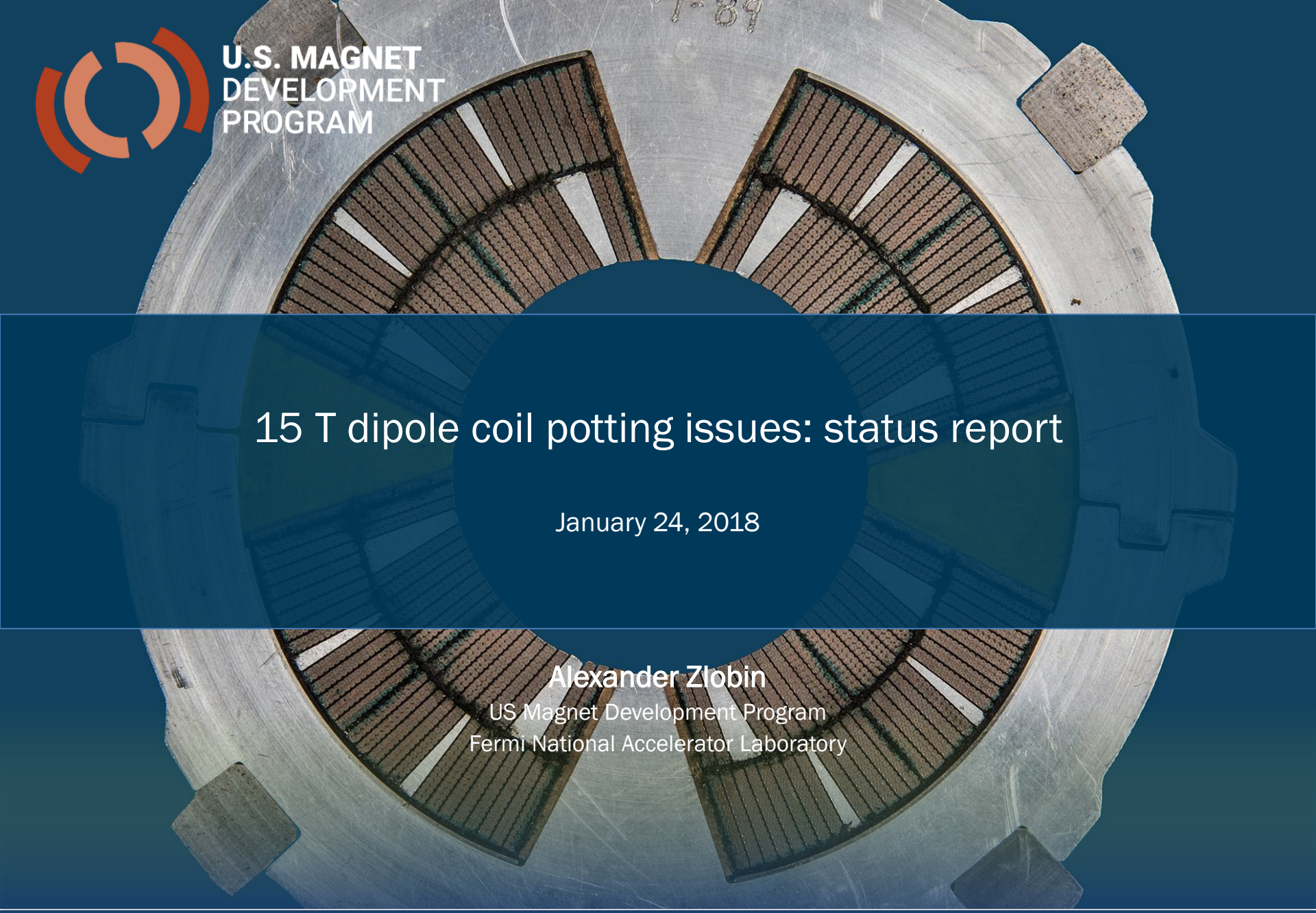


U.S. MAGNET DEVELOPMENT PROGRAM

15 T dipole coil potting issues: status report

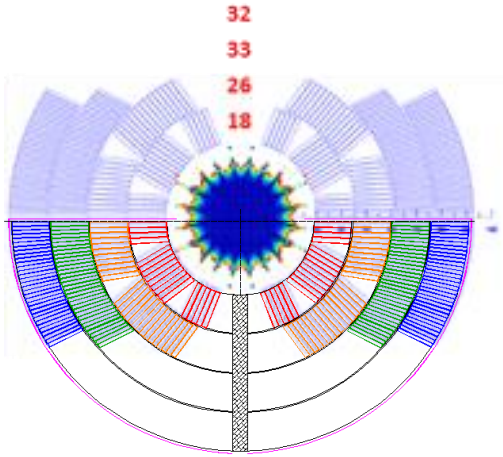
January 24, 2018

Alexander Zlobin
US Magnet Development Program
Fermi National Accelerator Laboratory

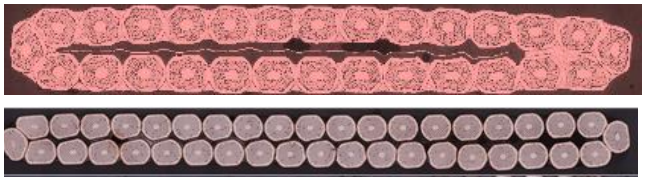
U.S. DEPARTMENT OF ENERGY | Office of Science

MDP High Field Dipole Demonstrator Design

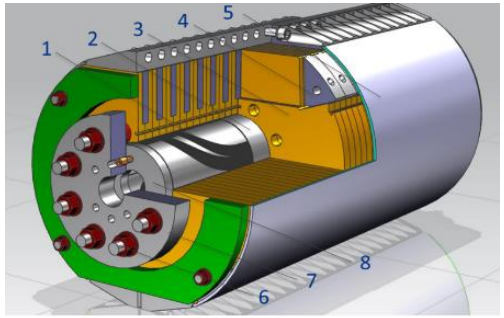
- Coil:
  - 60-mm aperture
  - 4-layer graded coil
  - W_{sc} = 68 kg/m/aperture

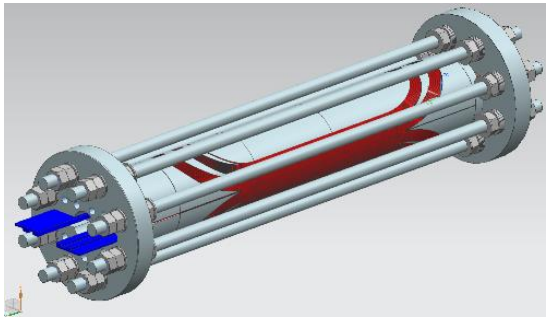


- Cable:
  - L1-L2: 28 strands, 1 mm RRP150/169
  - L3-L4: 40 strands, 0.7 mm RRP108/127
  - SS core
  - Insulation: E-glass tape



- Mechanical structure:
  - Thin StSt coil-yoke spacer
  - Vertically split iron laminations
  - Aluminum I-clamps
  - 12-mm thick StSt skin
  - Thick end plates and StSt rods
  - Cold mass OD<610 mm

