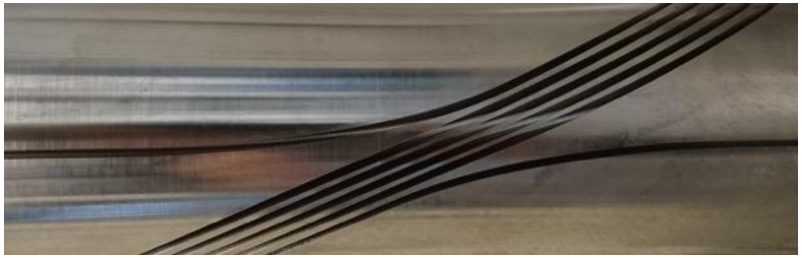
B. Auchmann (CERN/PSI), L. Brouwer (LBNL), S. Caspi (LBNL), R. Felder (PSI), J. Gao (PSI),
G. Montenero (PSI), M. Negrazus (PSI), G. Rolando (CERN), S. Sanfilippo (PSI), S. Sidorov (PSI)

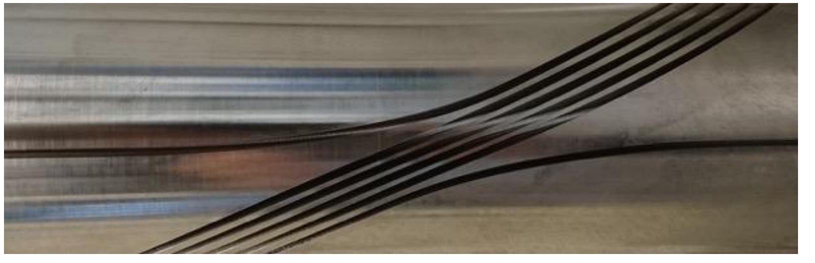
Update on CCT



09.10.2017, EuroCirCol WP5 Review, CERN.
Work supported by the Swiss State Secretariat for Education, Research and Innovation SERI.

Overview

- CCT for FCC
  - Electromagnetic design
  - Mechanical design
- The PSI CCT model program
  - Roadmap
  - Status



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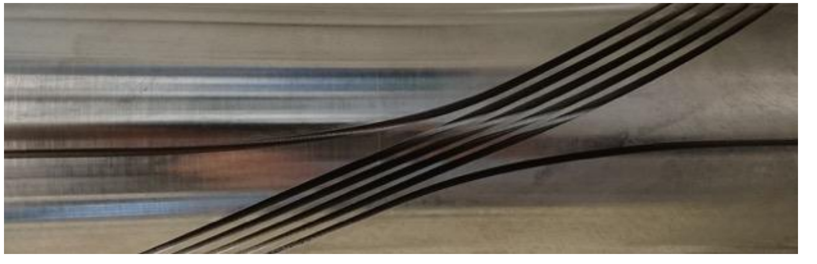
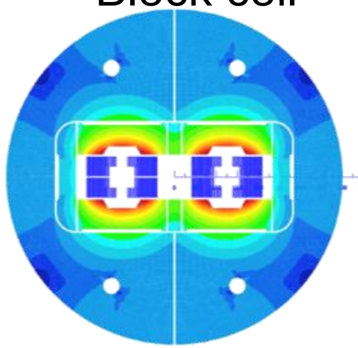
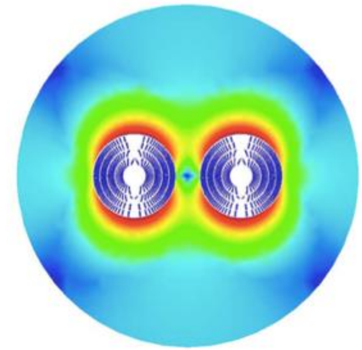


CCT joined the fold in Nov. 2016

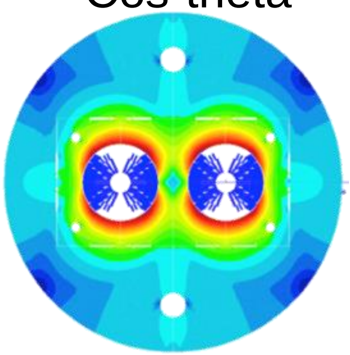
Block coil



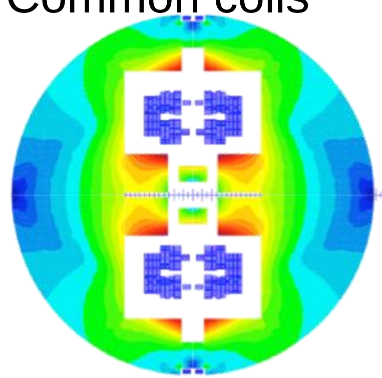
Canted Cosine Theta



Cos-theta



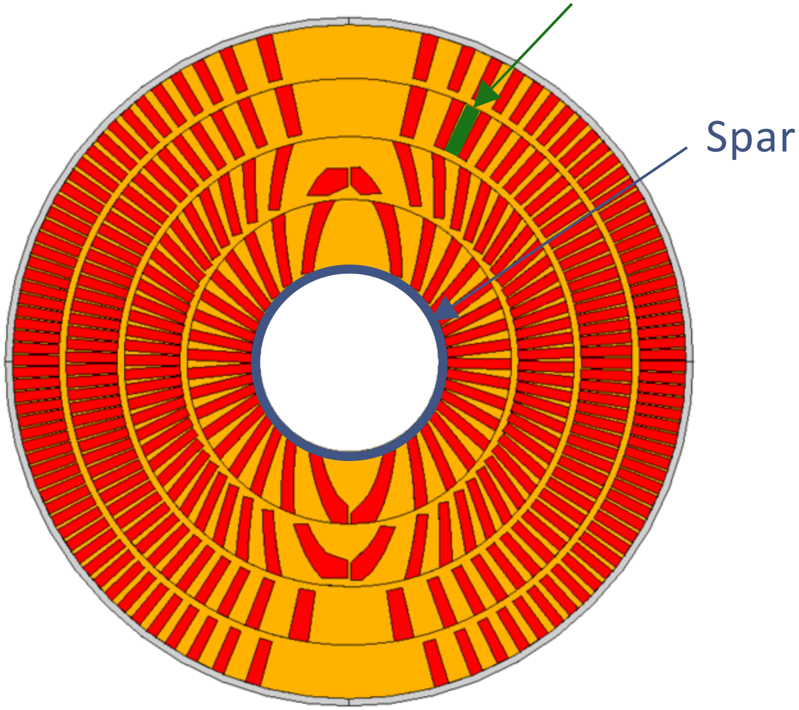
Common coils



CCT Design for FCC

- Keys to an efficient CCT design:
  1. Thin spars
  2. Wide cable, large strands
  3. Thin ribs.

