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Combined function superconducting magnets for light and compact proton therapy gantries

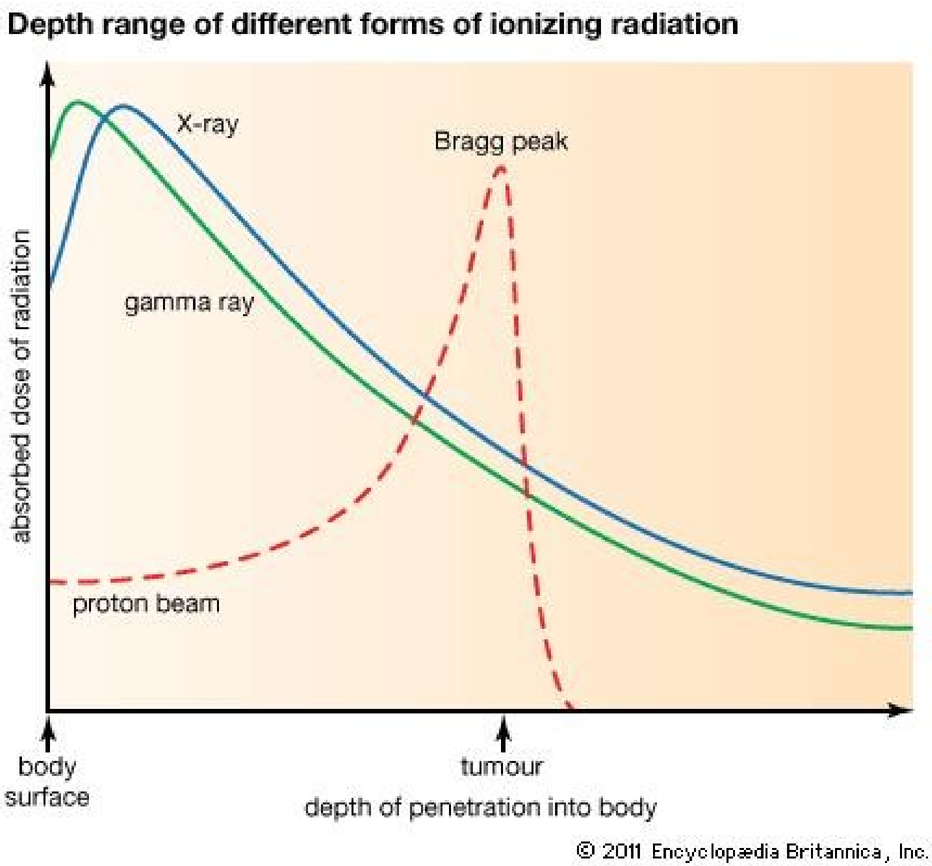
(Ciro Calzolaio, Stéphane Sanfilippo, Alexander Gabard, PSI)

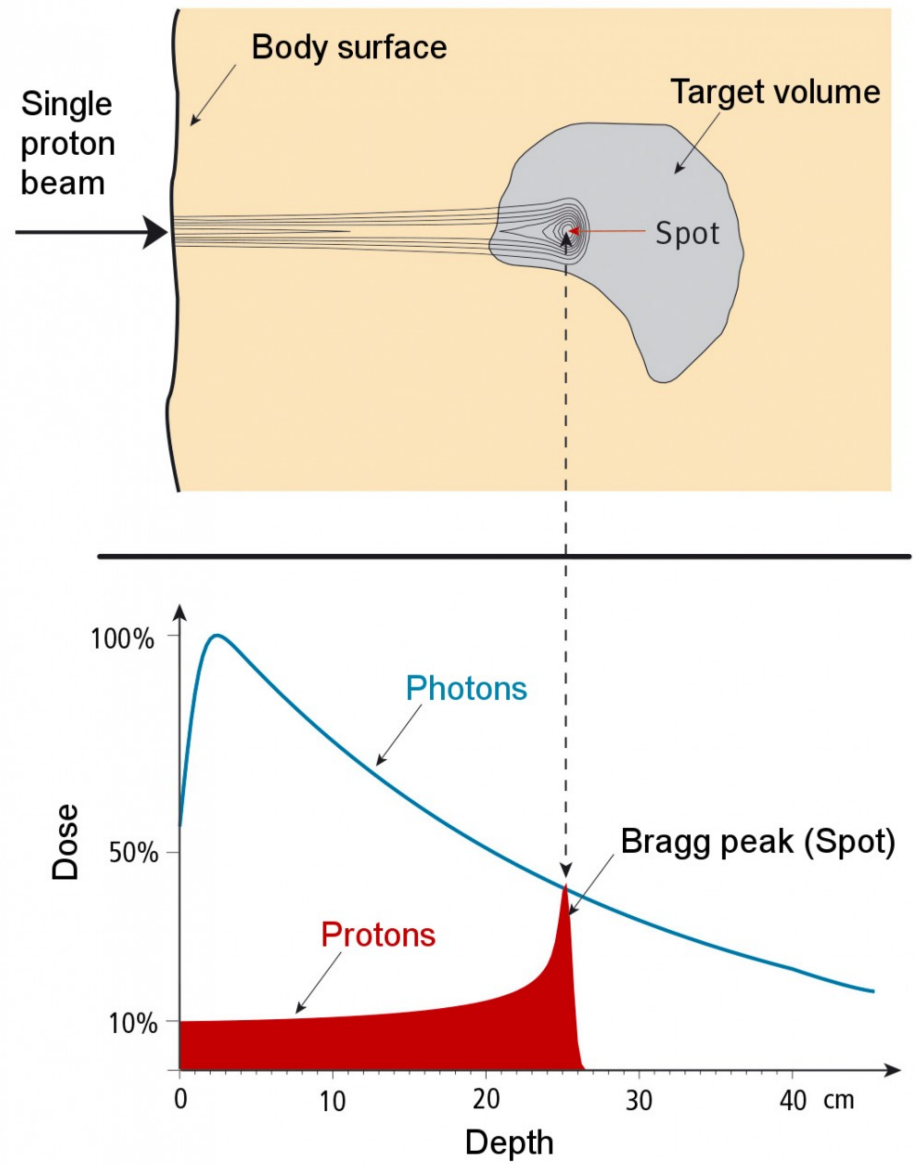
Wednesday, 23.08.2017

Outline

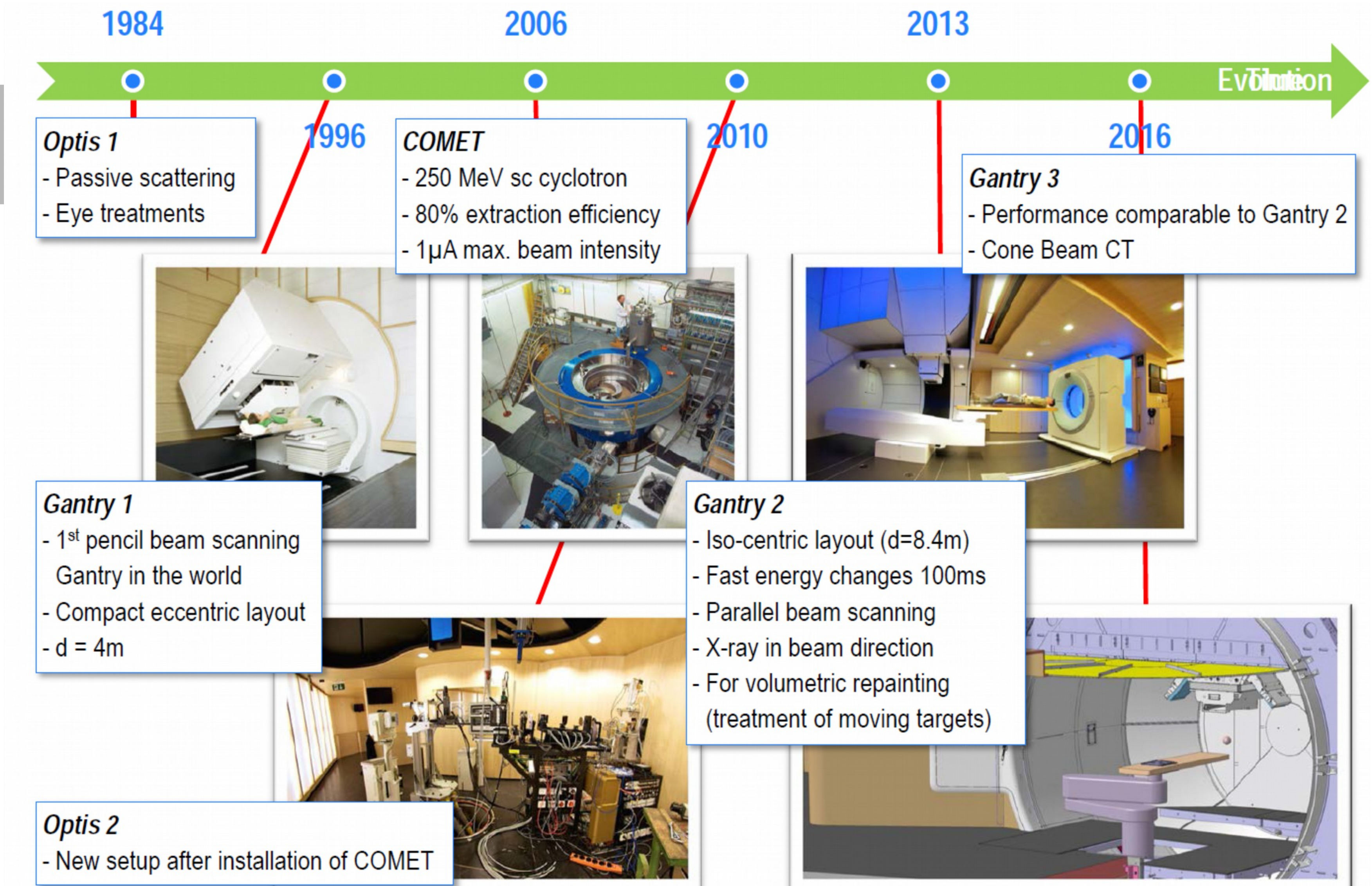
- Context and motivations
- Proton therapy at PSI;
- Why using superconducting magnets?
- Magnet specification and design.
- Synoptic about the Superconducting magnets for gantry applications;
- Conclusions and outlook.

