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CHART superconducting accelerator magnet R&D at PSI

TE MPE PE Section Meeting, 25.10.2018

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

Overview

- CCT @ FCC
- PSI Program – CD1 Design
- SC Magnet Lab @ PSI - Commissioning
- CD1 Manufacturing trials

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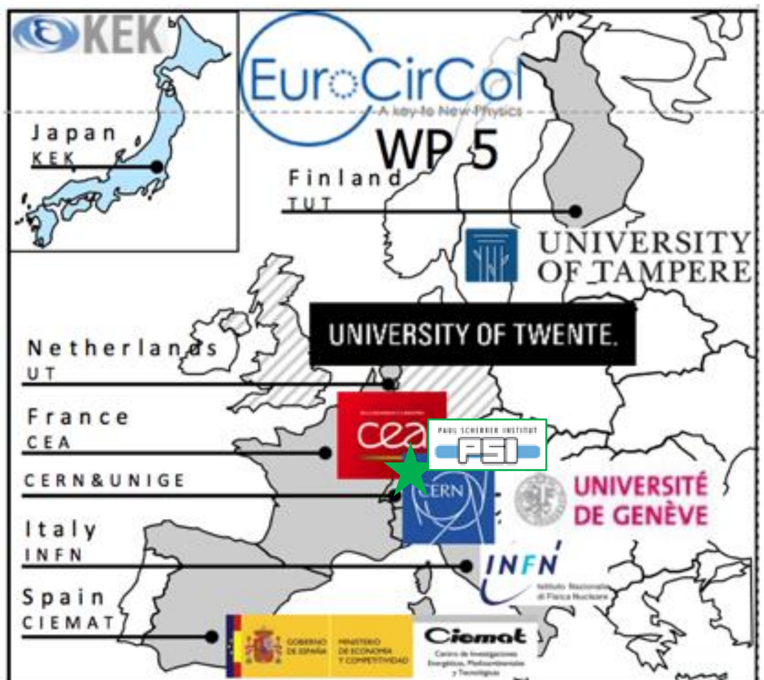
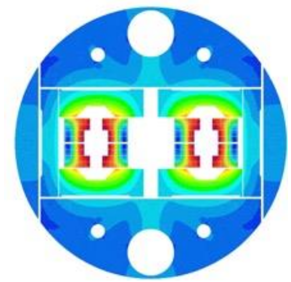
EuroCirCol WP5

- European Circular Energy-Frontier Collider Study started 2015
- PSI joined the effort in 2016 as an "associate member" of WP5
- Magnets fulfill specs for both, FCC-hh and HE-LHC.

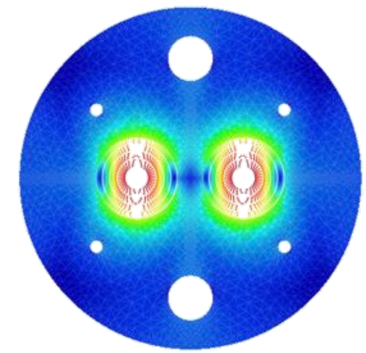


[D. Tommasini, http://cern.ch/fcc/eurocircol]

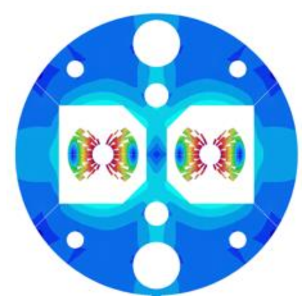
Block coil



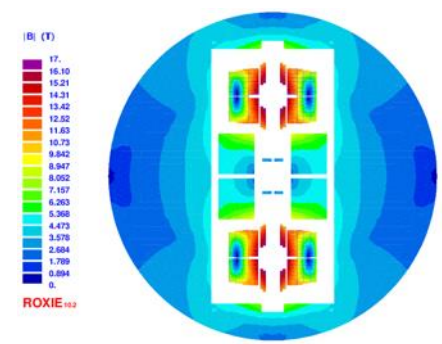
Canted Cosine Theta



Cos-theta



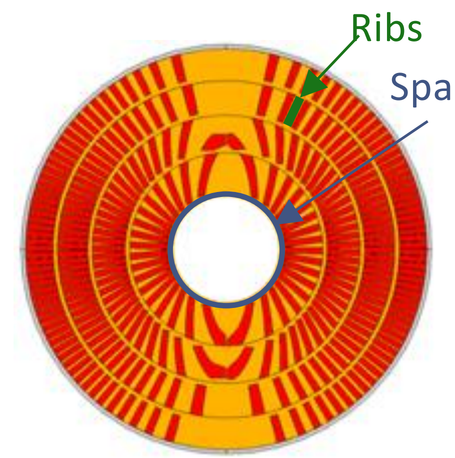
Common coils



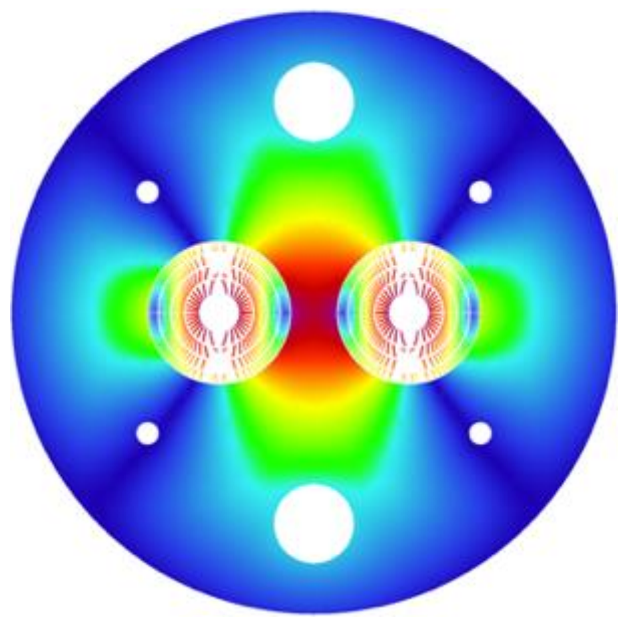
PSI's CCT Design for FCC

- 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



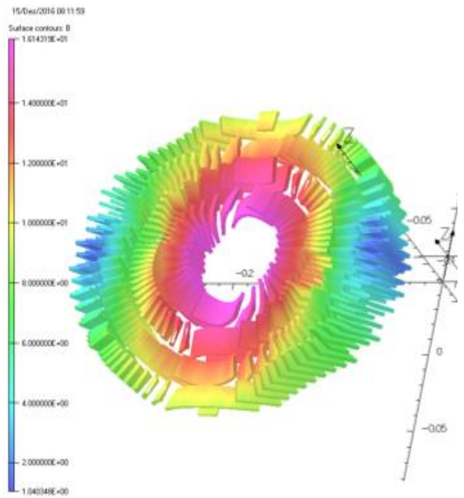
- Optimize J_e optimal winding angle, minimal spars, and ribs, wide cable.
- FCC-wide conductor use: **9.7 kt**
  Total inductance: 19.2 mH/m
  - Total energy: 3.2 MJ/m
- Opportunity to reduce unit length and peak voltage to ground via double-helix.

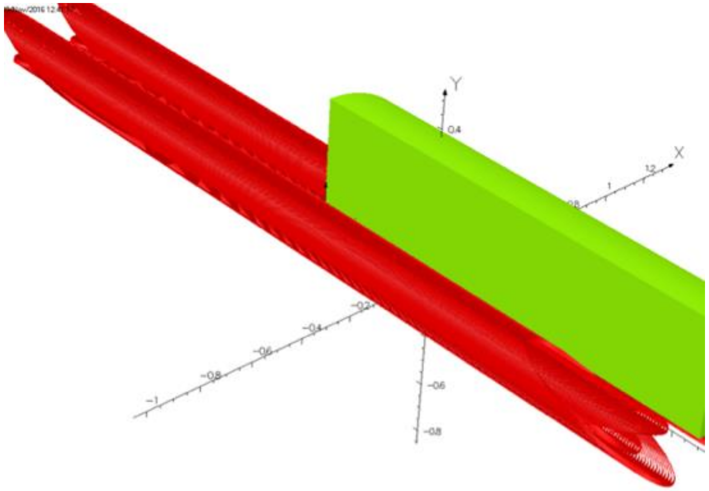


3-D Magnetic Design

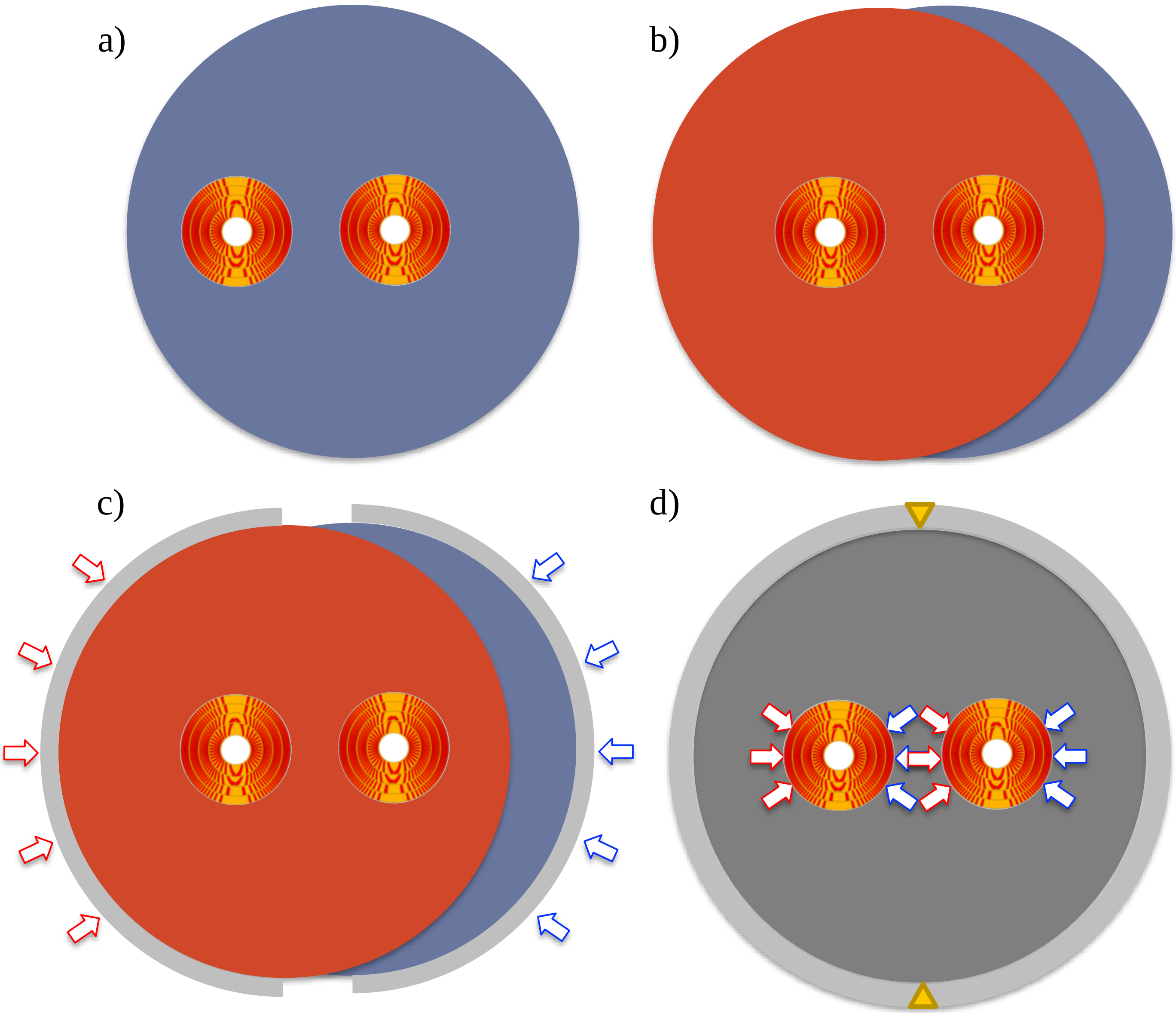
3-D modeling results:

- **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.



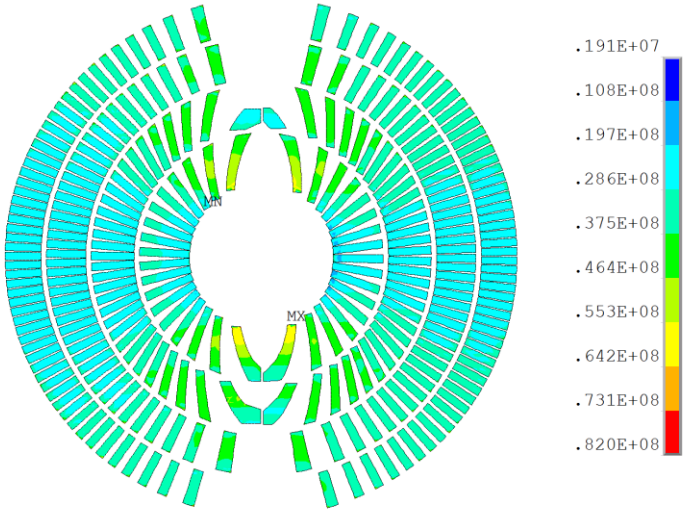


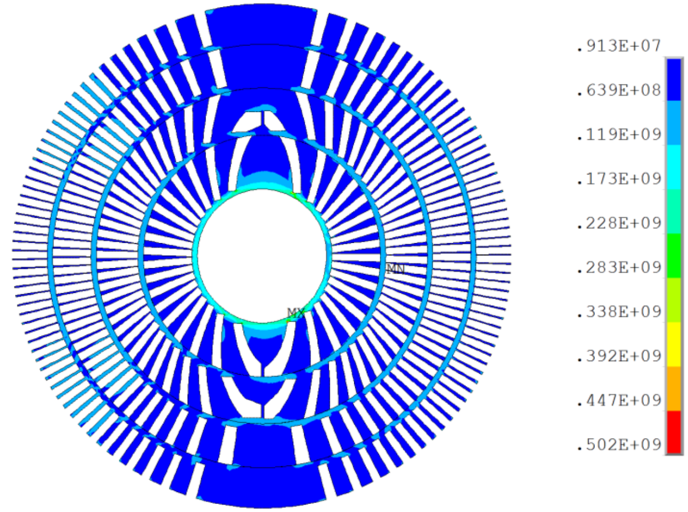
Courtesy M. Negrazus

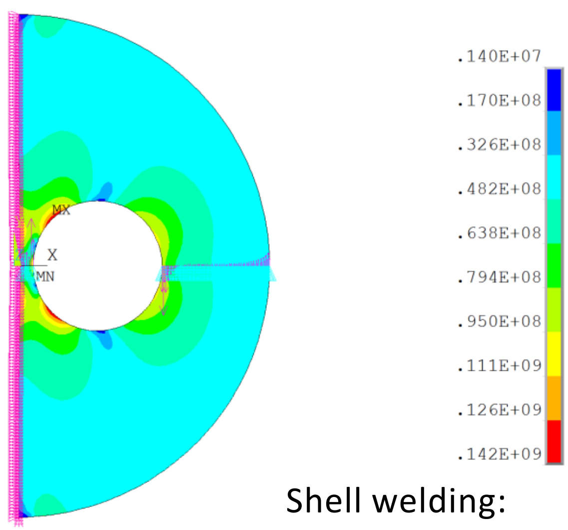

a)
b)
c)
d)

