Progress in GaToroid
A novel gantry for Hadron therapy

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Early-Career Researchers in Medical Applications Seminar,
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Knowledge Transfer to Medical Applications

Outline

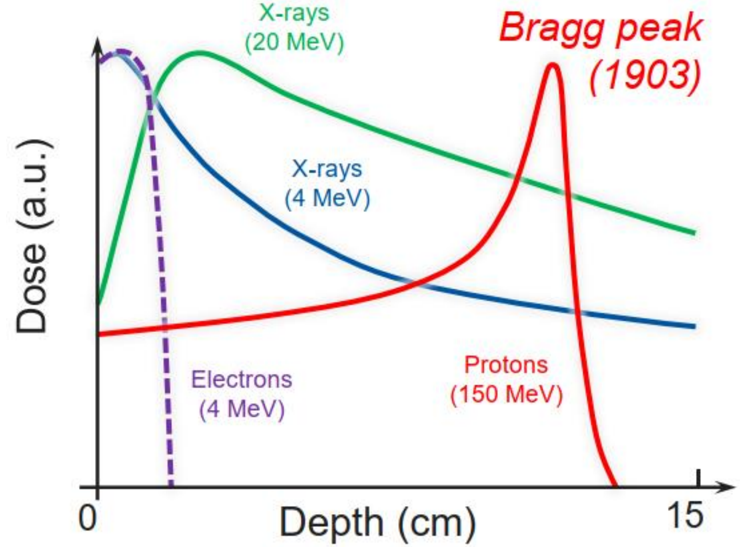
- Context (Hadron therapy / Gantries)
- From concept to demonstrator
- Demonstrator design & analysis
- Status on Technology developments
- Perspectives

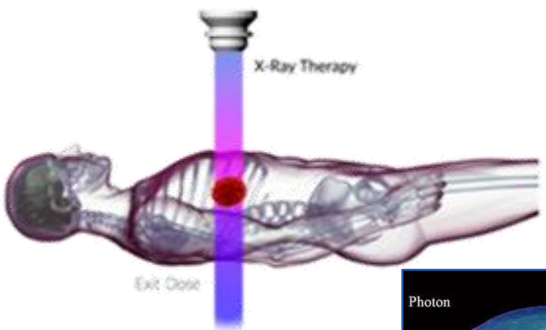
Context

Hadron therapy

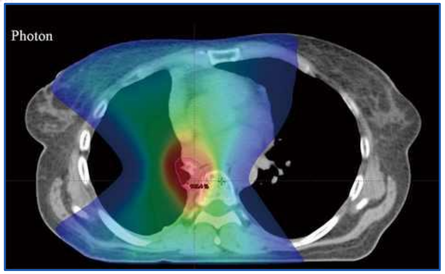
Various types of ionizing radiations can be used to kill cancerous cells:

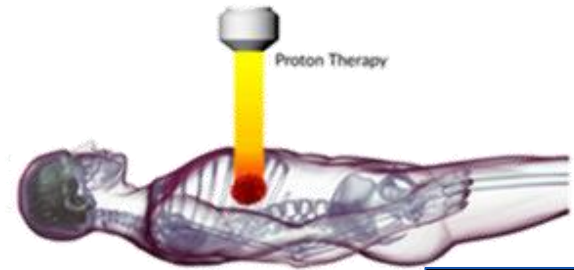
- Photons (X-rays)
- Electrons
- Hadrons
  - Protons
  - Ions (He, C, Ne,…)



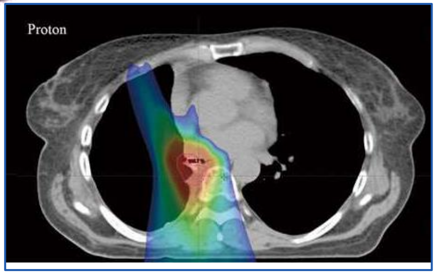


X-rays





Protons



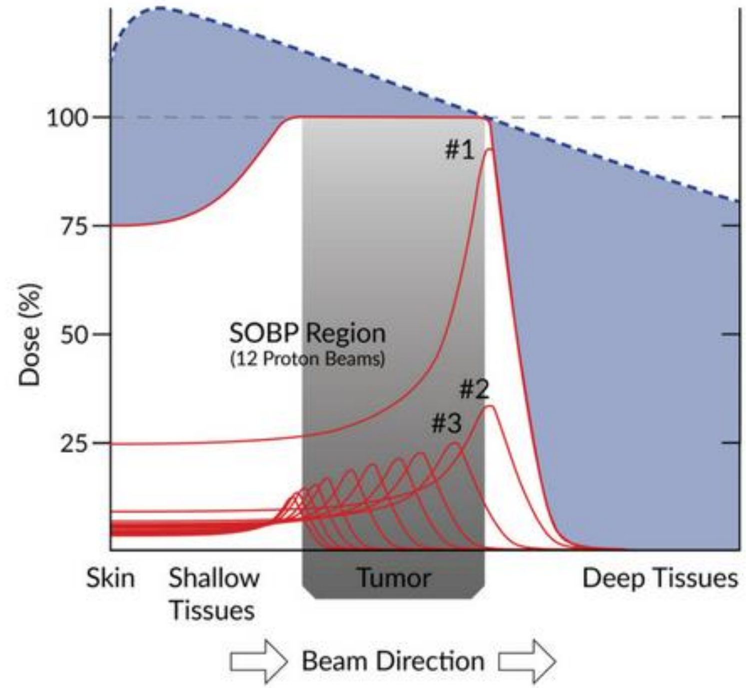
Translational Lung Cancer Research **6**(2) (2017)

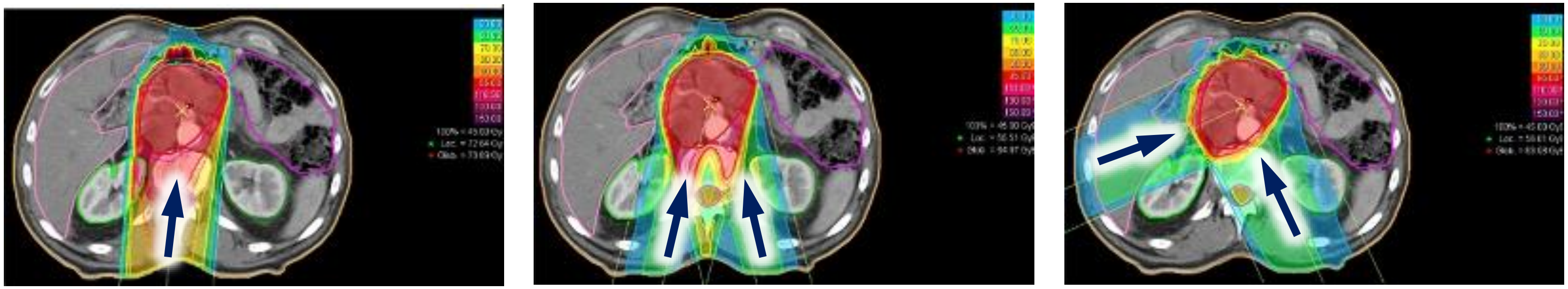
Context

Hadron therapy

The tumor is targeted by controlling 2 variables:

- The **depth** of the Bragg peak depends on the particle energy:
  - 70-250 MeV for protons
  - 100-500 MeV for C ions
- **Stereotaxis** superimposes several beams from different directions to map the volume.





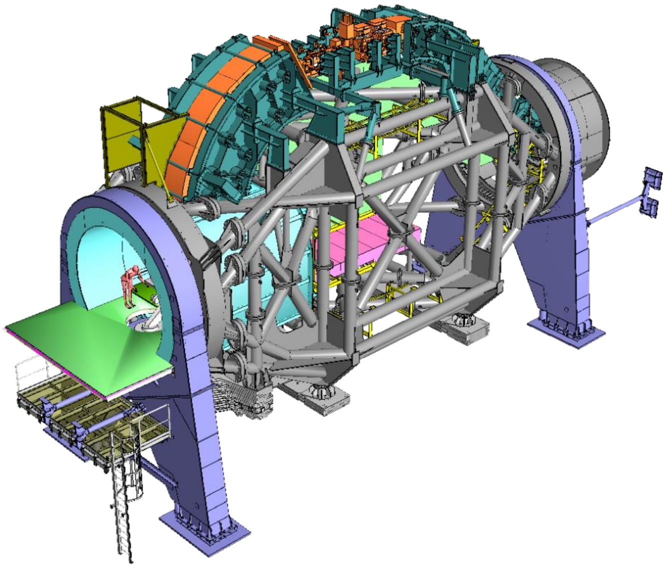
PLoS ONE **11**(10), e0164473 (2016)

Context

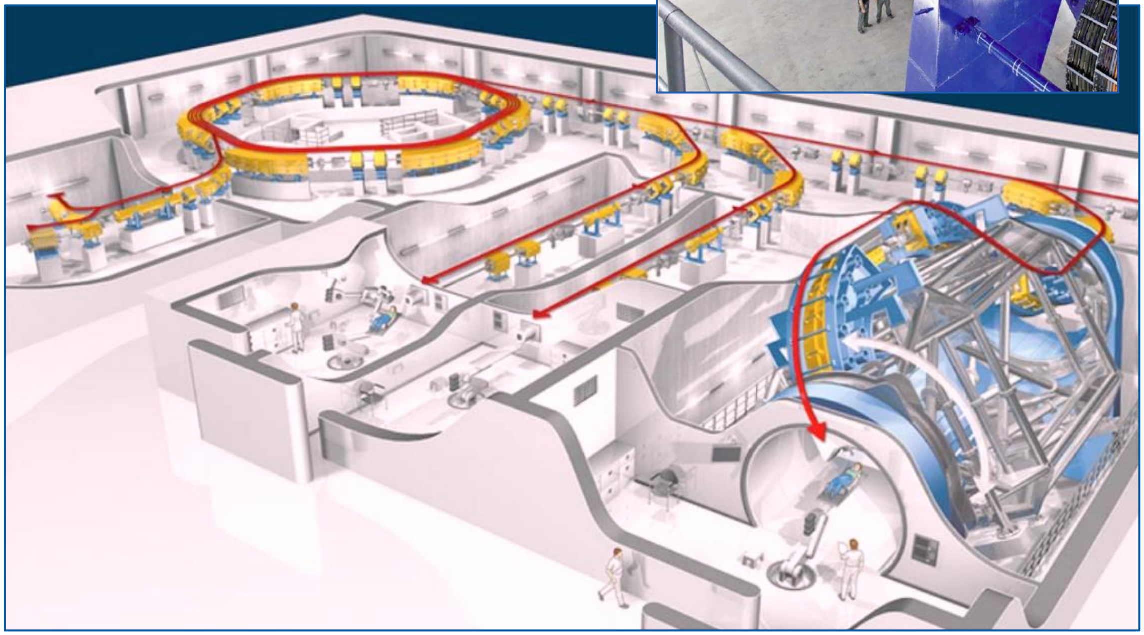
Gantries

Transfer lines able to irradiate from multiple directions.

Carried by a rigid and precise rotating structure.



The Heidelberg gantry (HIT)



- <u>Proton Gantries</u>: radius 4 - 10 m / weight 100 - 200 tons
- <u>C-ions Gantries</u>: radius 10 - 25 m / weight 350 - 670 tons

Context

Gantries

Gantries are massive and account for about half the whole installation.

What can we do ?

- Use superconductor to increase the bending field in large bore magnets. (more compact, lighter and more efficient)
- Find a magnetic configuration which does not need to be nor rotated nor ramped to focus the beam on the patient. (reduce stability req. and so mass and footprint)

Outline

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- From concept to demonstrator
- Demonstrator design & analysis
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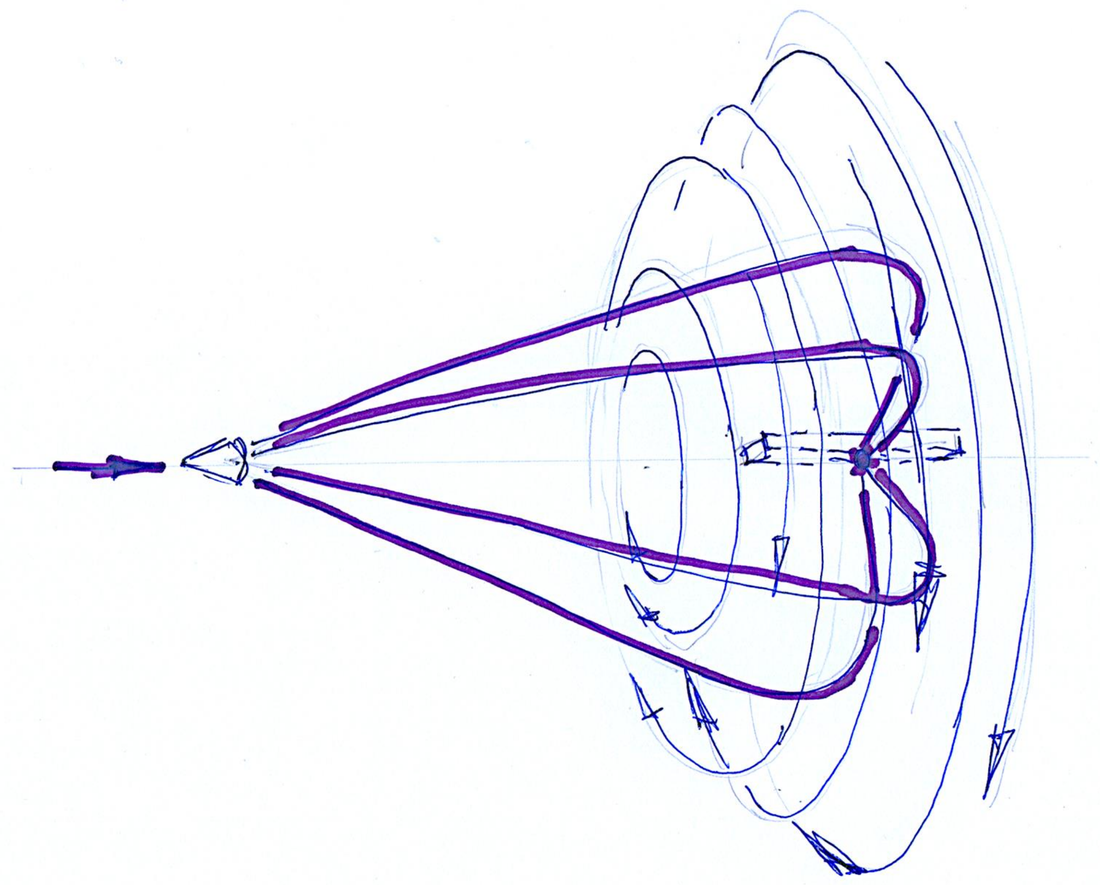
From concept to demonstrator

The idea by Luca Bottura

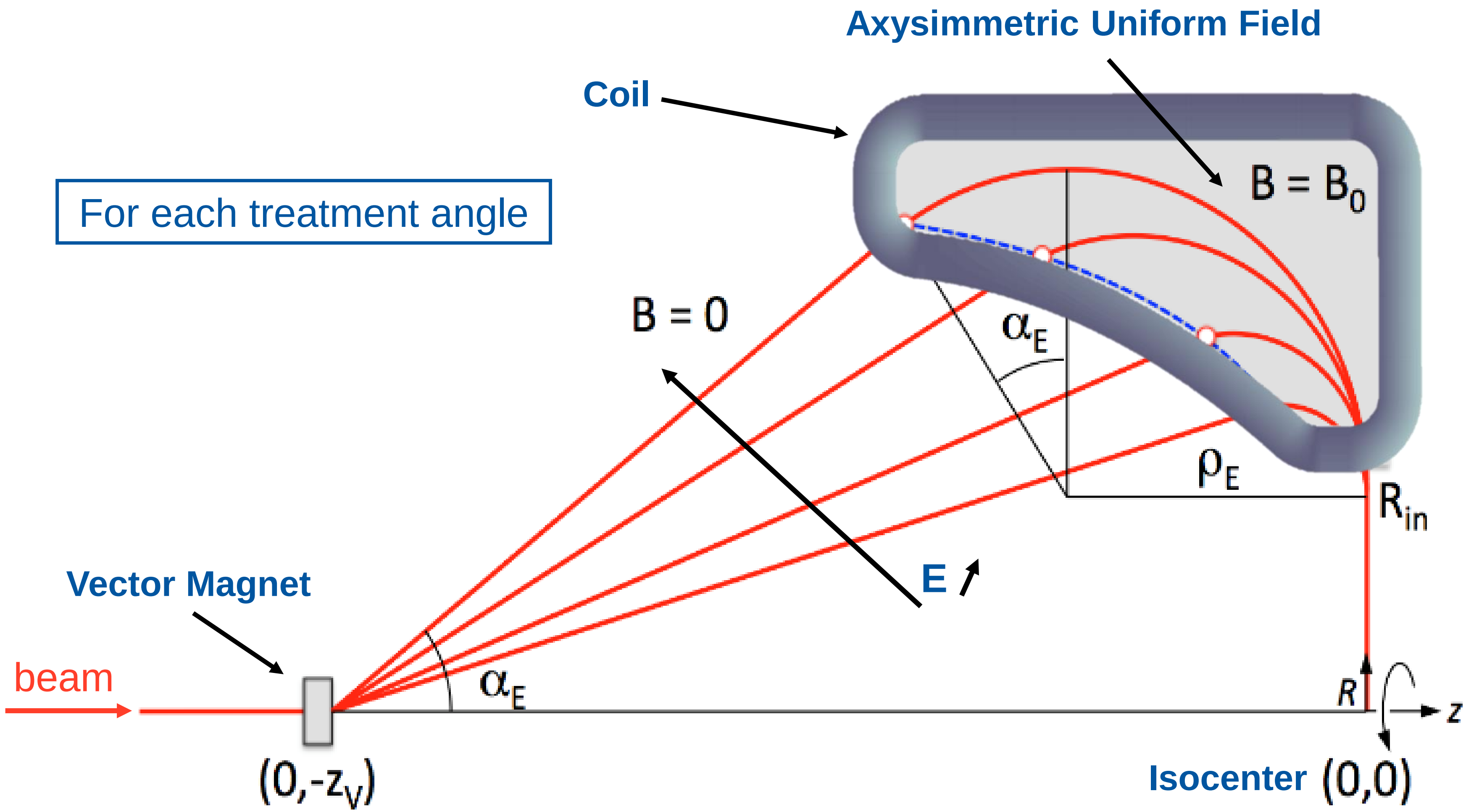


L. Bottura, **A Gantry and Apparatus for Focusing Beams of Charged Particles**, European Patent, Application EP 18173426.0, May 2018

