B. Auchmann CERN/PSI, R. Felder PSI, J. Gao PSI, G. Montenero PSI,
S. Sanfilippo PSI, S. Sidorov PSI, L. Brouwer LBNL, S. Caspi LBNL

Evolution of the canted costheta (CCT) design

26.06.2019, FCC Week 2019, Brussels.
Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI.

Overview

- CCT Design Evolution
- CHART1 Model-Magnet Program
  - Where we stood 1 year ago
  - Where we stand now
- CHART2 Program

Initial 2016 LBNL Design

- 2015/16 FCC Weeks, Shlomo Caspi

Clear bore ID=50mm,

Strand dia=0.8mm,

Coil OD=245mm

Clear bore ID=50mm,

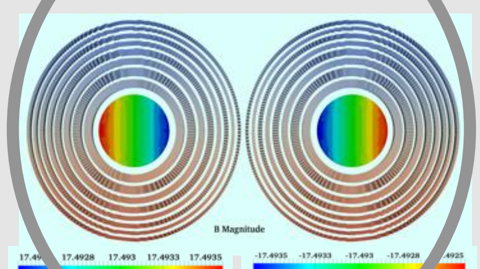
Strand dia=1.0mm,

Coil OD=322mm

Larger strands and spars

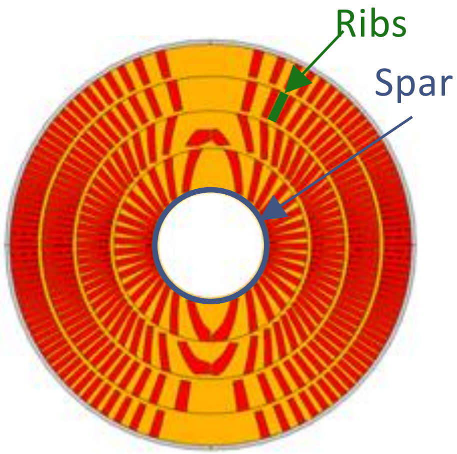
Strand /magnetic length = 16.2(Km/m)
Weight/magnetic-length = 72.6(Kg/m)
Weight/magnet = 1.0(Ton/magnet)
Weight/beam = 4.7 (Kton/beam)

Strand /magnetic length = 19.8(Km/m)
Weight/magnetic-length = 138(Kg/m)
Weight/magnet = 2.0(Ton/magnet)
Weight/beam = 9.06 (Kton/beam)



PSI's CCT Design for FCC

- Almost unchanged since FCC Week 2017
- Current: 18135 A

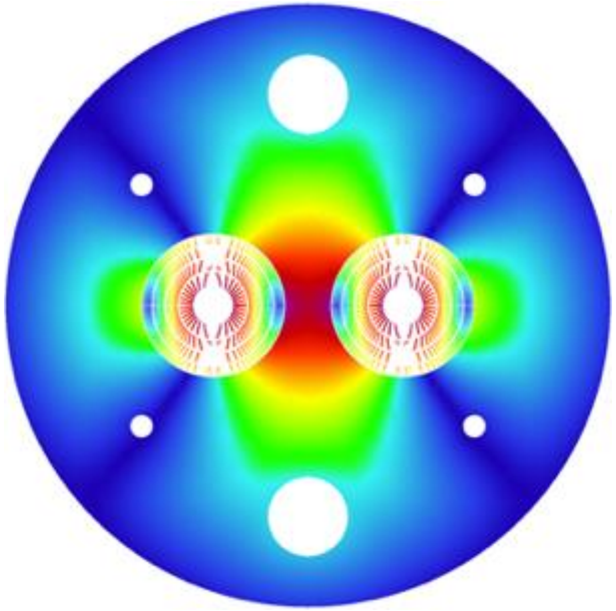


Layer #	n_S	diam [mm]	cuNc	loadline marg. [%]	current marg. [%]	T_{peak} [K]	V_{grnd} [V]	J_{cu} [A/mm²]
1	29	1.2	0.8	14.2	111	292	1133	1237
2	25	1.2	1.1	14.4	95	342	1264	1217
3	22	1.2	1.95	14.4	74	310	1156	1096
4	20	1.2	2.6	15.7	70	338	1144	1103

- Optimize J_e optimal winding angle, minimal spars, and ribs, wide cable.
- FCC-wide conductor use: **9.7 kt**

Total inductance: 19.2 mH/m

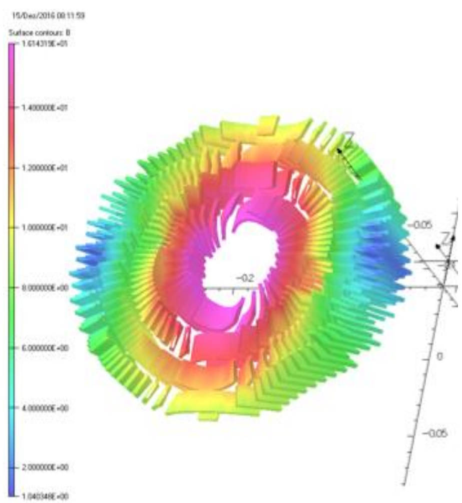
  - Total energy: 3.2 MJ/m

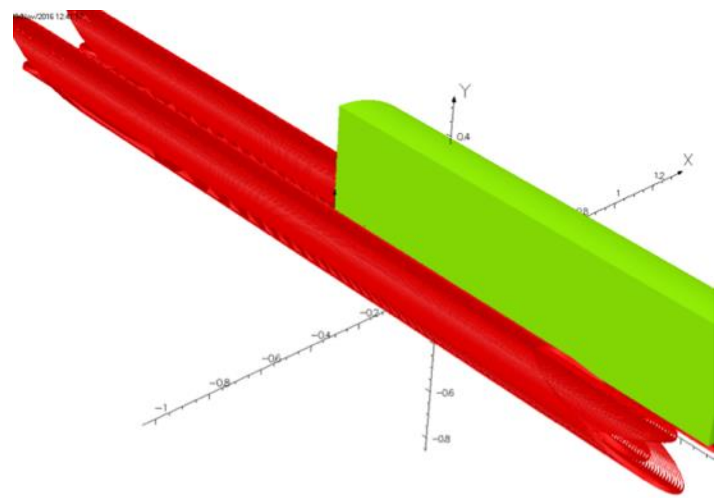


3-D Magnetic Design

3-D modeling results:

- **Yoke cut-back** not needed (20 mT peak-field enhancement in ends).
- **Magnetic length** with yoke equal to that of bare coil.
- **Physical length** minus magn. length = 53 cm; equal to 11 T magnet.
- **Peak field** minus main field at 16-T bore field: 0.14 T excluding self field.
  - comparable or lower than cos-theta due to continuous current distribution.

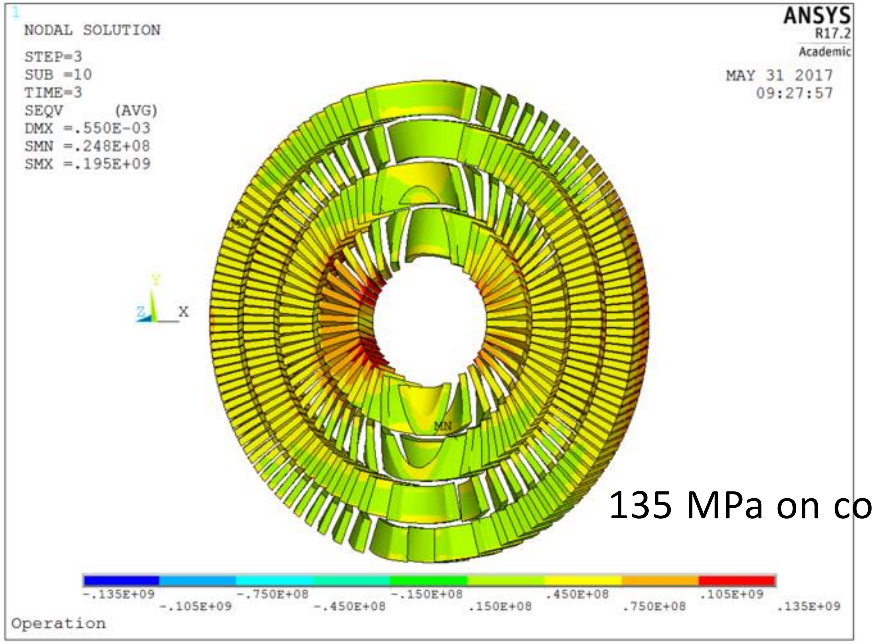




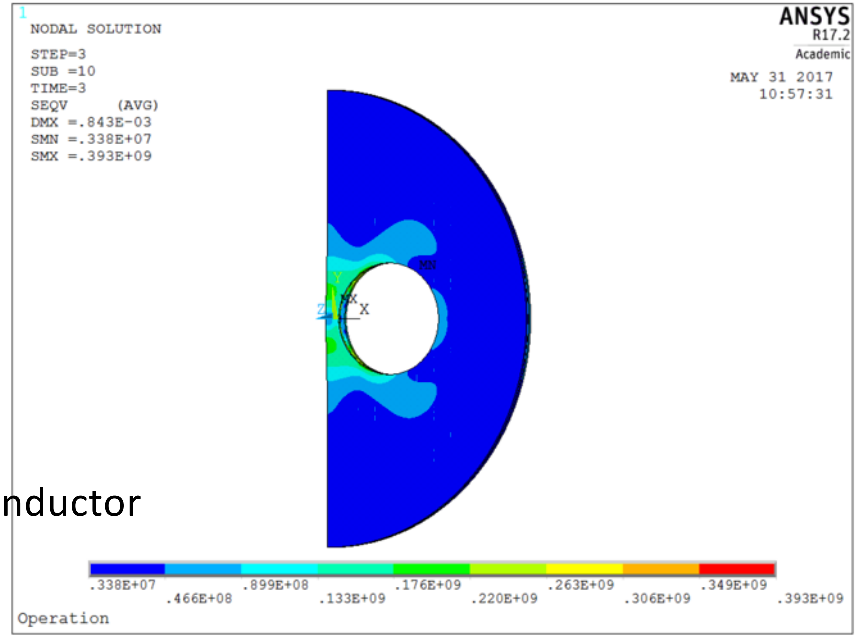
Courtesy M. Negrazus

3-D Periodic Simulation

- Generalized plane stress condition applied (following D. Arbelaez, L. Brouwer, LBNL)