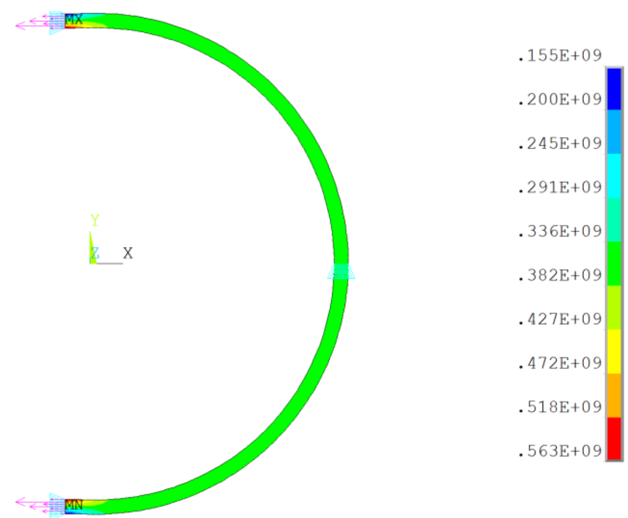
PAUL SCHERRER INSTITUT PSI

2D Mechanical Design – Room Temperature





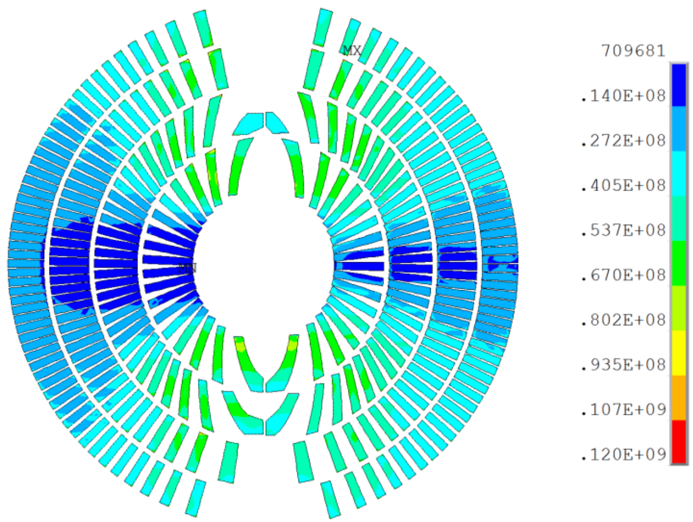


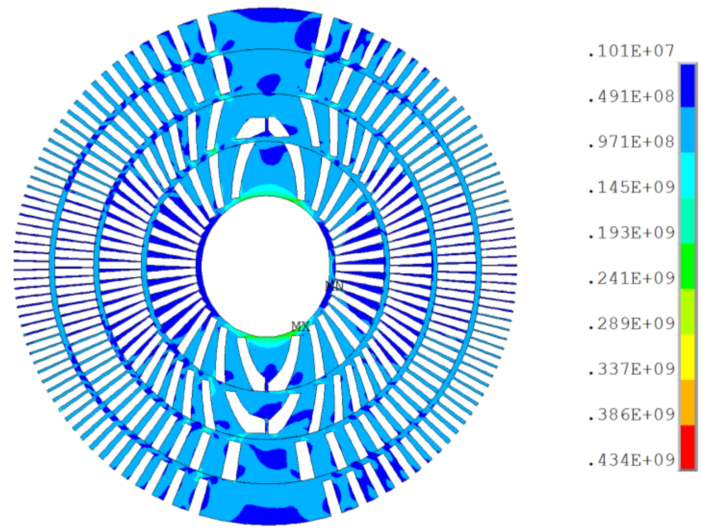


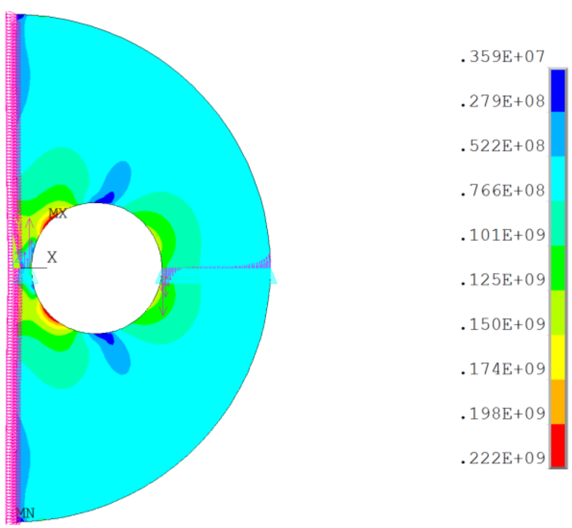
Shell welding:

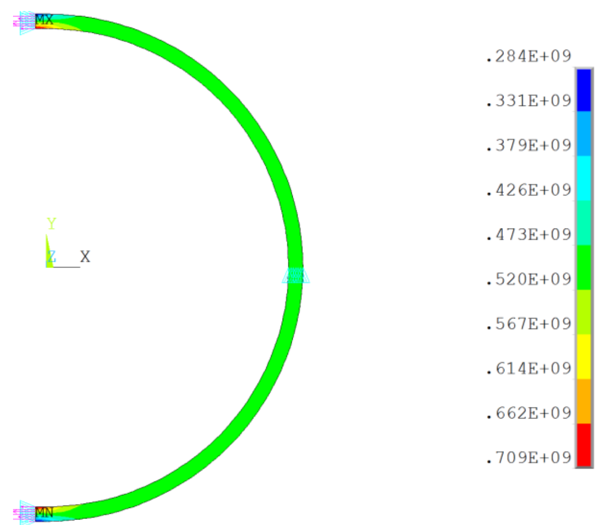
- here displacement constraint (0.9 mm, total 1.8 mm weld shrinkage).
- equivalent to 350 MPa pressure constraint (SS limit).

2D Mechanical Design – Cool-Down





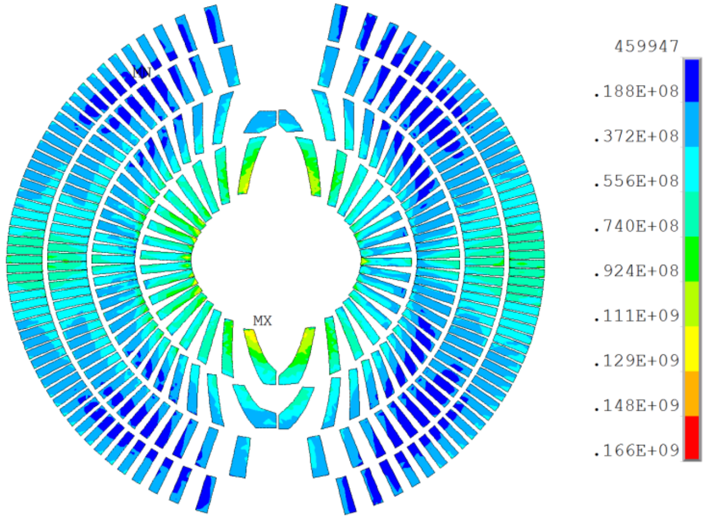


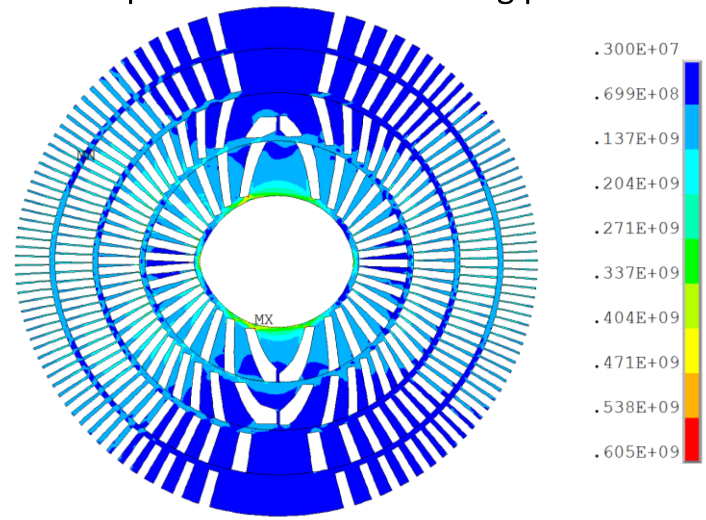


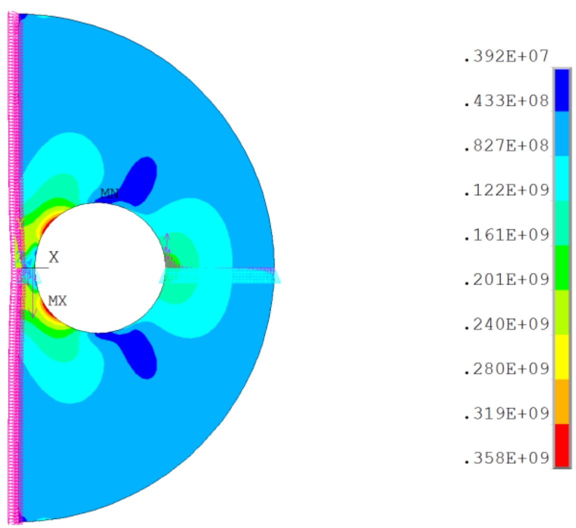
2D Mechanical Design – 16 T

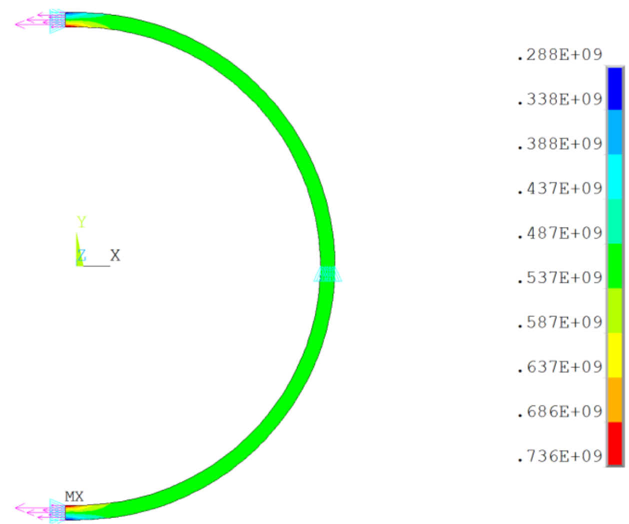
Al-bronze tensile strength measurements after HT under way.

Final former material depends on manufacturing process. Ideally Ti.



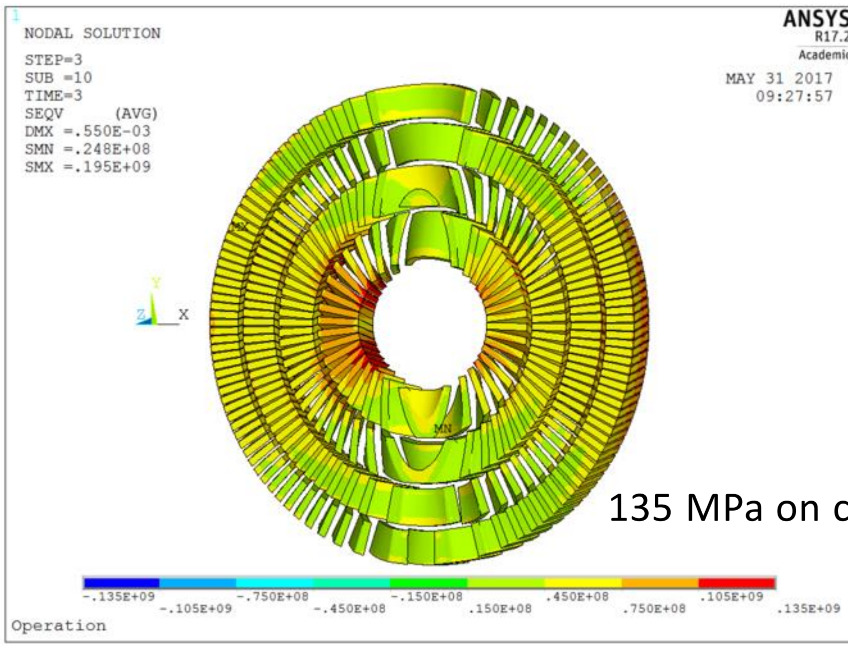




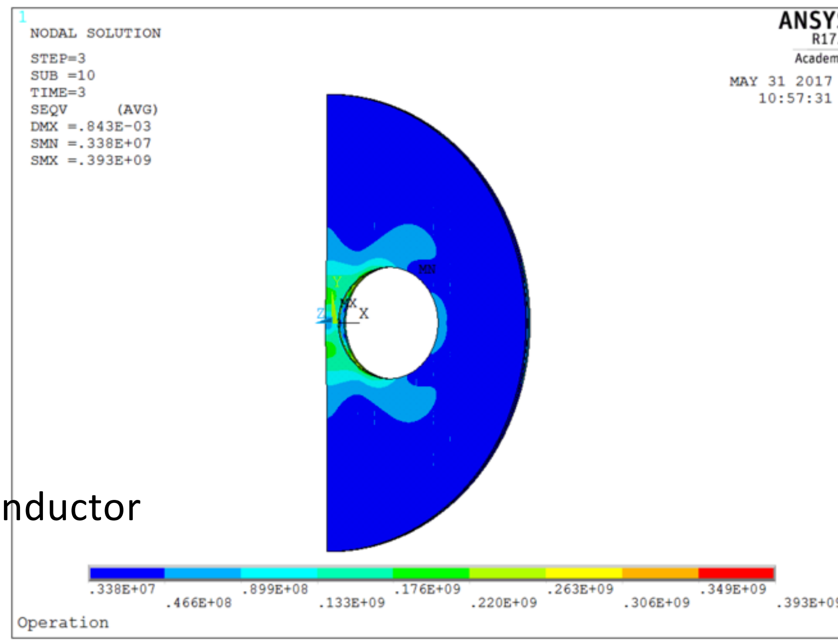


3-D Periodic Simulation

- Generalized plane stress condition applied (following D. Arbelaez, L. Brouwer, LBNL)
- Initial 3-D results confirm 2D, but show distinct imprint of scissors lams
  → increase protective shell thickness, change its material to iron
  → decrease lamination thickness.



135 MPa on conductor



Courtesy G. Rolando

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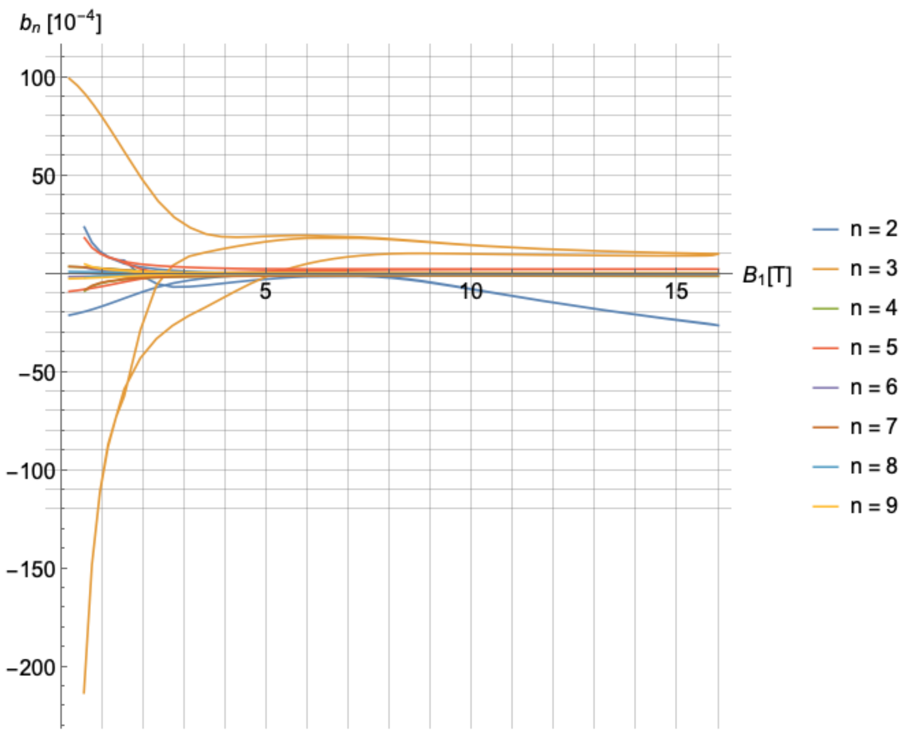
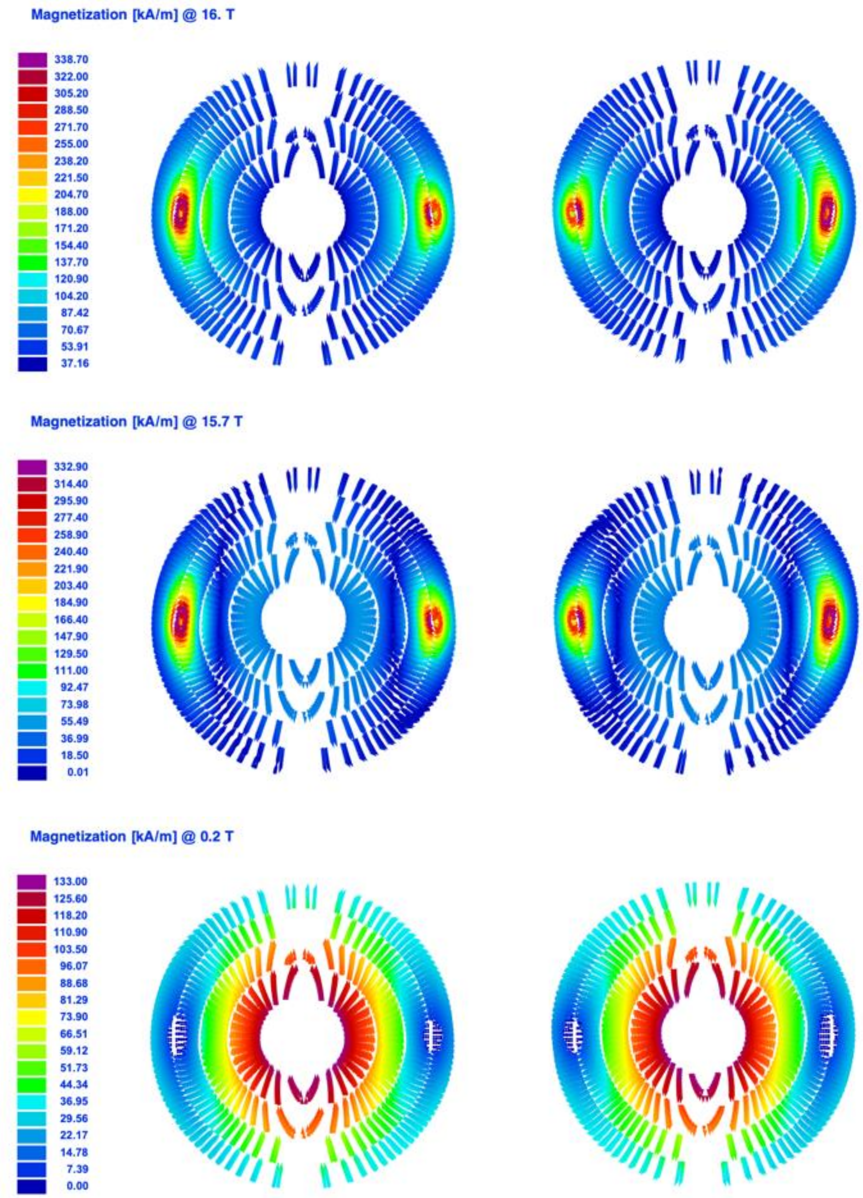
Persistent Currents

- 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.



