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Study of a compact curved superconducting dipole for the next generation of gantries at PSI using racetrack coils

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Content

- Motivation;
- Magnet design using racetrack geometry;
- Nb_3Sn cable preliminary design;
- Temperature increase due to a typical B cycle:
    - Dry magnet: cryocoolers;
    - Forced flow supercritical He (for comparison).
- Next steps.

Motivation

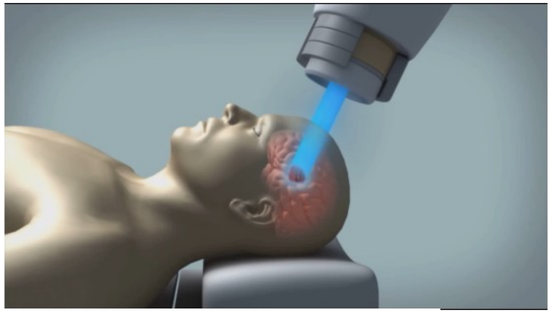
- Proton therapy is a rapidly developing technique in cancer treatment.

- There is a global trend in the proton therapy research in reducing size and weight of the gantry, so reducing the cost of the future facilities.

- Use of superconducting magnet(s):
  - No large size effect (footprint & hight) has to be expected using superconducting magnets for proton therapy gantries.

  - The implementation of a final bend superconducting dipole is very useful to reduce the overall weight of the gantry.

  - A significant weight reduction leads to a significant reduction of the cost of the mechanical support structures. This cost benefit is tempered by the cryogenic costs.



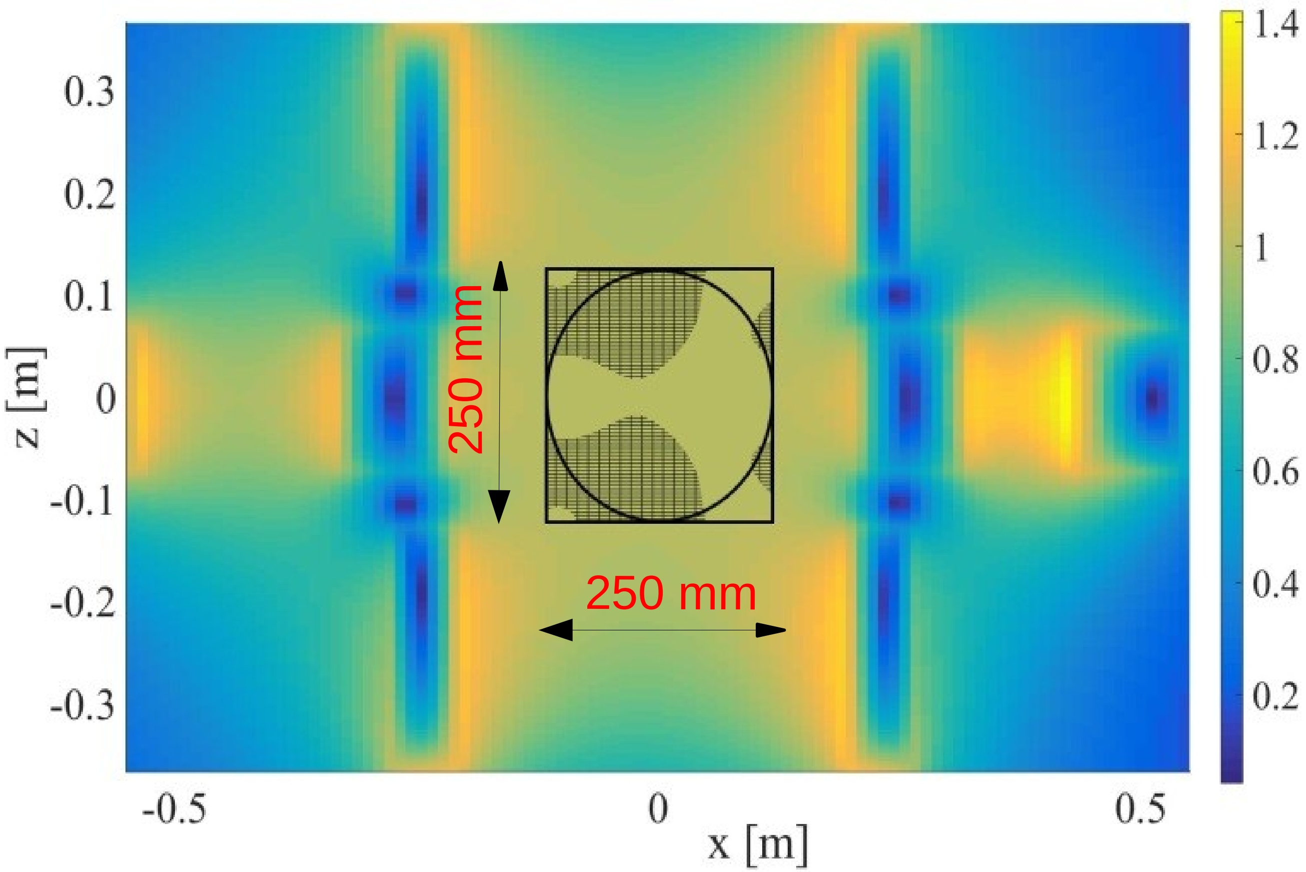
Challenging specifications:

Main technical specifications for the dipole design:

- Bending angle: 45° (achromatic layout);
- Dipole curvature radius <1 m;
- Good field region (GFR): 250 x 250 mm^2;
- Magnetic field in the GFR: 3 T;
- Field homogeneity in the GFR: ≤ 1%;
- Stray field at 1 m from the magnet exit ≤ 0.5 mT;
- Weight of the magnet < 10 tons;
- dB/dt = 0.1 T/s;
- The magnet has to rotate around the isocenter.

Magnet design using racetrack coils

The field quality has been evaluated calculating both the field homogeneity in the good field region (GFR) and the multipole decomposition.



$$Hom = \frac{\overline{B}}{s}(\%)\,;$$

$$\overline{B} = \frac{1}{A}\int_A B\,dA\,; \quad s = \sqrt{\frac{1}{A}\int_A \left(B - \overline{B}\right)^2 dA}$$

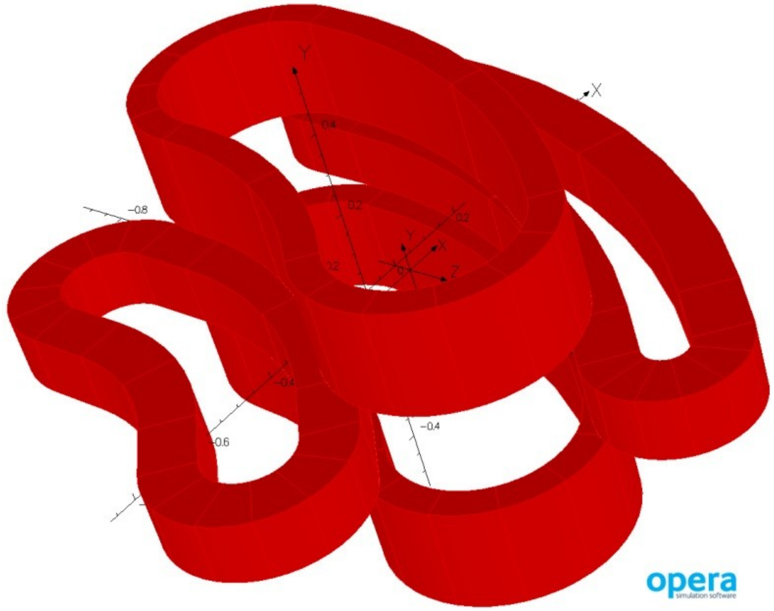
$$A_n = \frac{2}{N}\mathrm{Re}\left(F(\mathrm{B}_{rad,n})\right); \quad n = 1,\dots,N$$

$$B_n = \frac{2}{N}\mathrm{Im}\left(F(\mathrm{B}_{rad,n})\right); \quad n = 1,\dots,N$$

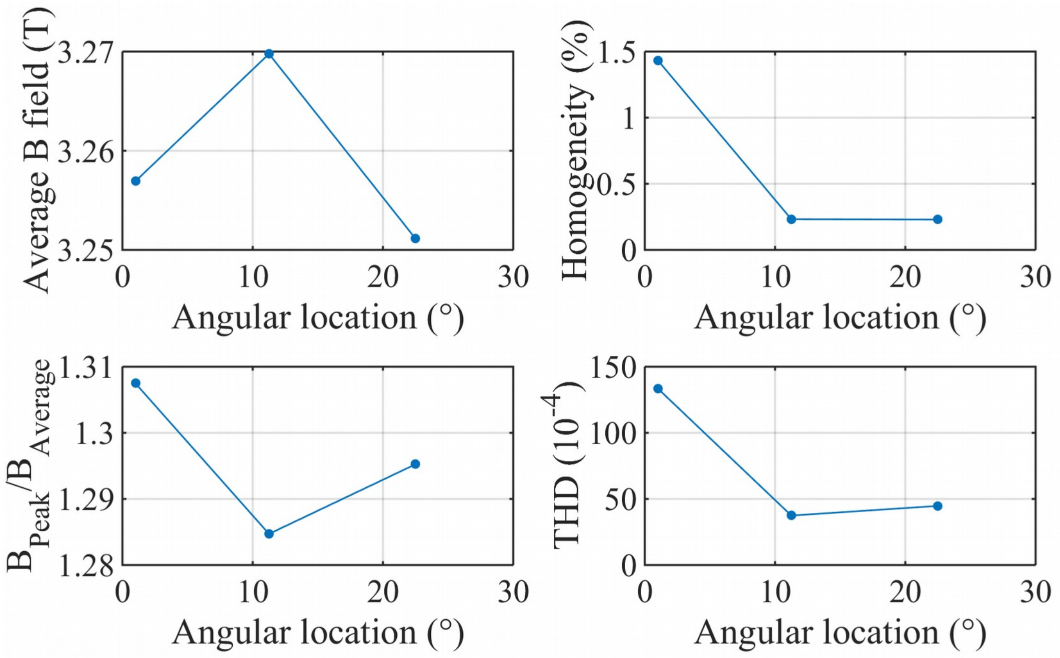
$$THD = \frac{10^4}{B_1}\sqrt{\sum_{n=2}^{M} A_n^{\,2} + B_n^2}$$

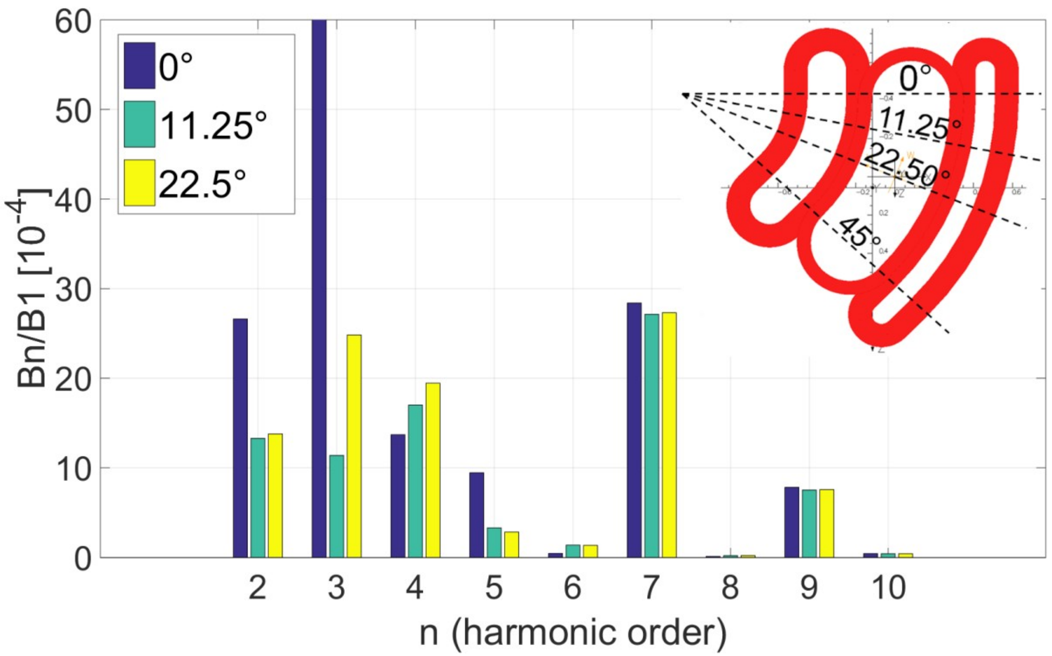
Magnet design proposal using racetrack coils:

We want to keep the manufacturing as easy as possible.



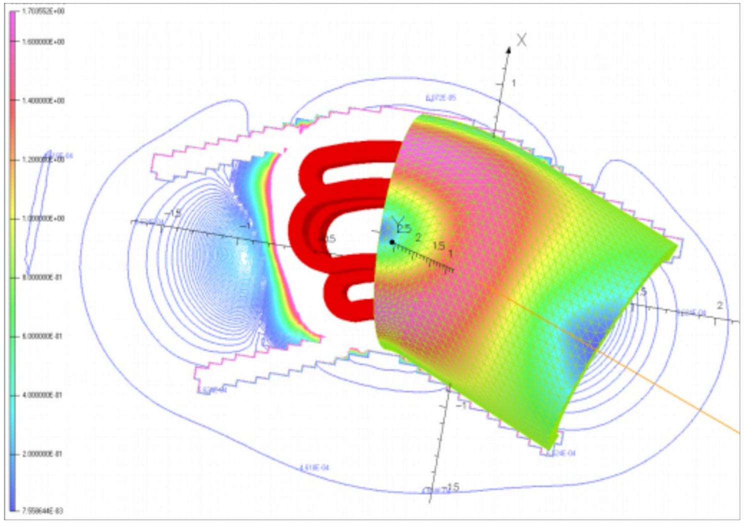
M=1450 kg

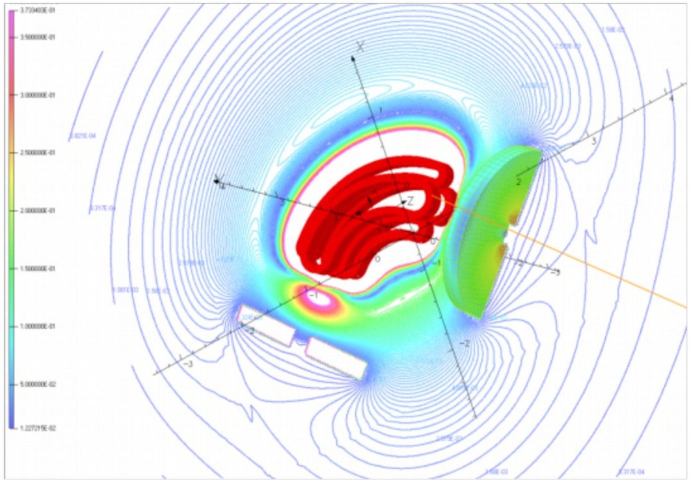


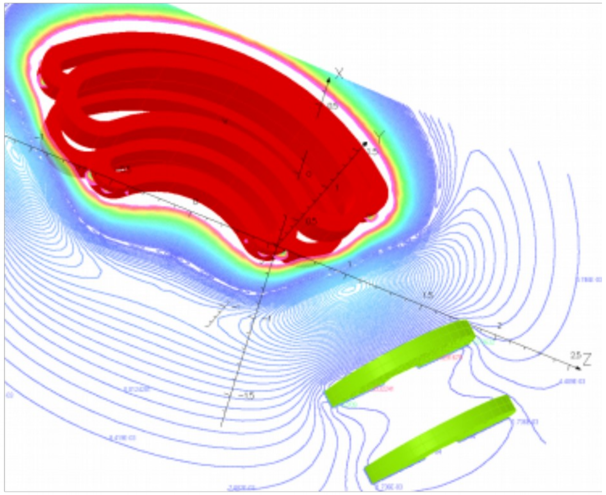


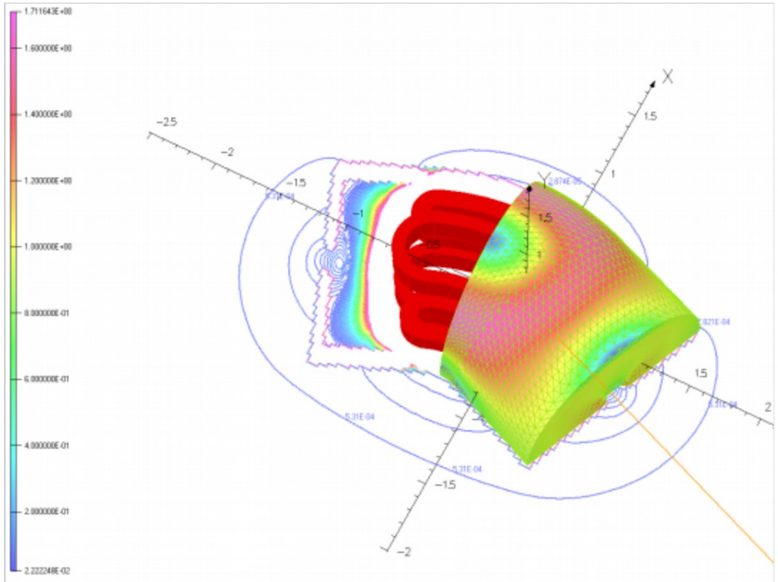
The main multipole errors (along a circle of 250 mm diameter), the sextupole (n=3), the octupole (n=4), the decapole (n=5) and the seventh pole (n=7) are not exceeding 0.6% of the main field.

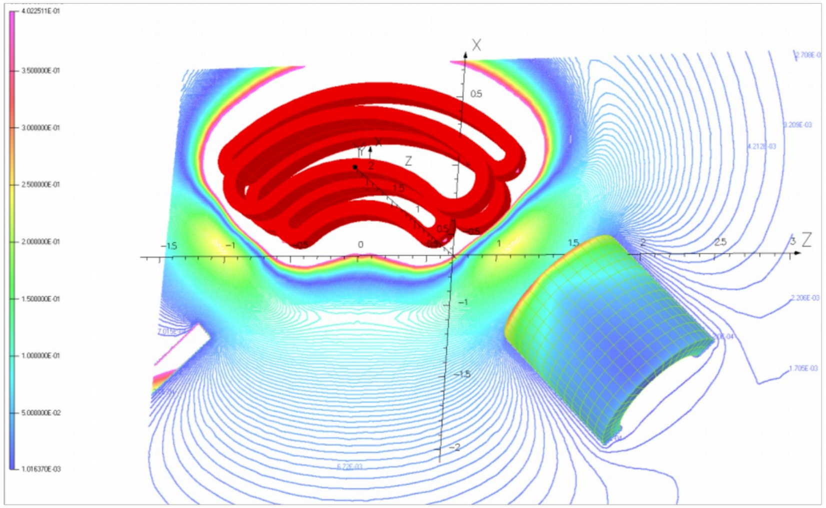
Active vs passive shielding (1)









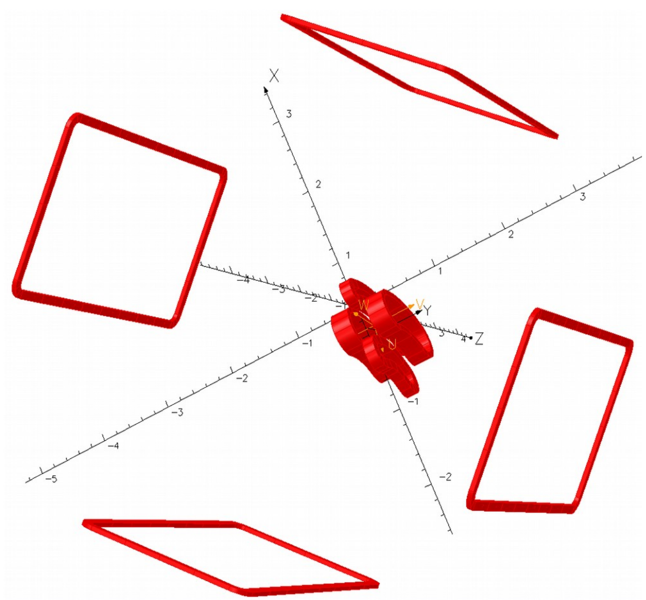


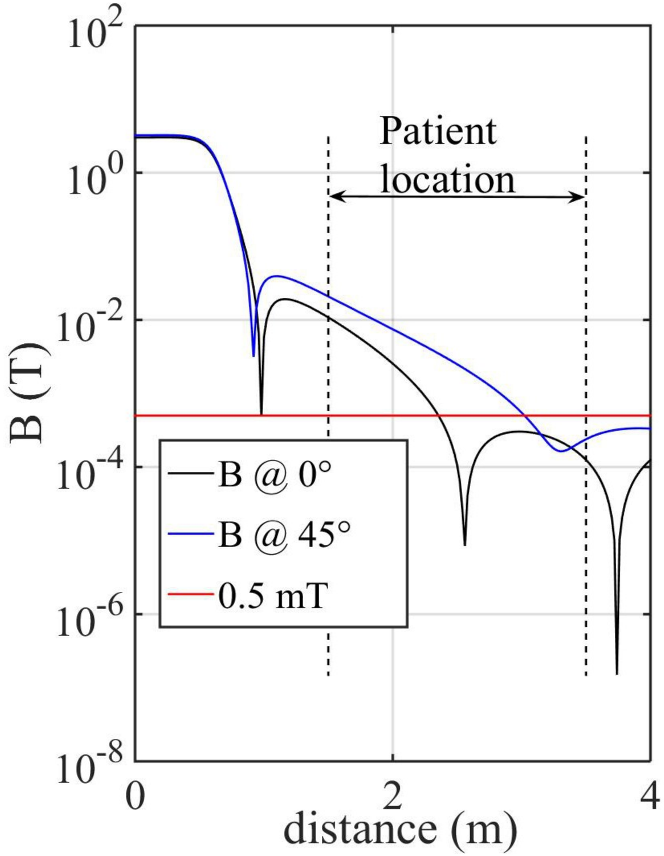
We tried different passive shielding options.

