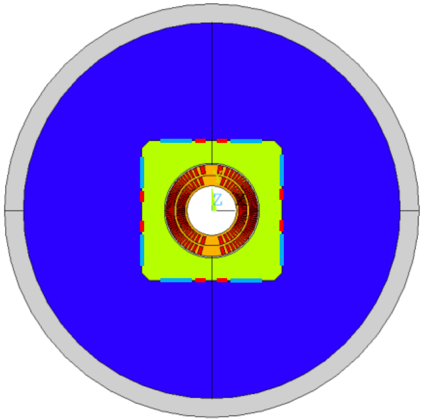
B. Auchmann (CERN/PSI), R. Felder (PSI), J. Gao (PSI), G. Montenero (PSI)
G. Rolando (CERN), S. Sanfilippo (PSI), S. Sidorov (PSI)

Technological Challenges, R&D Topics, and Infrastructure Plans

26.06.2017, CD1 Conceptual Design Review

Overview

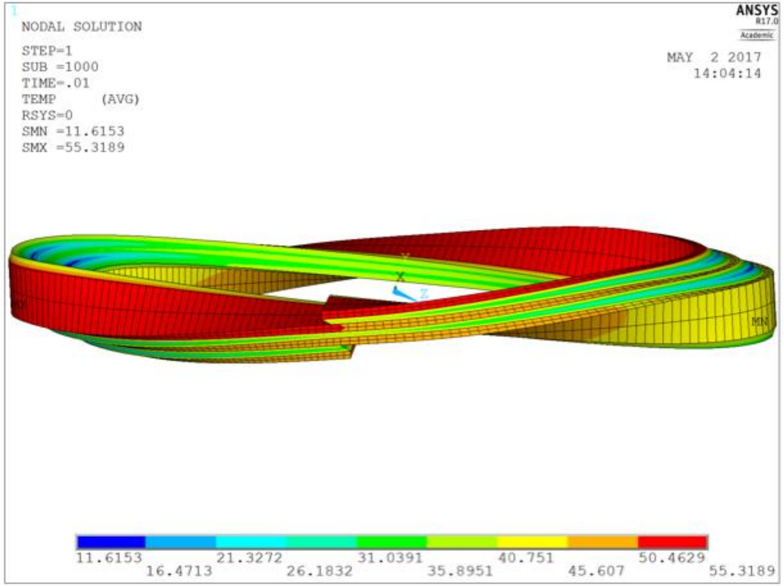
- Test and R&D Topics
  - Quench Protection
  - Smart Insulation
  - Former Manufacturing
  - Former-Material Characterization
  - Winding and Reaction Tests
  - Instrumentation and Soldering Trials
  - Impregnation Tests
  - Structure Assembly
- Infrastructure Plans

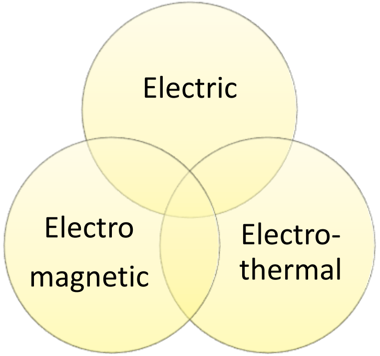


Quench Simulation

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

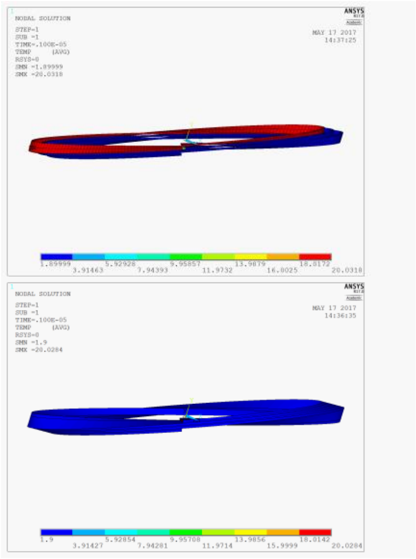
```
! Open the output file:
/DELETE,centroids,dat
*CFOPEN,centroids,dat
*VWRITE,elnb
(F6.0)
! LOOPING OVER ELEMENTS
*DO,q,emin,emax,1
  ! Obtain the centroid location:
  xc = CENTRX(enum)
