Magnetic Design of a Superconducting Toroidal Gantry for Hadron Therapy

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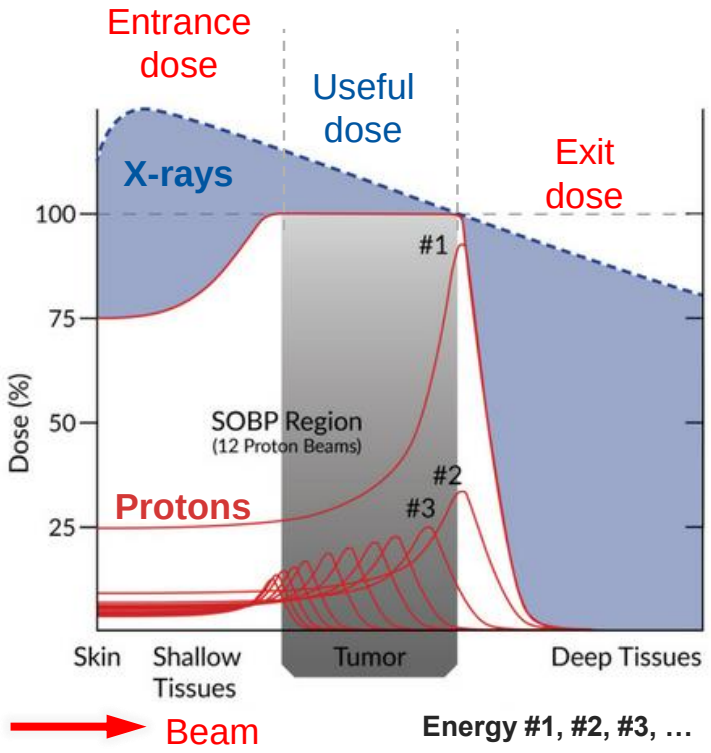
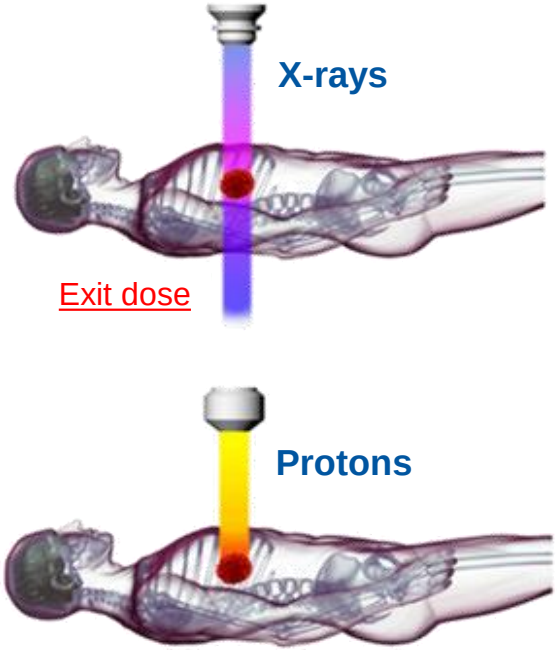
MT26, Vancouver, Canada | 26 September 2019

Project co-funded by the CERN Budget for Knowledge Transfer to Medical Applications

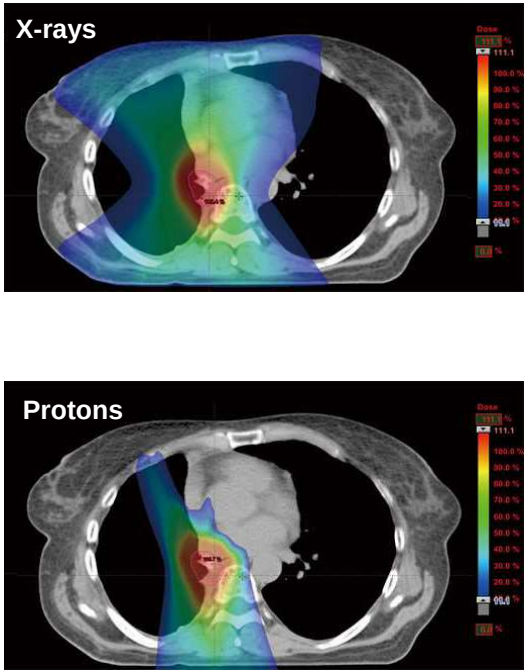
Hadron Therapy



SOBP: Spread Out Bragg Peak



[Graphics by courtesy of Protom]



