Assessment of Training Performance, Degradation and Robustness of Paraffin-Wax Impregnated Nb_3Sn Coil (BigBOX) under High Magnetic Field

D. M. Araujo, on behalf of PSI/CHART/Magdev

M. Kumar and R.Gupta on behalf of BNL/MDP

July 5th, 2023

Agenda

- Magnet R&D Approach for High Field Magnets (R. Gupta)
- Nb_3Sn Coil (BigBOX) integration into DCC17 Magnet (D. M. Araujo)
- Test Setup, Quench Detection and Results (M. Kumar)
- Analysis of Results and Conclusions (D. M. Araujo)
- DCC17 Performance with Stress-management Structure (R. Gupta)

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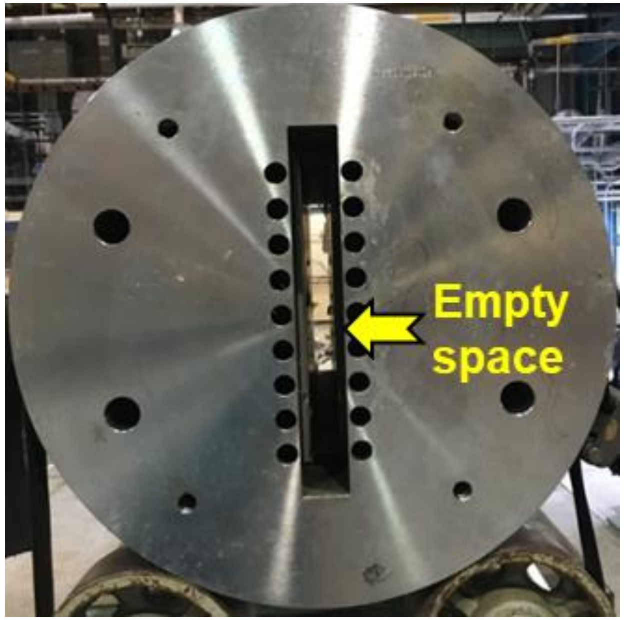
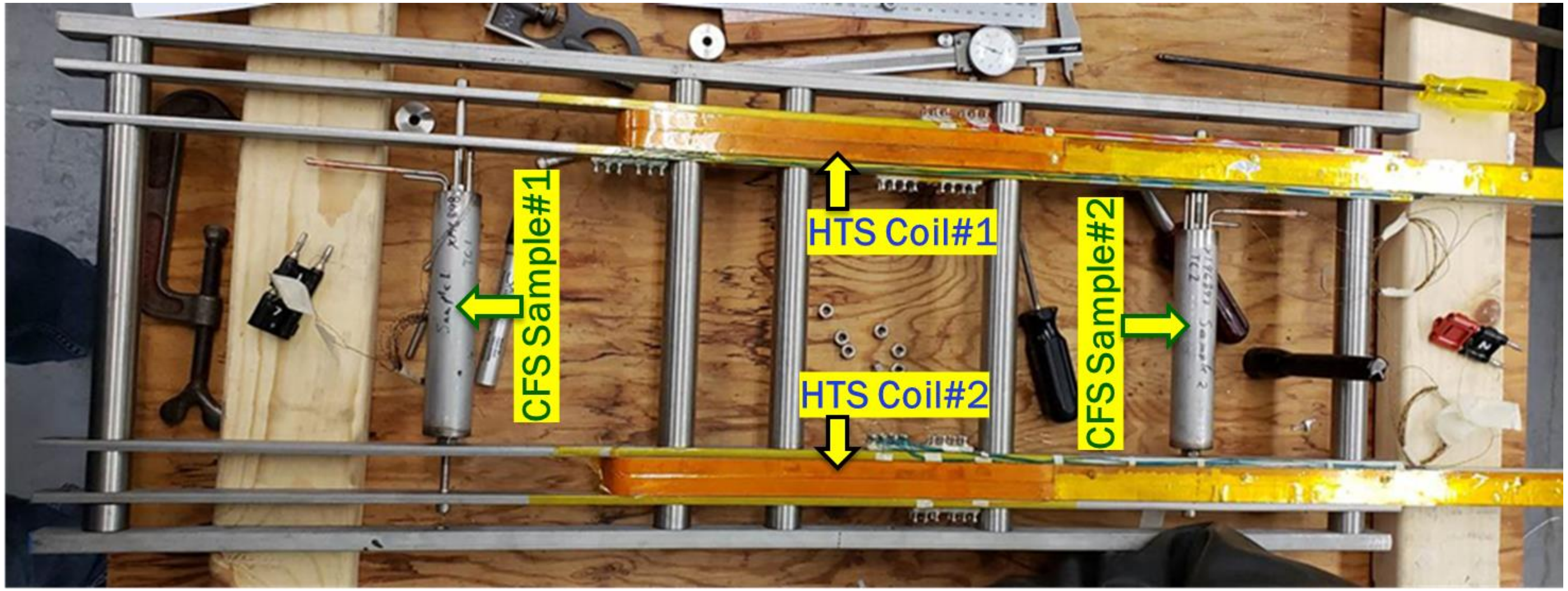
Magnet R&D Approach for High Field Magnets





