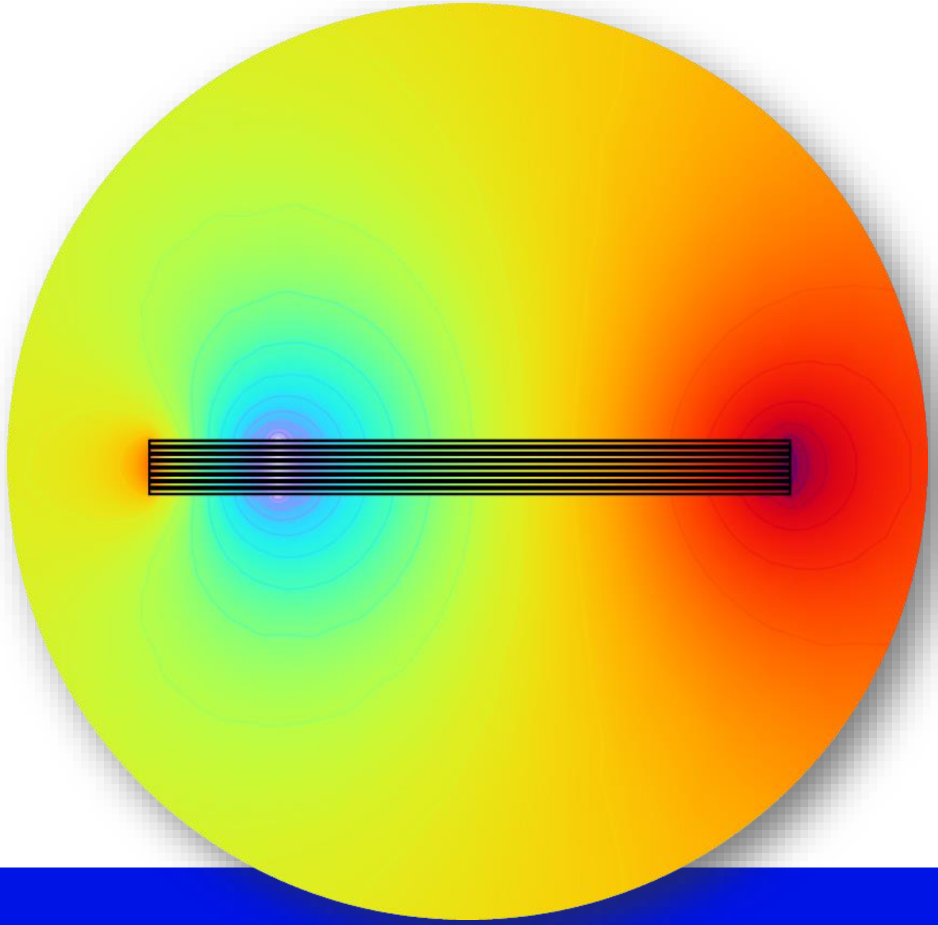
2D FEM electro-magnetic modelling of straight soldered ReBCO stack cable in high magnetic field



M. D. Araujo , B. Auchmann , A. Brem , M. Duda , H. Garcia , J. Kosse , D. Sotnikov :: PSI

9th International Workshop on Numerical Modelling of High Temperature Superconductors - HTS 2024, Bad Zurzach, 13 June 2024

This work was performed under the auspices of and with support from the Swiss Accelerator Research and Technology (CHART) program

Agenda

Preview – Magnet requirements

CDR dipole magnet for FCC-hh project expectations and requirements:

- Critical current density at 16 T (at 4.2 K): 1,500 A/mm^2
- Magnetization losses for full cycle (two apertures): **10 kJ/m**
- Distance between apertures: **250 mm**
- Coil physical aperture: **50 mm**
- Operating temperature: 1.9 K
- Length of magnet: **15 m**
- Cable material: Nb3Sn

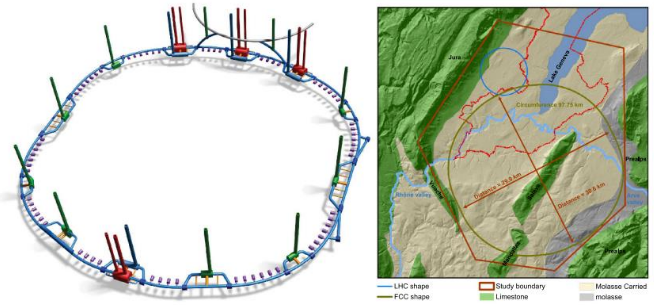


Fig. 2. Left: 3D, not-to-scale schematic of the underground structures. Right: study boundary (red polygon), showing the main topographical and geological structures, LHC (blue line) and FCC tunnel trace (olive green line).

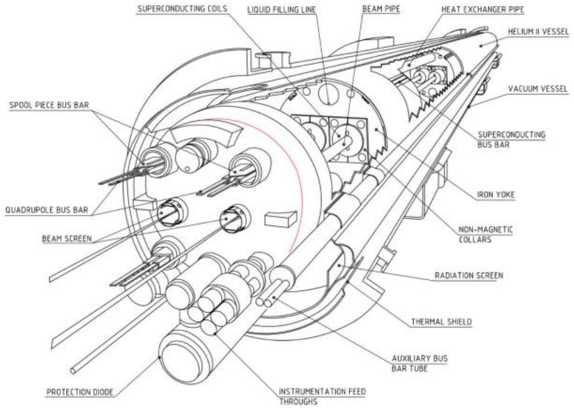


Fig. 3.2. 3D-view of main dipole cold mass assembly.

Criteria:

- **AC losses**
- **Field quality**

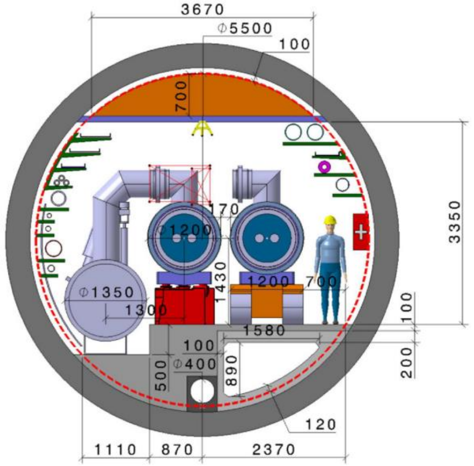


Fig. 3. Cross section of an FCC-hh arc. The grey equipment on the left side of the tunnel represents the cryogenic distribution line. A 16 T superconducting magnet can be seen in the middle, mounted on a red support element. Another superconducting magnet on a transport vehicle is shown next to it, in the transport passage.