[Translational Lung Cancer Research, 6(2), 2017]

Gantry

Rotating magnetic transfer line

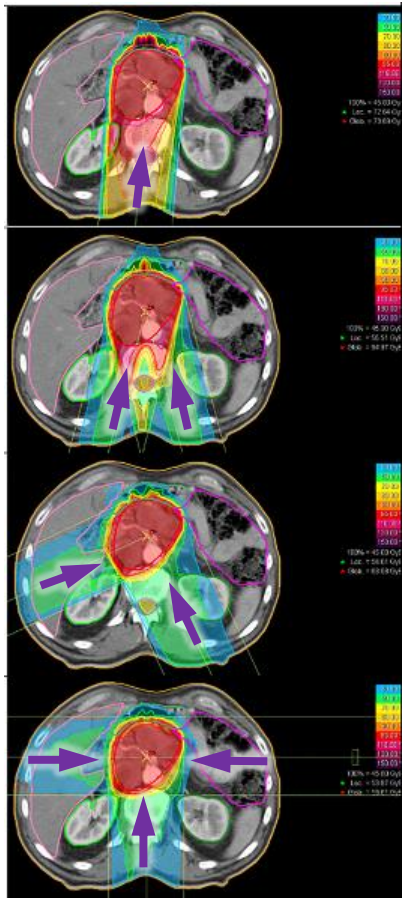
[P-ARTIS System, “The Next Generation Adaptive Proton Therapy”, June 2016 *https://www.youtube.com/watch?v=oO-EiDssSAw*]

Proton Gantries:

- radius 4…5 m
- weight 100…200 tons

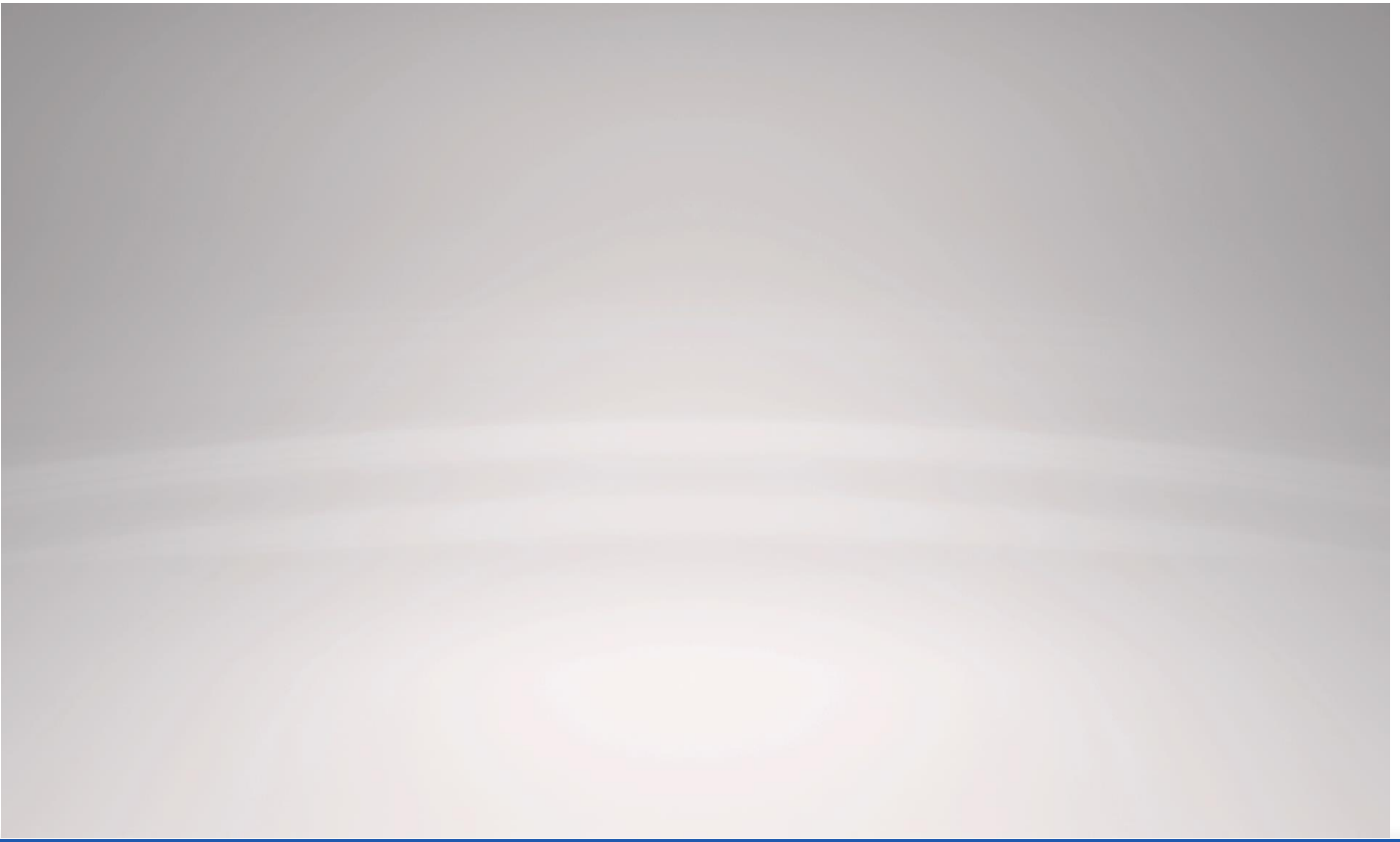
C-Ions Gantries:

