PAUL SCHERRER INSTITUT

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The PSI CCT programme

FCC Week 2018, Amsterdam

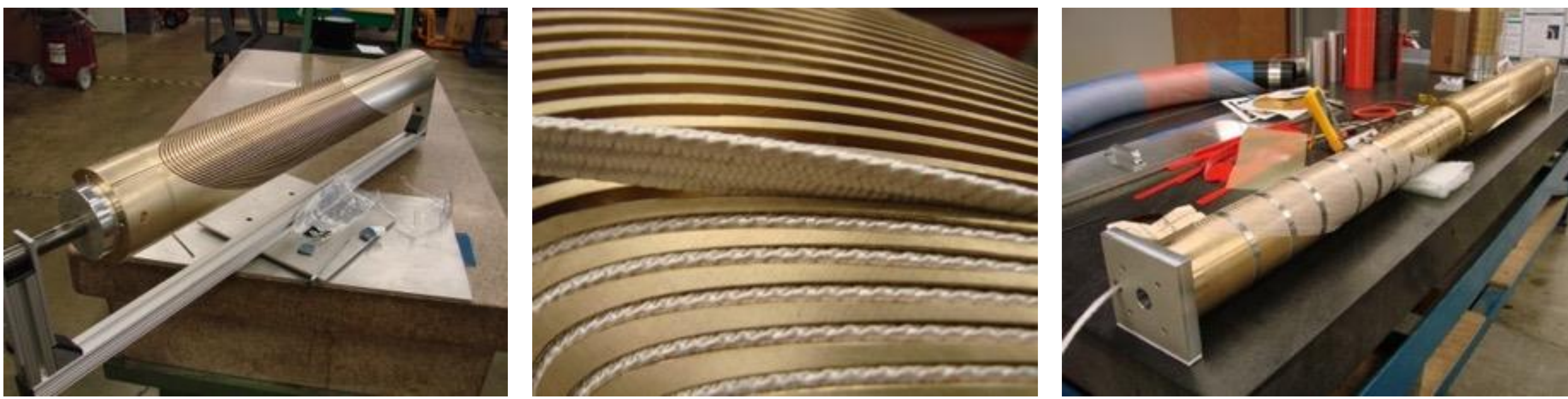
Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI.

Overview

- Canted-Cosine-Theta Technology for the FCC Main Dipole
- The PSI/FCC Superconducting-Magnet Program
- CD1 manufacturing status

Mechanics Challenge

- Canted Cosine Theta design originally advocated only by LBNL (US).
- PSI joined effort of EuroCirCol participants mid-2016 to study CCT for FCC.
- FCC-specific CCT goals to demonstrate:
  - CCT efficiency does not have to be a showstopper for FCC.
  - CCT coils on small ID are windable.
  - Lower coil stress can be achieved due to individual-turn support.
  - Absence of a pre-stressed coil-block composite can improve training
    - if resin cracks can be eliminated and resin/former interface bond is strong.

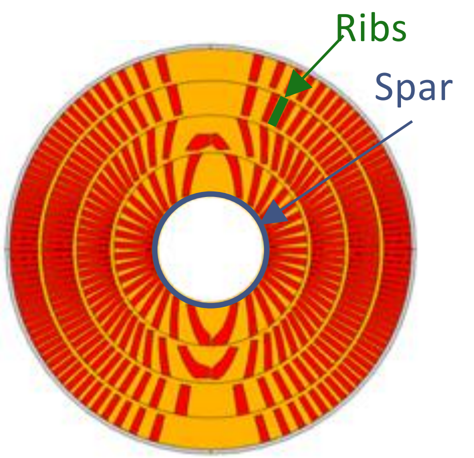


CCT winding and assembly, courtesy LBNL.

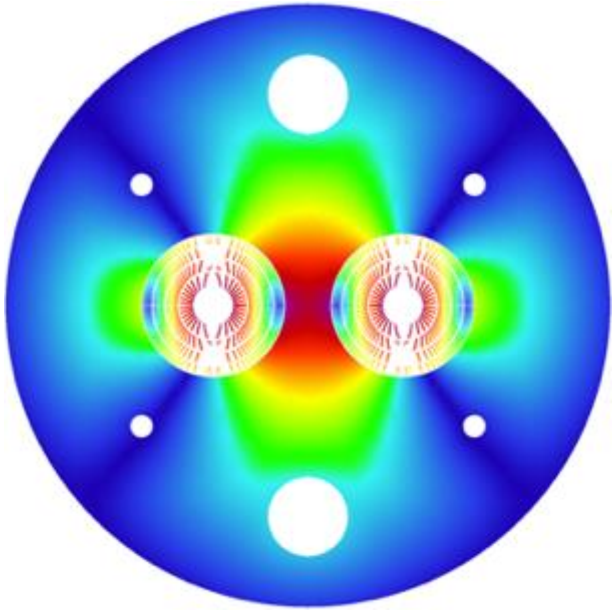
PSI's CCT Design for FCC

- 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

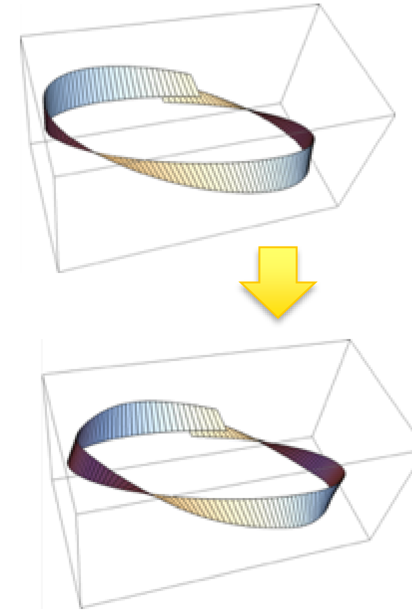


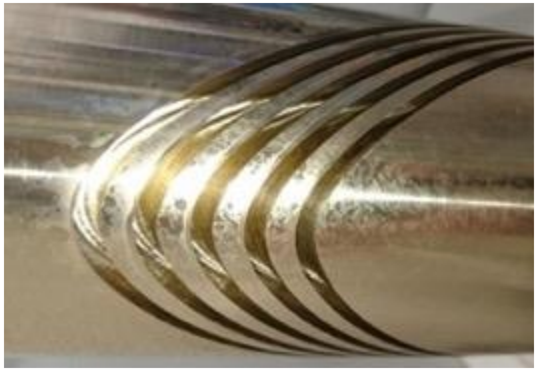
- Optimize J_e optimal winding angle, minimal spars, and ribs, wide cable.
- FCC-wide conductor use: **9.77 kt** (+25% wrt. block coil)
    - Total inductance: 19.2 mH/m
    - Total energy: 3.2 MJ/m
- Opportunity to reduce unit length and peak voltage to ground via double-helix.

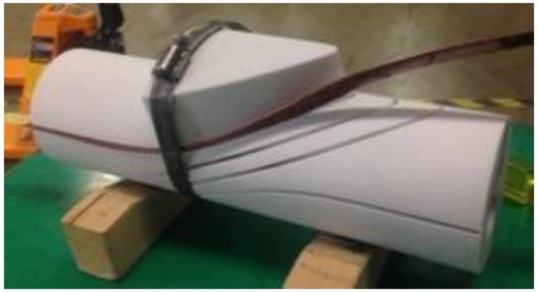


Windability

- Tilted-channel design to reduce hard-way bend.
- Successful machining of 5-turn former.
- FNAL supplied Nb_3Sn cable for winding tests:
  - 28 strands 1 mm RRP 150/169, close to FCC cable specs.
  - Glass-tape insulated.
- Manual winding possible, but not without difficulty.
- Reducing the risk for de-cabling requires tooling development to hold, support and pre-bend the cable.