  yc = CENTRY(enum)
  zc = MOD(CENTRZ(enum)+100*pitch,pitch)+pitch/2
  ! Write the data to the file:
  *VWRITE,xc,',',yc,',',zc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

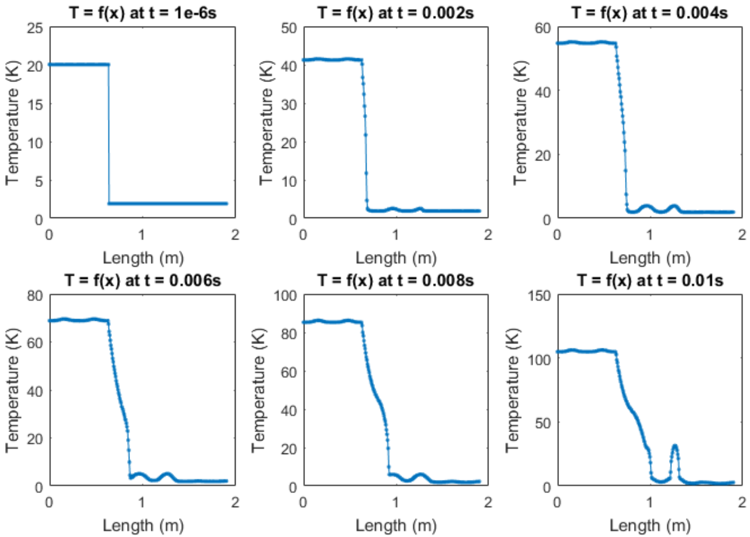




Quench Simulation

- 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 1^{st} turn

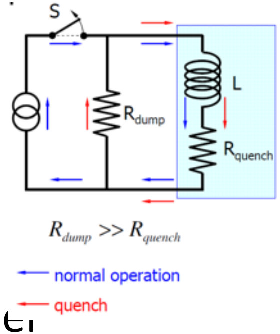




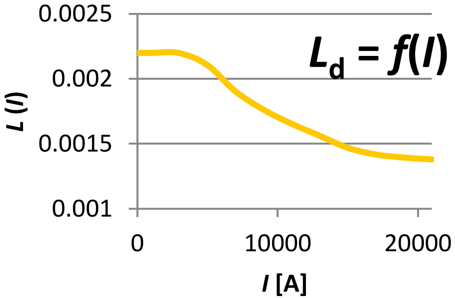
CD1 Quench Protection

- The energy is extracted from the magnet and dissipated in a dump resistor.
- To get an idea of time margin :
  – MIITs calculation gives the limit :

$$\mathrm{MIITs} = 10^{-6}\left[I_{\mathrm{op}}^{2}(\Delta t_{\mathrm{det}} + \Delta t_{\mathrm{valid}} + \Delta t_{\mathrm{switch}}) + \int_{t_{\mathrm{d}}}^{\infty} I(t)^{2}\mathrm{d}t\right]$$



  – Current decay : $\Delta I = -\Delta t \frac{R_{\mathrm{dump}}}{L_{\mathrm{d}}(I)} I_{\mathrm{op}}$ → $L_{\mathrm{d}}(\mathrm{I})$ extracted from 2D model validated with 3D model.
