PAUL SCHERRER INSTITUT

PSI

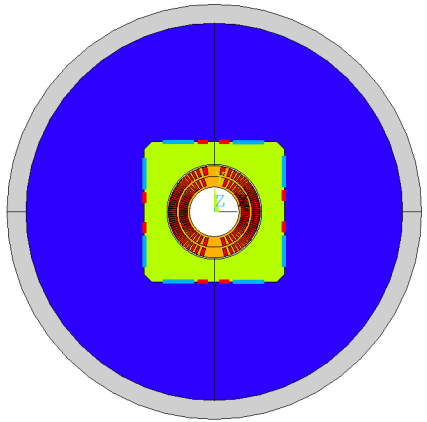
B. Auchmann (CERN/PSI), L. Brouwer (LBNL), S. Caspi (LBNL), J. Gao (PSI), G. Montenero (PSI), M. Negrazus (PSI), G. Rolando (CERN), S. Sanfilippo (PSI)

The PSI CCT Program

26.06.2017, CD1 Conceptual Design Review

Overview

- Review Charge
- CCT for FCC
- The PSI CCT Model Program



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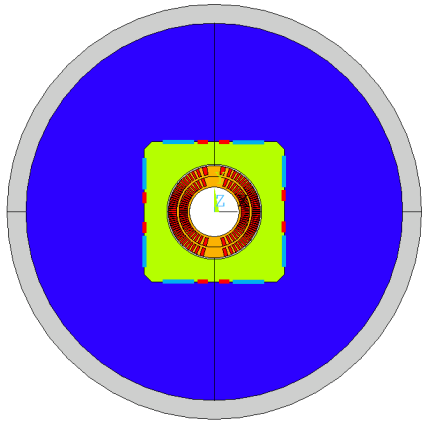
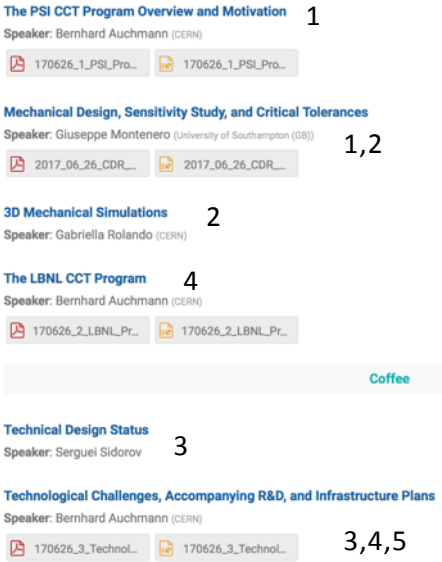


Review Charge

The goal of this review is to evaluate the current design of a first PSI-produced technology model dipole, identify technical risks, and provide feedback on technical issues and possible mitigation strategies. Note that this is the first step in the PSI program. A fabrication-readiness review is foreseen for the end of the year / beginning of 2018. The questions to the review committee are as follows:

1. Is the PSI program well motivated in view of the FCC design requirements?
   a) Is the staged approach with two different sets of coils, CD1 and CD2, in a shared mechanical structure appropriate?
   b) Is it reasonable for PSI, at this time, to move ahead with ordering conductor for CD2, given that conductor delivery times are ~1.5 years?
2. Is the mechanical design of the shared structure in CD1 and CD2 configuration sound, i.e. have risks been identified and addressed in a reasonable manner?
3. Is the electromagnetic and electro-thermal modelling sufficiently detailed to start the technical design and, eventually, the procurement of parts, or is there additional analysis that should be performed?
4. Have major technical risks been appropriately identified and are the foreseen tests adequate to address them?
5. Are the PSI infrastructure goals and plans realistic and appropriate from a technical perspective?

http://indico.cern.ch/e/cd1cdr



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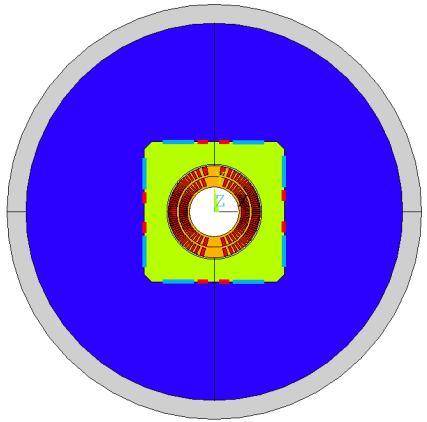

CERN-PSI(-EPFL) Agreement

FCC-GOV-CC-0062/EDMS 1703629/KE3392 VERSION 1.0 (RELEASED) December 7, 2016

ADDENDUM FCC-GOV-CC-0062 (KE 3392)

The European Organization for Nuclear Research ("CERN"), an Intergovernmental Organization having its seat at Geneva, Switzerland, the Paul Scherrer Institut (PSI), having its seat at Villigen, Switzerland and the Ecole Polytechnique Fédérale de Lausanne (EPFL), having its seat at Lausanne, Switzerland ("the Participants").	
This Addendum defines contributions by the Participants under Article 6 of the Memorandum of Understanding for the FCC Study (**FCC-GOV-CC-0004, EDMS 1390795**).	
Address for payment	EPFL – Swiss Plasma Center Station 13, Lausanne 1015, Switzerland **Suppliers Code:** EPFL50, **Address Code:** SC35, **Budget Code:** 10832

SCOPE OF WORK

The work described in this document is organised in two work packages.

- WP1

  Design of an optimised 16 T Canted Cosine Theta (CCT) dipole magnet, as an option for the FCC-hh main magnet using the EuroCirCol H2020 project baseline. This activity complements the EuroCirCol WP5 design study, which explores three designs (cosine-theta, block-coil, common coil) not including a CCT. The work also includes the support to EuroCirCol WP5 for the 16 T dipole circuits protection studies.

  Development (design and prototype) of a CCT dipole magnet demonstrator.

- WP2

  Development of reaction-resistant splicing techniques for Nb_3Sn-based accelerator magnets. Optimized splicing techniques between magnet layers, withstanding high-temperature heat treatment and compatible with conductors of different dimensions is an essential ingredient for the 16 T magnet designs, allowing for coil grading and more compact construction, impacting cost.

WORK UNIT	
PSI-RD-1	**16 T CCT design study**
Reference:	1.6.1.1 (Accelerator magnet design study for hadron collider)
Objectives:	Include the CCT design in a fully transparent comparison of design options for a 16 T dipole magnet.

WORK UNIT	
PSI-RD-2	CCT demonstrator design
Reference:	1.6.1.1 (Accelerator magnet design study for hadron collider)
Objectives:	Validate mechanical properties of CCT-type designs. A Nb_3Sn CCT dipole will be tested in Q1 of 2017 at LBNL. The lessons from this test will serve as additional input for the technological choices in the design of at least two layers of CCT coils. The mechanical structure surrounding the CCT coils shall be designed to allow for tests with Nb-Ti and Nb_3Sn technology.

WORK UNIT	
PSI-RD-3	CCT demonstrator construction and testing
Reference:	1.6.1.1 (Accelerator magnet design study for hadron collider)
Objectives:	Procurement of parts, quality assurance, coil winding, possibly reaction and impregnation, assembly, testing, and post-operational analyses of a CCT dipole. Standalone test of coils in a dedicated mechanical structure. They can possibly become part of a 16 T multi-layer CCT dipole constructed in collaboration with LBNL.

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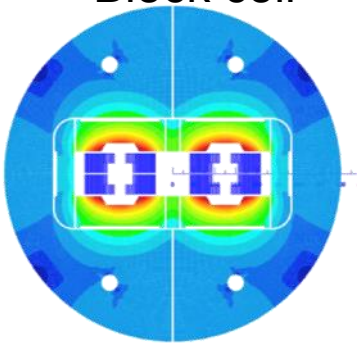
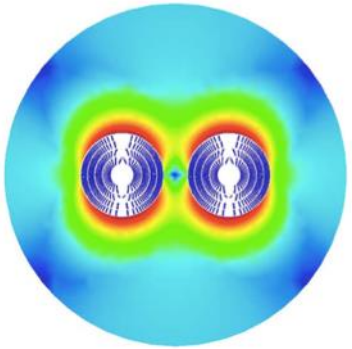
CERN Work Unit Contact:	Dr. Davide Tommasini, davide.tommasini@cern.ch, +41 75 411 06 92

