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RuPAC Russia St. Petersburg 21-25 November 2016

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SUPERCONDUCTING RACETRACK COMBINED-FUNCTION MAGNETS FOR BEAM CANCER THERAPY GANTRY – A CONCEPT DESIGN

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TH CD MH 01

Outline

- Context and Motivations
- Gantry layout and magnet design
- Thermo-mechanical calculations
- Conclusions

Considerations about the stray fields and the magnet quench protection are not presented here.

Context:
The Proscan Facility at PSI

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1984 — 1996 — 2006 — 2010 — 2013 — 2016 — Evolution

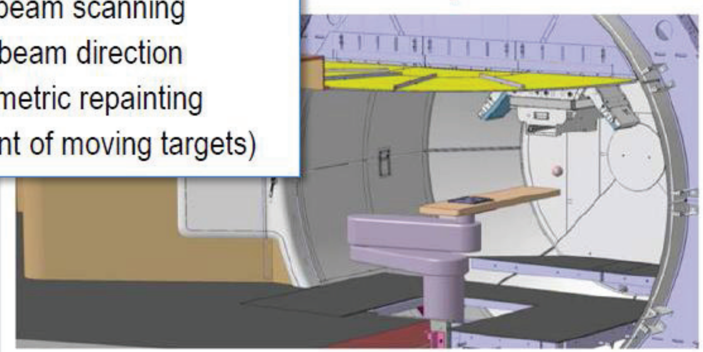
Optis 1
- Passive scattering
- Eye treatments

COMET
- 250 MeV sc cyclotron
- 80% extraction efficiency
- 1μA max. beam intensity

Gantry 3
- Performance comparable to Gantry 2
- Cone Beam CT

Gantry 1
- 1st pencil beam scanning Gantry in the world
- Compact eccentric layout
- d = 4m

Gantry 2
- Iso-centric layout (d=8.4m)
- Fast energy changes 100ms
- Parallel beam scanning
- X-ray in beam direction
- For volumetric repainting (treatment of moving targets)



Optis 2
- New setup after installation of COMET

Future : Superconducting technology for gantry magnets

Why a superconducting magnet?

- Work at higher B-field → reduce the gantry size
  bending radius : $\rho = B\rho/B_{Mag}$
- Work at higher Gradient-field → reduce dispersion
  high momentum acceptance, energy scanning without changing magnetic fields;
- Reduce the magnet weight in particular for carbon therapy;
- Reduce the complexity and cost on the gantry structure
- Reduce power consumption

Issues:

- Reliability (risks of quenches);
- Mechanical stability (huge Lorentz Forces);
- Cooling system complexity (magnet rotation);
- AC Losses;
- Challenges dealing with stray fields
  (0.5 mT at patient);

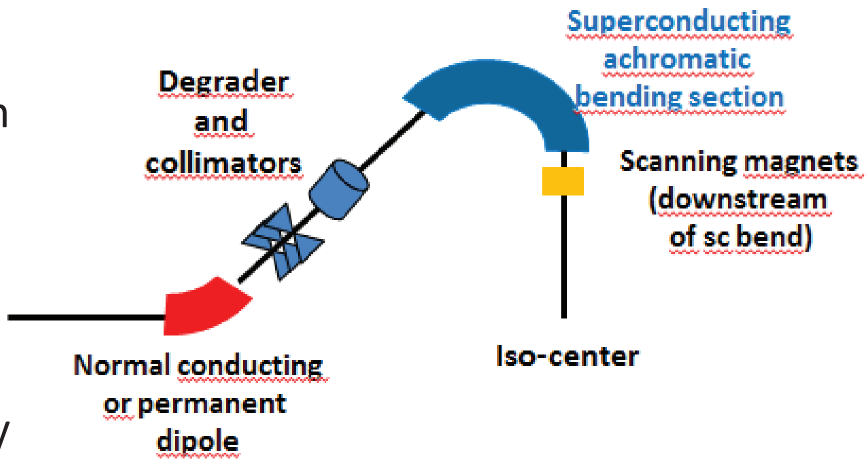
Proton therapy Gantry 2 (PSI)
8m x12m , 200 tons

Heidelberg Ion Therapy, Carbon Ion Gantry
22m x 13 m , 600 tons (1/10 of the Eiffel Tower)

Gantry design proposal

Optic design specificities

- Locally achromatic design (bending section);
(remove dependence of particle trajectory on beam energy)
- Downstream scanning
- Degrader mounted on the gantry (space saving)
- High momentum acceptance (±12%) → no energy selection needed→ higher transmission



Specifications

Energy modulation	Bρ	Type	Beam size	ΔP/P	Layer switching time	Bending section
70-230 MeV	1.2-2.3 Tm	Isocentric	2σ ≈ 5 mm	±12%	100 ms	135°

Two directions pursued for the magnet geometries of the bending section:

- NbTi Canted Cosine Theta design (LBNL)
- Nb_3Sn racetrack coils (PSI)

Magnet technical choices (PSI)