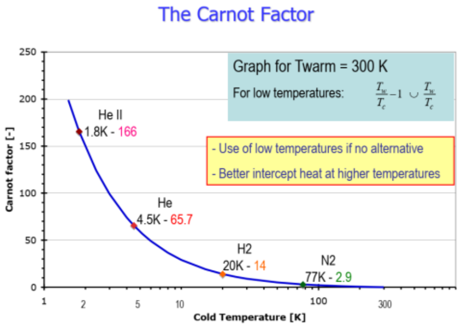
[1] A. Abada et al., FCC-hh: The Hadron Collider. Future Circular Collider Conceptual Design Report Volume 3, The European Physical Journal Special Topics volume 228, pages755–1107 (2019)

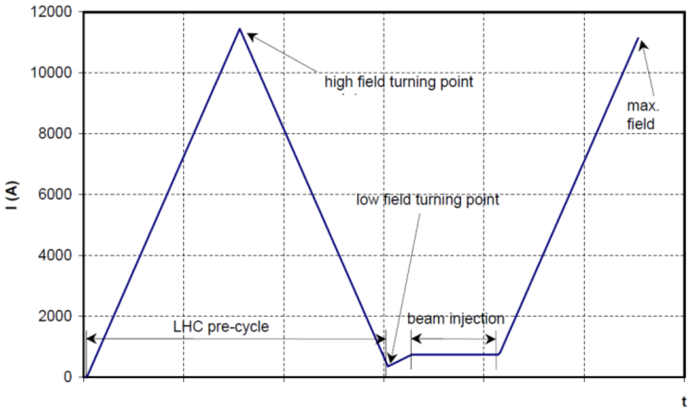
Initial data – HTS tape properties

The goal is to design a dipole magnet that fulfills FCC-hh requirements. Computation used interpolation of experimental data Jc(B) from [2] and [3].

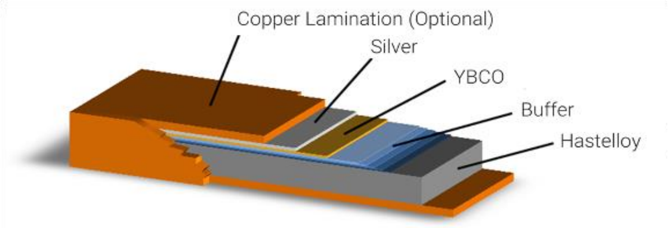
Applied current is DC. For simplification used only linear ramping up.

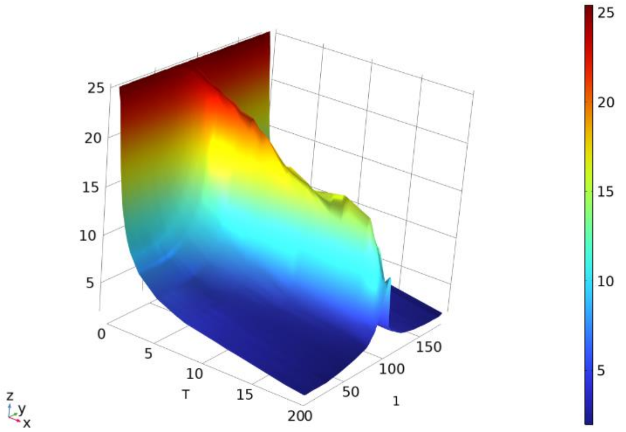
Parameter name	Values
Temperature	20 K
Maximal current	10 kA
Current ramp	Linear
HTS tape width	4, 12
HTS tape structure	FFJ
External magnetic field	up to 20 T
Time range	1,500 s
Ramp rate	10 A/s
AC losses @20K	120 kJ/m





$$Losses = \frac{166(@1.8K)}{14(@20K)} \times 10 \left[{}^{kJ}/{}_{m}\right]$$





[2] https://htsdb.wimbush.eu/
[3] https://www.faradaygroup.com/
[4] https://www.metoxtech.com/
[5] Christine Völlinger, Superconductor Magnetization Modeling for the Numerical Calculation of Field Errors in Accelerator Magnets, Doctor Dissertation, Berlin 2003

Initial data – HTS straight soldered stack cable

HTS wires are thin tapes (typically 4 and 12 mm width) with strong anisotropy of critical current to magnetic field direction.

Figure 1.10. *Three different geometries for assembling a cable with ReBCO coated conductor. Also refer to Table 1.2.*

Straight soldered stack cable:

Pros:

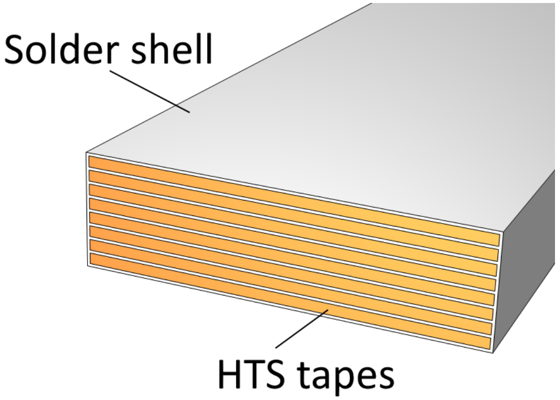
- Shape fits to racetrack design
- Fits to Block-coil and Common coil
- Highest packing factor
- Highest oriented critical current

Cons:

- AC losses (not known)
- Anisotropy Jc (B)
- Field quality

Cables:

- Roebel
- TSTC
- CORC
- CroCo
- CICC
- STAR
- Insulated Stack
- others



[6] J. van Nugteren, “High temperature superconductor accelerator magnets,” Ph.D. dissertation, Energy Materials Syst., Univ. Twente, Enschede, The Netherlands, 2016.

Computation model

2D FEM H-A formulation

Block and Common coil magnets design fit perfectly with racetrack coil. Criterion of 15 meter long dipole magnet creates a perfect opportunity to use 2D design approximation for this magnet design.

H-formulation has 2 components in 2D (Hx and Hy), while A-formulation uses just 1 component (Az). Coupled H-A formulation uses less unknowns for solution in 2D with the same results quality. **Coupling** of formulation done on **boundaries** by **Electric Field** and **Magnetic Field**.

H-formulation:

$$\frac{d}{dt}(\mu H) + \nabla \times \ (\rho \nabla \ \times \ H) \ = \ 0$$

A-formulation:

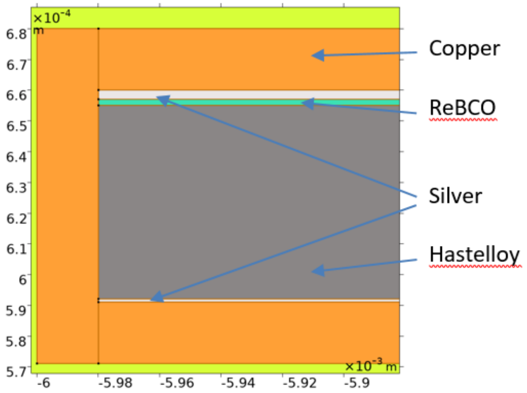
$$\frac{1}{\rho}\frac{dA}{dt} + \nabla \ \times (\mu^{-1} \nabla \ \times \ A) = \ 0$$

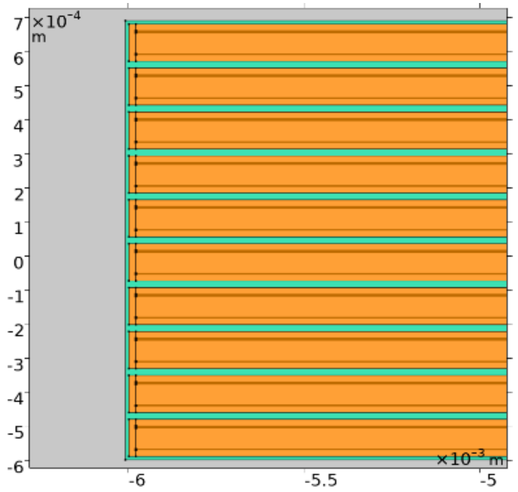
Stack structure and mesh selection

Purpose of this work is to define as accurate results as we can. Only detailed model (all layers of HTS tape) applied to this computation.