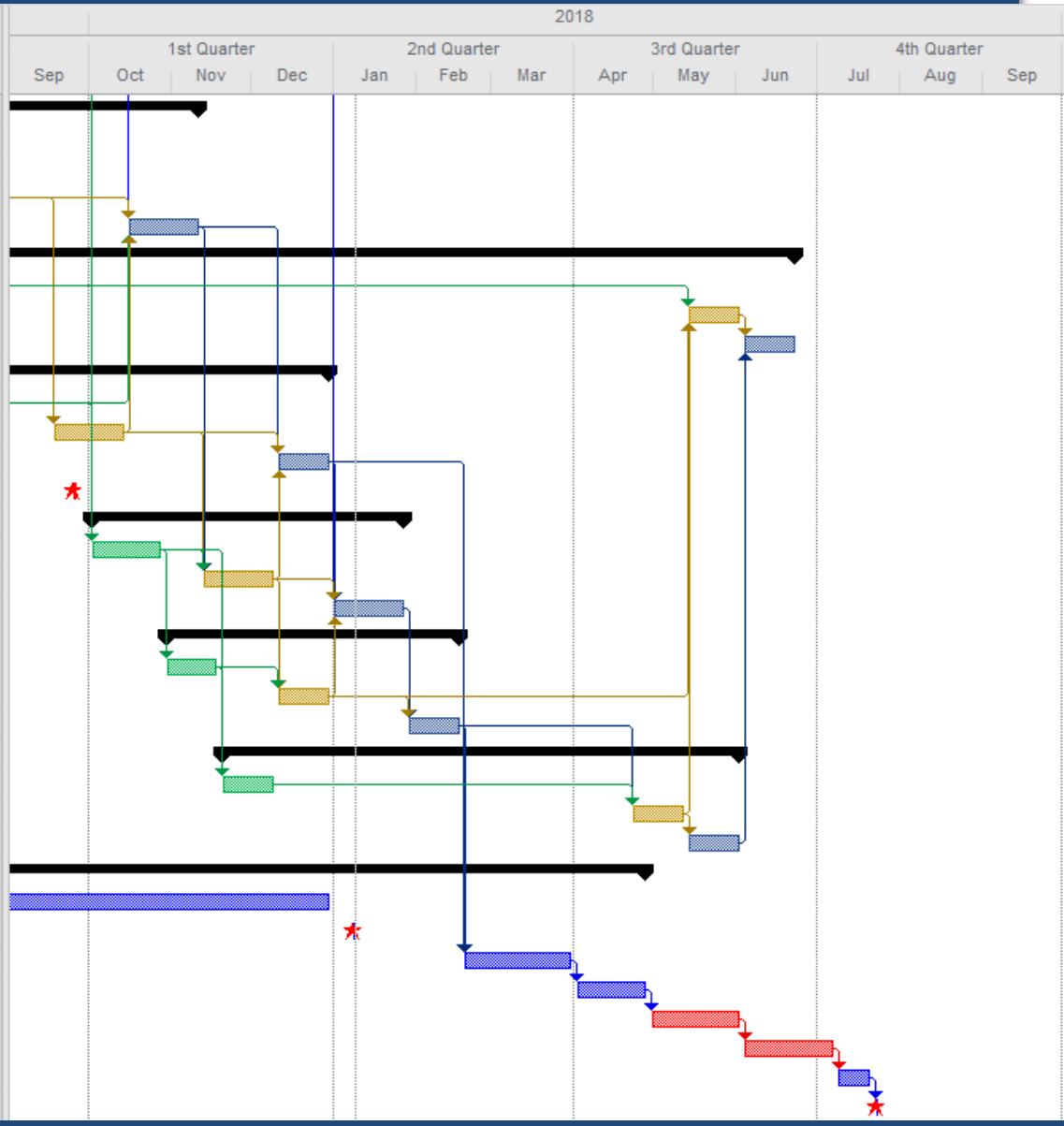




- Magnet SSL estimated based on the cable test data:
  - 11.05 kA (Bap=15.3 T) at 4.5 K
  - 12.2 kA (Bap=16.7 T) at 1.9 K.

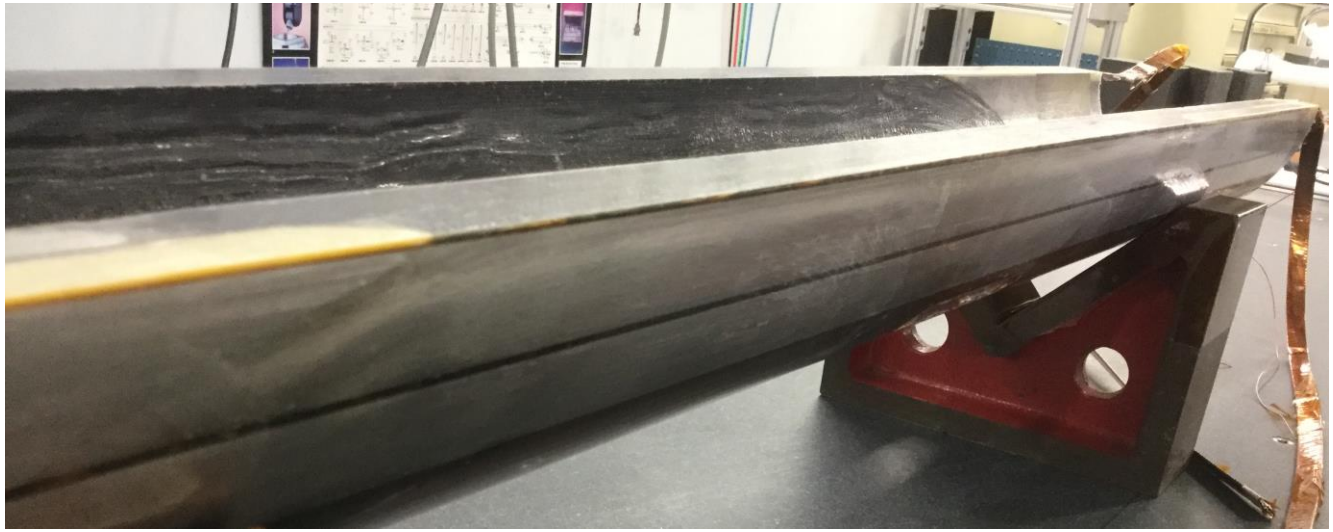
Original FY2018 plan

Task Name	Duration	Start	Finish
OL coil #1	**250 days**	**Mon 11/28/16**	**Fri 11/10/17**
winding/curing	17 wks	Mon 11/28/16	Fri 3/24/17
winding/curing	4 wks	Mon 3/27/17	Fri 4/21/17
reaction	4 wks	Mon 5/22/17	Fri 6/16/17
impregnation/instrumentation	4 wks	Mon 10/16/17	Fri 11/10/17
OL coil #2	**305 days**	**Mon 4/24/17**	**Fri 6/22/18**
winding/curing	4 wks	Mon 4/24/17	Fri 5/19/17
reaction	3 wks	Mon 5/14/18	Fri 6/1/18
impregnation/instrumentation	3 wks	Mon 6/4/18	Fri 6/22/18
OL coil #3	**135 days**	**Mon 6/26/17**	**Fri 12/29/17**
winding/curing	4 wks	Mon 6/26/17	Fri 7/21/17
reaction	4 wks	Mon 9/18/17	Fri 10/13/17
impregnation/instrumentation	3 wks	Mon 12/11/17	Fri 12/29/17
IL Coil production readiness review	1 day	Mon 9/25/17	Mon 9/25/17
IL coil #1	**85 days**	**Mon 10/2/17**	**Fri 1/26/18**
winding/curing	4 wks	Mon 10/2/17	Fri 10/27/17
reaction	4 wks	Mon 11/13/17	Fri 12/8/17
impregnation/instrumentation	4 wks	Mon 1/1/18	Fri 1/26/18
IL coil #2	**80 days**	**Mon 10/30/17**	**Fri 2/16/18**
winding/curing	3 wks	Mon 10/30/17	Fri 11/17/17
reaction	3 wks	Mon 12/11/17	Fri 12/29/17
impregnation/instrumentation	3 wks	Mon 1/29/18	Fri 2/16/18
IL coil #3	**140 days**	**Mon 11/20/17**	**Fri 6/1/18**
winding/curing	3 wks	Mon 11/20/17	Fri 12/8/17
reaction	3 wks	Mon 4/23/18	Fri 5/11/18
impregnation/instrumentation	3 wks	Mon 5/14/18	Fri 6/1/18
Demo #1 assembly and test	**205 days?**	**Mon 7/17/17**	**Fri 4/27/18**
mechanical model (baseline)	24 wks	Mon 7/17/17	Fri 12/29/17
readyness review	1 day?	Mon 1/8/18	Mon 1/8/18
assembly (IL-#1-2, OL-#1-2)	6 wks	Mon 2/19/18	Fri 3/30/18
test preparation	4 wks	Mon 4/2/18	Fri 4/27/18
model test TCI	5 wks	Mon 4/30/18	Fri 6/1/18
model test TCII	5 wks	Mon 6/4/18	Fri 7/6/18
test report	2 wks	Mon 7/9/18	Fri 7/20/18
15 T Dipole demonstrator #1 review	1 day	Mon 7/23/18	Mon 7/23/18