Why proton therapy?





A long tradition in proton therapy at PSI…



Why a superconducting gantry?

Motivations:

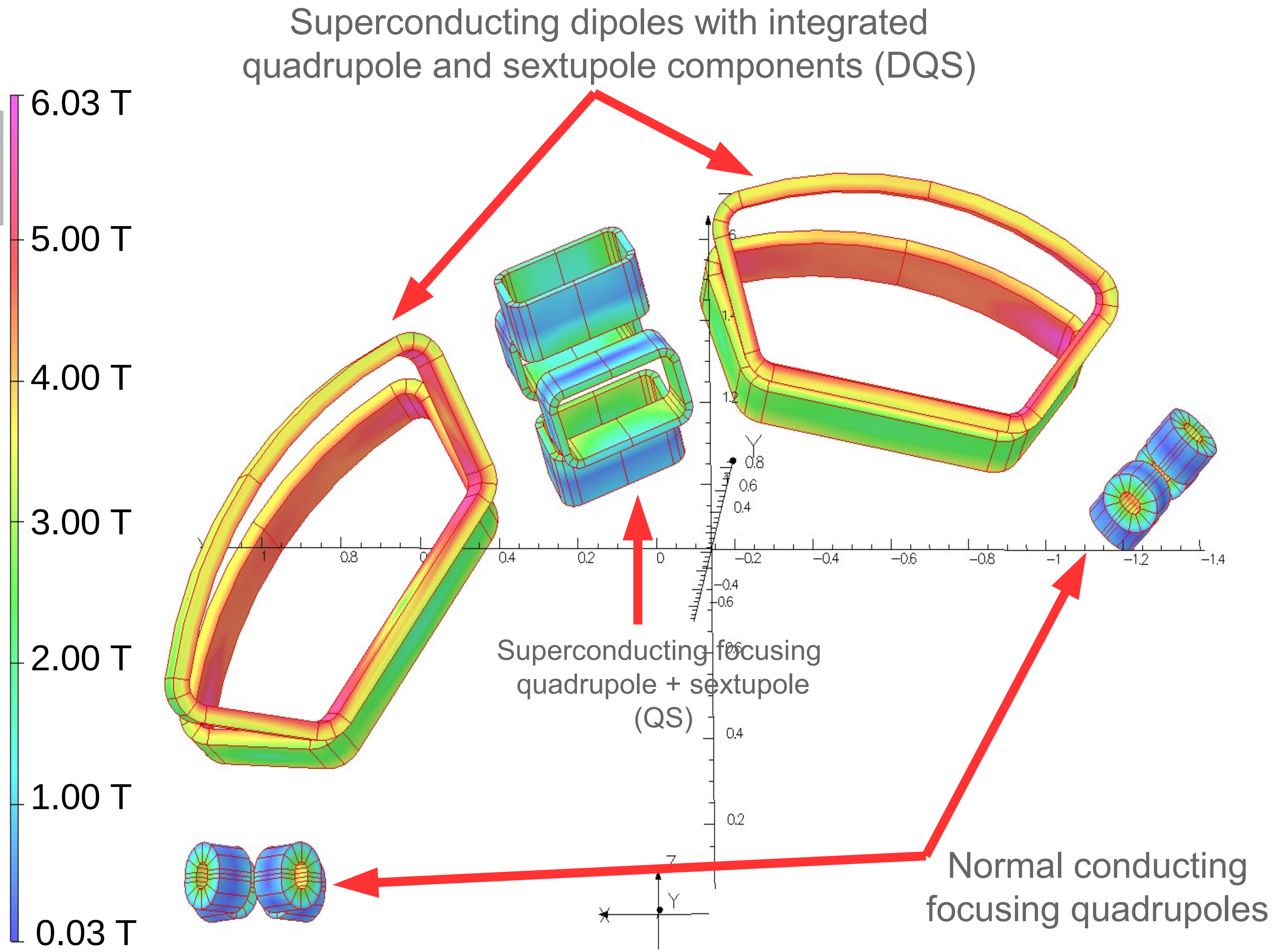
- High B-field → smaller bending radius → reduced machine footprint;
- High B-field gradient → reduced dispersion → high acceptance → fast energy scanning (without changing magnetic field);
- Reduce the magnet(s) weight, especially for carbon ion facilities;
- PSI proposal: Achromatic design with combined function magnet [1];

Challenges:

- Reliability (magnet quench);
- Cryogenic system (cooling complexity, T_{op} ~ 4.5 K);
- High operating B-field → large Lorentz forces;
  → large stray field.

[1] A. Gerbershagen et al., “A novel beam optics concept in a particle therapy gantry utilizing the advantages of superconducting magnets”, Z Med Phys. 2016 Sep;26(3):224-37. doi: 10.1016/j.zemedi.2016.03.006. Epub 2016 Apr 12.

Magnetic concept



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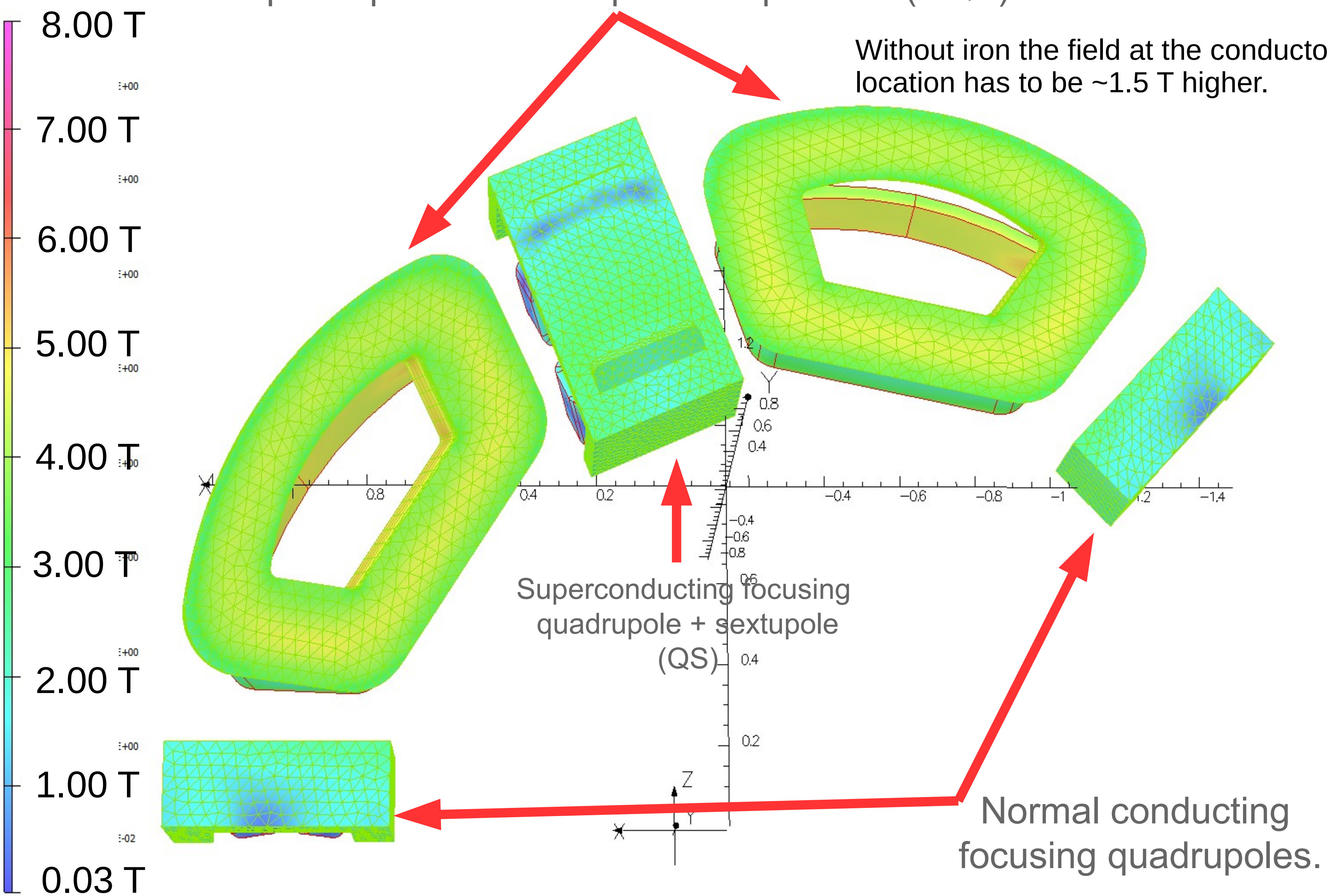
Magnetic concept: Fe to reduce the current at the conductor