From concept to demonstrator

Development of the idea

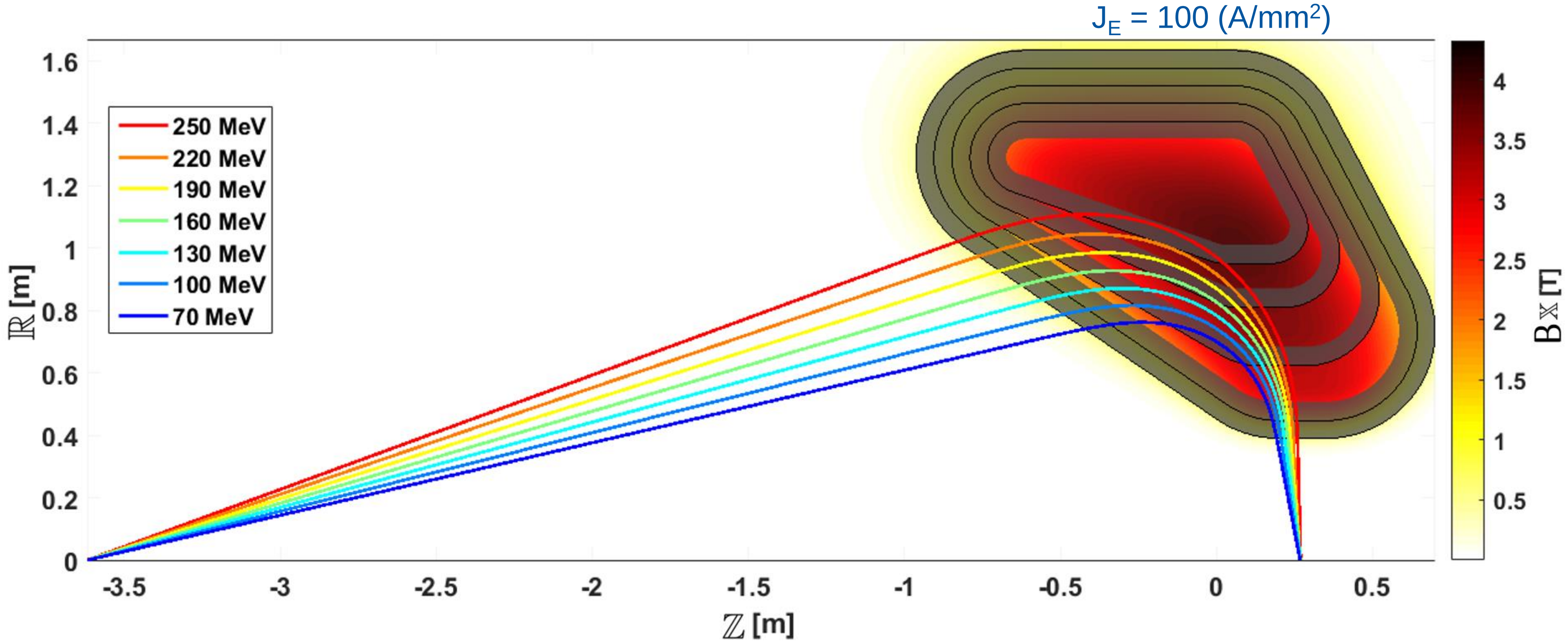
For each treatment angle



From concept to demonstrator

From concept to demonstrator

Proton version by Enrico Felcini



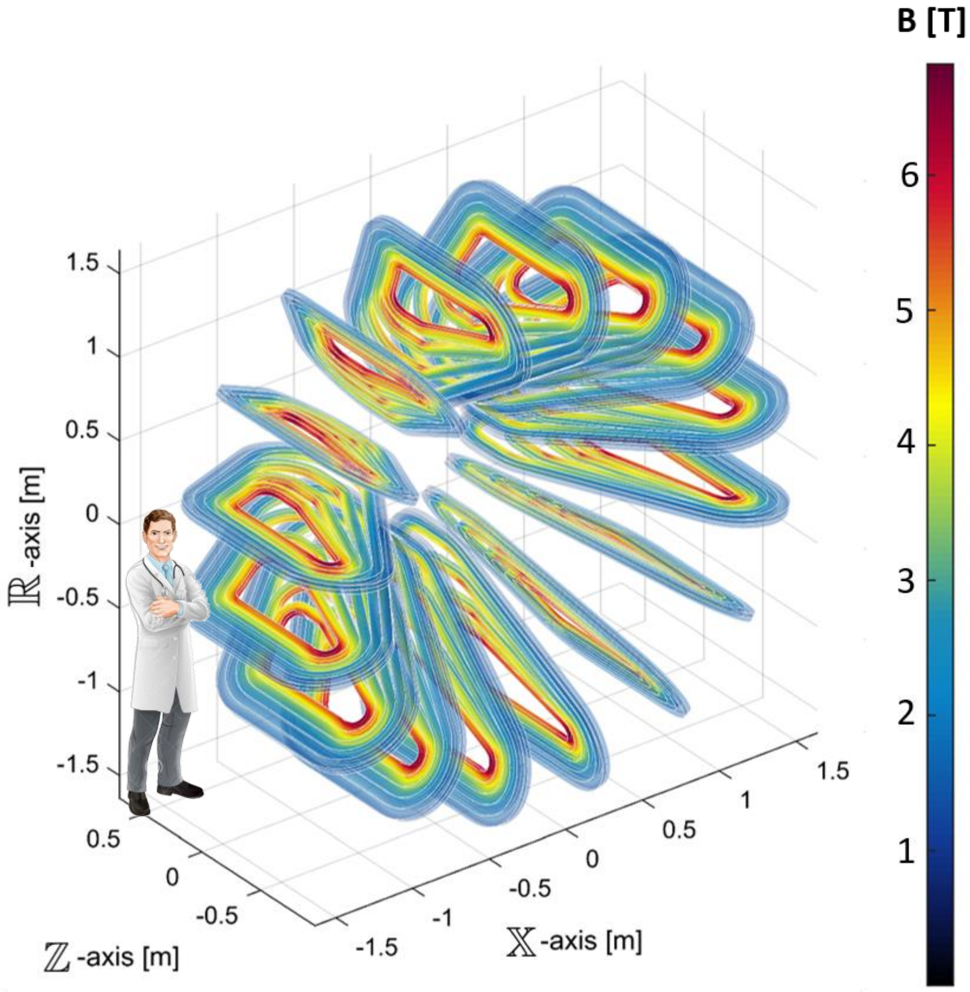
Beams directed at the isocenter within 1 mm, in the 70-250 MeV range

(Forward parametric optimization done with 7 variables)

E. Felcini *et al.*, **Magnetic design of a superconducting toroidal gantry for hadron therapy**, *IEEE Trans. Appl. Supercond.*, **30** (4) (2020)

From concept to demonstrator

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

From concept to demonstrator

Proton version by Enrico Felcini

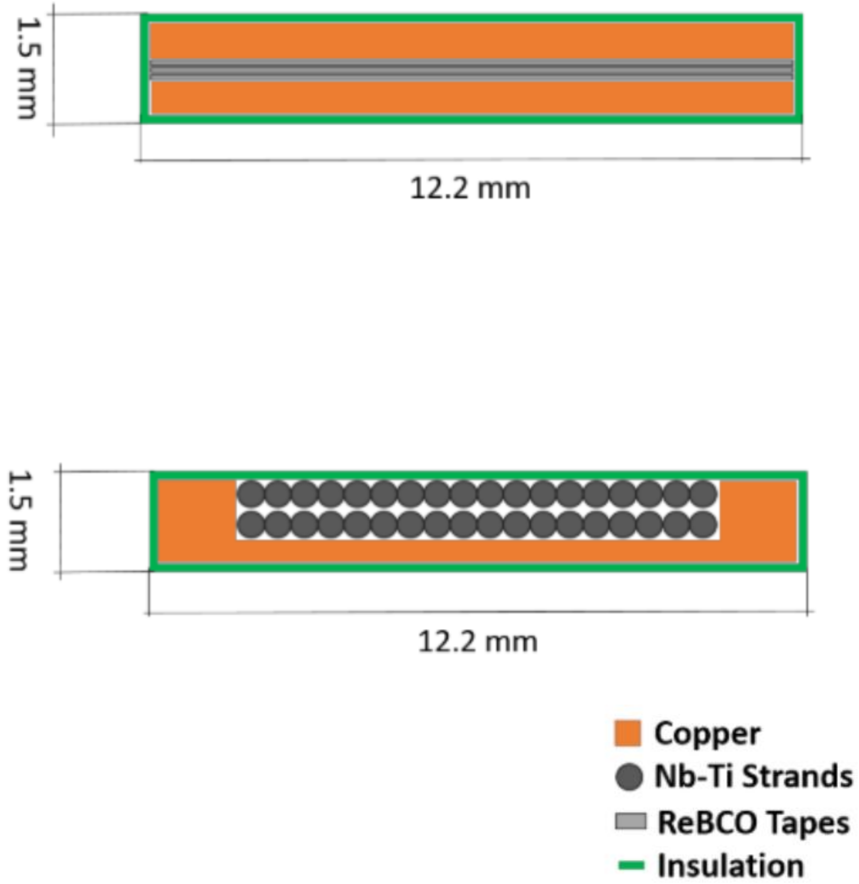
HTS

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

LTS

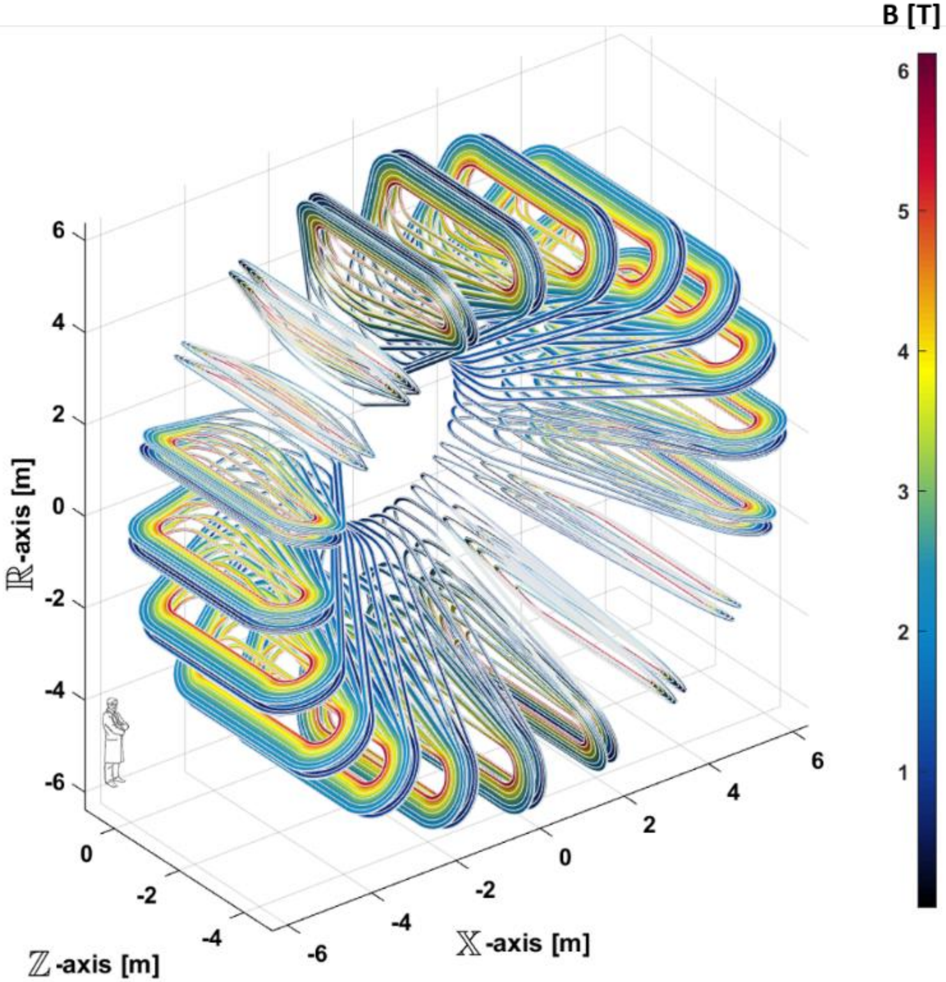
Superconductor	NbTi
Topology	Rutherford
Number of strands	36
Cu:Sc ratio	7.3
Operating temperature	4.2 K

Operating current	1800 A
Eng current density	100 A/mm2



From concept to demonstrator

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

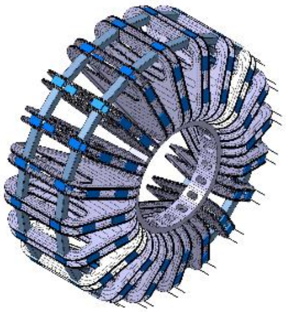
Operating temperature	4.2 K
Operating current	10.8 kA

Estimated total mass	300 tons

GaToroid – Status and Perspectives (NIMMS – Note – 003, EDMS: 2444379)

From concept to demonstrator

Carbon ions version



Protection

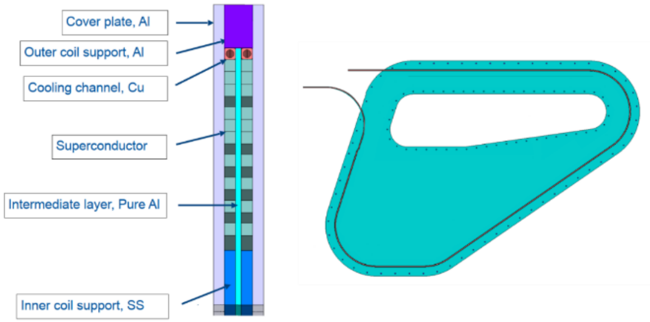
2 types of protection are feasible:

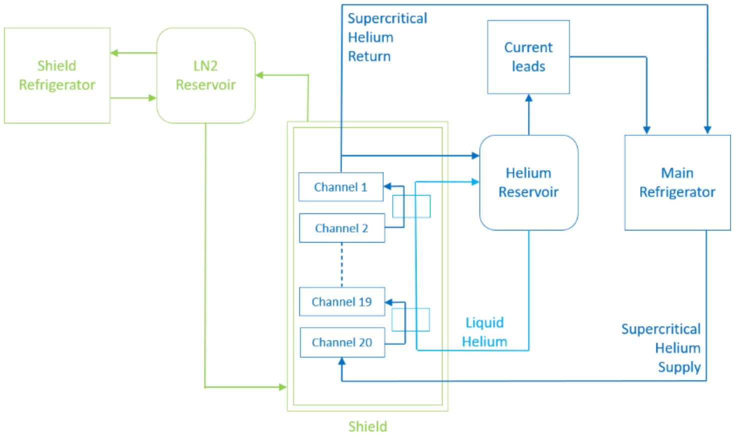
Low voltage (50 V)	Internal quench heaters	J_{eng} = 105 A/mm²	T_{max}= 130 K	Cu:Sc ~ 7
High voltage (500 V)	External dump resistors	J_{eng} = 70 A/mm²	T_{max}= 100 K	Cu:Sc ~ 12

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



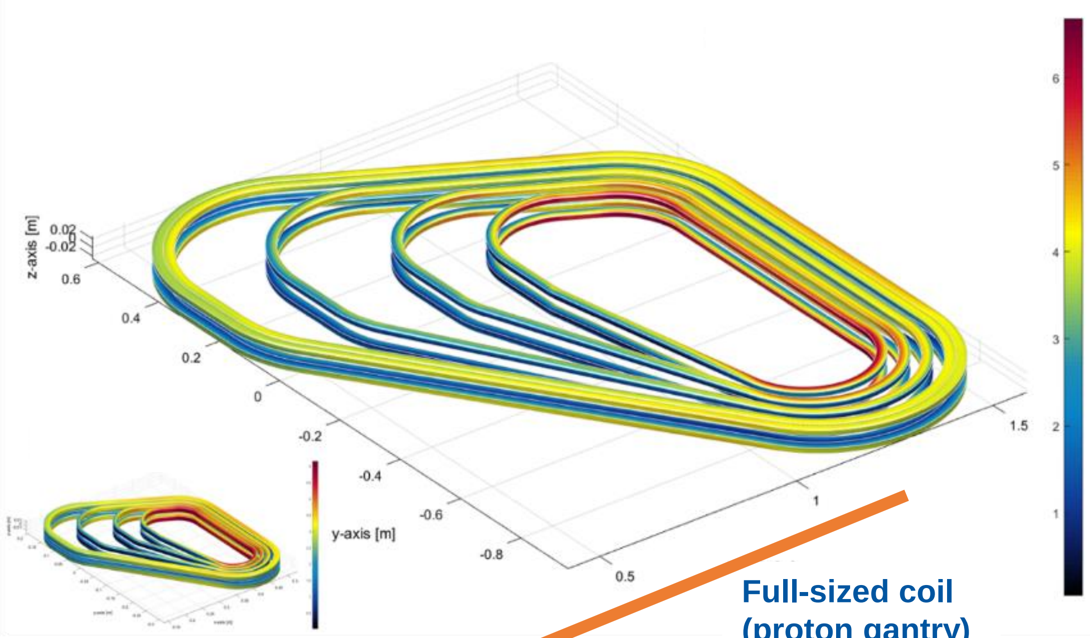


From concept to demonstrator

Demonstrator strategy

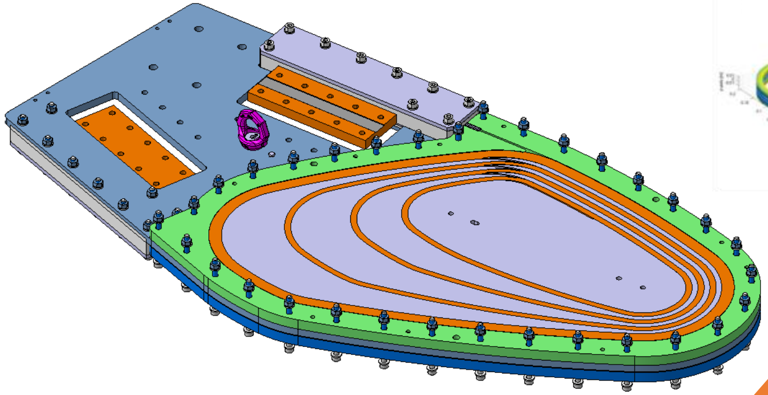
Build a Single coil scaled down from the proton design by a factor 3 so we can test it at CERN:

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



Full-sized coil (proton gantry)

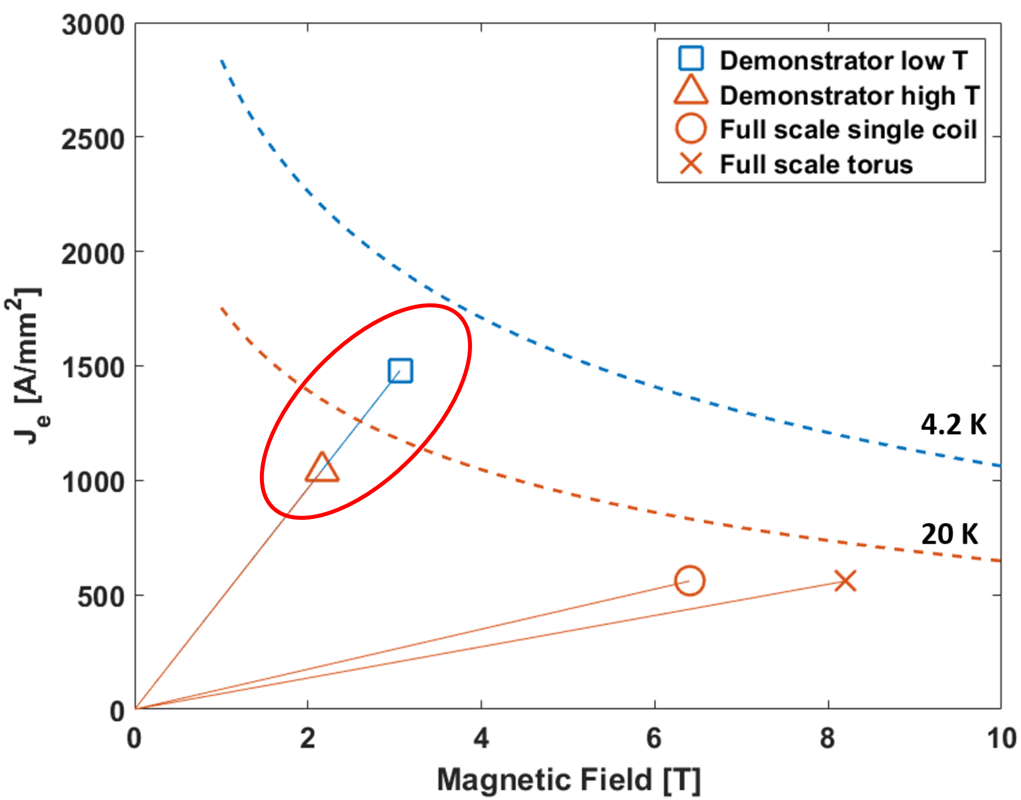
1:3 Scaled down



2x Demonstrators HTS & LTS

From concept to demonstrator

Operating conditions for HTS demonstrator



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

From concept to demonstrator

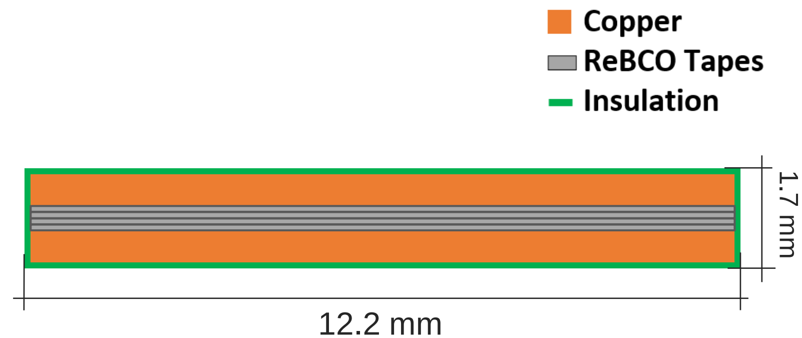
Demonstrator cable geometry

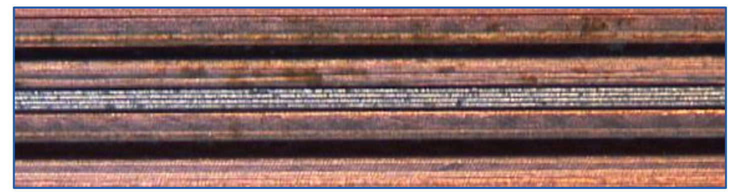
HTS

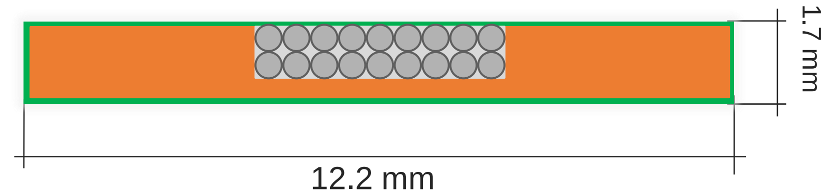
Superconductor	ReBCO
Topology	Non twisted stack
Number of HTS tape	4 (0.1 mm)
Number of Copper tape	2 (0.55 mm)
Cu:Sc ratio	5.3
Operating temperature	20 K

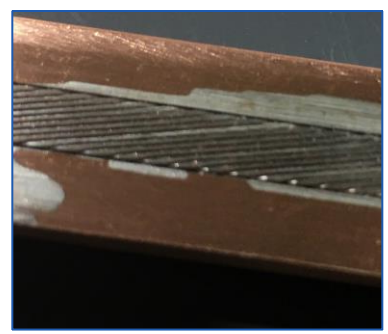
LTS

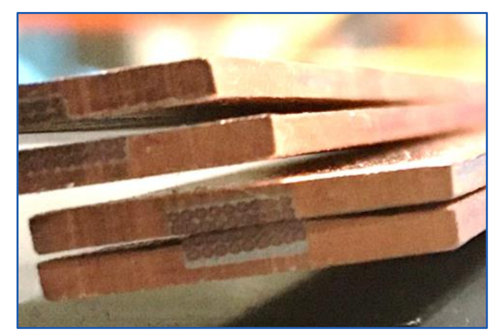
Superconductor	NbTi
Topology	Rutherford (MCBXF)
Number of strands	18
Cu:Sc ratio (with Cu profile)	10.8
Operating temperature	4.2 K











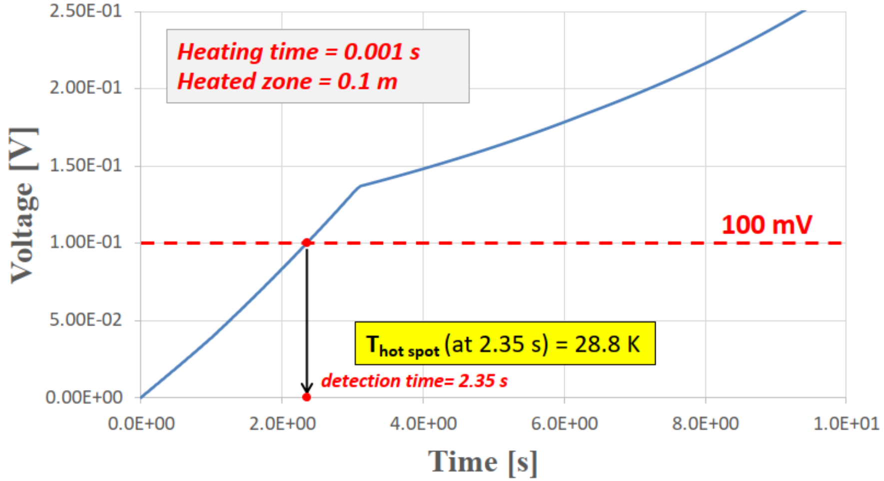
From concept to demonstrator

Quench protection

LTS (NbTi):
1D adiabatic model for quench propagation. Cable as single element.