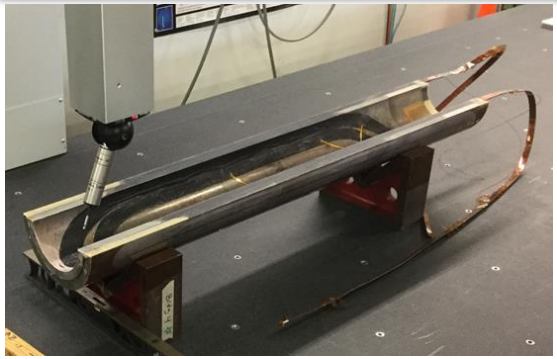


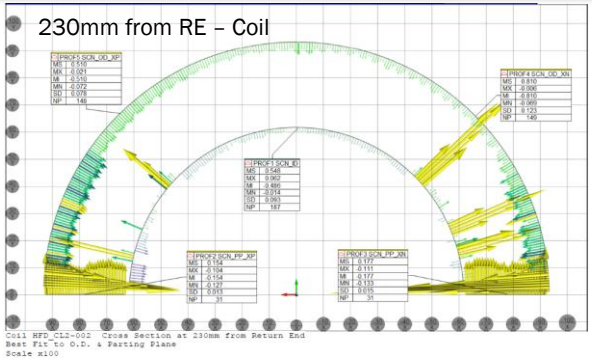
Introduction

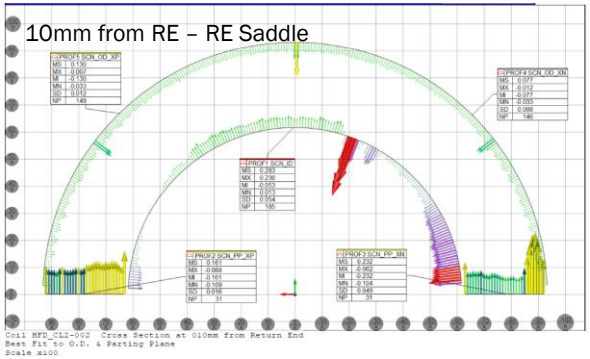
- Visual inspection of the 1st impregnated L3-L4 coil HFD-CL2-002 has revealed large dents on both sides of the coil outer surface and wrinkles on the coil inner surface
  - substantial degradation of the magnet quench performance
- The purpose of the coil review
  - to identify and correct possible effects related to the coil impregnation procedure
  - develop a plan to replace the lost coil with minimal impact on the program.