  – To ensure $\mathrm{T_{max}} < 300\ \mathrm{K}$ → $\mathrm{MIITs} < 9.22$ (cf. Excel Sheet):



At working point T = 4.2 K,
when I_{op} = 18 kA, $\Delta t_{det} + \Delta t_{valid} + \Delta t_{switch} < 28.5\ ms$
when I_{op} = 15.48 kA, $\Delta t_{det} + \Delta t_{valid} + \Delta t_{switch} < 38.5\ ms$
when I_{op} = 12 kA, $\Delta t_{det} + \Delta t_{valid} + \Delta t_{switch} < 64\ ms$

CD1 Quench Protection

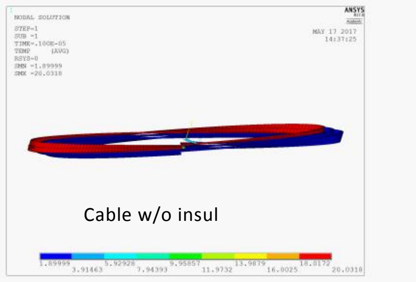
Due to the detection noise (flux jumps) of Nb_3Sn, a higher voltage threshold shall be used in case of quench → No need $\Delta t_{\mathrm{valid}}$

Suppose $\Delta t_{\mathrm{switch}} \approx 2$ ms, then according to MIITs

When I_{op} = 18 kA, $\Delta t_{\mathrm{det}} < 26.5$ ms

When I_{op} = 15.48 kA, $\Delta t_{\mathrm{det}} < 36.5$ ms

When I_{op} = 12 kA, $\Delta t_{\mathrm{det}} < 62$ ms

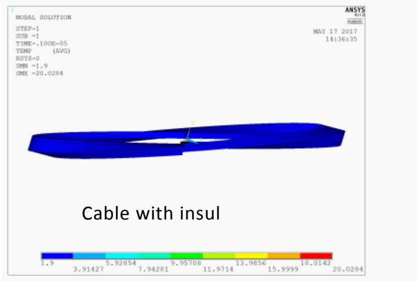


– MAPDL simulation predicts, for a voltage threshold ~ 500 mV :

When I_{op} = 18 kA, $\Delta t_{\mathrm{det}} \approx 3.8$ ms

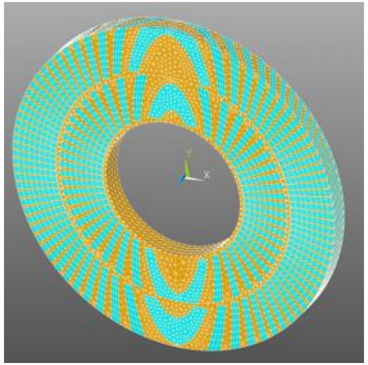
When I_{op} = 15.48 kA, $\Delta t_{\mathrm{det}} \approx 12$ ms

When I_{op} = 12 kA, $\Delta t_{\mathrm{det}} \approx 26.9$ ms

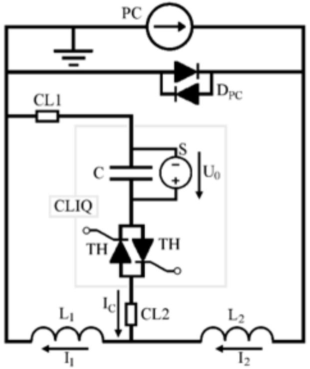


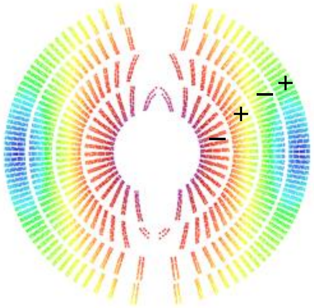
→ Good time margin → Protectable Magnet

MAPDL Quench Simulation with LBNL



- Next Simulation Goals:
  - Generation of slice model with continuous mesh for electro-thermal simulation.
  - With L. Brouwer (LBNL), creation of user-defined electrodynamic and thermal elements for cable-eddy current simulation and quench simulation, respectively.
  - Simulation of a CLIQ discharge in CD1 slice prior to its test.
  - Eventually, full CD1 quench simulation on cluster.

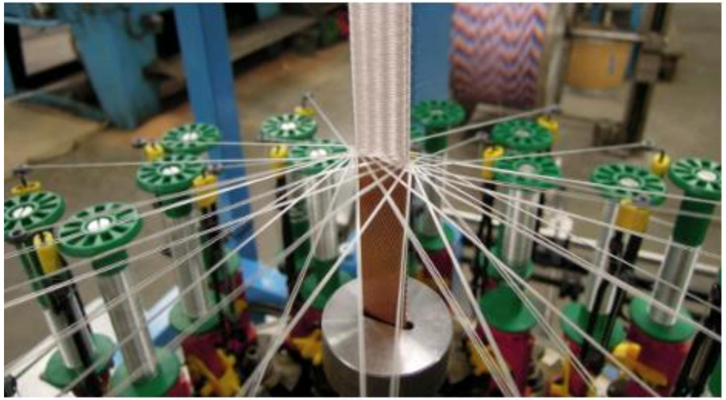


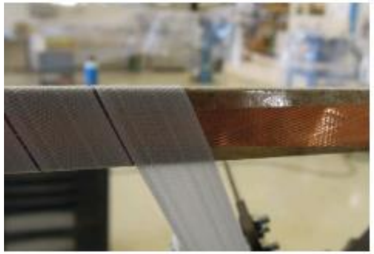


Courtesy: E. Ravaioli

Insulation

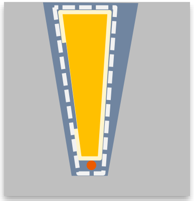
- Baseline: Copy-paste from 11-T insulation.
