# 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

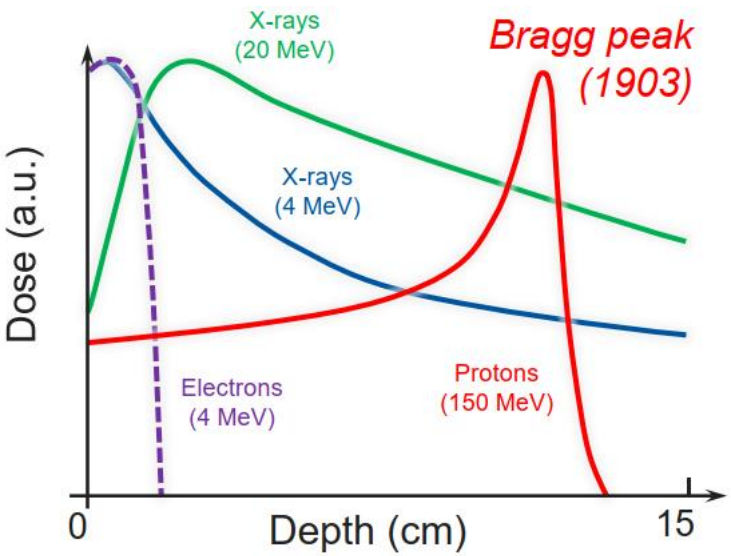
- Context (Hadron therapy / Gantries)
- GaToroid concept
- GaToroid demonstrator
- Technology developments
- Perspective

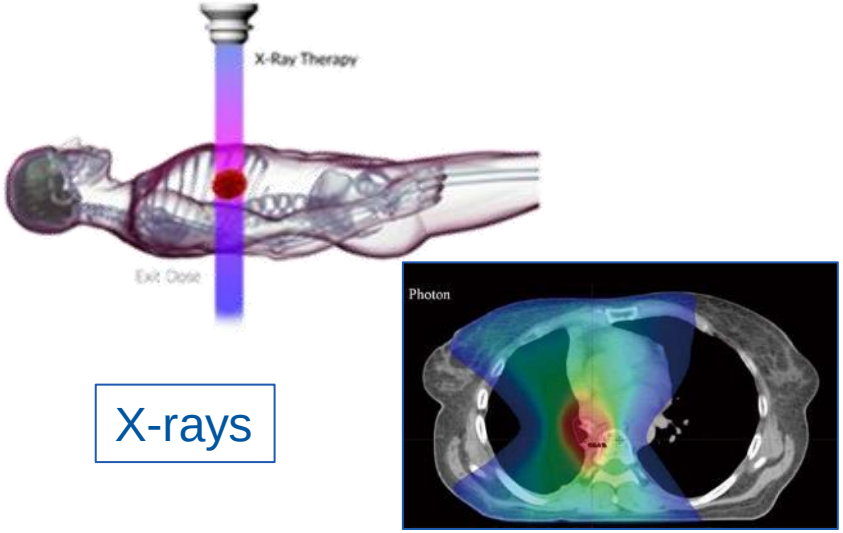
# Context

## Hadron therapy

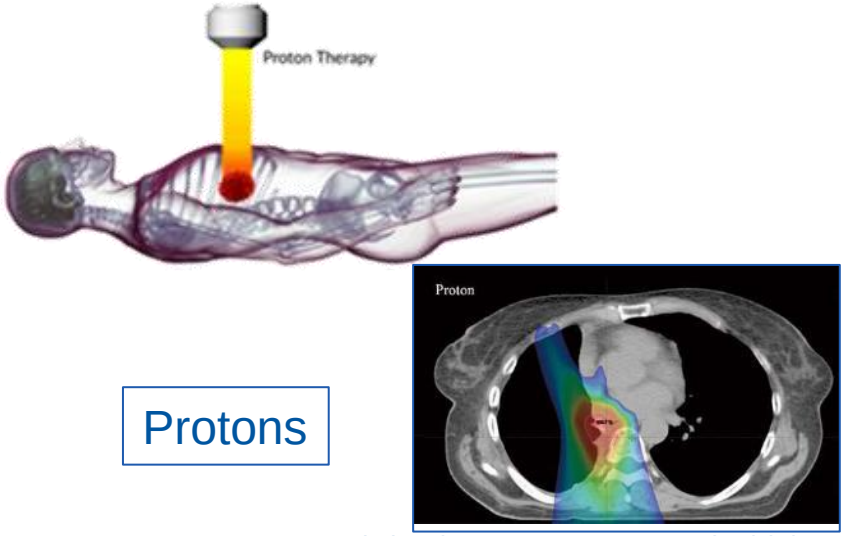
Various types of ionizing radiations can be used to kill cancerous cells:

- Photons (X-rays)
- Electrons
- Hadrons
  - Protons
  - Ions (He, C, Ne,…)




X-rays




Protons

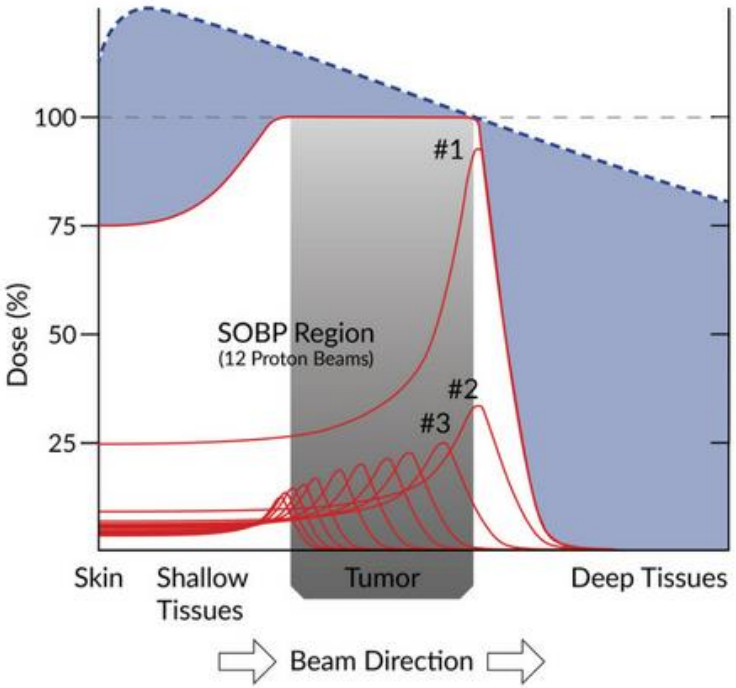
*Translational Lung Cancer Research* **6**(2) (2017)

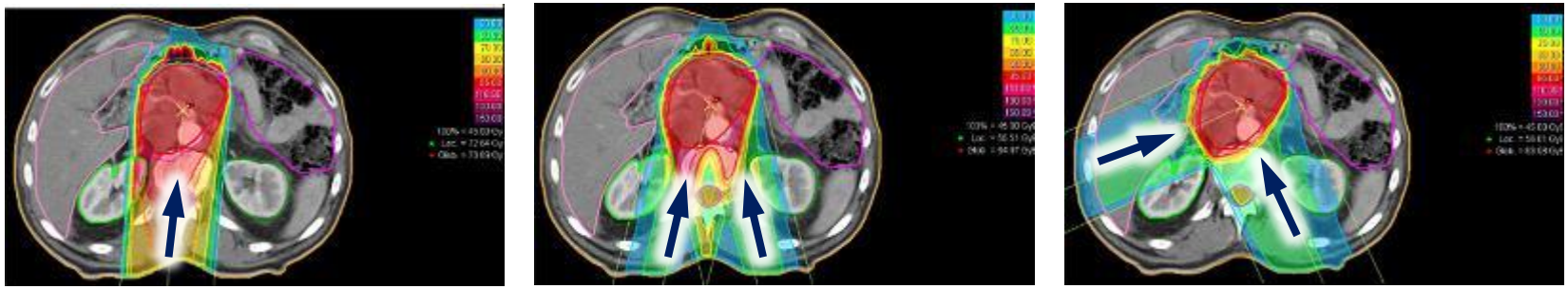
# Context

## Hadron therapy

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.



*PLoS ONE* **11**(10), e0164473 (2016)

# Context

## Gantries

Transfer lines able to irradiate from multiple directions.

Embarked in a rigid and precise rotating structure.

The Heidelberg gantry

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

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

# 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)

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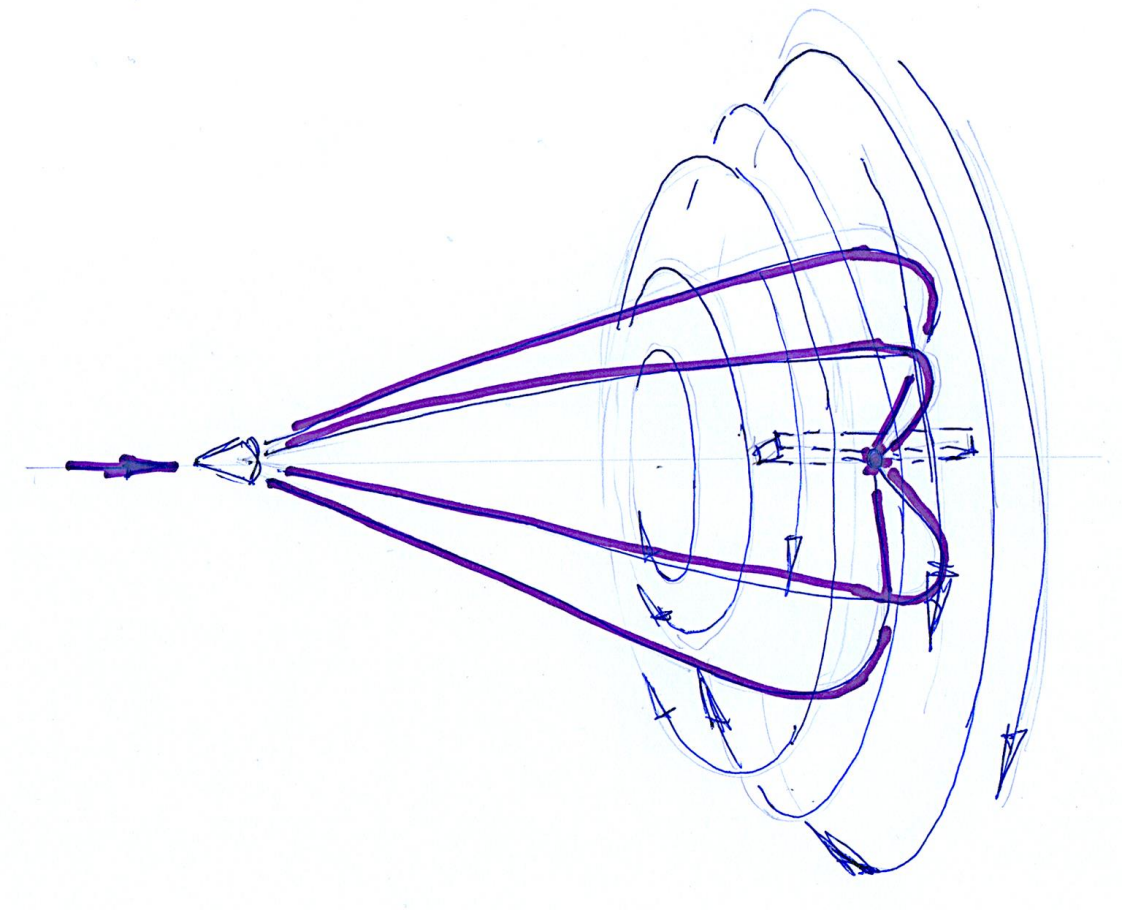
# GaToroid concept

## The idea by Luca Bottura

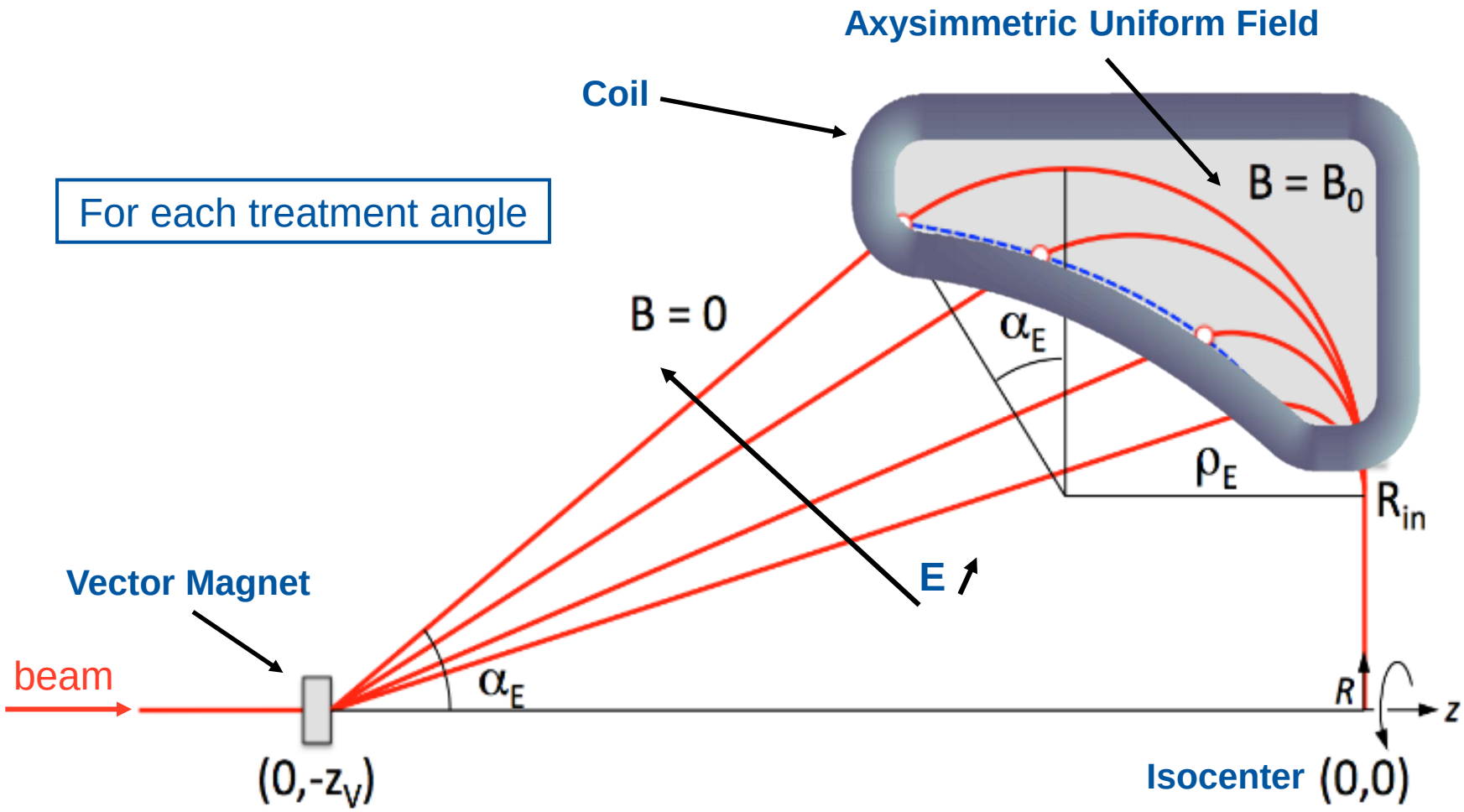


L. Bottura, **A Gantry and Apparatus for Focusing Beams of Charged Particles**, European Patent Application EP 18173426.0, May 2018

# GaToroid concept

## Development of the idea

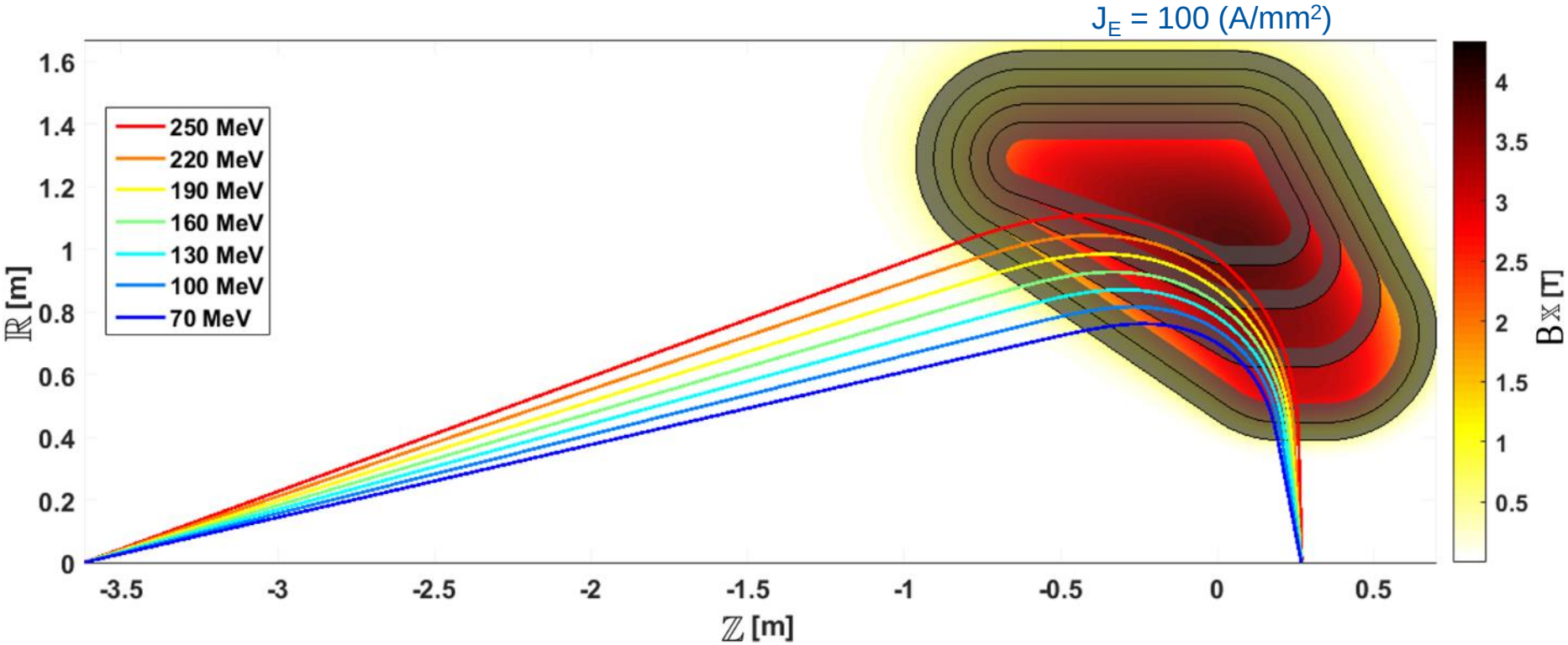
For each treatment angle



# GaToroid concept

# GaToroid concept

## Proton version by Enrico Felcini



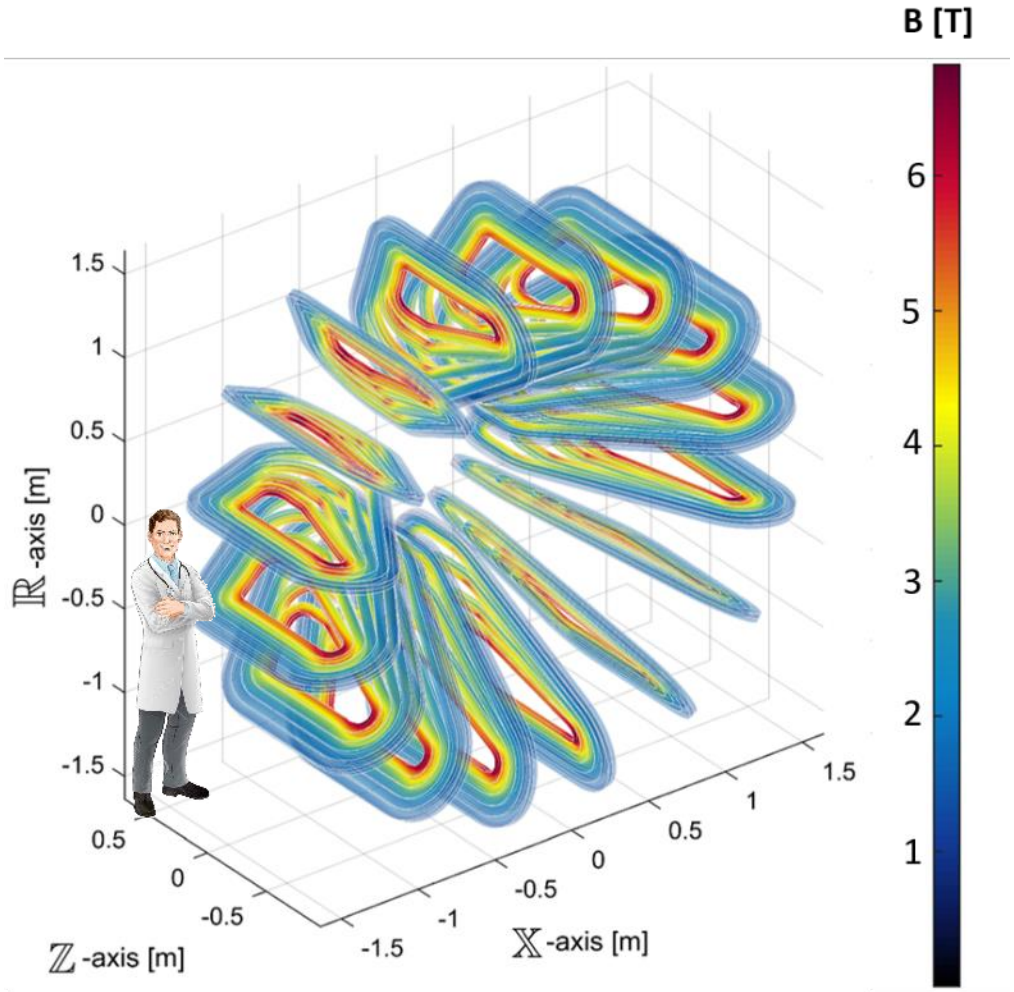

Beams directed at the isocenter within 1 mm, in the 70-250 MeV range

(Forward parametric optimization done with 7 variables)

