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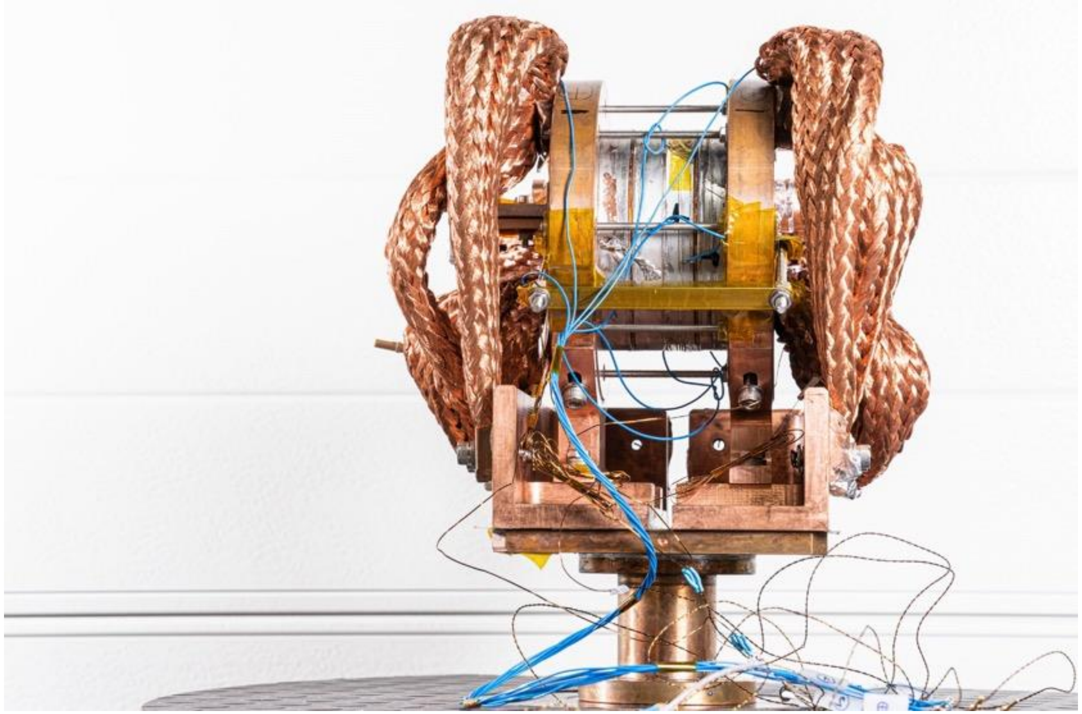
PSI

CHART

Swiss Accelerator
Research and
Technology



02.05.2023 – HFM RDL2 kickoff

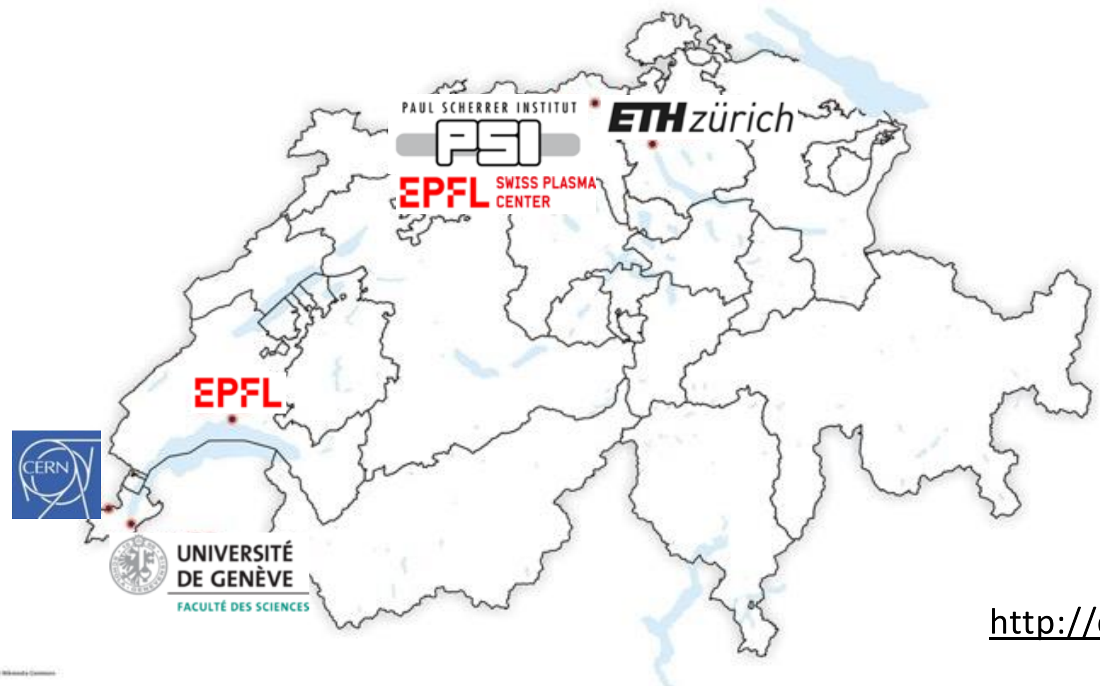
PSI R&D roadmap towards ReBCO cable and coil technology demonstrators