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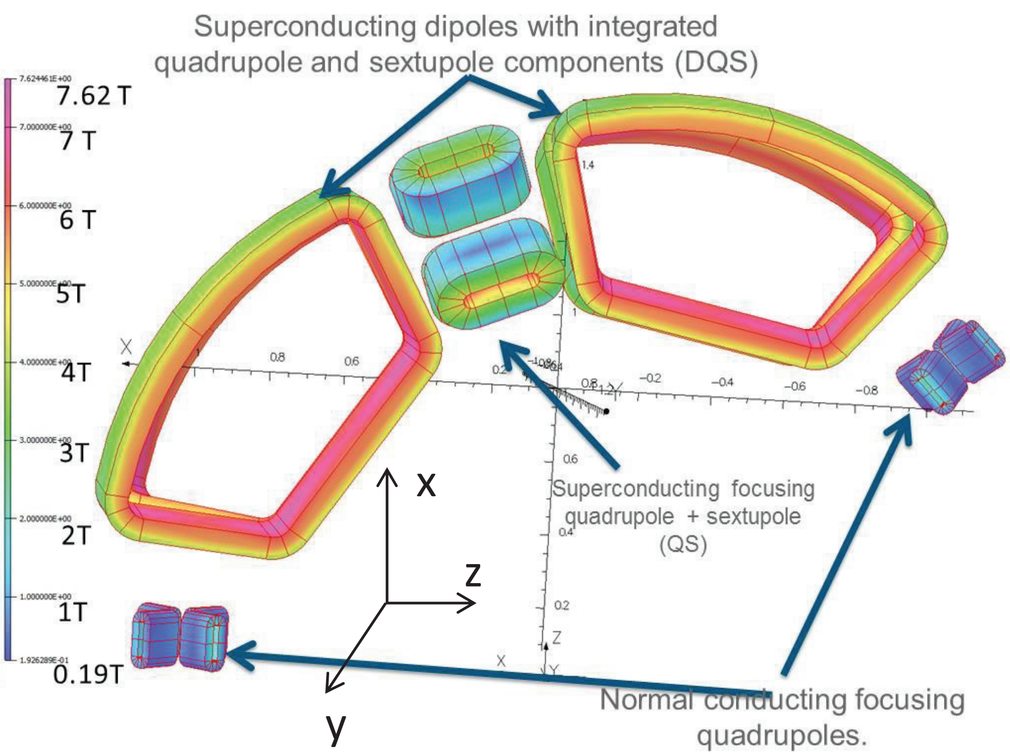
Choices	Impact
Racetrack geometry	Easier to manufacture (+)
Large aperture magnets	Magnet geometry: $B_{conductor}/B_{GFR}$ large (-)
Reduce ramp rate (0.1 T/s max)	Reduce the impact of the AC losses (+)
Cooling option: Cryocoolers directly coupled to the cold no cryogenic fluid in the magnet because of the gantry rotation, $\mathbf{T_{op}}$**~4.2 K**	Mass heat removal is limited (~1.5 W at 4.2 K)
Superconductor: Bronze routed Nb_3Sn	Comfortable temperature margin (+) Brittle : React and wind process (-) Cost of the conductor (-)

Bending section layout (PSI study)

Series of combined function magnets with a racetrack geometry



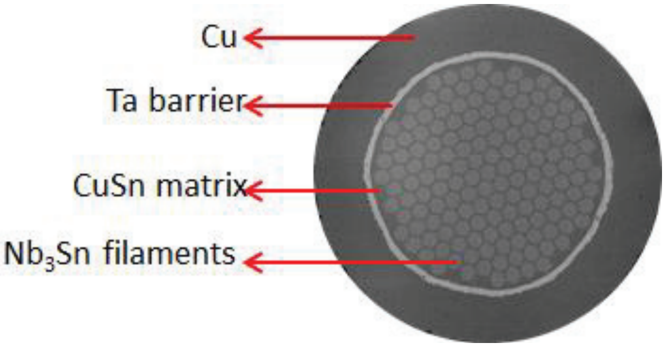
	SQC	DQS	NQ
Length (cm)/ Bending Angle (°)	35	67.5	10
Bending radius (m)		0.8	
Half aperture (cm)	12.5 (x) 2 (y)	10 (x) 4 (y)	5
Dipole (T)		2.57	
Gradient (T/m)	23.9	-6.90	23.6
Sextupole (T/m^2)	31.48	-17.2	
Op. current (A)	1700	1700	
Turns/layers	20/30	36/28	