The first analysis done on **10 tapes** in a stack.

ReBCO layer presented as **1 element by thickness** (strip).





[7] Lorenzo Bortot, et al., A coupled a–h formulation for magneto-thermal transients in high-temperature superconducting magnets, IEEE Transactions on Applied Superconductivity, 30(5):1–11, 2020
[8] https://www.comsol.com/

FEM modelling - Losses computation - plan

Most of the presented AC loss results for HTS stacks in literature are for AC current or AC field cases. In the case of a dipole magnet, both the current applied to the coil and the external magnetic field applied to the coil are DC with a low ramp rate (about 10 A/s).

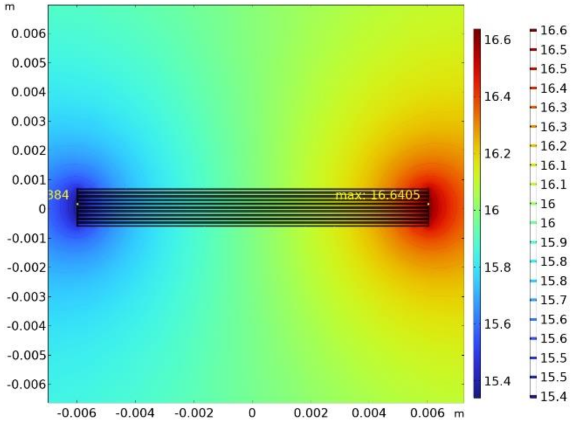
Agenda for single HTS straight soldered stack cable in external magnetic field computation:

- AC losses dependence on perpendicular magnetic field magnitude
- AC losses dependence on magnetic field direction at 16 T
- AC losses dependence on HTS tapes width
- Full cross-section 16 T dipole

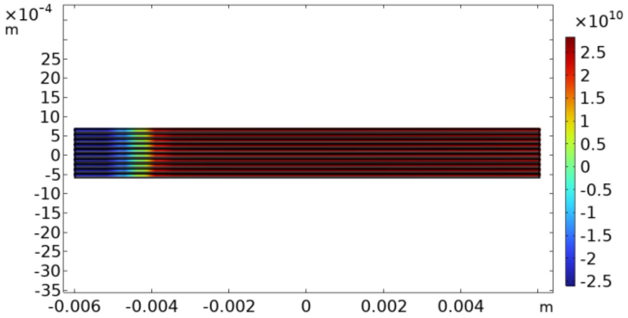
FEM modelling - Losses computation - field magnitude

Critical current of single tape dependence on magnetic field amplitude is a very well known experimental data published in many papers. It returns simple criterion for stack of insulated tapes, but it is different for soldered tape stack, where current can flow from almost transferred to normal state tape to others.

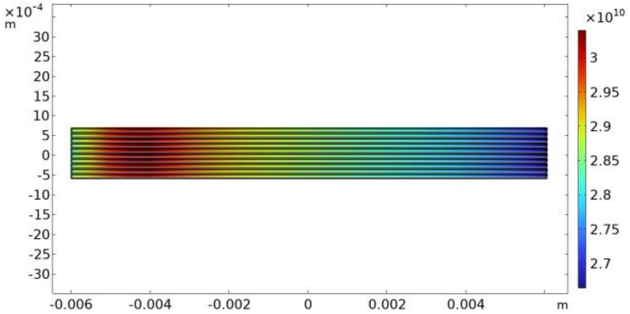
HTS tape stack in 16 T external magnetic field with 10 kA applied current



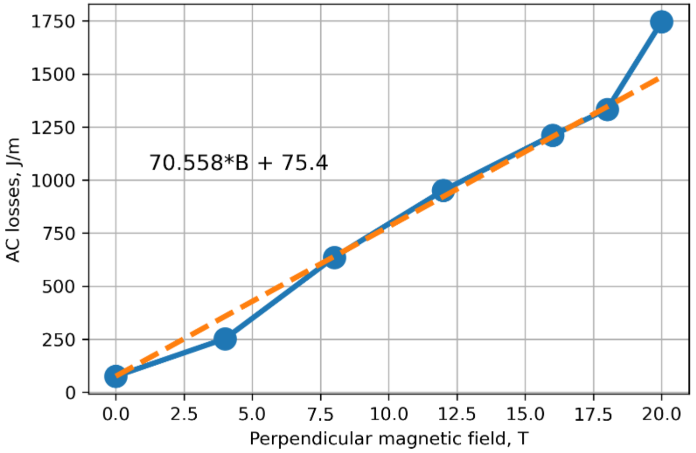
Jc distribution across the stack



Jz distribution across the stack



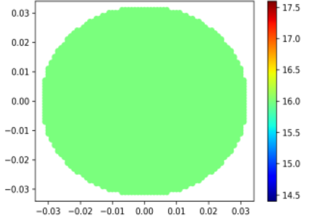
AC losses of HTS tape stack cable dependence on perpendicular magnetic field magnitude



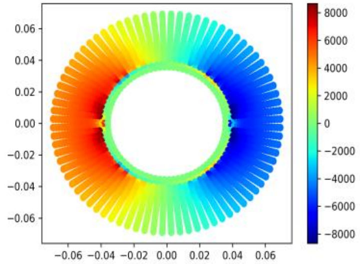
FEM modelling - Losses computation – field angular dependence

Current sharing between tapes could affect on critical current dependence on external magnetic field direction. It could be not so dramatic for perpendicular magnetic field as single tape is.