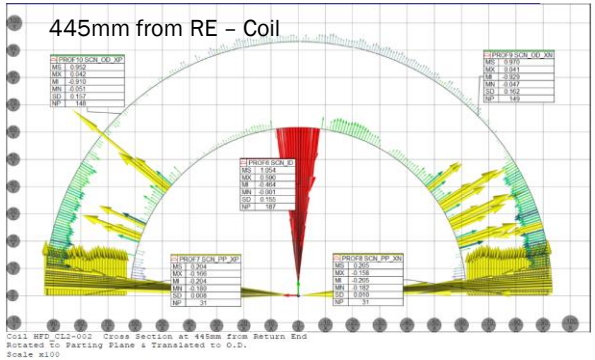


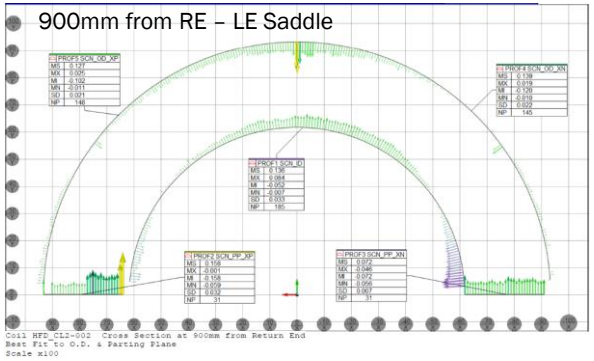
Coil size measurements

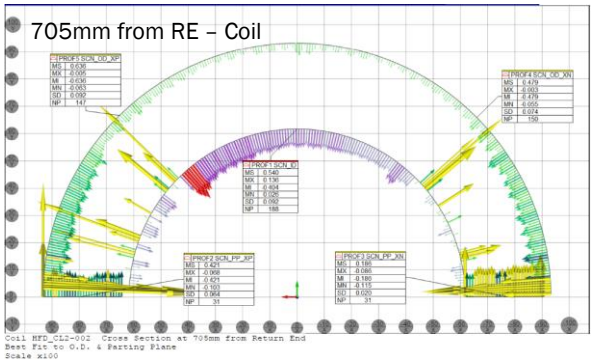


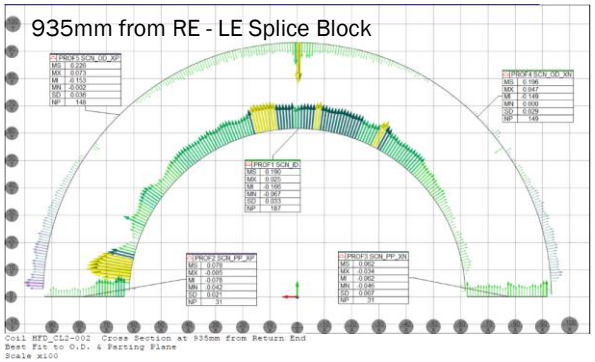






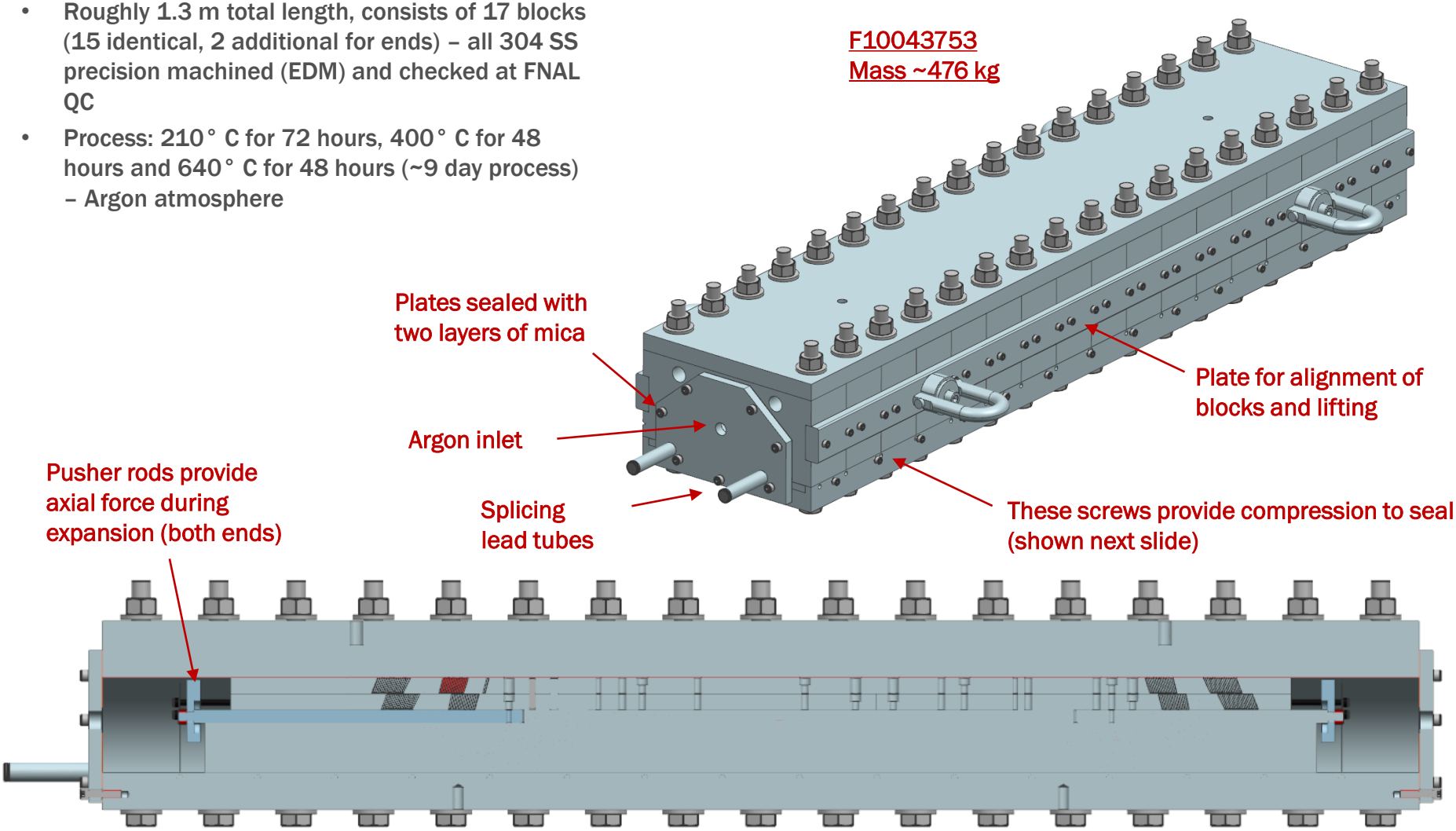






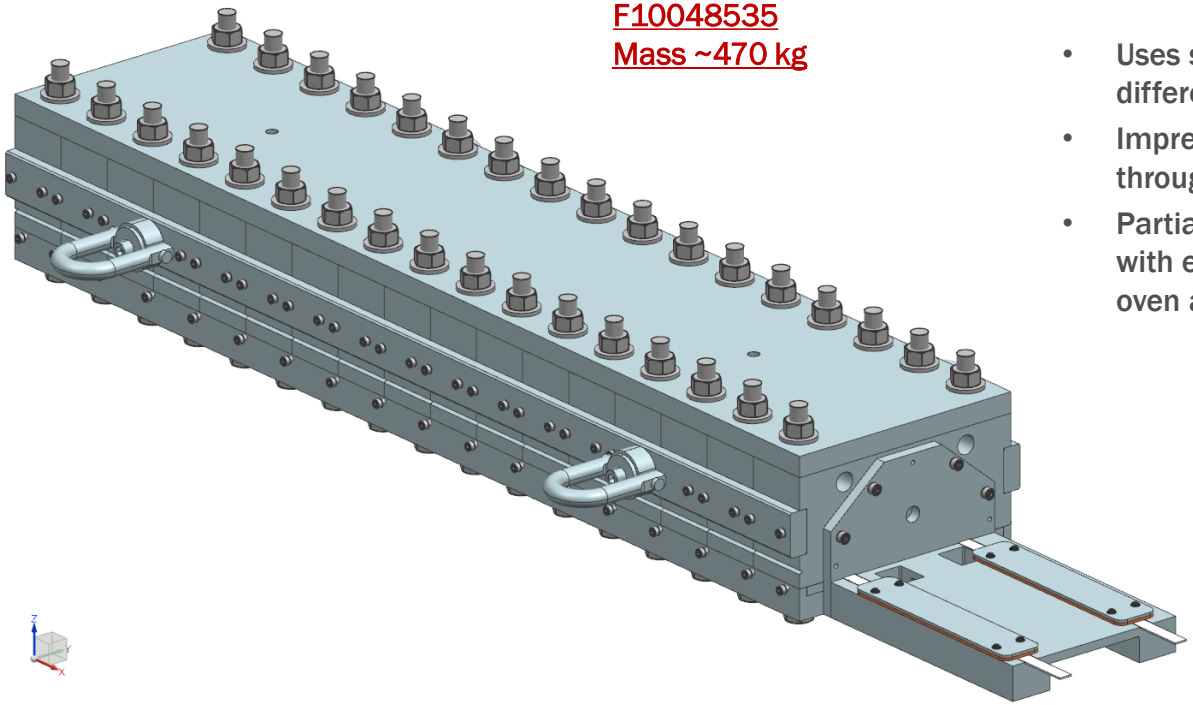
L3/L4 Reaction Tooling

- Roughly 1.3 m total length, consists of 17 blocks (15 identical, 2 additional for ends) – all 304 SS precision machined (EDM) and checked at FNAL QC
- Process: 210° C for 72 hours, 400° C for 48 hours and 640° C for 48 hours (~9 day process) – Argon atmosphere