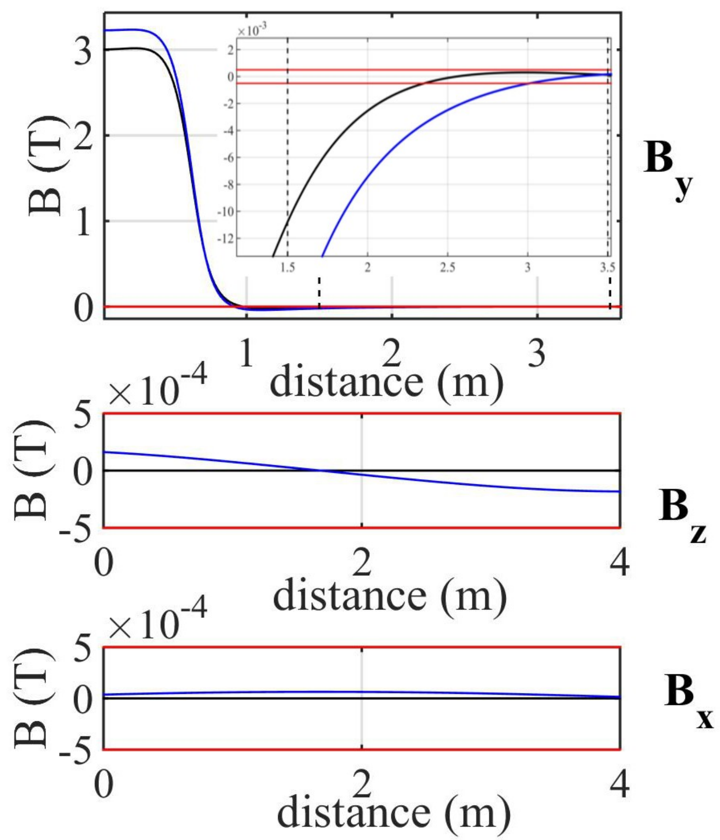
A passive shielding system alone does not allow to have 0.5mT at the patient location preserving the magnet mass below 6000 kg.

Active vs passive shielding (2)

Coils mounted on the treatment room walls.







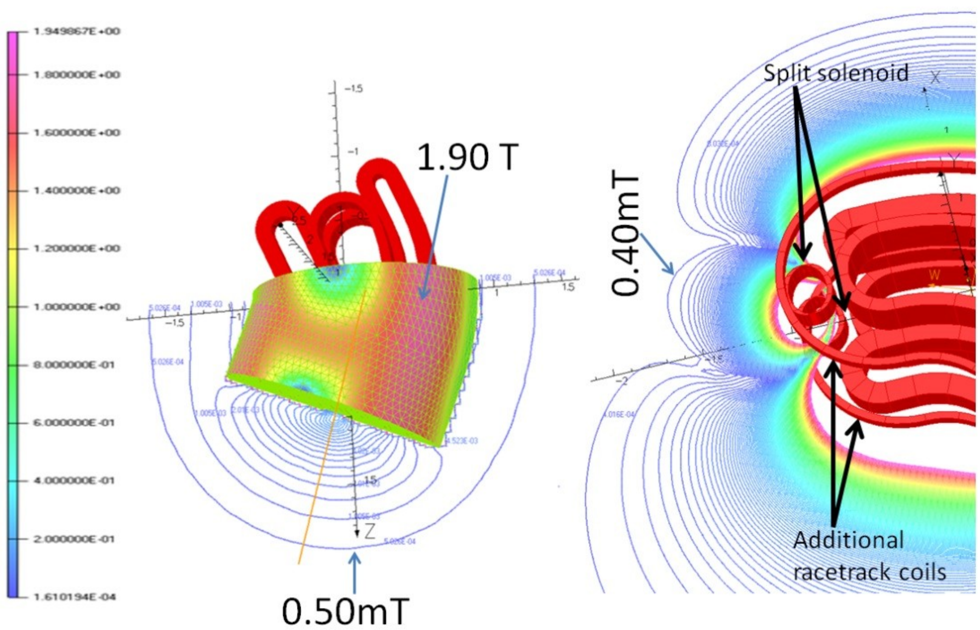
The current in each coil has to be changed as a function of the rotation angle.
Here in the simulations:

Angle	Current Top	Current Bottom	Current Left	Current Right	Dipole	Shaping
0°	24 A/mm^2	24 A/mm^2	0 A/mm^2	0 A/mm^2	73.8 A/mm^2	-64.6A/mm^2
45°	2 A/mm^2	-15 A/mm^2	3 A/mm^2	14 A/mm^2	82.0 A/mm^2	-61.5A/mm^2

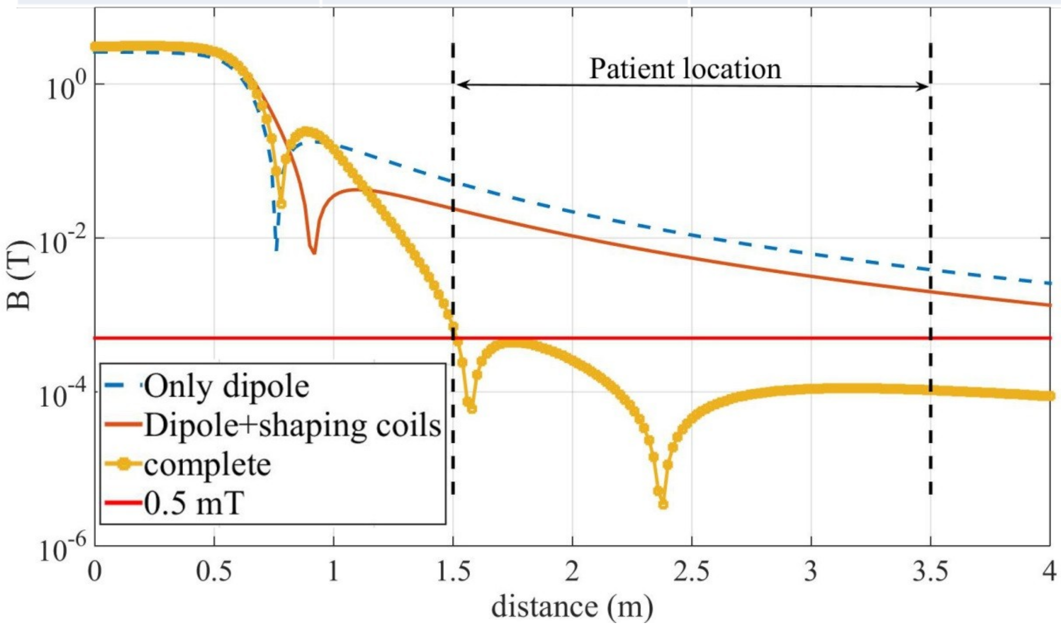
Active vs passive shielding (3)

The shaping coils (the racetrack coils arranged aside with respect to the main dipole) allows to:

- enhance the field quality in the GFR;
- reduce the stray field at the patient location. The shaping coils alone do not allow reaching the specifications in terms of stray field though. Specification: 0.5mT @ 1 m from the magnet exit.



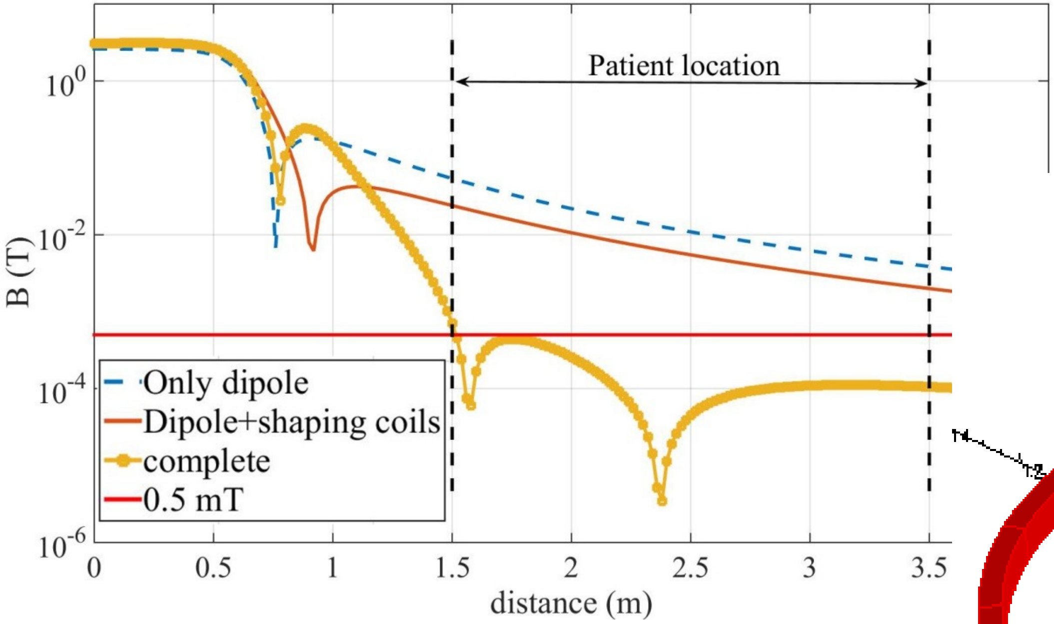
	Current density	Cross section
Dipole	82 A/mm^2	0.07x0.24 m^2
Shaping coils	68 A/mm^2	0.12x0.14 m^2
Additional racetracks	71 A/mm^2	0.04x0.06 m^2
Split solenoid	31 A/mm^2	0.03x0.14 m^2

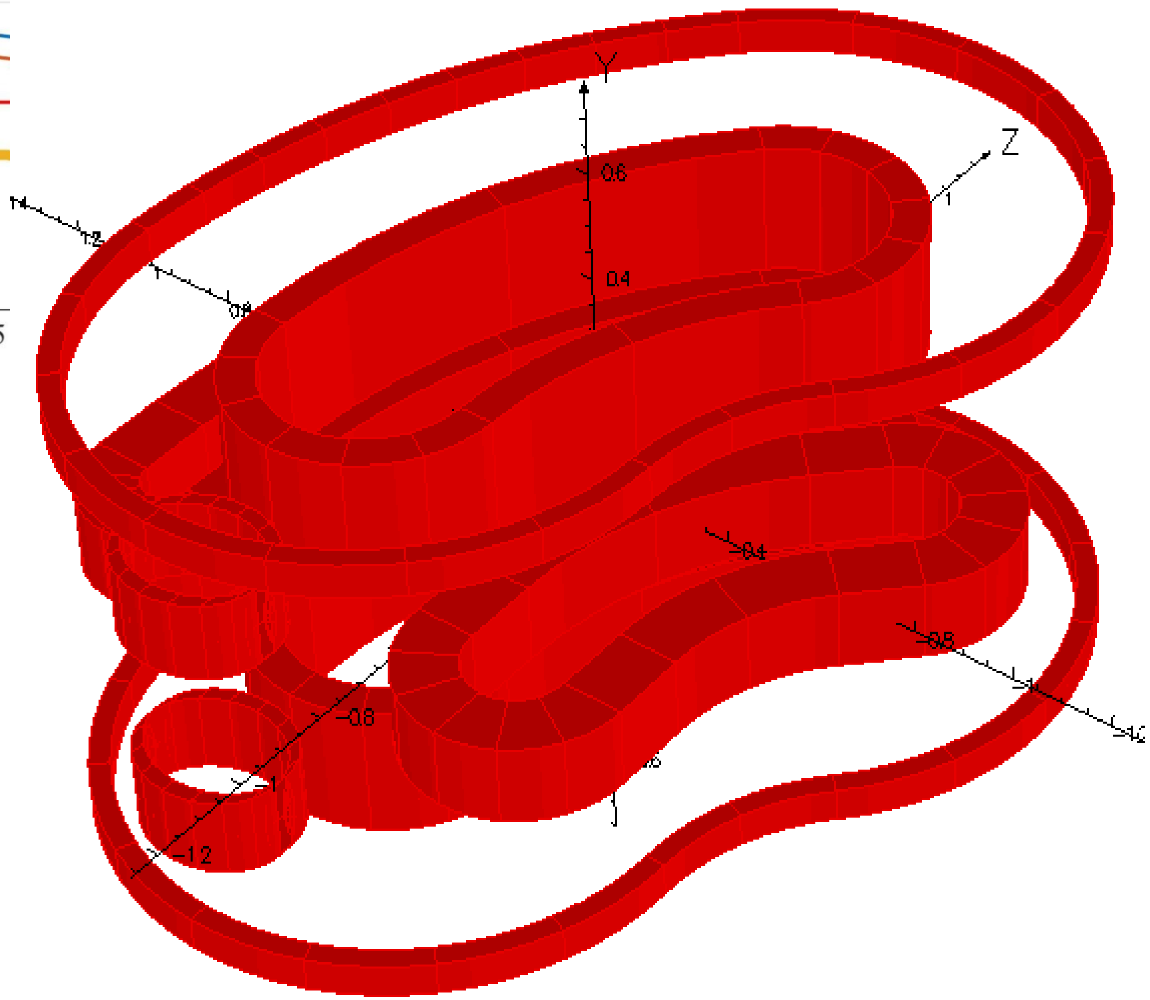


Specifications fulfilled with the additional racetrack coils and the split solenoid:

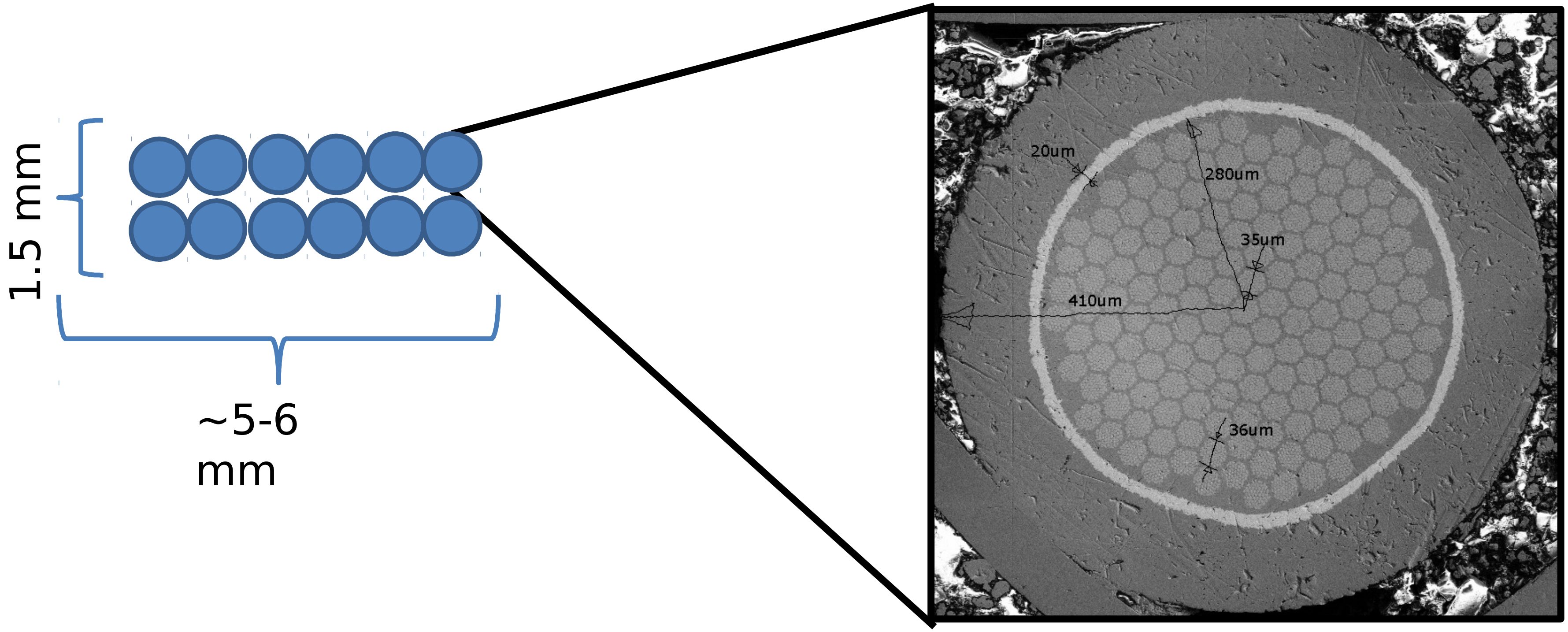
- ✓ B=0.4 mT @ patient locations;
- ✓ Total mass: 1620 kg.

Active shielding



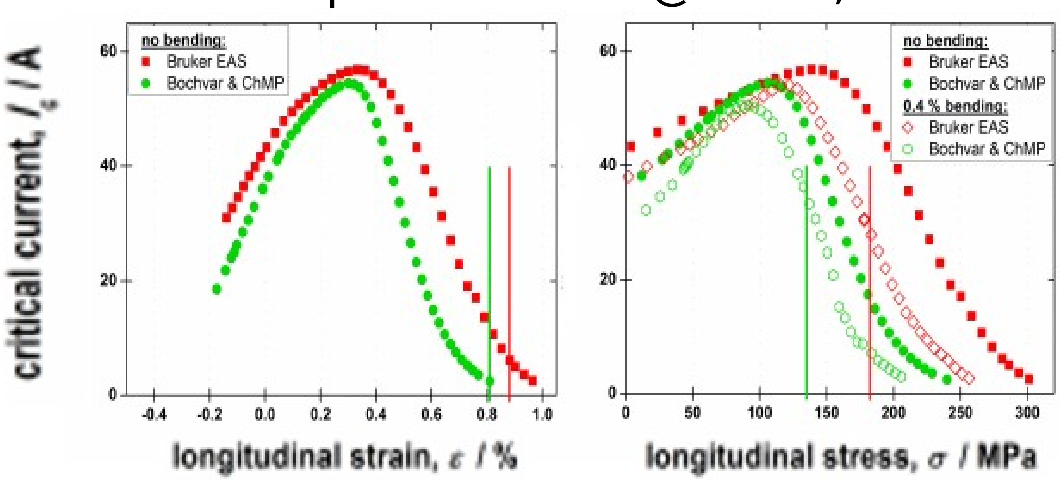


Superconducting strand: a proposal



Strand Φ	0.82 mm
Filaments twist pitch	~ 14 mm
n. filaments	8305
n. Bundles	151
n. Filaments per bundle	55
Filaments Φ	6-8 μm
Cu/non Cu	0.93
Ic @ B=4.5 T, T=4.2K, ε=0.2%	200.5 A

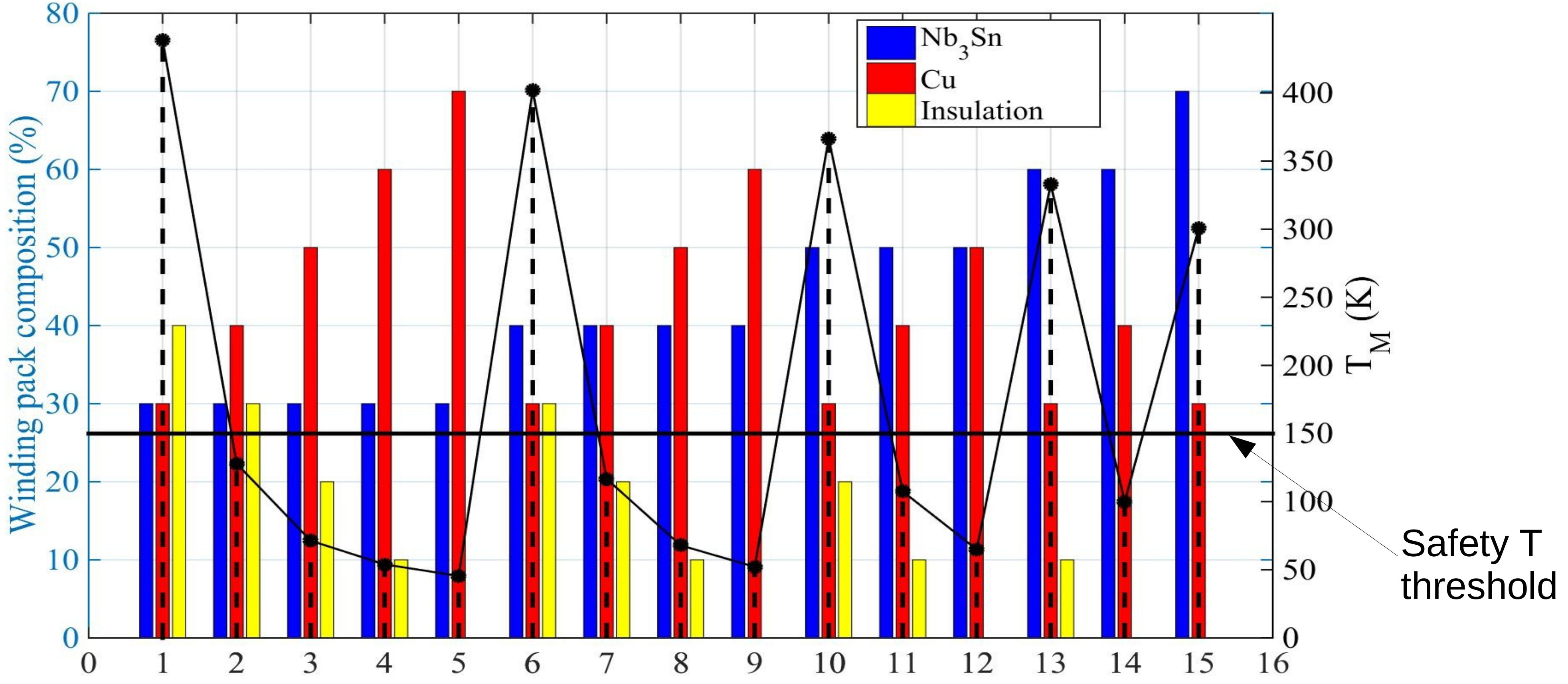
Strand performance @ 19 T, 4.2 K



Hot spot temperature after quench (1)

In order to calculate the amount of copper to be used in the winding pack (Nb_3Sn), the hot spot temperature (T_M) was estimated simulating a quench of the magnet.