  } Increase J_e.



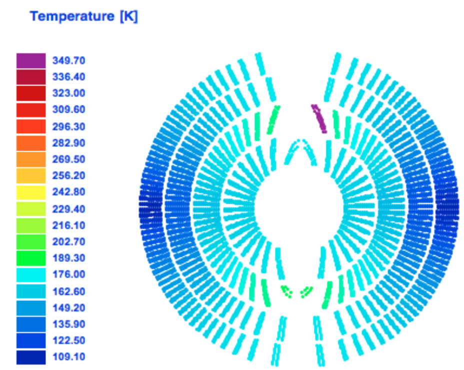
PSI's CCT Design for FCC

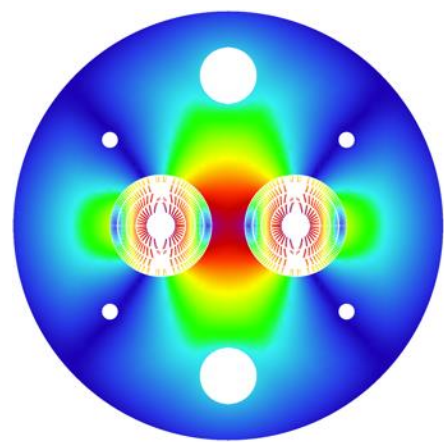
- Current: 18055 A

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

- FCC-wide conductor use:
  - Total: 9.77 kt (+30% wrt. cosine theta/block)
  - NonCu: 3.75 kt
  - Cu: 6.02 kt
- Total inductance: 19.2 mH/m
- Total energy: 3.2 MJ/m

Homogeneous coil temperature after quench.



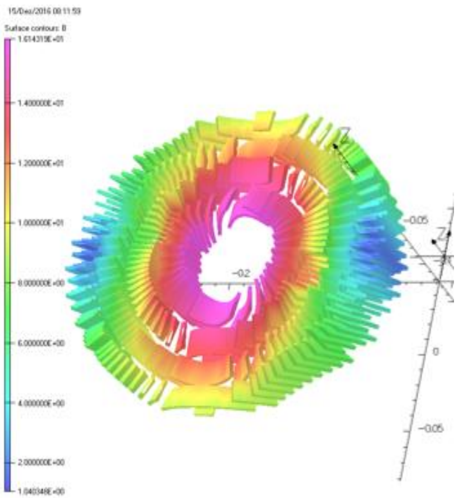


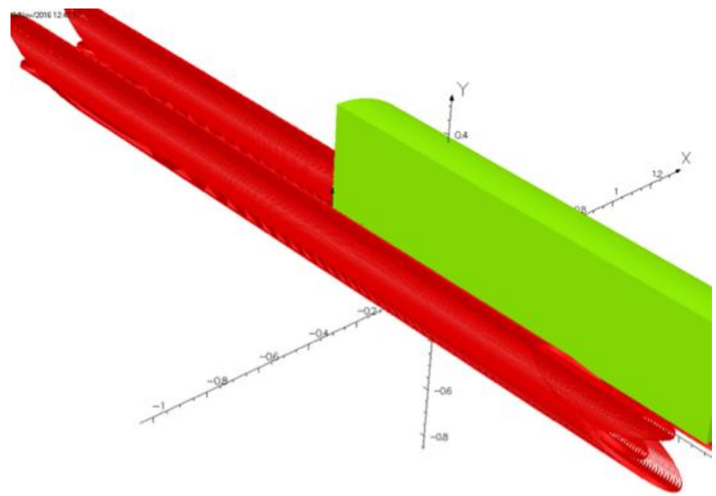
Geometric/nl. iron harmonics:
b2 <= 6 units
b3,4,5, .. <= 1 unit

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.





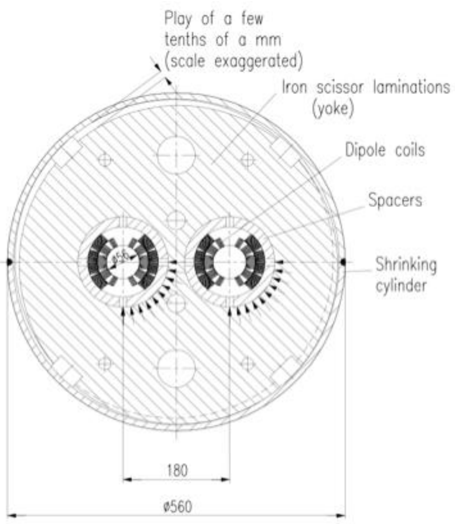
Courtesy M. Negrazus

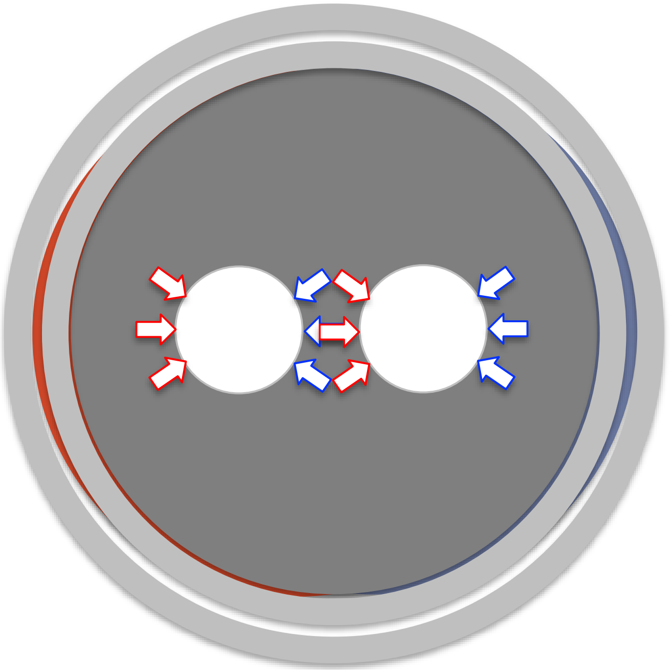
Mechanical Structure

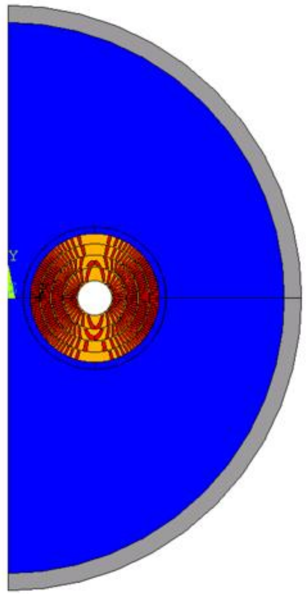
- CCT does not require azimuthal prestress.
- Radial prestress on the midplane provided by “scissor” laminations