E. Felcini E., Bottura L., van Nugteren J., de Rijk G., Kirby G., Dutoit B. Magnetic design of a superconducting toroidal gantry for hadron therapy, *IEEE Trans. Appl. Supercond.*, **30** (4) (2020)

# GaToroid concept

## Proton version by Enrico Felcini




| | |
|---|---|
| Number of angles | 16 |
| Peak magnetic field | 6.8 T |
| Eng current density | 100 A/mm2 |
| Stored Energy | 31 MJ |

| | |
|---|---|
| Coil dimension | 1.7 m x 1.2 m |
| Torus dimension | 1.7 m x 3.3 m |
| Bore size | 0.8 m |
| Vector Magnet position | 3.6 m |

| | |
|---|---|
| Operating temperature | 4.5 K - 20 K |
| Operating current | 1800 A |

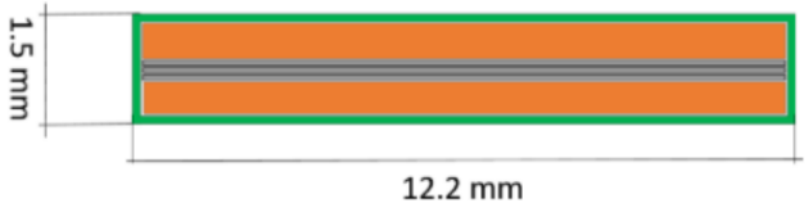
| | |
|---|---|
| Estimated total mass | 12 tons |

# GaToroid concept

## Proton version by Enrico Felcini

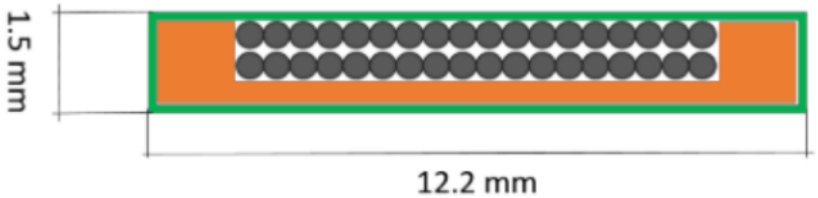
**HTS**

| | |
|---|---|
| Superconductor | ReBCO |
| Topology | Non twisted stack |
| Number of tapes | 3 |
| Cu:Sc ratio | 7.3 |
| Operating temperature | 20 K |




**LTS**

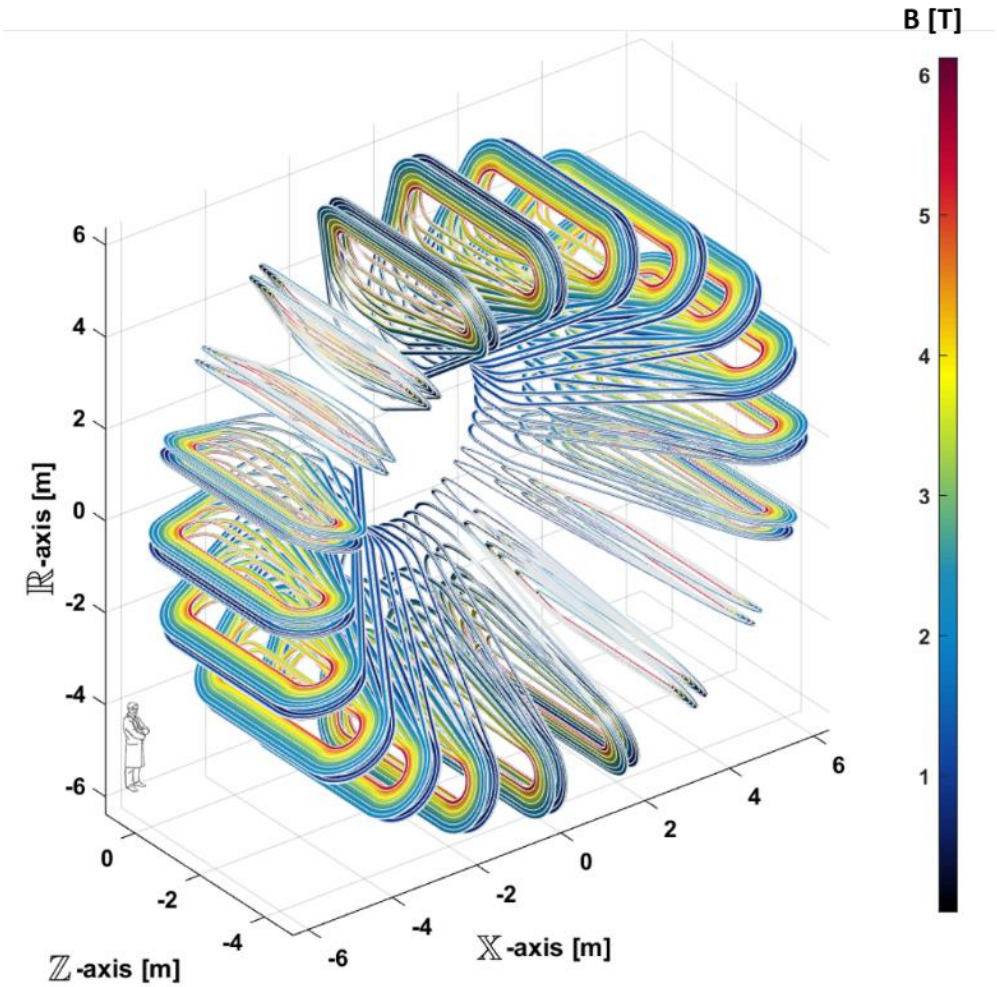
| | |
|---|---|
| Superconductor | NbTi |
| Topology | Rutherford |
| Number of strands | 36 |
| Cu:Sc ratio | 7.3 |
| Operating temperature | 4.2 K |




| | |
|---|---|
| Operating current | 1800 A |
| Eng current density | 100 A/mm2 |

# GaToroid concept

## Carbon ions version




| | |
|---|---|
| Number of angles | 20 |
| Peak magnetic field | 6.1 T |
| Stored Energy | 1300 MJ |

| | |
|---|---|
| Coil dimension | 5.8 m x 4.5 m |
| Torus dimension | 5.8 m x 12.8 m |
| Bore size | 3.7 m |
| Vector Magnet position | 9.2 m |

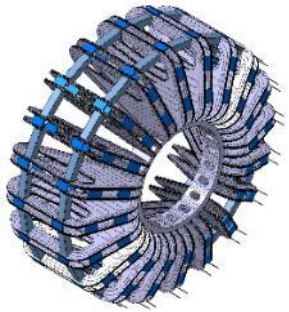
| | |
|---|---|
| Operating temperature | 4.2 K |
| Operating current | 10.8 kA |

| | |
|---|---|
| Estimated total mass | 300 tons |

GaToroid – Status and Perspectives (EDMS: 2444379)

# GaToroid concept

## Carbon ions version



### Protection

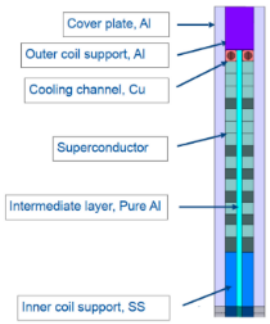
2 types of protection are feasible:

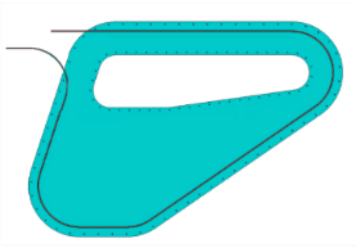
| | | | | |
|---|---|---|---|---|
| Low voltage (50 V) | Internal quench heaters | $J_{eng}$ = 105 A/mm² | $T_{max}$= 130 K | Cu:Sc ~ 7 |
| High voltage (500 V) | External dump resistors | $J_{eng}$ = 70 A/mm² | $T_{max}$= 100 K | Cu:Sc ~ 12 |

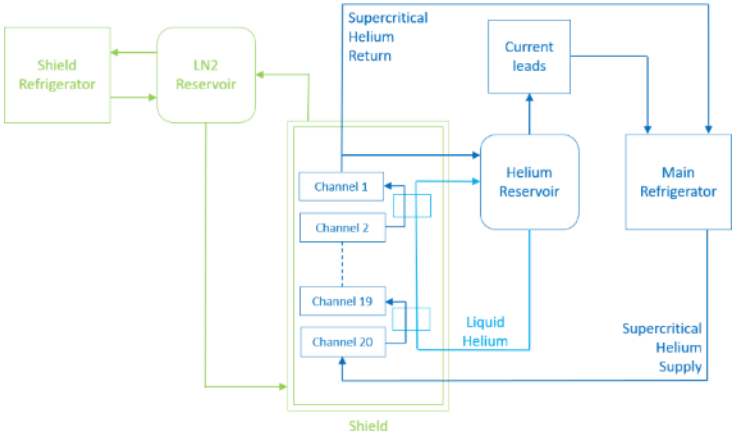
### Heat loads

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





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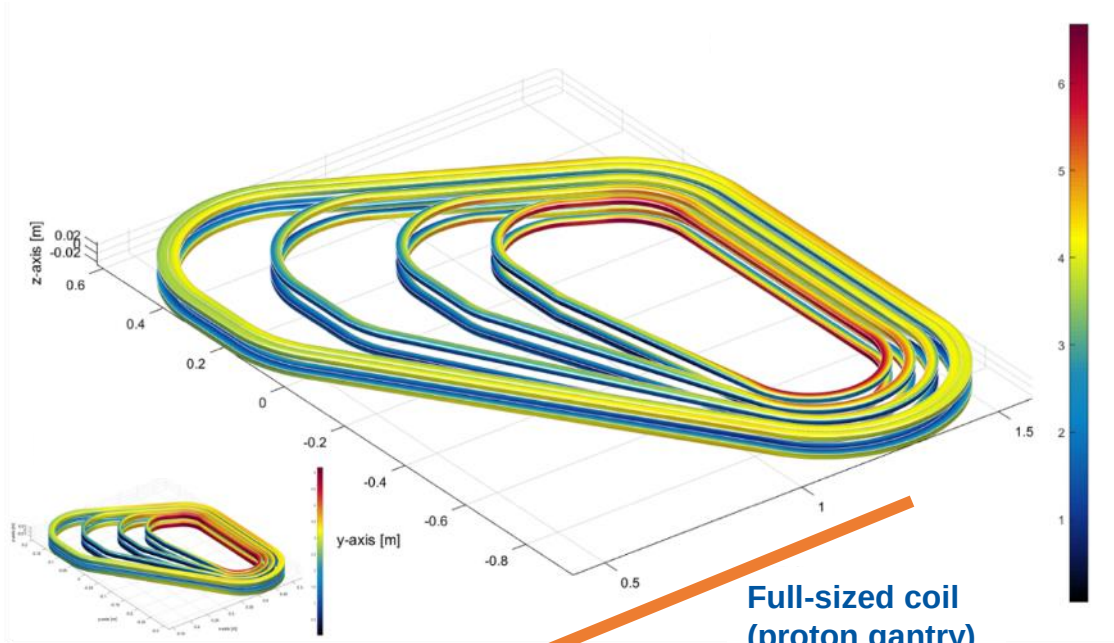
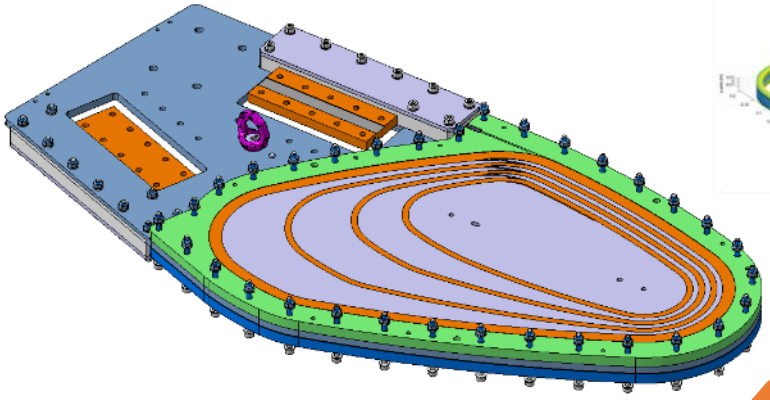
# GaToroid demonstrator

## 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



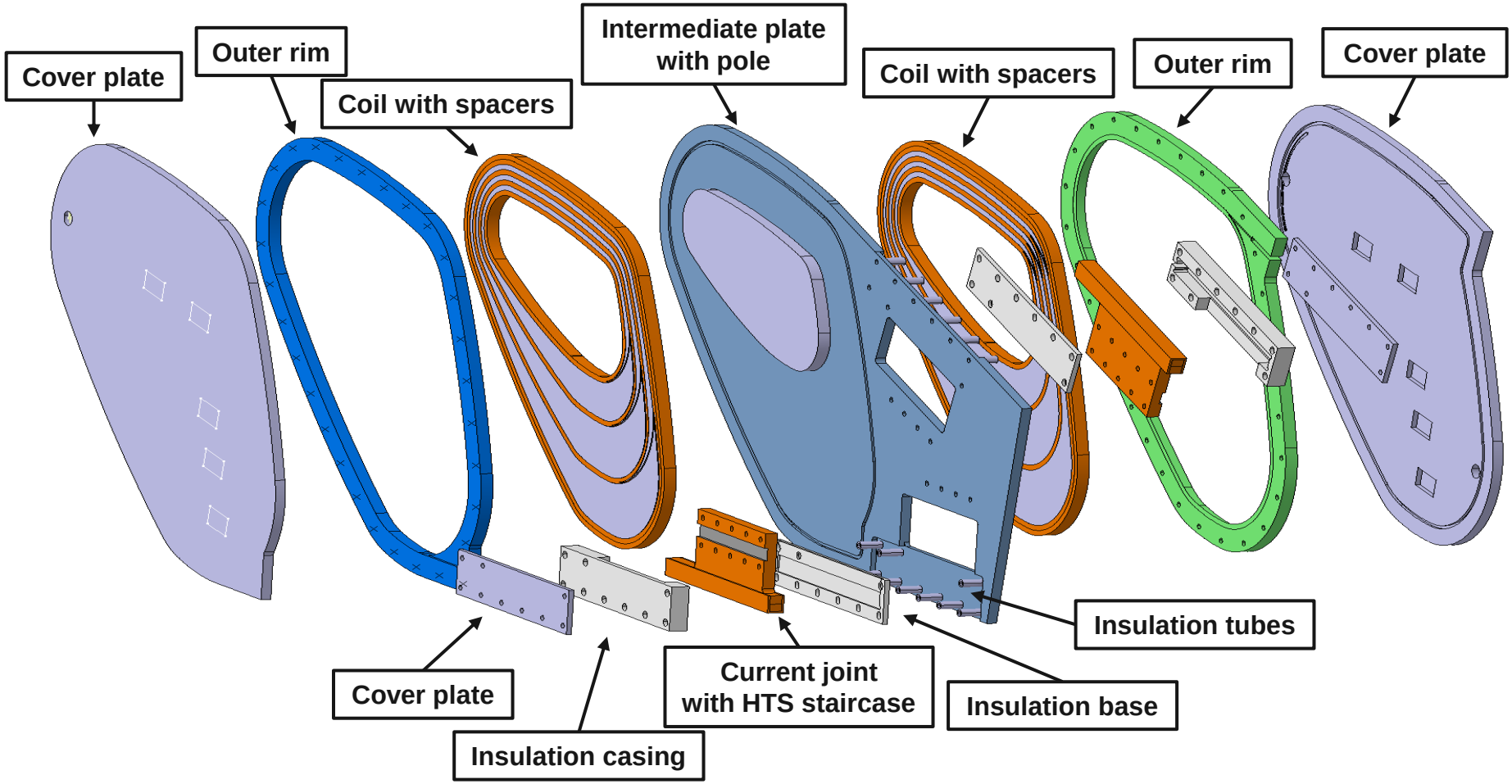
**Full-sized coil (proton gantry)**

**1:3 Scaled down**

**Demonstrator**

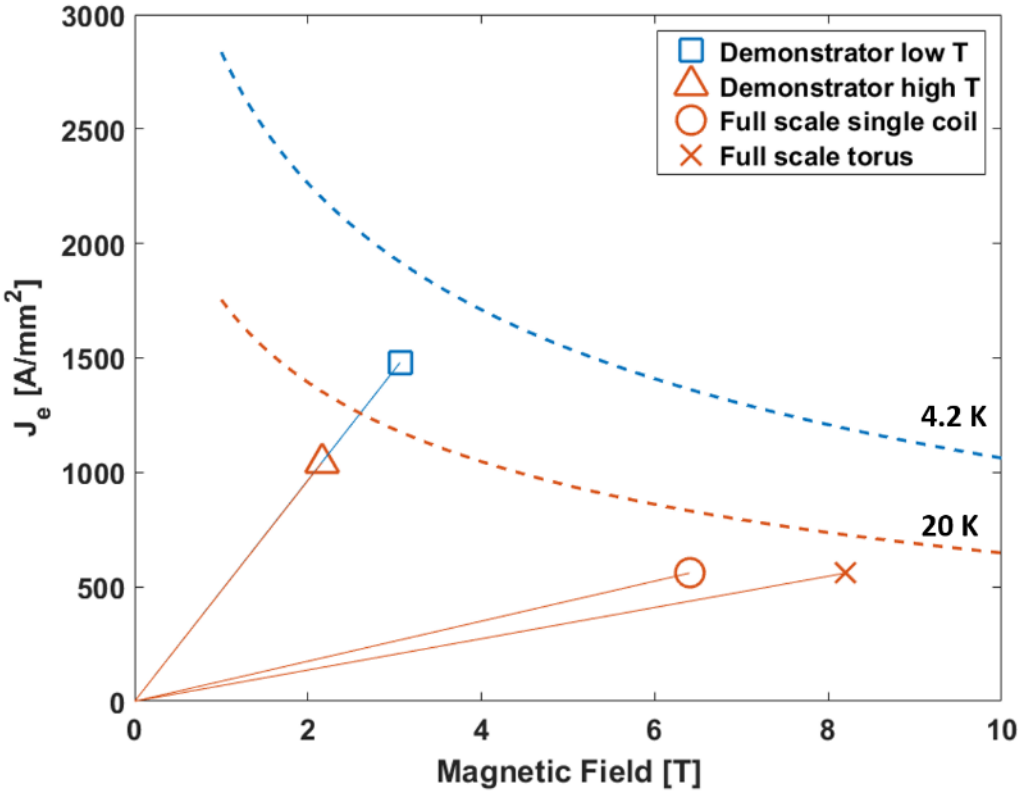
# GaToroid demonstrator

## Design



# 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

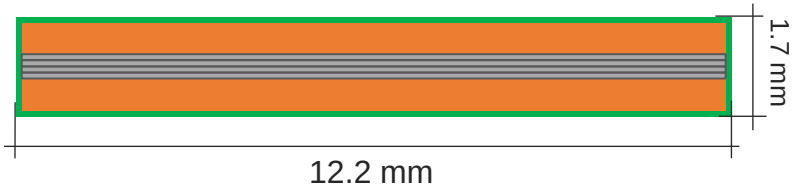
Copper
ReBCO Tapes
Insulation

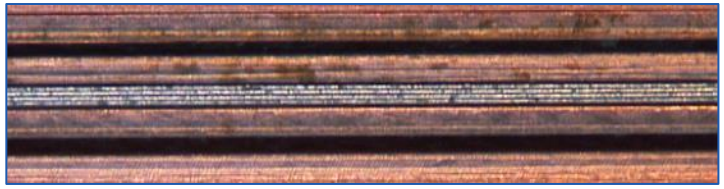
**HTS**

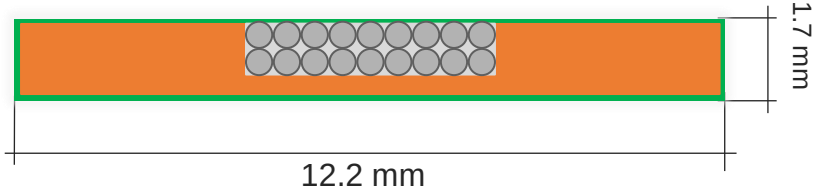
| | |
|---|---|
| Superconductor | ReBCO |
| Topology | Non twisted stack |
| Number of HTS tape | 4 (0.1 mm) |
| Number of Copper tape | 2 (0.55 mm) |
| Cu:Sc ratio | 5.3 |
| Operating temperature | 20 K |