Preliminary Designs

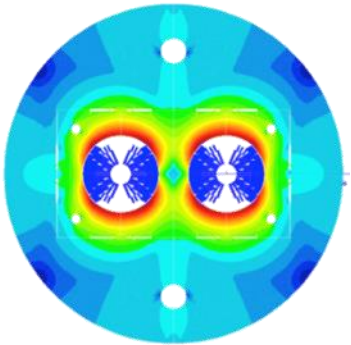
Block coil



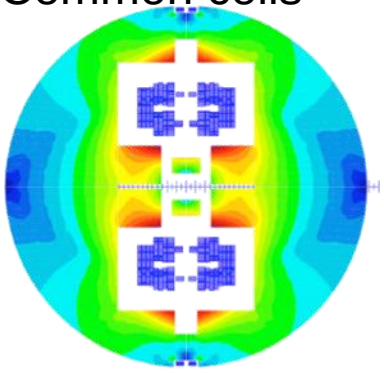
Canted Cosine Theta



Cos-theta

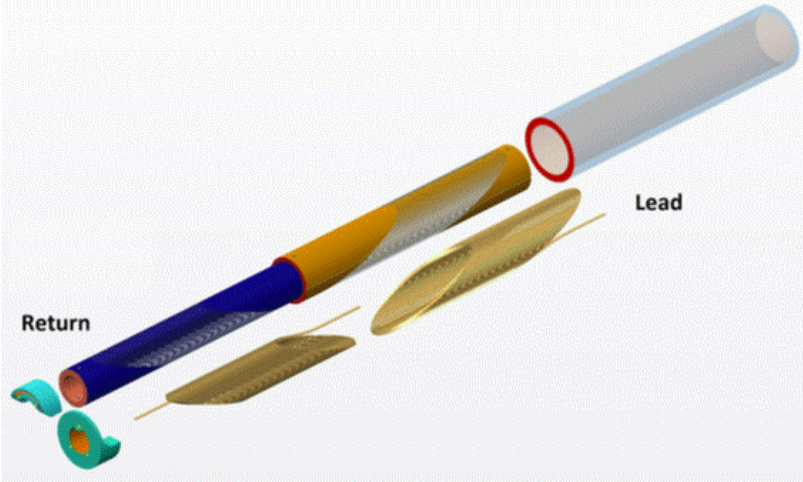


Common coils



Mechanics Challenge

- Canted Cosine Theta program for HFM started at LBNL (US).
- Promises a decisive reduction of coil transverse stress through individual support of turns.



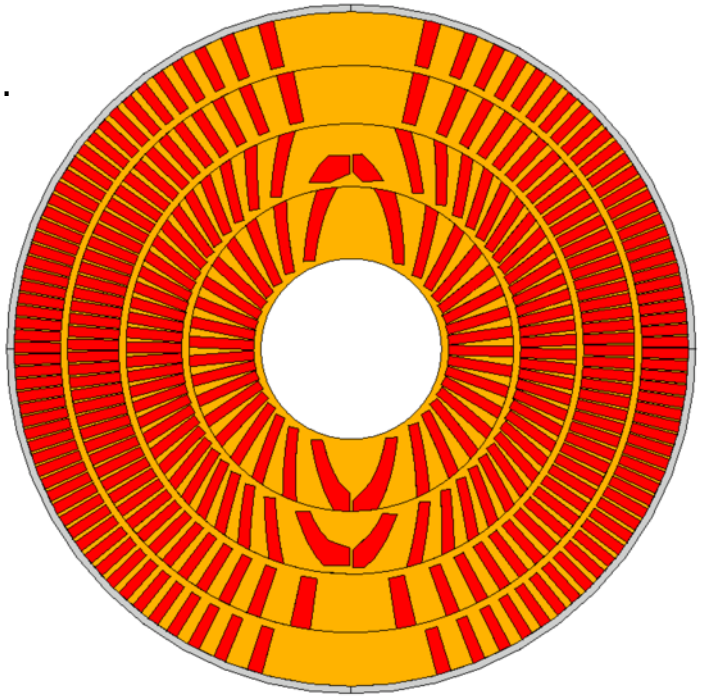
Courtesy: C. Senatore

- Many challenges ahead:
  - efficiency
  - former manufacturing
  - impregnation scheme and training performance

PSI's CCT Design for FCC

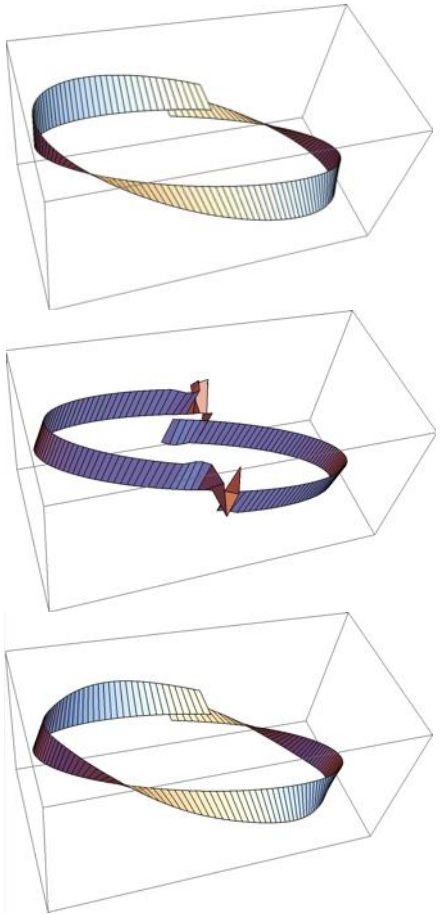
- Keys to an efficient CCT design:
  1. Thin spars
     (+ external mech. structure)
  2. Wide cable, large strands
  3. Thin ribs.

Increase J_e.



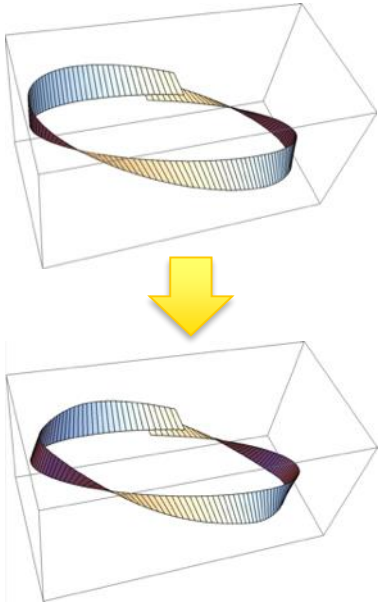
Windability

- The ideal CCT magnet places the cable radially on the mandrel.
- This approach induces moderate hardway bend on the midplane, and strong hardway bend (bending rad. ~ mandrel rad.) on the pole.
- A tilted-racetrack-shaped solution exists that has zero hardway bend (and a discontinuity on the midplane).
- Assumption: We can use an interpolation between the radial solution (around the midplane) and the tilted solution on the pole to improve windability.



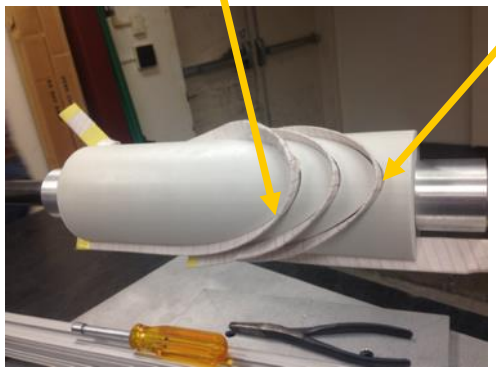
Winding Tests

- 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

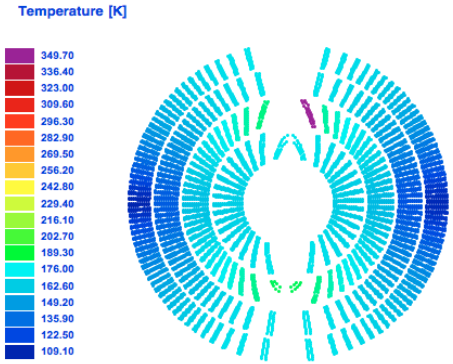
radial channel: de-cabeling



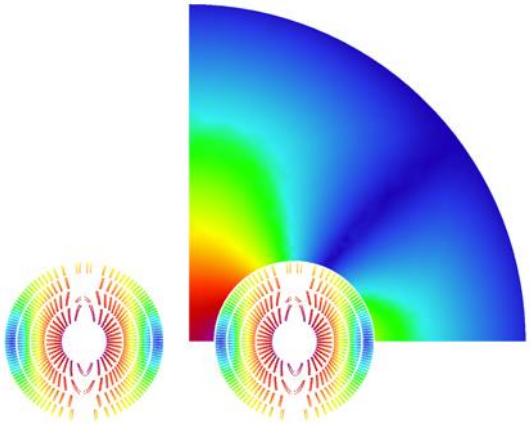
PSI's CCT Design for FCC

- Current: 18055 A

Layer #	n_S	cuNc	loadline marg. [%]	current marg. [%]	T_{peak} [K]	V_{grnd} [V]	J_{cu} [A/mm^2]
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