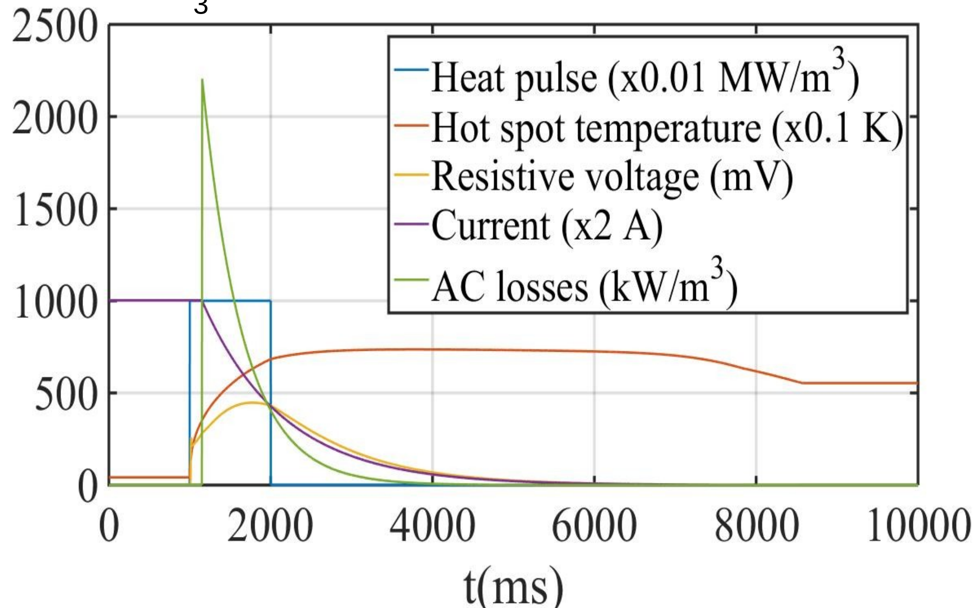
The behaviour of T_M with the winding pack composition was then analyzed.



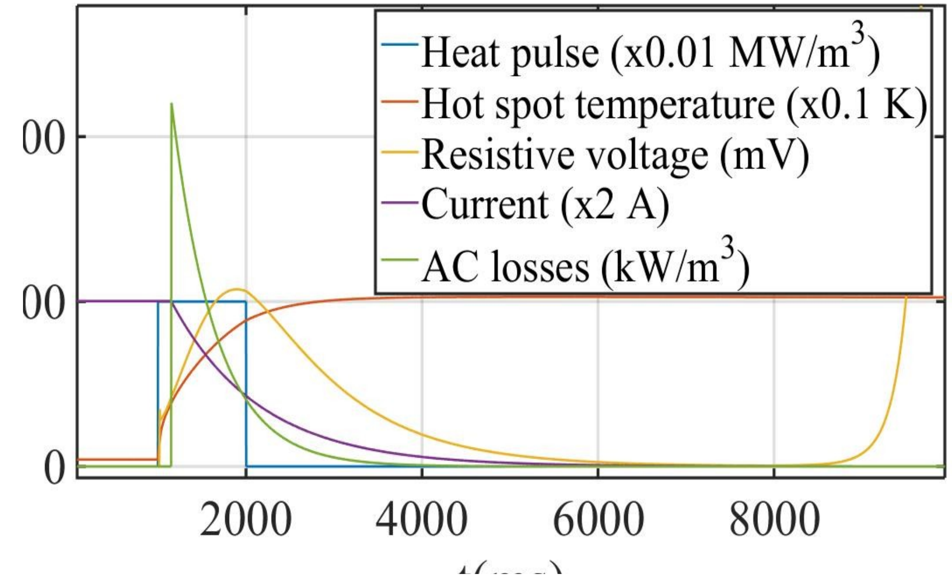
At least 40% of Cu is necessary in the winding pack to avoid too high hot spot temperature in case of quench.

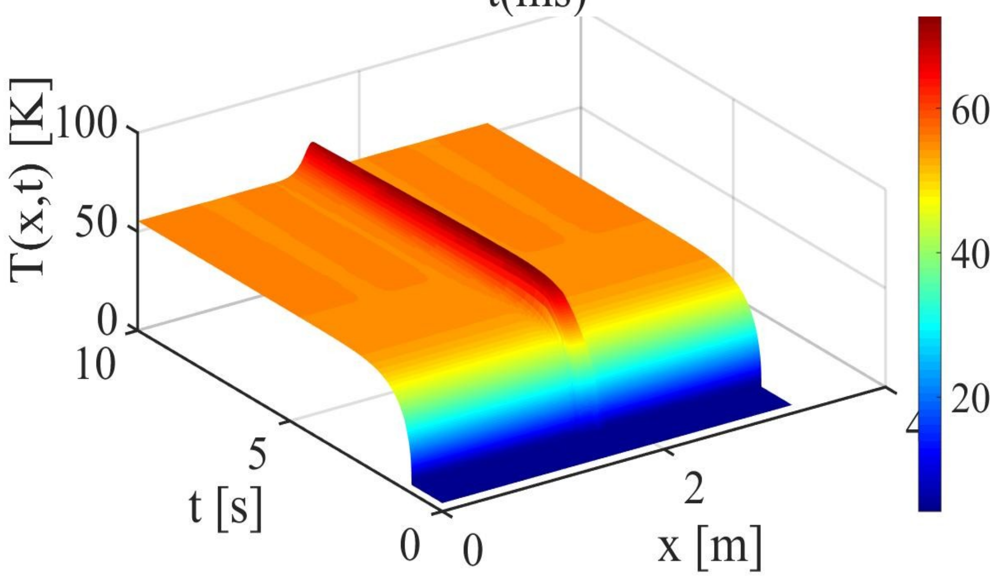
Hot spot temperature after quench (2)

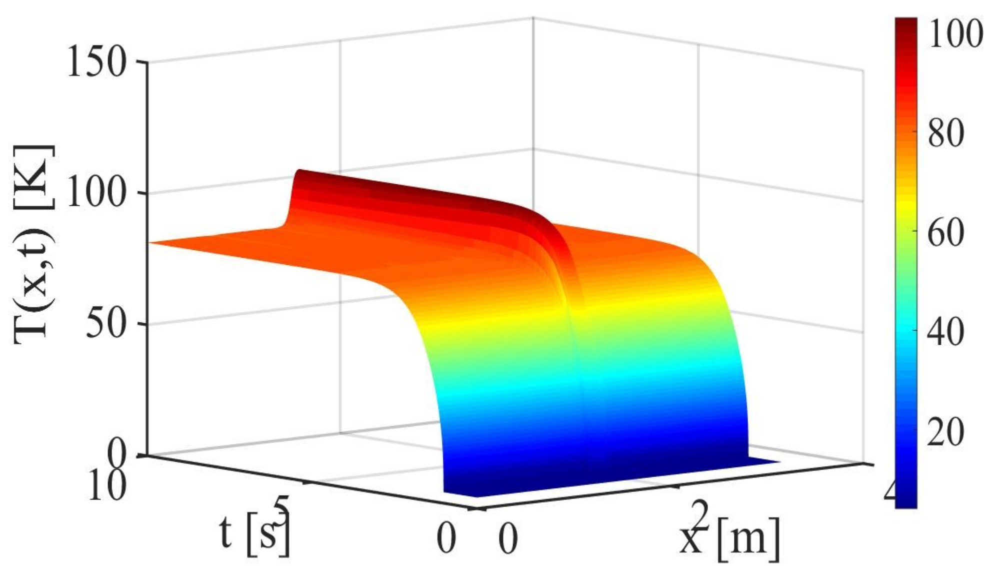
Composition:
30% Nb_3Sn, 40% Cu, 30% Insulation.



Composition:
50% Nb_3Sn, 30% Cu, 20% Insulation.

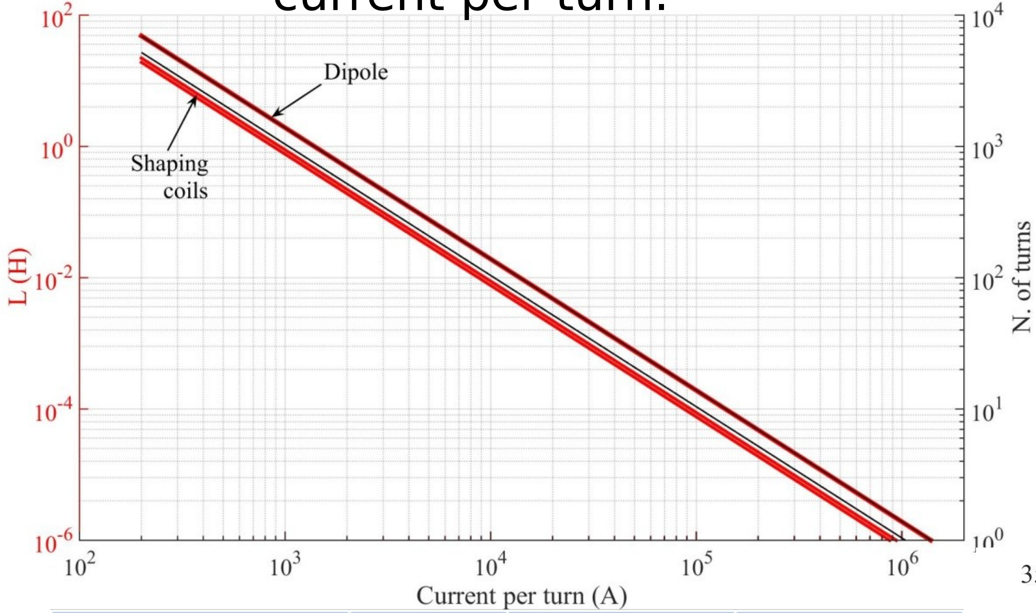




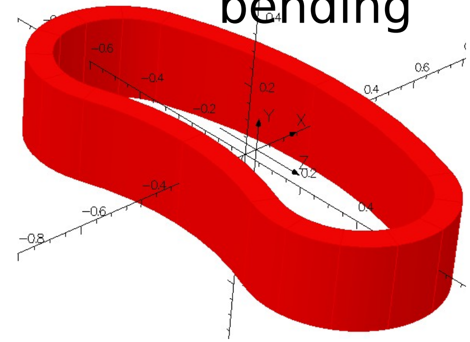


Winding pack

Scaling of the inductance with the current per turn.

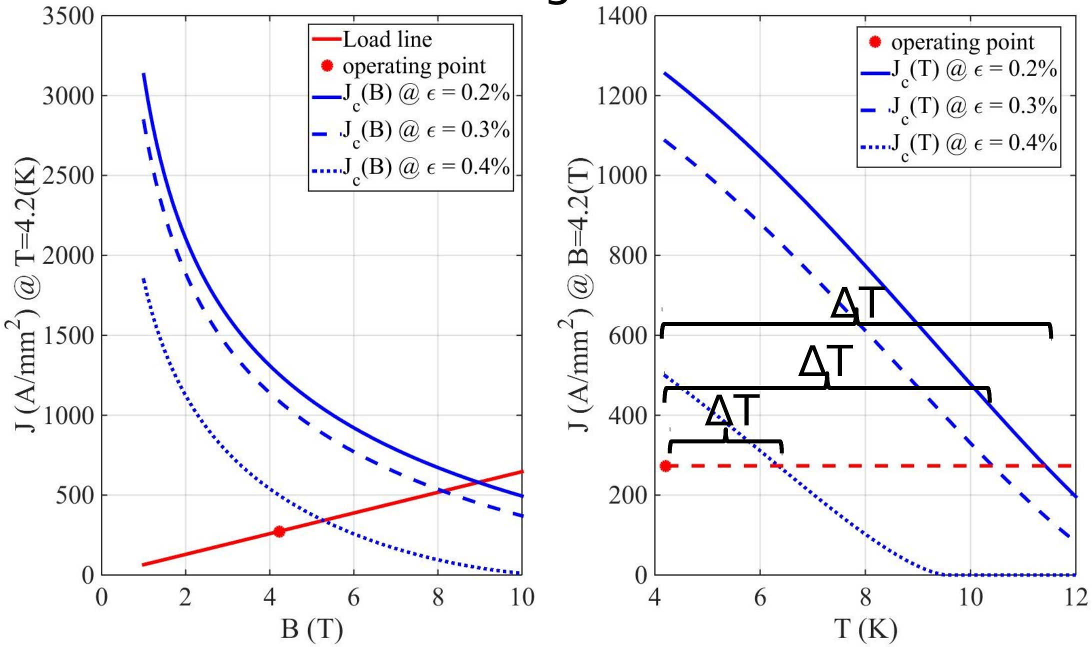


45° bending



	Dipole coil (1 coil)	Shaping coil Left	Shaping coil Right
Magnetic energy (MJ)	0.965	0.382	0.443
Inductance (H)	0.48	0.19	0.22
Current per turn (A)	2000	2000	2000
N. turns	693	521	521
Term. Volt. (V) (t_{damp}=1s)	965	382	443

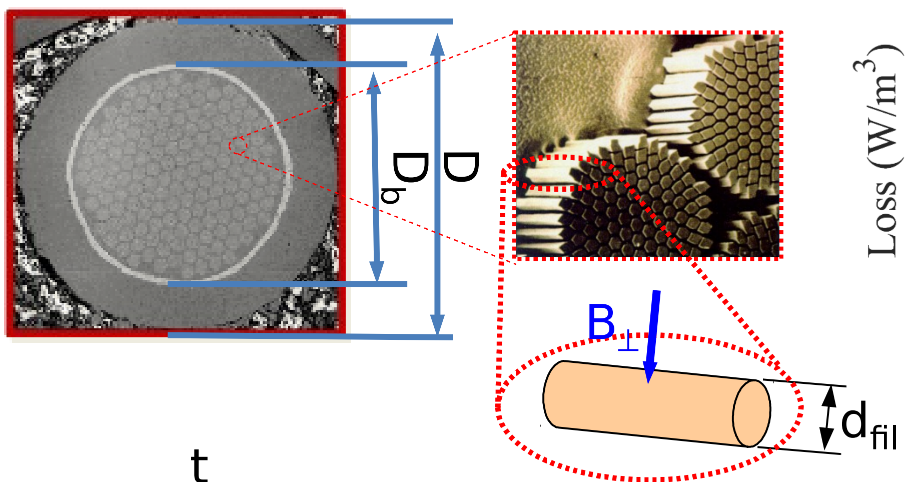
Magnet load line and temperature margin.

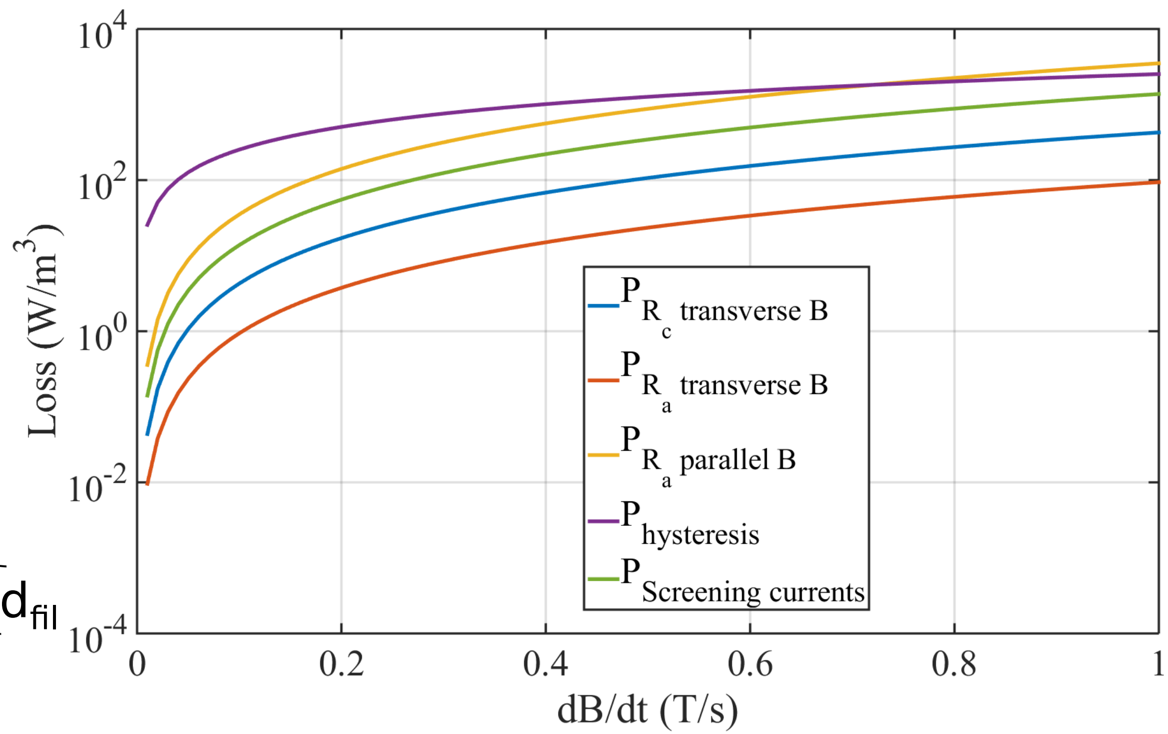


AC loss estimation for the superconducting cable

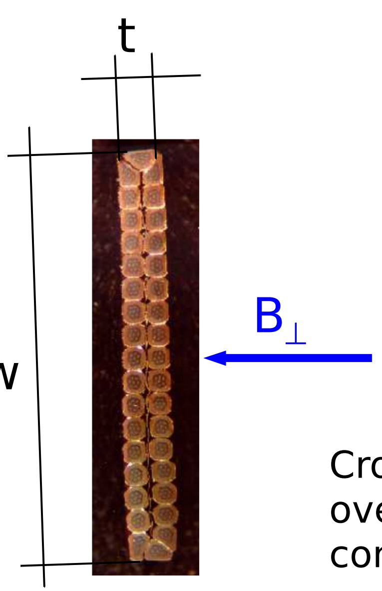
AC loss in strands and cables: ballpark estimate:

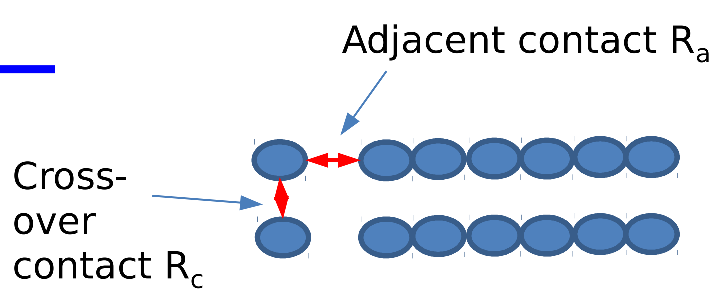
Hysteresis + coupling inside the strands