SUPERCONDUCTING COIL COMPRESSION BY SCISSOR LAMINATIONS

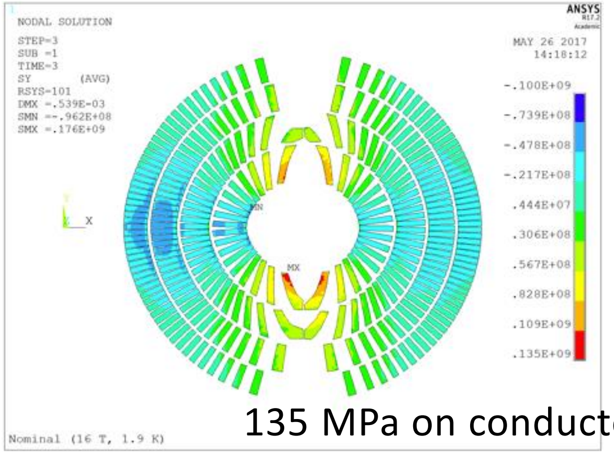
Albert Ijspeert, Jukka Salminen, CERN, Geneva, Switzerland



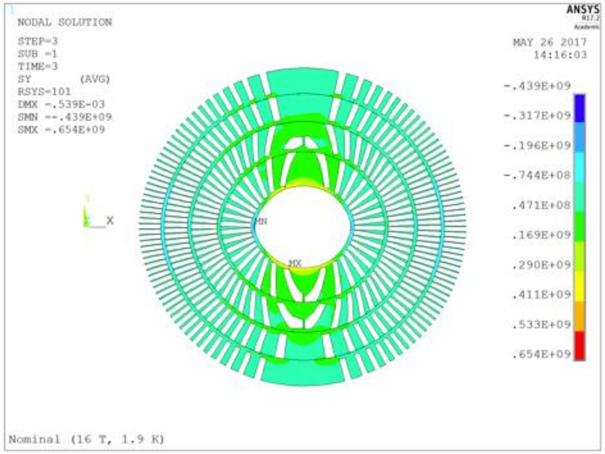


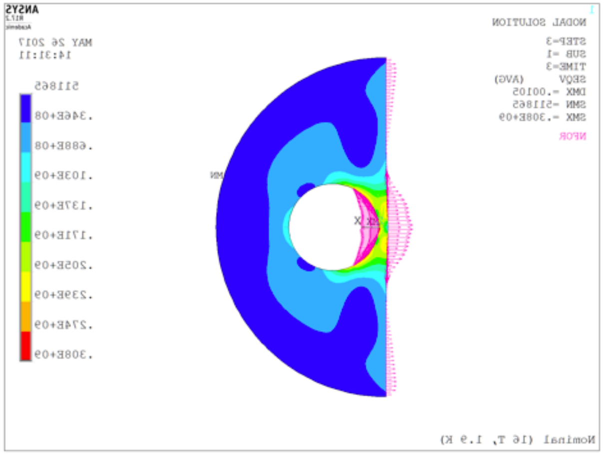


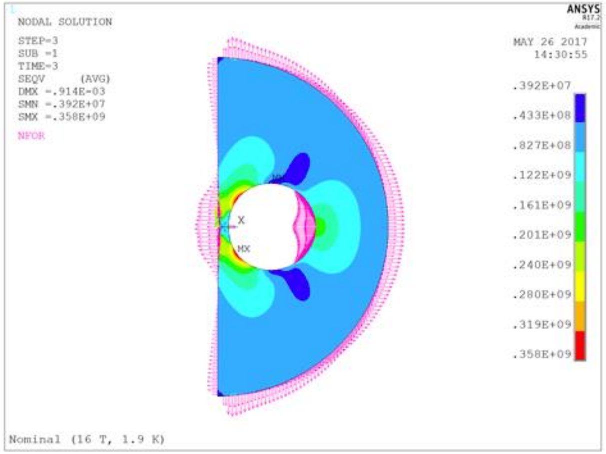
2D Mechanical Design



135 MPa on conductor



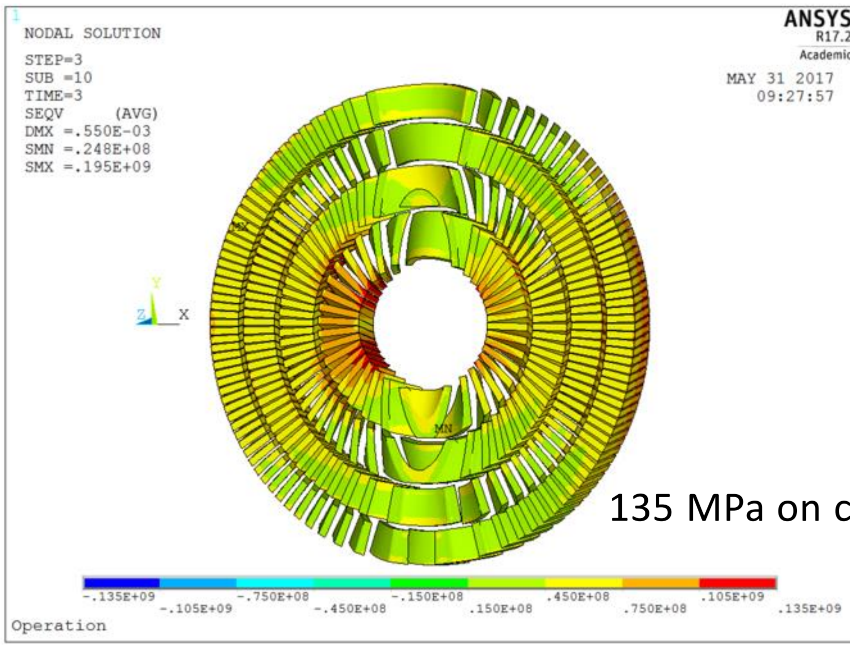




3-D Periodic Simulation

BERKELEY LAB
Lawrence Berkeley National Laboratory
CERN

- 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.



