Advances in the mechanical design and field quality of the GaToroid demonstrator magnet

Gianluca Vernassa (TECH) TE-MSC-SCD and EN-MME-EDS

TE-MSC Seminar, 15th July 2021

Outline

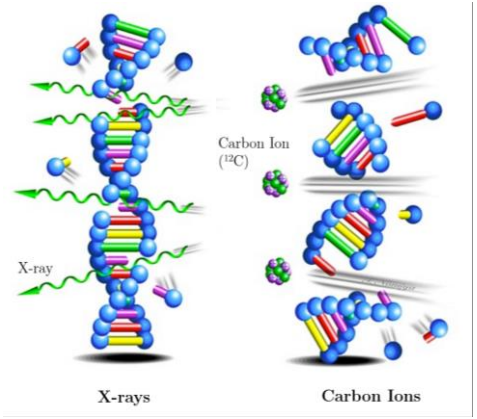
- Hadron Therapy and the GaToroid Project;
- The demonstrator magnet;
- Design process;
- Verification through FEA;
- Magnetic field;
- Instrumentation;
- Future perspectives.

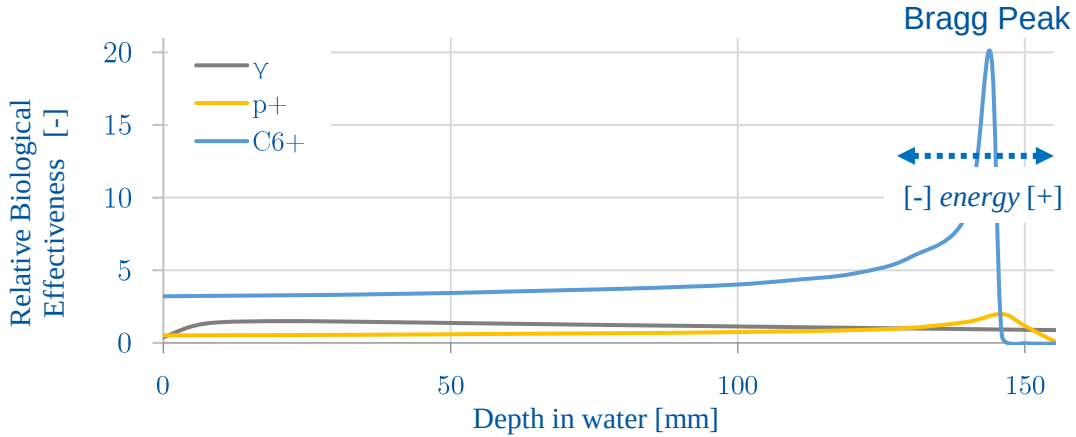
Outline

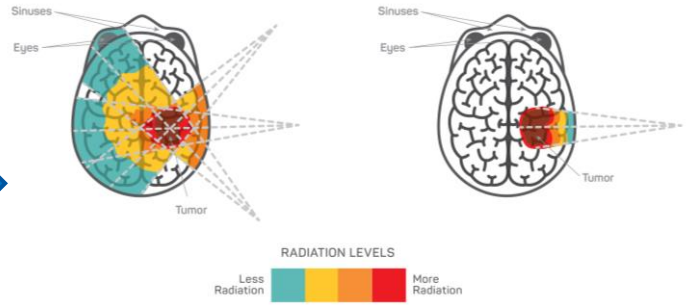
- Hadron Therapy and the GaToroid Project;
- The demonstrator magnet;
- Design process;
- Verification through FEA;
- Magnetic field;
- Instrumentation;
- Future perspectives.

Hadron Therapy in a nutshell

- Oncological treatment therapy to kill tumors using **hadrons** (**p⁺**, **C-ion**, n, *α*, O-ion, etc.)
- Nowadays a lot of interest around **heavy ions** (C, O, etc.) :
  1. More **localised** and **energetic** interactions
  2. Can **spare** healthy tissues from **parasitic doses**

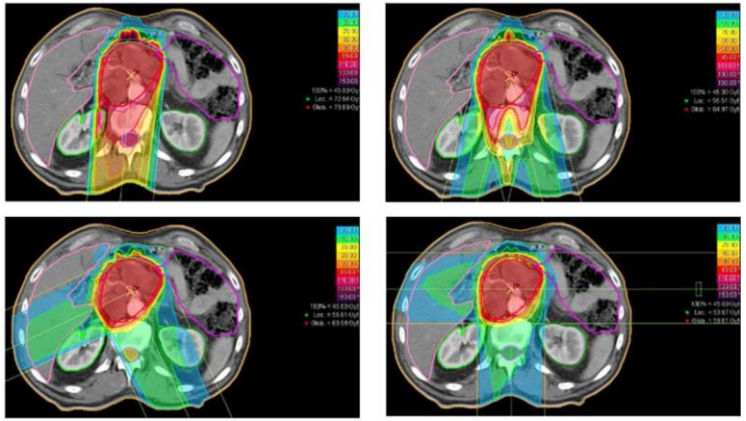


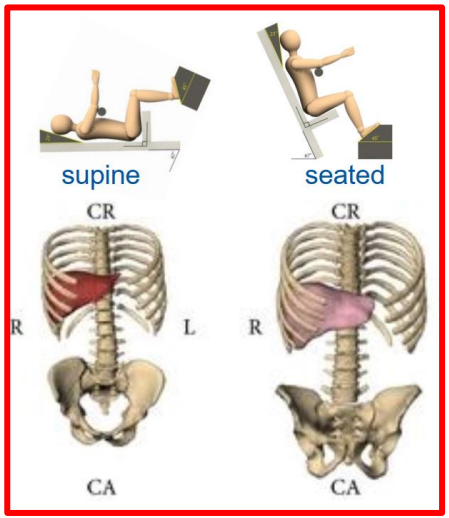




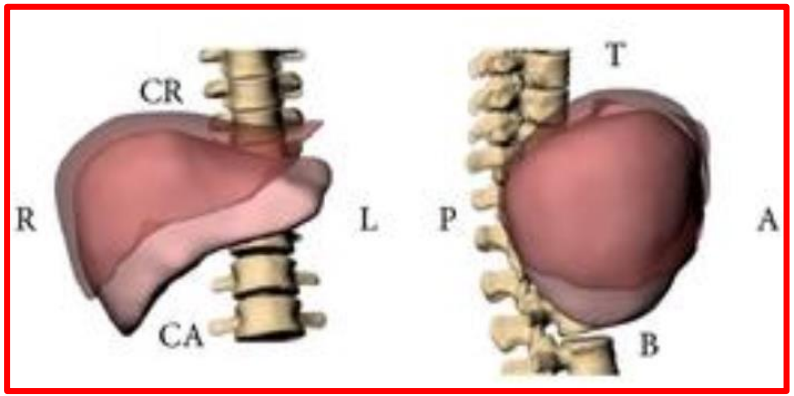
Hadron Therapy

- Even more benefits with **multiangled** therapy
- But the patient **shall not move!**





Up to 20 mm of relative displacements



Images: top-right: C.D. e Al. "Optimization of carbon ion treatment plans …" PLOS one, 2016
others: Computational and Mathematical Methods in Medicine, V. 2013, ID 419821

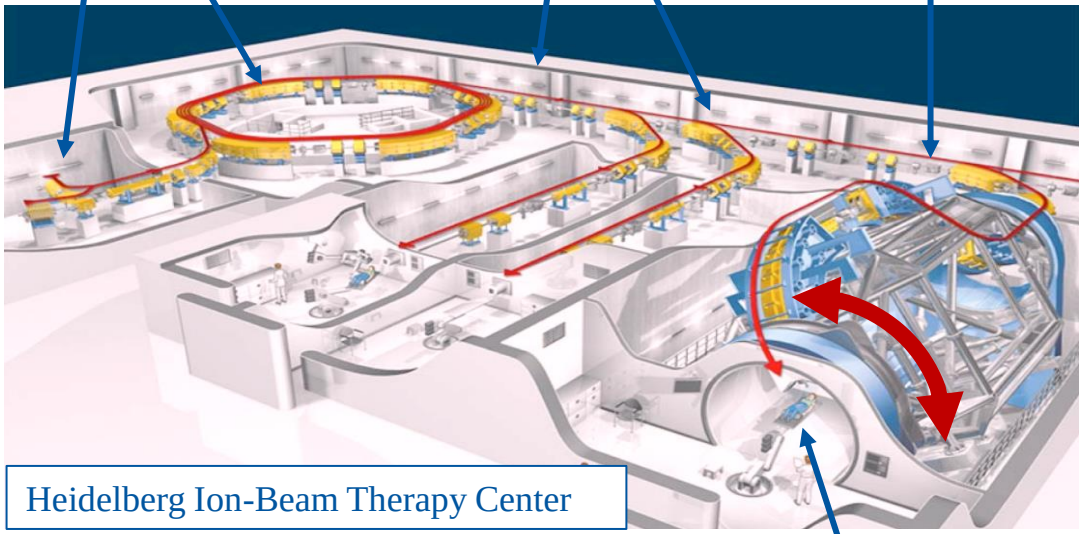
So, we want to deliver **heavy ions** …

… at various **energies** …

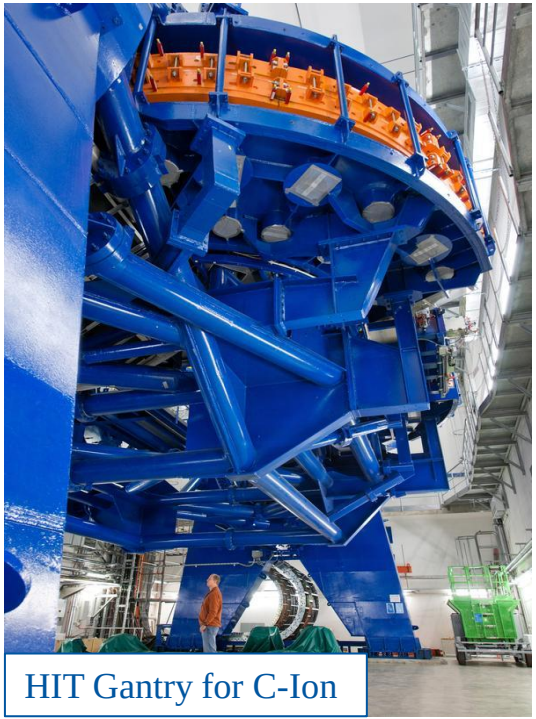
… from different **angles** …

How?

Technological aspects



Heidelberg Ion-Beam Therapy Center



HIT Gantry for C-Ion

Resistive magnets Peak field: 1.8 T
Length: 25 m Diameter: 13 m
Total weight ≈ 600 ton

Images: left: H.U, Hospital, "Heildelberg Ion Beam Therapy Center", Corporate Communication Office
right: "Medzin & Technik. Riesige Strahlenkanone Beschiesst Krebs", 5 November 2012

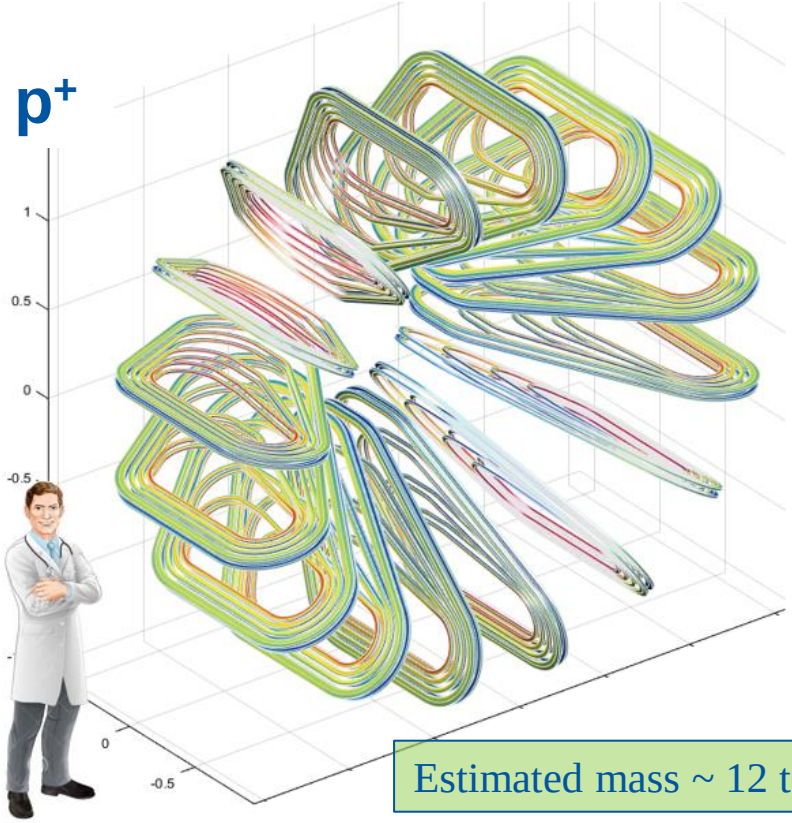
GaToroid project

toroidal
magnetic
field

vector
magnet

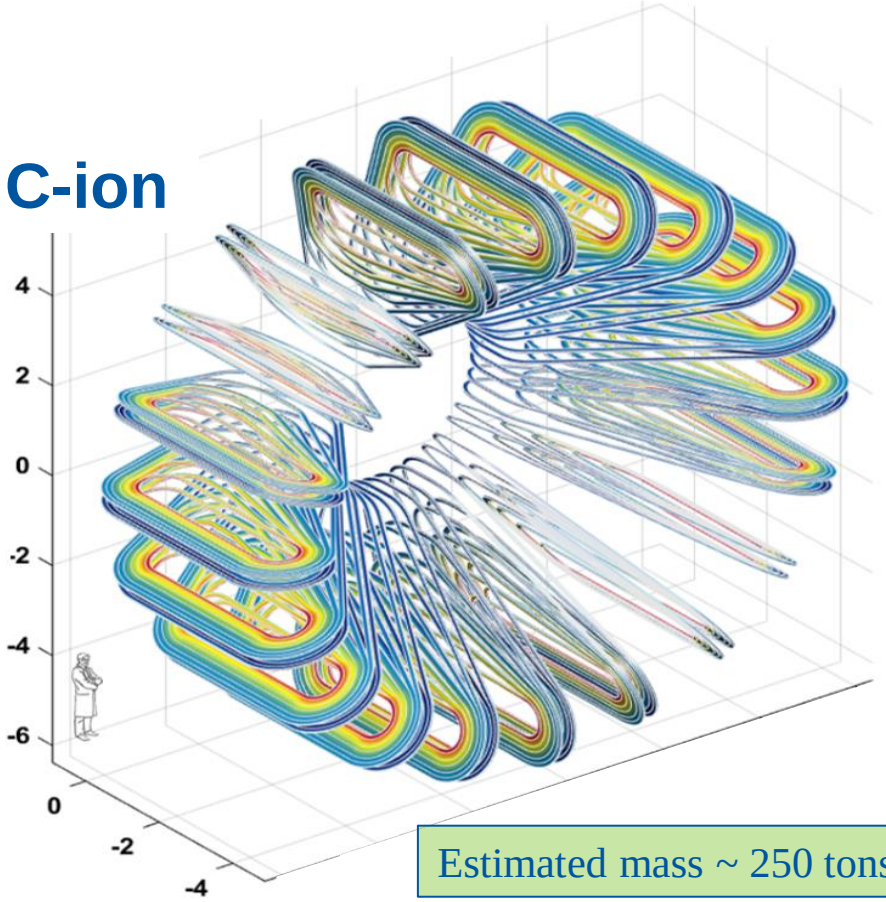
GaToroid idea

p⁺



Estimated mass ~ 12 tons

C-ion

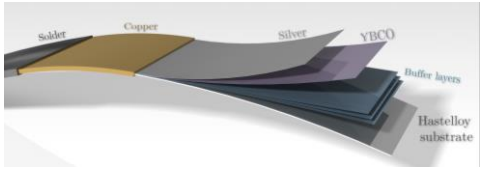


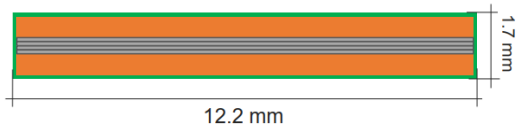
Estimated mass ~ 250 tons

Superconductors

HTS

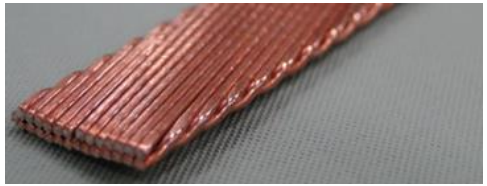
Superconductor	ReBCO
Topology	Non twisted stack
Number of HTS tape	4 (0.1 mm)
Number of Copper tape	2 (0.55 mm)
Cu:Sc ratio	5.3
Operating temperature	20 K

