GaToroid
Progress and developments

Presented by Ariel Haziot

MSC Seminar, CERN, June 24th, 2021

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

• Context (Hadron therapy / Gantries)

• GaToroid concept

• GaToroid demonstrator

• Technology developments

• Perspective
Various types of ionizing radiations can be used to kill cancerous cells:

- Photons (X-rays)
- Electrons
- Hadrons
  - Protons
  - Ions (He, C, Ne, …)
The tumor is targeted by controlling 2 variables:

- **The depth** of the Bragg peak depends on the particle energy:
  - 50-25 MeV for protons
  - 100-500 MeV for C ions

- **Stereotaxis** superimposes several collimated beams to map the volume.
Context
Gantries

Transfer lines able to irradiate from multiple directions.

Embarked in a rigid and precise rotating structure.

• Proton Gantries: radius 4 - 10 m - weight 100 - 200 tons
• C-ions Gantries: radius 10 - 25 m - weight 350 - 670 tons

P-ARTIS System, “The Next Generation Adaptive Proton Therapy”
Context

Gantries

Gantries are massive and account for about half the whole installation. Today the development of new gantries is going in two directions:

• Use superconductor to increase the bending field in large bore magnets. (more compact, lighter and more efficient)

• Find a magnetic configuration which does not need to be nor rotated nor ramped to focus the beam on the patient. (reduce stability req. and so mass and footprint)
Outline

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• GaToroid concept

• GaToroid demonstrator

• Technology developments

• Perspective
GaToroid concept
The idea by Luca Bottura

GaToroid concept
Development of the idea

For each treatment angle

Coil

Axysimmetric Uniform Field

Vector Magnet

beam

(0, -z_v)

Isocenter (0, 0)

B = 0

B = B_0

ρ_E

ρ_E

R_{in}

α_E

α_E

E

α_E

R

z
GaToroid concept
GaToroid concept
Proton version by Enrico Felcini

Beams directed at the isocenter within 1 mm, in the 70-250 MeV range
(Forward parametric optimization done with 7 variables)

J_E = 100 (A/mm^2)

GaToroid concept
Proton version by Enrico Felcini

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of angles</td>
<td>16</td>
</tr>
<tr>
<td>Peak magnetic field</td>
<td>6.8 T</td>
</tr>
<tr>
<td>Eng current density</td>
<td>100 A/mm²</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>31 MJ</td>
</tr>
<tr>
<td>Coil dimension</td>
<td>1.7 m x 1.2 m</td>
</tr>
<tr>
<td>Torus dimension</td>
<td>1.7 m x 3.3 m</td>
</tr>
<tr>
<td>Bore size</td>
<td>0.8 m</td>
</tr>
<tr>
<td>Vector Magnet position</td>
<td>3.6 m</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>4.5 K - 20 K</td>
</tr>
<tr>
<td>Operating current</td>
<td>1800 A</td>
</tr>
<tr>
<td>Estimated total mass</td>
<td>12 tons</td>
</tr>
</tbody>
</table>
## GaToroid concept
Proton version by Enrico Felcini

### HTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconductor</td>
<td>ReBCO</td>
</tr>
<tr>
<td>Topology</td>
<td>Non twisted stack</td>
</tr>
<tr>
<td>Number of tapes</td>
<td>3</td>
</tr>
<tr>
<td>Cu:Sc ratio</td>
<td>7.3</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>20 K</td>
</tr>
</tbody>
</table>

### LTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconductor</td>
<td>NbTi</td>
</tr>
<tr>
<td>Topology</td>
<td>Rutherford</td>
</tr>
<tr>
<td>Number of strands</td>
<td>36</td>
</tr>
<tr>
<td>Cu:Sc ratio</td>
<td>7.3</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>4.2 K</td>
</tr>
<tr>
<td>Operating current</td>
<td>1800 A</td>
</tr>
<tr>
<td>Eng current density</td>
<td>100 A/mm²</td>
</tr>
</tbody>
</table>
## GaToroid concept
### Carbon ions version