Superconducting dipoles with integrated quadrupole and sextupole components (DQS)



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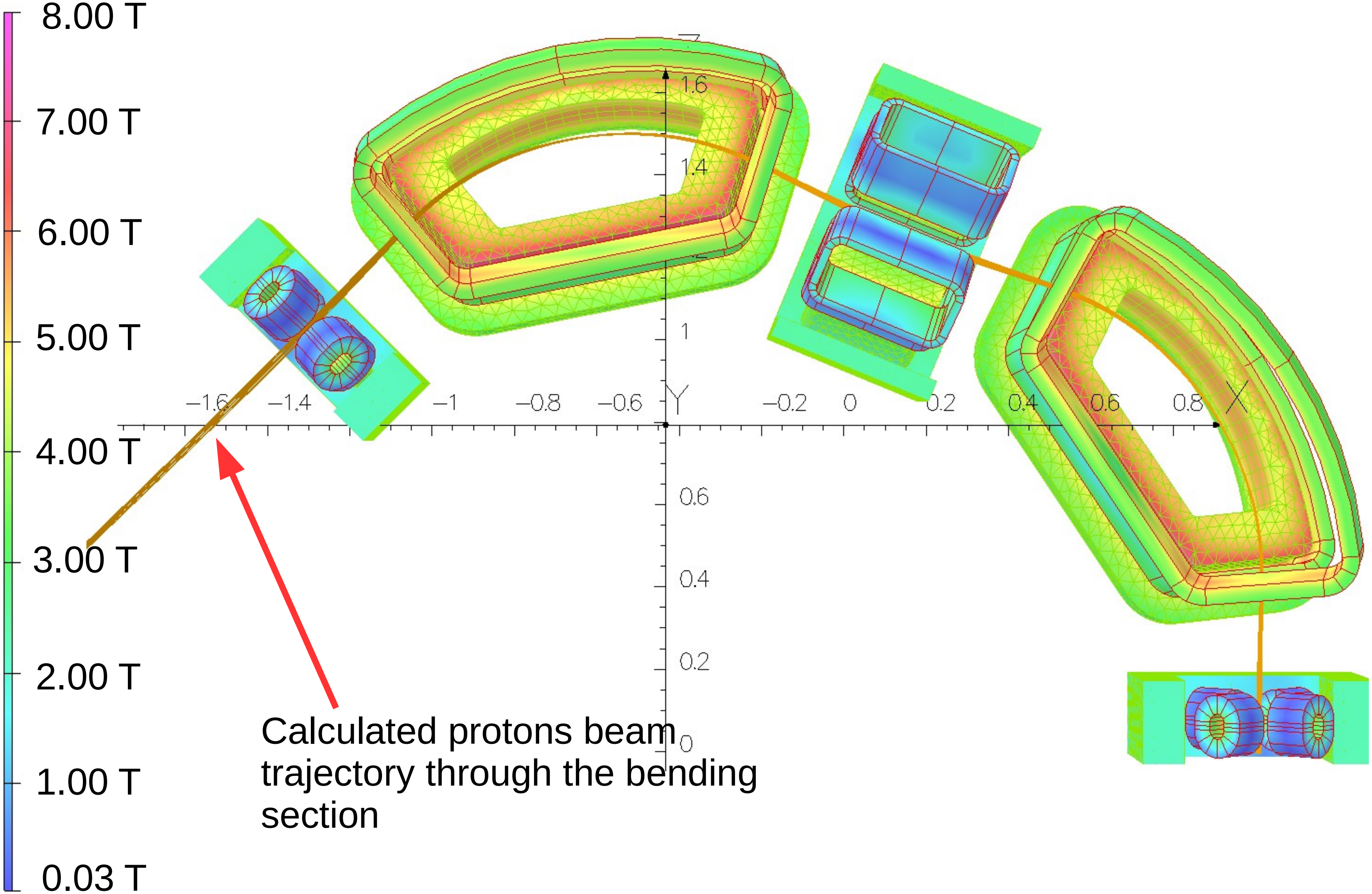


Synoptic about the main challenges related to superconducting magnets for gantry application

Choice of Sc. material: Nb_3Sn:

- Brittle and strain sensitive;
- React and wind process;
- Conductor cost;
- Allows coping with T>4.2 K (6-7 K);

Cooling system: cryocoolers:

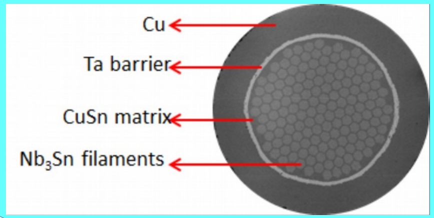
- Gantry rotation: ~360° → no helium bath;
- Cryocoolers: limited heat capacity at low T (≤ 1.5 W @ 4.2 K);
- They “only” require an electric plug to work.

Mechanical structure:

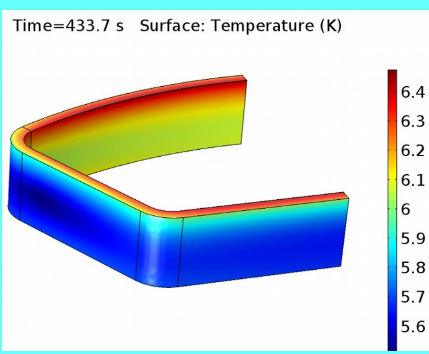
- Gantry rotation → support the magnet in all directions;
- Support the Lorentz forces;
- Avoid conductor movement in operation.

Synoptic about the main challenges related to superconducting magnets for gantry application

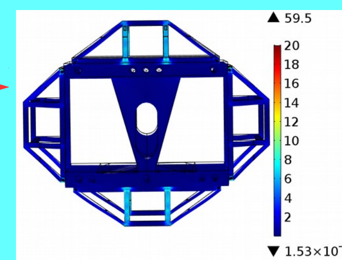
Choice of Sc. material: Nb_3Sn:

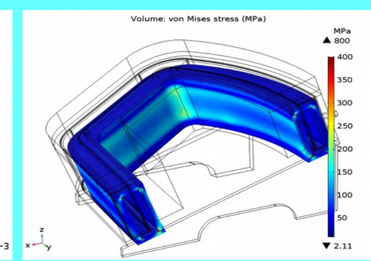


Cooling system: cryocoolers:

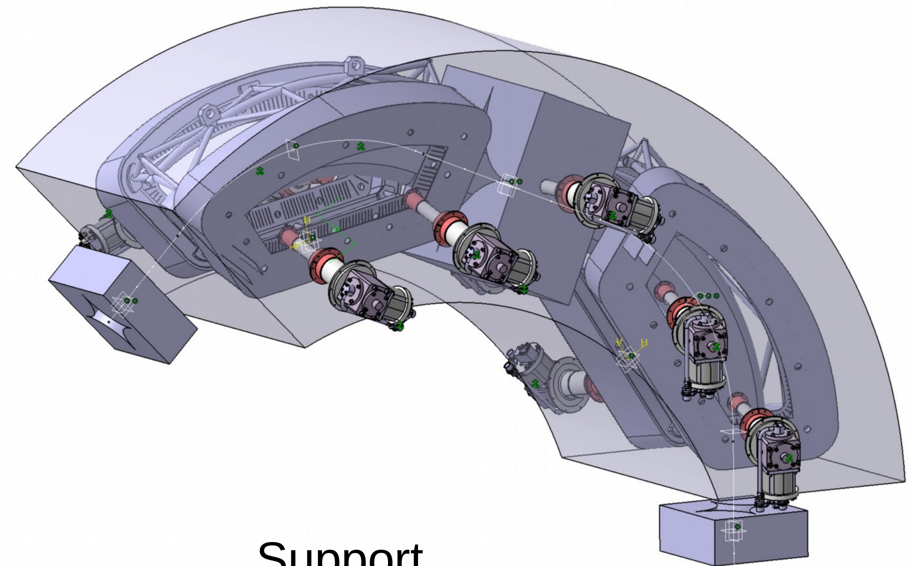


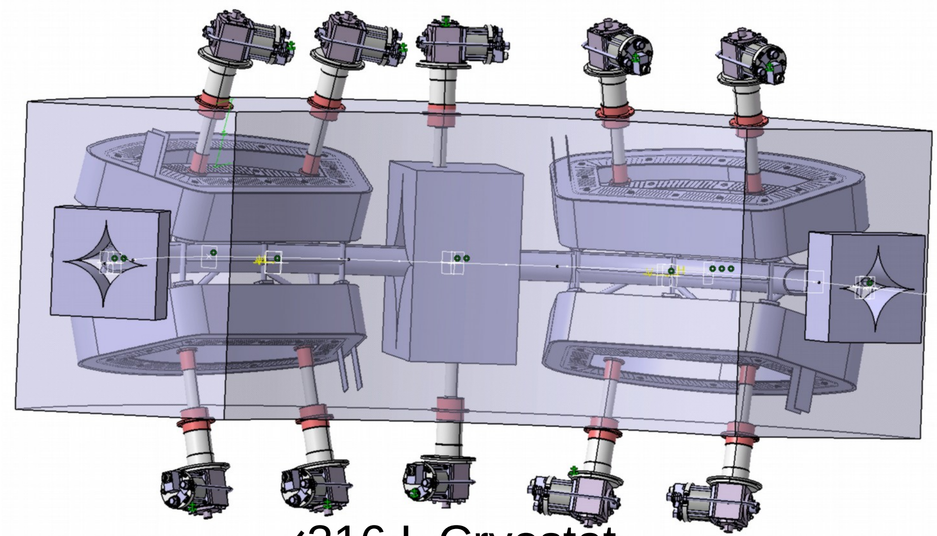
Mechanical structure:

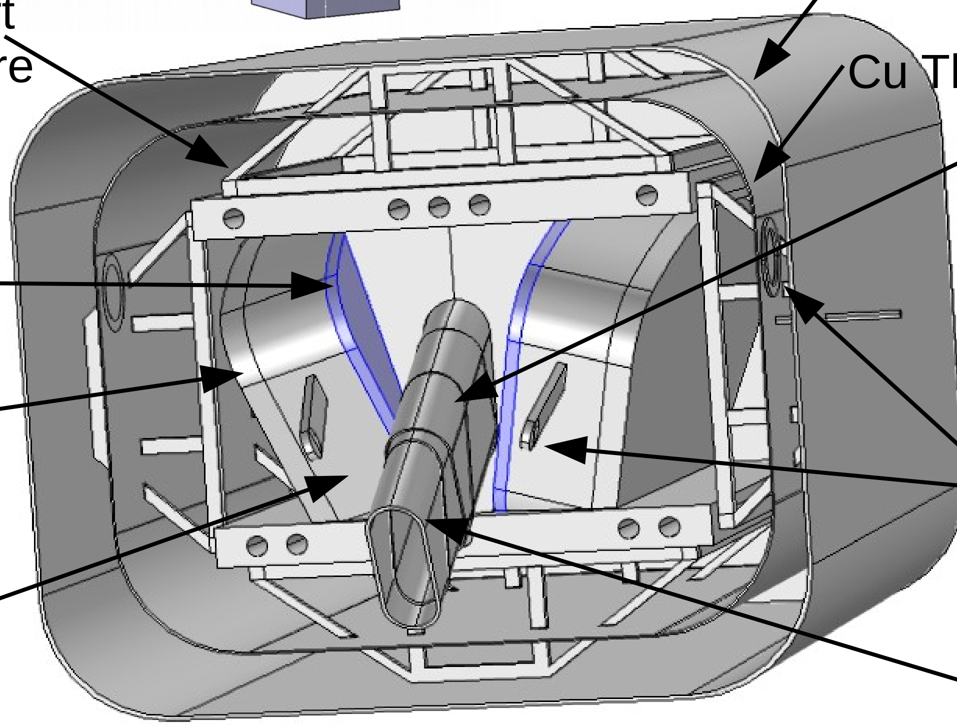




Whole bending section with iron yoke







Conclusions and outlook

- Numerical calculations show the feasibility of the presented concept.

- Next steps:
  - The technical design face is ongoing and has to be completed by middle 2018;
  - The manufacturing of a first prototype will start next year;
  - Tests at operating conditions are foreseen by middle 2020.

- **Progress in the <u>superconducting</u> technology**

- **Progress in the <u>cryocoolers</u> technology**

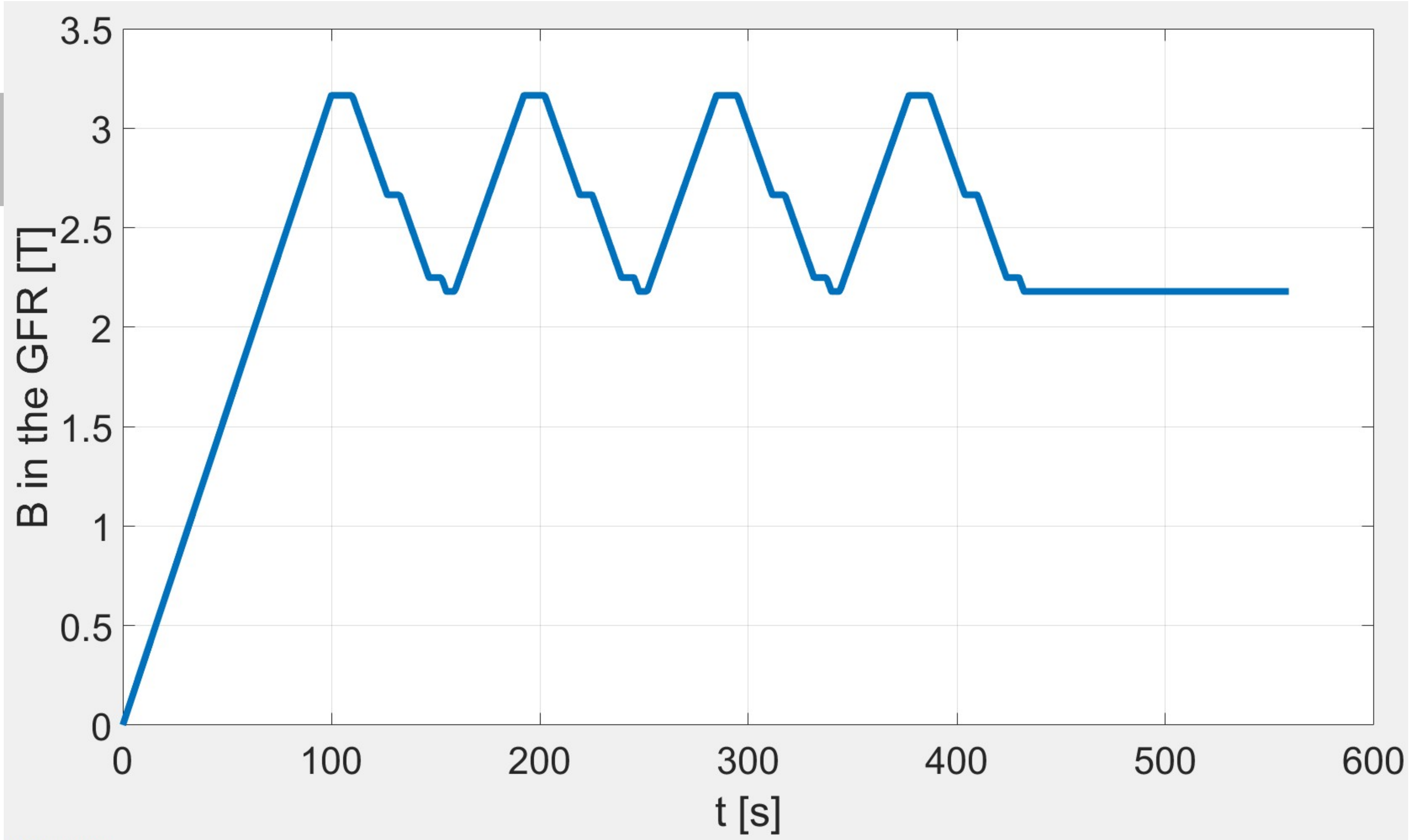
→

Progress in proton therapy:
- Faster treatments;
- More compact machines;
- Easier installation in hospital environments.