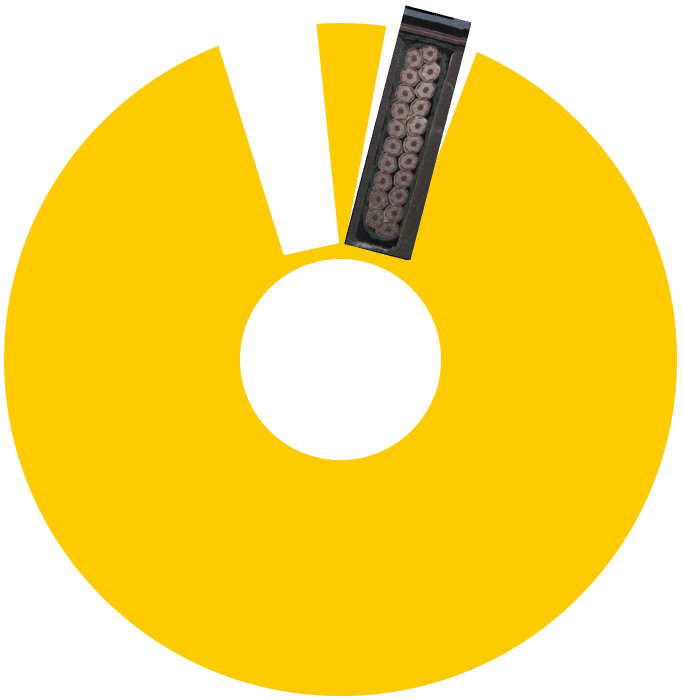


Field Quality

- b_2 correction (-26 to -16 units) by winding-path modification.
  - 25%-reduction in rib bottom thickness.
  - Chamfering/stepping of channel bottom may be required (could also be used to enhance efficiency).
  - Further FQ tuning is possible.

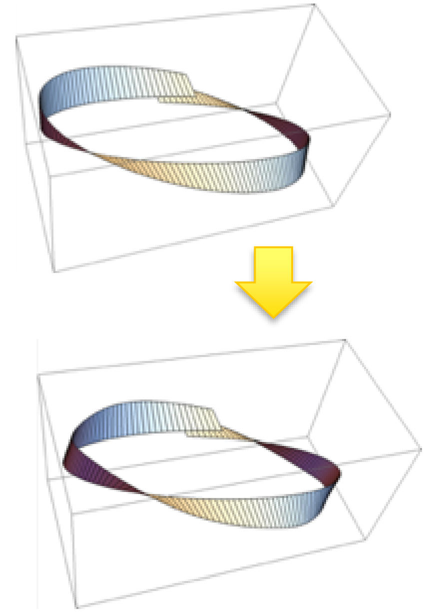
Main Field = 16.0015 T

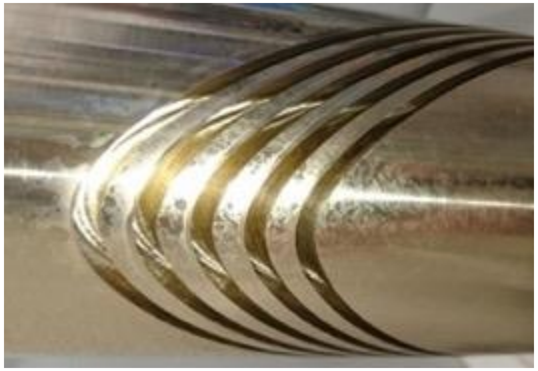
	an	bn
1	-0.458577	10 000.
2	1.46377	-16.9835
3	0.197922	9.41813
4	-0.518893	0.113957
5	0.0145285	2.37396
6	0.675784	-0.202357
7	-0.0930704	-0.985619
8	-0.53873	0.0595043
9	0.0626084	0.295271
10	0.293446	-0.0128189

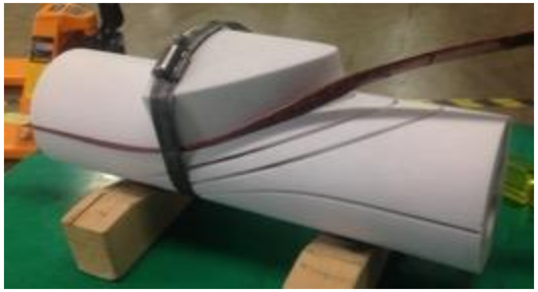


Windability

- 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.







Overview

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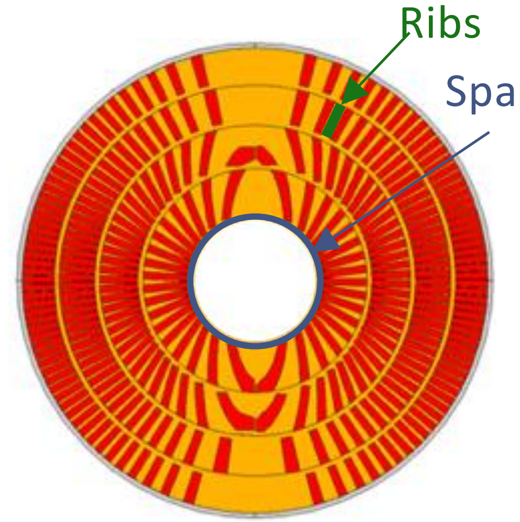
CHART-PSI Goals towards FCC Requirements

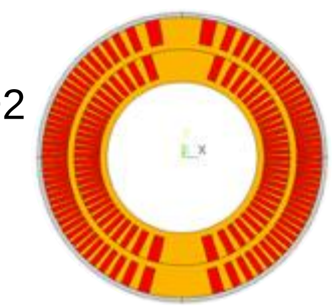


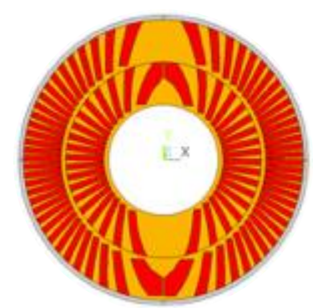
- Goal: Demonstrate key technological features of an **efficient** 16-T CCT in two-layer technology model magnets.

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

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

CD2: all of the above.



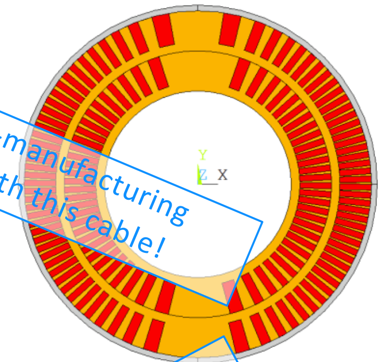


CD1 and CD2 Cable and Geom. Params.

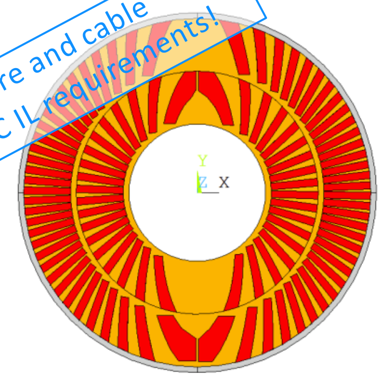
- PSI **builds one mechanical structure** for
  - **CD1**:
    - **LBNL CCT cable** (0.85 mm diam, RRP 108/127, 21 strand),
    - 10.6 mm channel depth, 3 mm spar, 0.5 mm assembly gap
    - Layer-2 OD = 122 mm, ID = 65.6 mm (clear bore).
  - **CD2**:
    - **15-T IL cable**, (1 mm diam, RRP 150/169, 28 strand)
    - 16 mm inclined channel,

    Layer-2 OD = 122 mm, ID = 48 mm (clear bore).
- CD1 introduces CCT technology to PSI.
- CD2 fits **into MDP 15-T outer layers 3&4**.

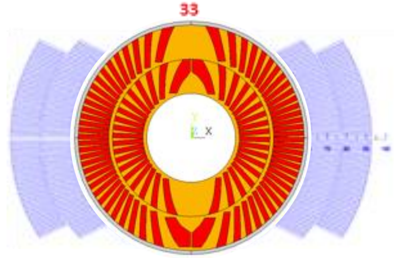
Use LBNL coil-manufacturing experience with this cable!



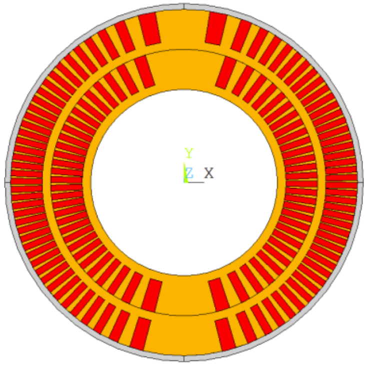
Use FNAL wire and cable resembling FCC IL requirements!



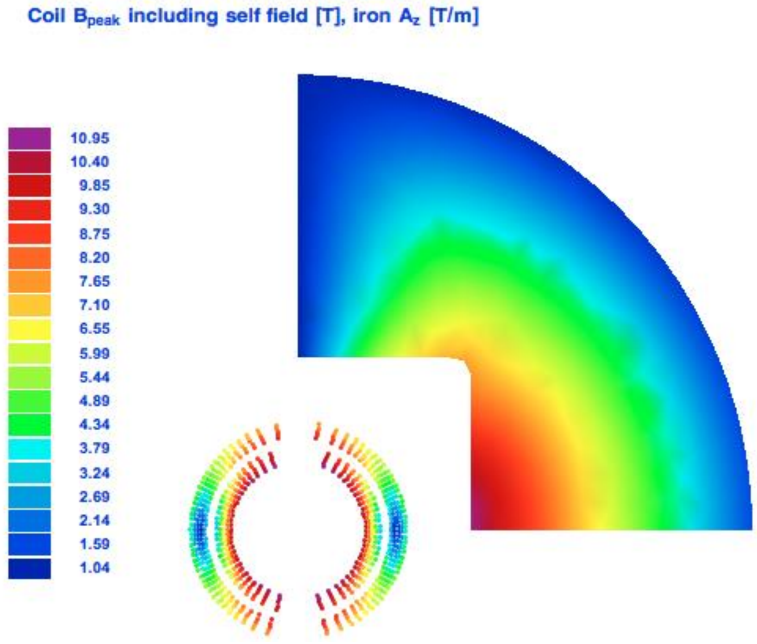
Demonstrate CCT ILs functioning in high-field (>15 T)

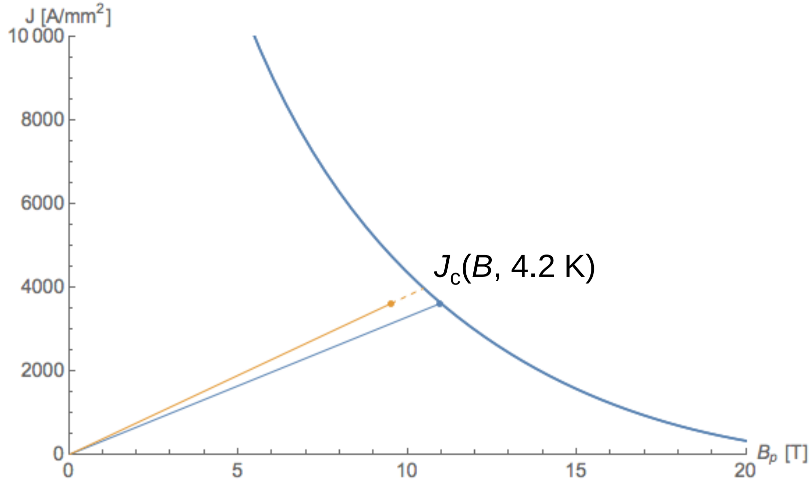


CD1 Magnetic Design



- At 4.2 K: I_{SS} = 20 kA, ~11 T bore field.
- At 1.9 K: I_{SS} = 21.6 kA, ~11.7 T bore field (NB: CERN I_{max} = 20 kA)

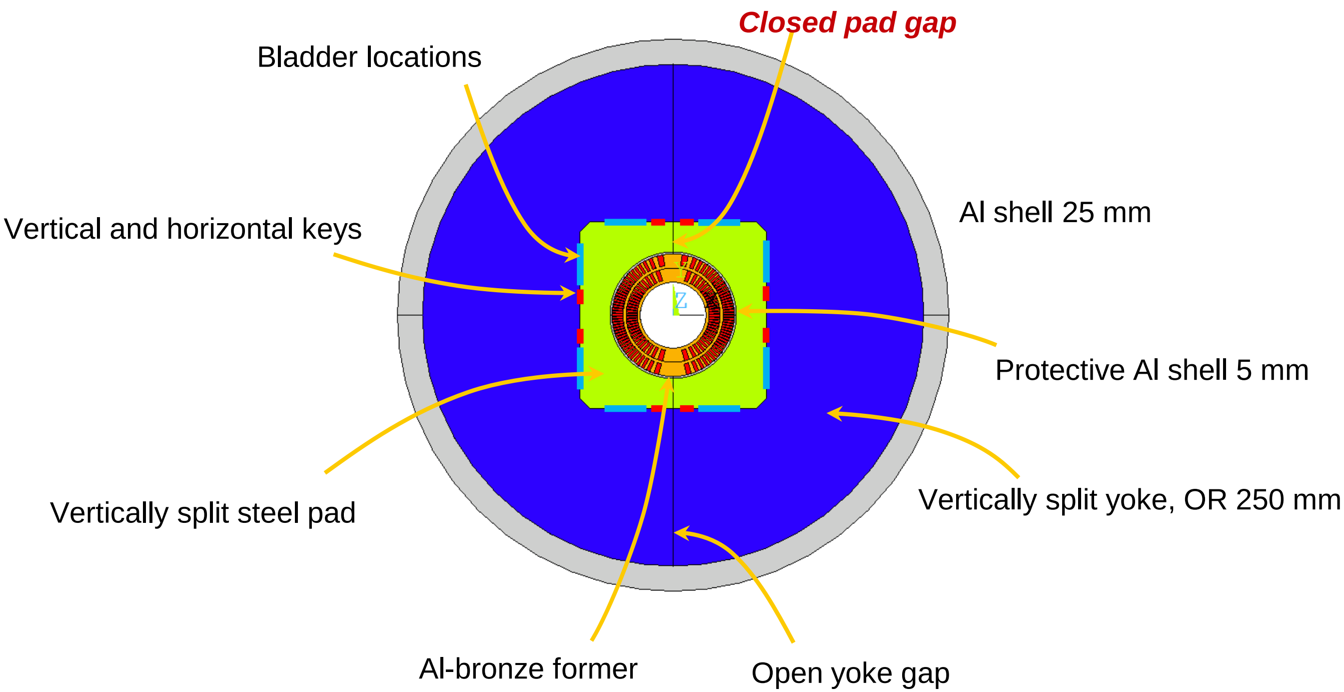




Mechanical Structure

Bladder and Key technology chosen for tuneability and relative simplicity.