Field maps of the magnet bending section

Peak field around **7.7 T**

Strand specifications

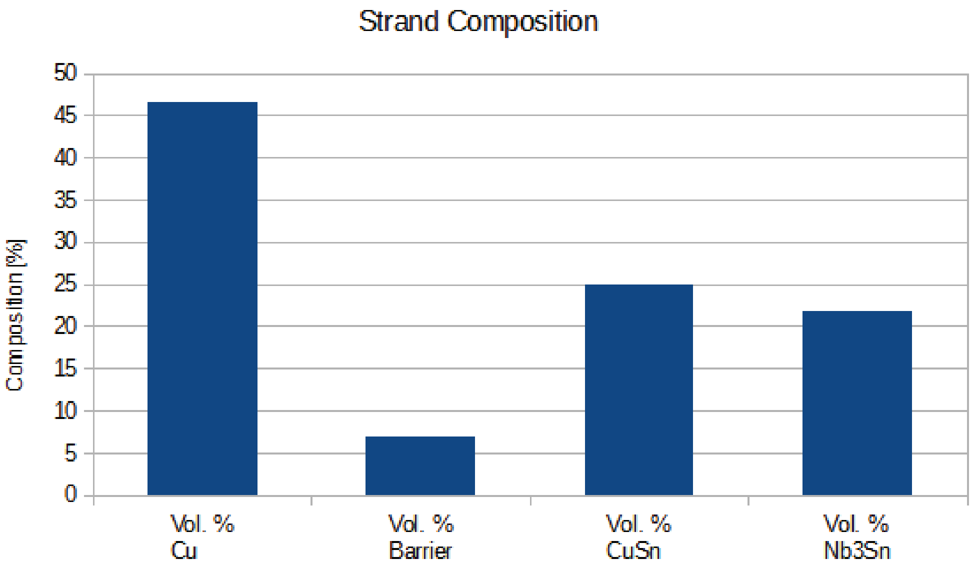
Nb_3Sn bronze route



Strand parameters	
Strand diameter (mm)	0.82
Filaments twist pitch (mm)	14
Filaments diameter (µm)	≈6-7
Filament number	8305
Cu to non-Cu ratio	0.93
RRR	>100
I_c @ 4.5 T, 4.2 K and 0.2% strain (A)	200

Strand composition

Hot spot temperature in case of quench below **150 K**

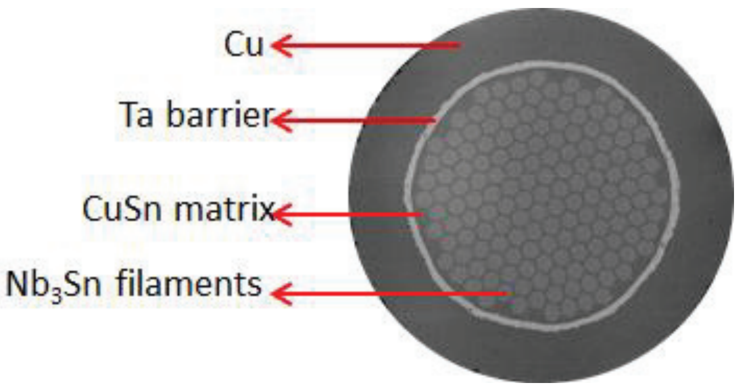


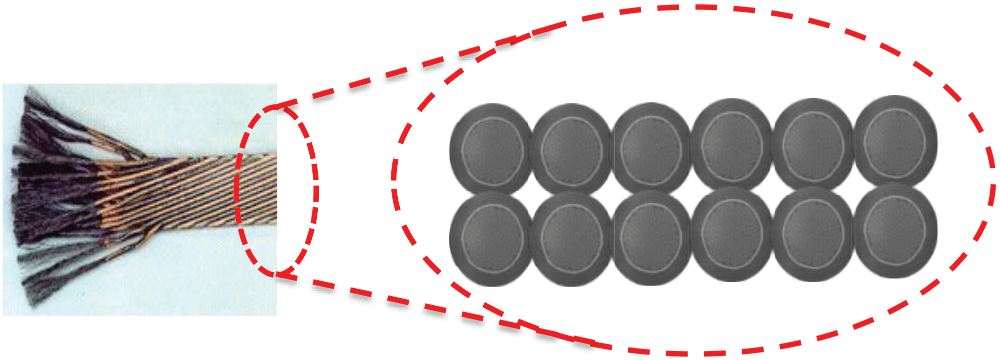
Selected winding pack composition:
70% strands + 30% insulation

Cable for the Combined function magnet (dipole + quadrupole + sextupole)

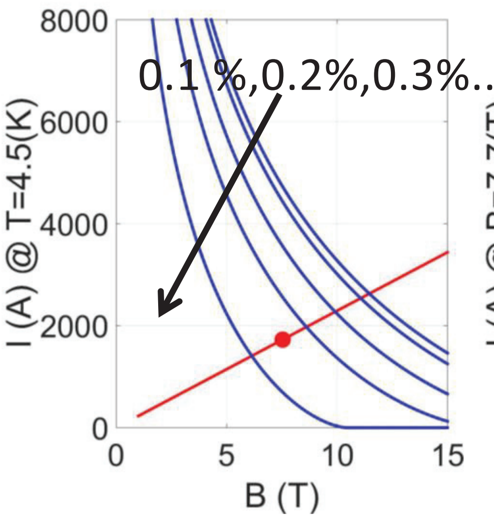
I=1.7 kA→Rutherford cable

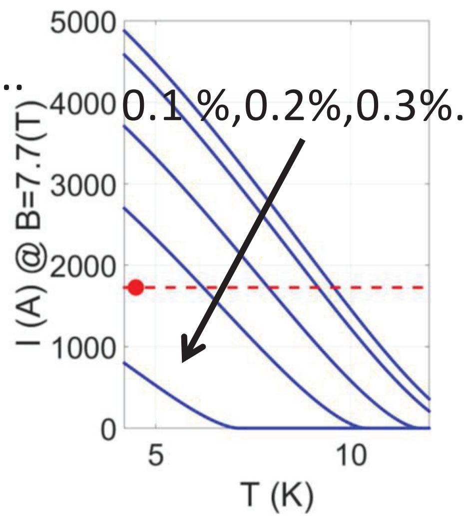
N. strand	Strand diameter (mm)	Width (mm)	Thickness (mm)	Twist pitch (mm)	Compaction (%)
12	0.82	4.7	1.5	70	~88