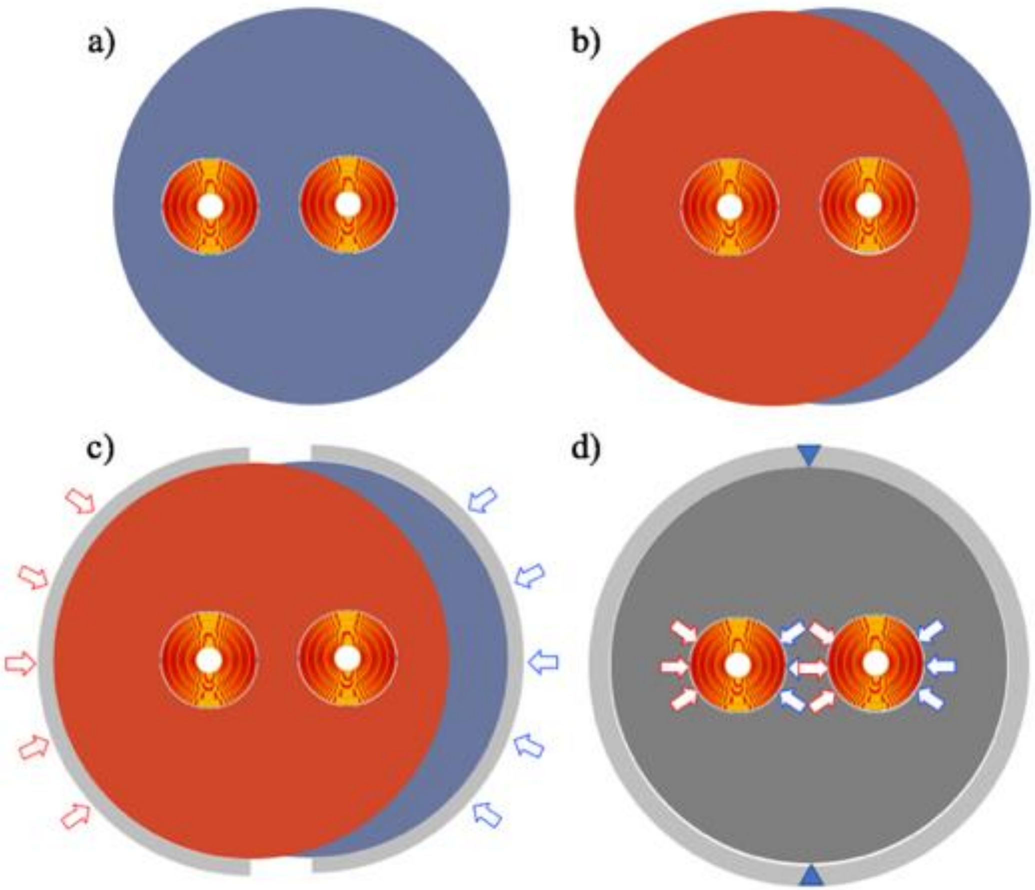






Scissors Lamination Principle

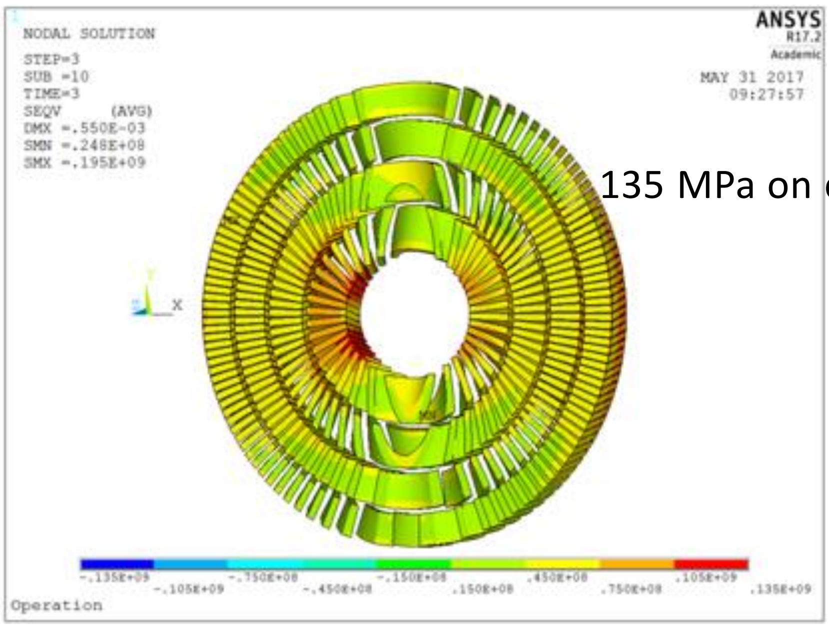
- CCT does not require azimuthal prestress.
- Radial prestress on the midplane provided by “scissor” laminations and 25-mm stainless steel shell (welding challenge!)
- No need for Al shell → no need for extra compact design to fit HE-LHC specs.

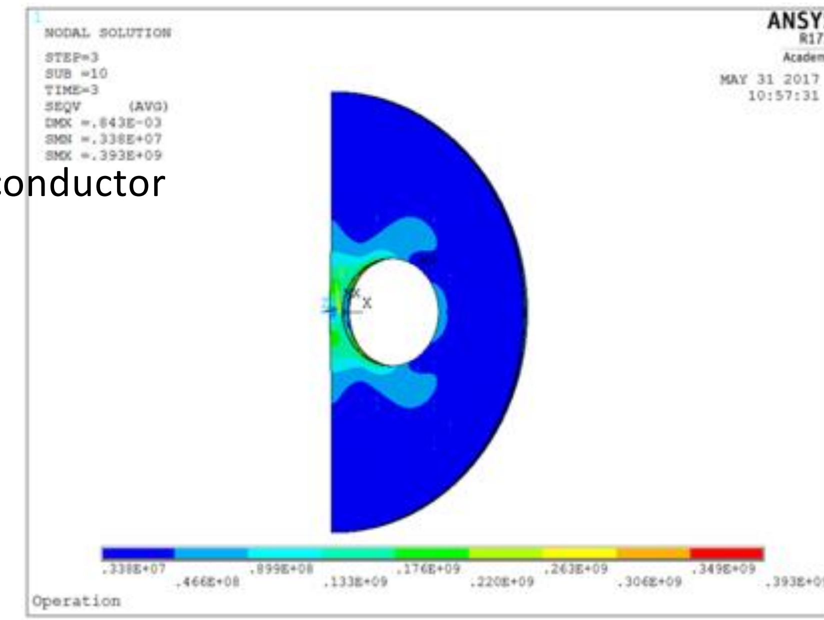


3-D Periodic Simulation

- Generalized plane stress condition applied (following D. Arbelaez, L. Brouwer, LBNL)
- 3-D results confirm 2D.
- 135 MPa peak stress below most estimates for reversible degradation.

135 MPa on conductor



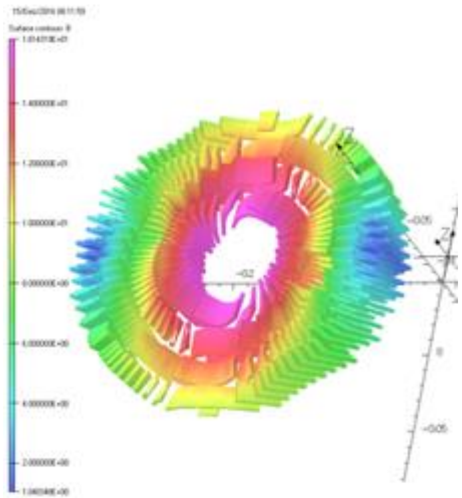


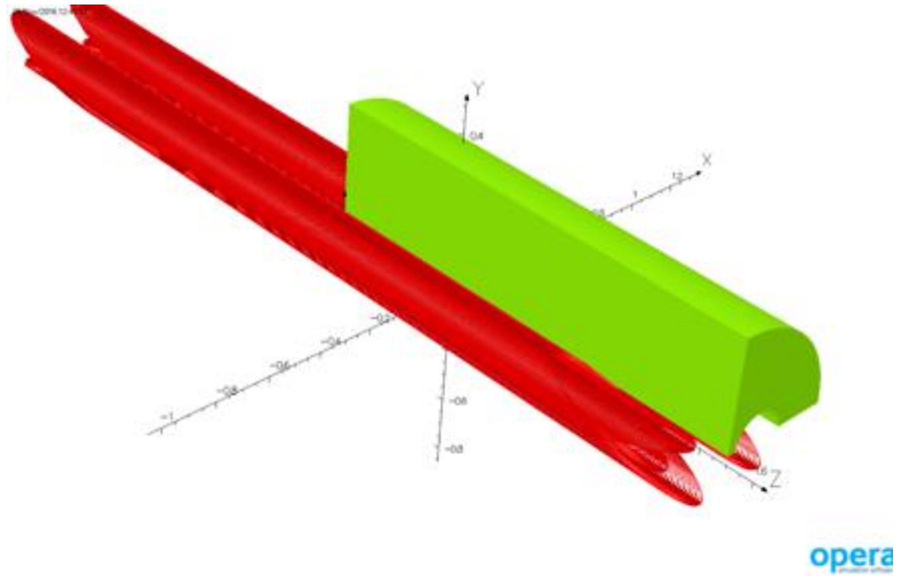
Courtesy G. Rolando

3-D Magnetic Design

3-D EM modeling results:

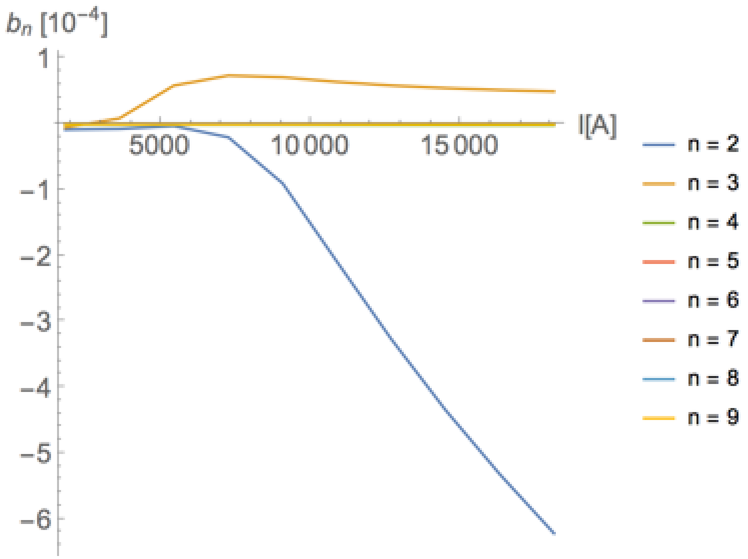
- No mechanical discontinuities in the ends.
- **Yoke cut-back** not needed (only 20 mT peak-field enhancement in ends).
- **Magnetic length** with yoke equal to that of bare coil.
- **Total physical length** minus total magn. length = 52 cm.
- **Peak field** minus main field at 16-T bore field: 0.14 T excl. self field, 0.35 T incl. self field.

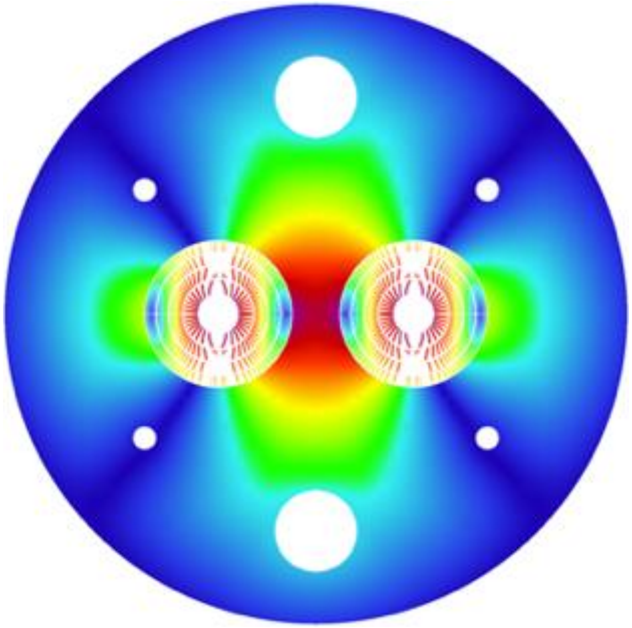




Courtesy M. Negrazus

Geometrical Field Quality

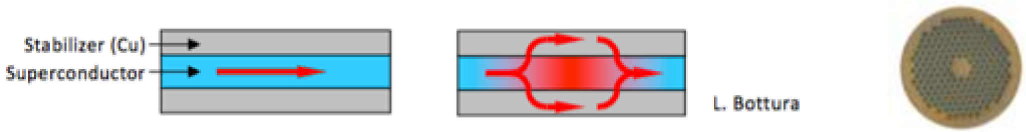


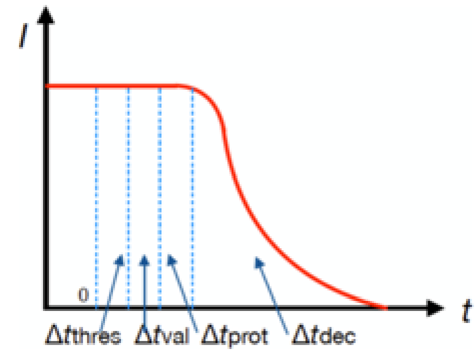


- Field quality due to non-linear iron + coil.
- Small sextupole.
- Good magnetic separation → reduced quadrupole.
- Shorter quadrupole in the lattice → main dipole field reduced by 1%
  - 15.84 T peak field
  - 9.215 kt or +16% wrt. block coil
- Persistent-current calculation not (yet) available.

CCT Protection

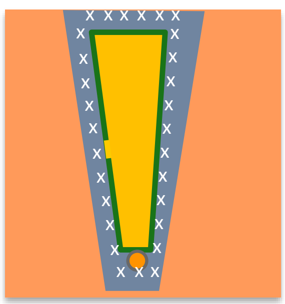
- Goal of PhD by Jiani Gao:
  - Design an efficient detection & protection system for CCT.

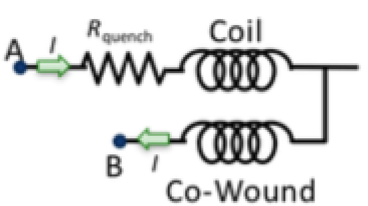




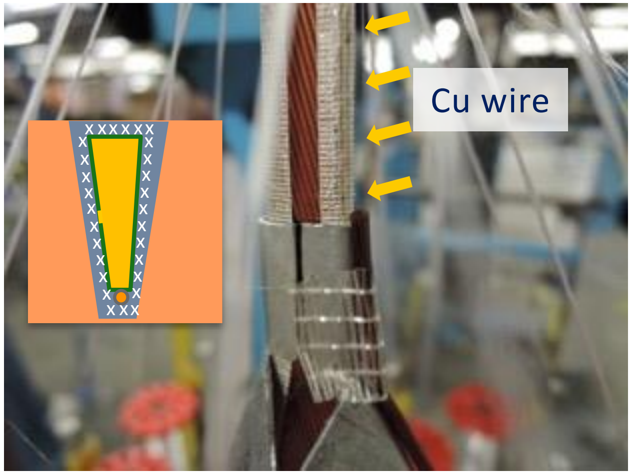
  - Prove that LHC-based EuroCirCol criterion (40 ms from quench init. to full protection efficiency) can be improved upon.
  - Many findings are expected to carry over to other magnet types

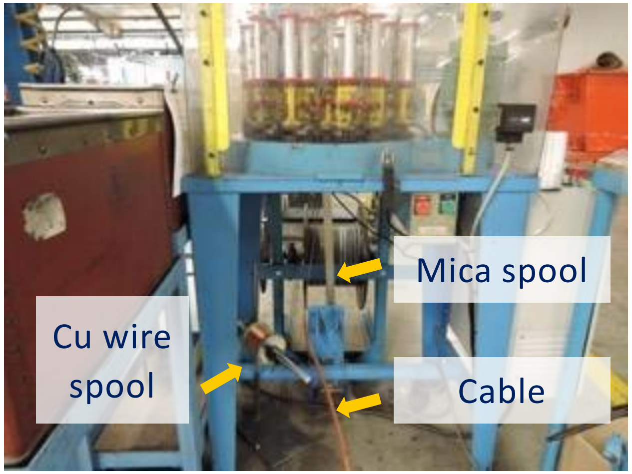
- Detection:
  - Co-wound Cu wire for optimal inductive compensation of voltage signals.
  - Co-wound SC wire for current-based detection: have ~ 1 A circulate in co-wound SC wire and main cable; propagation of quench to co-wound wire and the 1 A quickly drops; detect dI/dt.
  - Co-wound optical fiber (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





