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PSI

CHART

Swiss Accelerator Research and Technology

11.10.23 – CHART Workshop 2023

MagDev1/2

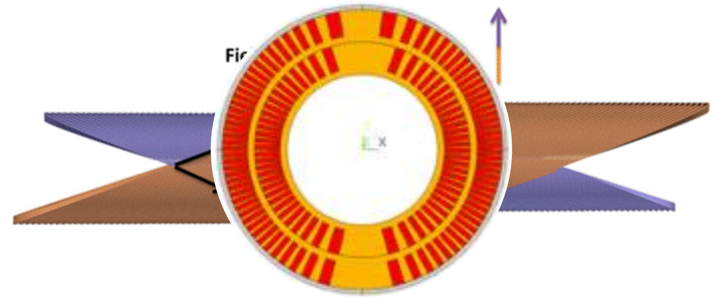
B. Auchmann (PSI/CERN) for the MagDev team: D. M. Araujo, A. Brem, M. Daly, J. Kosse, T. Michlmayr, C. Müller, H. G. Rodrigues (all PSI), A. Milanese (CERN) with support from PSI Magnet Section and M. Duda (CHART FCCee Injector Study)

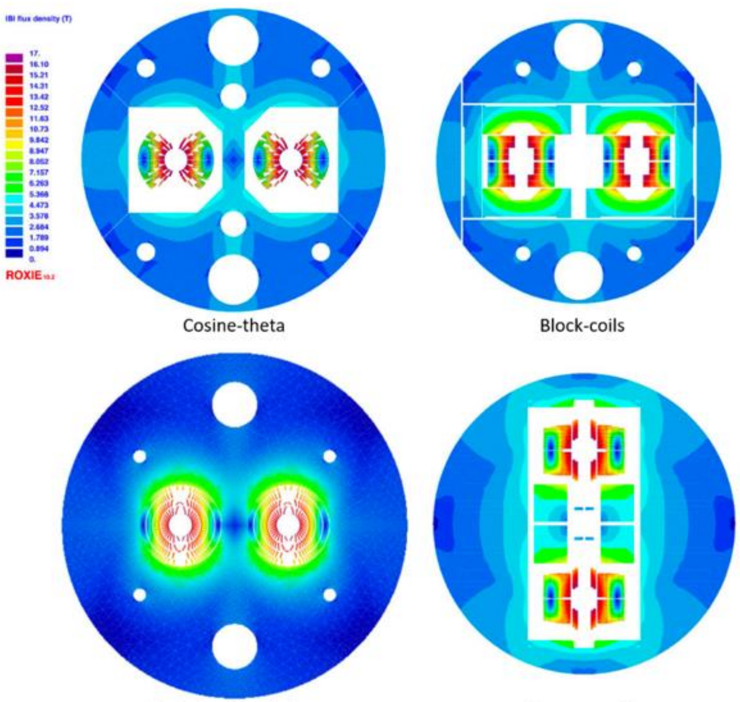
This work was performed under the auspices of and with support from the Swiss Accelerator Research and Technology (CHART) program (www.chart.ch).

EuroCirCol (2015-2019)

Swiss Accelerator Research and Technology

- CHART joined the Nb_3Sn HFM R&D during the Horizon2020 EuroCirCol effort.
- PSI studied the Canted Cosine Theta option.



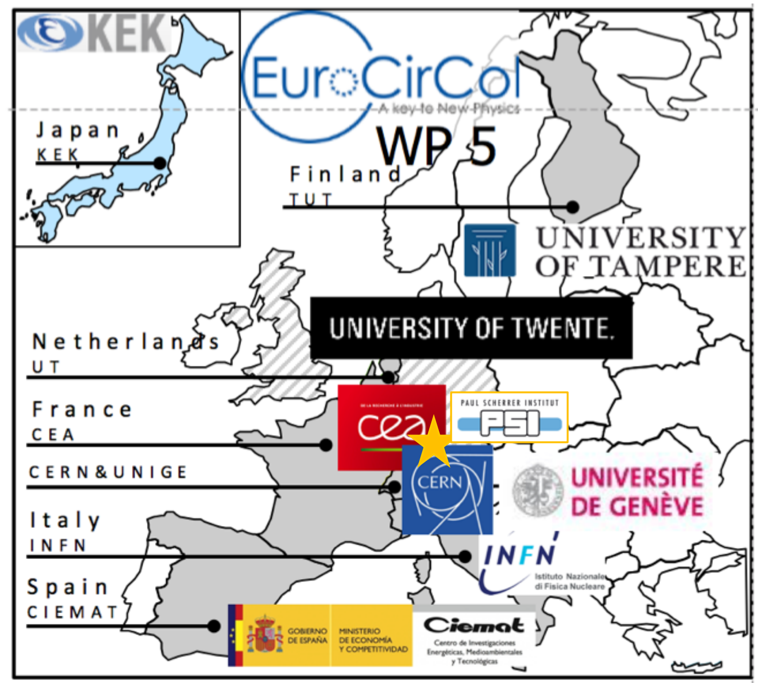


Cosine-theta

Block-coils

Canted cosine-theta

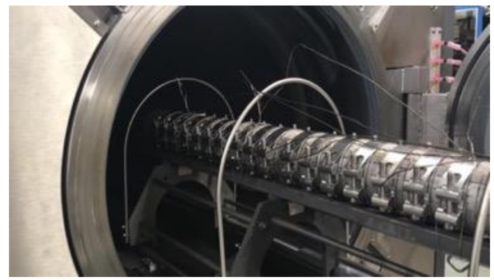
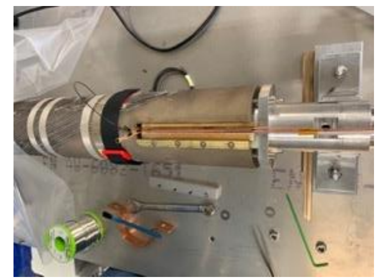
Common-coils

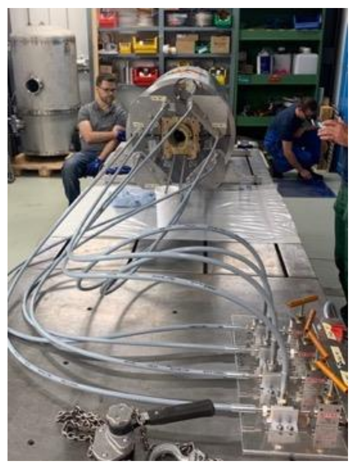


[M. Benedikt et al., *FCC Conceptual Design Report*, Vol. 3 – The Hadron Collider (FCC-hh), January 2019.]

Canted Dipole 1 built at PSI

- Magnet design, lab refurbishment, equipment, and commissioning, as well as magnet construction from 02.2017 to 10.2019.