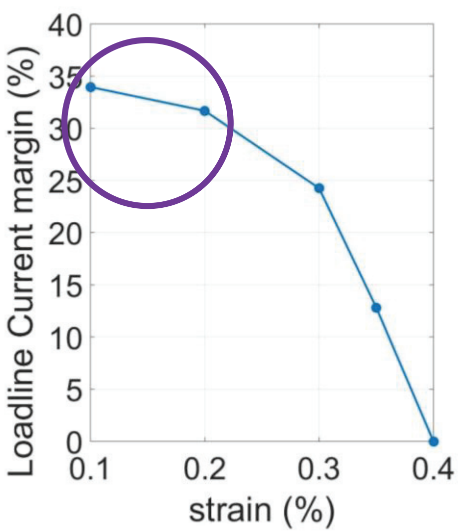
Operating margins: DQS magnets (steady state)

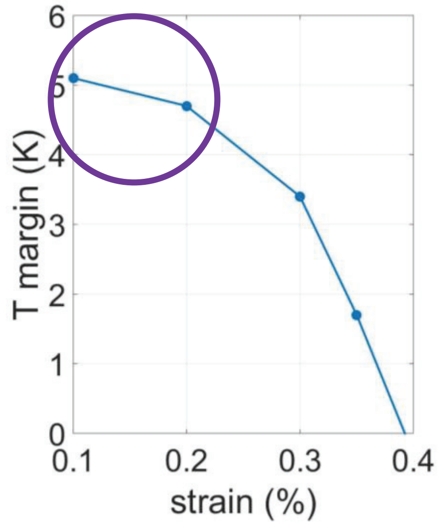




Critical current as a function of magnetic B-field and temperature for a Rutherford cable made by 12 strands, Nb_3Sn EUTF6 ITER type

In red: DQS magnet load line and DQS operating point against operating temperature





Steady state load line current and temperature margins for the DQS magnet as a function of the strain experienced by the Nb_3Sn filaments inside the strands.

For a strain between 0.1% and 0.2 %:
Margin along the load line ~ 30 %
Temperature margin 4.5 K

Operating margins: SQC magnet (steady state)

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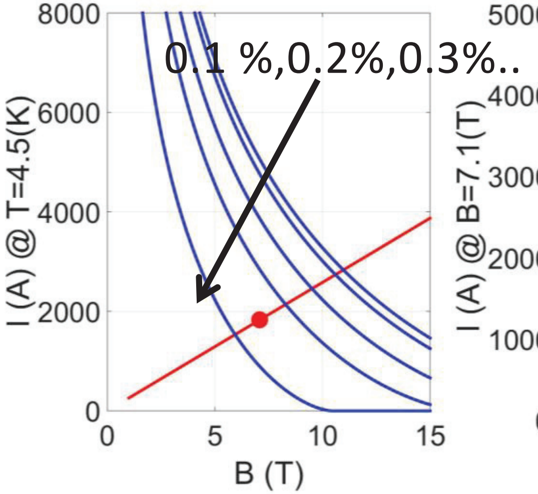
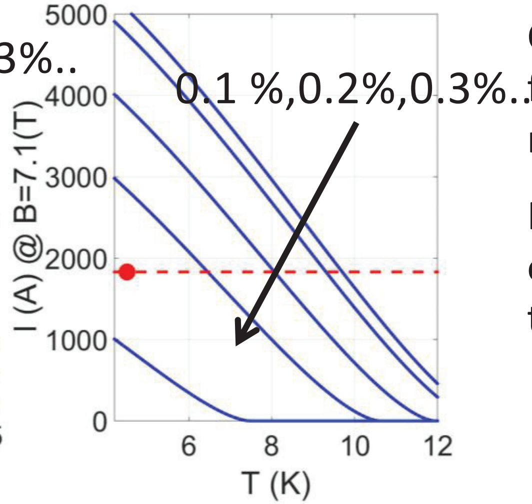
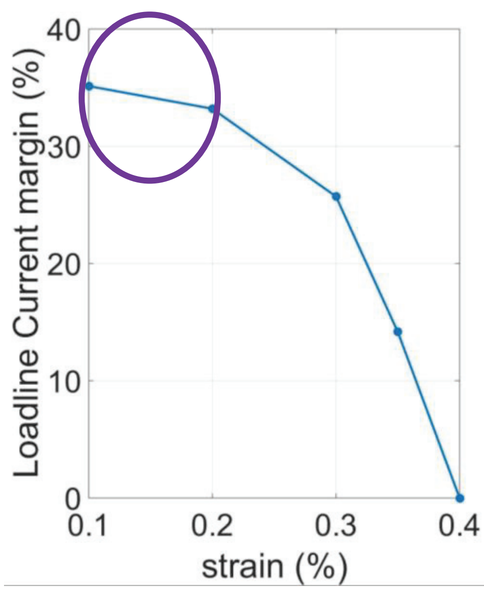
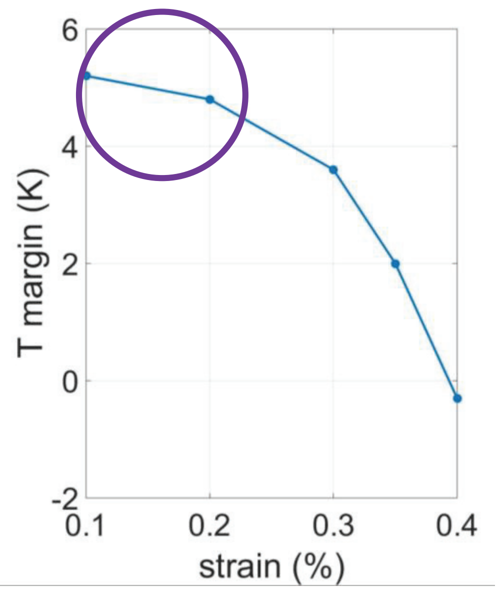




Critical current as a function of magnetic B-field and temperature for a Rutherford cable made by 12 strands, Nb_3Sn EUTF6 ITER type

In red: SQC magnet load line and SQC operating point against operating temperature





Steady state load line current and temperature margins for the SQC magnet as a function of the strain experienced by the Nb_3Sn filaments inside the strands.