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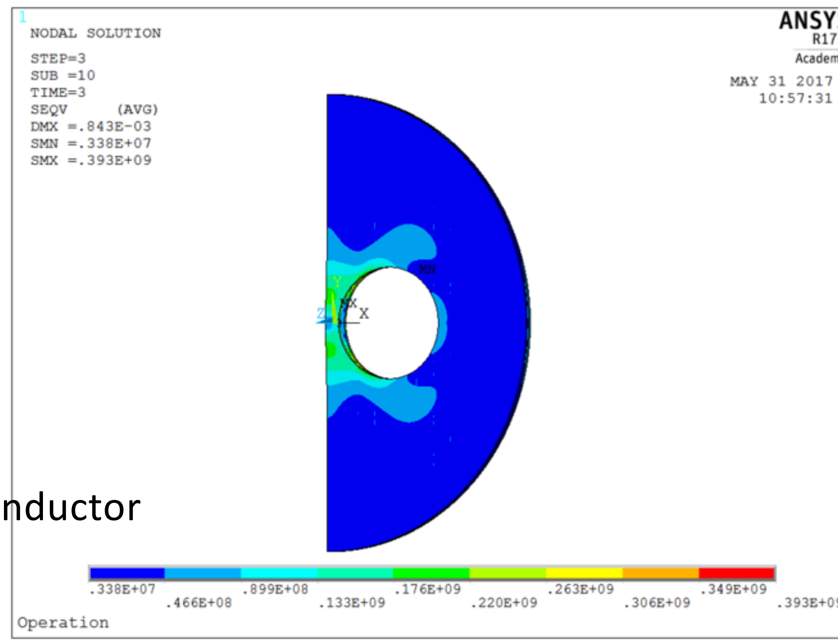
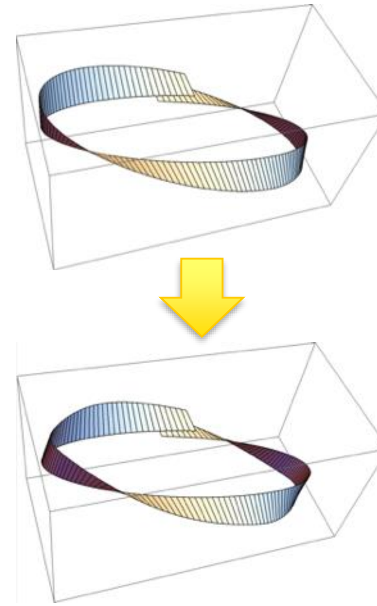


Courtesy G. Rolando

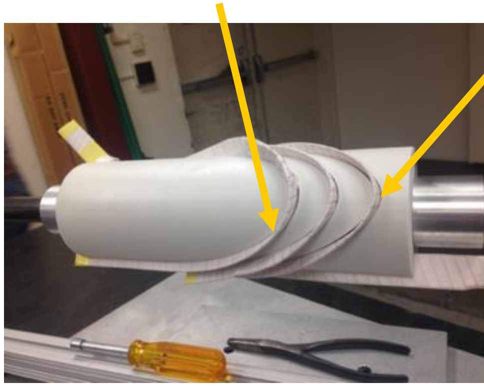
Windability

- Improve windability through inclined channels.
- Winding tests at LBNL and PSI.
- Successful tests with LD1 cable (@LBNL), LBNL CCT cable, and 11-T cable (@PSI).



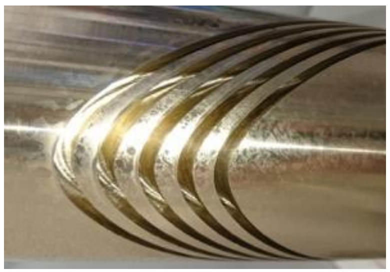
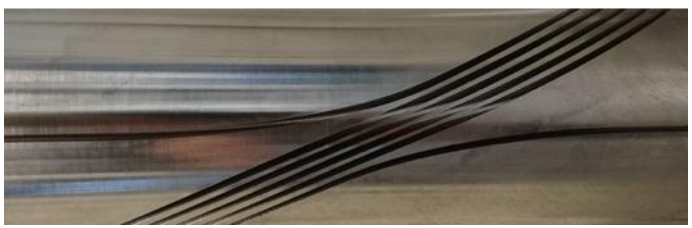
inclined channel: successful

radial channel: de-cabeling



Machinability

- Successful test machining of 16-mm-deep 2-mm-wide 15-degree-inclined channels.

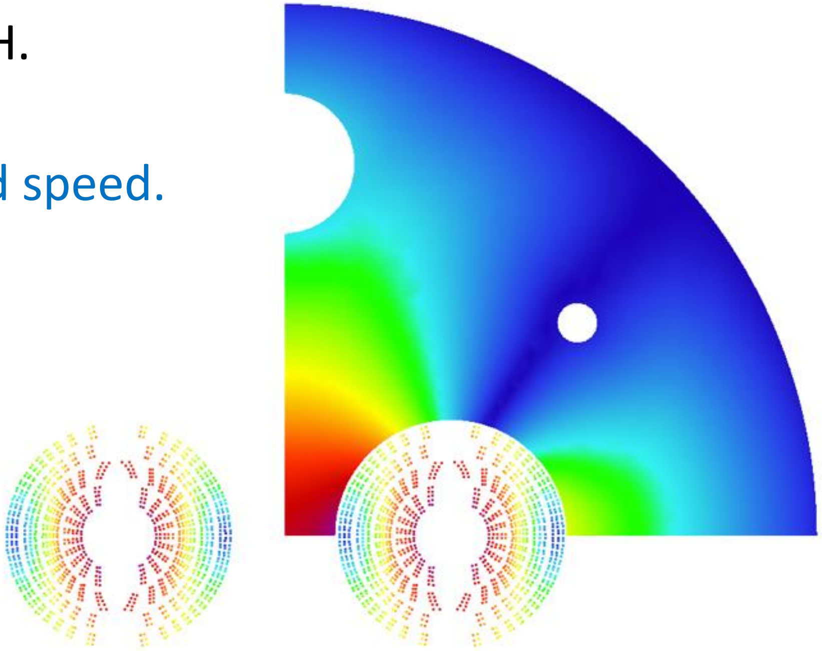

Courtesy Heinz Baumgartner AG

- FNAL gives some meters of cable for winding test.