L3/L4 Impregnation Tooling

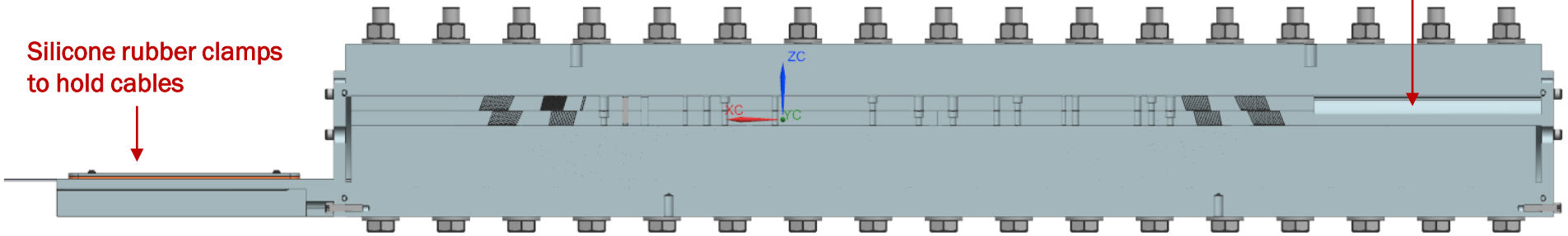
F10048535
Mass ~470 kg



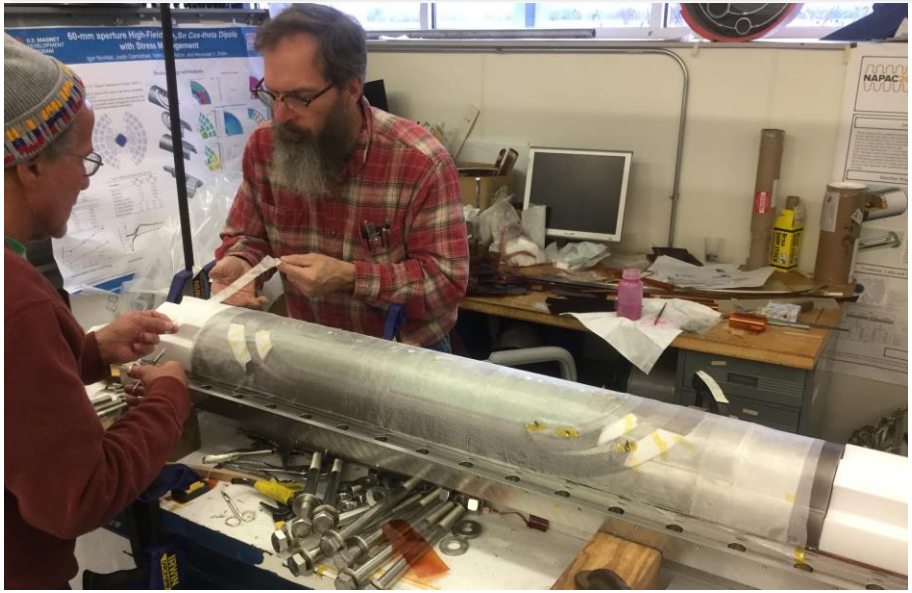
- Uses same tooling used for reaction, but with different insulation and sealing material
- Impregnation end plates allow leads to extend through plate, sealed using o-ring
- Partial vacuum pulled around assembly (in IB2) with epoxy temperature of 60 °C, cured in other oven at 125 °C for 21 hours