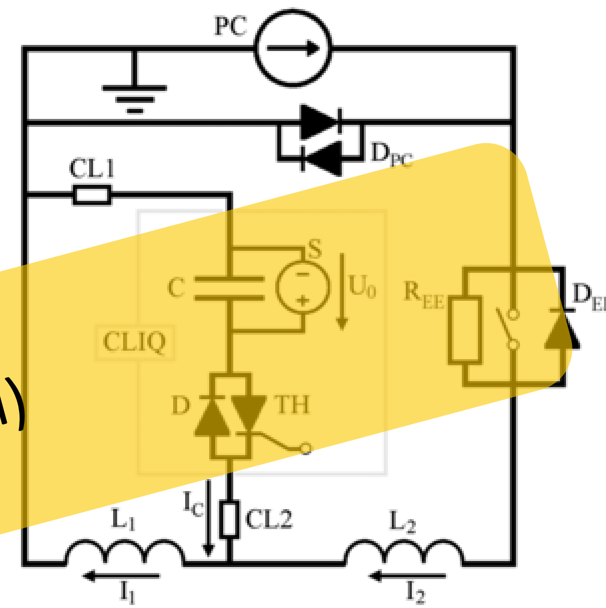
J. Mazet (CERN)

CCT Protection

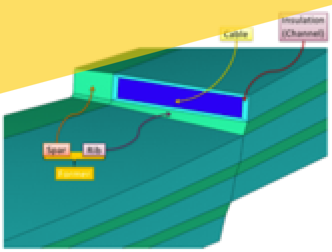
- Protection:
  - CLIQ discharge
    - between layers.
    - Alternatively, in case of double-helix winding, within each layer between strands of double helix.

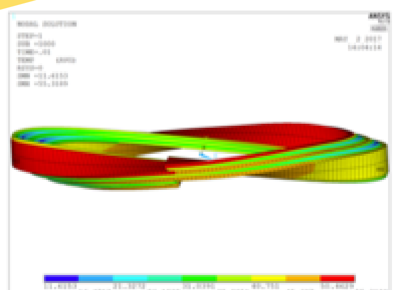
- Simulation:
  - 3-D simulation of initial voltage rise.
  - Apply L. Brouwer’s (LBNL) ANSYS user defined eleme
    - 2-D simulation of CLIQ protection.

See Poster by Jiani Gao (PSI)



CLIQ
Courtesy of E. Ravaioli



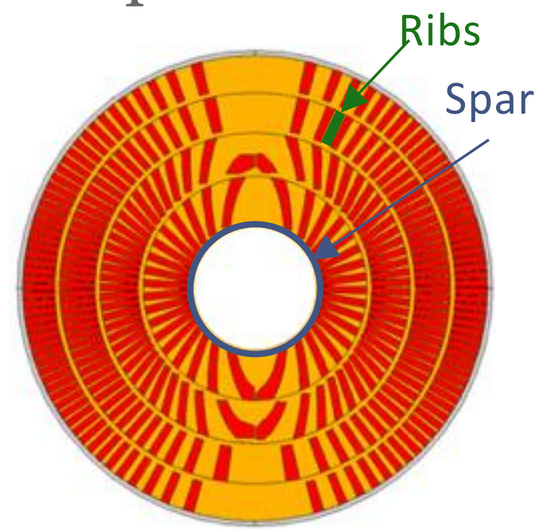


Overview

- Canted-Cosine-Theta Technology for the FCC Main Dipole
- The PSI/FCC Superconducting-Magnet Program
- CD1 manufacturing status

PSI/CHART Goals towards FCC Requirements

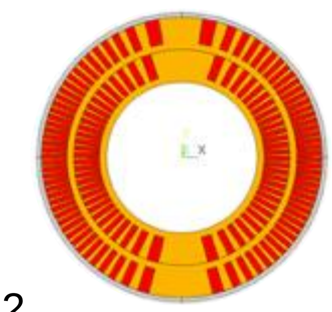
- Joint funding from CHART and the FCC design study from mid 2016 until the end of 2019.
- Goal: Demonstrate key technological features of an **efficient** 16-T CCT in two-layer technology model magnets.

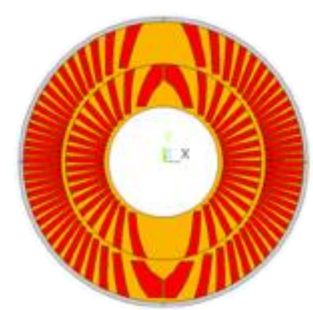


- Thin ribs and spars
- Exterior mechanical structure
- Fast quench detection and CLIQ protection.
- Wide Rutherford cable.
- Inclined channels.
- Improved impregnation procedures.

CD1: Thin ribs and spars; Exterior mechanical structure; Fast quench detection and CLIQ protection.

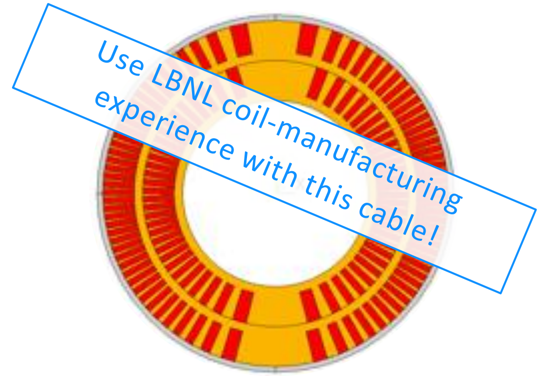
CD2: Thin ribs and spars; Exterior mechanical structure; Fast quench detection and CLIQ protection; Wide Rutherford cable; Inclined channels; Improved impregnation procedures.

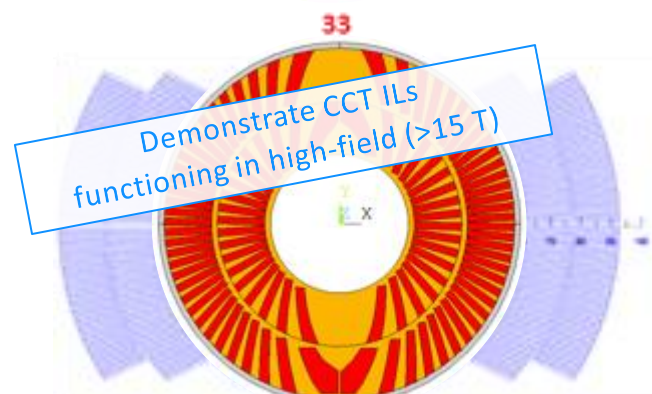




CD1 & CD2 Details – Synergies with US Labs

- PSI **builds one mechanical structure** for
  - **CD1, 2018**:
    - **LBNL CCT cable** (0.85 mm diam, RRP 108/127, 21 strand),
    - 10.6 mm channel depth, 3 mm spar, 0.5 mm assembly gap
    - Layer-2 OD = 122 mm, ID = 65.6 mm (clear bore).
    - CD1 introduces CCT technology to PSI.
  - **CD2, 2019**:
    - **15-T IL cable**, (1 mm diam, RRP 150/169, 28 strand)
    - 16 mm inclined channel, Layer-2 OD = 122 mm, ID = 48 mm (clear bore).
- CD2 fits **into MDP 15-T outer layers 3&4** or could become layers **1&2 in an all-CCT 4-layer magnet** in collaboration with LBNL.
  - *Caveat*: CD2 according to above specs only if CD1 is reasonably successful. Else CD2 will be an improved CD1.

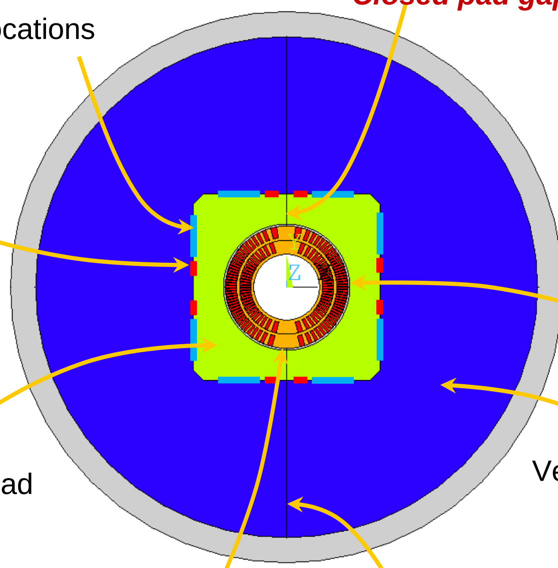




Mechanical Structure

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.