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

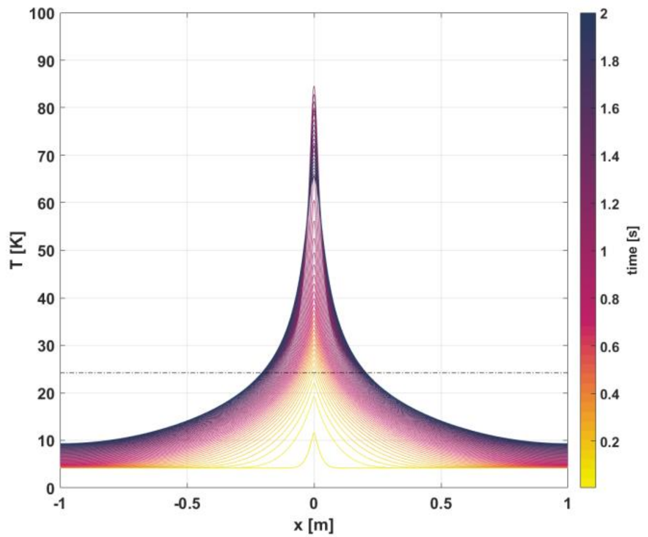
- Time to reach threshold (100 mV): 2.35 s
- Peak temperature: 30 K
- Quench velocity 3.1 m/s



HTS:
1D adiabatic model for quench propagation. Cable as single element.

- 1 cm local defect as MQE is too high (16 J/cc)

- Time to reach threshold (50 mV): 1.1 s
- Peak temperature: <100 K
- Quench velocity 25 cm/s



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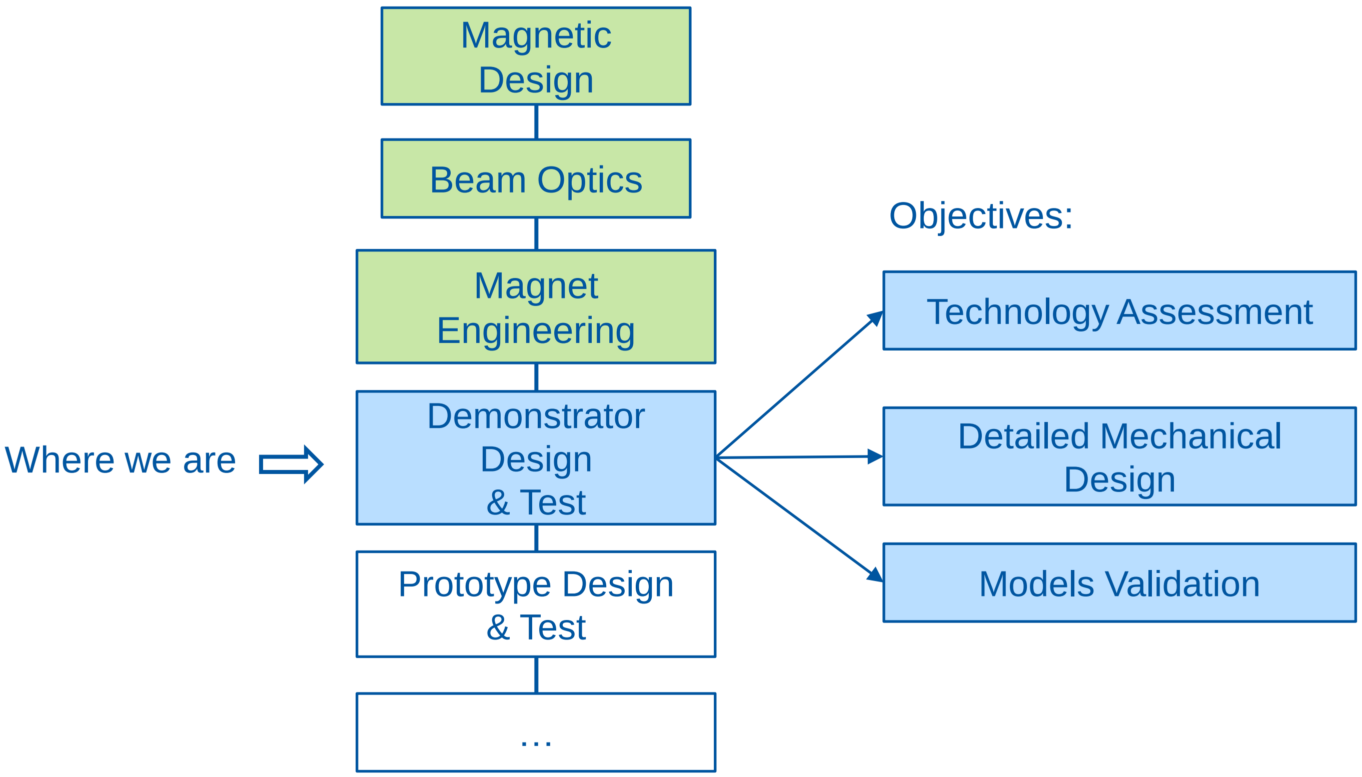
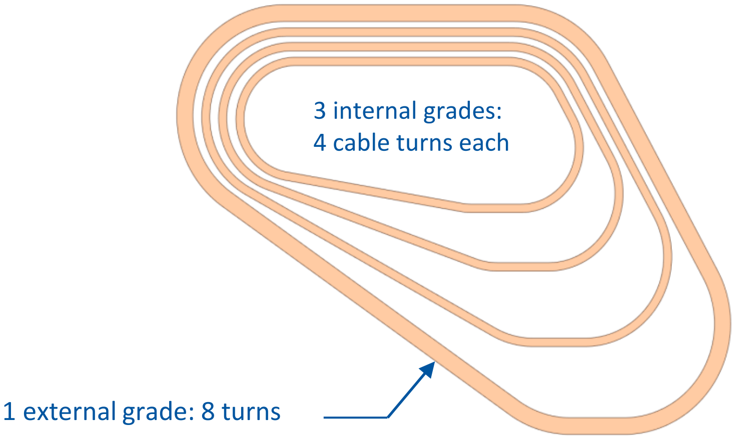
Demonstrator design & analysis

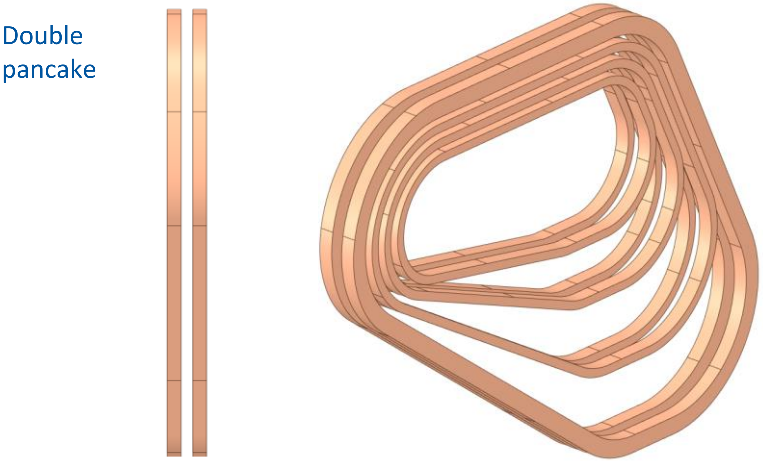
Project workflow



Demonstrator design & analysis

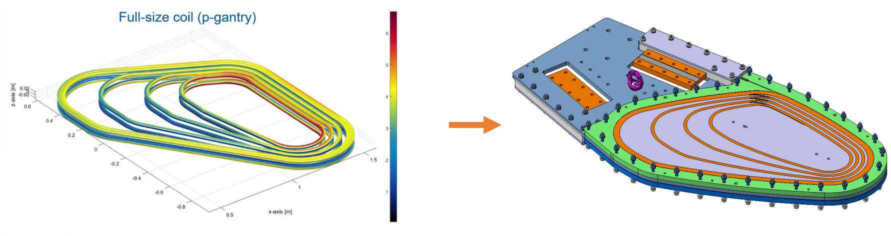
- Geometry: Coil of the **proton gantry** scaled down of a factor 3
- Baseline version meets **only field requirements**
- The goal now is to design a magnet whose geometry can be manufactured **both** in HTS and LTS versions.
- The design of the demonstrator should be representative of the full scale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

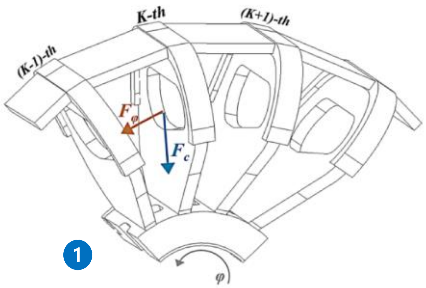




Demonstrator design & analysis

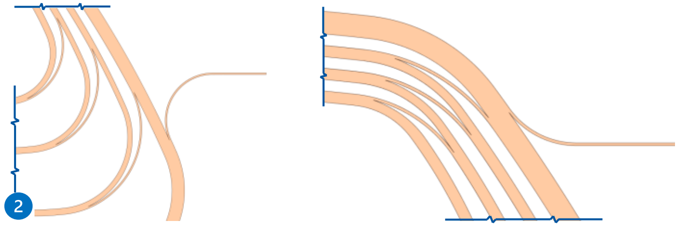
Requirements to be fulfilled moving from an ideal coil to the real one:



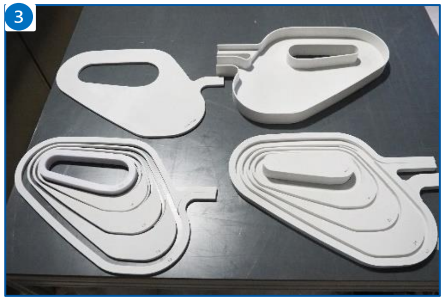


Structurally stable magnet 1

To be powered at cold 2



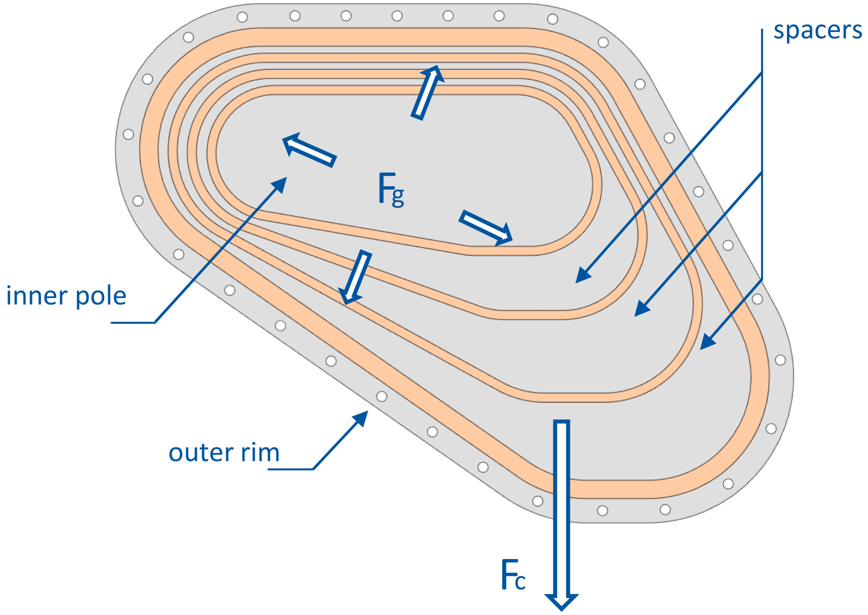
To be manufactured/assembled 3

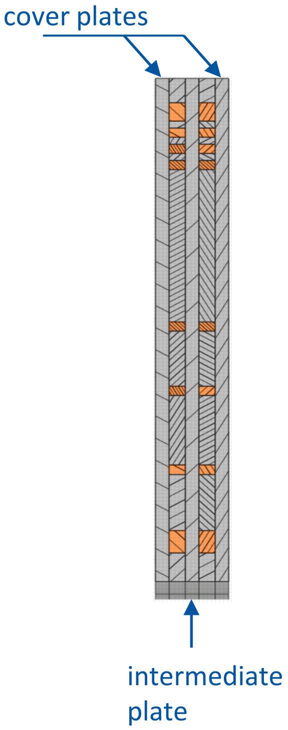


Demonstrator design & analysis

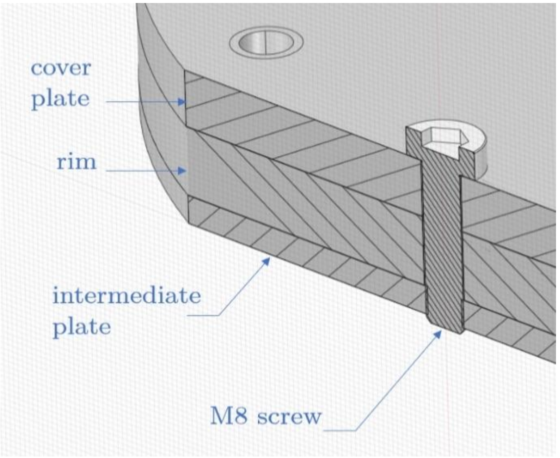
Design process

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

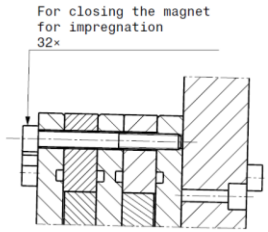
Demonstrator design & analysis

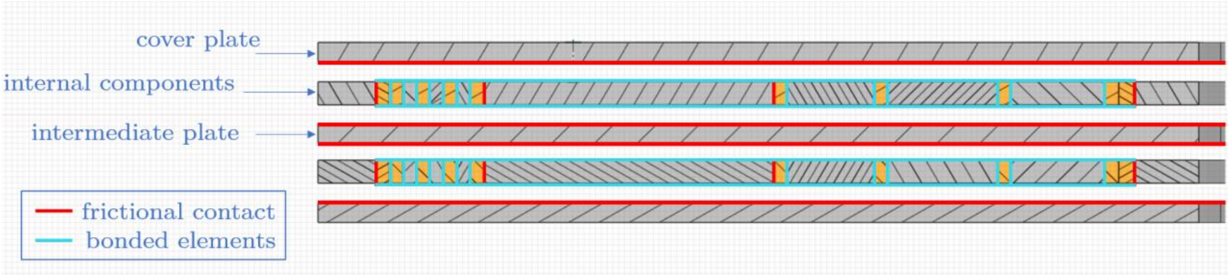
Design process

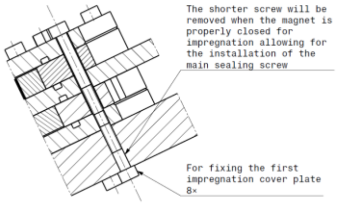
Impregnation

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*).







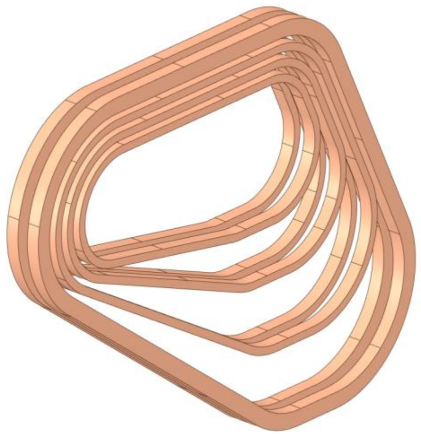
*Surface contact properties (μ) from experimental tests' results – courtesy of G. Spigo

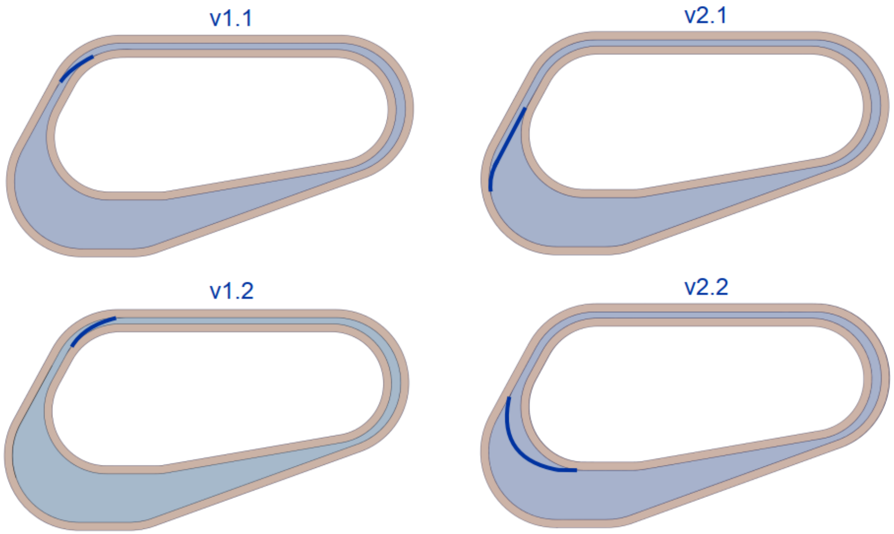
Demonstrator design & analysis

Design process

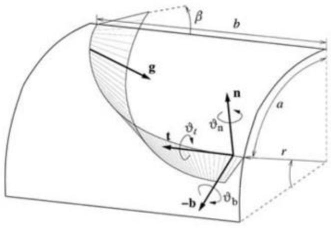
Operational apsects

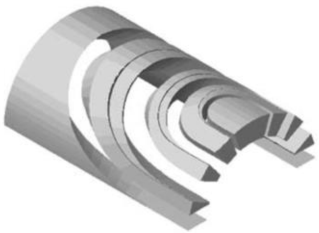
- Need for **electrical connection** to the power source;
- Electrical continuity between layers: **layer jump**;
- Electrical continuity between grades*: **grade jumps**;





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





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

Demonstrator design & analysis

Design process

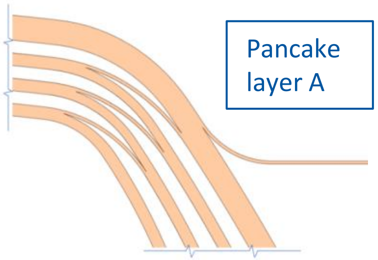
Grade and layer jumps

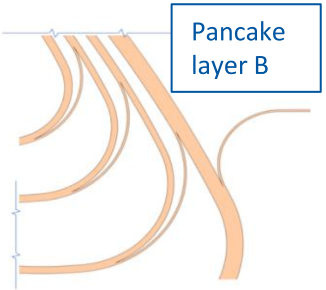
Jumps between grades and pancacke layers **perturbate** the magnetic field map in two ways:

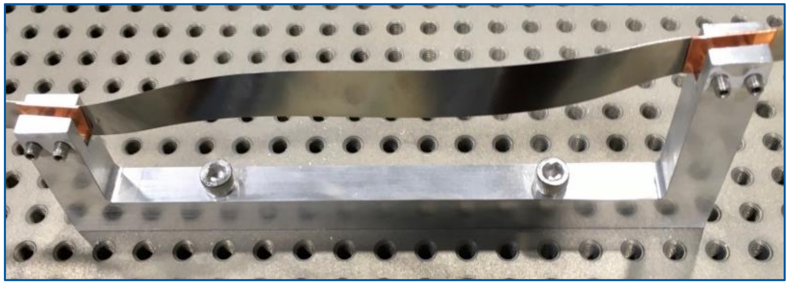
1. Contribution due to the current flowing inside the conductor itself;
2. Local reduction of the number of cable turns in grades.