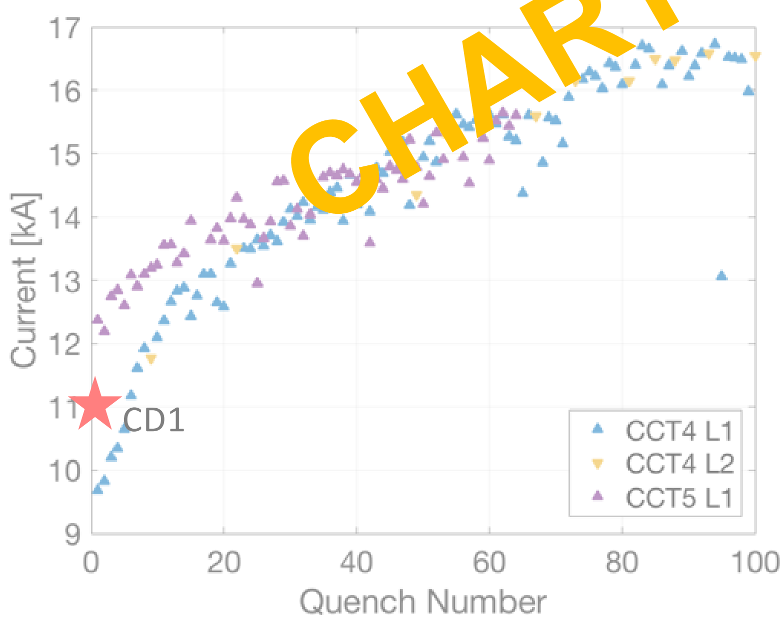




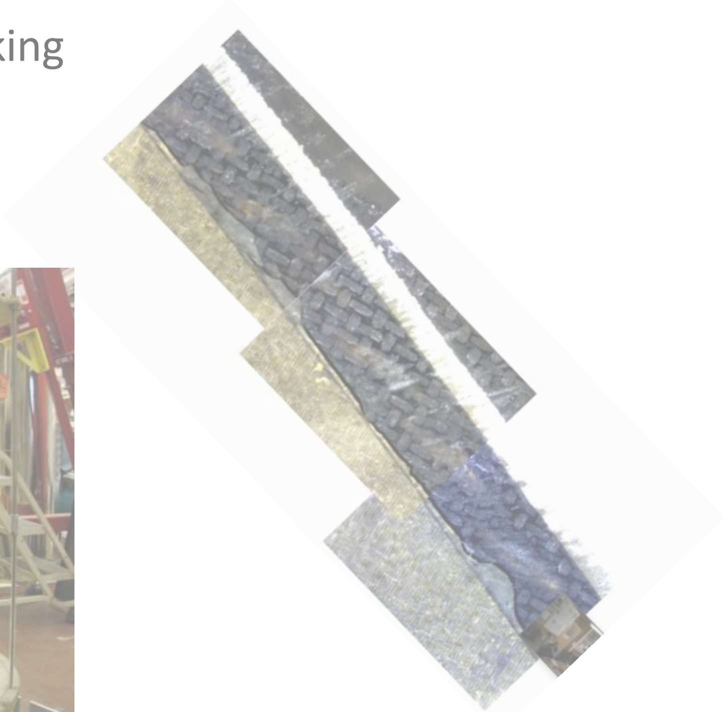




[G. Montenero et al., *Coil Manufacturing Process of the First 1-m-Long Canted-Cosine-Theta (CCT) Model Magnet at PSI*, IEEE Trans. on App. SC., Vol 29(5), 2019.
G. Montenero et al., *Mechanical Structure for the PSI Canted-Cosine-Theta (CCT) Magnet Program*, IEEE Trans. on Appl. SC., Vol 28(3), 2018.]

CD1 Testing Odyssey

- Magnet was shipped to LBNL in Nov. 2019.
- The test preparation was interrupted by COVID 19 and resumed in Aug. 2020.
- Magnet test started in Sept. 2020 but interrupted by cryo problem.
- Max. current after 2 quenches: 11.1 kA or 62.5% of short sample, 6 T in the bore.
- **CHART has built a *magnet*** (no more and no less can be said at this stage).
- **Test to be continued at CERN in Q1 Q2’22**
- LBNL experience points to a debonding and cracking problem in the impregnated channels, causing excessive training.

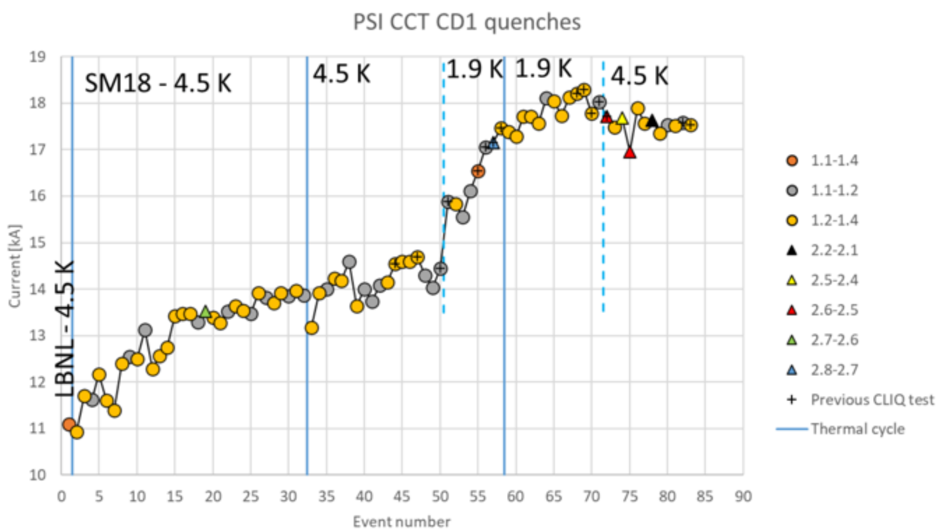


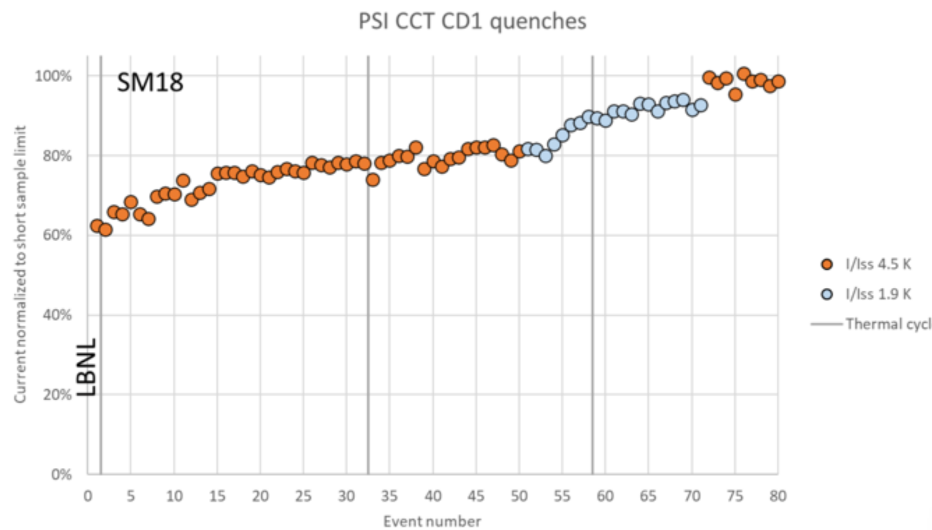


Courtesy D. Arbelaez, LBNL.

CD1 Robustness and Performance

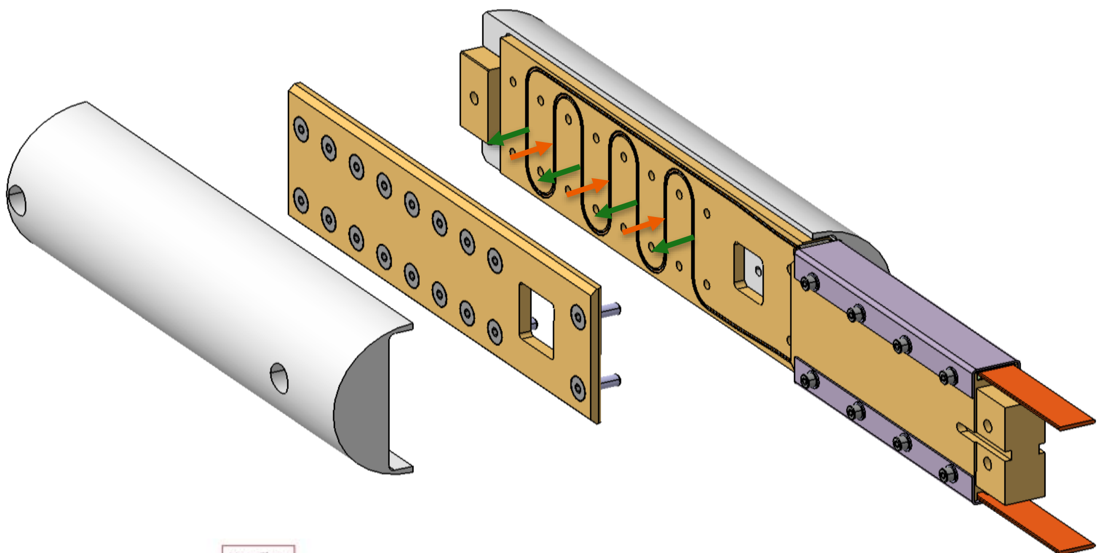
- CD1 main test was carried out in 2022/23.
- **It trained *A LOT*.**
- It reached **10.1 T in the bore** at 94% of Iss at 1.9 K; 9.9 T and 100% of Iss at 4.5 K.
- **But, it reached 100% of maximum field at 4.5 K.**
- These were the very first Nb_3Sn training coils at PSI:
  - No conductor degradation occurred from handling, assembly, powering, or thermal cycling.
- **Stress-management works, CD1 is a robust magnet.**

