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CHART
Swiss Accelerator Research and Technology

D. Araujo, B. Auchmann, A. Brem, T. Michlmayr, C. Müller, H. Rodrigues, D. Sotnikov and A. Milanese

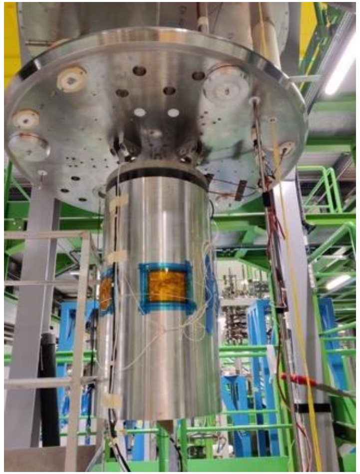
Progress Report on the PSI CHART LTS and Hybrid HFM Roadmap

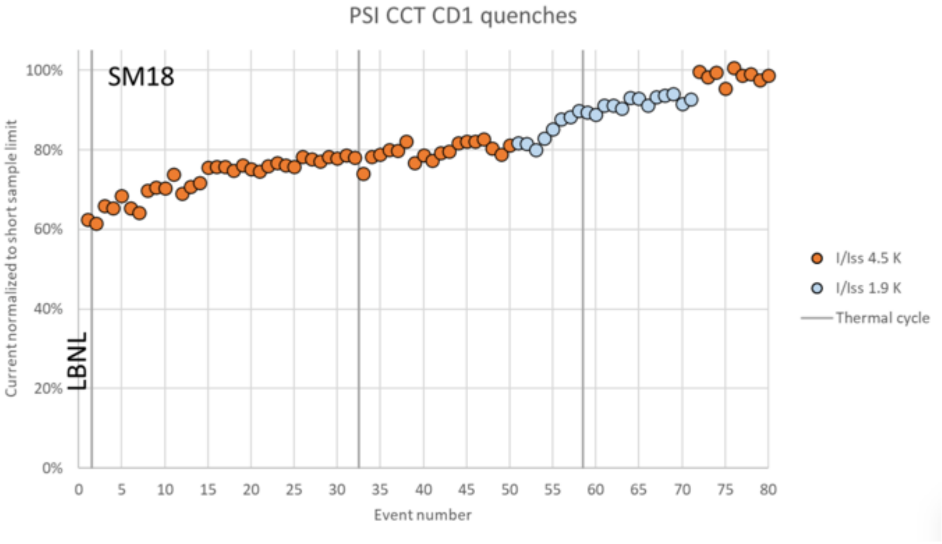
HFM annual meeting, 2023

Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI.
This work was performed under the auspices and with support from the Swiss Accelerator Research and Technology (CHART) program

CD1 Testing Results and CCT Conclusions

- Canted-Cosine-Theta Magnet CD1 and Overview of the testing campaign of January 2023





Courtesy F. Mangiarotti (CERN) and M. Daly (PSI).

Training behavior:

the magnet trained a lot. How can we make it training less?

Nb_3Sn limit:

The magnet reached 100% of the maximum field at 4.5 K

Degradation:

After 80 quenches and thermal cycles the magnet shows no degradation

Stress-management works!

G. Montenero et al., *Coil Manufacturing Process of the First 1-m-Long Canted-Cosine-Theta (CCT) Model Magnet at PSI*, IEEE Trans. on App. SC., Vol 29(5), 2019.
G. Montenero et al., *Mechanical Structure for the PSI Canted-Cosine-Theta (CCT) Magnet Program*, IEEE Trans. on Appl. SC., Vol 28(3), 2018.

LTS and Hybrid LTS/HTS HFM Roadmap

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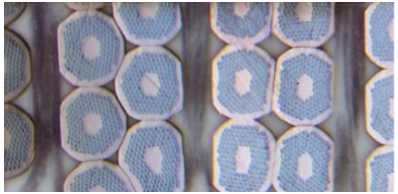
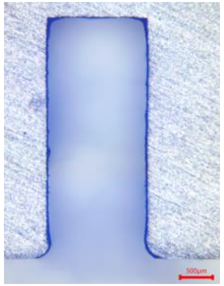
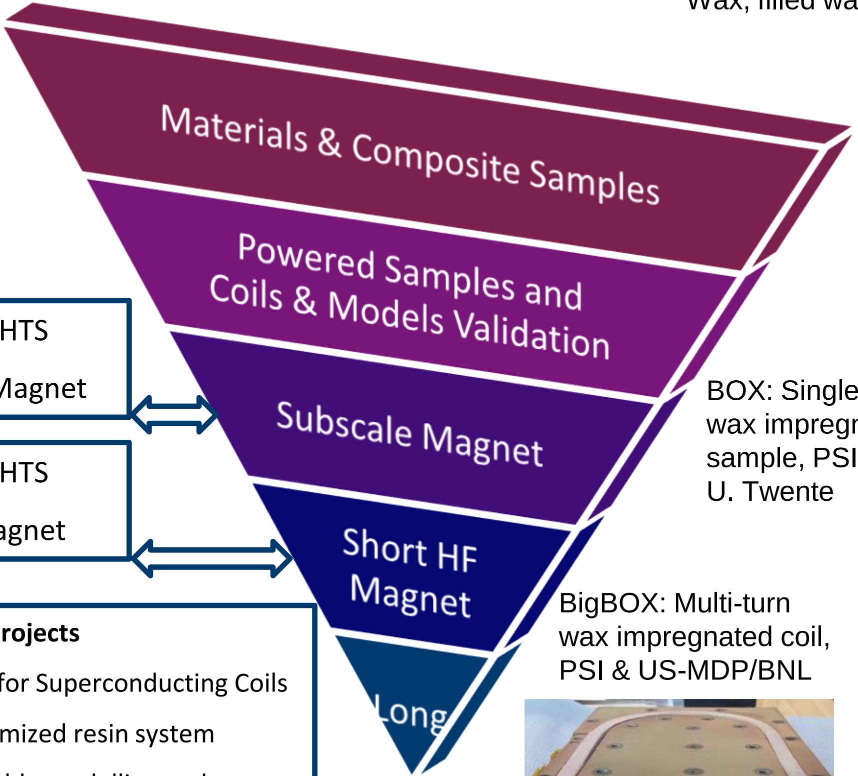
Wax, filled wax / epoxy process development, insulating ceramic coating, etc A. Brem







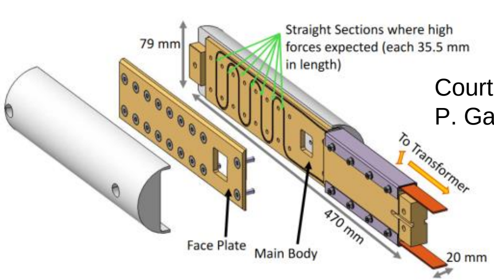
Hybrid HTS

Subscale Magnet

Hybrid HTS

Short Magnet

BOX: Single-turn wax impregnated sample, PSI & U. Twente



Courtesy P. Gao

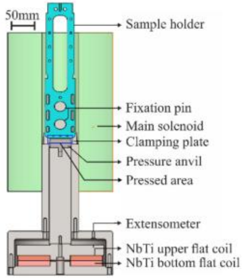


CHART Mag Projects

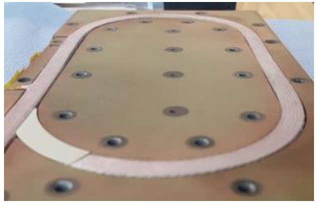
MagAM: AM for Superconducting Coils

MagRes: Optimized resin system

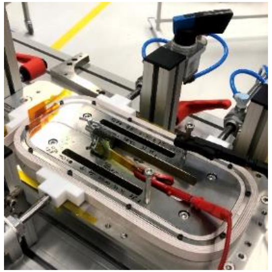
MagComp: Cable modelling and caracterization