D. M. Araujo, B. Auchmann, J. Kosse, T. Michlmayr, H. G. Rodrigues,
D. Sotnikov, A. Milanese, S. Sanfilippo

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

CHART

- “CHART, the Swiss Center for Accelerator Research and Technology, was founded to support the future oriented accelerator project Future Circular Collider (FCC) at CERN and the development of **advanced accelerator concepts in Switzerland beyond the existing technology**. […] The high field magnet R&D has strong synergies with PSI projects […]”
  [Application for support of the Swiss Accelerator Research and Technology Initiative, 2018]
- ~50% of the effort directed to Applied Superconductivity for accelerators.



http://chart.ch

CHART HTS Team at PSI

- HTS Engineers:

Dmitry Sotnikovs
HFM

Henrique Rodrigues
HFM

Jaap Kosse
FCCee HTS4

- Transverse LTS/HTS roles:

André Brem
Material Scientist

Thomas Michlmayr
CAD, Technical Design

The Promises of HTS

- 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)”

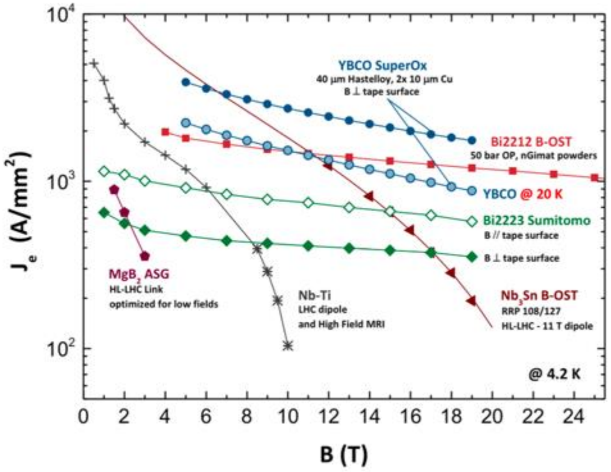
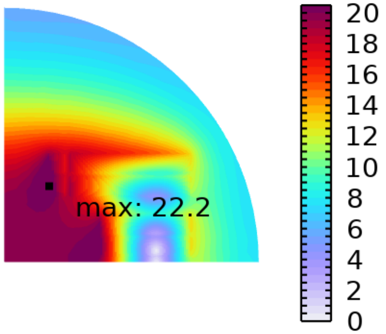


Fig. 2.3: Engineering current density J_e vs. magnetic field for several LTS and HTS conductors at 4.2 K. Latest results for REBCO tapes are reported both at 4.2 K as well as 20 K.

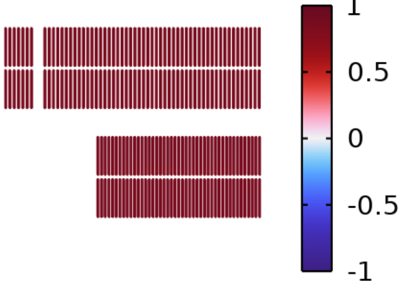
[LDG Accelerator R&D Roadmap, High-Field Magnets, https://arxiv.org/abs/2201.07895]

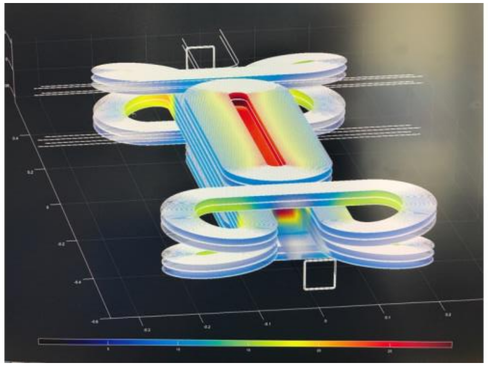
A First Look at Ramp Losses

- What are ramp losses in an all-HTS 20 T magnet at 4.2 K?
  - The geometry is a block-coil design by J. v. Nugteren. Simulation carried out by L. Bortot.
  - Part-homogenized model, ramping 0 to 20 T in 1150 s, operating at 4.2 K – to be validated.
  - 65 kJ/m cycle losses.
  - FCC-hh CDR target: 10 kJ/m at 1.9 K.
- How do losses scale to higher operating temperature?
  - Multiple x-section models required.
- How quickly can losses be transferred to cryogenic system?
  - Fast enough for 2-6 h operational turnaround?
  - By how much does the coil temperature rise?
  - Is field quality affected from local temperature in cryogenic circuit?
- Which cable geometry can make a difference?
  - Can tape-stack cable fulfill the specs?
- How important is the cable orientation?
  - What coil geometries are eligible?



[Courtesy L. Bortot]

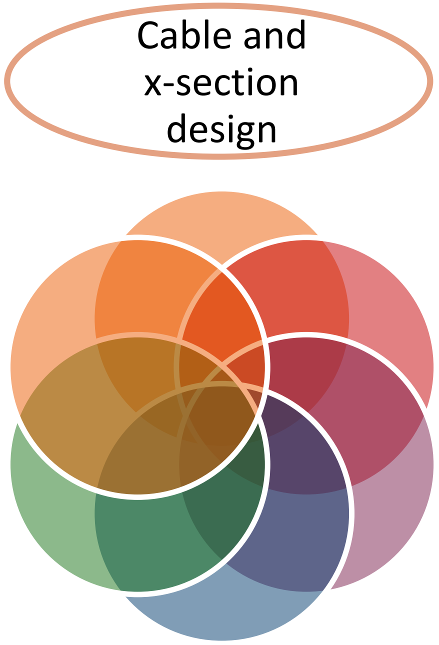




[Courtesy G. Kirby, J. v. Nugteren, J. S. Murtomäki, et al.]