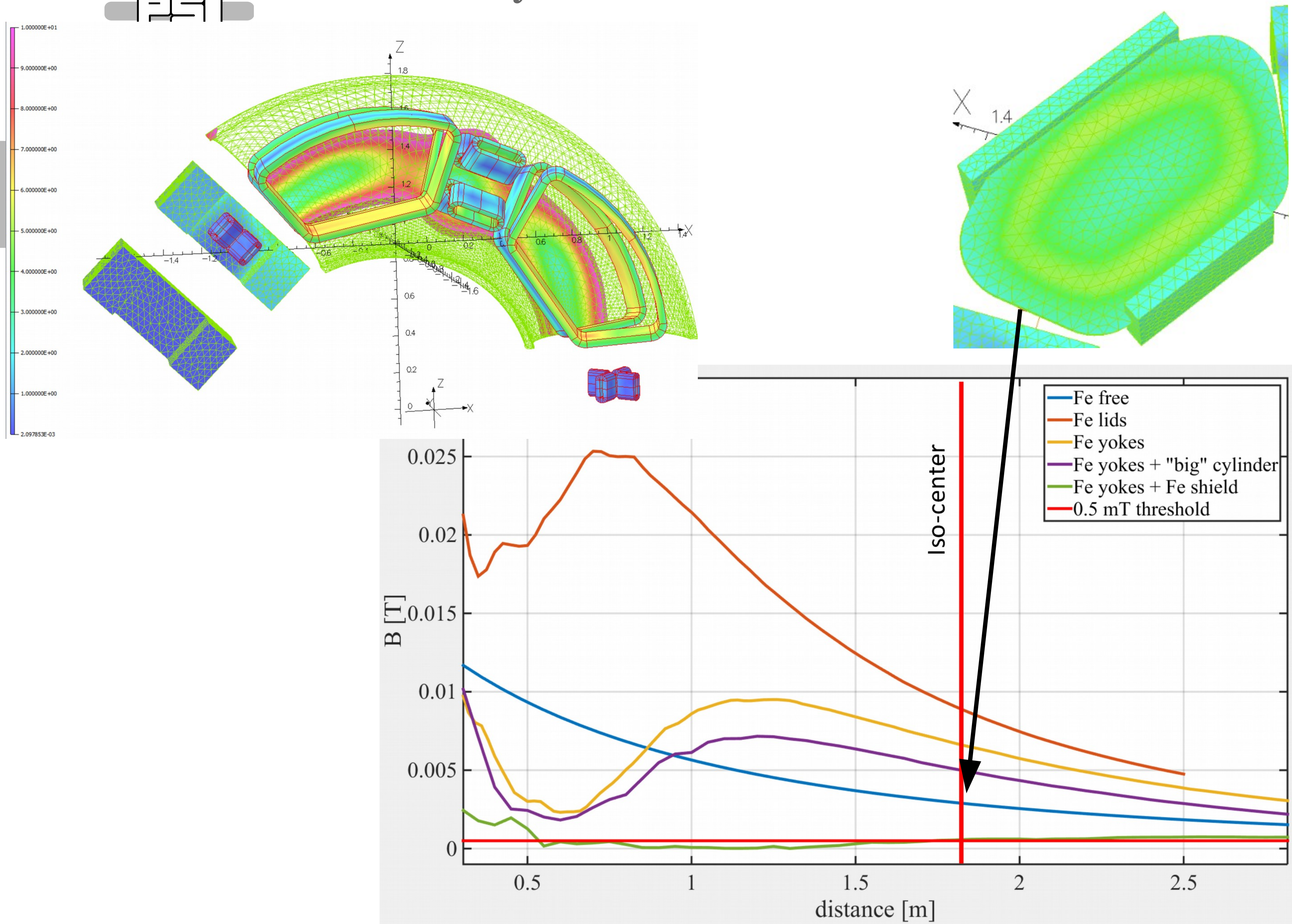
Thanks
for the attention

APPENDIX

DQS: field quality



Stray field issues



Thermal Analysis

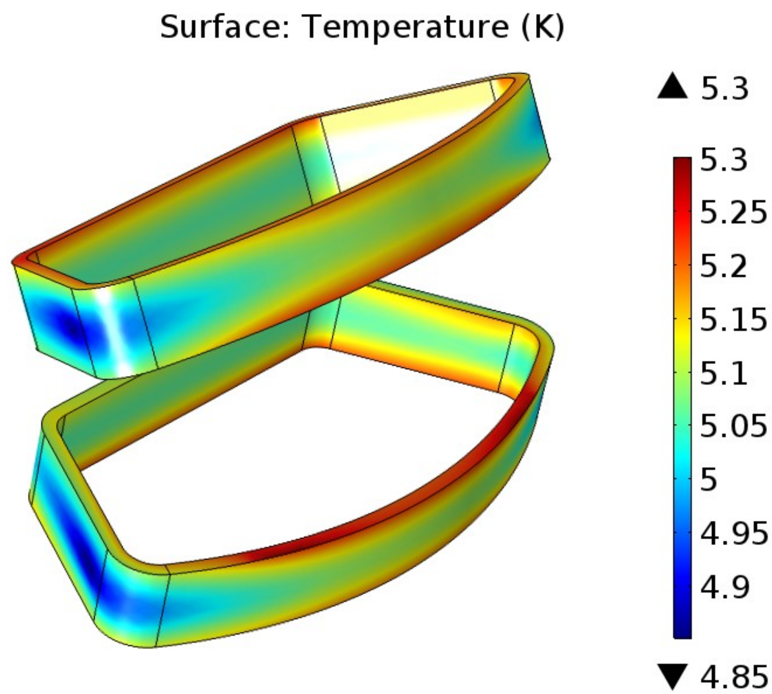
Heat capacity

Joule heating

AC losses coils

Eddy currents

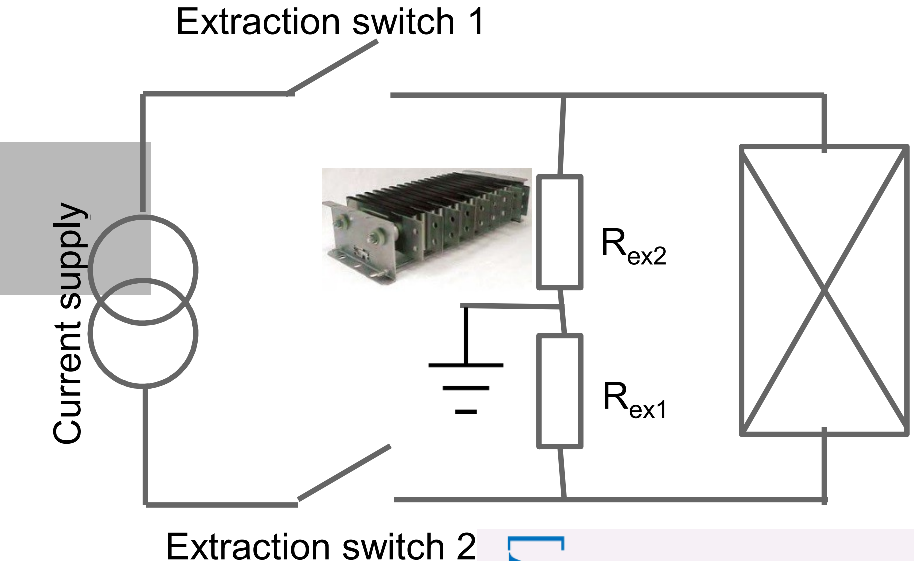
Magnetization Fe



Cryocoolers

Conduction

Quench scenario

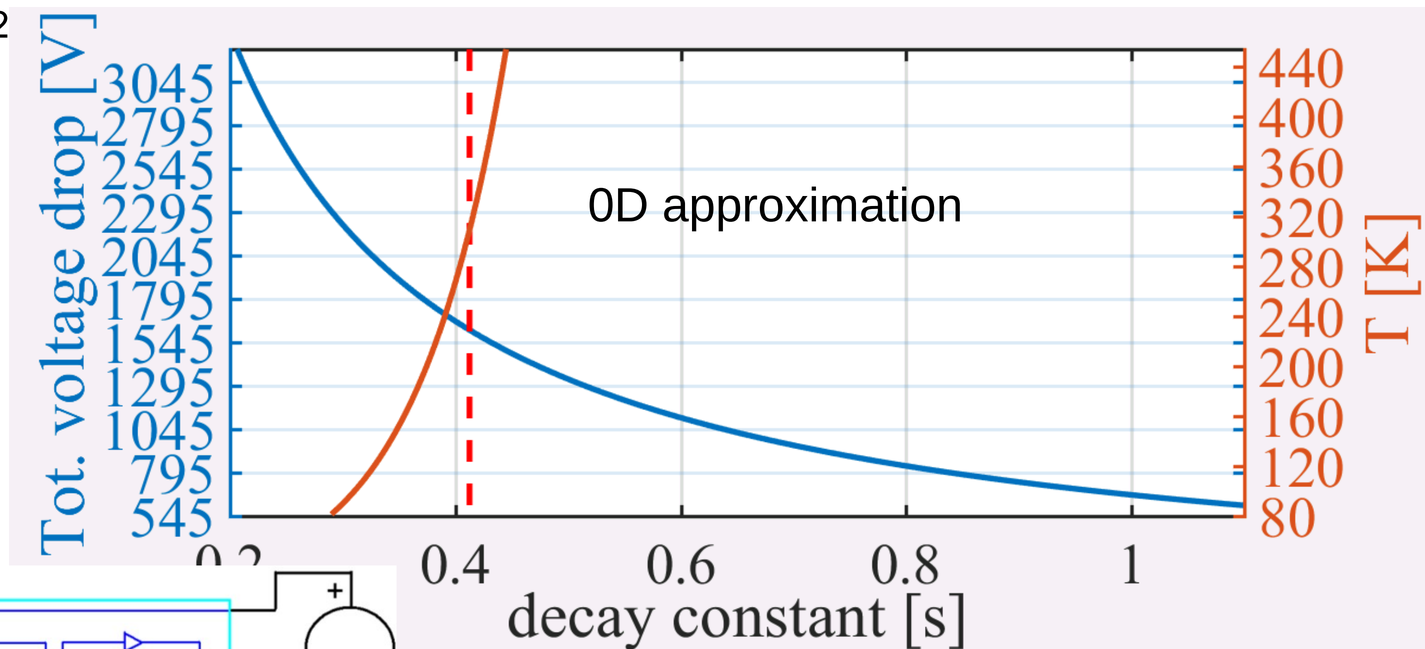


Mechanical switch:

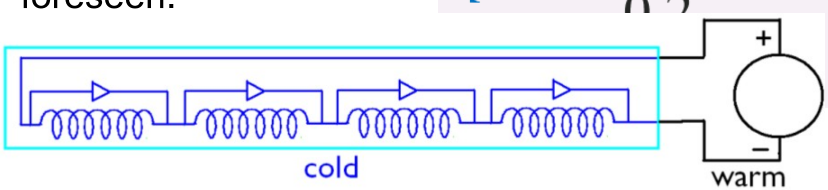
- It opens in less than 50 ms;
- It sustains voltages up to 2kV;
- It sustains currents up to 5 kA.