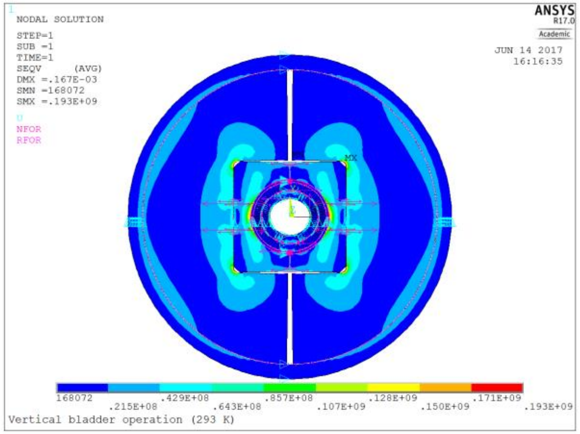
- Closed and pre-loaded pad gap for maximum-rigidity cage around coils.
- Steel pads to better match coil differential contraction.



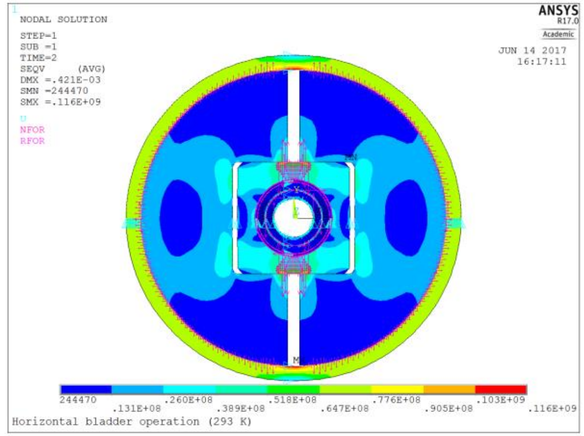
2D Mechanical Model Results

Room Temp.

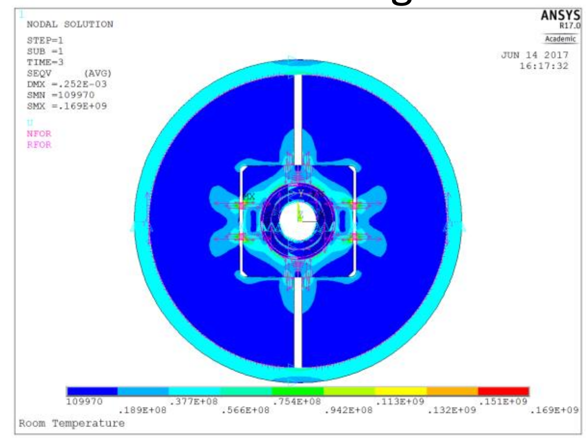
Vertical bladders



Horizontal bladders

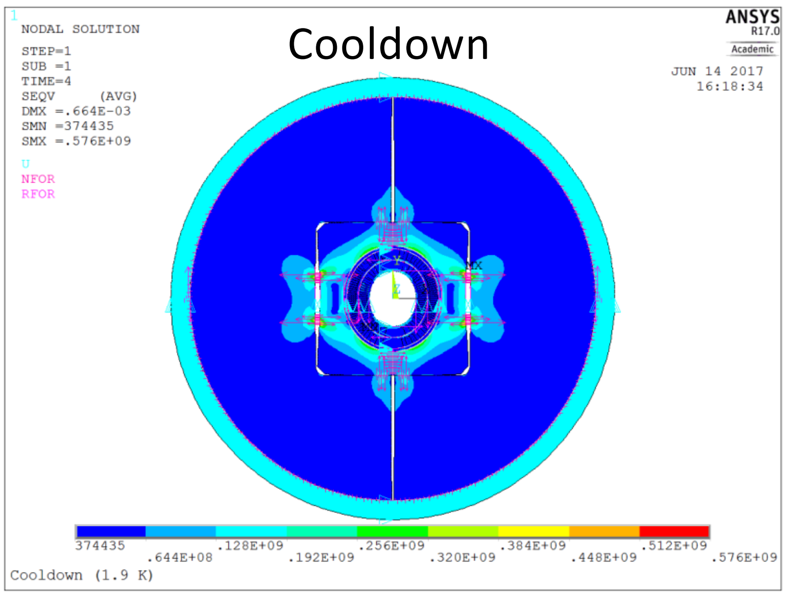


RT loading

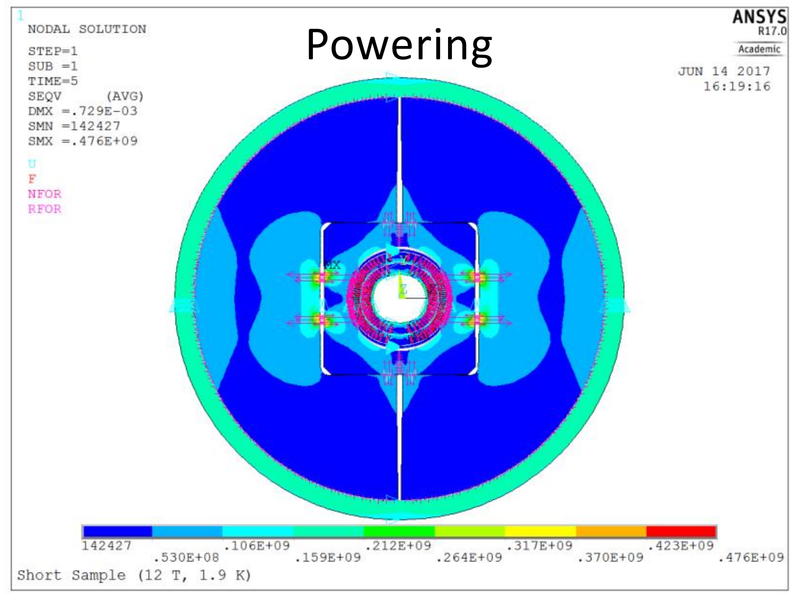


4.2 K

Cooldown



Powering

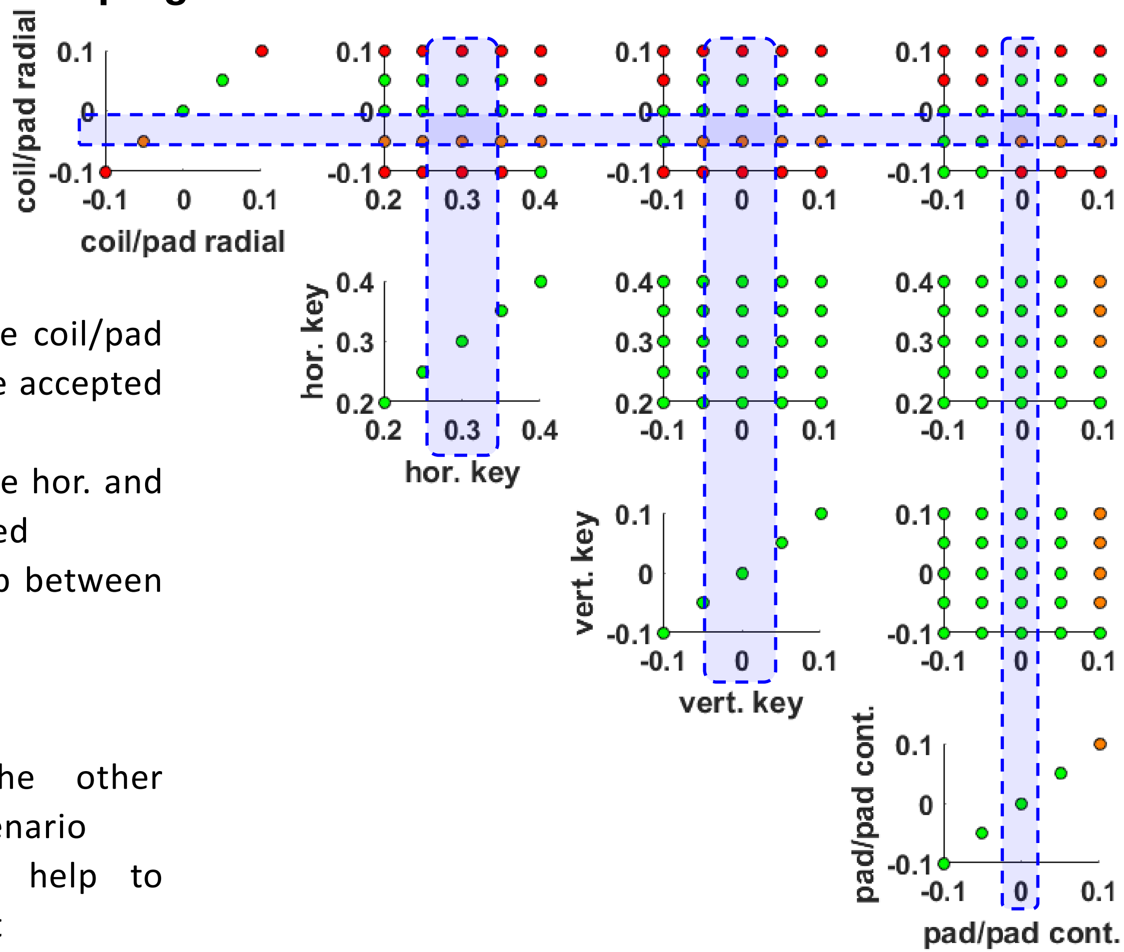


Courtesy G. Montenero

CD1 Sensitivity Analysis

Varying two parameters while keeping the others at their nominal value:

- All good
- Pad/pad interface opens
- Stresses values exceeded

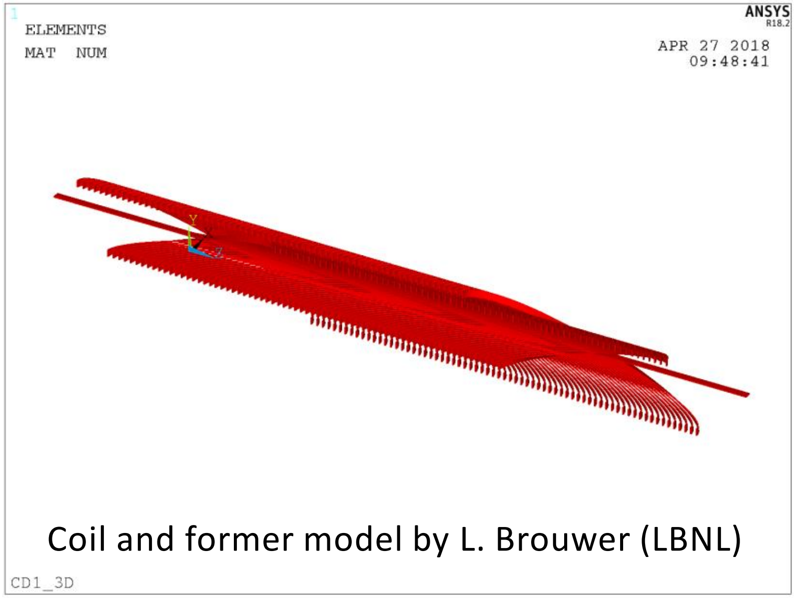


- **FIRST ROW**
  1. ± 100 μm tolerance on the coil/pad radial mismatch can not be accepted (required below 50 μm);
  2. A ± 50 μm tolerance on the hor. and vert. key must be considered
  3. Better to leave a small gap between coil and pad (≤ 50 μm)

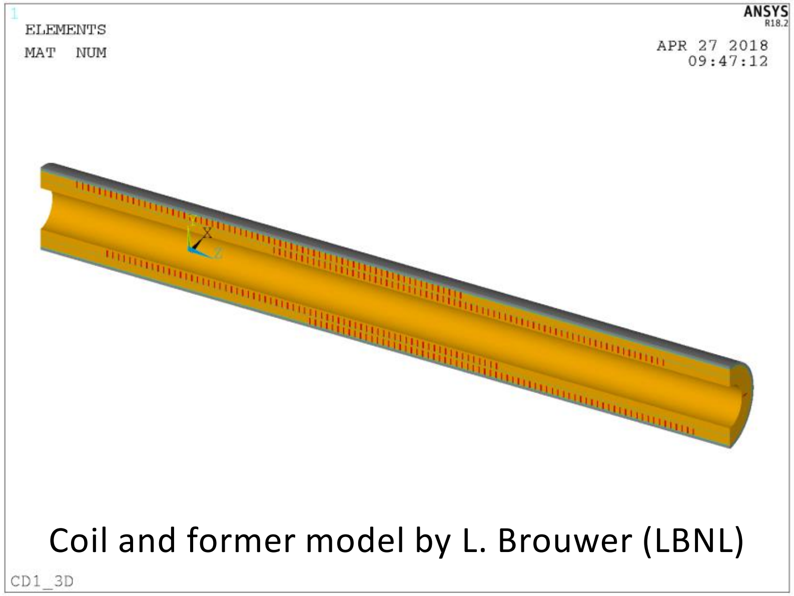
- **2nd, 3rd and 4th ROWS**
  1. Any combination of the other parameters gives a safe scenario
  2. Using tighter tolerances help to guarantee pad/pad contact

Courtesy G. Montenero

Full 3D Mechanical Model



Coil and former model by L. Brouwer (LBNL)



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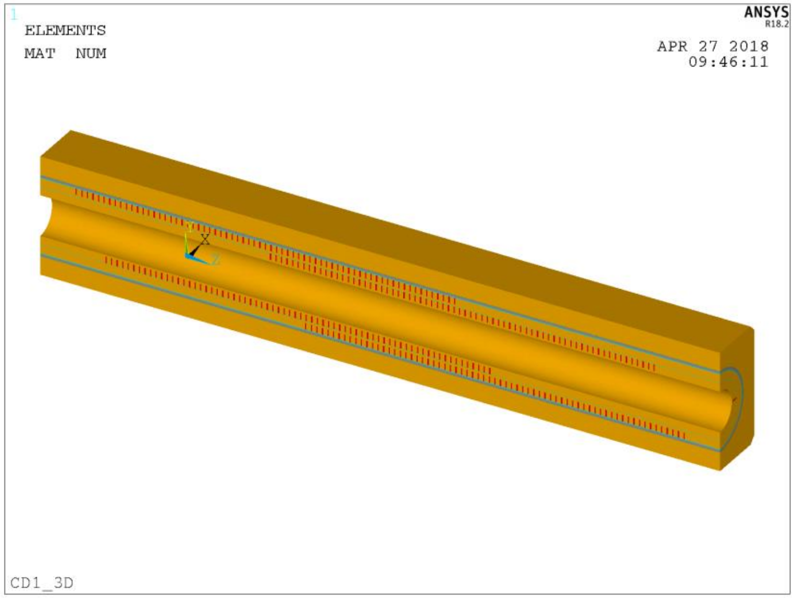
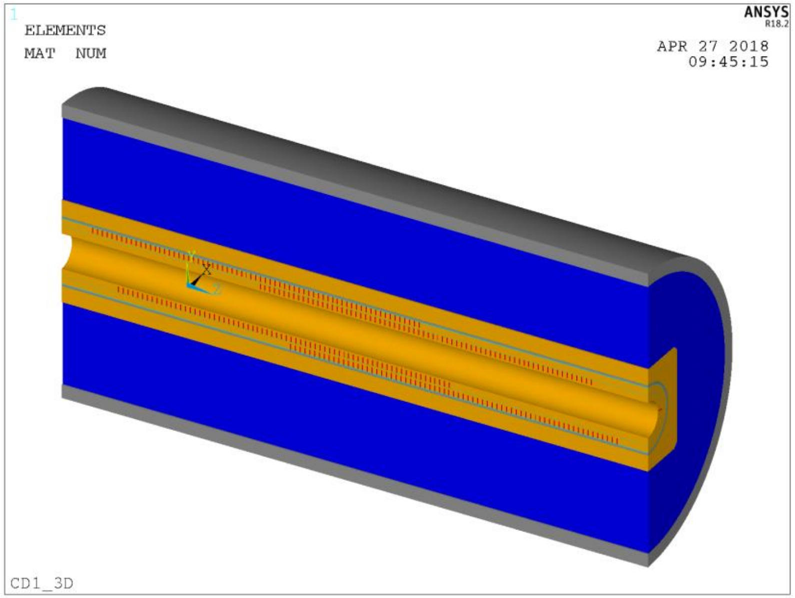
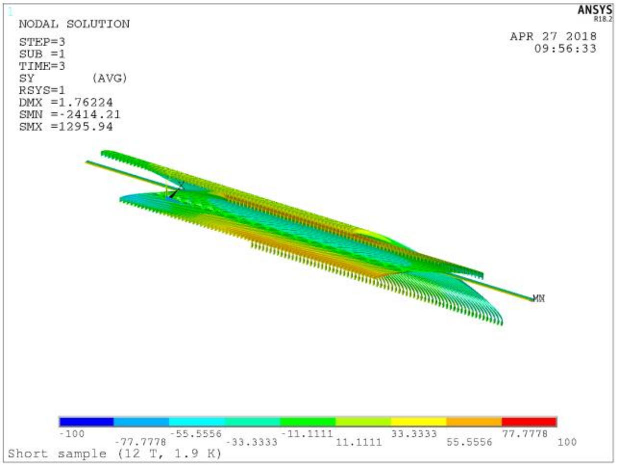
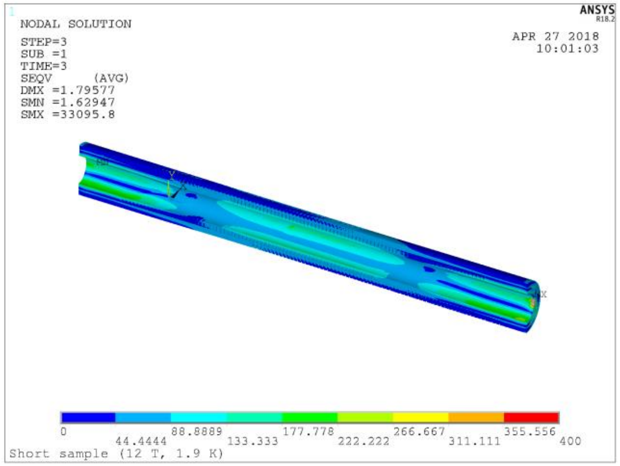
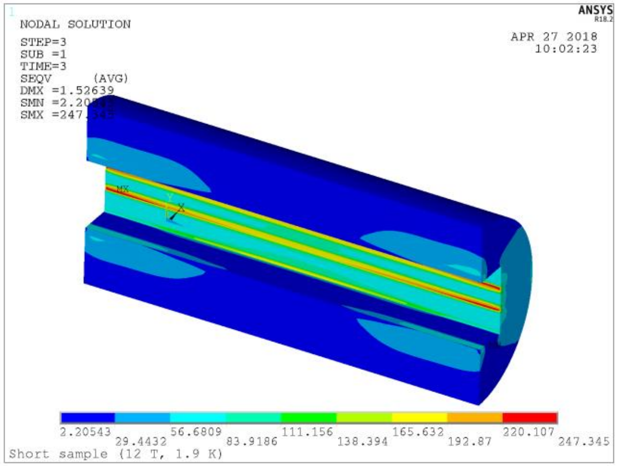