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of angles</td>
<td>20</td>
</tr>
<tr>
<td>Peak magnetic field</td>
<td>6.1 T</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>1300 MJ</td>
</tr>
<tr>
<td>Coil dimension</td>
<td>5.8 m x 4.5 m</td>
</tr>
<tr>
<td>Torus dimension</td>
<td>5.8 m x 12.8 m</td>
</tr>
<tr>
<td>Bore size</td>
<td>3.7 m</td>
</tr>
<tr>
<td>Vector Magnet position</td>
<td>9.2 m</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>4.2 K</td>
</tr>
<tr>
<td>Operating current</td>
<td>10.8 kA</td>
</tr>
<tr>
<td>Estimated total mass</td>
<td>300 tons</td>
</tr>
</tbody>
</table>

GaToroid – Status and Perspectives (EDMS: 2444379)
GaToroid concept
Carbon ions version

Protection

2 types of protection are feasible:

<table>
<thead>
<tr>
<th>Type</th>
<th>Protection Method</th>
<th>$J_{eng}$ (A/mm²)</th>
<th>$T_{max}$ (K)</th>
<th>Cu:Sc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low voltage (50 V)</td>
<td>Internal quench heaters</td>
<td>105</td>
<td>130</td>
<td>7</td>
</tr>
<tr>
<td>High voltage (500 V)</td>
<td>External dump resistors</td>
<td>70</td>
<td>100</td>
<td>12</td>
</tr>
</tbody>
</table>

Heat loads

Broad estimations (50 W at 4 K and 650 W at 50 K) are not out of order and the thermal loads on the Carbon ions GaToroid are very manageable.

Cryogenics
Outline

• Context (Hadron therapy / Gantries)

• GaToroid concept

• GaToroid demonstrator

• Technology developments

• Perspective
GaToroid demonstrator

Strategy

Build a Single coil scaled down from the proton design by a factor 3 so we can test it at CERN:

- Magnet performance
- Quench protection
- Field quality
- Coil manufacturing
GaToroid demonstrator
Design

- Cover plate
- Outer rim
- Coil with spacers
- Intermediate plate with pole
- Insulation casing
- Current joint with HTS staircase
- Insulation tubes
- Insulation base
- Tuukka Lehtinen (EN-MME-EDS)
- Technical personnel of Lab. 927
GaToroid demonstrator
Operating conditions for ReBCo

High T / Low I
- Operating temperature: 20 K
- Operating current: 5000 A
- Peak magnetic field: 2.16 T
- Op. current density (tape): 1042 A/mm²
- Eng. current density (cable): 241 A/mm²

Low T / High I
- Operating temperature: 4.2 K
- Operating current: 7100 A
- Peak magnetic field: 3.06 T
- Op. current density (tape): 1479 A/mm²
- Eng. current density (cable): 342 A/mm²
# GaToroid demonstrator

## Cable geometry

### HTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconductor</td>
<td>ReBCO</td>
</tr>
<tr>
<td>Topology</td>
<td>Non twisted stack</td>
</tr>
<tr>
<td>Number of HTS tape</td>
<td>4 (0.1 mm)</td>
</tr>
<tr>
<td>Number of Copper tape</td>
<td>2 (0.55 mm)</td>
</tr>
<tr>
<td>Cu:Sc ratio</td>
<td>5.3</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>20 K</td>
</tr>
</tbody>
</table>

### LTS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconductor</td>
<td>NbTi</td>
</tr>
<tr>
<td>Topology</td>
<td>Rutherford (MCBXF)</td>
</tr>
<tr>
<td>Number of strands</td>
<td>18</td>
</tr>
<tr>
<td>Cu:Sc ratio (with Cu profile)</td>
<td>10.8</td>
</tr>
<tr>
<td>Operating temperature</td>
<td>4.2 K</td>
</tr>
</tbody>
</table>
GaToroid demonstrator
Quench protection LTS

1D adiabatic model for quench propagation:
(THEA Cryosoft)

- Local heated zone: 10 cm for 1 ms
- Cable as single element
- 100 mV of Voltage threshold
- Minimum quench energy for heating lengths of 1 m and 0.1 m during 1 ms is below 10 mJ/cc.
- Time to reach threshold: 2.35 s
- Peak temperature: 30 K
- Quench velocity 3.1 m/s

A comparison of this velocity with a transverse heat propagation is on progress to determine in which direction the quench propagates the fastest.
GaToroid demonstrator
Quench protection HTS

Minimum quench energy of the cable without stabilizer in adiabatic conditions for heating lengths 1 cm during 1 ms is 16 J/cc.