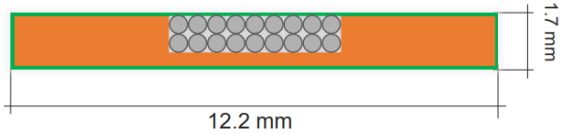




LTS

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



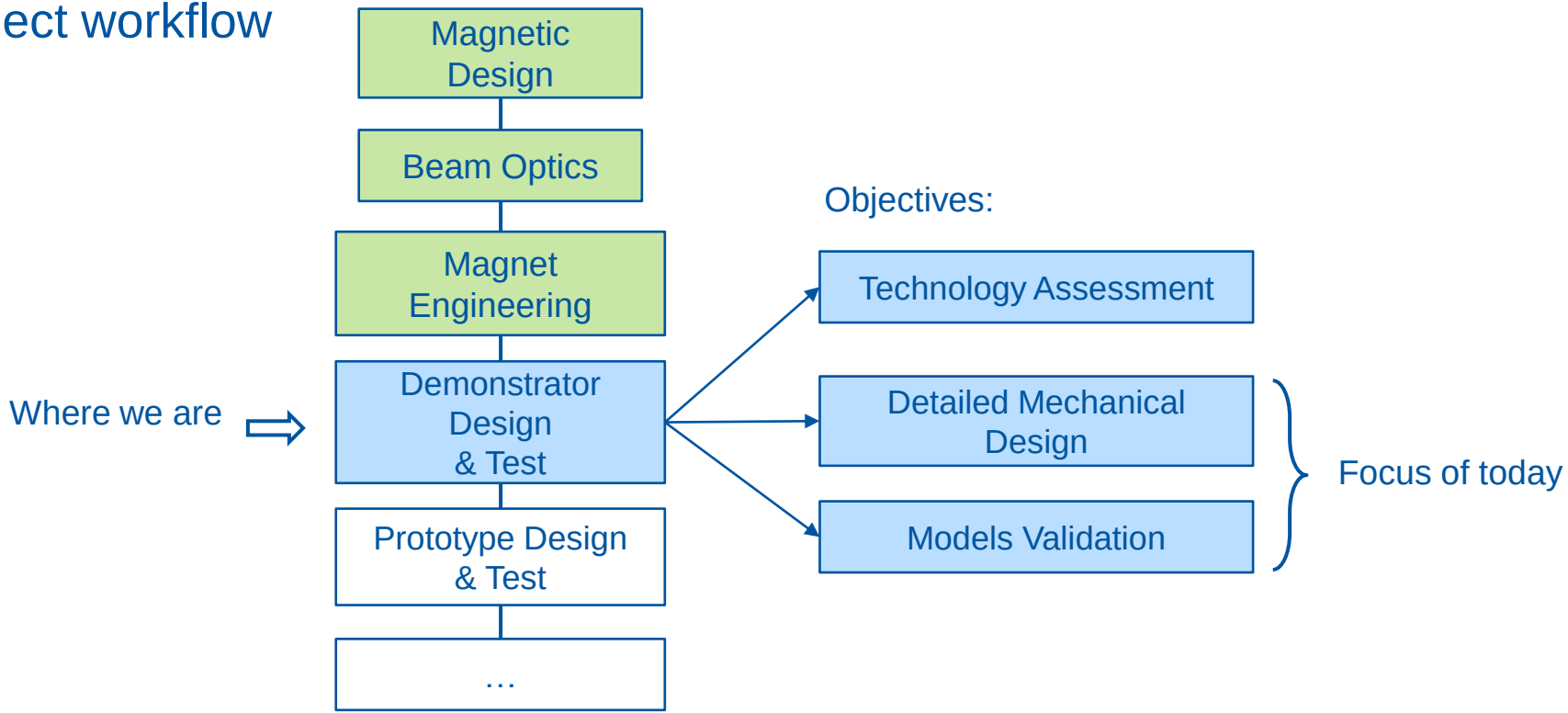


Copper
ReBCO Tapes
Insulation

Outline

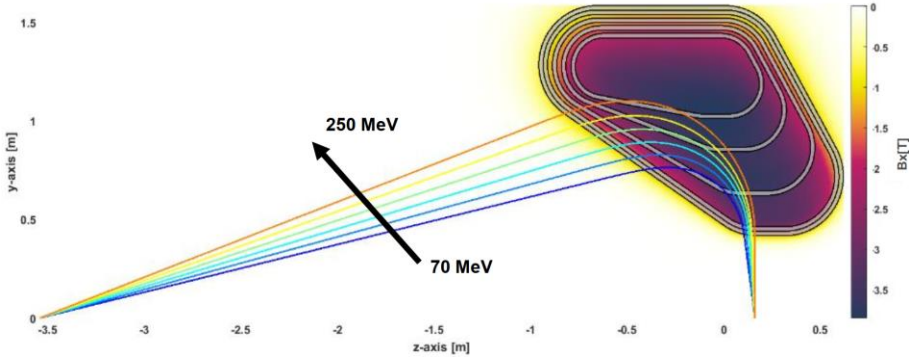
- Hadron Therapy and the GaToroid Project;
- The demonstrator magnet;
- Design process;
- Verification through FEA;
- Magnetic field;
- Instrumentation;
- Future perspectives.

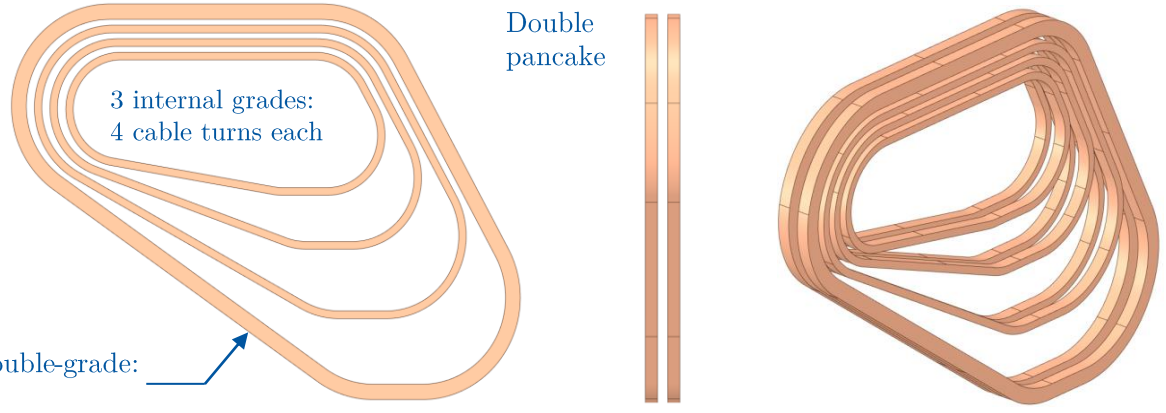
Project workflow



Demonstrator magnet

- Geometry: Coil of the **proton gantry** scaled down of a factor 3
- Baseline version meets **only field requirements**
- The goal now is to design a magnet whose geometry can be manufactured **both** in HTS and LTS versions.
- The design of the demonstrator should be representative of the full scale coil for the toroidal gantry.





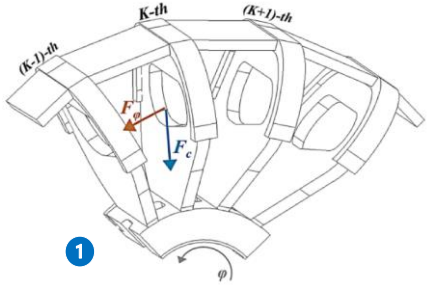
Detailed design

Requirements to be fulfilled moving from an ideal coil to the real one:

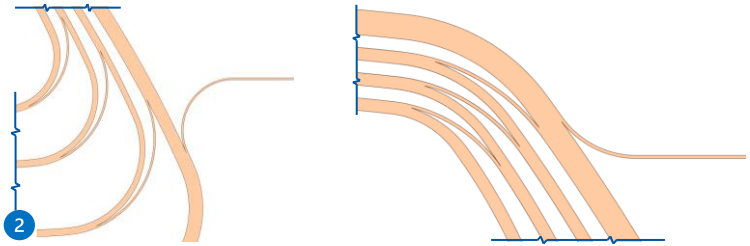
Structurally stable magnet 1

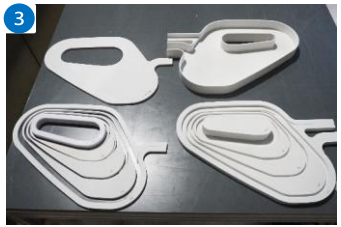
To be powered at cold 2

To be manufactured/assembled 3



1

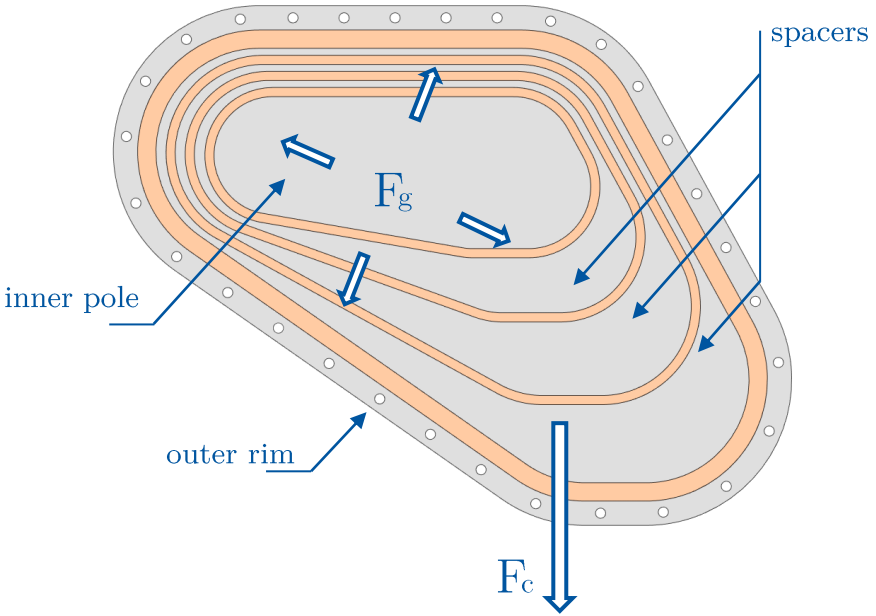

2

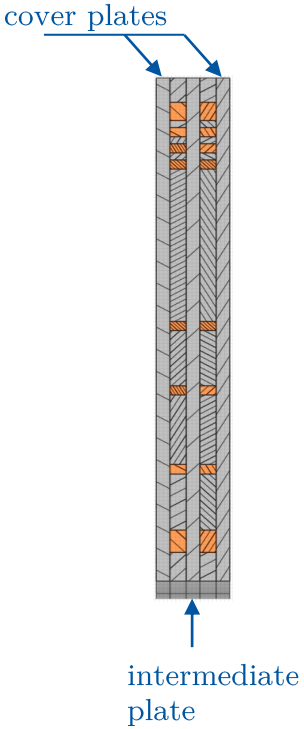

3

Outline

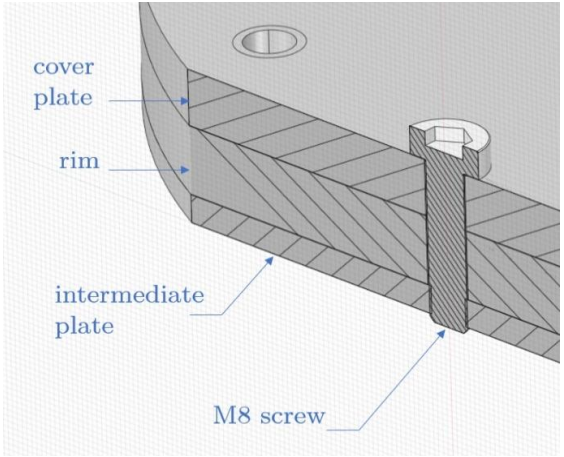
- Hadron Therapy and the GaToroid Project;
- The demonstrator magnet;
- Design process;
- Verification through FEA;
- Magnetic field;
- Instrumentation;
- Future perspectives.

Structural aspects: Casing





AISI 316 L - Stainless Steel



Fg: Operational forces acting on grades (always present)
Fc: Centering force on coils only when in **toroidal** configuration

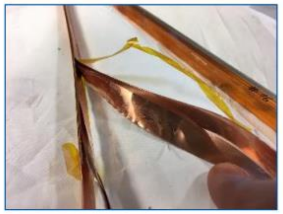
Materials selection for spacers

- Hypothesis: **Magnetic forces** tend to expand the coil, hence a **preload** could be benificial.
- Hence take advantage of the **cooldown phase** using materials with different CTEs' .
- Several combinations of materials have been tried (stainless steels, aluminium alloys, titanium) but the least dangerous is the one with only stainless steel (SS) components (**AISI 316L**).
- FEA's show that the stress state is **dominated** by the cooldown phase. Operational forces have minor effect.

- Stainless Steel then guarantees **minimal mismatch** of CTE with respect to the cables' material one.

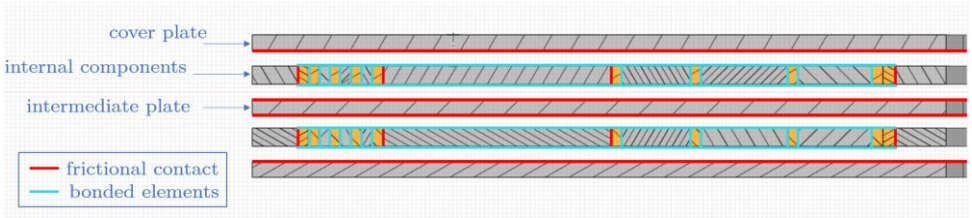
Impregnation

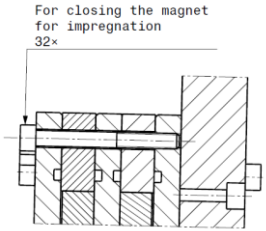
Stack samples			Glass fiber sleeve					Polymide C-shape		
			High compression		Low compression			Low compression		
			MY750	CTD101K	MY750	CTD101K	Mix61	MY750	CTD101K	Mix61
Peeling observations			Hard to peel. A fair continuous pull is necessary	Easy to peel after a first crack	Hard to peel. A fair continuous 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 polyimide 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

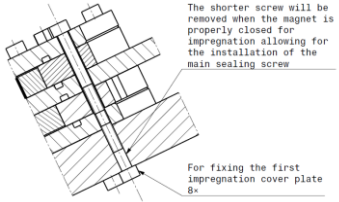


Brings to a **monolithic** structure, **preventing** reciprocal **movements** of components.
Two **consequences** on the design:

- **Details** in the magnet casing for it to be used as impregnation mould;
- Clear definition of the **behavior** of components **at interfaces** (relevant for FEA*).