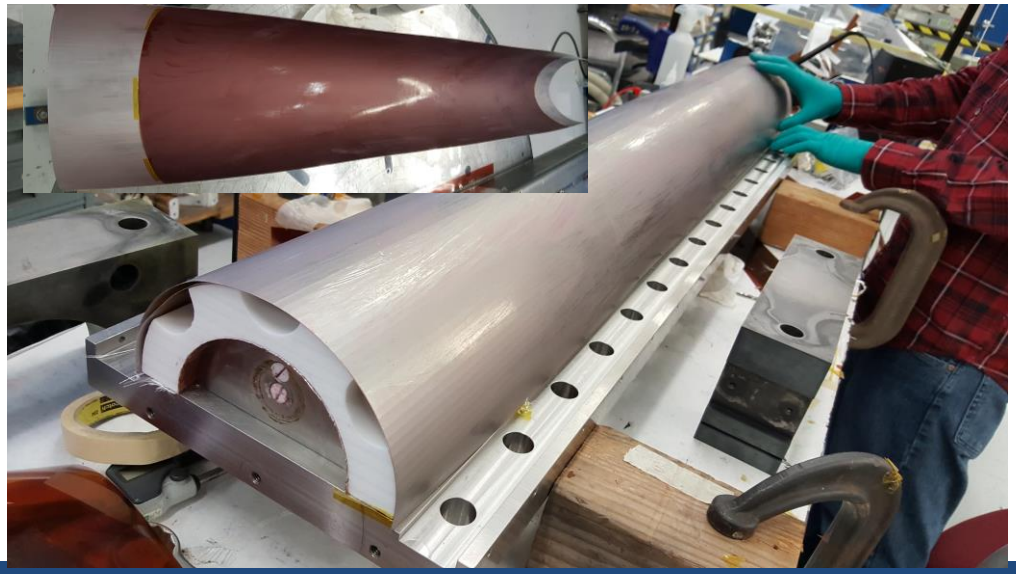
Teflon filler

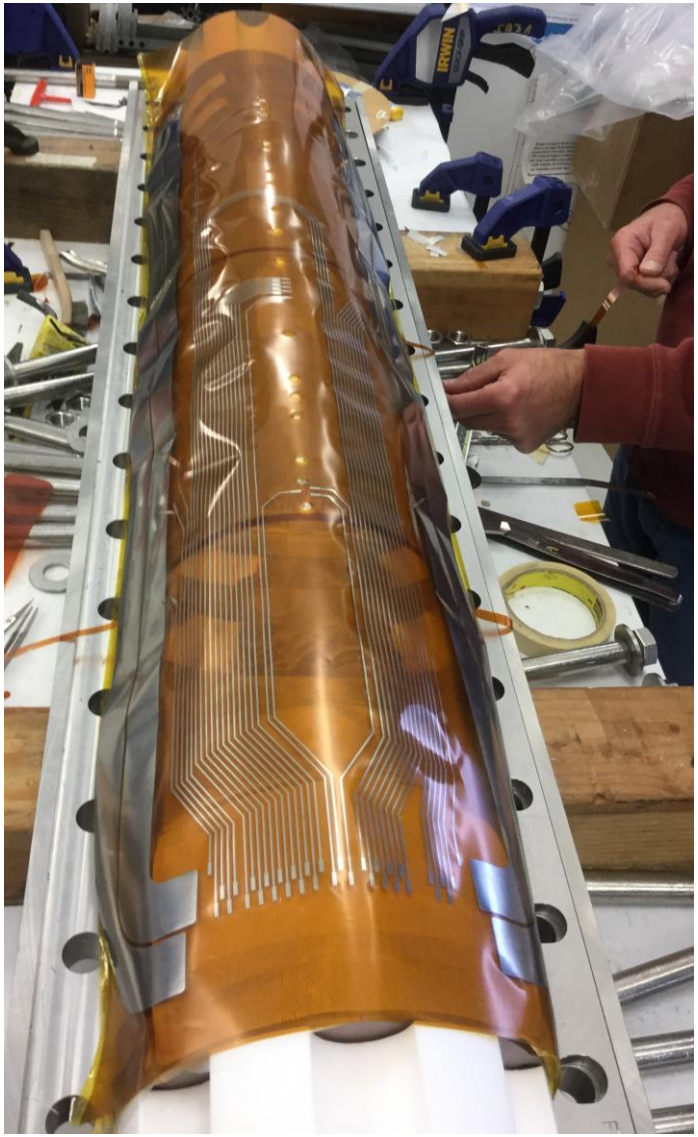
Silicone rubber clamps to hold cables



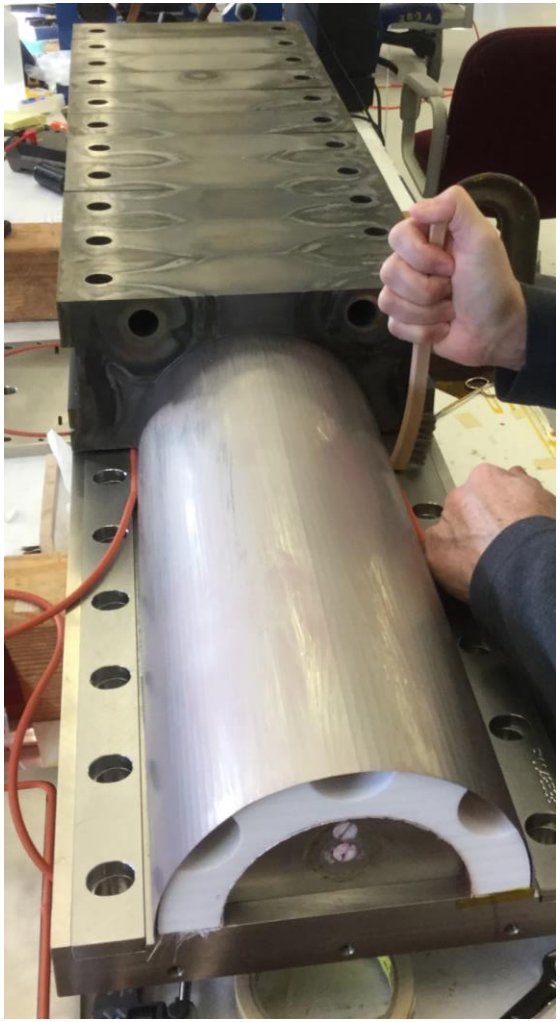
Preparation to impregnation

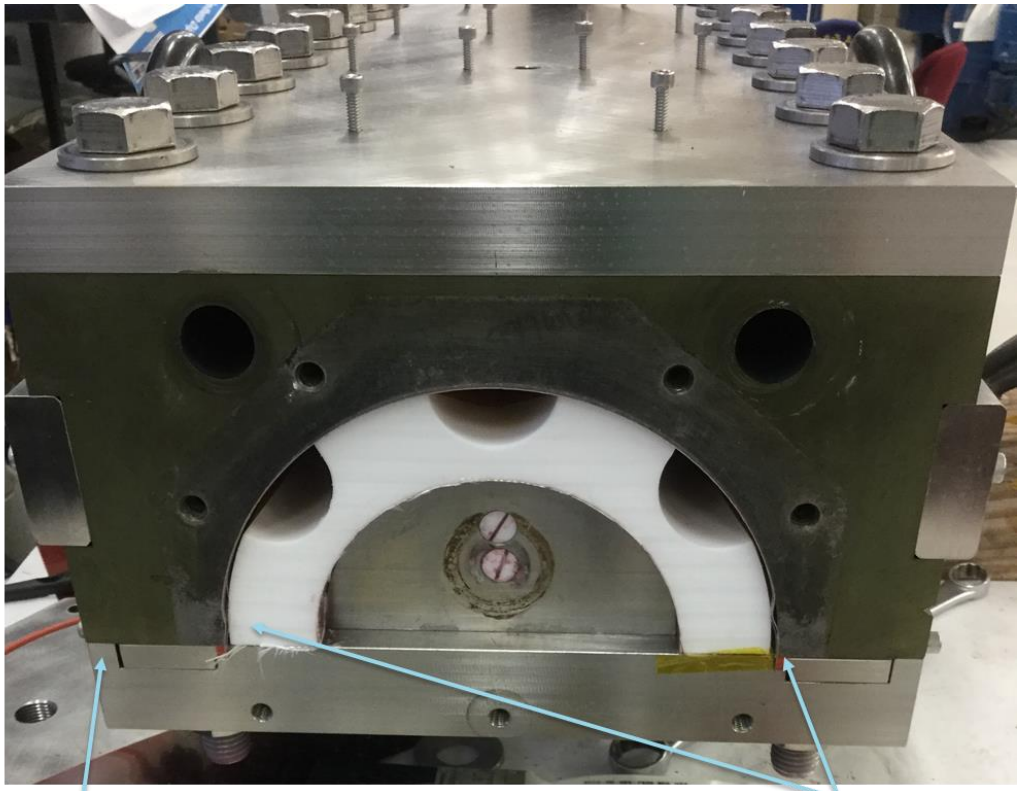






Impregnation tooling assembly





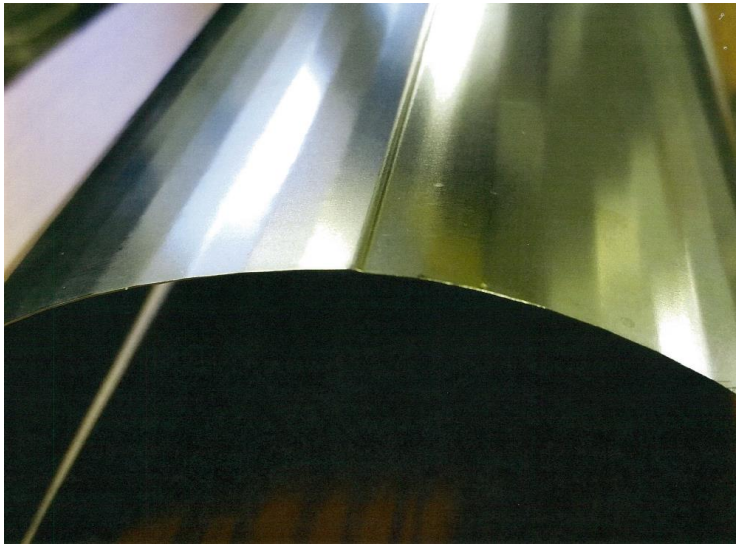
Started from 35mil SS Shims

Shell buckling

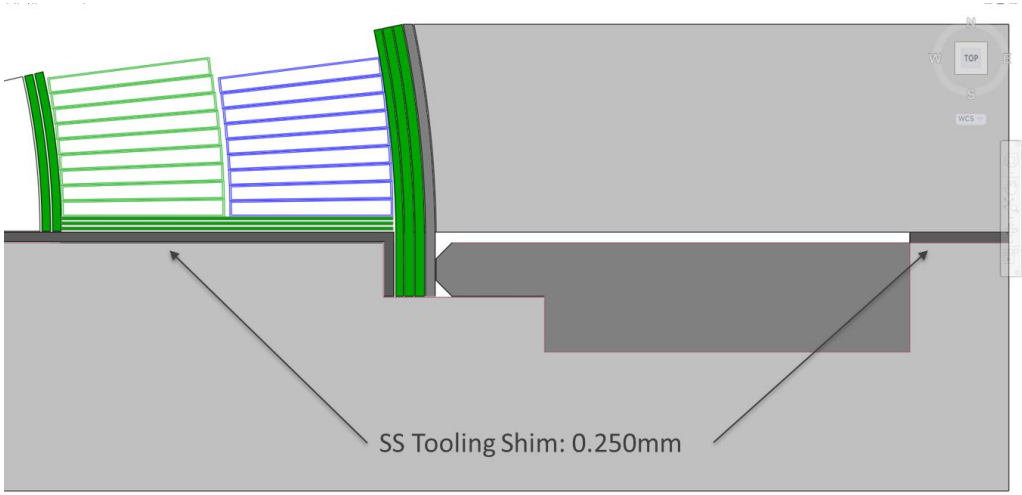
Buckling in shell

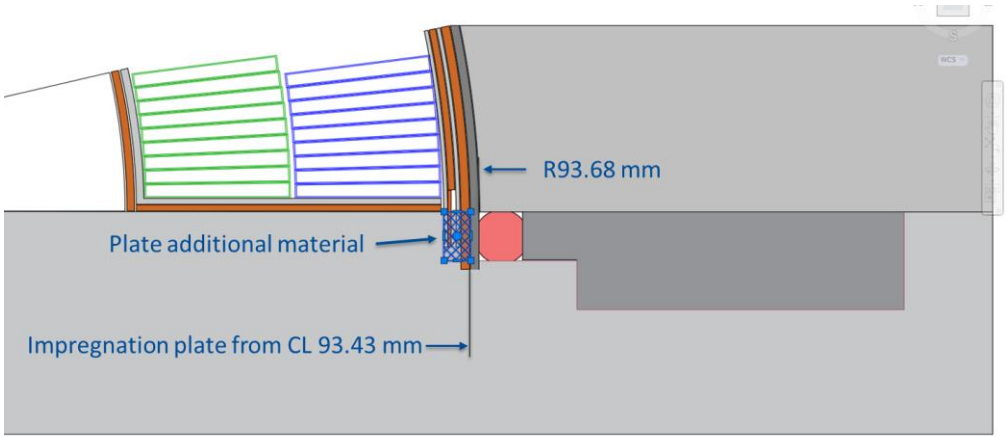
Causes of impregnation shell buckling

$\frown_{spec}$ = 305.9 mm



- Shell was initially rejected due to crease and it was slightly “short”
- Crease was rolled out by Igor and heavy duty rolling pin
- Undersize on arc length probably caused by crease





