PAUL SCHERRER INSTITUT

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WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

D. Sotnikov, H. Garcia, J. Kosse, M. D. Araujo, M. Duda, B. Auchmann :: Paul Scherrer Institute

Transient effects in tape-stack cable and the PSI roadmap towards HTS HFMs

HFM – insulated solder-stack – block coil 16-T benchmark

Preview

As a basis for comparing HTS and LTS solutions, we use the FCC-hh CDR report [1] description of the project. This project assumes 4 700 dipole 16 T magnets to install in FCC-hh.

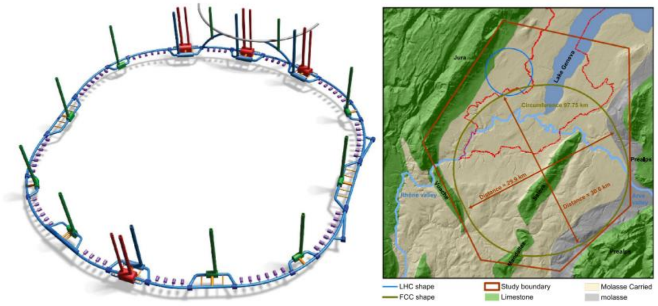


Fig. 2. Left: 3D, not-to-scale schematic of the underground structures. Right: study boundary (red polygon), showing the main topographical and geological structures, LHC (blue line) and FCC tunnel trace (olive green line).

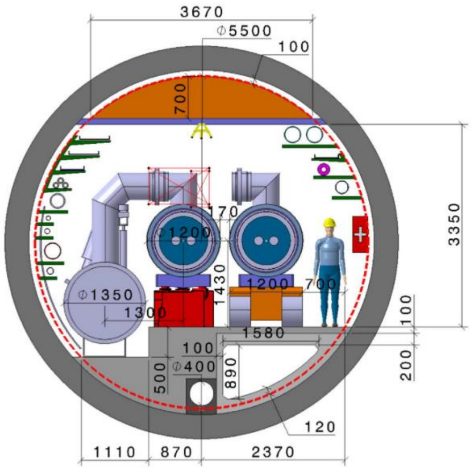


Fig. 3. Cross section of an FCC-hh arc. The grey equipment on the left side of the tunnel represents the cryogenic distribution line. A 16 T superconducting magnet can be seen in the middle, mounted on a red support element. Another superconducting magnet on a transport vehicle is shown next to it, in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

Preview – Magnet requirements

Dipole magnet for this 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

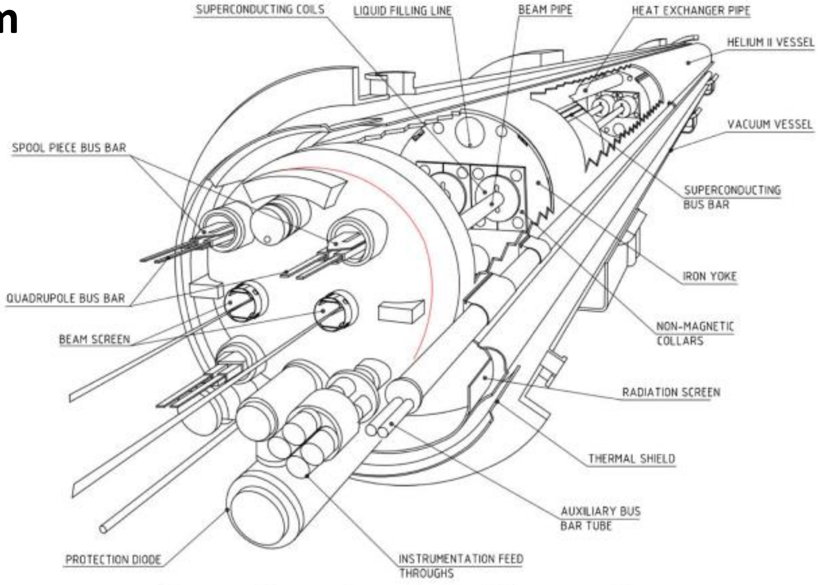


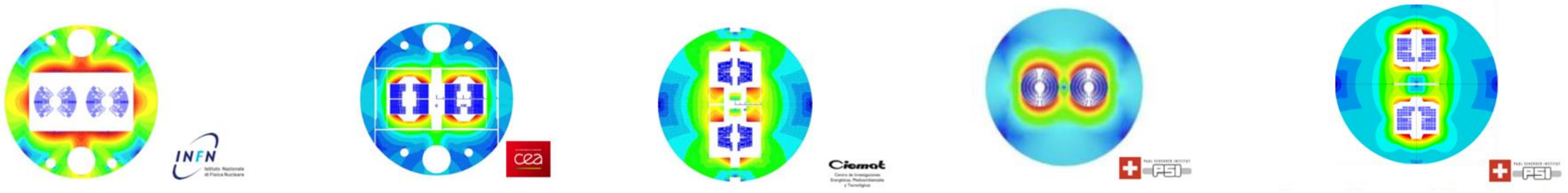
Fig. 3.2. 3D-view of main dipole cold mass assembly.

[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)

Preview – Status of magnets

There are 4 main concepts of 16 T magnets:

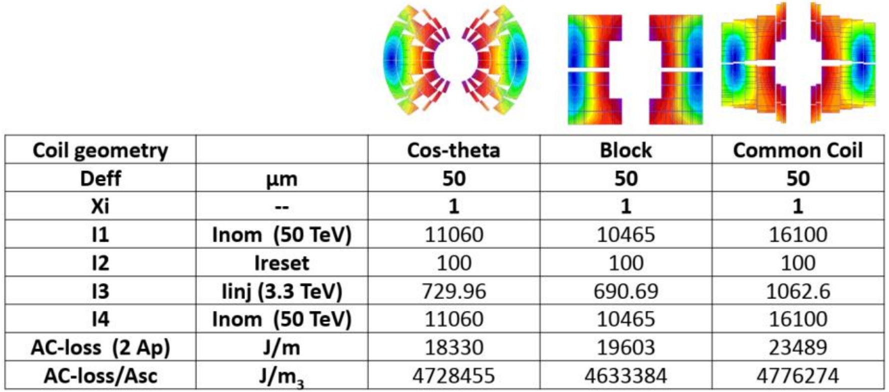
- Cos-theta Operating current: 11 390 A
- Block-coil Operating current: 10 123 A
- Common-coil Operating current: 16 100 A
- Canted cosine-theta: Operating current: 18 055 A



[2] Susana Izquierdo Bermudez, 16 T Magnet R&D Overview, FCC Week 2018
[3] Barbara Caiffi, EuroCirCol Cosθ 16 T dipole, FCC Week 2018
[4] E. Rochepault, Block-coil 16T Design for the FCC, FCC Week 2018
[5] F. Toral, Magnetic and Mechanical Design of a 16 T Common Coil Dipole for FCC, FCC Week 2018

Preview – AC loss data of LTS magnets

Analysis of HTS cables and magnet is based on the current level of technology. That’s why for benchmark we used the data of LTS magnet for existed level of technology. AC losses presented at **1.9 K**.