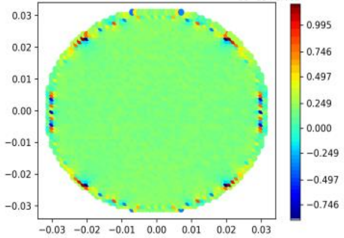
Required By

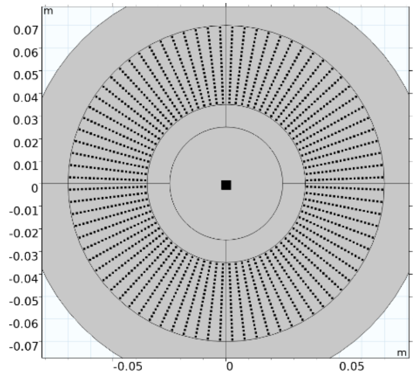


Linear current distribution

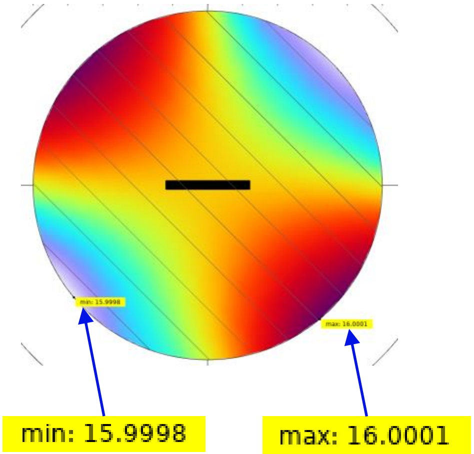


Returned By

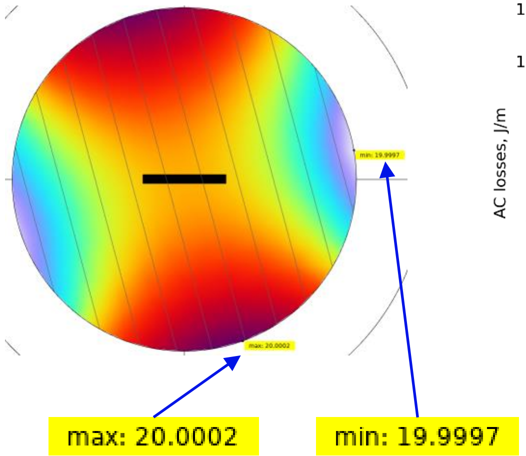


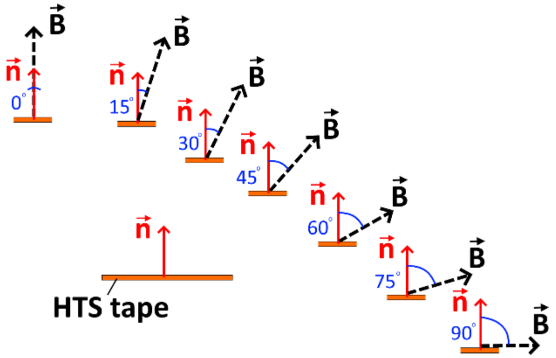


16 T and 45 deg

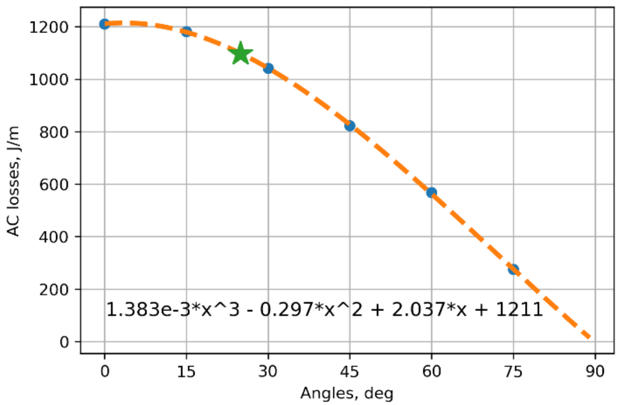


20 T and 15 deg





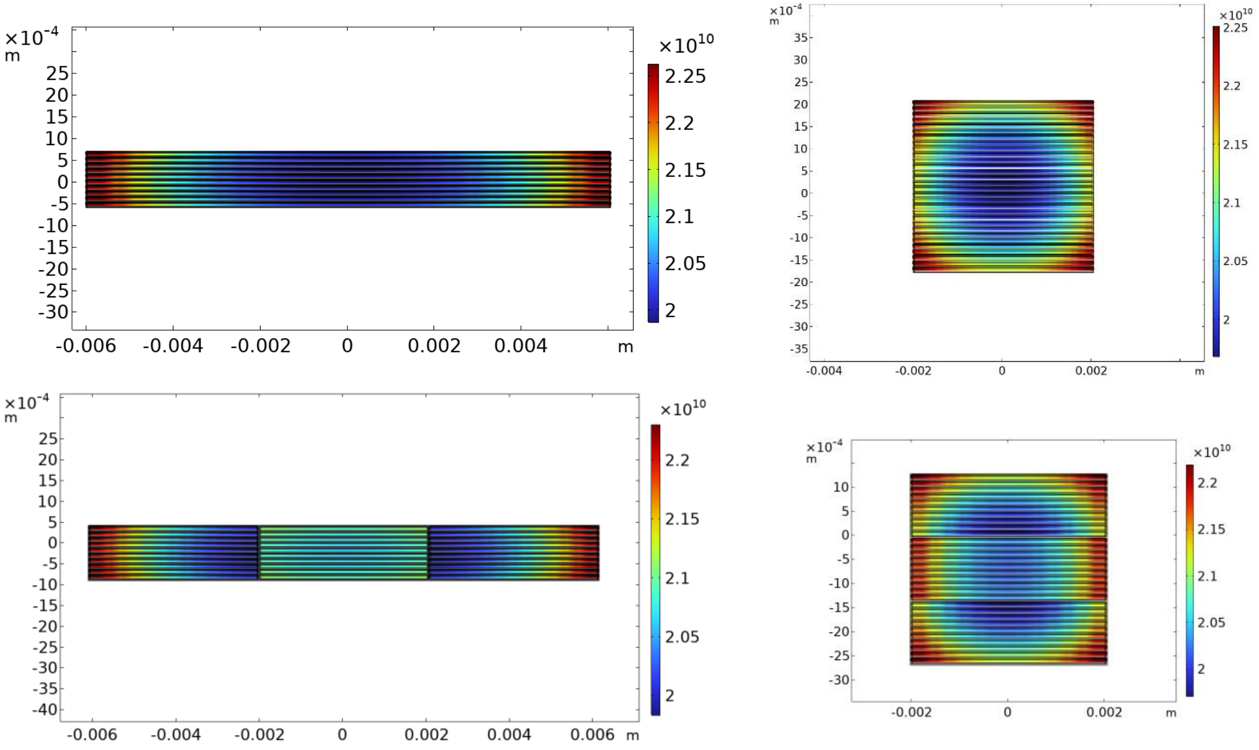
AC losses vs Angle



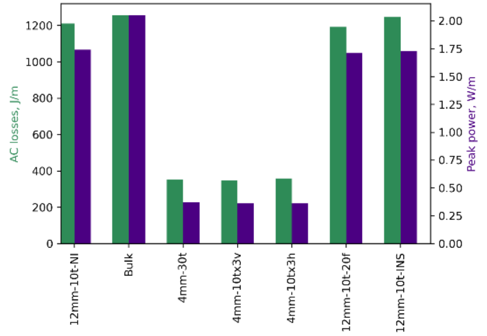
FEM modelling - Losses computation – tape width

It is well-known that narrower ReBCO tape has lower AC losses. Proper cable configuration can further reduce AC losses in the magnet.