Systems Engineering Challenge

Interrelated elements of an HTS HFM technology:



Cable and x-section design

Key component for AC losses, field quality, mechanical compliance, protectability

Beam dynamics interface

Structural design

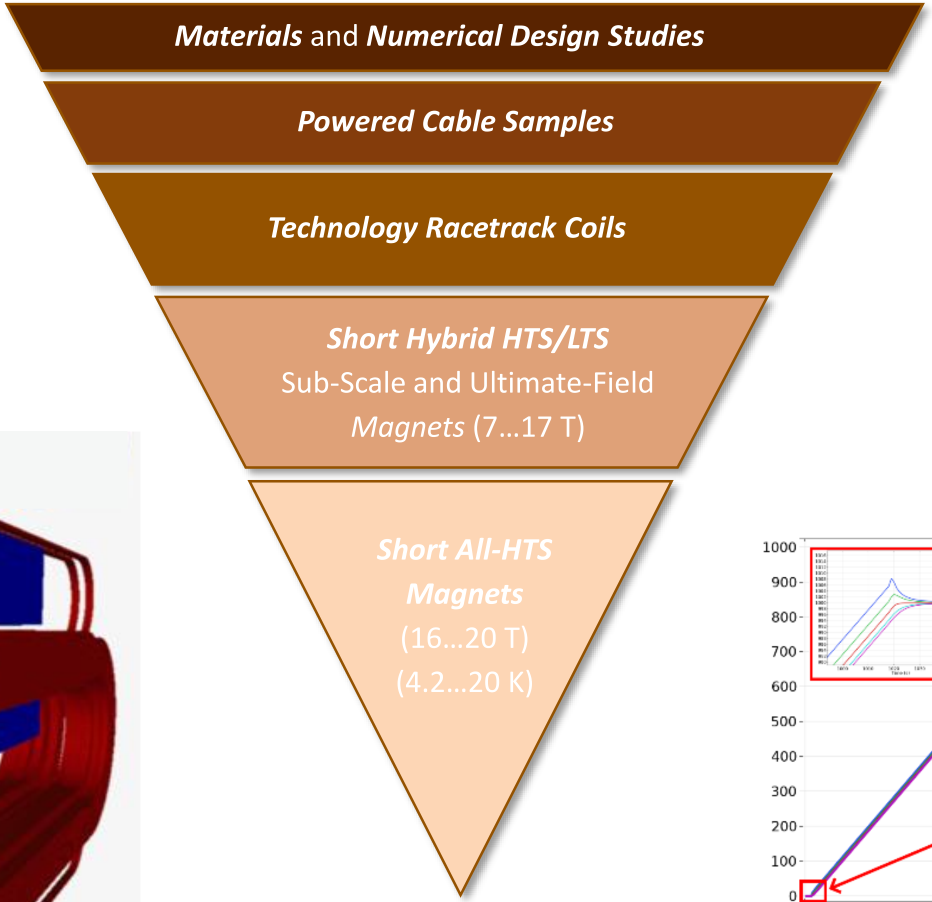
Cryogenics interface

Thermal design

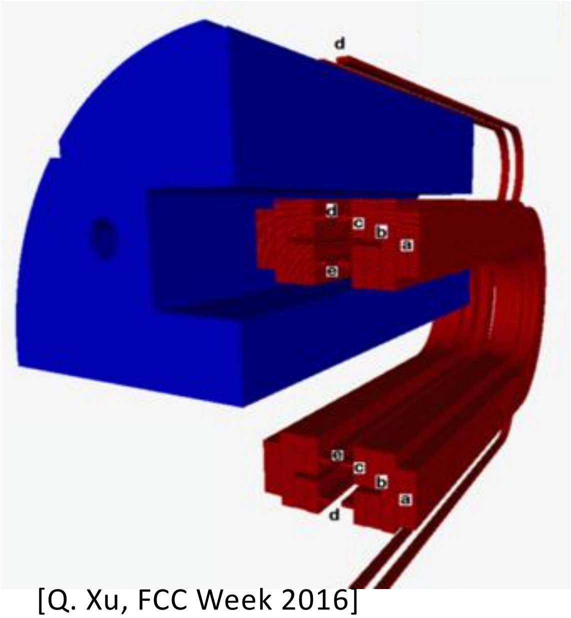
Protection design

Roadmap Towards HTS for HFM

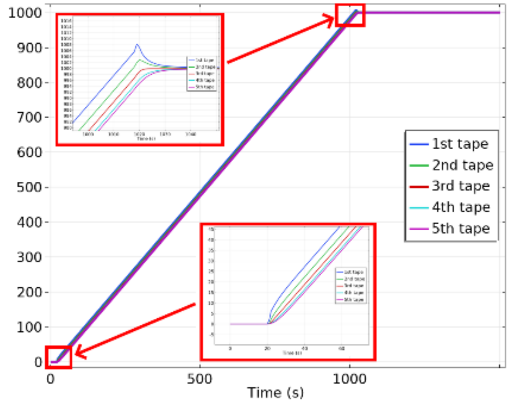
Innovation funnel for HTS HFM R&D:



First deliverable		*#Deliverables / year*
2023	***Materials* and *Numerical Design Studies***	100s
2023	***Powered Cable Samples***	10
2024	***Technology Racetrack Coils***	2
2026	***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)	



[Q. Xu, FCC Week 2016]



Current distribution Jz through tapes in the stack.