For a strain between 0.1% and 0.2 %:

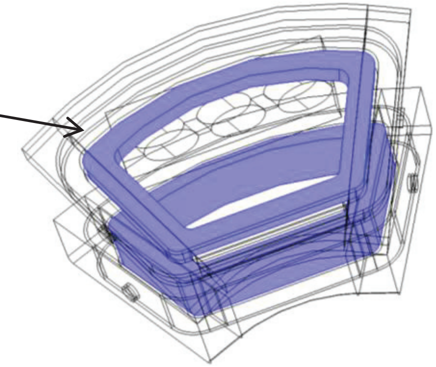
Margin along the load line ~ 35 %

Temperature margin ~ 5 K

Combined function Dipole Main-parts

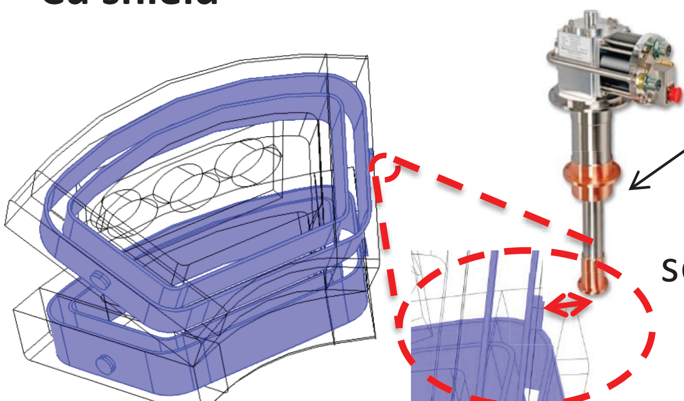
- 316 LN stainless steel former;
- CuBe rings (compression);
- 316 LN steel for the support
- 316 LN steel for columns;
- Cu shield