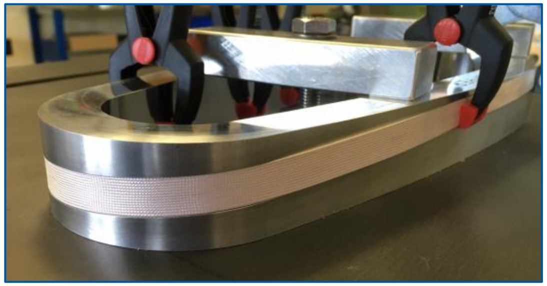
Minimal field variations and beam delivery properties close to nominal are granted if the jumps' **length** is **minimized**, and if these happen in the "**back**" of the magnet.

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.





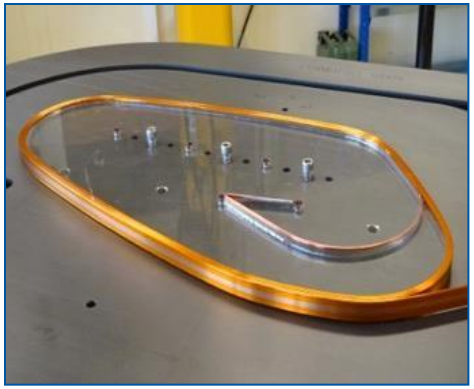




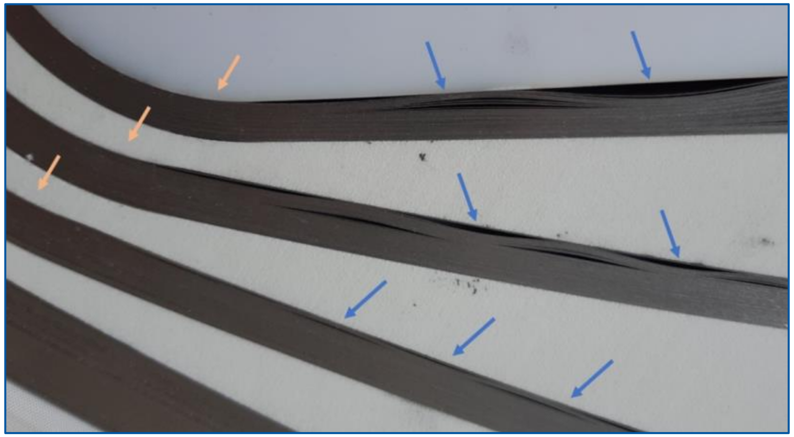
Demonstrator design & analysis

Design process

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) →

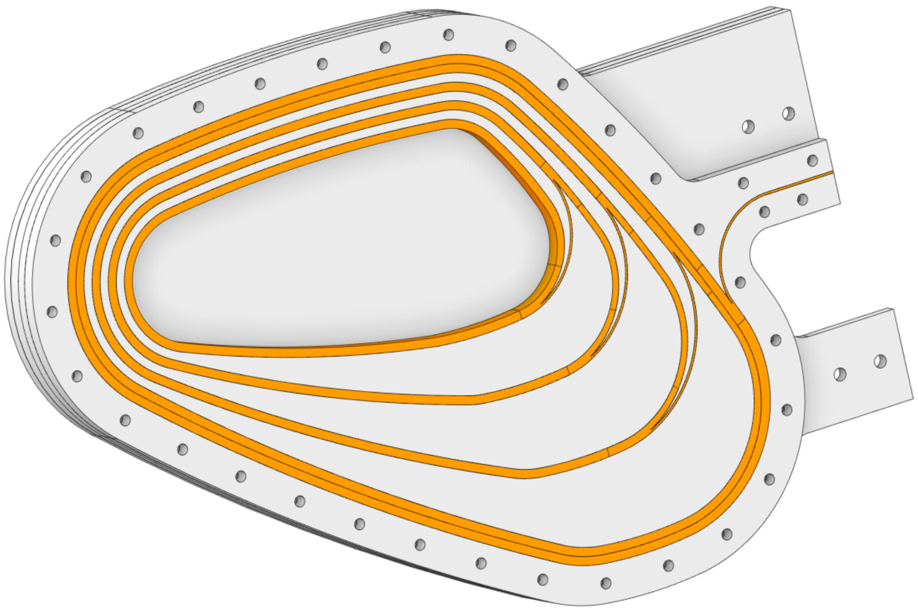
  - possible cause: too rapid transition from circular sectors to the straight ones

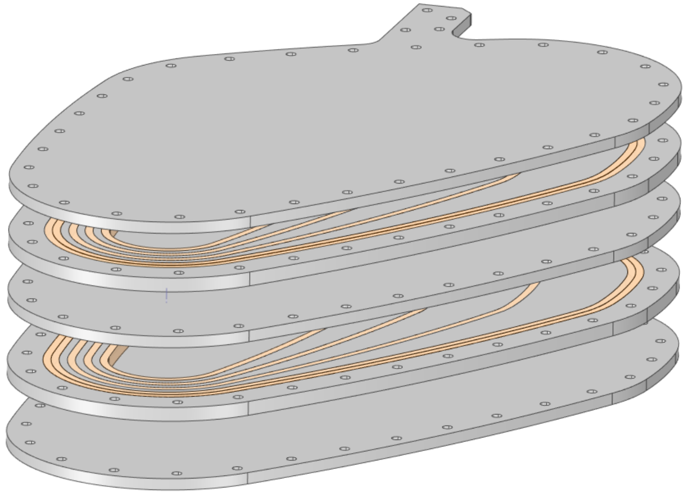
  - possible solution: change grades shape, and use **large radius arcs**

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

Demonstrator design & analysis

Baseline for FEA



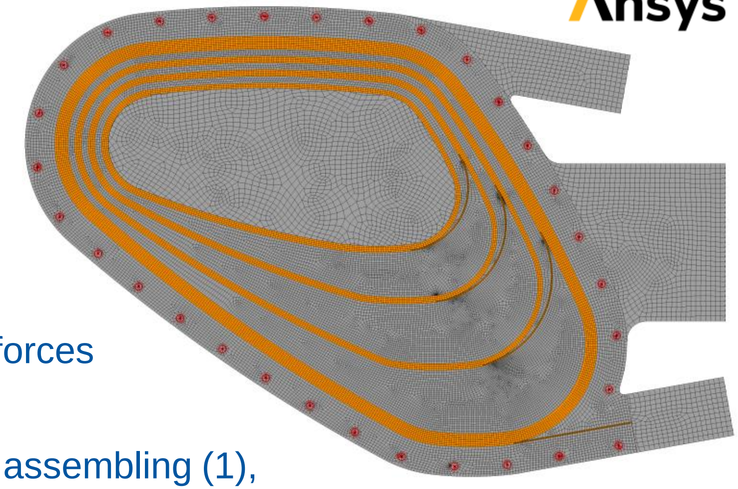


Geometries prepared for FEA in SPACECLAIM

Demonstrator design & analysis

Verification through FEA

Approach



3D Finite Element Analyses using Ansys APDL.

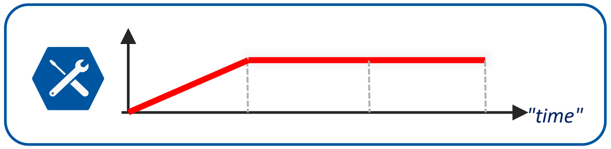
Three steps analyses:

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).

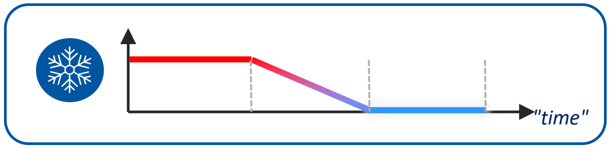
Elements ~ 500 000 (second order)
Runtime ~ 48 h per model

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

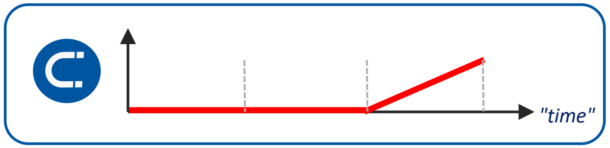
1. Bolts' pretension to 13.3 kN



2. Cryogenic cool down to 4.2 K



3. Magnetic (Lorentz) forces



Demonstrator design & analysis

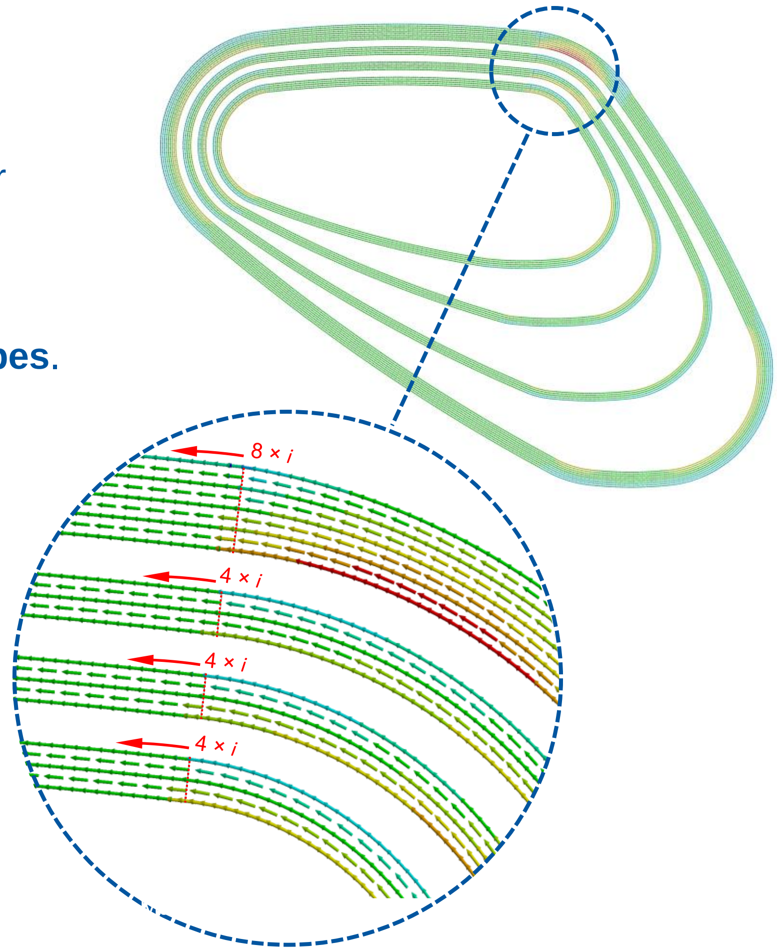
Verification through FEA

Electrical analysis

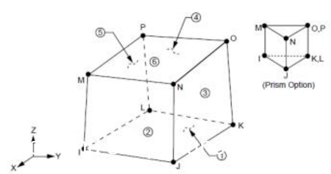
Fairly simple geometry, but direct assignment of current densities ($\mathbf{J}_i$) requires definition of local coordinate system for each arc (or even element).

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).

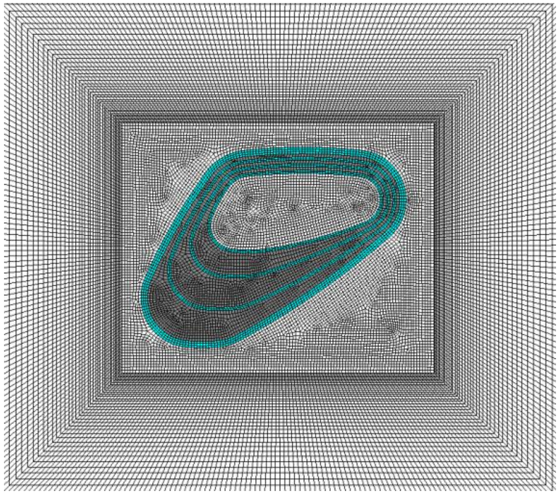


Ansys Element*: SOLID5
DOF: Volt



Demonstrator design & analysis
Verification through FEA

Magnetostatic analysis



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

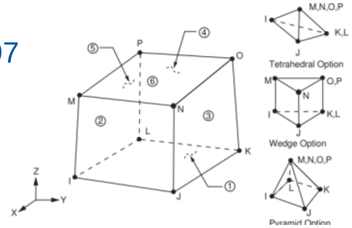
Ansys Element SOLID97* uses a differential formulation in terms of magnetic vector potential **A**.

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

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

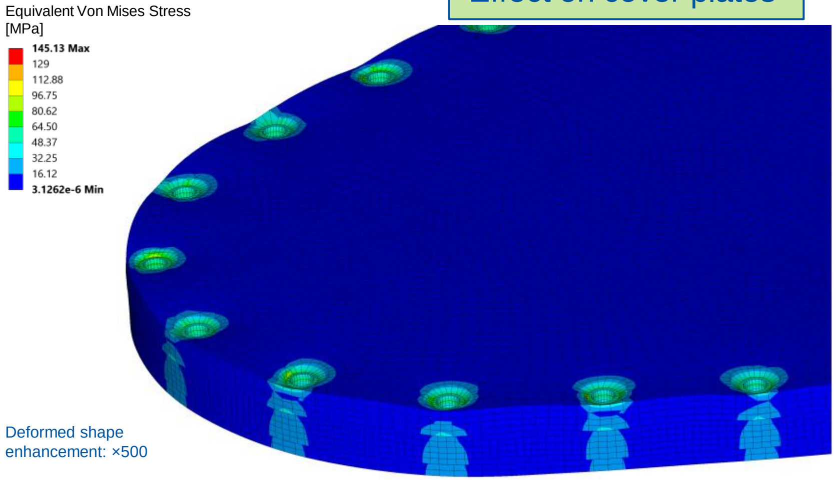


Demonstrator design & analysis
Verification through FEA

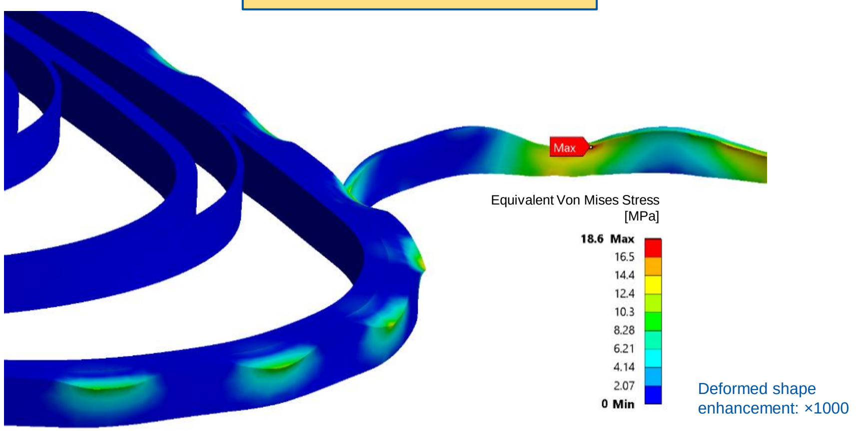
Mechanical analyses: Bolts’ pretention

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

Effect on cover plates



Effect on windings



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

Demonstrator design & analysis

Verification through FEA

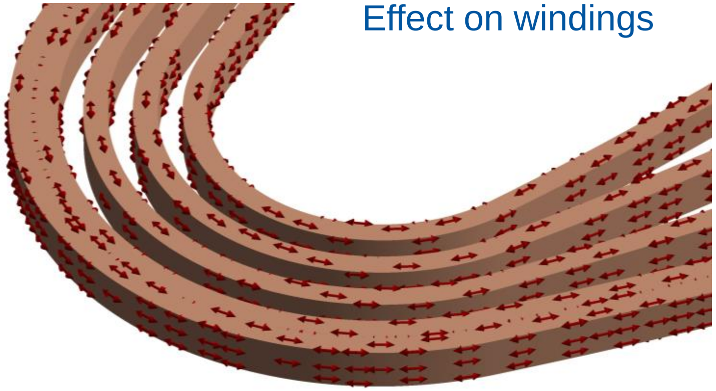
Mechanics: Cryogenic cooldown

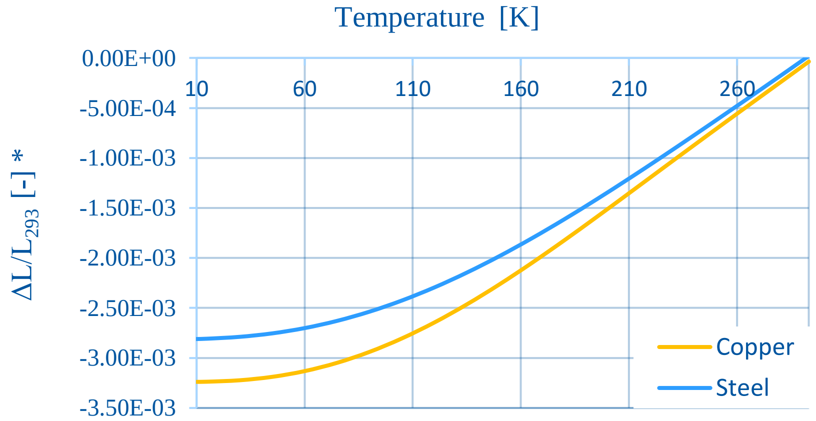
Stresses develop due to **CTE differences**:

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

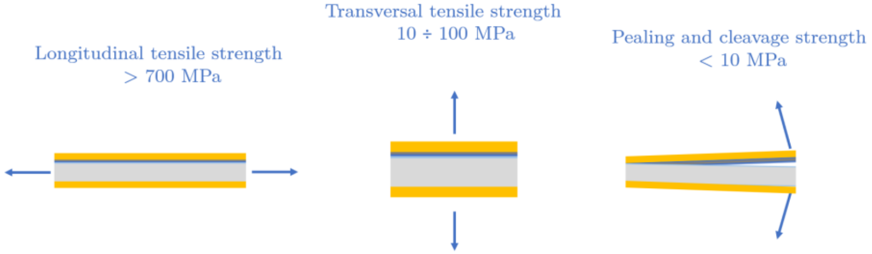
Values refer to integrated CTEs.

Effect on windings





ReBCO tapes (**laminated**) strength characteristics



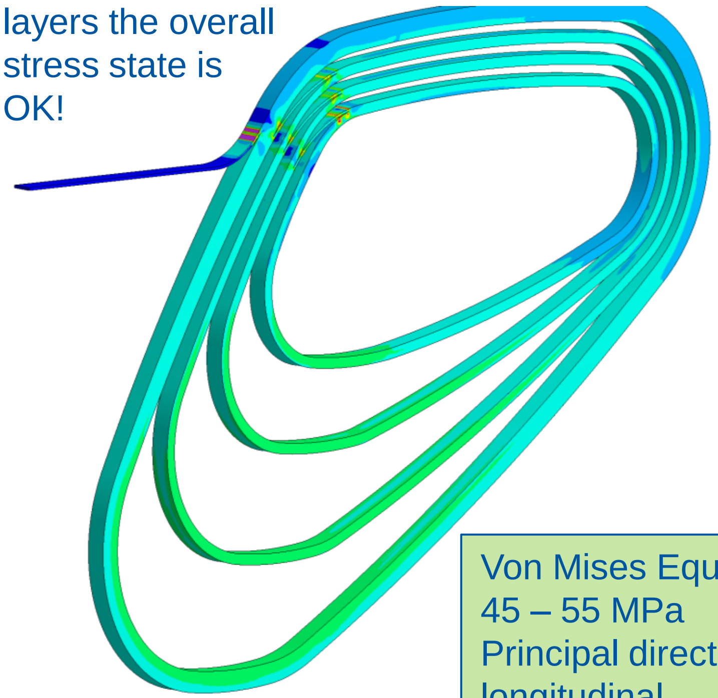
*Thermoelasic properties from EuCARD[2] - Thermal Contraction Data – Glyn Kirby et Al.

Demonstrator design & analysis

Verification through FEA

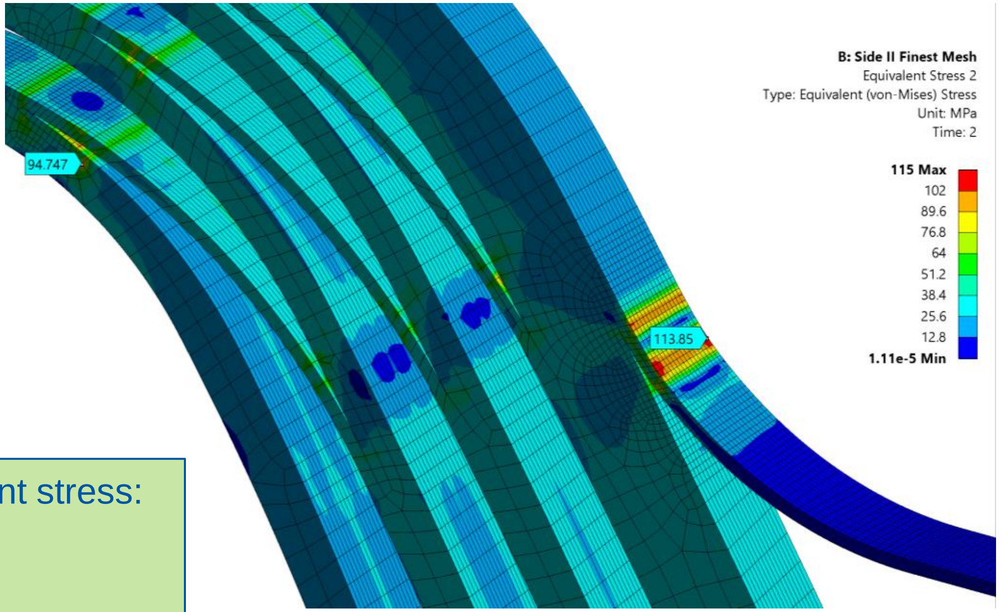
Cryogenic cooldown

For both pancake layers the overall stress state is OK!