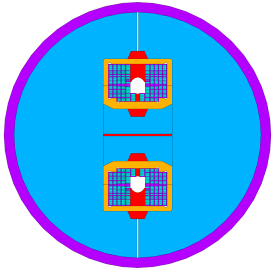
MagNum: Modelling & Optimization

BigBOX: Multi-turn wax impregnated coil, PSI & US-MDP/BNL



Subscale Stress-Managed Common-coils





High-Field Stress-managed common coils

HFM annual meeting

- Tuesday, 31 October: Transient effects in tape-stack cable and the PSI roadmap towards HTS HFMs – PSI, D. Sotnikov
- Wednesday, 1 November: Progress in materials and processes at PSI, A. Brem
- Wednesday, 1 November: WP4.4 - Determination of deformation via image-based measurements and design of epoxy systems for Nb_3Sn Rutherford cables - ETHZ/CHART, P. Studer and X. Kong
- Thursday, 2 November: HFM infrastructure needs at PSI, B. Auchmann
- This presentation focus on the subscale and 14+ T Stress-Managed Common-Coils

BOX, Compression BOX and BigBOX

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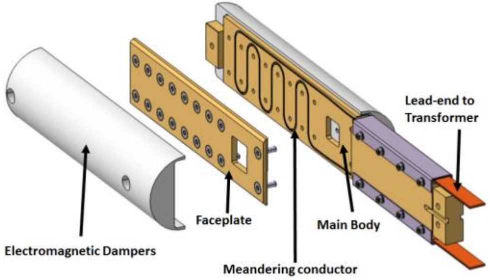
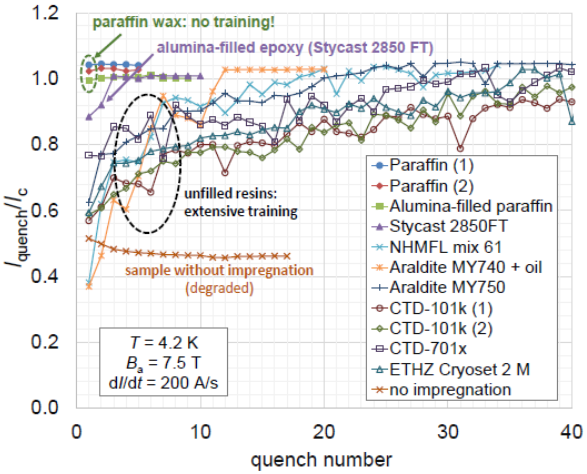
PAUL SCHERRER INSTITUT PSI

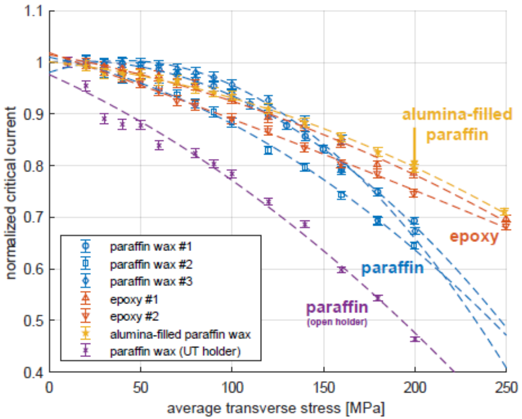
UNIVERSITY OF TWENTE.



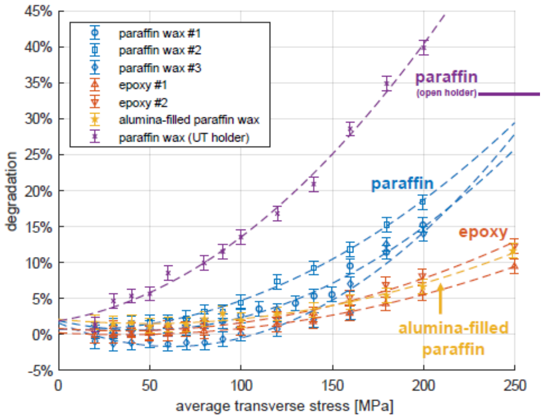


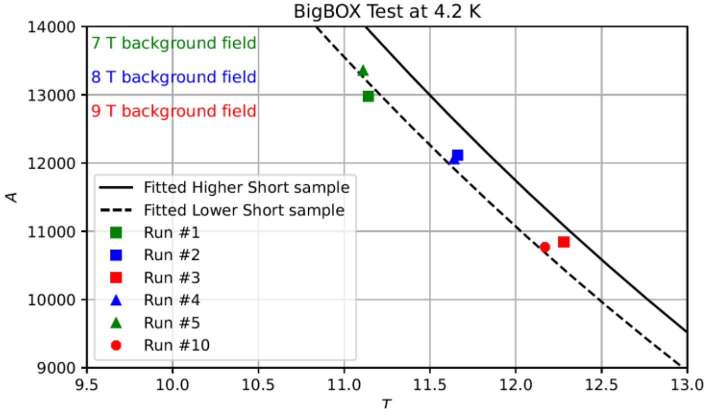
“Influence of fillers and debonding layers on training of short Nb_3Sn Rutherford cables studied in the BOX facility” & “Transverse pressure performance of paraffin-impregnated Nb3Sn Rutherford cables compared to epoxy-impregnated cables”, S. Olten et al, MT-28

Normalized critical currents (11 T, 4.2 K)



Degradation:
Irreversible reduction in current after unloading to 10 MPa





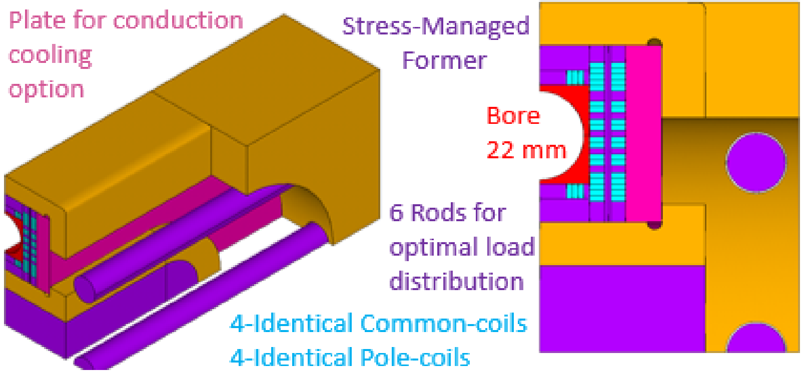
U.S. MAGNET DEVELOPMENT PROGRAM

BNL

“Assessment of Training Performance, Degradation and Robustness of Paraffin-Wax Impregnated Nb3Sn Demonstrator under High Magnetic Field”, D. Araujo et al, MT-28

Subscale Platform for LTS and Hybrid Magnets 1/2

- Validating manufacturing process and introducing advanced concepts: coil pre-load free, at room temperature; stress-management structure and splicing on the low-field region.
- Fast turn-around platform for testing matrix systems; protection concepts and cooling options.
- Hybrid magnet with LTS Common-Coils and HTS racetracks
- LTS conductor manufactured by LBNL (cct subscale cable)



Magnet parameters for testing all coils or the common-coils. The coils straight section is 150 mm. The values refer to the fitted wire Ic curve at 4.2 K values.