Double-Helix CCT for FCC

Winding two Rutherford-cables into one groove, connected in series:

- Conductor weight from 9.77 kt to 9.22 kt (fewer ribs).
- Operating current from 18 kA to 16 kA.
- Inductance from 19 mH to 24 mH.
- ½ Cable unit length.
- ½ Machining path with increased speed.



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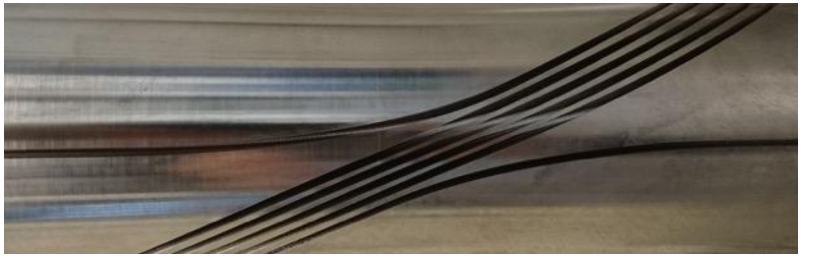
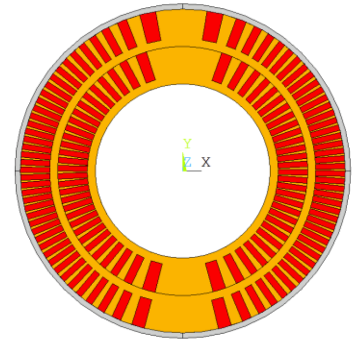


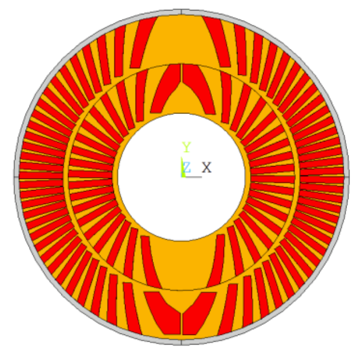
PSI Goals towards FCC Requirements

- Thin spars
- Exterior Bladder and Key structure
- Impregnation system (NHMFL resin, etc.).
- Fast quench detection and CLIQ protection.
- Wide Rutherford cable.
- Inclined channels manufacturing.

CD1

CD2

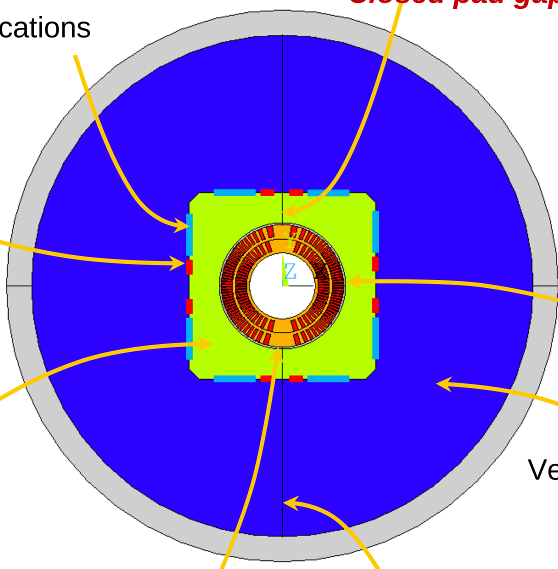




Mechanical Structure

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.



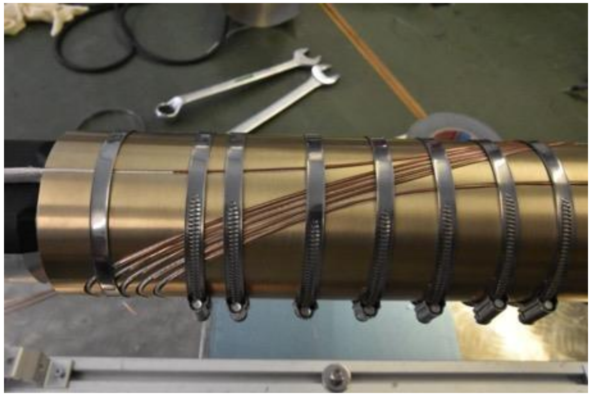
International conceptual design review of CD1 on June 26 at CERN (http://indico.cern.ch/e/cd1cdr).

Machining and Reaction Tests.

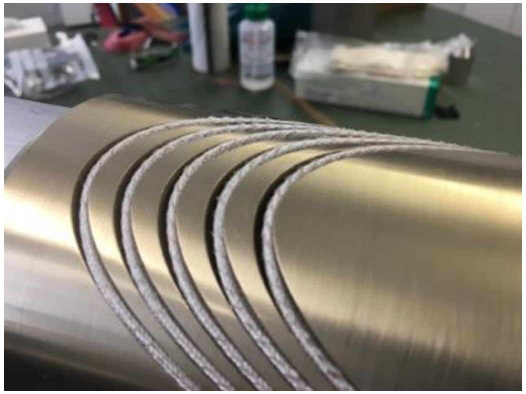
- First machining-, and winding-tests.
- Reaction-trial at CERN successful, channel-geometry validated.

Test formers delivered.

Test winding completed.



Preparation for heat treatment.