- radius 6…7 m
- weight 350…670 tons



[PLoS ONE 11(10): e0164473, 2016]

GaToroid



Steady-State

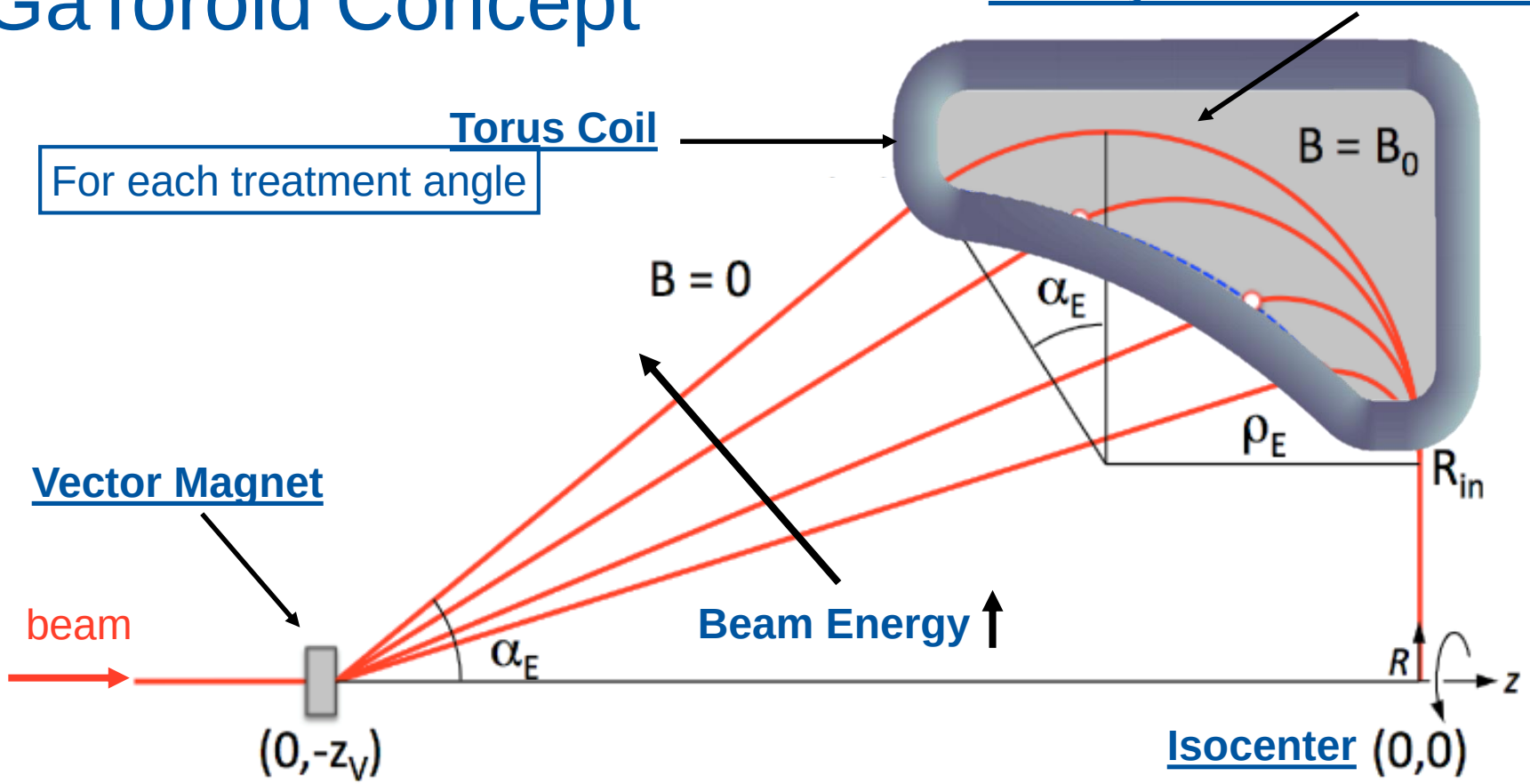
Non-Rotating

Toroidal Magnet

Discrete Angles

Superconducting

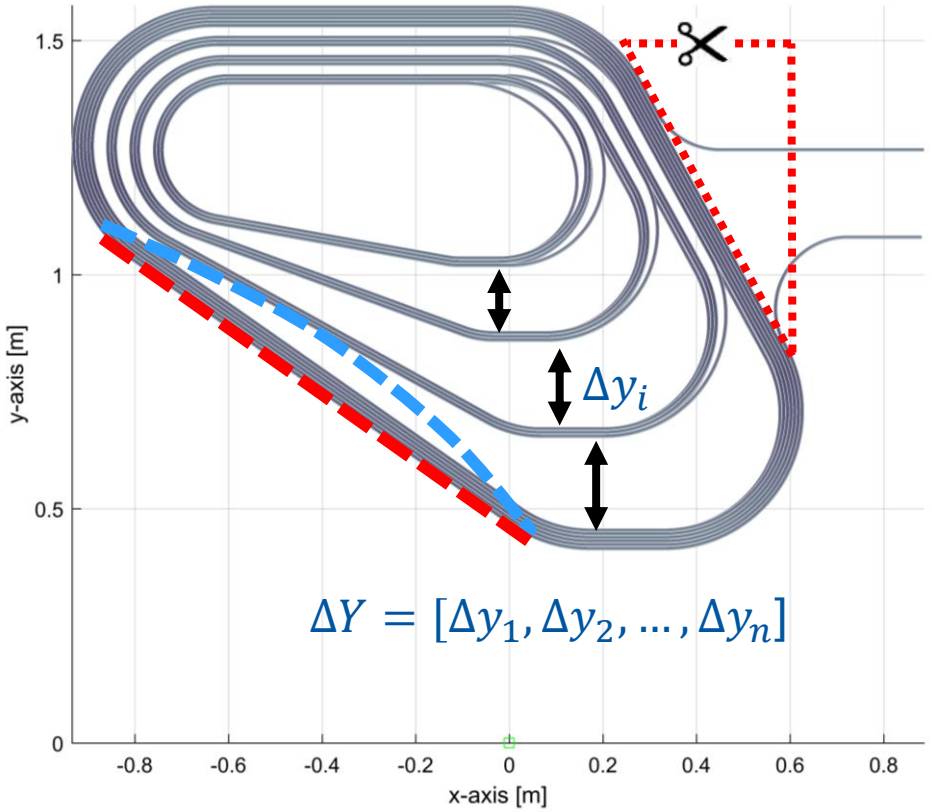
GaToroid Concept



Coil Design and Optimization

- Linearize the profile to simplify the winding
- Optimize ΔY grading to obtain proper magnetic field $B \neq f\left(\frac{1}{r}\right)$
- Minimize the conductor to reduce stored energy and costs

- Multi-tape 3D winding geometry
- Double Pancake
- Grade and layer jumps
- Current leads
- ...