  - Mechanical reinforcement of frail cable edges via mica.
  - No particular worries about strain-enhancement due to open mica C due to CCT stress management.
  - In contact with Jacky Mazet to coordinate requests and develop tooling for mica and co-wound wire (see next slide).
- Alternative: closed mica wrap (all 4 sides with overlap)
  - Use sleeve and do impregnation tests.





Smart Insulation

- Goal: Accelerate quench detection in CCT HFMs.
  1. Baseline: Co-wound copper wire for inductive compensation (see Feather 2, G. Kirby et al.).
  2. Co-wound copper wire terminated with diodes for inductive compensation and passive quench-back heater (see HL-LHC D2 corrector, G. Kirby et al.).
  3. Co-wound SC wire with series resistance shorting SC cable; apply stationary bias current (~1 A) for thermal quench detection (sudden current drop; see G. Montenero idea for HL-LHC SC link protection).
  4. Co-wound Rayleigh-scattering Interrogated Optical Fiber.
- Work with Jacky and firm to include wire in between mica and S2 braid.



Manufacturing Trials

- Ongoing at Swiss (CuAl7Si2) and Dutch (CuAl10Fe5Ni5) companies.
- Baseline is CuAl7Si2 to avoid magnetic-field distortion.
- 5 turns per layer.
- CD1 IL and OL, followed by CD2 IL.

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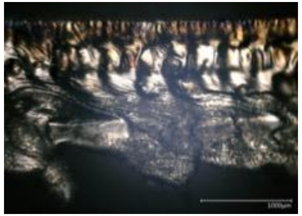
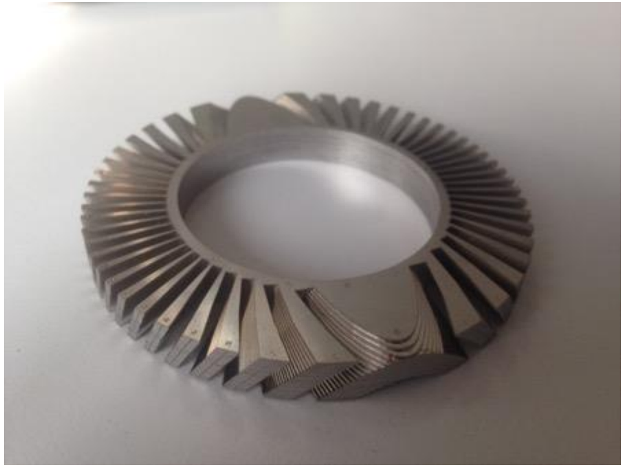
Manufacturability and Cost

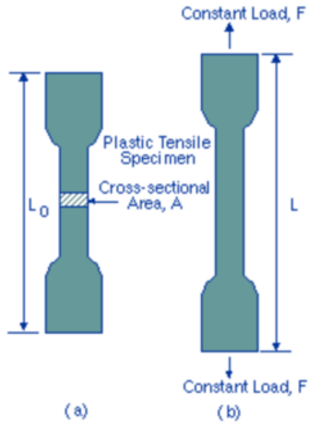
- **Collaboration with IWS Fraunhofer** on fabrication of **thin-lamination formers**.
  - Laser weld-cutting.
  - Goal: improve scalability and cost.
- If proof-of-concept successful, we plan to apply for D/A/CH funding to develop a mature manufacturing technology.
- Potentially interesting for manufacturing of curved CCT formers.