316LN former

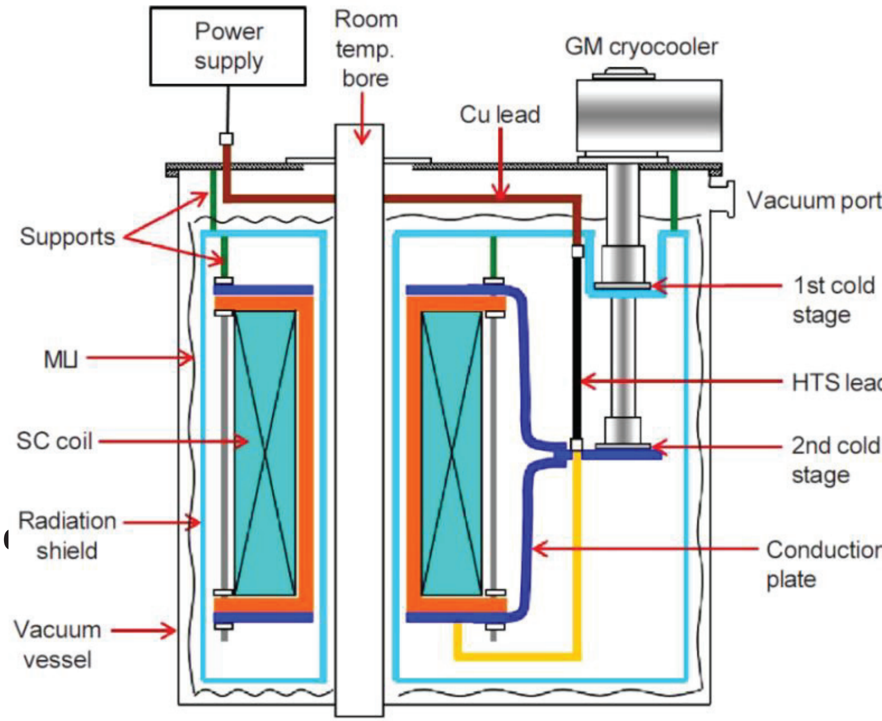


First stage

second stage

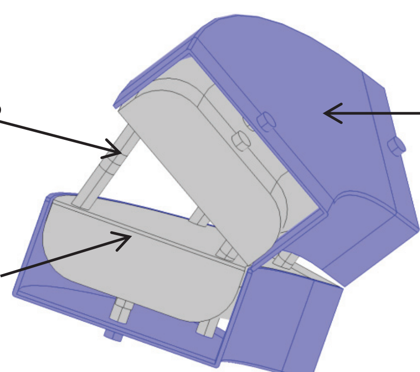


CuBe thermal anchor



316 LN columns

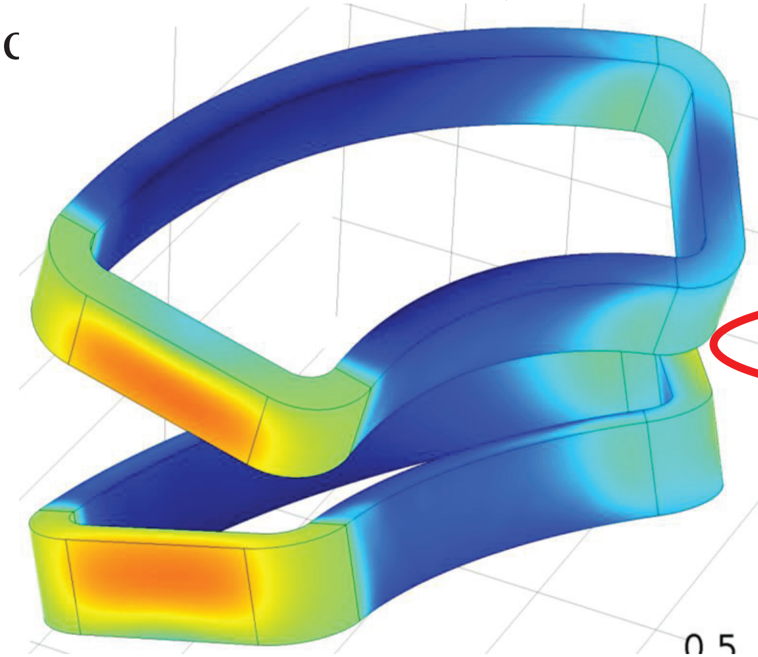
316 LN support



Cu shield anchored to the 1st stage of the cryocoolers

Thermal analysis at 4.2 K

For the thermal analysis the following contributions were c

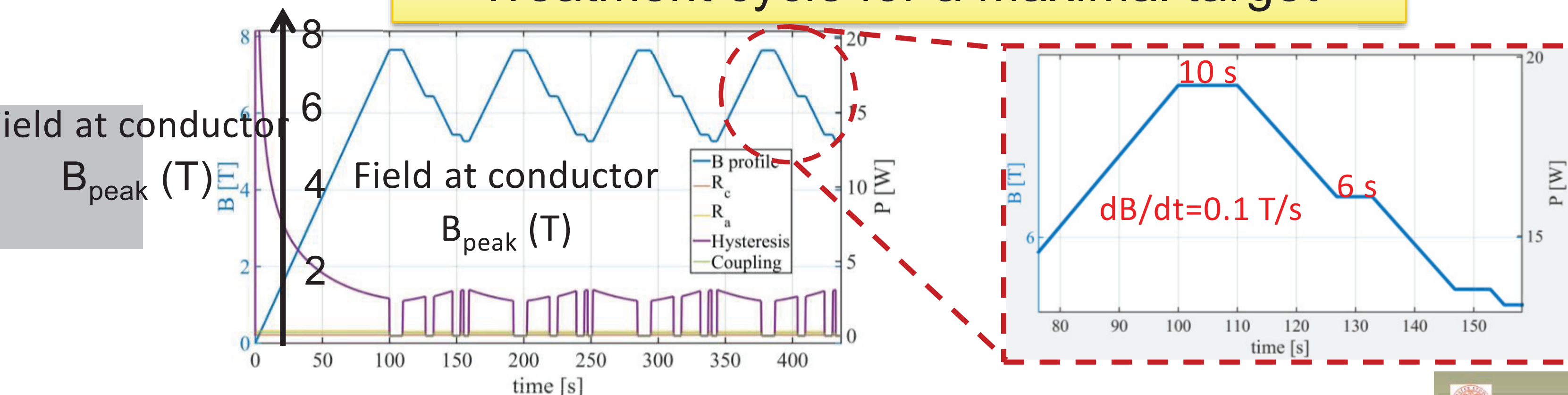


- **Joule heating;**
- **Thermal conduction (support)**
- **Thermal radiation (thermal shield)**
- **AC Losses**

- AC losses in the conductor
  - Within superconducting filaments (Hysteretic)
  - Between filaments and strands (Coupling)
  - Eddy current in the matrix
- Eddy currents in the structures.

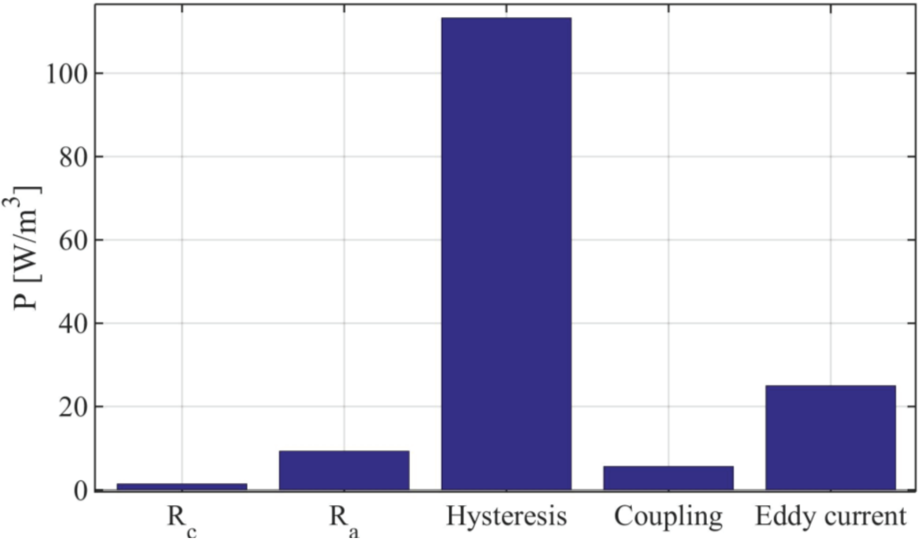
AC losses calculation

Treatment cycle for a maximal target



Summary of the results for the SDC magnet

Contributions to the total losses (integrated along the four cycles)