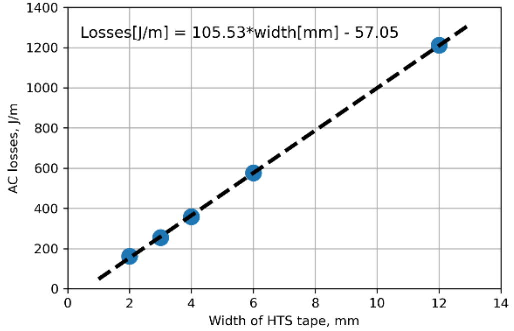
Jz distribution across the stacks of different configurations



AC losses of different stack configurations

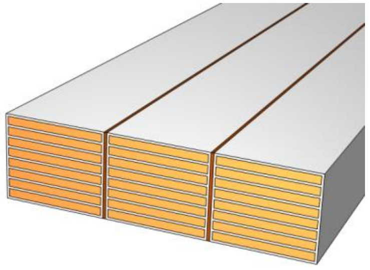


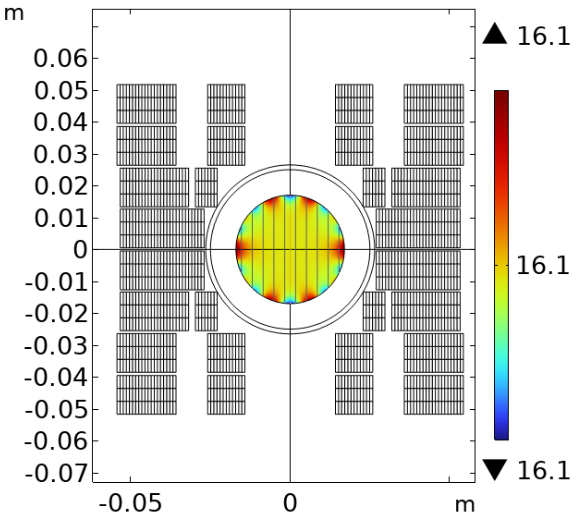
AC losses vs Width of tapes in stack



FEM modelling - Losses computation – 16 T dipole

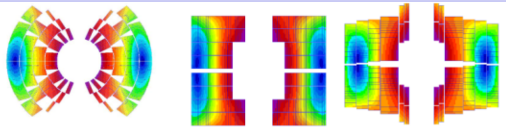
Based on previous analysis, for the first draft of the 16 T dipole magnet, we selected a block-type magnet (where the magnetic field is mostly parallel to the cable surface near the aperture) with 3 parallel stacks of 4-mm tapes, each stack containing 8 tapes. This design is based only on electromagnetic computations and does not account for the protectability of the coil.

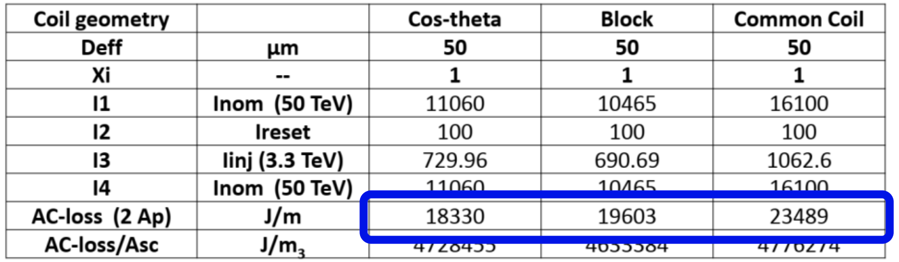




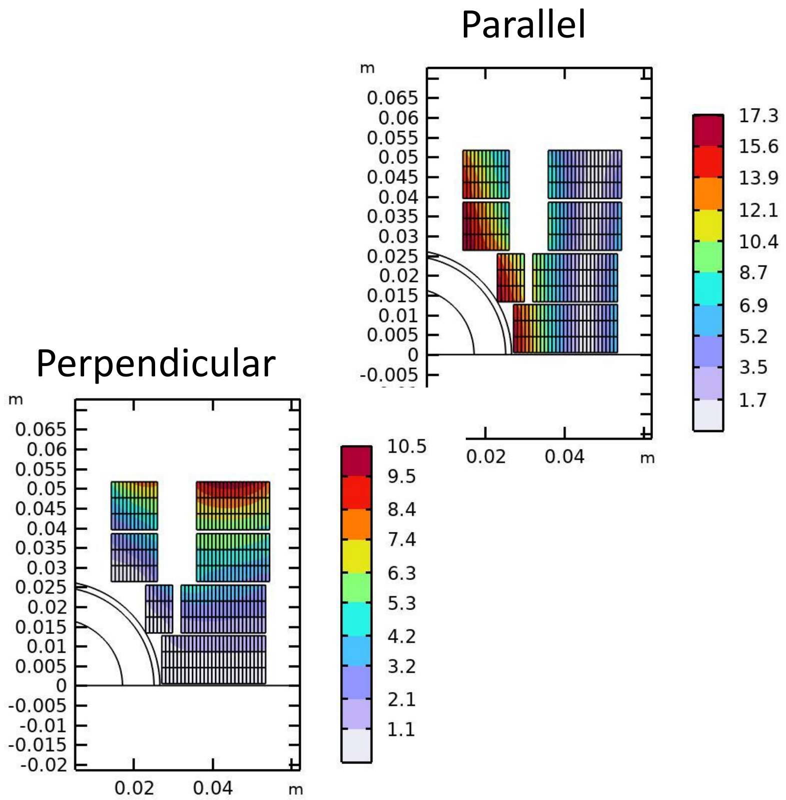
Parameter	Value
Magnetic field in center	16.120 T
b3	0.0067340
b5	0.44438
b7	0.78468
b9	-0.30249

224 [kJ/m](@20K) ↔19[kJ/m](@1.8K)





Coil geometry		Cos-theta	Block	Common Coil
Deff	µm	50	50	50
Xi	--	1	1	1
I1	Inom (50 TeV)	11060	10465	16100
I2	Ireset	100	100	100
I3	Iinj (3.3 TeV)	729.96	690.69	1062.6
I4	Inom (50 TeV)	11060	10465	16100
AC-loss (2 Ap)	J/m	18330	19603	23489
AC-loss/Asc	J/m$_3$	4728455	4633384	4776274