1D quench analysis (Low T – High I)

- Local defect in the cable: 1 cm
- Cable as single element
- 50 mV of Voltage threshold
- 20 ms for validation and reaction time
- RRR = 100
- n-value = 30

- Time to reach threshold: 1.1 s
- Peak temperature: < 100 K
GaToroid demonstrator
Mechanical analysis

Mechanical analysis are using Lorentz forces from magnetic simulations and effect of temperature to help in determining several key concepts and then update the design:

- Material
- Importance of impregnation
- Grade jumps shape
- ...

For a complete presentation of this aspect: Gianluca Vernassa’s seminar on the 15th of July.
Outline

• Context (Hadron therapy / Gantries)
• GaToroid concept
• GaToroid demonstrator
• Technology developments
• Perspective
Technology developments

1. Insulation and impregnation
2. Layer jump
3. Cable exit sealing
4. Winding
5. Instrumentation
6. Current joint
Technology developments
Insulation and impregnation

- Impregnated HTS tape coils have shown degradation after thermal cycles.
  - Feather.M0, Feather.M2
  - HTS Roebel cable (Peng Gao - Twente)

- The degradation could be caused by:
  - Delamination of the tape due to resin thermo-mechanical properties
  - Cracks in the resin causing points of defect on the tape

- We want to investigate the compatibility between the impregnation resin and the HTS tape.

**Phase 1:** Select the best candidates for resin and insulation with a study on dummy stacks.
**Phase 2:** Prepare samples with HTS and test degradation with cooling cycles.
Technology developments

Insulation and impregnation

- Dummy stacks samples representing 1 grade of the coil (4 turns) with Copper tape instead of HTS.
Technology developments
Insulation and impregnation

Plan for Phase 1

To check:
• Impregnation quality (voids, bubbles)
• Mechanical properties (peeling, cracking)
• Insulation between cables
• Contact between tapes in a cable

Our tools:
• Peeling and visual inspection
• Cutting and microscopic inspection
• Electrical tests at room Temp. and at 77K
• Electrical tests after 10 Temp. cycles

Preparation: Lukas Henschel, Ariel Haziot
Impregnation: Sebastien Clement, Romain Gavaggio, Ahmed Benfkih
Electrical tests: Pierre-Antoine Contat, Francois-Olivier Pincot
Cut and microscope: Ana Teresa Perez Fontenla
Supervision: Ariel Haziot, Nicolas Bourcey, Juan Carlos Perez
# Technology developments

## Insulation and impregnation

<table>
<thead>
<tr>
<th>Stack samples</th>
<th>Glass fiber sleeve</th>
<th>Polymide C-shape</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>High compression</td>
<td>Low compression</td>
</tr>
<tr>
<td></td>
<td>MY750</td>
<td>CTD101K</td>
</tr>
<tr>
<td>Peeling observations</td>
<td>Hard to peel. A fair continuous pull is necessary</td>
<td>Easy to peel after a first crack</td>
</tr>
<tr>
<td>Impregnation between cables</td>
<td>GF is impregnated but it did not wet the cable</td>
<td>GF is impregnated but it did not wet the cable</td>
</tr>
<tr>
<td>Resin between tapes</td>
<td>several traces</td>
<td>very few traces</td>
</tr>
<tr>
<td>Gap between cables</td>
<td>329 µm</td>
<td>334 µm</td>
</tr>
</tbody>
</table>

**Visual observation**

**Electrical tests**

<table>
<thead>
<tr>
<th>Resistance between cables [Ω]</th>
<th>Before thermal cycles</th>
<th>After thermal cycles</th>
<th>Resistance between tapes [mΩ]</th>
<th>Before thermal cycles</th>
<th>After thermal cycles</th>
<th>At 77K</th>
</tr>
</thead>
<tbody>
<tr>
<td>MY750</td>
<td>1869</td>
<td>2162</td>
<td>&gt; 2610</td>
<td>285</td>
<td>&gt; 3000</td>
<td>829</td>
</tr>
<tr>
<td>CTD101K</td>
<td>705</td>
<td>593</td>
<td>-</td>
<td>426 µm</td>
<td>-</td>
<td>Not homogeneous</td>
</tr>
<tr>
<td>Mix61</td>
<td>1.403</td>
<td>1.370</td>
<td>1.403</td>
<td>1.944</td>
<td>1.682</td>
<td>1.608</td>
</tr>
</tbody>
</table>