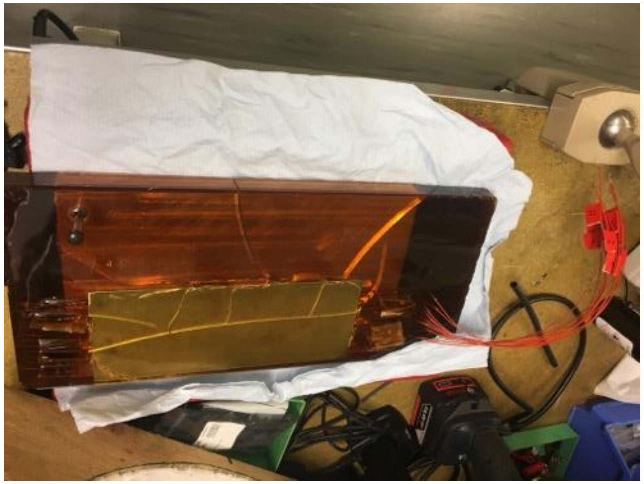


Before heat treatment

After heat treatment

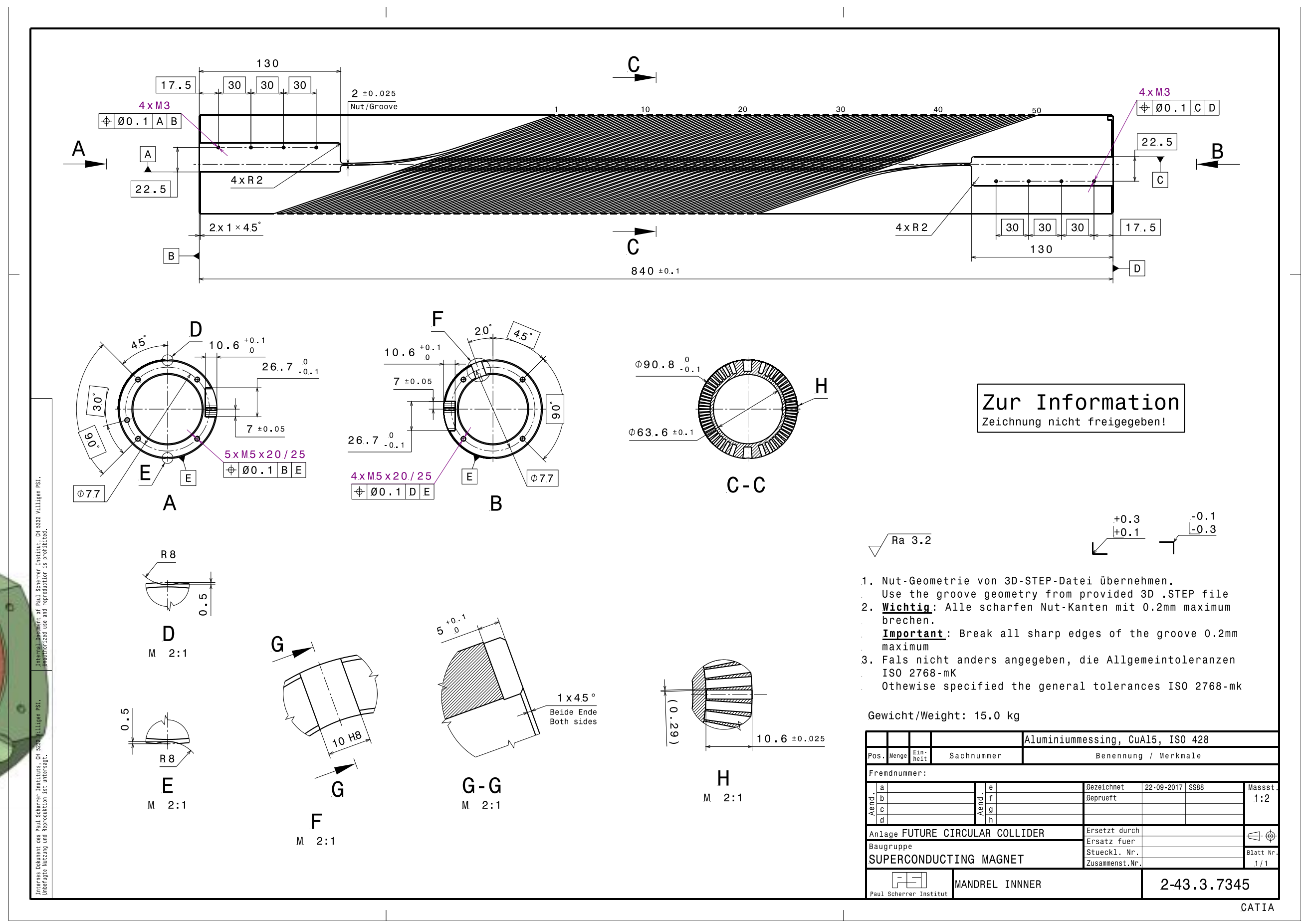
High-Voltage and Impregnation Tests

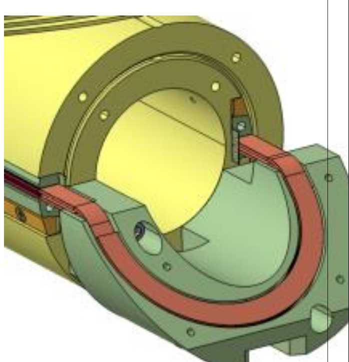
- Mica-reinforced glass-sleeve insulation, impregnated with CTD 101-K at CERN.
- Tested so far up to 5 kV without breakdown.
- Next steps: test up to 10 kV.
- Cut the sample for microscopic control of impregnation.



Technical Coil Design

- With essential LBNL input from drawings and discussions, we are launching procurement of CD1 winding former and splice box.