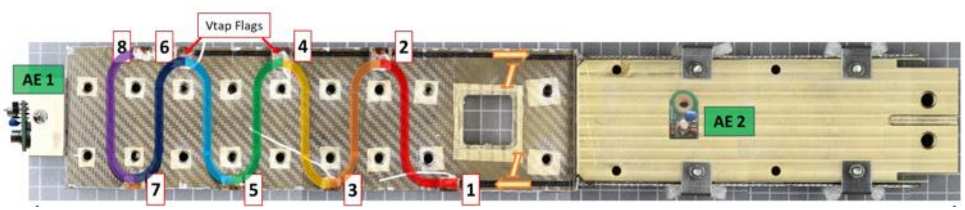




Courtesy F. Mangiarotti (CERN) and M. Daly (PSI).

BOX Program





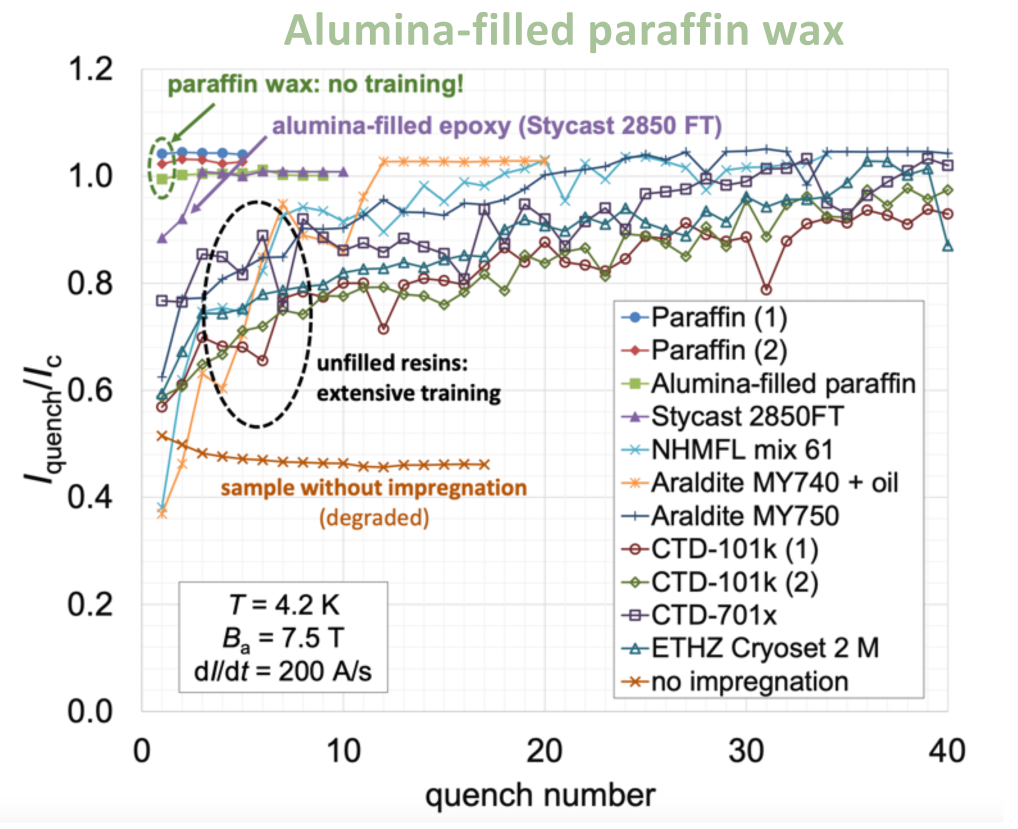
Pictures by M. Daly, S. Sidorov, S. Otten

SC Transformer

11-T solenoid

BOX Program

2PoM01-08
S. Otten



Courtesy, S. Otten, uTwente

BOX (BOnding eXperiment) program with uTwente has shown a wide variety of results, from complete conductor ***degradation (no impregnation)*** to substantial ***training (epoxy)*** to ***no-training (wax, Stycast, filled wax),*** with ***20 BOX samples*** successfully and tested to date.

BOX Compression

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UNIVERSITY OF TWENTE.

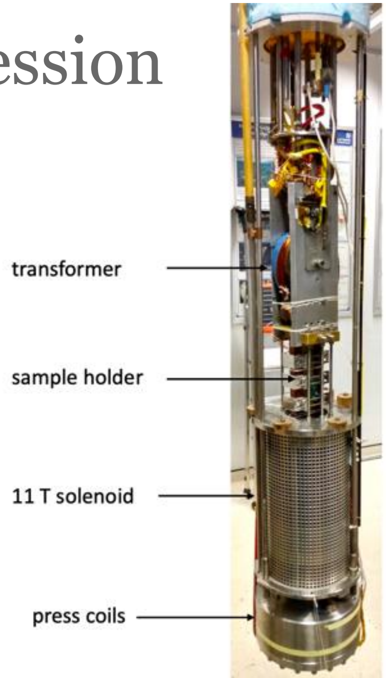
CHART Swiss Accelerator Research and Technology

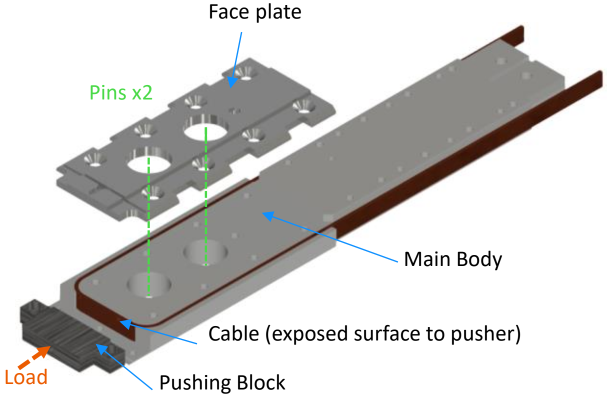
2PoM01-07
S. Otten

Successful systems are characterized in U Twente's transverse-compression setup.

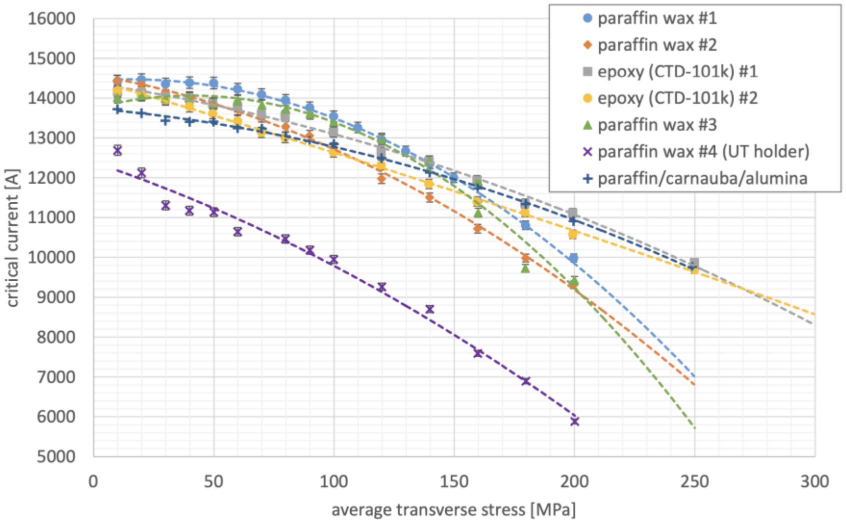
CTD 101-K measurements reproduce previous results of Twente U-shaped samples.