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

[6] Susana Izquierdo Bermudez et al., AC loss for EuroCirCol 16 T designs, CERN 01-11-2017

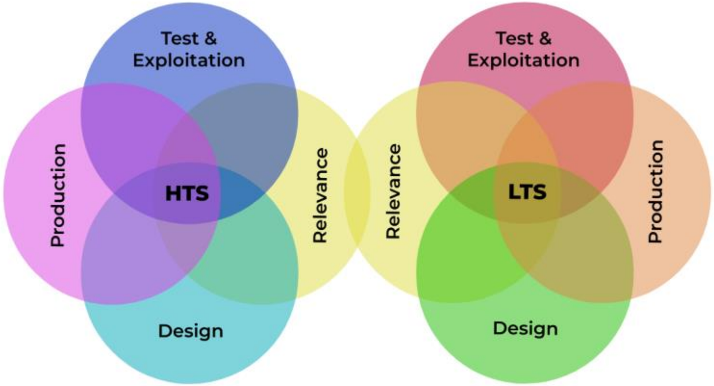
HTS vs LTS magnet – relevance

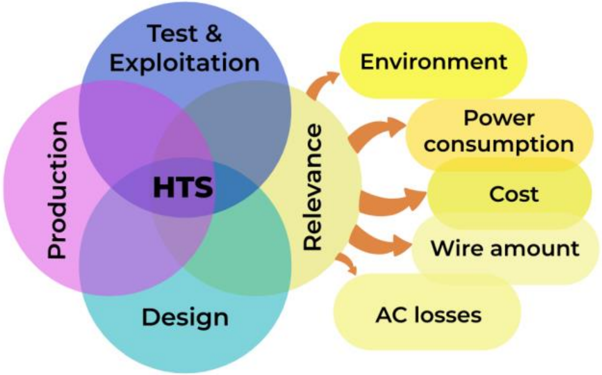
Comparison between different magnets should have strong criteria.

Cost depends on many factors that are hard to predict on a long time scale.

Chosen criteria:

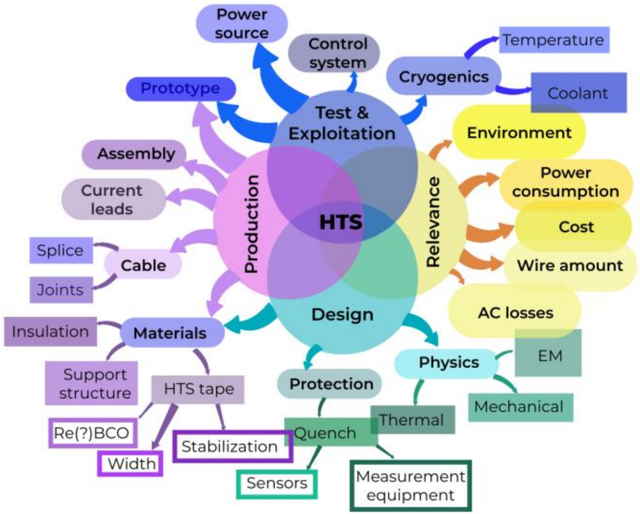
- AC losses
- Power efficiency (temperature, coolant)
- Geometry efficiency (amount of wire, magnet size)





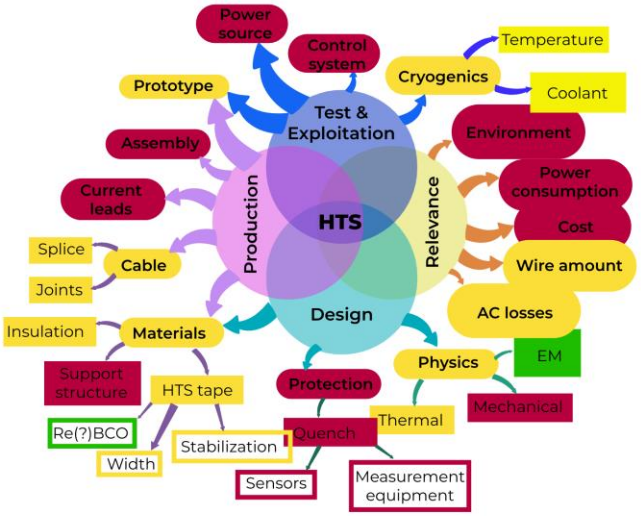
HTS magnet – Structure

Design and estimation of the magnet is much more complicated with many mutual connections between parameters. Moreover, many of parameters have recursive dependence with re-launch of design process in case of inconsistent solutions.



HTS magnet – Structure

Some of processes we almost solved (electro-magnetic computation of ReBCO coil cross-section). Some of processes are in progress stage. Some others are not started or are not in focus of analysis.



🟩 Green – solved

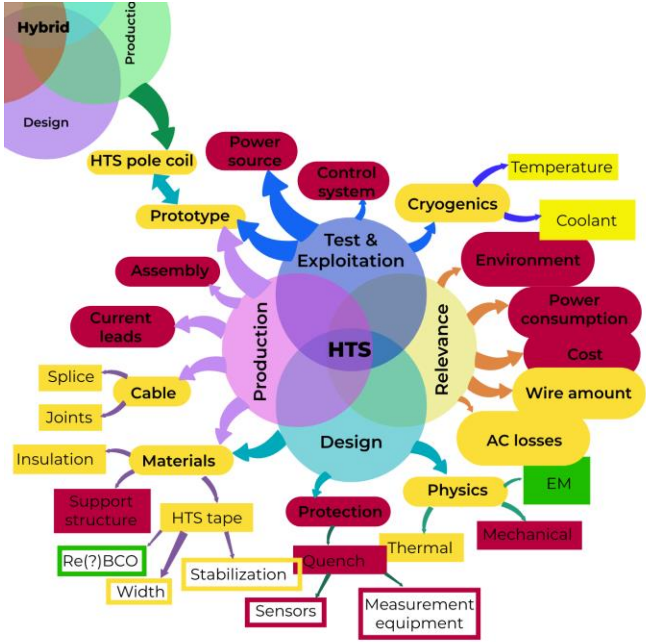
🟨 Yellow – in progress

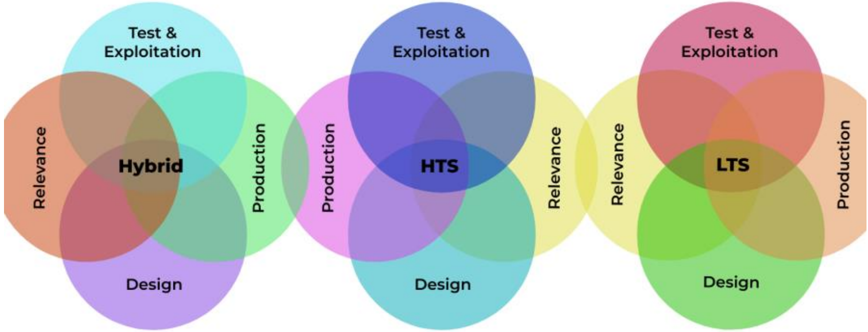
🟥 Red – haven’t started

HTS magnet – Structure

And at some moment it becomes even more complicated, as it is now: we have strong correlation of experimental results with Hybrid magnet project.