Parameter	All coils	CCs
B_0 in T	5.15	5.1
B_{peak} in T	6.45	6.3
I_{op} in kA	8.25	9.2
E_{mag} in kJ	15.2	16.4

Subscale Platform for LTS and Hybrid Magnets 2/2

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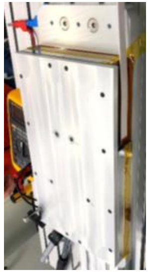
- Progress on R&D and engineering design (testing in Q2/2024)

Winding method validation

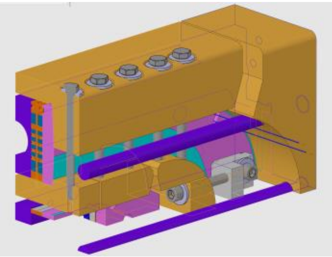
Instrumented mock-up for assembling validation

Pre-scaled paper after disassembling the Mock-up

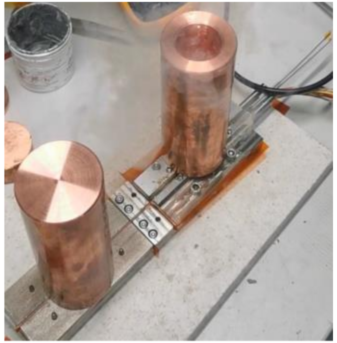
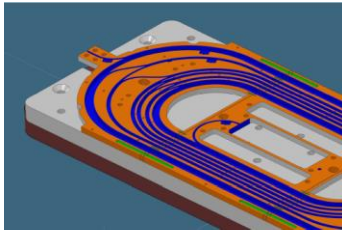
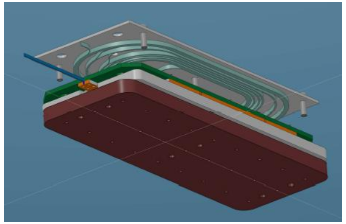
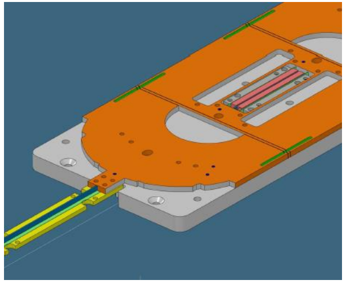

Mock-up for axial pre-load

Low-temperature splicing process trials

Completed engineering design



T. Michlmayr

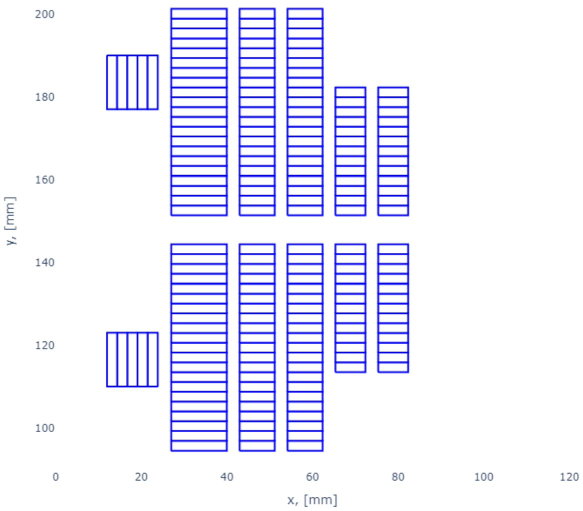
D. Araujo, A. Brem, R. Felder, T. Michlmayr, C. Müller and H. Rodrigues

Stress-Managed Asymmetric Common-Coils 1/2

In respect to a standard common-coils magnet, we would like to explore solutions on how to:

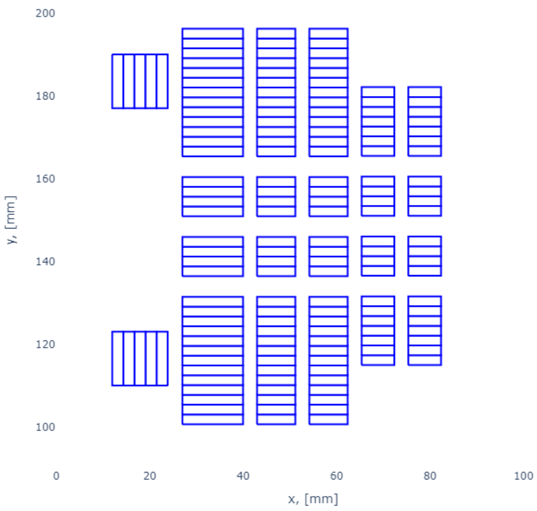
- deal with high Lorentz forces
- simplify the common-coils architecture for accelerator magnets
- allowing a full common coils architecture and eventually reacting & winding