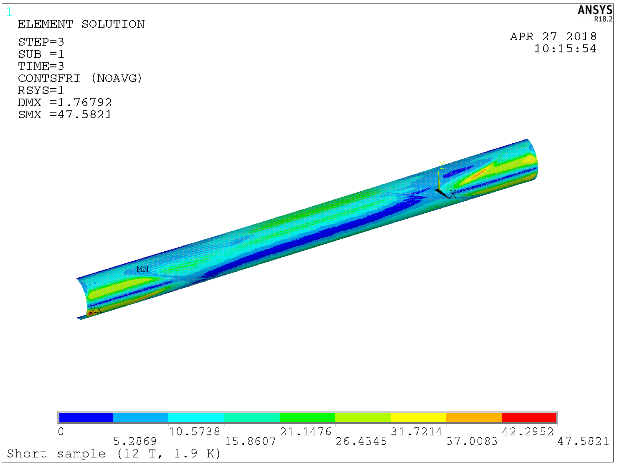


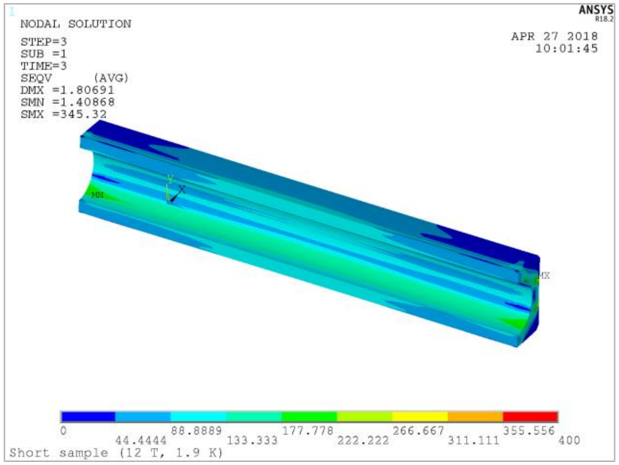
Full 3D Mechanical Model

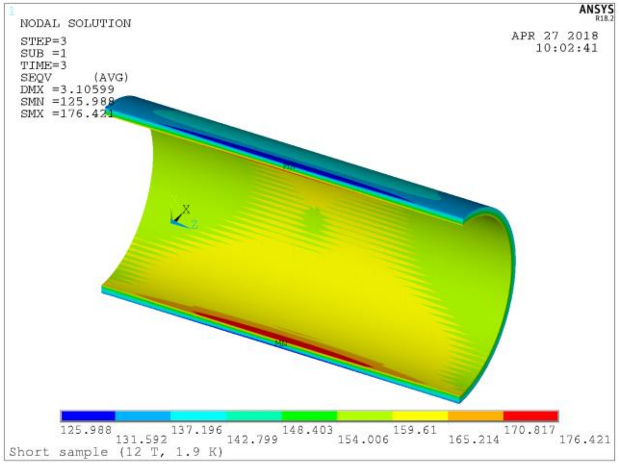






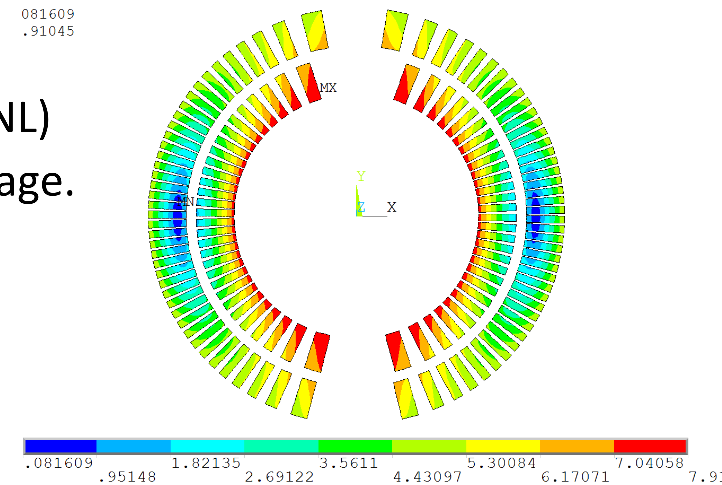


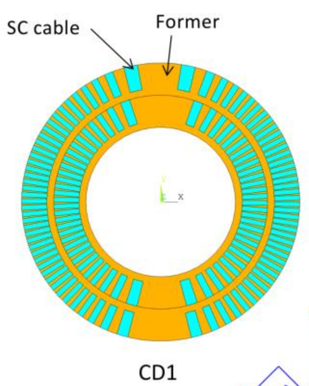


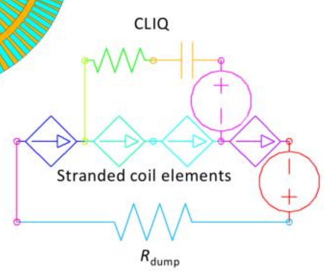


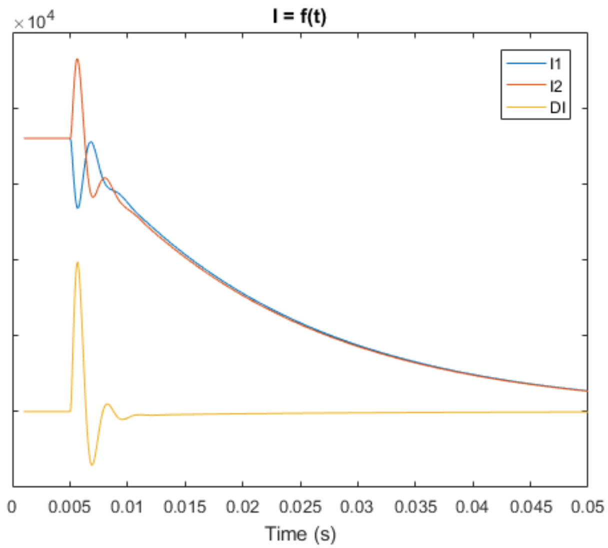
Quench Simulation for CCT

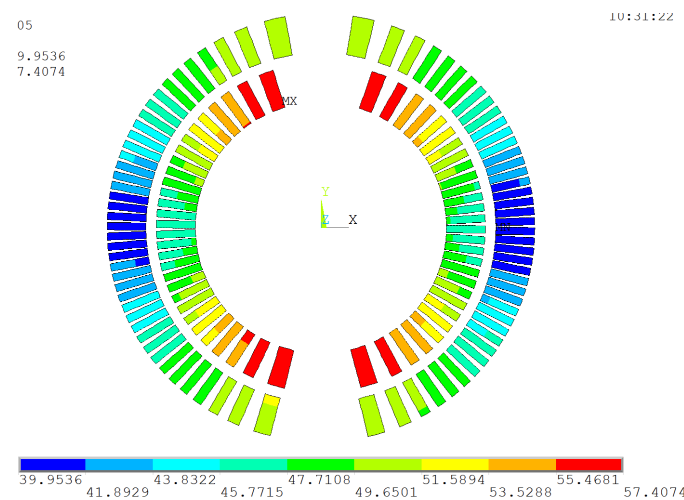
- ANSYS user-defined elements by L. Brouwer (LBNL)
- CLIQ sim. on CD1 geometry in final debugging stage.
- 4-layer FCC CCT to follow.

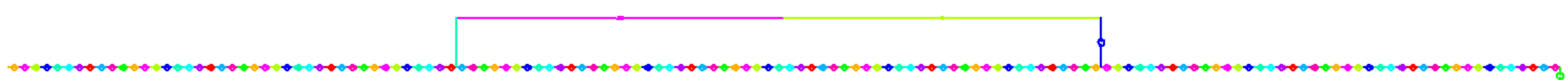










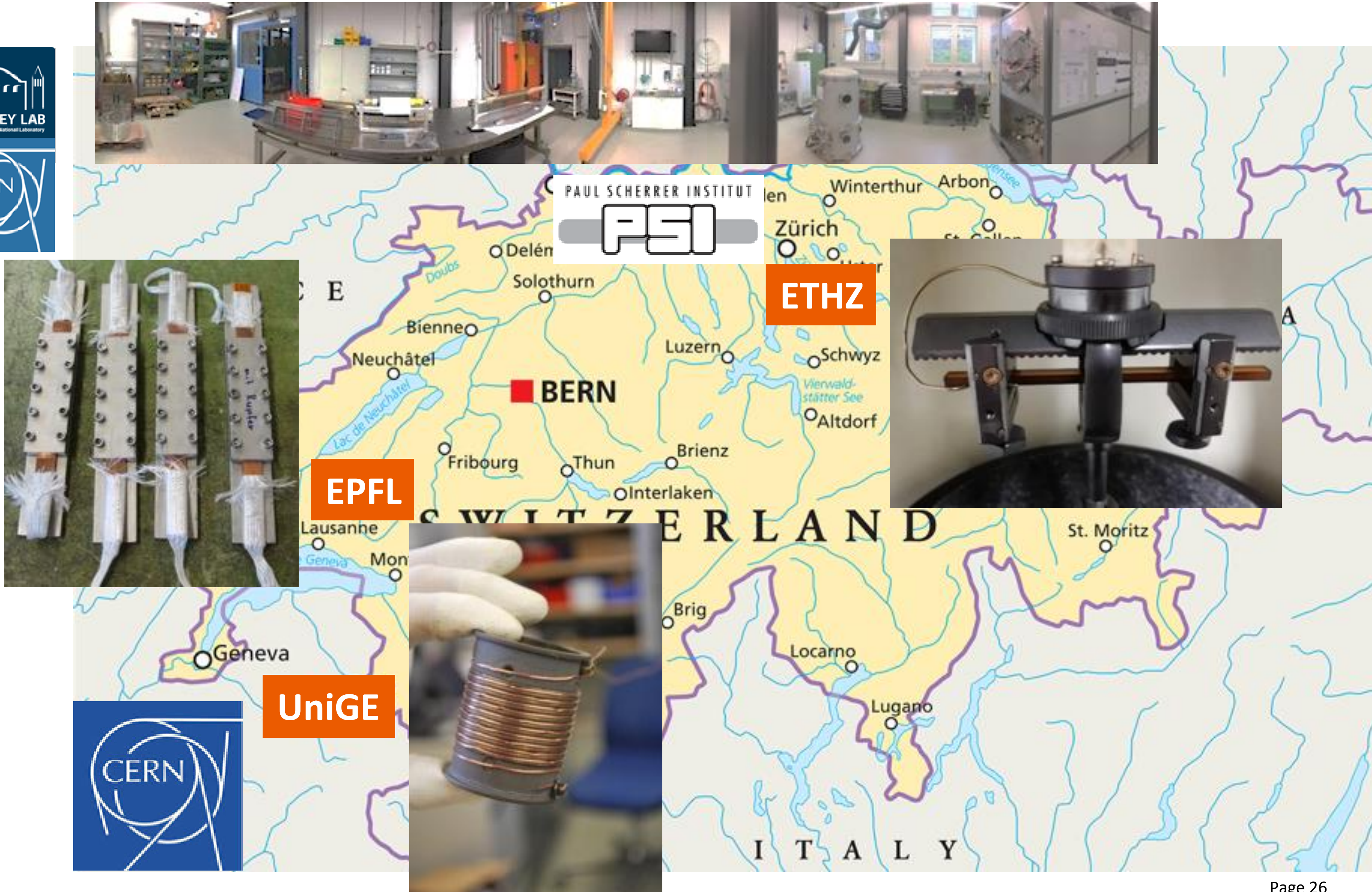


Courtesy J. Gao PSI and L. Brouwer LBNL

Overview

- CCT @ FCC
- PSI Program – CD1 Design
- SC Magnet Lab @ PSI - Commissioning
- CD1 Manufacturing trials

CHART (Swiss Accelerator Research and Technology Center) – Magnet Activities



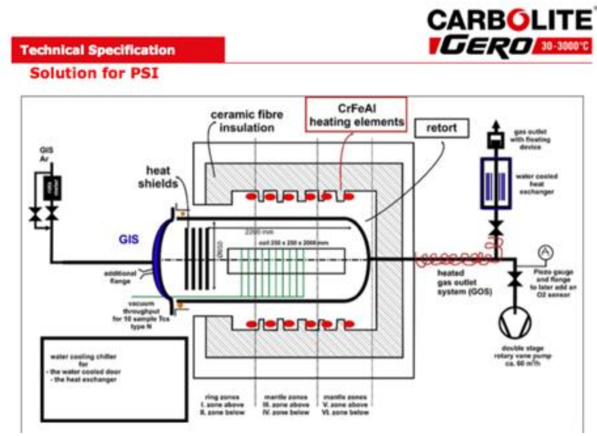
PSI SC Magnet Lab

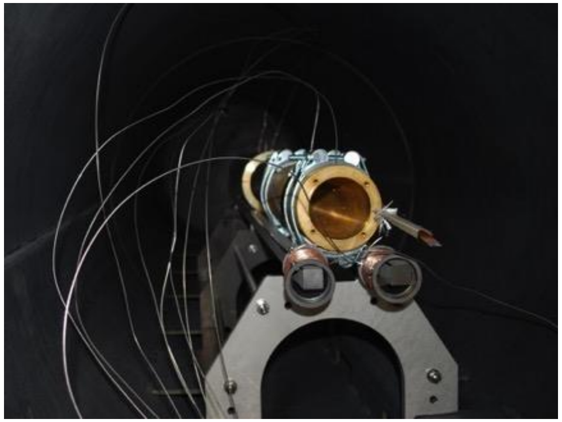
PAUL SCHERRER INSTITUT PSI

Reaction Commissioning

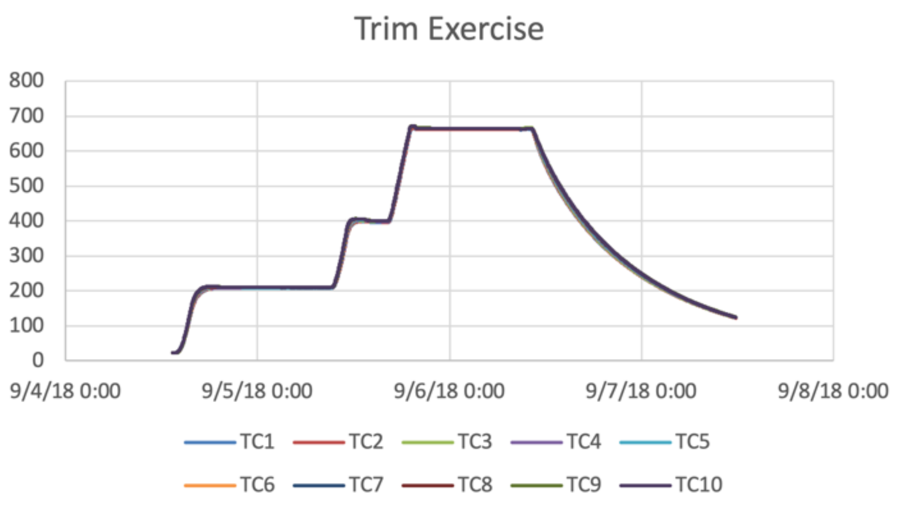
BERKELEY LAB
Lawrence Berkeley National Laboratory
CERN

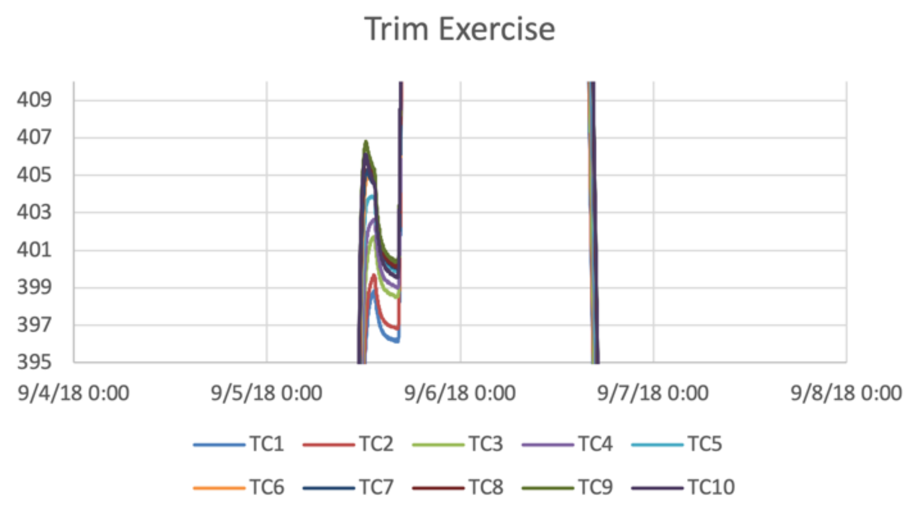
- Furnace fully operational (Ar supply, water chiller, ventilation, electricity, DAQ).
- Loading tooling complete and tested.
- Reaction of 5-turn test former complete.
- Short-sample confirmation by UniGE not before ASC.
- First coil reaction expected for Week 44.