- Next generation high field magnets require development of several new technologies.
- New technologies must be demonstrated in an R&D magnet before they can be accepted.
- Common coil dipole DCC017 at BNL was specifically designed and built so that new coils can inserted and tested as an integral part of the magnet for a low-cost, rapid-turn-around R&D.
- This was used in demonstrating record hybrid 12.3 T HTS/LTS field (MDP 2020 test) and multiple R&D tests of very different programs in one go (see insert above used in HEP/FES test)
- PSI test was designed to demonstrate (a) wax impregnated coil technology, (b) stress-managed structures, (c) record HTS/LTS hybrid field, and (d) pole coil for field quality in common coil.

Past Proposals for Demonstration of Pole Coils for Field Quality in Common Coil Dipole DCC017

A proposal was submitted to MDP. It was not funded. However, a few Phase I SBIRs were funded.

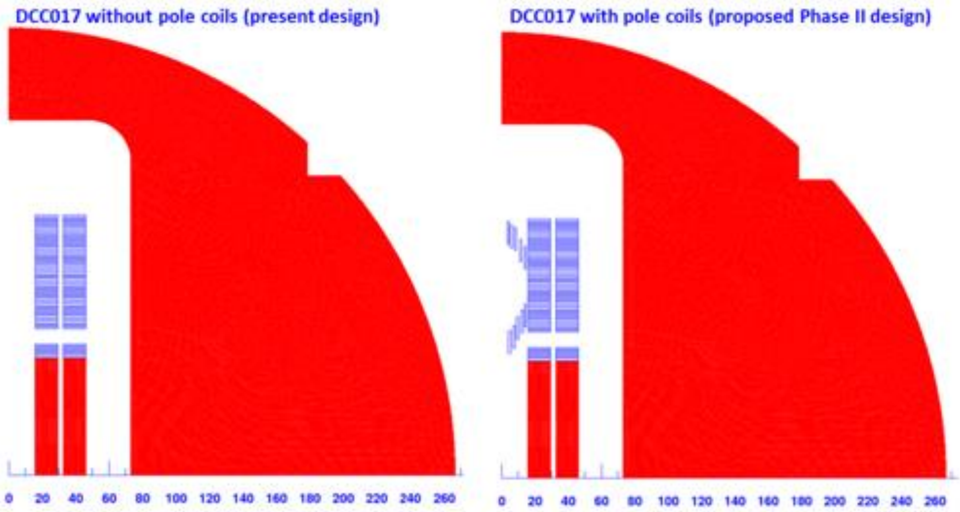


Figure 6: DCC017 as-built, without pole coils (left), and with pole coils to improve field quality (right).

20 T design study goal: all harmonics <3 units

Table II. Left-calculated multipoles in as-built DCC017, showing a large value for b_3 (180 units) and a_2 (-192 units). Right-calculated multipoles with pole coils added, showing all values below 3 units.