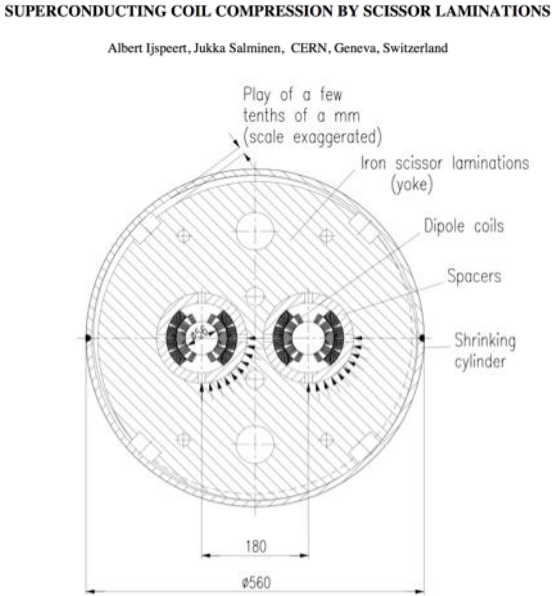


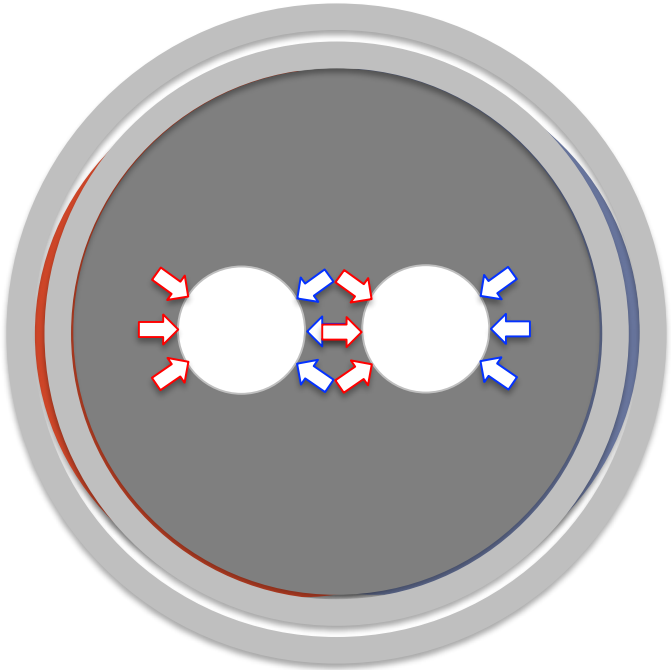
- FCC-wide conductor use
- Total: 9.77 kt (~ +30% wrt. CT)
- NonCu: 3.75 kt
- Cu: 6.02 kt
- Total inductance: 19.2 mH/m
- Total energy: 3.2 MJ/m

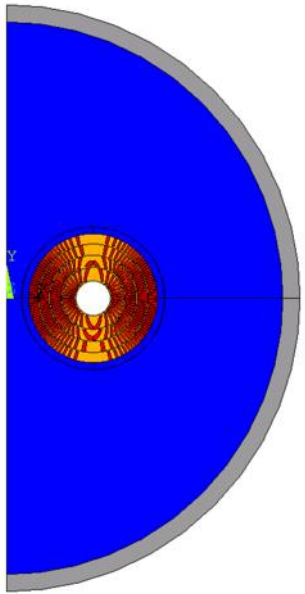


Mechanical Structure

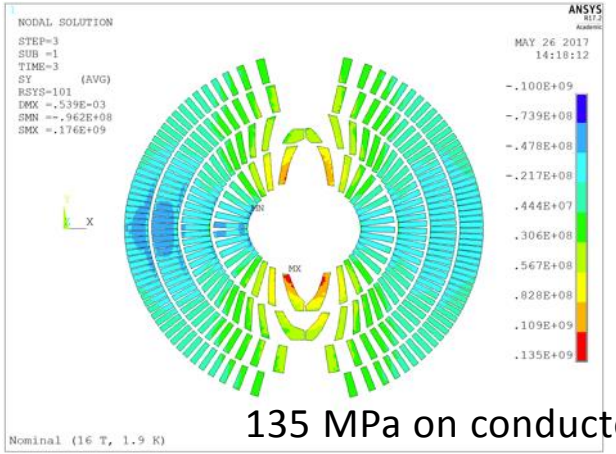
- CCT does not require azimuthal prestress.
- Radial prestress on the midplane provided by “scissor” laminations.



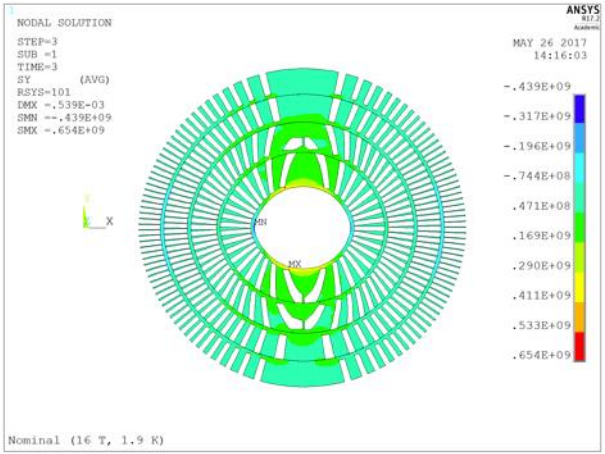


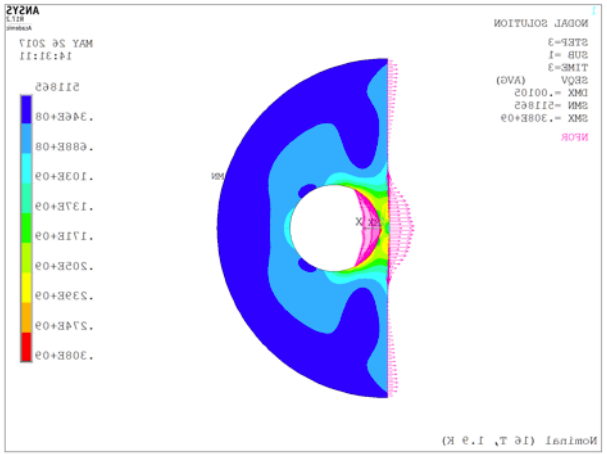


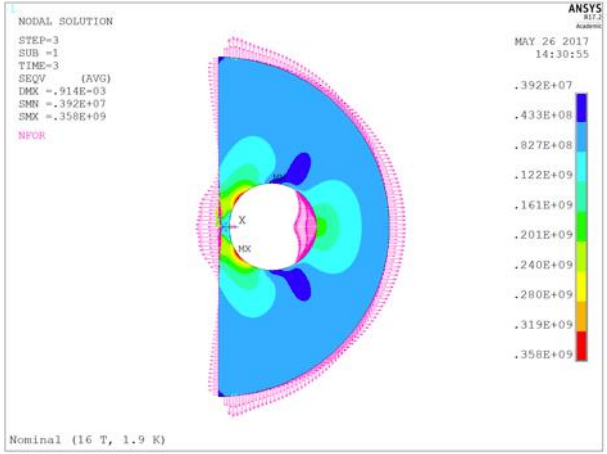
FCC 2D Mechanical Design



135 MPa on conductor

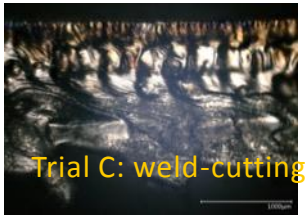






Manufacturability and Cost

- Deep channels, aspect-ratio ~10 with inclined, tapered channels.
  - **Machining** trials started – limited room for cost reduction.
  - Selective Laser Melting (3-D printing) not successful in keeping tolerances.
  - **Thin-lamination formers**, R&D in collaboration with IWS Fraunhofer.
    - Laser “weld-cutting”.
    - Goal: improve scalability and cost.



Trial C: weld-cutting two discs.

Trial A: SLS.

Trial B: laser cutting, laser spot welding.

