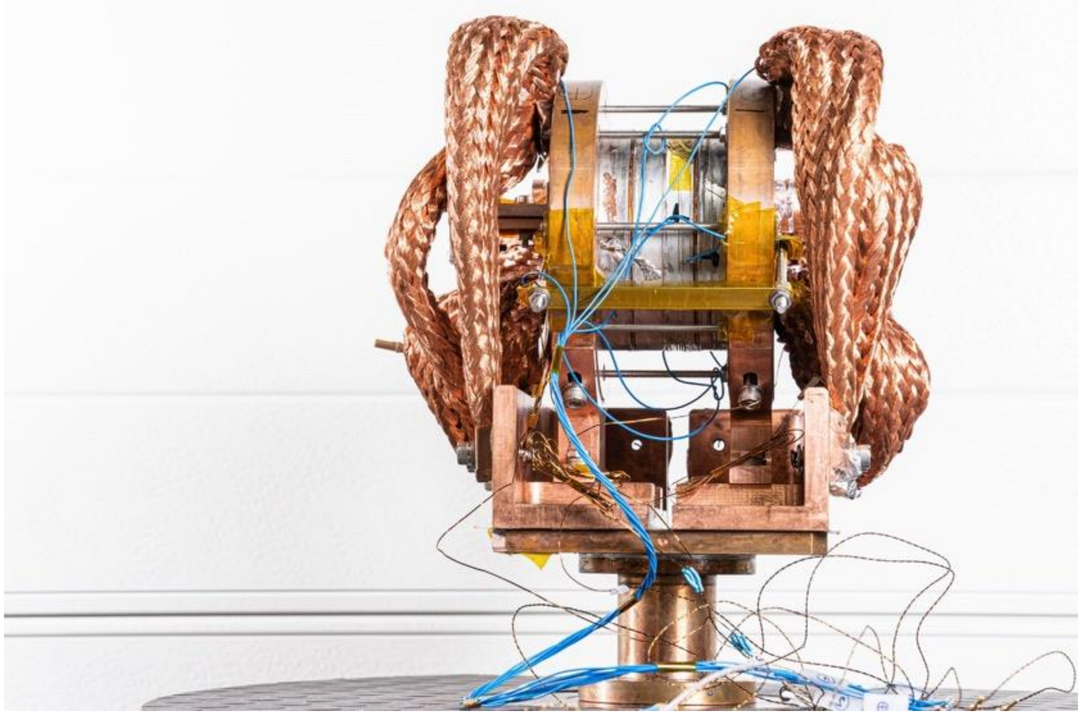

02.05.2023 – Future Colliders seminar

Status of High-Field Magnet R&D for Future Colliders in CHART

D. M. Araujo, B. Auchmann, A. Brem, M. Daly, M. Duda, O. Kirby, M. Koratzinos, J. Kosse, T. Michlmayr,
H. G. Rodrigues, S. Sanfilippo, D. Sotnikov

MuCol slides by L. Bottura for the Muon Magnets Working Group

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

Overview

- CHART – Swiss Accelerator Research and Technology
- CHART contributions to FCChh HFMs
  - Nb_3Sn
  - HTS (ReBCO)
- FCCee
  - Baseline magnet system
    - Arc cells
    - MDI
  - CHART contributions to HTS-based feasibility studies
    - P^3: Positron source capture solenoid
    - HTS4: HTS Short Straight Section
- Muon Collider magnet requirements
- PSI Synergies

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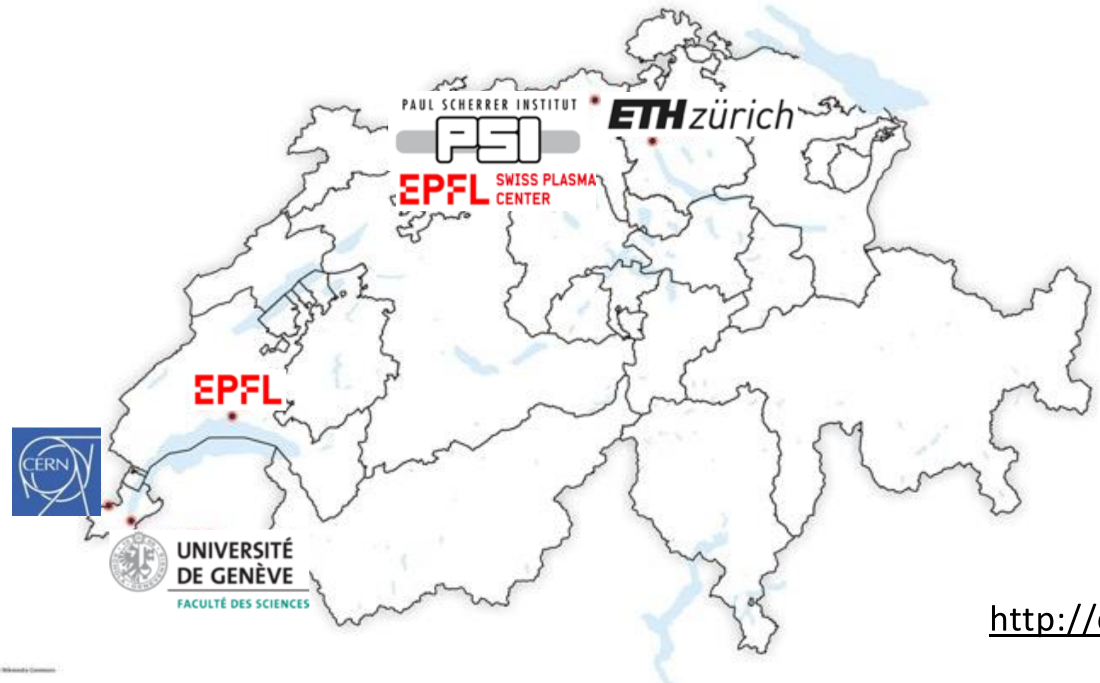
CHART

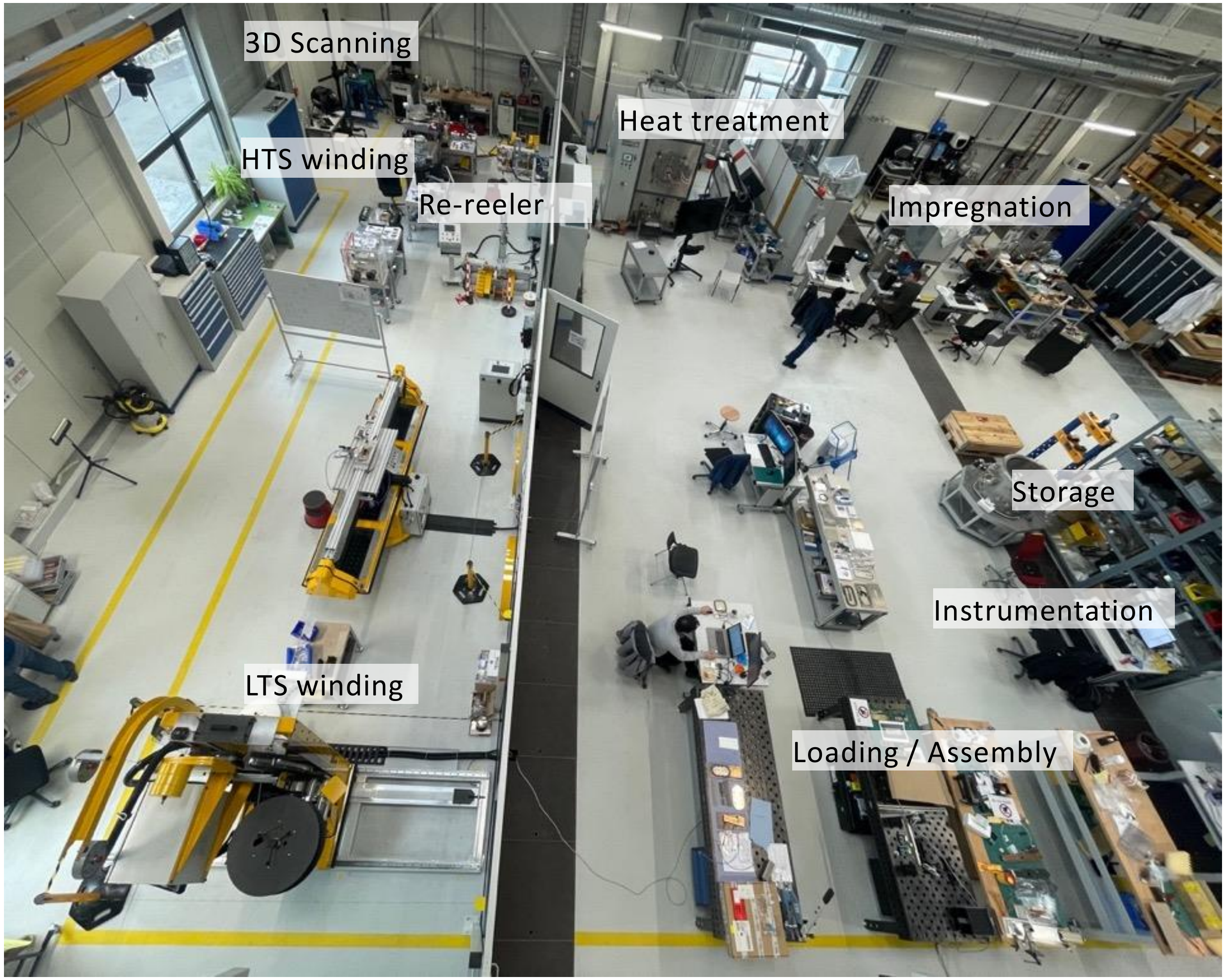
- “CHART, the Swiss Center for Accelerator Research and Technology, was founded to support the future oriented accelerator project Future Circular Collider (FCC) at CERN and the development of **advanced accelerator concepts in Switzerland beyond the existing technology**. […] The high field magnet R&D 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

MagDev Laboratory

- New extension to building WLHA next to SLS2.0.
- Hand-over in August 2020.



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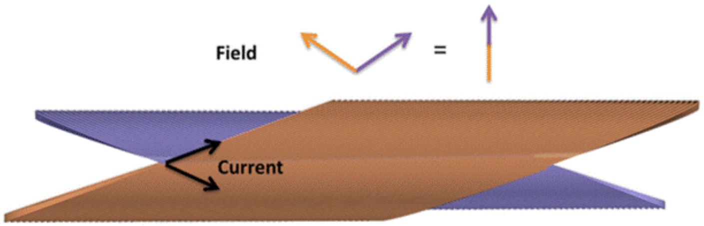
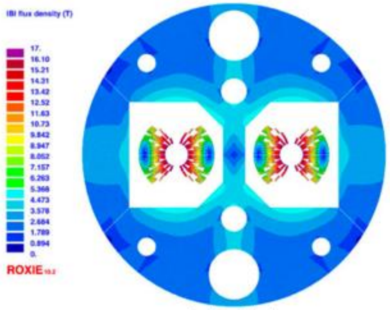
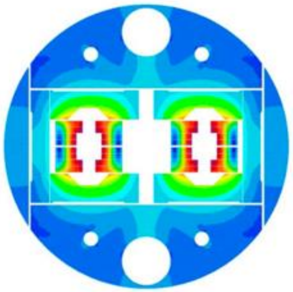
FCC-hh Nb$_3$Sn after EuroCirCol (2015-2019)

- CHART joined the Nb3Sn HFM R&D during the Horizon2020 EuroCirCol effort.
- PSI studied the Canted Cosine Theta option.

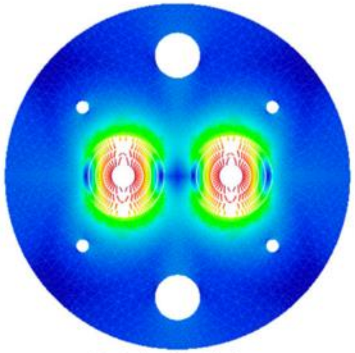




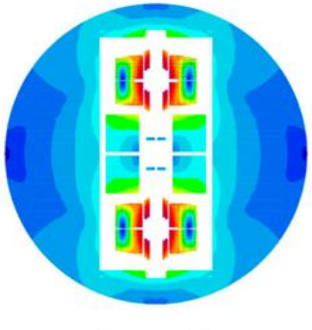
Cosine-theta



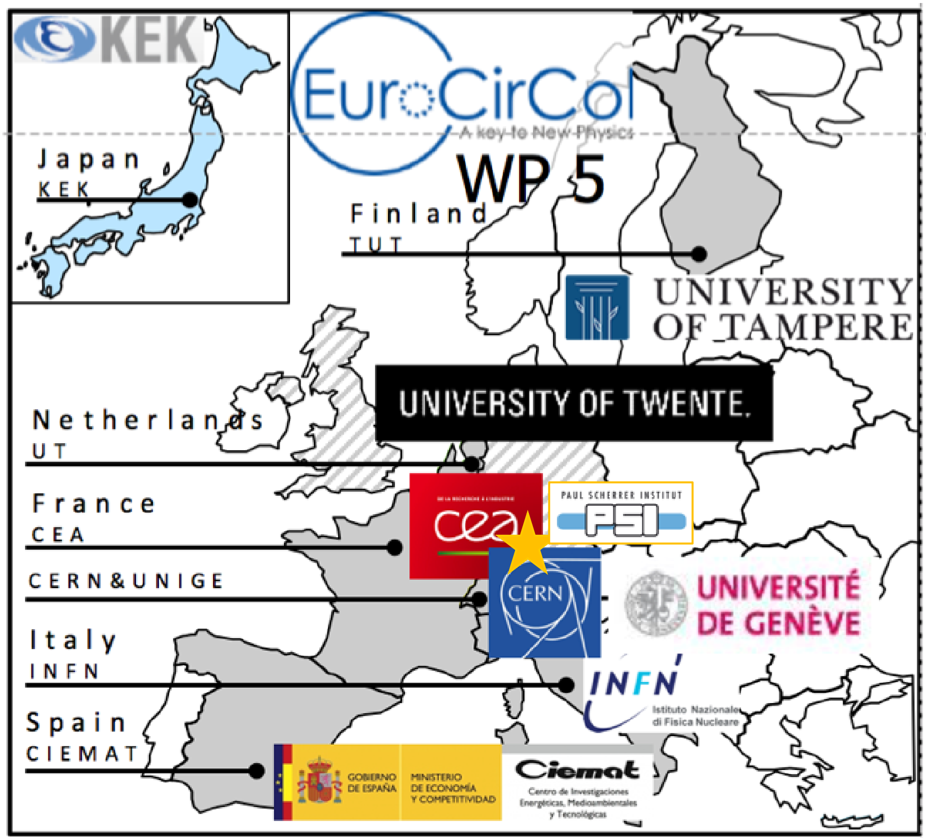
Block-coils



Canted cosine-theta



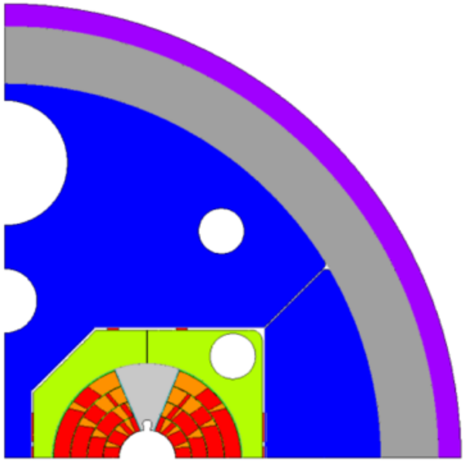
Common-coils

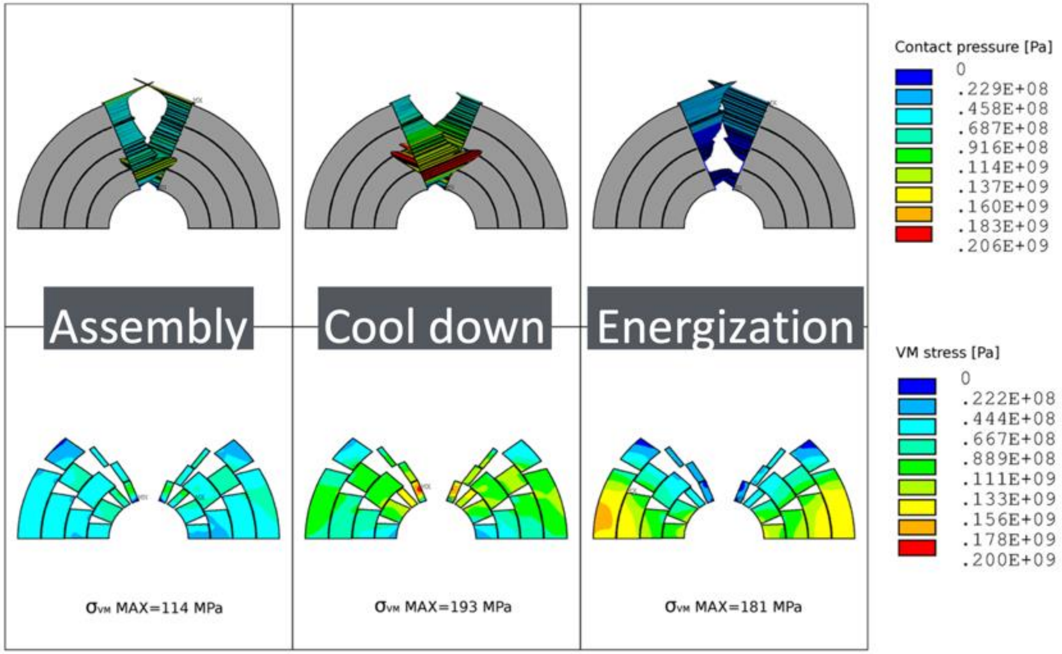


[M. Benedikt et al., *FCC Conceptual Design Report*, Vol. 3 – The Hadron Collider (FCC-hh), January 2019.]