DCC017 without pole coils (present design)

MAIN FIELD (T) 0.995409
MAGNET STRENGTH (T/(m^(n-1)) 0.9954

NORMAL RELATIVE MULTIPOLES (1.D-4):

b 1:	10000.00000	b 2:	0.00000	b 3:	187.58719
b 4:	-0.00000	b 5:	-2.01358	b 6:	0.00000
b 7:	-0.13995	b 8:	-0.00000	b 9:	0.00365
b10:	0.00000	b11:	0.00136	b12:	-0.00000
b13:	-0.00014	b14:	0.00000	b15:	-0.00000
b16:	-0.00000	b17:	0.00000	b18:	0.00000
b19:	-0.00000	b20:	-0.00000	b	

SKEW RELATIVE MULTIPOLES (1.D-4):

a 1:	-0.00000	a 2:	-192.09501	a 3:	0.00000
a 4:	6.49804	a 5:	-0.00000	a 6:	0.33413
a 7:	0.00000	a 8:	-0.03499	a 9:	-0.00000
a10:	-0.00209	a11:	0.00000	a12:	0.00053

DCC017 with pole coils (proposed Phase II design)

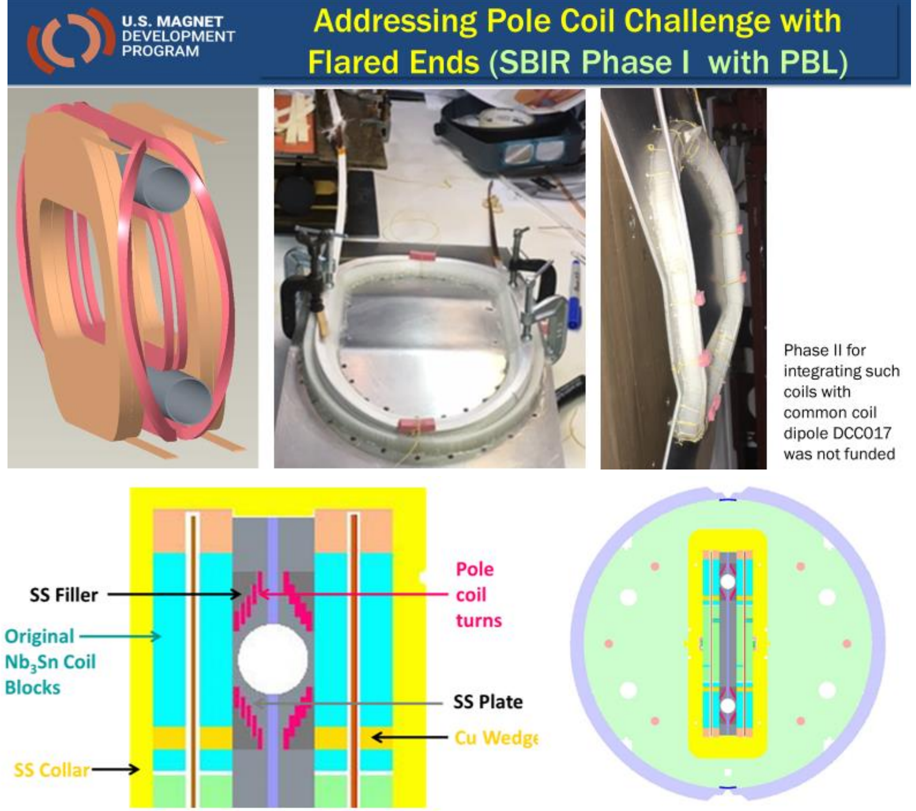
MAIN FIELD (T) 1.065489
MAGNET STRENGTH (T/(m^(n-1)) 1.0655

NORMAL RELATIVE MULTIPOLES (1.D-4):