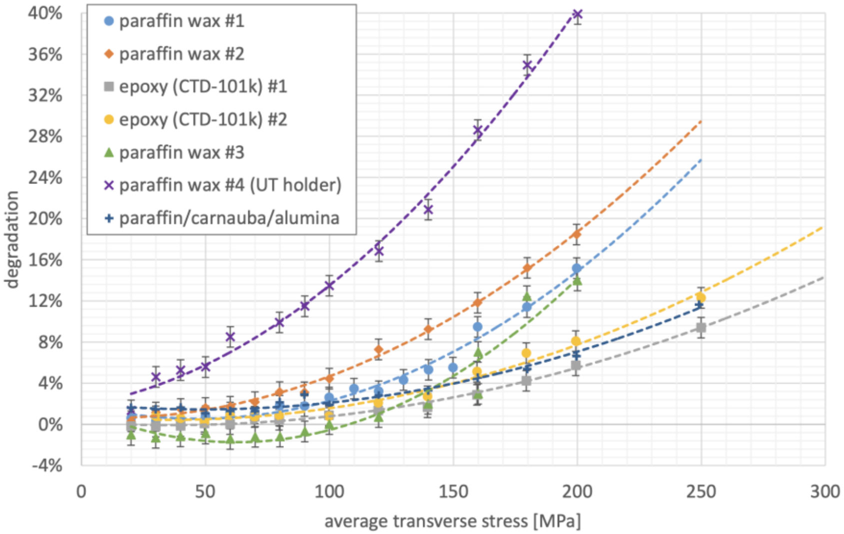
Paraffin wax's lower modulus and degradation.
Filled wax bumps wax up to CTD 101-K support.





Courtesy M. Daly





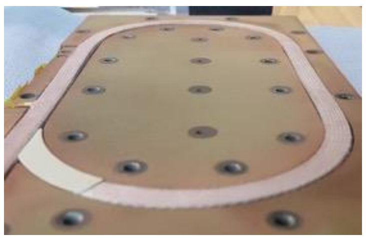
Courtesy S. Ott et al.

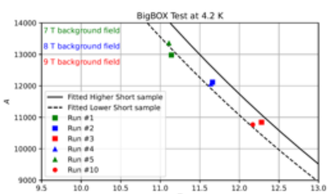
Feedback to Magnet Programs

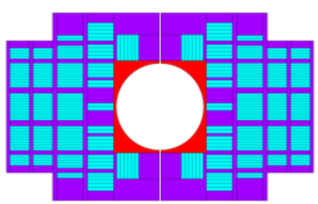
PSI's BigBOX: a 13-turn stress-managed racetrack.

- No training with 12.3 T coil field, 170 MPa coil stress at BNL's DCC17 facility.

2PoM01-06, D. Araujo







Courtesy D. Araujo et al

LBNL's wax impregnated sub-scale (5 T) CCT.

- First Nb_3Sn CCT without training.
- Alumina-filled wax considered for CCT6.

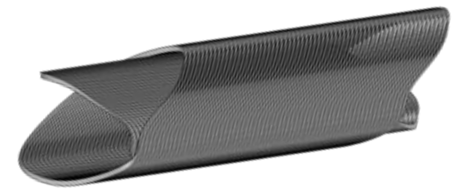
3PoA03-02, D. Arbelaez

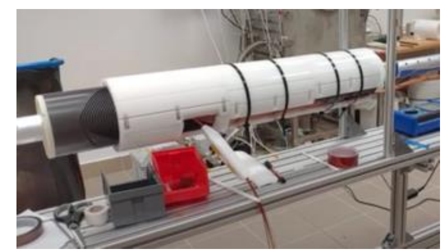
Courtesy J.L. Rudeiros Fernandez, LBNL

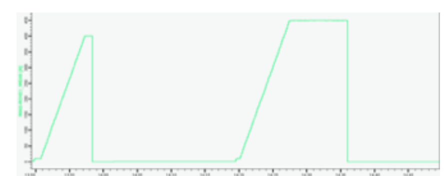
Wigner Inst. / CERN collaboration on SuShi septum for FCC-hh

- Wax impregnated CCT required no training to nominal current.

3OrM1-4, D. Barna







Courtesy D. Barna et al., Wigner Institute

Fast-Turnaround Stress-Management R&D

- HFM R&D has suffered from slow turnaround and late feedback on technology.
- "We propose […] a succession of meaningful fast-turnaround demonstrations […]. In this way, new technologies can be tested under realistic conditions at the earliest possible stage, the smallest relevant scale and cost, and the fastest pace."
  [LDG Roadmap for High-Field Magnets. https://arxiv.org/abs/2201.07895]

ETH zürich

First deliverable

2019

2020

2023

2025/26

Materials and Composite Samples (not powered)

Powered Samples and Mechanical Models

Sub-scale Magnets (5 T)

Short Magnets
Ultimate Field (14…16T)

Long Magnets
Ultimate Field
Magnets
(14…16 T)

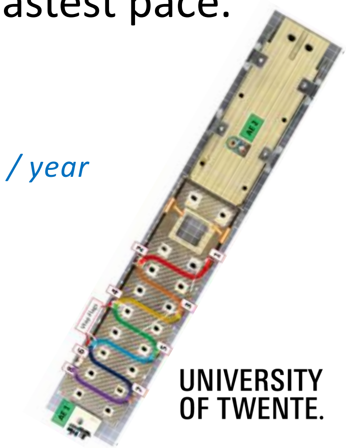
#Deliverables / year

100s

10

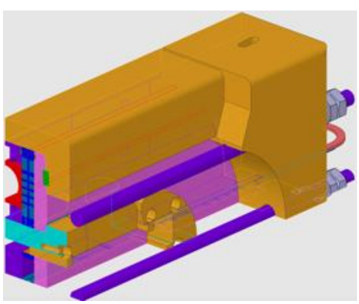
2-3

0.5-1



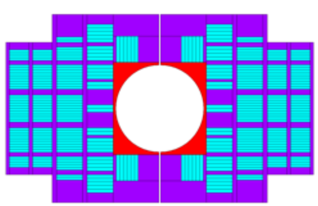
UNIVERSITY OF TWENTE.

Courtesy M. Daly

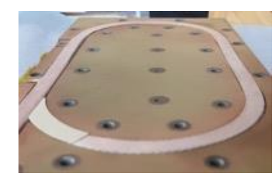


Courtesy D. Araujo

2PoM01-01, D. Araujo



Long-magnet infrastructure available only at CERN.