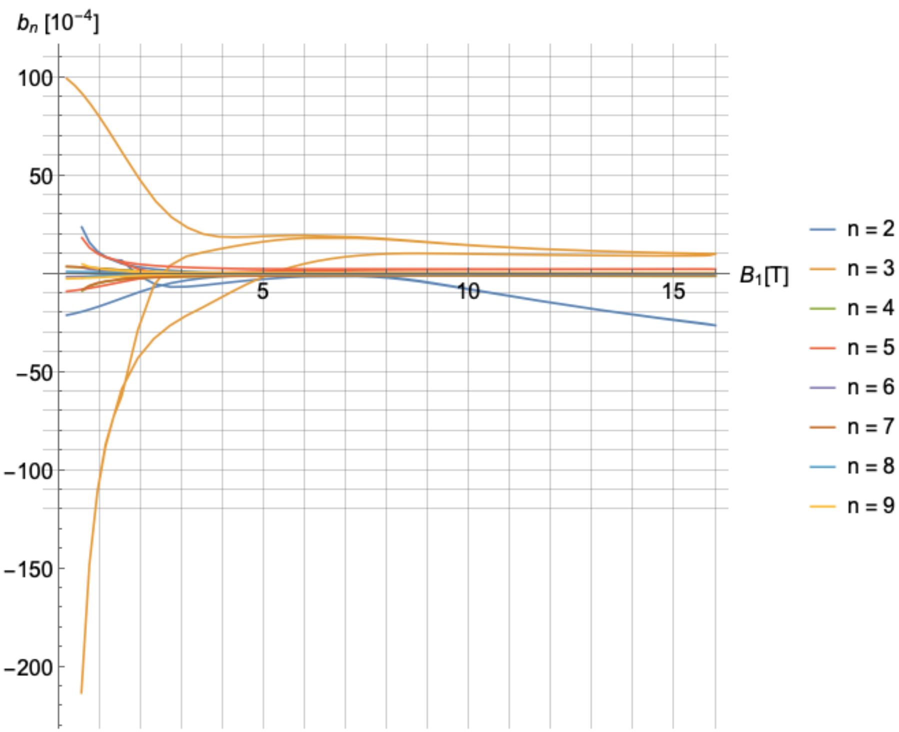
135 MPa on conductor

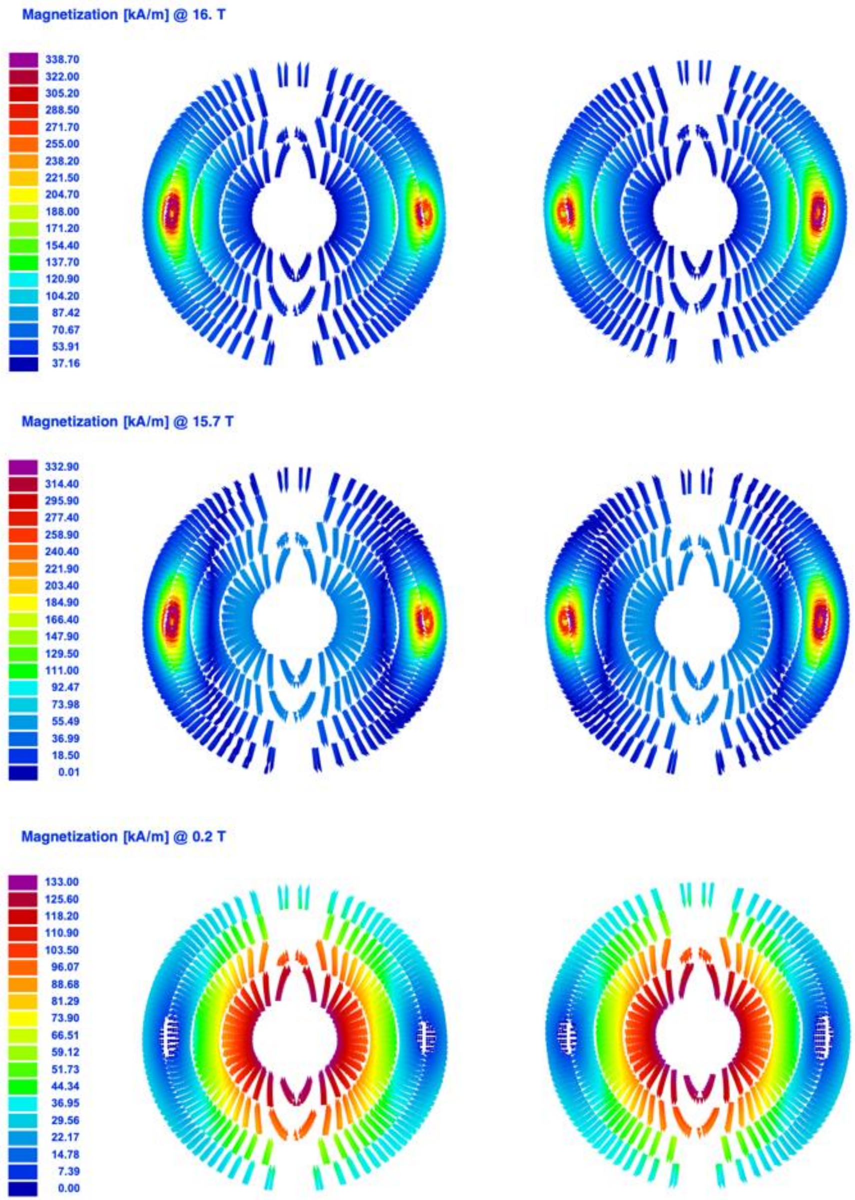


Courtesy G. Rolando

Persistent Currents

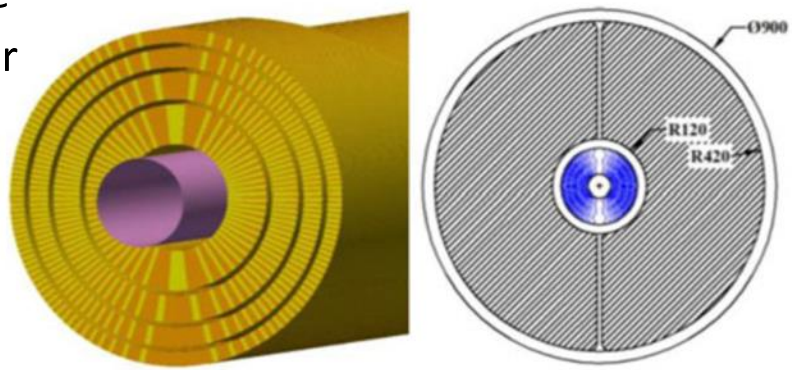
- First-of-a-kind CCT persistent-current simulation assuming axial current-flow like in any 2-D electromagnetic simulation.
- Similar order of magnitude as other designs.

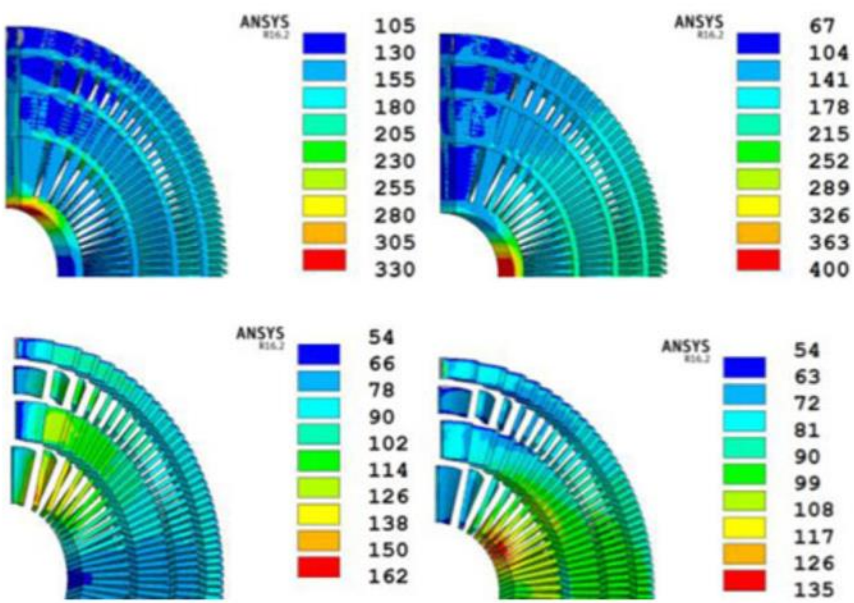


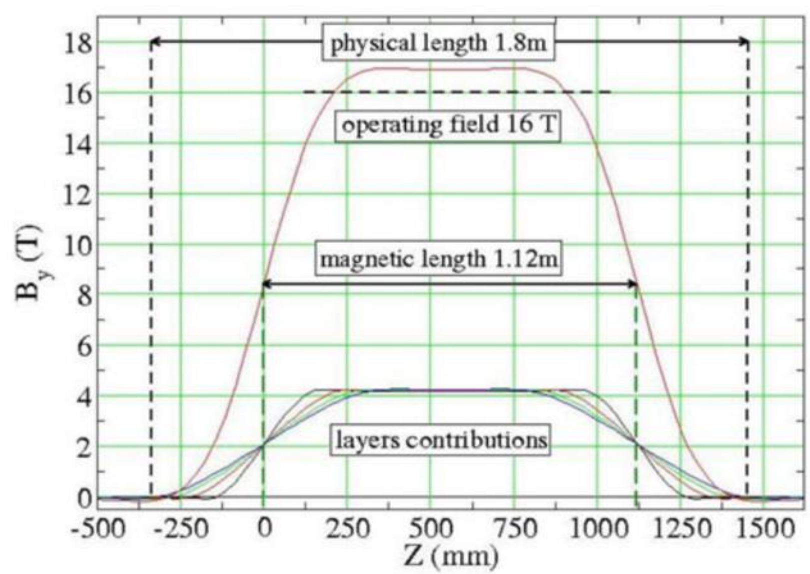


Updated LBNL Design, 2017

- S. Caspi et al., “Design of a Canted-Cosine-Theta Superconducting Dipole Magnet for Future Colliders”, IEEE Trans. On Appl. SC., Vol 27, No 4, June 2017
- Uses same design features to increase effective current density.