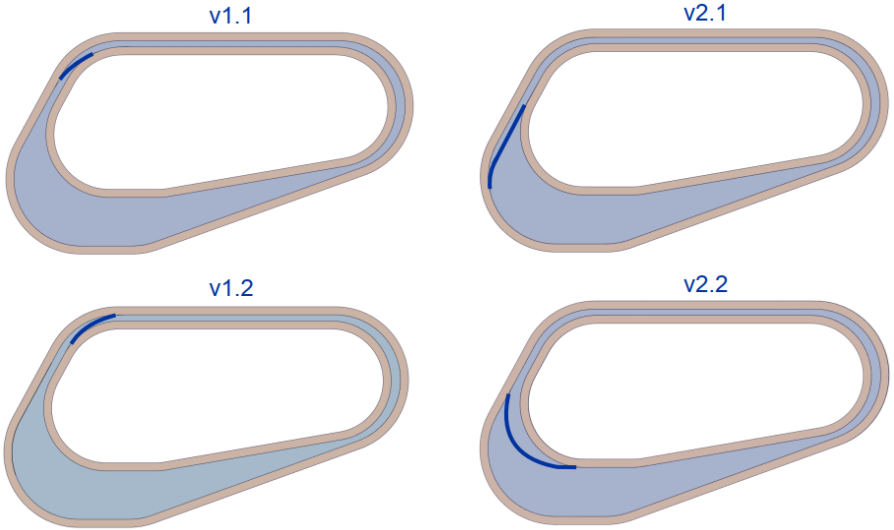


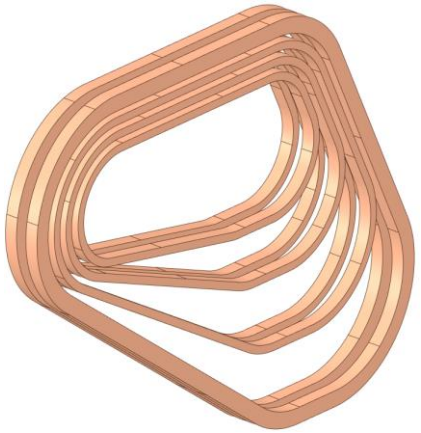


*Surface contact properties (μ) from experimental tests' results – courtesy of G. Spigo

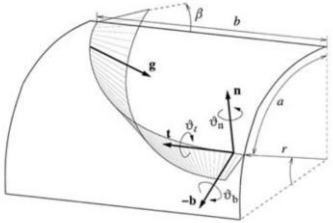
Operational aspects

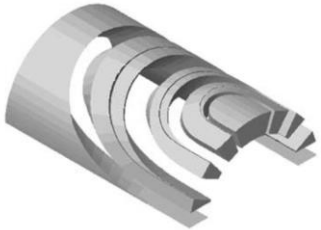
- Need for **electrical connection** to the power source;
- Electrical continuity between layers: **layer jump**;
- Electrical continuity between grades*: **grade jumps**;





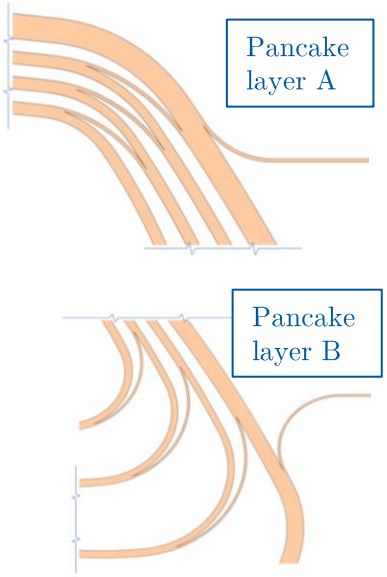
$$E = \frac{1}{2}\int_0^{s_c} \left(f_\tau\,\tau(s)^2 + f_{\kappa_n}\,\kappa_n(s)^2 + f_{\kappa_g}\,\kappa_g(s)^2\right) \mathrm{d}s$$





* Concepts developed and studied by J. Harray, T. Lehtinen, E. Felcini, et al.

Grade and layer jumps

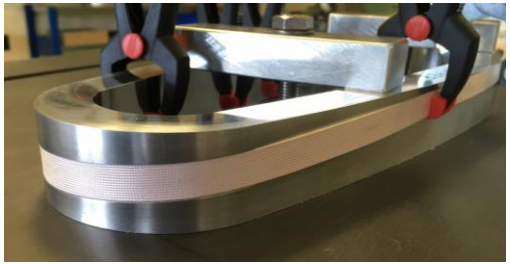


Jumps between grades and pancacke layers **perturbate** the magnetic field map in two ways:

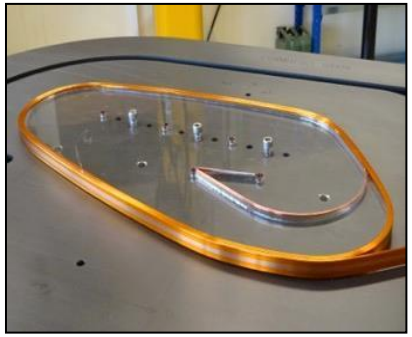
1. Contribution due to the current flowing inside the conductor itself;
2. Local reduction of the number of cable turns in grades.

Minimal field variations and beam delivery properties close to nominal are granted if the jumps' **length** is **minimized**, and if these happen in the "**back**" of the magnet.

Regarding the layer jump, added complexity due to hard-way **bending** of the cable. Multiple options proposed and **manual tests** carried to find the easier and more robust solution.



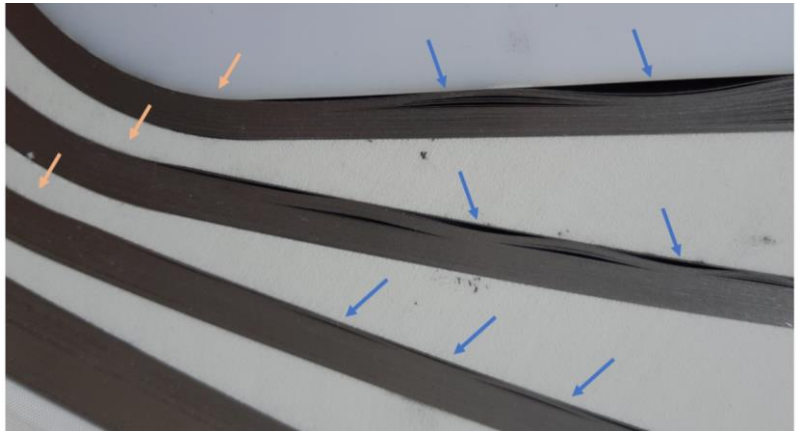
Manufacturing aspects



- “Dummy” windings with Cu or SS strips
- Winding tension to apply initial tension of ≈ 2 MPa to the cables
- “**Snaking**” effect noticed (blue arrows) →

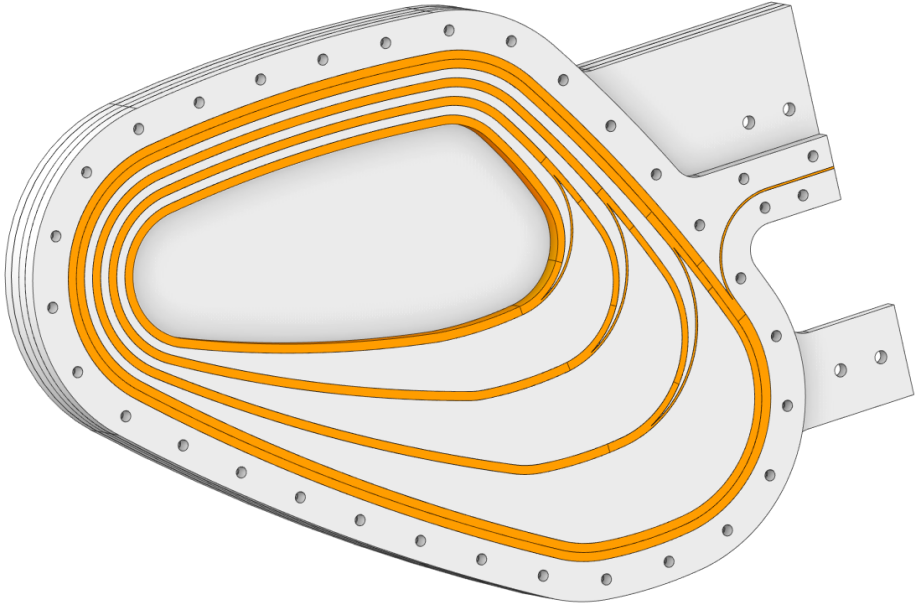
  - possible cause: too rapid transition from circular sectors to the straight ones

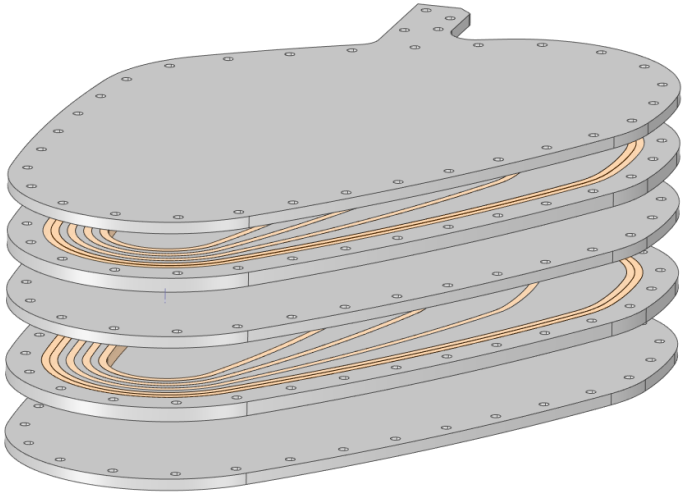
  - possible solution: change grades shape, and use **large radius arcs**



Tangency maintained and less abrupt **curvature** variation. **Convexity** of the grade ensures constant contact with underlying spacers.

Baseline geometry for FEA



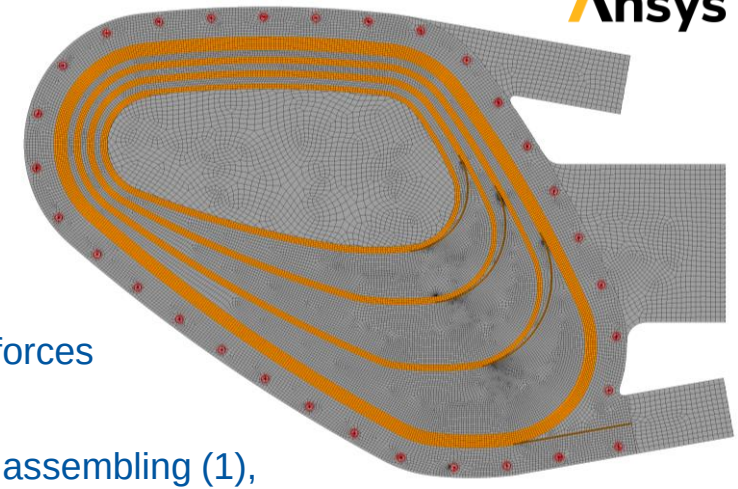


Geometries prepared for FEA in SPACECLAIM

Outline

- Hadron Therapy and the GaToroid Project;
- The demonstrator magnet;
- Design process;
- Verification through FEA;
- Magnetic field;
- Instrumentation;
- Future perspectives.

FEA: approach



3D Finite Element Analyses using Ansys APDL.

Three steps analyses:

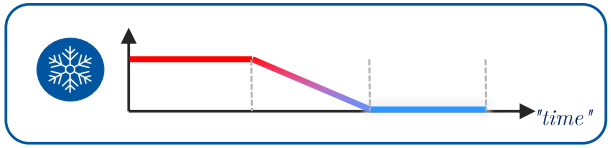
1. **Electric**: to find the current density distribution inside the coils;
2. **Magnetostatic**: to compute the field and retrieve the forces acting on the conductor;
3. **Thermomechanical**: to assess the stress state after assembling (1), cooling (2) and powering (3).

Elements ~ 500 000 (second order)
Runtime ~ 48 h per model

Geometric non-linearities;
Non-linear **boundary conditions**;
Symmetry modeling

1. Bolts' pretension to 13.3 kN

2. Cryogenic cool down to 4.2 K



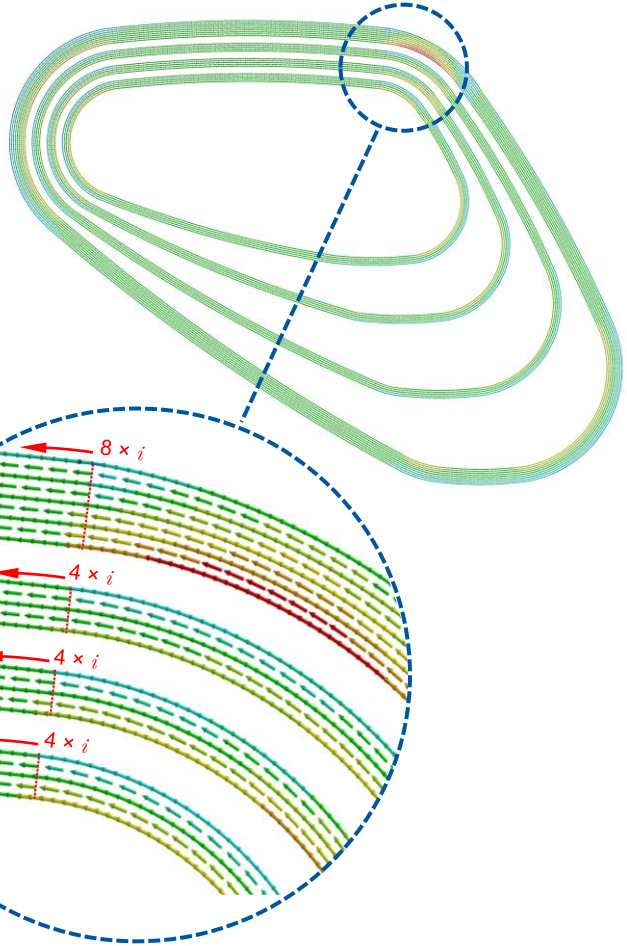
3. Magnetic (Lorentz) forces

Electric analysis

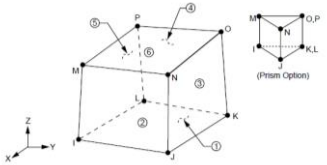
Fairly simple geometry, but direct assignment of current densities ($\mathbf{J}_i$) requires definition of local coordinate system for each arc (or even element).

Electric (stationary) analysis instead allows for a quick determination of the current densities also for **complex shapes**.

- Definition of a cross section where elements are not to be connected (i.e. different nodes existing at same location);
- Coupling the DOFs for nodes relying on the same cross-section;
- Application of boundary conditions (i and V).



Ansys Element*: SOLID5
DOF: Volt



Magnetostatic analysis

Subsequently $\mathbf{J}_i$ are used as input for computing the magnetic field.

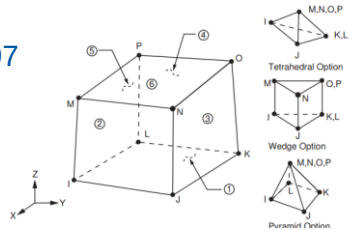
Ansys Element SOLID97* uses a differential formulation in terms of magnetic vector potential $\mathbf{A}$.

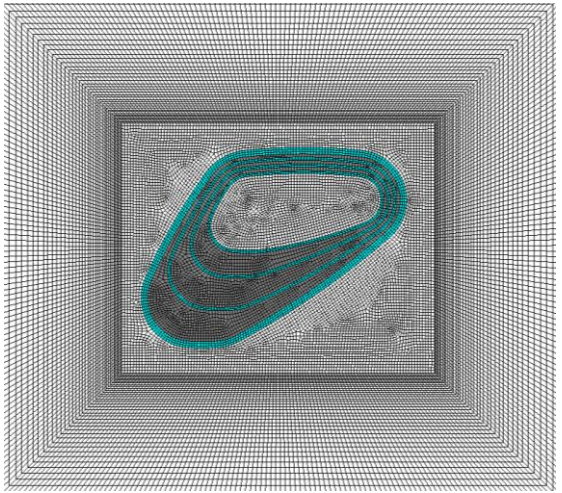
Allows for extraction of **magnetic forces** but is also subjected to approximations and differentiation errors.

Only one pancake layer is modelled, with **symmetry** boundary conditions on the middle plane.

Ansys Element*: SOLID97
DOF: Ax, Ay, Az

$$\mathbf{B} = \nabla \times \mathbf{A}$$

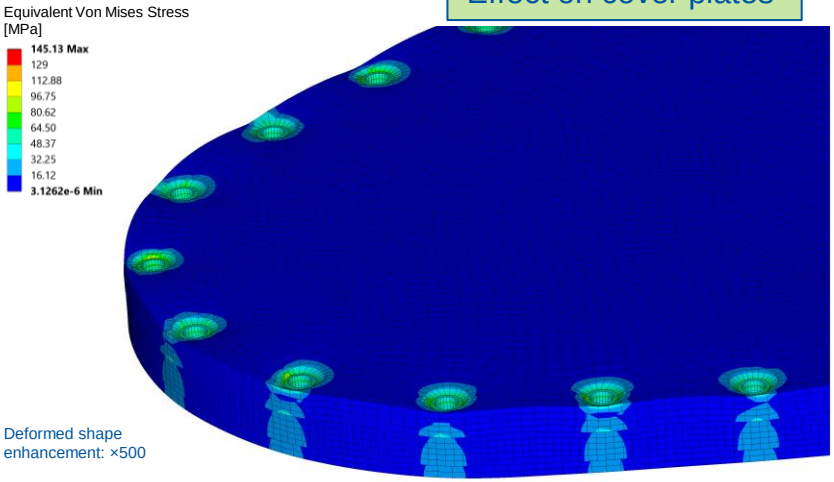




Mechanical Analyses: Bolts' pretension

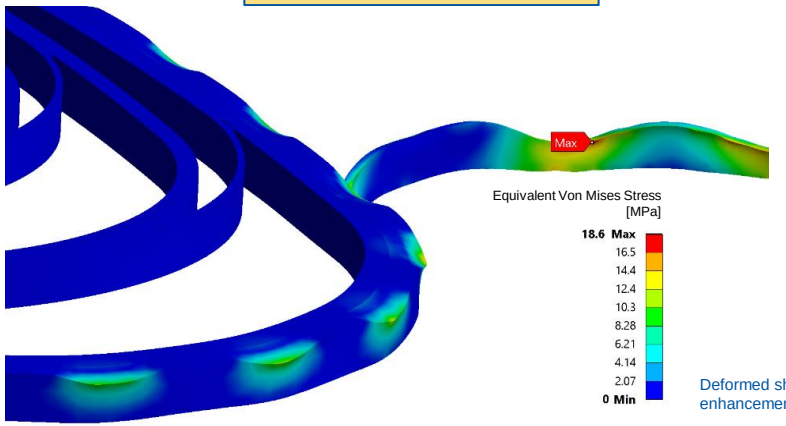
Preliminary bolted joint dimensioning according to VDI 2230 and ISO 3505.
Preload of 13.3 kN

Effect on cover plates



Deformed shape
enhancement: ×500

Effect on windings



Deformed shape
enhancement: ×1000

Suggestion:

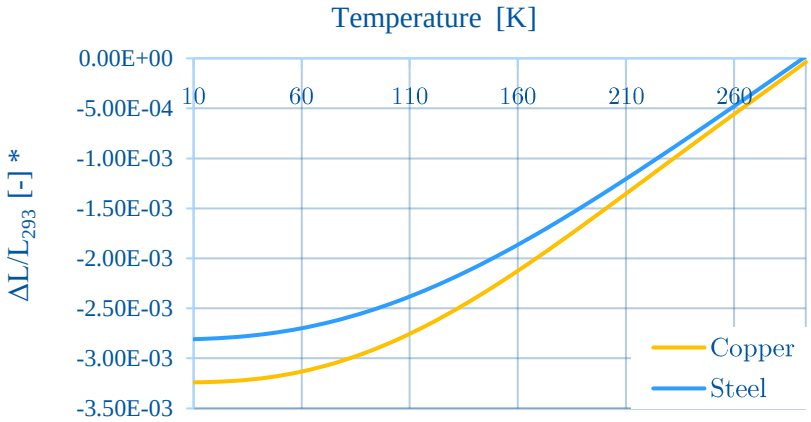
PTFE (Teflon) or MoS_2 (molykote) **coating** on steel components to prevent **frictional stresses** at the interface.