a: racetracks / clover-leaf coils and wide blocks



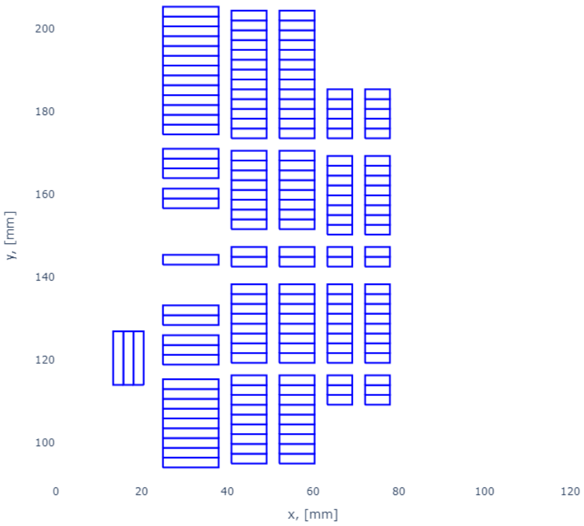
Stress-management with spars

b: racetracks / clover-leaf coils and thin blocks



Stress-management with spars and ribs

c: only common-coils and thin blocks



Asymmetric design

Stress-Managed Asymmetric Common-Coils 2/2

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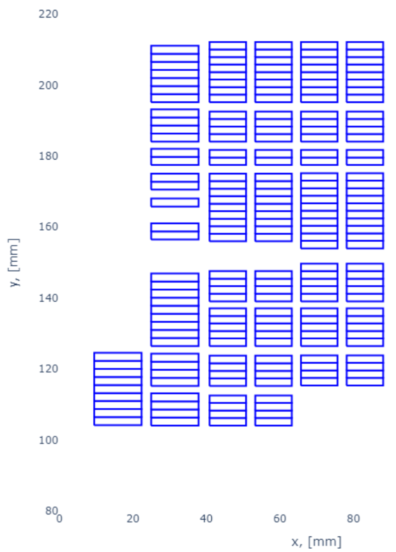
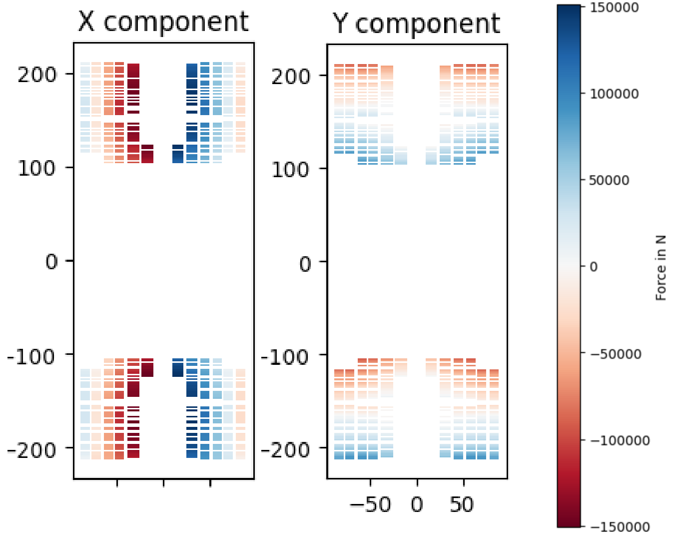
We can further simply option C, by having only easy-way bend coils

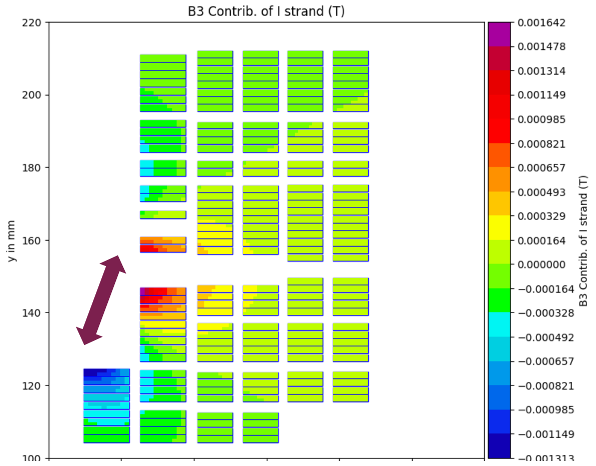
Ribs and spar thickness were optimized for mechanics

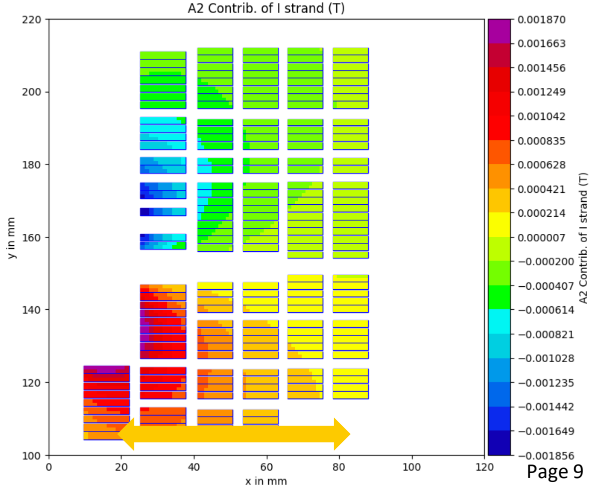
Compensation example on b3 and a2

Layers: 1 2 3 4 5 6



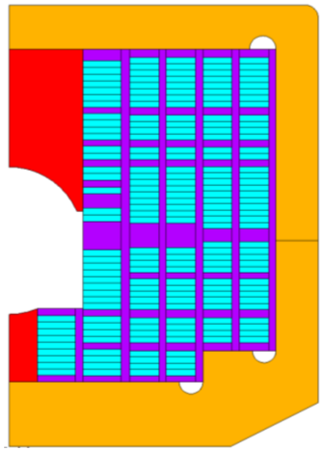






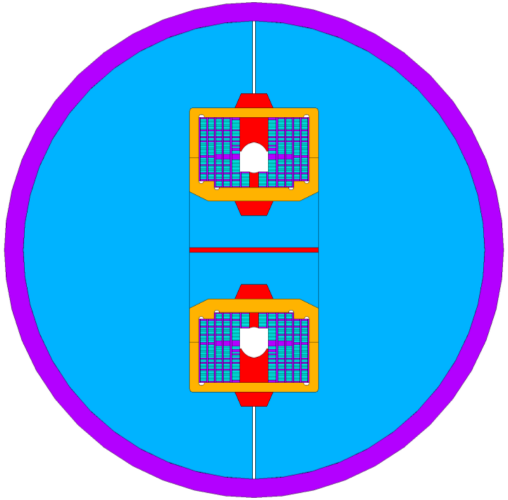
D. Araujo

SMACC: Cross-Section



The asymmetric common-coils magnet was designed with a intra-beam distance of 300 mm, 50 mm **bore**, **yoke** diameter of 740 mm and 30 mm thick stainless steel **shell.**

The magnet has 4 different types of coils (layer 1, layer 2, layer 3,4 and layer 5,6) and 12 coils in total (for a double aperture magnet). The coils are placed in the stress-management **formers**. The preload is transferred towards the inner-most layers through the **ribs**.



The massive **iron pole,** combined with the asymmetric concept, helps on the balance vertical force balance.

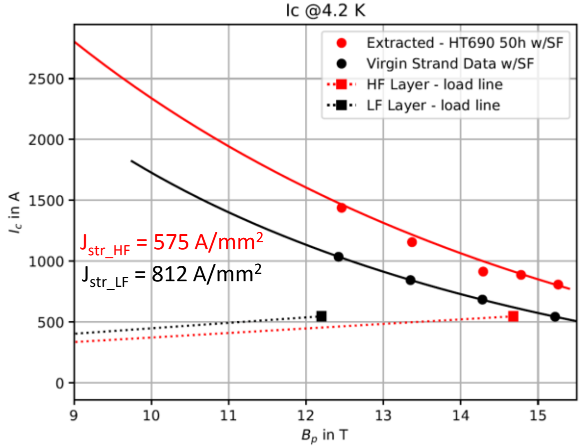
The load, due to Lorentz forces, is distributed between **pads** and **shell,** which limits the thickness of the **shell**.

The magnet concept is based on bladder & keys technology for room temperature preload. The structure is loaded, but thanks to the stress-management formers, the coil stress after loading and after cooling is < 40 MPa.

SMACC: Magnet Parameters

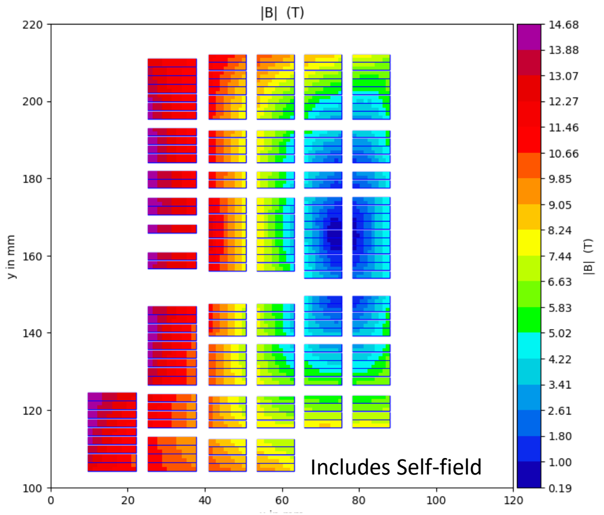
Layers 1 and 2 with 21 x 1.1 mm RRP® 162/169 strand cu/n_Cu 0.9 and layers 3 to 6 with 18 x 1.0 mm RRP® 132/169 strand cu/n_Cu 1.3.