1. **<u>Coupling losses are always negligible</u> with respect to the hysteresis losses in all the configurations (< 10 % of hysteresis losses)**
2. **Hysteresis losses ~110 W/m³**
3. **total of losses ~ 3W at 4.2 K**

Temperature evolution in the winding pack (for the DQS)

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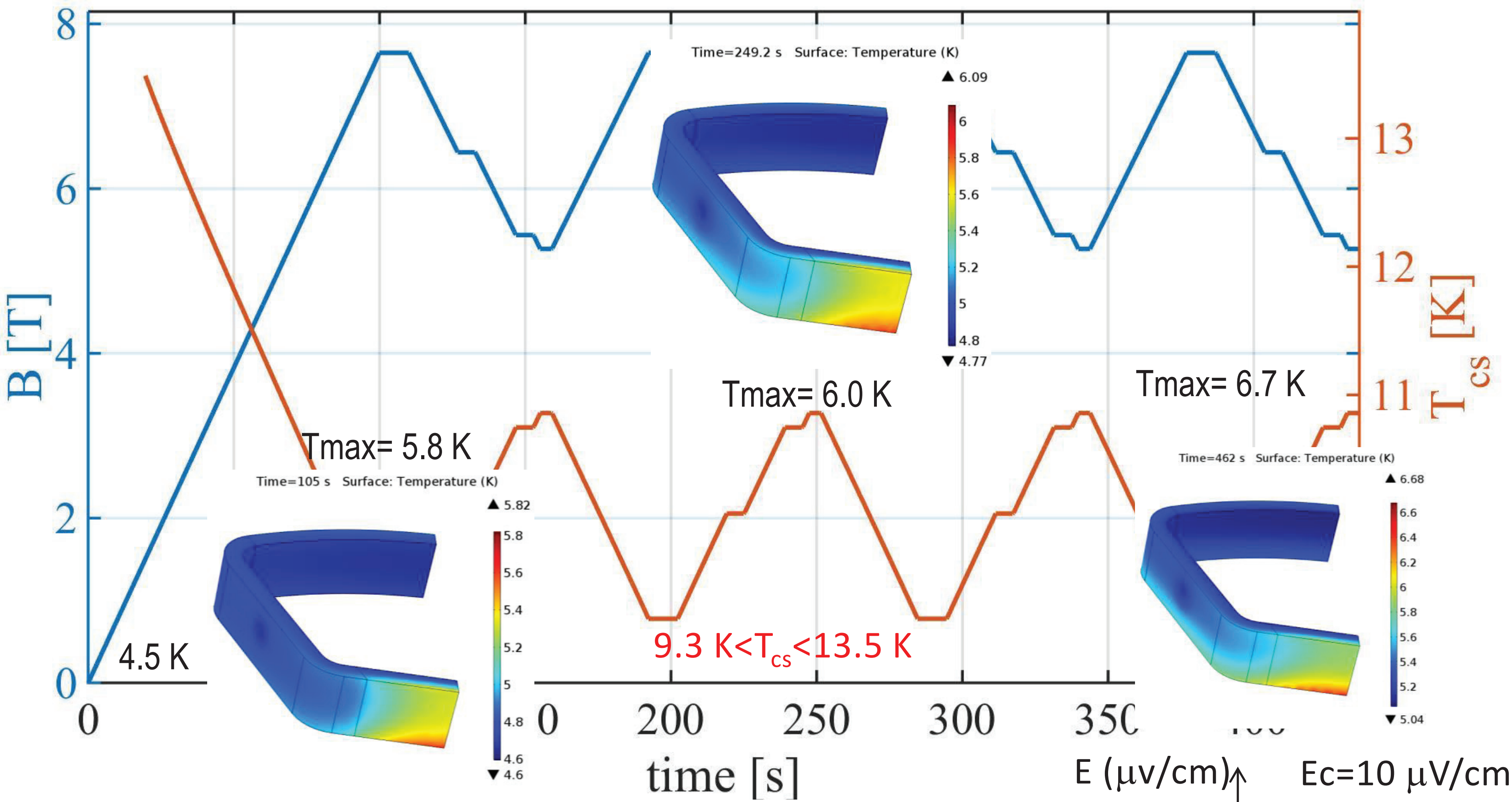

T_{max} < 7 K : Comfortable temperature margin even with limited number of cryocoolers per magnet