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

But stress peaks on one side!

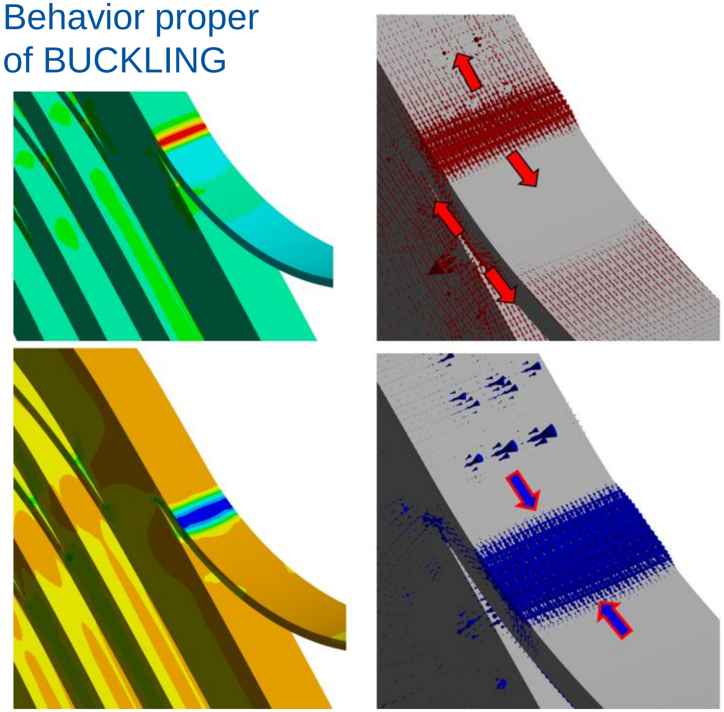


Demonstrator design & analysis

Verification through FEA

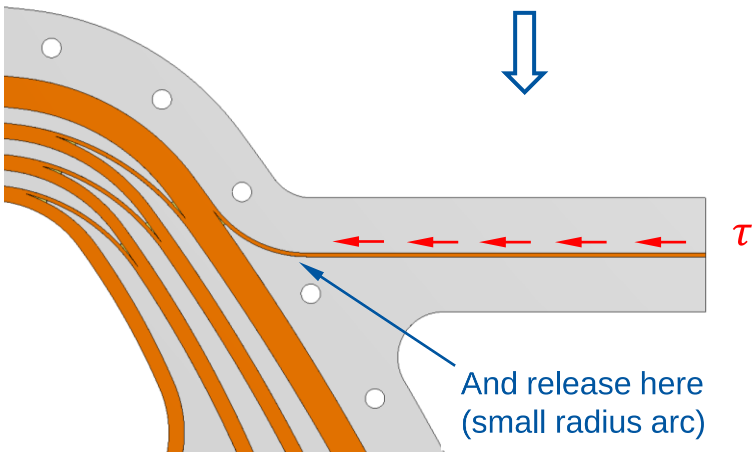
Critical phase: cooldown

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.

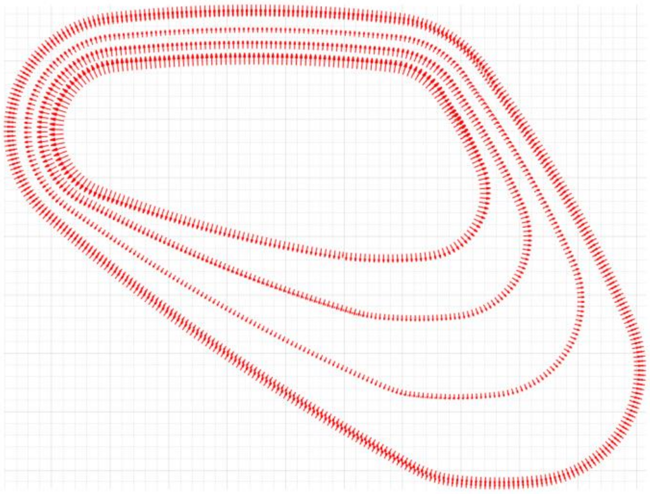
Demonstrator design & analysis

Verification through FEA

Lorentz forces

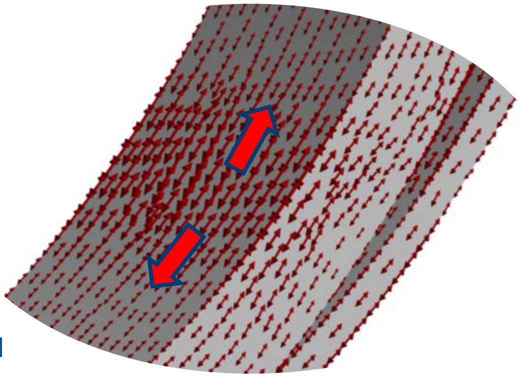
Minor effects of Lorentz forces.

Tend to expand the coil
→
longitudinal stresses



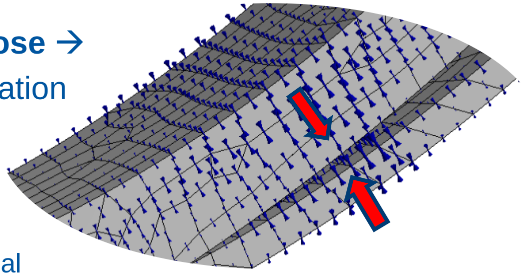
Von Mises Equivalent stress increments of 5 – 20 MPa
Mean value inside windings: **60 MPa**

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

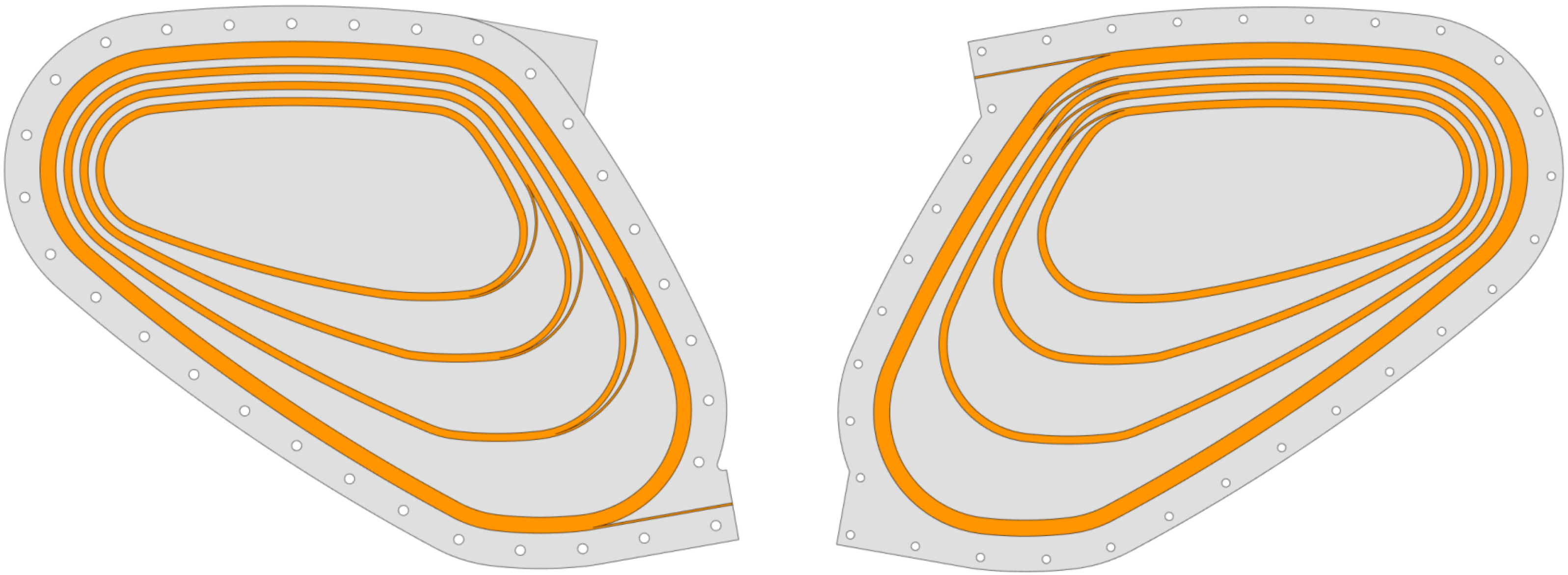


Vector-plot of **minimum** principal stresses

Demonstrator design & analysis

New geometry

Straighter cable inlet and outlet and new behavior at interfaces.



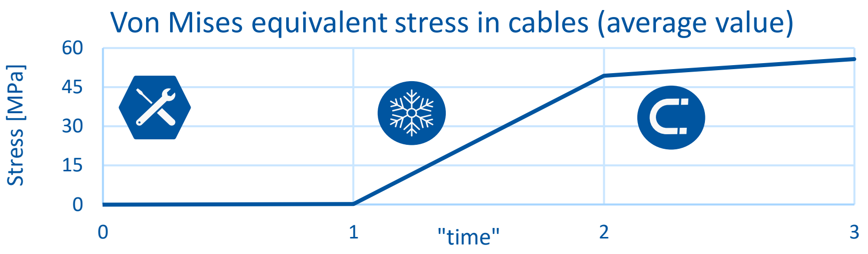
Demonstrator design & analysis

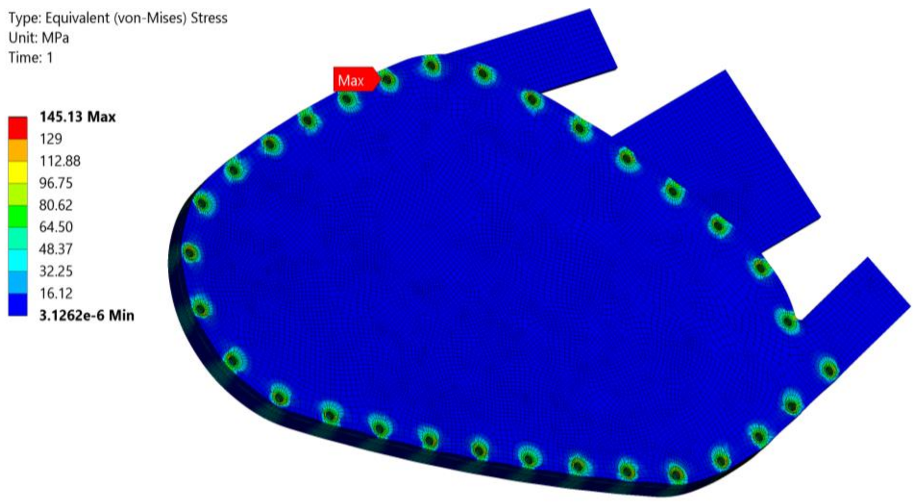
Final configuration results

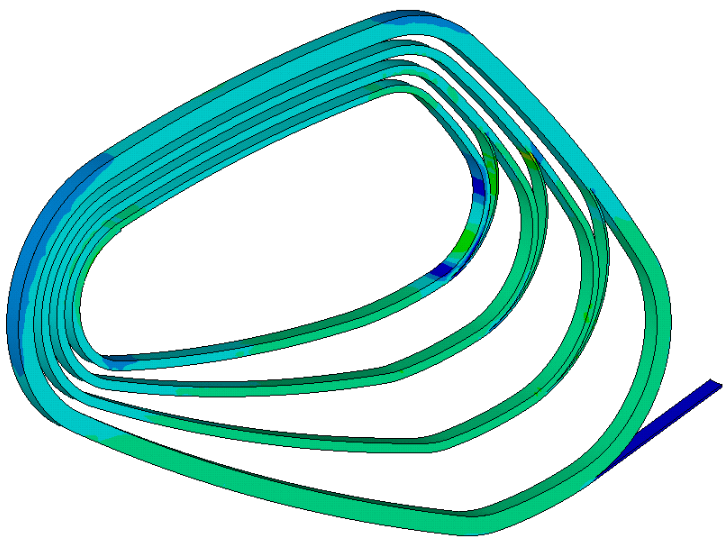
Stress state is stable.

Von Mises Equivalent stress intensity:

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

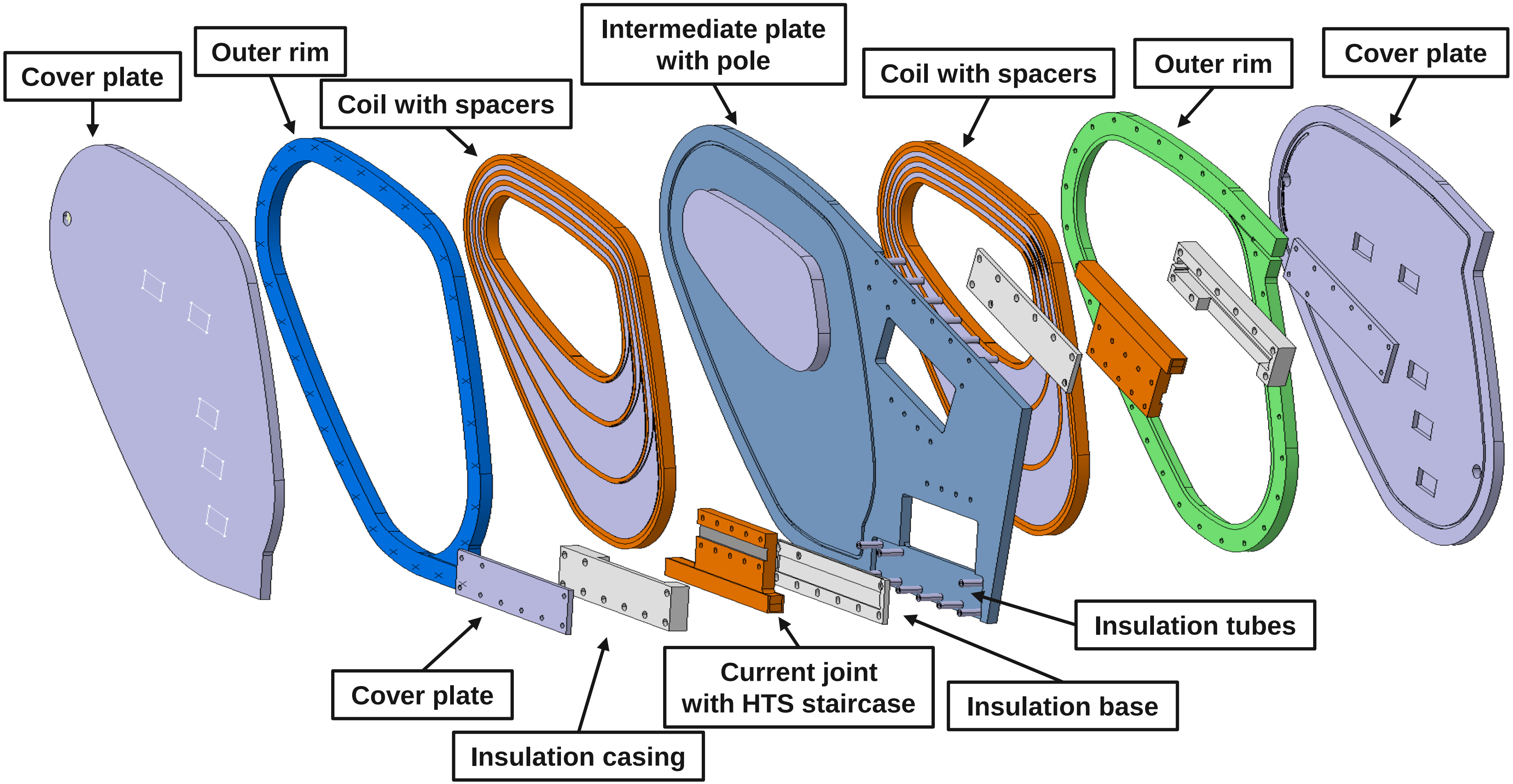






Demonstrator design & analysis

Final design



Demonstrator design & analysis

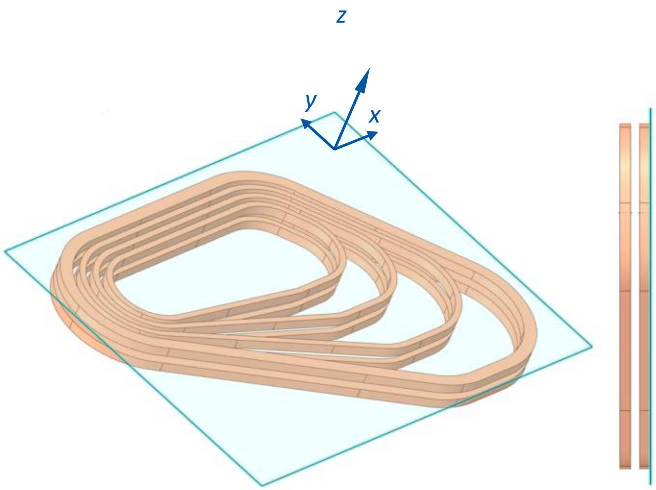
Magnetic field and instrumentation

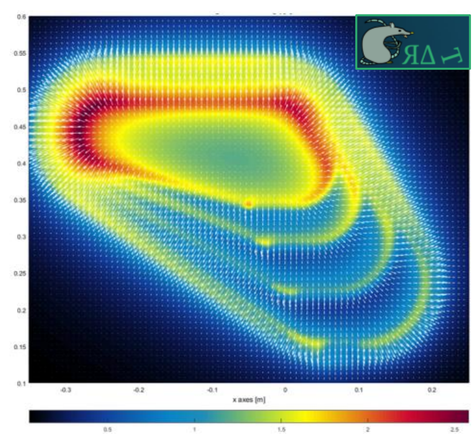
To **validate** the FE procedure, Ansys results on the ideal coil have been compared to those previously calculated with RAT* (E. Felcini) in its Matlab version.

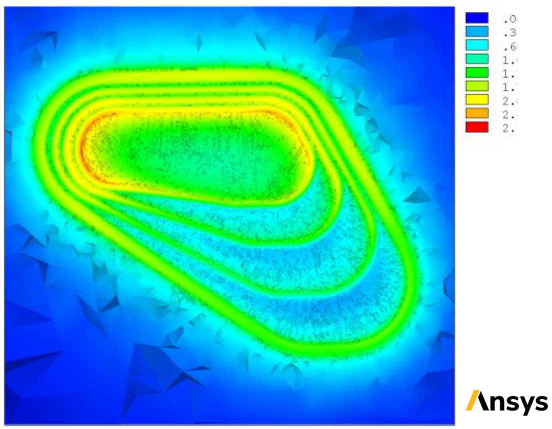
The comparison is done on a **referece plane**, where the magnetic sensors will be ideally positioned.

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.





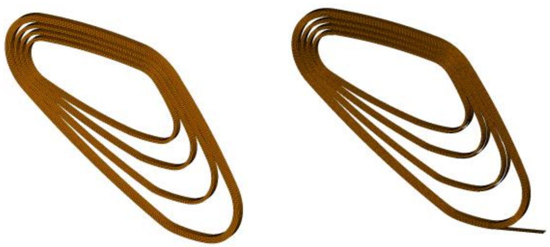


* Jeroen van Nugteren - https://indico.cern.ch/event/856850/

Demonstrator design & analysis

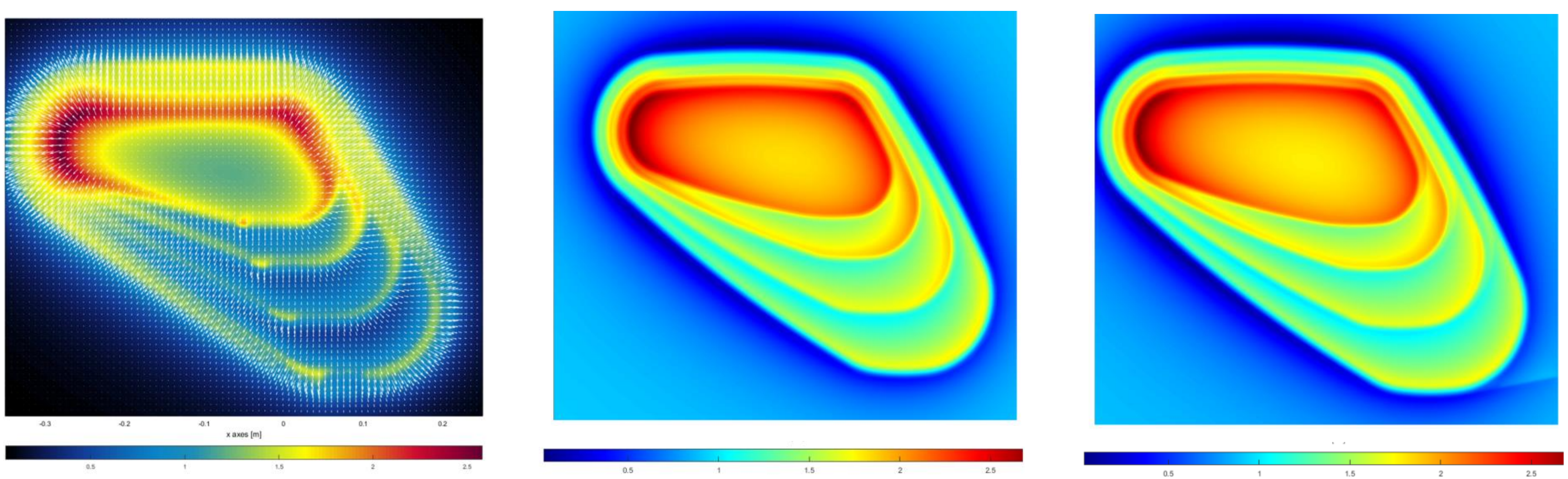
Magnetic field and instrumentation

Procedure



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

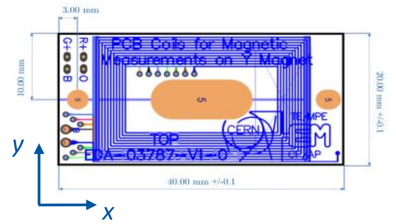
Beside this being usual practice in FE modelling, it helps **understanding the errors committed** with different levels of approximations.



