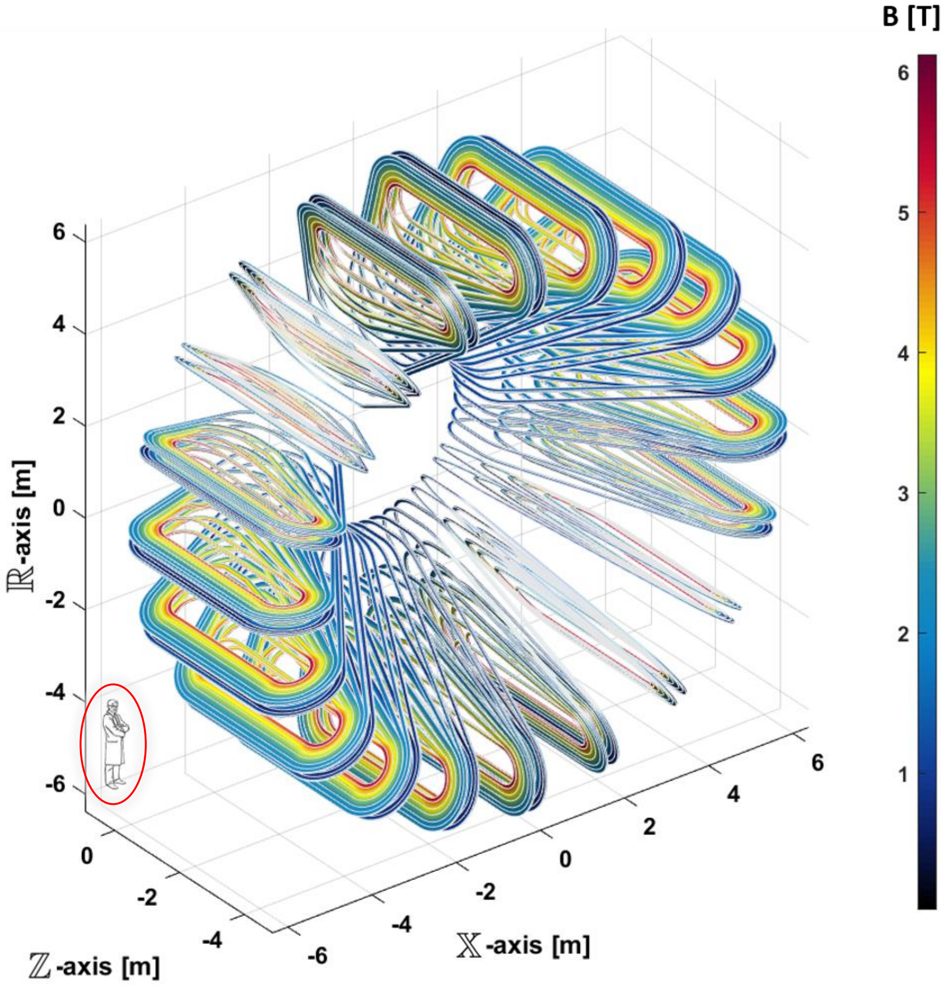
$J_E = 100\ (A/mm^2)$



Beams directed at the vector magnet within 1 mm, in the 120-430 MeV/u range

(Reverse tracking optimization done with 12 variables)