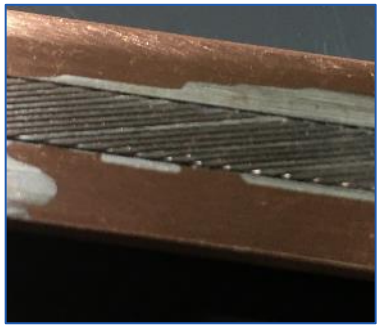
**LTS**

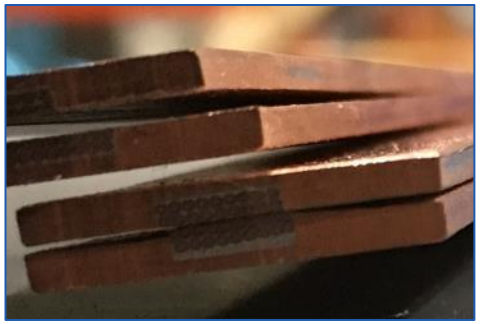
| | |
|---|---|
| Superconductor | NbTi |
| Topology | Rutherford (MCBXF) |
| Number of strands | 18 |
| Cu:Sc ratio (with Cu profile) | 10.8 |
| Operating temperature | 4.2 K |



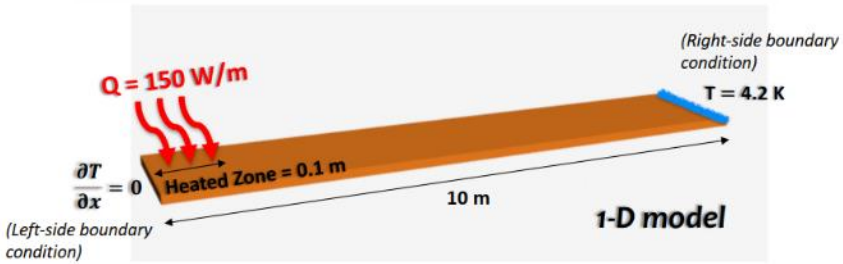




# GaToroid demonstrator

## Quench protection LTS




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

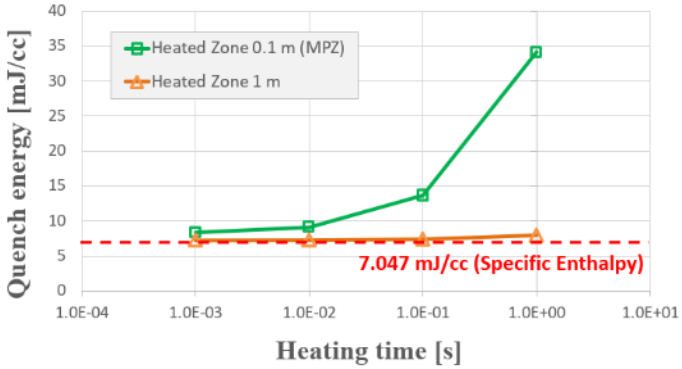
- Local heated zone: 10 cm for 1 ms
- Cable as single element
- 100 mV of Voltage threshold

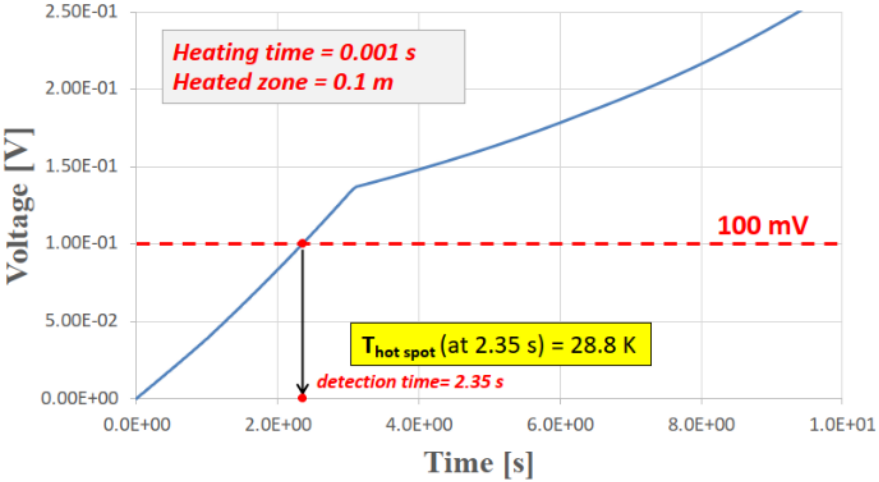
- Minimum quench energy for heating lengths of 1 m and 0.1 m during 1 ms is below 10 mJ/cc .

- 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

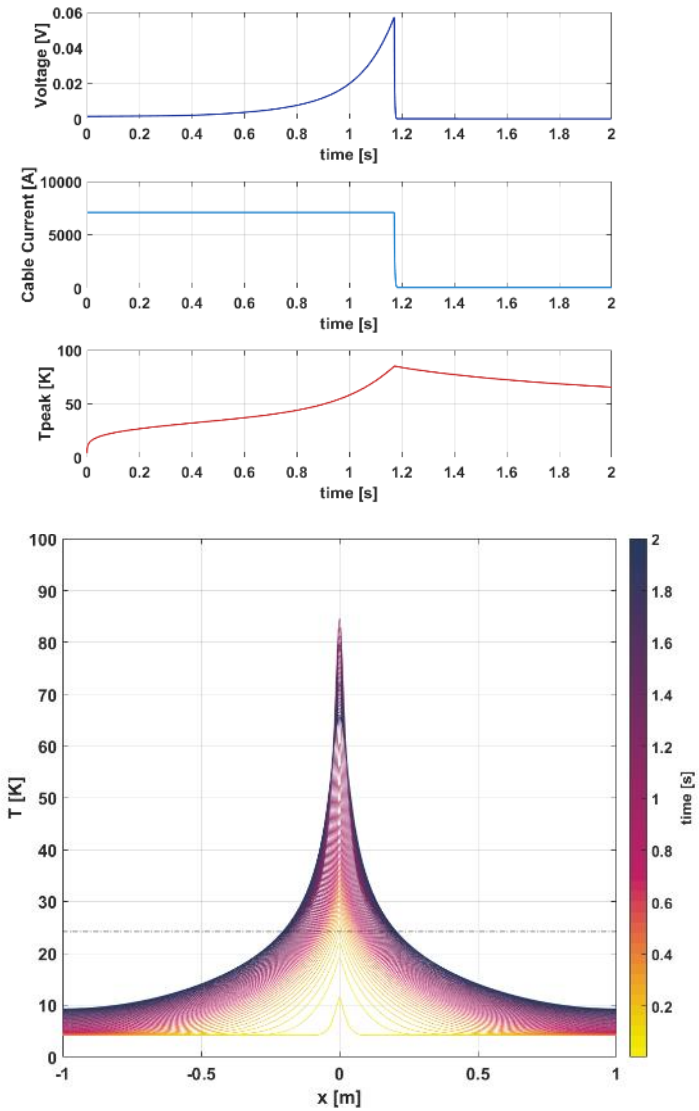
## Quench protection HTS

Minimum quench energy of the cable without stabilizer in adiabatic conditions for heating lengths 1cm 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

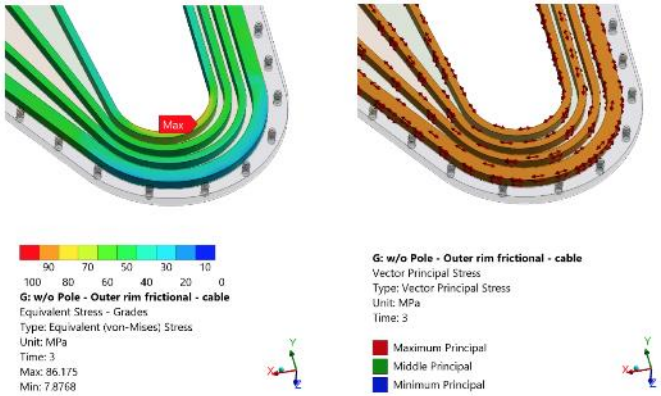


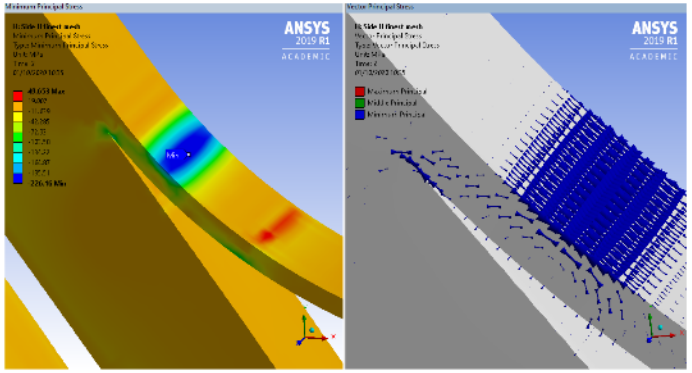
# GaToroid demonstrator

## 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.**

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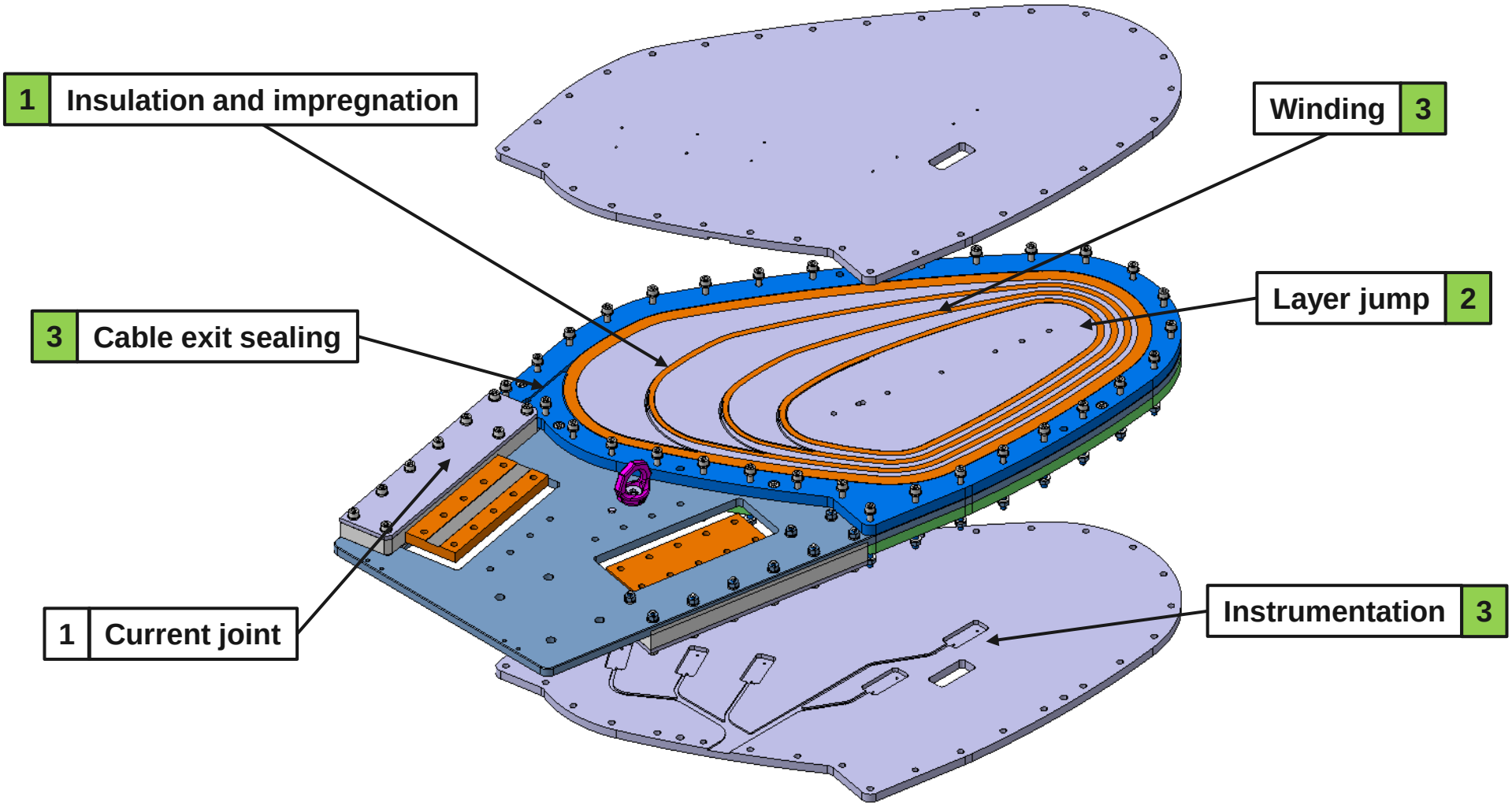
# Technology developments



# 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

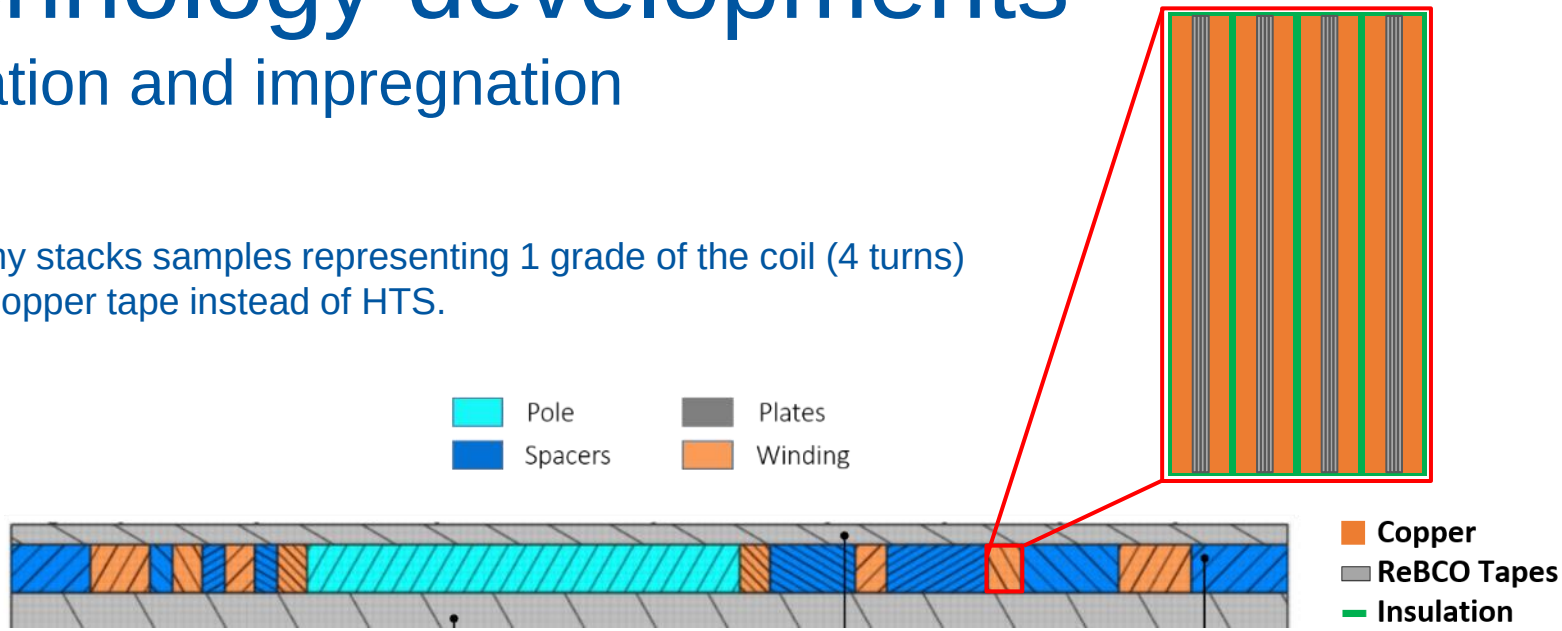
- We want to investigate the compatibility between the impregnation resin and the HTS tape.