Mechanics: Cryogenic cooldown

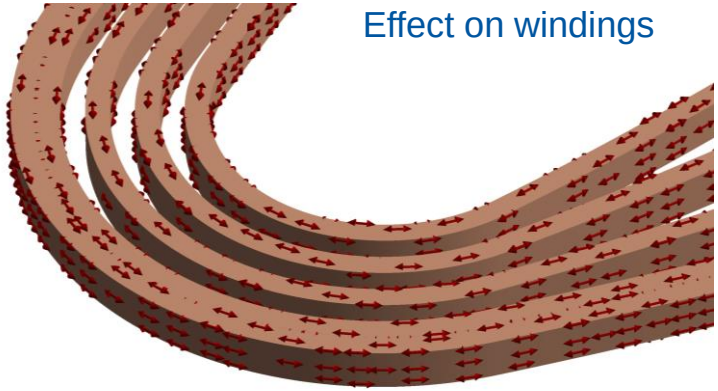
Stresses develop due to **CTE differences**:

CTE_{SS}	=	$9.9 \times 10^{-6}\ K^{-1}$
CTE_{cables}	=	$11 \times 10^{-6}\ K^{-1}$

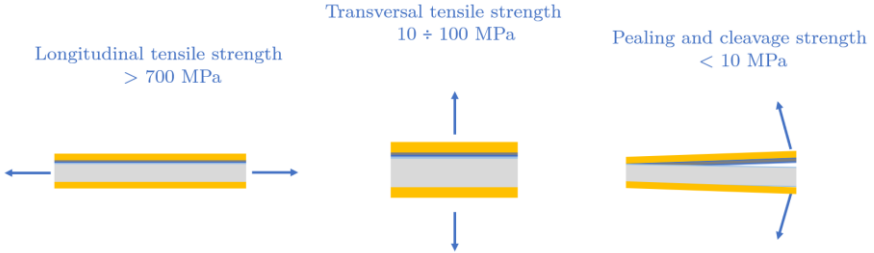
Values refer to integrated CTEs.



Effect on windings



ReBCO tapes (**laminated**) strength characteristics



*Thermoelasic properties from EuCARD² - Thermal Contraction Data – Glyn Kirby et Al.

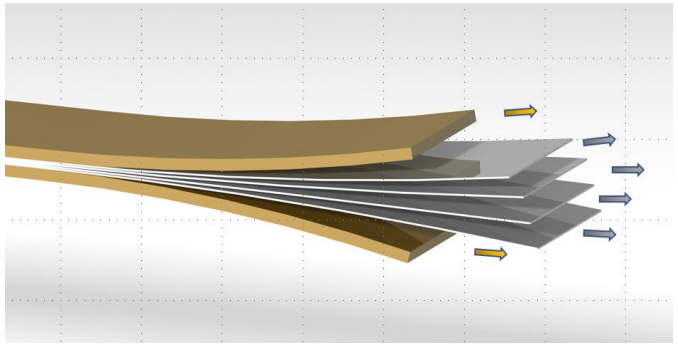
Mechanics: material model

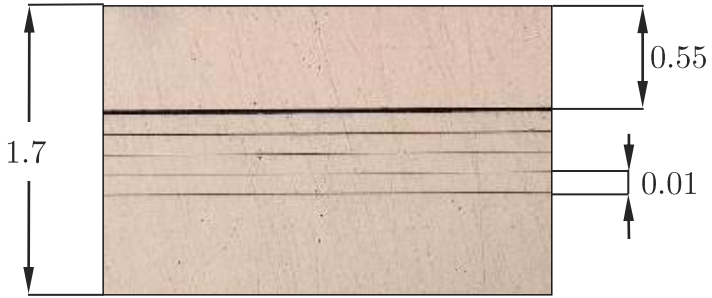
While experimental tests on cable stack are being prepared, an **isotropic** material model has been adopted.

- The preliminary stress state assessment shows that the **principal stress** directions are **longitudinal** to the cables.
- In this case ReBCO tapes and copper strips act as a **parallel** of "springs".
- **Rule of mixtures** can be used to average the elastic properties depending on phases' **fractions** (x_i) in a cross-section:

$$\mathrm{E_{tape}} = \mathrm{E_{t/}} \cdot\ x_{\mathrm{t/}} + \ \mathrm{E_{Cu}} \cdot x_{\mathrm{Cu}} \quad ;$$

$$\mathrm{E_{cable}} = \mathrm{E_{tape}} \cdot\ x_{\mathrm{tape}} + \ \mathrm{E_{st}} \cdot x_{\mathrm{st}} = 135.6\ \mathrm{GPa}$$



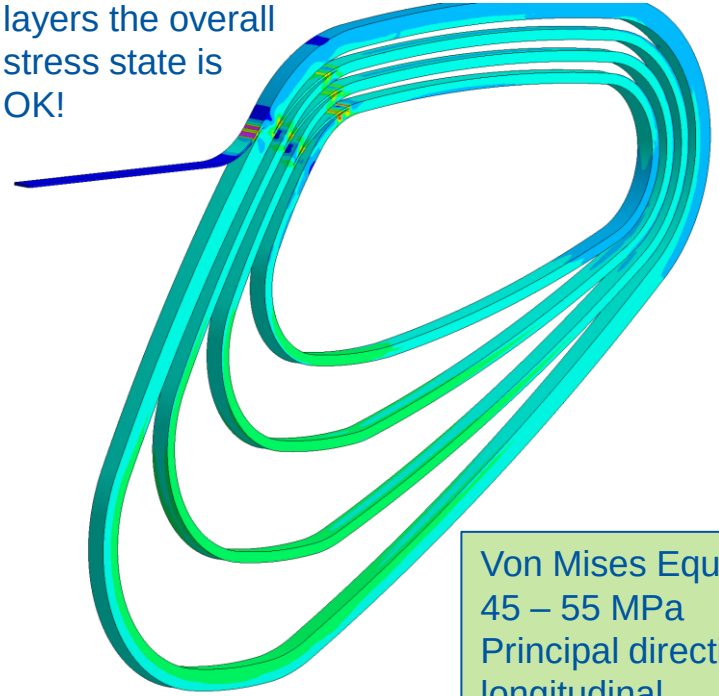


$\mathrm{E_{tape}}$: Young Modulus of ReBCO tapes; $\mathrm{E_{sb}}$: Y. M. of Hastelloy substrate;
$\mathrm{E_{Cu}}$: Y. M. of copper stabilizer in tapes; $\mathrm{E_{st}}$: Y. M. of copper stabilizer in cables.

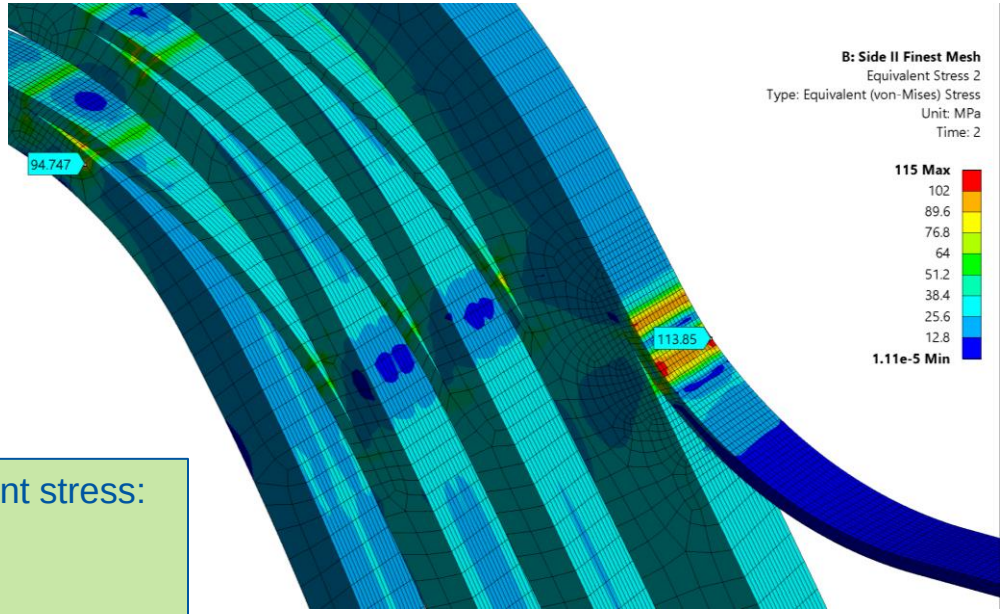
Fractions x_i follow the same logic.

Cryogenic cooldown

For both pancake layers the overall stress state is OK!



But stress peaks on one side!

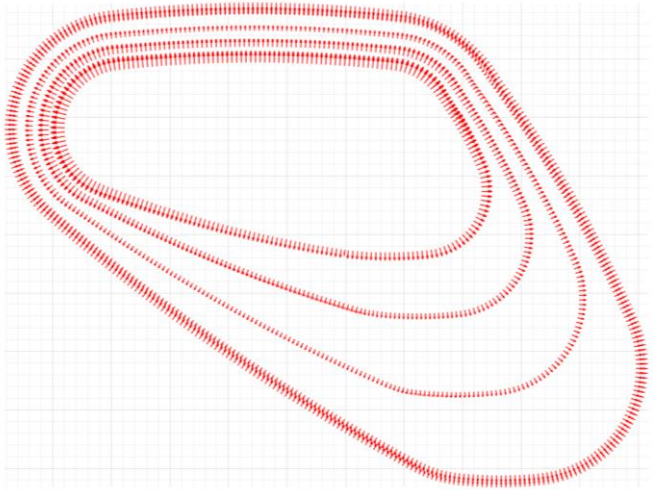


Von Mises Equivalent stress:
45 – 55 MPa
Principal direction:
longitudinal

Lorentz forces

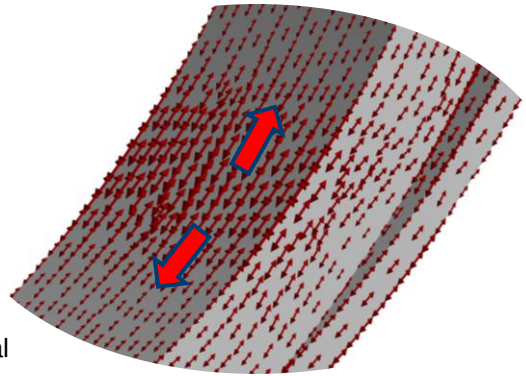
Minor effects of Lorentz forces.

Tend to expand the coil
→
longitudinal stresses



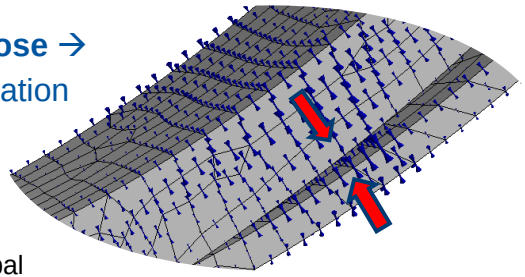
Von Mises Equivalent stress increments of 5 – 20 MPa
Mean value inside windings: **60 MPa**

Maximum principal **stress direction** remains **longitudinal**
→ compatible with cable's characteristics



Vector-plot of **maximum** principal stresses

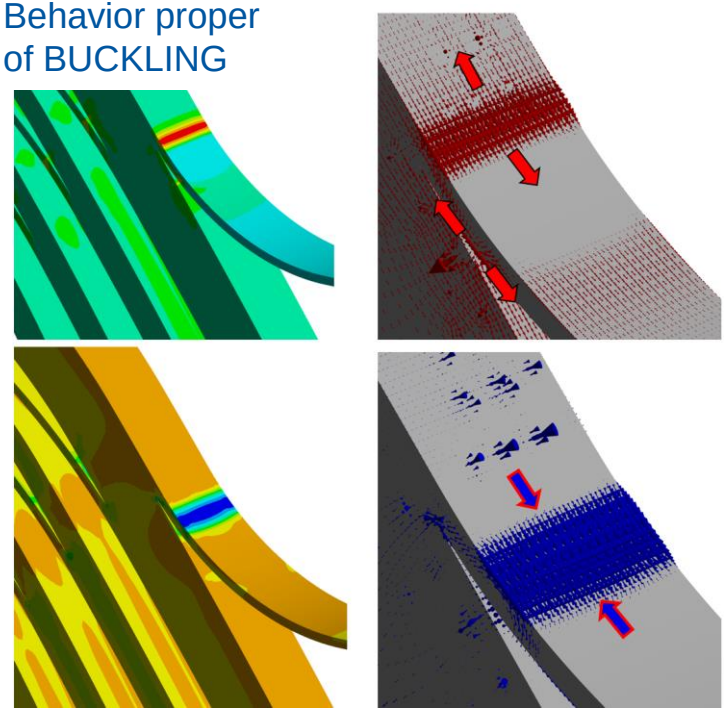
Cable jumps tend **to close** →
reduced risk of delamination near grade jumps



Vector-plot of **minimum** principal stresses

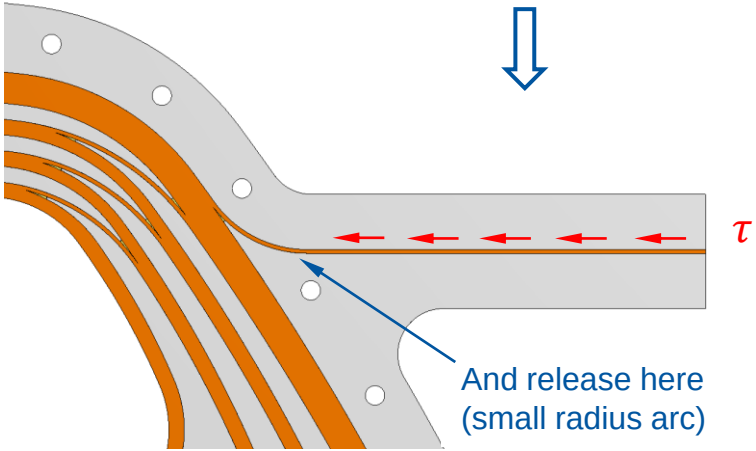
Critical phase: **cooldown**

Behavior proper of BUCKLING



Possible cause:

sum of tangential stresses along the cable

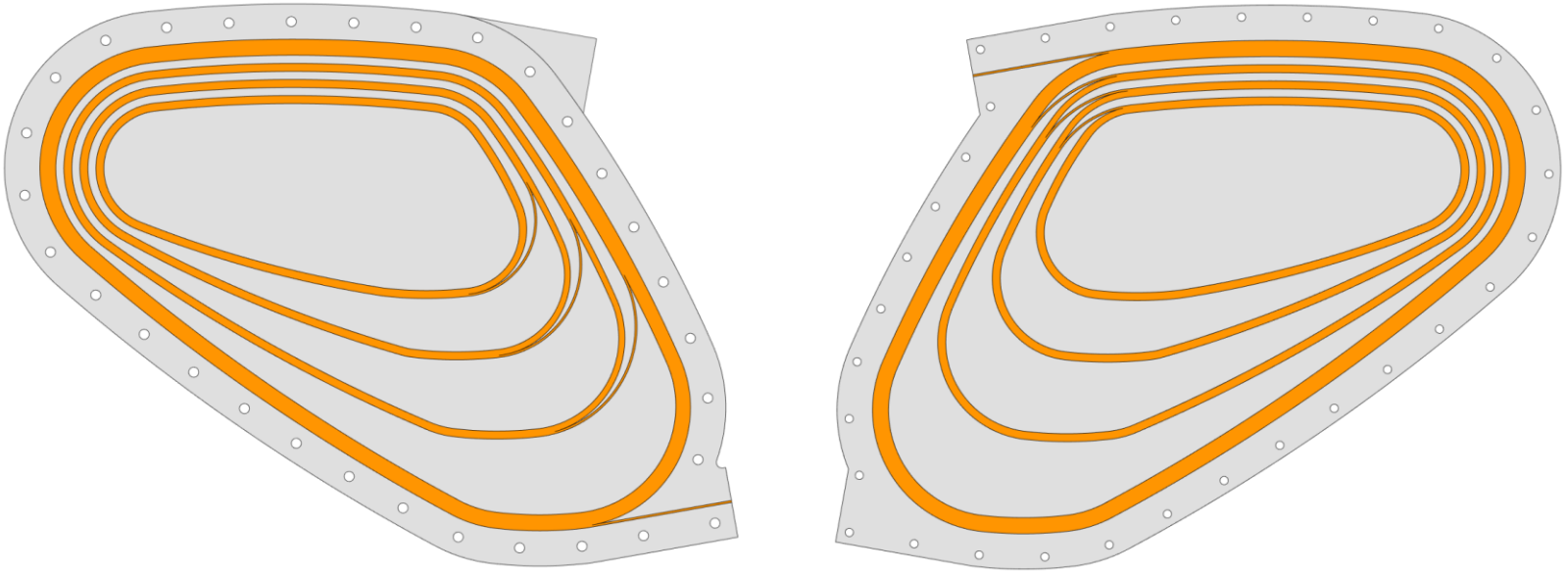


Suggestion:

Modify the geometry and PTFE (Teflon) or MoS_2 (molykote) **coating** to reduce frictional stresses.