GaToroid for C-ions Baseline Version

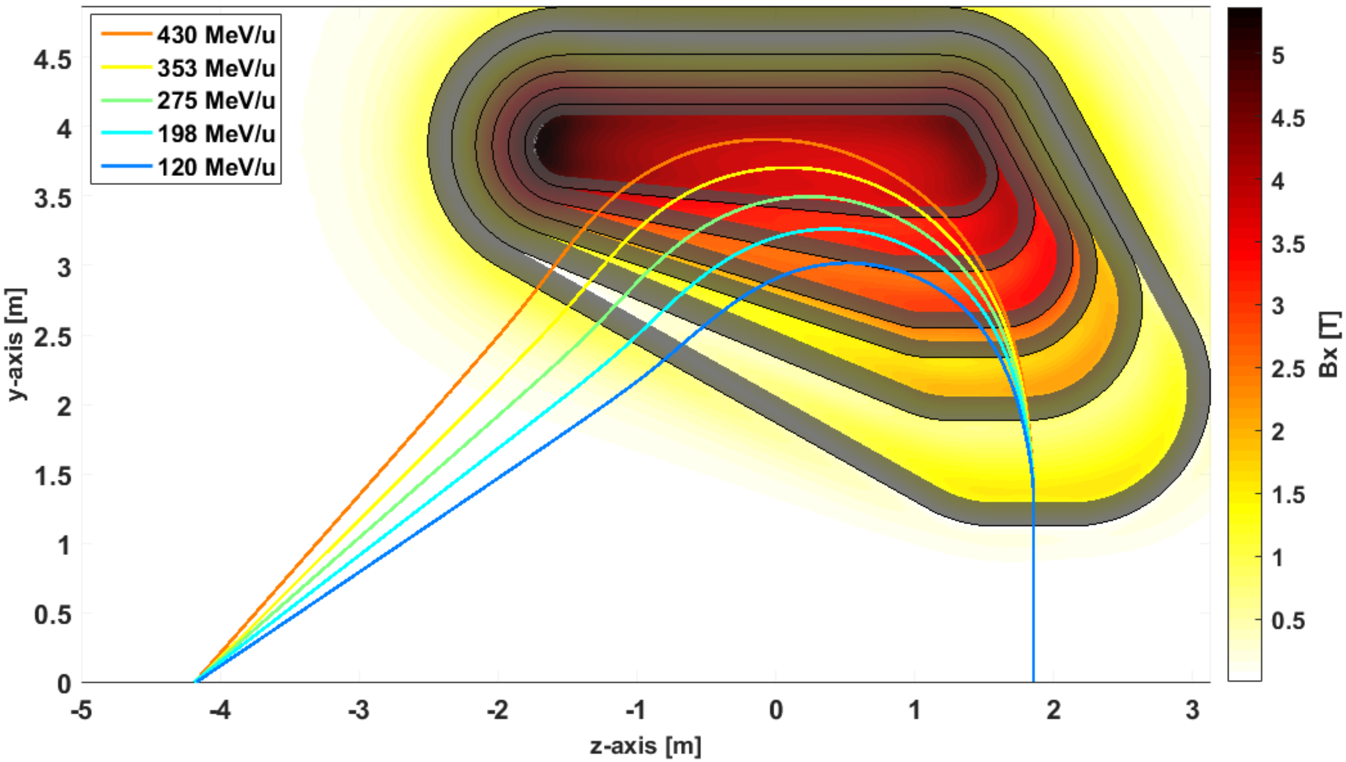


- Number of directions: 20 (-)
- Ampere-turns: 90 (MA-turn)
- Peak Field on coil: 6.1 (T)
- Coil dimension: 5.8 x 4.5 (m x m)
- External Diameter:12.8 (m)
- Internal Diameter: 3.7 (m)
- Estimated mass*: 270 (tons)
- Total Stored energy: 1300 (MJ)

*estimated mass of the mechanical structure required to handle centering (normal operation) and overturning (fault scenario) forces in the whole torus