**Resistance between cables [µΩ]**

Before thermal cycles: 3.012, 2.222, 2.323, 2.491, 1.403, 1.535
After thermal cycles: 3.205, 2.263, 2.198, 1.748, 1.890, 1.535
At 77K: 0.520, 0.362, 0.333, 0.349, 0.242, 0.212
Technology developments
Insulation and impregnation

Conclusion Phase 1

**Glass fiber**
- Better distribution of the cable stack
- Better structural resistance
- Let some resin flow in between the tapes, less electrical contact

**Polyimide**
- Does not keep the cables away from each other
- Less resistance to peeling
- Very good insulation between cables
- Prevent the resin from flowing in the cable, better electrical contact

**MY750 + HY5922**
- Not too brittle
- Does not wet too much
- Can be found between tapes

**CTD101K**
- Brittle, it cracks
- Good wetting properties
- Flows less between tapes

**Mix61**
- Not too brittle
Technology developments
Insulation and impregnation

Conclusion Phase 1

Glass fiber
+ Better distribution of the cable stack
+ Better structural resistance
- Let some resin flow in between the tapes, less electrical contact

MY750 + HY5922
+ Not too brittle
- Does not wet too much
- Can be found between tapes

Perspectives
Study the combine use of polyimide for cable protection and glass fiber for structure.

Test impregnation with polyurethane instead of epoxy resins.

Numerical model to simulate peeling stress and the delamination caused by the resin on tape.
Technology developments
Insulation and impregnation

Plan for Phase 2

To check:

a. Critical current of 1 tape
   • Before impregnation
   • After impregnation
   • After 5 thermal cycles

b. Critical current of 4 tapes together

c. Contact resistance measurements between 2-4 tapes

Our tools:
• The LN2 station at 288

The LN2 station allows precise measurements (nV) of 16 channels up to 1.8 kA and with 4 protection devices.

Thank you to the personal of TE-MSC-SCD for their support in using the LN2 station:
C. Barth, G. Lenoir, J. Hurte, A. Carlon Zurita and P. Denis
Technology developments

Insulation and impregnation

HTS for GaToroid demonstrator

4 spools: Theva TPL 5000 series, 12 mm wide
- 6-10 μm Cu/PbSn
- Min Ic: 380 A / 550 A / 340 A / 520 A

The critical current along the tape is very inhomogeneous globally and locally.

TAPE STAR data - Spool QS200004
Technology developments
Insulation and impregnation

**HTS for GaToroid demonstrator**

4 spools: Theva TPL 5000 series, 12 mm wide
- 6-10 μm Cu/PbSn
- Min I_c: 380 A / 550 A / 340 A / 520 A

The critical current along the tape is very inhomogeneous globally and locally.

[Graph showing TAPE STAR data - Spool QS200008]

**Mean over 1 m**
**Minimum over 1 m**
Technology developments
Insulation and impregnation

Measure of the critical current in a single tape

Sample: QS200004 – 11.2 m

Resistive slope: 0.4 nΩ/m

\[ I_c = 626.1 \quad \text{error: 0.0386} \]

\[ n = 34.8 \quad \text{error: 0.1296} \]

\[ E_C = 100 \, \mu \text{V/m} \]
Technology developments
Insulation and impregnation

Stacks are prepared with MY 750 + HY 5922
• 3x 4 cables (2 HTS and 2 dummies)
• longer silicon caps to clear more cable ends

Thanks to A. Benfkih and R. Gavaggio for the impregnation
Technology developments
Insulation and impregnation

Preparation of HTS stack samples

- Referencing the tape location
- Soldering extension: 3 cm² (Fujikura, 12 mm, 717 A)
- Clamping the stack to the holder

2 tapes can be tested during the same cooldown
Technology developments
Insulation and impregnation

Measure of HTS stack samples

For each cooling cycle the stack was removed from the liquid and warmed up before being plunged again.
Technology developments
Insulation and impregnation