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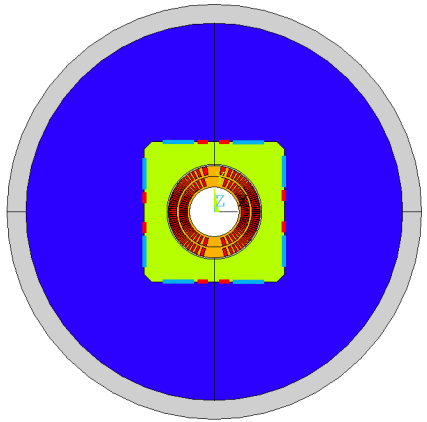


PSI Goals towards FCC Requirements

- Thin spars
- Exterior Bladder and Key structure
- Impregnation system (NHMFL resin, etc.).
- Fast quench detection and CLIQ protection.
- Wide Rutherford cable.
- Inclined channels manufacturing.
- Former manufacturability and cost reduction (with Fraunhofer/industry).

CD1

CD2

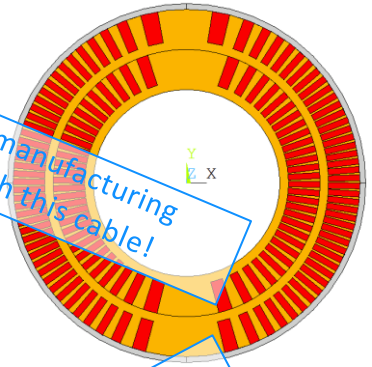
PSI program to be complementary to US MDP program.

CD1 and CD2 Cable and Geom. Params.

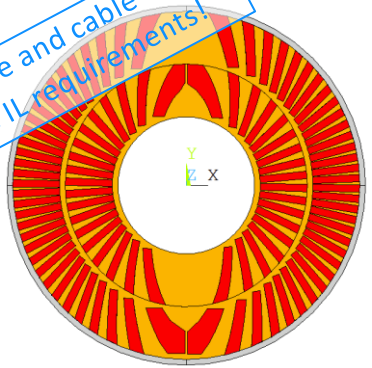
- PSI **builds one mechanical structure** for
  - **CD1**:
    - **LBNL CCT cable** (0.85 mm diam, RRP 108/127, 21 strand),
    - 10.6 mm channel depth, 3 mm spar, 0.5 mm assembly gap
    - Layer-2 OD = 122 mm, ID = 65.6 mm (clear bore).
  - **CD2**:
    - **15-T IL cable**, (1 mm diam, RRP 150/169,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

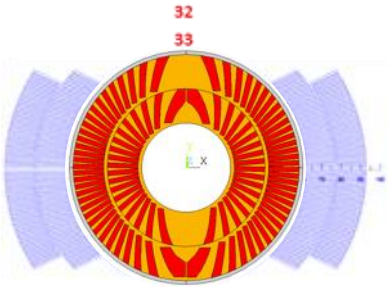
Use LBNL coil-manufacturing experience with this cable!



Use FNAL wire and cable resembling FCC IL requirements!



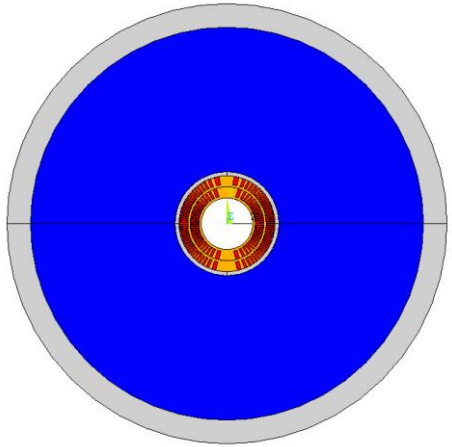
Demonstrate CCT ILs functioning in high-field (>15 T)

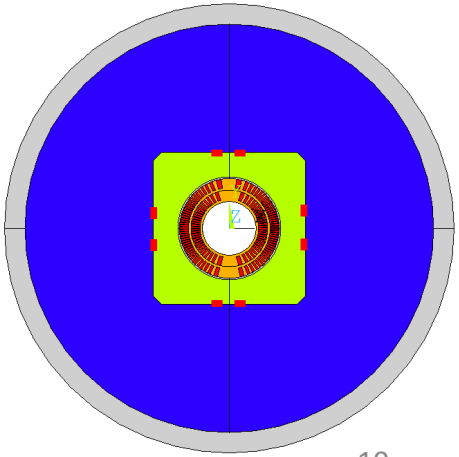


Mechanical Structure Evolution

1. Scissors laminations with Al shrink cylinder.
   - System proposed for FCC
   - Al cylinder rather than stainless welded shell due to lack of welding-press infrastructure.
   - Open questions concerning assembly, mounting/dismounting risk, tuneability.

2. Classical bladder&key structure with open vertical gaps in yoke and pad.
   - Difference to SMC/RMC/HD1: 2-part pad (no need for azimutal pre-stress).
   - Structure found too elastic to effectively limit peak stresses in formers.

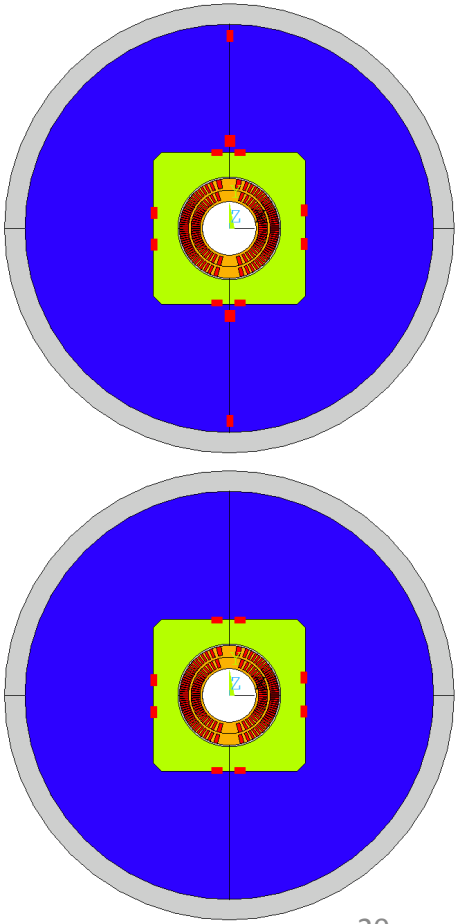




Mechanical Structure Evolution

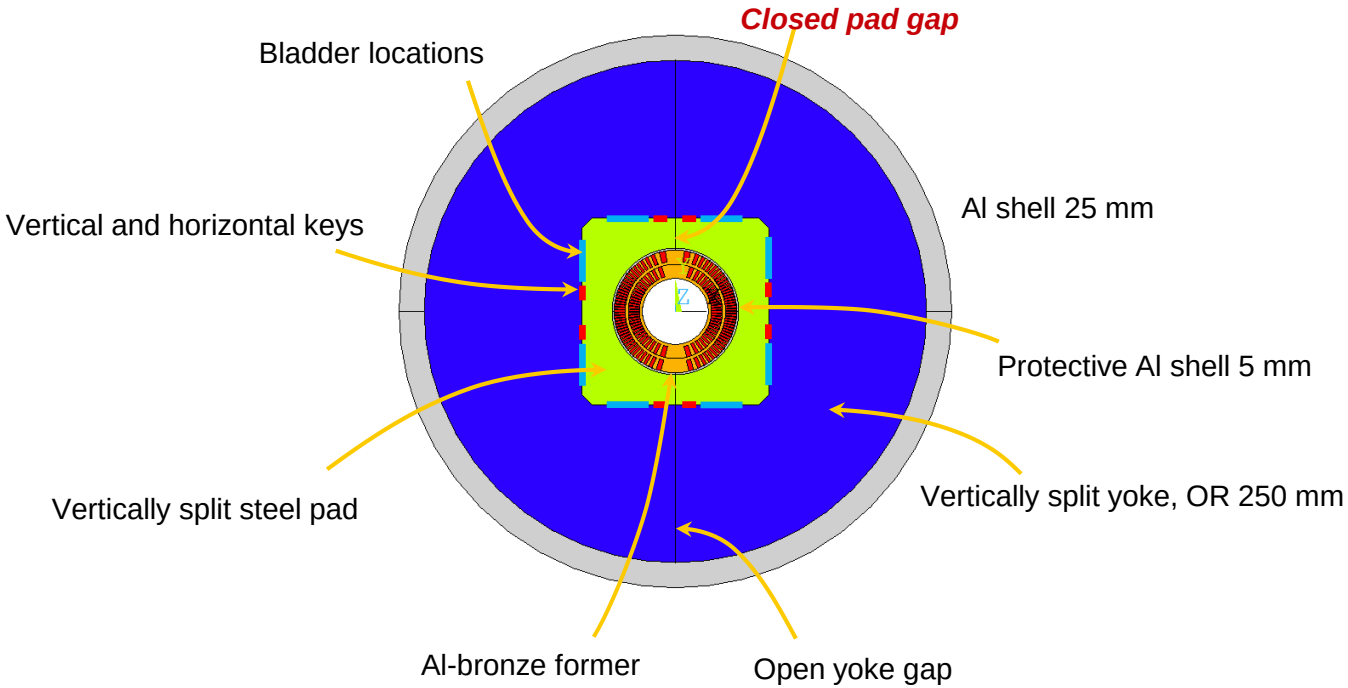
3. Bladder&key structure with ***closed yoke gap***.
   - Tapered interface like MFISC, 11-T, etc. through graded yoke keys.
   - Could not provide enough pre-stress to limit former stress AND keep the gap closed at room temperature.