Problems Solution

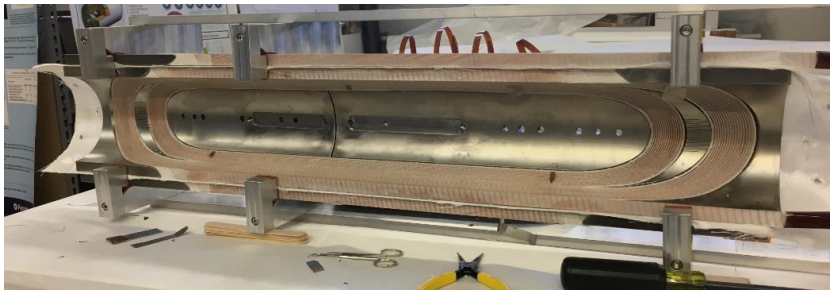
- Outer surface dents
  - Modify the impregnation base plate [186.3mm]
  - Trim the impregnation shell [2mm]

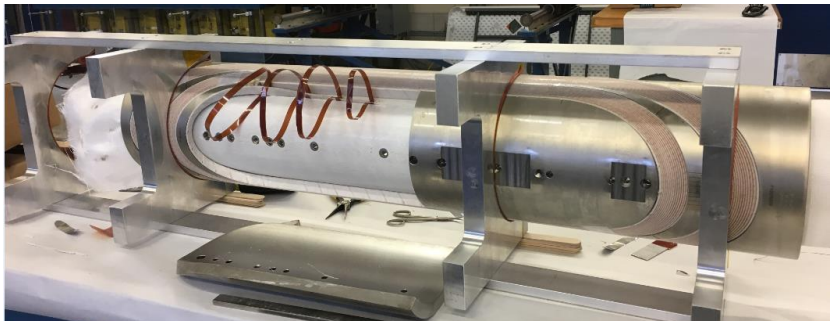
- Inner surface pockets
  - Increase mandrel OR by 0.127mm [sticky Kapton or Teflon tape]
  - Fill pockets with Stycast and re-cure

Coil replacement plan – option #1

Repair coil HFD-CL2-003

1. Remove OL pole blocks (done before)
2. Cut and open interlayer insulation
3. Remove IL-LE pole block (? Decision point #1)
4. Modify transition area
5. Put back the IL-LE pole block (? Decision point #2)
6. Fix interlayer insulation
7. Install OL pole blocks





Duration – 2-3 weeks (January)

Coil replacement plan – option #2

Wind new coil HFD-CL2-005

1. Remove old cable insulation – 1w
2. Re-calibrate the cable – 0.2w
3. Insulate the cable – 0.8w
4. Un-wide coil HFD-CL2-003 to remove coil parts – 0.1w
   - 2 sets of new parts may not be available
5. Wind and cure coil – 4w

or use new cable

Duration – ~7 weeks (start cable preparation in February)

Review questions and answers

1. Is the L3-L4 reaction/impregnation tooling and procedure well understood and adequate to produce high quality coils?

   The tooling and procedure are well understood. The committee believes, however, that expanding the procedure to include more dry runs and fit-ups might have caught the design flaw earlier.

2. Are the possible causes of the coil HFD-CL-002 damage during impregnation well understood?

   Yes.

3. Are the proposed improvements of the coil impregnation tooling, process, and quality control sufficient to achieve the required coil quality after impregnation?

   Yes, but It is critical to adhere to the discipline of the travelers and discrepancy reports.

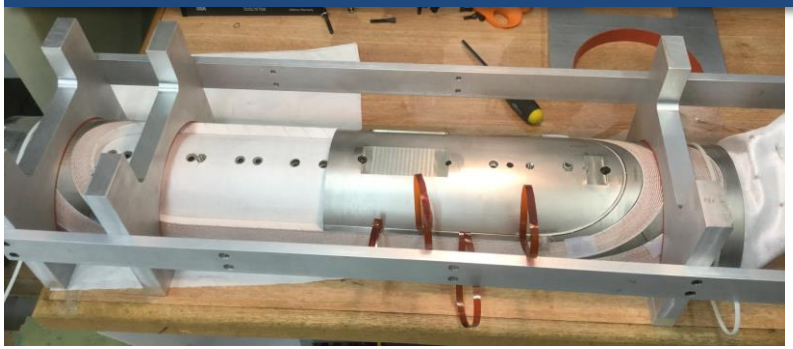
4. Does the plan for coil replacement exist and is it optimal (new coil fabrication vs. fixing HFD-CL-003)?

   The proposed plan of repairing coil HFD-CL2-003 appears viable, and would be the most efficient course. The back-up plan of winding a new coil using cable recovered from HFD-CL-001 also appears viable, but would be slower and use more resources.