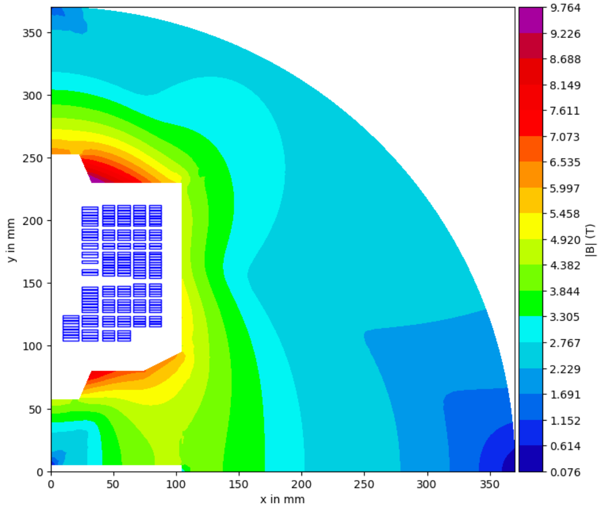
Field quality is < 15 units spread between injection and 14 T nominal field operation and < 15 units at nominal (to be further optimized after decision on LF cable).



High-Field and **Low-Field** strand experimental data, fitting and load lines

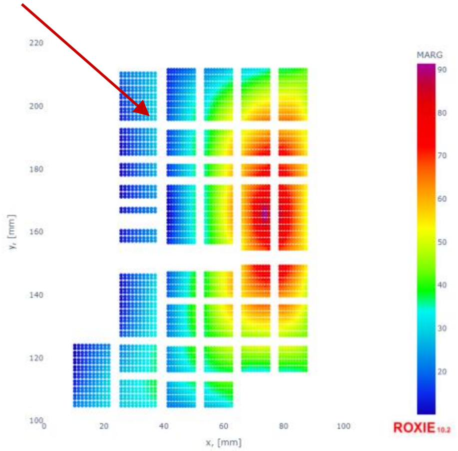
parameter		value	
Op. temperature	T_{op}	4.2	K
Op. current	I_{op}	11.48	kA
Central field	B_0	13.98	T
Peak field w/sf	B_p	14.68	T
Eng. margin		10	%
Inductance	L	41	mH/m
Magnetic energy	E_{mag}	2.7	MJ/m



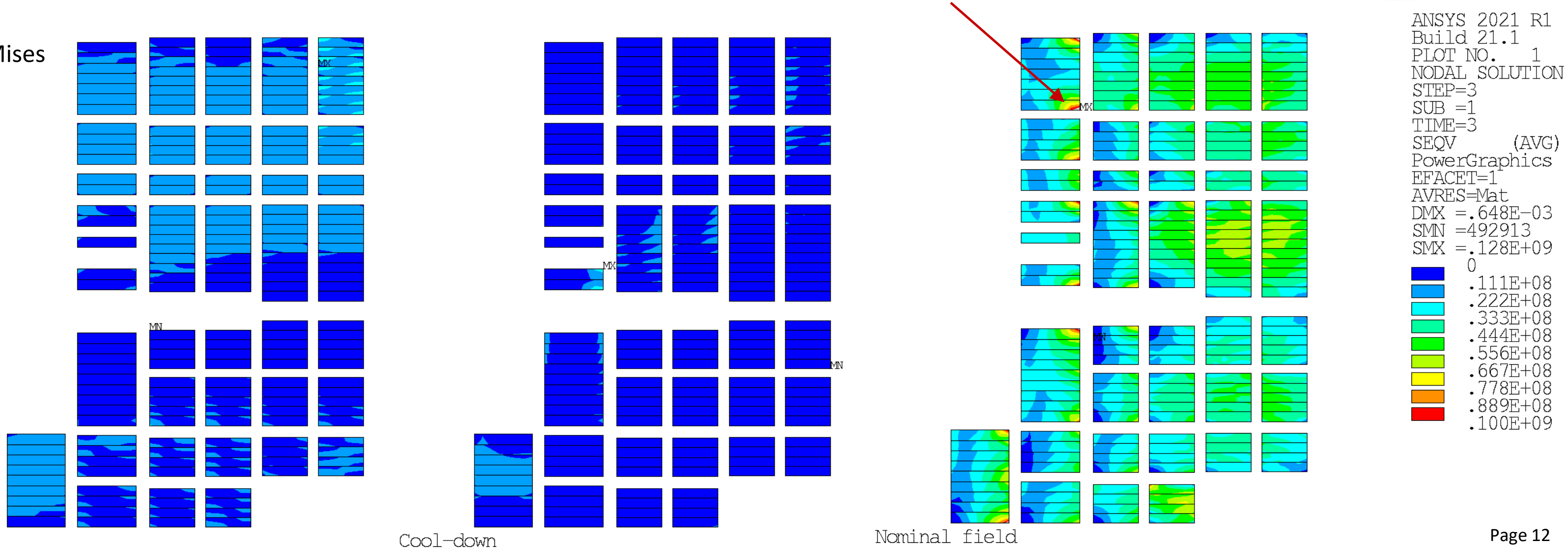


SMACC: Mechanical Analysis

- Pre-load with 0.5 mm interference on the keys.
- Low-stress on coils after loading and
- Cooling-down: 37 MPa
- Peak of stress on the low-field side of layers
- All magnet components respect material limits



Von-Mises



SMACC: Protection 1/2

- Re-use of tooling for several coils
- Optimized Electrical order for CLIQ protection
- Same side Magnet & CLIQ leads
- Study for 15 m long magnet

LF Cable Outer Coils: layers 5, 6, 11, 12

LF Cable Intermediate Coils: layers 3, 4, 9, 10

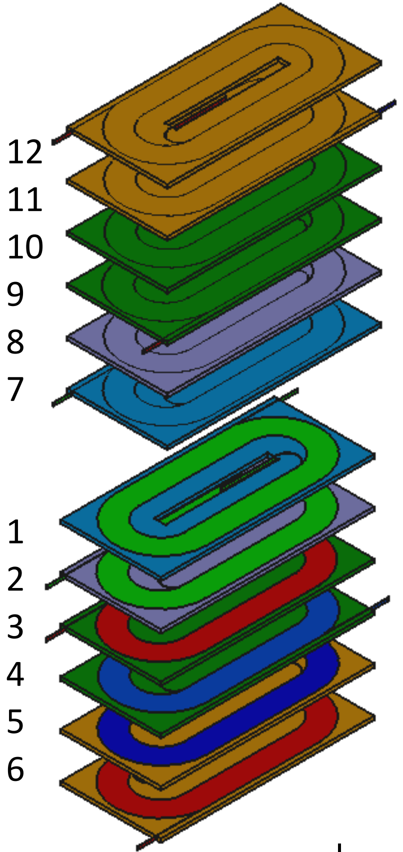
HF Cable Inner Coils: layers 1, 7

HF Cable Inner Coils: layers 2, 8

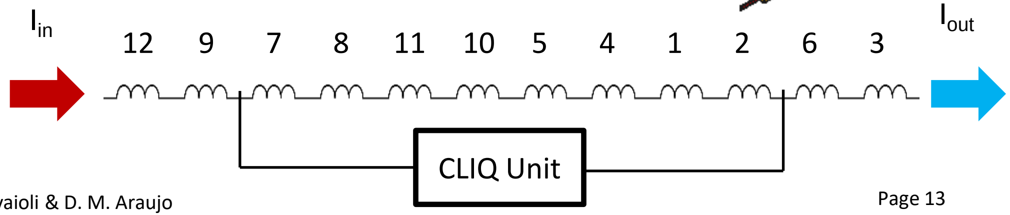
Intra-layer splice: layers 1-2 and 7-8

Intra-layer splice: layers 3-6 and 9-12

Intra-layer splice: layers 4-5 and 10-11



CLIQ optimization study
- 25 CLIQ configurations studied
- 5 CLIQ unit types studied
- Optimized coil electrical order