(lead by M. D. Araujo)

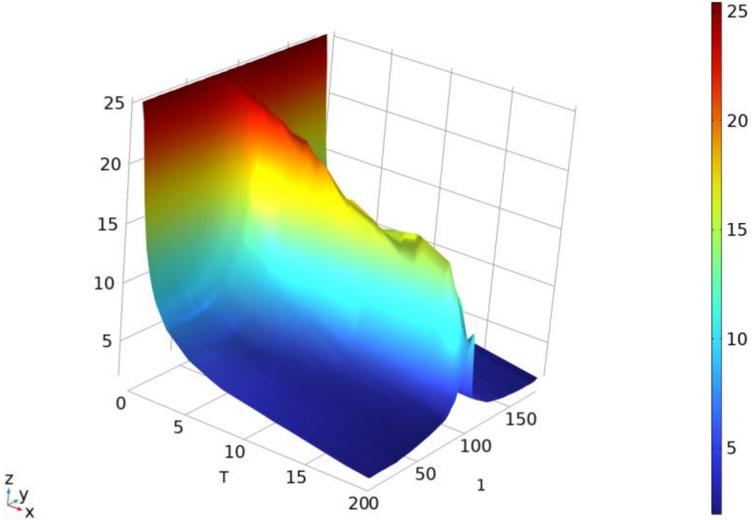




Purpose and Initial data

Design and development of 16 T dipole magnet based on HTS tapes for benchmark with already existing projects.

Parameter name	Values
Temperature	20 K
Applied current	10 kA
Current ramp	Linear
HTS tape width	4, 12 mm
HTS tape structure	FFJ
Magnetic field	up to 20 T
Time range	1,500 s



Critical current of FFJ HTS tape at 20 K vs magnetic field at different angles to normal of surface

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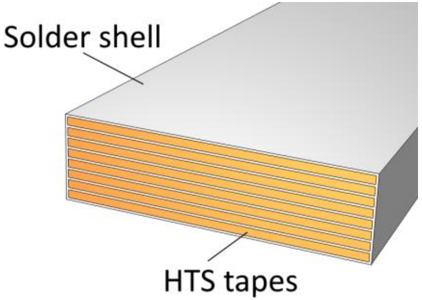
[6] https://htsdb.wimbush.eu/
[7] https://www.faradaygroup.com/

Initial data – Type of 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 stack cable:

Pros:

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

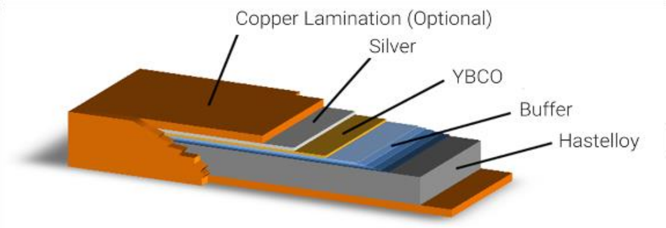
Cons:

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

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

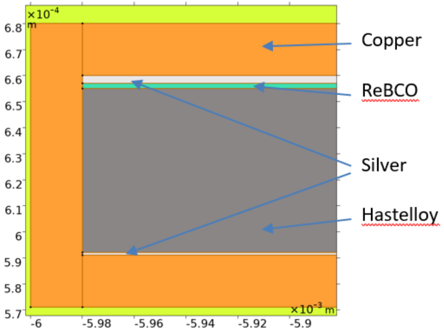
Initial data – Model

Computation is done in Comsol Multiphysics with using all layers of HTS tape (Detailed model) with H-A formulation (H- is for cables).



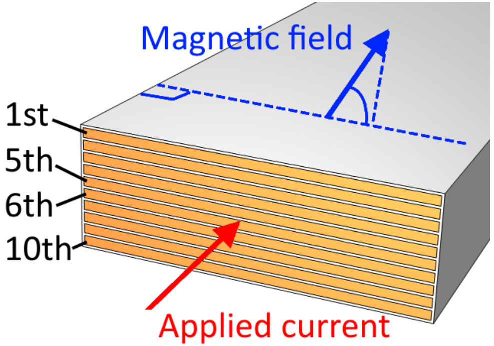
$$\frac{\partial(\mu_0\mu_r \boldsymbol{H})}{\partial t} + \nabla\times(\rho\nabla\times\boldsymbol{H}) = 0$$

$$\sigma\frac{\partial\mathbf{A}}{\partial t} - \nabla\times\frac{1}{\mu_0\mu_r}\nabla\times\mathbf{A} = 0$$



We started from:

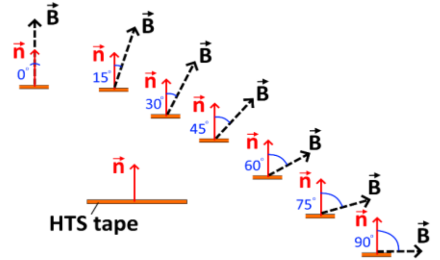
- 10 tapes of 12-mm width soldered in stack
- Magnetic field up to 20 T
- Any applied angle of magnetic field



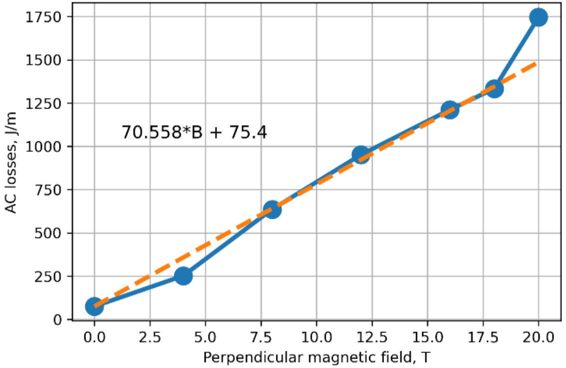
[10] https://www.comsol.com/
[11] https://www.metoxtech.com/
[12] Lorenzo Bortot et al., A Coupled A–H Formulation for Magneto-Thermal Transients in High-Temperature Superconducting Magnets, IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 30, NO. 5, AUGUST 2020
[13] M. D. Ainslie et al., Numerical Simulation of the Performance of High-Temperature Superconducting Coils, J Supercond Nov Magn
[14] Solovyov Mykola et al., A-formulation method for full 3D FEM computation of the superconductor magnetization, Chats2019 Applied Superconductivity

Stacks – AC losses – variable conditions

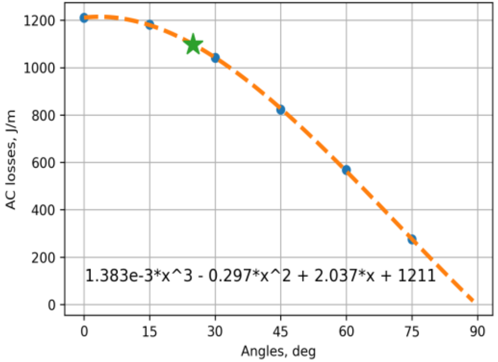
We solved soldered 10 tapes of 12-mm width for various conditions and got AC losses with linear ramp of 10 kA over 1000 s, followed by 500 s plateau, estimation for initial estimation of stack cable application in magnets.