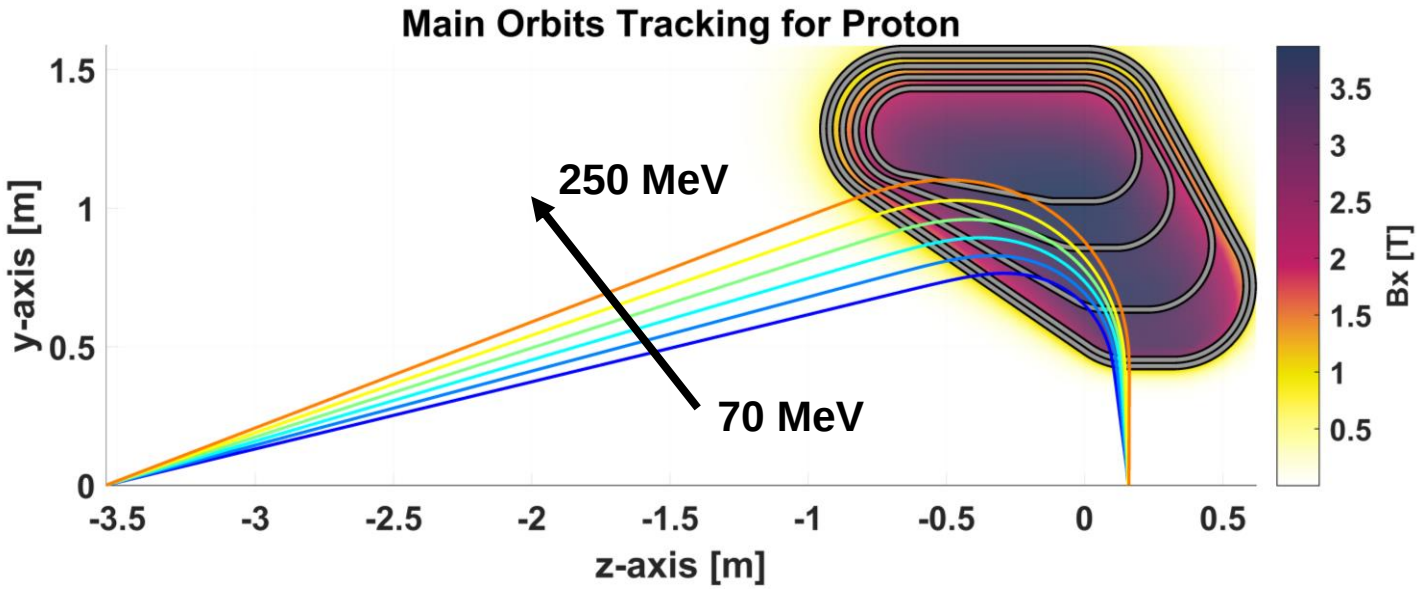
Single Particle Tracking

Symmetry plane between two coils

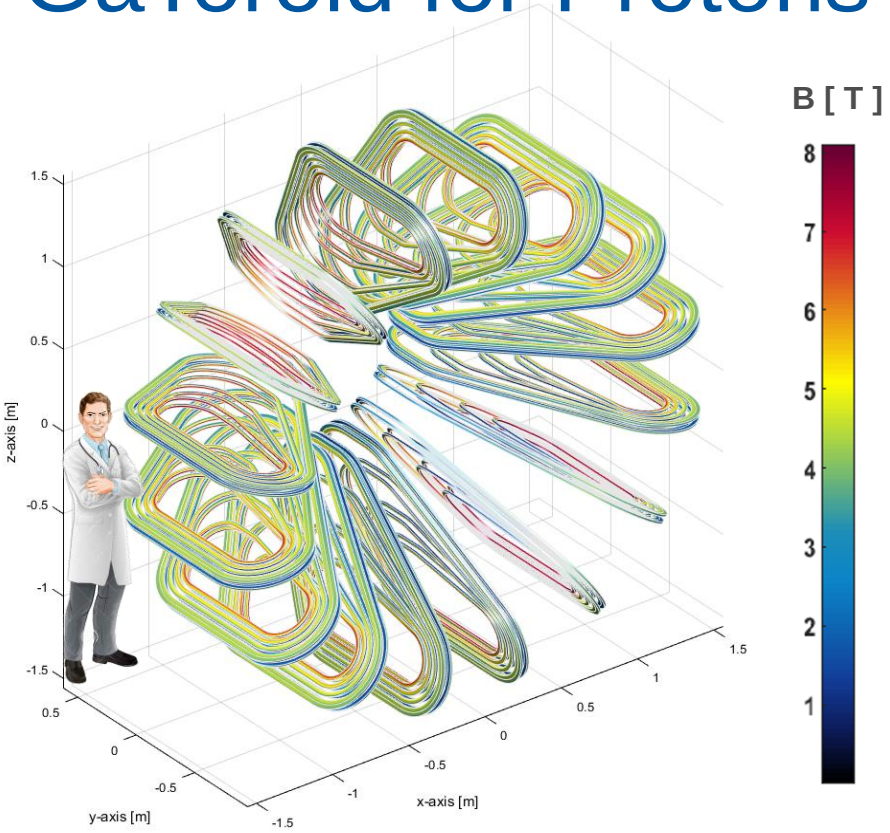
2D tracking

Orbit definition for each energy

Null magnetic field at the patient



GaToroid for Protons



- Number of coils: 16 (-)
- Peak Field on coil: 8.2 (T)

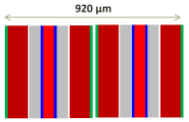
- **Torus dimensions: ~1.5 x 3 (m x m)**
- Bore: ~ 0.8 m (MRI-like)
- **Estimated mass: 12 (tons)**

- Total Stored energy: 30 MJ
  (LHC dipole ~7 MJ)