Demonstrator design & analysis

Magnetic field and instrumentation

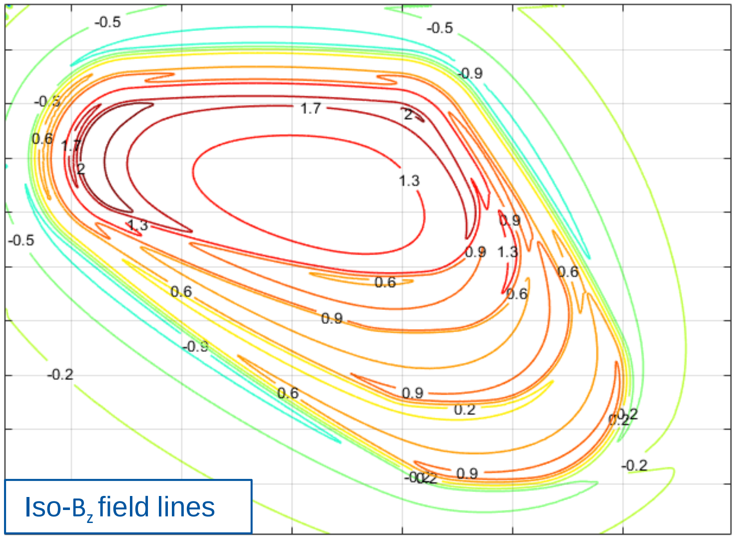
Positioning of magnetic sensors (PCB)

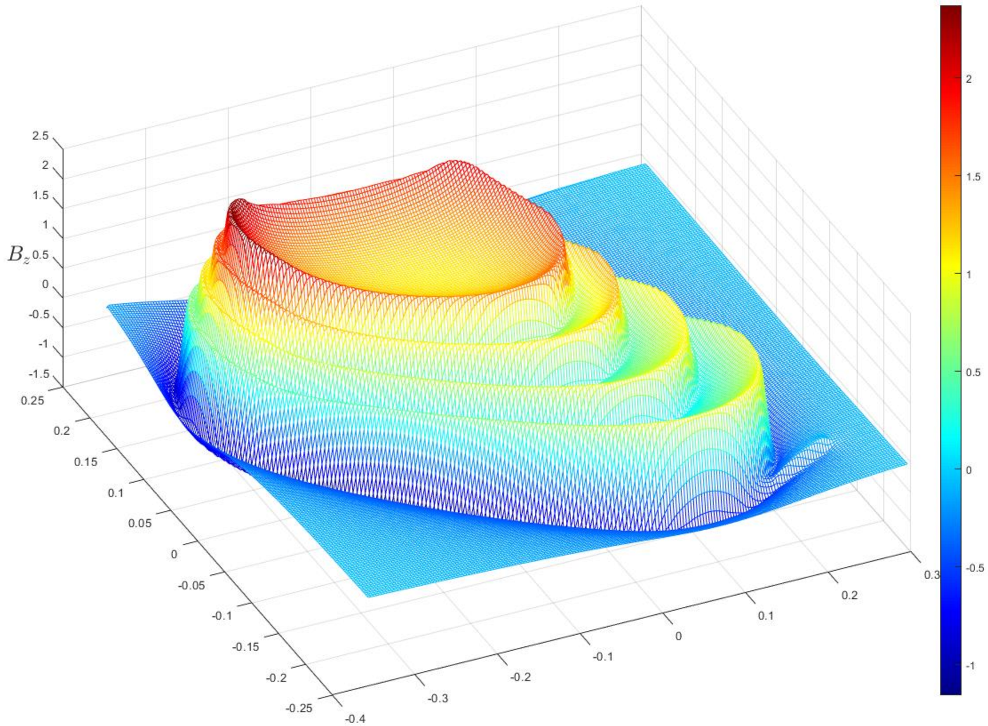


Final field map from FE taken **as a reference**.

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

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





Demonstrator design & analysis

Magnetic field and instrumentation

Positioning of magnetic sensors

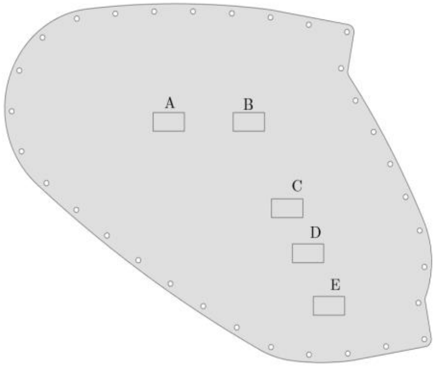
First hypothesis on **sensors' positions** and calculation of expected measures.

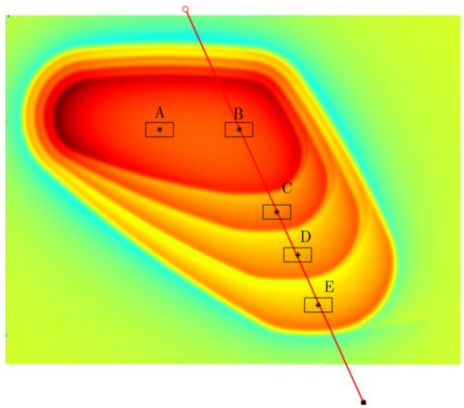
Mean field **perpendicular** to PCB : $\widehat{B}_z$

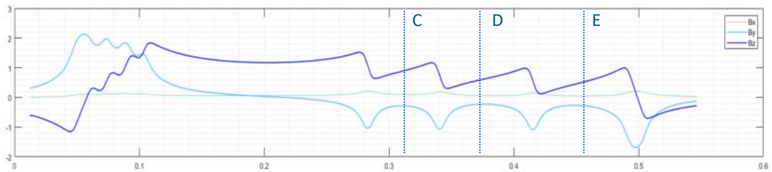
$$\widehat{B}_z = \frac{\phi}{A} = \frac{1}{A}\iint_{PCB} B_z \cdot dA$$

Mean field **parallel** to PCB: $\widehat{B}_p$

$$\widehat{B}_p = \frac{1}{A}\iint_{PCB} \sqrt{{B_x}^2 + {B_y}^2} \cdot dA$$







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

Very good. We don't move them.

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

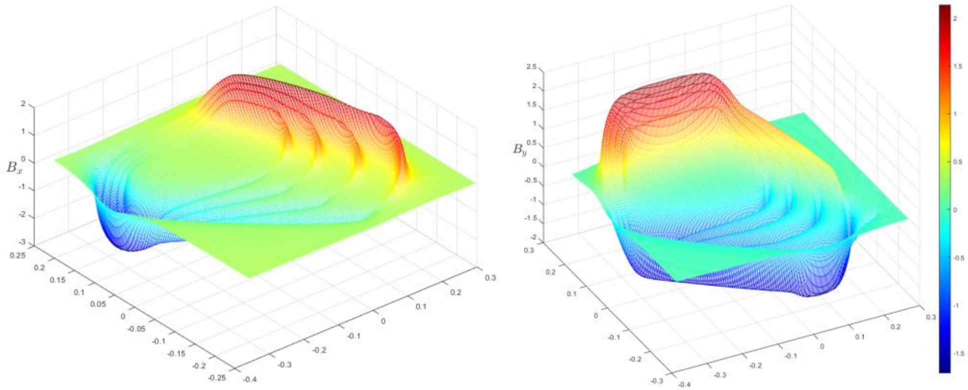
Demonstrator design & analysis

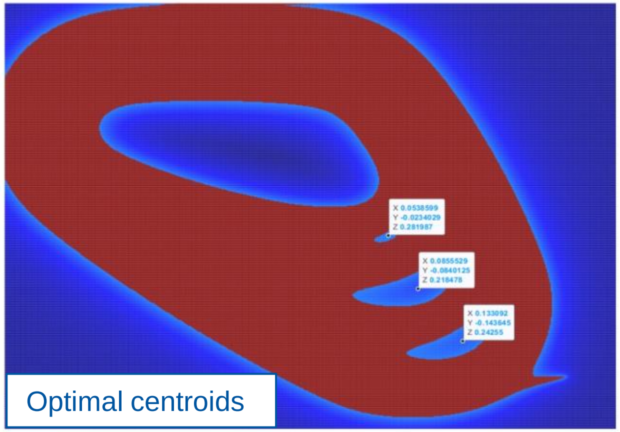
Magnetic field and instrumentation

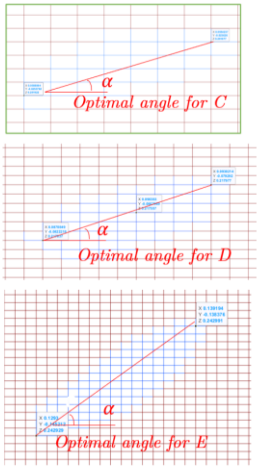
Finding the optima

- We can observe the **in plane-components** of **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 B_z
- And finally **rotate** the coordinate system with a rotation matrix [R]

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





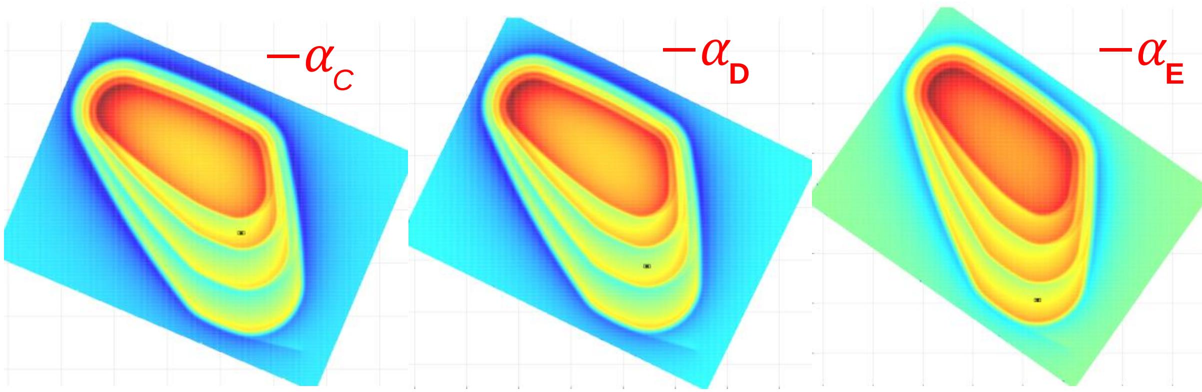


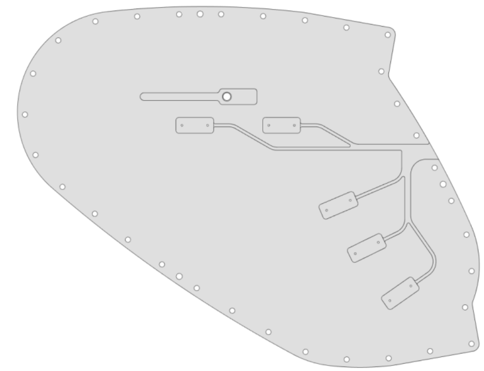
Demonstrator design & analysis

Magnetic field and instrumentation

New results after rotation

Numerical integration at new locations, on tilted areas.





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

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

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

Demonstrator design & analysis

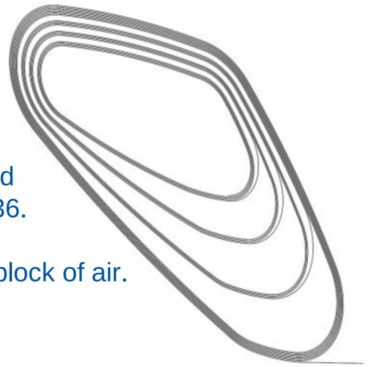
Future perspective

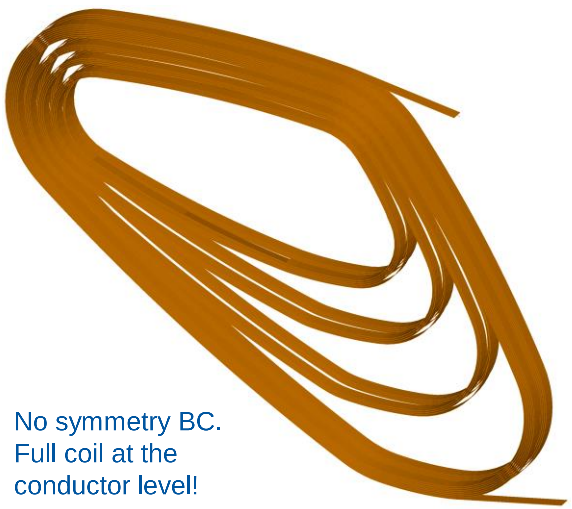
Magnetic scalar potential model

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

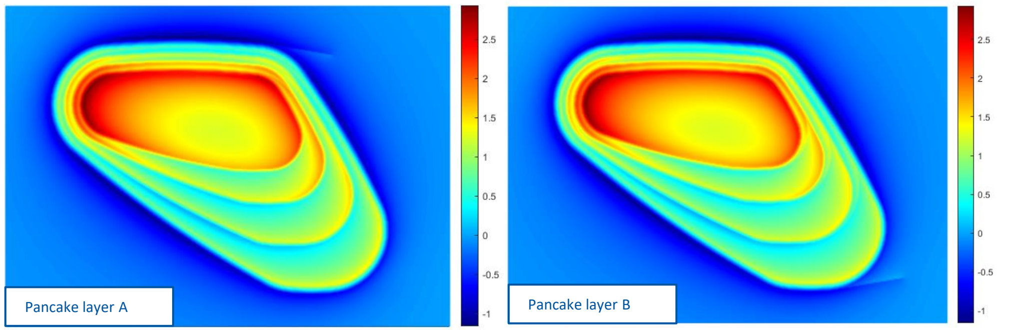
Only conductors' traces meshed with SOURC36.

The rest is a block of air.

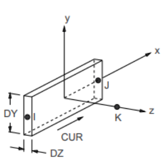




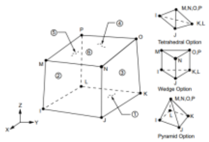
No symmetry BC.
Full coil at the conductor level!



Ansys Element: SOURC36
Properties: Current



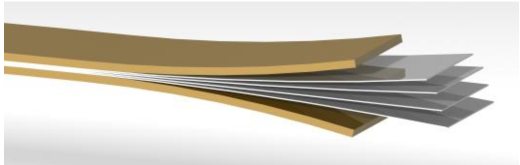
Ansys Element: SOLID96
DOF: MAG (Φ)

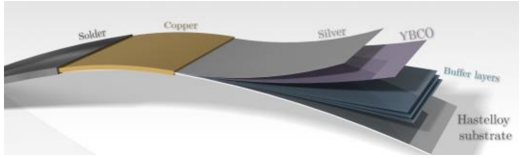


Demonstrator design & analysis

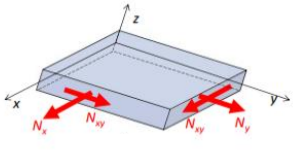
Future perspective

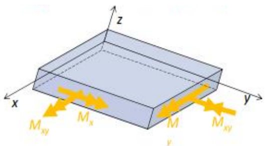
Mechanical models





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



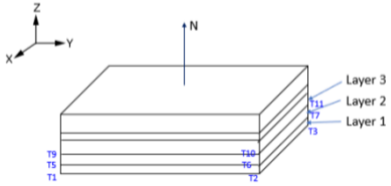


$$\begin{Bmatrix} N_x \\ N_y \\ N_{xy} \end{Bmatrix} = \sum_{k=1}^{N} \int_{z_{k-1}}^{z_k} \begin{Bmatrix} \sigma_{xx}(z) \\ \sigma_{yy}(z) \\ \tau_{xy}(z) \end{Bmatrix} dz$$

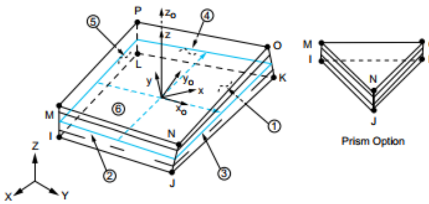
$$\begin{Bmatrix} M_x \\ M_y \\ M_{xy} \end{Bmatrix} = \sum_{k=1}^{N} \int_{z_{k-1}}^{z_k} \begin{Bmatrix} \sigma_{xx}(z) \\ \sigma_{yy}(z) \\ \tau_{xy}(z) \end{Bmatrix} z dz$$

Several Ansys elements could serve this purpose:

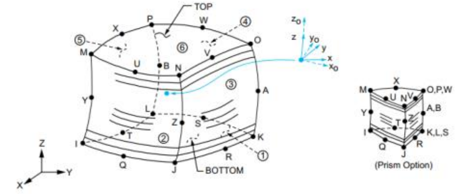
Ansys Element: **SHELL181**
Theory: **Kirchhoff** (thin plates and shells)
4 nodes, DOF: U_i, ROT_i



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

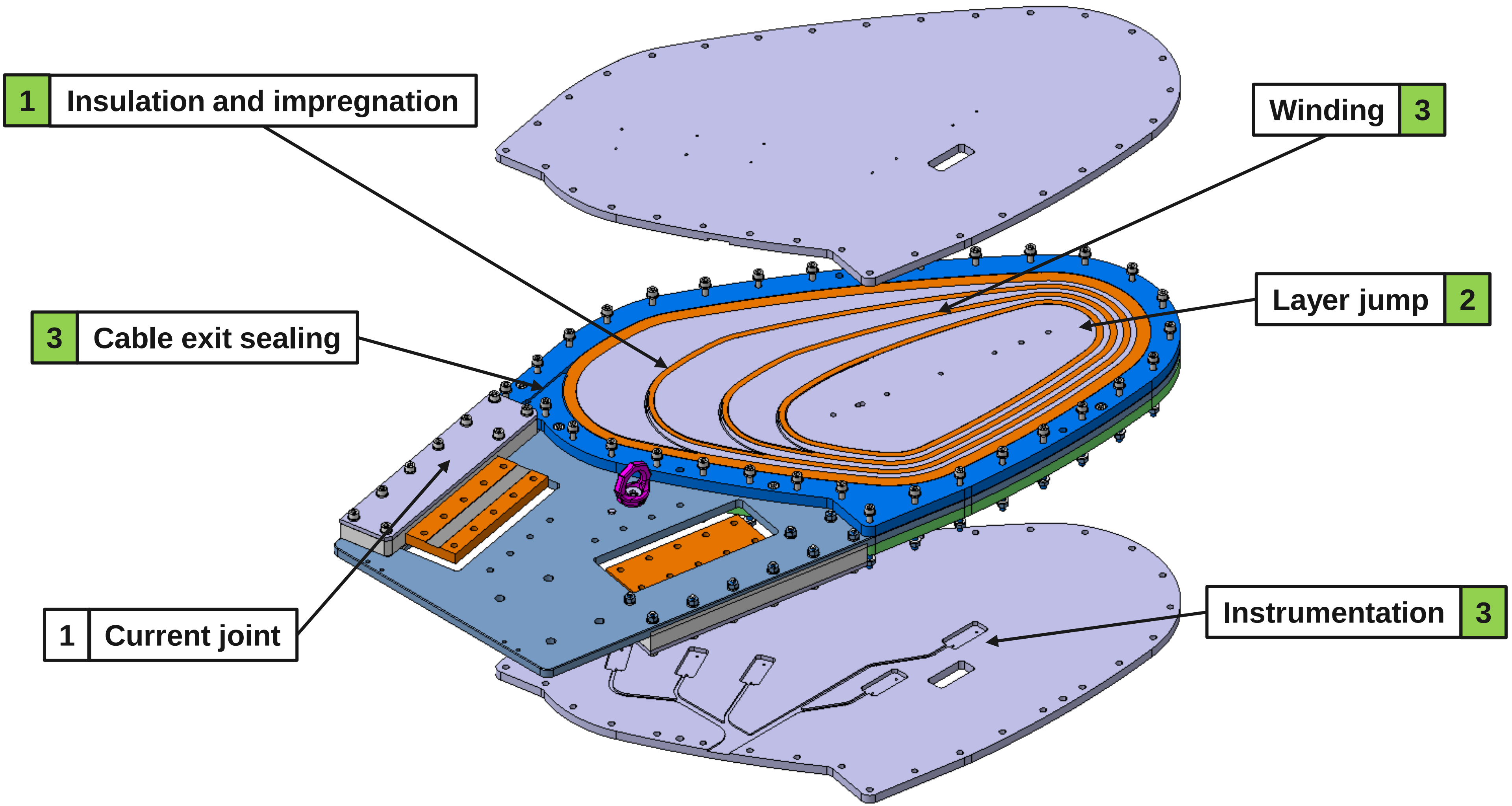


For formulation and shape functions refer to ANSYS Element Reference Manual

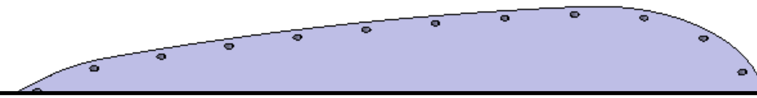
Outline

- Context (Hadron therapy / Gantries)
- From concept to demonstrator
- Demonstrator design & analysis
- Status on technology developments
- Perspectives