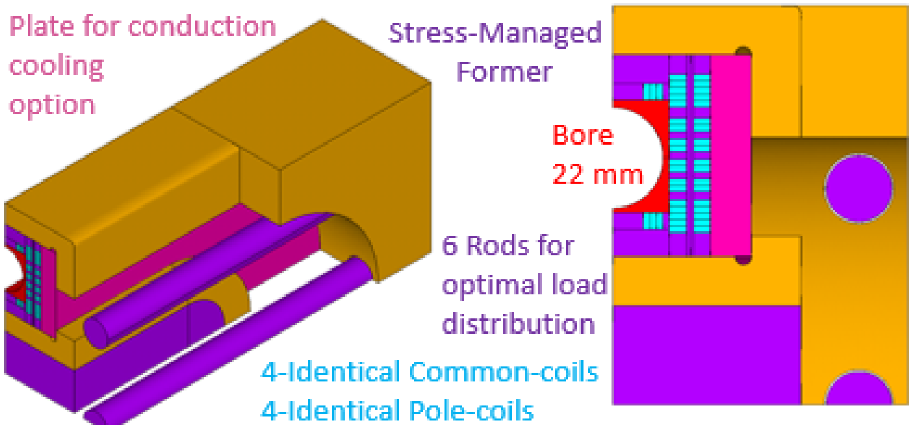


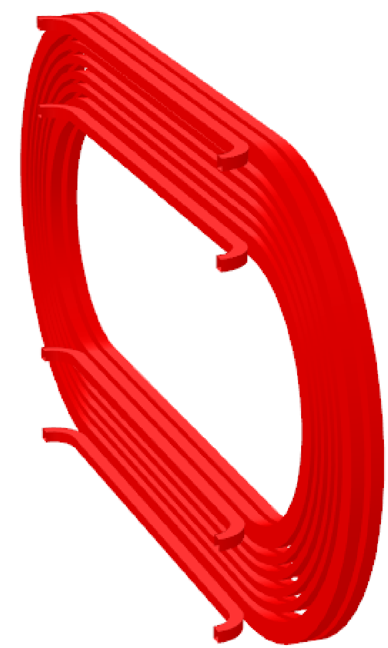
Courtesy D. Araujo

Brookhaven National Laboratory

Next Up: Subscale SM Common Coil

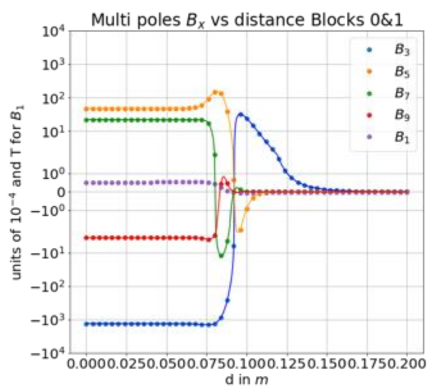
- SM-CC will bring new technologies and innovation in the areas of winding, reaction, impregnation, splicing, assembly, and loading.
- Subscale validates all manufacturing processes and reveals major design flaws early in the process.





Courtesy D. Araujo

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

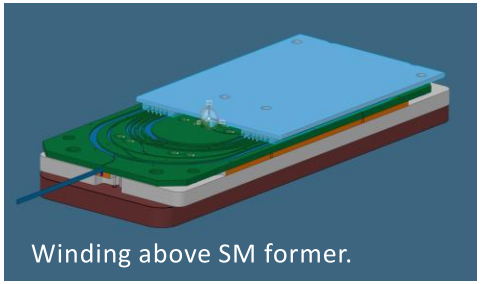


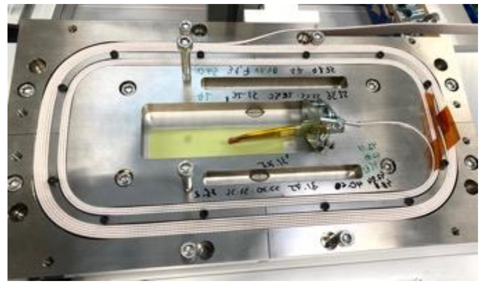
Magnet parameters for testing all coils or the common-coils. The coils straight section is 150 mm. The values refer to the fitted wire Ic curve at 4.2 K values.

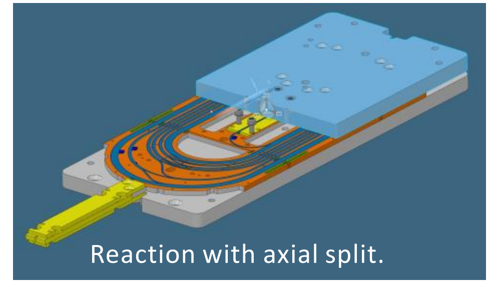
Subscale Technical Design Status

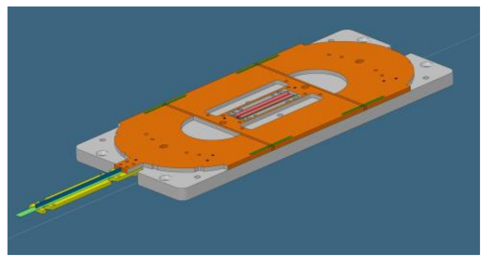
Swiss Accelerator Research and Technology

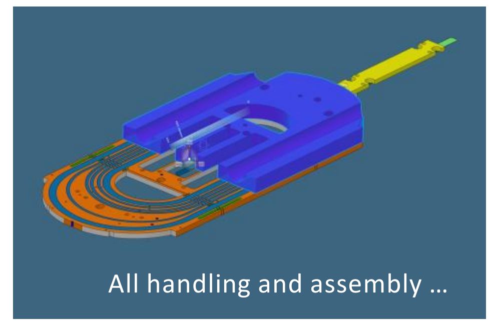
Technical design moving forward; construction for Q2’24.

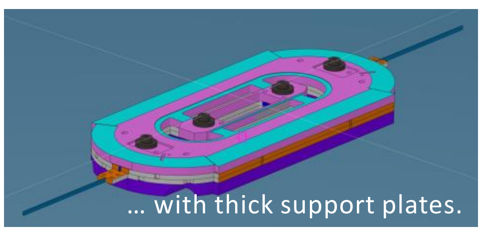

Winding above SM former.

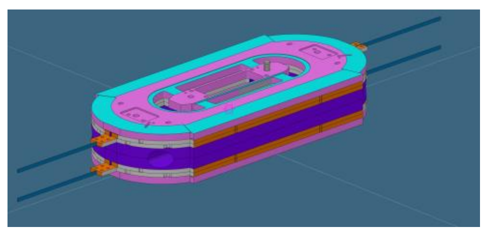


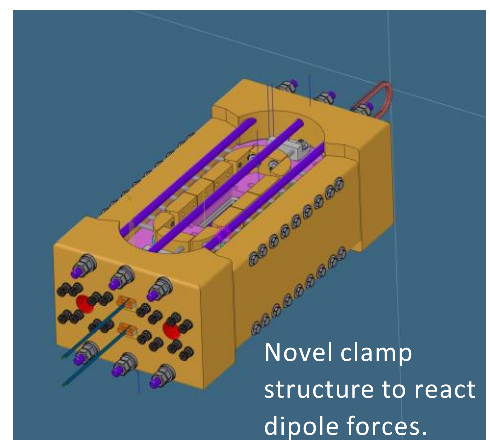

Reaction with axial split.




All handling and assembly …


… with thick support plates.



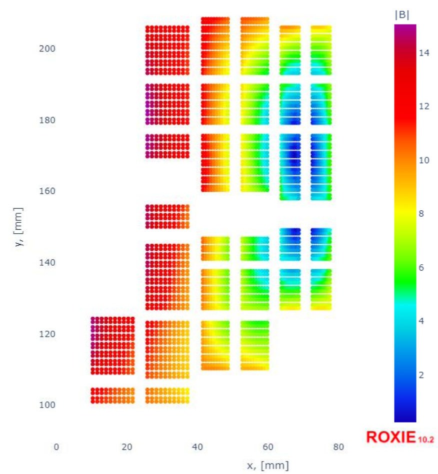

Novel clamp structure to react dipole forces.