Full Pre-Stress Paradigm

- A lesson learned from the Nb-Ti era.
- Keep coils under compression at all stages of operation → avoid stick-slip motion.
  - Forces scale quadratically with field. For 16 T dipole, forces equivalent of 1.5 kt/m pull coil-halves apart.
  - 10 µm abrupt movement is enough to cause quench.
- However, need to limit stress on Nb_3Sn to 150-200 MPa.

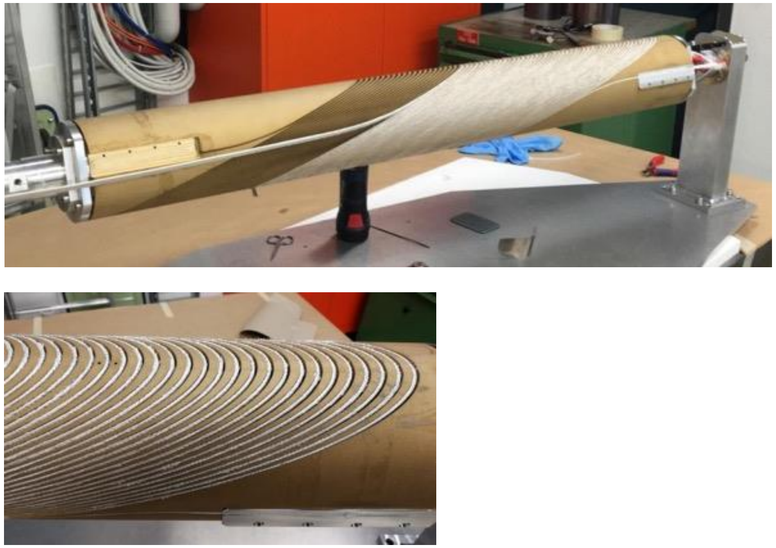




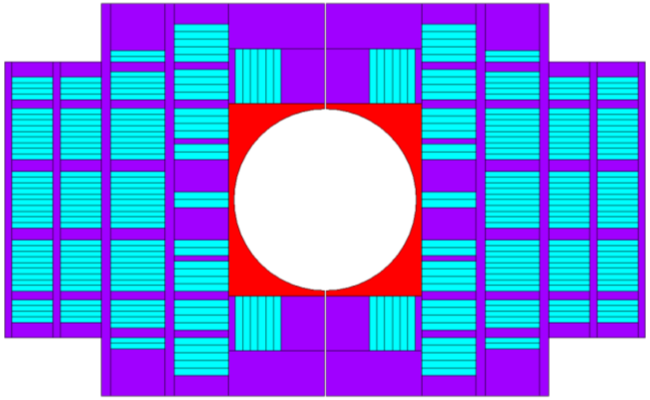
[S. Farinon et al., in M. Benedikt et al., *FCC Conceptual Design Report*, Vol. 3 – The Hadron Collider (FCC-hh), January 2019.]

Stress Management Paradigm

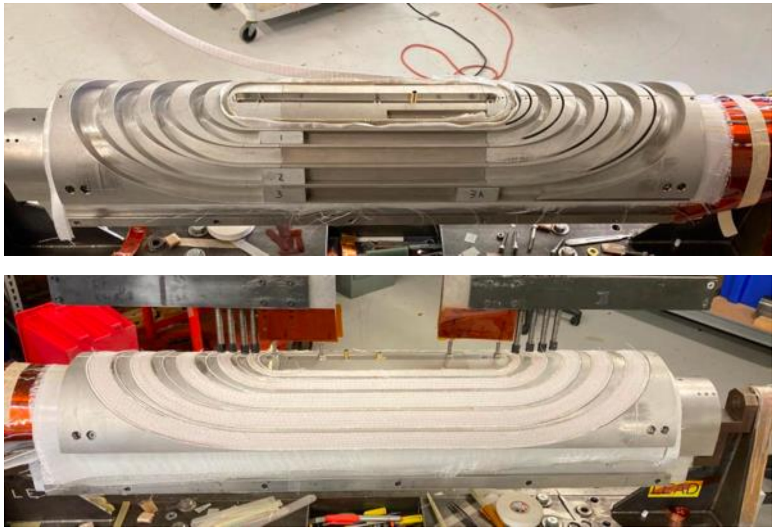
- For stress-managed coils, the winding mandrel acts as an endo-skeleton, intercepting forces, conferring rigid support, and protecting the conductor.
- Stress-managed coils see (nearly) no stress before powering.
- The mandrel acts as winding, reaction, and impregnation tooing.
- CCT is the extreme case with force interception at every single turn.



[CCT winding, G. Montenero]



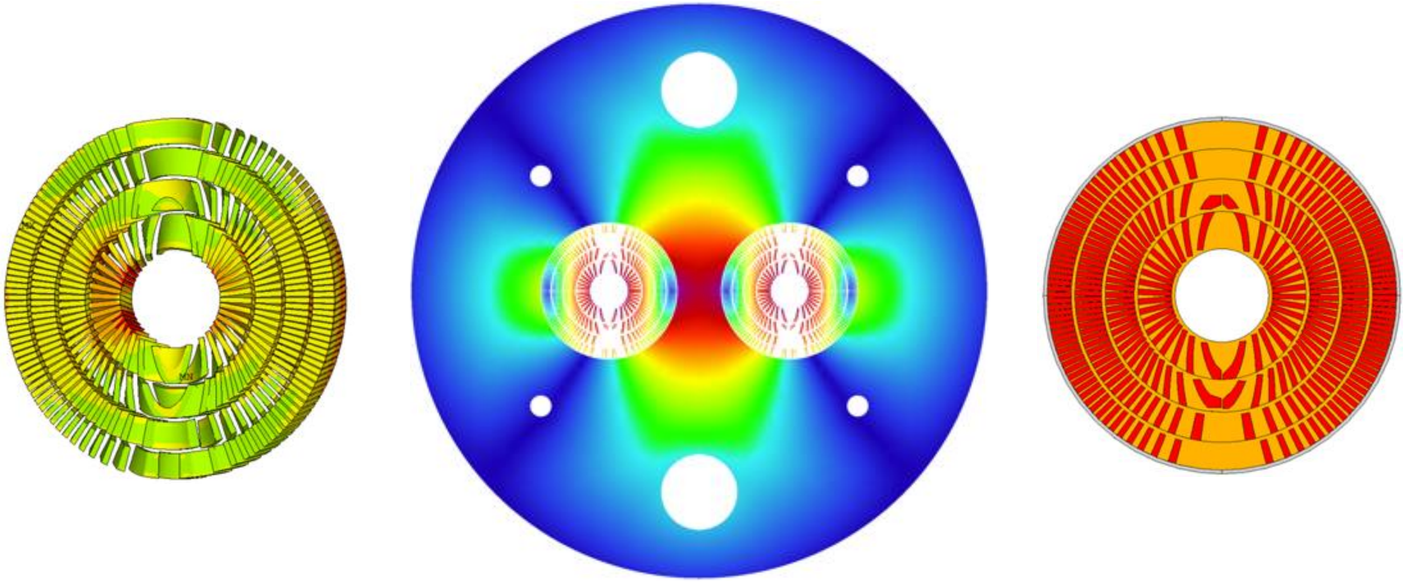
[Stress-managed common-coil concept, D. Araujo]



[SMCT winding; courtesy of A. Zlobin and I. Novitski, FNAL]

Design Goal for CHART HFM R&D

- EuroCirCol Design Goal: Shared specs and *minimization of conductor volume*.
- Stress Management adds mechanical margins and dilutes current density.
- CCT has 1/3 lower conductor stress (135 MPa) for 20% more conductor vol.



[B. Auchmann et al., *Electromechanical Design of a 16-T CCT Twin-Aperture Dipole for FCC*, IEEE Trans. on Appl. SC 28 (April, 2018) no. 3.]

[M. Benedikt et al., *FCC Conceptual Design Report*, Vol. 3 – The Hadron Collider (FCC-hh), pp. 50-52.]

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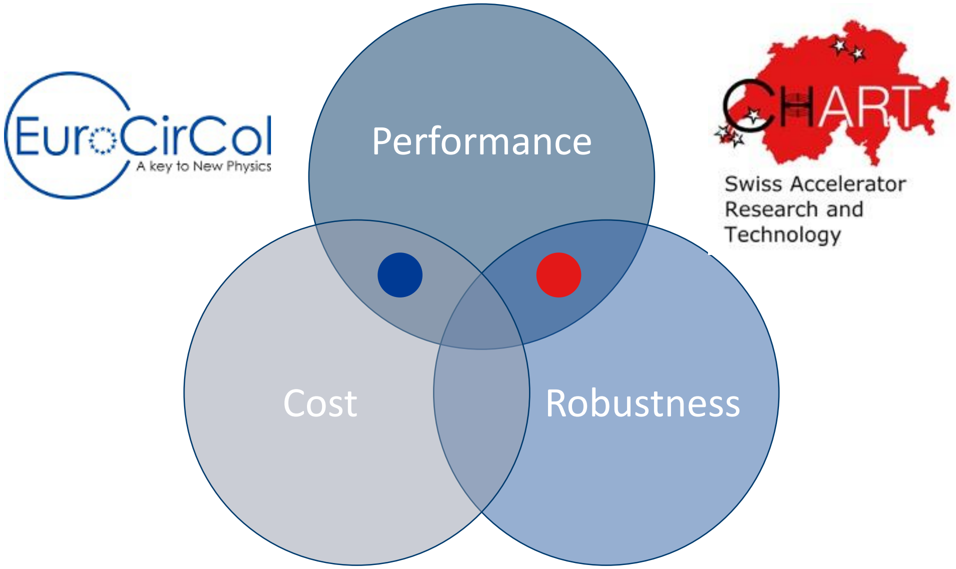


- Conductor cost is not the only cost component: simple procedures, high production yield, and robustness in operation constitute additional savings and accelerate R&D.

Canted Dipole 1 built at PSI

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

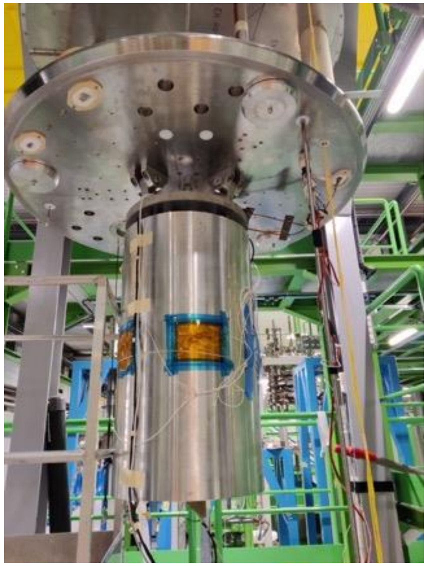
Canted Dipole 1 built at PSI

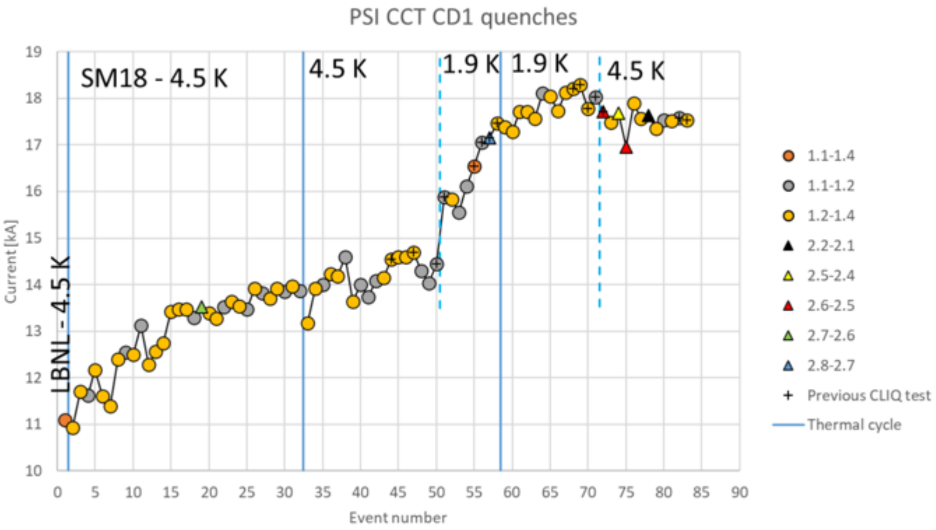
- Magnet design, lab refurbishment, equipment, and commissioning, as well as magnet construction from 02.2017 to 10.2019.

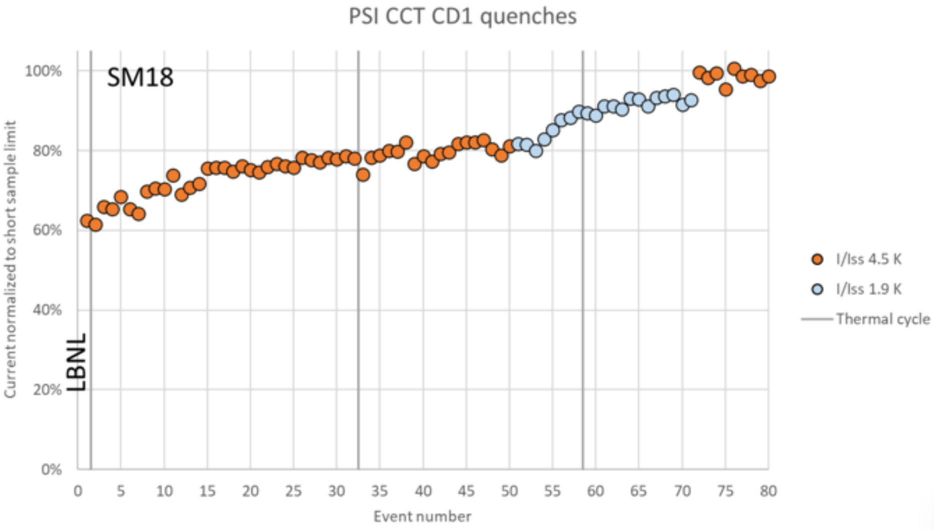
[G. Montenero et al., *Coil Manufacturing Process of the First 1-m-Long Canted-Cosine-Theta (CCT) Model Magnet at PSI*, IEEE Trans. on App. SC., Vol 29(5), 2019.
G. Montenero et al., *Mechanical Structure for the PSI Canted-Cosine-Theta (CCT) Magnet Program*, IEEE Trans. on Appl. SC., Vol 28(3), 2018.]