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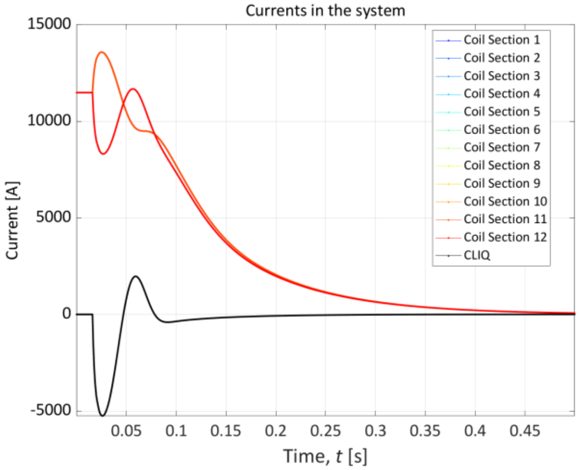
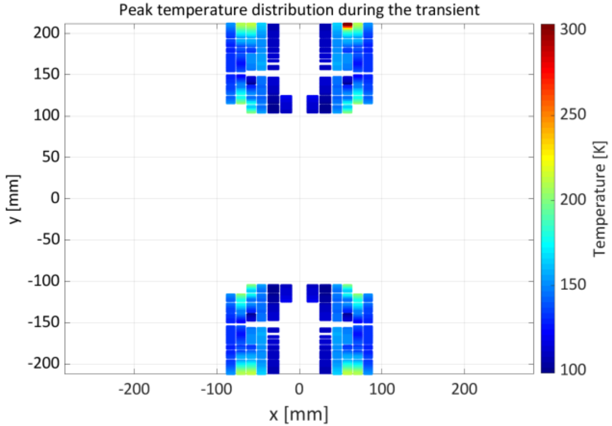
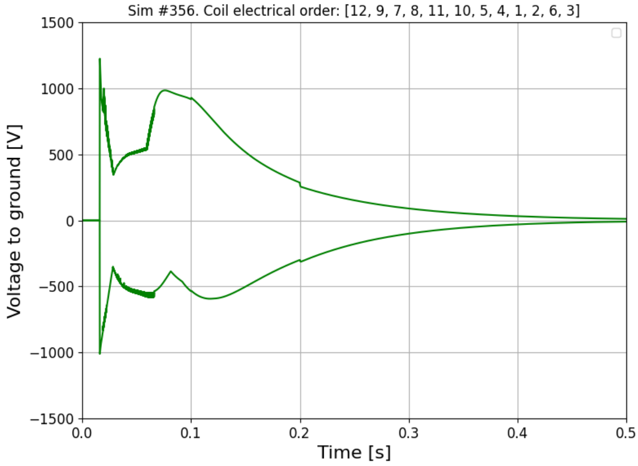
SMACC: Protection 2/2

One 50 mF, 2 kV CLIQ unit can effectively protect a 15 m long SMACC magnet.
Further optimization of the quench protection system in progress.
All simulations performed with the STEAM-LEDET program.







Peak CLIQ current
~5 kA

Hot-spot temperature
~300 K

Peak voltage to ground
~1250 V

Summary

Progress on the roadmap:

… BOX impregnated with filled-wax -> no training

… Compression BOX impregnated with filled-wax -> degradation behaviour similar to epoxy

… BigBOX, wax impregnated multi-turn coil under background field -> no training

… Subscale Stress-Managed Common-Coils (LTS) -> engineering design finalized, procuring the parts

Introduction of

… Stress-Managed Common-Coils Concept

… Asymmetric Common-Coils Concept

Interesting SMACC features

… Simple geometry (no pole coils) for fully automated coil winding and reduced number of manufacturing steps

... Splices on the low-field region -> facilitating grading

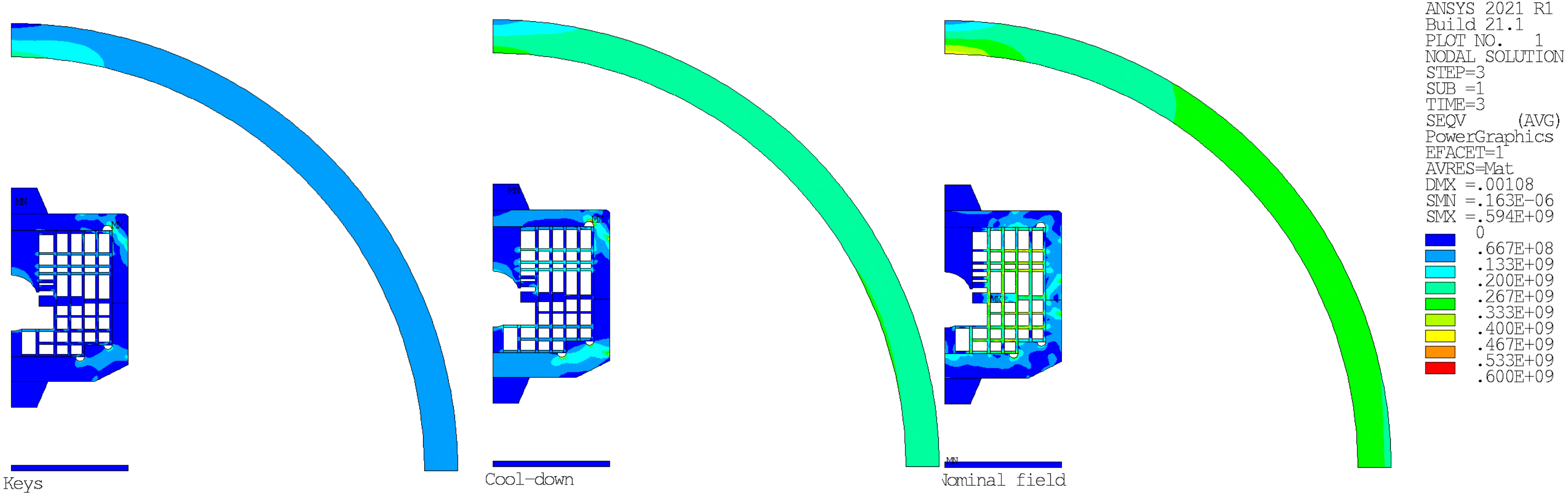
… Possibly easily implementation of Reaction & Winding technique