Critical current on HTS stack samples

- From the 6 tapes (2 per sample) only 2 could be tested:

<table>
<thead>
<tr>
<th>Tape No.</th>
<th>Current (expected)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.1.1</td>
<td>~ 530 A</td>
</tr>
<tr>
<td>1.3.1.1</td>
<td>~ 560 A</td>
</tr>
</tbody>
</table>

- The other were resistive:

<table>
<thead>
<tr>
<th>Tape No.</th>
<th>Resistance (μΩ/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1.4.4</td>
<td>~ 600</td>
</tr>
<tr>
<td>1.2.1.1</td>
<td>~ 40</td>
</tr>
<tr>
<td>1.2.4.4</td>
<td>~ 70</td>
</tr>
<tr>
<td>1.3.4.4</td>
<td>~ 15</td>
</tr>
</tbody>
</table>

- Connection resistance: ~ 60 nΩ.cm²

## Technology developments

**Insulation and impregnation**

### Critical current on HTS stack samples

No degradations with cooling cycles were observed on the 2 tested tapes. This seems to confirm that the resin MY750 is not present inside the cable as it was observed previously.

<table>
<thead>
<tr>
<th>Cycle</th>
<th>1.1.1.1</th>
<th>1.3.1.1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1&lt;sup&gt;st&lt;/sup&gt;</td>
<td>$I_c = 532.1$ A</td>
<td>$n = 27.9$</td>
</tr>
<tr>
<td>2&lt;sup&gt;nd&lt;/sup&gt;</td>
<td>$I_c = 531.9$ A</td>
<td>$n = 28.5$</td>
</tr>
<tr>
<td>3&lt;sup&gt;rd&lt;/sup&gt;</td>
<td>$I_c = 532.7$ A</td>
<td>$n = 28.9$</td>
</tr>
<tr>
<td>4&lt;sup&gt;th&lt;/sup&gt;</td>
<td>$I_c = 533.5$ A</td>
<td>$n = 28.6$</td>
</tr>
<tr>
<td>5&lt;sup&gt;th&lt;/sup&gt;</td>
<td>$I_c = 534.7$ A</td>
<td>$n = 28.8$</td>
</tr>
<tr>
<td>6&lt;sup&gt;th&lt;/sup&gt;</td>
<td>$I_c = 532.8$ A</td>
<td>$n = 29.1$</td>
</tr>
<tr>
<td>7&lt;sup&gt;th&lt;/sup&gt;</td>
<td>$I_c = 534.9$ A</td>
<td>$n = 28.6$</td>
</tr>
<tr>
<td>8&lt;sup&gt;th&lt;/sup&gt;</td>
<td>$I_c = 535.7$ A</td>
<td>$n = 29.1$</td>
</tr>
</tbody>
</table>
Technology developments
Insulation and impregnation

Test with impregnated single tape

Sample:
QS200004 – 11.2 m with MY 750 (few mm layer)

- 70% degradation of $I_c$ at the first cooling cycle.
- No cracks but detachment from the tape.

<table>
<thead>
<tr>
<th></th>
<th>Before</th>
<th>$I_c$</th>
<th>$n$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$I_c$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1st</td>
<td>626.1 A</td>
<td>34.8</td>
<td></td>
</tr>
<tr>
<td>2nd</td>
<td>184.2 A</td>
<td>21.8</td>
<td></td>
</tr>
<tr>
<td>3rd</td>
<td>184.2 A</td>
<td>20.8</td>
<td></td>
</tr>
<tr>
<td>4th</td>
<td>183.3 A</td>
<td>20.3</td>
<td></td>
</tr>
<tr>
<td>5th</td>
<td>183.6 A</td>
<td>19.9</td>
<td></td>
</tr>
</tbody>
</table>
Technology developments
Insulation and impregnation

Resistance measurements between 4 tapes in stack
• Measure of 3 contacts each 35 cm²
• Current from 0.1 A to 14 A
• Temperature: 77 K

Values similar to the contact resistance measured in a Metal co-winding configuration.