- Operating current: 1800 A
- Coil Inductance: 1.1 H

- Operating Temperature
  - 4.5 K (LTS) $
  - 20 K (HTS) $$$

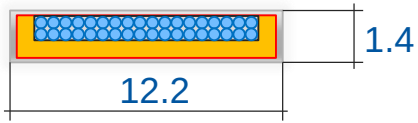
Conductors

Similar to EUCARD HTS Insert (CEA):
6 co-woud tapes : 2 sc, 4 CuBe2



LTS option (Nb-Ti)

- 36 strands (0.5 mm) Rutherford
- Soldered Cu-profile
- Polyimide/glass insulation
- Epoxy impregnated



- I_{op} = 1800 A
- T_{op} = 4.5 K
- J_E = 105 A/mm^2

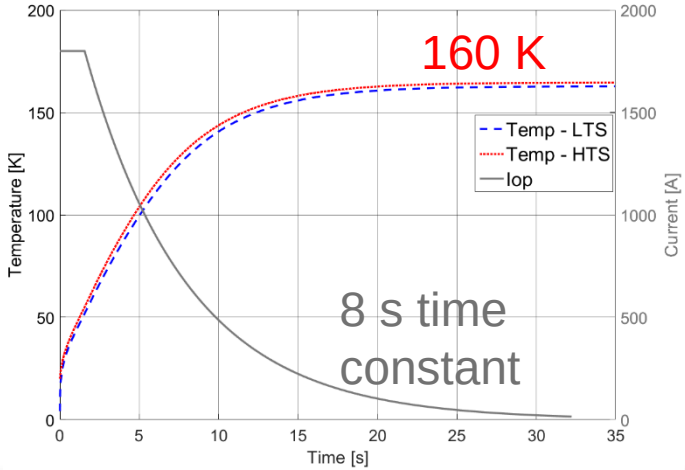
HTS option (ReBCO)