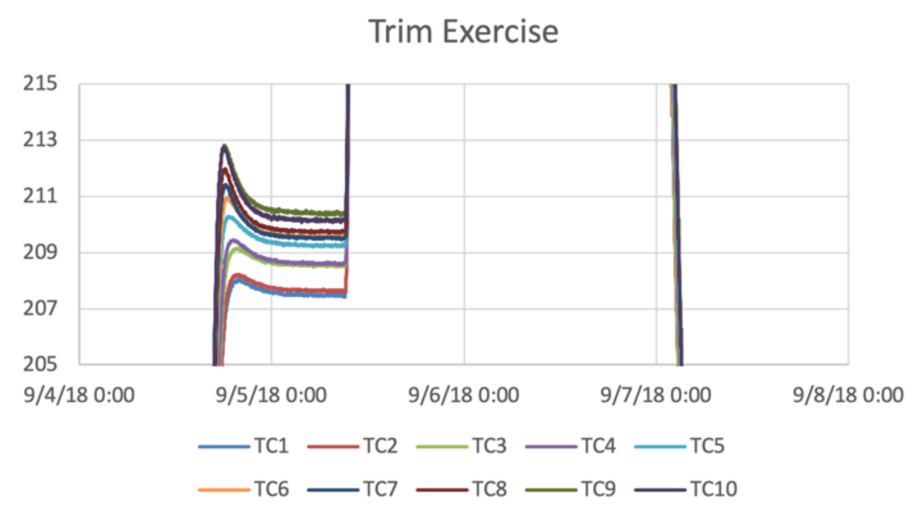


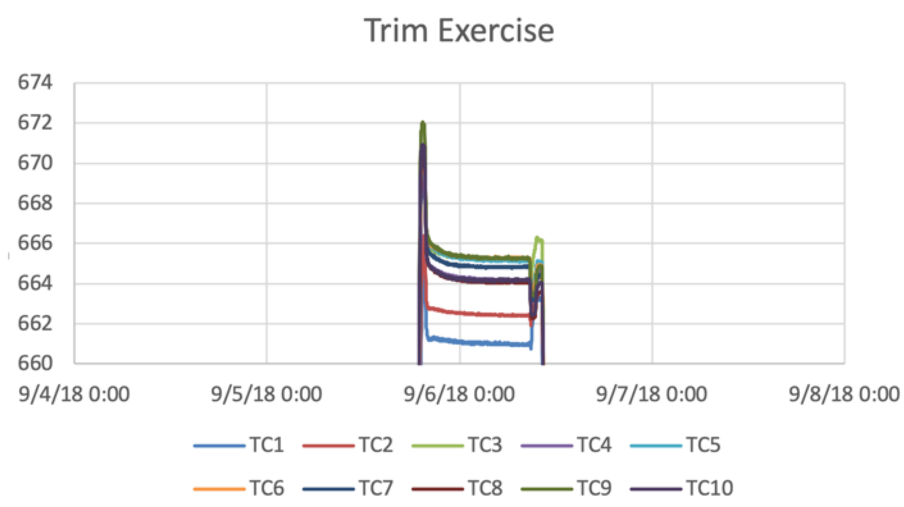


Reaction Furnace Trimming



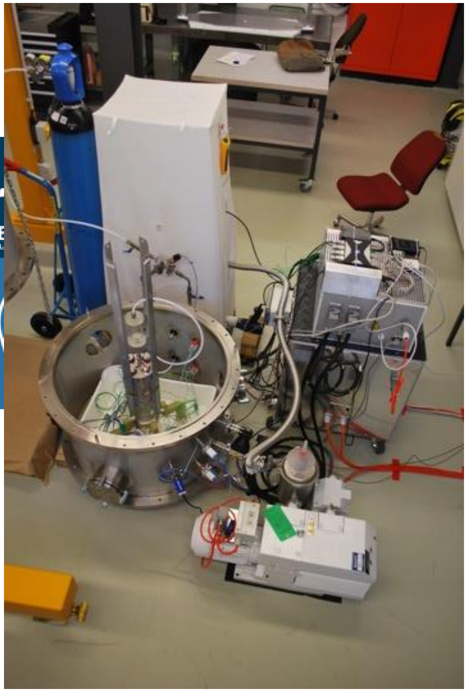


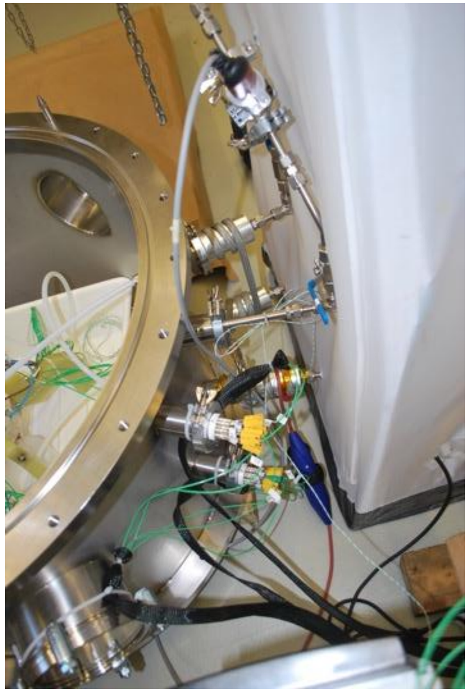


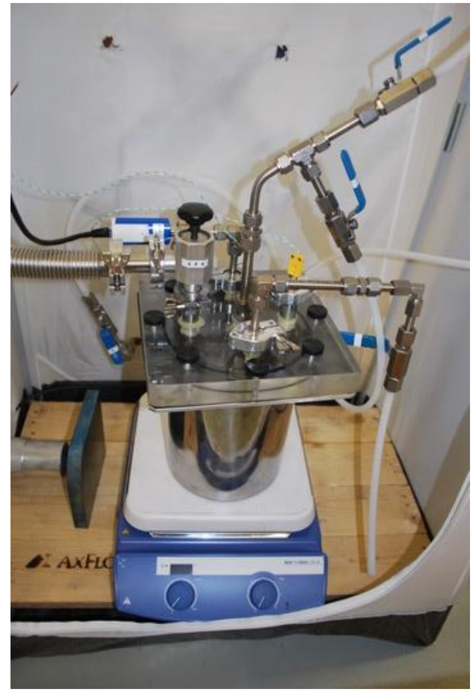


All plateau axial maps within +/- 3 K.

Impregnation Infrastructure







Vacuum vessel with feed-throughs in bottom part.
50 m^3/h vacuum pump with LN_2 trap
N_2 bottle for over-pressure and purging.
Control and powering units with voltage selection
Heated "green-house"
Heated feed-throughs into the vessel
See-through mixing pot
DAQ and alarm PCs
Capacitive monitoring as level indicator
Box oven for ingredient heating, sample and waste curing

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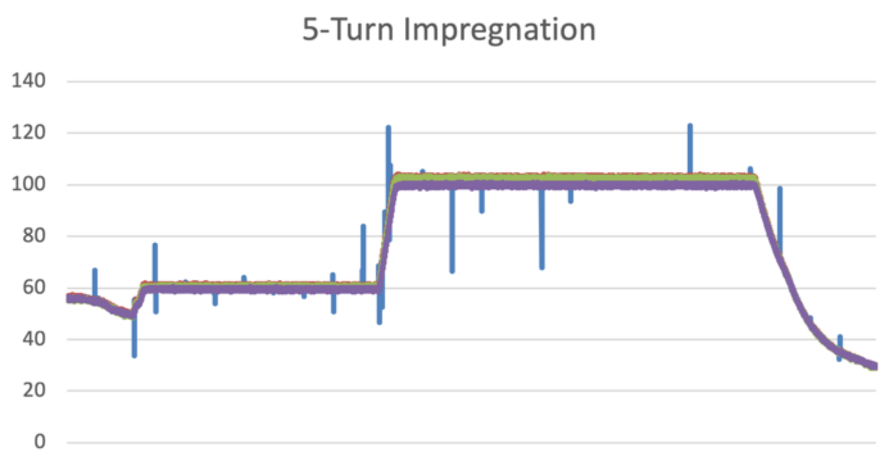
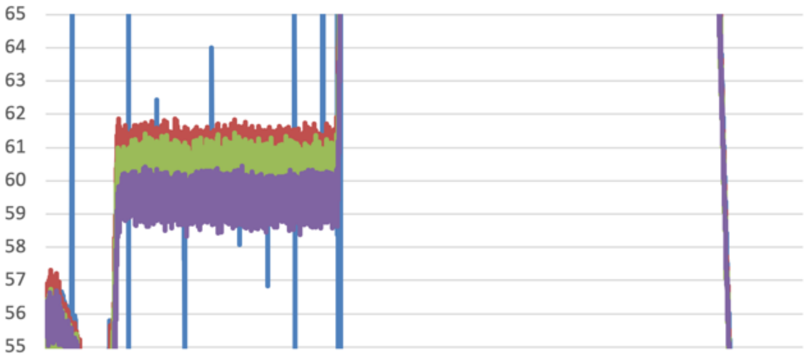
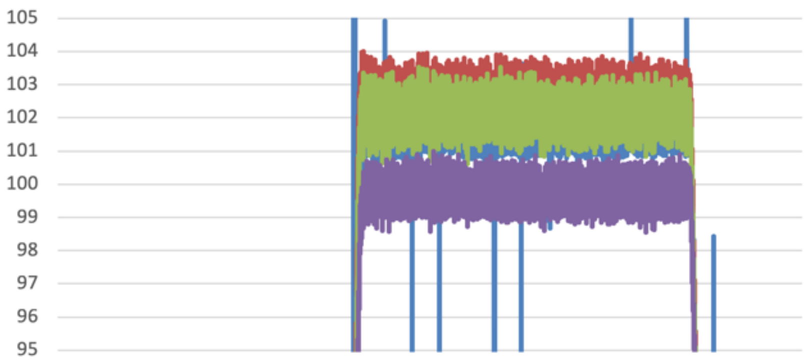
Impregnation Commissioning

- 5-turn coil impregnation.
- Coil temperatures (Top, Center, Down, Heater) within 3 K at curing plateaus.







Overview

- CCT @ FCC
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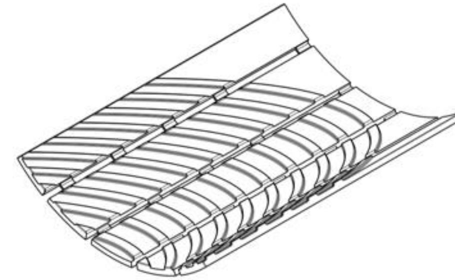
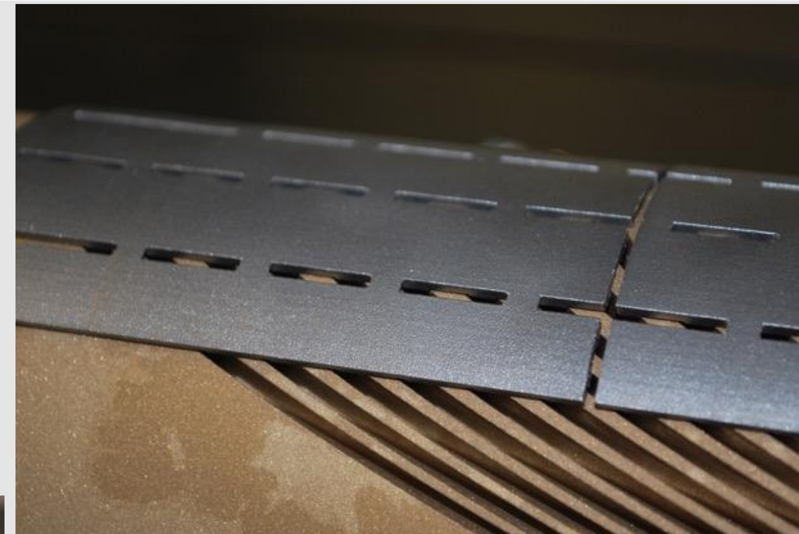
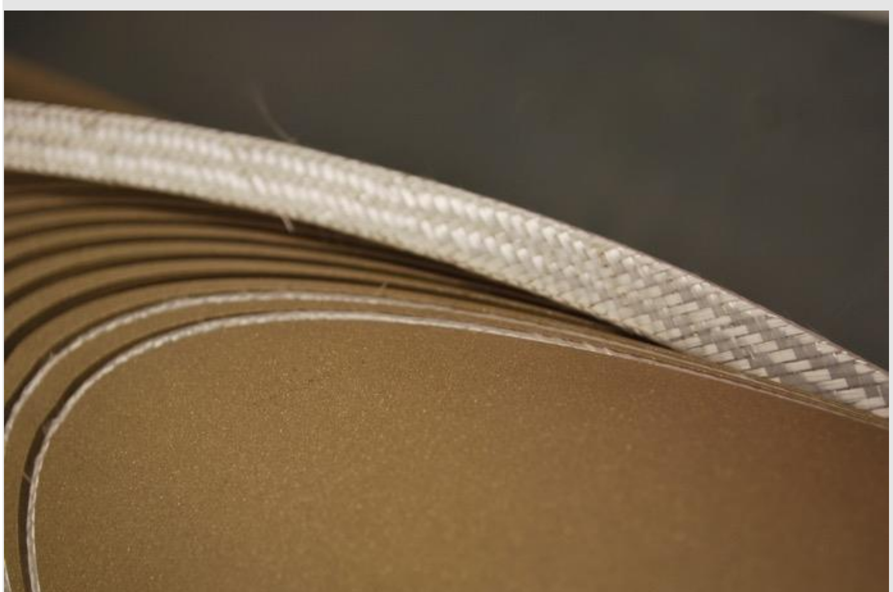
CCT Winding