4. Bladder&key structure with ***closed pad gap***.
   - Closed and pre-loaded pad gap for maximum-rigidity cage around coils.
   - Steel pads to better match coil differential contraction.



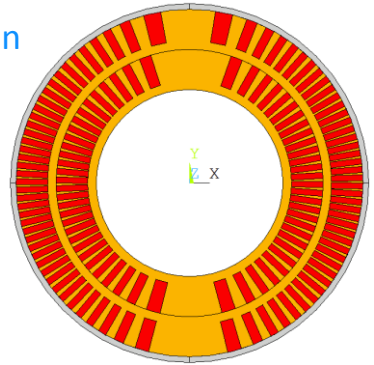
Mechanical Structure

4. 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.

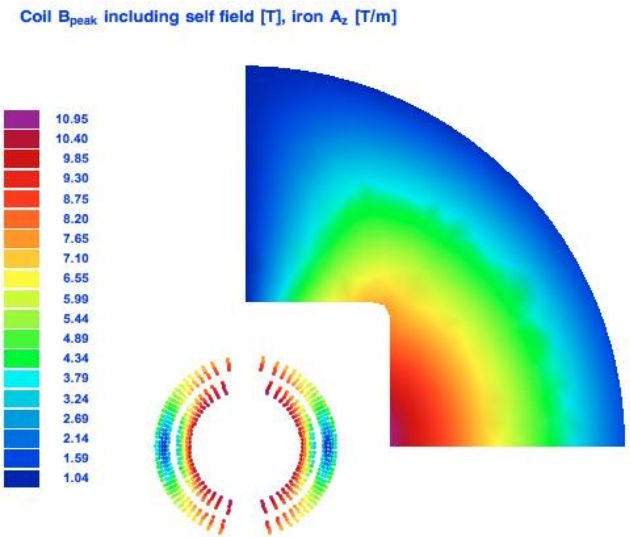


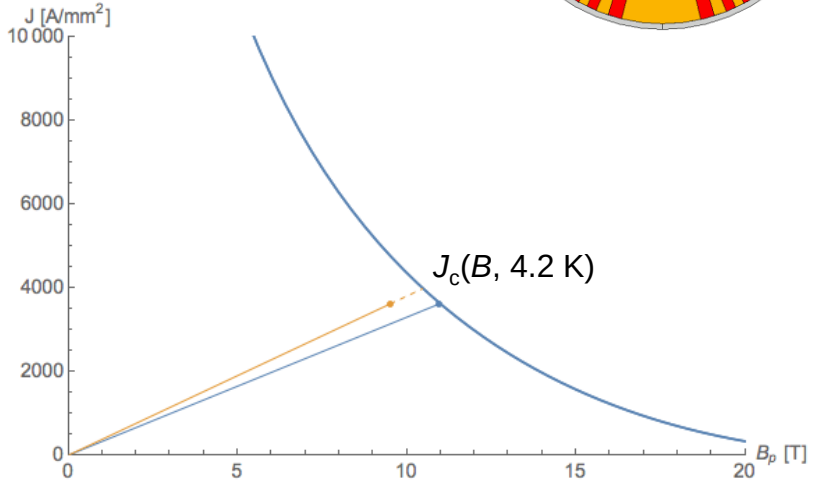
CD1 Magnetic Design

Selected for mechanical design
→ ***ultimate load***.



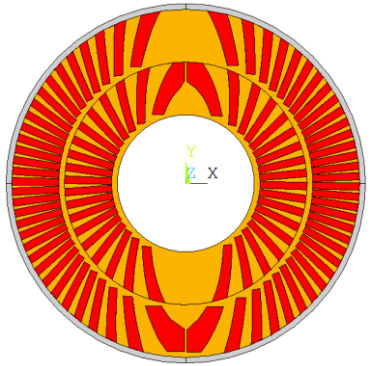
- At 4.2 K: I_{SS} = 20 kA, ~11 T bore field.
- At 1.9 K: I_{SS} = 21.6 kA, ~11.7 T bore field (NB: CERN I_{max} = 20 kA)
- With iron pads at 4.2 K: I_{SS} = 19 kA, ~11.35 T bore field
- With iron pads at 1.9 K: I_{SS} = 20 kA, ~12 T bore field

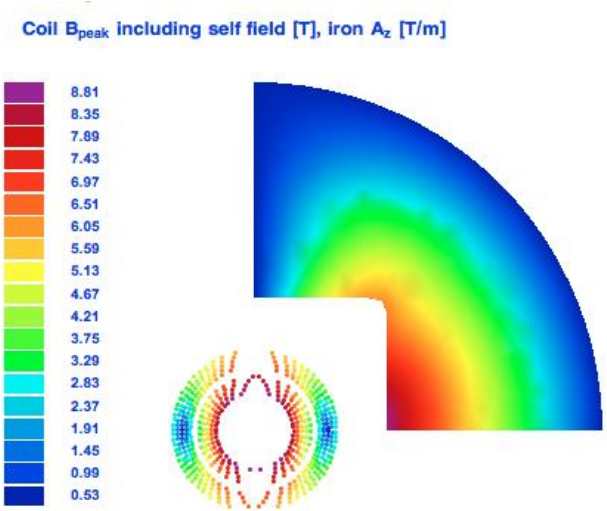


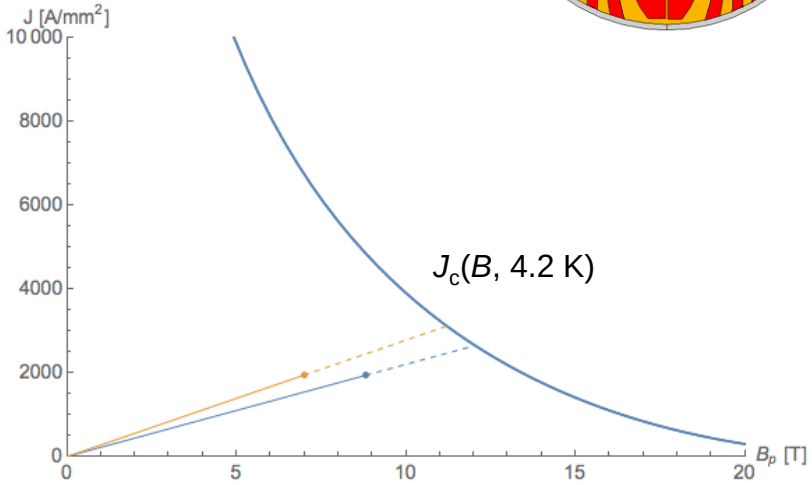


CD2 Magnetic Design

- I_{max} = 22 kA; 9.5 T bore field, 81% on LL at 4.2.
- I_{max} limited by LBNL test station.
- Cable is oversize for a 2-layer magnet!