**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

**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

### Plan for Phase 1

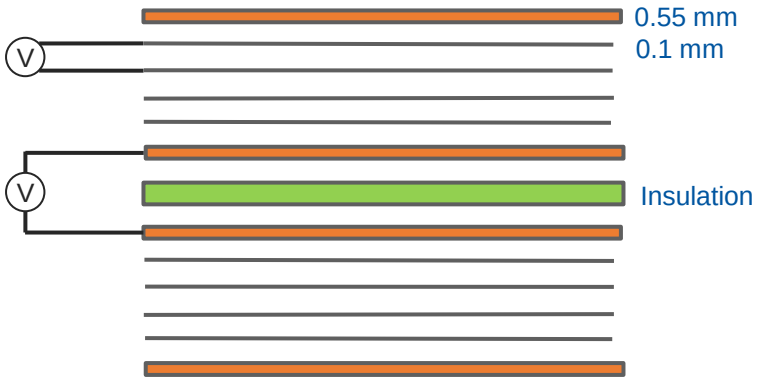
**To check:**

- Impregnation quality (voids, bubbles)
- Mechanical properties (peeling, cracking)
- Insulation between cables
- Contact between tapes in a cable

**Our tools:**

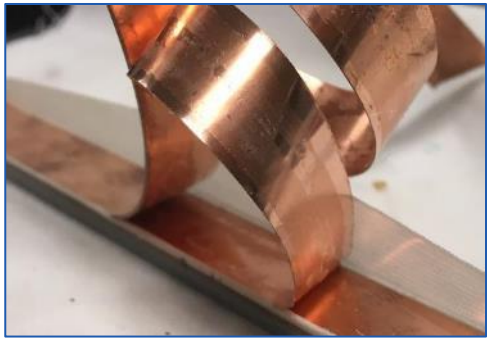
- Peeling and visual inspection
- Cutting and microscopic inspection

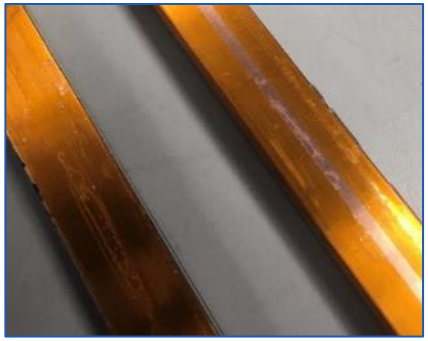
- Electrical tests at room Temp. and at 77K
- Electrical tests after 10 Temp. cycles

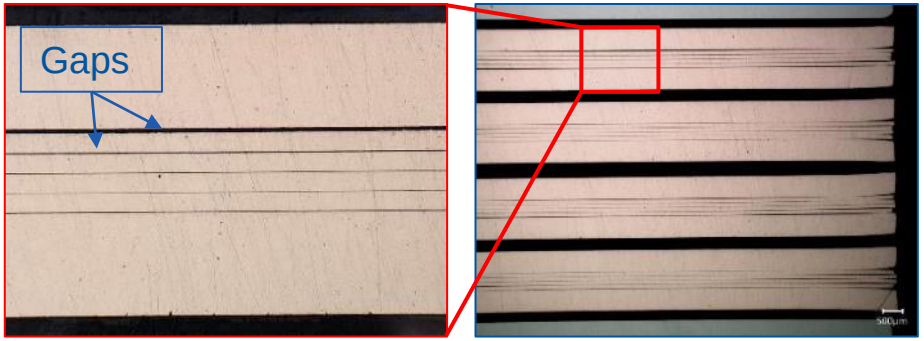


# Technology developments

## Insulation and impregnation








| Stack samples | | | Glass fiber sleeve | | | | | Polymide C-shape | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | High compression | | Low compression | | | Low compression | | |
| | | | MY750 | CTD101K | MY750 | CTD101K | Mix61 | MY750 | CTD101K | Mix61 |
| Peeling observations | | | Hard to peel. A fair continuous pull is necessary | Easy to peel after a first crack | Hard to peel. A fair continuous pull is necessary | Easy to peel after a first crack | Hard to peel. A fair continuous pull is necessary | Very easy once the polyimide removed | Very easy, don't even need to remove polyimide | Very easy to peel no adhesion. Resin is pretty flexible |
| Visual observation | Impregnation between cables | | GF is impregnated but it did not wet the cable | GF is impregnated and it partially wet the cable | GF is impregnated but it did not wet the cable at all | GF is impregnated and it partially wet the cable | GF is impregnated but it did not wet the cable very well | Not Homogeneous some resin under the polymide on both side of the "C" | Not homogeneous. No resin under the polyimide. | Not homogeneous |
| | Resin between tapes | | several traces | very few traces | several traces | very few traces | few traces | very few traces | almost none | almost none |
| | Gap between cables | | 329 µm | 334 µm | - | 426 µm | - | Not homogeneous | Not homogeneous | Not homogeneous |
| Electrical tests | Resistance between cables [GΩ] | Before thermal cycles | 705 | 1869 | 2162 | > 2610 | 285 | > 3000 | > 3000 | 829 |
| | | After thermal cycles | 593 | 1964 | 882 | 1269 | 633 | > 2823 | 2913 | 536 |
| | Resistance between tapes [mΩ] | Before thermal cycles | 3.012 | 2.222 | 2.323 | 2.491 | 1.882 | 1.403 | 1.944 | 1.535 |
| | | After thermal cycles | 3.205 | 2.263 | 2.198 | 1.748 | 1.890 | 1.370 | 1.682 | 1.608 |
| | | At 77K | 0.520 | 0.362 | 0.333 | 0.349 | 0.242 | 0.212 | 0.165 | 0.234 |

# 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:**

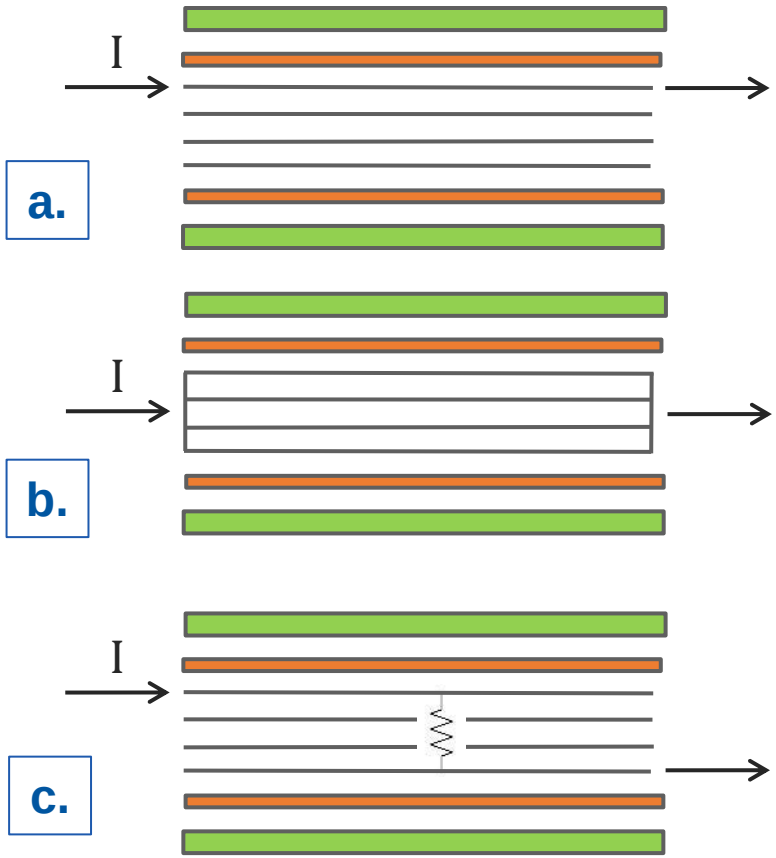
a. Critical current of 1 tape
   - Before impregnation
   - After impregnation
   - After 5 thermal cycles

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

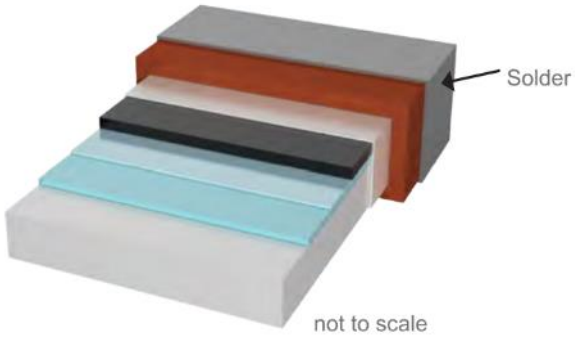
## Insulation and impregnation

**HTS for GaToroid demonstrator**

4 spools: Theva TPL 5000 series, 12 mm wide

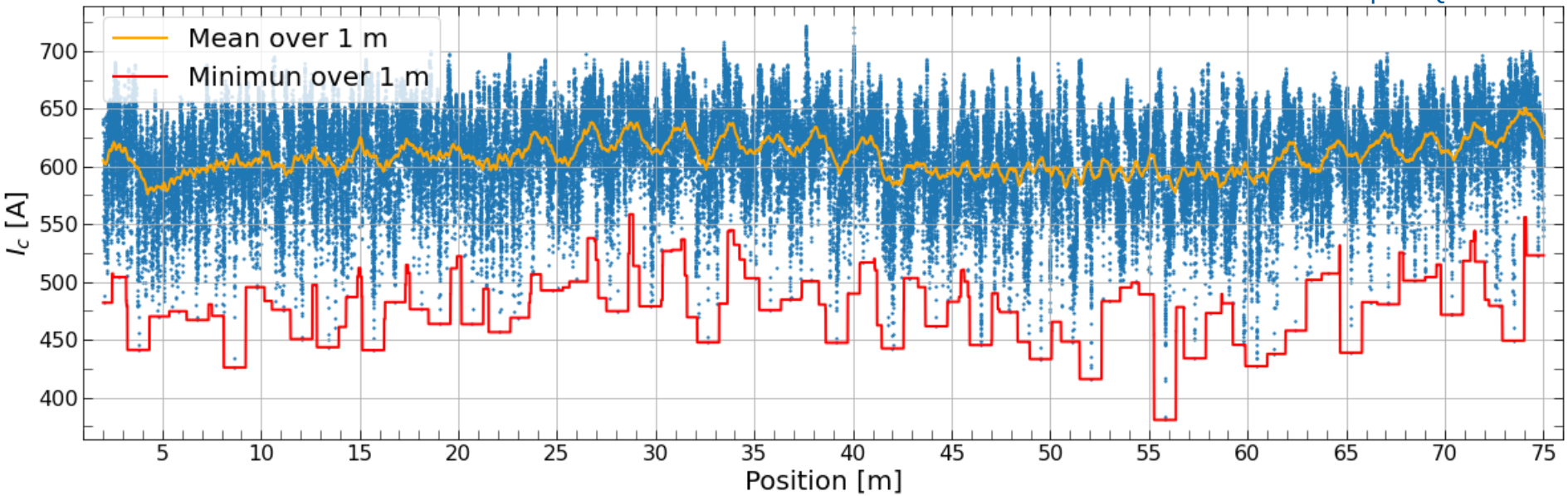
- 6-10 µm Cu/PbSn
- Min Ic: 380 A / 550 A / 340 A / 520 A

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




Architecture of the TPL5000-series

TAPE STAR data - Spool QS200004



# Technology developments

## Insulation and impregnation

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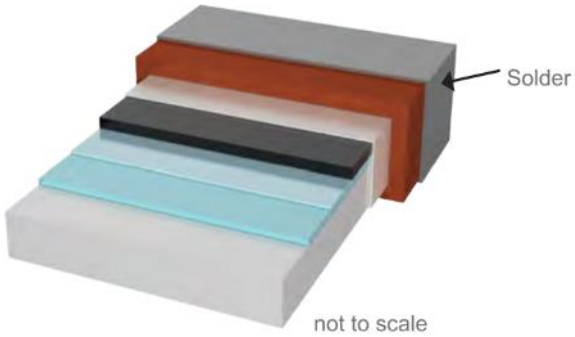
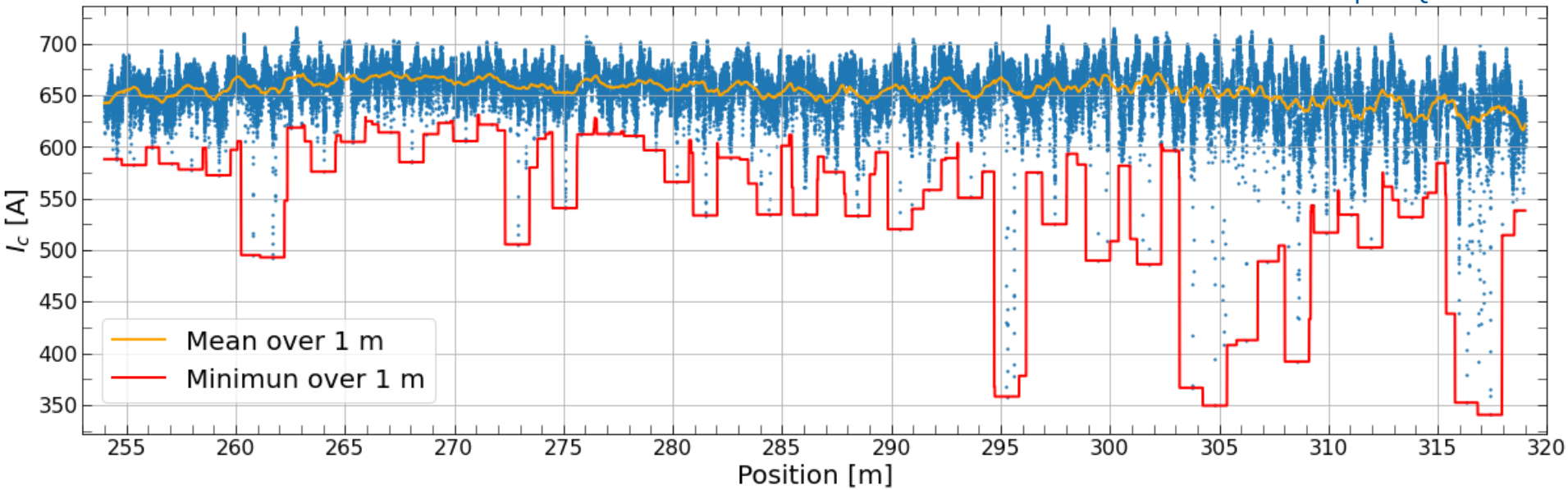


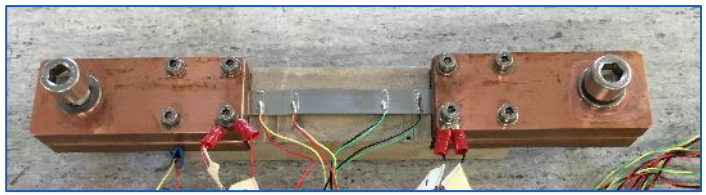

Architecture of the TPL5000-series

TAPE STAR data - Spool QS200008



# Technology developments

## Insulation and impregnation



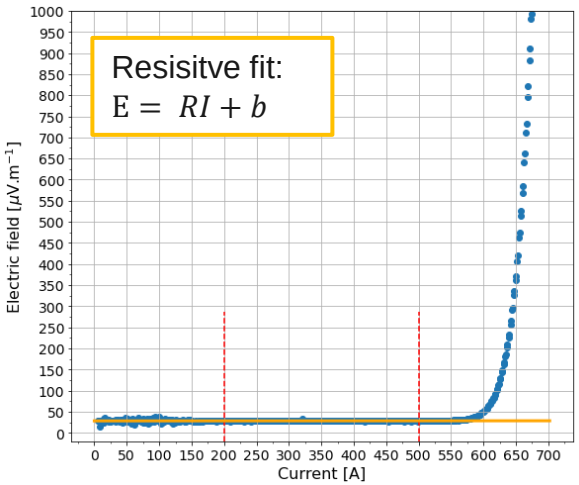
**Measure of the critical current in a single tape**

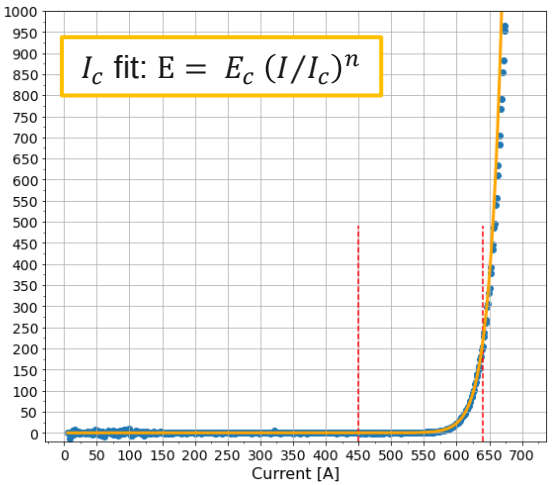
Sample: QS200004 – 11.2 m

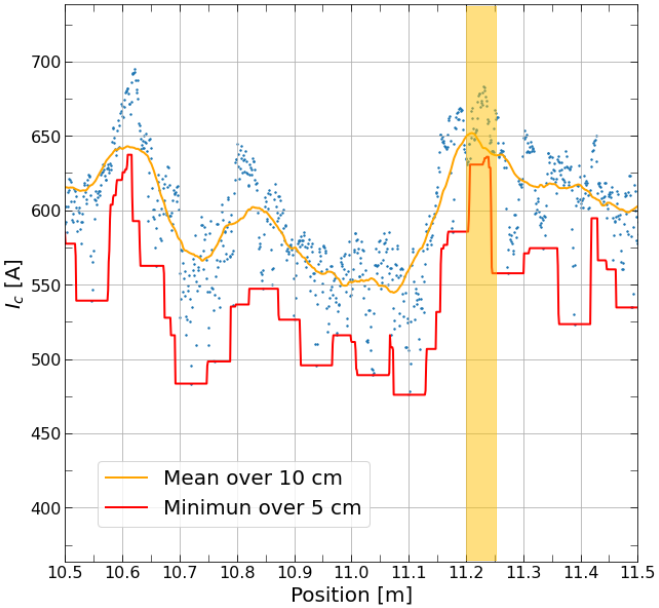
Resistive slope: 0.4 nΩ/m

| | |
|---|---|
| $I_c$ = 626.1 | error: 0.0386 |
| $n$ = 34.8 | error: 0.1296 |

$E_C$ = 100 μV/m



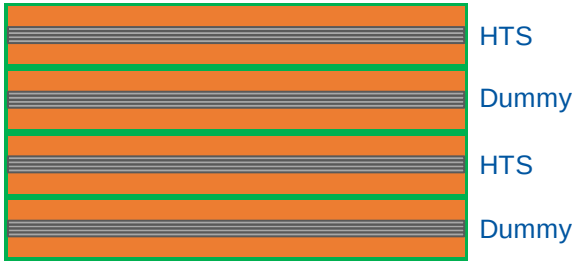



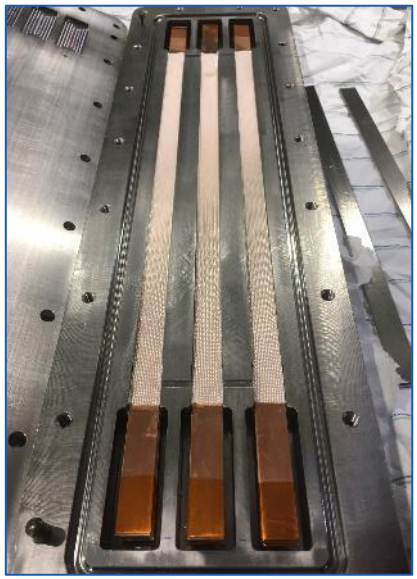
# Technology developments

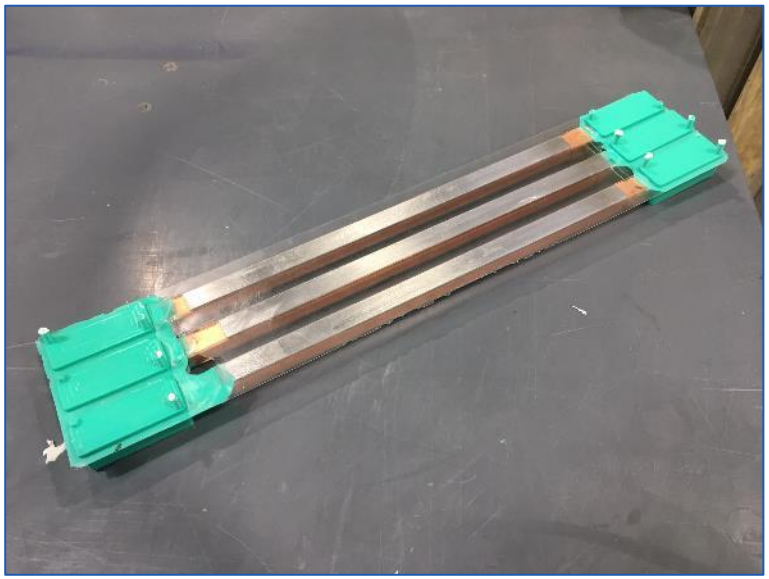
## Insulation and impregnation

Stacks are prepared with MY 750 + HY 5922

- 3x 4 cables (2 HTS and 2 dummies)
- longer silicon caps to clear more cable ends