Dump resistor:

2.25 Ω (L=0.37 H → $\tau = L/R_{ex} = 0.16$ s)

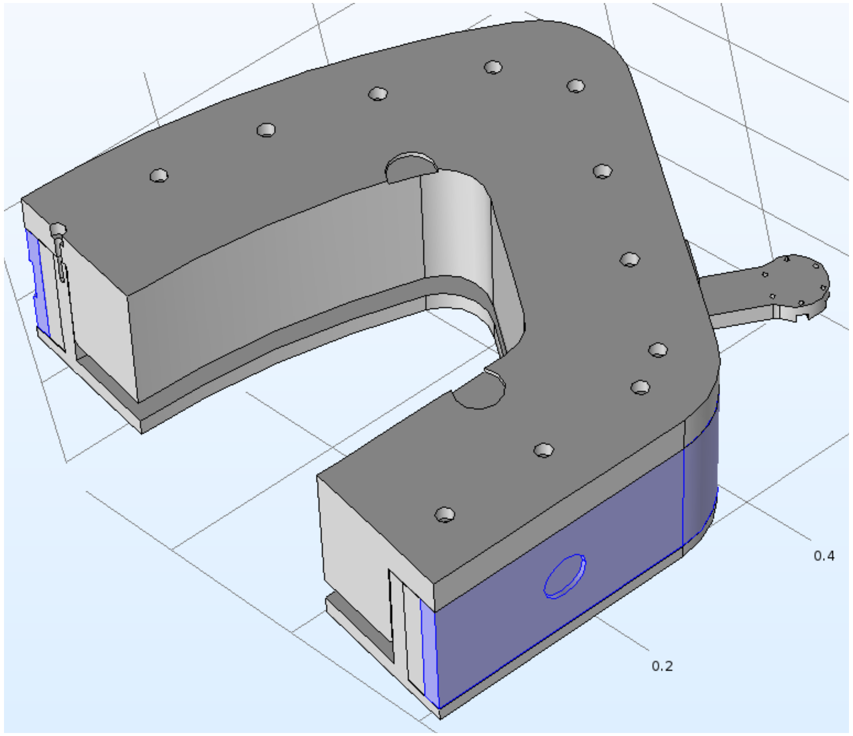


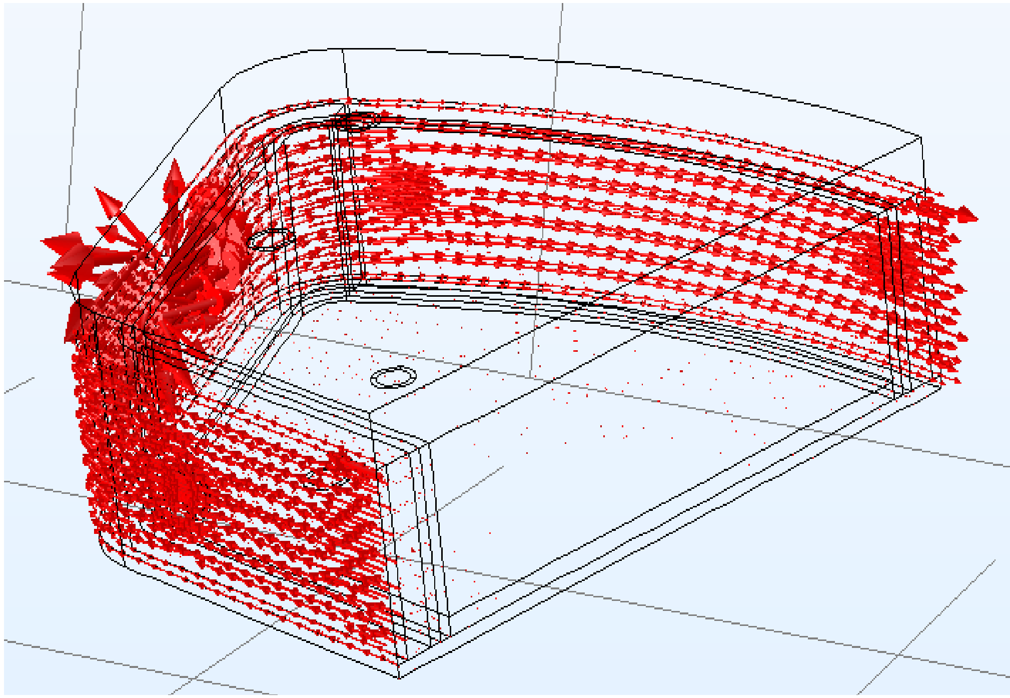
In case of connection in series, a cold diode per magnet may be also foreseen.



DQS, thermal study→ AC losses and eddy currents

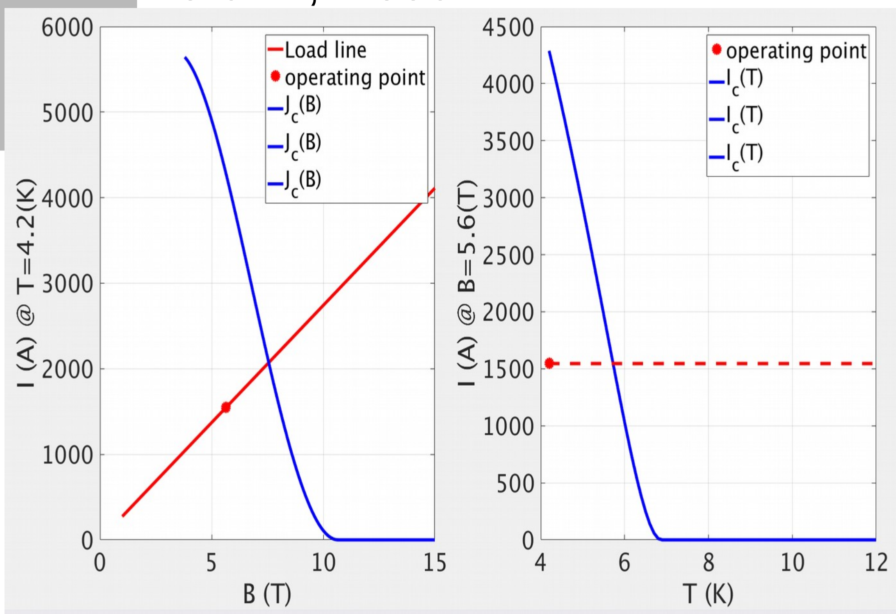
- The iron yoke is laminated → reduced eddy currents;
- Apart from the AC losses in the winding pack, the eddy currents in the coil support ring contribute largely to warm up the coil temperature.