Angle of applied magnetic field



AC losses vs applied perpendicular magnetic field



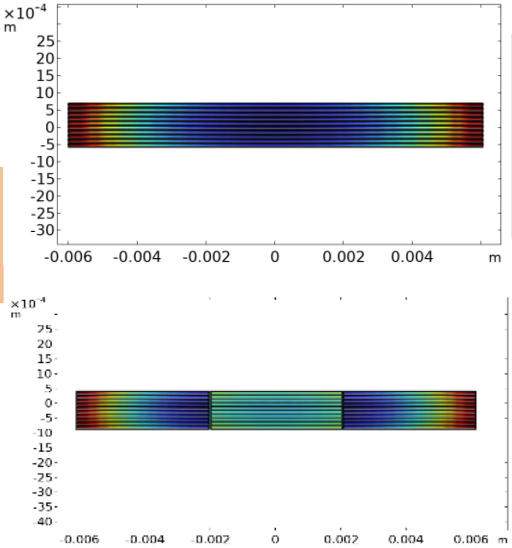
AC losses depending on angle

$$Q(normB) = 70.558\left[\frac{\mathrm{J}}{\mathrm{m*T}}\right] * normB + 75.4\ \left[\frac{\mathrm{J}}{\mathrm{m}}\right] \qquad (1)$$

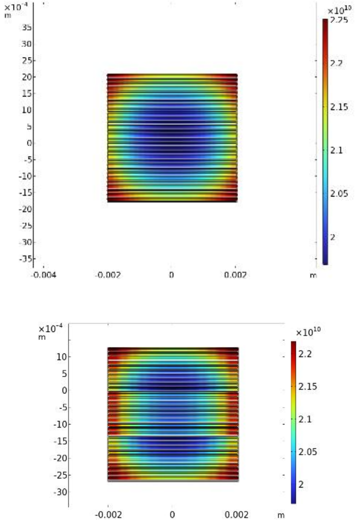
$$Q(angle) = 1.383e - 3 * ang^3 - 0.297 * ang^2 + 2.037 * ang + 1211\ (2)$$

Stacks – HTS tape width

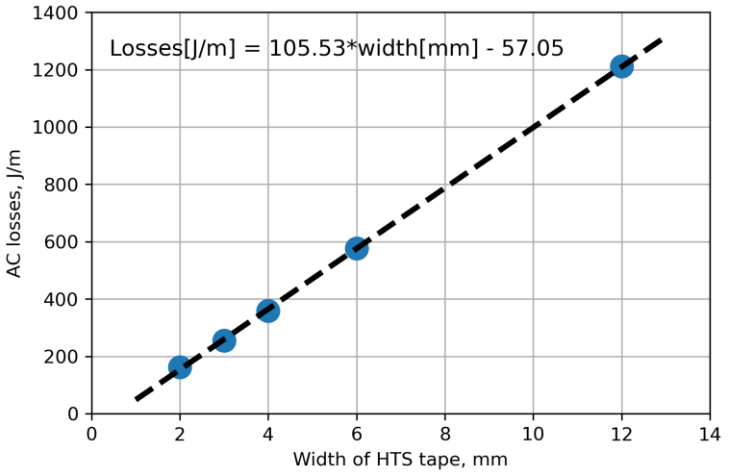
Using the same computation models, we provided computation of AC losses with various combination of 4-mm and 12-mm tapes with the same 10 kA in total and 16 T of applied magnetic field (linearly increased with applied current).



12-mm 10 tapes and 4-mm 10 tapes 3 stacks in horizontal current distribution



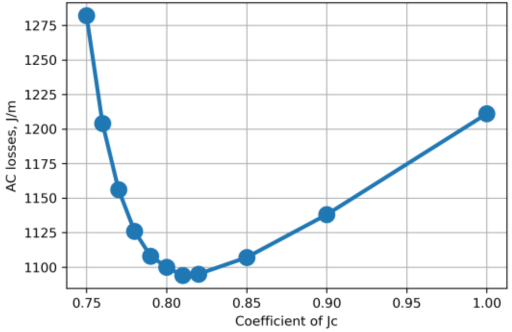
4-mm 30 tapes and 4-mm 10 tapes 3 stacks in vertical current distribution



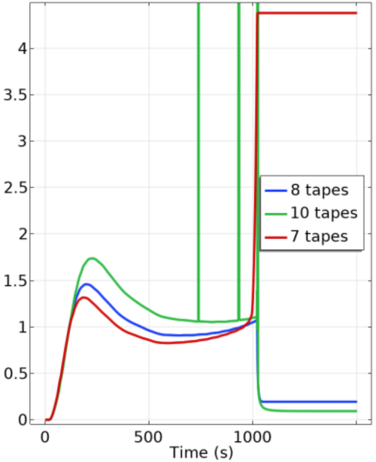
AC losses are linearly dependent on HTS tape width

Stacks – AC losses min – 16 T Different Jc

The next step is determine optimal number of tapes in the soldered stack at 16 T. For this purpose we changed HTS tapes critical current by coefficient at the same conditions: 10 kA in total and ramping perpendicular magnetic field up to 16 T. We can see that at coefficient less than 0.8 we have strong increase of losses (the transition to normal state) and higher than 0.8 we have smooth increasing of losses (magnetization losses are higher).



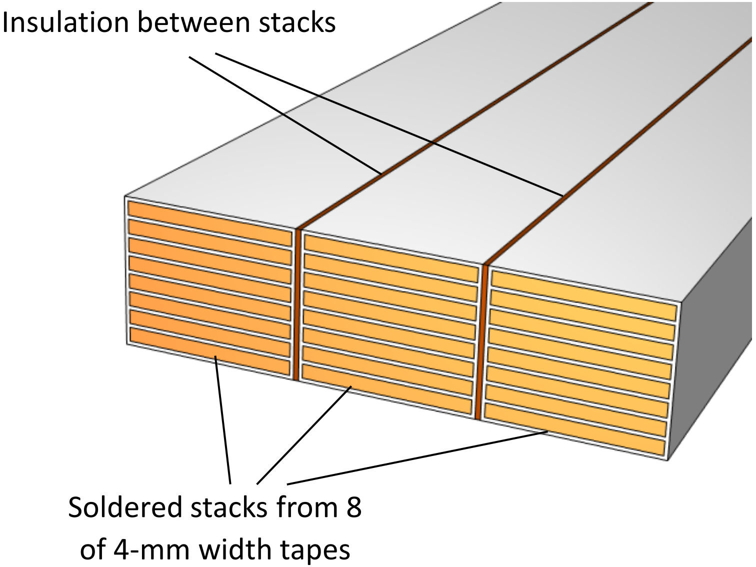
AC losses in stack depending on critical current coefficient



We assumed that **8 tapes soldered stack** should have minimal AC losses for 16 T and 12-mm width, and checked it by modelling of different stacks.

Block coil – adjusted for HTS – aperture

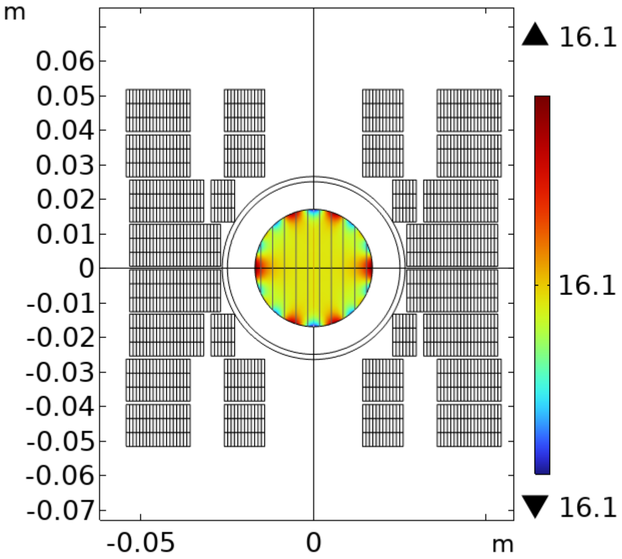
Using previous results for minimization of AC losses, we designed simple block-coil type magnet with geometric field quality parameters less than 1 unit for estimations of soldered stack-cable application. It was 3 sets of 8 tapes of 4-mm width in parallel.