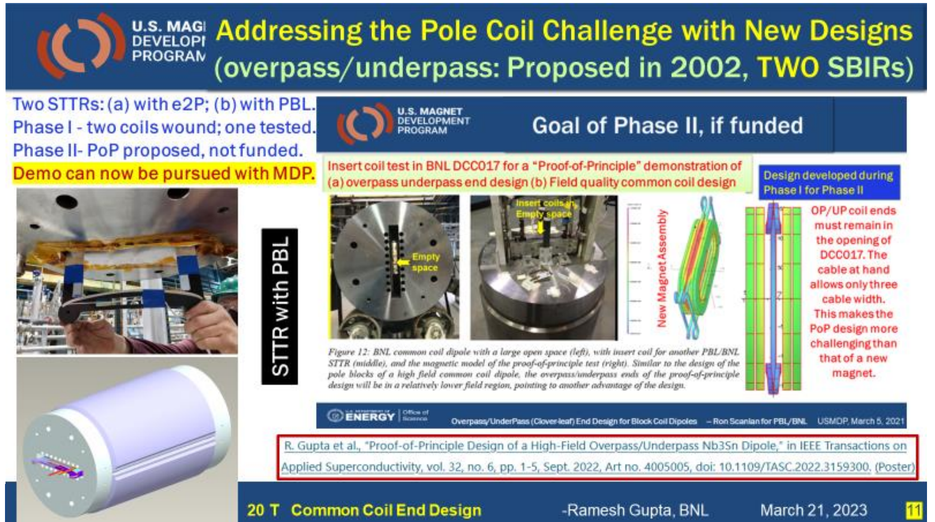
b 1:	10000.00000	b 2:	-0.00000	b 3:	0.00071
b 4:	-0.00000	b 5:	0.00045	b 6:	-0.00000
b 7:	2.69589	b 8:	-0.00000	b 9:	0.38260
b10:	-0.00000	b11:	-0.06197	b12:	0.00000
b13:	-0.02446	b14:	0.00000	b15:	-0.00522
b16:	0.00000	b17:	0.00080	b18:	0.00000
b19:	0.00096	b20:	0.00000	b	

SKEW RELATIVE MULTIPOLES (1.D-4):

a 1:	0.00000	a 2:	0.00049	a 3:	0.00000
a 4:	-0.00002	a 5:	0.00000	a 6:	0.30753
a 7:	-0.00000	a 8:	0.26673	a 9:	-0.00000
a10:	-0.01777	a11:	-0.00000	a12:	-0.01224