Coupling among the strands in the cable





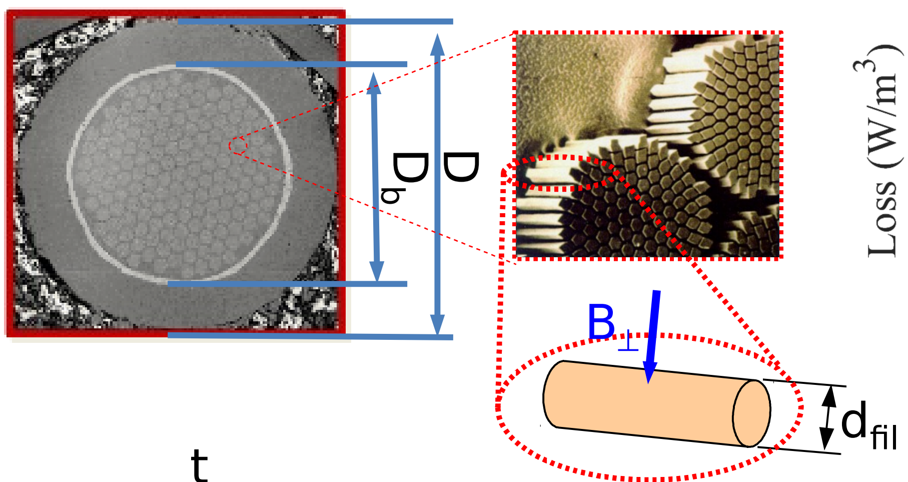
Parameter	Value
R_c	100 μΩ
R_a	10 μΩ
ρ_{matrix}	3.6 10^{-8} Ω m
Filaments diameter and twist pitch	8 μm, 14 mm
Strands twist pitch	70 mm

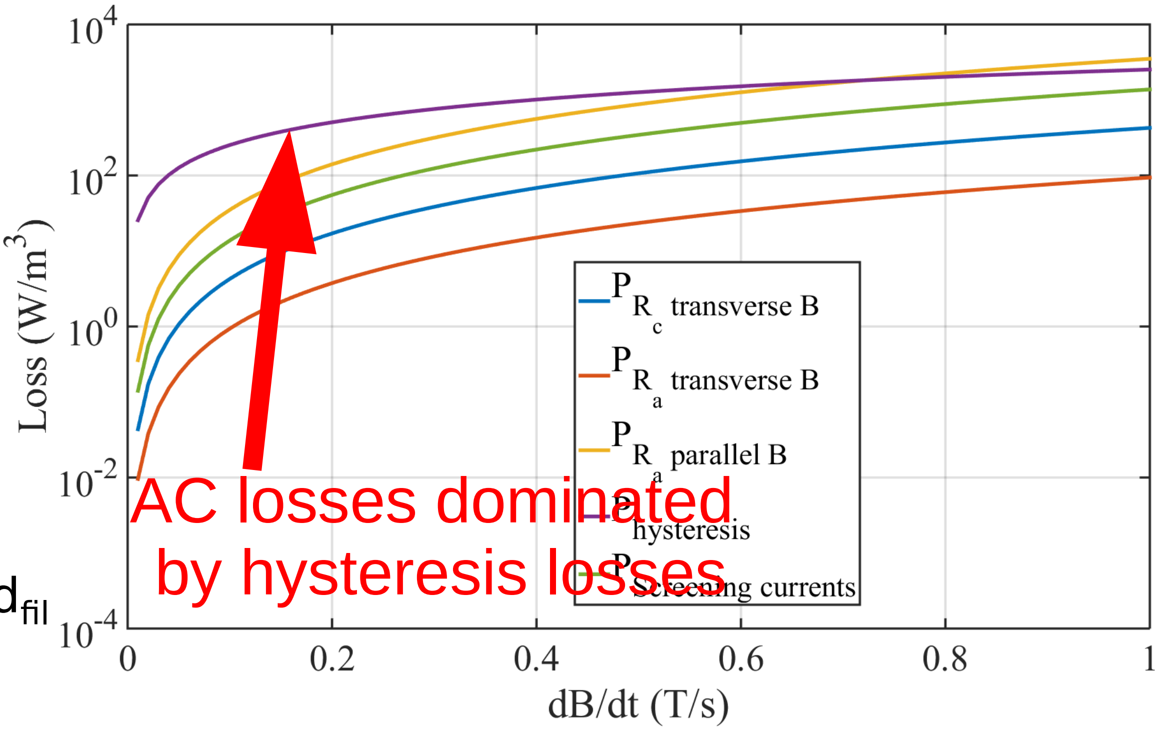
To be measured

AC loss estimation for the superconducting cable

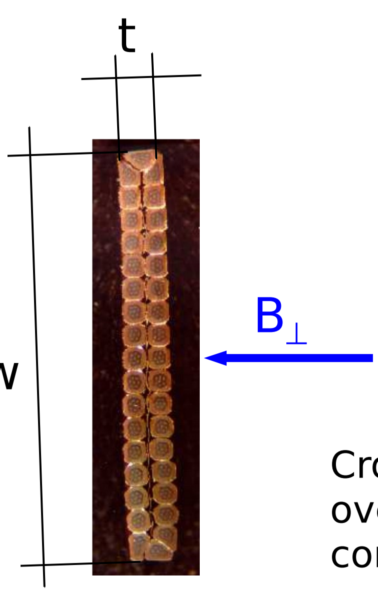
AC loss in strands and cables:
ballpark estimate:

Hysteresis + coupling inside the strands



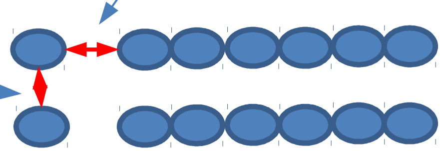


Coupling among the strands in the cable



Adjacent contact R_a

Cross-over contact R_c



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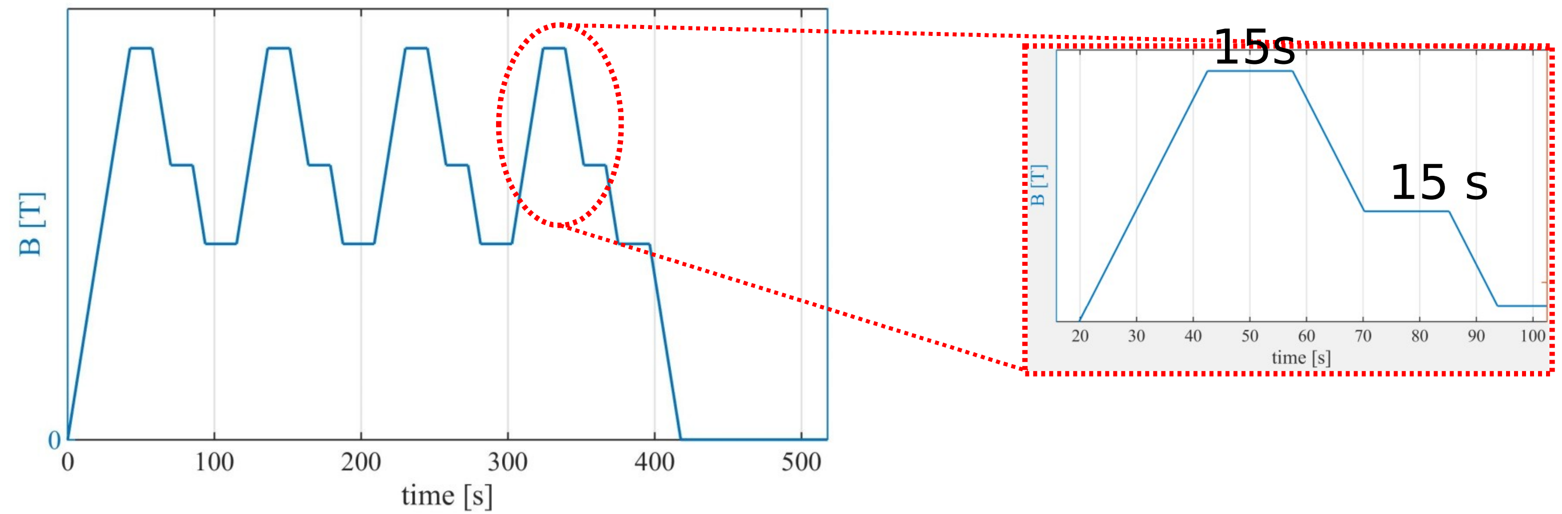
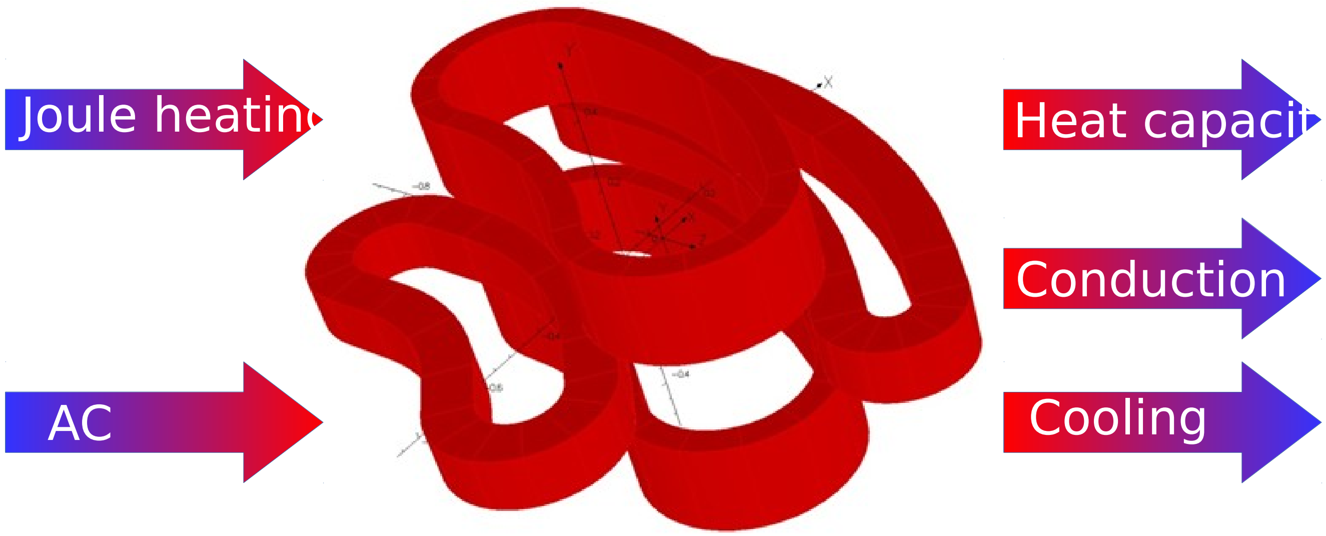
Filaments diameter and twist pitch	8 μm, 14 mm
Strands twist pitch	70 mm

To be measured

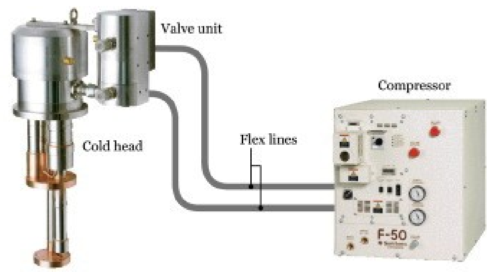
Heating induced by AC losses

B-field profile





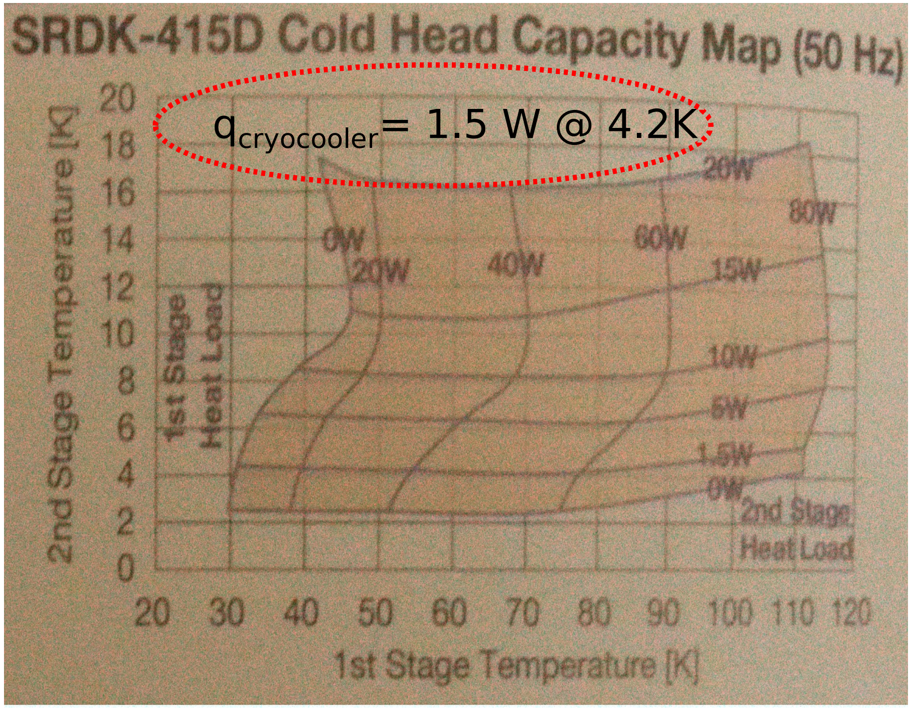
Cooling system 1: cryocoolers



We would need flexible lines:

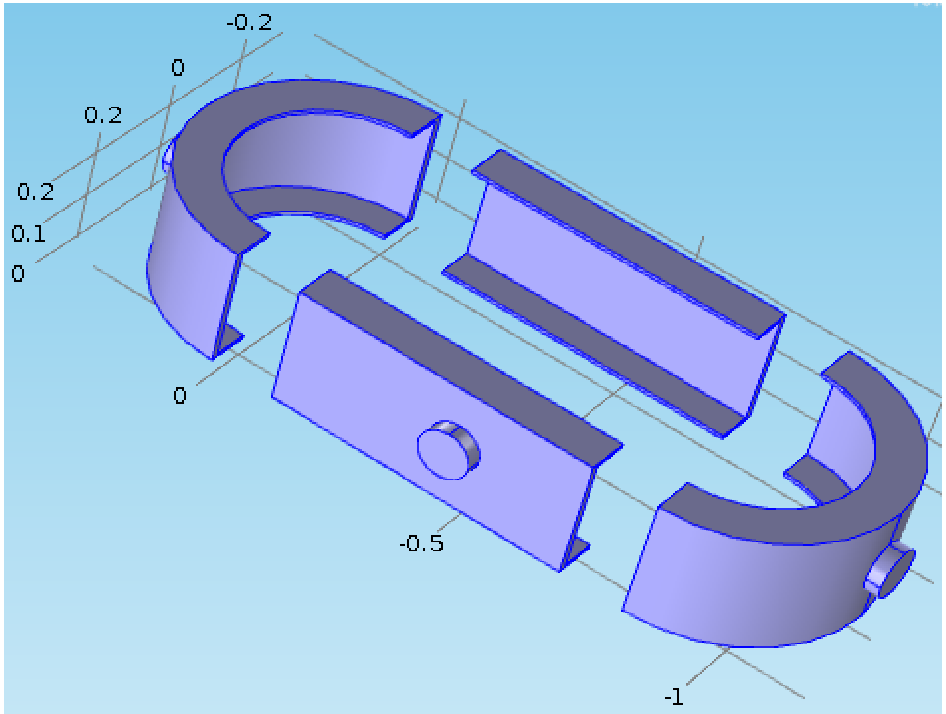
- To avoid the compressor to be mounted on the rotating gantry;
- To reduce the vibrations transmitted to the winding pack;
- Long flexible lines result in performance reduction but work as well as reservoir.

Sumitomo Heavy Industries, Ltd. 40-50 k€



- If the cold head rotates, a cooling power decrease has to be considered: ~10% from 0° to 90°

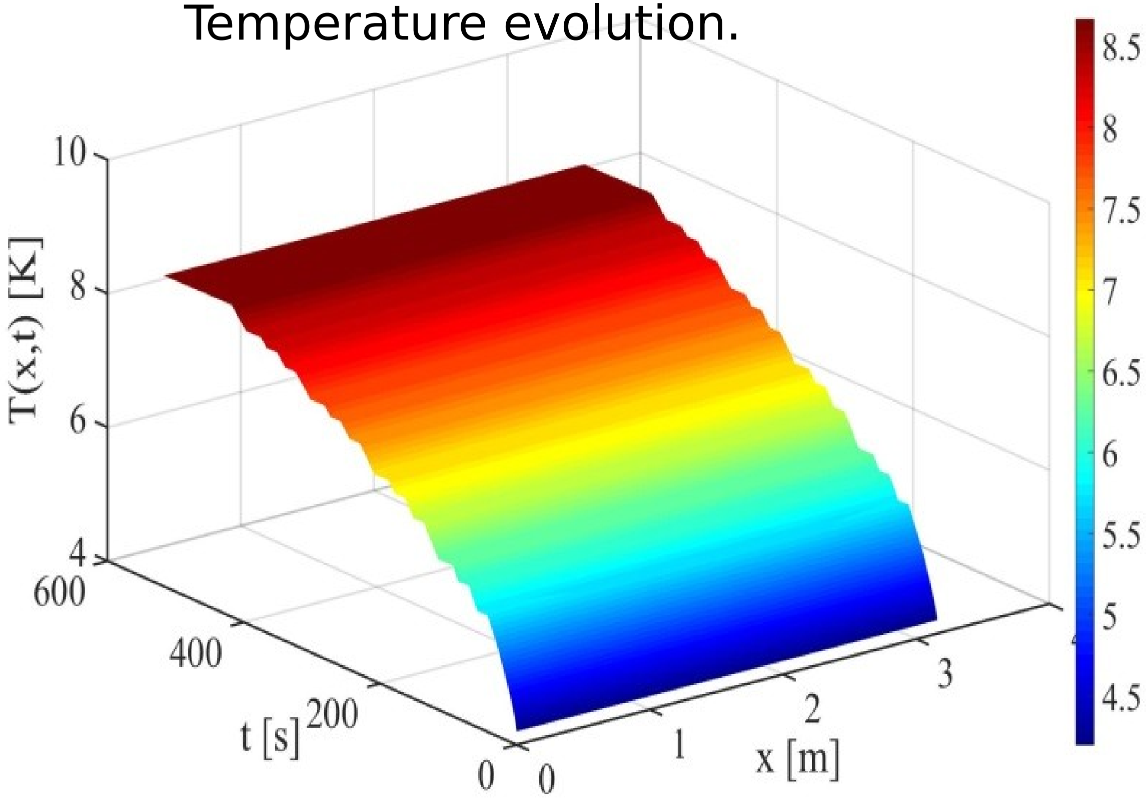
Cu thermal path for heat distribution

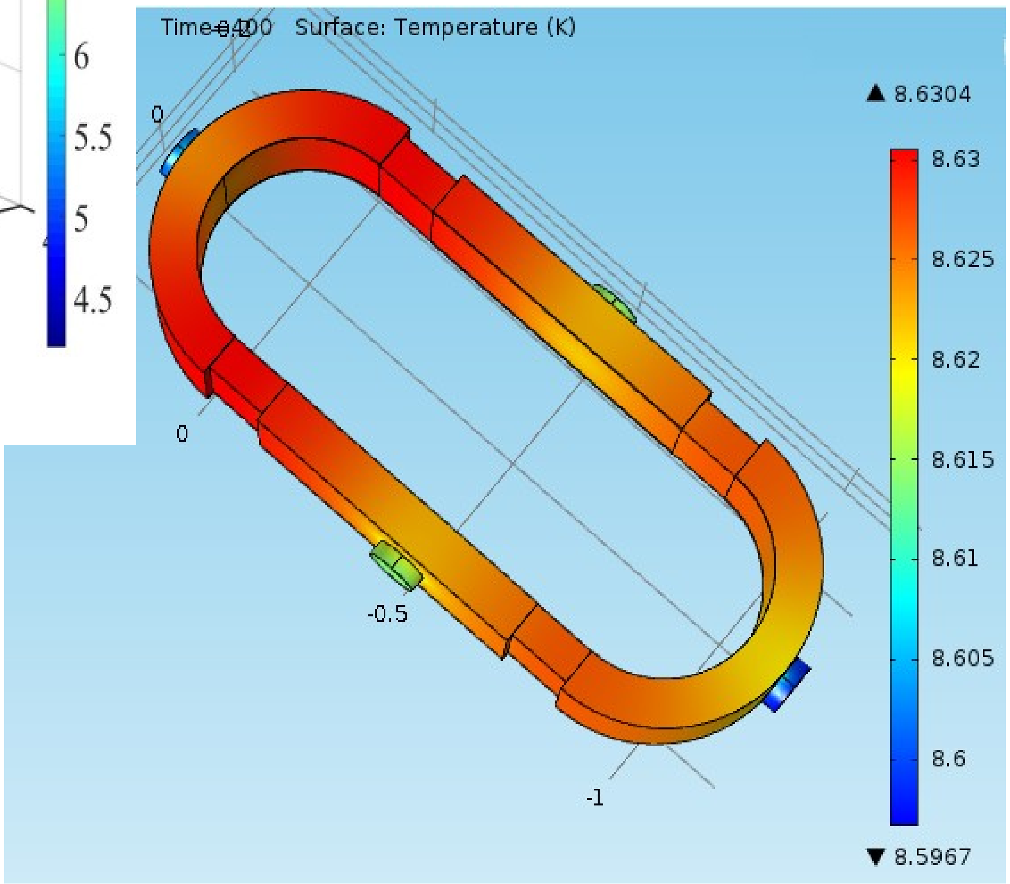


It would be much better if we could work at around 20 K!!!