New geometry

Straighter cable inlet and outlet and new behavior at interfaces.

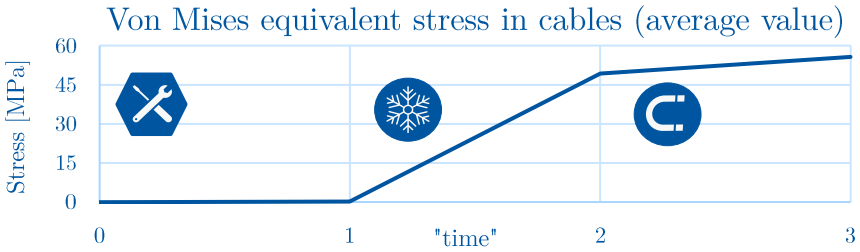


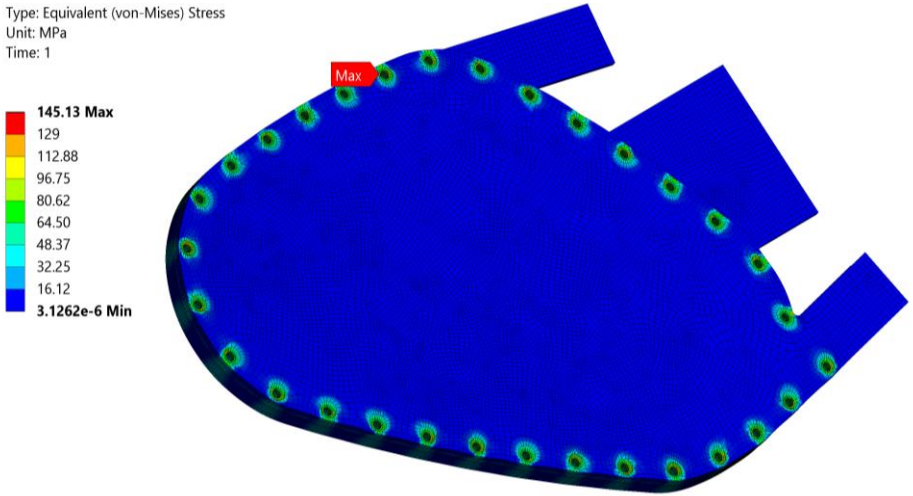
Final configuration results

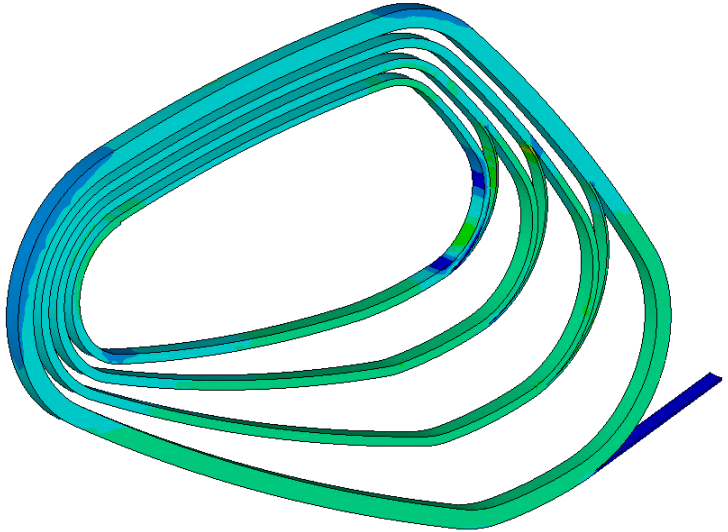
Stress state is stable.

Von Mises Equivalent stress intensity:

- At the end of cooldown : 45 – 50 MPa
- At the end of powering : 55 – 60 MPa (+10 MPa)







Outline

- Hadron Therapy and the GaToroid Project;
- The demonstrator magnet;
- Design process;
- Verification through FEA;
- Magnetic field;
- Instrumentation;
- Future perspectives.

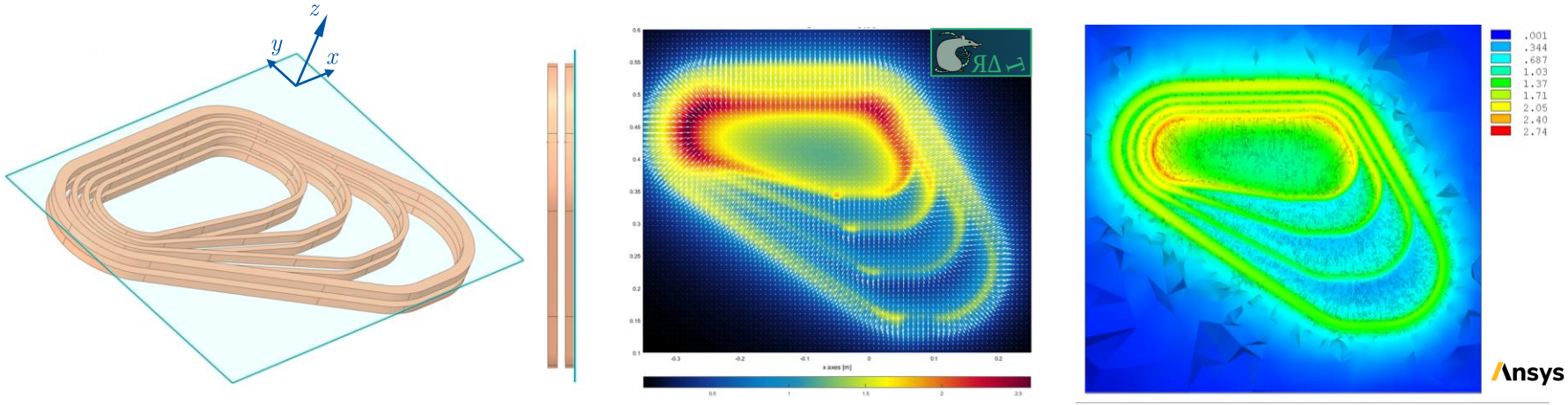
Electromagnetic analyses' results

To **validate** the FE procedure, Ansys results on the ideal coil have been compared to those previously calculated with RAT* (E. Felcini) in its Matlab version.

The comparison is done on a **referece plane**, where the magnetic sensors will be ideally positioned.

The computed field show the same **trend**, and the **peak field** differs for less than 5 %.

The procedure is therefore considered **valid** and it can be applied to the newer geometry.

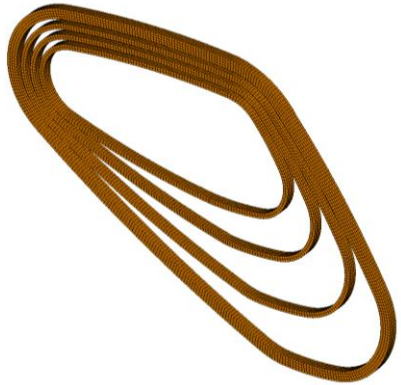


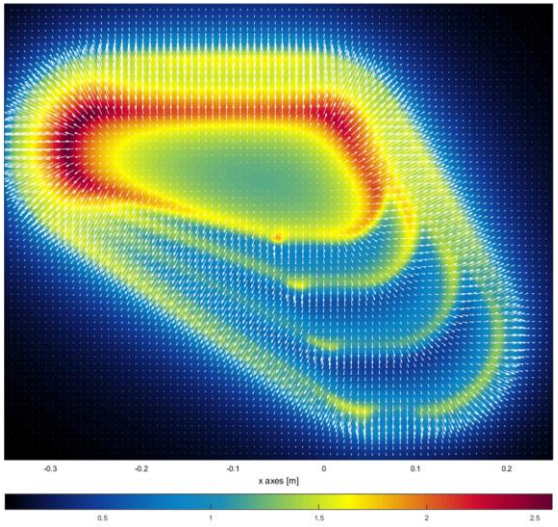
* Jeroen van Nugteren - https://indico.cern.ch/event/856850/

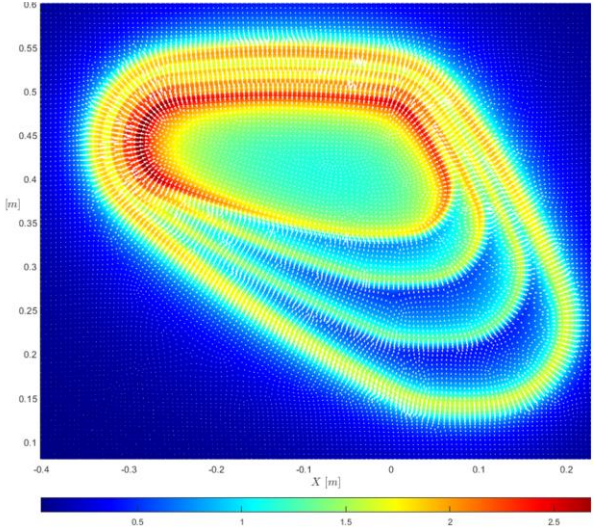
Procedure

The subsequent magnetic analyses have been carried with an **increasing level** of detail.

Beside this being usual practice in FE modelling, it helps **understanding the errors committed** with different levels of approximations.

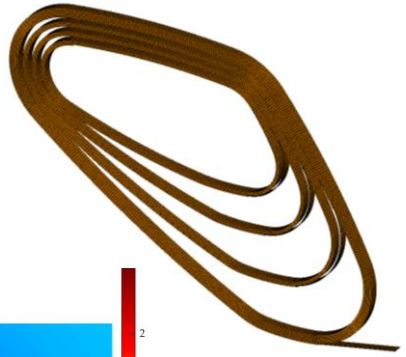


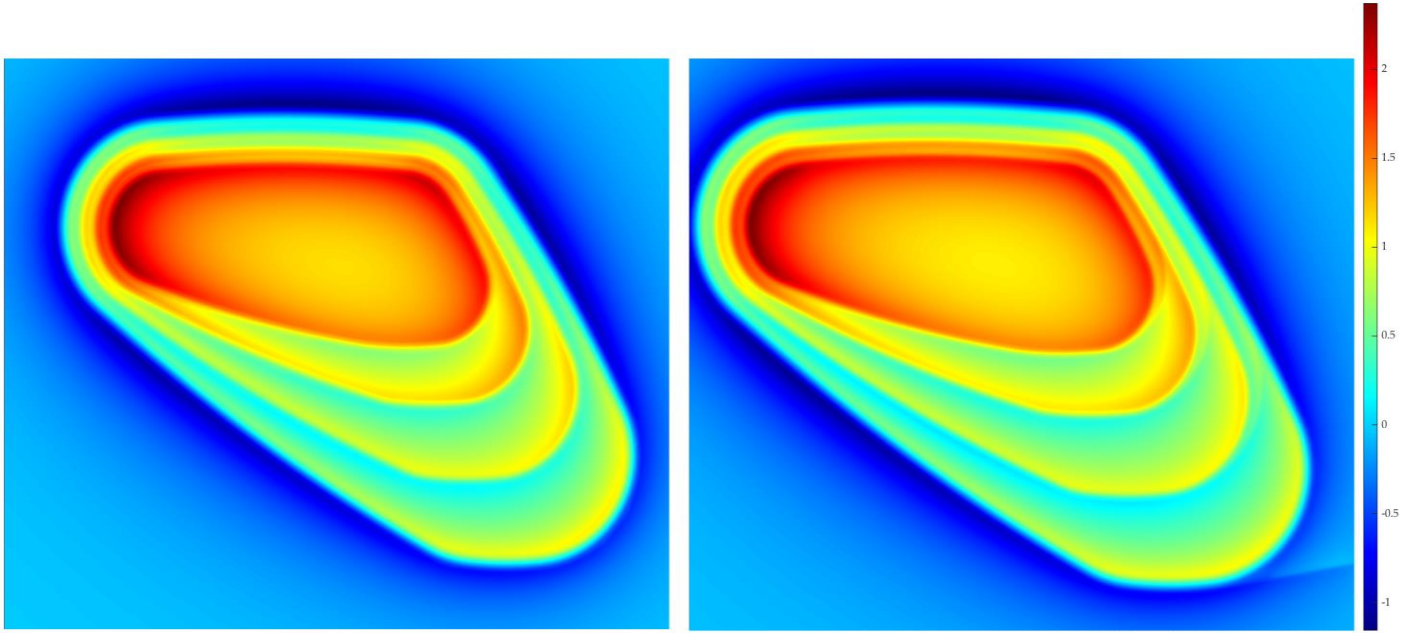




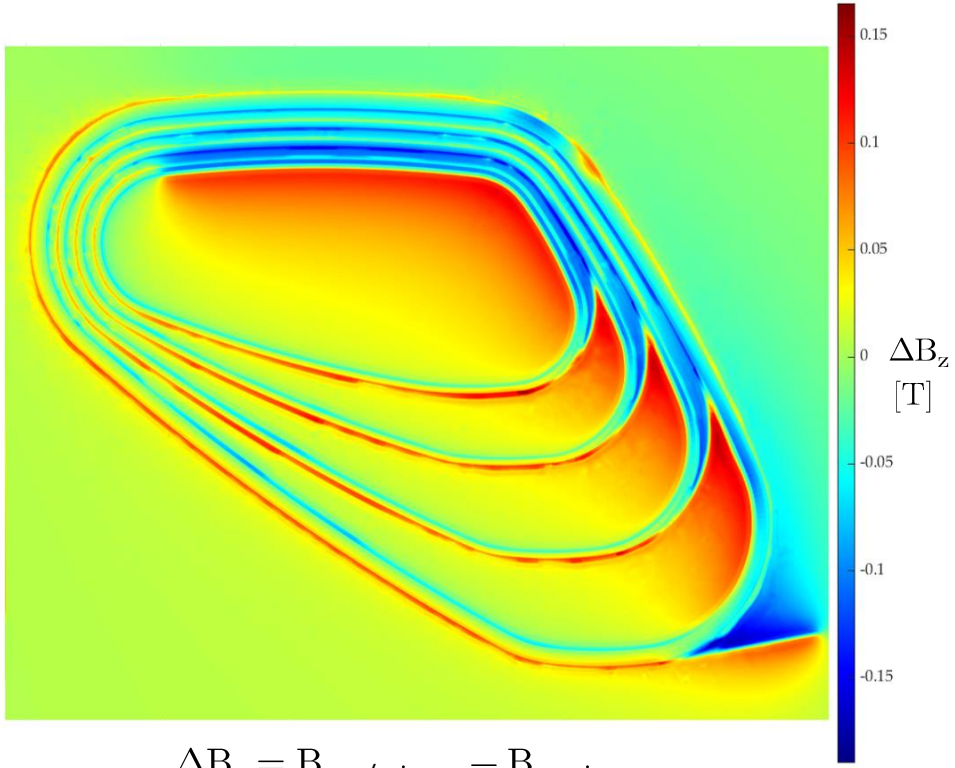
Procedure

Secondarily we have introduced the current **inlet/outlet** and the grade **jumps**.