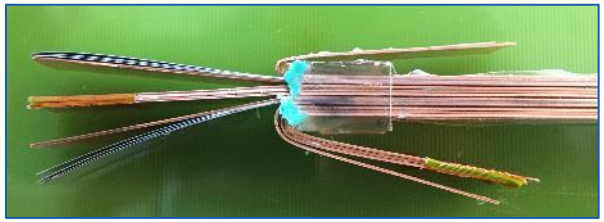




Thanks to A. Benfkih and R. Gavaggio for the impregnation

# Technology developments

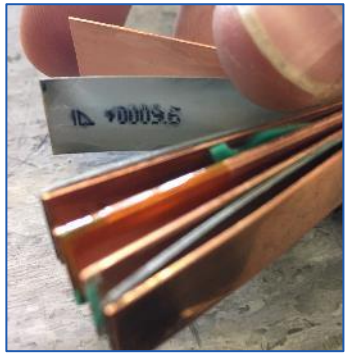
## Insulation and impregnation

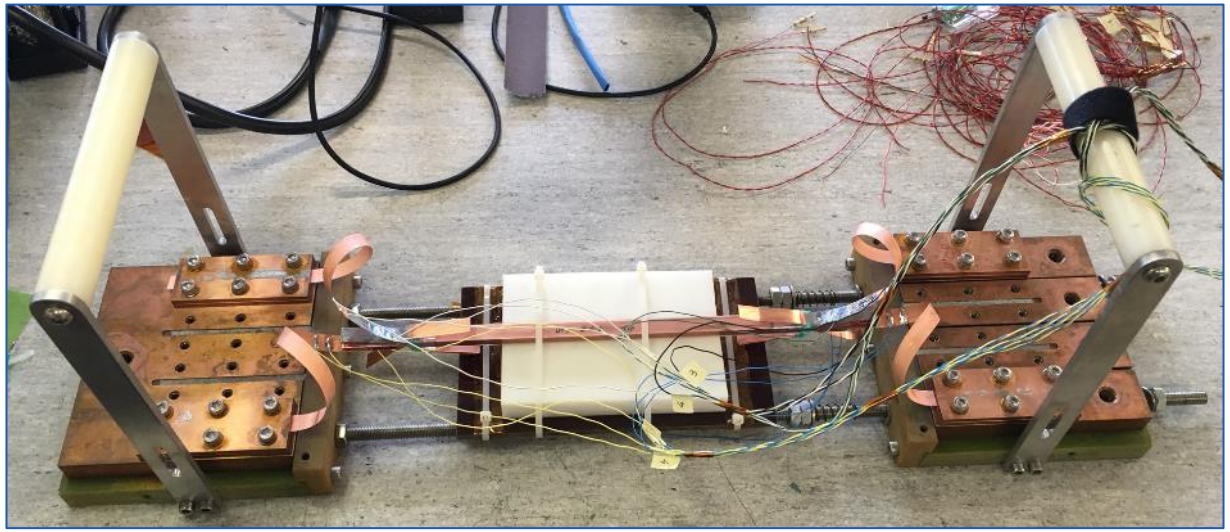


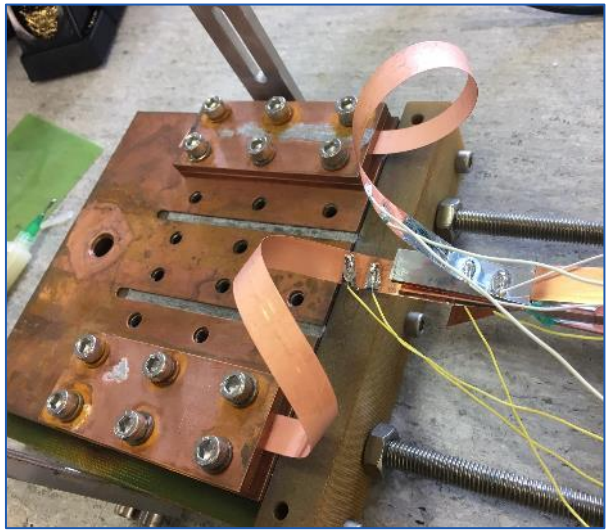
**Preparation of HTS stack samples**

- 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





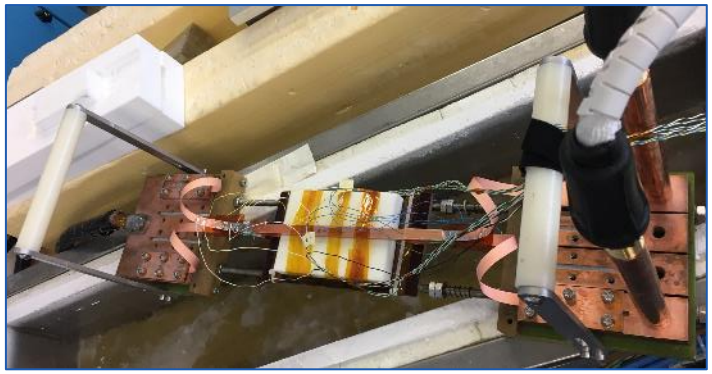


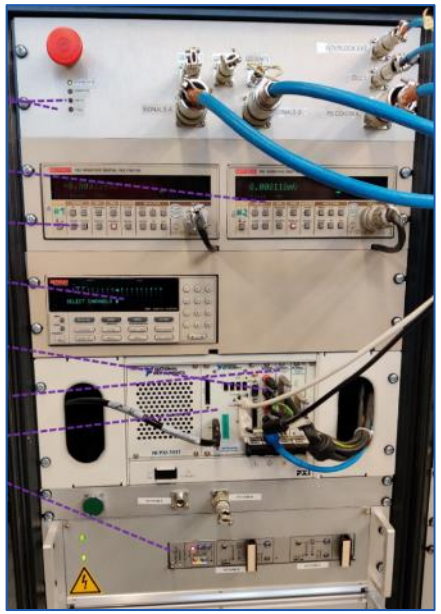
# Technology developments

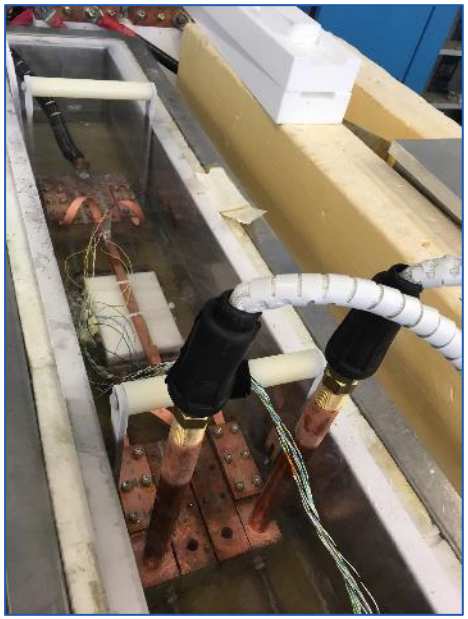
## Insulation and impregnation

**Measure of HTS stack samples**

For each cooling cycle the stack was removed form the liquid and warmed up before being plunged again.

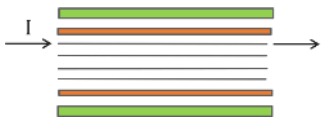






# Technology developments

## Insulation and impregnation




TAPE STAR - Spool QS200004

**Critical current on HTS stack samples**

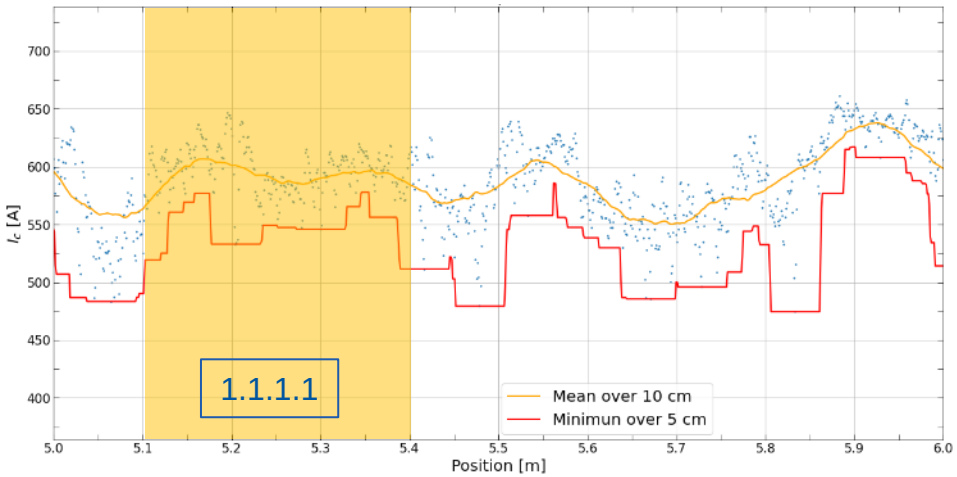
- From the 6 tapes (2 per sample) only 2 could be tested:

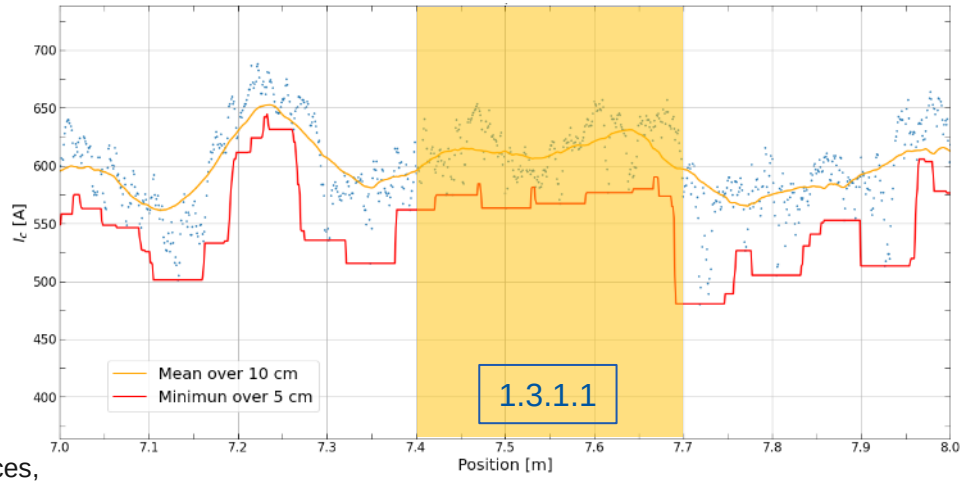
| | |
|---|---|
| 1.1.1.1 | $I_c(expected) \sim 530$ A |
| 1.3.1.1 | $I_c(expected) \sim 560$ A |

- The other were resistive:

| | |
|---|---|
| 1.1.4.4 | $R \sim 600$ μΩ /m |
| 1.2.1.1 | $R \sim 40$ μΩ/m |
| 1.2.4.4 | $R \sim 70$ μΩ/m |
| 1.3.4.4 | $R \sim 15$ μΩ/m |

- Connection resistance: ~ 60 nΩ.cm²




J. Fleiter and A. Ballarino,In Field Electrical Resistance at 4.2K of ReBCo Splices, *IEEE Trans. Appl. Supercond.*, **27** (4) (2017)

# Technology developments

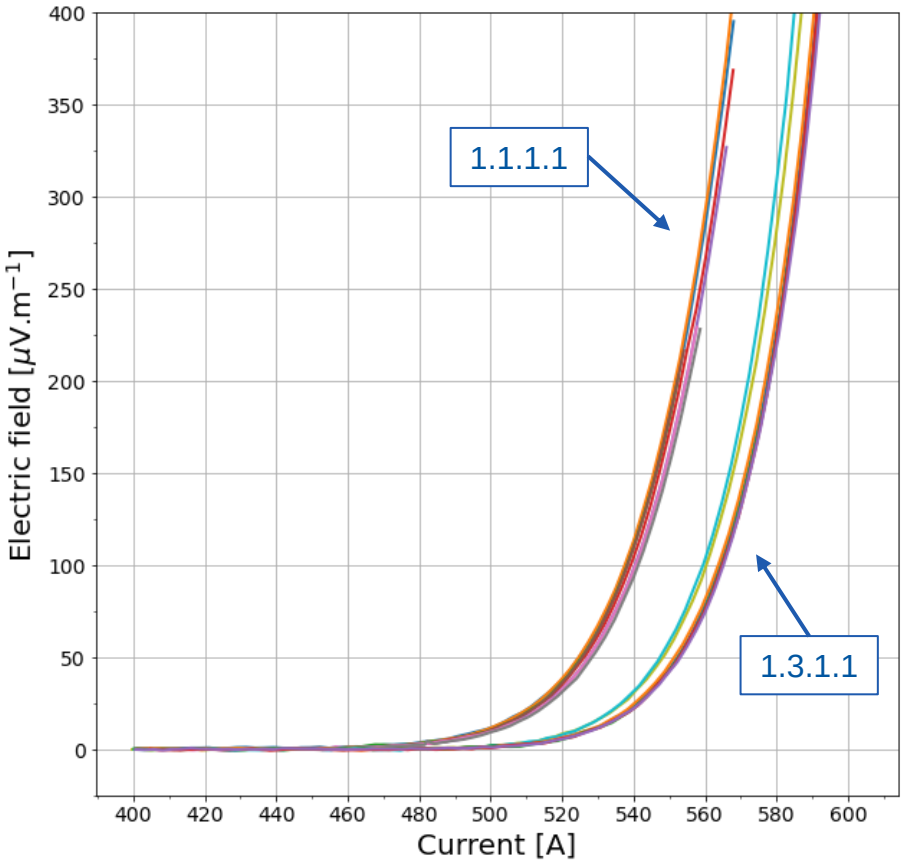
## Insulation and impregnation


**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

| Cycle | 1.1.1.1 | | 1.3.1.1 | |
|---|---|---|---|---|
| 1st | $I_c$ = 532.1 A | $n$ = 27.9 | $I_c$ = 555.0 A | $n$ = 30.9 |
| 2nd | $I_c$ = 531.9 A | $n$ = 28.5 | $I_c$ = 554.2 A | $n$ = 31.8 |
| 3rd | $I_c$ = 532.7 A | $n$ = 28.9 | $I_c$ = 558.5 A | $n$ = 30.6 |
| 4th | $I_c$ = 533.5 A | $n$ = 28.6 | $I_c$ = 558.4 A | $n$ = 31.2 |
| 5th | $I_c$ = 534.7 A | $n$ = 28.8 | $I_c$ = 559.6 A | $n$ = 31.7 |
| 6th | $I_c$ = 532.8 A | $n$ = 29.1 | $I_c$ = 559.6 A | $n$ = 31.4 |
| 7th | $I_c$ = 534.9 A | $n$ = 28.6 | $I_c$ = 559.9 A | $n$ = 31.8 |
| 8th | $I_c$ = 535.7 A | $n$ = 29.1 | | |



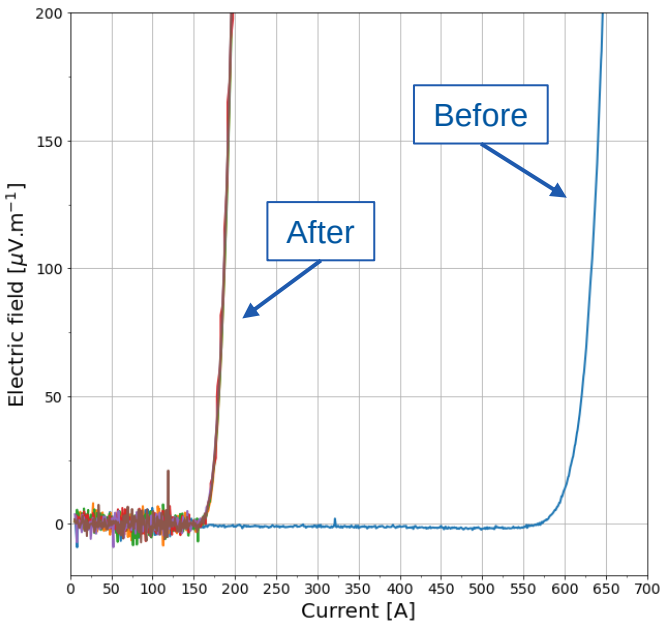
# Technology developments

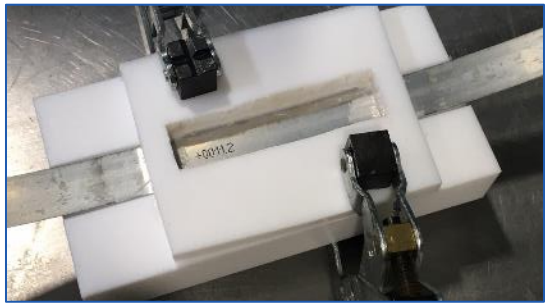
## Insulation and impregnation

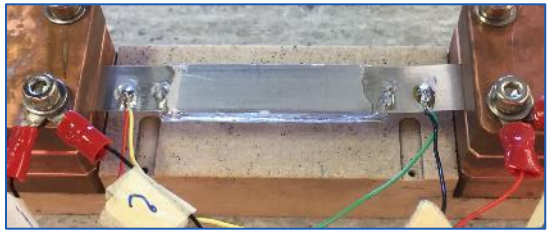
**Test with impregnated single tape**

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.



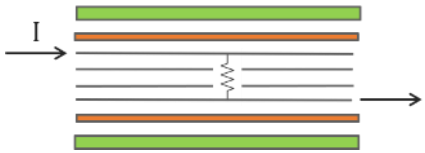



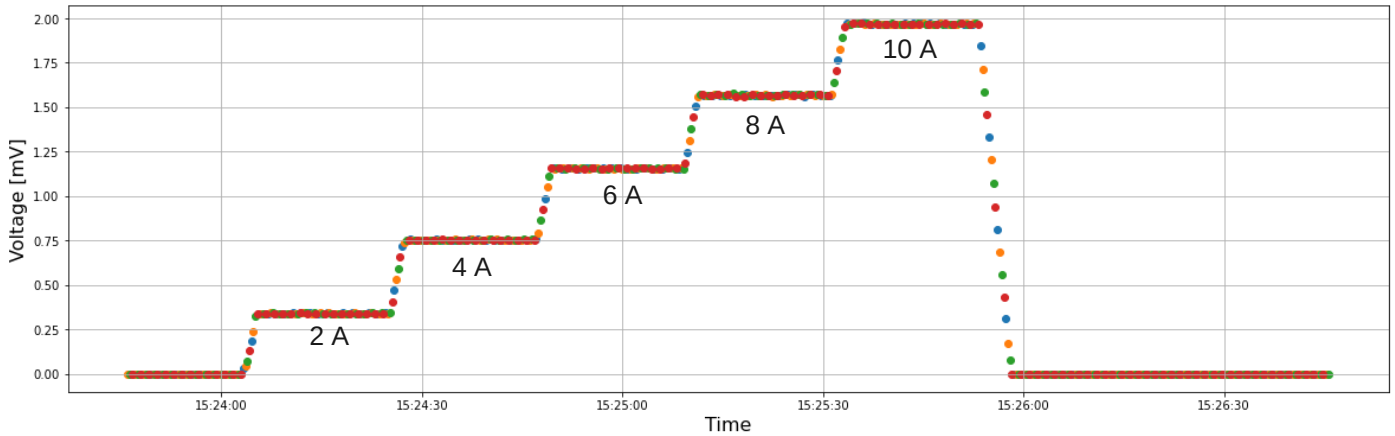


| Before | $I_c$ = 626.1 A | $n$ = 34.8 |
|---|---|---|
| 1st | $I_c$ = 184.2 A | $n$ = 21.8 |
| 2nd | $I_c$ = 184.2 A | $n$ = 20.8 |
| 3rd | $I_c$ = 183.3 A | $n$ = 20.3 |
| 4th | $I_c$ = 183.6 A | $n$ = 19.9 |
| 5th | $I_c$ = 183.6 A | $n$ = 20.8 |

# 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.

| Current | Resistance | Contact Res. |
|---|---|---|
| 2 A | 70 μΩ | 2.45 mΩ.cm² |
| 6 A | 68 μΩ | 2.38 mΩ.cm² |
| 8 A | 67 μΩ | 2.35 mΩ.cm² |
| 10 A | 67 μΩ | 2.35 mΩ.cm² |
| 12 A | 67 μΩ | 2.35 mΩ.cm² |
| 14 A | 67 μΩ | 2.35 mΩ.cm² |

M. Bonura *et al.*, Systematic Study of the Contact Resistance Between REBCO Tapes, *IEEE Trans. Appl. Supercond.*, **29** (5) (2019)

# Technology developments

## Insulation and impregnation

### Conclusion and next steps

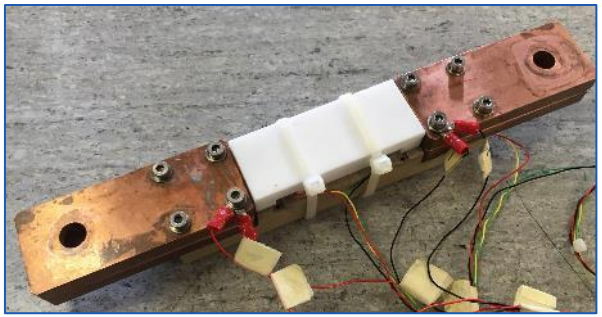
In the actual design (MY 750 + Fiberglass), the impregnation does not influence the properties of the tape after cooling.

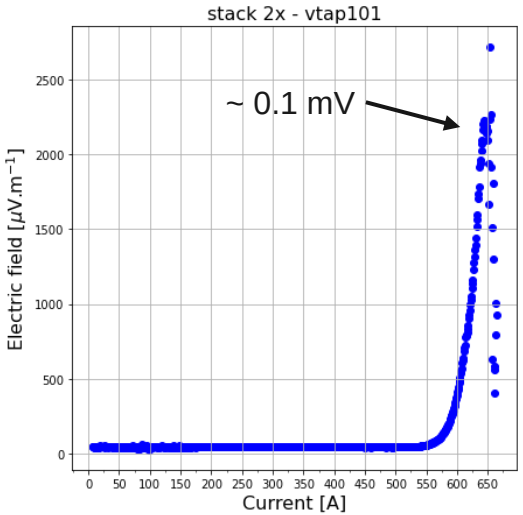
It seems that the tape inside the insulated cable has almost no contact with the resin.