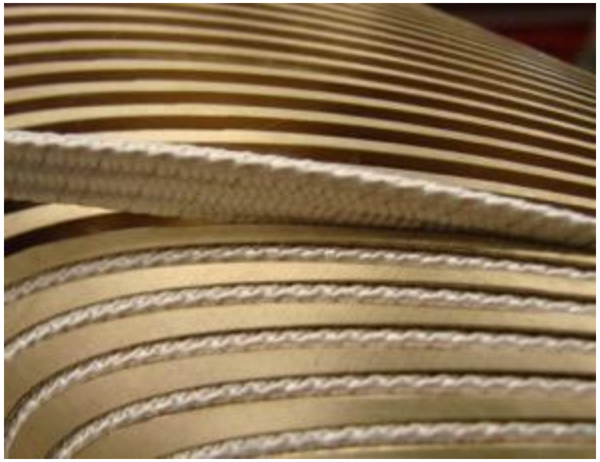


International conceptual design review of CD1 on June 26 at CERN (http://indico.cern.ch/e/cd1cdr).

Assembly and collaboration with ETHZ

BERKELEY LAB

CERN



- **Turns** are in direct contact with former.
  - Perfect adhesion must be ensured to avoid delamination and friction movement.
- **Layer-to-layer** contacts transmit forces radially and axially in the ends.
  - Either perfect adhesion or perfect sliding must be ensured.
- FSU Mix-61 on sandblasted surfaces has shown compression-shear strength up to 100 MPa – sufficient for our CD1 magnet. → We plan to glue the layers.
- **Collaboration of CERN/PSI with ETHZ Soft-Materials Laboratory**, Prof. Tervoort
  - Characterize range of known epoxies (CTD 101-K, MY750, FSU Mix 61, ..)
  - Find state-of-the-art resin system that is radiation-resistant, crack-resistant, ….
  - Find optimized conditioning and impregnation procedure to ensure maximum bonding to metal surfaces and glass fibers.
  - Test of cable/glass/epoxy composite.
  - Implement new developments in CD2 magnet.

ETH zürich

Overview

- Canted-Cosine-Theta Technology for the FCC Main Dipole
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See Poster by Giuseppe Montenero (PSI)

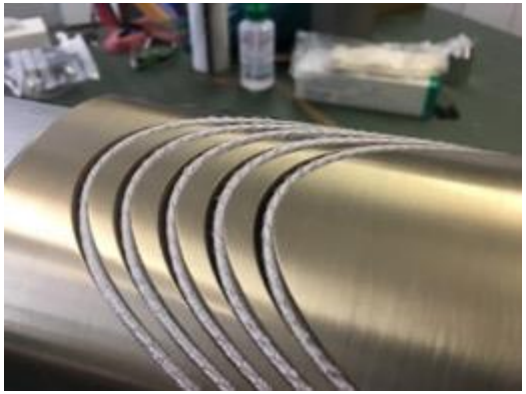
Machining and Reaction Tests.

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

Test formers delivered.

Test winding completed.

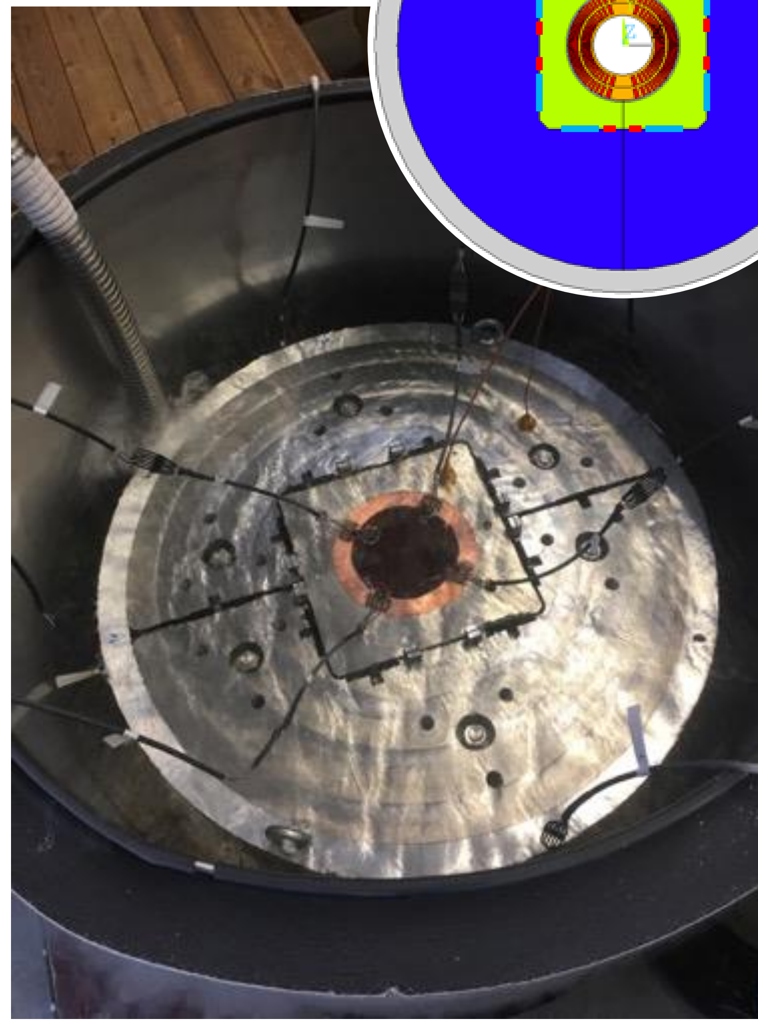
Preparation for heat treatment.

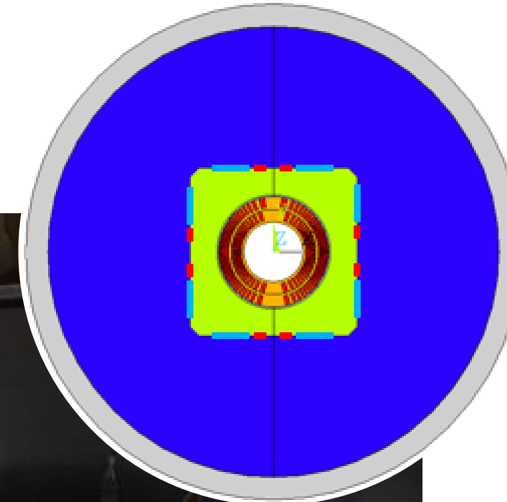


Before heat treatment

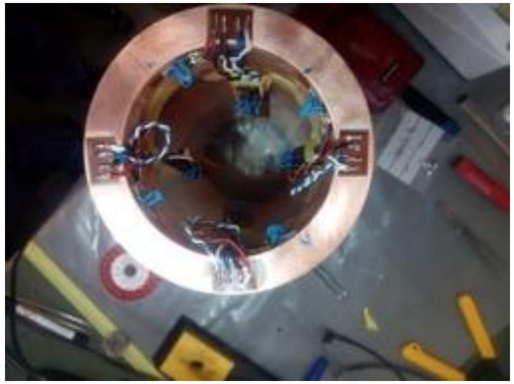
After heat treatment

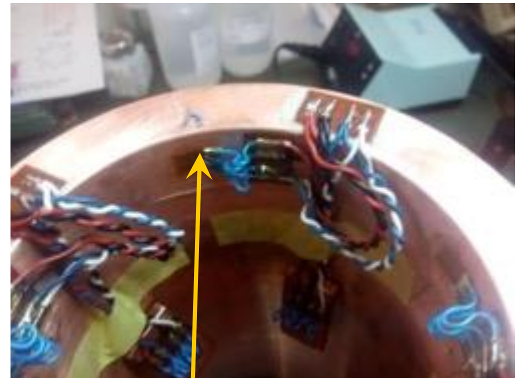
Short Mechanical Model

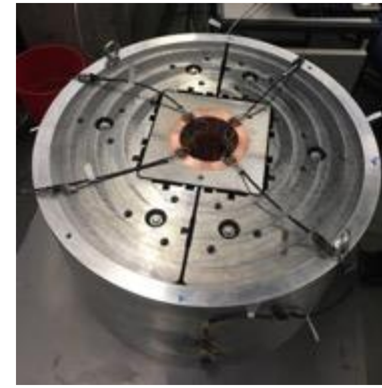




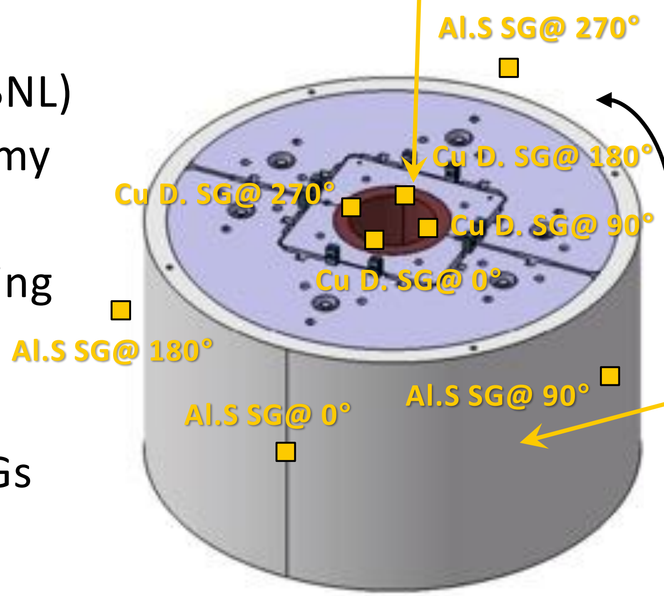
Short Mechanical Model - Instrumentation