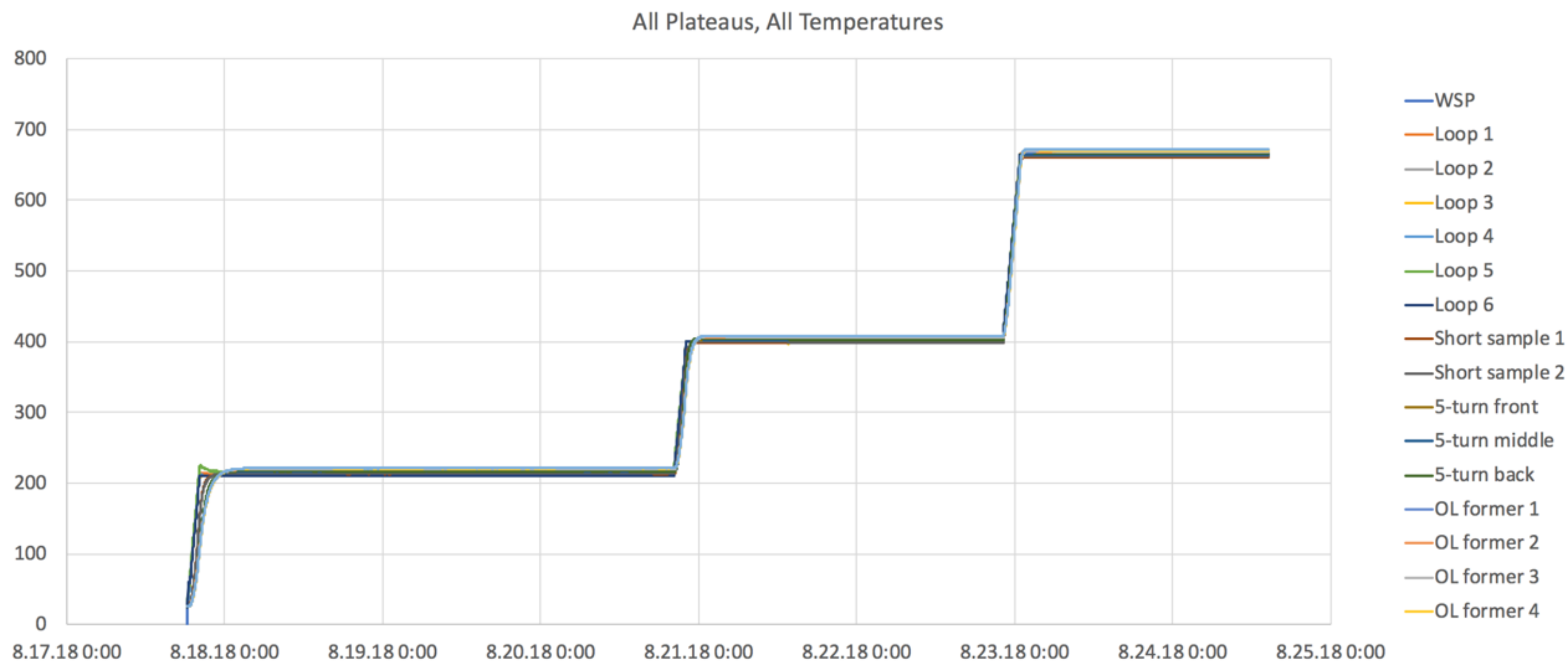


- Sandblasted, ultrasound cleaning
- OL winds easily and without cable popping up (see below).
- IL has tendency to pop up from the channels.
- Cable keepers were designed, tested, and printed in steel for the CD1 IL.





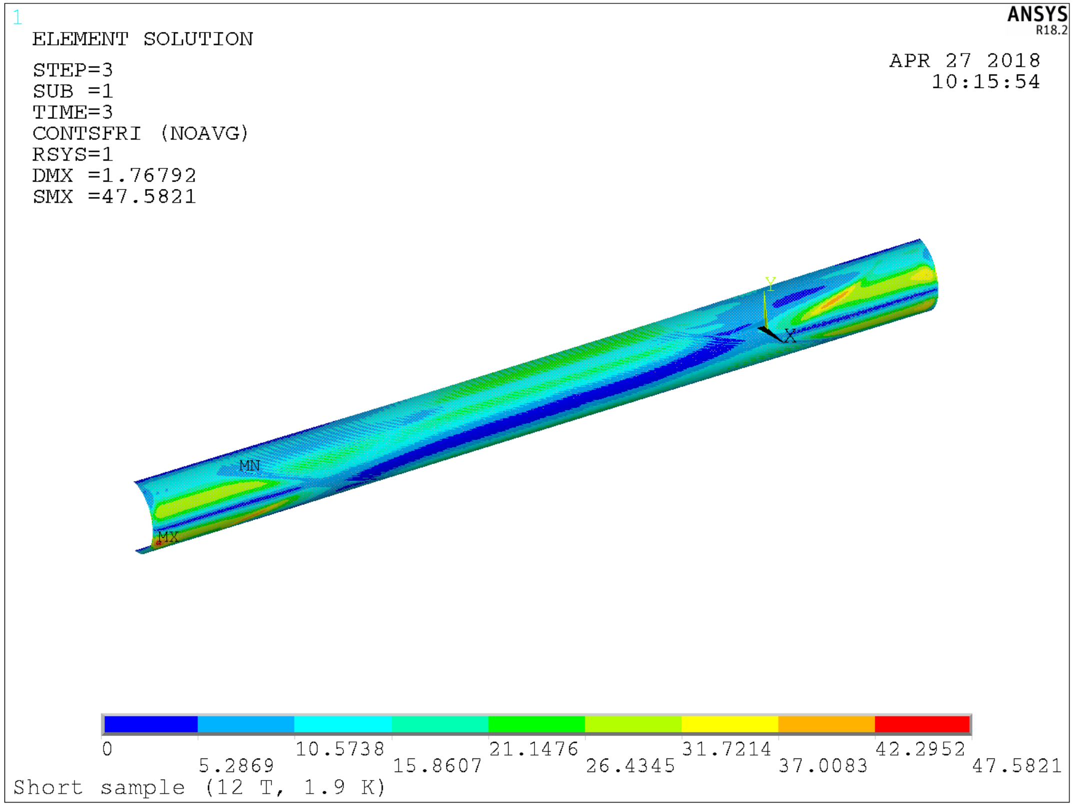
5-Turn Reaction



- Overshoots of loop temperatures diminish with temperature.
- Back-side probes arrive on
  - 210°C reached 6-7 hours after WSP out of 72 h on plateau.
  - 400°C reached 3 hours after WSP out of 48 h on plateau.
  - 665°C reached 50 min after WSP out of 50 h on plateau.

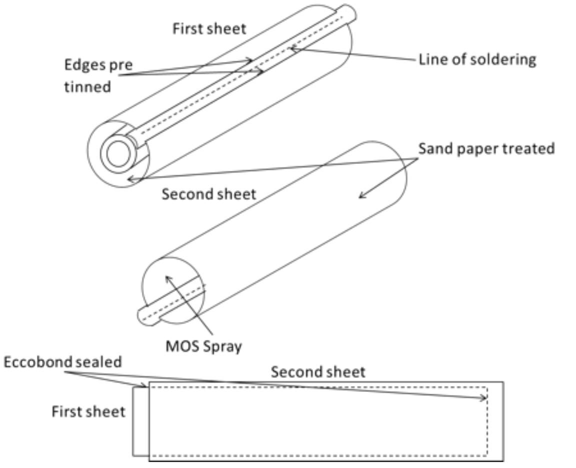
Layer/Layer Interface

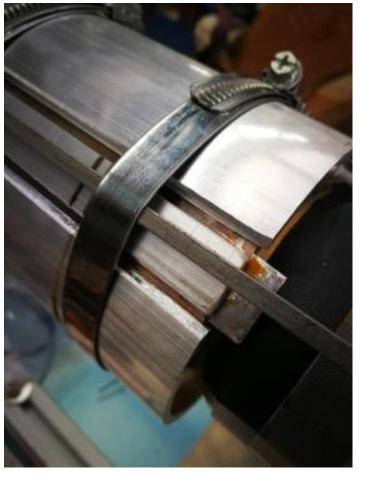
- ANSYS simulation of the full magnet model suggest shear stresses on a bonded layer/layer interface are too high to confidently glue.
- PSI solution: implement a dedicated sliding plane, inspired by MSUT (H. ten Kate et al.).

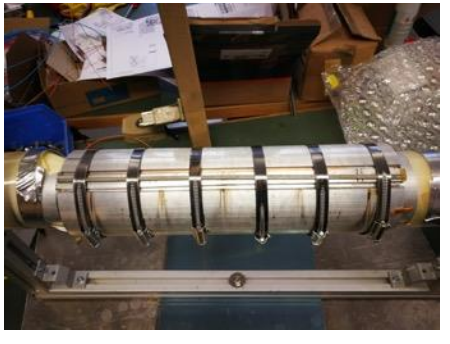


Sliding Plane Installation

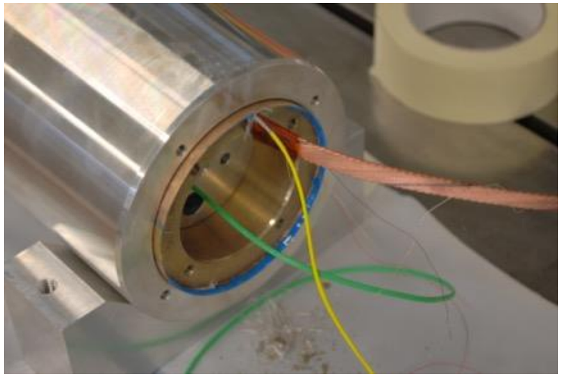
- ANSYS simulation of the full magnet model suggest shear stresses on a bonded layer/layer interface are too high to confidently glue.
- PSI solution: implement a dedicated sliding plane, inspired by MSUT (H. ten Kate et al.).

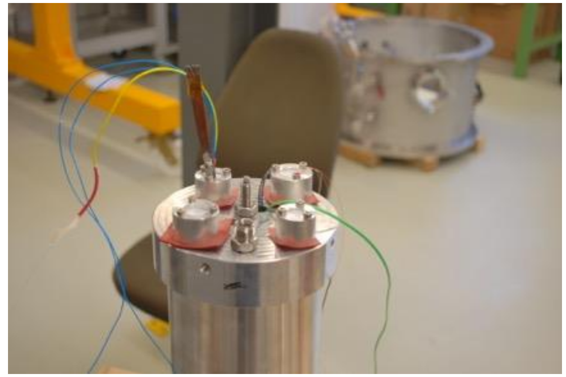


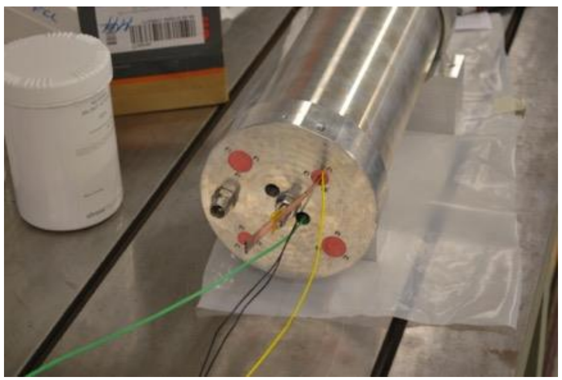


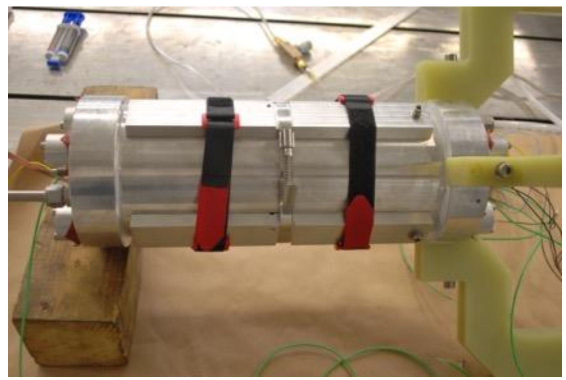


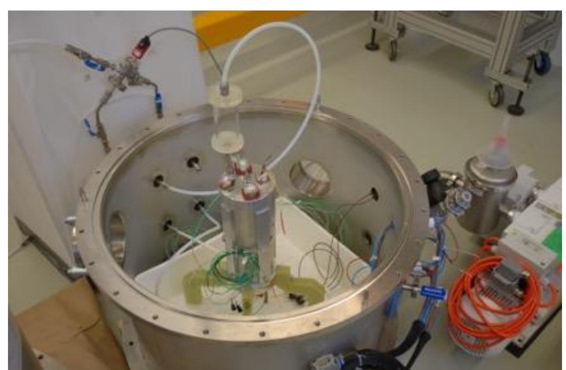
5-Turn Sample Preparation, CD1 Mold

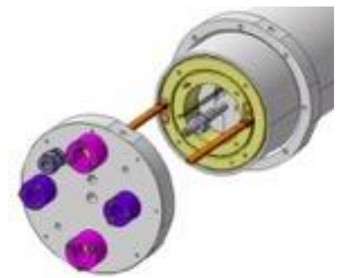






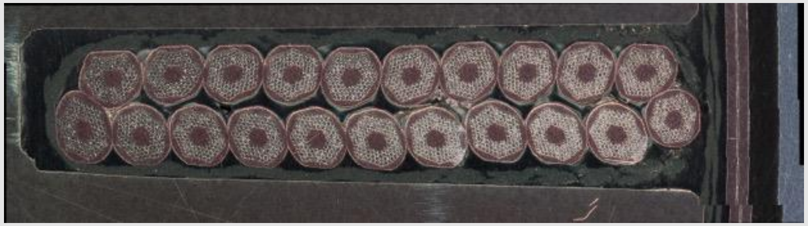


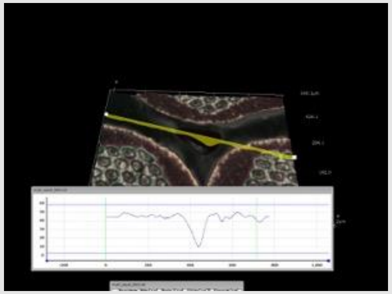




Impregnation Results

- Some potential bubbles visible.

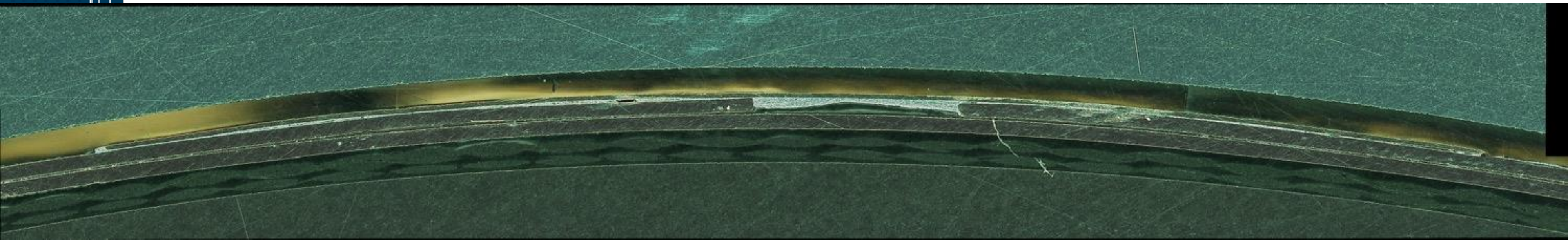




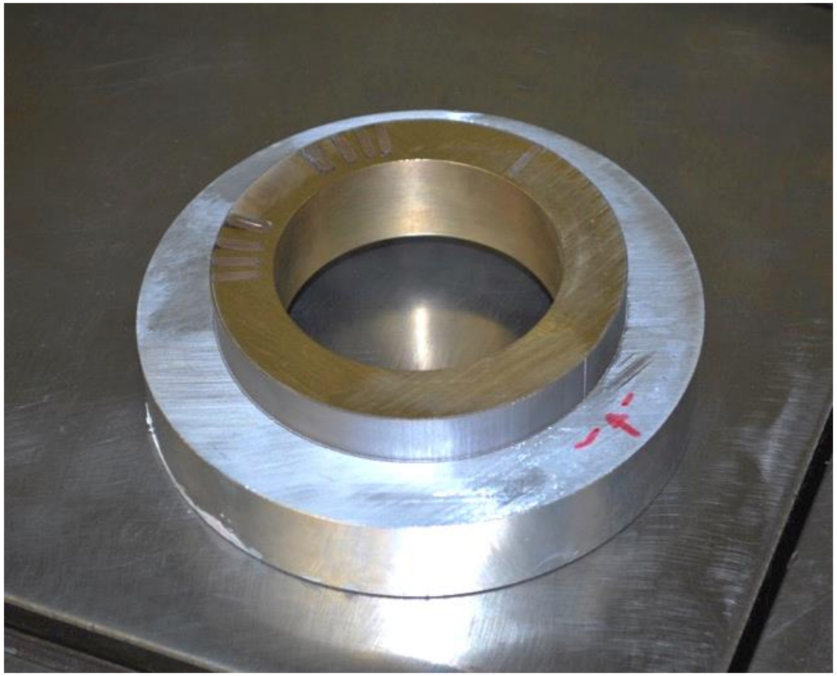
- Next step: improve control of injection flow rate via peristaltic pump.

