Magnetic Design of a Superconducting Toroidal Gantry for Hadron Therapy

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Hadron Therapy

Entrance dose  Useful dose  Exit dose

X-rays  Protons

SOBP: Spread Out Bragg Peak

X-rays  Protons

[Graphics by courtesy of Protom]

[Translational Lung Cancer Research, 6(2), 2017]
Rotating magnetic transfer line

Proton Gantries:
- radius 4…5 m
- weight 100…200 tons

C-ions Gantries:
- radius 6…7 m
- weight 350…670 tons
GaToroid

Steady-State
Non-Rotating
Toroidal Magnet
Discrete Angles
Superconducting
GaToroid Concept

For each treatment angle

Torus Coil

Vector Magnet

Beam Energy

Isocenter

Axial-symmetric Toroidal Field

Coil Design and Optimization

- Linearize the profile to simplify the winding
- Optimize $\Delta Y$ 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

Excellent acceptance and isocentric properties
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**

**LTS option (Nb-Ti)**
- 36 strands (0.5 mm) Rutherford
- Soldered Cu-profile
- Polyimide/glass insulation
- Epoxy impregnated
- \( I_{op} = 1800 \text{ A} \)
- \( T_{op} = 4.5 \text{ K} \)
- \( J_E = 105 \text{ A/mm}^2 \)

**HTS option (ReBCO)**
- 3 SC tapes (12x0.1 mm) transposed
- 6 Co-wound Cu tapes (12x0.2 mm)
- Polyimide/glass insulation
- Epoxy impregnated
- \( I_{op} = 1800 \text{ A} \)
- \( T_{op} = 20 \text{ K} \)
- \( J_E = 90 \text{ A/mm}^2 \)

**Protection, e.g.**
- Two powering circuits
- 2 s quench detection
- ± 1 kV dump voltage

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

**12.2**
**1.4**

**12.2**
**1.7**

**HTS with Non and Partial Insulation are very appealing!**

160 K

8 s time constant
Mechanical design concept

Winding force
- $F_w = 2$ MN/coil
- $w_{coil} = 50$ mm
- $t_{coil} = 300$ mm
- $\sigma_{coil} = 150$ MPa

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

Out-of-plane force (quench)
- $F_\phi = 1.5$ MN/coil
- $t_{intercoil} = 60$ mm
- $\sigma_{inter-coil} = 50$ MPa

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

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