- 3 SC tapes (12x0.1 mm) ~~transposed~~
- 6 Co-wound Cu tapes (12x0.2 mm)
- Polyimide/glass insulation
- Epoxy impregnated

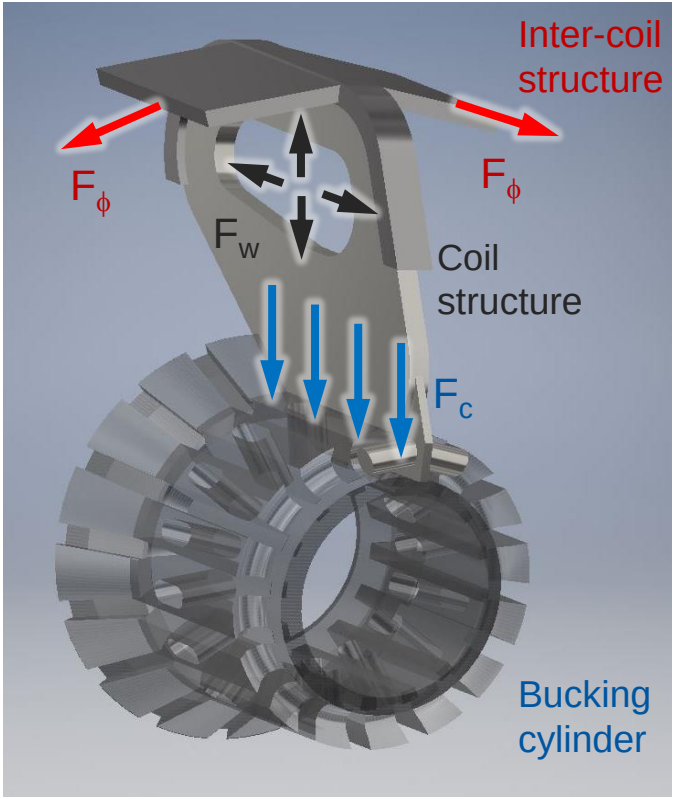
- I_{op} = 1800 A
- T_{op} = 20 K
- J_E = 90 A/mm^2

Protection, e.g. External Dump

- Two powering circuits
- 2 s quench detection
- ± 1 kV dump voltage



Mechanical design concept



Winding force

- F_w = 2 MN/coil
- w_{coil} = 50 mm
- t_{coil} = 300 mm
- σ_{coil} = 150 MPa

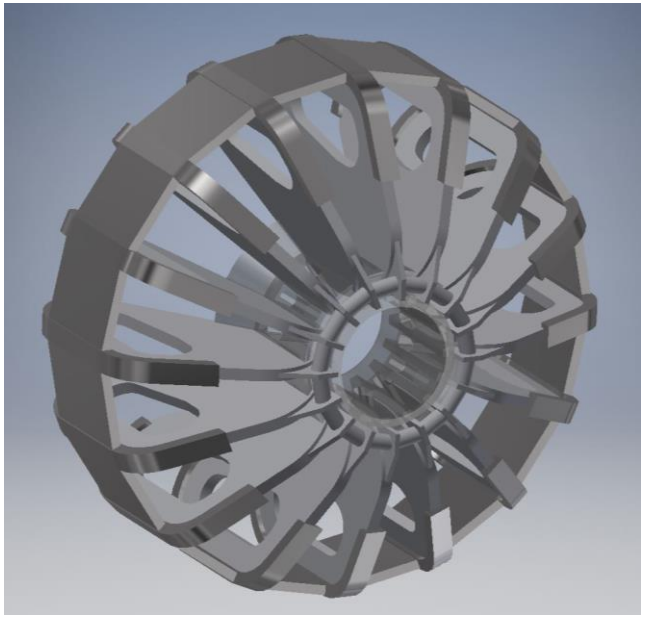
Centering force

- F_c = 1.4 MN/coil
- $t_{cylinder}$ = 60 mm
- $\sigma_{cylinder}$ = 120 MPa

Out-of-plane force (quench)