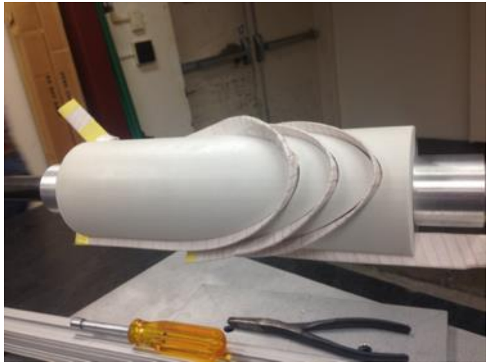
Al-Bronze Characterization

- Determine Al-bronze tensile strength post reaction at room temperature and in cryogenic conditions.
- Manufacture normed sample and ask CERN EN/MME for characterization (PSI team account).



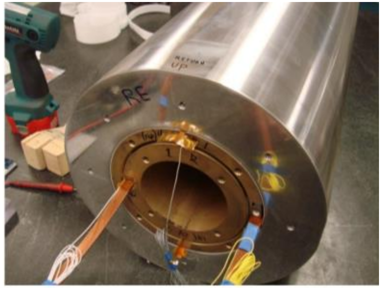
Winding and Reaction Tests

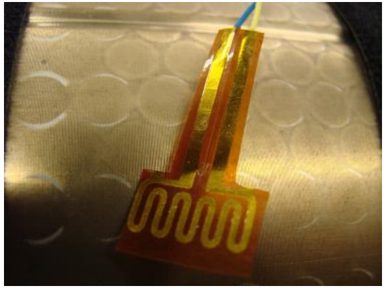
- CD1 winding test with metal and 3-D printed test formers.
- CD2 winding test with metal test former and FNAL-supplied copper cable.
- CD1 test reaction with 5-turn Al-bronze test former. Determine cable elongation and verify channel dimensions. Validate clamping technique (below: copper wires and hose clamps).

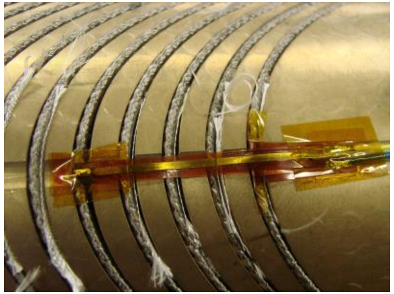


Instrumentation and Soldering Trials

- Learn from CERN and PSI:
  - Nb3Sn/Nb-Ti splices.
  - Nb-Ti/Nb-Ti joints.
  - PCB wiring.
  - Voltage taps.







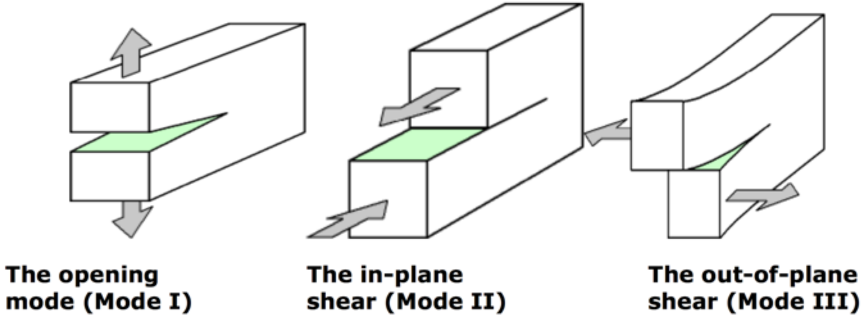
Impregnation Trials

- CD1 test impregnations with 3D printed formers (probably Duraform, following advice by Remy and Sebastien).
  - Set up impregnation process.
  - First trials, vacuum-bag impregnation of single layer.
  - Compare CTD 101K with NHMFL61.
  - Sleeve insulation with mica C and mica wrap.
  - Cut up samples to observe filling quality.

D. Markiewicz (NHMFL): "I cannot say strongly enough how different the NHMFL epoxies are from CTD101 in fracture toughness."