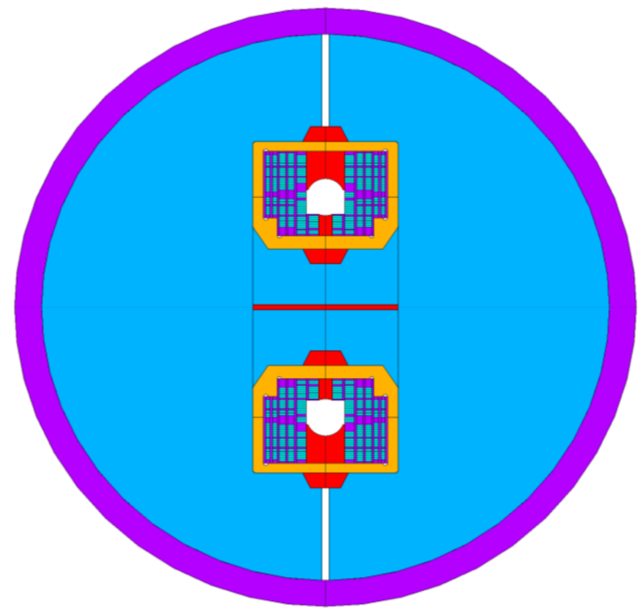
Courtesy T. Michlmayr, D. Araujo, C. Müller, H. Rodrigues

FCC-hh SM-CC Demonstrator

- Goal, demonstrate robust and cost-efficient Nb3Sn technology for next ESPPU.
- **Novel concept: Stress-managed and asymmetric common coils.** Design by D. Araujo.

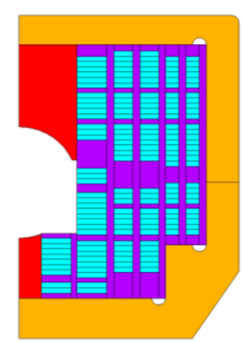
B_0 target of 14 T
T_{op}: 4.2 K
Eng margin of 10%
a_x, b_x < 15 units (r = 16.67 mm) from 1.5 T (injection) to 14 T
I_{op}: 13.1 kA
B_0 short sample @ 1.9 K: 16 T



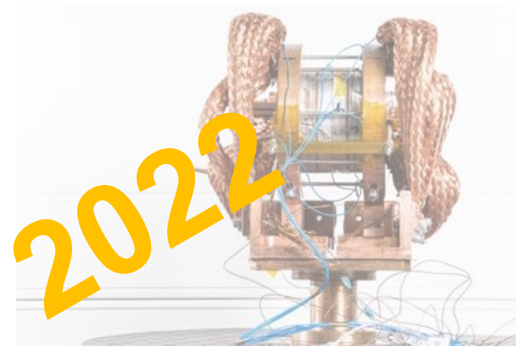


Intra-beam distance: 300 mm
Clear aperture of 50 mm
Straight-section of 500 mm
Yoke dia: 720 mm
Shell thickness: 35 mm
Total number of coils: 10
Coil types: 3 (re-use of tooling)
Cable types: 3

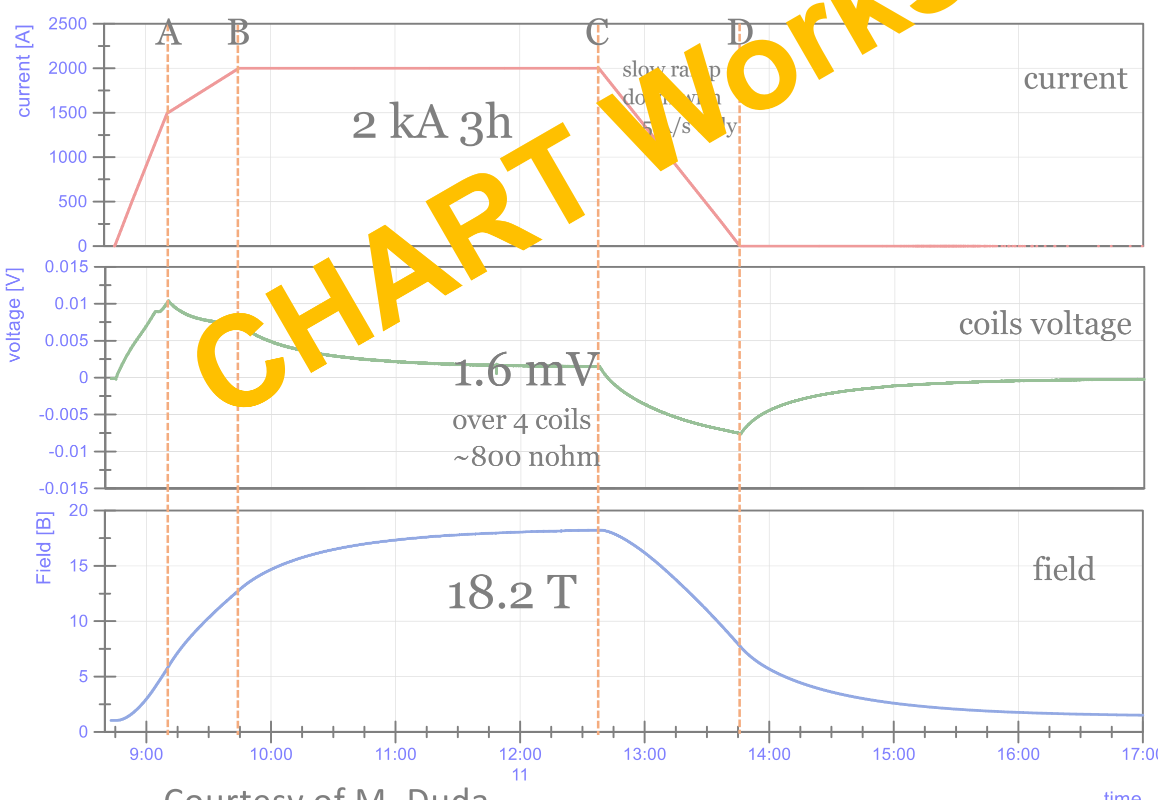
Stainless steel shell
Iron yoke
Coil collar
Former
Non-magnetic poles
Nb_3Sn conductor



4-Stack Technology Solenoid in the Cryogen-Free Test Station



- Gained experience with NI coils.
- Thermal runaway as consequence of bad electro-thermal contact (indium contact sheet was re-used).
- Axial contacting plates needed to be re-soldered.
- No SC degradation observed.



Courtesy of M. Duda

0-A:
- fast ramp up with 1 A/s
- voltage over coils increasing because of current radial path

A-B:
- slower ramp up with 0.2 A/s to stabilize coils voltage increase

B-C:
- 2 kA 3h plateau
- coils voltage decreasing because of current redistribution
- field is increasing – not reaching plateau

C-D:
- slow ramp down with 0.5 A/s to avoid quench back

Update on P3 Capture solenoid (PSI Positron Production)

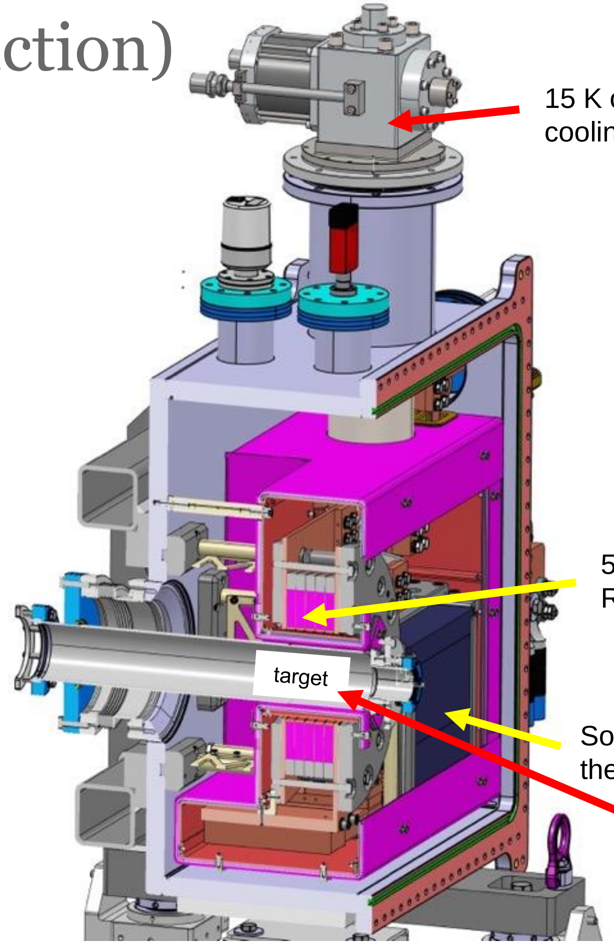
HTS NI target solenoid, to demonstrate high-yield positron source concept