GaToroid for C-ions

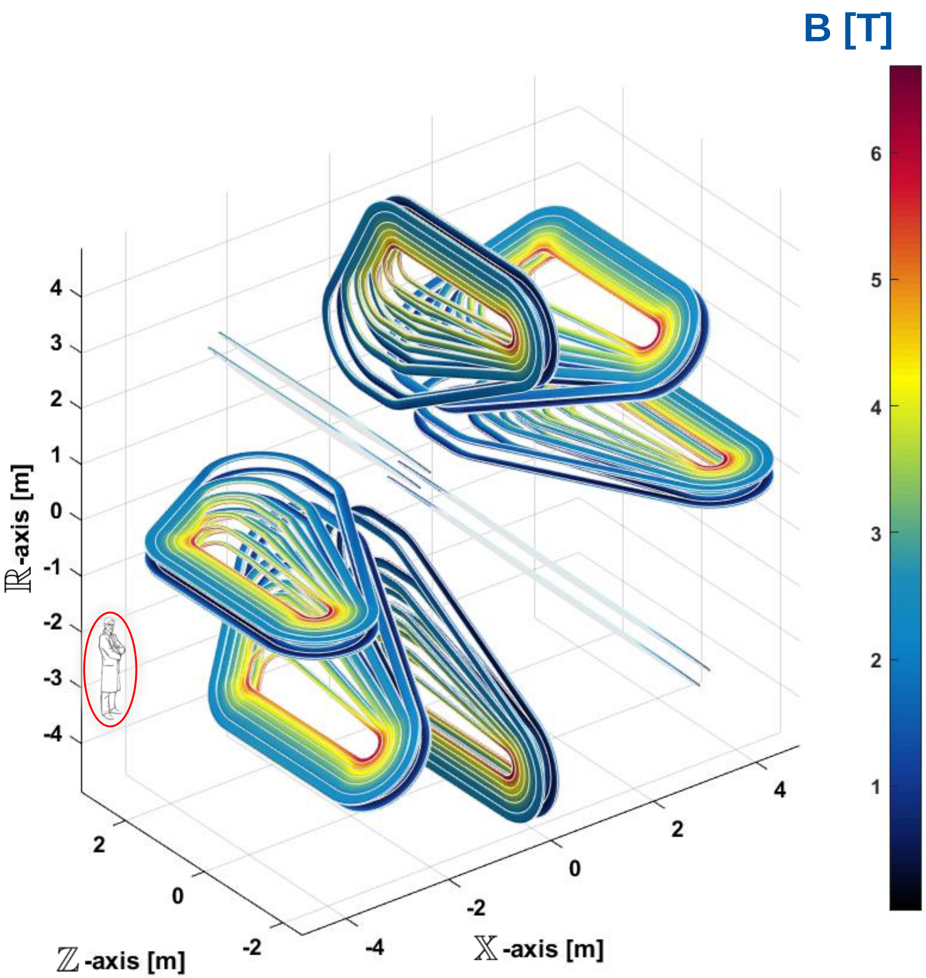
J_E = 100 (A/mm^2)



Beams directed at the vector magnet within 1 mm, in the 120-430 MeV/u range

(Reverse tracking optimization done with 12 variables)

GaToroid for C-ions Compact Version



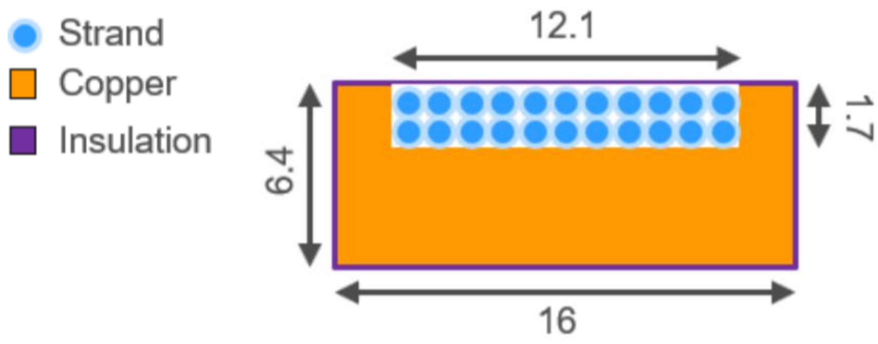
- Number of directions: 8 (-)
- Ampere-turns: 45 (MA-turn)
- Peak Field on coil: 6.7 (T)
- Coil dimension: 5.6 x 3.7 (m x m)
- External Diameter: 9.7 (m)
- Internal Diameter: 2.25 (m)
- Estimated mass*: 115 (tons)
- Total Stored energy: 420 (MJ)

*estimated mass of the mechanical structure required to handle centering (normal operation) and overturning (fault scenario) forces in the whole torus