Cooling system 1: cryocoolers

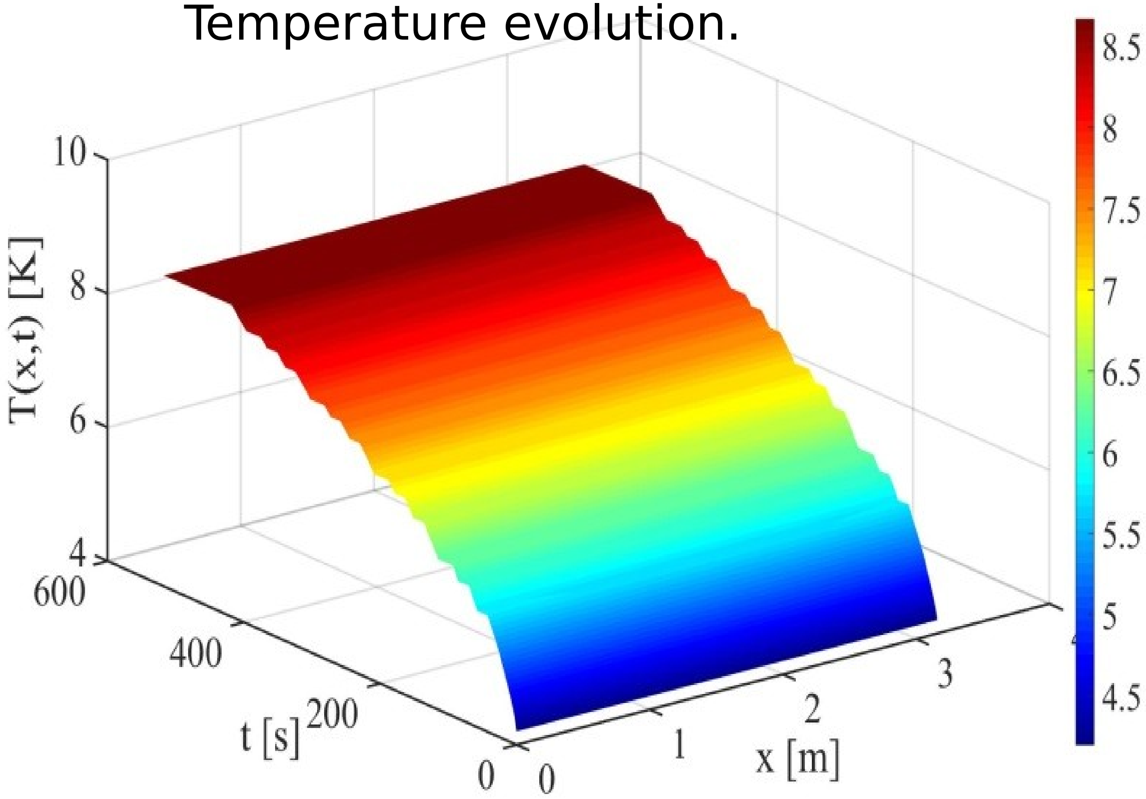
Temperature evolution.

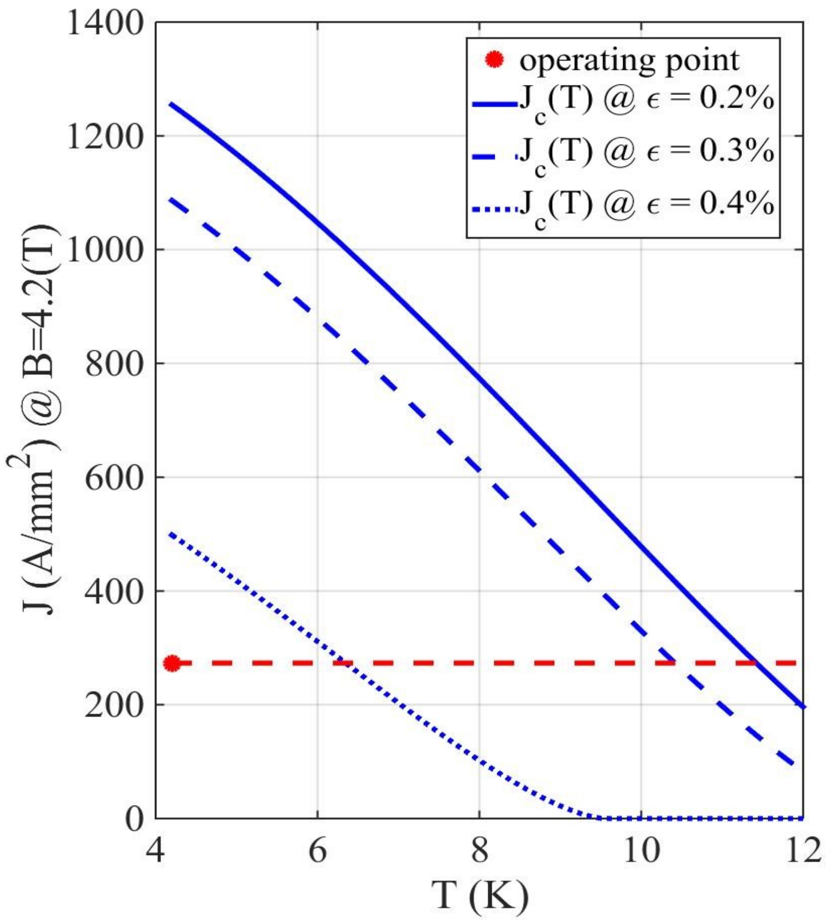




Cooling system 1: cryocoolers

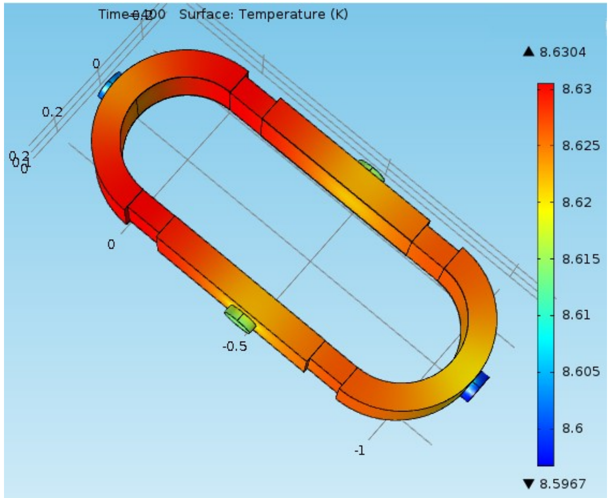
Temperature evolution.

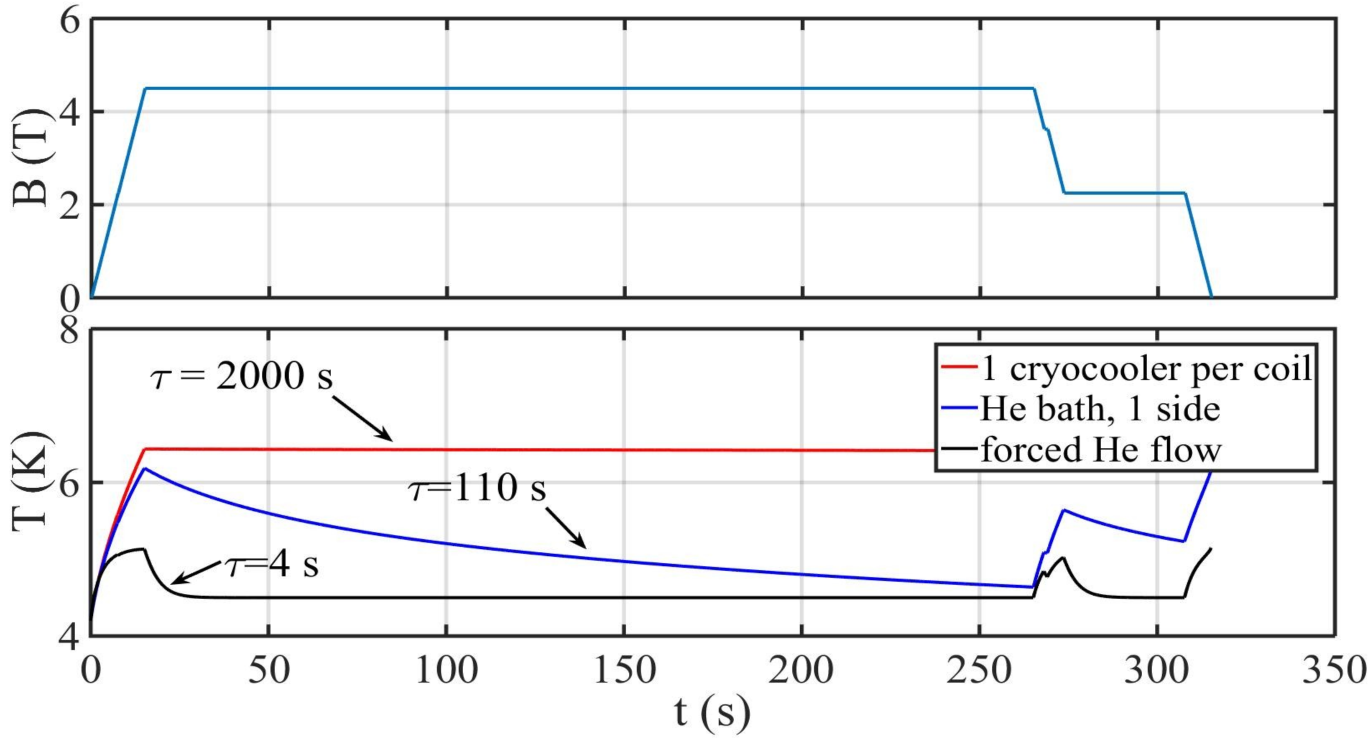




Cooling system 1: cryocoolers

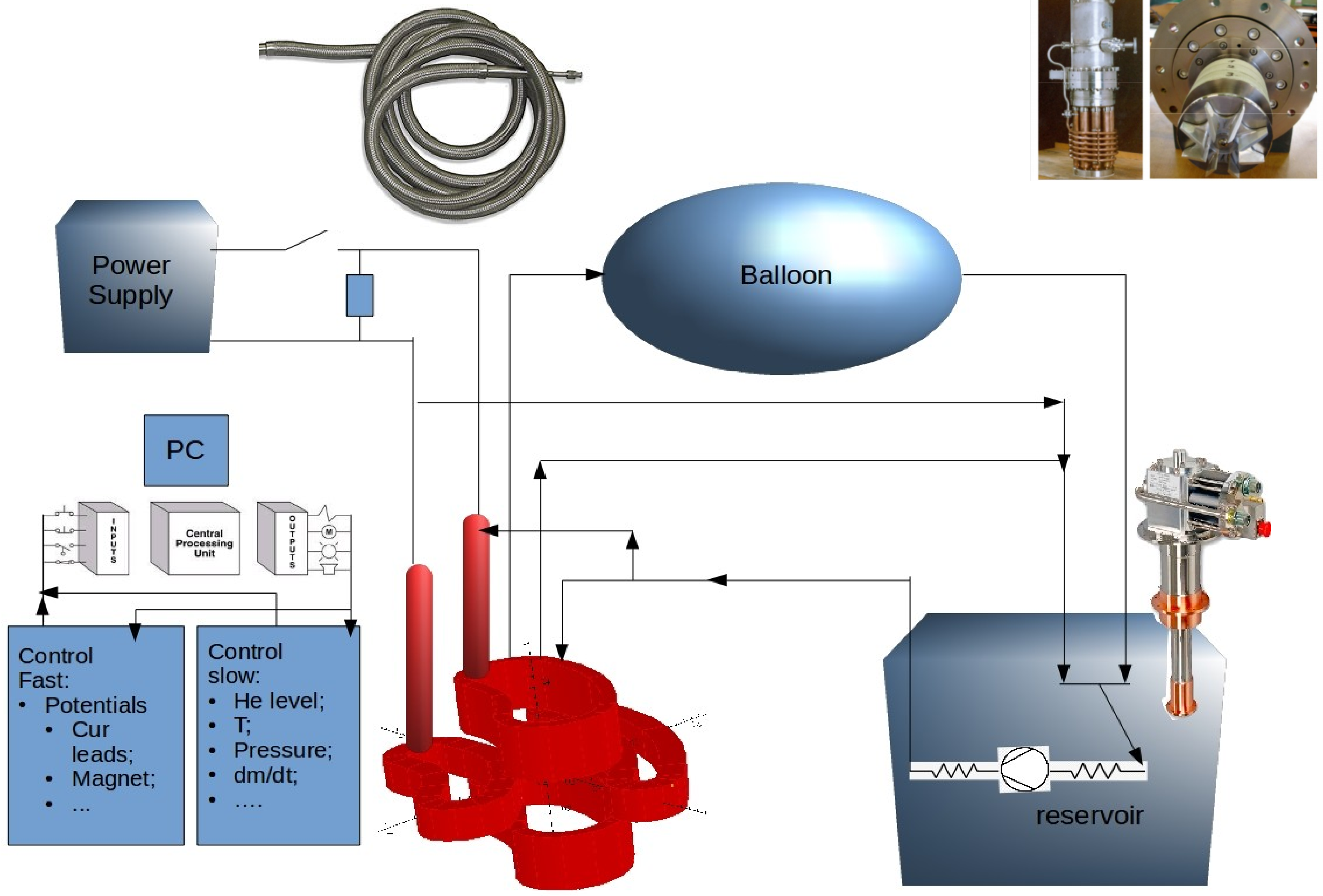
Cool-down may take a while....



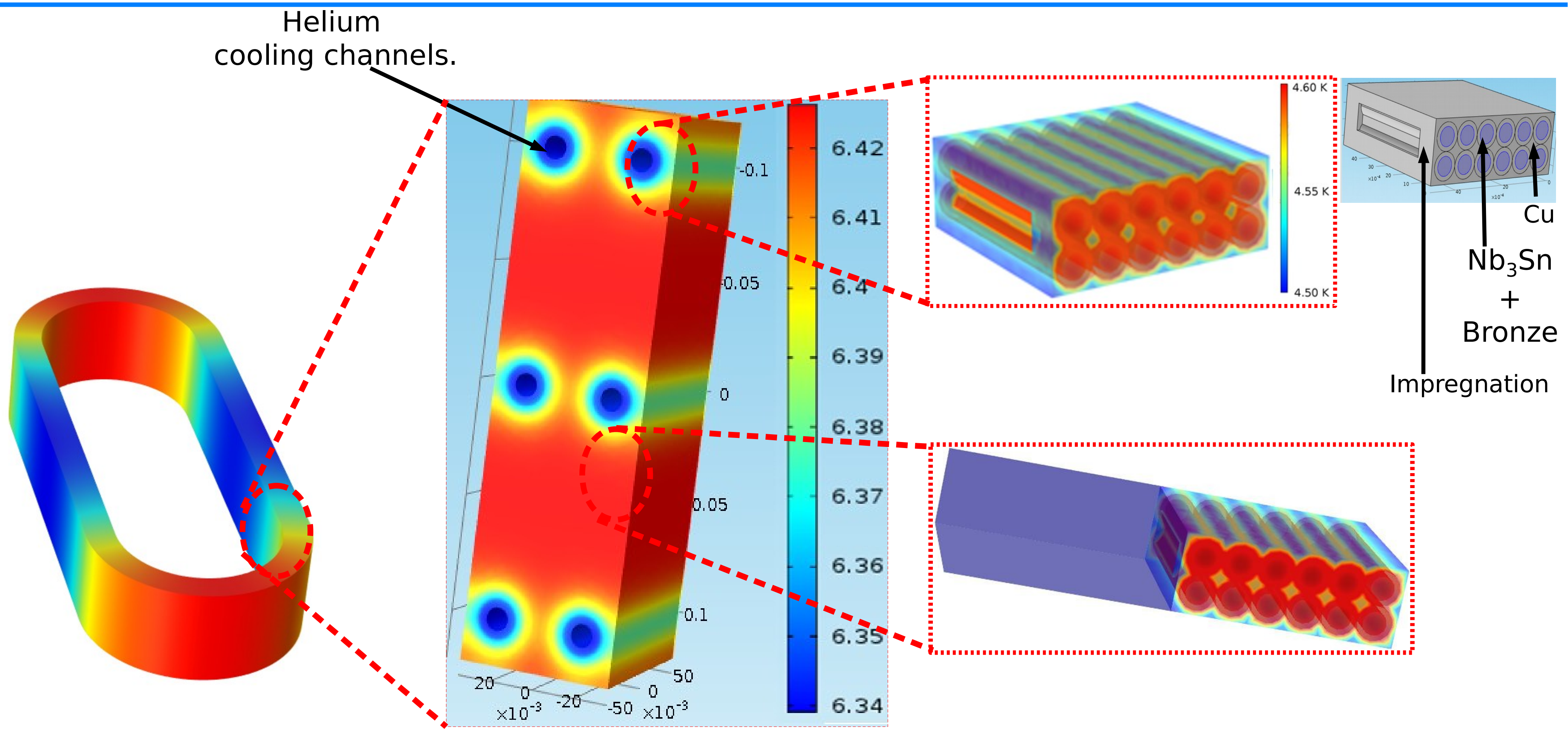


Cooling system 2: forced flow supercritical He (1)

Flexible liquid Helium transfer line.



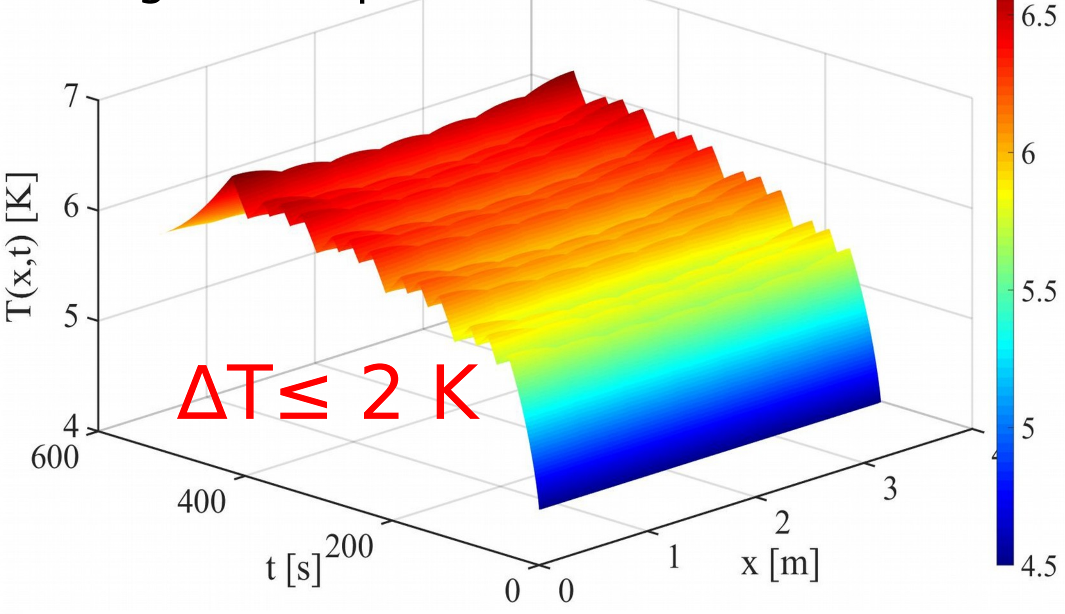
Cooling system 2: forced flow supercritical He (2)



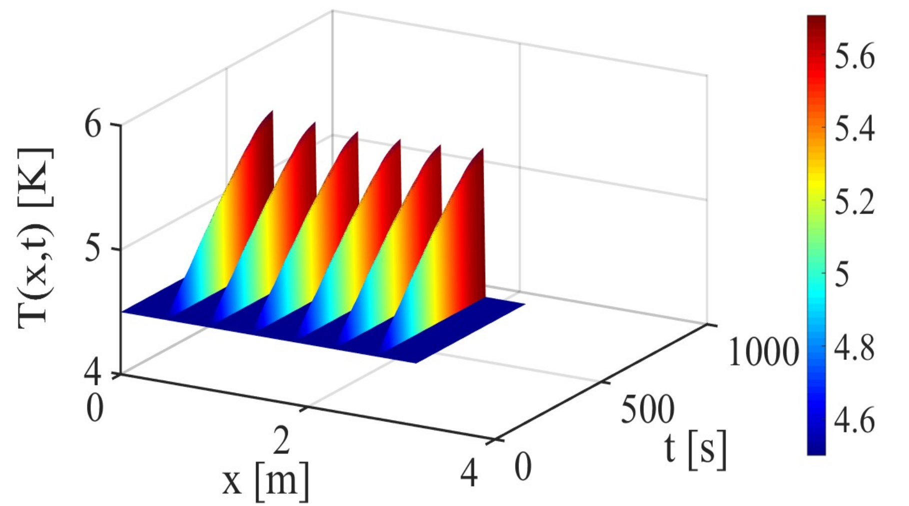
He mass flow rate	5 g/s
He inlet pressure	0.4 MPa
He inlet temperature	4.5 K