CD1 Lessons on Robustness and Performance

- The magnet **trained *A LOT***.
- **But, it reached 100% of maximum field at 4.5 K.**
- These were the 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.**



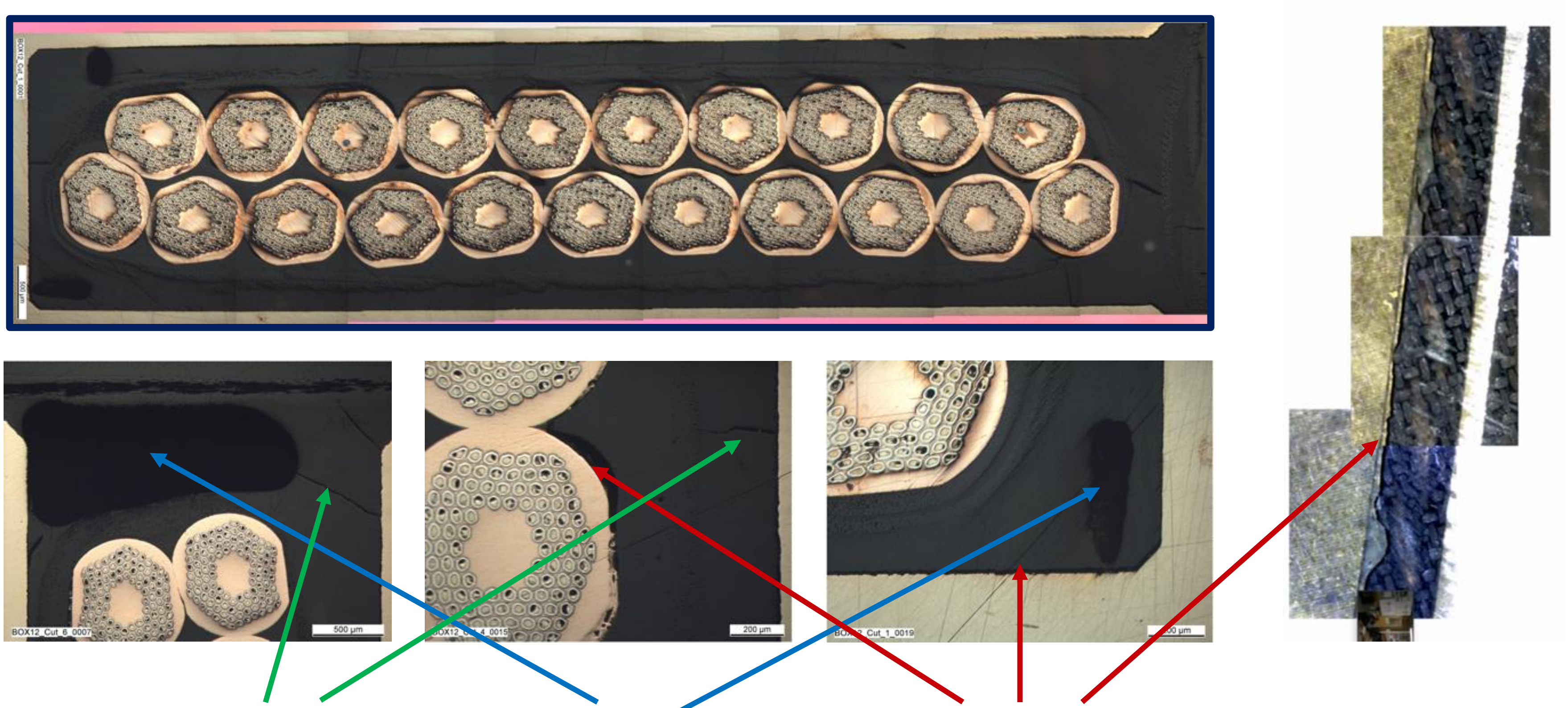




Courtesy F. Mangiarotti (CERN) and M. Daly (PSI).

Training – Root Causes

- Resin cracking.
- De-bonding from winding former or strand diameter.
- Voids due to processing → wire movement and/or crack initiation.

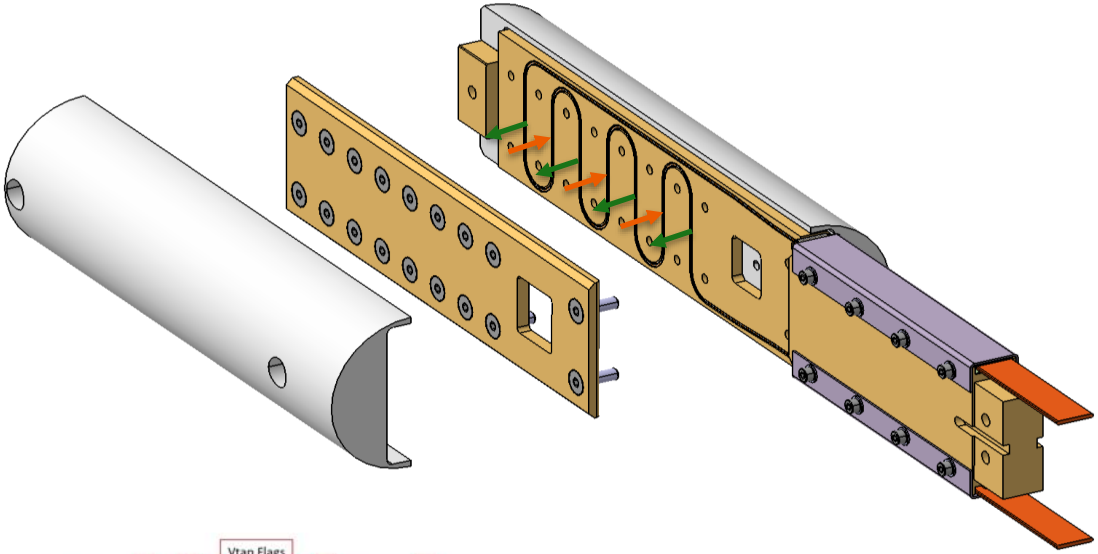


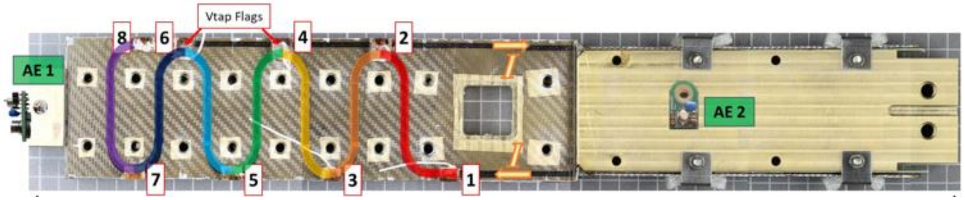
Cracks Voids Surface defects (de-bonding)

[Courtesy of O. Kirby, M. Daly.]

[Courtesy D. Arbelaez, LBNL.]

BOX Program



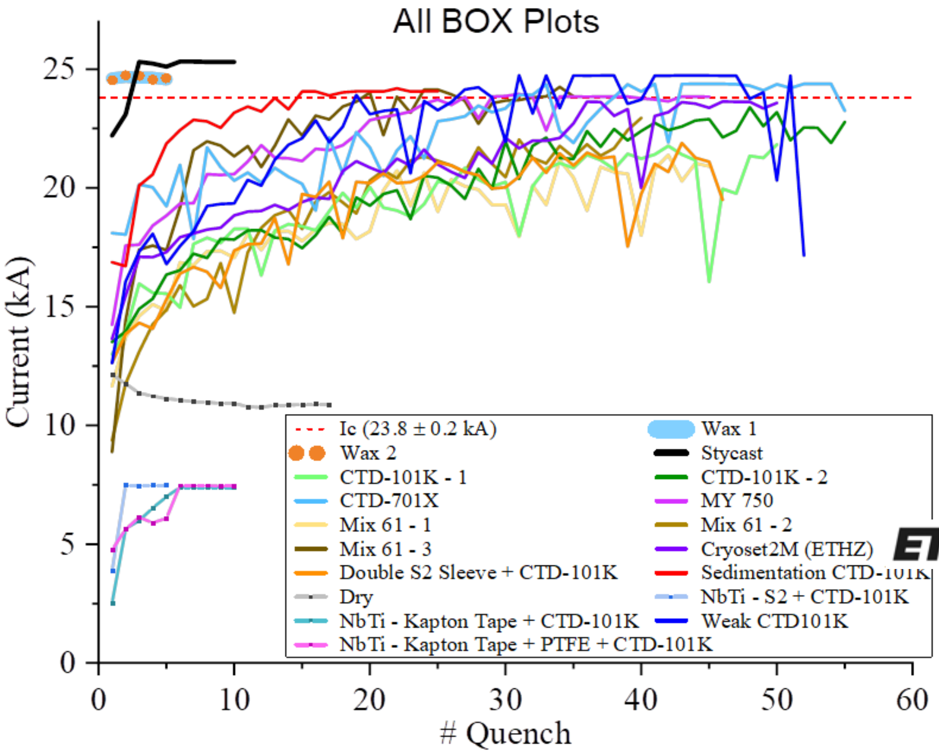


Pictures by M. Daly, S. Sidorov, S. Otten

SC Transformer

11-T solenoid

BOX Program

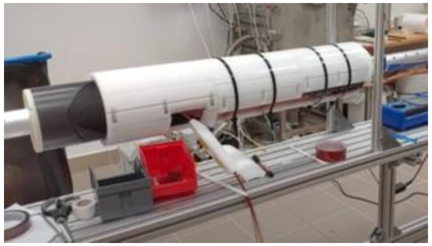
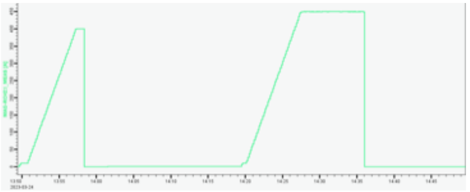


Pictures by M. Daly, S. Sidorov, S. Otten

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),*** with ***18 BOX samples*** successfully manufactured and tested to date.

BOX Findings Implemented in Other Projects:

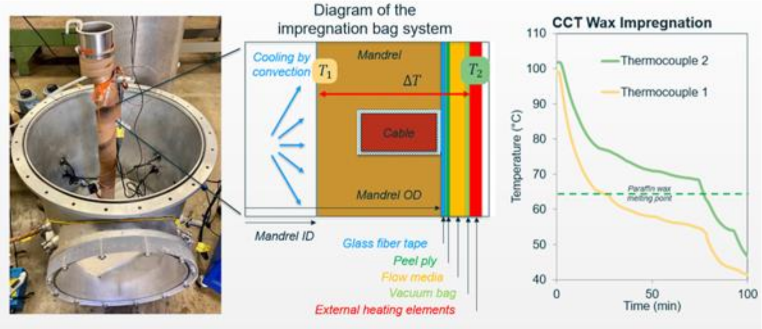
- Wigner Institute and CERN collaboration for SuShi septum for FCC-hh:
  - Wax impregnated CCT required no training to nominal current.


[Courtesy D. Barna et al., Wigner Institute]

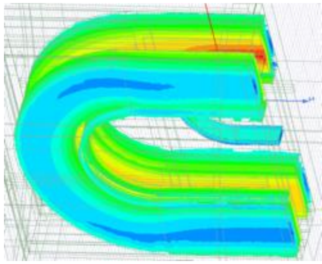
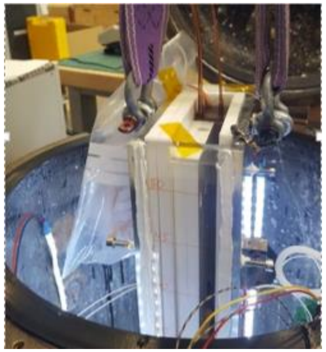
- LBNL's wax impregnated sub-scale (5 T) CCT.
  - First Nb3Sn CCT without training.
  - Next up: filled-epoxysub-scale.

Paraffin wax
(CCT Sub5)



[Courtesy J.L. Rudeiros Fernandez, LBNL]

- PSI's BigBOX: a 13-turn stress-managed racetrack.
  - No training in 9 T background field of BNL's DCC17 facility.

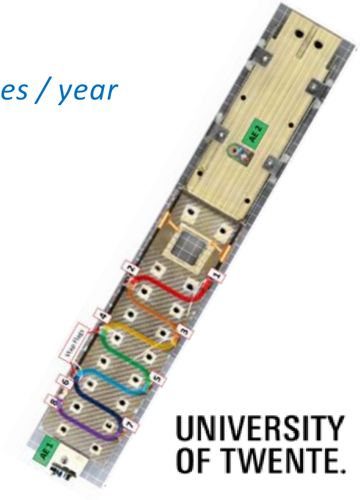




[Courtesy D. Araujo et al]

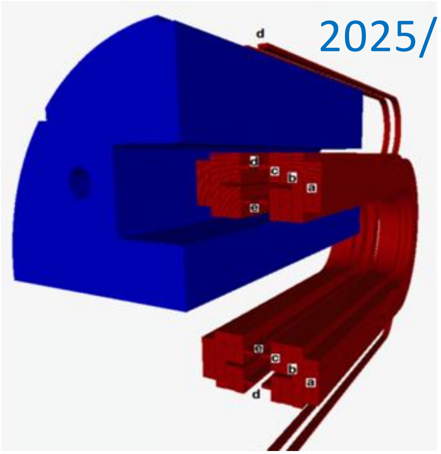
Turnaround, Innovation, and Risk Mitigation

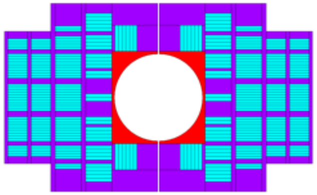
- HFM R&D has suffered from slow turnaround and late feedback on technology.
- “We propose […] a succession of meaningful fast-turnaround demonstrations […]. In this way, new technologies can be tested under realistic conditions at the earliest possible stage, the smallest relevant scale and cost, and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

First deliverable		*#Deliverables / year*
2019	***Materials*** and Composite Samples (not powered)	100s
2020	***Powered Samples*** and Mechanical Models	10
2023	***Sub-scale Magnets*** (5 T)	2-3
2025/26	***Short Magnets Ultimate Field*** (14…16T)	0.5-1
	Long Magnets Ultimate Field Magnets (14…16 T)	



Long-magnet infrastructure available only at CERN.





[Q. Xu, FCC Week 2016]

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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)”

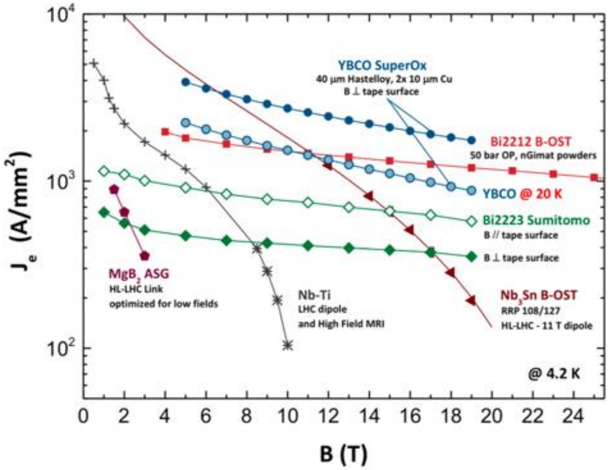


Fig. 2.3: Engineering current density J_e vs. magnetic field for several LTS and HTS conductors at 4.2 K. Latest results for REBCO tapes are reported both at 4.2 K as well as 20 K.