ReBCO Tape and ReBCO Cables

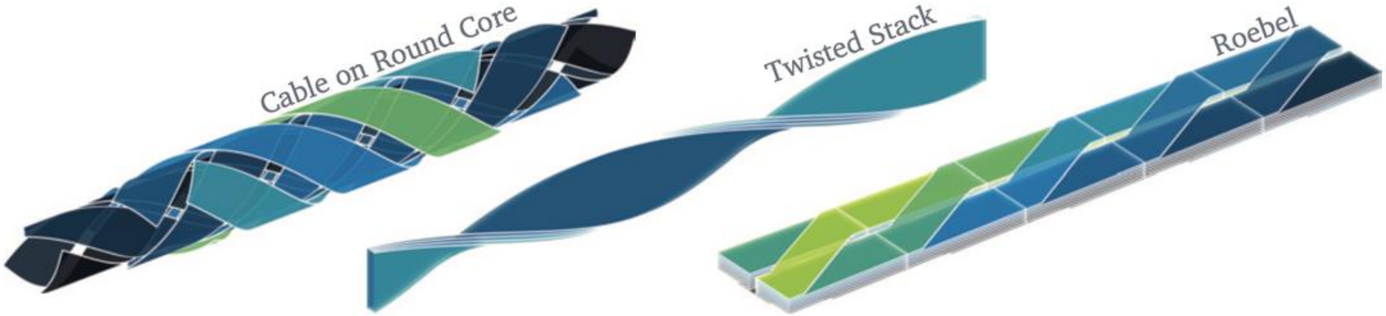
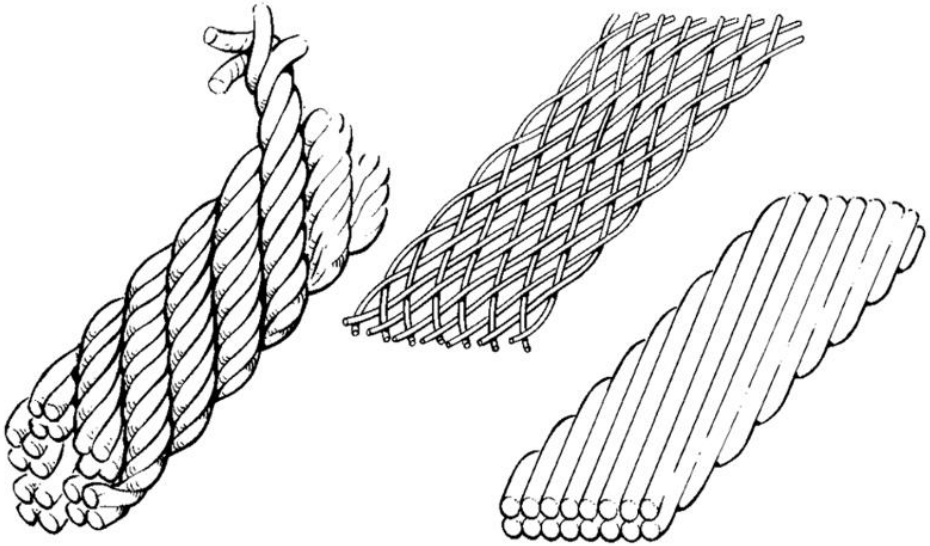
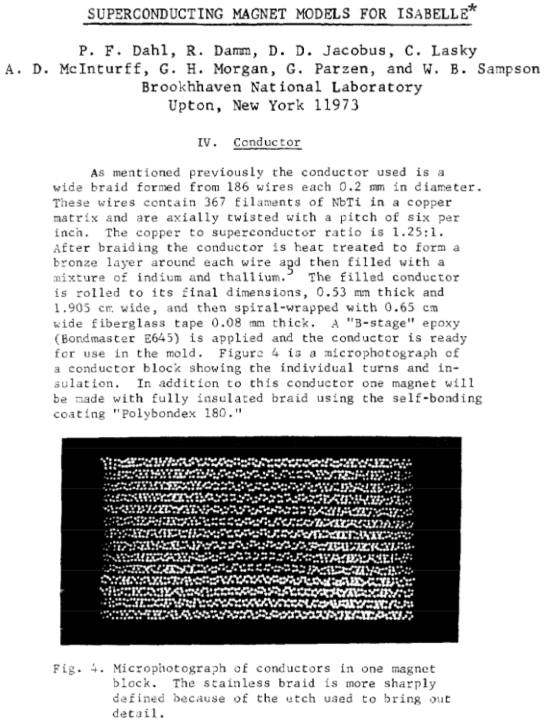


Figure 1.10. *Three different geometries for assembling a cable with ReBCO coated conductor. Also refer to Table 1.2.*