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

Block coil – adjusted for HTS – aperture

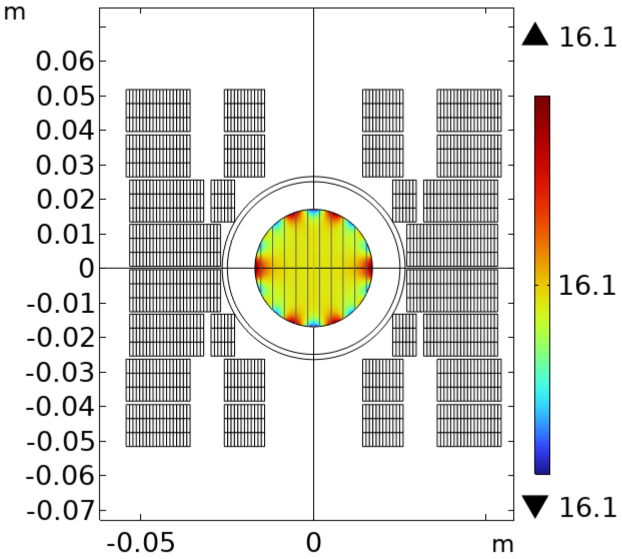
The magnet shape looks unusual, but it works for our purpose of parameters comparison and AC losses estimation and optimization.

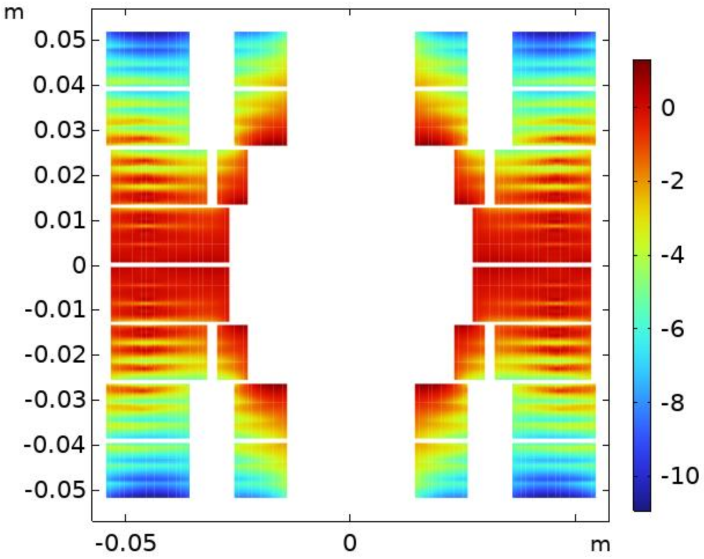


Parameter	Value
Magnetic field in center	16.120 T
b3	0.0067340
b5	0.44438
b7	0.78468
b9	-0.30249

Block coil – adjusted for HTS – aperture

For this shape of magnet we can see, that perpendicular component of magnetic field is far away from maximal magnetic field, and less than 11 T.

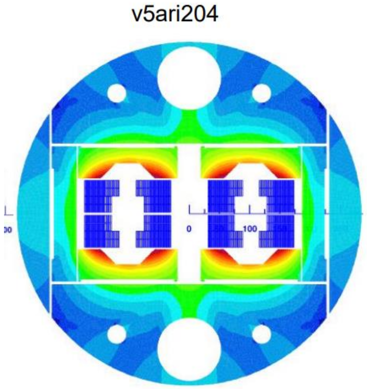




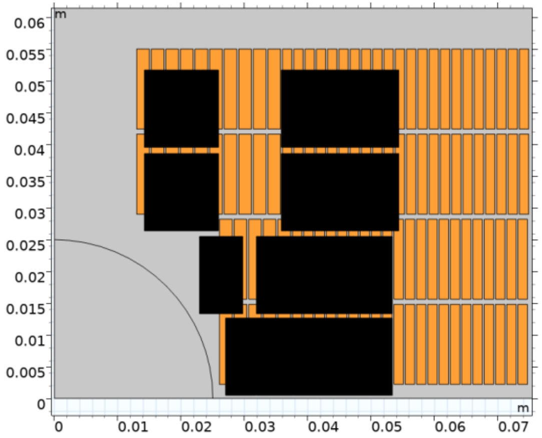
Perpendicular component of magnetic field

Block coil – LTS vs HTS

Even at temperature 20 K, HTS coil is much smaller than LTS at 1.9 K with the same applied current and magnetic field values.



Block coil design

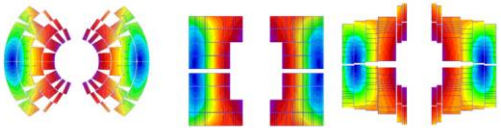


HTS (black) in compare with LTS (orange)
block coil cross section

[4] E. Rochepault et al., Block-coil 16T Design for the FCC, FCC week 2018, 10/04/2018

AC losses benchmark

AC losses of LTS magnets at 1.9 K for the current level of technology are presented in [11], and AC losses are about 20 kJ/m (that is 2 times higher than criteria 10 kJ/m). HTS block coil AC losses are 224.6 kJ/m (assuming that ramp-down has same losses as ramp-up) and much higher (about 11 times) than traditional LTS magnets.



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
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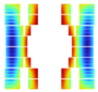


4-mm width

REQUIRES VALIDATION

224680

[6] Susana Izquierdo Bermudez et al., AC loss for EuroCirCol 16 T designs, CERN 01-11-2017

Block coil – AC losses in HTS adjusted

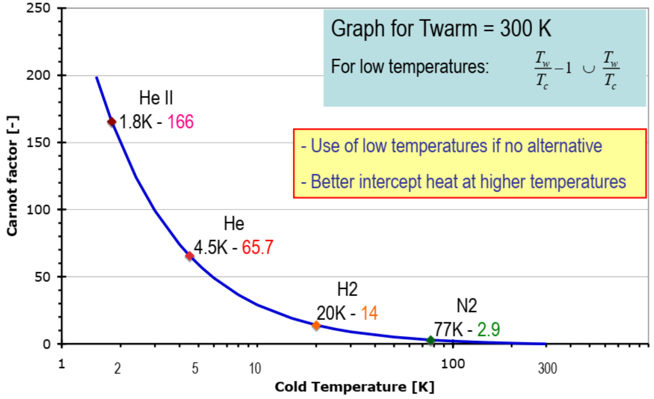
In accordance with [1, p. 919], required energy for this magnet is 10 kJ/m for ramping up and down at 1.9 K. Based on Carnot Factor 166 for 1.8 K and 14 for 20 K, we got 224 [kJ/m] at 20 K corresponds to 19 [kJ/m] at 1.8 K efficiency that is very close to average 20 [kJ/m] of LTS magnets.

Even with this not finally optimized shape of Block coil, we can say that HTS tapes at 20 K could be a way for a 16 T magnet.