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

ReBCO Tape and ReBCO Cables

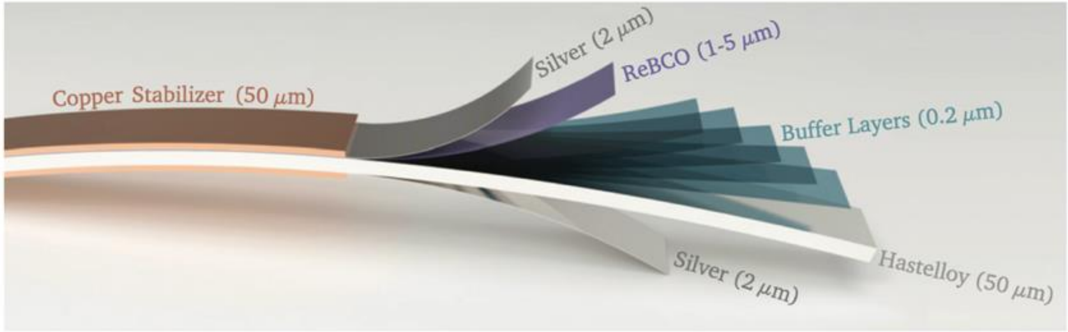


Figure 1.7. *Material composition of ReBCO coated conductor. For visual clearness the tape is cut in half along its length such that the inside becomes visible. In reality the copper and the silver layers fully surround the hastelloy substrate carrier.*

LTS wires have filament sizes of few microns (Nb-Ti) to 50 µm (Nb_3Sn). ReBCO tapes are 2-12 mm wide. Screening currents and associated losses are substantially increased.

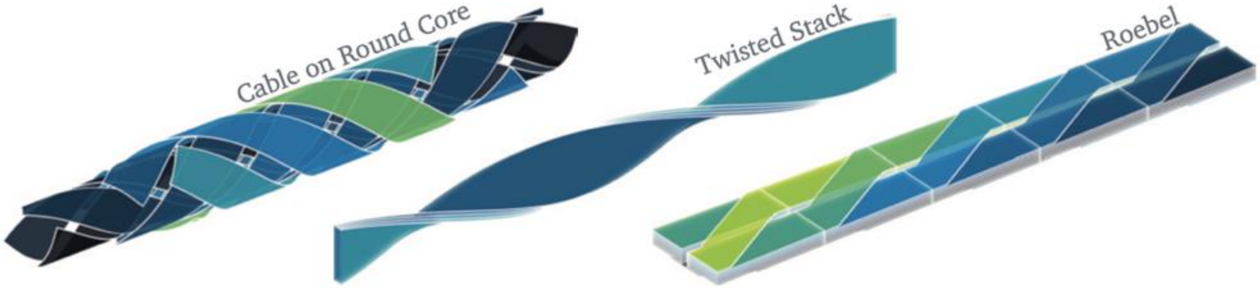
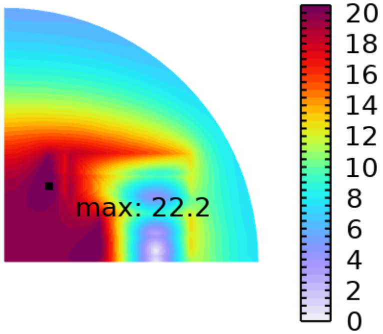


Figure 1.10. *Three different geometries for assembling a cable with ReBCO coated conductor. Also refer to Table 1.2.*

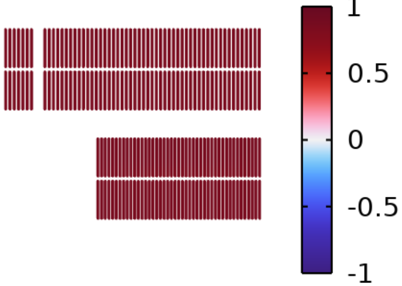
[J. v. Nugteren, High Temperature Superconductor Accelerator Magnets. PhD thesis, UTwente, 2016.]

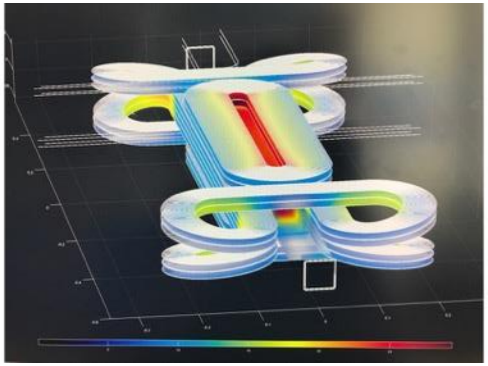
A First Look at Ramp Losses

- 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]

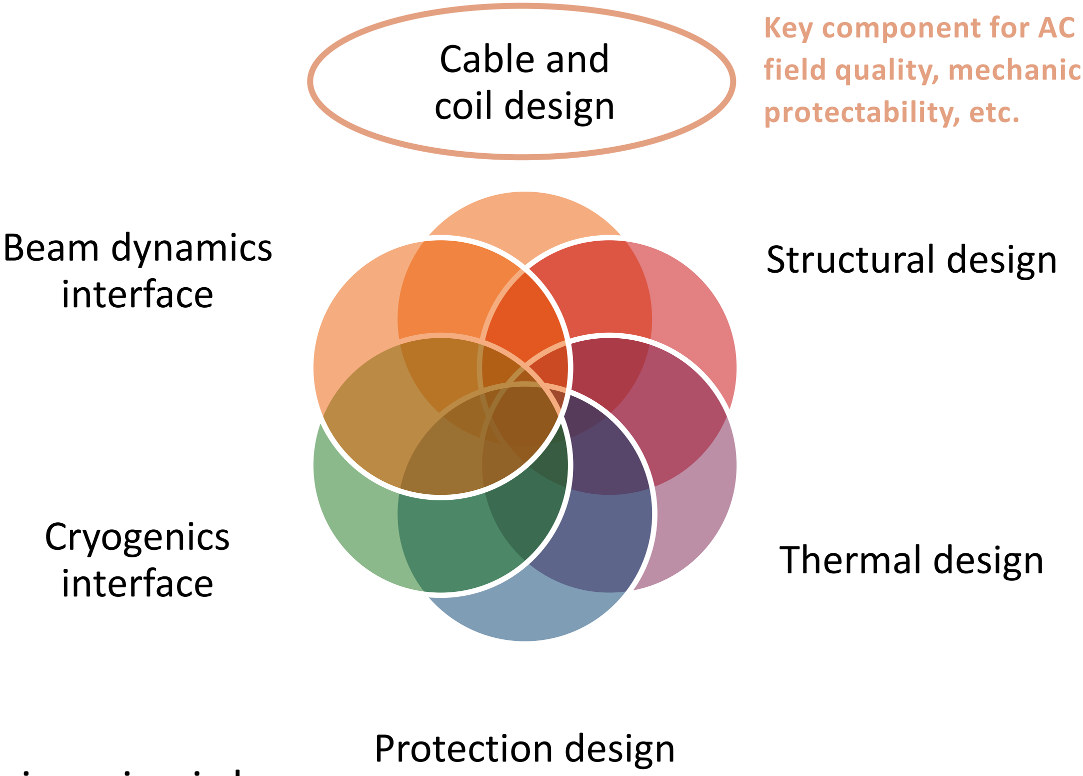




[Courtesy G. Kirby, J. v. Nugteren, J. S. Murtomäki, et al.]

Systems Engineering Challenge

Interrelated elements of an HTS HFM technology:



Cable and coil design

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

Beam dynamics interface

Structural design

Cryogenics interface

Thermal design

Protection design

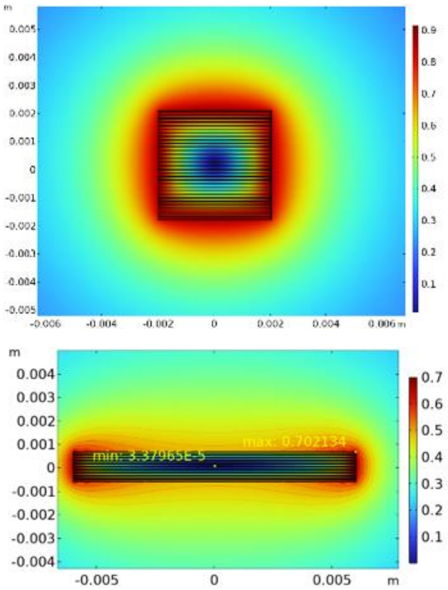
Systems engineering is key.

- CHART/MagNum at ETHZ has developed pyMBSE, a python package for **Model-Based Systems Engineering**.

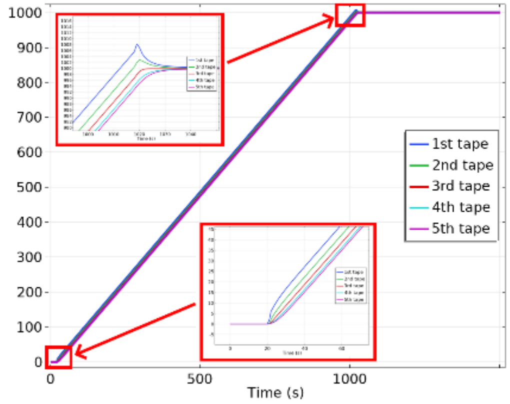
Roadmap Towards HTS for HFM

Innovation funnel for HTS HFM R&D:

First deliverable		*#Deliverables / year*
2023	***Materials*** and ***Numerical Design Studies***	100s
2023	***Powered Cable Samples***	3
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)	



Magnetic field.



Current distribution Jz through tapes in the stack.

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FCC-ee NC Magnets

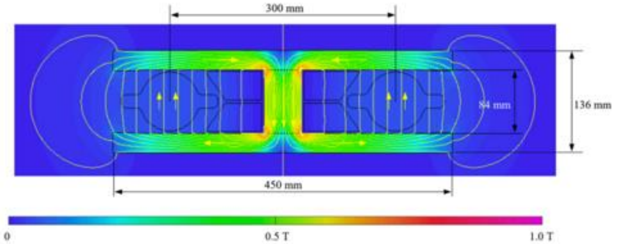
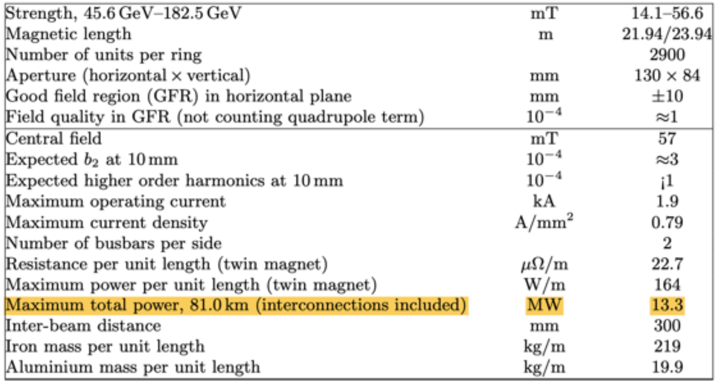


Fig. 3.1. Cross-section of the main bending magnet; the flux density corresponds to 57 mT in the gap; the outline of vacuum chambers with side winglets is also shown.

2900 magnets
Strength: 57 mT
Apert.: 130x84 mm
Power: 13.3 MW

Table 3.1. Parameters of the main bending magnets.



Strength, 45.6 GeV–182.5 GeV	mT	14.1–56.6
Magnetic length	m	21.94/23.94
Number of units per ring		2900
Aperture (horizontal × vertical)	mm	130 × 84
Good field region (GFR) in horizontal plane	mm	±10
Field quality in GFR (not counting quadrupole term)	10^{-4}	≈1
Central field	mT	57
Expected b_2 at 10 mm	10^{-4}	≈3
Expected higher order harmonics at 10 mm	10^{-4}	¡1
Maximum operating current	kA	1.9
Maximum current density	A/mm^2	0.79
Number of busbars per side		2
Resistance per unit length (twin magnet)	$\mu\Omega$/m	22.7
Maximum power per unit length (twin magnet)	W/m	164
Maximum total power, 81.0 km (interconnections included)	MW	13.3
Inter-beam distance	mm	300
Iron mass per unit length	kg/m	219
Aluminium mass per unit length	kg/m	19.9

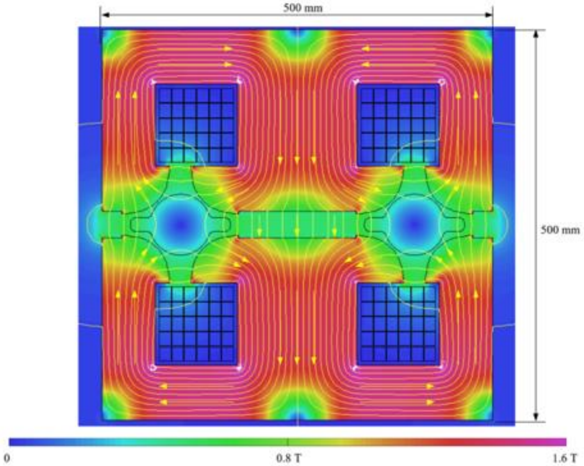
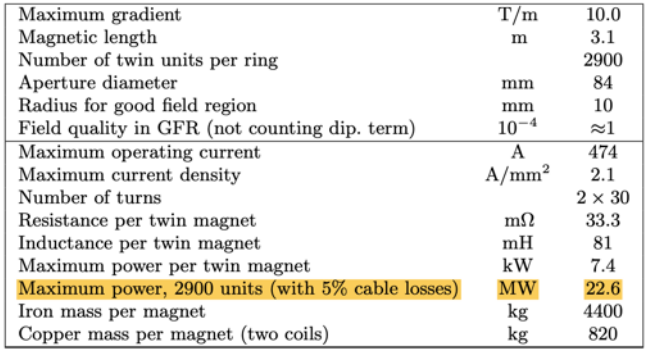


Fig. 3.3. Cross-section of the FCC-ee main quadrupole, for a 10 T/m gradient.

2900 magnets
Strength: 10 T/m
ID: 84 mm
Power: 22.6 MW

Table 3.2. Parameters of the main quadrupole magnets.



Maximum gradient	T/m	10.0
Magnetic length	m	3.1
Number of twin units per ring		2900
Aperture diameter	mm	84
Radius for good field region	mm	10
Field quality in GFR (not counting dip. term)	10^{-4}	≈1
Maximum operating current	A	474
Maximum current density	A/mm^2	2.1
Number of turns		2 × 30
Resistance per twin magnet	mΩ	33.3
Inductance per twin magnet	mH	81
Maximum power per twin magnet	kW	7.4
Maximum power, 2900 units (with 5% cable losses)	MW	22.6
Iron mass per magnet	kg	4400
Copper mass per magnet (two coils)	kg	820

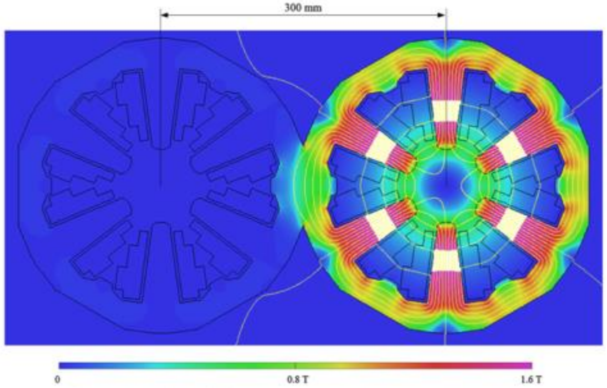
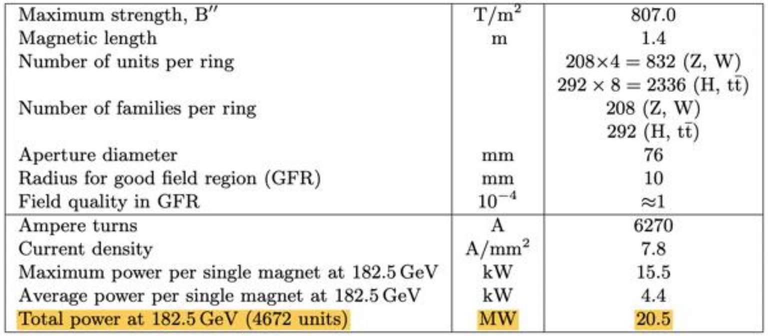


Fig. 3.6. Cross-section of the FCC-ee main sextupole magnet. The position of the sextupole for the other beam is outlined on the left.