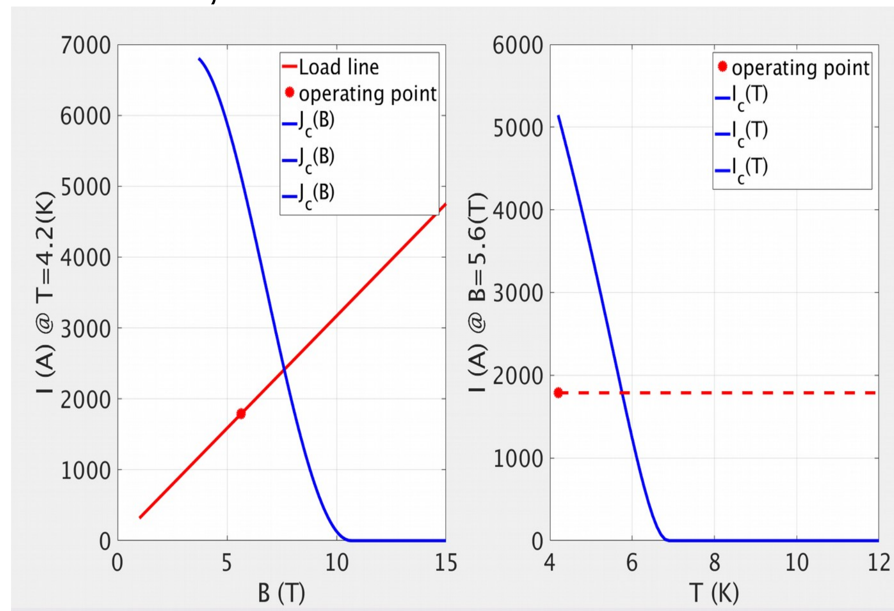
DQS: Nb-Ti with iron yoke

10 Nb-Ti strands, 0.73 mm diameter
5.64 T, 1550A



Quench margin: 23%
T margin: 1.5 K

12 Nb-Ti strands, 0.73 mm diameter
5.64 T, 1788A

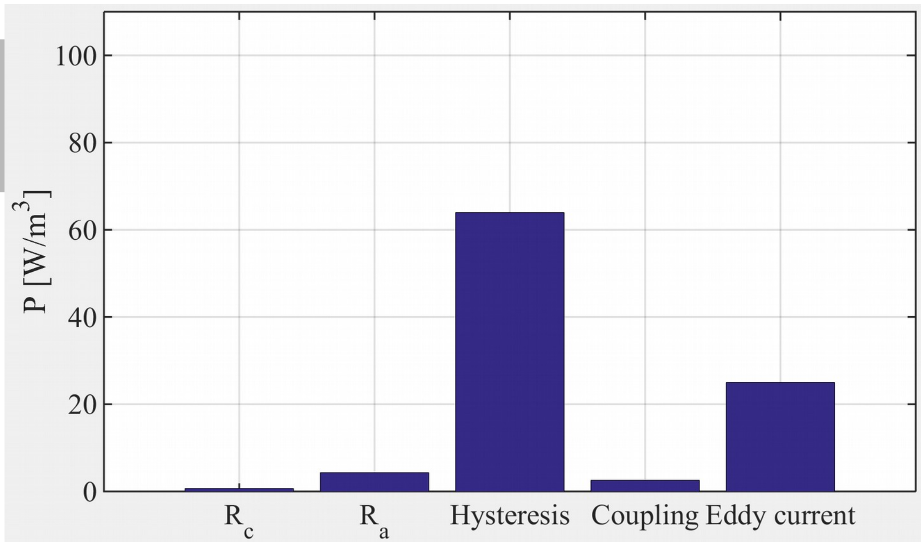


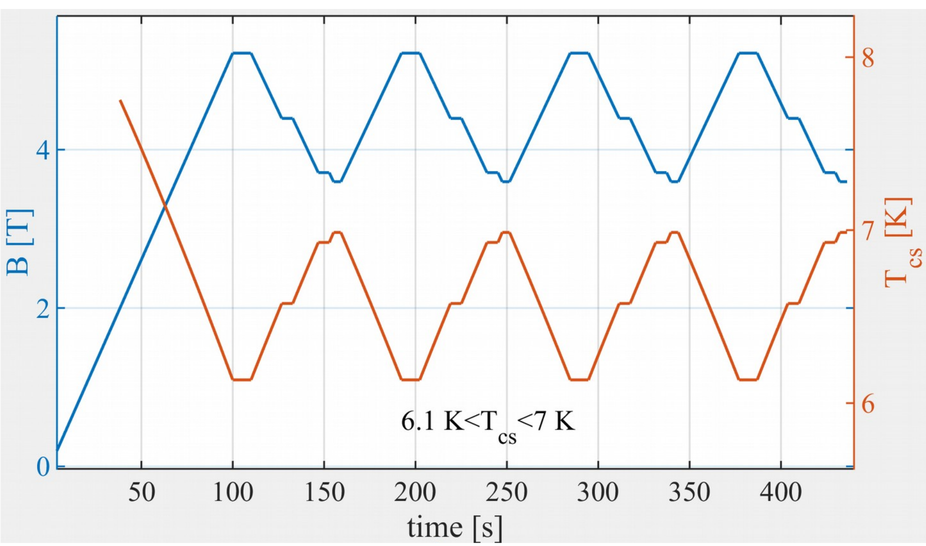
Quench margin: 27%
T margin: 1.6 K

Scaling law from:
L. Zani et al., “Jc(B,T) characterization of NbTi strands used in ITER PF-relevant Insert and Full-scale sample”

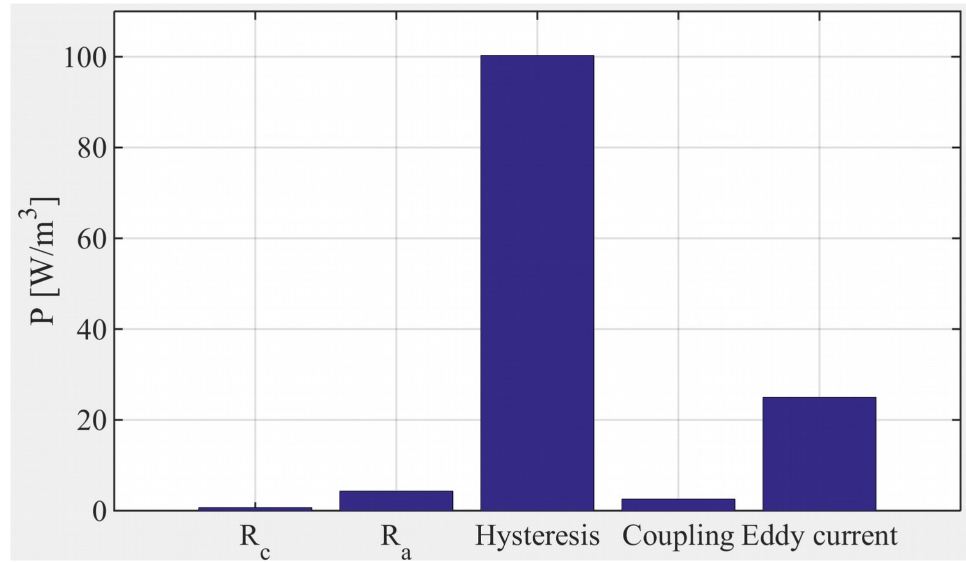
DQS, thermal study→ AC losses and eddy currents

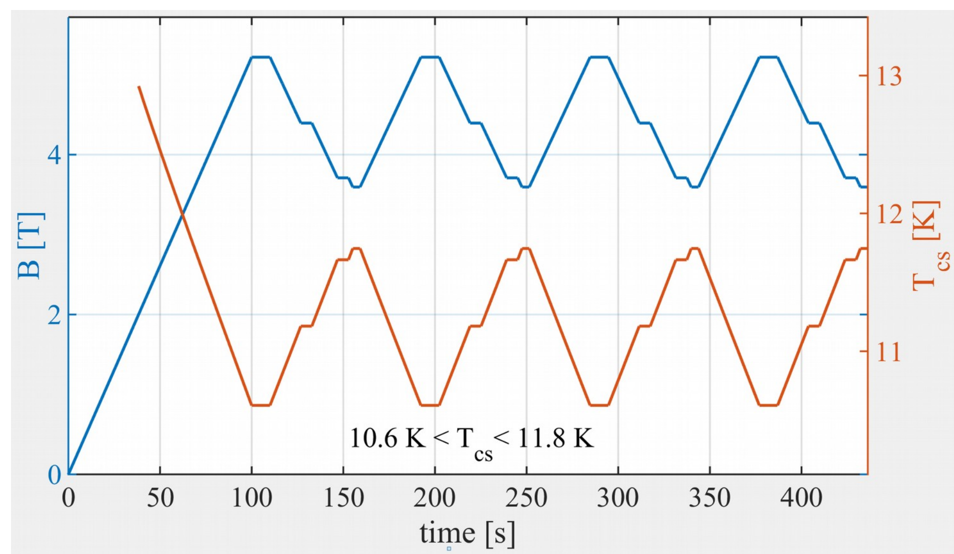
- Nb-Ti (PF3)