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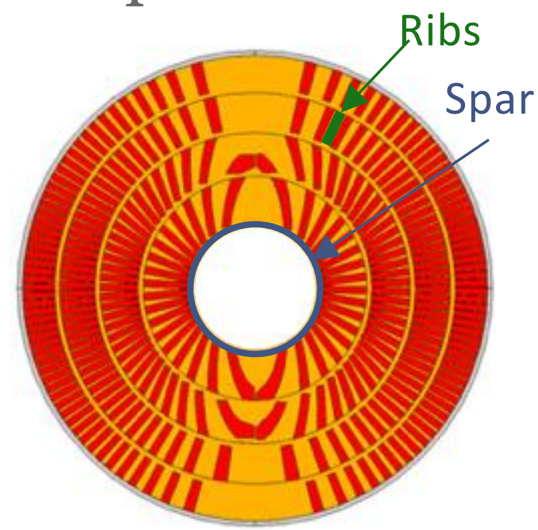
PSI/CHART Goals towards FCC Requirements

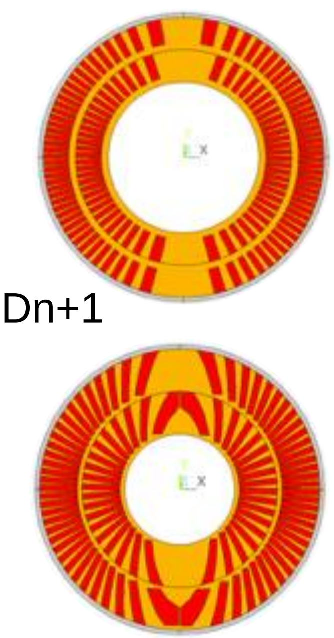


- Joint funding from CHART and the FCC design study from mid 2016
  until the end of 2019.
- Goal: Demonstrate key technological features of an **efficient** 16-T CCT in two-layer technology model magnets.

- Thin ribs and spars
- Exterior mechanical structure
- Fast quench detection and CLIQ protection.
- Wide Rutherford cable.
- Inclined channels.
- Improved impregnation procedures.

CD1..n

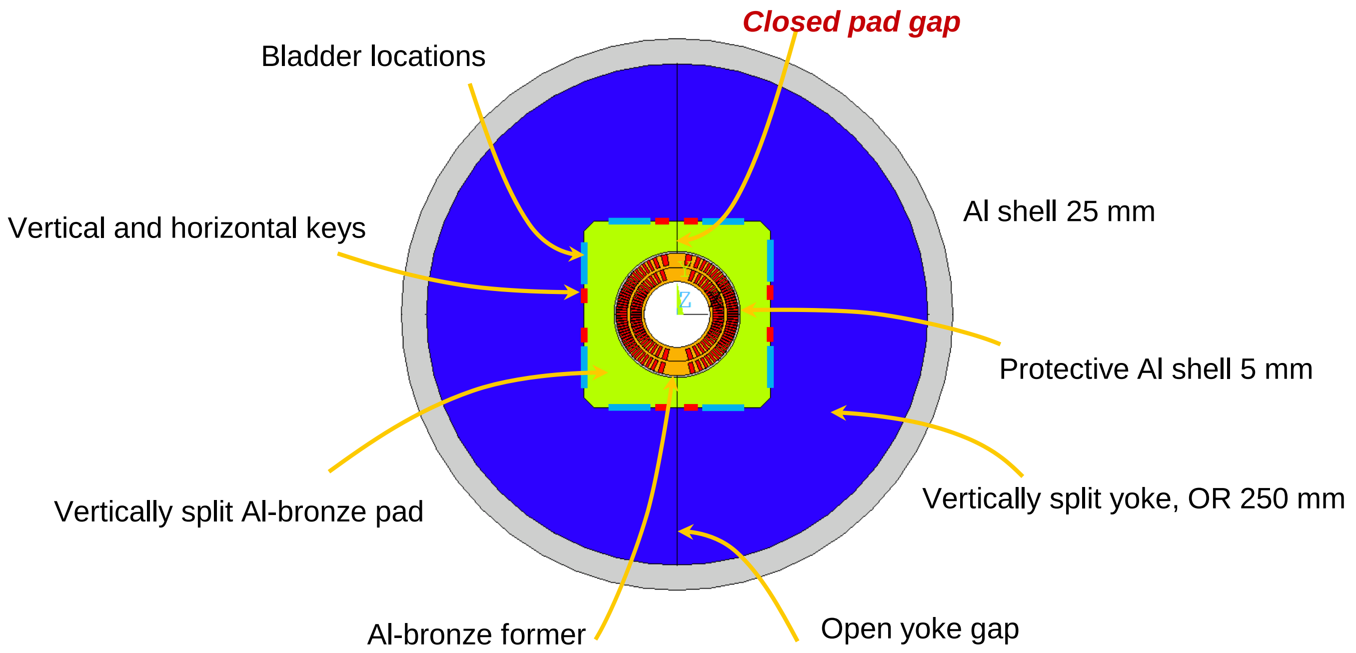
CDn+1



Mechanical Structure

Bladder and Key technology chosen for tuneability and relative simplicity.

- Closed and pre-loaded pad gap for maximum-rigidity cage around coils.
- Steel pads to better match coil differential contraction.
- Designed with S. Caspi, LBNL.



International conceptual design review of CD1 on June 26 at CERN (http://indico.cern.ch/e/cd1cdr).

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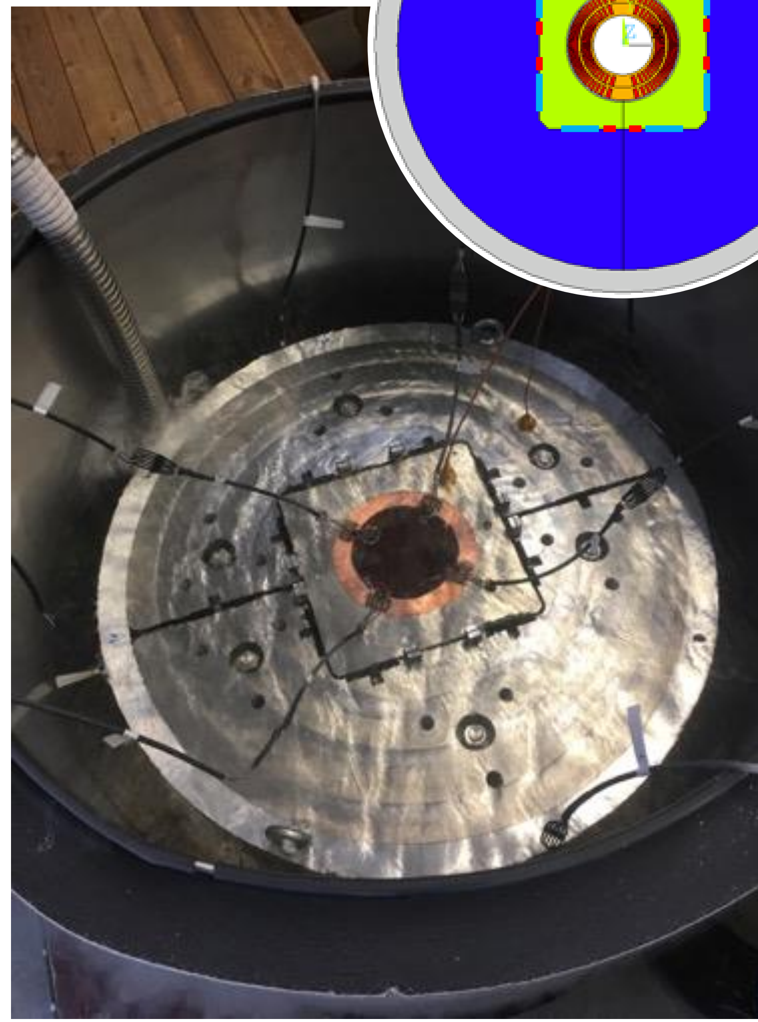
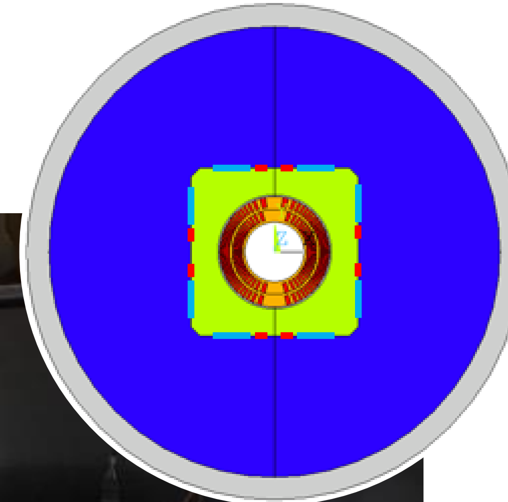
Short Mechanical Model





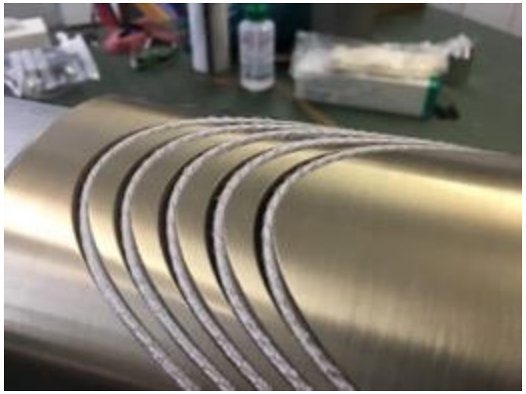
Machining and Reaction Tests.