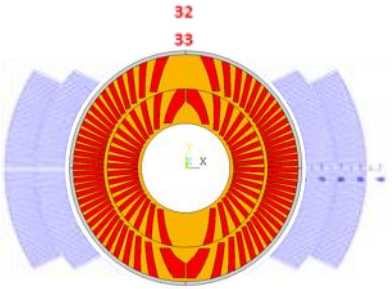


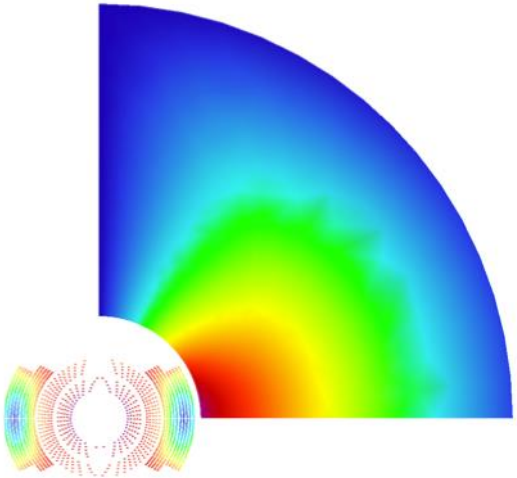


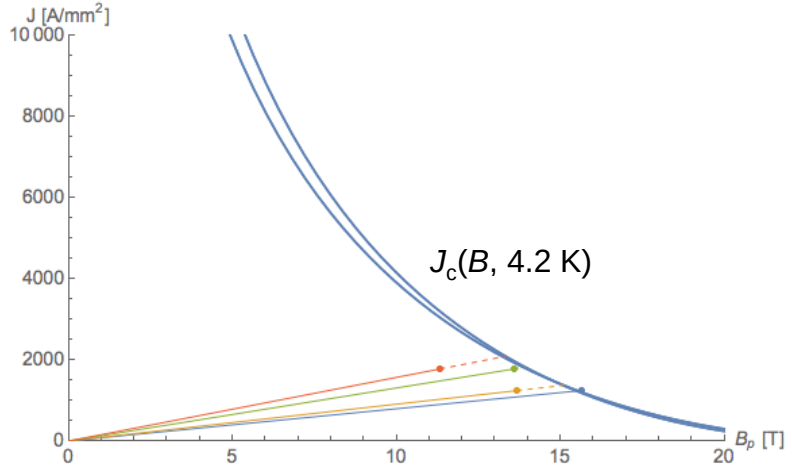


CD2 in MDP 15-T Layers 3&4

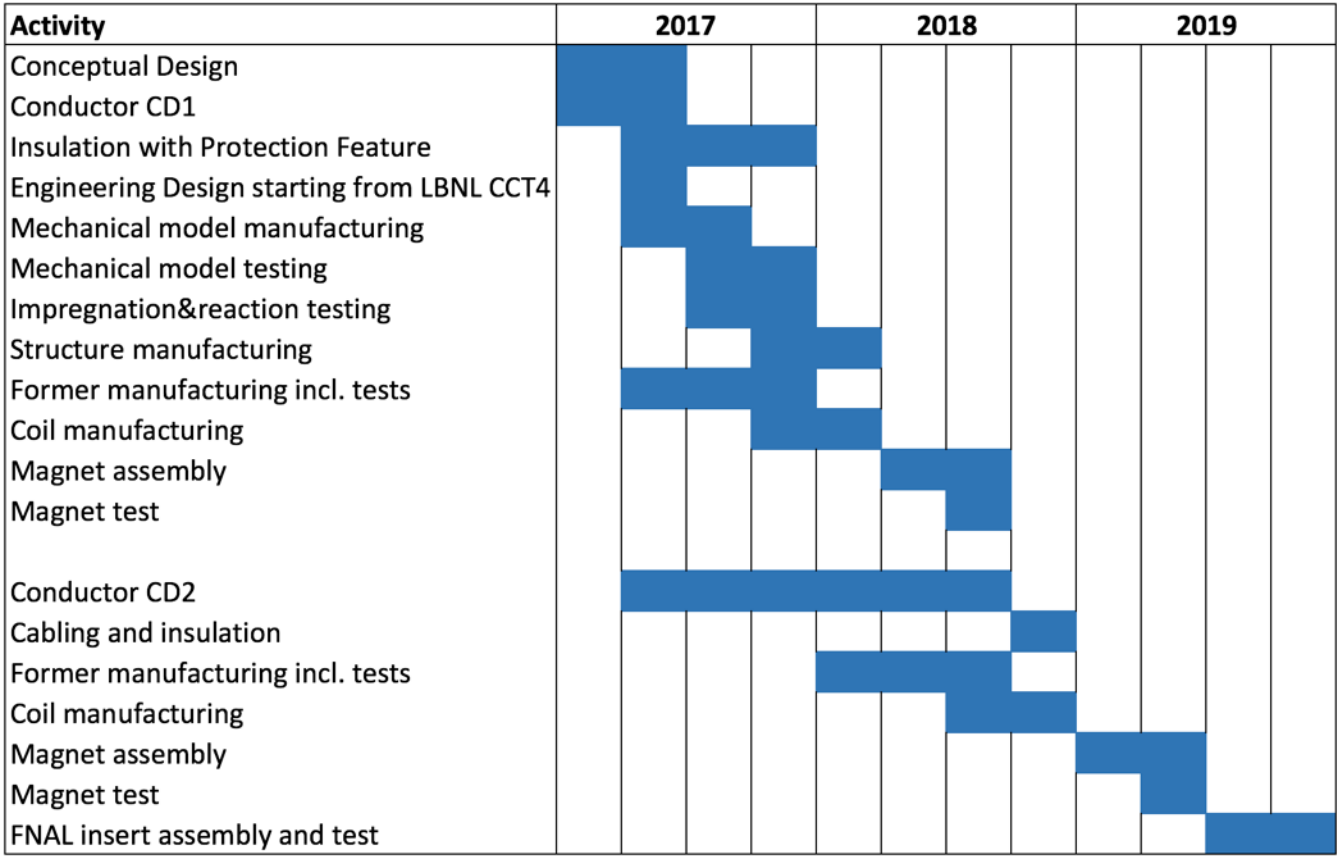
- B_{SS} = 15.4 T (Iss = 12.8 kA) at 4.2 K .
- B_{SS} = 16.8 T (Iss = 14.1 kA) A at 1.9 K.
- Field quality not optimized (140 units b3), peak field on midplane.







First Planning (Feb. ‘17)



CD1 Conductor Plans

- CD1 unit lengths for a 70-turn magnet: Layer 1: 44.3 m, layer 2: 60.7 m. Total: 106.5 m.
- Tests in 4 areas:
  - *insulation*: 10 m
  - *winding*: 10 m
  - *reaction*: 15 m
  - *impregnation*: 38 m

- 179 m of CD1 cable have been produced by LBNL and are being shipped to PSI.
- Cable for tests insulated with sleeve.
- Company contacted to insulate magnet cable with mica and braided S2 glass.

CD2 conductor plans

- PSI plans to order Bruker OST strand (1 mm diam, RRP 150/169).
- Quantity for 150 m of 28-strand cable, using the specifications of FNAL 15-T-magnet program.
- FNAL agreed to perform cabling for PSI end of 2018.
- In the meantime FNAL provides copper cable for winding and impregnation tests.
- *Risk mitigation*: If more CD1-type coils are needed, and if CD1-strand is difficult to come by, the above strand could be drawn down to 0.85 mm diameter, which yields conductor in excess of two more CD1 coils.
- The cabling must not happen before the CD1 test!

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.
- CD1 benefits fully from LBNL coil-manufacturing experience.
- CD2 conductor needs to be ordered now.
- Support by LBNL and CERN, but also FNAL are essential for our program. We are grateful for the generosity.

Outlook

- CD1 design will be discussed in more detail in the following presentations.
  - 2-D Mechanical Design and Tolerances (Giuseppe)
  - 3-D Mechanical Models (Gabriella)
  - LBNL CCT Program (Bernhard)
  - (coffee)
  - Technical Design (Serguei)
- Technological Challenges, R&D Topics, and Infrastructure Plans are covered in the last presentation (Bernhard)

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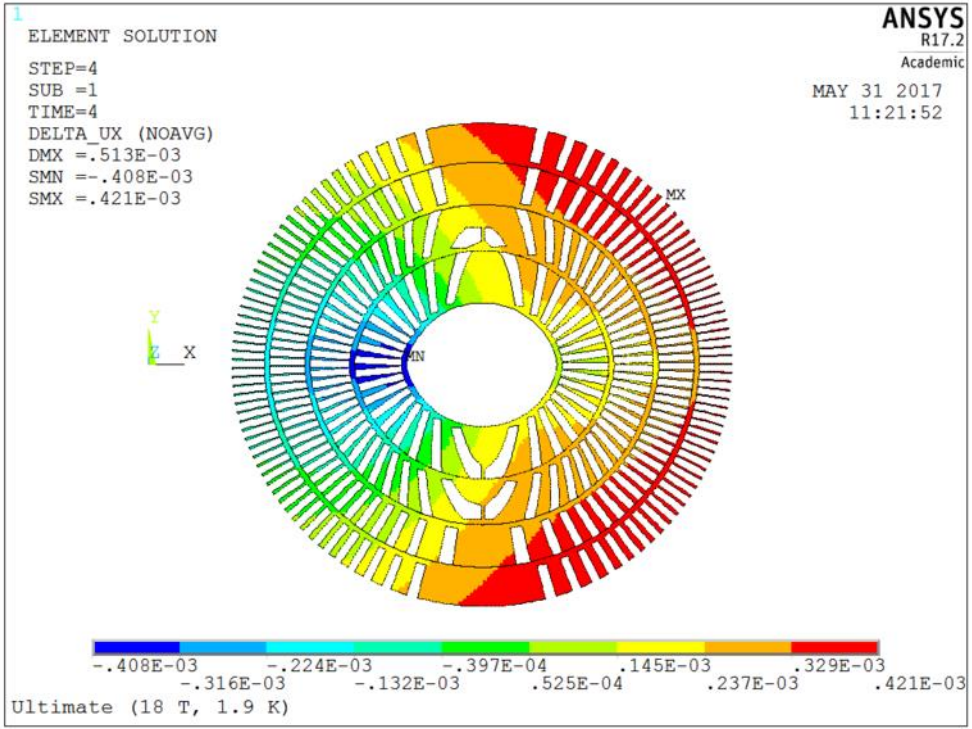
END