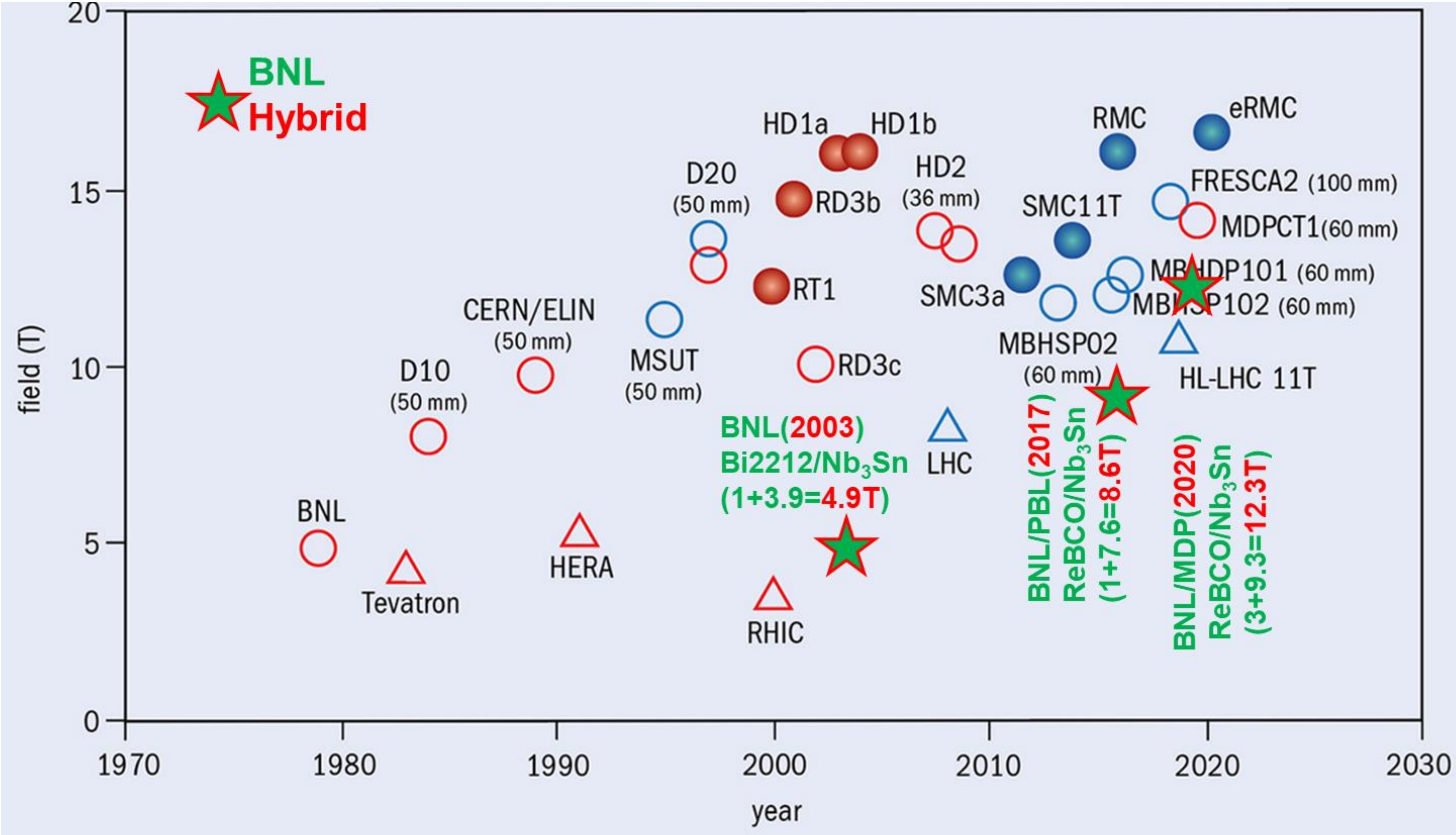


Figures 8 a&b: CAD cross section of support-structure concept, with structure (gray), pole coils (pink), main coils (cyan), wedges & SS collars (yellow), and magnetic iron (pale chartreuse). Left: Detail of support structure for the upper aperture. Right: Cross section through both apertures.



Updated Bottura (CERN) Chart

(includes BNL HTS/LTS hybrid R&D dipoles)



Attempt to reach a higher HTS/LTS hybrid field in the PSI test with HTS coil in structure

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LTS & Hybrid Roadmap Outlook