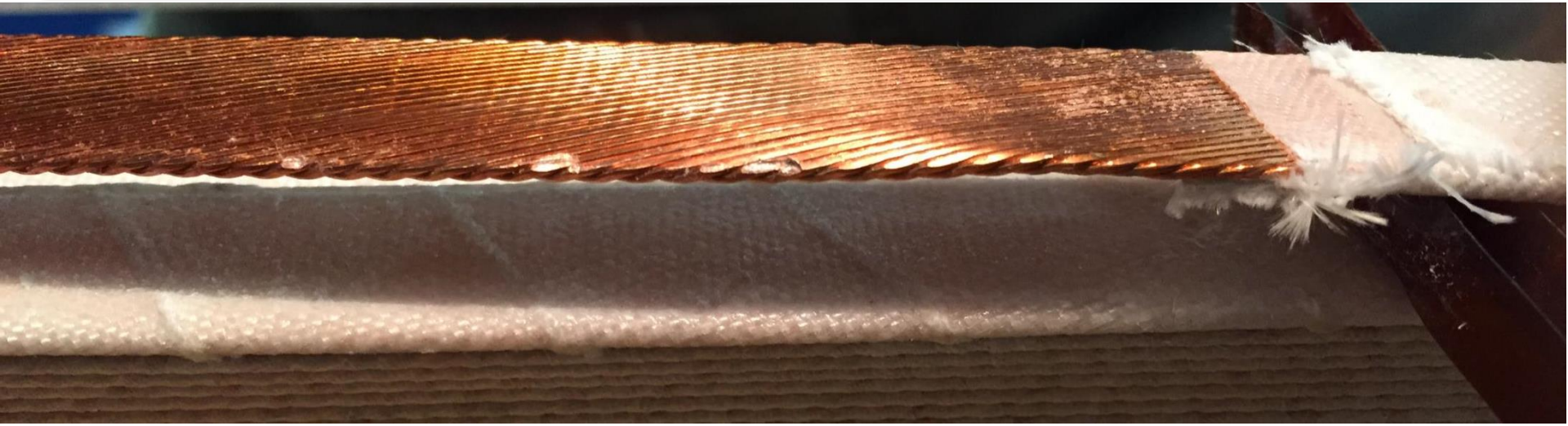
Recommendations

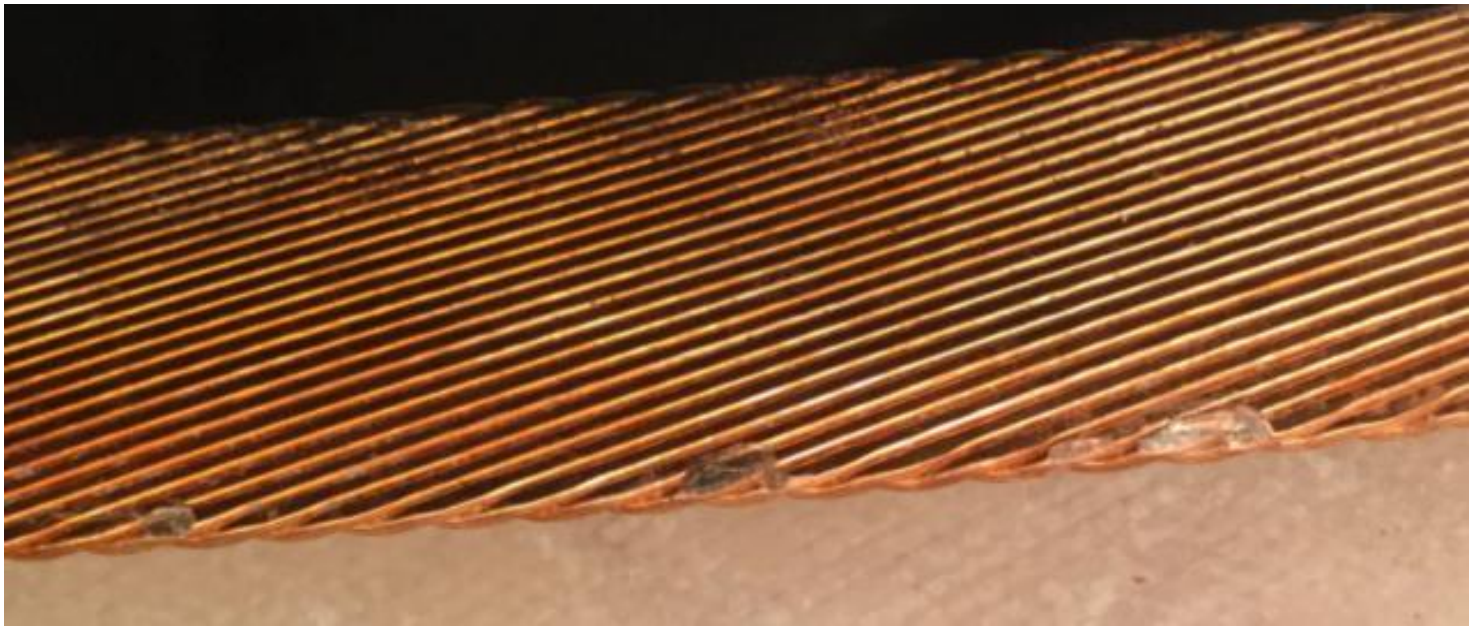
1. After internal review, modify the parts and tooling as proposed.
    a. Shell
    b. Impregnation base plate
    c. Mandrel
2. Adopt Recovery Option #1 to repair coil HFD-CL2-003. Develop a detailed plan through internal discussions, including consideration of the committee's comments. Conduct another readiness review before removing any more pole pieces and also before reinstalling the pole pieces.
3. If it becomes necessary to move to Option #2, wind a new coil using cable from HFD-CL2-001. Preserve the marked locations of the transition and other features by not stripping the old insulation from the cable. Develop a detailed plan addressing the differences from the standard procedure and conduct a readiness review.
4. Use more dry runs, fit-ups, and internal reviews, and discussions of discrepancy reports to avoid more schedule-killing mistakes. Apply the lessons learned to the L1/2 coils. Re-make the previously hand-modified shell for L1/2.
5. Use the existing damaged coil to practice filling the interior gaps with Stycast. This same coil could also be placed into the mold for a test fit-up after the tooling has been modified.

Coil HFD-CL2-003 inspection



Transition cable damage





New coil (opt. #2)

Task Name	Duration	Start	Finish
OL coil #1 HFD-CL2-002	**285 days**	**Mon 11/28/16**	**Fri 12/29/17**
winding/curing	17 wks	Mon 11/28/16	Fri 3/24/17
winding/curing	4 wks	Mon 3/27/17	Fri 4/21/17
reaction	4 wks	Mon 5/22/17	Fri 6/16/17
impregnation/instrumentation	4 wks	Mon 12/4/17	Fri 12/29/17
OL coil #2 HFD-CL2-003	**330 days**	**Mon 7/17/17**	**Fri 10/19/18**
winding/curing	4 wks	Mon 7/17/17	Fri 8/11/17
repair	3 wks	Mon 8/13/18	Fri 8/31/18
reaction	3 wks	Mon 9/3/18	Fri 9/21/18
impregnation/instrumentation	4 wks	Mon 9/24/18	Fri 10/19/18
OL coil #3 HFD-CL2-004	**160 days**	**Mon 6/26/17**	**Fri 2/2/18**
winding/curing	4 wks	Mon 6/26/17	Fri 7/21/17
reaction	4 wks	Mon 9/18/17	Fri 10/13/17
impregnation/instrumentation	4 wks	Mon 1/8/18	Fri 2/2/18
OL coil #4 HFD-CL2-005	**70 days**	**Mon 3/5/18**	**Fri 6/8/18**
winding/curing	7 wks	Mon 3/5/18	Fri 4/20/18
reaction	3 wks	Mon 4/23/18	Fri 5/11/18
impregnation/instrumentation	4 wks	Mon 5/14/18	Fri 6/8/18
IL Coil production readiness review	1 day	Mon 9/25/17	Mon 9/25/17
IL coil #1 HFD-CL1-001	**105 days**	**Mon 11/20/17**	**Fri 4/13/18**
winding/curing	4 wks	Mon 11/20/17	Fri 12/15/17
reaction	3 wks	Mon 2/5/18	Fri 2/23/18
impregnation/instrumentation	4 wks	Mon 3/19/18	Fri 4/13/18
IL coil #2 HFD-CL1-002	**90 days**	**Mon 1/8/18**	**Fri 5/11/18**
winding/curing	4 wks	Mon 1/8/18	Fri 2/2/18
reaction	3 wks	Mon 2/26/18	Fri 3/16/18
impregnation/instrumentation	4 wks	Mon 4/16/18	Fri 5/11/18
IL coil #3 HFD-CL1-003	**155 days**	**Mon 2/5/18**	**Fri 9/7/18**
winding/curing	4 wks	Mon 2/5/18	Fri 3/2/18
reaction	3 wks	Mon 7/23/18	Fri 8/10/18
impregnation/instrumentation	4 wks	Mon 8/13/18	Fri 9/7/18
Demo #1 assembly and test	**285 days?**	**Mon 7/17/17**	**Fri 8/17/18**
mechanical model (baseline)	33 wks	Mon 7/17/17	Fri 3/2/18
readyness review	1 day?	Thu 3/8/18	Thu 3/8/18
assembly (IL-#1-2, OL-#1-2)	6 wks	Mon 6/11/18	Fri 7/20/18
test preparation	4 wks	Mon 7/23/18	Fri 8/17/18
model test TCI	5 wks	Mon 8/20/18	Fri 9/21/18
model test TCII	5 wks	Mon 9/24/18	Fri 10/26/18