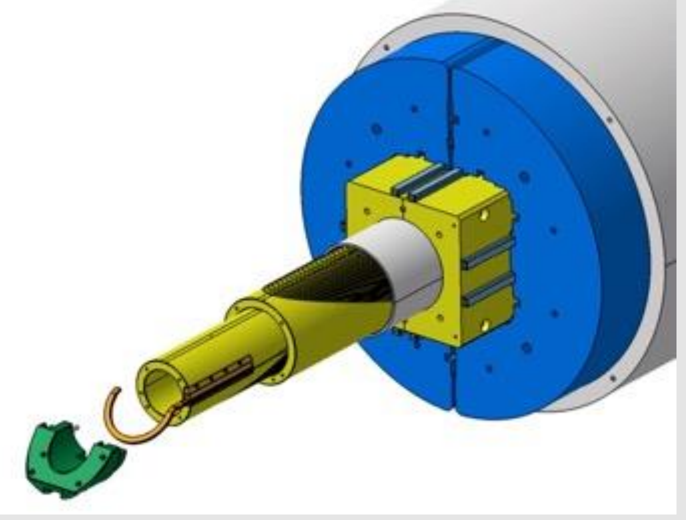
- HBM setup (like CERN, LBNL)
- 4 full-bridge SGs on dummy and shell, resp.
- Solved bonding issues using Araldite adhesive
- Better cable routing and strain management on SGs using intermediate pads



G. Montenero

CD1 Design and Procurement

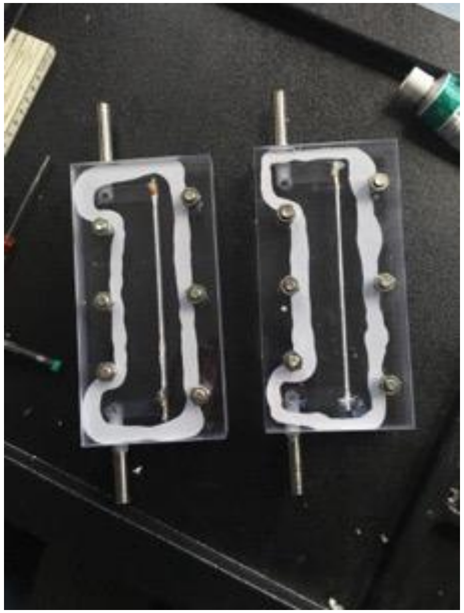
- Cable received from LBNL mid ‘17
- Cable insulation: in April ‘18 by CERN
- Coil formers: delivery April ’18
- Outer shell and protective shell: April ‘18
- Yokes, pads, keys: delivery May ‘18
- Bladders: received
- Layer-to-layer splice box in procurement
- Splicing tooling received
- Impregnation tooling: delivery April ‘18
- Heater powering and controls built
- Capacitive level gauge tested

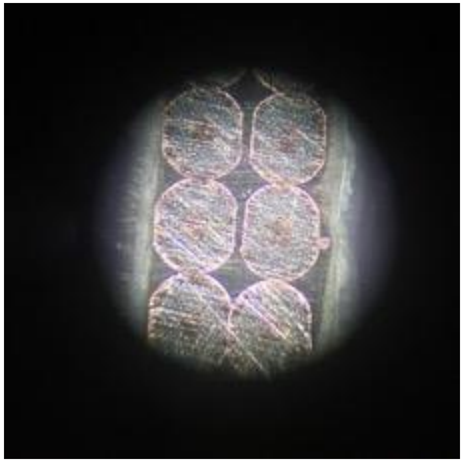


S. Sidorov

- **All CD1 components are designed and ordered or received.**
- **Conductor for CD2 ordered.**

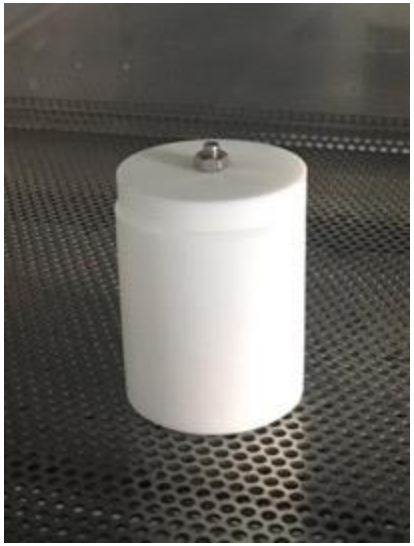
Impregnation Trials

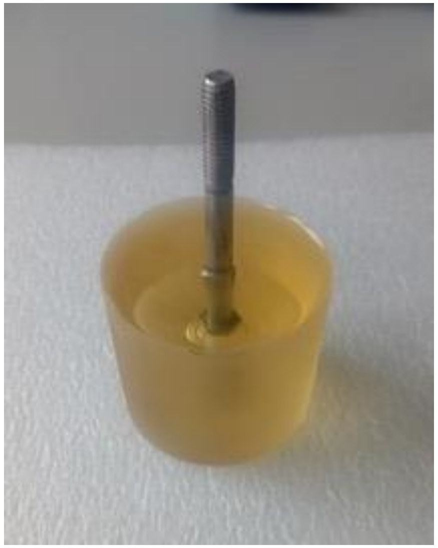




Bolt Tests

- Bolt suspended in cup
  - CTD 101-K: loud banging noise during shock-freezing in LN2; large part expulsed by ~15 cm during warm-up at RT.
  - CTD 101-G: hair-like fissures, increasing in number and size with repeated thermal shocks.
  - Florida-State Mix 61: no sign of cracking after three thermal shocks.

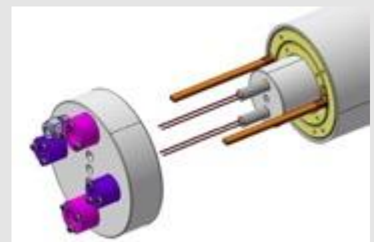
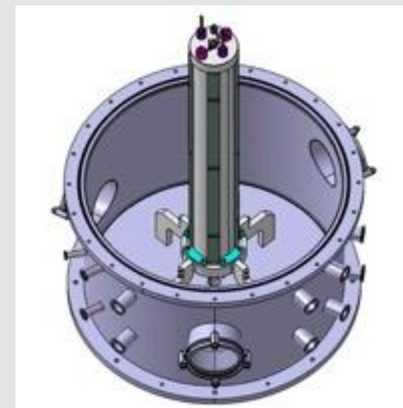




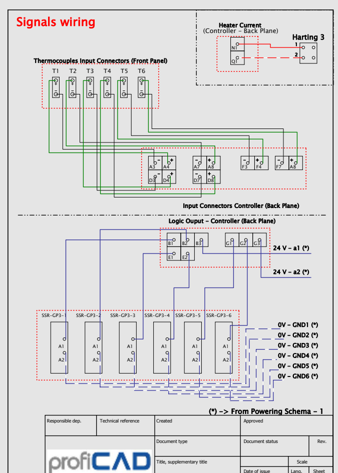
Thanks to Iain Dixon and Denis Markiewicz for their support!

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.