224 [kJ/m](@20K)↔19[kJ/m](@1.8K)

HTS is a relevant way for 16 T dipole magnet design.

The Carnot Factor



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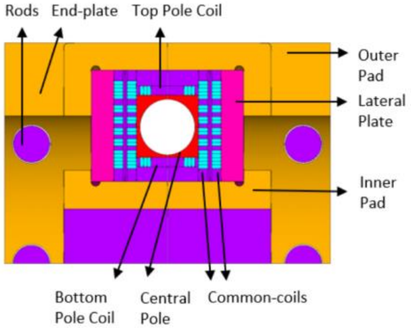
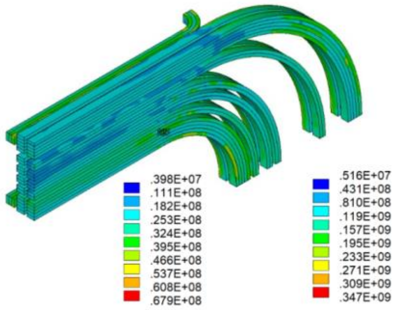
[1] [A. Abada et al., FCC-hh: The Hadron Collider. Future Circular Collider Conceptual Design Report Volume 3, The European Physical Journal Special Topics volume 228, pages755–1107 (2019)

[15] Serge Claudet, Introduction to Cryogenics for accelerators, CAS on Vacuum for Particule Accelerators Glumslöv-ESS, SE 7-15 June 2017

Subscaling

ReBCO racetracks chosen for pole coils in upcoming Hybrid common-coil (LTS/HTS) magnet at 4.2 K (design by D. M. Araujo and CHART team).

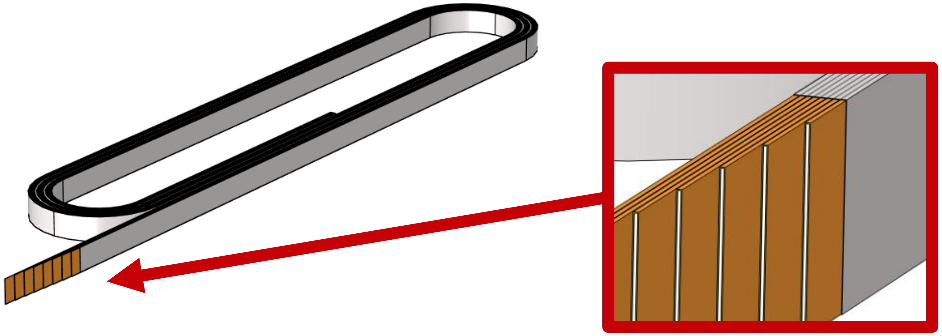




Pictures taken from pending paper of Douglas Martins Araujo

Based on current design of Hybrid magnet, we have the following requirements for ReBCO racetrack :

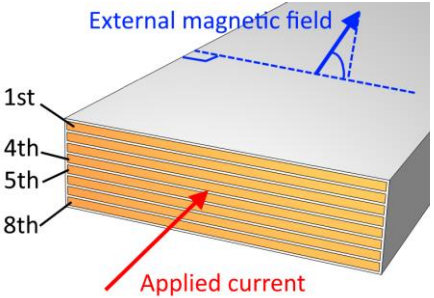
- **4-mm** tape **width**
- **8 tapes** in soldered **stack**
- **7.5 mm** – minimal bending **radius**

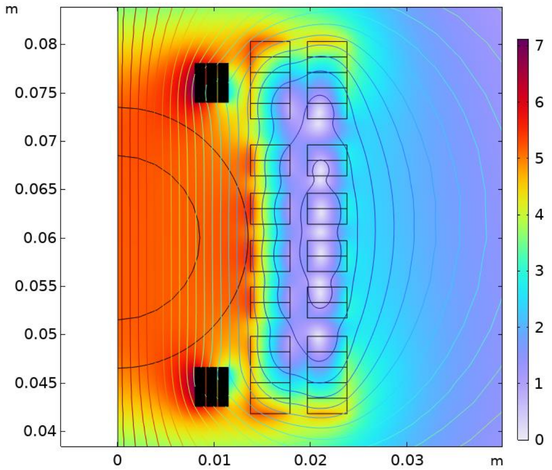


Current sharing in soldered HTS tape stack

Current sharing in soldered HTS tape stack cable is uncertain and very difficult for validation. It has impact on magnetic field quality, critical current values, and probably on AC losses.

We did a set of computation in design of Hybrid magnet at 4.2 K with **8 tapes 4-mm** HTS tapes soldered tape stack with various parameters.

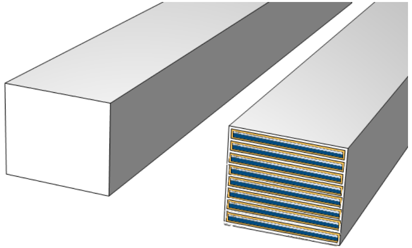


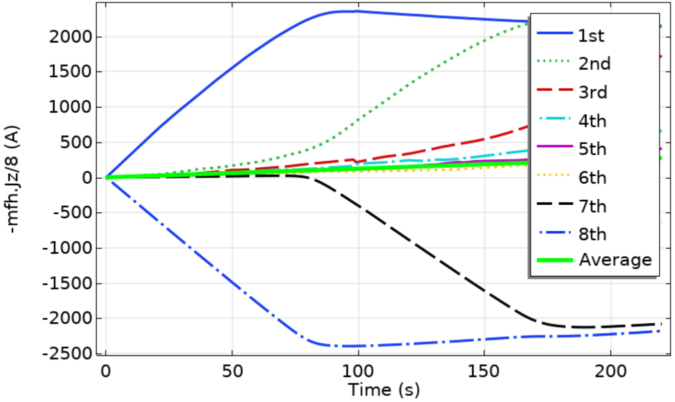


Common coil geometry taken from Hybrid magnet design of Douglas Martins Araujo

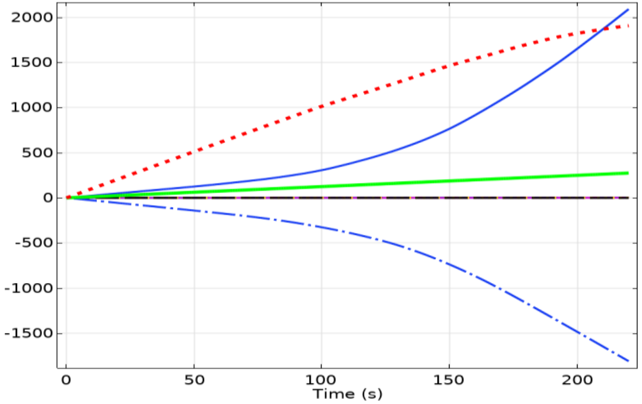
Current distribution – Detailed vs Homogenized

Finally, fully homogenized model has completely different current distribution as compared to the detailed model. Current firstly penetrates in the area which corresponds to solder in detailed model (red dotted line on right picture), and then uniformly goes inside stack from all sides.





Pure H-formulation with power law



Homogenized model

Homogenized model for soldered stack returns incorrect current sharing.