Quantitative comparison



$$\Delta B_z = B_{z_w/o_jump} - B_{z_w_jump}$$

Results of **engineering practical interest** are compared:

- Field
- Forces

Parameter		*Straight Cables*	*Curved (no jumps)*	*Final*
$\|B\|_{max}$ on cables	[T]	2.89	2.87	3.09
$\|B\|_{max}$	[T]	3.02	3.03	3.13
B_{z_max}	[T]	2.97	3.00	3.10
Fx	[N]	80	20	680
Fy	[N]	130	40	550
Fz	[N]	101’500	109’100	104’500

Outline

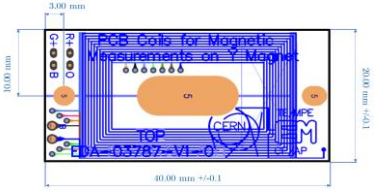
- Hadron Therapy and the GaToroid Project;
- The demonstrator magnet;
- Design process;
- Verification through FEA;
- Magnetic field;
- Instrumentation;
- Future perspectives.

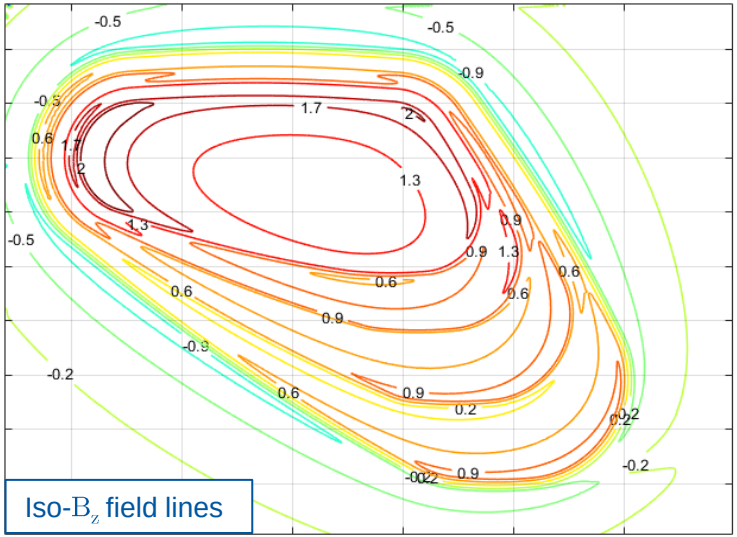
Positioning of magnetic sensors: Printed Circuit Boards (PCB)

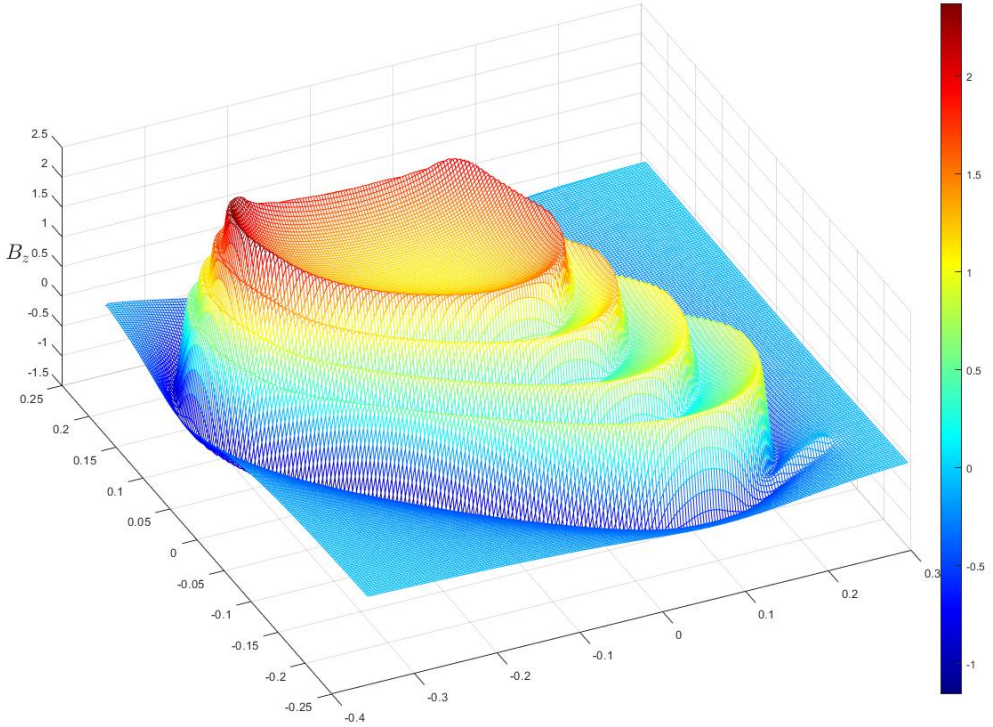
Final field map from FE taken **as a reference**.

To be validated by **measurements** during cold test.

PCB: **pick up coil** + **Hall probe** sensitive to out-of plane component (B_z)

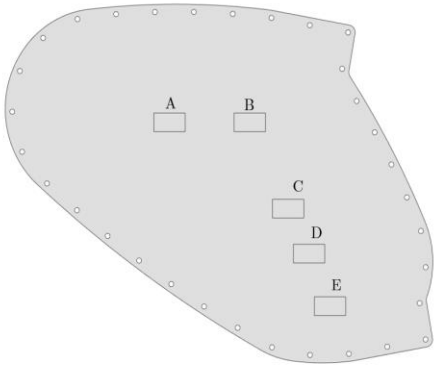


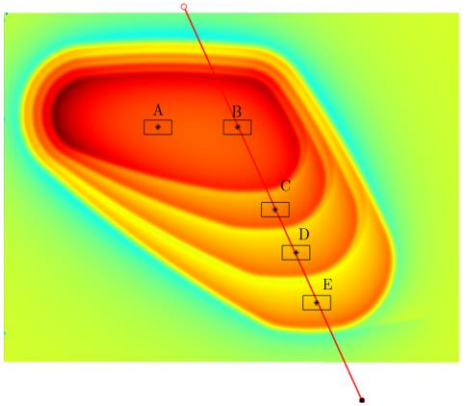




Positioning of magnetic sensors

First hypothesis on **sensors' positions** and calculation of expected measures.



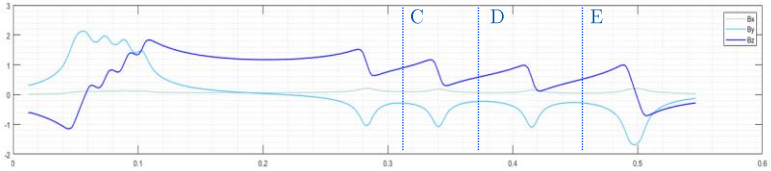


Mean field **perpendicular** to PCB : $\hat{B}_z$

$$\hat{B}_z = \frac{\Phi}{A} = \frac{1}{A}\iint_{PCB} B_z \cdot dA$$

Mean field **parallel** to PCB: $\hat{B}_\Pi$

$$\hat{B}_\Pi = \frac{1}{A}\iint_{PCB} \sqrt{{B_x}^2 + {B_y}^2} \cdot dA$$



	A	B	C	D	E
$\hat{B}_z$ [T]	1.165	1.188	0.935	0.672	0.549
$\hat{B}_p$ [T]	0.036	0.089	0.312	0.247	0.297

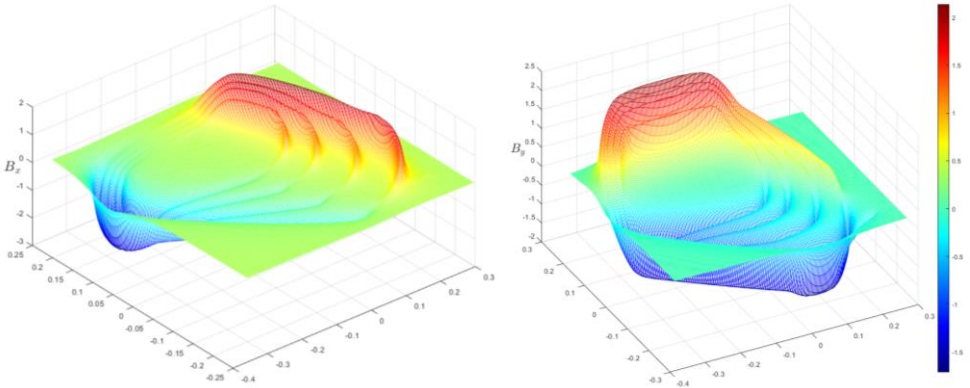
Very good. We don't move them.

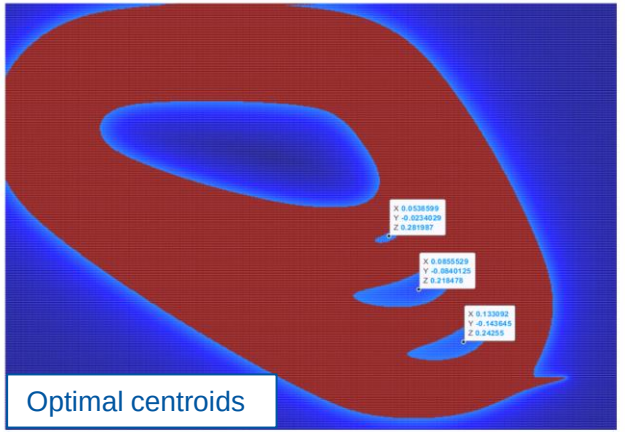
High ratio $\hat{B}_p / \hat{B}_z$, need to be re-thought

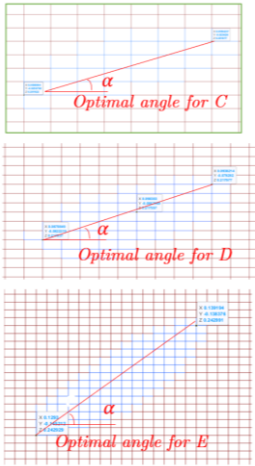
Finding the optima

- We can observe the **in plane-components** of $\mathbf{B}$ to understand the field map better.
- And the hypothesis of **tilting** the PCBs' in the plane emerges.
- We can then identify the best **center points** based on $\mathrm{B_z}$
- And finally **rotate** the coordinate system with a rotation matrix [R]

$$\overline{x_{new}} = \overline{x_{old}} \cdot [R] = \overline{x_{old}} \cdot \begin{bmatrix} \cos(-\alpha) & \sin(-\alpha) \\ \sin(\alpha) & \cos(-\alpha) \end{bmatrix}$$

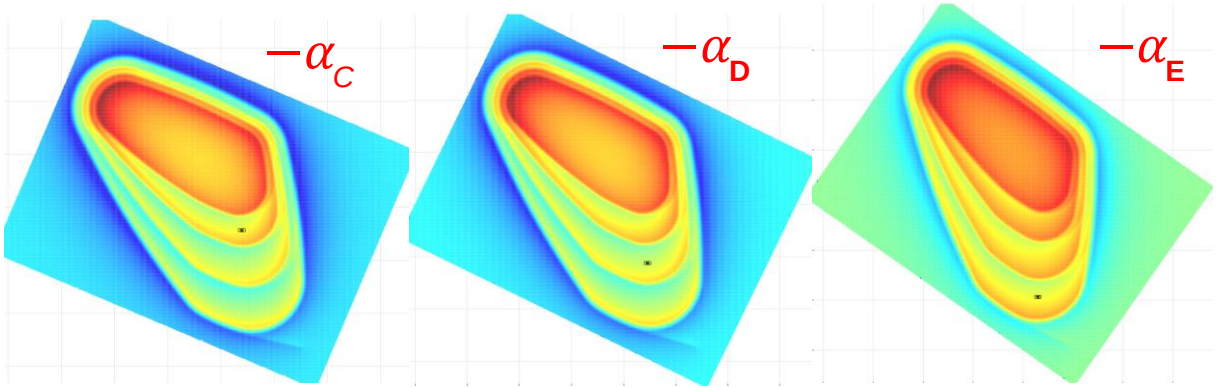






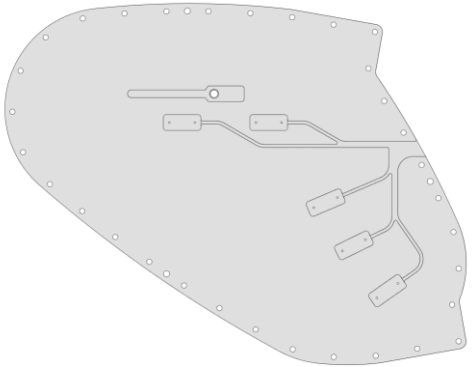
New Results after rotation

Numerical integration at new locations, on tilted areas.



	A	B	C	D	E
$\hat{B}_z$[T] *	1.165	1.188	0.944	0.699	0.472
$\hat{B}_p$[T] **	0.036	0.089	0.287	0.231	0.238

Minimized the ratio $\hat{B}_p / \hat{B}_z$



New CAD coordinates of PCB centers, and inclinations:

PCB	*X* [mm]	*Y* [mm]	α [deg]
C	53	316.5	23
D	90.5	260	26
E	135	200	35

Outline

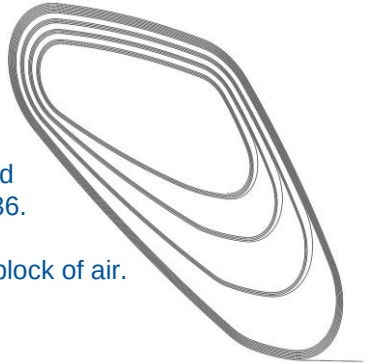
- Hadron Therapy and the GaToroid Project;
- The demonstrator magnet;
- Design process;
- Verification through FEA;
- Magnetic field;
- Instrumentation;
- Future perspectives.

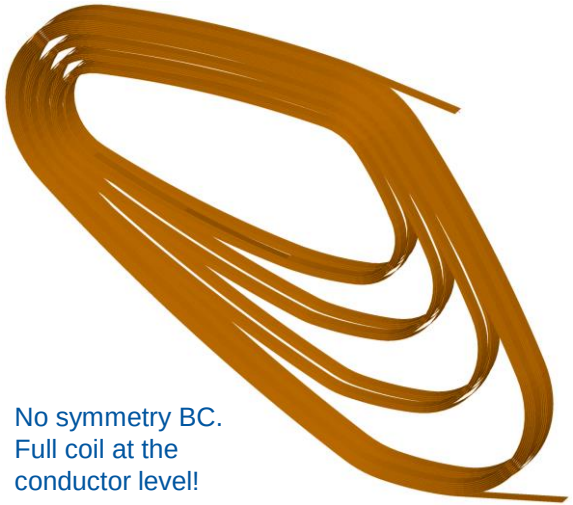
Magnetic scalar potential model

- Reduce computational resources
- Ease of direct generation of conductors' path (**parametrically**)
- Integro-differential formulation **less** subjected to **approximations**
- But **no forces** on conductors

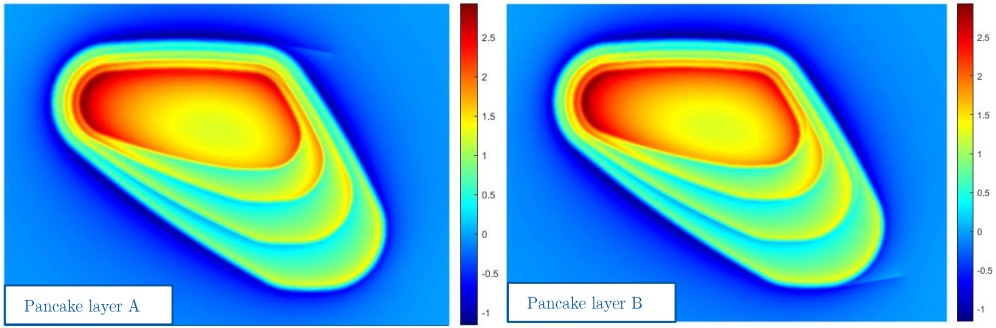
Only conductors' traces meshed with SOURC36.

The rest is a block of air.

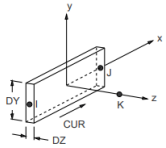




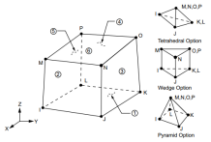
No symmetry BC.
Full coil at the conductor level!