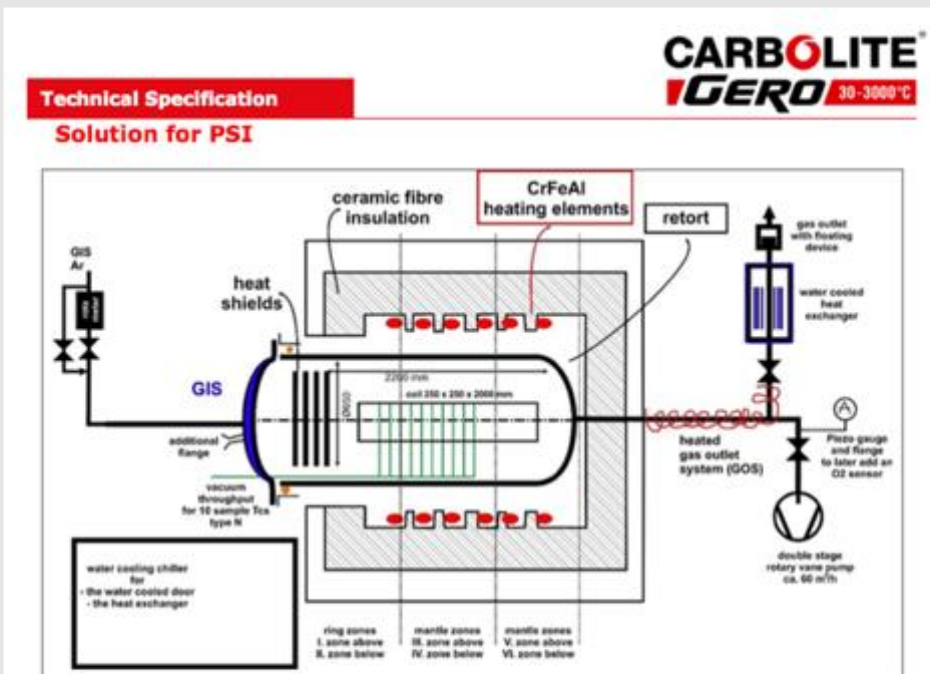



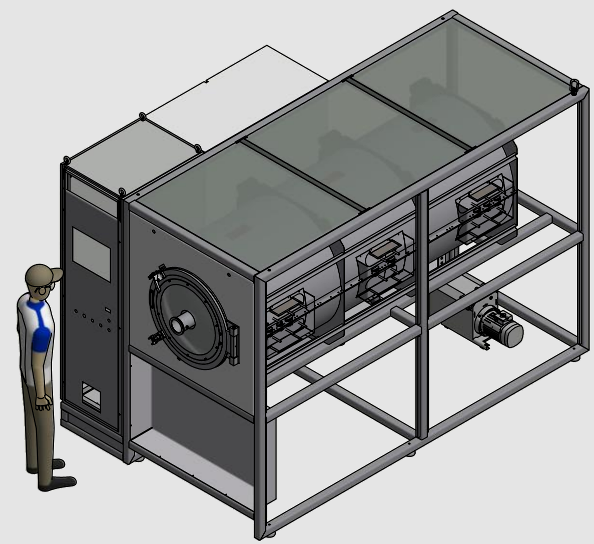
G. Montenero and R. Felder

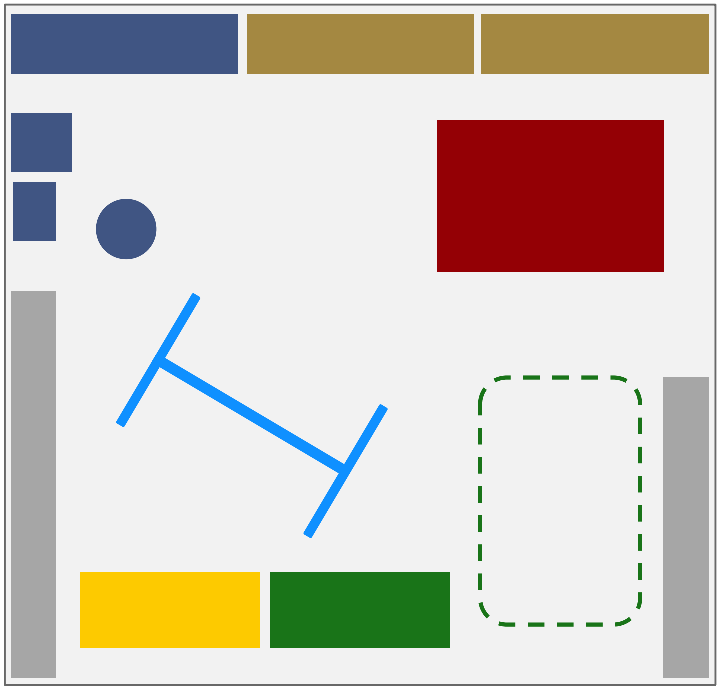

Procurement of Reaction Furnace

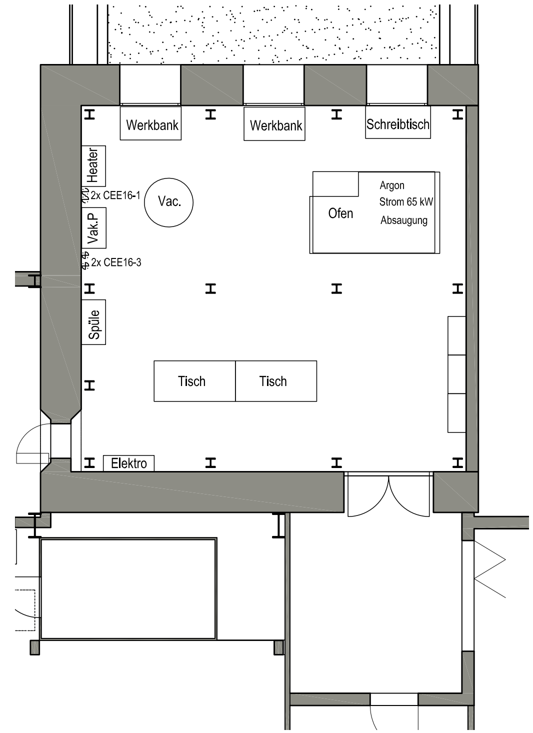
- Heat treatment furnace with Argon flow.
- Order placed following CERN specs.
- Working volume 2 m in length, >30 cm in diameter.
- Expected on-site commissioning June ‘18.