Status on technology developments

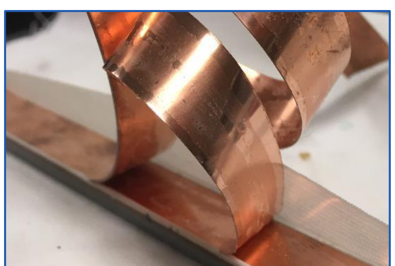


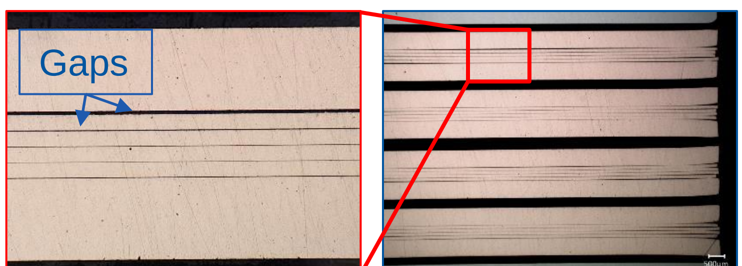
Status on technology developments



1 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





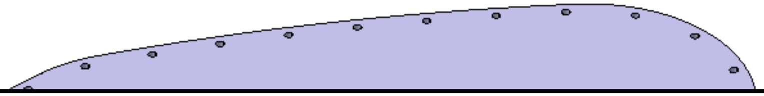
Phase 1: tests with dummy copper stacks selecting with:

- Impregnation quality
- Mechanical properties
- Electrical insulation/contact

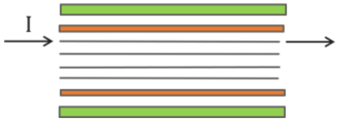
Phase 2: compatibility with HTS

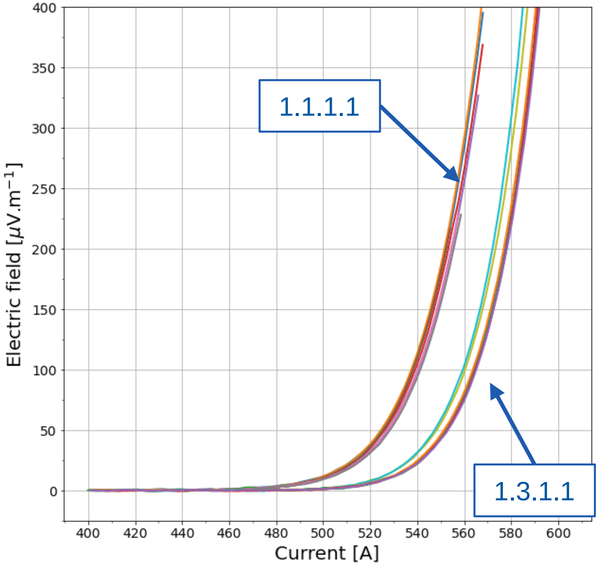
Thanks to the personal of lab-927 for their support:
L. Henschel, P.A. Contact, F.O. Pincot, N. Bourcey,
S. Clement, R. Gavaggio, A. Benfkih, J.C. Perez

Status on technology developments

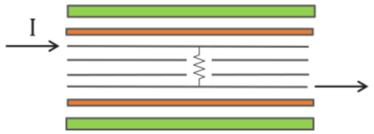


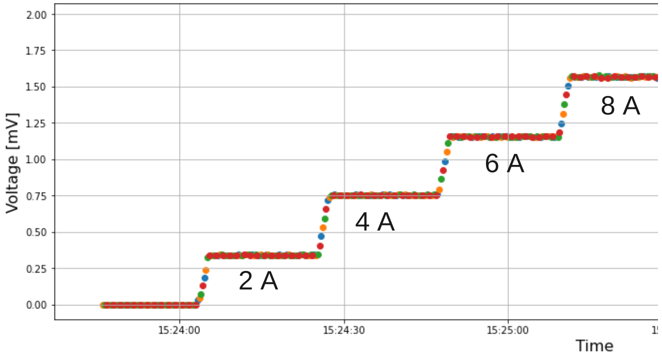
1 Insulation and impregnation





Ic measurements (single)
No degradations with cooling cycles were observed.

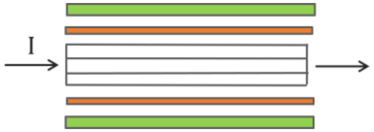


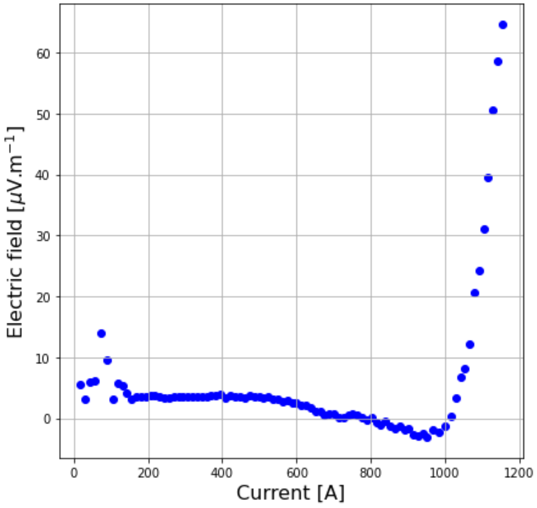


Resistance measurements

- Current from 0.1 A to 14 A
- Temperature: 77 K

~2.35 mΩ.cm² similar to the contact resistance measured in a Metal co-winding configuration.





Ic measurements (stack)

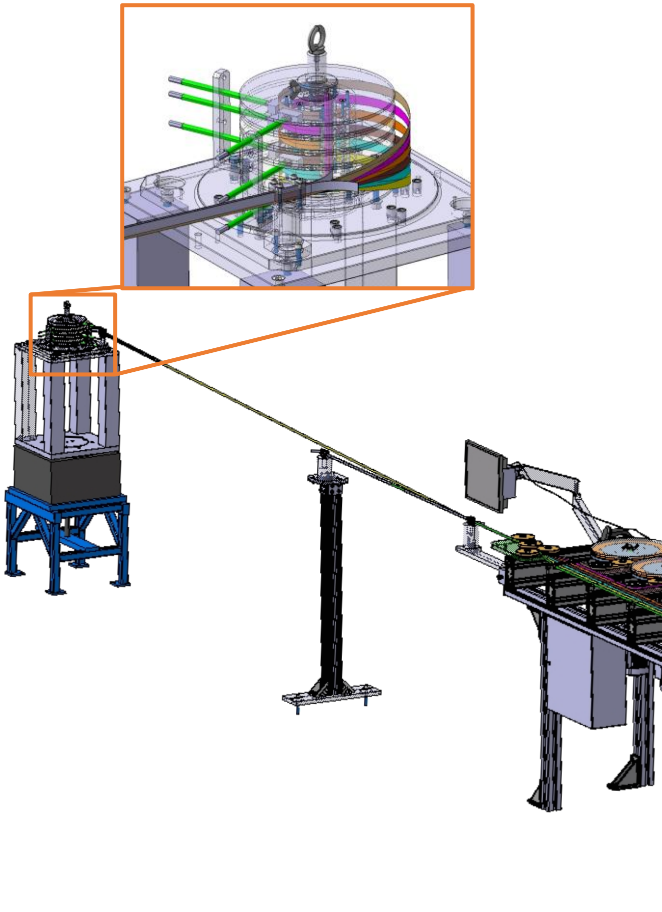
- Higher current reached.
- Signs of current sharing between tapes.

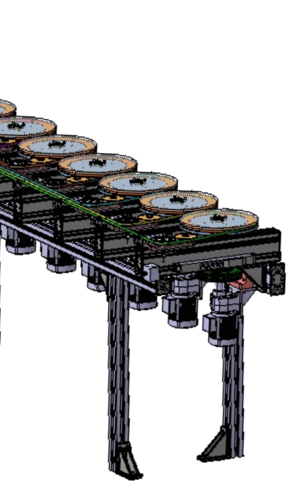
Thanks to the personal of TE-MSC-SCD for their support in using the LN2 station:
C. Barth, G. Lenoir, J. Hurte, A. Carlon Zurita and P. Denis

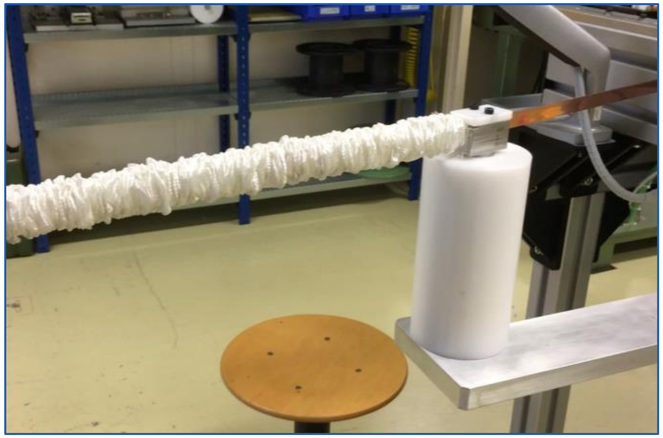
Status on technology developments

1

Winding **3**



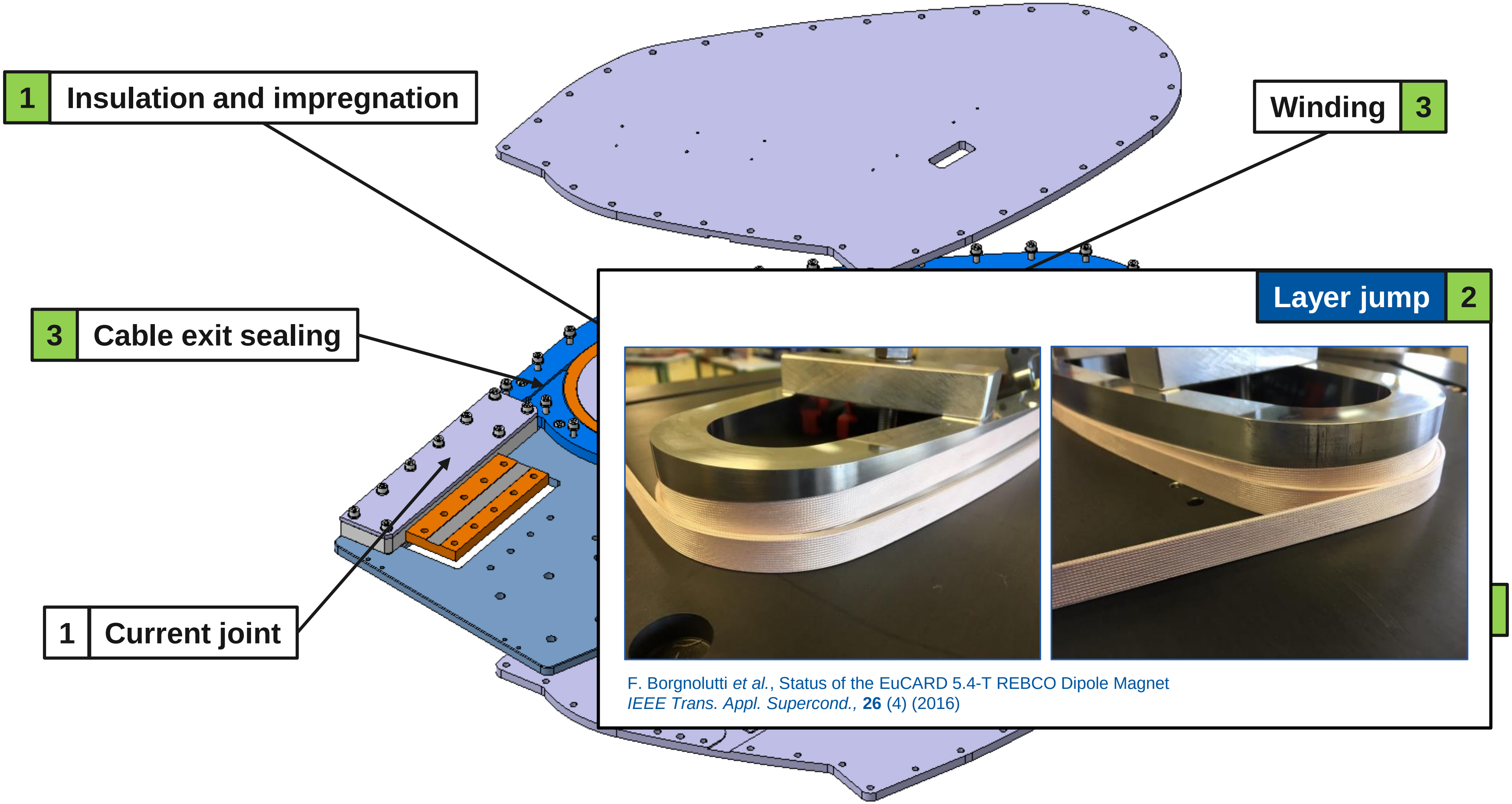




2

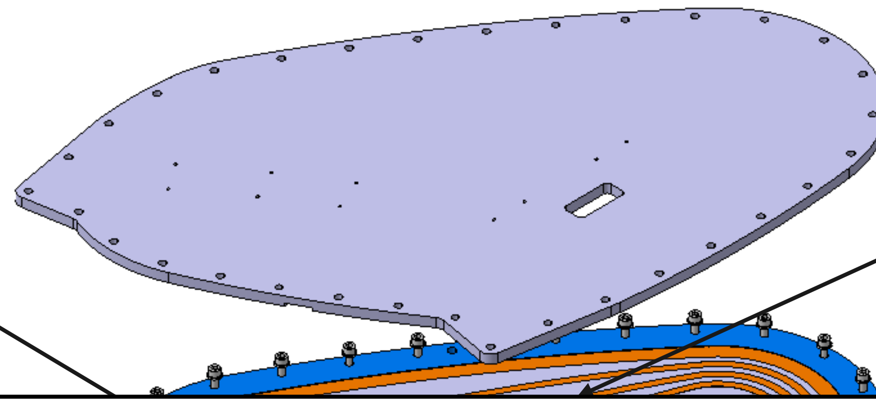
3

Status on technology developments



F. Borgnolutti *et al.*, Status of the EuCARD 5.4-T REBCO Dipole Magnet
IEEE Trans. Appl. Supercond., **26** (4) (2016)

Status on technology developments



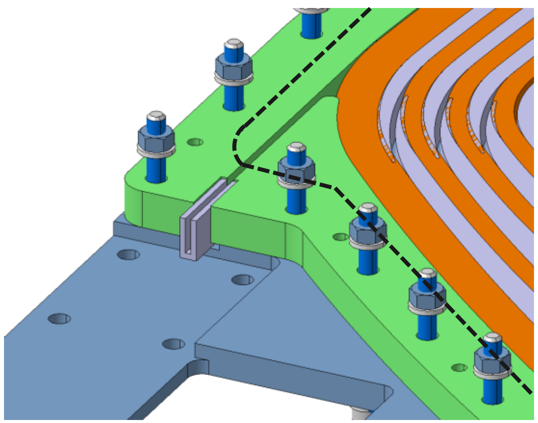
1 Insulation and impregnation

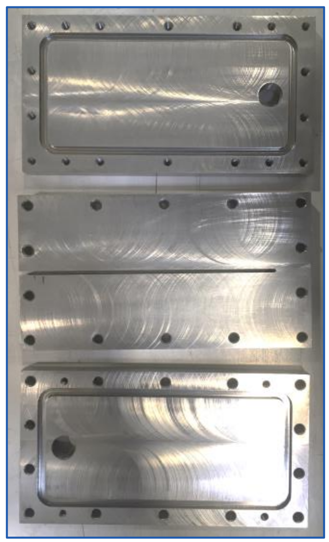
Winding 3

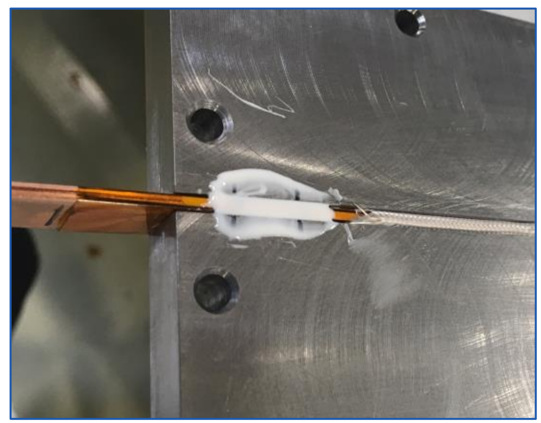
Layer jump 2

Instrumentation 3

3 Cable exit sealing

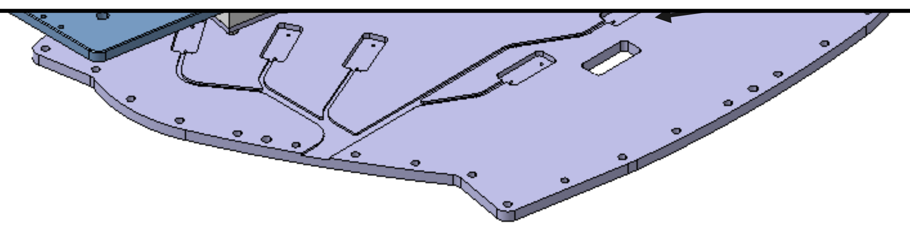






Use of a mock-up to define a reliable sealing procedure for the cable

Status on technology developments



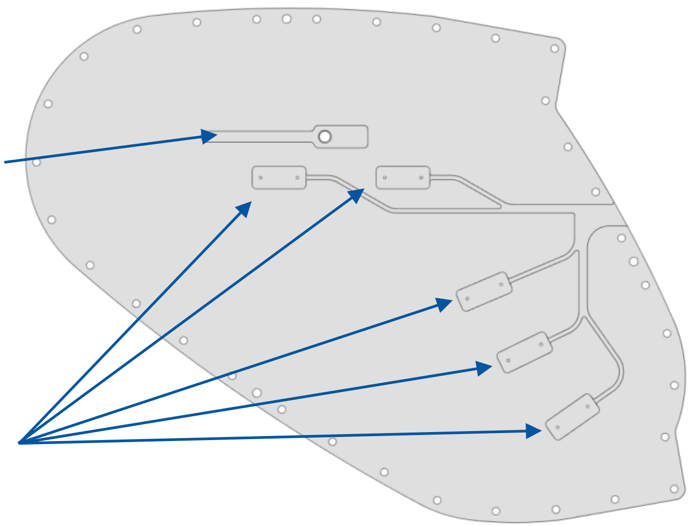
1 Ins

3 C

1 Current joint

2 sets of sensors on each side:

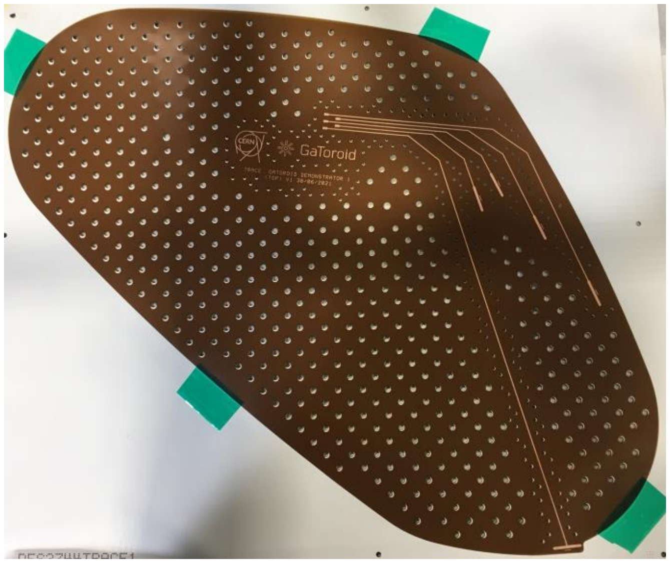
1 thermometer



5 PCBs with:

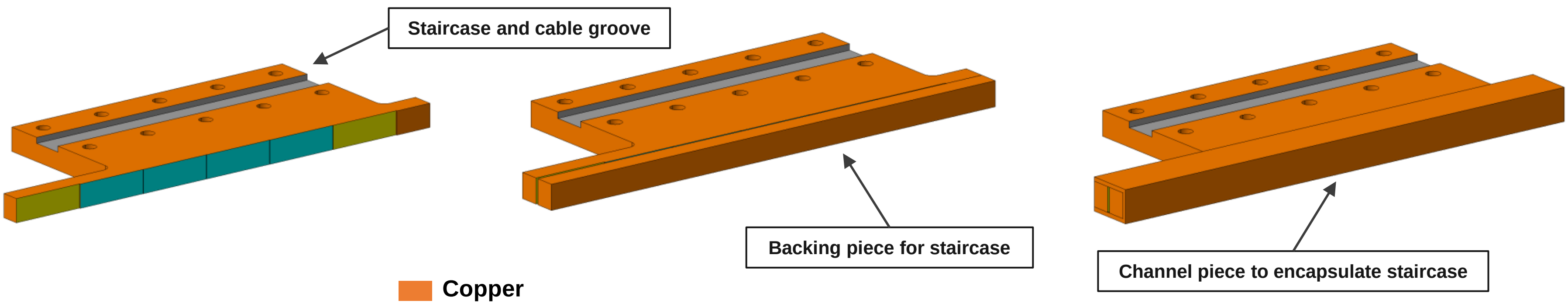
- Pick-up coils
- Hall probes

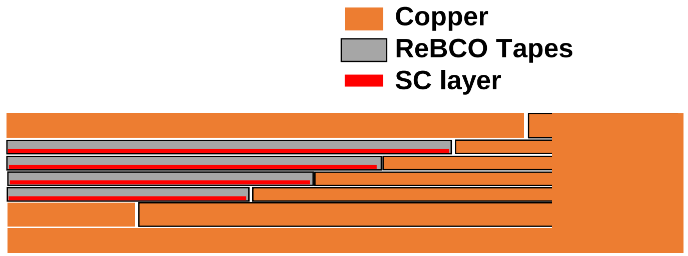
5 Vtaps with a connecting port in the centre on flex PCB

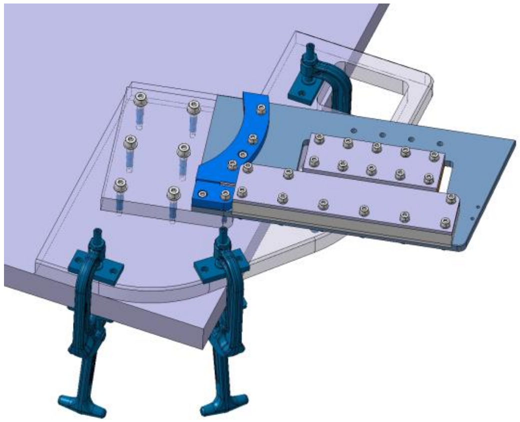


Instrumentation **3**

Status on technology developments



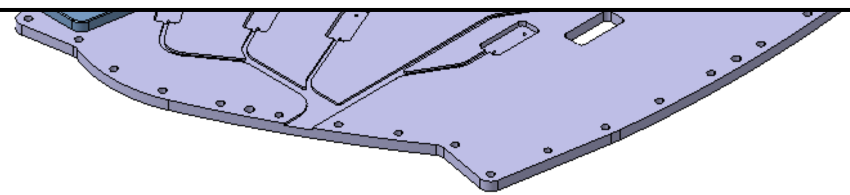




A staircase configuration allow independent contact on each tape of the cable.

Soldering tests using a mock-up are undergoing to define the tools and procedure.

1 Current joint



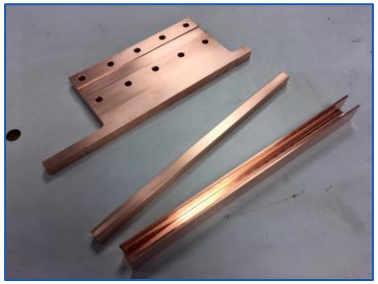
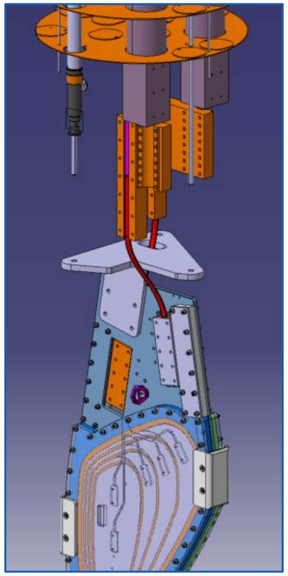
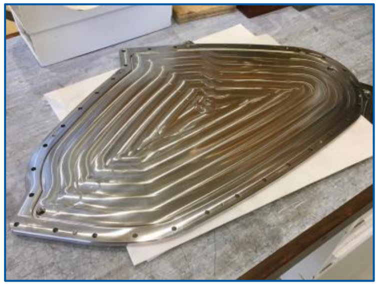
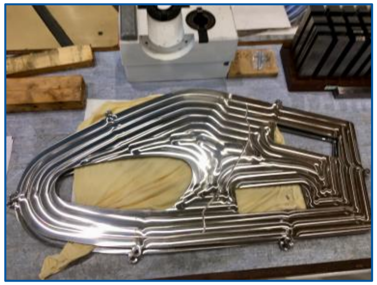
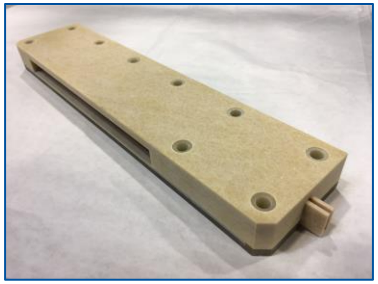
Status on technology developments

Timeline 2021

June | August | July | September | October | November | December

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



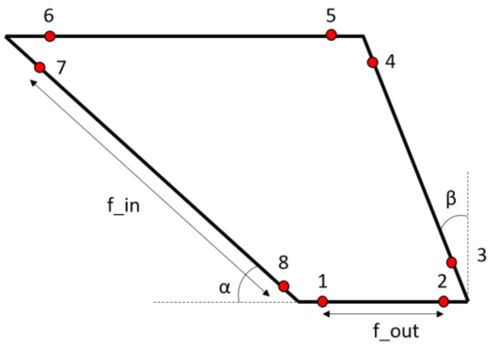
Outline

- Context (Hadron therapy / Gantries)
- From concept to demonstrator
- Demonstrator design & analysis
- Status on technology developments
- Perspectives

Perspective

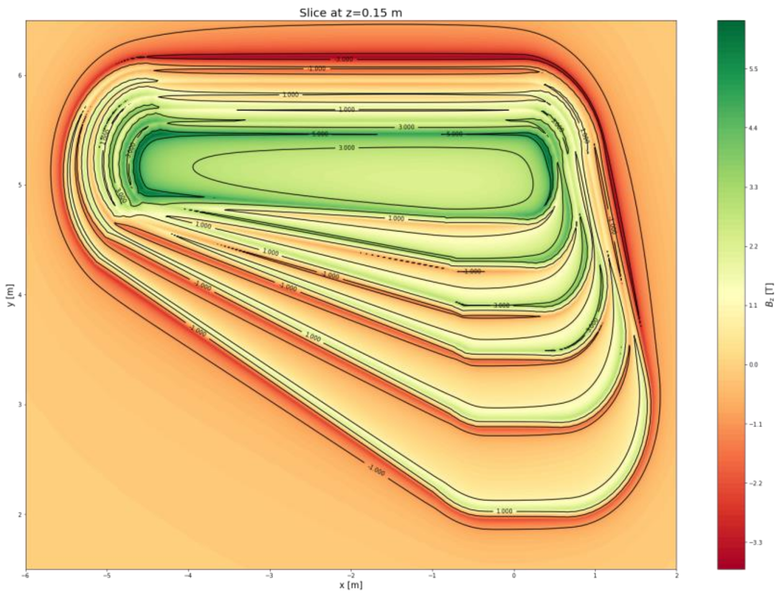
Optic/magnetic optimization

No theory for the optics in toroidal magnets as for dipoles.
Simulations are the only tool for optimization

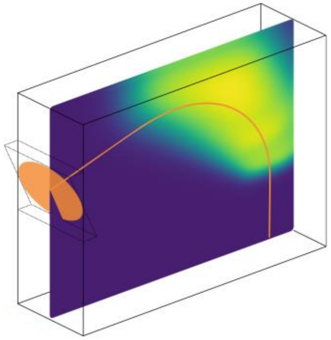


Development of a Python code to calculate analytically 3D magnetic field maps from few parameters defining one coil.

In association with a tracking code:
Routine for optimizing the magnetic field with the clinical requirements on optics.



In collaboration with Ewa Oponowicz and Yann Dutheil (SY-ABT-BTP)



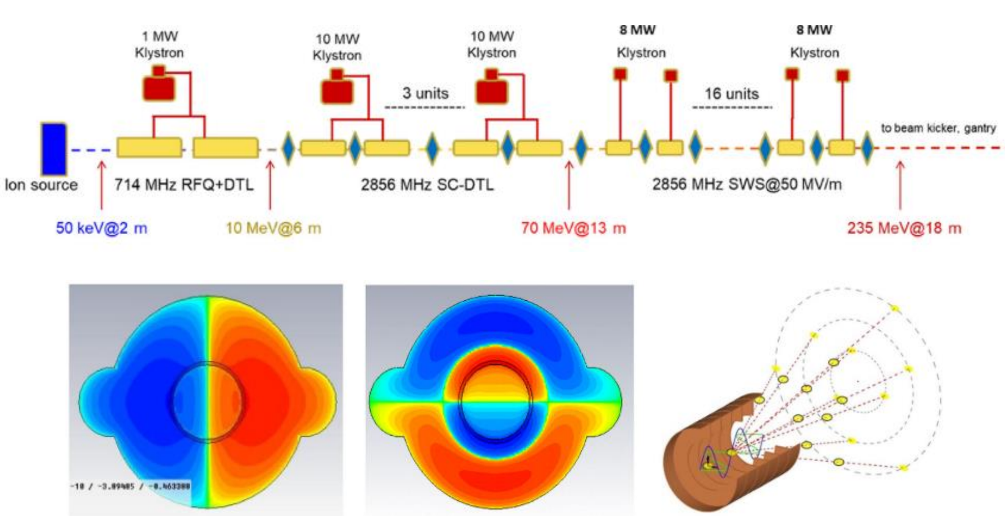
Perspective

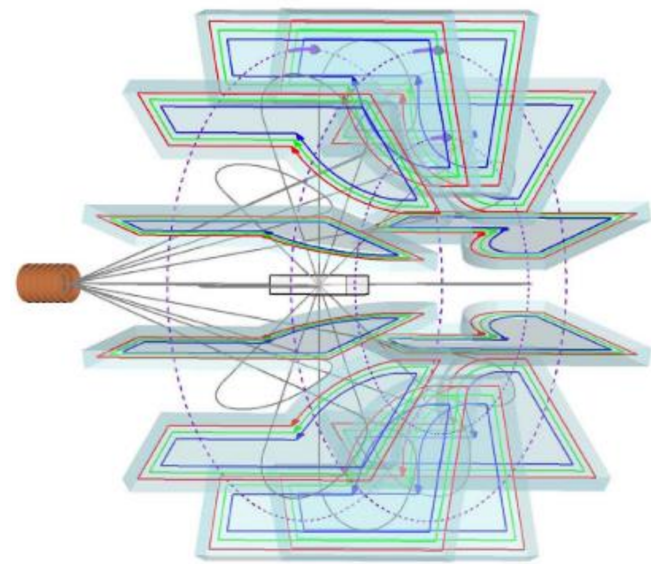
Flash therapy

Flash is a promising new form of cancer therapy where a high dose of radiation is applied in millisecond instead of minutes improving the ratio of damaged tumor/normal tissue.

It works with every particles: photons, electrons (~100 MeV), protons (70-250 MeV),…

Provide multiple irradiation angles in less than 100 ms: **no time for mechanical gantry**





W.C. Fang *et al.*, **Proton linac based therapy facility for ultra-high dose rate (FLASH) treatment**, *Nucl. Sci. Tech.*, **32** (4) (2021)

Perspective
Flash therapy

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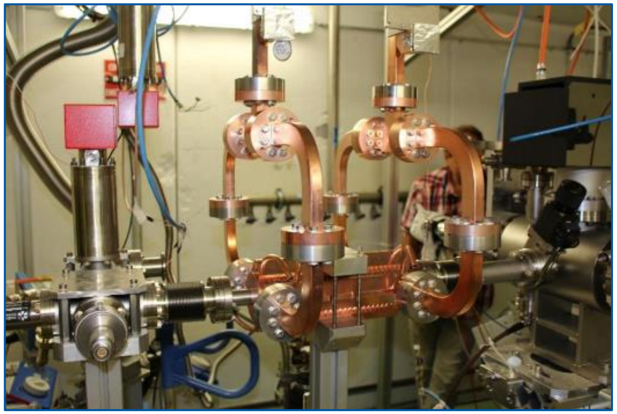
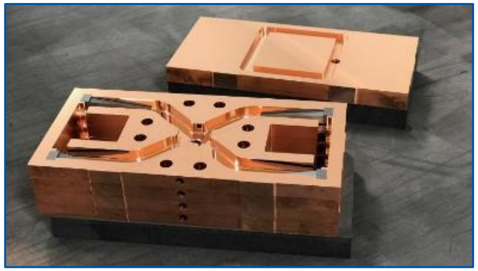
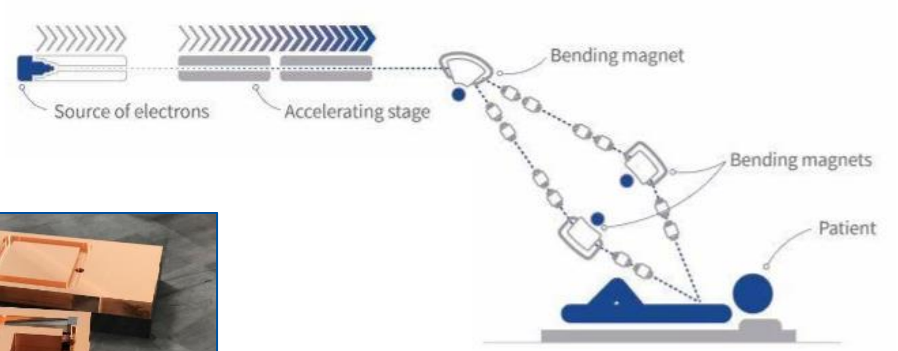




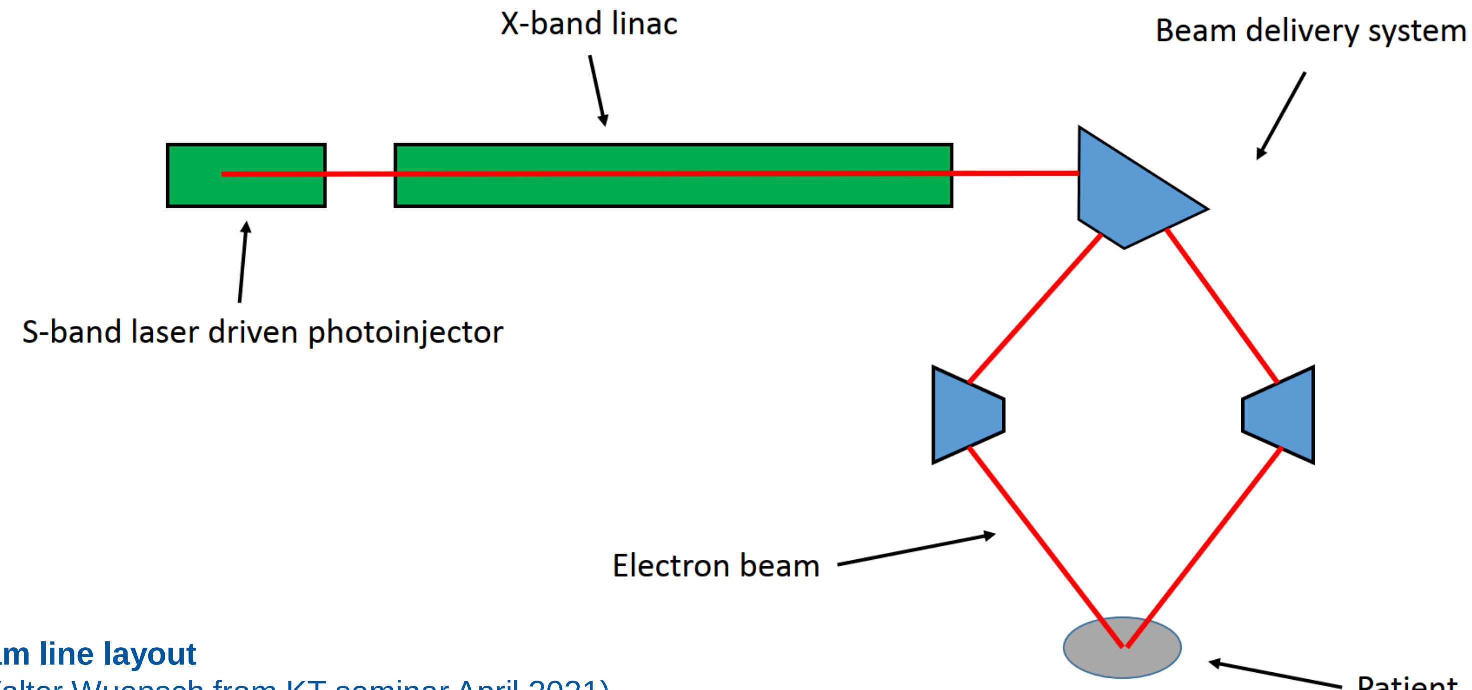


The DEFT (Deep Electron FLASH Therapy) facility
(courtesy to W. Wuensh from KT seminar April 2021)

Perspective

Flash therapy

Associating the DEFT linac with an electron version of Gatoroid



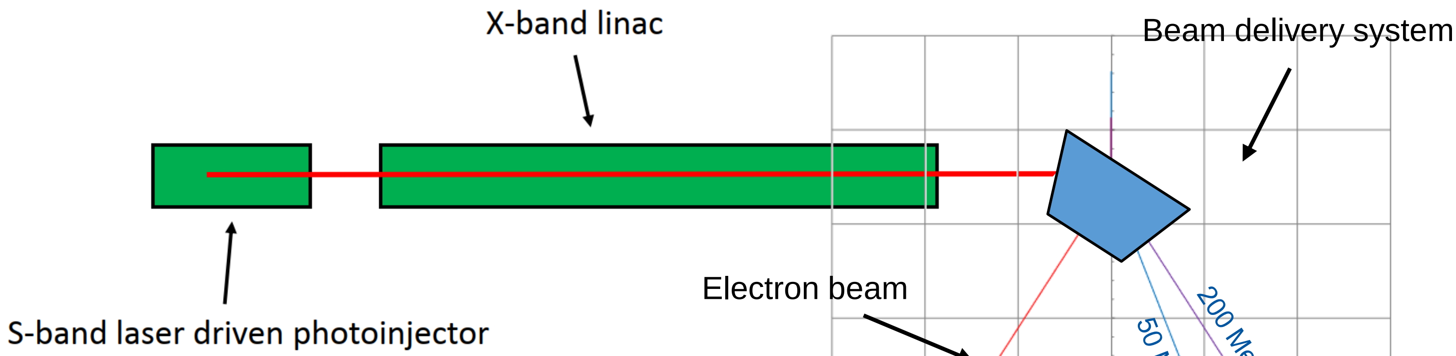
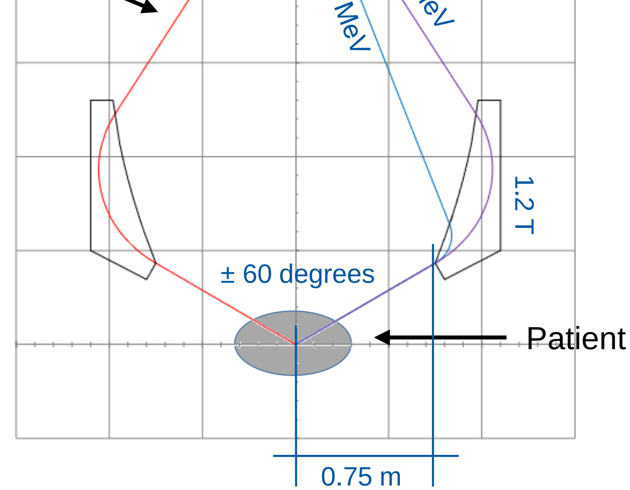
The DEFT beam line layout
(Courtesy to Walter Wuensch from KT seminar April 2021)

Beam delivery system is limited to:

- 2 energies
- 2 directions

Perspective
Flash therapy

Associating the DEFT linac with an electron version of Gatoroid

With GaToroid :

- 6 delivery directions
- All energy range from 50 to 200 Mev

- The bending field is ~1/3 than for protons: **the demonstrator size !**
- Based on a super-ferric toroidal magnet (iron dominated): easy shaping
- Current: 1 MAturn
- Approximated Mass: 10 tons

- High frequency kicker (*i.e.* RF deflectors) as vector magnet

GaToroid

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