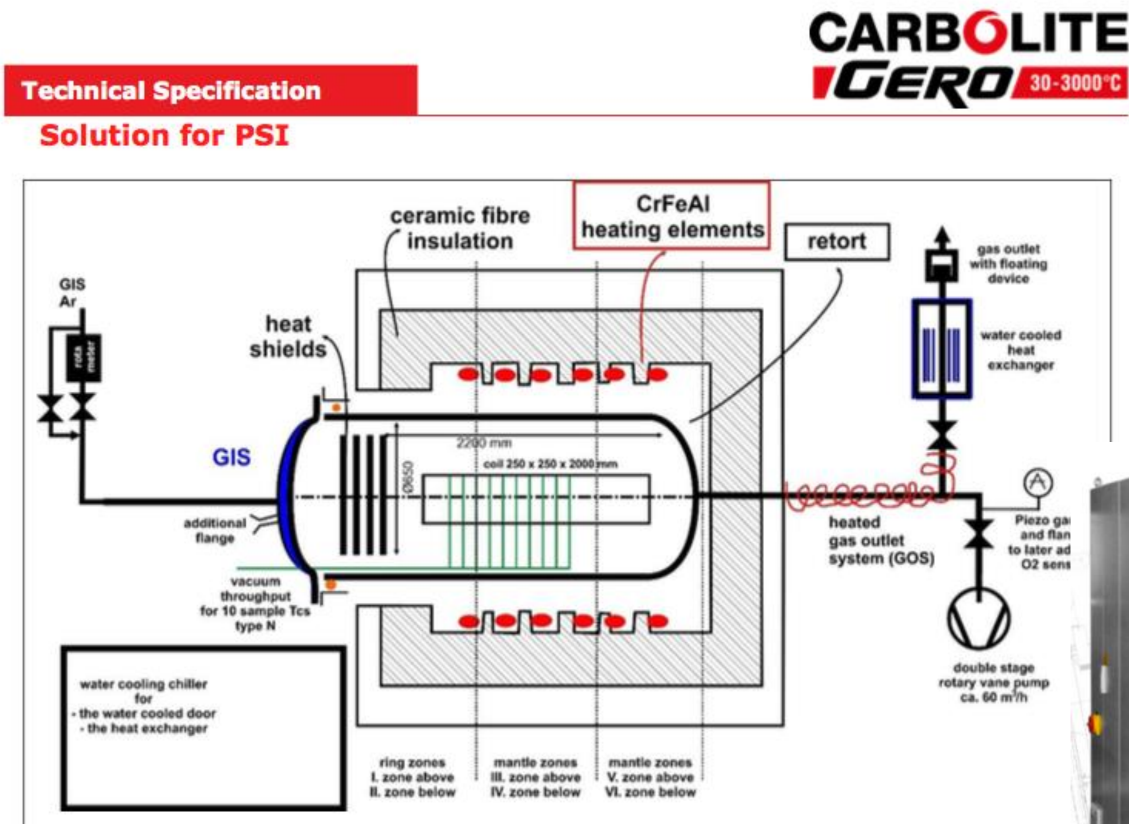




Courtesy S. Sidorov

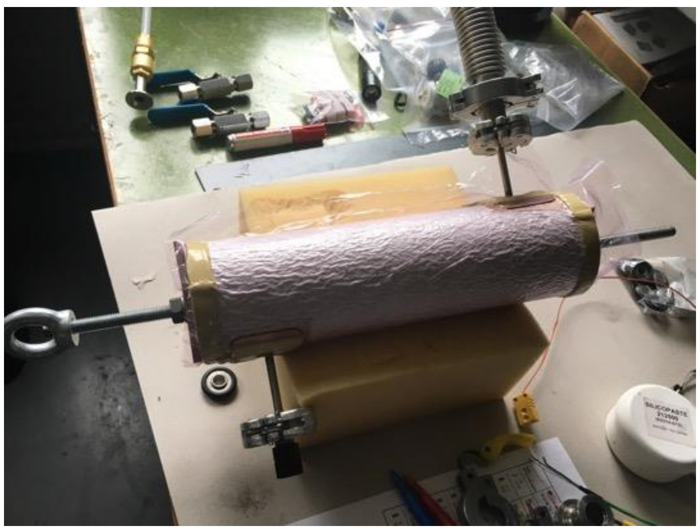
Procurement of Reaction Furnace

- Order placed, expected commissioning: April 2018.



Impregnation Trials

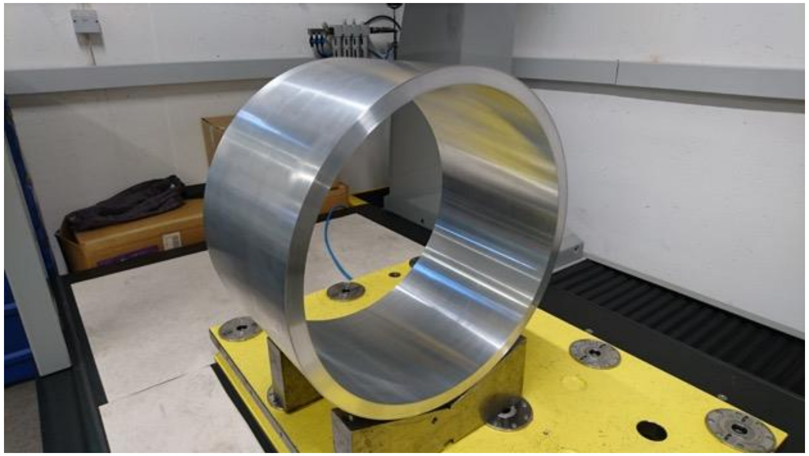
- Vacuum-bag impregnation training @CERN.
- First vacuum-bag impregnation at PSI in refurbished curing oven.
- Vacuum-vessel and heating-system procurement started.

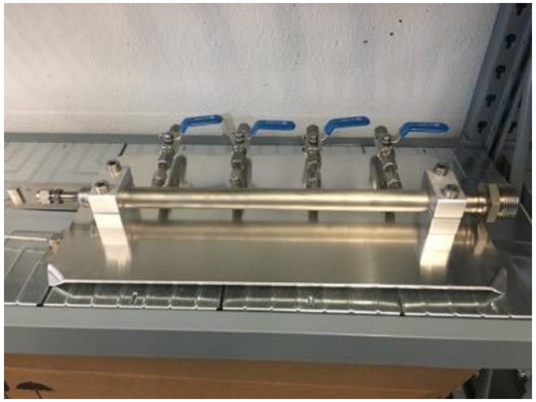


Courtesy G. Montenero

Mechanical-Model Preparation

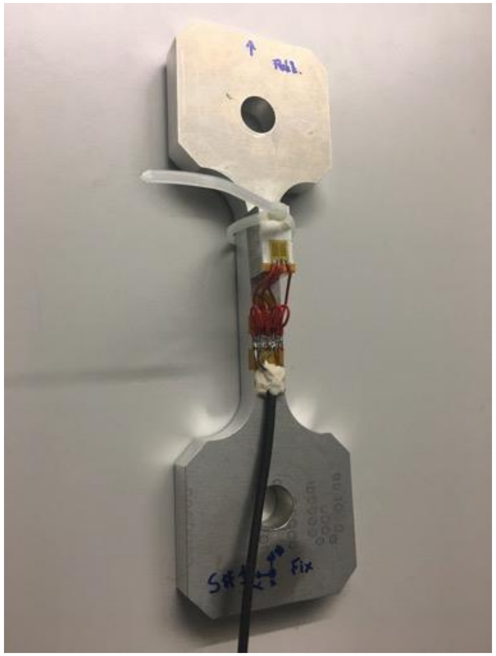
- Shell- and pads shipped.
- All other components delivered.