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:

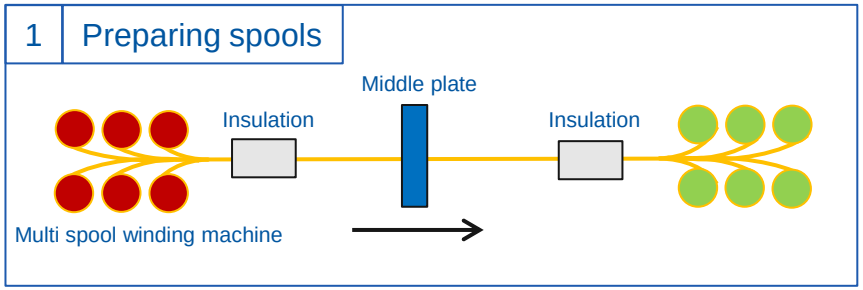
- 4 tapes measurements *in-situ* in the stack

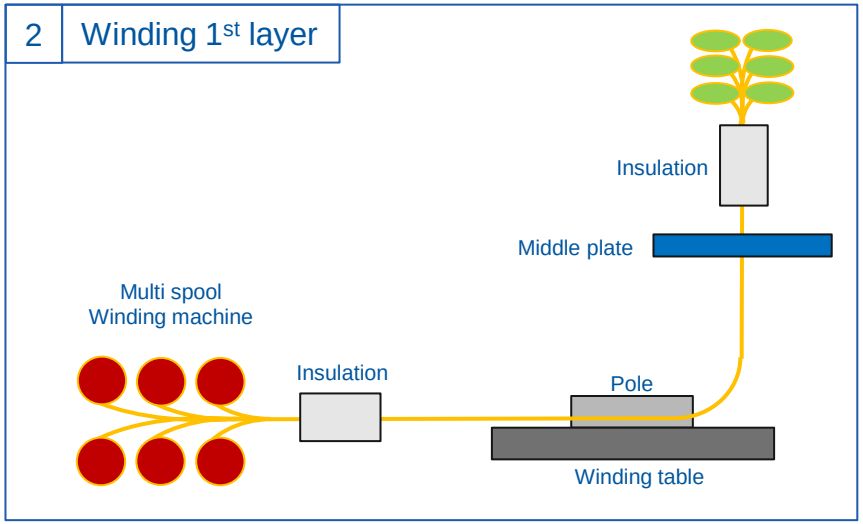



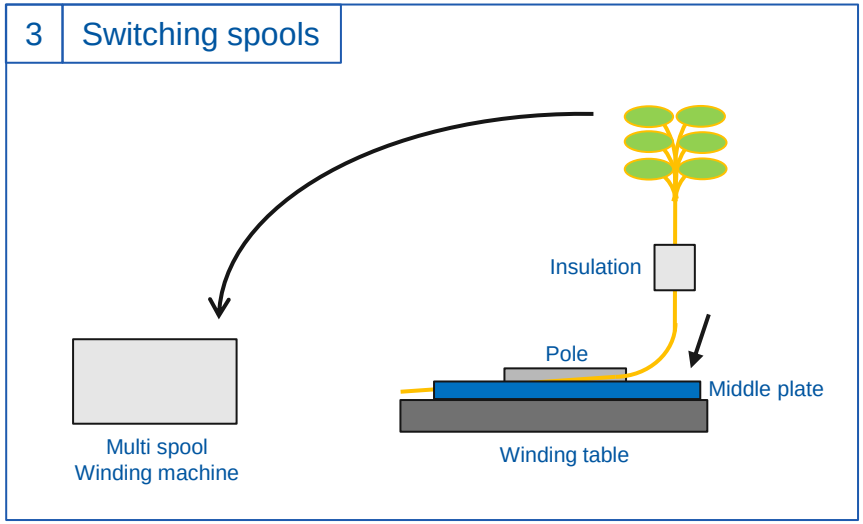


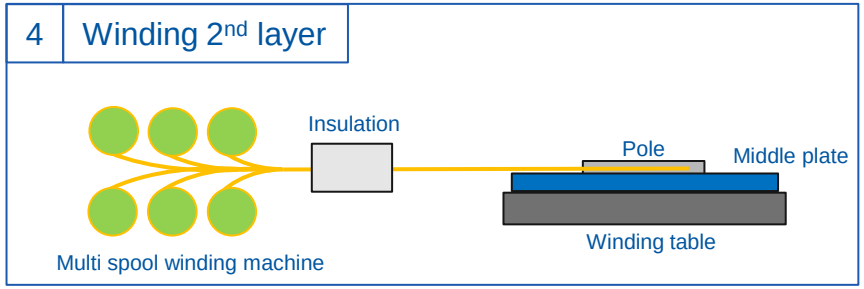
# Technology developments

## Winding



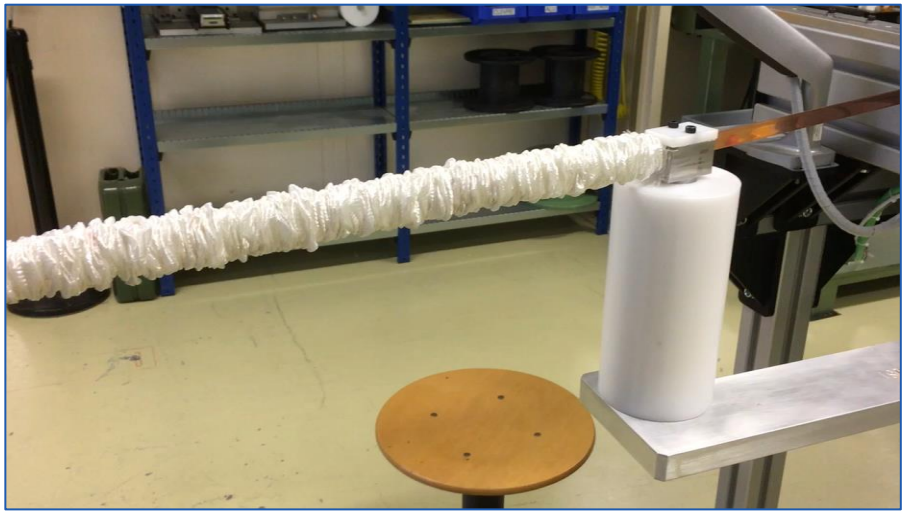

Procedure and tools developed at 927 supervised by J.C. Perez:
G. Maury, J. Mazet, F. Garnier And P. Vazquez

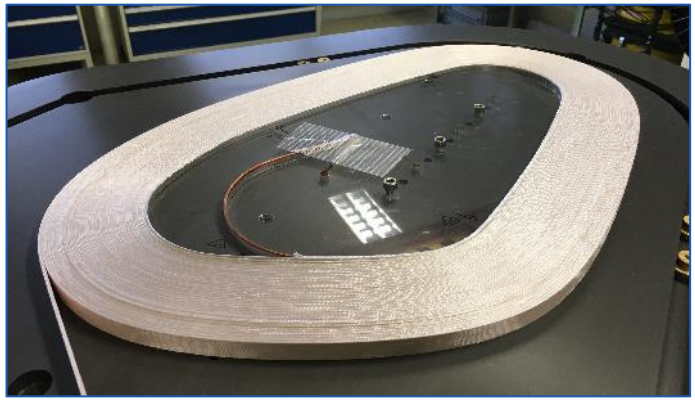
# Technology developments

## 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.



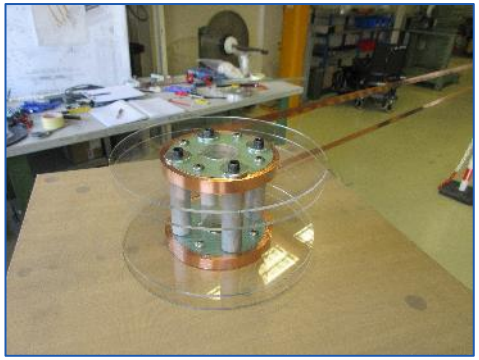


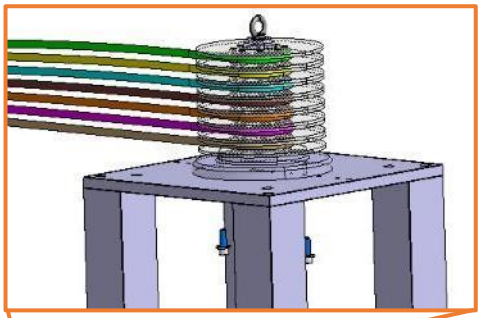
# Technology developments

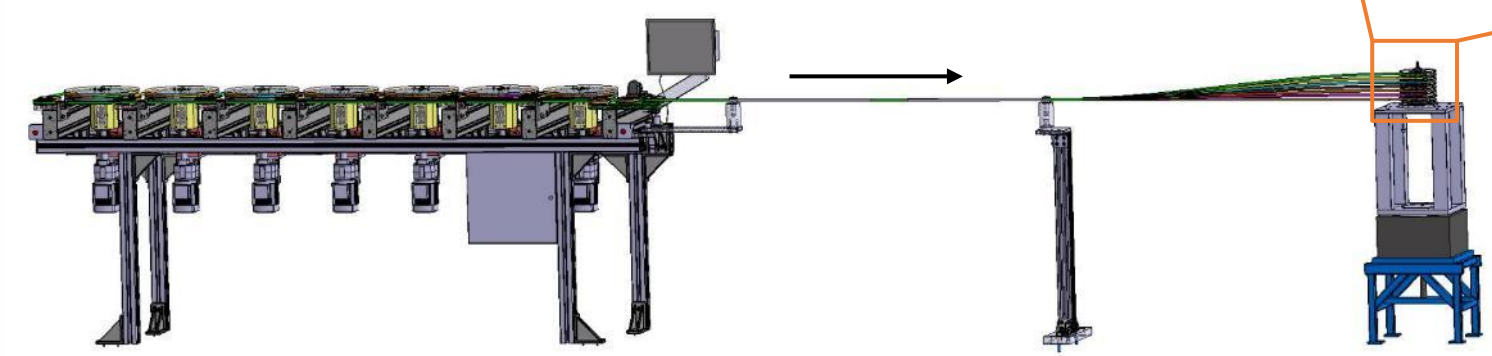
## Winding

### 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.



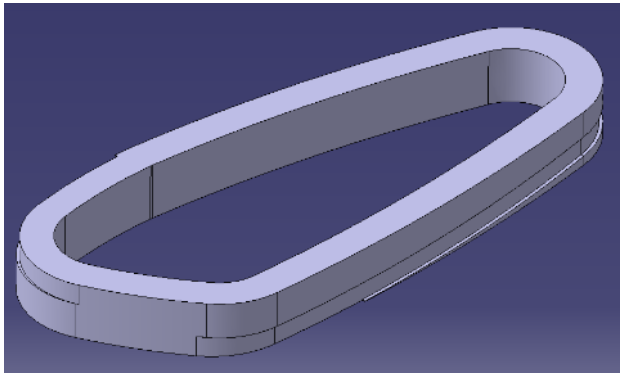


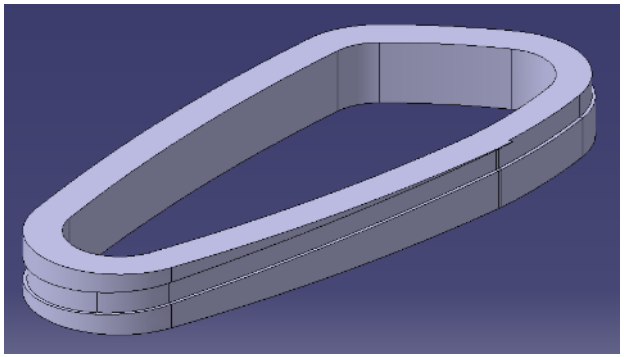


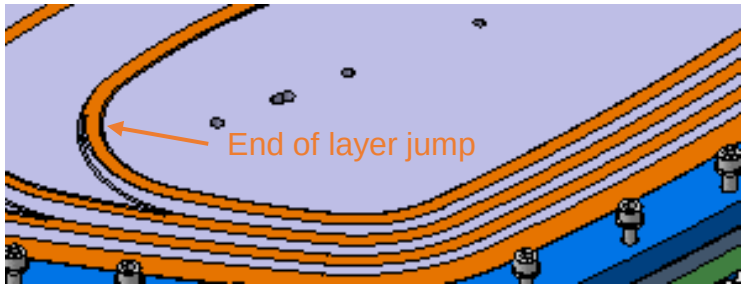
# Technology developments

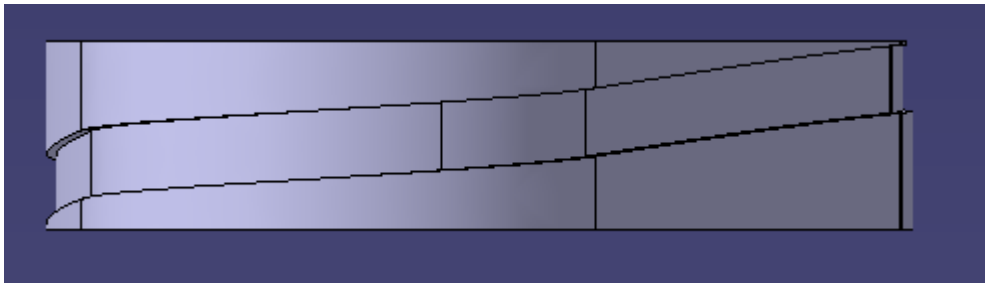
## Layer jump

- 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.







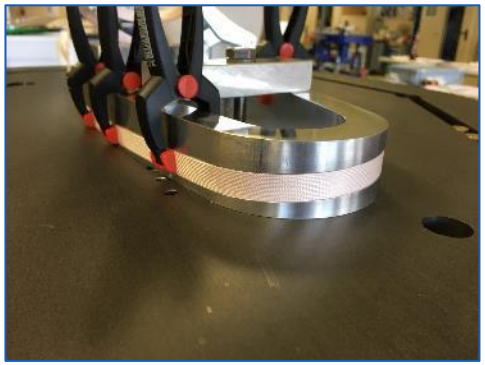



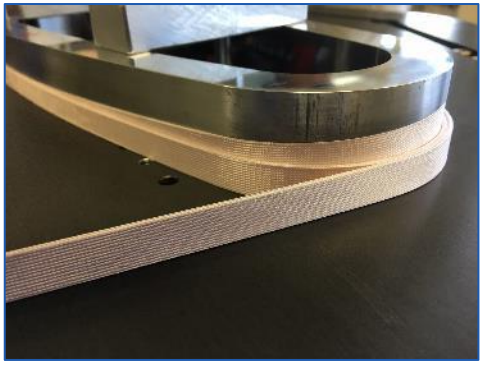
# Technology developments

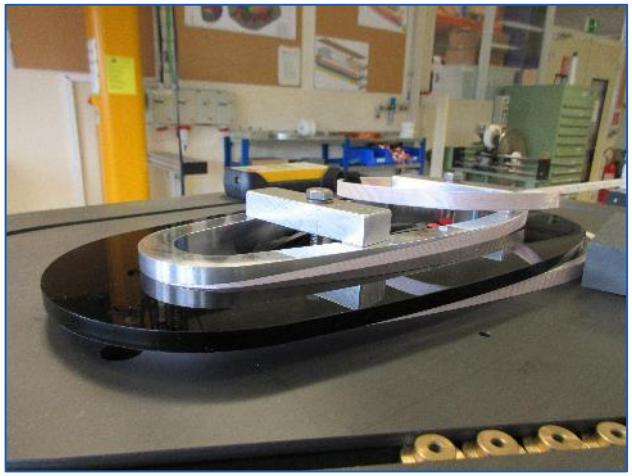
## Layer jump

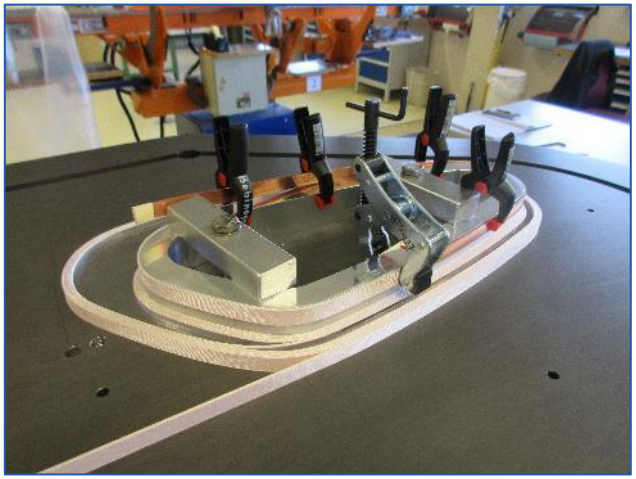
**Test with the HTS cable on Aluminum pole**

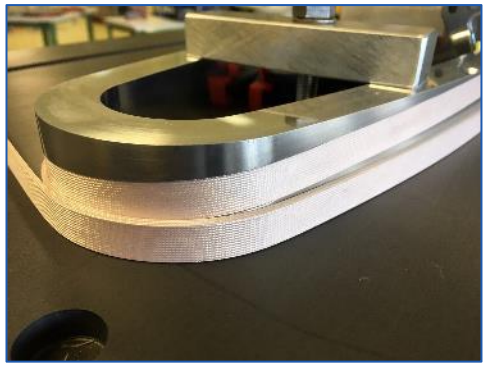
- This configuration was tested successfully with 6 tapes + insulation.
- The winding of several grades was not altered by the layer jump. Once in the groove, it makes a perfectly flat surface on the pole.
- The positioning of a fake intermediate plate completes to validate this set-up.