… Possibly lower-margin operation due to the low stress on high-field regions

SMACC: Mechanical Analysis

Stainless-steel 316-L components

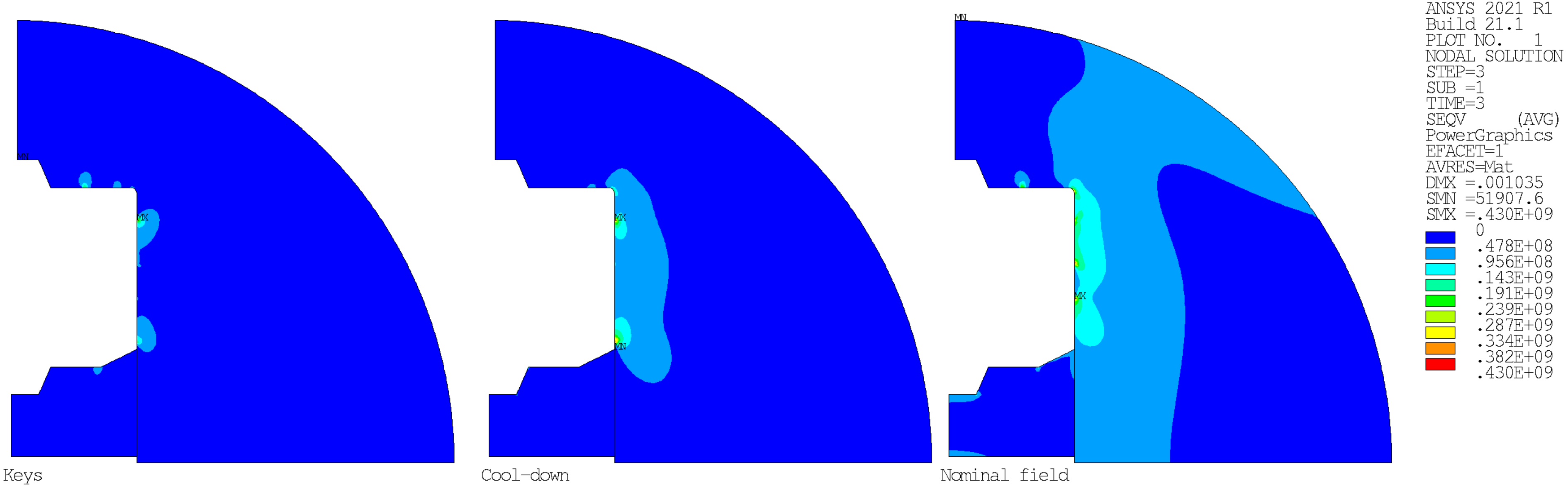
Von-Mises



SMACC: Mechanical Analysis

Magnetic yoke and pole

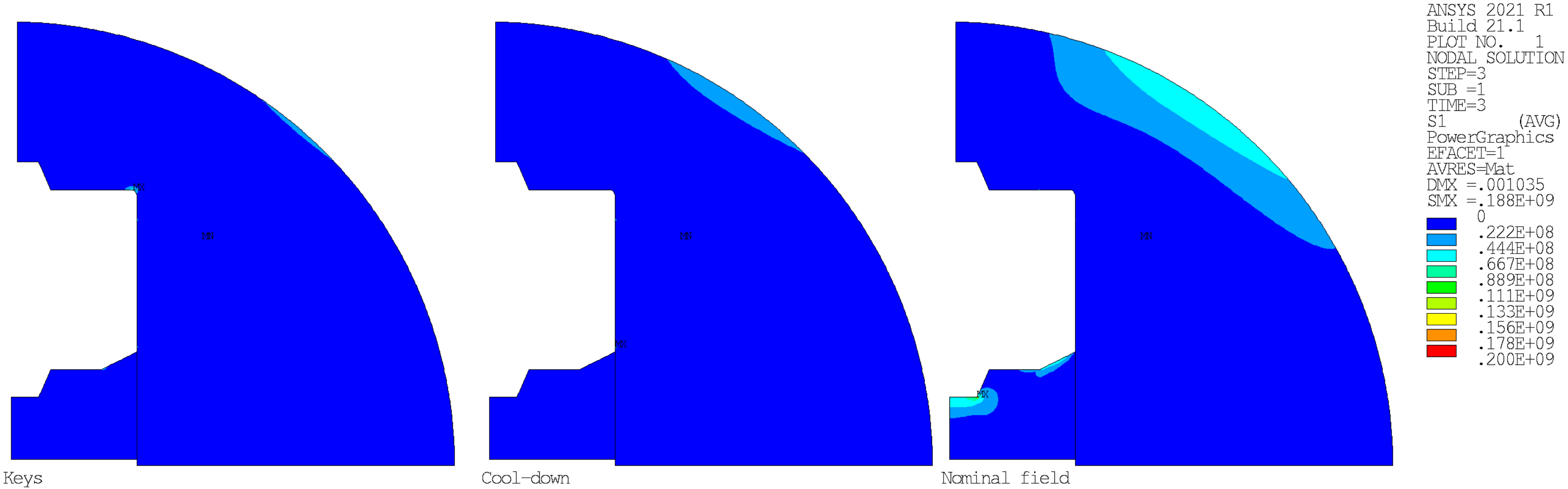
Von-Mises



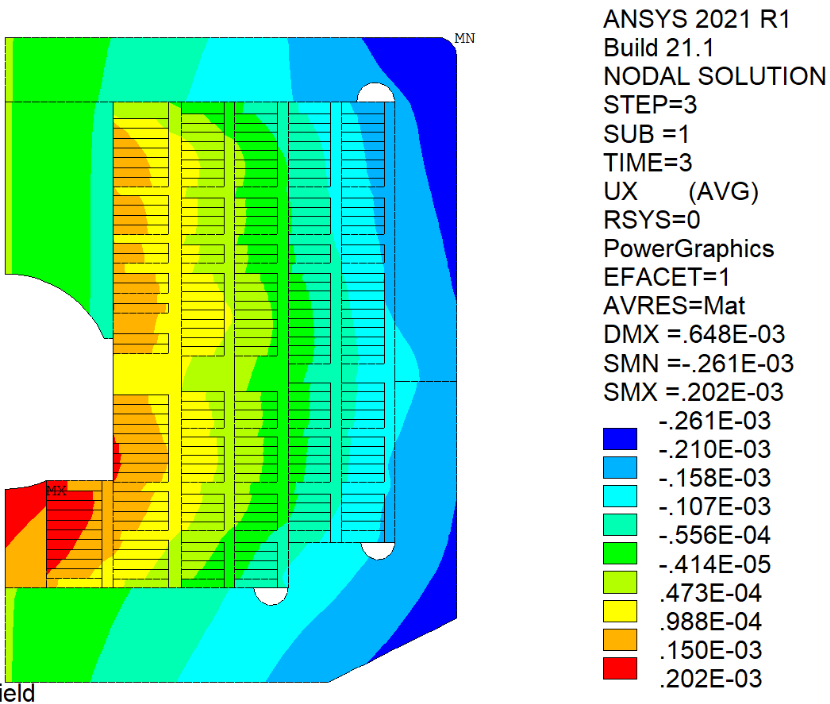
SMACC: Mechanical Analysis

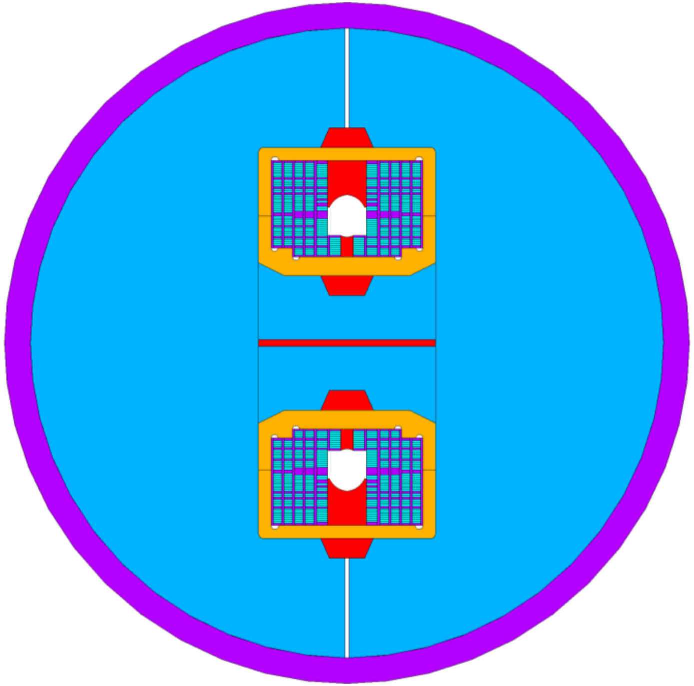
Magnetic yoke and pole

S1



Displacement at nominal field operation





Nominal field

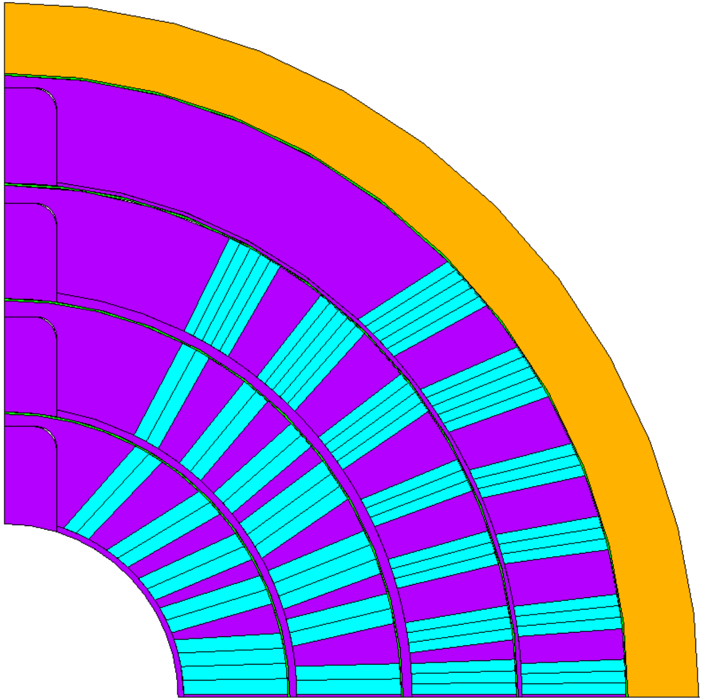
0.2 mm

SM-CT vs SM-CC 1/2: Cable Properties

- **High-field cable** (common coil first layer and pole coils)
  - 28 strands
  - 1 mm strand RRP-150/169
  - Cooper% = 48%
  - Width 14.7 mm and Thickness of 1.8 mm
  - Insulation thickness 155 µm
- **Low-field cable** (common coil second layer)
  - 40 strands
  - 0.7 mm strand RRP-108/127
  - Cooper% = 53%
  - Width 14.7 mm and Thickness of 1.27 mm