- CD1 reaction-trial at CERN successful, channel-geometry validated.

Test formers delivered.

Test winding completed.

Preparation for heat treatment.

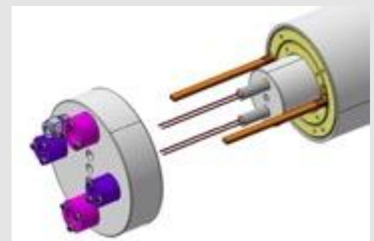


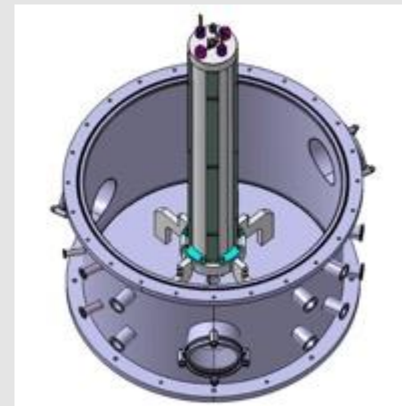
Before heat treatment

After heat treatment

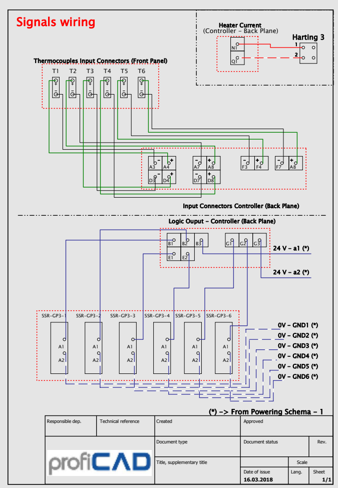
Vacuum Impregnation Equipment

- Vacuum vessel designed from CERN specs.
- Factory-Acceptance-Test passed and delivered.
- Heater powering and control units designed and built.
- Commissioned last week.



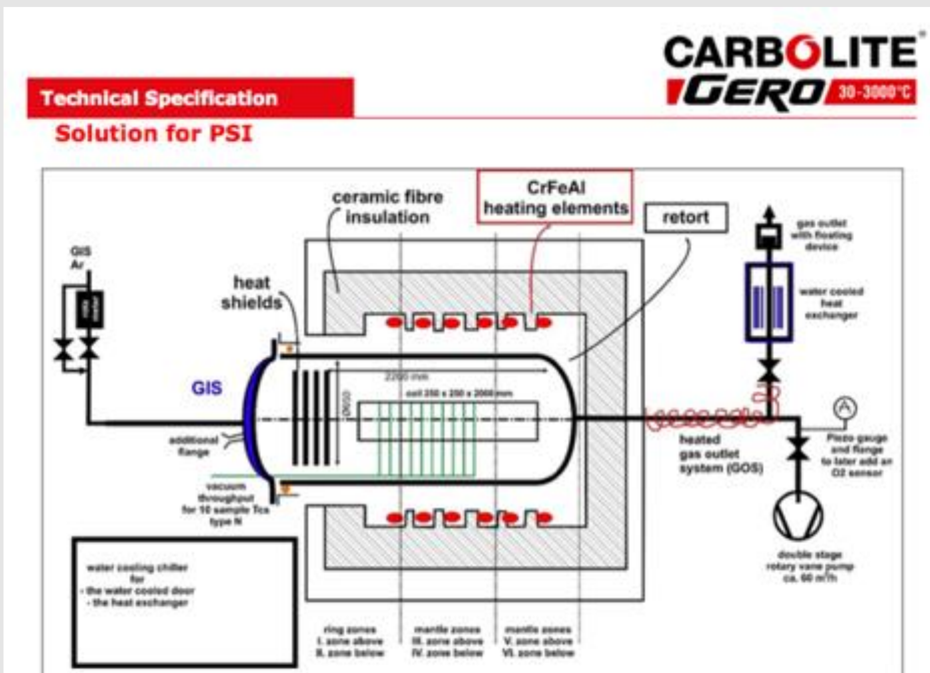


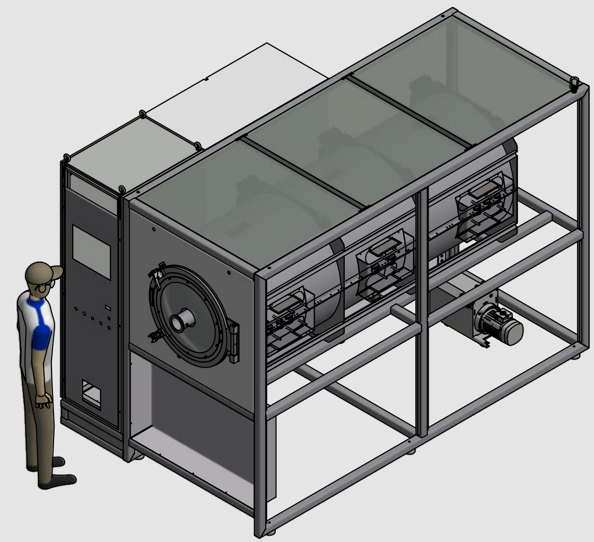
G. Montenero and R. Felder



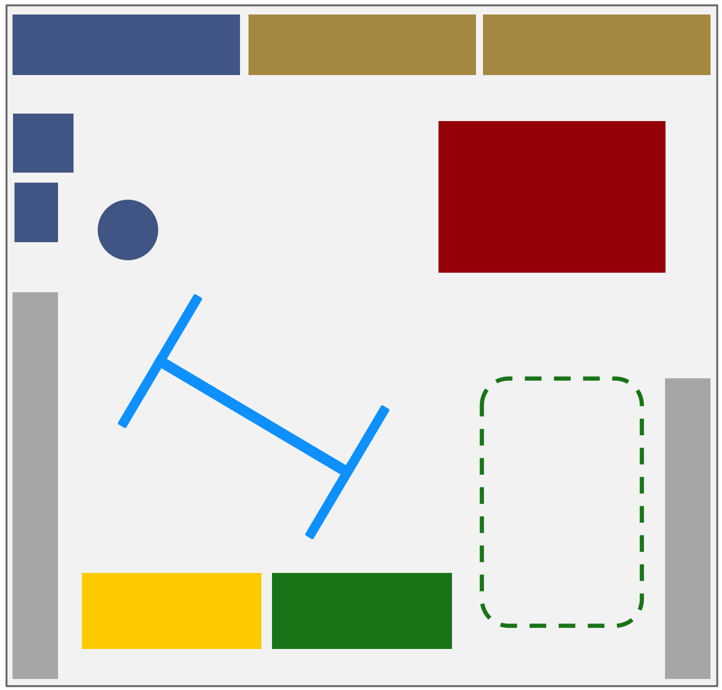
Procurement of Reaction Furnace

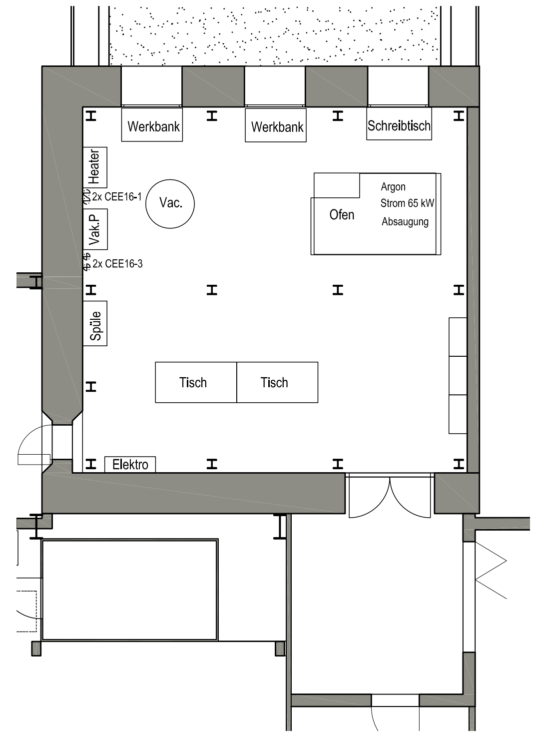
- Heat treatment furnace with Argon flow.
- Order placed following CERN specs.
- Working volume 2 m in length, >30 cm in diameter.
- Expected on-site commissioning June ‘18.