Strain-Gauge Measurement Setup

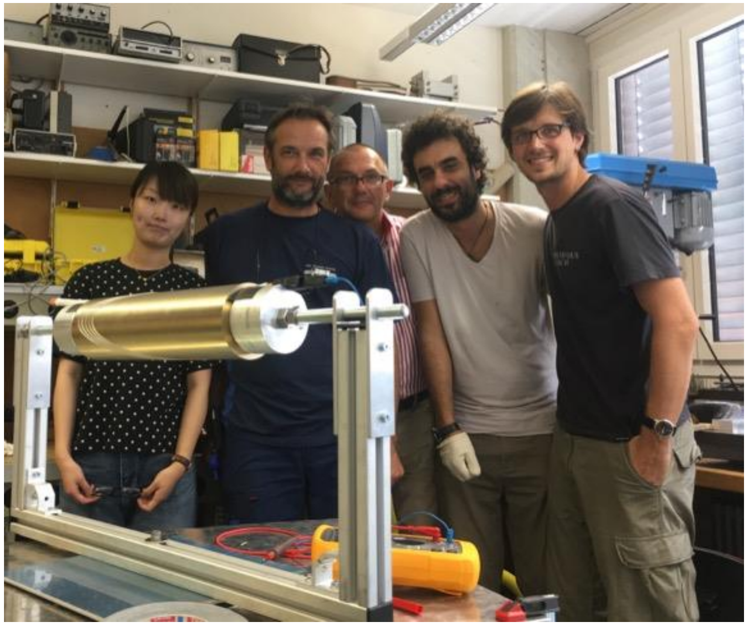
- Strain-gauges mounted, tested, and validated at PSI.
- Dedicated training @CERN in the near future?



Courtesy G. Montenero

Summary

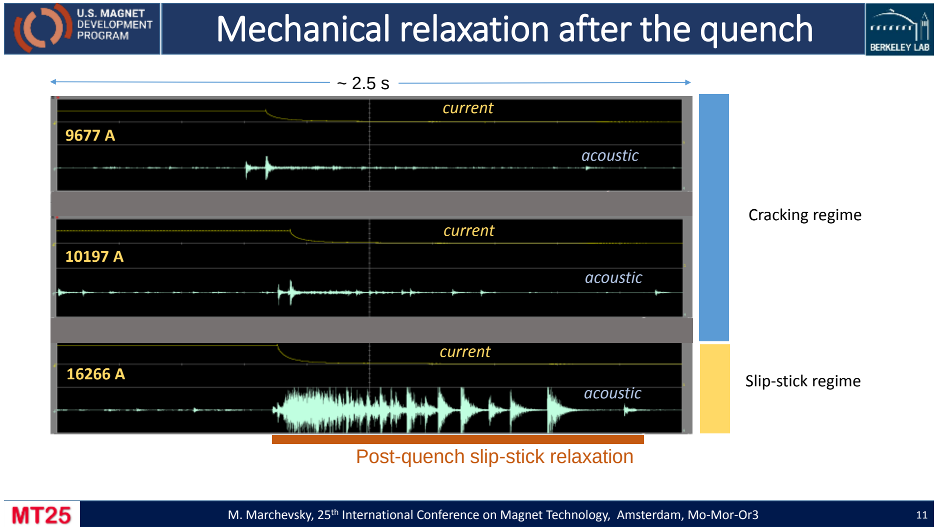
- The CCT option was established as a valid contender in the FCC design study.
- The PSI program has been designed to be complementary to and closely coordinated with the LBNL program, pushing towards specific features needed in an FCC magnet.
- PSI benefits from generous support by LBNL, integrating deeply with their program, as well as from regular exchanges and training with CERN staff who share freely and are most helpful – **THANK YOU**!



END

Lessons from CCT4 Test:

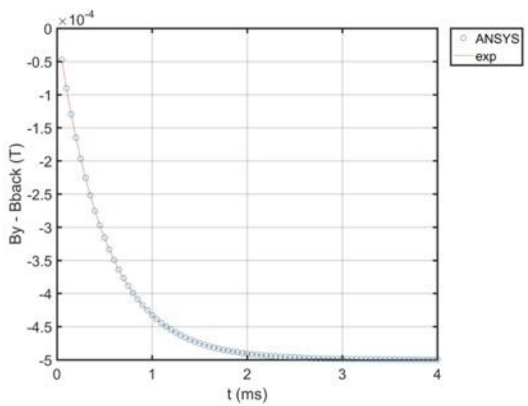
1. the magnet was not performance limited - it only had subpar training.
2. three issues must be addressed to improve (and eventually eliminate) the training:
   a) epoxy cracking (strong evidence in acoustic data),
      – alternatives to CTD-101-K will be tested.
      – alternative filling-schemes will be tested.
   b) epoxy de-lamination from the metal former,
      – chemical etching to increase surface roughness will be tested.
   c) friction due to intra-layer movement (strong evidence in acoustic data),
      – a slip-plane will be introduced.

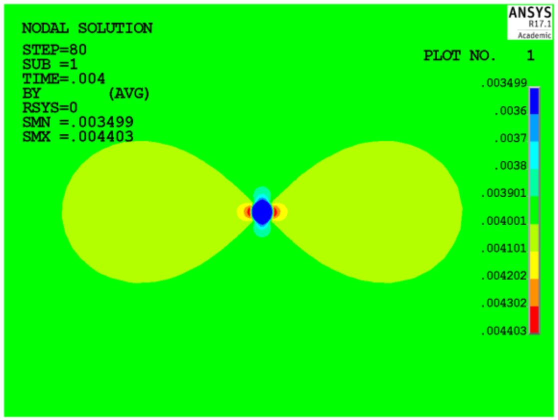


Protection Studies

- Co-wound copper secondary windings significantly accelerate the current decay.
- Relevant only if detection and active-protection can be made more efficient.
- Cowound wire and/or interrogated optical fibers have potential to bring detection time to the order several milliseconds.
- CLIQ on CCTs promises to be effective.

- Numerical studies under way.
- About to join LBNL (L. Brouwer) effort to create user-defined ANSYS “quench elements” for consistent and efficient CLIQ modeling in ANSYS.





courtesy: L. Brouwer

PAUL SCHERRER INSTITUT

Manufacturability and Cost

- Deep channels, aspect-ratio ~10.
- Inclined channels → 5-axis machining on long rotating cyl., **machining tests under way**.
- Selective Laser Melting (3-D printing) not successful.
- **Collaboration with IWS Fraunhofer** on fabrication of **thin-lamination formers**.
  - Laser cutting, spot welding + diffusion welding.
  - Goal: improve scalability and cost.