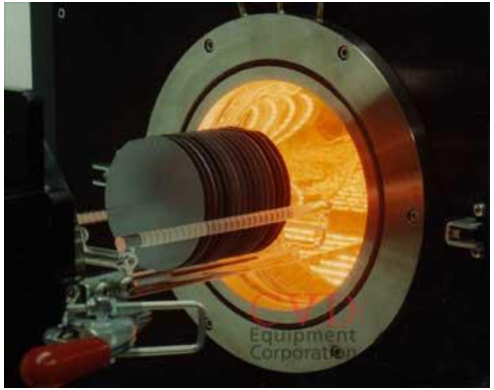
Metal-Resin Adhesion

- R&D on improved metal-resin bonding strength.
- Determine effective primary to improve metal-resin adhesion.
- Test different metal surface conditions (sandblasting, vs. polishing).



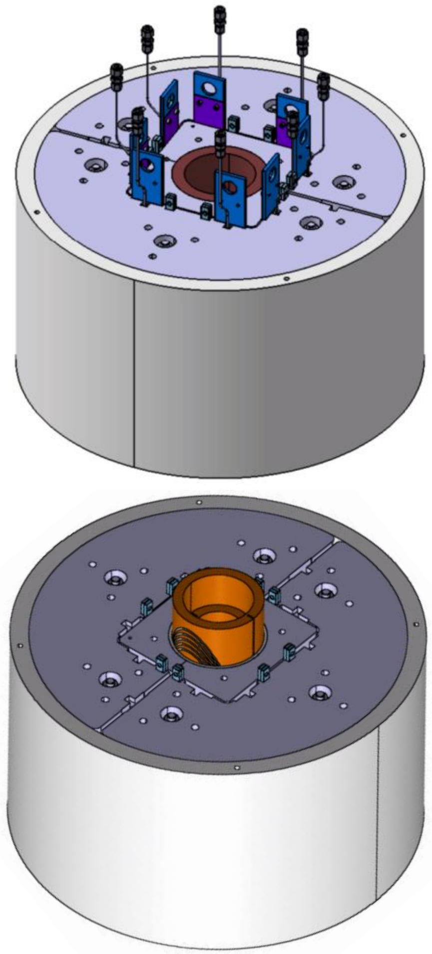
Former Coating

- Discuss SiOx chemical vapor deposition coating for enhanced and reaction-hard former insulation.
- Contact experts at PSI and ETHZ.
- Study consequences for resin adhesion.



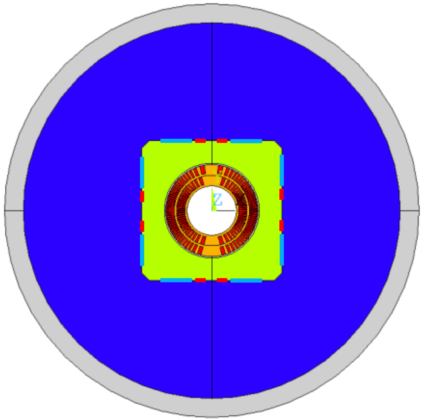
Short Mechanical Model

- Mechanical model with dummy coil:
  - Set up mechanical measurement system.
  - Equip short model with dummy coil with strain gauges.
  - Validate structure vs. ANSYS model.
- Mechanical model with assembled 5-layer test formers:
  - Impregnate 5-layer test formers.
  - Load them in, both, vertical and horizontal position in the mechanical model.
  - Study cracking, delamination, etc.

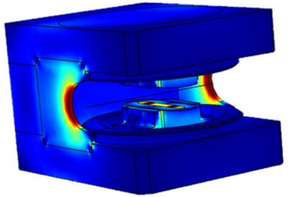


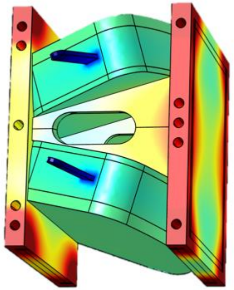
Overview

- Test and R&D Topics
- Infrastructure Plans
  - Mechanical Measurements
  - Impregnation System
  - Reaction Furnace



Preface





- PSI is currently involved in four different project involving Nb3Sn technology:
  - FCC Design Study CD1/2.
  - SLS 2.0 SuperBend magnet (Nb3Sn racetrack).
  - Superconducting gantry (tilted racetracks, with industry).
  - Racetracks for magnetization of bulk-HTS SC undulators.
- SC magnets for light sources and proton therapy are of strategic long-term interest for PSI.