- F_ϕ = 1.5 MN/coil
- $t_{intercoil}$ = 60 mm
- $\sigma_{inter\text{-}coil}$ = 50 MPa

Complete torus structure:

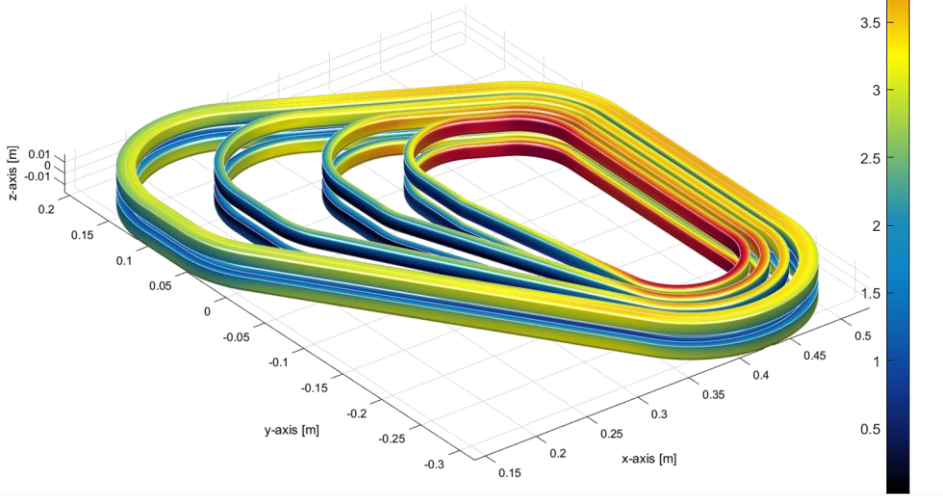


It could be conveniently built with lightweight Al alloys

Demonstrator

1:3 Scaled Model in HTS (ReBCO)

- Magnet performance
- Quench protection
- Coil manufacturing
- Field quality



Dummy coil winding, with SS tape

Conclusions

- GaToroid (“*has a touch of insanity*”[1], *but…*) could result in a quantum step towards compact gantries and new treatment possibilities

- Among all the challenges of this new idea…
  - Magnet design (torus and vector magnet)
  - High & Low temperature Superconductors
  - Mechanical structure (of coil and torus), forces and stresses
  - Powering and Quench protection
  - Beam optics, from accelerator to patient
  - Cryogenics, Vacuum, Diagnostic, Validation for Therapy, Costs …

- In next years, further studies and prototyping will be used to evaluate possible solutions and new configurations

(1) L. Bottura, “GaToroid: A Novel Superconducting Compact and Lightweight Gantry for Hadron Therapy”, KT Seminar, November 2018, CERN

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With our grateful thanks to:

Manuela Cirilli, Rita Ferreira, Giovanni Porcellana, Amy Bilton (KT) for the motivation, experience, opportunities and ideas that they steadily provide;

Linn Tvede (KT), Daniel Dominguez (IR) and the CERN Design and Visual Identity Service for some astounding graphics;

Mar Capeans and Miguel Jimenez (TE) for the appreciation and support of this crazy idea;

Jacky Mazet, Francois-Olivier Pincot, Juan Carlos Perez**,** Sebastien Clement and Jeremie Massard (TE) for actually doing the work;

Laura Gambini and Marco Breschi (UniBo) for their tireless dedication to the study of toroidal harmonics;

Alexander Gerbershagen (EN), Andrea Latina (BE), Vittorio Bencini (BE) and Stefano Benedetti (BE)
for the mentoring on beam optics;

Alfredo Portone (F4E), Gabriele D'Amico (F4E), Arnaud Pascal Foussat (TE) and Paolo Ferracin (TE) for the fruitful discussions on mechanics.