Ansys Element: SOURC36
Properties: Current

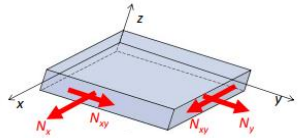


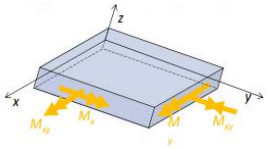
Ansys Element: SOLID96
DOF: MAG (Φ)



Mechanical models

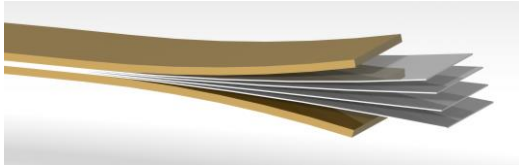
In light of the layered nature of the cables and tapes we can think of applying the modelling techniques proper of **composites**.

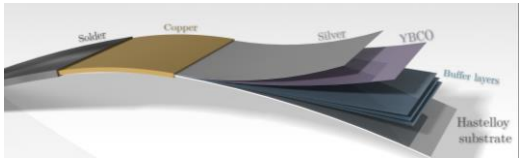




$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} = \sum_{k=1}^{N} \int_{z_{k-1}}^{z_k} \begin{Bmatrix} \sigma_{xx}(z) \\ \sigma_{yy}(z) \\ \tau_{xy}(z) \end{Bmatrix} dz$$

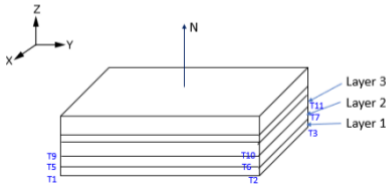
$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \sum_{k=1}^{N} \int_{z_{k-1}}^{z_k} \begin{Bmatrix} \sigma_{xx}(z) \\ \sigma_{yy}(z) \\ \tau_{xy}(z) \end{Bmatrix} z dz$$



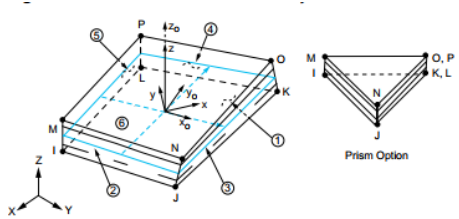


Several Ansys elements could serve this purpose:

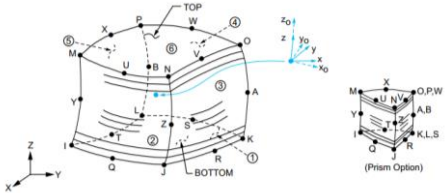
Ansys Element: SHELL181
Theory: Kirchhoff (thin plates and shells)
4 nodes, DOF: U_i, ROT_i



Ansys Element: **SOLSH190**
Theory: **Mindlin** (thik plates and shells)
8 nodes, DOF: U_i



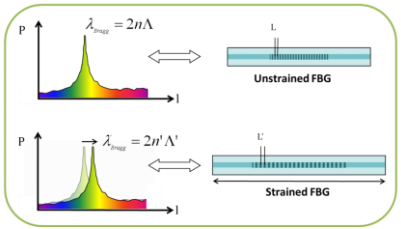
Ansys Element: SOLID186
Theory: Solid mechanics
8 nodes, DOF: U_i



Materials characterization and test

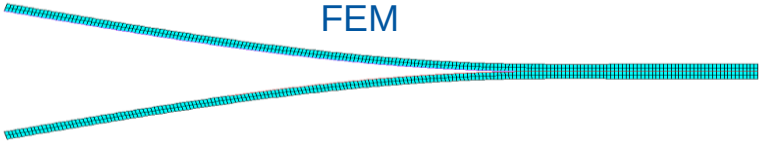
Full magnet
during test at cold with optical strain gauges

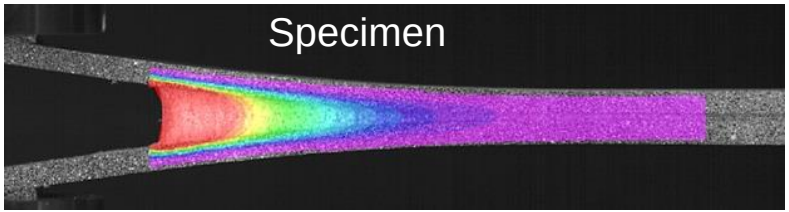
Bragg grating



Cable stack
characterization, also at cold, with Digital Image Correlation systems

FEM



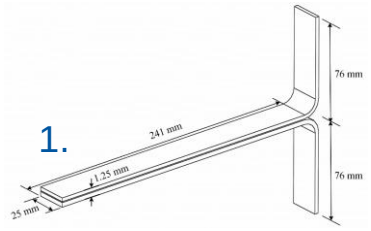


Adhesion characterization

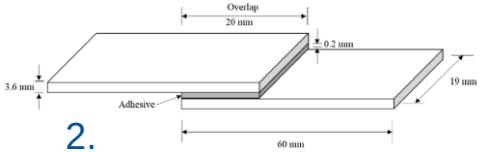
Collaboration with the research group of TE-MSC-GLO for the characterization of the **polymer's adhesion** to metallic surfaces.

Design of **tools** and **moulds** for

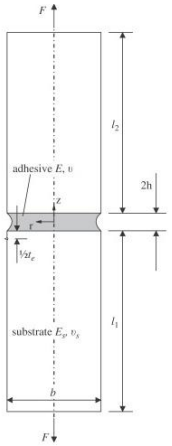
1. Peel-off test
2. Shear test
3. Butt joint test



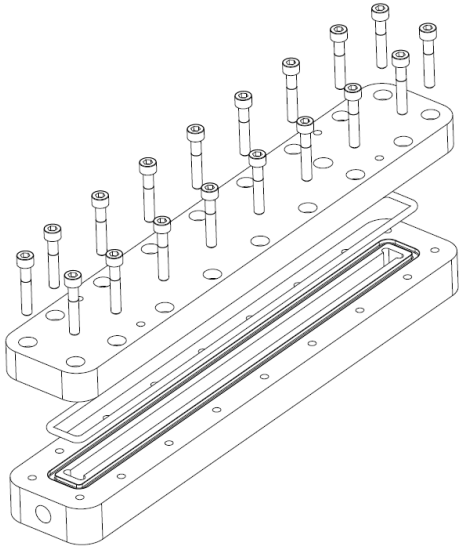
1.

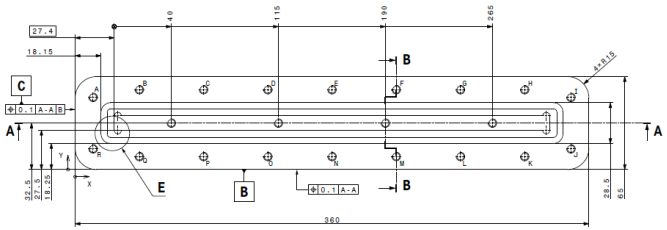


2.



3.



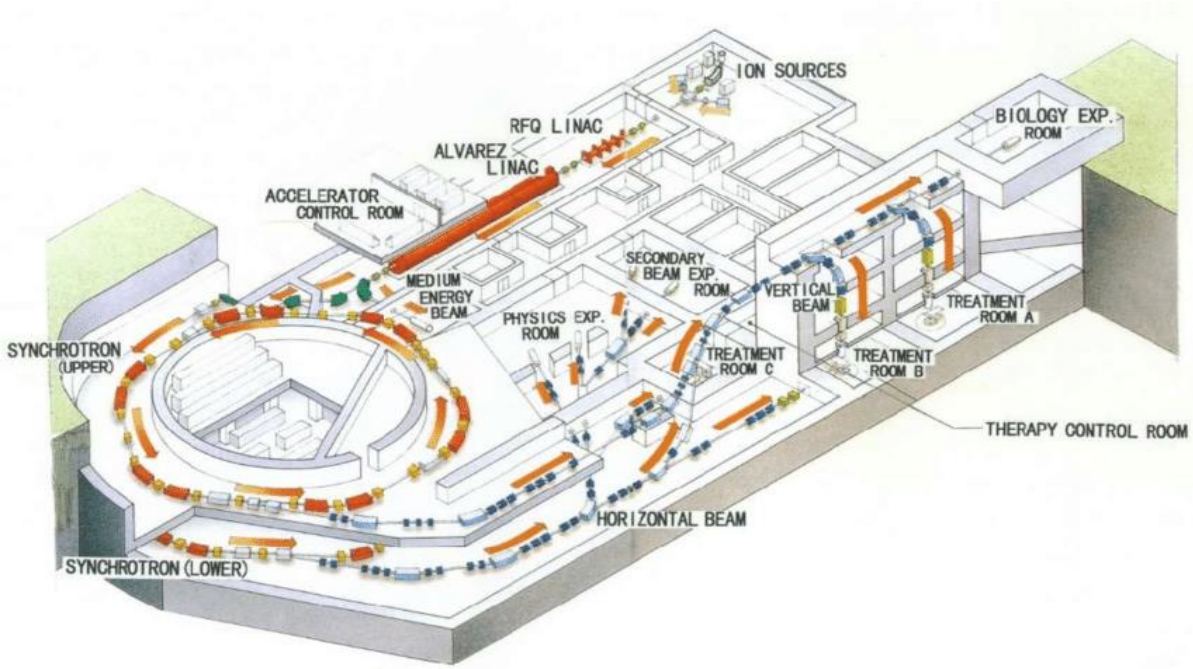


Thank you for your attention

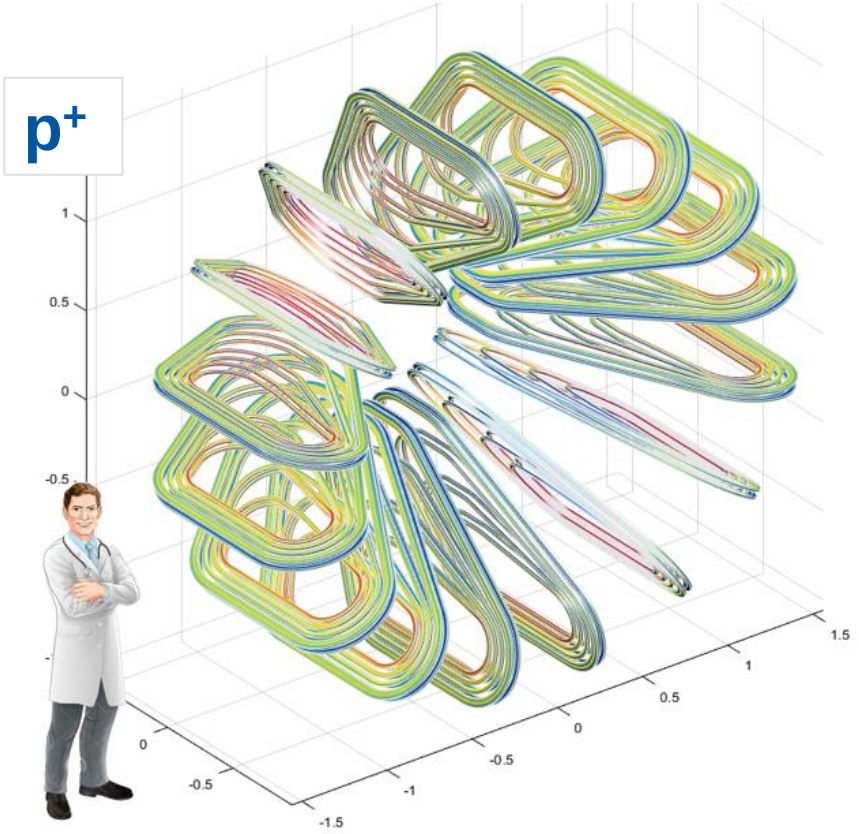
Many topics remained uncovered,
for further details I invite you to take a look at my MSc thesis

Backup slides

Fixed beam lines



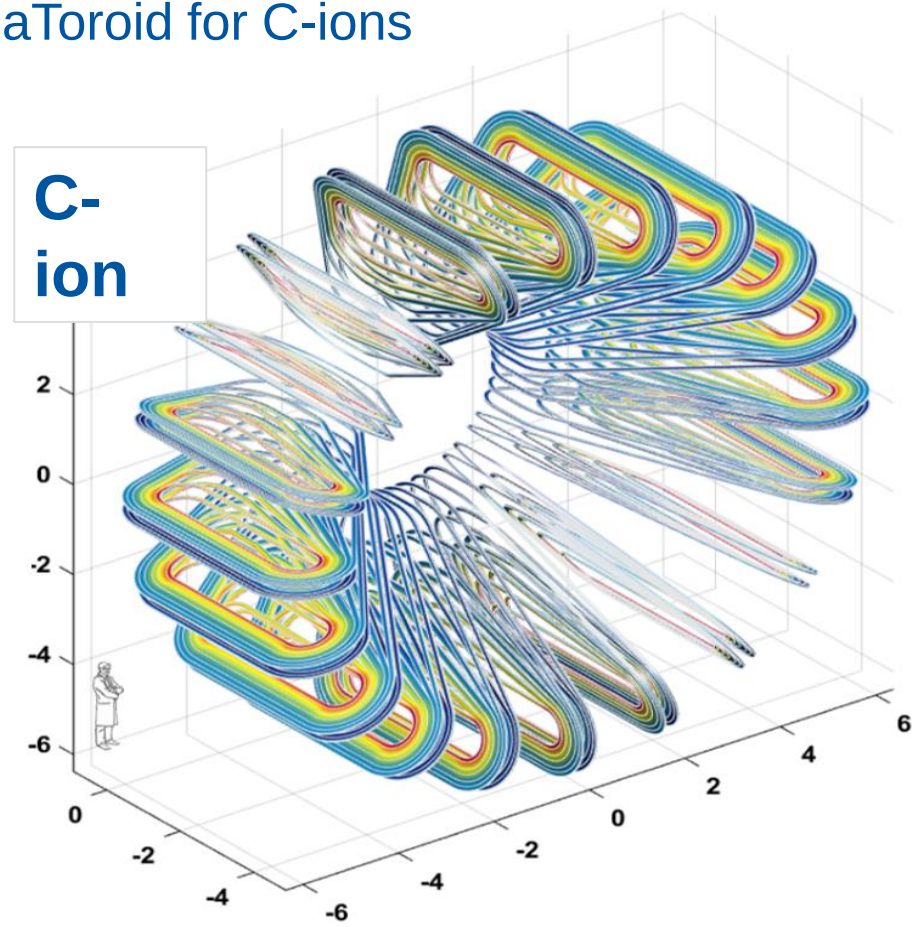
GaToroid for protons



Material type	Superconductor
LTS option	NbTi
HTS option	**ReBCO**
Operating temperature	LTS: 4.5 (K)
	HTS: 20 (K)

Number of coils	16 (-)
Peak field on coil	8 (T)
Coil dimensions	~ 1.5 x 1 (m x m)
Torus dimensions	~ 3 x 1.5 (m x m)
Estimated mass	**12 (tons)**

GaToroid for C-ions



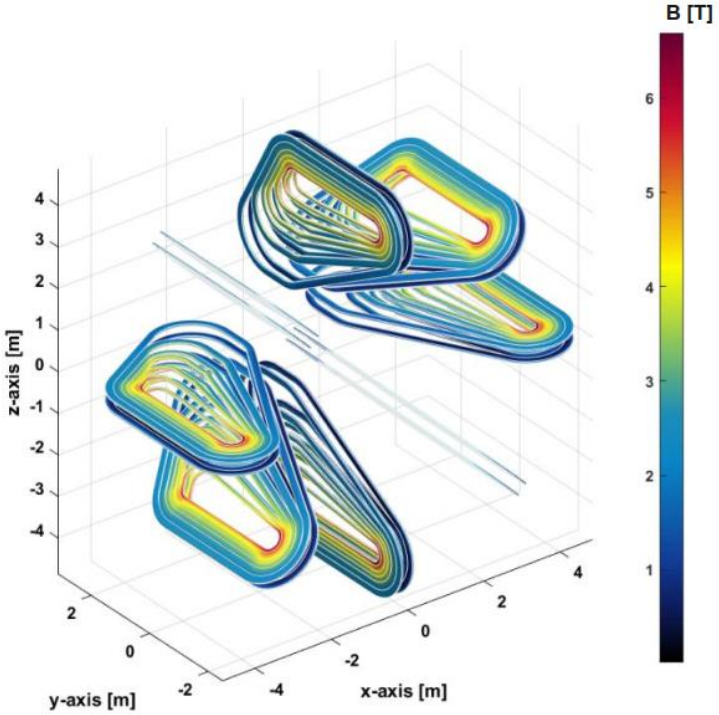
Material type	Superconductor
LTS option	NbTi
Operating temperature	LTS: 4.5 (K)

Number of coils	20 (-)
Peak field on coil	6.1 (T)
Coil dimensions	~ 5.8 x 4.5 (m x m)
Torus dimensions	~ 5.8 x 12 (m x m)
Estimated mass	**270 (tons)**

⇒ A reduced size-version is under discussion.