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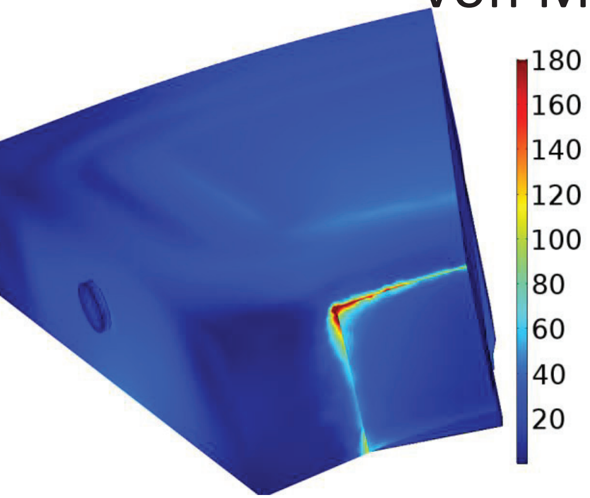
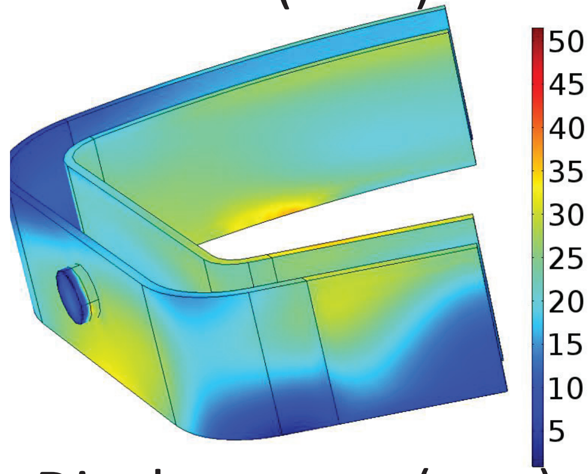
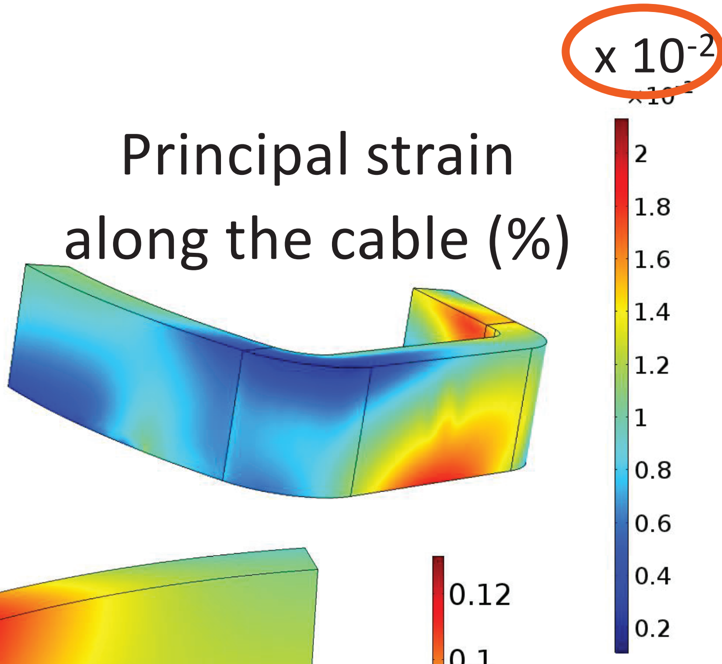
Mechanical analysis: the effect of the Lorentz forces

Von Mises stress (MPa)

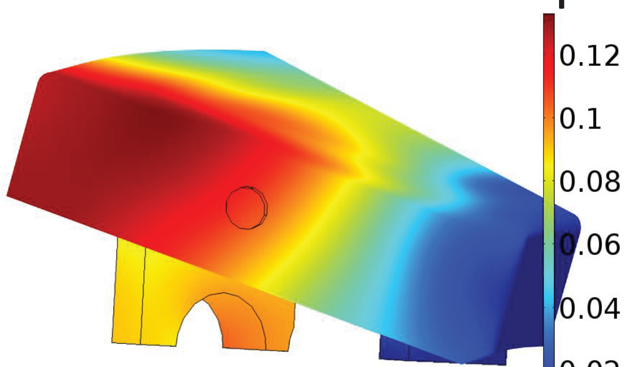


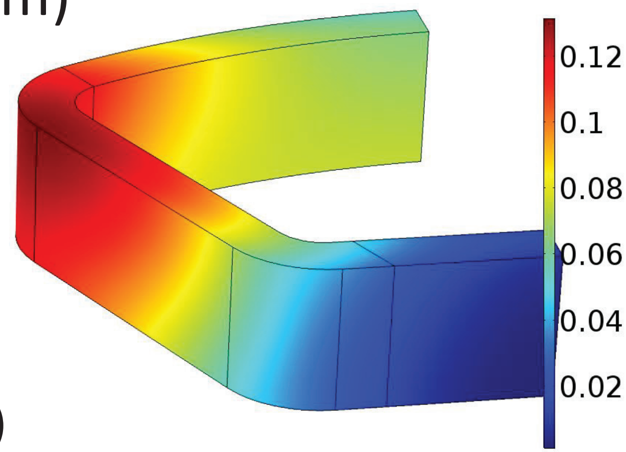


Principal strain along the cable (%)



Displacement (mm)





- **COMSOL simulations results (room temperature)**
- **Stresses well below the Yield points**
- **Cable Principal Strain < 0.05% → Intrinsic strain ≤0.1% (upon cooldown)**
- **Displacement: ≤ 0.15 mm**

Conclusions

- An achromatic design of a gantry using a series of combined function racetrack Nb_3Sn coils for the bending section was proposed.
- The selected design allows a high momentum acceptance
- The selected conductor is bronze route Nb_3Sn strands. Small Rutehrford cables will be used for the winding pack.
- The magnets will operate at 4.2 K cooled down by limited number of cryocoolers.
- Thermo-mechanical calculations showed that the magnets will operate with a comfortable temperature margin ;

Thank you for the attention

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Back up slides

The Proscan Facility layout