- The FCC Design Study also serves to build up competence as well as infrastructure at PSI.
- This investment, in turn, can help HFM R&D for FCC.

Mechanical Measurements

- Invest in 16-channel HBM measurement system (same as CERN and LBNL)
- Strain gauges
- LVDTs
- Temperature sensors
- Quote received, ready to launch procurement.

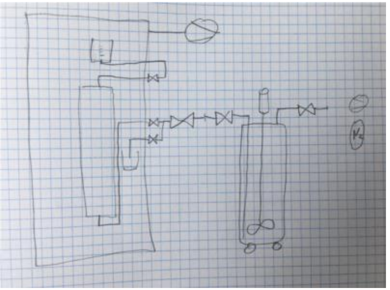
Impregnation System

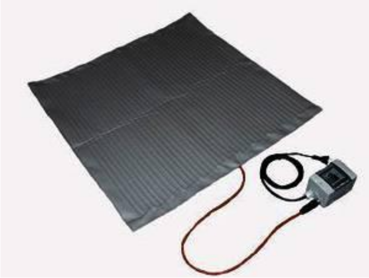
- Baseline:
  - Build mixer pot.
  - Heating plate with magnetic mixer.
- Alternative:
  - buy mixer with impeller and heating mats.
- Perform first trials directly in PSI heating chamber.

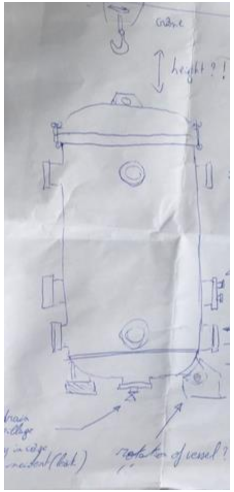
Skype consulting with Jim Swanson (LBNL).

Impregnation System

- In preparation of CD1 coil manufacturing, buy heaters and heat-regulation system.
- Procure a vacuum vessel (initial market survey completed).
- Procure vacuum system from PSI Vacuum group.





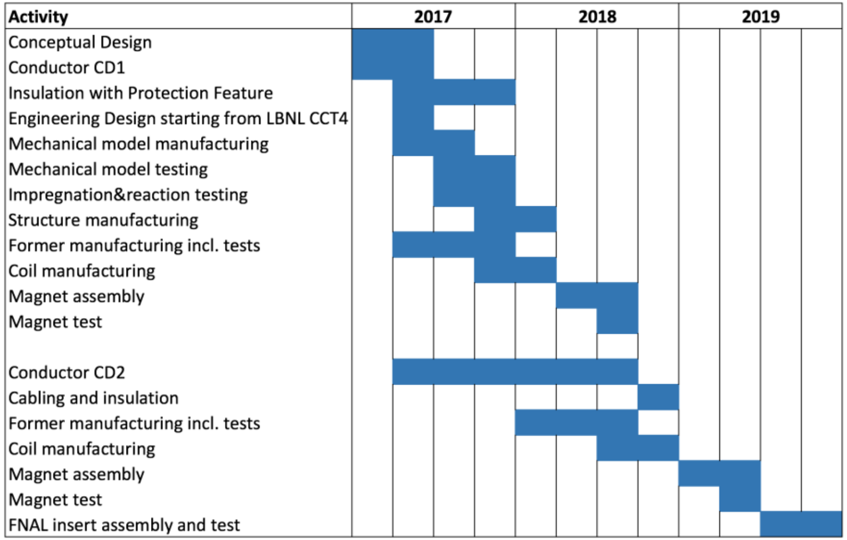


Reaction Furnace

- Invest in reaction furnace of adequate size for all foreseeable (next 4-5 years) projects.
- Operational volume: 250x250x1200 mm.
- Fulfilling slightly adjusted specs from CERN reaction furnaces (latest CERN spec dates from 2014).
- Initial market survey completed.