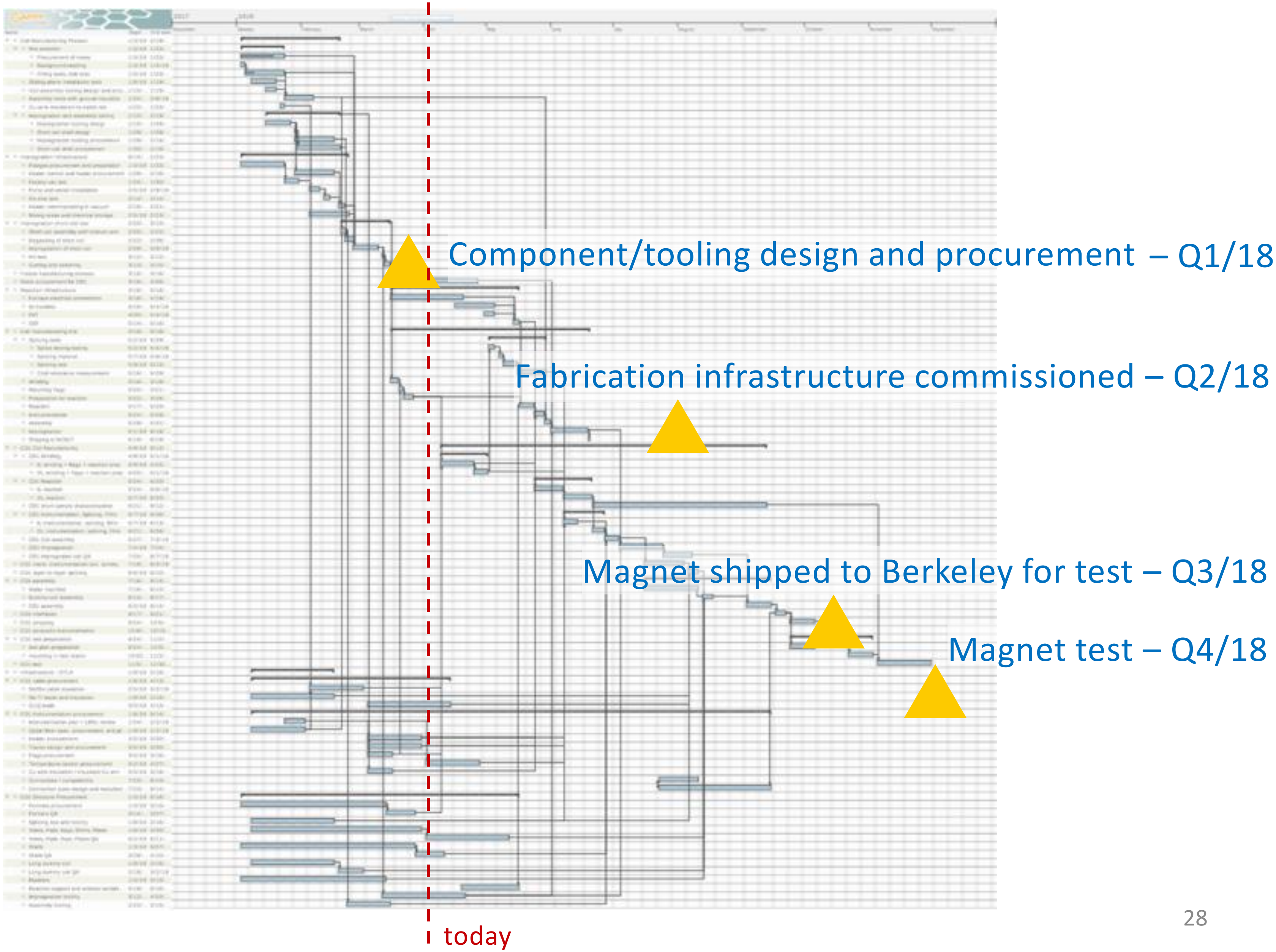
Superconducting Magnet Fabrication Lab





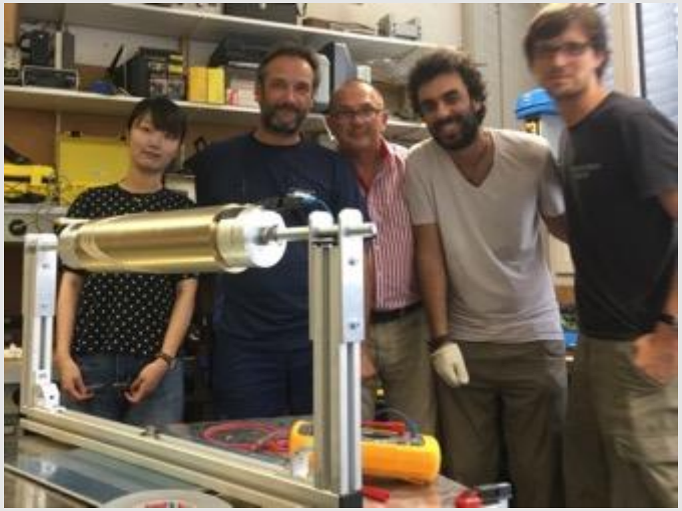
- Coil winding, instrumentation, assembly
- Reaction
- Impregnation, mixing
- Assembly and RT mag. meas.
- Storage
- Workplace
- Crane

CD1 Schedule v2



Conclusion

- With CHART and FCC funding, PSI builds two technology model magnets until the end of 2019.
- Close coordination with CERN, LBNL, and collaborations with FNAL, UniGE, ETHZ, and Penn-State make this ambitious plan possible.
- The coming year will see tests of LBNL's CCT5 and CD1.
- Insights gained from these tests, together with resin & impregnation R&D with ETHZ should open the way for 16-T CCT magnets for FCC.
- Scalability of former manufacturing and automated-winding will be addressed after a successful test in the PSI program.



CCT Pros and Cons

- Mechanical support of each turn → reduced coil stress and avoidance of stress-induced degradation.
- Easy field quality.
- Simple and safe coil-manufacturing process; little tooling needed; coil protected by former.
- Ideally suited for LTS/HTS hybrid magnets due to easy stacking of heterogeneous layers.
- Simpler external mechanical structure → more iron between the apertures and better magnetic separation → less cross-talk.
- To be proven: efficient CLIQ protection as every turn is a high-field turn.
- Hope to fix training: getting one turn "right", the entire magnet would work; no discontinuities towards the end regions
- Co-winding of instrumentation (fibers, wires, etc.) is easy.
- Possibility of double-helix winding for reduced unit length and voltage to ground.

- Reduced efficiency by winding angle, rib thickness, and spar thickness.
- Every turn must be glued to metal surfaces; delamination would preclude good performance.
- Involved former manufacturing; cost and time consuming; difficult to scale to 15 m.
- Tricky winding of innermost layers with wide cable.
- Some axial strain on cable in every turn.
- To be proven: less efficient CLIQ protection as a conductive former may absorb some the CLIQ energy.
- No heater protection possible.

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Wir schaffen Wissen – heute für morgen

BERKELEY LAB

CERN

Collaborations 1/2

- CERN:
  - Financial support through FCC design study.
  - Knowledge transfer bi-weekly (specs for infrastructure, drawings, etc.).
  - Cable insulation.
- LBNL Lawrence Berkeley National Lab (CA, USA):
  - Close coordination of LBNL and PSI R&D on CCT magnets.
  - Design and manufacturing process of CCT magnets.
  - Drawings, experience, review of technical design.
  - Direct conceptual-design input.
  - Provided cable for CD1.
  - Will test CD1.
  - Exchange on resin and impregnation systems.

Collaborations 2/2

- FNAL Fermi National Lab (IL, USA)
  - Cable specs and Rutherford-cable production for CD2
  - 4-layer testing of CD2
- UniGE Applied Superconductivity Group
  - Strand testing
- ETHZ Soft-Materials Lab
  - Characterization of known resin systems for SC magnets.
  - Development of new epoxy resin systems.
  - Study of nano-fillers
  - Study of impregnated-coil composite enhancements.
- Penn State University
  - Distributed sensing with optical fibers

Short-Model SG Data vs. 2D Simulation

Position (Degrees)	0	90	180	270	0	90	180	270
Data SG	Dummy (µm/m)				Al Shell (µm/m)			
Assembly RT	271.5	-116	123	-270	484	-82	521	1
CoolDown	1066	-734	878	-1048	1637	760	1557	1012

G. Montenero

- *Asymmetry observed during key insertion and in SG data*:
  - Improve tolerances, discussion of results with structure manufacturer.
  - Set up proper reception QA at PSI.
  - Procure hydraulic 8x manifold with valves.

Persistent Current Effects

- S. Russenschuck et al., “Design Challenges for a Wide-Aperture Insertion Quadrupole Magnet”, IEEE Trans. On Appl. SC, 21(3), July 2011.
- Optimization of field quality in each coil layer reduces persistent-current-induced field errors.
- Could this be an effect in the CCT?

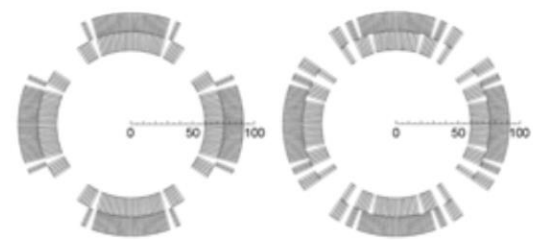

Fig. 7. Two coil cross sections for a 120-mm-aperture quadrupole, referred to as (left) the 4-block [3] and (right) the 6-block design.

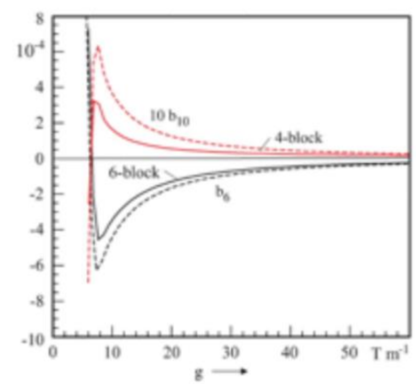

Fig. 8. Multipole field errors b6 and b10 at the reference radius of 40 mm as a function of the gradient. No iron saturation has been taken into account. The memory sequence is $\{0, I_{nom}/2, 0.05 I_{nom}, I_{inj}\}$. (Solid line) The 6-block coil and (dashed line) the 4-block coil.