Parallel

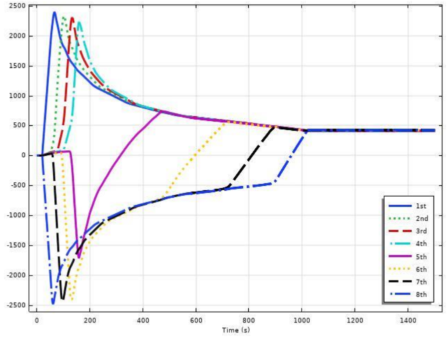
Perpendicular

FEM modelling - Current sharing

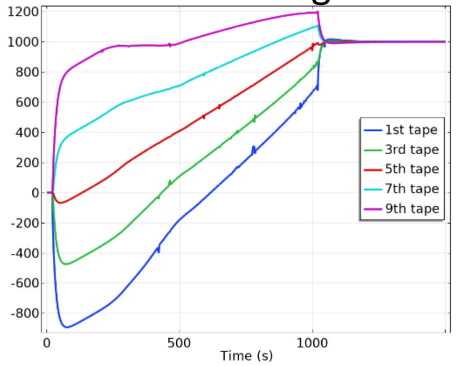
PSI

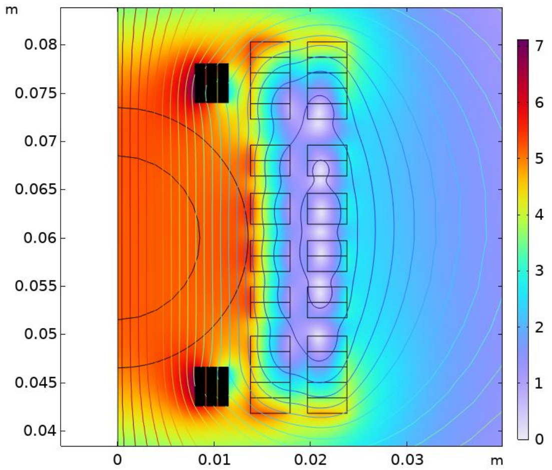
Current sharing in tapes of HTS straight soldered stack has mutual direction during DC ramping up.

Current sharing in 8 tapes stack of one of cables in 16 T dipole

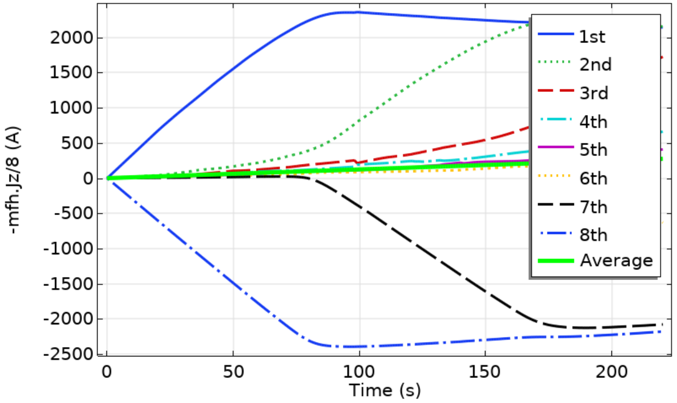


Current sharing in stack in 16 T field at 75 degrees

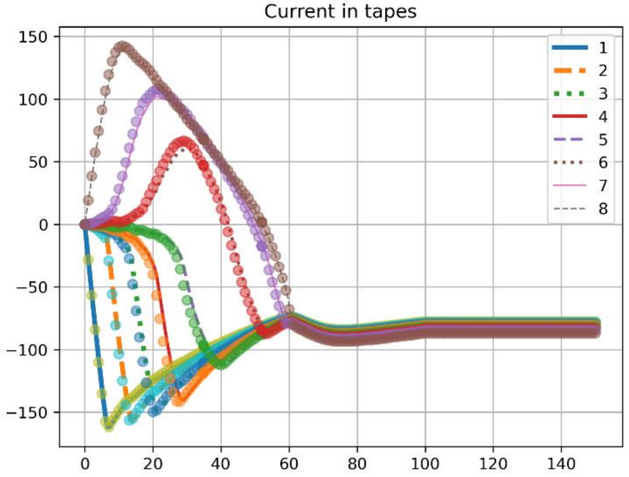




Designed by M.D.Araujo



Current sharing in 8 tapes stack



circles – Comsol Multiphysics

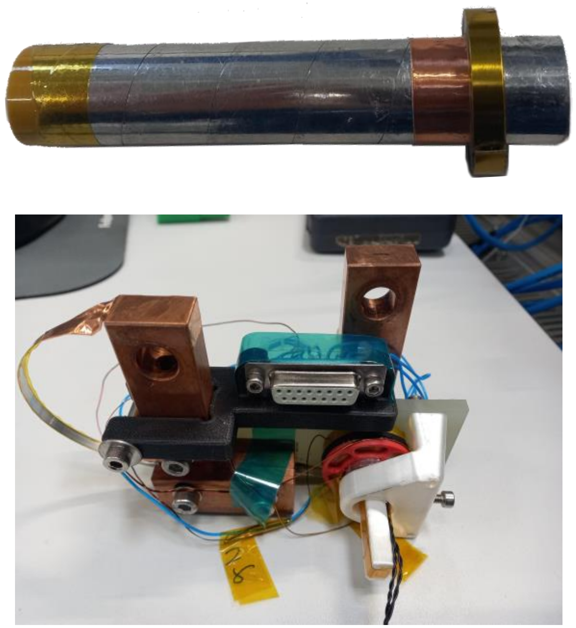
lines – Quanscient AllSolve

QUANSCIENT

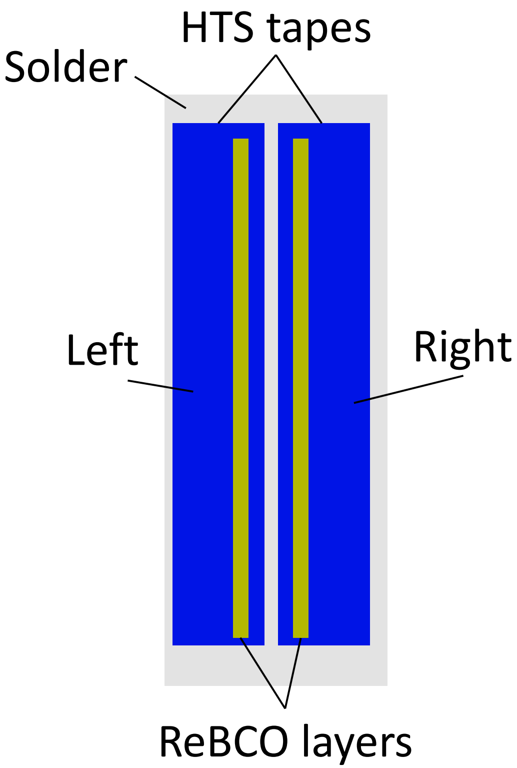
Acknowledgement to J. Ruuskanen & M. Lyly

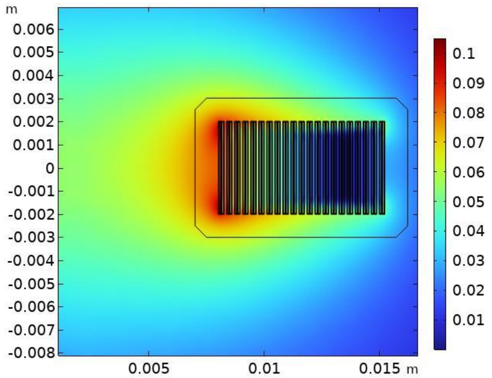
Data analysis and validation - Experimental approval of Losses

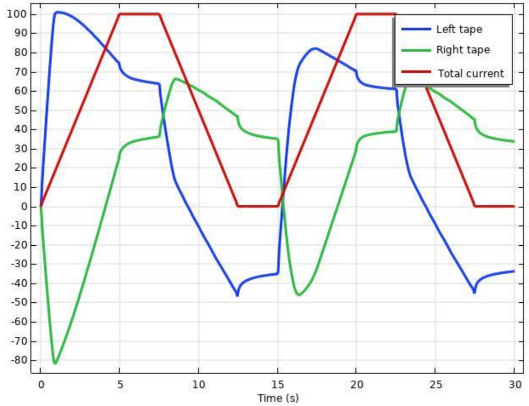
We plan to validate the AC losses of a small pancake coil made from 4-mm soldered face-to-face HTS tape from FFJ. This experiment will be conducted both in our lab and at Twente University. The production and testing process is ongoing with advice from A. Kario and S. Otten at Twente.