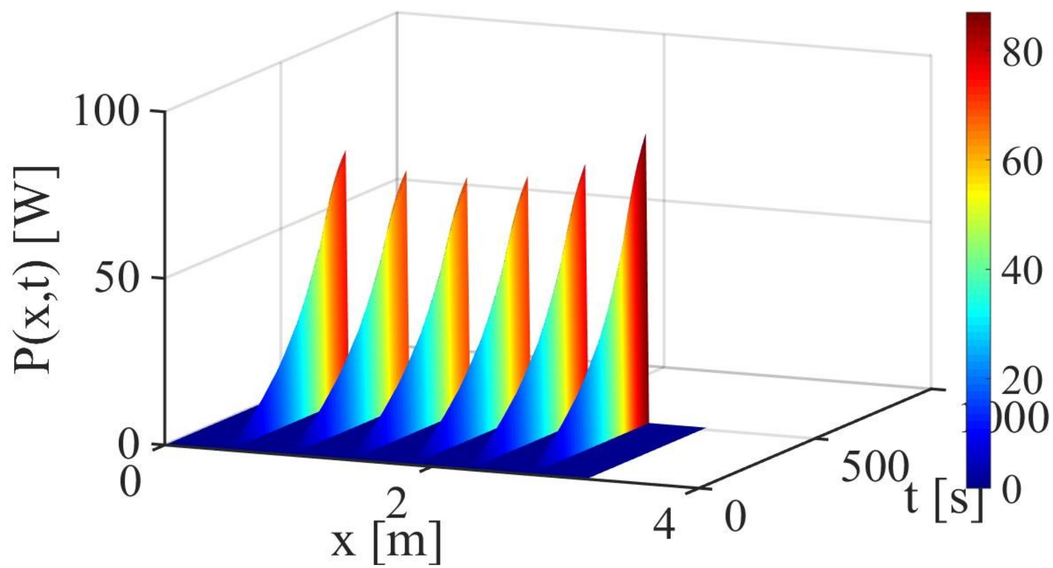
Cooling system 2: forced flow supercritical He (3)

Magnet temperature evolution (K)

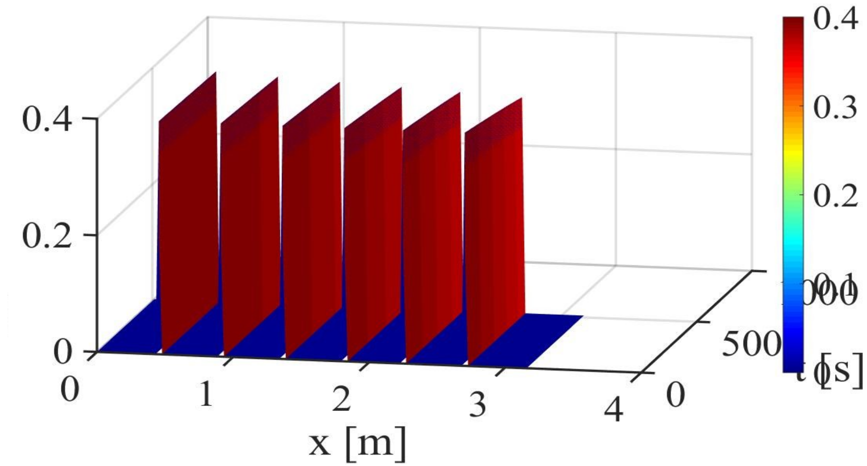


He temperature evolution (K)



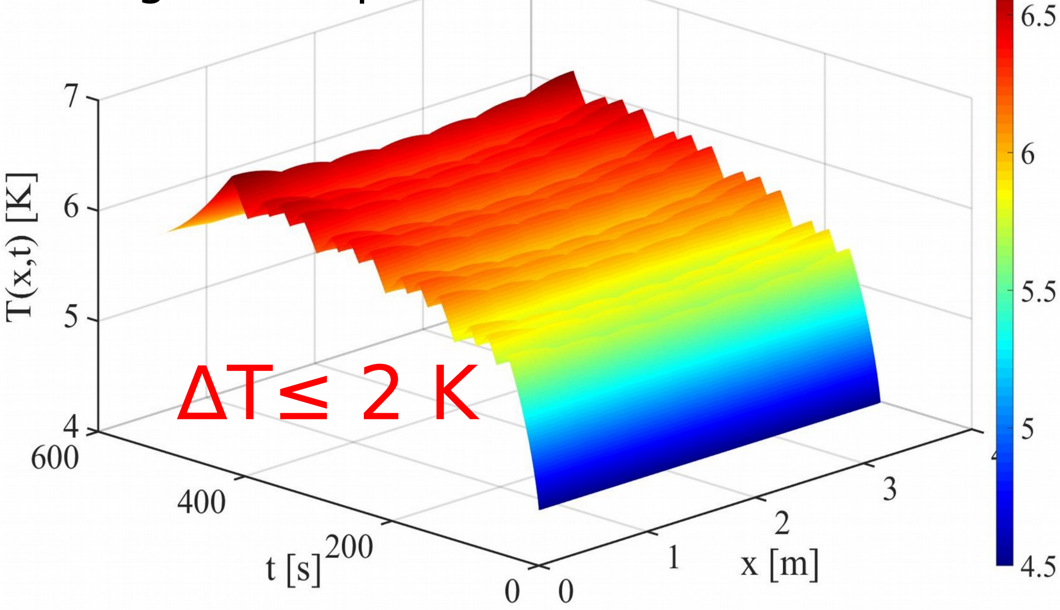


He pressure (MPa)

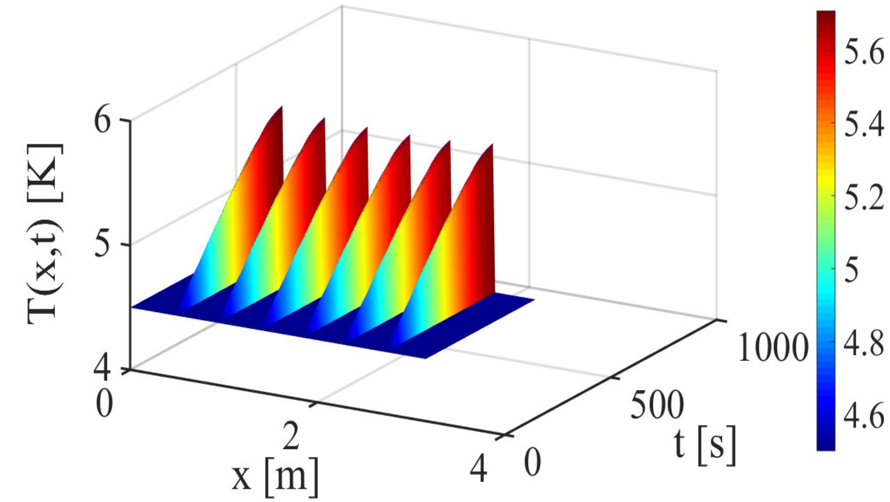


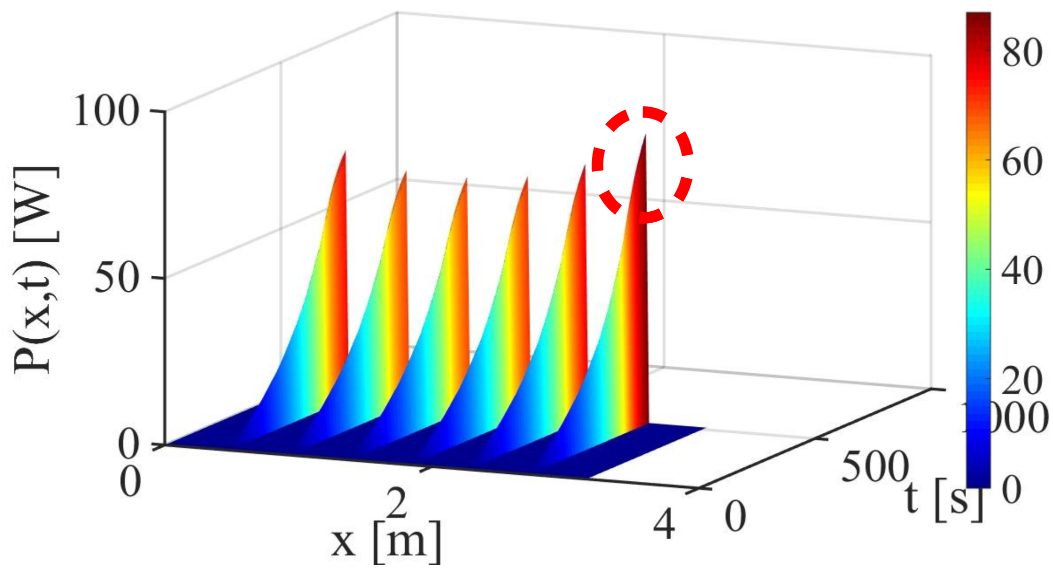
Cooling system 2: forced flow supercritical He (3)

Magnet temperature evolution (K)

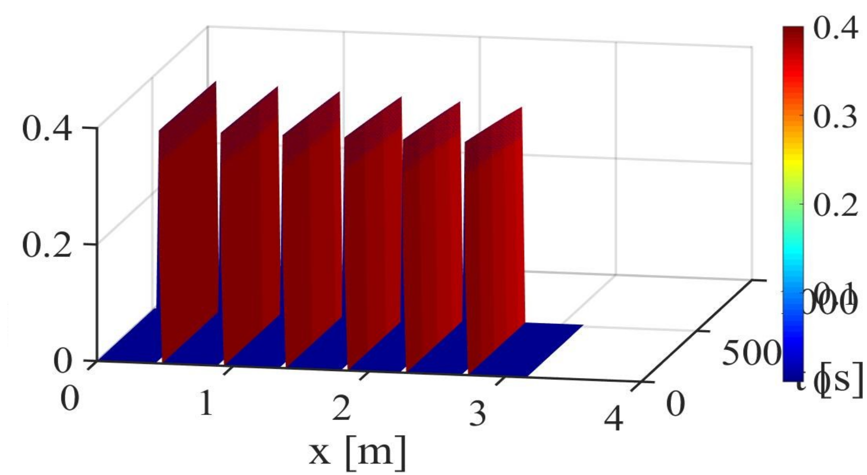


He temperature evolution (K)



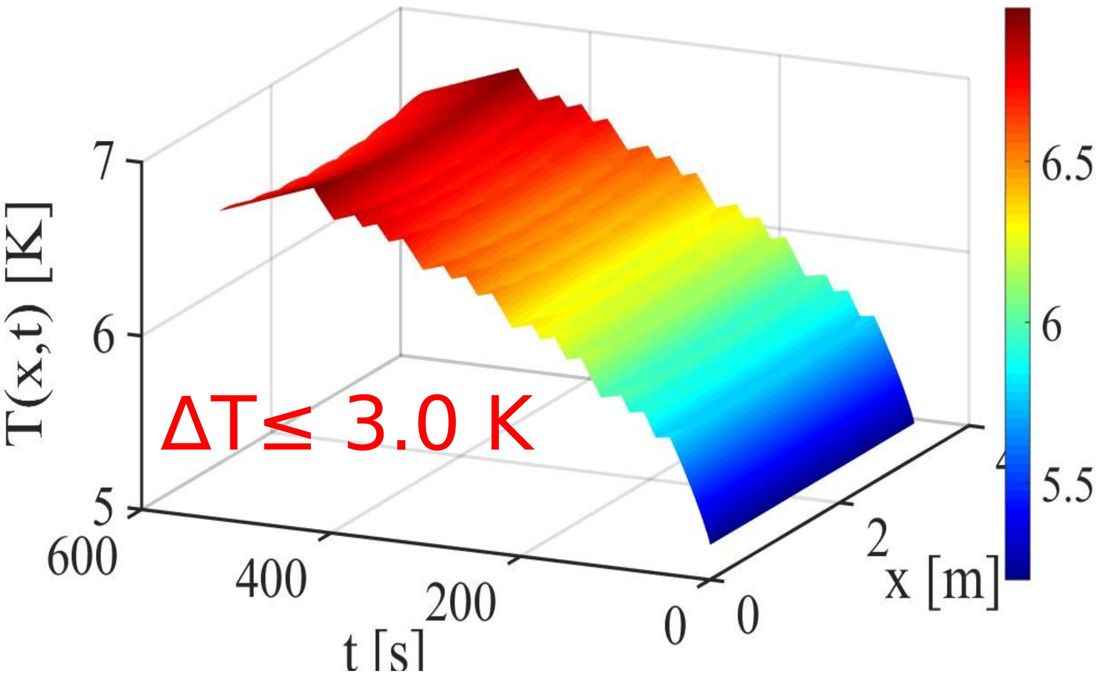


He pressure (MPa)

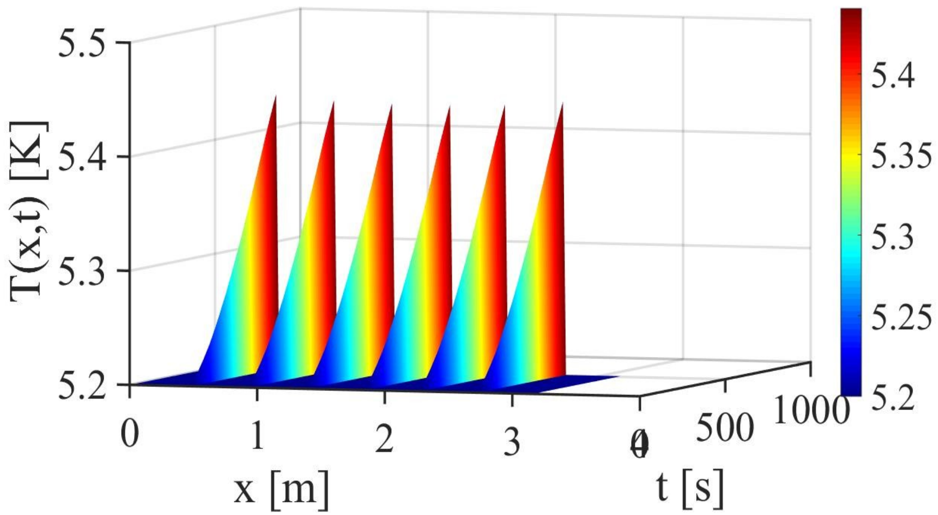


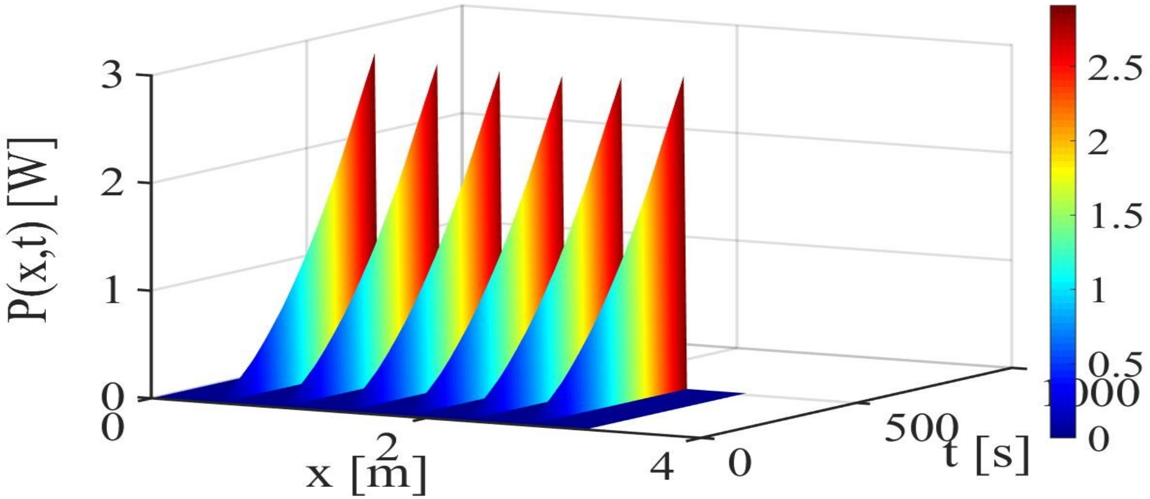
Cooling system 2: forced flow supercritical He (4)

Magnet temperature evolution (K)



He temperature evolution (K)

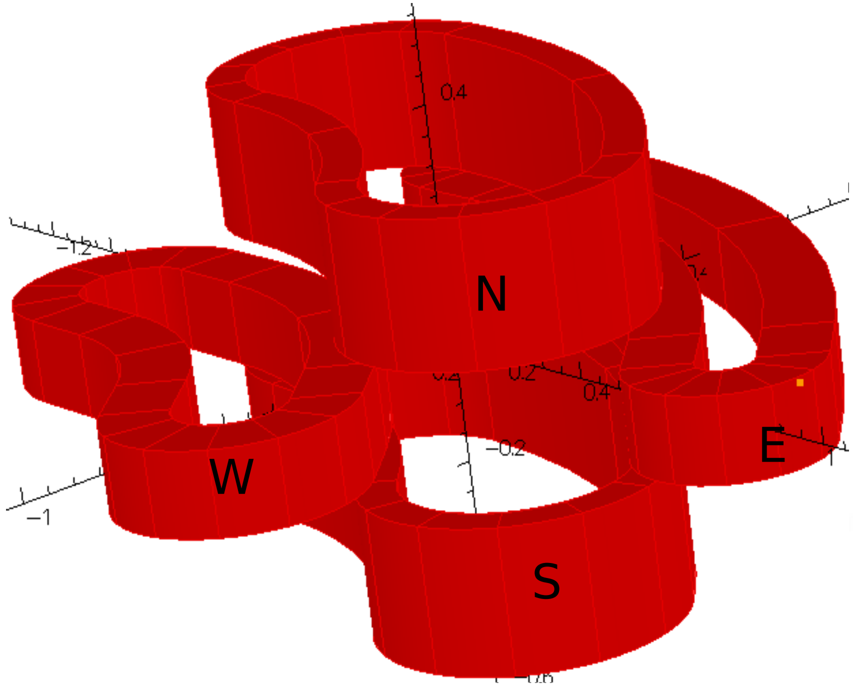


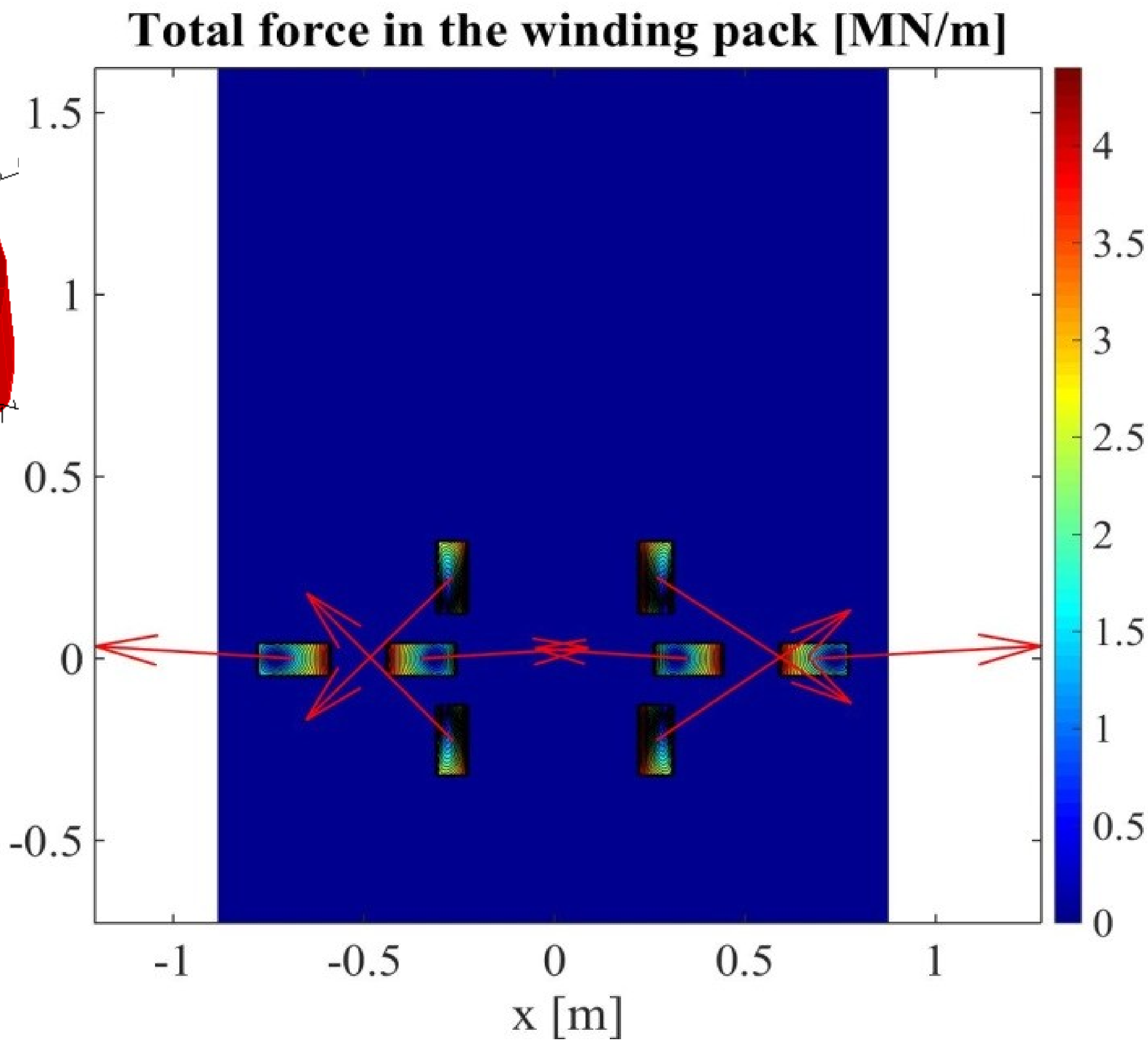


He mass flow rate	1 .5g/s
He inlet pressure	0.4 MPa
He inlet temperature	5.2 K

Mechanical supports

The forces on the winding pack were calculated in the OPERA 3D model: the highest forces were found on the south (S) dipole coil. I considered the mechanical support for this coil.