Superconducting Magnet Fabrication Lab





- Coil winding, instrumentation, assembly
- Reaction
- Impregnation, mixing
- Assembly and RT mag. meas.
- Storage
- Workplace
- Crane

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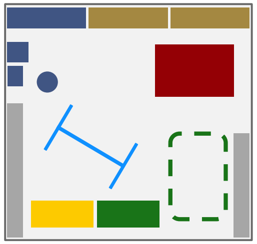
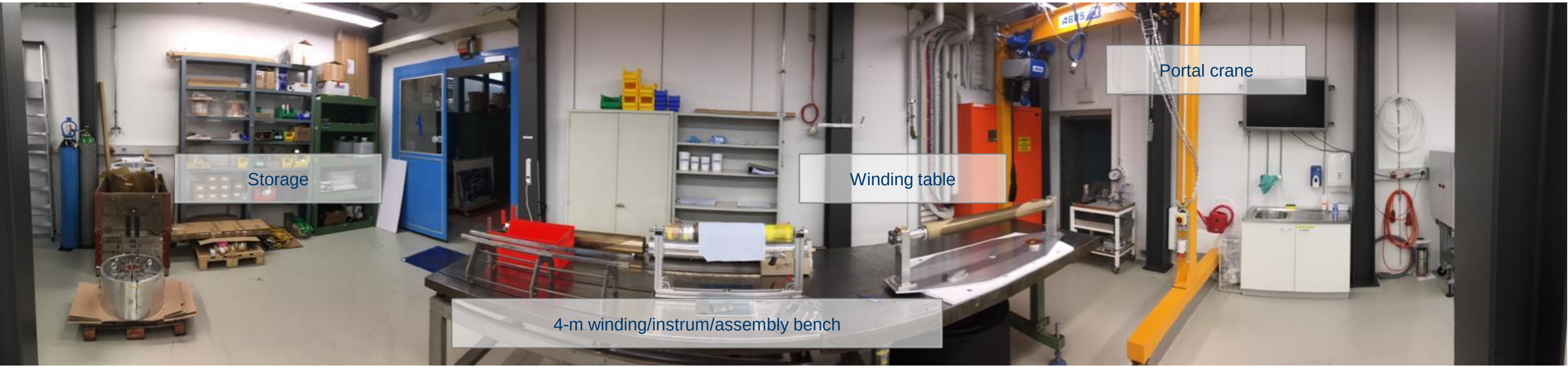
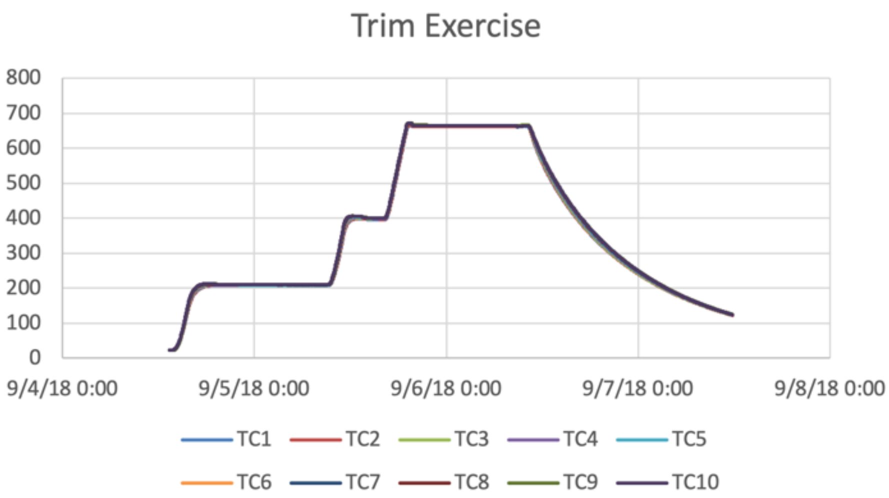
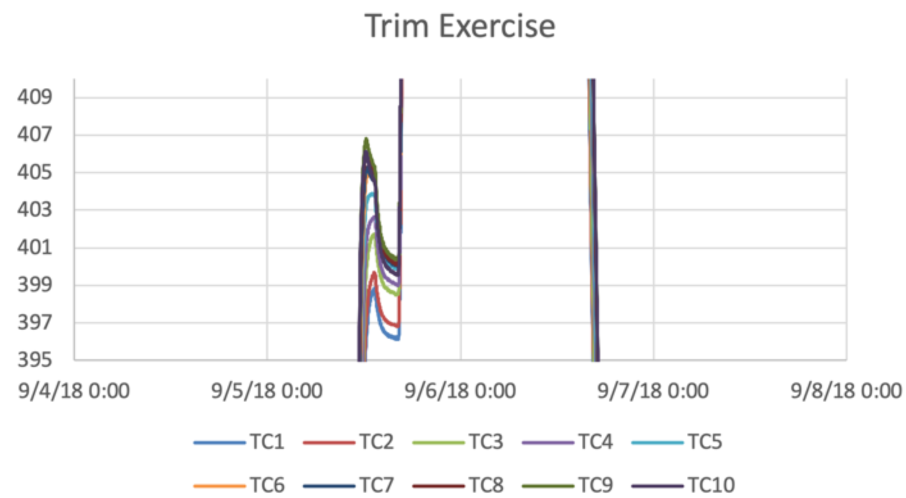
PSI SC Magnet Lab

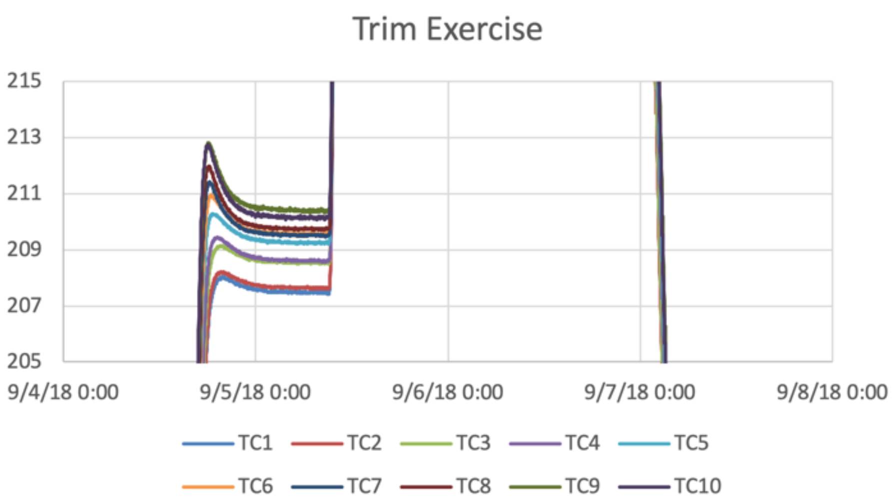


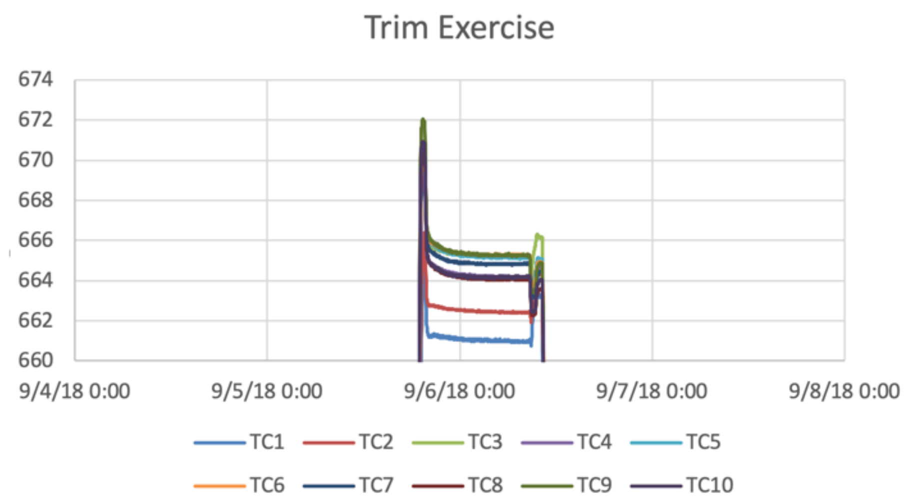


Reaction Furnace Trimming



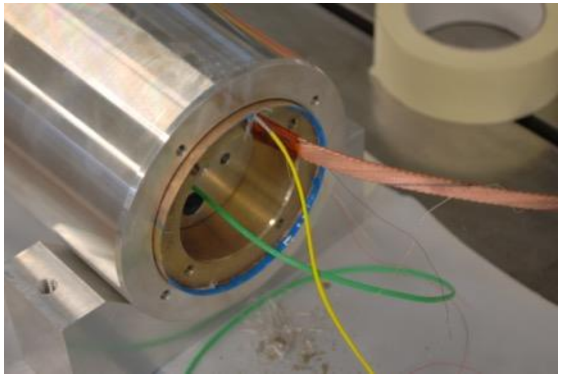
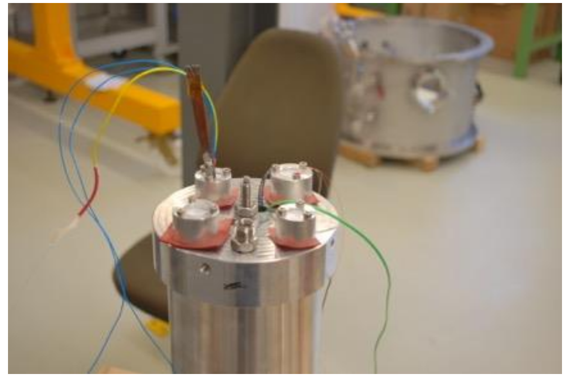