SUPERCONDUCTING MAGNET MODELS FOR ISABELLE*

P. F. Dahl, R. Damm, D. D. Jacobus, C. Lasky
A. D. McInturff, G. H. Morgan, G. Parzen, and W. B. Sampson
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IV. Conductor

As mentioned previously the conductor used is a wide braid formed from 186 wires each 0.2 mm in diameter. These wires contain 367 filaments of NbTi in a copper matrix and are axially twisted with a pitch of six per inch. The copper to superconductor ratio is 1.25:1. After braiding the conductor is heat treated to form a bronze layer around each wire and then filled with a mixture of indium and thallium.[5] The filled conductor is rolled to its final dimensions, 0.53 mm thick and 1.905 cm wide, and then spiral-wrapped with 0.65 cm wide fiberglass tape 0.08 mm thick. A "B-stage" epoxy (Bondmaster E645) is applied and the conductor is ready for use in the mold. Figure 4 is a microphotograph of a conductor block showing the individual turns and insulation. In addition to this conductor one magnet will be made with fully insulated braid using the self-bonding coating "Polybondex 180."

Fig. 4. Microphotograph of conductors in one magnet block. The stainless braid is more sharply defined because of the etch used to bring out detail.

[J. v. Nugteren, High Temperature Superconductor Accelerator Magnets. PhD thesis, UTwente, 2016.]
[M. Wilson, Pulsed Superconducting Magnets' CERN Academic Training May 2006]

Conclusion

- We find ourselves in a situation akin to LTS in the 1970ies.
- First order of the day: what cable/coil technology is needed to make an HTS FCChh feasible?
- There are many other technical challenges ahead.
- Looking forward to exchange and collaboration!

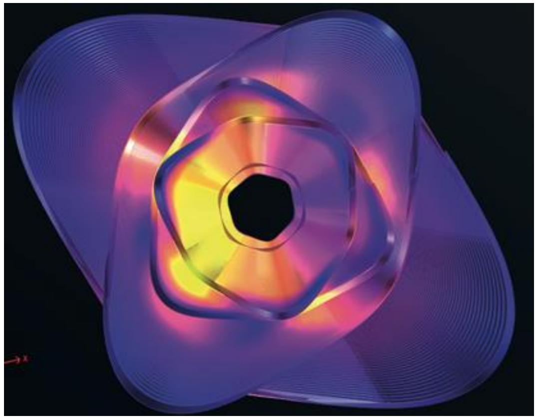
HTS4: **HTS S**hort **S**traight **S**ections for FCC-ee

By using **HTS sextupoles and quadrupoles** instead of the RT baseline, HTS4 aims to:

- **Reduce energy consumption** from up to 80 MW (43 MW in CDR) to <10 MW
- Increase dipole filling factor – decrease SR
- Enhance optics flexibility

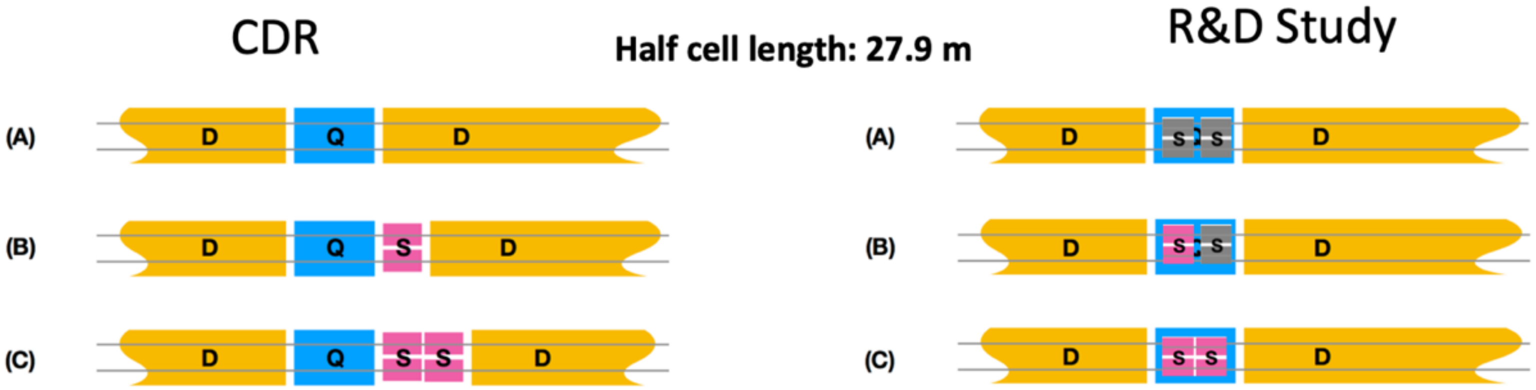
Challenges:

- **Accelerator-grade field quality** with HTS
- Balance **cooling** power with **conductor** volume
- **High-reliability** cryocooler-based operation
- **Low heat-load** powering
- Mitigation of **radiation** issues on electronics