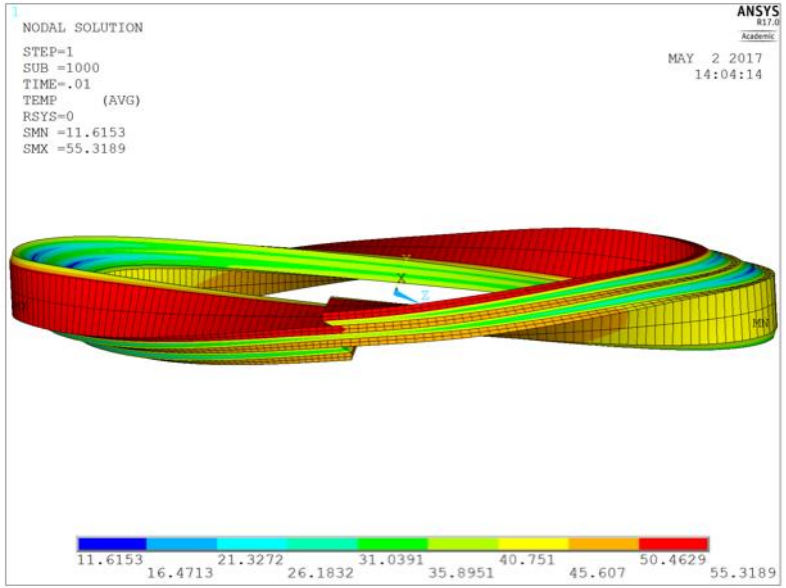
Movement Cryo to 16 T

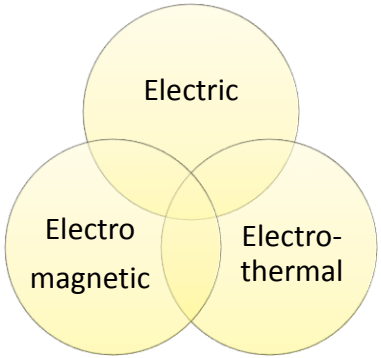


Quench Simulation

- Tool : Mechanical APDL (ANSYS Parametric Design Language)
  - A scripting language to build models & analyses
  - Features : design optimization & adaptive meshing

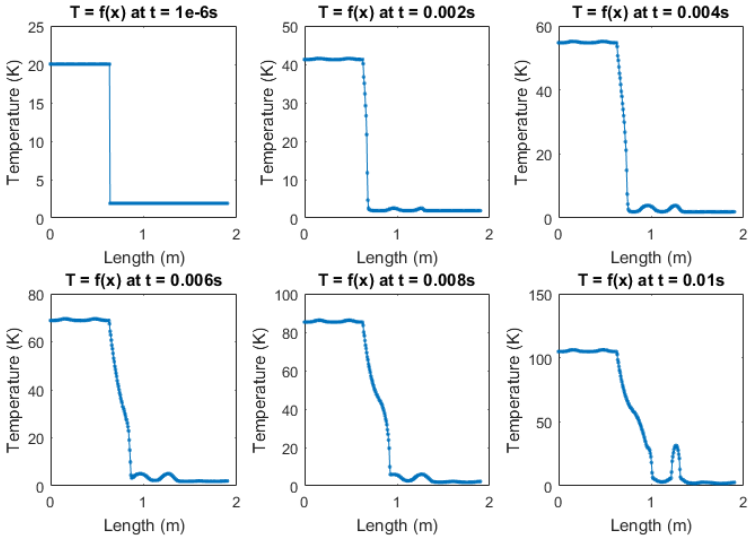
```
! Open the output file:
/DELETE,centroids,dat
*CFOPEN,centroids,dat
*VWRITE,elnb
(F6.0)
! LOOPING OVER ELEMENTS
*DO,q,emin,emax,1
  ! Obtain the centroid location:
  xc = CENTRX(enum)
  yc = CENTRY(enum)
  zc = MOD(CENTRZ(enum)+100*pitch,pitch)+pitch/2
  ! Write the data to the file:
  *VWRITE,xc,',',yc,',',zc
  (e20.5,a3,e20.5,a3,e20.5)
  *GET,enum,ELEM,ENUM,NXTH
*ENDDO
*CFCLOS

ALLSEL
! IMPORT ELEMENT DATA
/INQUIRE,numlines,LINES,eldata,dat
*DEL,eltab,,NOPR
*DIM,eltab,TABLE,numlines-1,8
*TREAD,eltab,eldata,dat
! Move data to numerical Array
*DEL,elarr,,NOPR
*DIM,elarr,ARRAY,numlines,9
! Shift down and right
*DO,j,0,8,1
  *vfun,elarr(1,j+1),copy,eltab(0,j)
*ENDDO
```





Quench Simulation

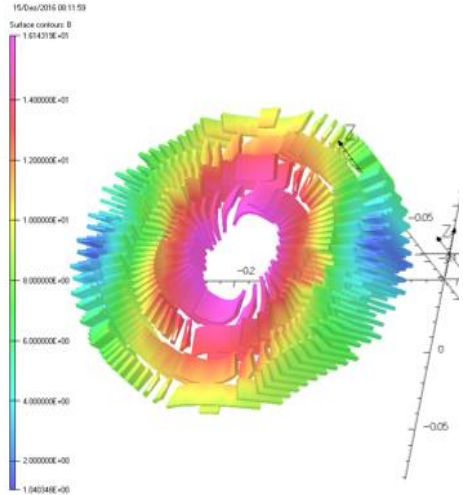
- Model I : Helical Propagation
  - Determination of propagation velocity per layer and per excitation level.
  - Quantification of detection problem.
  - CD1 Layer1 3-turn model results, working at I_{ss} = 20kA, IC : T = 20K for 1st turn

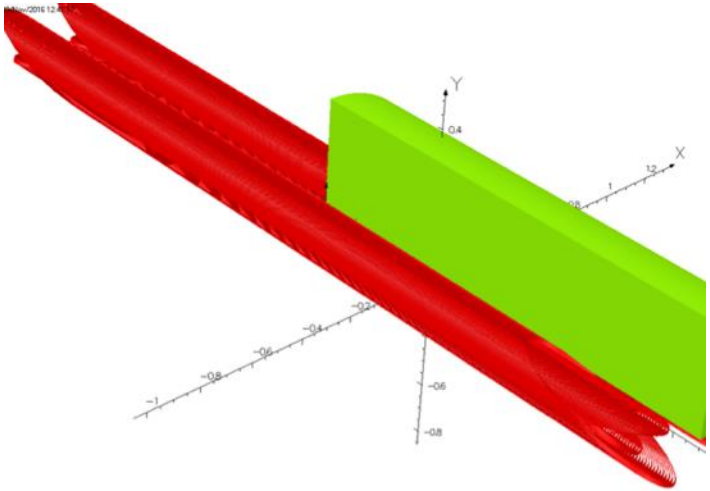


3-D Magnetic Design

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.