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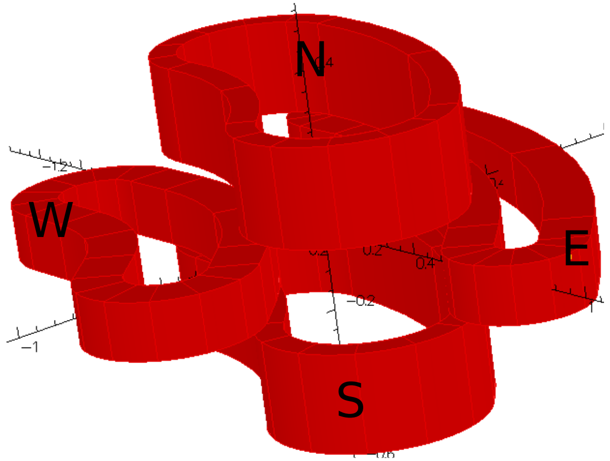
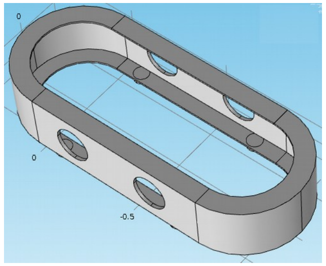
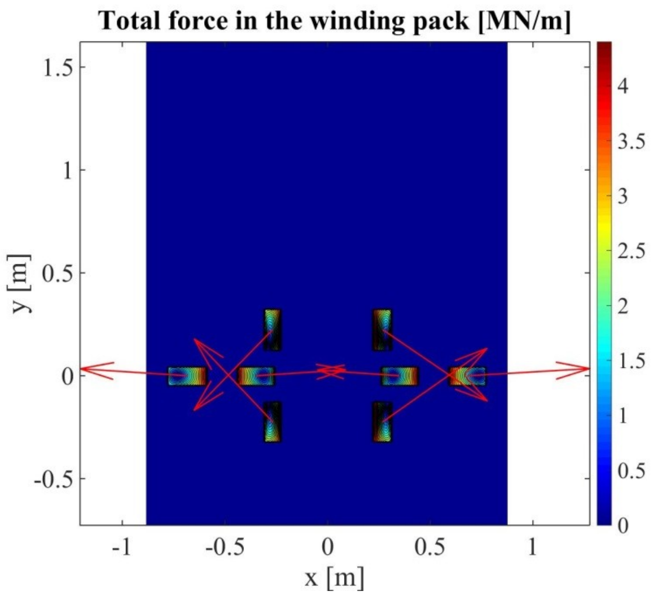
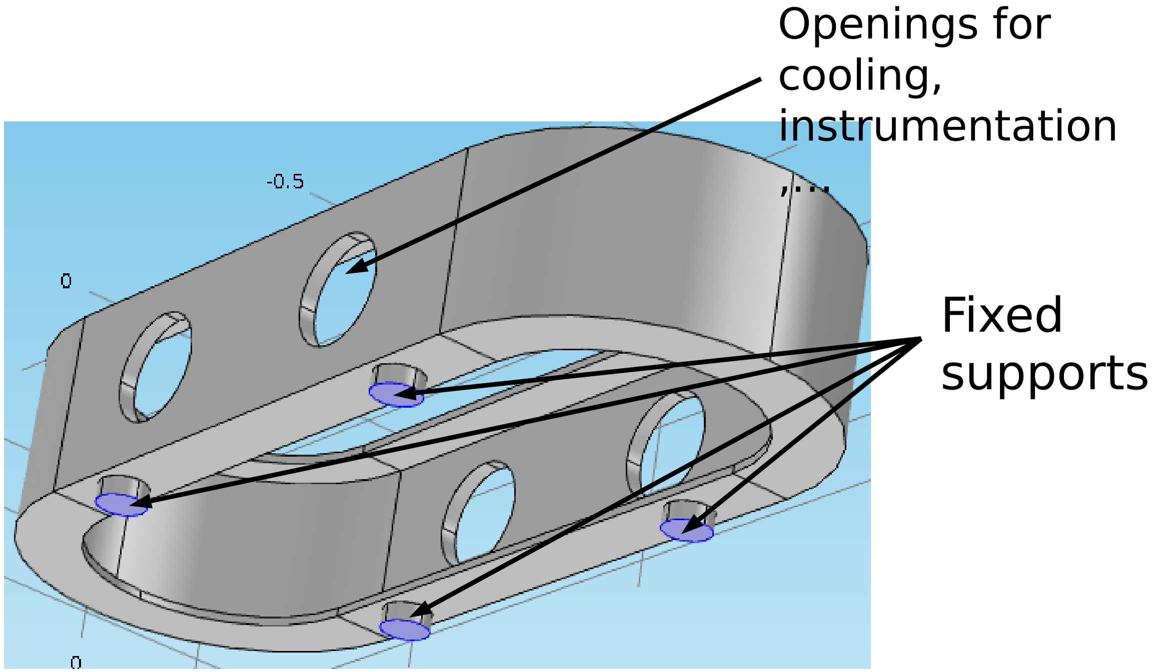


Material	Stainless steel 316LN
Yielding strength σ_y	700-1000 MPa @ 4.5K
Thickness	1.5 cm
Total mass	4 x 150 kg

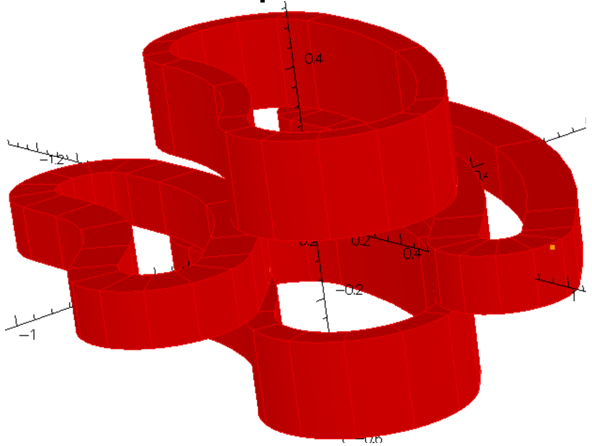


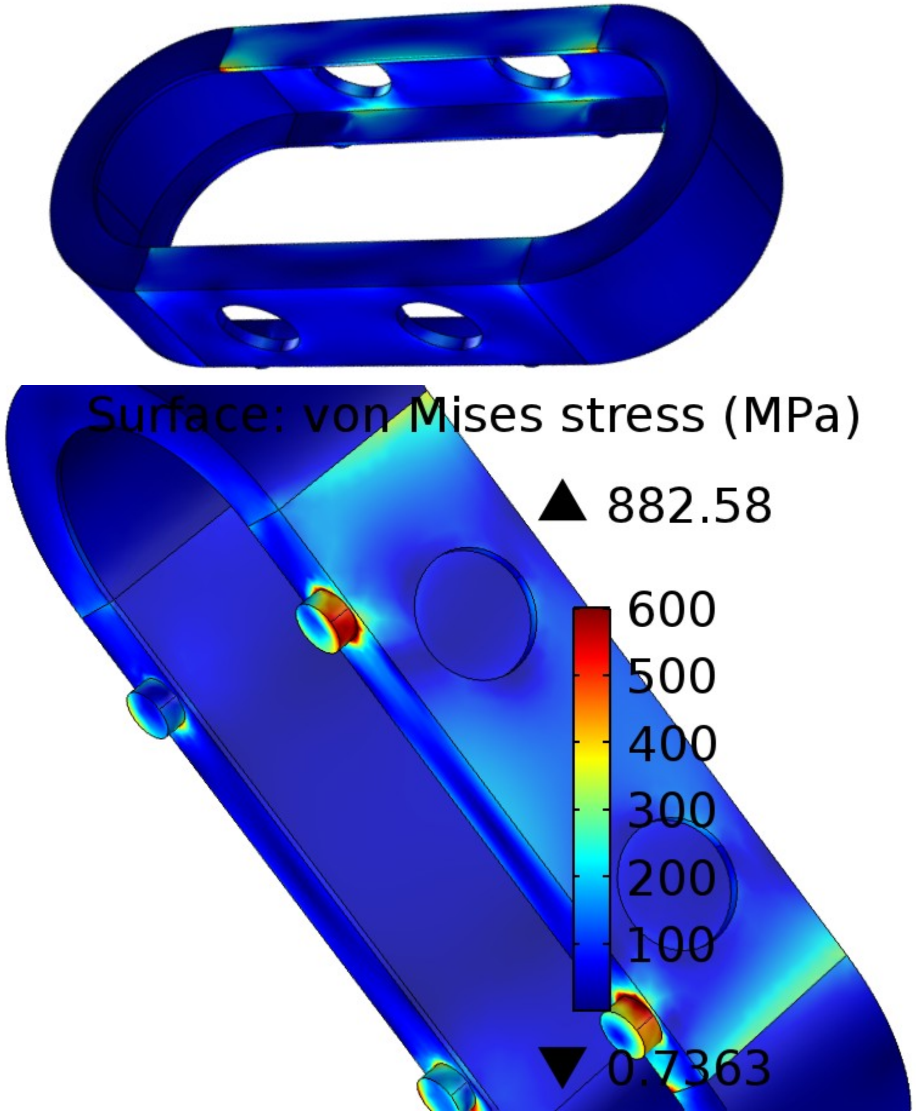




Mechanical supports: von Mises stress calculation

For structural material and welds, the limiting stress for plastic collapse (equivalent to the ’limiting stress intensity’ value) at design temperature is usually defined as 2/3 σ_y. Special care has to be used especially in all the connection parts.





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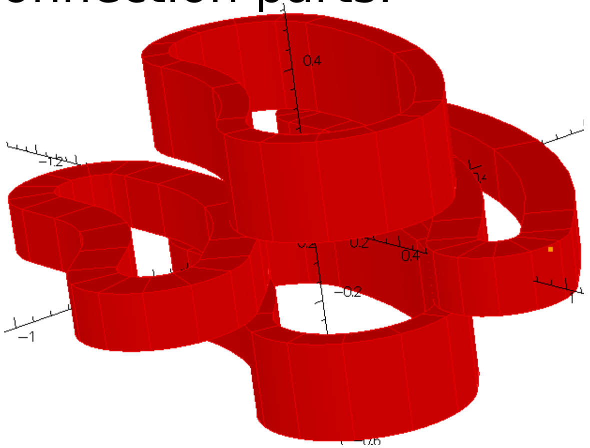

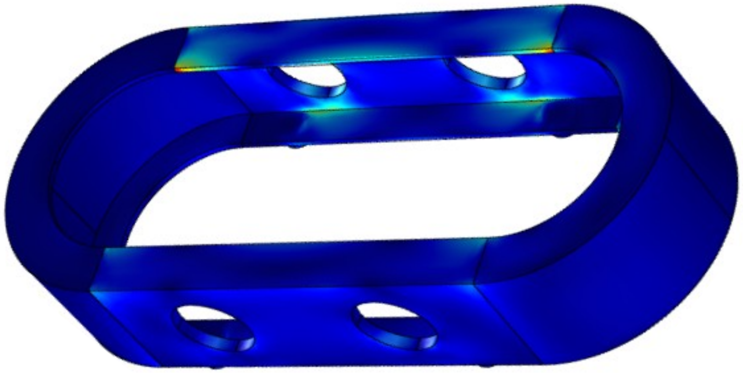

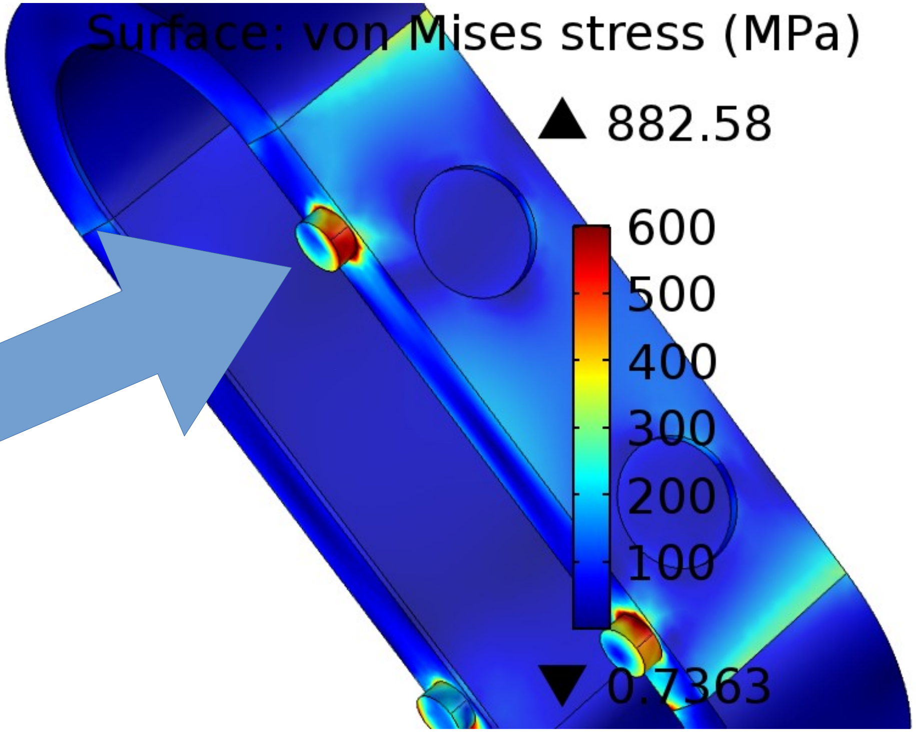

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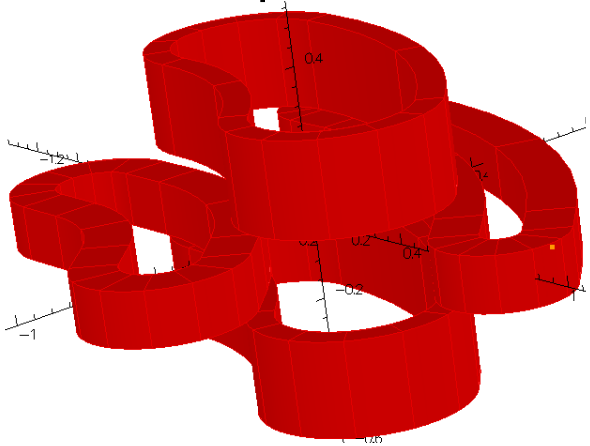
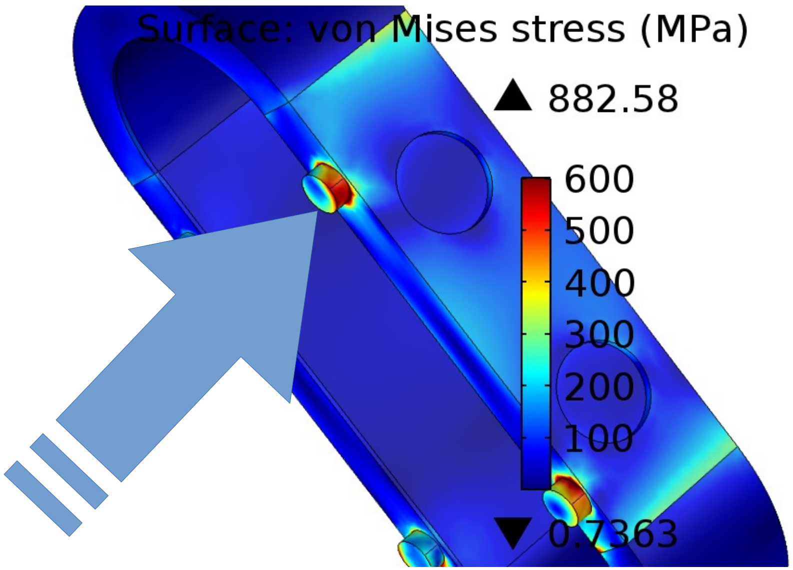
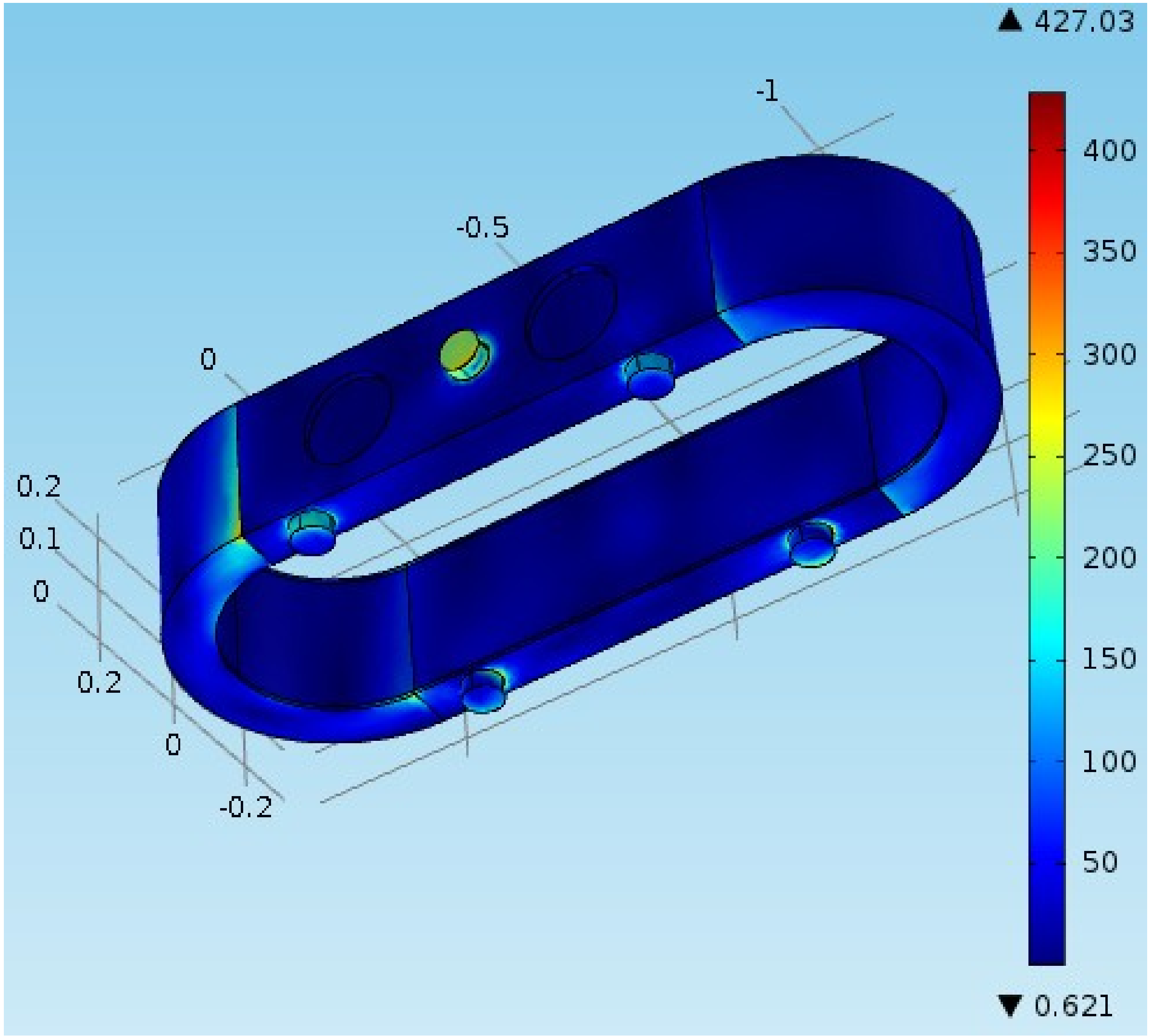






Conclusions

- A magnet geometry with 4 coils + active shielding (4 coils) allows to fulfill the specifications without using an iron shield.
- A bronze routed Nb_3Sn strand has been considered for the dipole magnet winding;
- Rutherford cables may be used to wind the magnet;

- Cooling system may be a challenge as the magnet has to be cycled and it has to rotate around the patient.
- Cooling by means of cryocoolers may be problematic (unless a large number of units is employed and/or a dB/dt as lower as 0.05-0.1T/s).
- Forced flow would be effective but extremely challenging (and expensive).
- A detailed model of AC losses is mandatory to design (and optimize) the cryogenic system.