D. Sotnikov, H. Garcia

Hybrid HTS Subscale Magnet

Hybrid HTS Short Magnet

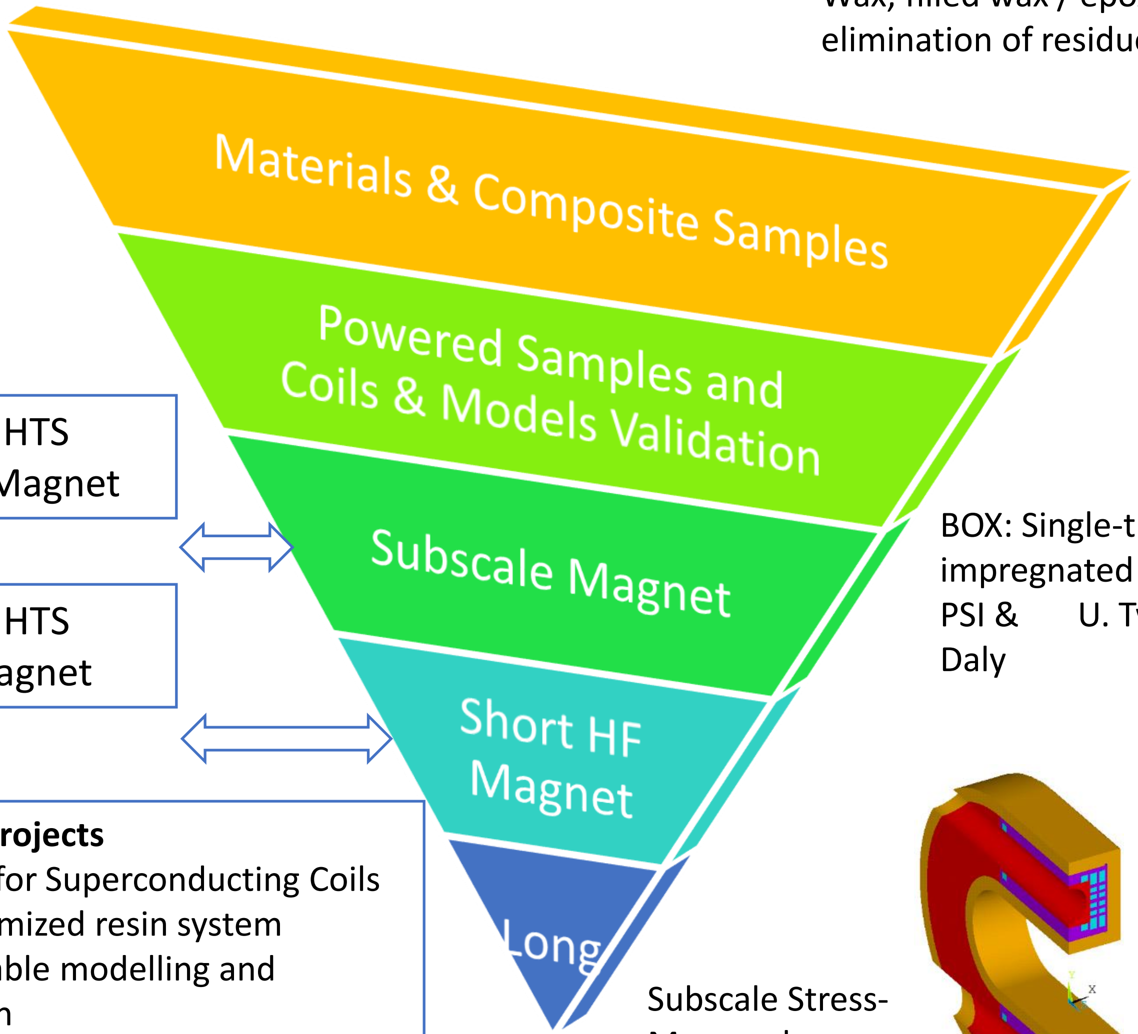
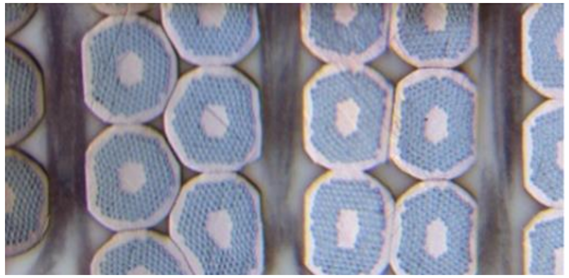
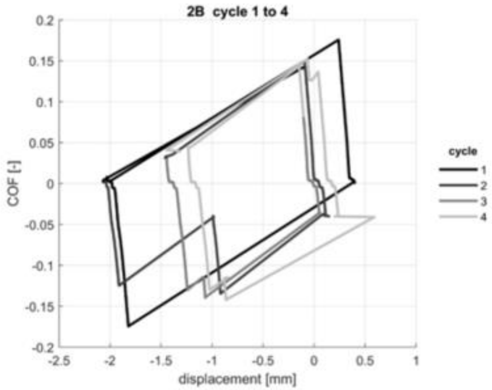


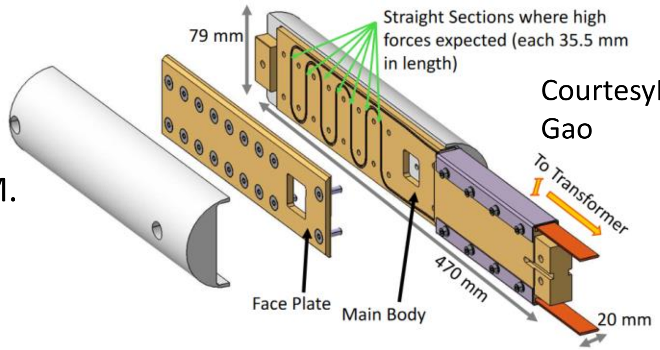
CHART Mag Projects
MagAM: AM for Superconducting Coils
MagRes: Optimized resin system
MagComp: Cable modelling and caracterization
MagNum: Modelling & Optimization