CCT variant courtesy M. Koratzinos

Sub-scale coils and **1-m prototype module** to be constructed and tested at PSI



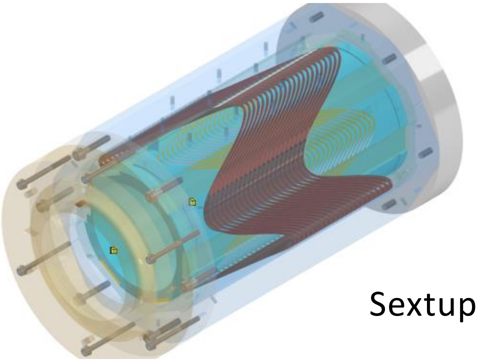
HTS4: HTS Short Straight Sections for FCC-ee

- Can magnets be cooled by cryocoolers with high availability?
  - First estimates say **YES**, IF redundancy is implemented
  - Total system coldhead reliability >0.999 over 3 year period possible

k	number of required operational coolers
n	Installed coolers per magnet

R	$k=1$	$k=2$	$k=3$	$k=4$	$k=5$	$k=6$
$n=1$	0.0000					
$n=2$	0.9817	0.0000				
$n=3$	1.0000	0.9462	0.0000			
$n=4$	1.0000	0.9998	0.8954	0.0000		
$n=5$	1.0000	1.0000	0.9995	0.8321	0.0000	
$n=6$	1.0000	1.0000	1.0000	0.9991	0.7594	0.0000

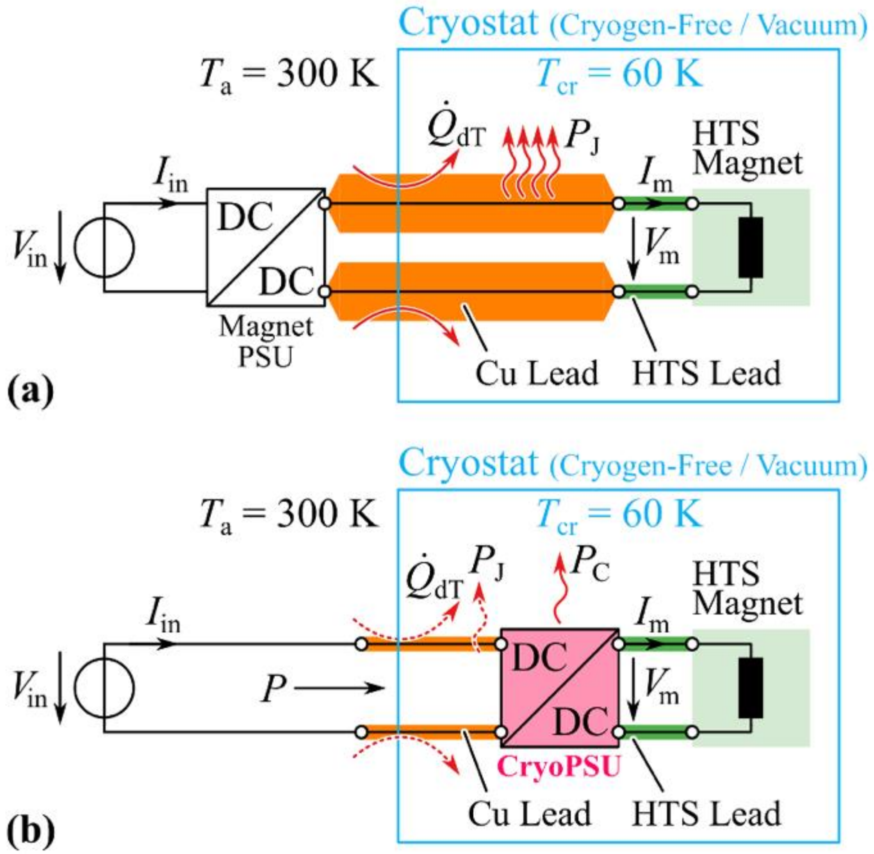
- Two competing sub-scale demonstrators are under preparation.



Courtesy, M. Koratzinos.
Sextupole CCT subscale magnet.