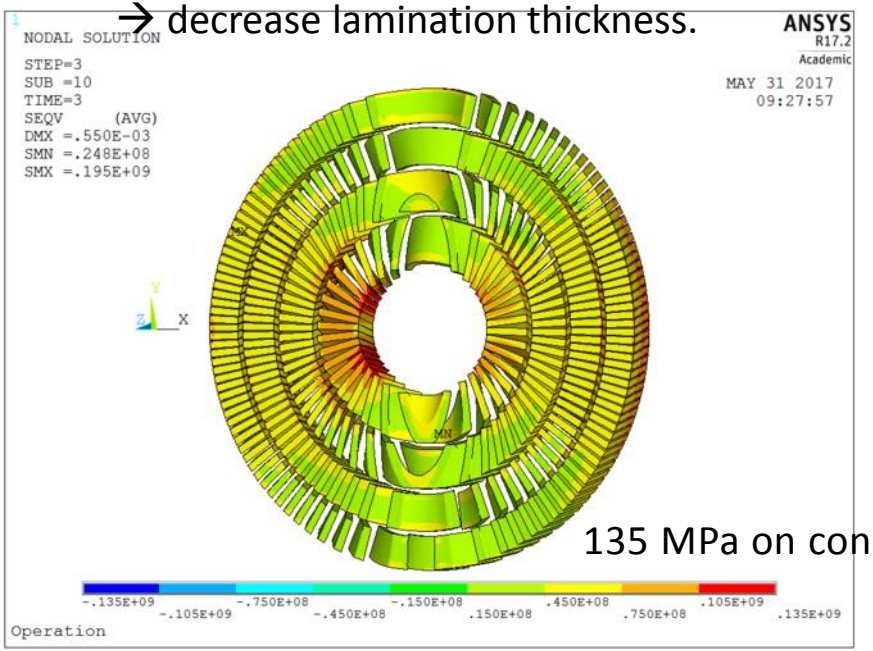




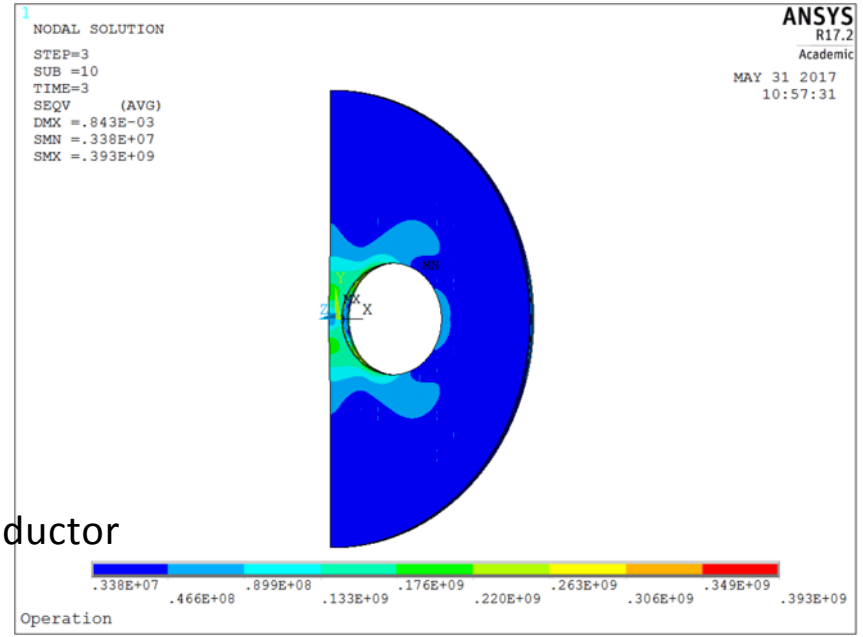
Courtesy M. Negrazus

3-D Periodic Simulation

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

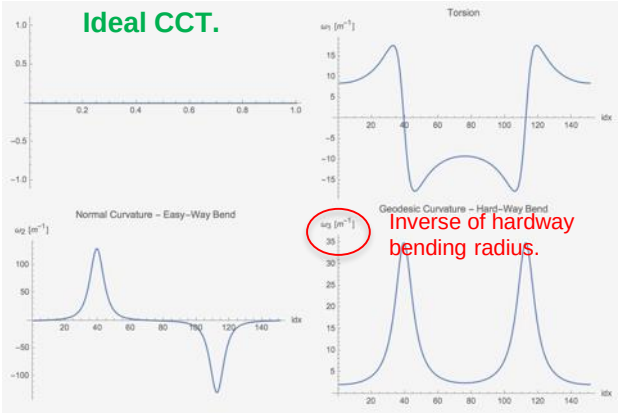


135 MPa on conductor

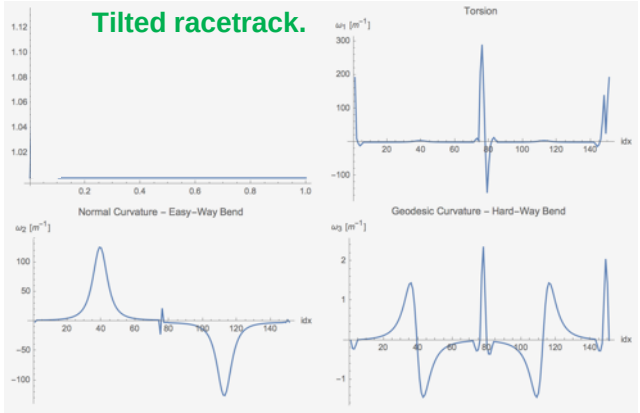


Curvature parameters

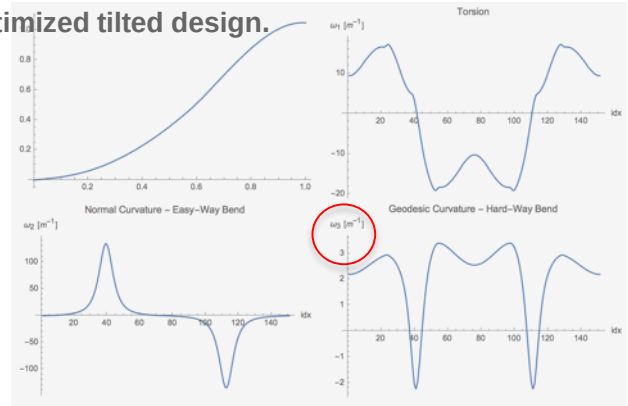
Ideal CCT.



Tilted racetrack.



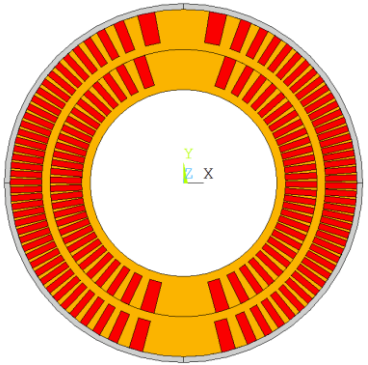
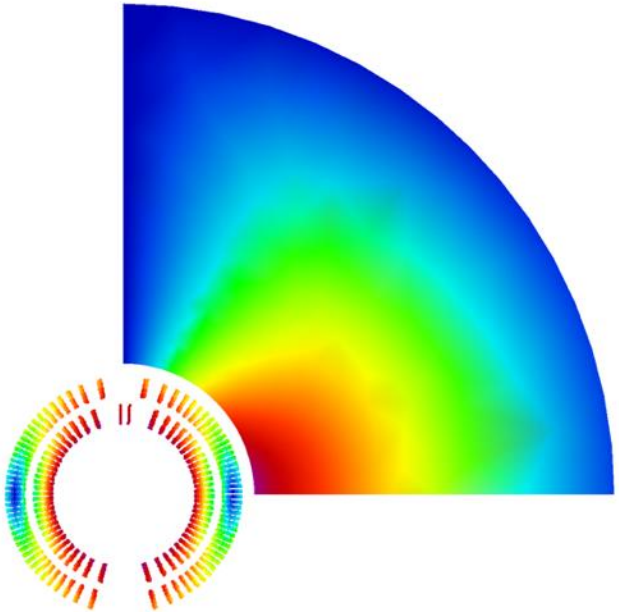
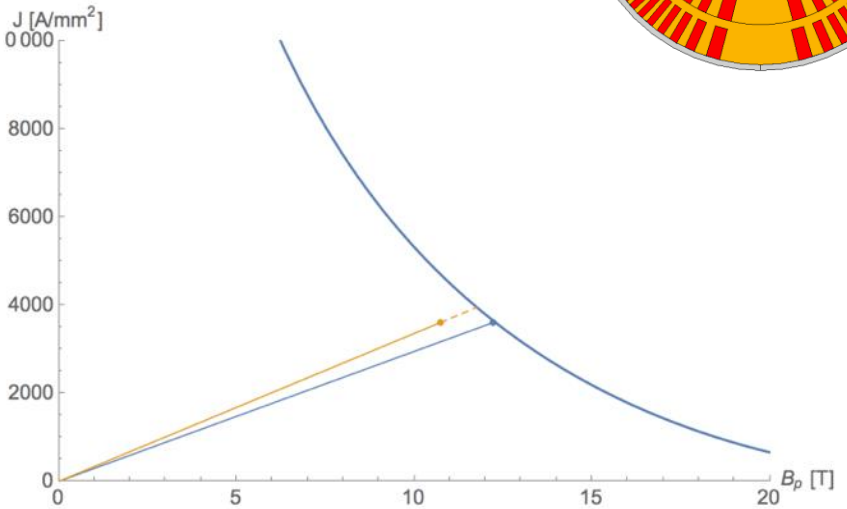
Optimized tilted design.



Slightly reduced torsion.

10-fold reduced hard-way bend.

Unchanged easy-way bend.

CD1 Magnetic Design

- I_{SS} = 20 kA at 1.9 K (~12 T bore field).
- For steel pad we would reach short sample at 4.2 K and 11 T.