  - Insulation thickness 155 µm
- **Low-field cable** (common coil third and fourth layer)
  - 30 strands
  - 0.7 mm strand RRP-108/127
  - Cooper% = 53%
  - Width 11.02 mm and Thickness of 1.27 mm
  - Insulation thickness 155 µm

SM-CT vs SM-CC 1/2: Geometry Comparison

- Stress-Managed Cosine-Theta



- Stress-Managed Common coils

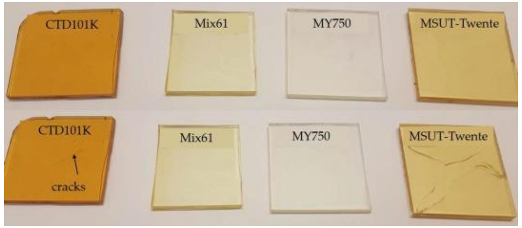
Solution	N turns HF	N turns LF	Total Strand Area
SM-CT	28	48	1355 mm^2 **(+ 13.1%)**
SM-CC	19.5	53.5	1198 mm^2

Collaborative Integration with CHART Projects

https://chart.ch/chart-projects/

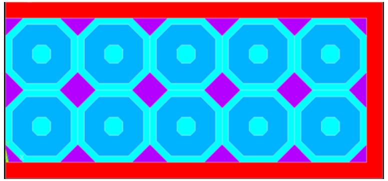
ETH zürich

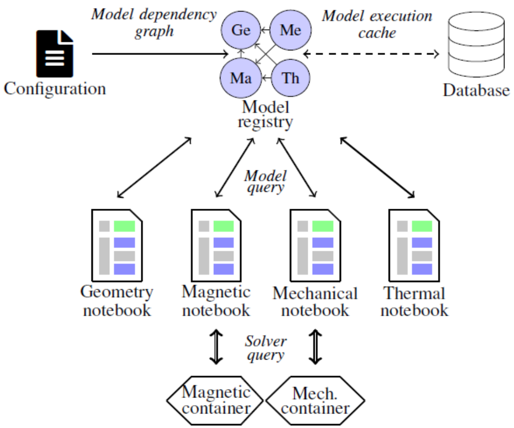
- MagRes
- WireChar
- MagComp
- MagAM
- MagNum



A. Brem

J. Ferchow

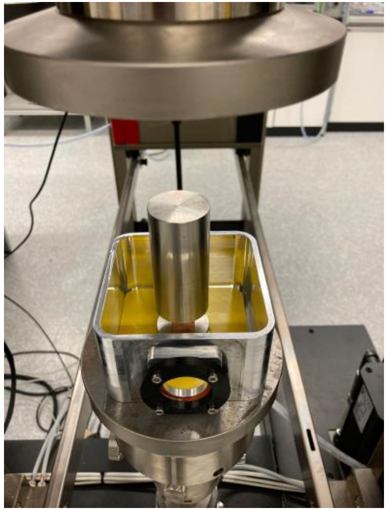




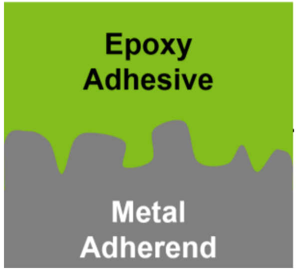
M. Maciejewski

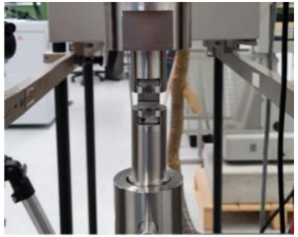
C. Senatore

UNIVERSITÉ DE GENÈVE



X. Kong





P. Müller