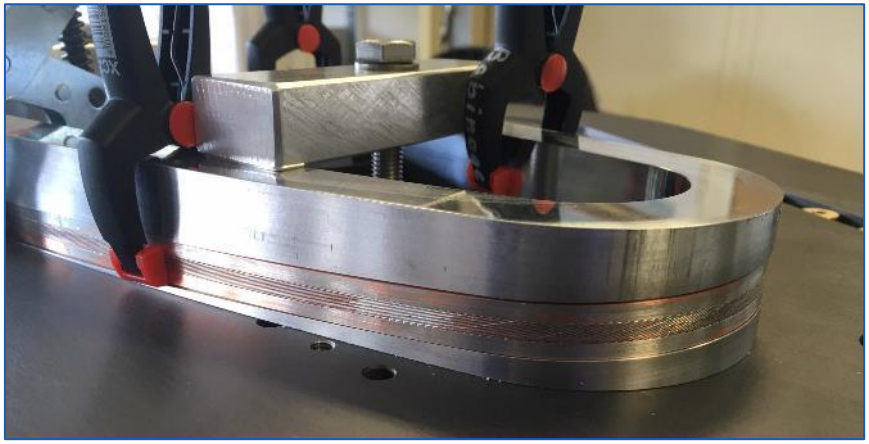


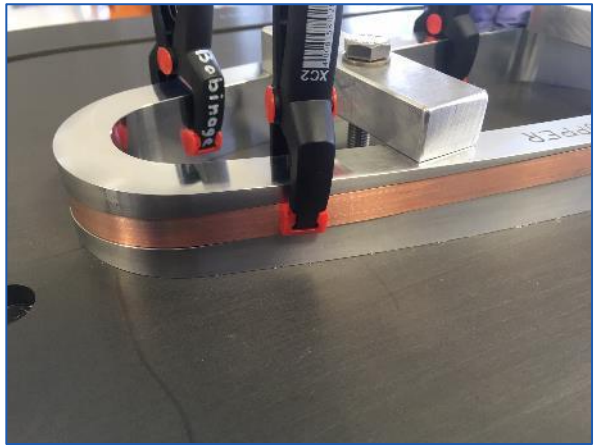
# Technology developments

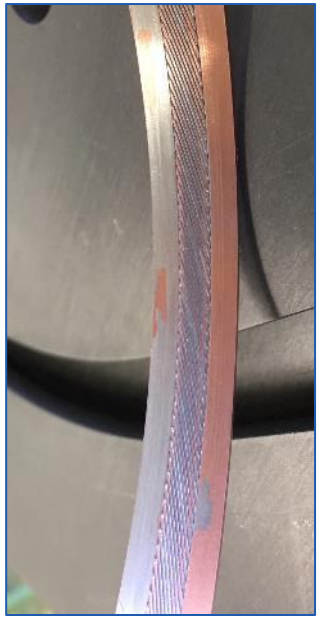
## Layer jump

**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.



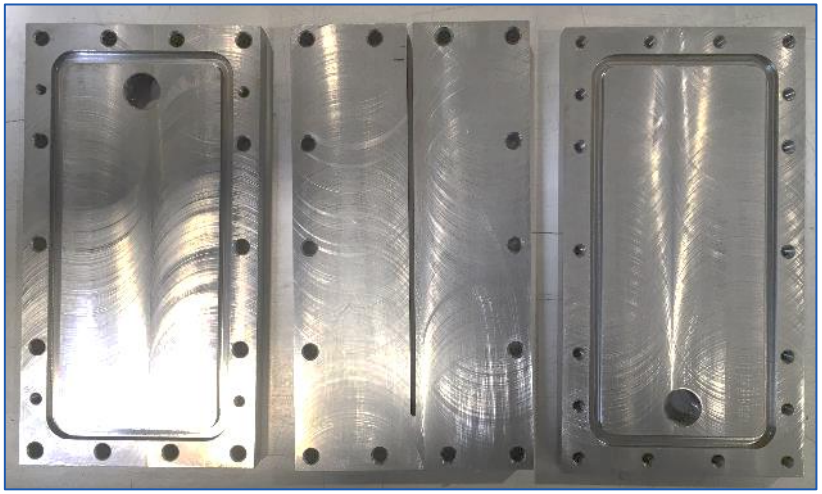


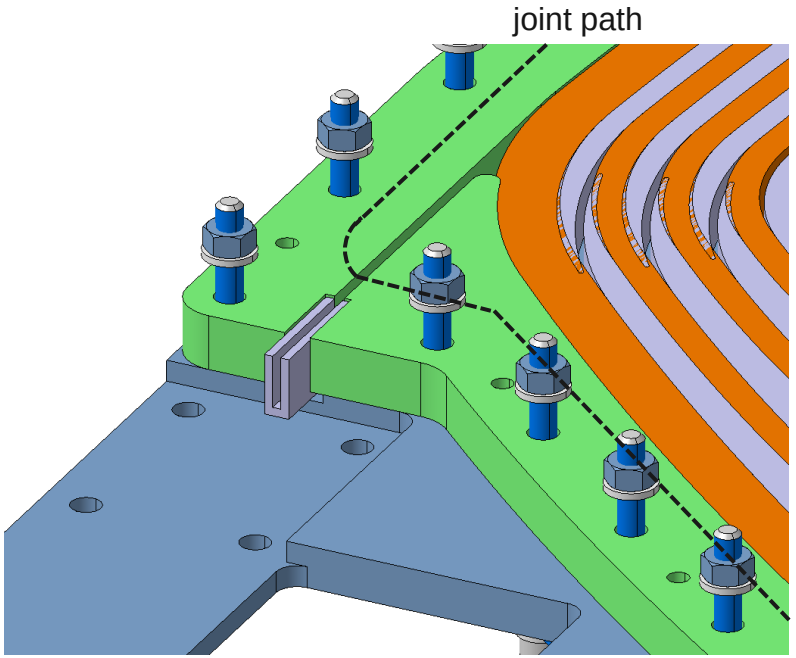


# Technology developments

## 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.



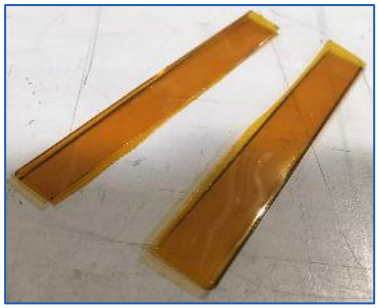


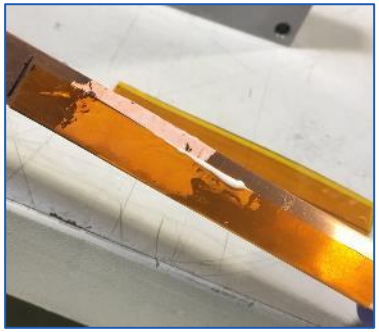
# Technology developments

## Cable exit sealing

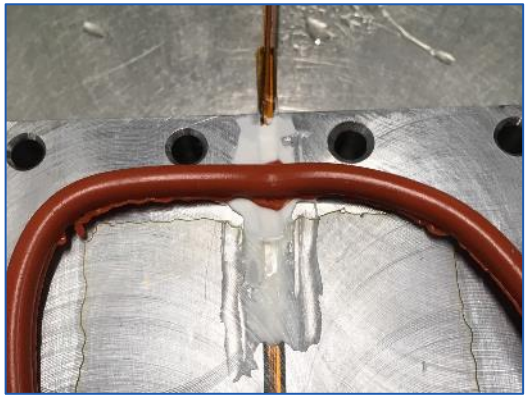
**Test representative of the configuration and assembly sequence**

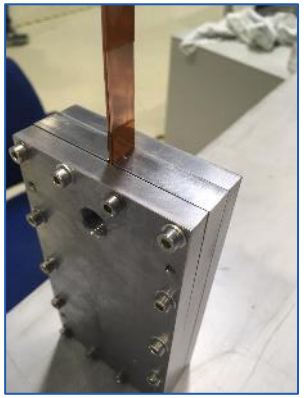
- The insulation for the passage consists of 2 U-shape 0.75 mm thick polyimide layers.
- The CAF4 for the sealing is applied on both faces of each tape and on the insulation while the cable is still unstacked.
- The part with the groove is push on the cable as the outer rim will be during the assembly procedure.
- Impregnation with MY 750 worked perfectly using this procedure.

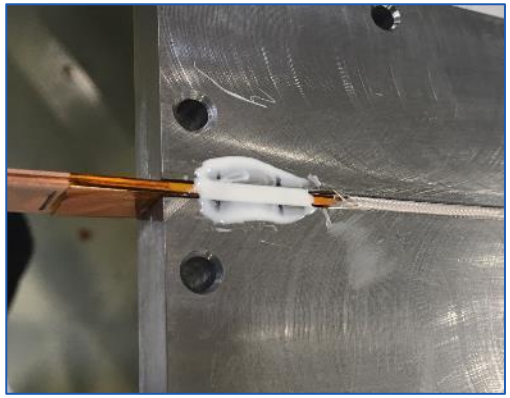




No major modification on the main design were made except for a slight increase of the groove width to allow easier handling.





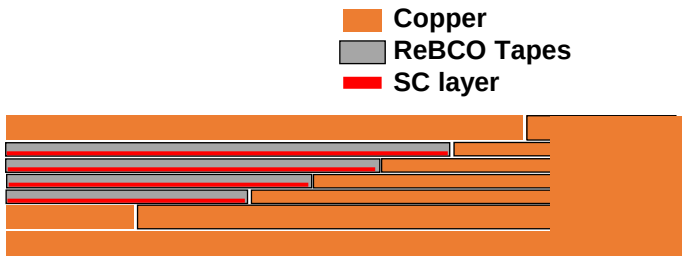


# Technology developments

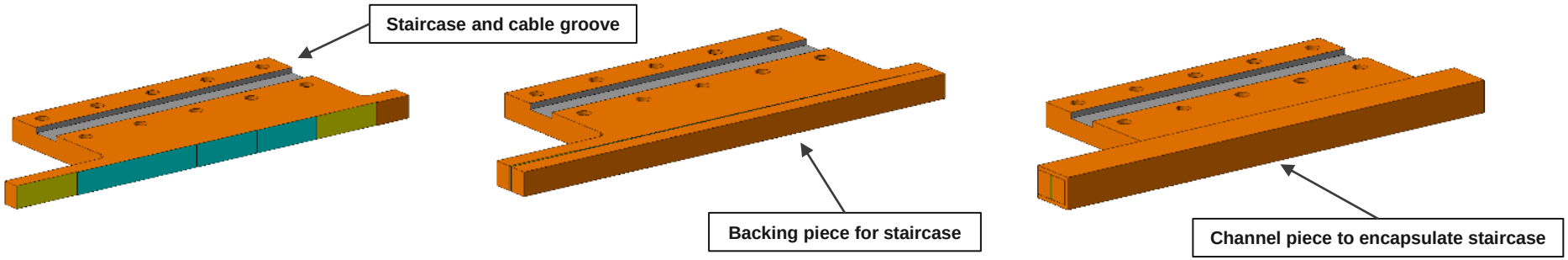
## Current joints

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).

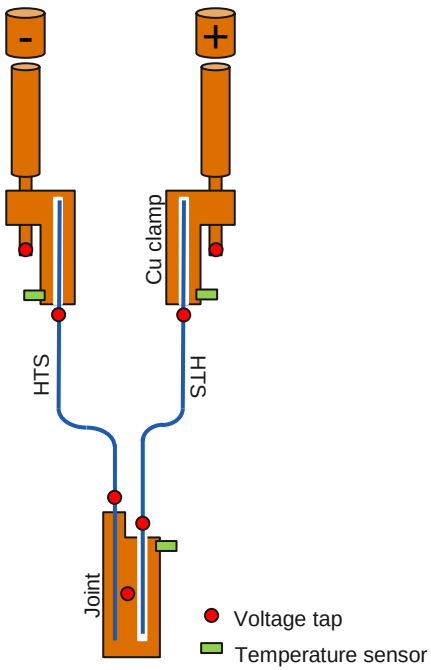


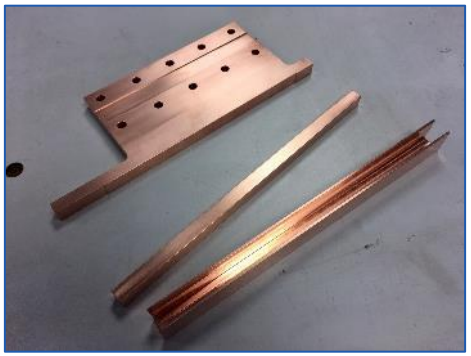
# Technology developments

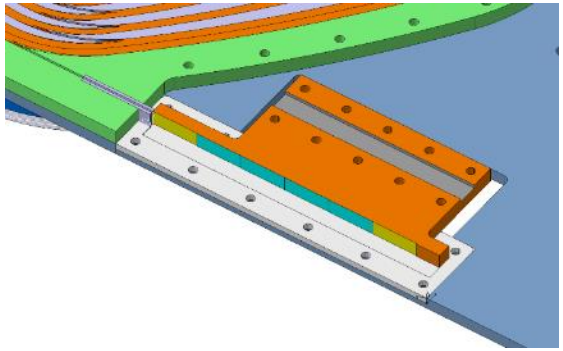
## Current joint

**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.



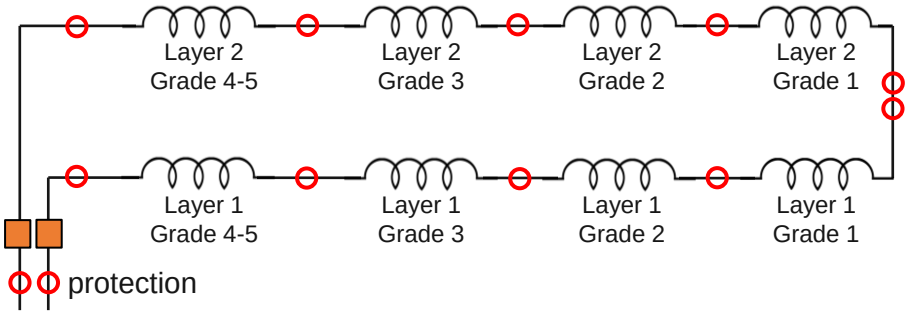


# Technology developments

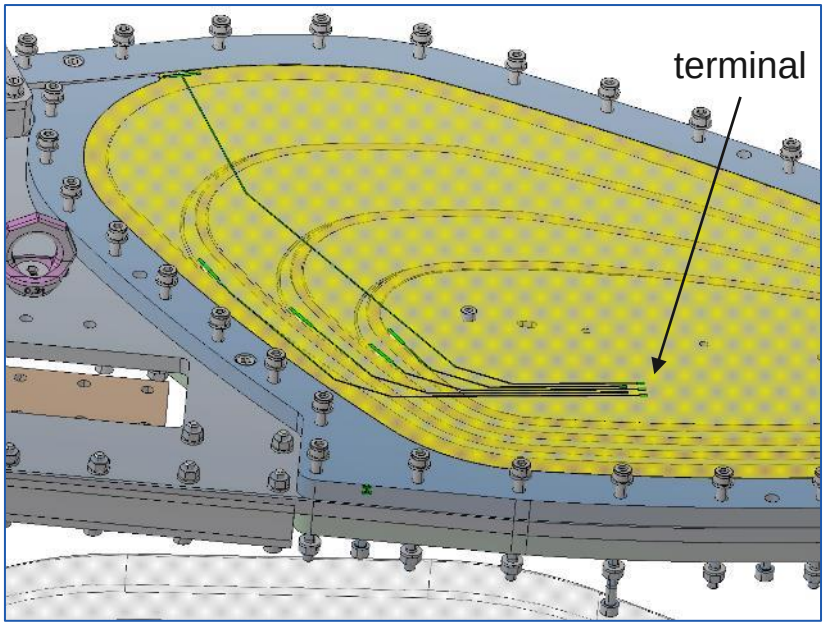
## Instrumentation

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.

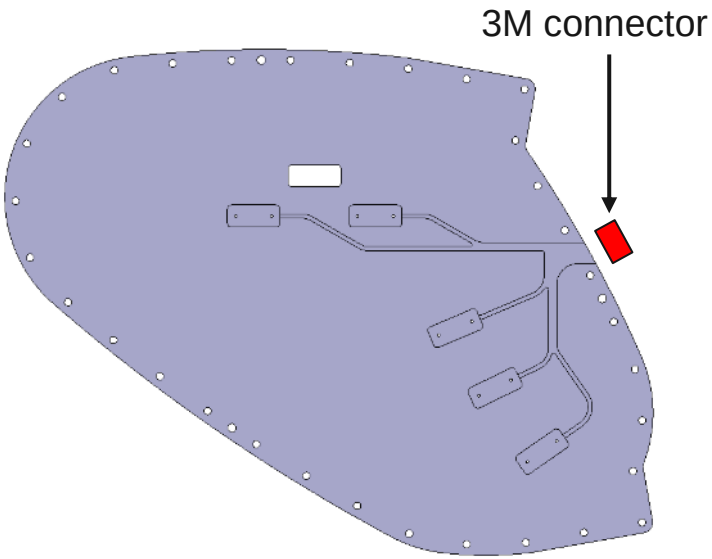
# Technology developments

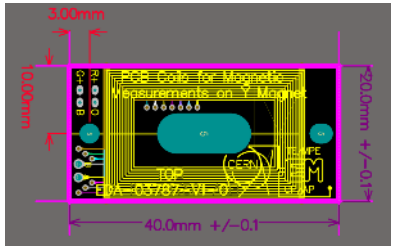
## Instrumentation

The magnetic instrumentation is composed on each side by:

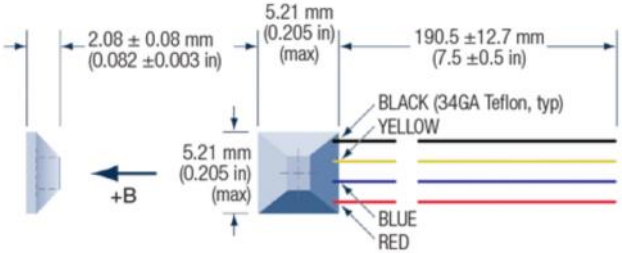
- 5 PCBs with pick-up coils
- 5 Hall probes glued on each PCB

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




PCB with pick-up coil

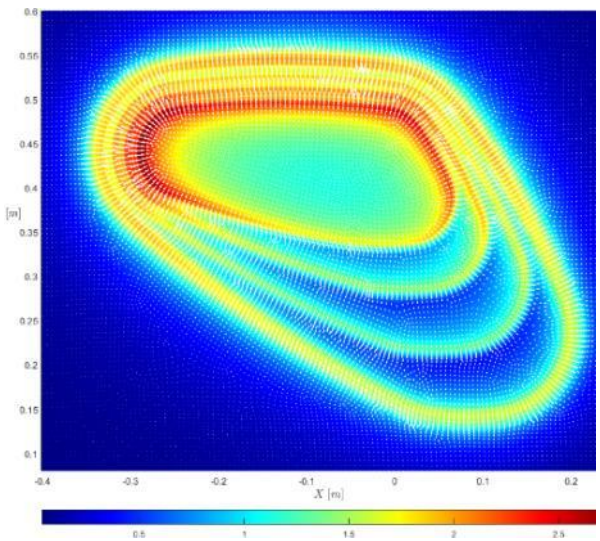



Hall probe

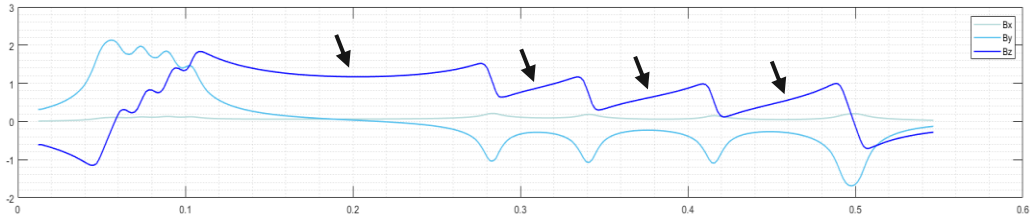
# Technology developments

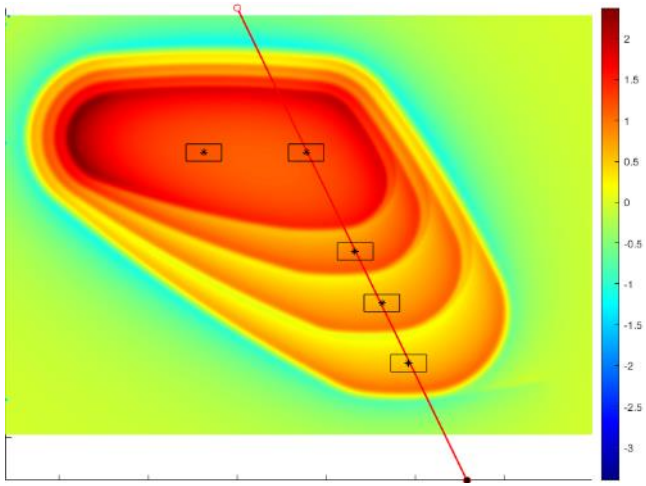
## Instrumentation

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

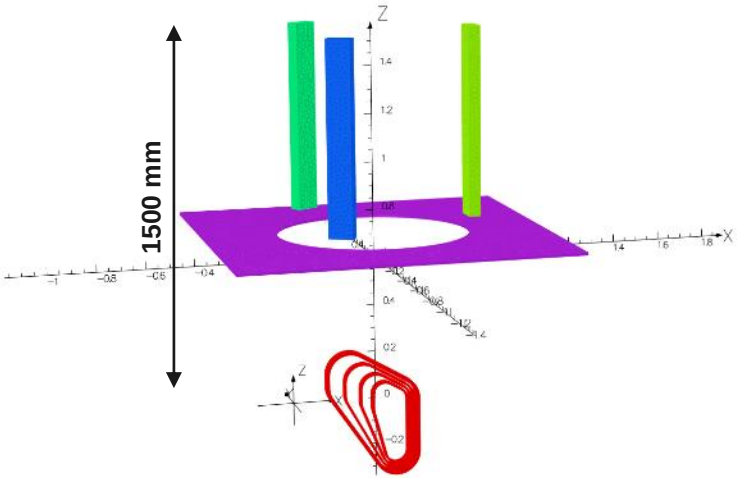
## Fixation in the diode cryostat SM18

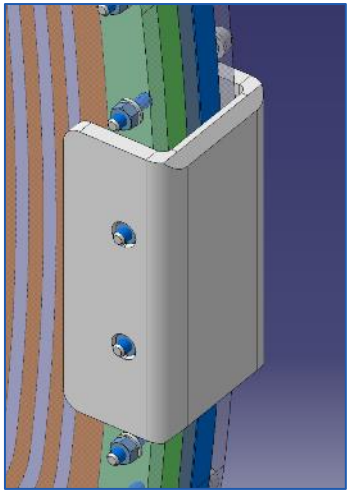
Tolerances in the cryostat are very small: 12 mm on each side.