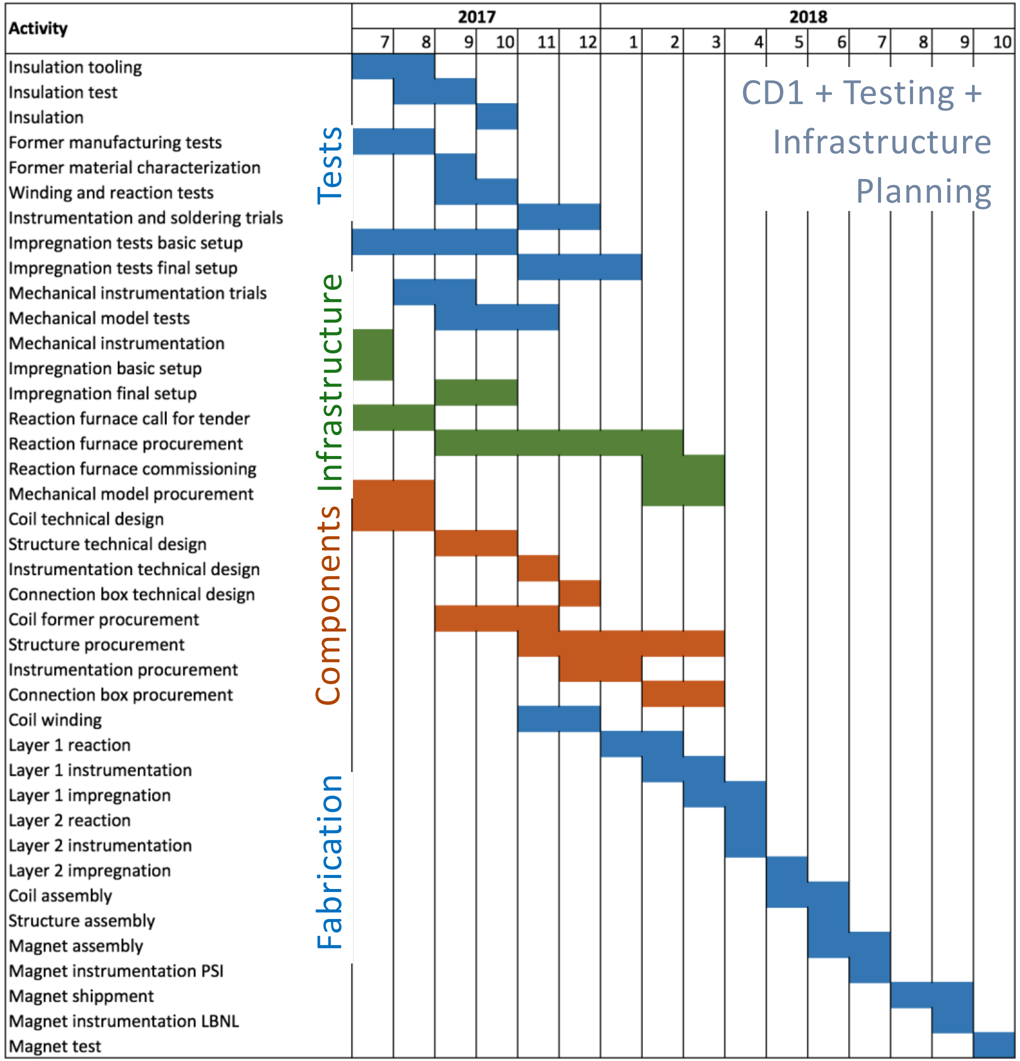
Planning

General Planning



Team:

- Bernhard (cable, furnace procurement)
- Jiani (quench simulation and quench instrumentation)
- Giuseppe (FEA, mech. instrumentation, impregnation)
- Marco (3D EM FEA)
- Roland (instrumentation, impregnation, assembly)
- Serguei (tech. design, procurement, QA)



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Discussion

- Every step in the project is new for PSI and requires external support, training and testing.
- The schedule is packed and we need to defend PSI resources (Serguei and Roland) against competing PSI projects.
- PSI has approved funds to invest in infrastructure, pending the opinion of the review committee.
- Planning uncertainties/risks:
  - Reaction infrastructure may arrive late for the first CD1 layer(s), in which case we would seek support to react at CERN.
  - Coil fabrication schedule could change if both layers are impregnated together and/or coils are reacted at CERN.
  - CD2 component procurement must start before CD1 test results arrive.
- Additional info:
  - CD1 magnet testing will occur at LBNL (contrary to previous baseline which foresaw testing at CERN).