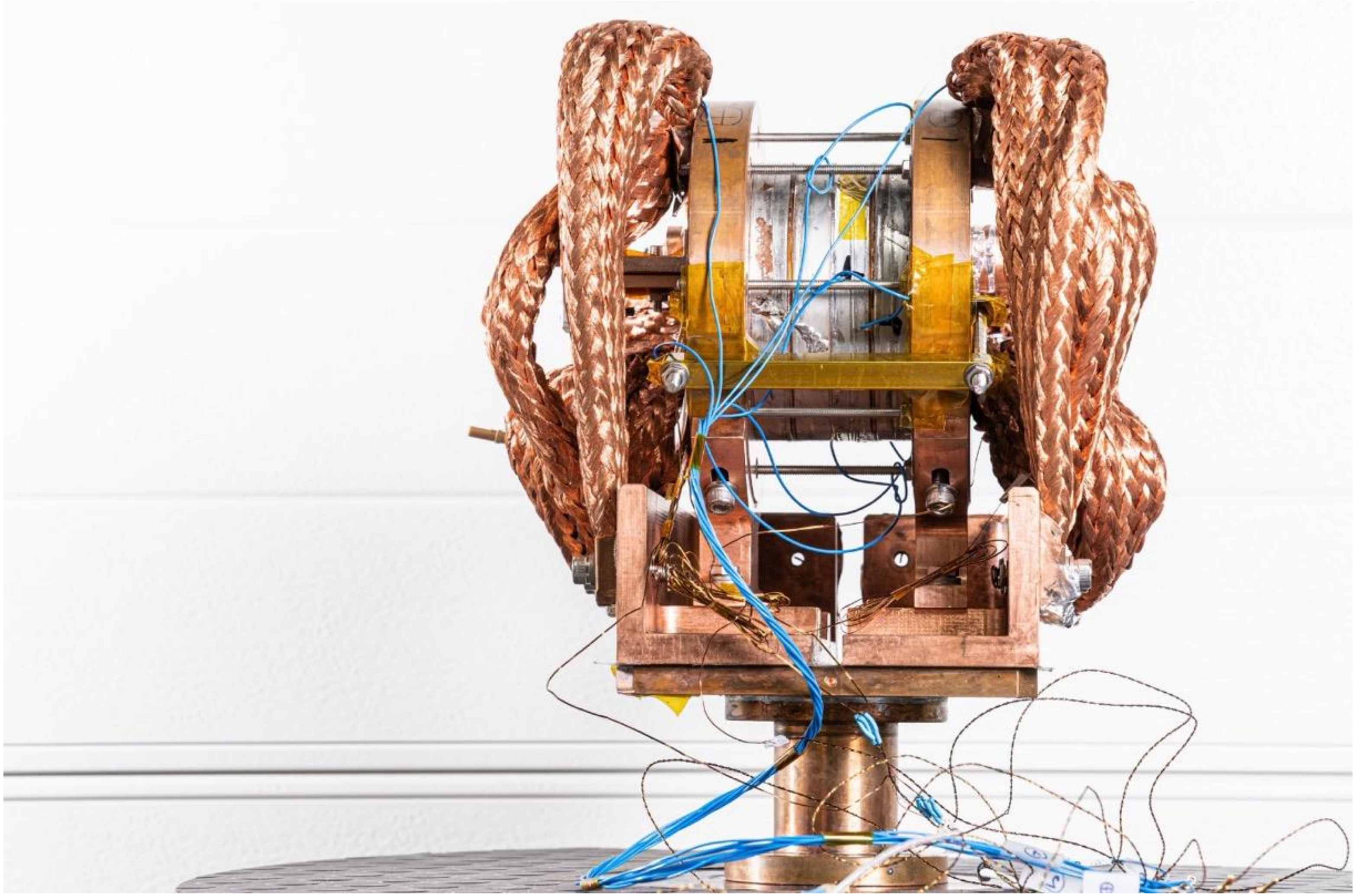
Cryogenic Power Supply CHART Project at ETHZ

- In support of FCCee HTS4, CPES develops a cryogenic power supply which, in its first iteration, may reduce heat load to the cryo-cooler by 50%.
- CPES development follows specifications provided by CERN power-supply specialists.
- The CPES unit may incorporate magnet protection functionality.
- Cold-testing and integration studies at PSI cryogen-free test station.



Courtesy J. Huber

4-Stack Technology Solenoid

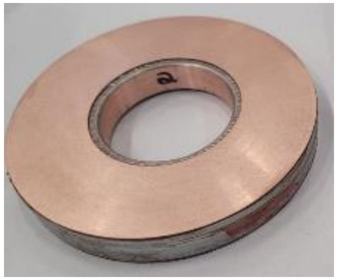


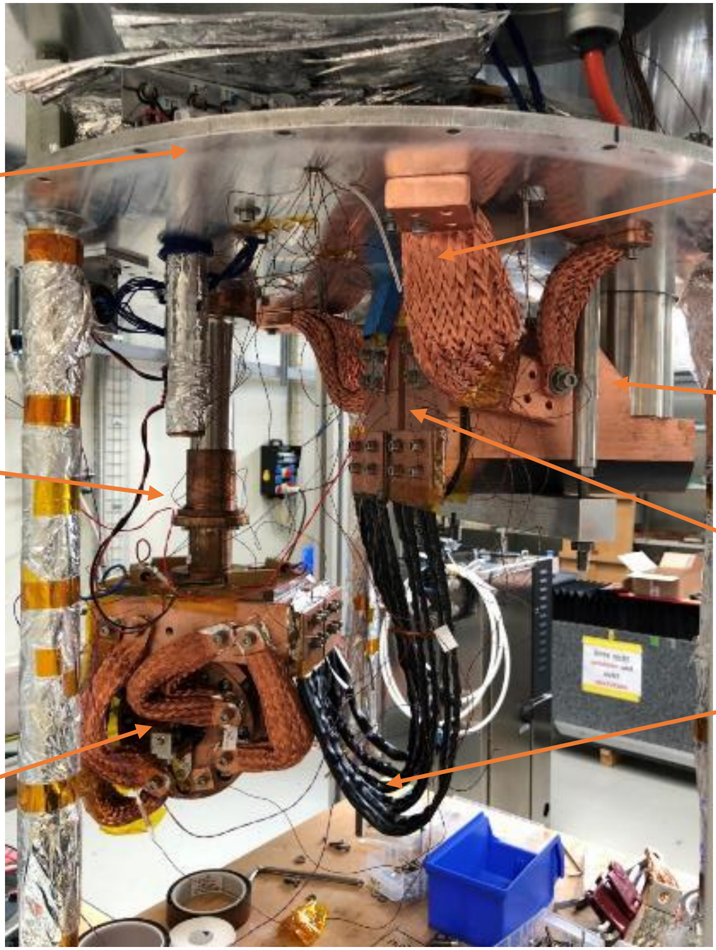
4-Stack Technology Solenoid Cold Test

- Successful test in cryogen-free test station of 4-pancake HTS NI solenoid, built in-house at PSI and using licensed Tokamak Energy Ltd technology.
- Coil reached **18.2 T** in the center, **20.3 T** on the conductor at the maximum current of the power converter of **2 kA** and **12 K** coil temp.
- Hall probes were qualified at UniGE up to 19 T.