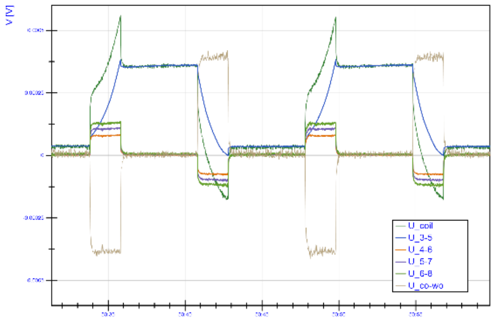


Courtesy by H.Garcia

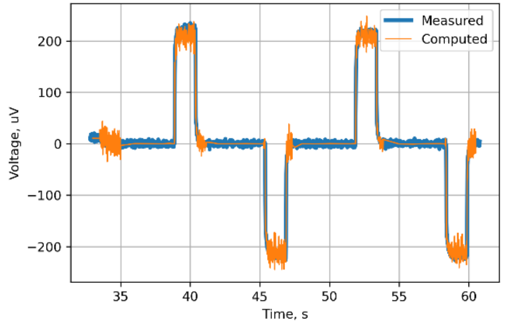








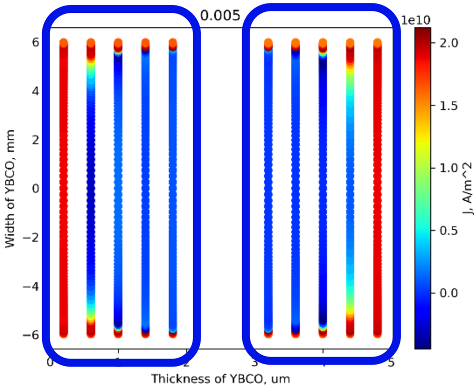
Courtesy by M.Duda



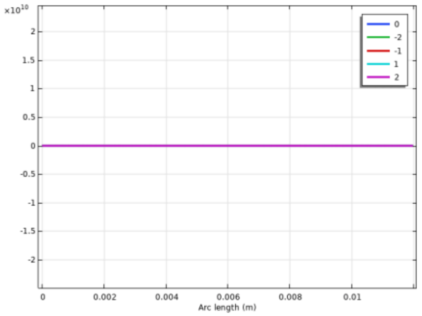
Data analysis and validation - Mesh quality

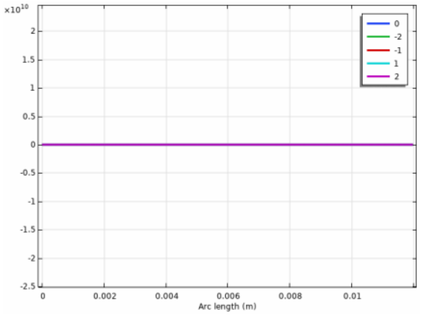
During computation for the experimental pancake, mesh quality significantly impacted AC losses in the face-to-face 2-tape stack.

YBCO layer
Left



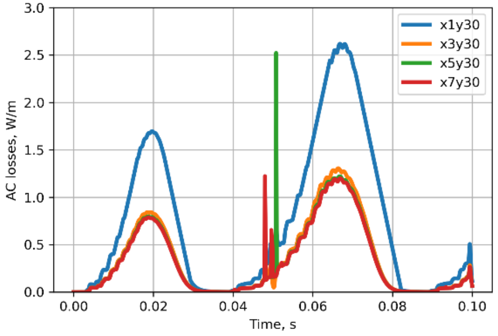
YBCO layer
Right



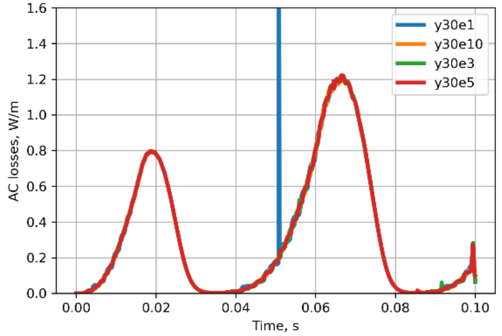


Best fit: 5 elements by thickness and more than 20 elements by width

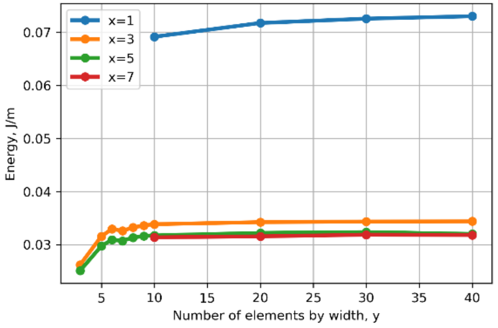
AC losses from number of elements by thickness ReBCO layer



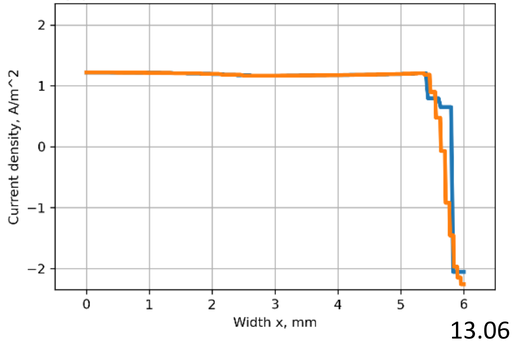
AC losses from exponential ratio of distribution by width



AC losses from number of elements by width ReBCO layer



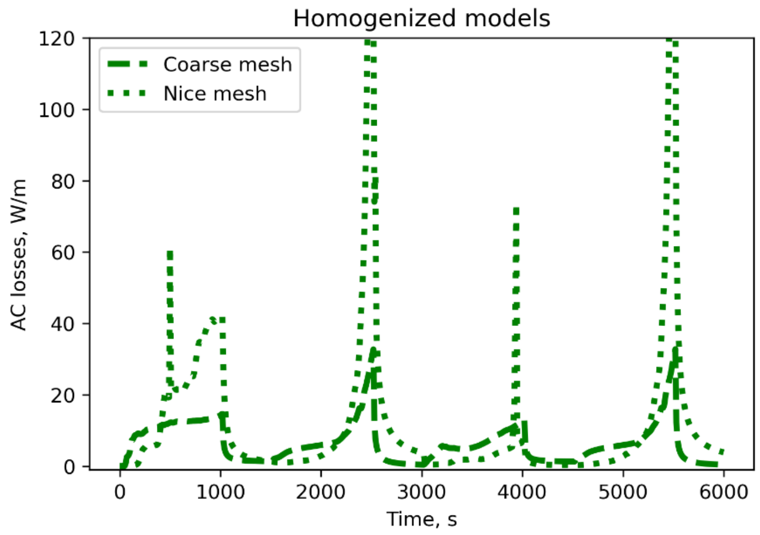
Current distribution by width half of tape for linear (blue) and exponential (orange)



Data analysis and validation - Losses computation – 16 T dipole – different meshes

Computation results for two cycles of the magnet ramping up and down for homogenized mesh.