4672 magnets
Strenth: 807 T/m2
ID: 76 mm
Power: 20.5 MW

Table 3.3. Parameters of the main sextupole magnets.

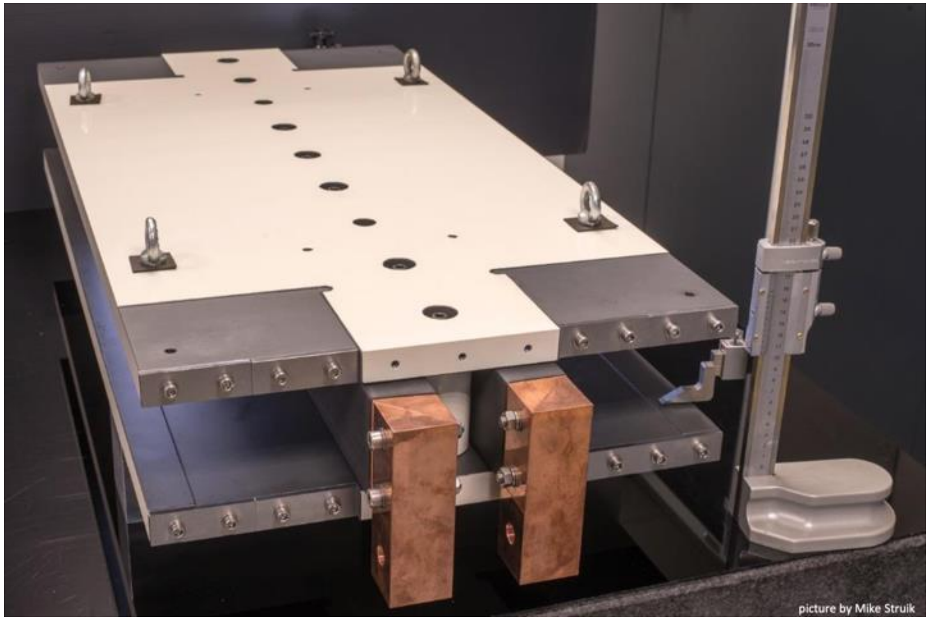


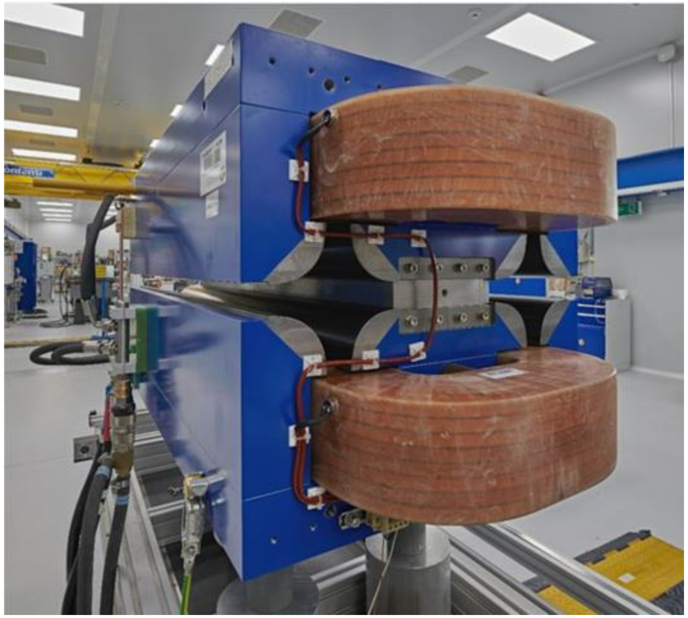
Maximum strength, B″	T/m^2	807.0
Magnetic length	m	1.4
Number of units per ring		208×4 = 832 (Z, W) 292 × 8 = 2336 (H, $t\bar{t}$)
Number of families per ring		208 (Z, W) 292 (H, $t\bar{t}$)
Aperture diameter	mm	76
Radius for good field region (GFR)	mm	10
Field quality in GFR	10^{-4}	≈1
Ampere turns	A	6270
Current density	A/mm^2	7.8
Maximum power per single magnet at 182.5 GeV	kW	15.5
Average power per single magnet at 182.5 GeV	kW	4.4
Total power at 182.5 GeV (4672 units)	MW	20.5

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

FCC-ee Main Magnet Prototypes

- “Magnetically coupled [twin-]apertures for main dipole and quadrupole magnets offer significant energy savings and reduce the number of coils, thus simplifying the construction of these magnets.”

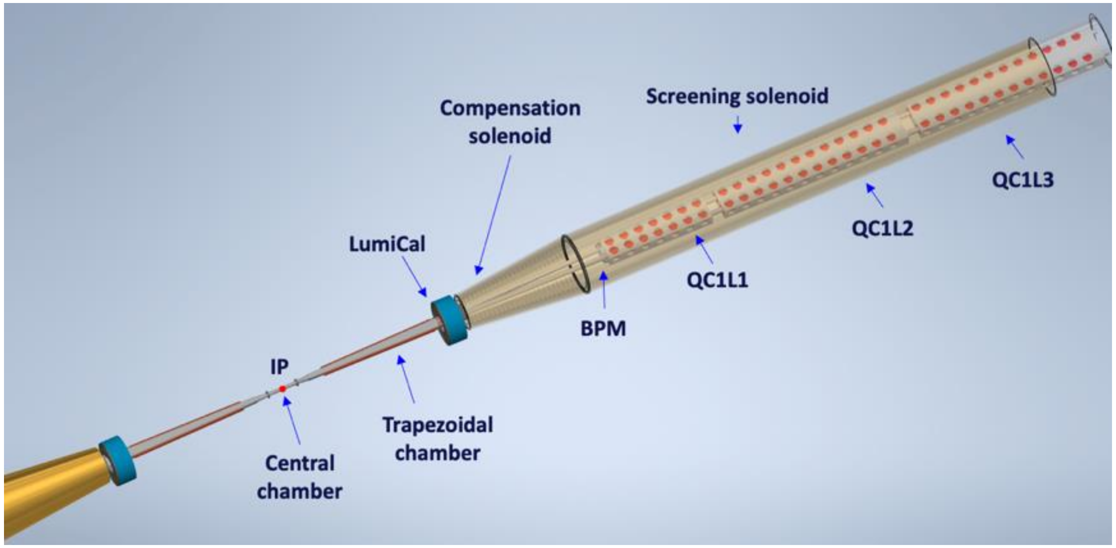




[A. Milanese, M. Bohdanowicz, Twin aperture bending magnets and quadrupoles for FCC-ee, August 2017 https://indico.cern.ch/event/445667/contributions/2561905/attachments/1514144/2362295/FCC_ee_warm_magnets.pdf]

FCC-ee Machine-Detector-Interface

- 22 superconducting magnets:
  - 6 final focus (ID 40 mm, 100 T/m),
  - 12 correctors
  - 2 compensation solenoids (4.9 T, 118-195 mm tapered)
  - 2 screening solenoids (2 T, OD 390 mm)
- Most located SC magnets in the heart of the detector.
- High complexity due to multiple strongly coupled systems: IP, detector solenoid (forces and protection), mechanics and alignment, beam dynamics, etc.



[M. Boscolo, Pre-engineering design review and roadmap discussion for FCC-ee IR magnets, April 2022]

FCC-ee Machine-Detector-Interface

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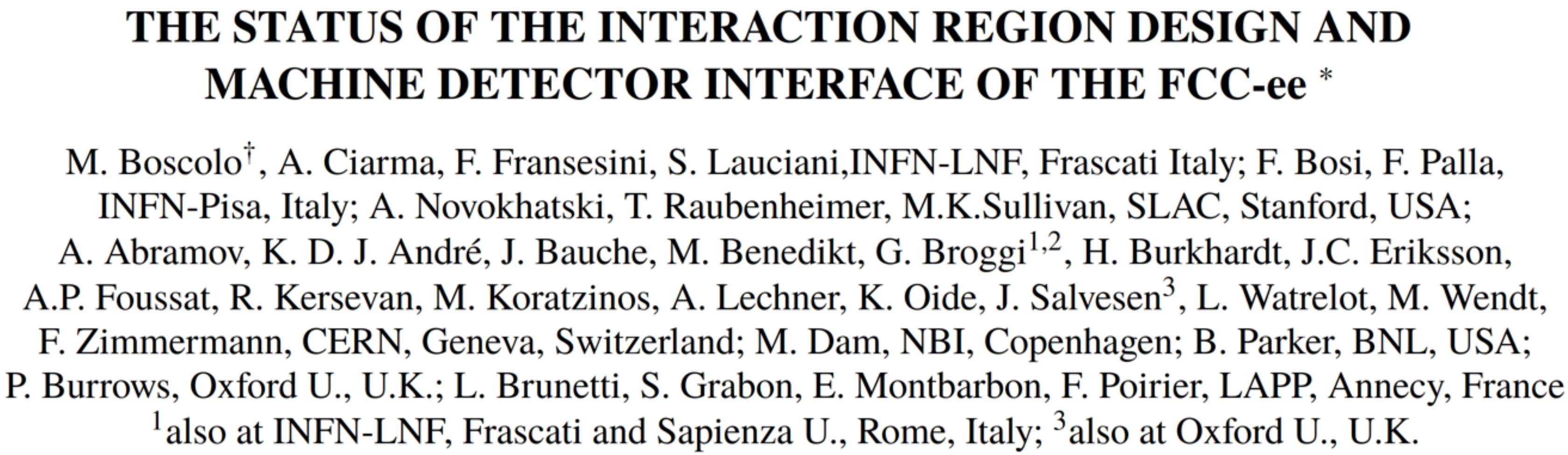


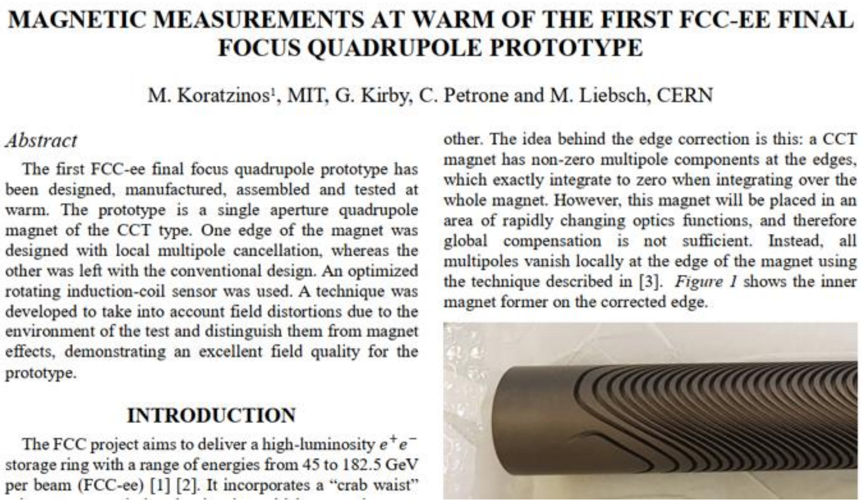
THE STATUS OF THE INTERACTION REGION DESIGN AND MACHINE DETECTOR INTERFACE OF THE FCC-ee *

M. Boscolo†, A. Ciarma, F. Fransesini, S. Lauciani,INFN-LNF, Frascati Italy; F. Bosi, F. Palla,
INFN-Pisa, Italy; A. Novokhatski, T. Raubenheimer, M.K.Sullivan, SLAC, Stanford, USA;
A. Abramov, K. D. J. André, J. Bauche, M. Benedikt, G. Broggi[1,2], H. Burkhardt, J.C. Eriksson,
A.P. Foussat, R. Kersevan, M. Koratzinos, A. Lechner, K. Oide, J. Salvesen[3], L. Watrelot, M. Wendt,
F. Zimmermann, CERN, Geneva, Switzerland; M. Dam, NBI, Copenhagen; B. Parker, BNL, USA;
P. Burrows, Oxford U., U.K.; L. Brunetti, S. Grabon, E. Montbarbon, F. Poirier, LAPP, Annecy, France
[1]also at INFN-LNF, Frascati and Sapienza U., Rome, Italy; [3]also at Oxford U., U.K.

[M. Boscolo, Pre-engineering design review and roadmap discussion for FCC-ee IR magnets, April 2022]

FCC-ee Final Focus Quadrupoles

- Current final focus design based on CCT concept.
- Room-temperature measurement of field quality < 0.15 units.
- May soon be impregnated with wax at PSI.
- To be tested at cold at CERN.



MAGNETIC MEASUREMENTS AT WARM OF THE FIRST FCC-EE FINAL FOCUS QUADRUPOLE PROTOTYPE

M. Koratzinos[1], MIT, G. Kirby, C. Petrone and M. Liebsch, CERN

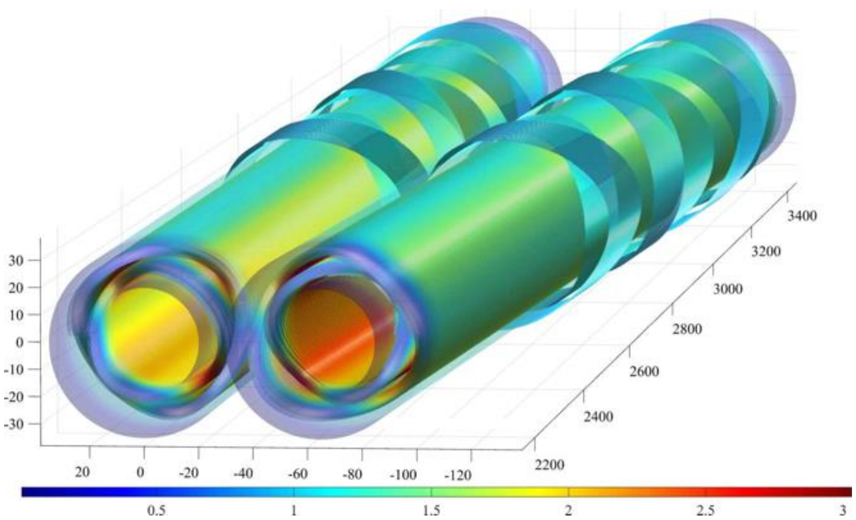
Abstract

The first FCC-ee final focus quadrupole prototype has been designed, manufactured, assembled and tested at warm. The prototype is a single aperture quadrupole magnet of the CCT type. One edge of the magnet was designed with local multipole cancellation, whereas the other was left with the conventional design. An optimized rotating induction-coil sensor was used. A technique was developed to take into account field distortions due to the environment of the test and distinguish them from magnet effects, demonstrating an excellent field quality for the prototype.

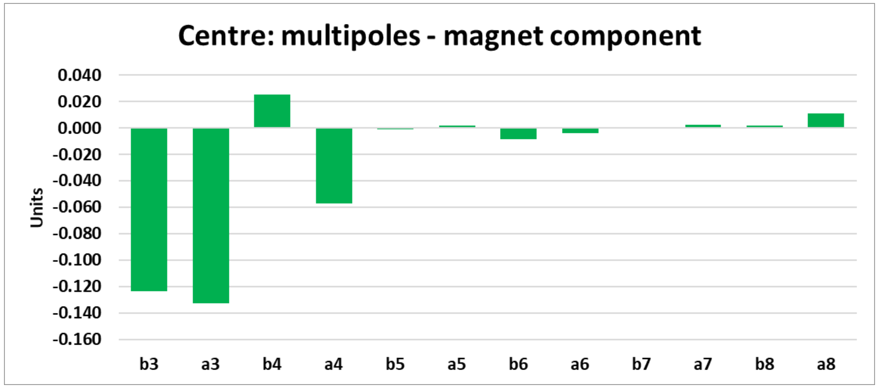
INTRODUCTION

The FCC project aims to deliver a high-luminosity e^+e^- storage ring with a range of energies from 45 to 182.5 GeV per beam (FCC-ee) [1] [2]. It incorporates a "crab waist"

other. The idea behind the edge correction is this: a CCT magnet has non-zero multipole components at the edges, which exactly integrate to zero when integrating over the whole magnet. However, this magnet will be placed in an area of rapidly changing optics functions, and therefore global compensation is not sufficient. Instead, all multipoles vanish locally at the edge of the magnet using the technique described in [3]. *Figure 1* shows the inner magnet former on the corrected edge.