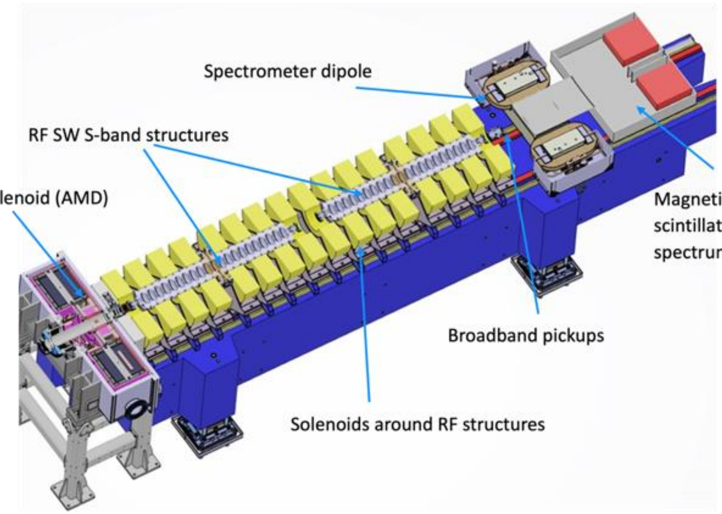
- stable DC operation,
- high thermal conduction due to solde impregnation to extract heat deposited in coils,
- radiation robustness due to absence of insulators.

All components in procurement.

Construction starting soon.

Experiment at PSI's SwissFEL 2026





Coil diameter	122 mm inner, 219 mm outer
Stored energy	331 kJ
Operating current	1.17 kA
Charging constant	11 hours

Courtesy J. Kosse, T. Michlmayr, H. Rodrigues

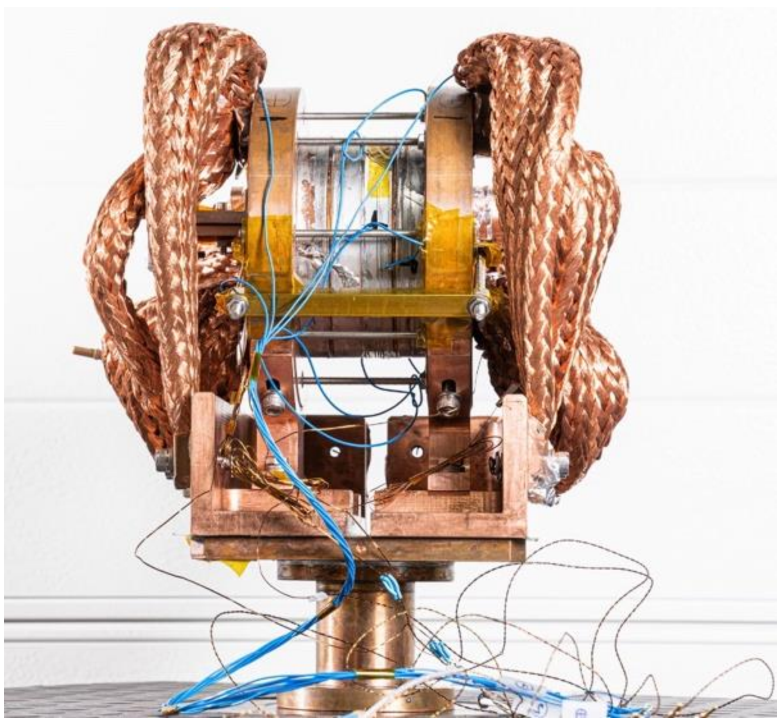
Split Solenoid for Neutron Scattering?

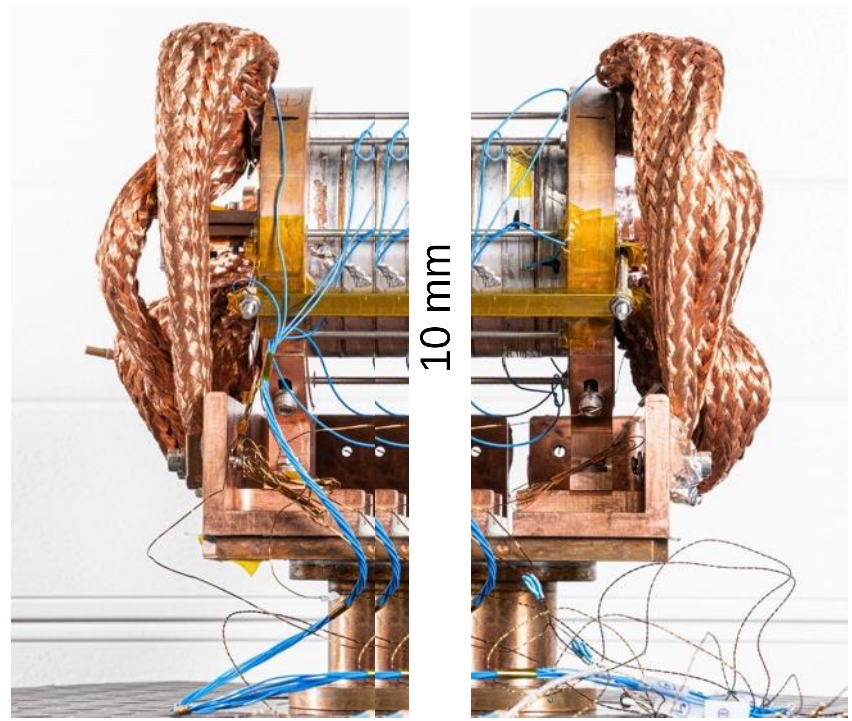
18 T NI HTS solenoid → 10 mm split NI HTS solenoid

18 T at 2 kA, 12 K
4 coils

Predict with simulation

~18 T at max 2 kA
6 coils

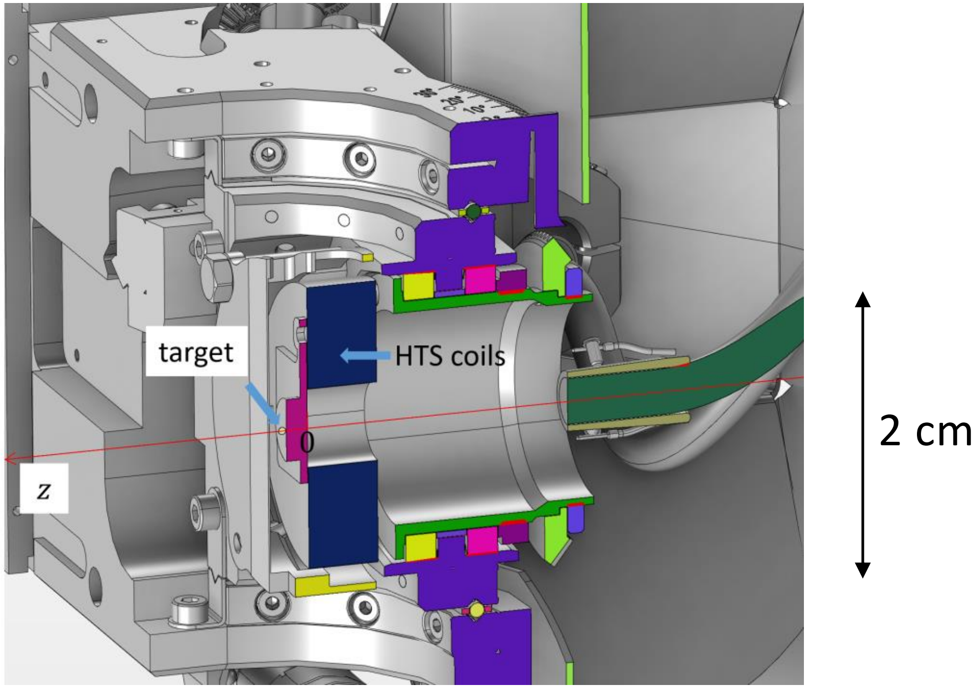




Courtesy J. Kosse

R'Equip RIXS Manipulator Solenoid

- Proposed upgrade of the manipulator used in the RIXS beamline at SLS for soft X-ray scattering experiments.
- Supply a high magnetic field (up to 6 T) on the target.