Two different meshes of the same geometry for homogenized models returned different AC loss dependences.

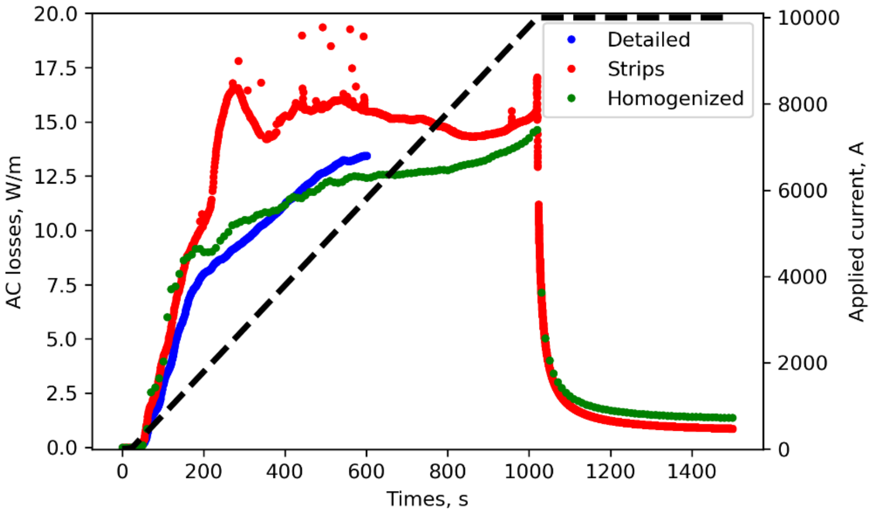


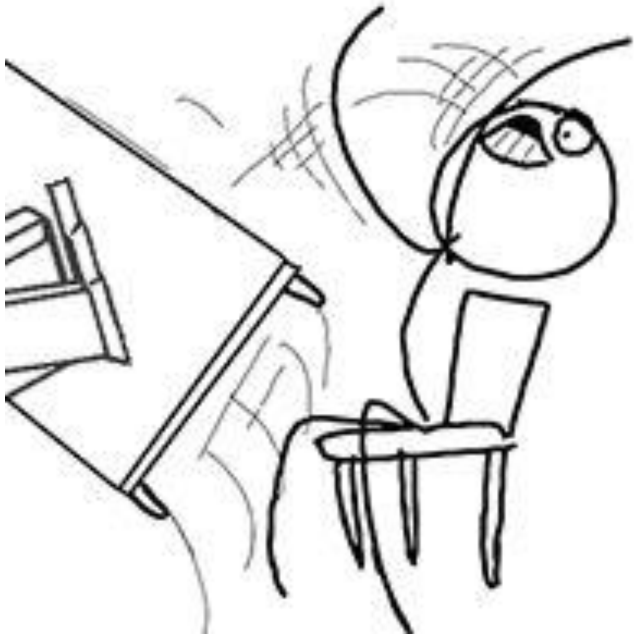
Data analysis and validation - Losses computation – 16 T dipole – different meshes

The previous model of the 16 T dipole magnet required an update after new requirements for mesh quality were established. AC losses for the more detailed model (blue line) are significantly lower than those for the strip layer model (red line). This model solves 4 mln DoF.

Best fit: 5 elements by thickness and more than 20 elements by width

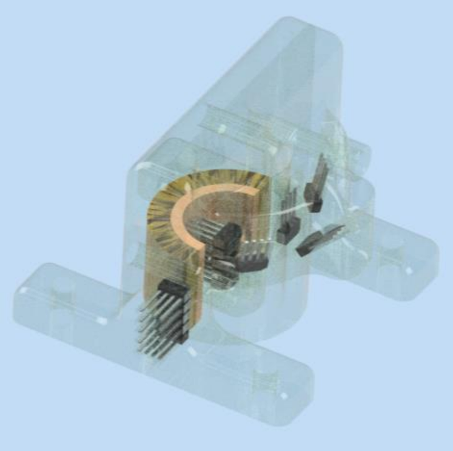
Steady computation at 0.1 s time step. Estimated time of computation: 120 days



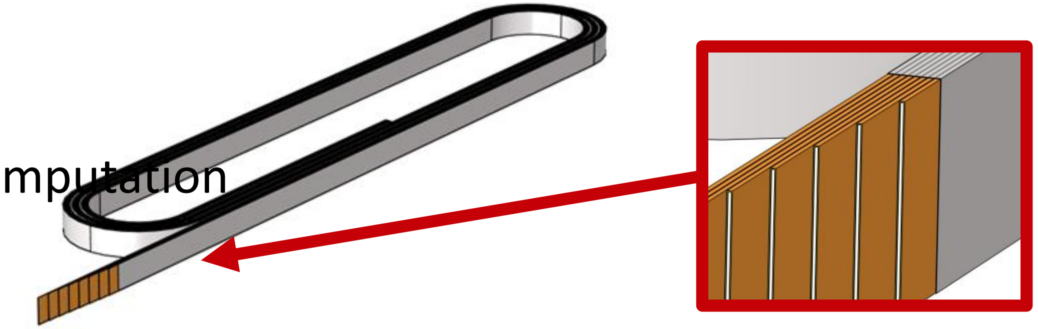


Plans

1. Finish AC losses validation measurements.
2. Try to measure current distribution in the pancake coil using Hall probes.
3. Modelling (including 3D), production and test of racetrack coil based on HTS straight soldered stack cable for pole coils of the Subscale Hybrid magnet.
4. Improve computation speed by using alternative computation software.
5. Enhance the design of the 16 T dipole magnet according to new computations.



Courtesy by H.Garcia



Conclusion

Selection of the correct geometry of the magnet, design optimization, and number of tapes in HTS straight soldered stack cable optimization can make this type of cable reliable for high-field magnets.

The shape of the cable allows for 2D computations of very detailed structures. Computation of each cable is sufficient, as computation of the whole magnet takes too long.

Next steps are the validation of the computation model and speeding up computations.