[M. Koratzinos, Pre-engineering design review and roadmap discussion for FCC-ee IR magnets, April 2022]



Overview

- CHART – Swiss Accelerator Research and Technology
- CHART contributions to FCChh HFMs
  - Nb_3Sn
  - HTS (ReBCO)
- FCCee
  - Baseline magnet system
    - Arc cells
    - MDI
  - CHART contributions to HTS-based feasibility studies
    - P^3: Positron source capture solenoid
    - HTS4: HTS Short Straight Section
- Muon Collider magnet requirements
- PSI Synergies

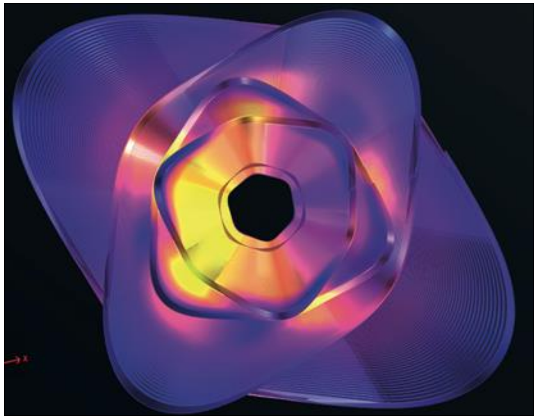
HTS4: **HTS S**hort **S**traight **S**ections for FCC-ee

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

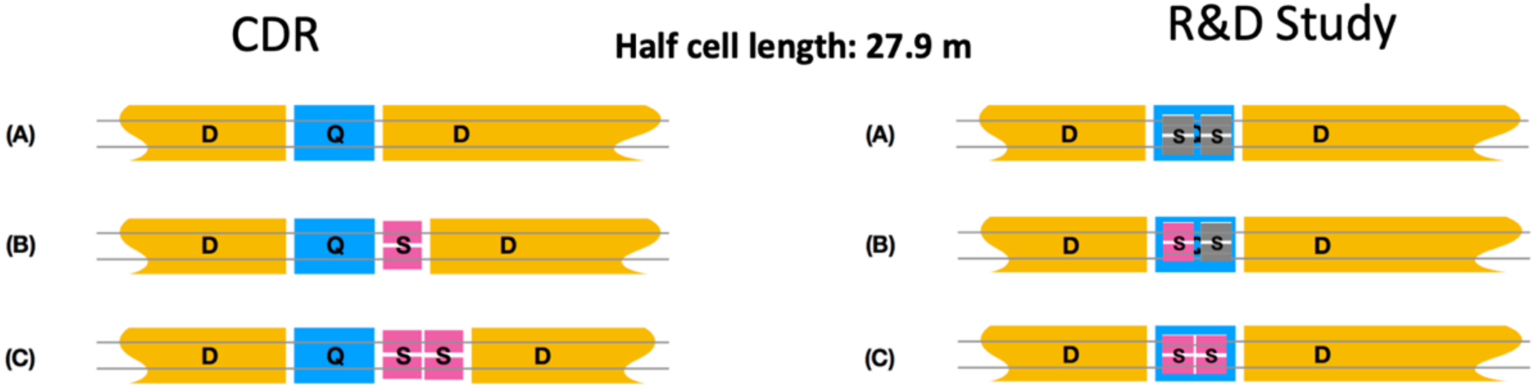
Challenges:

- **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



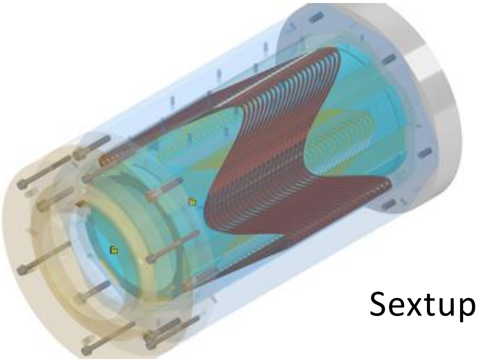
HTS4: HTS Short Straight Sections for FCC-ee

- 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

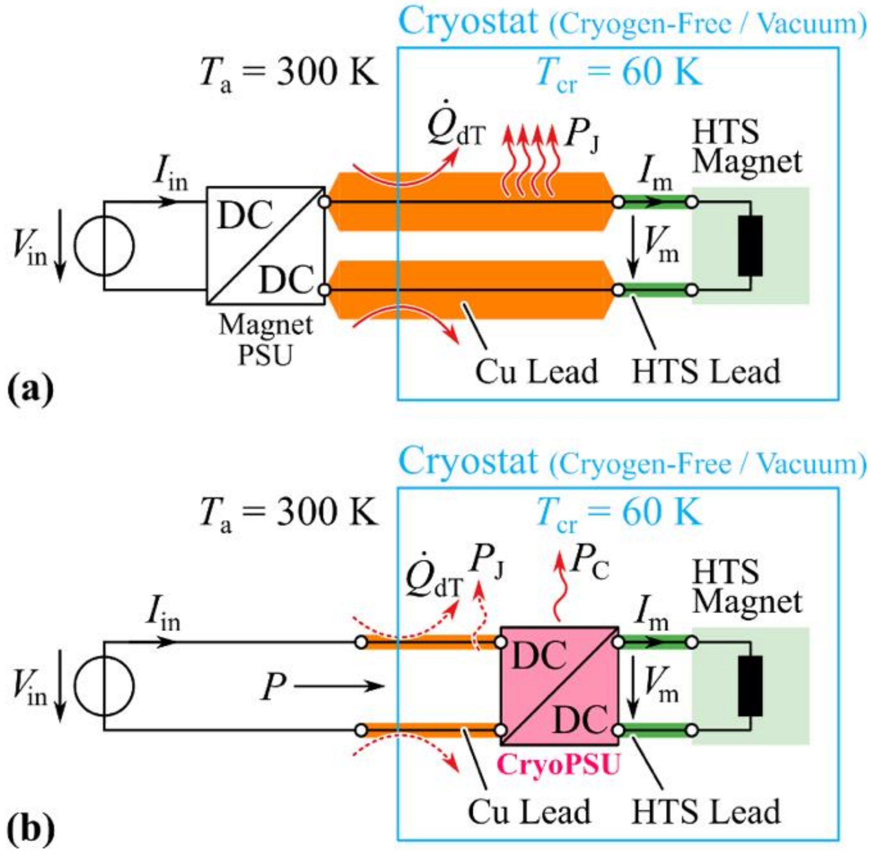
- Two competing sub-scale demonstrators are under preparation.



Courtesy, M. Koratzinos.
Sextupole CCT subscale magnet.

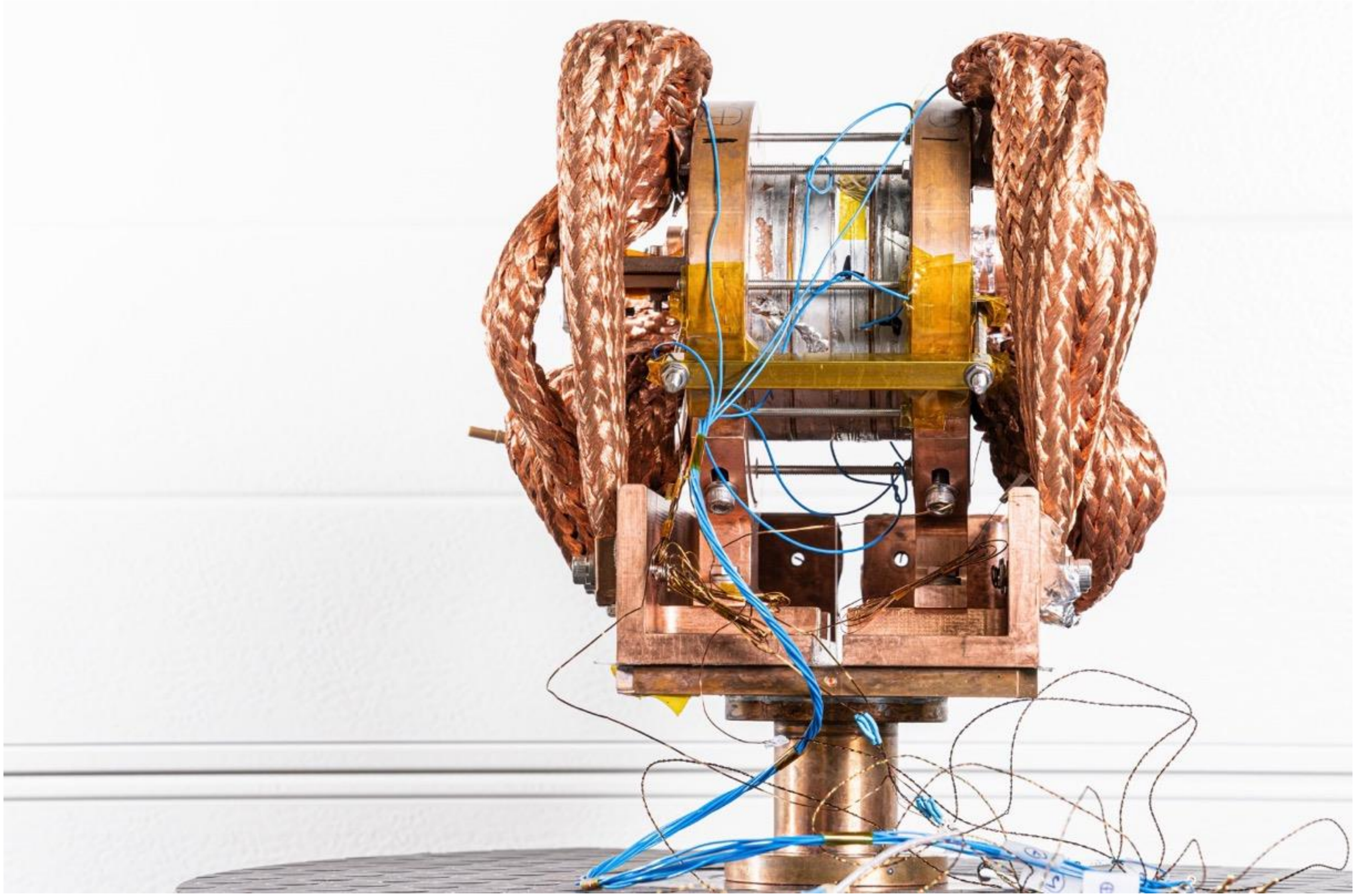
Cryogenic Power Supply CHART Project at ETHZ

- 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



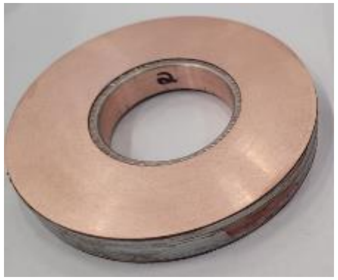
4-Stack Technology Solenoid Cold Test

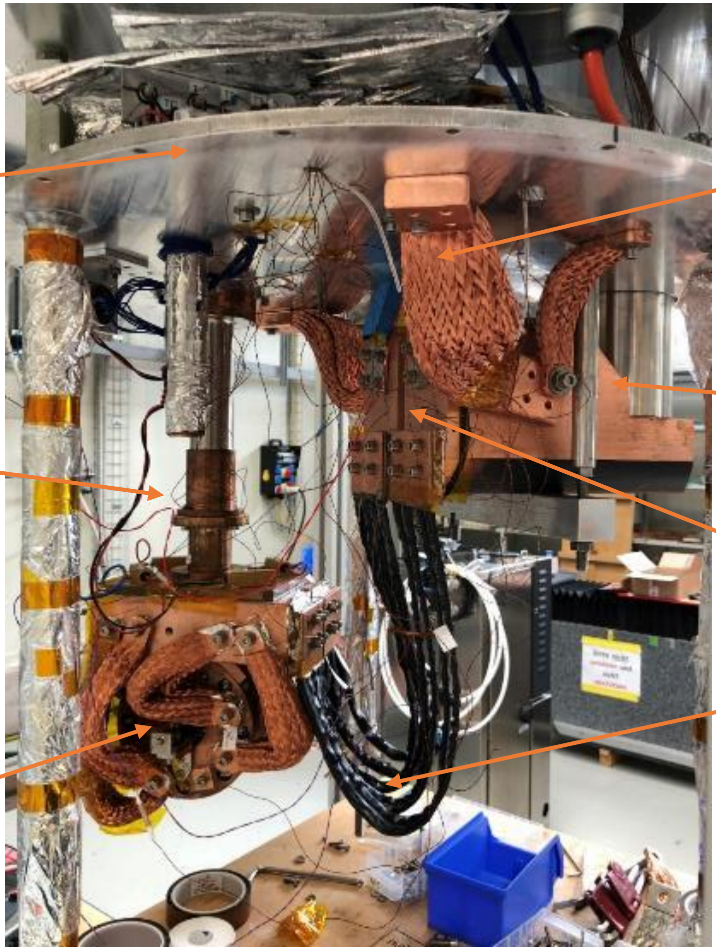
- Successful test in cryogen-free test station of 4-pancake HTS NI solenoid, built in-house at PSI and using licensed Tokamak Energy Ltd technology.
- Coil reached **18.2 T** in the center, **20.3 T** on the conductor at the maximum current of the power converter of **2 kA** and **12 K** coil temp.
-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

Tokamak Energy

Diameter: 100 mm
Aperture: 50 mm

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





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

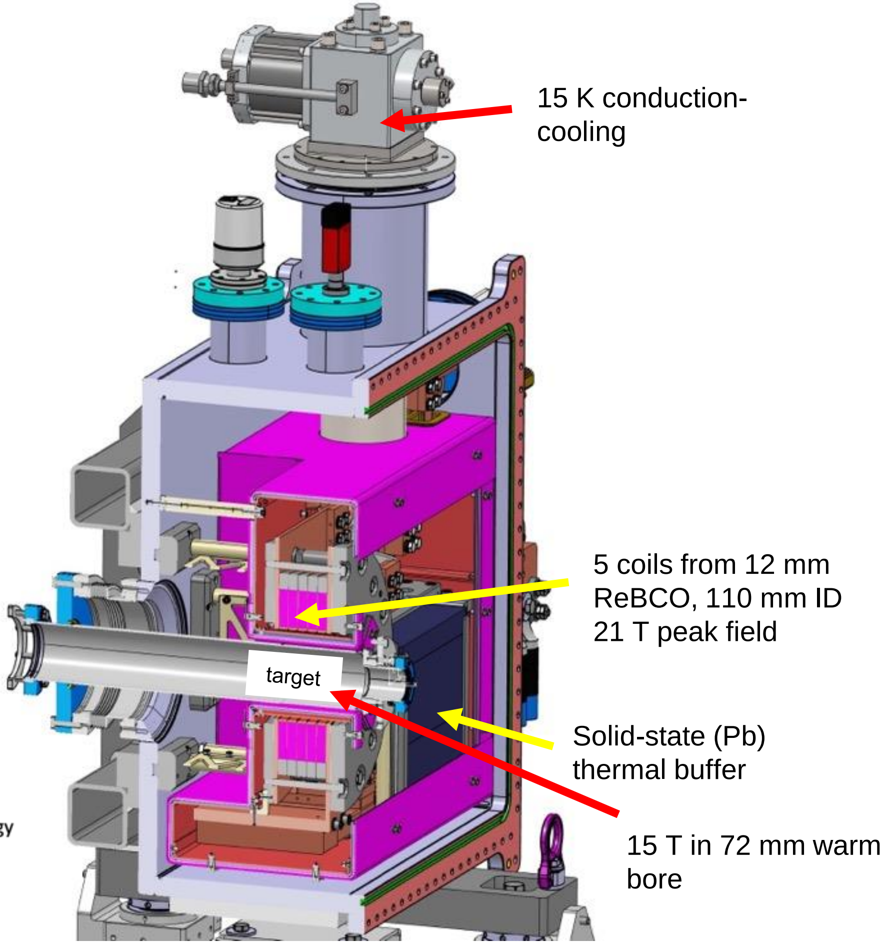
FCCee Injector Study:P^3 (PSI Positron Production)

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

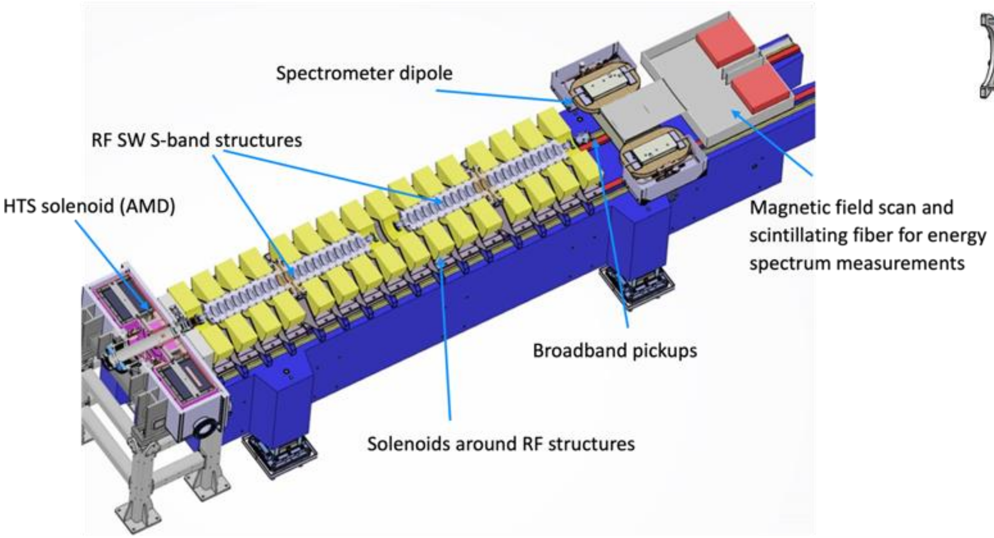
- stable DC operation,
- high thermal conduction due to solder impregnation to extract heat deposited in coils,
- radiation robustness due to absence of insulators.