Sliding Plane Tests

- Microscopic analysis – note glass wrap layers, inner and outer sliding planes, soldering, and filling of assembly gap with resin.

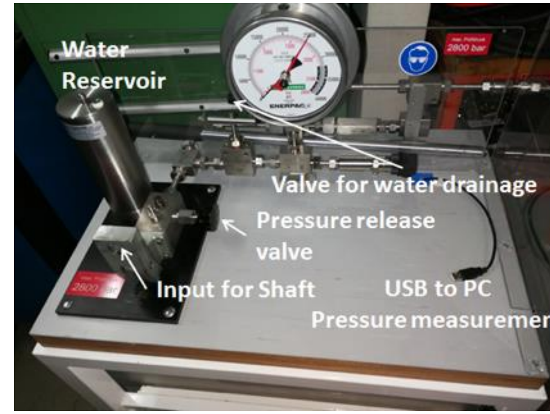


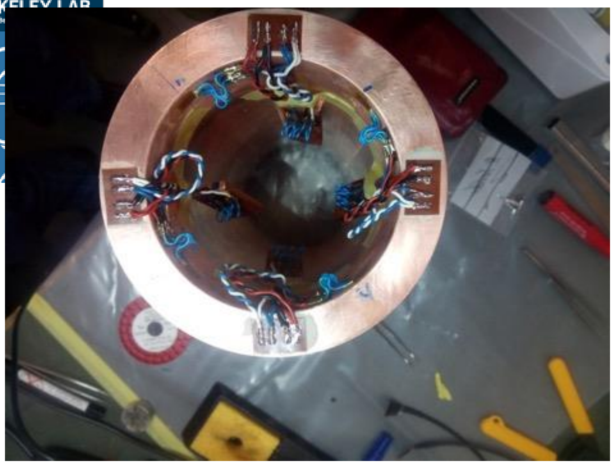
- Separation of layers post impregnation – sliding planes in action:

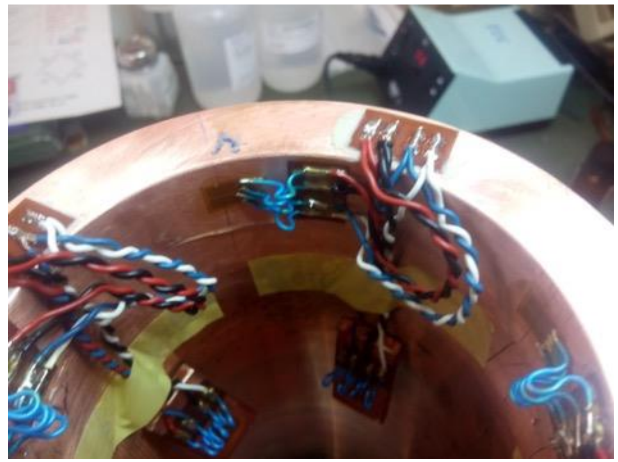


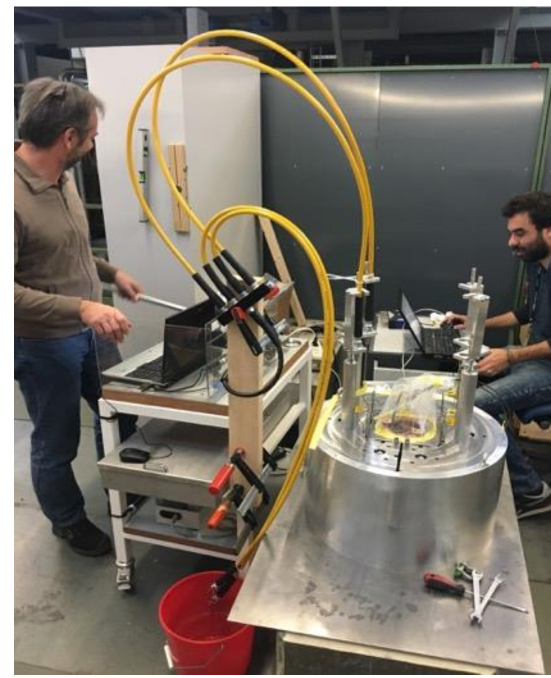
Mechanical Instrumentation and Assembly

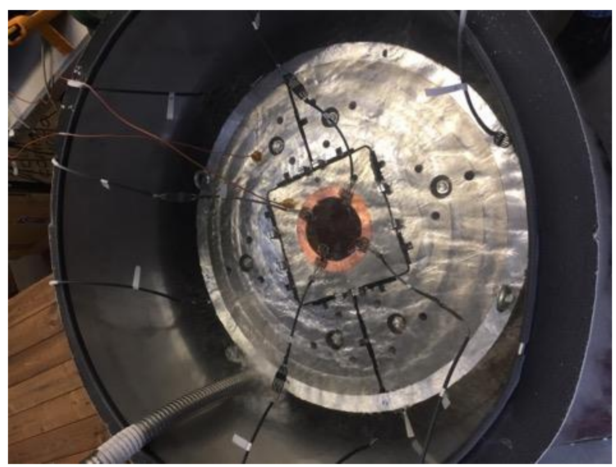
- Mechanical model test in Dec. 2017.





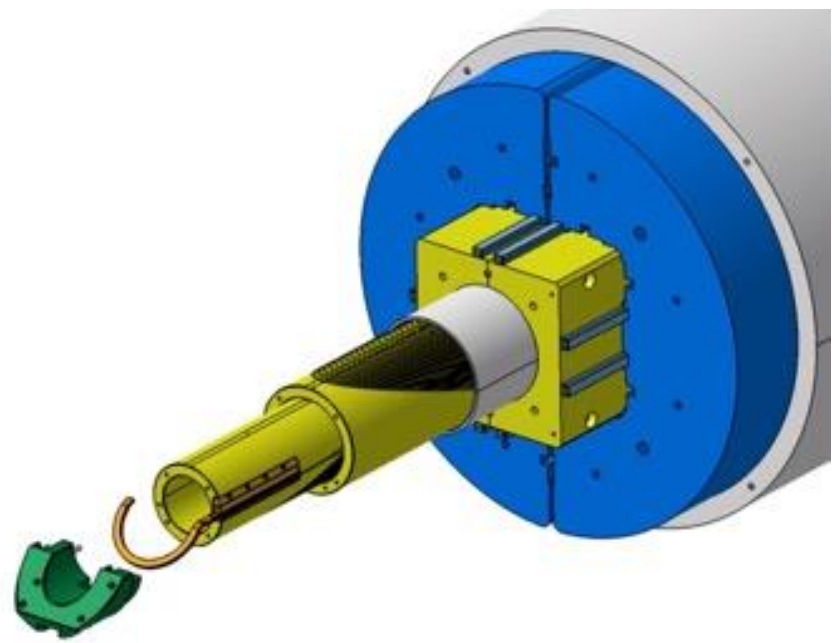




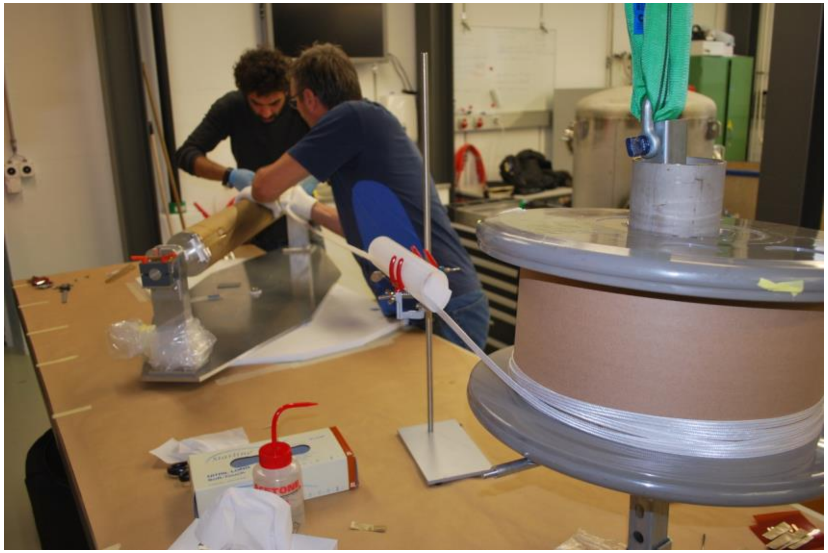


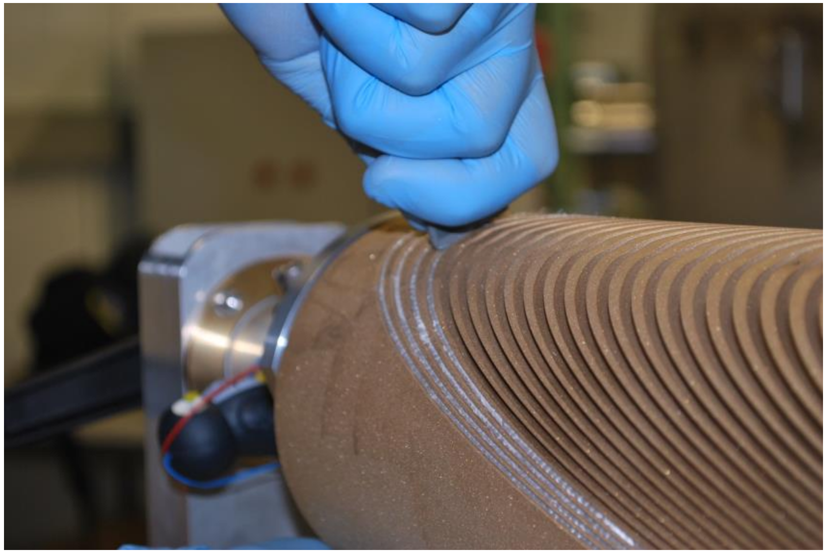
CD1 Status

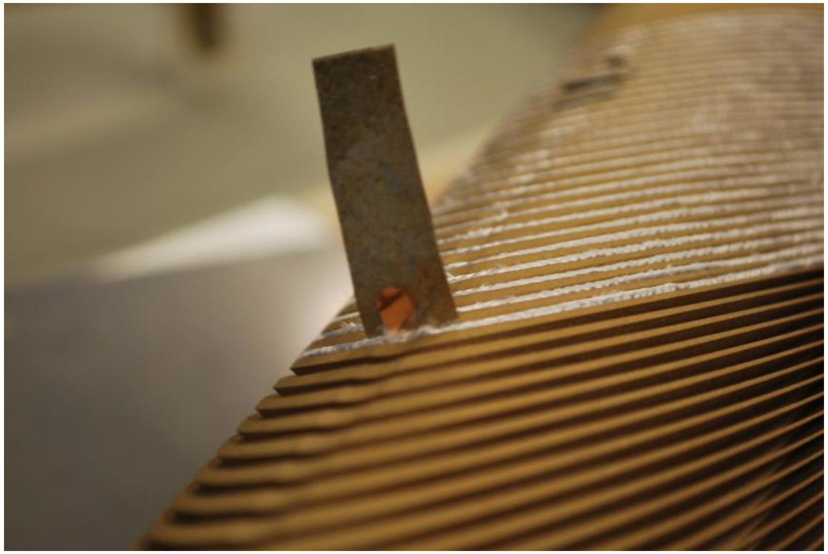
- Coil winding to started Tuesday.
- Reaction cycle to launch Friday.
- Splice testing and final IL winding tests during reaction week.
- Coil manufacturing until end of 2018.
- Mechanical assembly and instrumentation early 2019.
- Magnet test in LBNL by April 2019.



CD1 Coil Manufacturing Started!







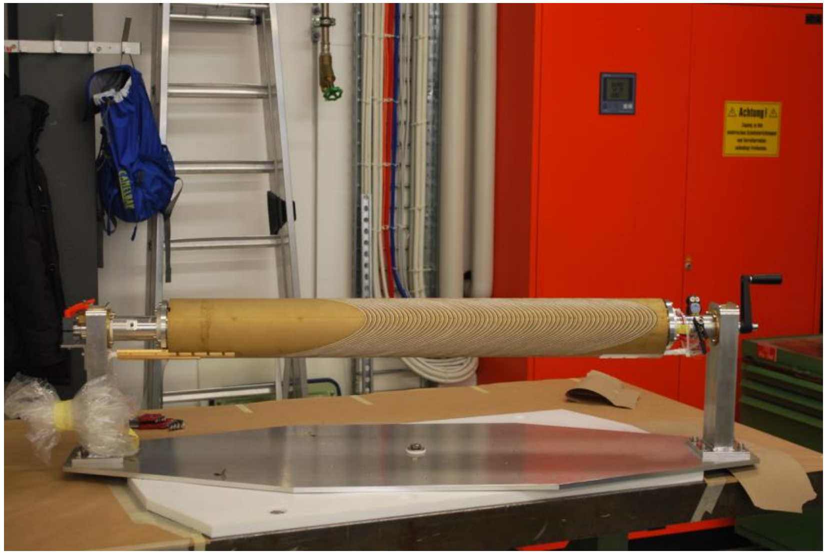


CHART 1 Timeline

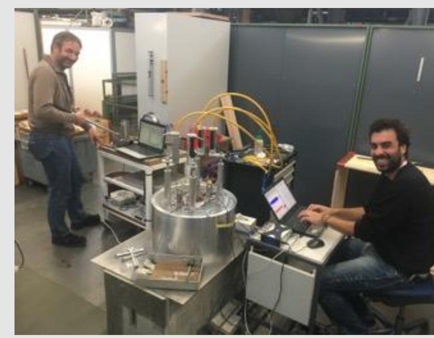
FCC CCT Design Option	CHART 1 Setting	CHART 1 program and CD1 design	Launch infrastructure program	Technical design, mech. mod
May-Nov '16 Mathematica with ROXIE's BEMFEM Winding tests at LBNL	Nov '16 – Jan '17 Search cable supplier, hiring, partner for reaction, impregnation, testing	Feb-May '17 Shlomo Caspi (LBNL) @ PSI, PSI program outline, CD1 conceptual design	June '17 Conceptual Design Review; Memorandum for creation of PSI coil-manufacturing infrastructure	July-Dec '17 CD1 technical design, mech. Instrumentation, mech. short model production and test

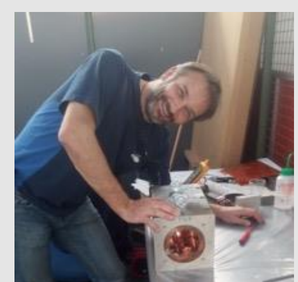
Tooling, procurement, QA, lab	Infrastructure commissioning	CD1 coil manufacturing	CD1 mechanical assembly	CD1 test
Jan-May '18 Tooling design, procurement, QA, infrastructure development, lab location and refurbishment	June-Sep '18 Furnace and vac.-impregnation setup commissioning	Oct-Dec '18 CD1 coil manufacturing	Jan-Mar '19 CD1 mechanical instrumentation, assembly, loading, shipping to LBNL	Apr-May '19 CD1 test at LBNL, prep of FCC Week 2019

The FCC Magnet Team (1/2)

- Jiani Gao:
  - PhD (CHART) for efficient quench protection
  - Multiphysics FEA
  - Instrumentation

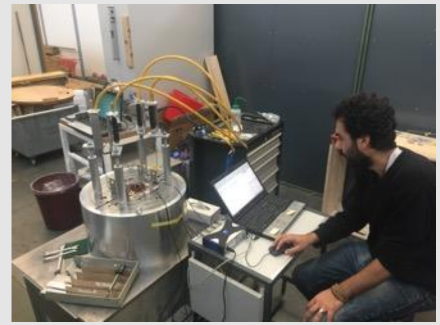
- Roland Felder:
  - Technician (PSI) for
    - Mechanics
    - Electronics
    - Instrumentation
    - Hydraulics
    - Controls
    - Vacuum
    - Etc.





The FCC Magnet Team (2/2)

- Giuseppe Montenero:
  - PostDoc (CHART)
    - Magnet design.
    - Multiphysics FEA.
    - Design and commissioning of impregnation infrastructure.
    - Mechanical instrumentation.
    - Coil instrumentation and splicing.



- Serguei Sidorov:
  - Engineer (PSI)
    - Design
    - Procurement
    - Quality Control

Summary

- FCC magnet design:
  - Important mechanical advantages.
  - 25% more SC than cos-theta or block coil.
  - Winding on inner-most layers will be challenging – must be automated.
  - Former manufacturing must become cheaper.
- Significant progress in infrastructure at PSI.
  - **Commissioning complete**.
- Technology model magnet CD1:
  - Part design, procurement, QA complete.
  - **Coil manufacturing started**.
- LBNL's CCT5 test next week.
- Hopefully important lessons from CCT5 and CD1 tests for FCC week 2019.
- Hopefully CHART 2 will continue the efforts over the coming years.