SC AC losses – Detailed vs Homogenized

By the way, we used this example for comparison of Detailed and Homogenized models AC losses. We can see large difference of that results. We are not sure of relevance homogenized model usage for electro-magnetic computations of soldered stack.

$$\rho_N = \left(\left(\frac{S_{Cu}}{\rho_{Cu}} + \frac{S_{Ag}}{\rho_{Ag}} + \frac{S_{Hs}}{\rho_{Hs}} + \frac{S_{So}}{\rho_{So}}\right)/S_N\right)^{-1}$$

where

S_{Cu}, S_{Ag}, S_{Hs} and S_{So} are the total cross-section area of copper, silver, Hastelloy and solder in soldered stack correspondently;

ρ_{Cu}, ρ_{Ag}, ρ_{Hs} and ρ_{So} are resistivities correspondently;

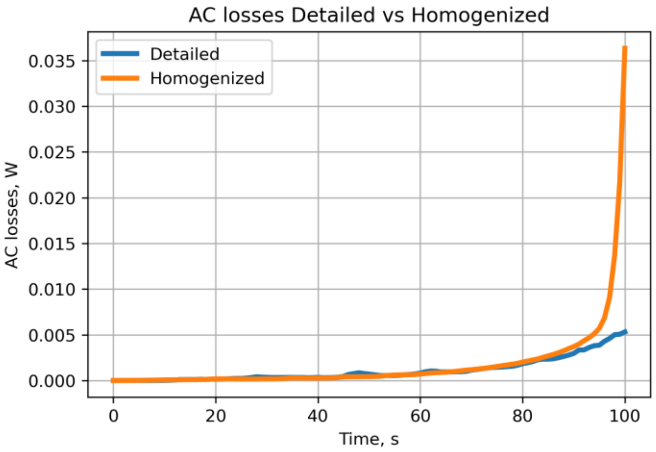
S_N is the total cross-section area of all metal conducting layers.

$$\rho_{Homogenized} = \left(\frac{1}{\rho_N} + \frac{8}{\rho_{ReBCO}}\right)^{-1}$$

where

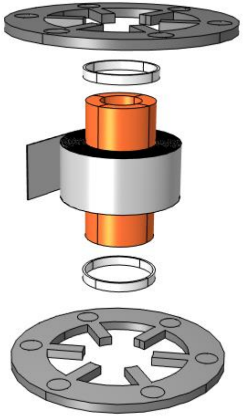
ρ_{ReBCO} is resistivity of HTS by power law;

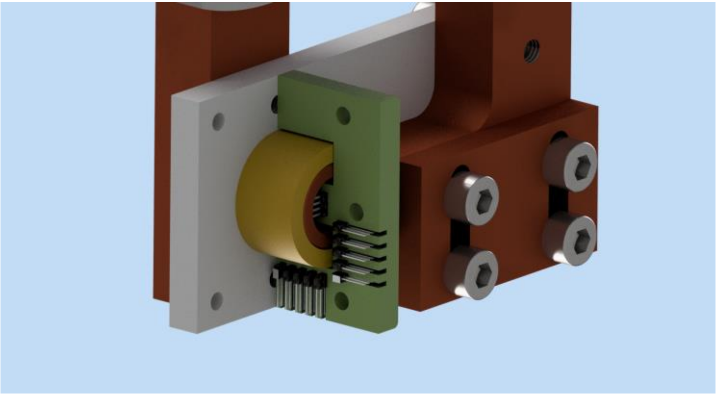
8 corresponds to number of ReBCO layers in the soldered stack.



SC pancake results

To validate magnetic field behavior for our H-A formulation results, we are preparing to build a 20-turn pancake coil wound from insulated solder-impregnated 2-tape-stack. Pancake generates around 0.5 T maximal magnetic field at 400 A. Minimal critical current is in the closest to axis stack (turn #1).

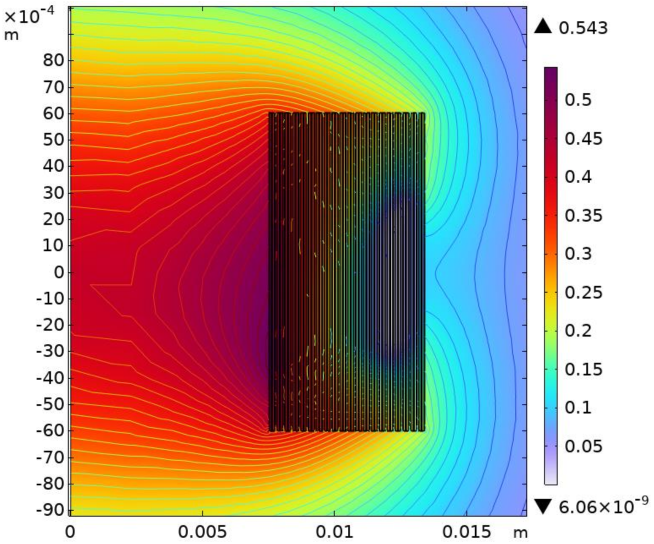


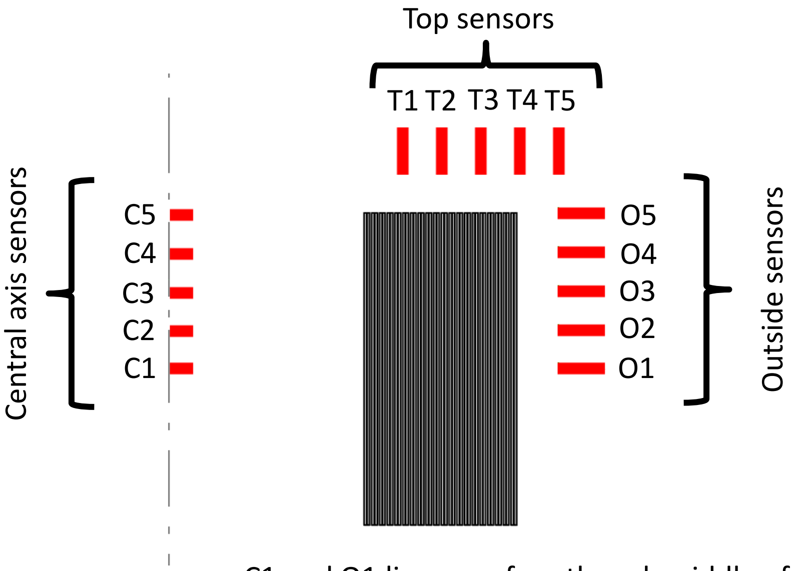


Design by H. Garcia

SC pancake results

Pancake with 20 turns of double 12-mm HTS tape stack generates around 0.5 T maximal magnetic field at 400 A. Minimal critical current is in the closest to axis stack (turn #1).