- Using Nb_3Sn at low current density may provide a large temperature margin (~5 K) that can cope with the temperature increase due to AC losses.

Next steps

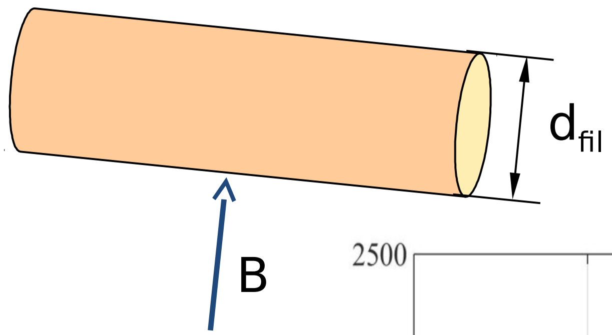
- Detailed cable model for AC losses calculation:
  Collaboration with University of Bologna;
- Cryogenic design study;
- Mechanical structure design;
- Cost estimation.

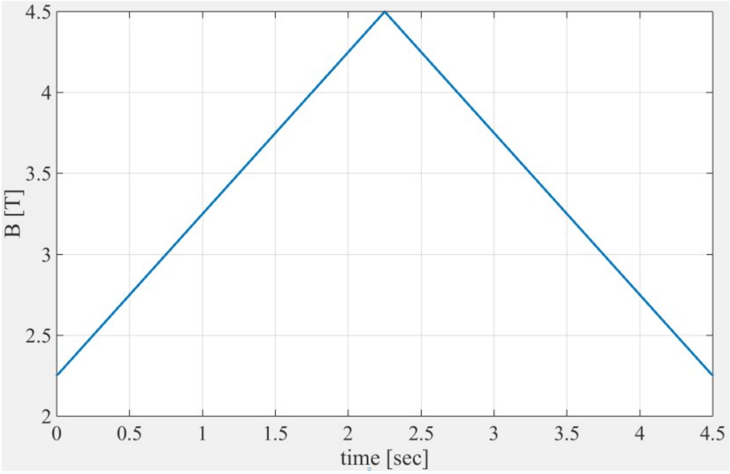
Thank you
for the attention

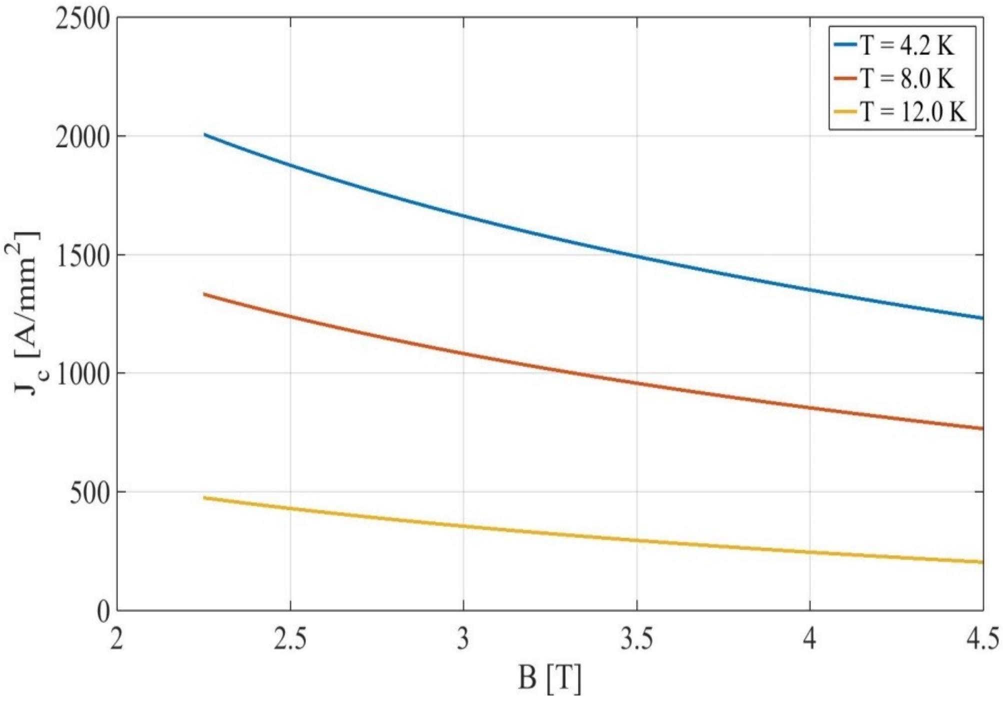
APPENDIX

AC loss: hysteresis in the filaments

- Hysteresis in filaments; $q_H = \int_{B1}^{B_{max}} \frac{8}{3\,\pi} \frac{d_f}{2} J_c(T,B)dB \left[\frac{J}{m^3}\right]$

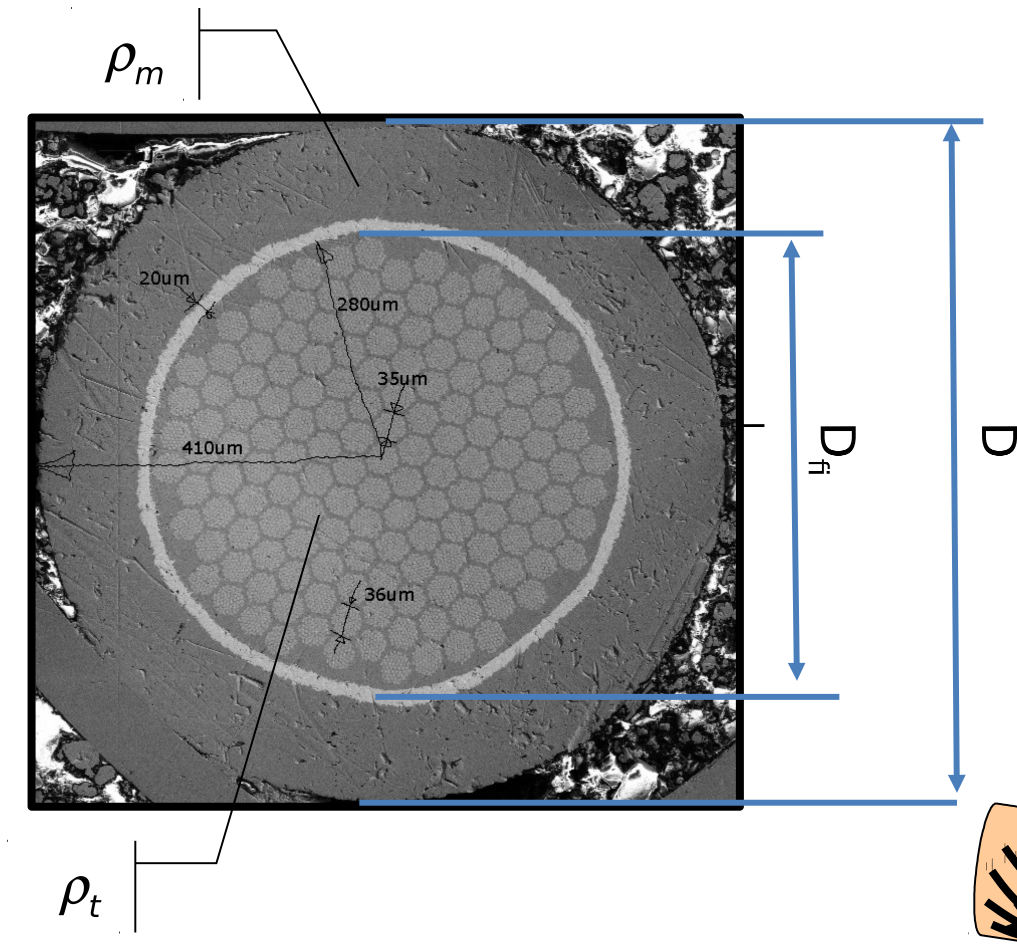






AC loss: coupling in the strand

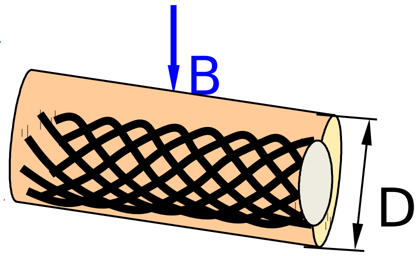
- Strand coupling (at low frequency);



$$\tau = \frac{\mu_0}{2\rho_e}\left(\frac{L_p}{2\pi}\right)^2$$

$$\rho_t = \begin{cases} \rho_m \dfrac{1-\lambda}{1+\lambda} & \textit{SC filament} \\ \rho_m \dfrac{1+\lambda}{1-\lambda} & \textit{insulated filament} \end{cases}$$

$$\frac{1}{\rho_e} = \frac{1}{\rho_t} + \frac{D - D_{fil}}{D_{fil}\rho_m} + \frac{D_{fil}\left(D - D_{fil}\right)}{4\rho_m}\left(\frac{2\pi}{L_p}\right)^2$$



$$E_\perp = \frac{4\tau}{\mu_0} B_{max} \dot{B}_\perp$$

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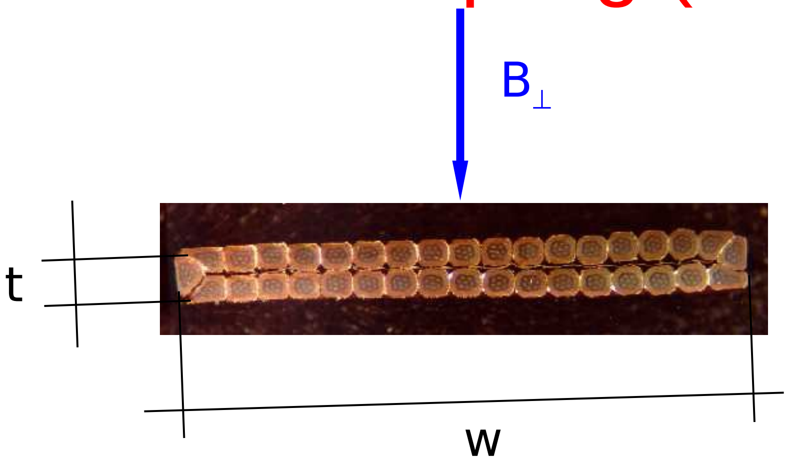
AC loss: coupling among the strands

- Cable coupling (at low frequency);

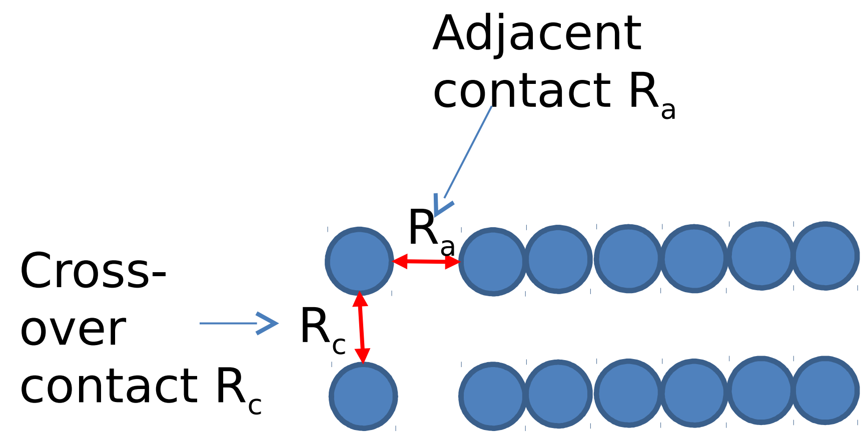


$$E_\perp = \frac{1}{3}\frac{wL_p}{t}\left(\frac{N^2}{20R_c}+\frac{1}{R_a}\right)\Delta B_\perp \dot{B}_\perp$$

- Dynamic resistance

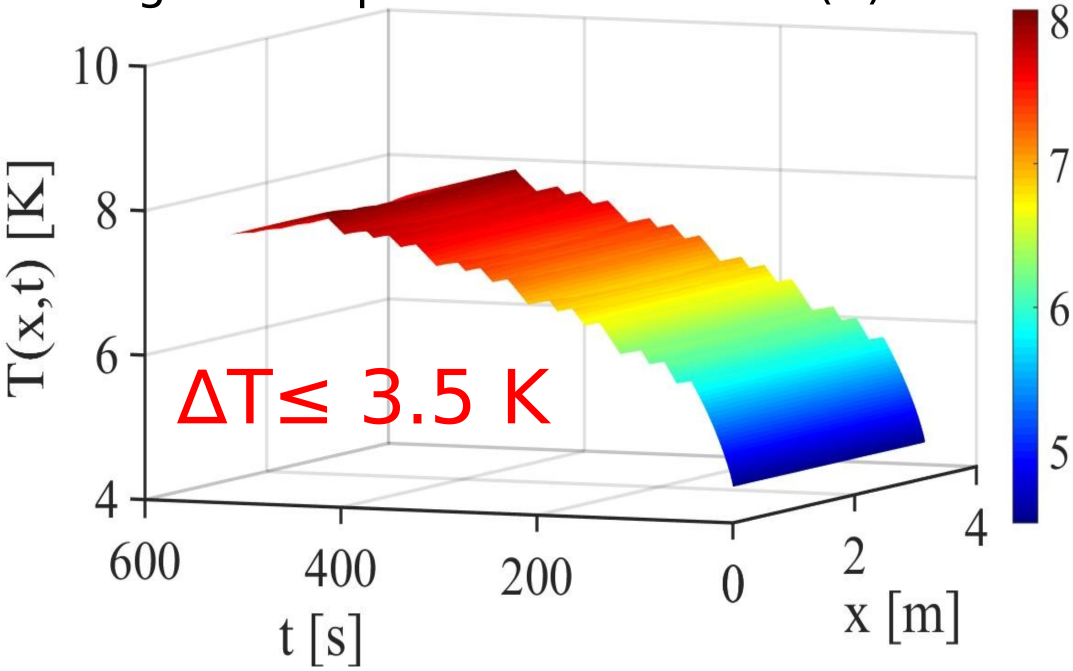
A dynamic resistance appears against transport current, causing an increase in AC loss

$$K_{dR} \approx \left(1+\left(\frac{I_{op}}{I_c}\right)^2\right)$$



Cooling system 2: forced flow supercritical He (4)

Magnet temperature evolution (K)



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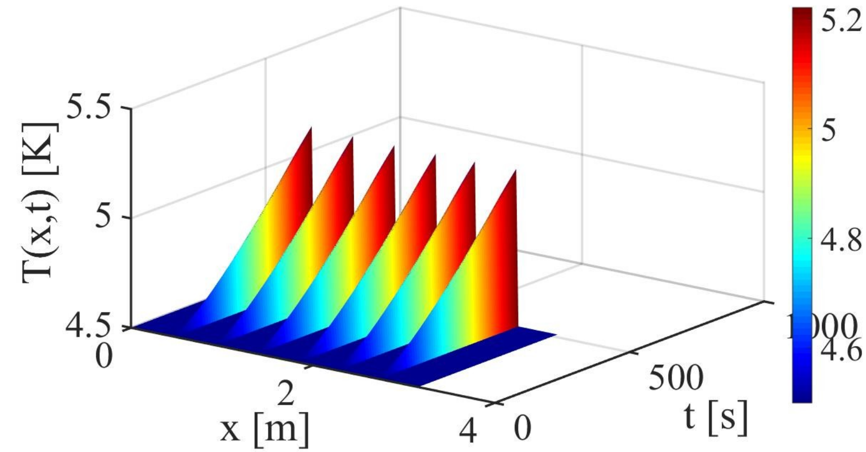
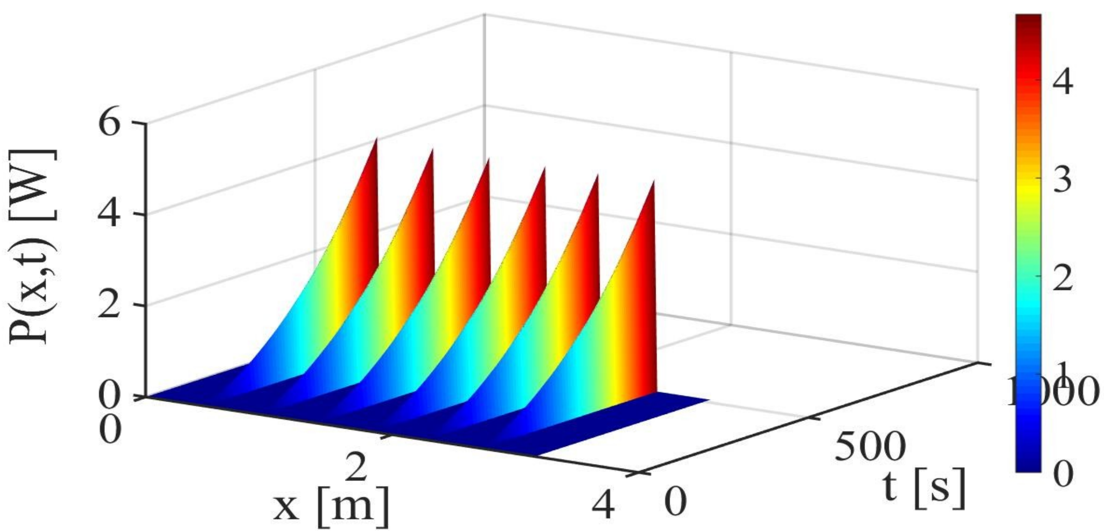
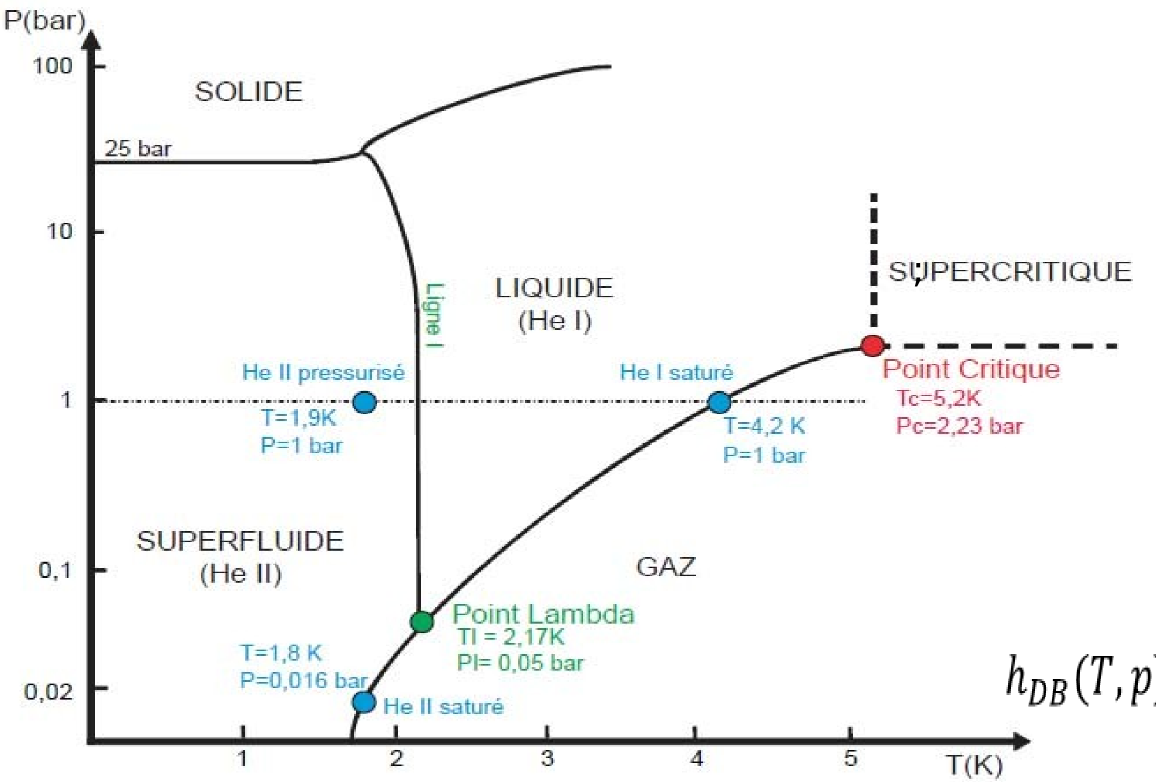




He mass flow rate	1 g/s
He inlet pressure	0.4 MPa
He inlet temperature	4.5 K

Cooling system: forced flow



$$h_{DB}(T,p) = 0.0259\,\frac{K_{He}(T,p)}{D_H}\,Re(T,p)^{0.8}\Pr(T,p)^{0.4}\left(\frac{T_{He}}{T_s}\right)^{0.716}$$

$$Re(T,p) = \frac{\rho(T,p)\,v(T,p)\,D_H}{\mu(T,p)};\quad \Pr(T,p) = \frac{\mu(T,p)C_p(T,p)}{K_{He}(T,p)}$$

$$f = \frac{64}{Re} \Leftrightarrow L$$

$$\frac{1}{2\sqrt{f}} = 2log_{10}(2Re\sqrt{f}) - 0.8 \Leftrightarrow Turbolent\,flow$$