Diameter: 100 mm
Aperture: 50 mm

SC type: ReBCO
tapes: 2
turns: 2 x 170
SC length: 2 x 49 m





radiation shield top plate

1st cryocooler 4K coldhead

Stack of 4 NI HTS coils with thermal/ electrical connectors

thermal connectors

2nd cryocooler 20K coldhead

Cu leads

HTS leads

Courtesy of M. Duda, J. Kosse, H. Rodrigues

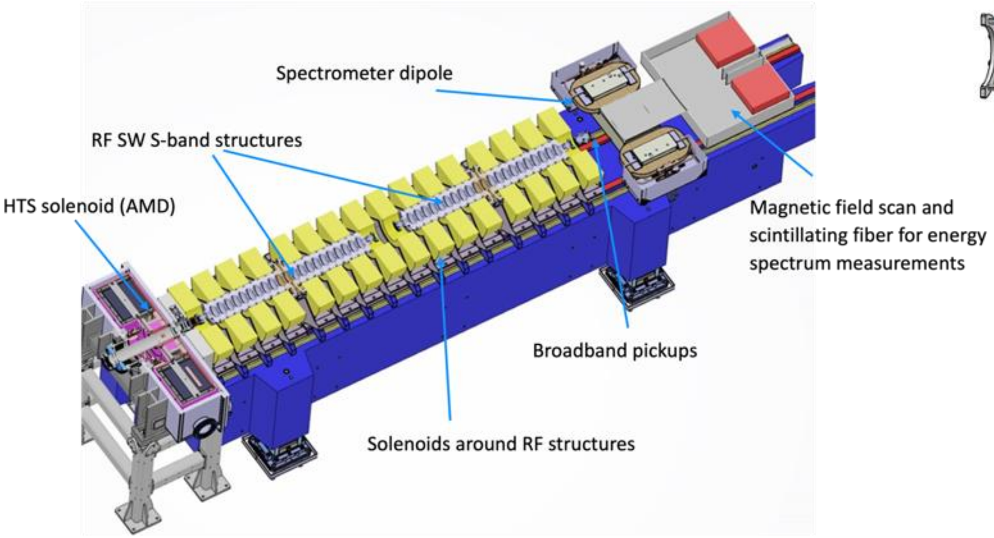
FCCee Injector Study:P^3 (PSI Positron Production)

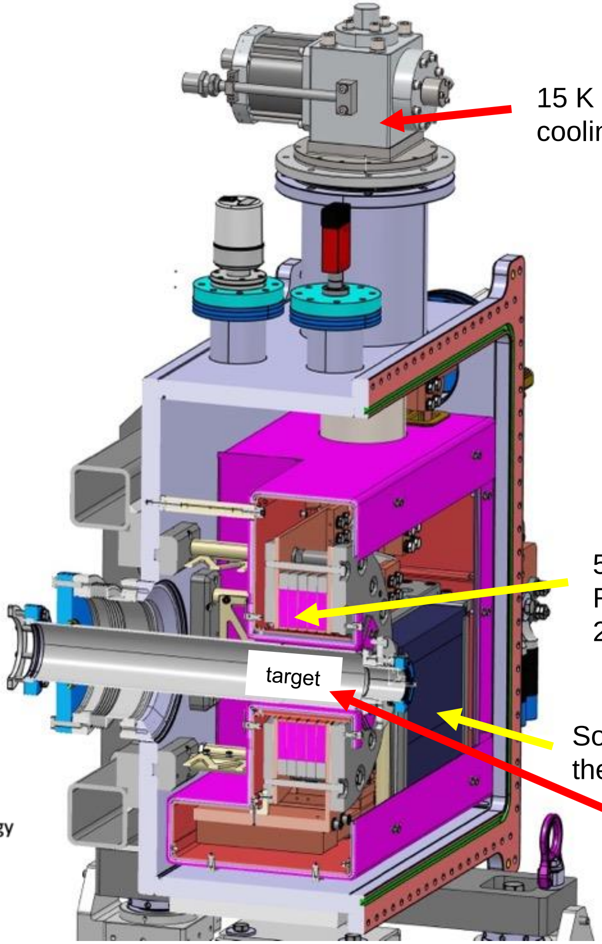
HTS NI target solenoid, to demonstrate high-yield positron source concept

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

Manufacturing/commissioning Q3’23-Q2’24

Experiment at PSI’s SwissFEL 2025/26





15 K conduction-cooling

5 coils from 12 mm ReBCO, 110 mm ID 21 T peak field

Solid-state (Pb) thermal buffer

15 T in 72 mm warm bore

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