Geometry and design

Reduced size version

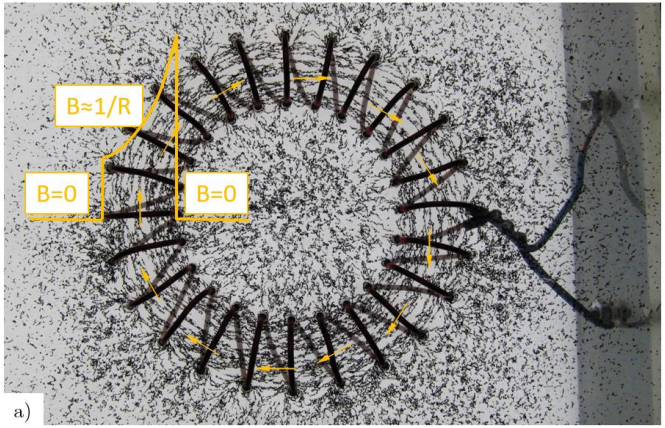


Number of angles	8
Peak magnetic field	6.7 T
Stored Energy	420 MJ

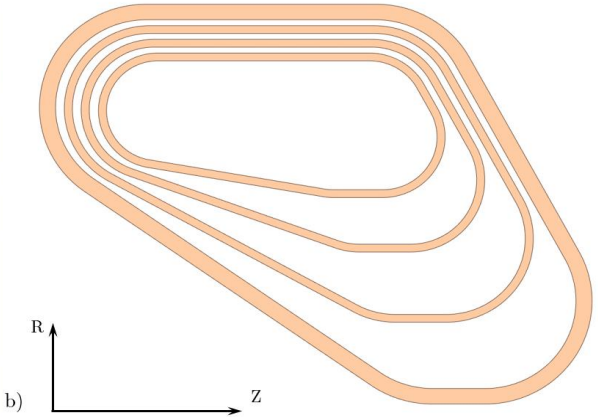
Coil dimension	5.6 m x 3.7 m
Torus dimension	5.6 m x 9.7 m
Bore size	2.25 m
Vector Magnet position	4.2 m

Operating temperature	4.2 K
Operating current	10.8 kA

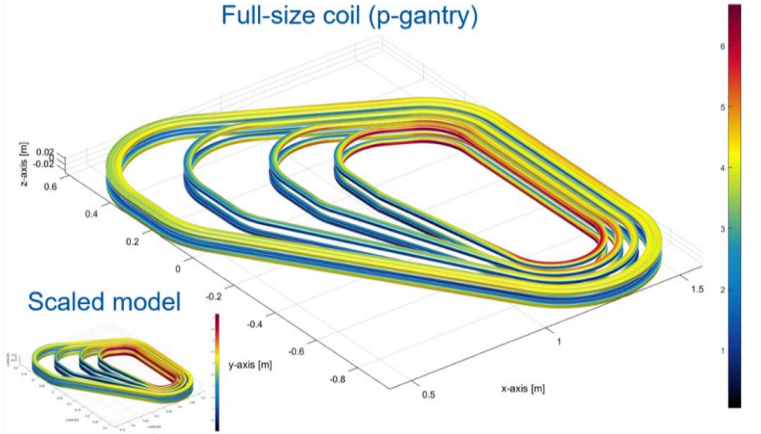
Estimated total mass	130 tons


B≈1/R
B=0
B=0

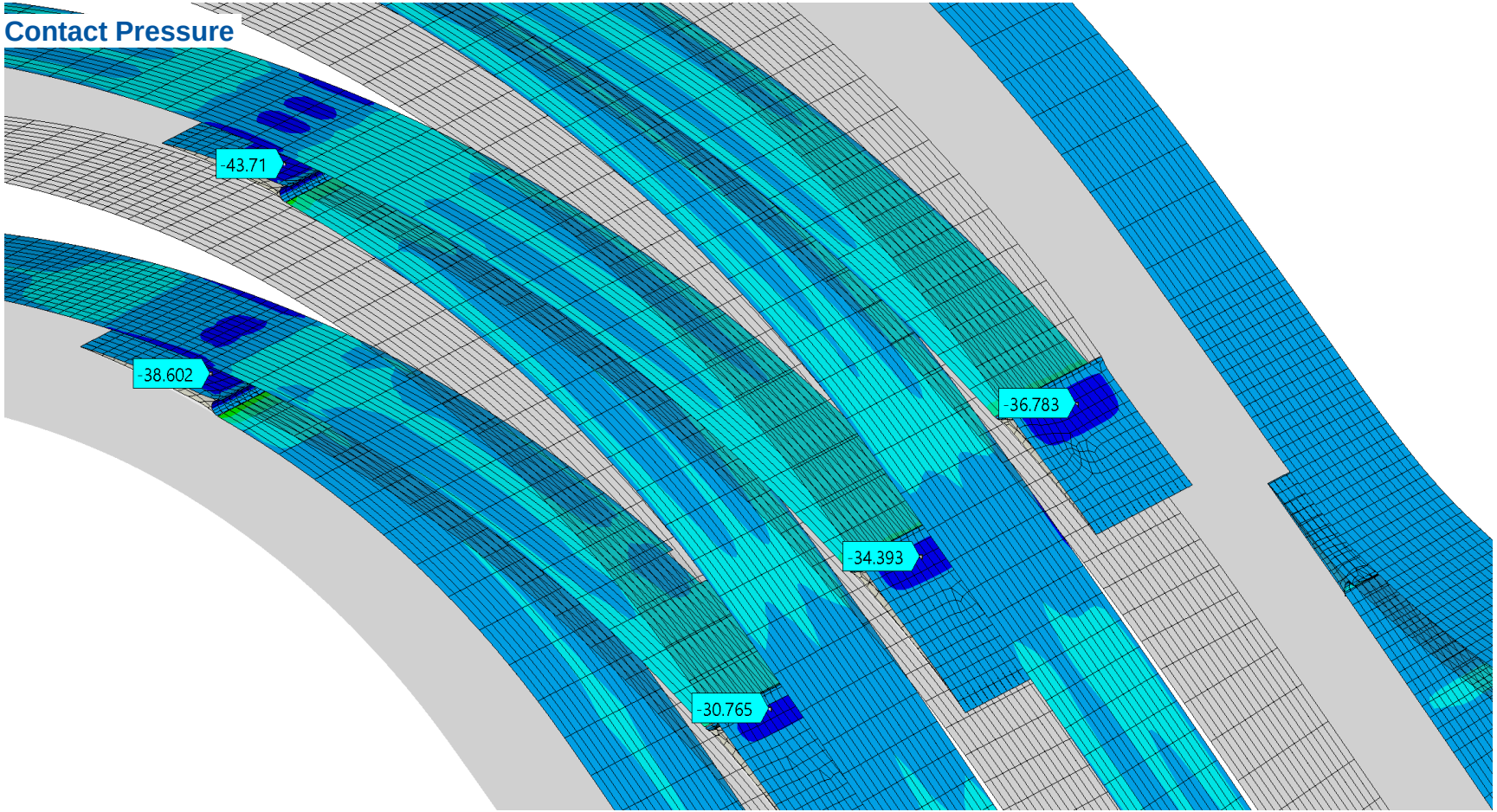
a)

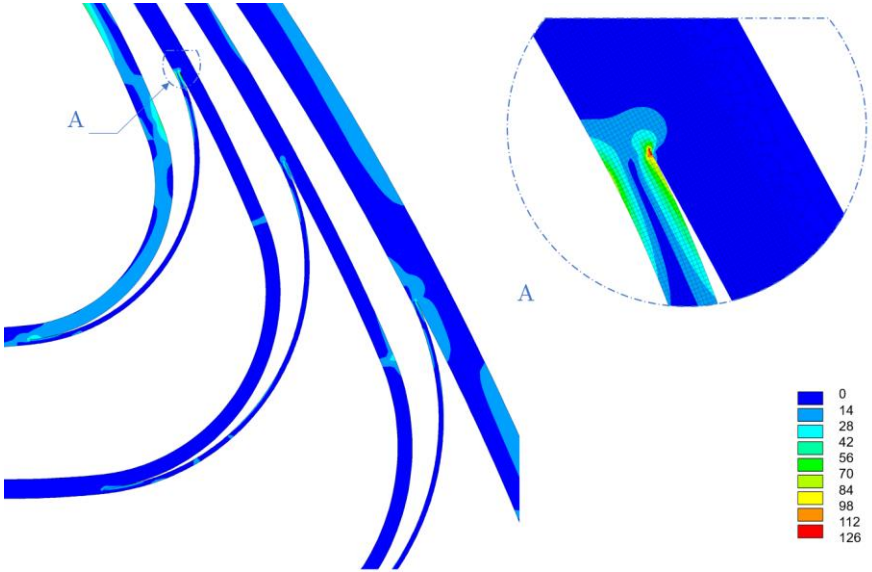

R
Z

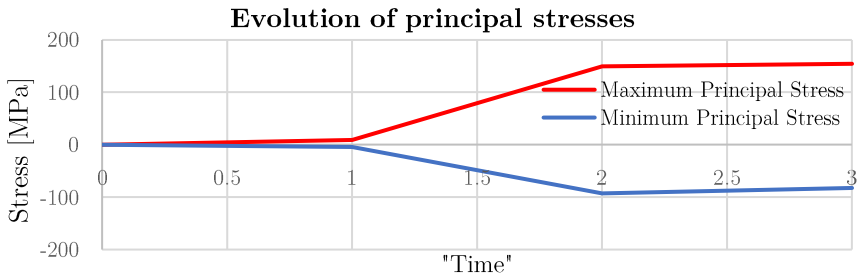
b)

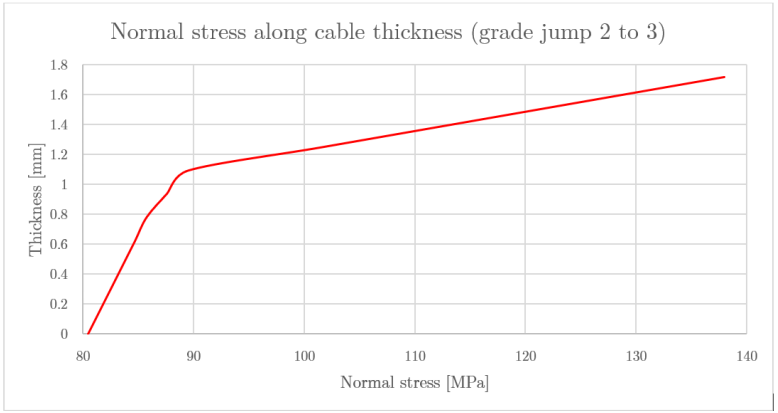

Full-size coil (p-gantry)
Scaled model
z-axis [m]
y-axis [m]
x-axis [m]

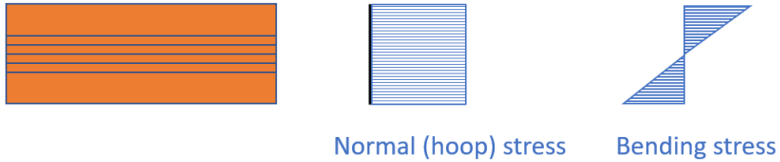
Contact Pressure




A
A
0
14
28
42
56
70
84
98
112
126


Evolution of principal stresses
Stress [MPa]
200
100
0
-100
-200
0
0.5
1
1.5
2
2.5
3
"Time"
Maximum Principal Stress
Minimum Principal Stress


Normal stress along cable thickness (grade jump 2 to 3)
Thickness [mm]
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
80
90
100
110
120
130
140
Normal stress [MPa]


Normal (hoop) stress
Bending stress

Ampere's law

$$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$$

Magnetic induction continuity

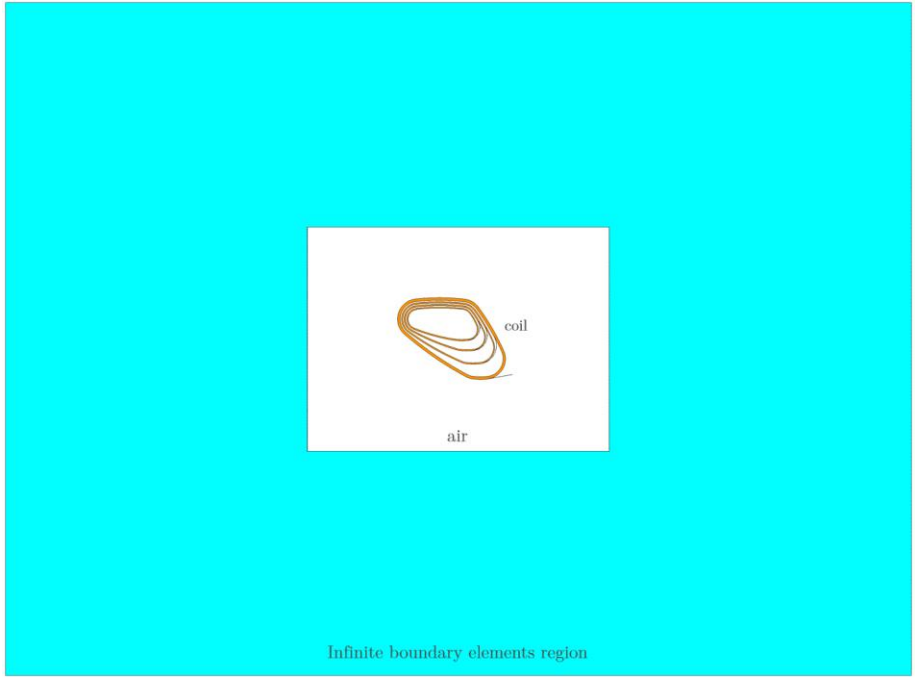
$$\nabla \cdot \mathbf{B} = 0$$

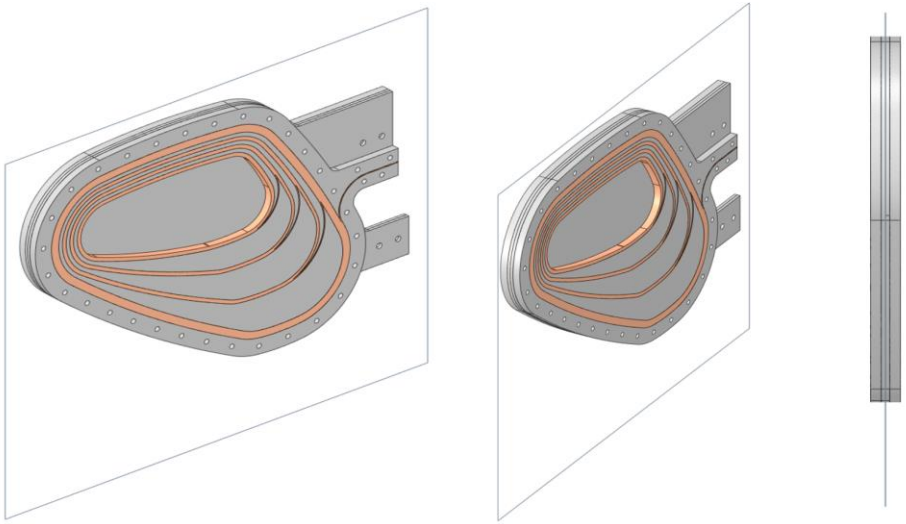
Introduction of m.v.p.

$$\nabla \times \mathbf{A} = \mathbf{B}$$

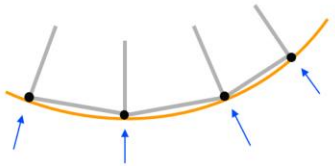
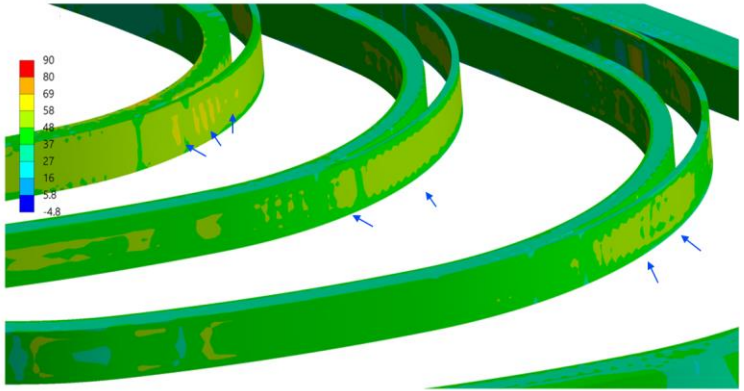
FE formulation

$$\nabla \times ([\boldsymbol{\nu}] \nabla \times \mathbf{A}\ ) = \mathbf{J}$$





In principle:



Contact pressure peaks