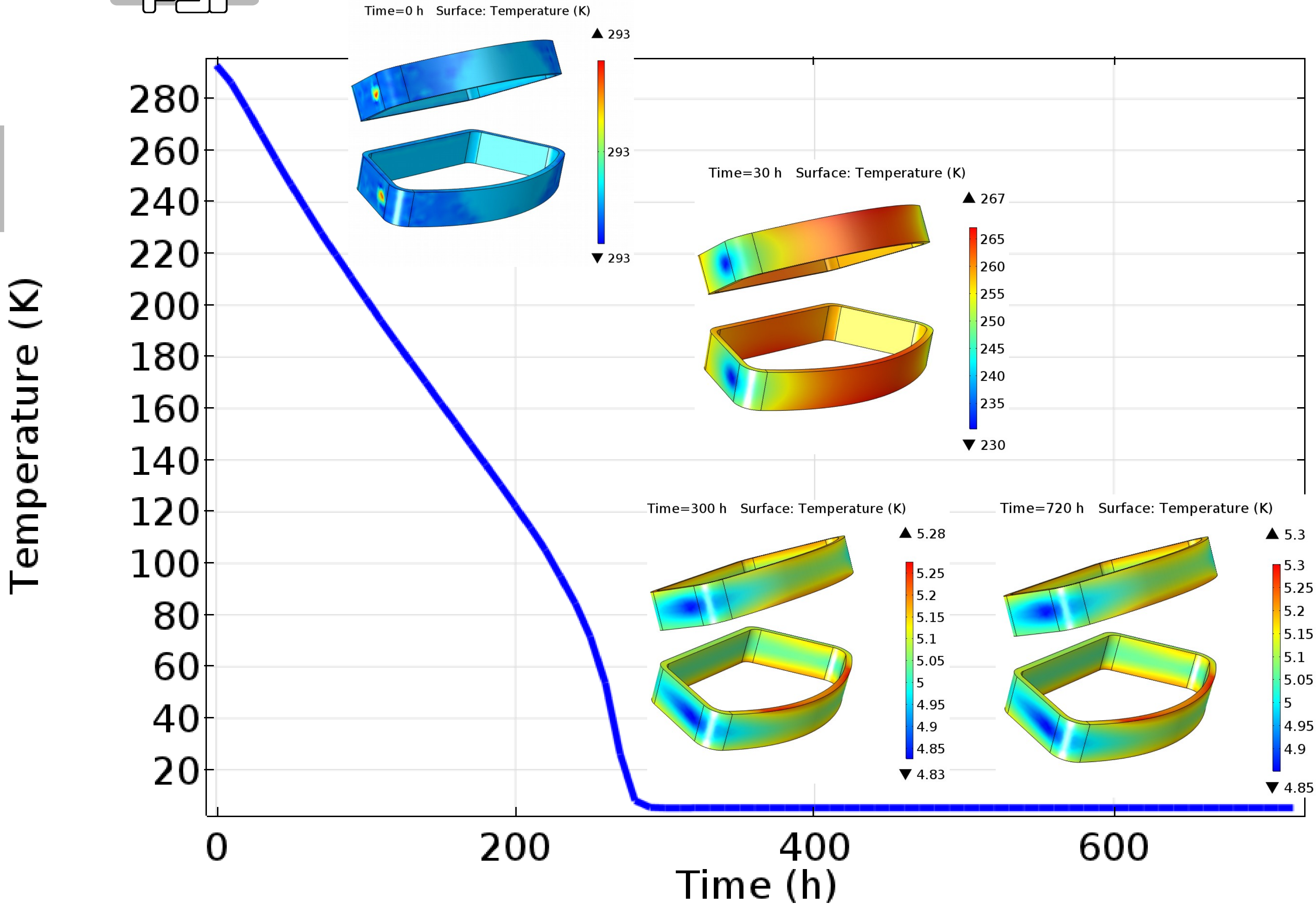


- Nb_3Sn (Bruker-EAS)

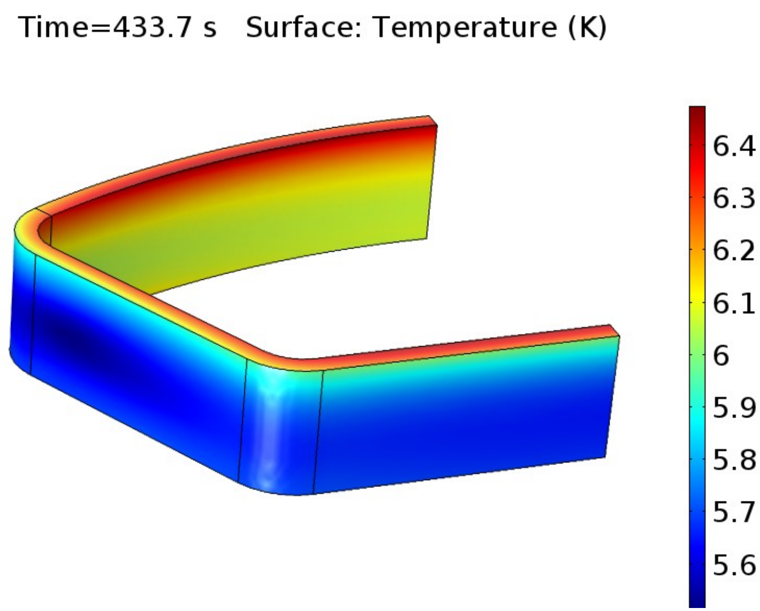




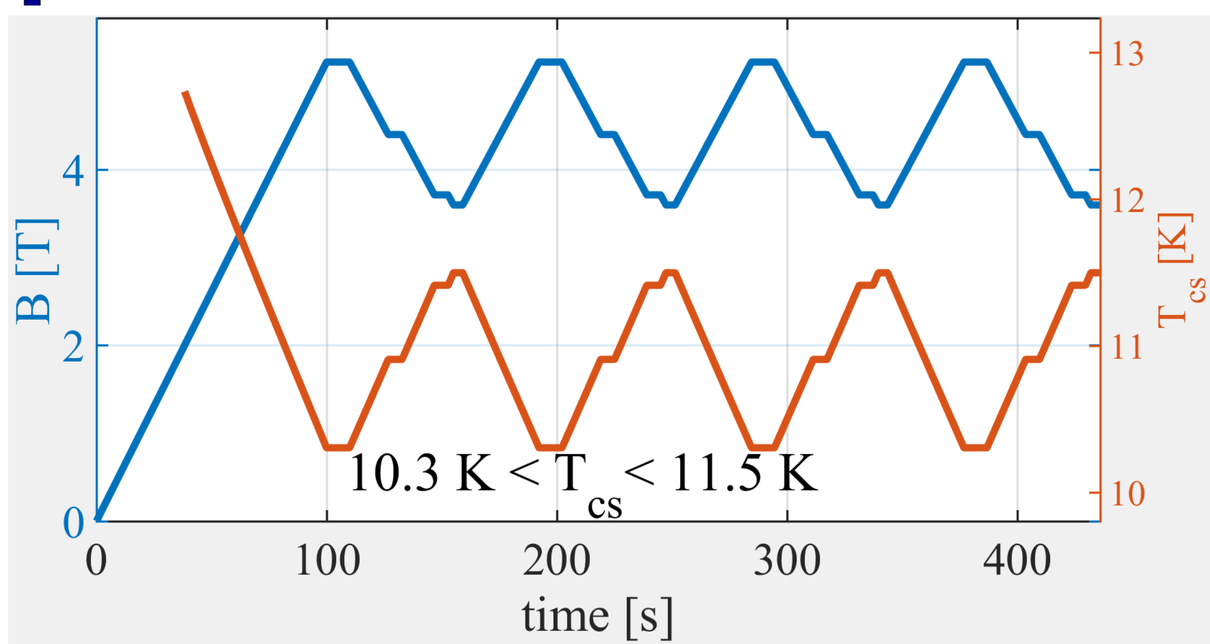
Thermal Analysis: cool-down



Thermal Analysis: heating during operation



Bruker Nb_3Sn:
$D_{f,effective}$=8.2 μm
I_c (4K, 12 T, 0%) = 204 A



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Support structure 2 : von Mises stress [MPa] upon rotation