Manufacturing/commissioning Q3’23-Q2’24

Experiment at PSI’s SwissFEL 2025/26



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



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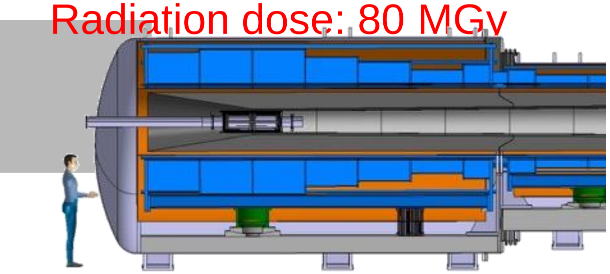
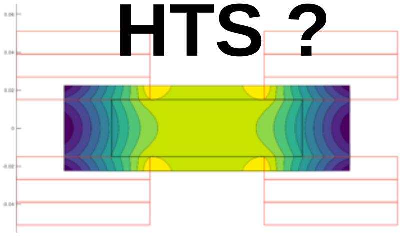
Muon Collider magnets

20 T, 200 mm
Radiation heat load ≈ 5…10 kW
Radiation dose: 80 MGy

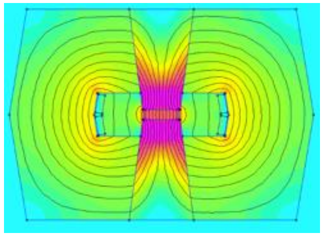
HTS !



HTS ?

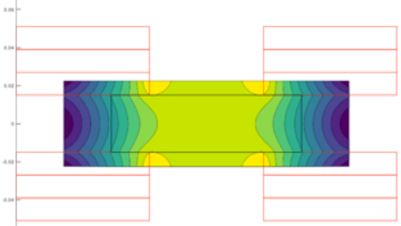


NC ±1.8 T, 400 Hz
100 mm x 30 mm

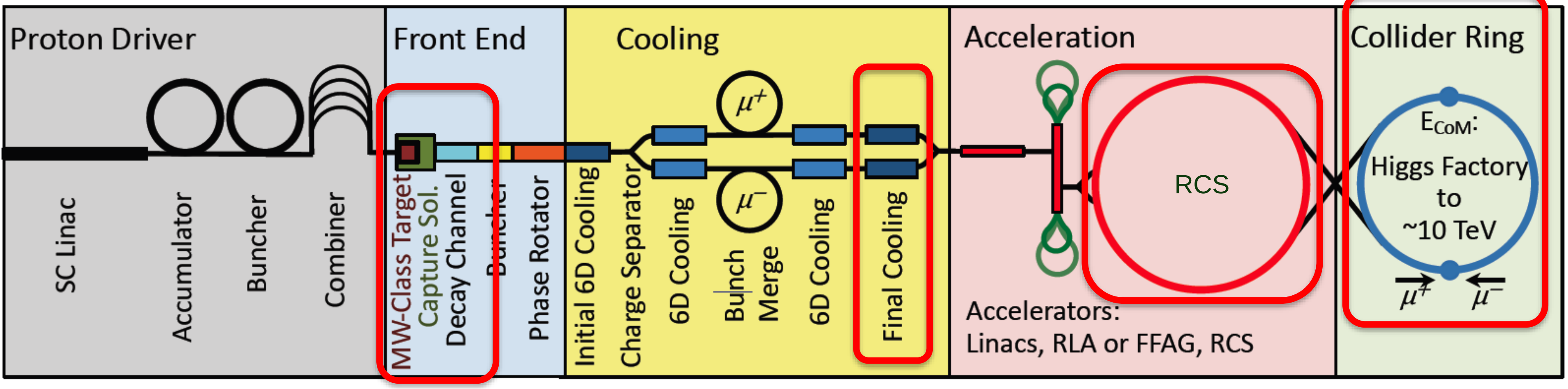


SC < 10T

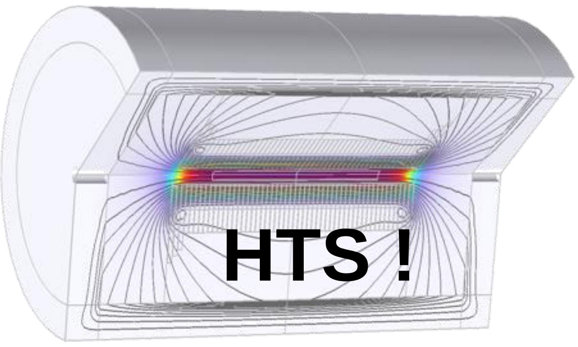
100 mm x 30 mm



SC dipole | NC dipole | NC dipole | SC dipole

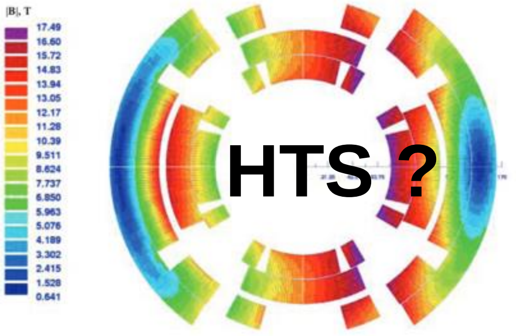


> 40 T, 60 mm



HTS !

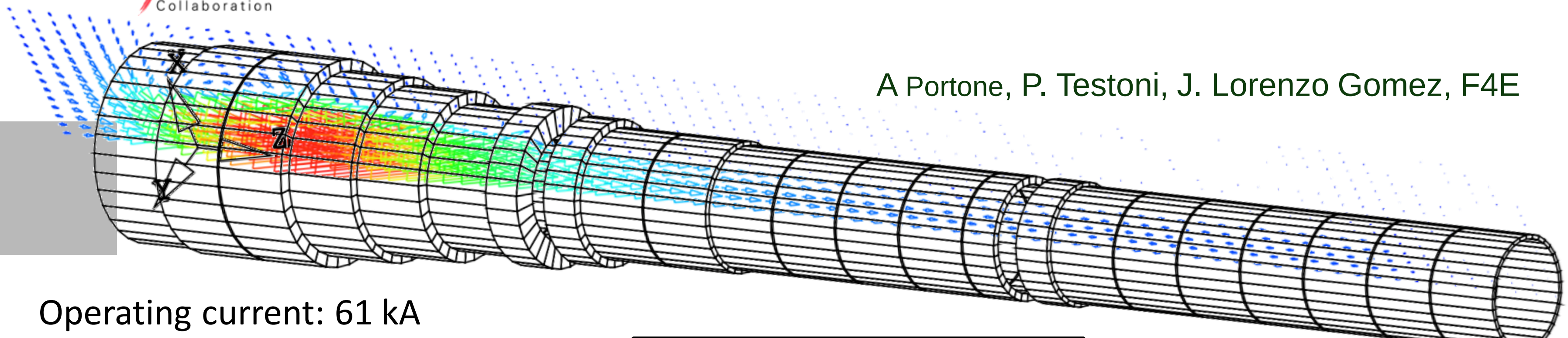
16 T peak, 150 mm
Radiation heat load ≈ 5 W/m
Radiation dose ≈ 20…40 MGy



HTS ?

Slides courtesy of L. Bottura for the for the Muon Magnets Working Group

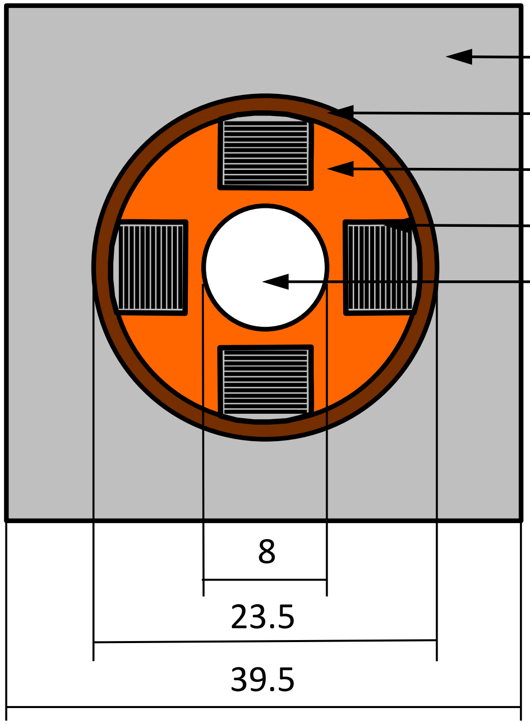
Target and capture solenoid (20 T)

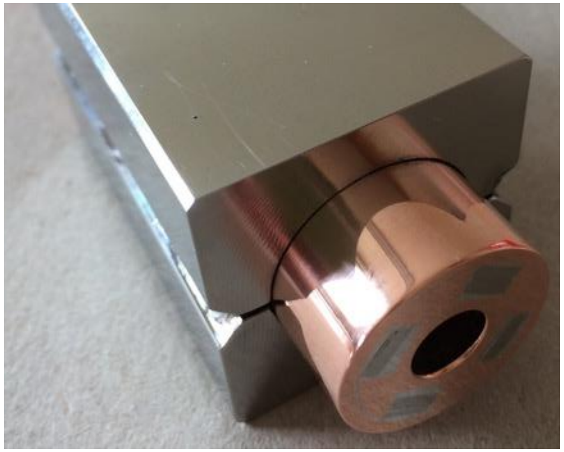


A Portone, P. Testoni, J. Lorenzo Gomez, F4E

Operating current: 61 kA
Operating field: 20 T
Operating temperature: 20 K


MIT “VIPER” conductor


SS JACKET
SS WRAP
COPPER FORMER
SOLDERED HTS STACK
COOLING CHANNEL



M. Takayasu et al., IEEE TAS, 21 (2011) 2340

Z. S. Hartwig et al., SUST, 33 (2020) 11LT01

Strong connection to HTS magnets for fusion

Slides courtesy of L. Bottura for the for the Muon Magnets Working Group

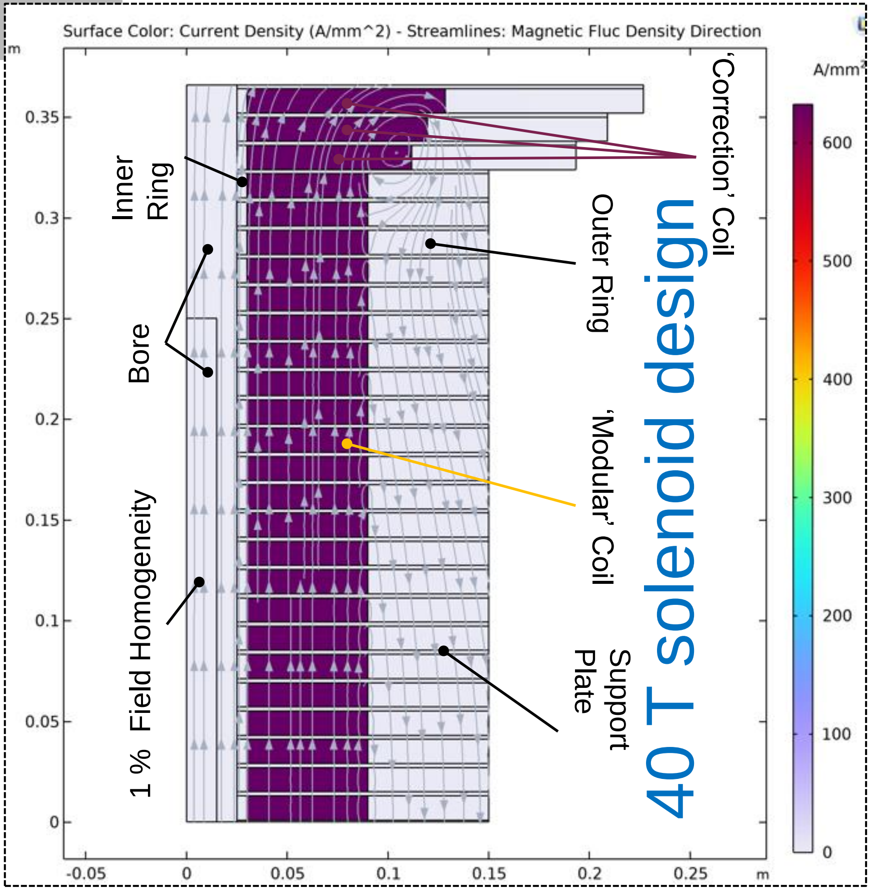
CHART
Swiss Accelerator
Research and
Technology

International
MUON Collider
Collaboration

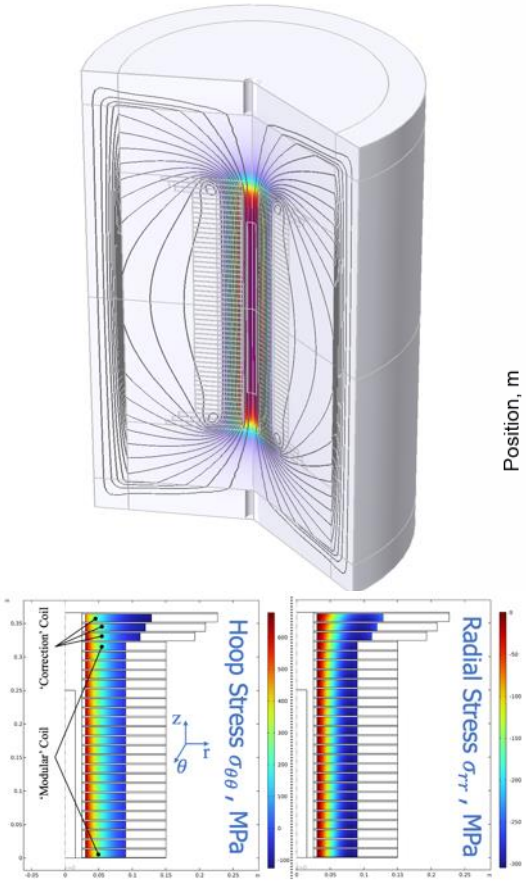
Final cooling (40 T)

$$B_{max} = 2\cdot\sqrt{\sigma_{max}\cdot\mu_0} \xrightarrow{\sigma_{max} = 600\text{ MPa}} B_{max} \approx 55\text{ T}$$