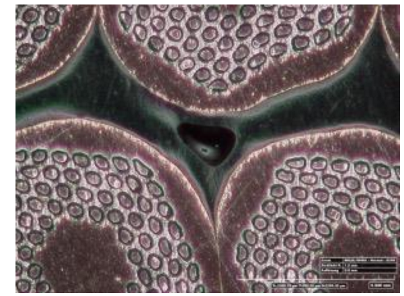
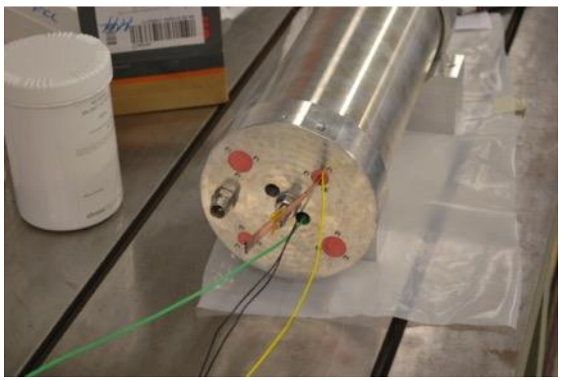
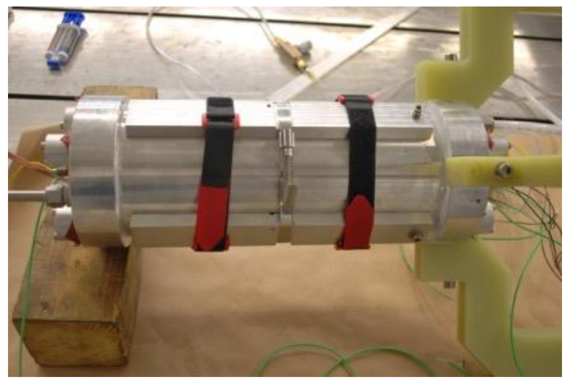


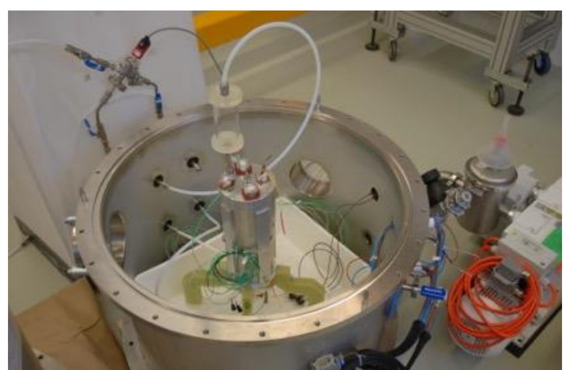


All plateau axial maps well within +/- 3 K.

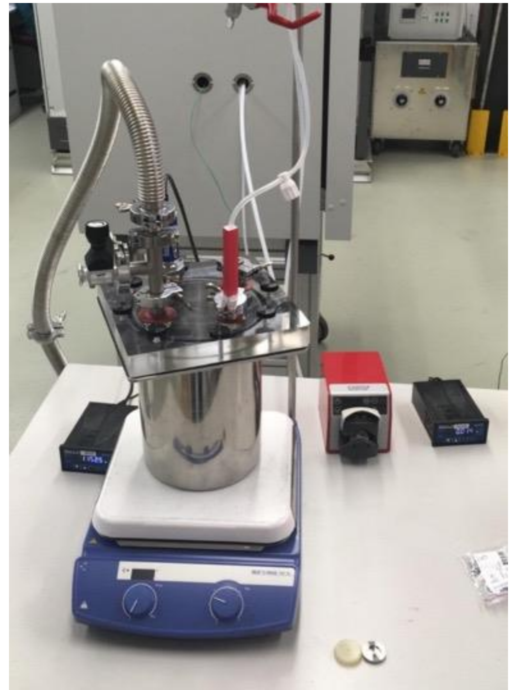
5-Turn Sample Preparation, CD1 Mold

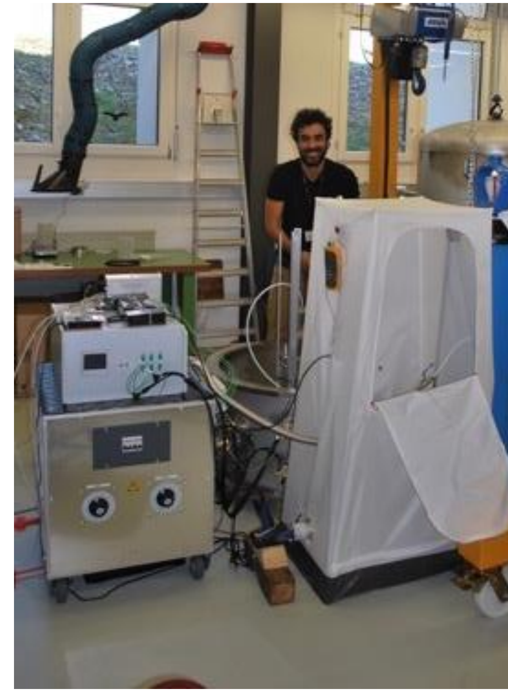






Impregnation Infrastructure





Thanks to generous
advice by David Smekens (CERN),
Jim Swanson (LBNL), and Steven Krave (FNAL)

For better control of flow velocity
and more reliable setup, introduced
peristaltic pump and single tube from de-gassing
pot to mold with pinch-on valves.

Production Readiness Review

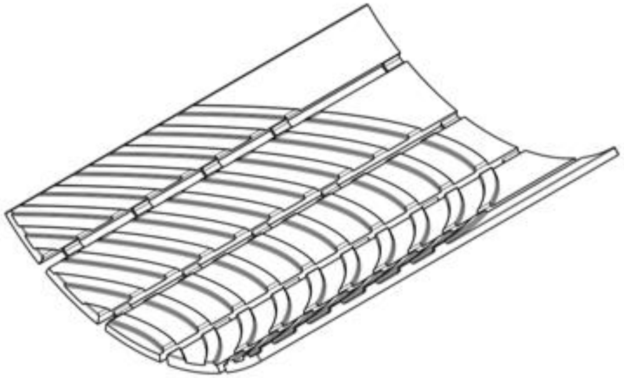
- End of August '18.
- Reviewers: Davide Tommasini (Chair), Paolo Ferracin, Herman ten Kate, Glyn Kirby, Juan Carlos Perez
- Some comments and recommendations report at http://indico.psi.ch/event/cd1prr:
  - Overall, the RC was positively impressed by the status of advancement of the project and of the associated infrastructure …
  - Furthermore, the proactive and networking attitude with other laboratories, in particular LBNL and CERN, was also greatly appreciated.
  - A weakness has been identified in the integrity of the dielectric insulation during winding ...

Insulation Challenge

- Winding with "mica-C + glass braid" insulated cable.
- Winding complete with 12 MΩ low-voltage resistance to former.
- The following day this had dropped to 0.2 Ω.

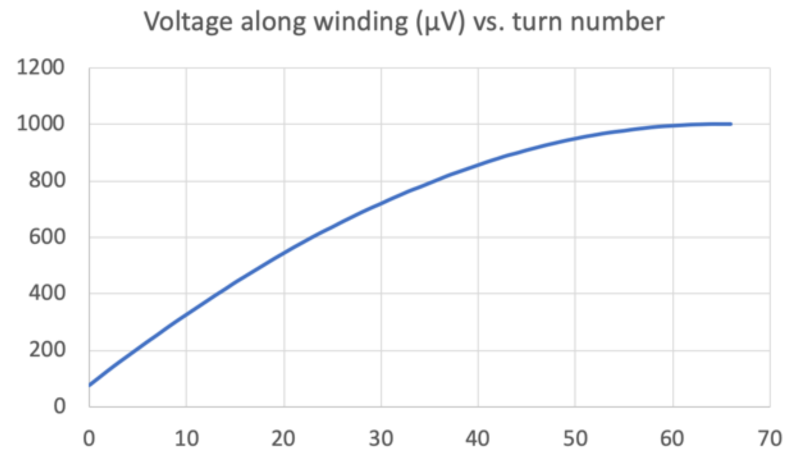
Insulation Challenge and “Cable Keepers”

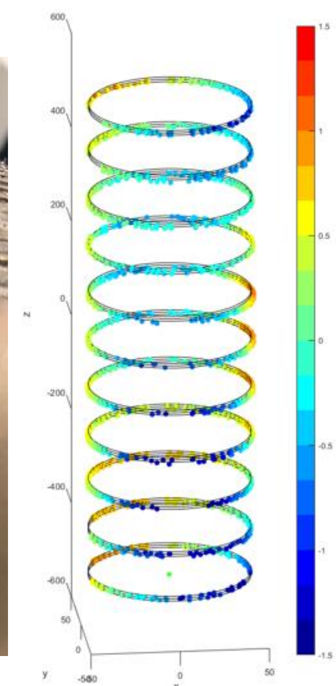
- Removing of insulation and straightening of cable.
- Re-insulation with thicker glass braid (no mica).
- Winding restarted – same result!
- Inserting glass tape (U-shaped) around the cable along the poles:
  - Immediate improvement in insulation.
  - better conductor placement by application of winding tension.
  - better success with “cable-keeper” concept.



IL Reaction

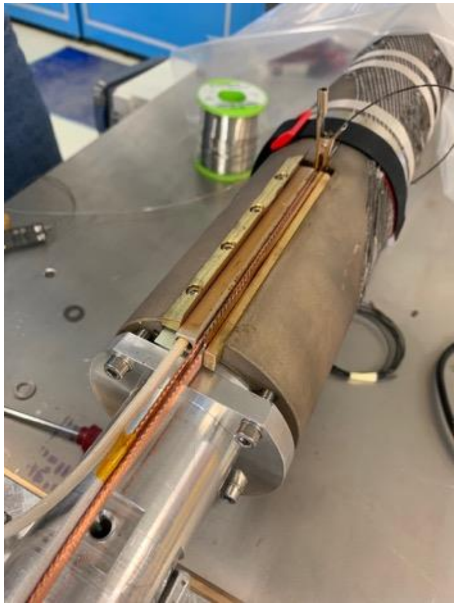
- After reaction,
  - Insulation has turned resistive.
    - Likely culprit: reinforcing glass ribbon.
    - Final resistance after impregnation to be seen.
  - Cable is below IL OD, but …
  - … Faro arm shows substantial former deformation.
    - Al-bronze loses >90% of strength at 665ºC.
    - Annealing step at max. 400 degrees needed.