<table>
<thead>
<tr>
<th>Current</th>
<th>Resistance</th>
<th>Contact Res.</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 A</td>
<td>70 μΩ</td>
<td>2.45 mΩ.cm²</td>
</tr>
<tr>
<td>6 A</td>
<td>68 μΩ</td>
<td>2.38 mΩ.cm²</td>
</tr>
<tr>
<td>8 A</td>
<td>67 μΩ</td>
<td>2.35 mΩ.cm²</td>
</tr>
<tr>
<td>10 A</td>
<td>67 μΩ</td>
<td>2.35 mΩ.cm²</td>
</tr>
<tr>
<td>12 A</td>
<td>67 μΩ</td>
<td>2.35 mΩ.cm²</td>
</tr>
<tr>
<td>14 A</td>
<td>67 μΩ</td>
<td>2.35 mΩ.cm²</td>
</tr>
</tbody>
</table>

Technology developments
Insulation and impregnation

Conclusion and next steps

In the actual design (MY 750 + Fiberglass), the impregnation does not influence the properties of the tape after cooling.

It seems that the tape inside the insulated cable has almost no contact with the resin.

However, we need to understand why most of the samples are broken. Does it happen during the impregnation process or during the instrumentation on the sample holder?

Further measures need to be performed following the test plan:
- 4 tapes measurements *in-situ* in the stack

![Graph showing electric field vs. current](image)
Technology developments
Winding

1. Preparing spools

2. Winding 1st layer

3. Switching spools

4. Winding 2nd layer

Procedure and tools developed at 927 supervised by J.C. Perez: G. Maury, J. Mazet, F. Garnier And P. Vazquez
Technology developments

Winding

The multi spool winding machine

- Able to wind up to 7 spool with independent tensions
- The winding was successfully tested with a dummy cable of 6 tapes and winding tension around 20-30 N (15-25 Mpa).
- The whole length of glass fiber insulation is stored in-line and wrapped along the cable while winding.
Technology developments

Winding

Preparing spools for second layer

- The 6 tapes are gathered, passed through the insulations and separated again on 6 independent spools.

- The light spools can be hanged while winding the 1st layer and then installed easily on the winding machine.

- Tested successfully with the 2 spools at the extremities.
Technology developments

Layer jump

- The layer jump in the coil is continue (no junction) and does not require to introduce any hard way bending.

- The path for the layer jump is designed along the pole before the first turn similar to the one in EuCARD.

- A groove on the pole allows the positioning and the insertion of the cable.

- No spacers were added to correct for the angle as it was small enough to be buffered by the fiberglass insulation.
Technology developments
Layer jump

Test with the HTS cable on Aluminum pole

• This configuration was tested successfully with 6 tapes + insulation.

• The winding of several grades was not altered by the layer jump. Once in the groove, it makes a perfectly flat surface on the pole.

• The positioning of a fake intermediate plate completes to validate this set-up.
Technology developments

Layer jump

Test with the LTS cable on Aluminum pole

- This configuration was tested successfully with both side of a 1 m cable: Rutherford in and out.
- Even in the highest curvature section, no sign of detachment was observed between the Rutherford cable and the Copper profile.
Technology developments
Cable exit sealing

- The passage of the cable through the outer rim must be sealed prior impregnation.
- A new insulation must be made for this section as the glass fiber will be removed at the sealing.
- A test mold was made reproducing a cut of the actual assembly.
Technology developments
Cable exit sealing

Test representative of the configuration and assembly sequence

• The insulation for the passage consists of 2 U-shape 0.75 mm thick polyimide layers.

• The CAF4 for the sealing is applied on both faces of each tape and on the insulation while the cable is still unstacked.

• The part with the groove is push on the cable as the outer rim will be during the assembly procedure.

• Impregnation with MY 750 worked perfectly using this procedure.

No major modification on the main design were made except for a slight increase of the groove width to allow easier handling.
The current joints is designed as a staircase copper piece on which each HTS tape is soldered. It has multiple roles:

- Bring the current on each tape.
- Protect mechanically the HTS cable.
- Allow the clamping of a bus bar coming from the cryostat current leads.