Conductor and Protection

As a reference conductor
we selected a

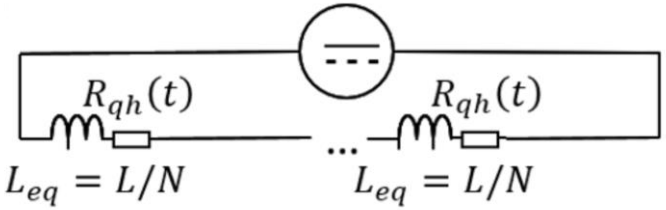
- Rutherford cable composed by 22 Nb-Ti strands
- Highly stabilized with a Copper profile



Operating current: 10.8 kA

For both gantry versions, we evaluated a protection scheme based on:

Quench Heaters



$V_{max} = 50$ V

	Baseline	**Compact**
Cable Cu:Sc	8.12	5.42
Eng. current density [A/mm^2]	105	125
Maximum temperature [K]	130	120
Heater power /channel [kW]	43	44

Conductor and Protection

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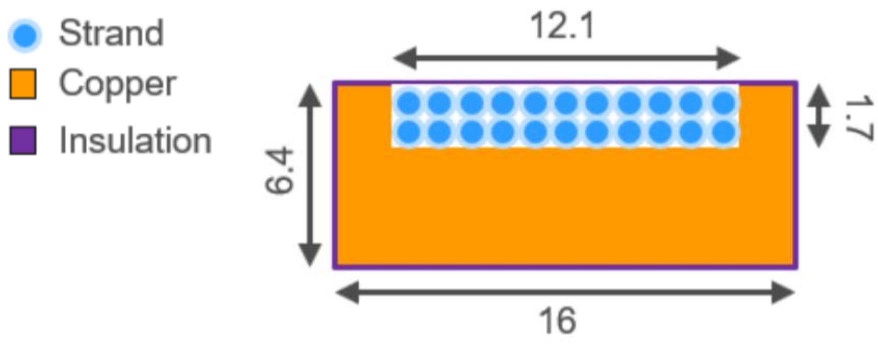
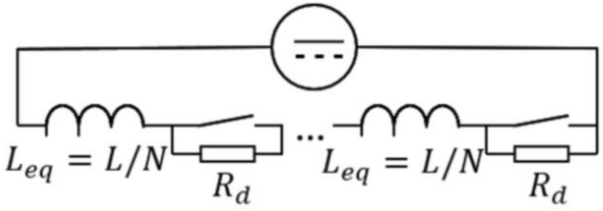
- Highly stabilized with a Copper profile



Operating current: 10.8 kA

For both gantry versions, we evaluated a protection scheme based on:

N dump resistors



V_{max} = 500V / R_d = 46 mΩ

	Baseline	Compact
Cable Cu:Sc	12.4	9.01
Eng. current density [A/mm^2]	68	74
Maximum temperature [K]	96	84

Conclusions

- GaToroid may offer an interesting alternative to the present state-of-the-art design of gantries for hadron therapy
- Two versions of GaToroid for carbon ions were studied:
  - Baseline: to push toward the functionalities of classical rotating gantry
  - Compact: to profit of the GaToroid concept to reduce size and weight
- Coil parametrization and optimization, integrated with particle tracking, is an effective and flexible tool to explore different solutions of a GaToroid gantry
- Even though no main showstoppers were identified, pushing GaToroid toward the functionalities of a rotating gantry may not be effective in terms of complexity and costs.

Future perspectives

As every new idea, the GaToroid presents several challenges:

- Magnet engineering and manufacturing
- Large cryogenic and vacuum systems
- Fast and precise vector magnet
- Beam physics and toroidal field multipoles[1]
- Integration with beam diagnostic and clinical devices[2]
- Qualification for therapy

Nevertheless, it is a stimulating research project and may lead to the construction of a new generation of gantries and may open the door to new treatment possibilities

[1] L. Gambini, M. Breschi, E. Felcini et al., “An algorithm for toroidal field harmonics computation in arbitrary magnetic configurations”, IEEE Trans. Appl. Supercond. (2020)

[2] L. Bottura, E. Felcini, *et al.*, “Delivery, beam and range monitoring in Particle Therapy in a highly innovative integrated design”, Frontiers in Physics (2020)

Thank you very much for your attention!