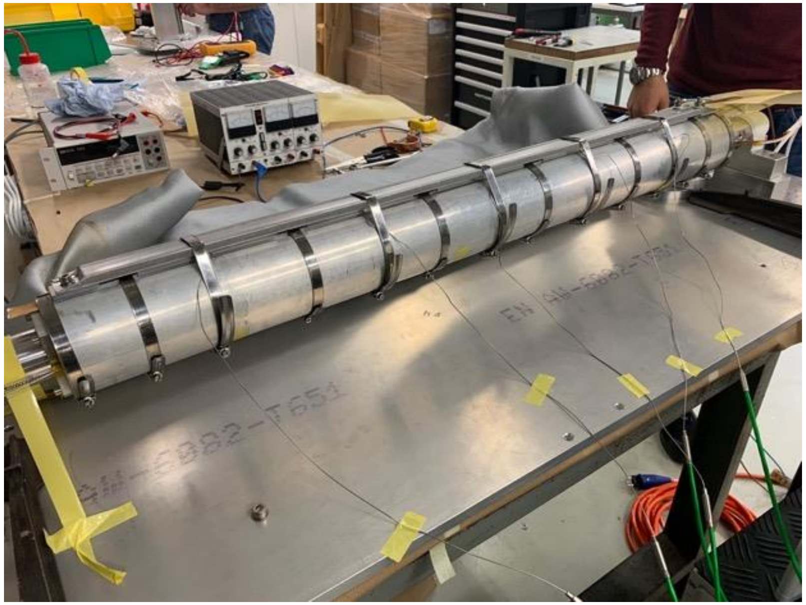




Splicing, Instrumentation, OL Re-Machining

- Splicing of IL and OL without incidents (after extensive training @LBNL and CERN).
- Sliding planes soldered and sealed around IL.
- The OL ID was drilled to accommodate deformed IL shape. Test assembly successful.





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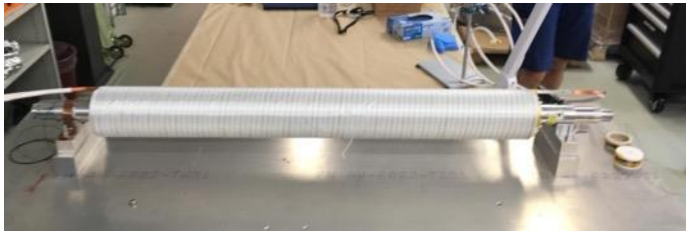
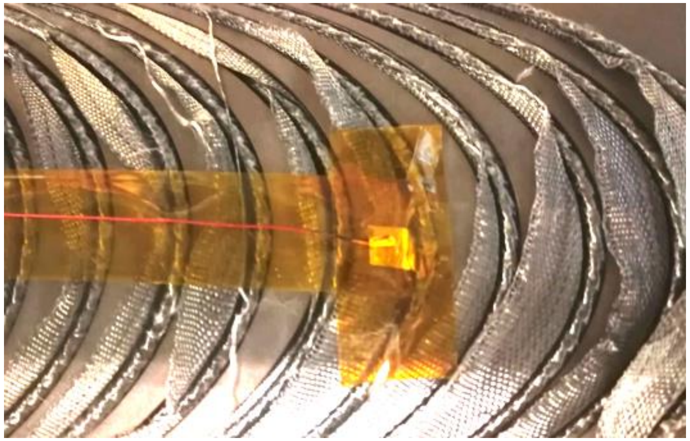
OL Preparation and Assembly

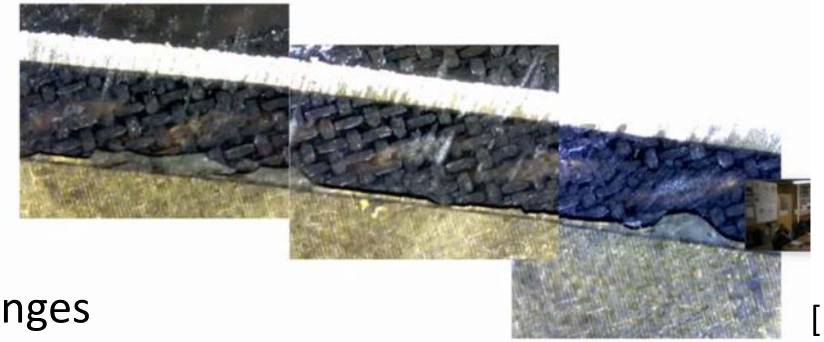
- OL winding and reaction without incidents.
- Same insulation problem as IL.
- However, cable was pushed out of channel OD!
  - Next time channels on poles need additional space.
  - PTFE-coated glass fiber will be installed instead of sliding plane between OL and Al protective shell.
- Assembly for impregnation is under way.
- Testing expected at LBNL in autumn.





Main challenges to be overcome …

- CCT specific challenges
  - **Bonding of cable inside channels** (as seen @LBNL, CCT5 post-training analysis).
  - **Reliable insulation** against former.



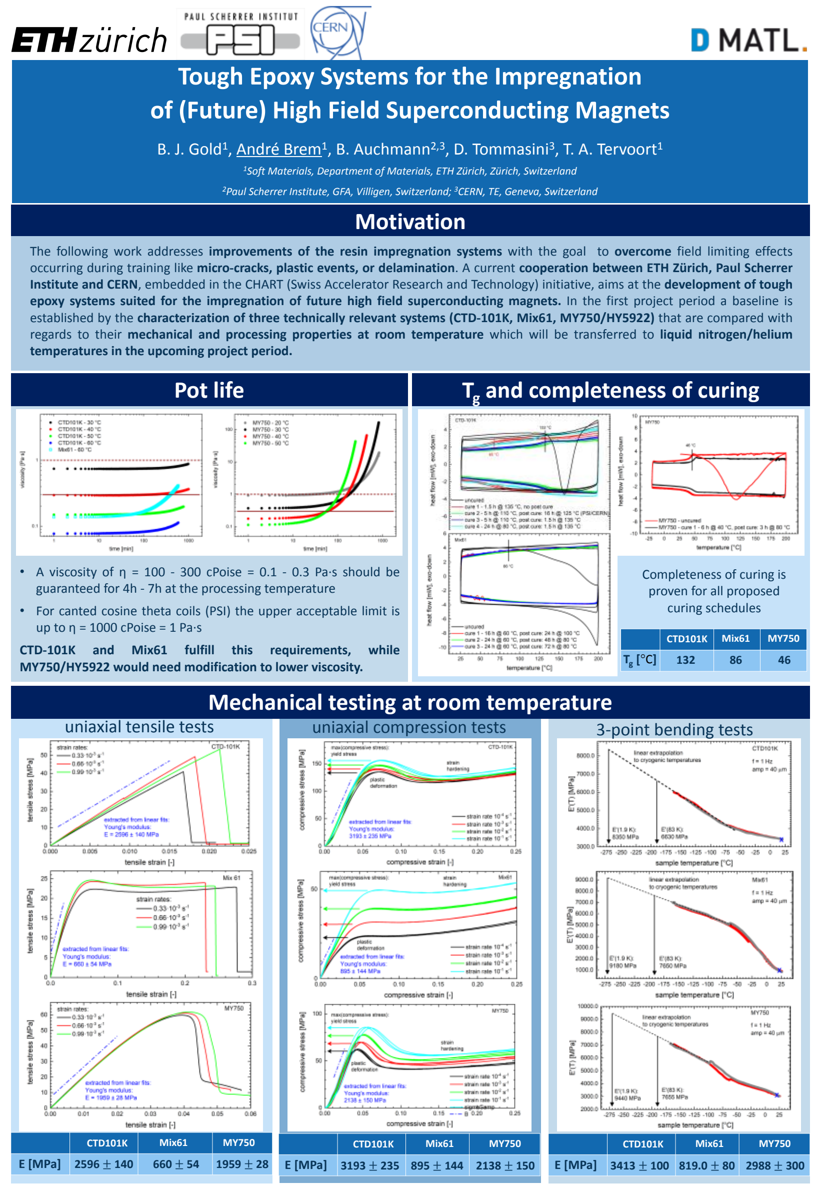
[Courtesy D. Arbelaez, LBNL]

- FCC specific challenges
  - *Smaller ID* and *thinner insulation* lead to
    - more difficult winding, **need for clamping**.
    - more **mechanical wear of insulation** during winding.
  - *Thinner spar* leads to
    - **higher risk for former deformation**.
    - need for **annealing <= 400ºC** or reaction mold

Enabling R&D Actions Started …

1. **Polymer-system** characterization and development and **adhesion testing** with of ETHZ Soft-Mat Group, CERN, and PSI. Poster by B. Gold, A. Brem.
2. **Al_2O_3 coating of channels** at Oerlikon Metco AG.
   - First trials show room for improvement.
   - Second trial for parameter tuning under way.
3. Search **for alternative insulation** materials and thermal/chemical de-sizing with von Roll AG.
4. Study of **additive manufacturing** for formers with ETHZ's Inspire AG, incl. enhanced adhesion.
5. **Annealing** trials at PSI.

1.