Top sensors

T1 T2 T3 T4 T5

Central axis sensors

C5
C4
C3
C2
C1

O5
O4
O3
O2
O1

Outside sensors

C1 and O1 lie on surface though middle of the coil

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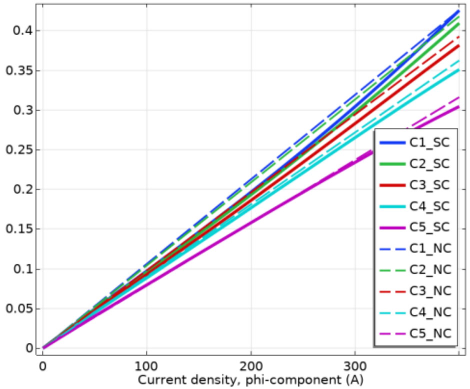
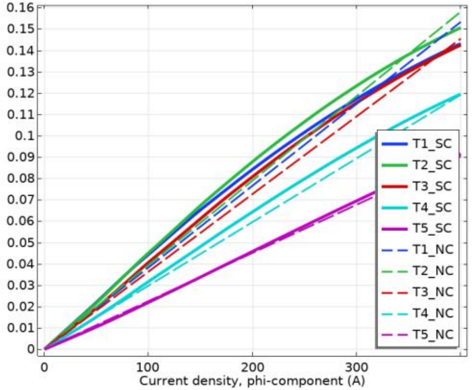
Validation of magnetic field computations

And finally, we can compare SC and geometric (NC) results. Central axis does not show difference. But Outside sensors returns clear difference between NC and SC.
This computation of magnetic field returns approval of non-linear distribution of current inside the turns, and could be an instrument of current distribution analysis.

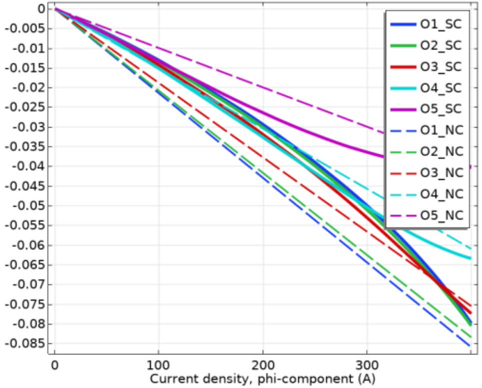
Central axis sensors



Top sensors



Outside sensors



Roadmap of HFM's HTS in PSI

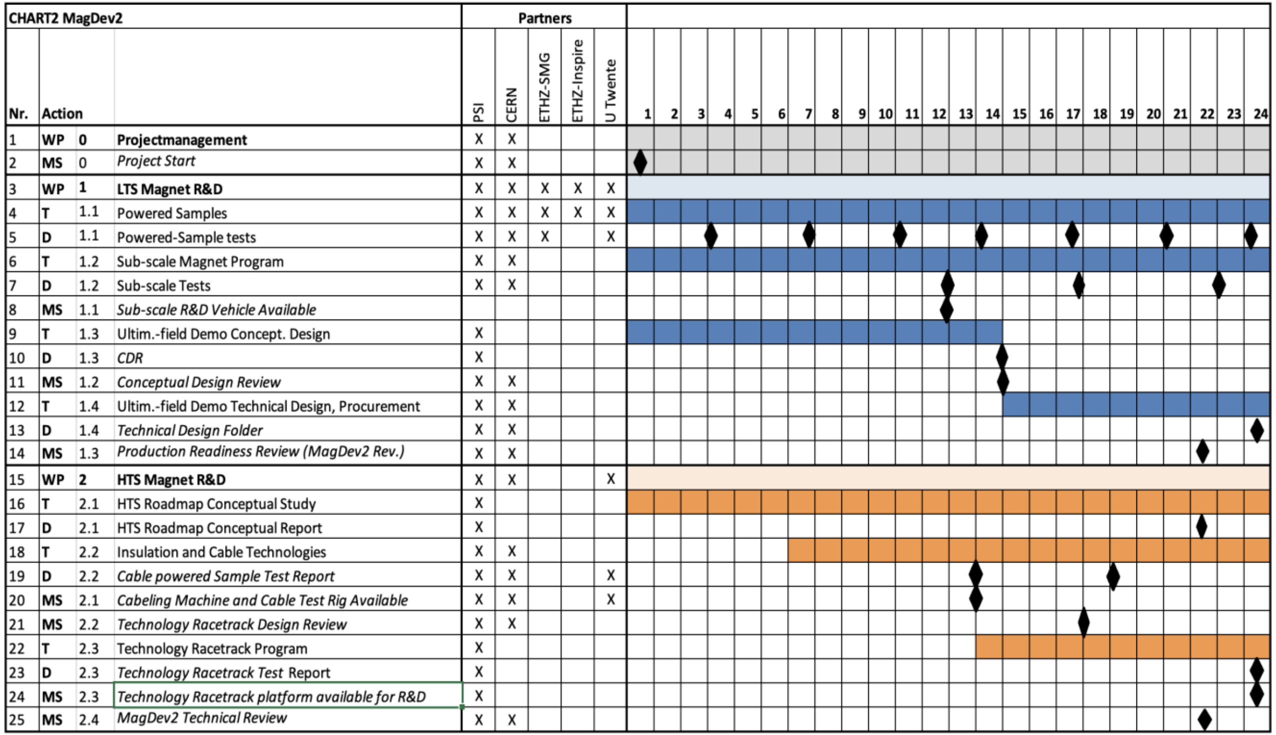


CHART2 MagDev2				**Partners**																												
Nr.	**Action**			PSI	CERN	ETHZ-SMG	ETHZ-Inspire	U Twente	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
1	**WP**	**0**	**Projectmanagement**	X	X																											
2	**MS**	0	*Project Start*	X	X				◆																							
3	**WP**	**1**	**LTS Magnet R&D**	X	X	X	X	X																								
4	**T**	1.1	Powered Samples	X	X	X	X	X	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
5	**D**	1.1	Powered-Sample tests	X	X	X		X				◆			◆				◆			◆			◆				◆			◆
6	**T**	1.2	Sub-scale Magnet Program	X	X				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
7	**D**	1.2	Sub-scale Tests	X	X															◆					◆						◆	
8	**MS**	1.1	*Sub-scale R&D Vehicle Available*																	◆												
9	**T**	1.3	Ultim.-field Demo Concept. Design	X					🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦										
10	**D**	1.3	*CDR*	X																		◆										
11	**MS**	1.2	*Conceptual Design Review*	X	X																	◆										
12	**T**	1.4	Ultim.-field Demo Technical Design, Procurement	X	X																		🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
13	**D**	1.4	*Technical Design Folder*	X	X																											◆
14	**MS**	1.3	*Production Readiness Review (MagDev2 Rev.)*	X	X																									◆		
15	**WP**	**2**	**HTS Magnet R&D**	X	X			X																								
16	**T**	2.1	HTS Roadmap Conceptual Study	X					🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
17	**D**	2.1	HTS Roadmap Conceptual Report	X																										◆		
18	**T**	2.2	Insulation and Cable Technologies	X	X										🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
19	**D**	2.2	*Cable powered Sample Test Report*	X	X			X													◆					◆						
20	**MS**	2.1	*Cabeling Machine and Cable Test Rig Available*	X	X			X													◆											
21	**MS**	2.2	*Technology Racetrack Design Review*	X	X																				◆							
22	**T**	2.3	Technology Racetrack Program	X																		🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
23	**D**	2.3	*Technology Racetrack Test Report*	X																												◆
24	**MS**	2.3	*Technology Racetrack platform available for R&D*	X																												◆
25	**MS**	2.4	*MagDev2 Technical Review*	X	X																									◆		

HTS stack cable in HFM

We have effective instrumentation for HTS magnet computation (even with thousands of HTS tapes).

First estimation of HTS magnet at 20 K shows results with AC losses competitive with existing LTS magnet designs.

Huge work for production and test of cables from HTS.