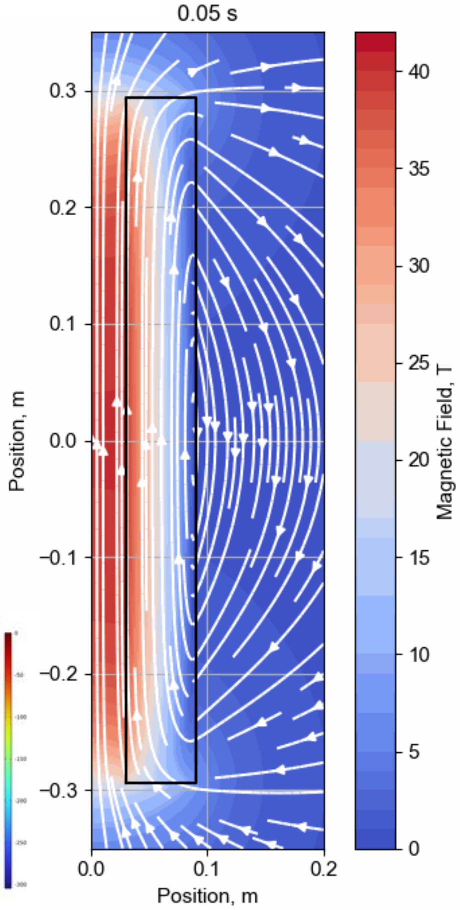
A. Dudarev, CERN



B. Bordini, CERN



B. Bordini, CERN



T. Mulder, CERN

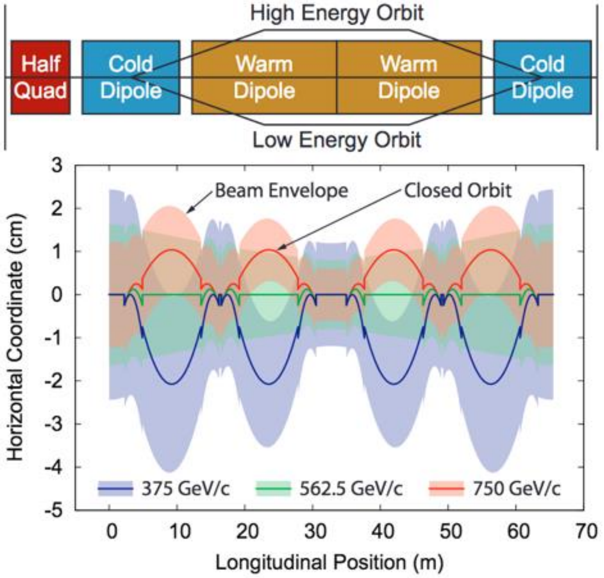
Strong connection to HTS magnets for science

Slides courtesy of L. Bottura for the for the Muon Magnets Working Group

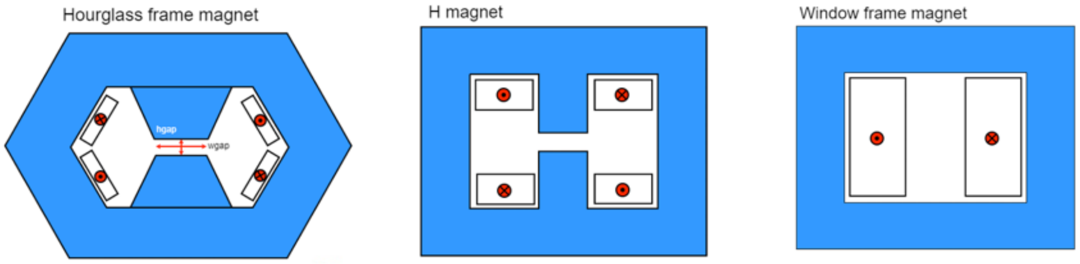
Accelerator magnets (±1.8 T)

Warm dipoles are pulsed from

-Bmax to +Bmax at high speed (0.35 to 6.37 ms) every 200 ms



Cold dipoles provide a steady baseline field of about 10 T



5.07 kJ/m

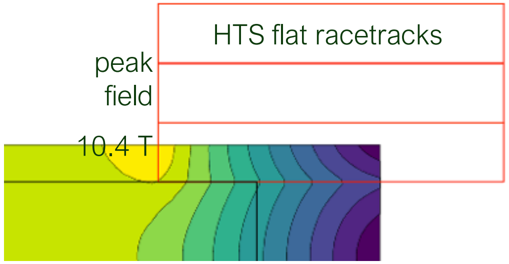
5.65…7.14 kJ/m

5.89 kJ/m

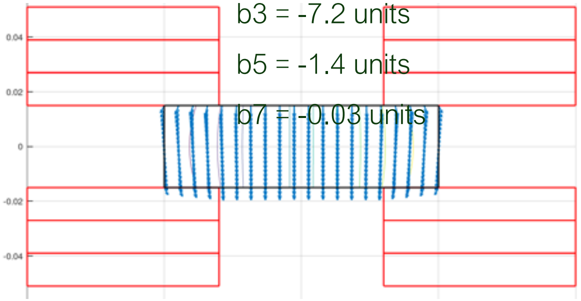
The main challenge is the management of the power in the resistive dipoles (several tens of GW):

- Minimum stored magnetic energy
- Highly efficient energy storage and recovery

A *simple* HTS racetrack dipole could match the beam requirements and aperture



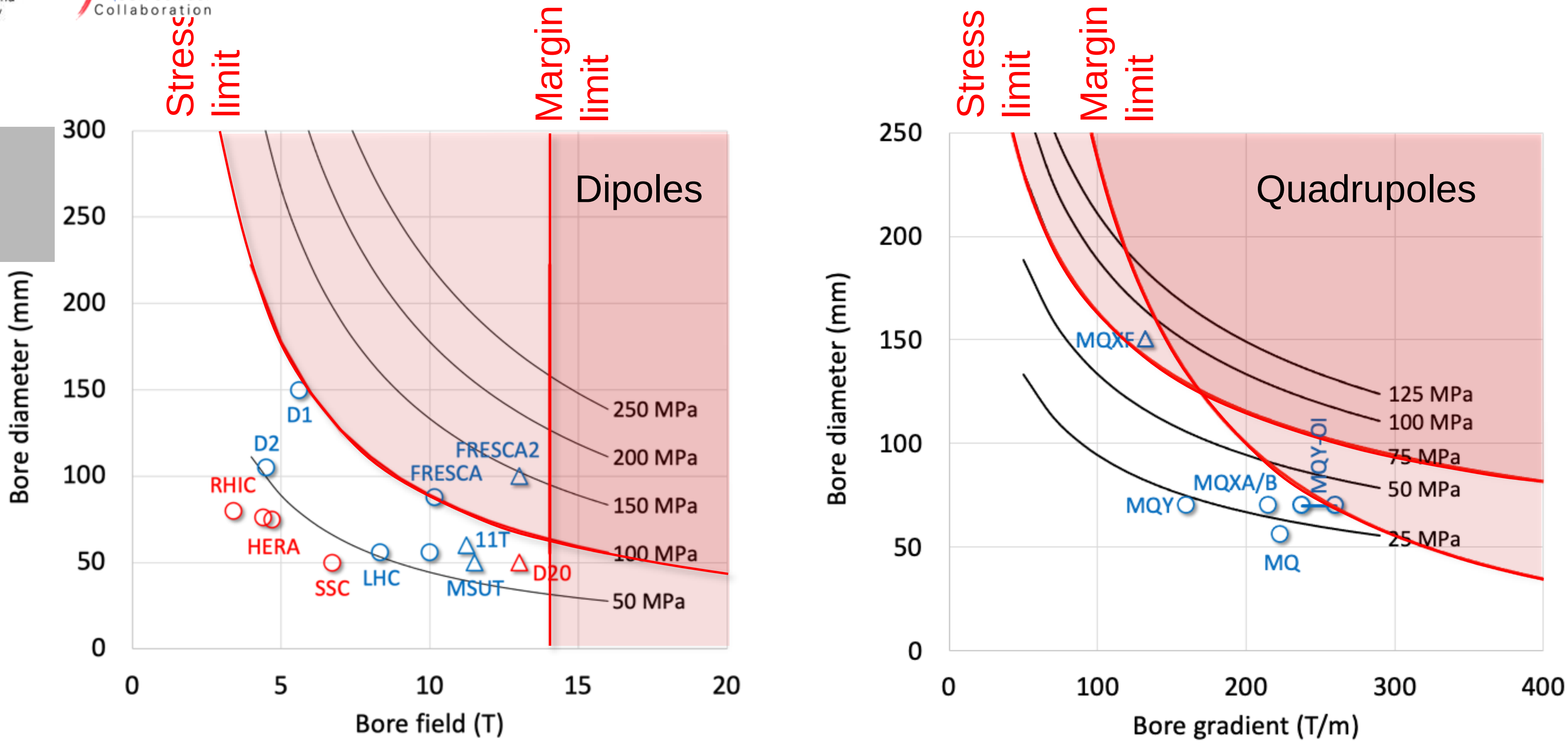
Rectangular magnet bore 100 mm x 30 mm



F. Boattini, CERN

Slides courtesy of L. Bottura for the for the Muon Magnets Working Group

Collider magnets limits (Nb_3Sn)

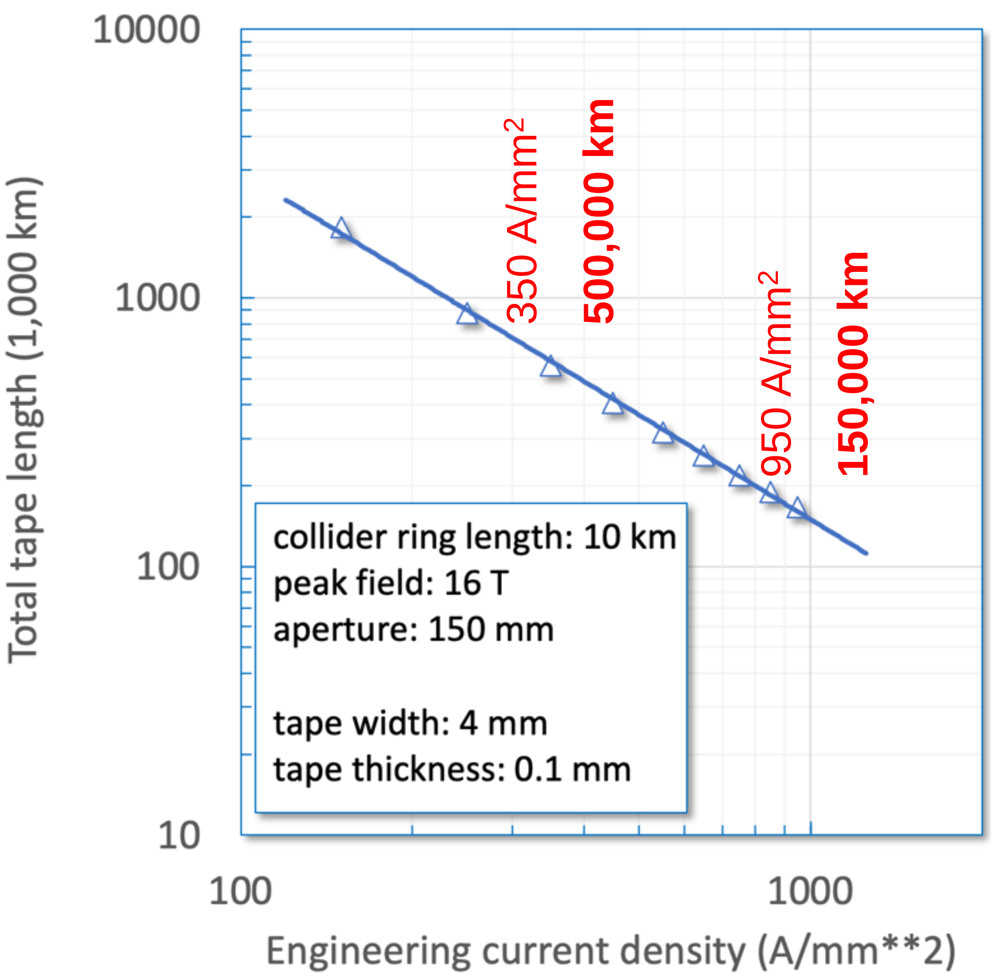


- Work in progress to provide analytical expression for the magnet design limits (including protection and cost)
  - – Maximum field and gradient vs. magnet aperture in LTS and HTS
  - – Combined function limits B+G and B/G
- **Proposal: take provisionally 9 T for NbTi and 14 T for Nb_3Sn**

Slides courtesy of L. Bottura for the for the Muon Magnets Working Group

Compact windings

Example of 16 T muon collider main dipole built with HTS



We need to **increase the winding current density** to fall in a *reasonable* range of **conductor mass** (applies both to LTS and HTS)

Unresolved issues:

- Winding geometry for tapes and stacks (ends, alignment, transposition possibly superfluous ?)
- Mechanics of coils under the exceptional electromagnetic loads (longitudinal stress in the range of 600 MPa, transverse stress in the range of 400 MPa)
- Quench management at high current and energy density (above 100 MJ/m^3)
- Radiation hardness of materials and coils (40…80 MGy and 10^{22} n/m^2)

Slides courtesy of L. Bottura for the for the Muon Magnets Working Group

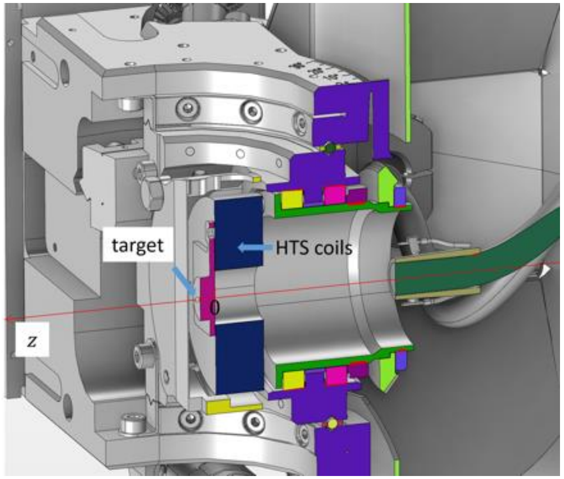
Overview

- CHART – Swiss Accelerator Research and Technology
- CHART contributions to FCChh HFMs
  - Nb_3Sn
  - HTS (ReBCO)
- FCCee
  - Baseline magnet system
    - Arc cells
    - MDI
  - CHART contributions to HTS-based feasibility studies
    - P^3: Positron source capture solenoid
    - HTS4: HTS Short Straight Section
- Muon Collider magnet requirements
- PSI Synergies

Synergies for PSI and Swiss Research Landscape

Magnetic field improves the physics reach in many experiments.
Ongoing discussions at PSI

- X-ray scattering
  - Miniaturized (2 cm ID, 1 cm height) source of 6 T on sample.
- Neutron Scattering
  - Split coils for vertical-field scattering; wide-aperture horizontal solenoids.
- HIMB project (High-Intensity Muon Beams)
  - Radiation hard, large-aperture capture solenoid.



RIXS manipulator mockup.
Courtesy J. Kosse

All projects have direct synergies with FCCee capture solenoid, MuCol target and cooling system.

Conclusion

- An ambitious SC magnet R&D program has been set up within CHART at PSI and in other national labs (CEA, CIEMAT, INFN) and at CERN.
- These are exciting times to work on SC accelerator magnets.
  - LTS magnets will see innovative technological solutions in the coming years to reach performance, robustness, and cost targets.
  - The HTS revolution is becoming real.
    - We are researching the building blocks of HTS accelerator magnet technology.
    - Challenges are real and should not be underestimated.
    - Momentum is building and ideas abound.
- Collaboration, coordination, and communication will be the key to an innovative and ultimately successful European R&D network that creates technology to enables the HEP adventures of the future.

Choice of a Cable