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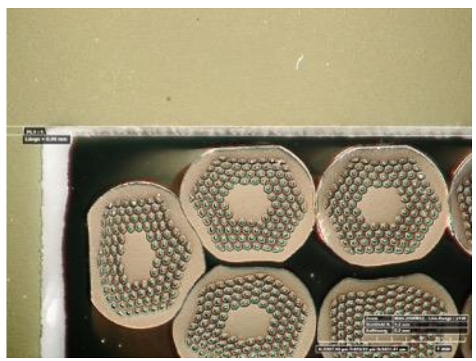

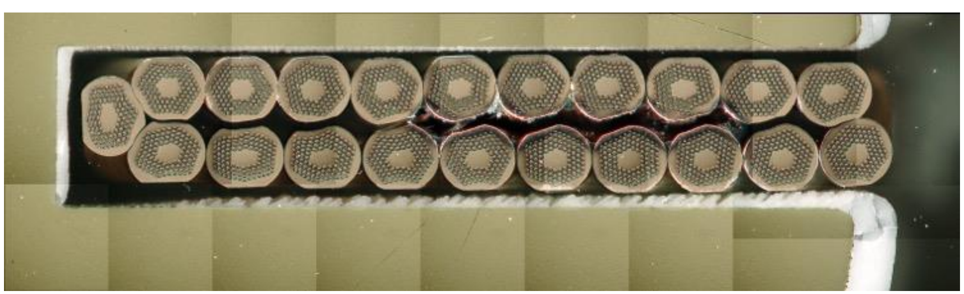

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- Mission with regard to applied superconductivity:
  - Develop a sustainable and Swiss-based expertise in applied superconductivity and superconducting magnets for HEP, in view of a possible FCC-hh or HE-LHC. This shall be anchored in the existing institutes and universities, and further developed thanks to additional recruitment and hands-on training of applied scientists and technicians in the practical objectives described below (R&D, prototyping and testing).
- High-field magnets:
  - evaluate CCT technology for Nb_3Sn 16-T dipoles,
  - develop an up to 2-m-long high-field demonstrator – possibly of different coil geometry.
  - contribute to the development of Nb_3Sn conductors that match the performance targets [...] and of the cable optimization and test.
- HTS magnets:
  - develop technologies for HTS based accelerator magnets,
  - design, build, and test an HTS variant of the SLS 2.0 superbend magnet.
  - design, build, and test several periods of an HTS undulator magnet.
- Infrastructure:
  - To establish the infrastructure needed to build and test all aspects of FCC-hh, HE-LHC magnets and other SC accelerator magnets.

Infrastructure | Enabling Technologies | Wire R&D | LTS Magnet R&D | HTS Magnet R&D | HFM Demonstrator

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CHART Applied Superconductivity Network

Strand / Tape

LTS and HTS strand/tape R&D, Procurement, QA

Université de Genève, CERN

Cable

Rutherford / Roebel production

BERKELEY LAB

KIT Karlsruher Institut für Technologie

Fermilab

Magnet Design

FCC-hh / HE-LHC conceptual and technical

Coil Manufacturing

Nb3Sn and HTS coils

PAUL SCHERRER INSTITUT PSI

ETH zürich

Mechanical Assembly

Mechanical loading

Magnet Testing

LTS and HTS magnet tests

EPFL SWISS PLASMA CENTER

PAUL SCHERRER INSTITUT PSI

BERKELEY LAB

CHART Applied Superconductivity Network

Polymer R&D
Insulation and composite R&D
Splices

Strand / Tape

LTS and HTS strand/tape R&D, Procurement, QA

Cable

Rutherford / Roebel production

Magnet Design

FCC-hh / HE-LHC conceptual and technical

Coil Manufacturing

Nb3Sn and HTS coils

Mechanical Assembly

Mechanical loading

Magnet Testing

LTS and HTS magnet tests

CHART Applied Superconductivity Network

PAUL SCHERRER INSTITUT PSI

oerlikon metco

ETH zürich

HB Heinz Baumgartner AG Innovation in Mechanics

CCT CNC former manufacturing
CCT former coating
Additive manufacturing
Winding automation
Coil interfaces

Strand / Tape

LTS and HTS strand/tape R&D, Procurement, QA

Université de Genève (Schola Genevensis)

CERN

Cable

Rutherford / Roebel production

BERKELEY LAB

KIT Karlsruher Institut für Technologie

Fermilab

Magnet Design

FCC-hh / HE-LHC conceptual and technical

Coil Manufacturing

Nb3Sn and HTS coils

PAUL SCHERRER INSTITUT PSI

ETH zürich

Mechanical Assembly

Mechanical loading

Magnet Testing

LTS and HTS magnet tests

EPFL SWISS PLASMA CENTER

PAUL SCHERRER INSTITUT PSI

BERKELEY LAB

CHART Applied Superconductivity Network

Quench Protection System R&D for Nb3sn (FCC-hh) and HTS

Strand / Tape

LTS and HTS strand/tape R&D, Procurement, QA

Cable

Rutherford / Roebel production

Magnet Design

FCC-hh / HE-LHC conceptual and technical

Coil Manufacturing

Nb3Sn and HTS coils

Mechanical Assembly

Mechanical loading

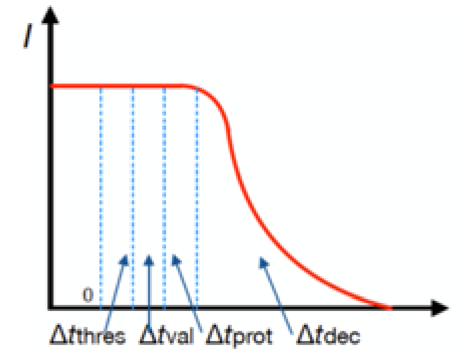
Magnet Testing

LTS and HTS magnet tests

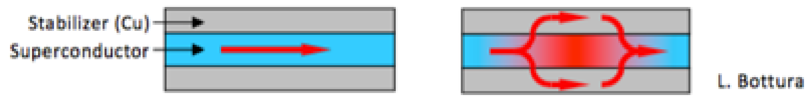
Summary

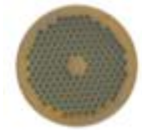
- CHART1 has
  - established CCT as an alternative for FCC worth studying.
  - built and commissioned a SC-magnet laboratory.
  - introduced Nb_3Sn CCT magnet technology at PSI.
  - identified the key R&D challenges of CCT for FCC.
  - launched enabling-technology R&D activities.
  - and will finish and test CD1.
- For CHART2 we plan to
  - engage in enabling-technology R&D targeted for CCT, but also useful for tightly-packed coils.
  - build, equip, and commission a larger lab at PSI.
  - further evaluate CCT technology for high-fields through subscale and demo magnets.
  - enter the field of HTS magnet R&D.
  - design and build a high-field demonstrator magnet.
- Thanks to the continued support by CERN, LBNL, FNAL and others

CCT Protection



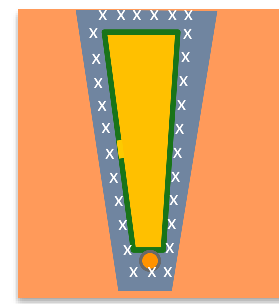
- Goal of PhD by Jiani Gao:
  – Design an efficient detection & protection system for CCT.



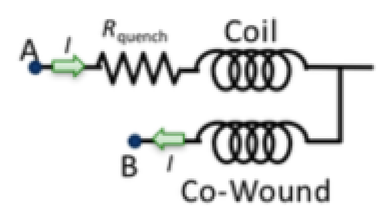


  – Prove that LHC-based EuroCirCol criterion (40 ms from quench init. to full protection efficiency) can be improved upon.
  – Many findings are expected to carry over to other magnet types

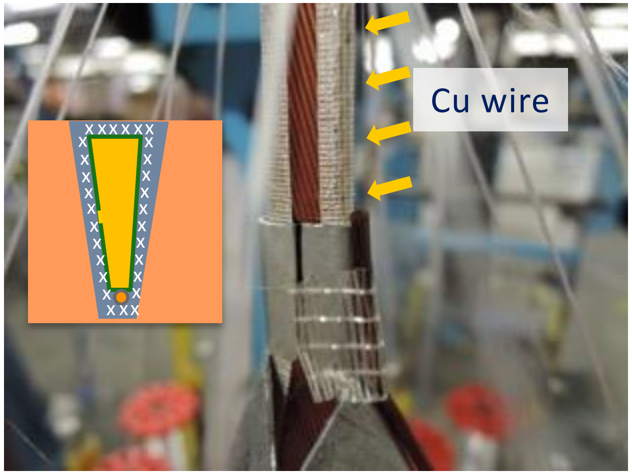
- Detection:
  – Co-wound Cu wire for optimal inductive compensation of voltage signals.

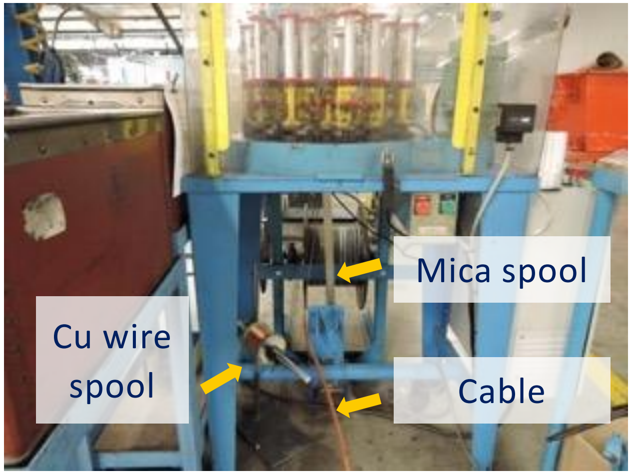


  – Co-wound SC wire for current-based detection: have ~ 1 A circulate in co-wound SC wire and main cable; propagation of quench to co-wound wire and the 1 A quickly drops; detect dI/dt.
  – Co-wound optical fiber (Federico Scurti, Justin-Schwartz Group) on top of channel post-reaction – use Rayleigh backscattering.
    – Mostly for diagnostics with distributed hot-spot sensing; evaluate potential for detection.



Insulation Trial





J. Mazet (CERN)