MagDev Laboratory Layout

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MagDev Laboratory

CHART Swiss Accelerator Research and Technology

New winding machine, autoclave (to be commissioned soon), wire-saw and polishing equipment.
Custom-developed winder is being adopted by CERN’s 927 lab.

Douglas Araujo
Engineer LTS

Jaap Kosse
Engineer ReBCO

Colin Müller
Mechanic LTS

Henrique Rodrigues
Process Engineer ReBCO

Dmitry Sotnikovs
Design Engineer ReBCO

André Brem
Material Scientist

Thomas Michlmayr
CAD, Technical Design

HTS in the LDG Accelerator R&D Roadmap

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CHART Swiss Accelerator Research and Technology

- LDG Roadmap on High-Field Magnets, p. 33
  - "Consideration of only engineering current density would suggest that magnetic fields in the range of 25 T could be generated by HTS"
  - "… performance of HTS in the range 10 to 20K has reached values of Je well in excess of 500 to 800A/mm2, i.e., the level that is required for compact accelerator coils. […] it would open a pathway towards a reduction of cryogenic power, [and] a reduction of helium inventory (e.g., dry magnets)"

Aspirational Goals

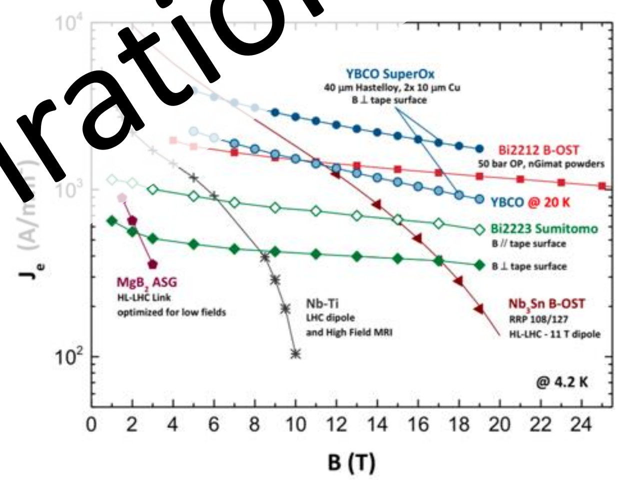
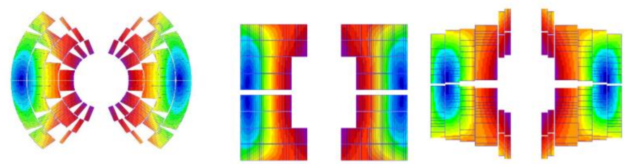


Fig. 2.3: Engineering current density J_e vs. magnetic field for several LTS and HTS conductors at 4.2 K. Latest results for REBCO tapes are reported both at 4.2 K as well as 20 K.

[LDG Accelerator R&D Roadmap, High-Field Magnets, https://arxiv.org/abs/2201.07895]

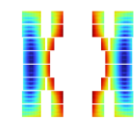
Ramp-Loss Studies

- An HTS 16-T block coil at 20 K has simulated AC losses of 224 kJ/m*.
- LTS magnets feature about 20 kJ/m and powering cycle (that is 2 times higher the CDR target of 10 kJ/m).



Coil geometry		Cos-theta	Block	Common Coil
Deff	µm	50	50	50
AC-loss (2 Ap)	J/m	18330	19603	23489

[S. I. Bermudez, et al., AC loss for EuroCirCol 16 T designs, CERN 01-11-2017]



4-mm width
224680

Courtesy D. Sotnikov

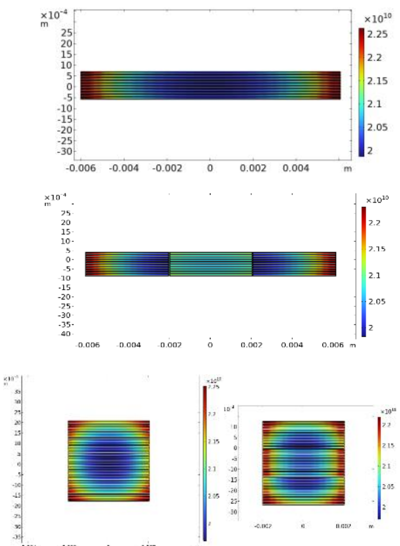
- Carnot efficiency increases 10-fold from 1.9 to 20 K, and 4-fold from 4.2 to 20 K.

- Total Cost = CAPEX (tape) + OPEX (cryo power)
- CAPEX is reduced and OPEX increased at lower temperatures.
- Affordable 20-T magnets with reduced cryo power are still beyond the horizon.

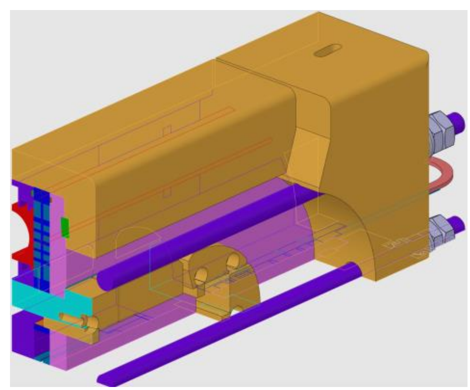
*** Caveat: models need to be validated!**

HTS Innovation Funnel for HFM

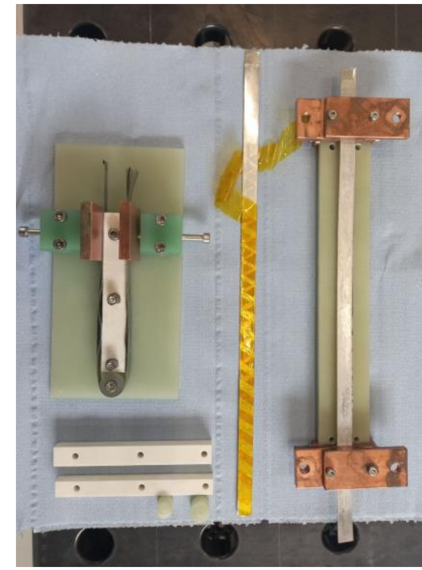
First deliverable	Stage	#Deliverables / year
2023	***Materials*** and ***Numerical Design Studies***	100s
2023	***Powered Cable Samples***	10
2024	***Technology Racetrack Coils***	2
2025	***Short Hybrid HTS/LTS*** Sub-Scale and Ultimate-Field *Magnets* (7…17 T)	1
	Short All-HTS Magnets (16…20 T) (4.2…20 K)	



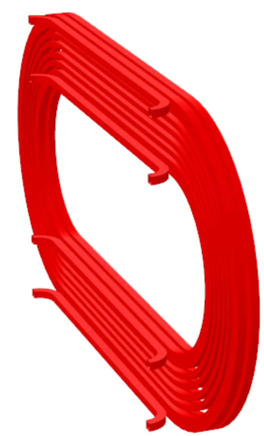
Courtesy D. Sotnikov



Courtesy D. Araujo, T. Michlmayr



Courtesy H. G. Rodrigues



Contributions

- 10-T Nb3Sn CCT magnet reaches 100% of short sample!
- Novel impregnation systems validated – new baseline and expectation for stress-managed magnets.
- Fast-turnaround subscale magnet to validate novel technologies, manage risk, and accelerate learning.
- Innovative asymmetric common coil solution – road to full automation and wind&react?
- High-field solenoid for in-beam operation designed and procured as side-project.
- Prospect of synergies in neutron scattering and x-ray scattering.
- Upcoming: MagMu, MagNum2