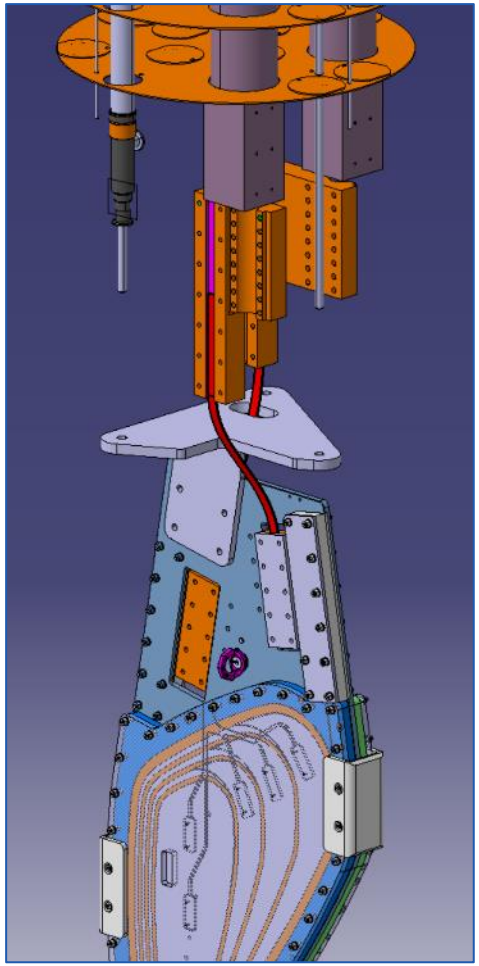
Teflon bumpers will help the positioning and avoid hard thermal links in case of contact.

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

Bus bar connections and current leads designs are in progress.



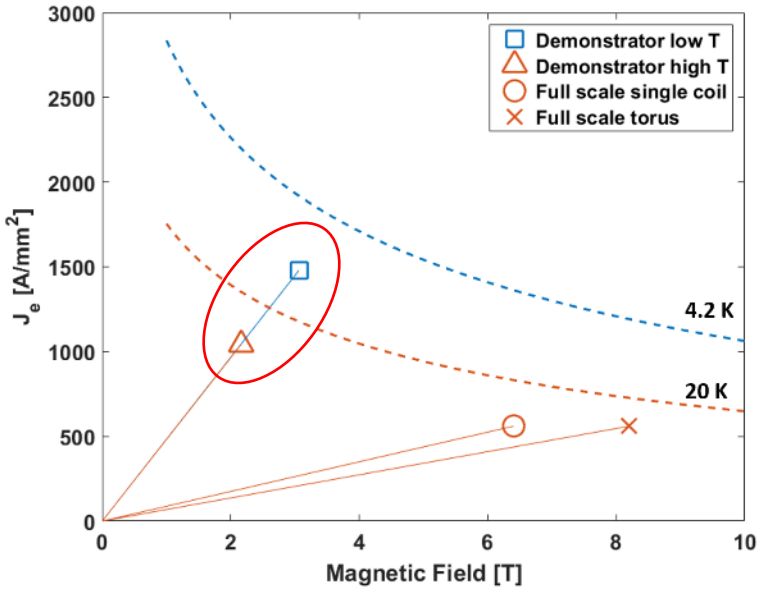


# GaToroid demonstrator

## Test objectives

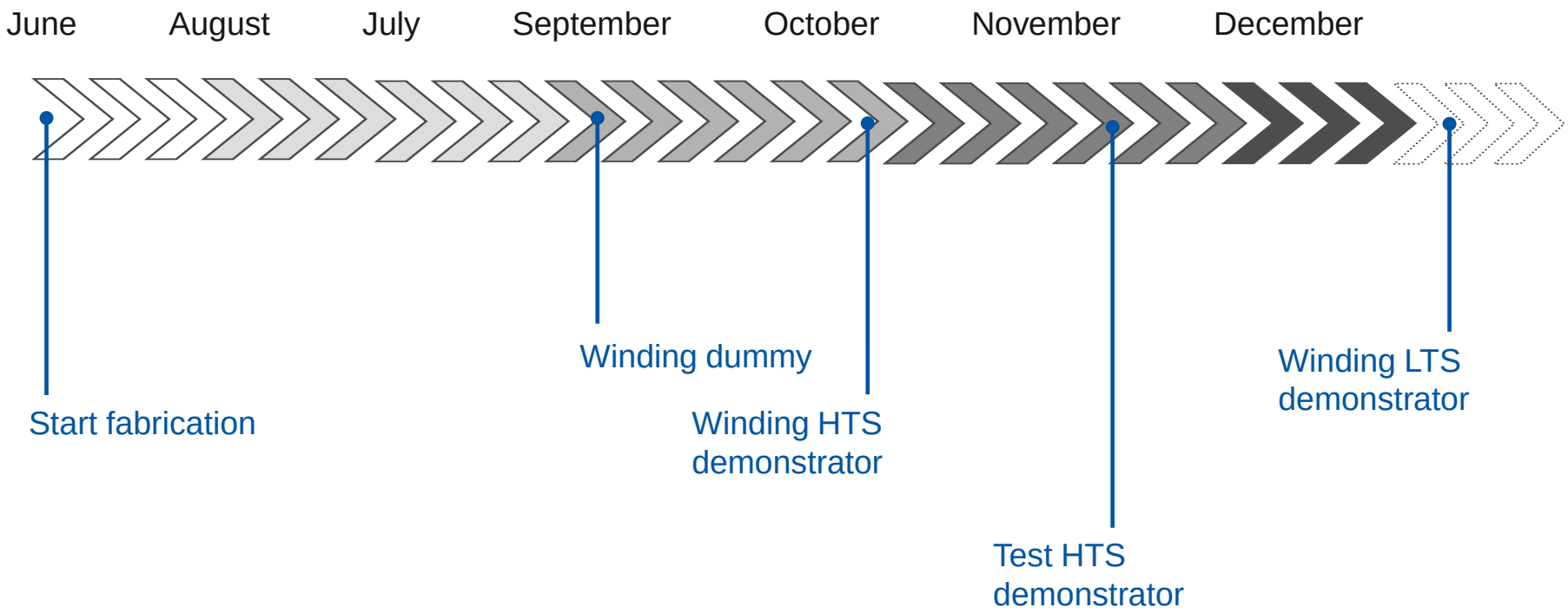
We would like to check:

- 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



# Outline

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

# GaToroid for C-ions

## Optics

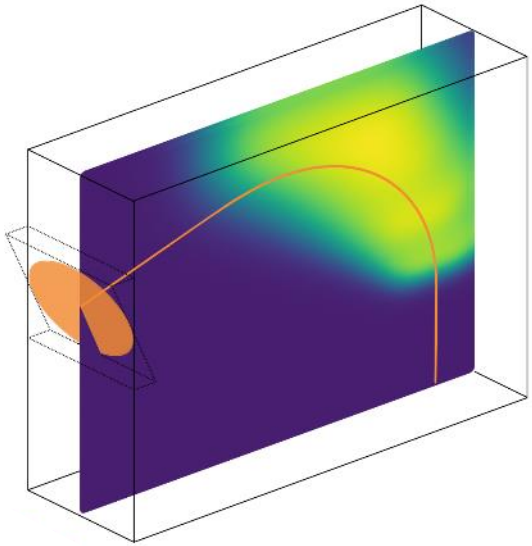
by Ewa Oponowicz and Yann Dutheil (SY-ABT-BTP)

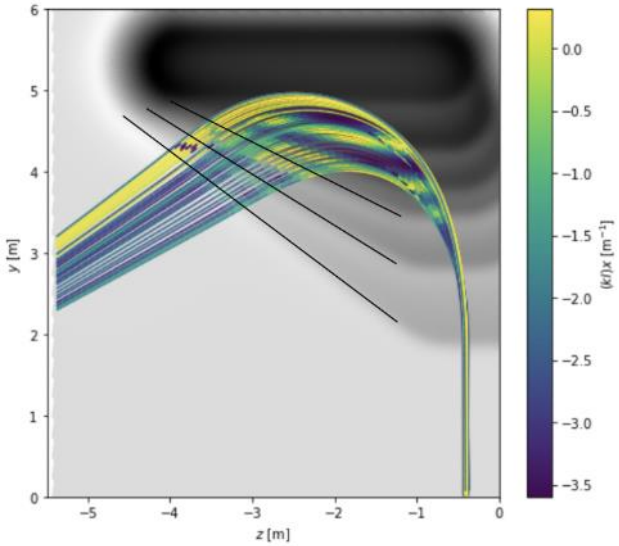
**Optimized the generated magnetic field and the beam line to provide the needed beam characteristics for clinical purpose.**

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.



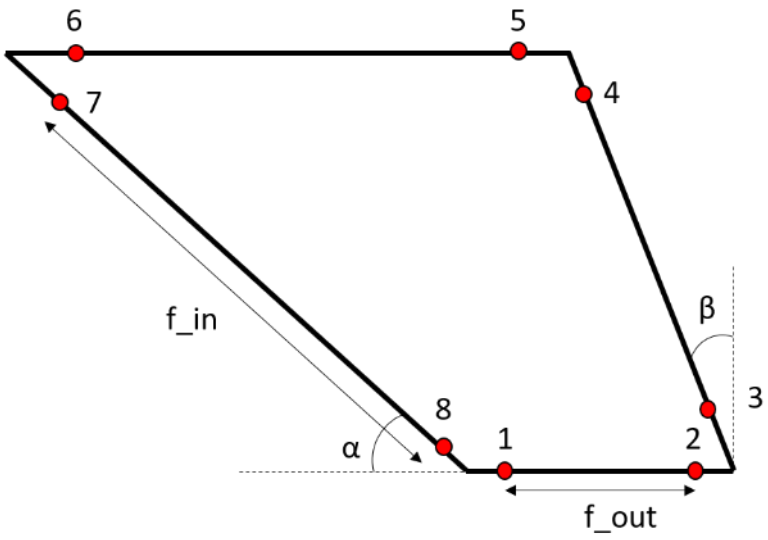


# GaToroid for C ions

## Parametric design

4 parameters to describe the coil:

| | |
|---|---|
| f_in | Length of the front side |
| f_out | Length of the exit side |
| α | Angle of the front side |
| β | Angle of the backside |



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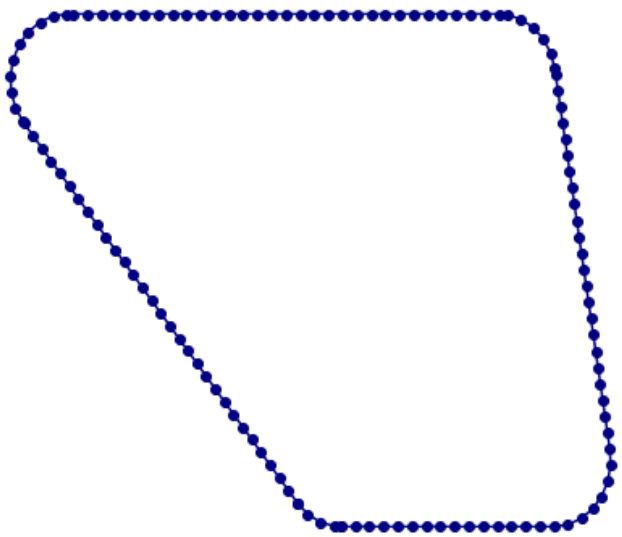

# GaToroid for C ions

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1 parameter to describe the grade:

| | |
|---|---|
| grade | Percentage of the total height |

# GaToroid for C ions

## Parametric design

4 parameters to describe the coil:

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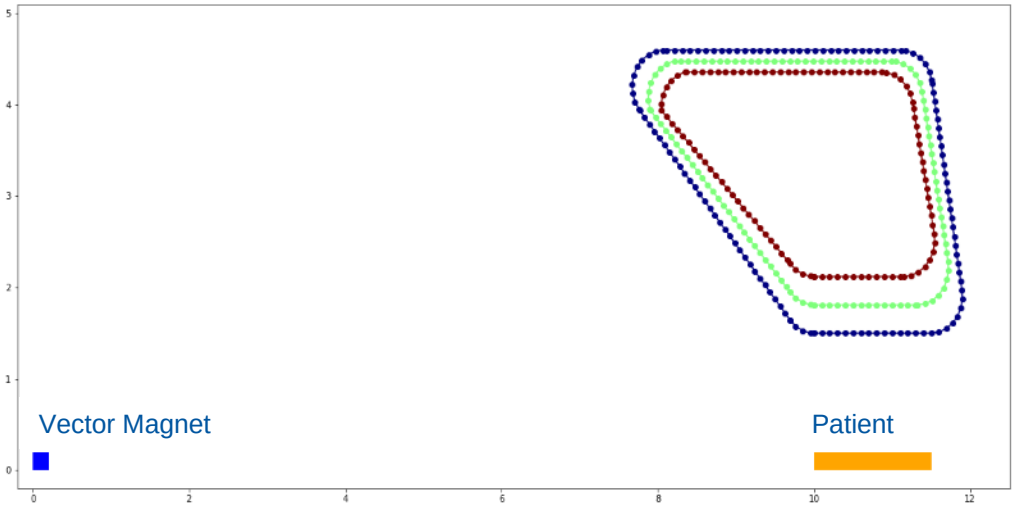
| α | Angle of the front side |
| β | Angle of the backside |

1 parameter to describe the grade:

| | |
|---|---|
| grade | Percentage of the total height |

2 parameters related to the Gantry:

| | |
|---|---|
| bore | Bore diameter |
| dist | distance to vector magnet |

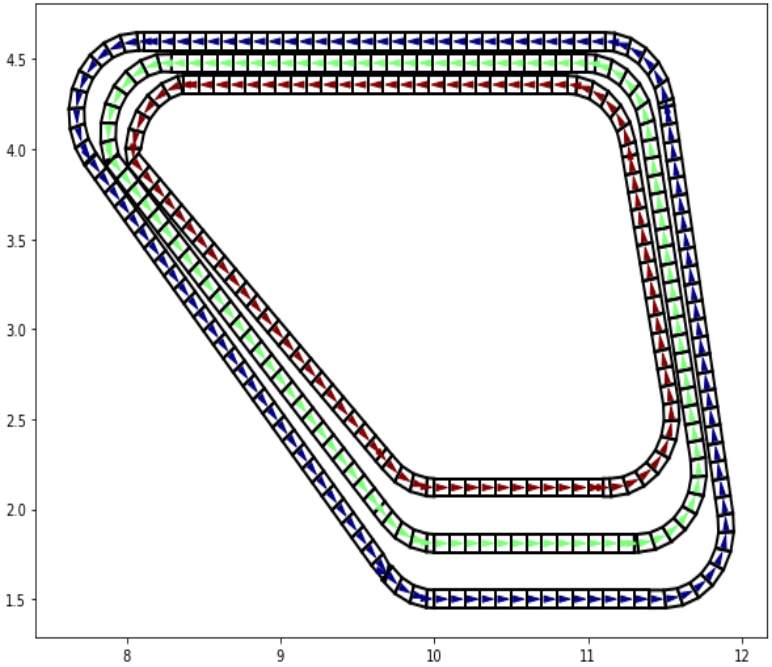


# GaToroid for C ions

## Parametric design

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

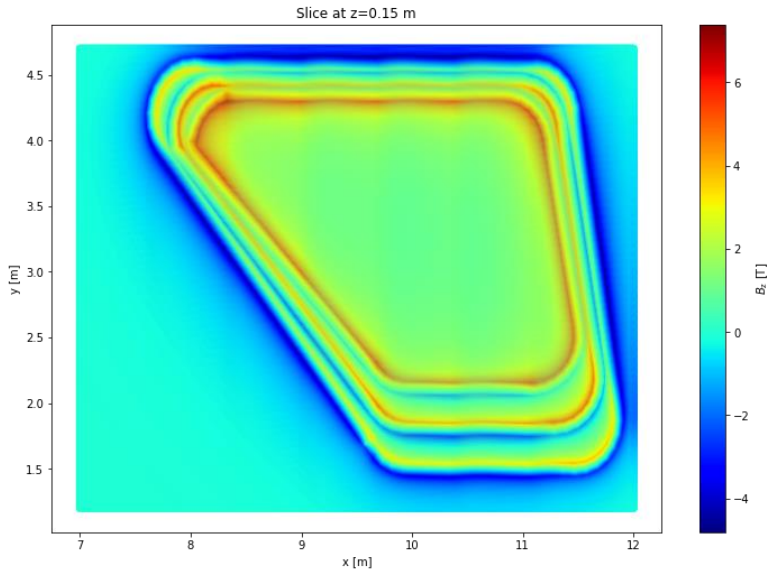
A current density and a direction is attached to each element.

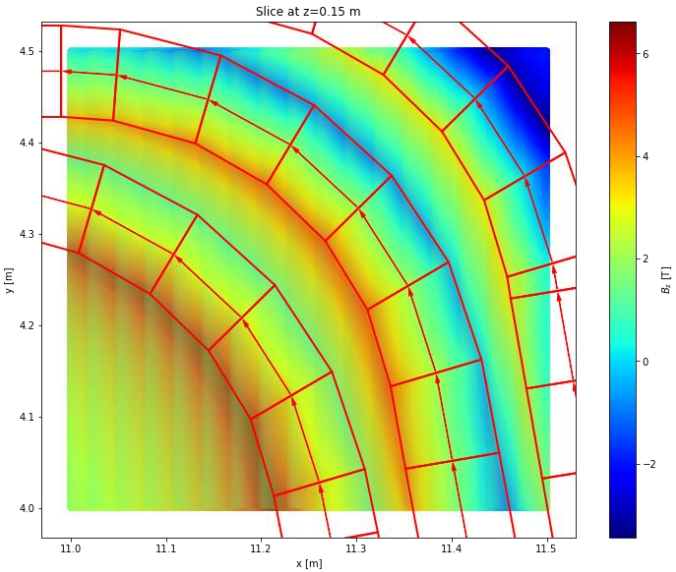


# GaToroid for C ions

## 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.

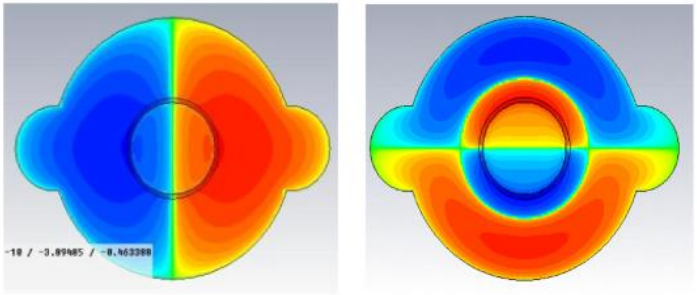
# Summary

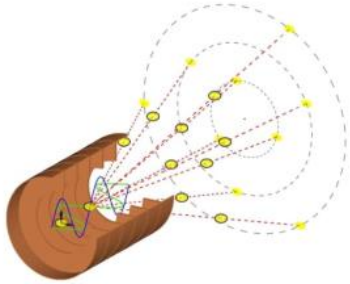
**Recently the use of GaToroid for FLASH therapy is being considered as there seems to be a huge potential in this domain.**

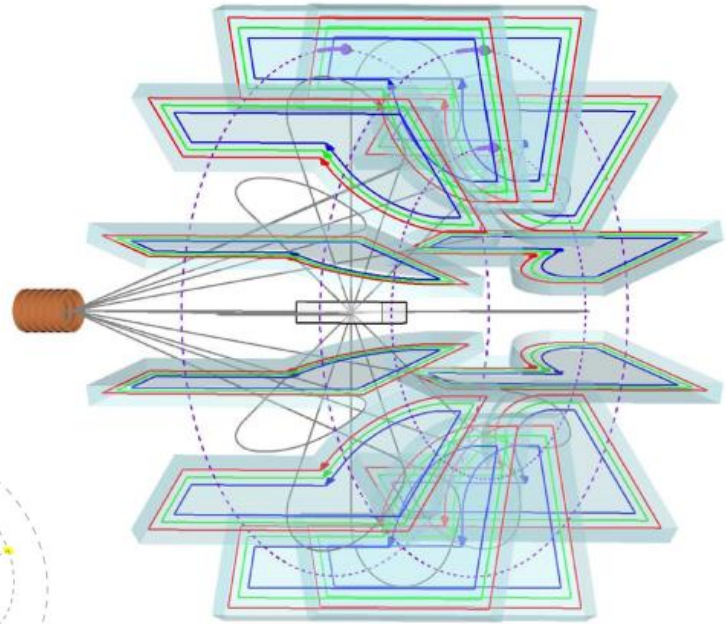
NUCL SCI TECH (2021) 32:34
https://doi.org/10.1007/s41365-021-00872-4

**Proton linac-based therapy facility for ultra-high dose rate (FLASH) treatment**

Wen-Cheng Fang[1,2] · Xiao-Xia Huang[1] · Jian-Hao Tan[1] · Chao-Peng Wang[3] · Cheng-Cheng Xiao[1] · Yi-Xing Lu[1,2,4] · Yu Zhang[1,2,4] · Yu-Qing Yang[1,2,4] · Yi-Ming Xu[1,2,4] · Han-Yu Gong[1,2,4] · Jun-Qiang Zhang[1] · Shao-Peng Zhong[1] · Zhen-Tang Zhao[1,2]







# GaToroid

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