To fit the cable, it has 4 steps of 0.1 mm and 2 steps of 0.55 mm. The surface of each step is designed to reduce the contact resistance below 10 nΩ (in perfect condition).
Technology developments
Current joint

Status

- Few prototypes have been produced to develop the soldering tools.
- This procedure is delicate as it is done *in situ* with a fragile HTS cable and with the constrains of the rest of the coil.
- A low temperature test should validate the joint. Still TBD.
- However, it will be difficult to really discriminate one side or the other and a more detailed study will be difficult with this design.
Technology developments

Instrumentation

Voltage taps will be located:
- Outside the coil at the current joints
- At the exit/entrance of the layer jump
- At each grade jump
- At the exit of the coil

The voltage taps are used for protection and for monitoring different sensitive parts of the coils: layer jump, current joints,…

A trace connects the voltage taps to a terminal located on the pole and accessible from the outside of the cover plate.
Technology developments
Instrumentation

The magnetic instrumentation is composed on each side by:

- 5 PCBs with pick-up coils
- 5 Hall probes glued on each PCB

They are bolted in grooves inside of the cover plate and wired to a connector on the outside of the cover place.
Technology developments

Instrumentation

The location of the magnetic sensors was defined using the simulation of the magnetic field, placed on location where errors in positioning are not too critical.

For a complete presentation of this aspect: Gianluca Vernassa’s seminar on the 15th of July.
GaToroid demonstrator
Fixation in the diode cryostat SM18

Tolerances in the cryostat are very small: 12 mm on each side.

Teflon bumpers will help the positioning and avoid hard thermal links in case of contact.

Lorentz forces due to iron parts are negligible (<40 N in z).

Bus bar connections and current leads designs are in progress.
GaToroid demonstrator
Test objectives

We would like to check:

- **Coil performance:**
  - Field at the nominal operating conditions
  - Field quality (comparison with simulation)
  - Field time dependency

- **Critical current after thermal cycles** (impregnated HTS coil).

- **Quench Detection and protection**

- **Current joint resistance.**
GaToroid demonstrator
Timeline

- Start fabrication
- Winding dummy
- Winding HTS demonstrator
- Test HTS demonstrator
- Winding LTS demonstrator
Outline

• Context (Hadron therapy / Gantries)

• GaToroid concept

• GaToroid demonstrator

• Technology developments

• Perspective
GaToroid for C-ions

Optics

by Ewa Oponowicz and Yann Dutheil (SY-ABT-BTP)

Optimized the generated magnetic field and the beam line to provide the needed beam characteristics for clinical purpose.

2D/3D particle tracking (forward/backward) to study:
- Positioning
- Focusing
- Twiss parameters

Need: Easy way to generate a new magnetic field by controlling specific parameters of the coil.
GaToroid for C ions
Parametric design

4 parameters to describe the coil:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>f_in</td>
<td>Length of the front side</td>
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<tr>
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<tr>
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GaToroid for C ions
Parametric design

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Parametric design

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1 parameter to describe the grade:

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GaToroid for C ions
Parametric design

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2 parameters related to the Gantry:

<table>
<thead>
<tr>
<th>Parameter</th>
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<tbody>
<tr>
<td>bore</td>
<td>Bore diameter</td>
</tr>
<tr>
<td>dist</td>
<td>distance to vector magnet</td>
</tr>
</tbody>
</table>
GaToroid for C ions
Parametric design

From the coil shape, the contour is divided in segments (mesh parameter) and 8-nodes elements are defined.

A current density and a direction is attached to each element.
GaToroid for C ions
Parametric design

A Fortran routine (Magnum library from Cryosoft) calculates analytically the magnetic field at each point of the map as the sum of the contributions from each 8-nodes elements.

Objective: implement this code with a particle tracking code also developed in Python so we could loop with the parameters of the coils in order to converge to the optimized design for both optics and magnetics.
Summary

GaToroid is a new concept of gantry for hadrontherapy using an axis-symmetric field configuration to bend beams from several directions and energies onto the patient location.

The toroidal magnet producing the field is scalable to the particle of the beam:

- Protons, Ions (C, He,...), Electrons,...

A demonstrator was designed and is being build. We expect the first cold tests by the end of the year.

Multiple technological developments concerning the use of ReBCo tape as conductor were carried:

- Impregnation/insulation
- Winding
- Current joint
- ...

There exist no theory for the optics in toroidal magnets as for dipoles and more studies and tools need to be made in this direction.
Recently the use of GaToroid for FLASH therapy is being considered as there seems to be a huge potential in this domain.
Project co-funded by the CERN Budget for Knowledge Transfer to Medical Applications