Wax, filled wax / epoxy process development, HT elimination of residues and sliding interfaces, A. Brem

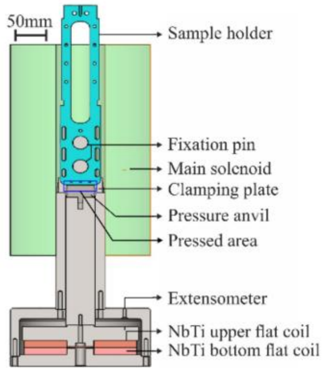




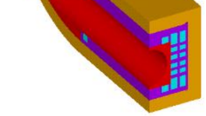
BOX: Single-turn wax impregnated sample, PSI & U. Twente, M. Daly

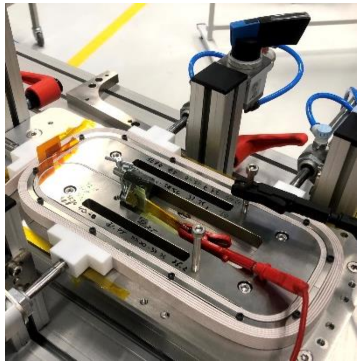


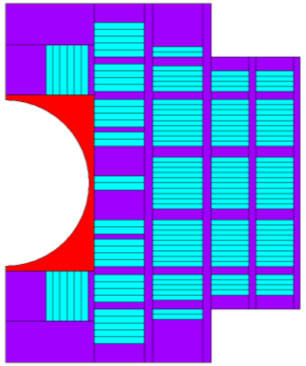
CourtesyP. Gao



Subscale Stress-Managed Common-coils





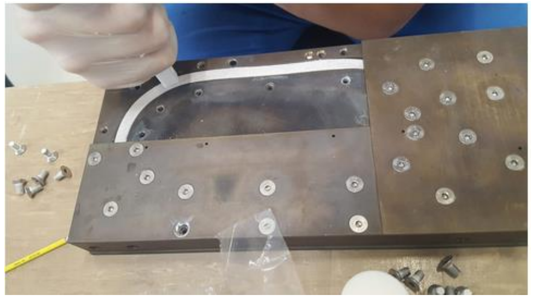


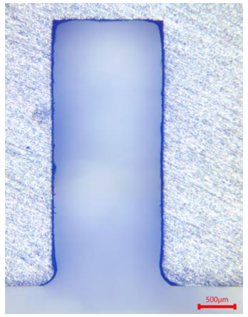
High-Field Stress-managed common coils

Goals

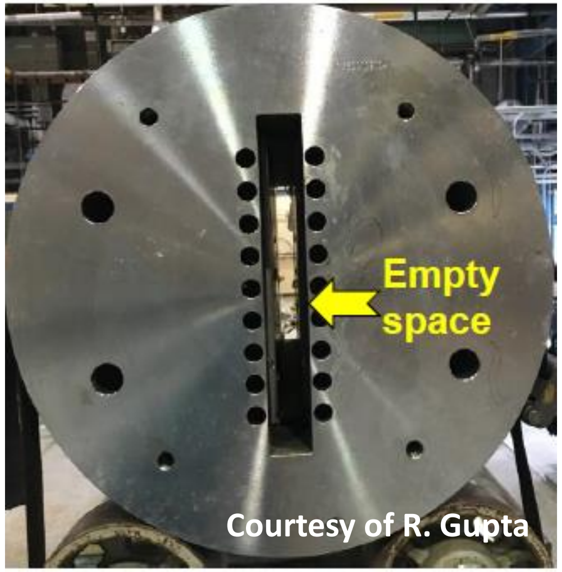
- Assessing
  - SC margin, with the conductor under transversal pressure
  - Training performance

- … and validating new technologies
  - load free magnet
  - Wax impregnation process
  - Stress-managed structure
  - New ceramic insulation
  - Interface conditions

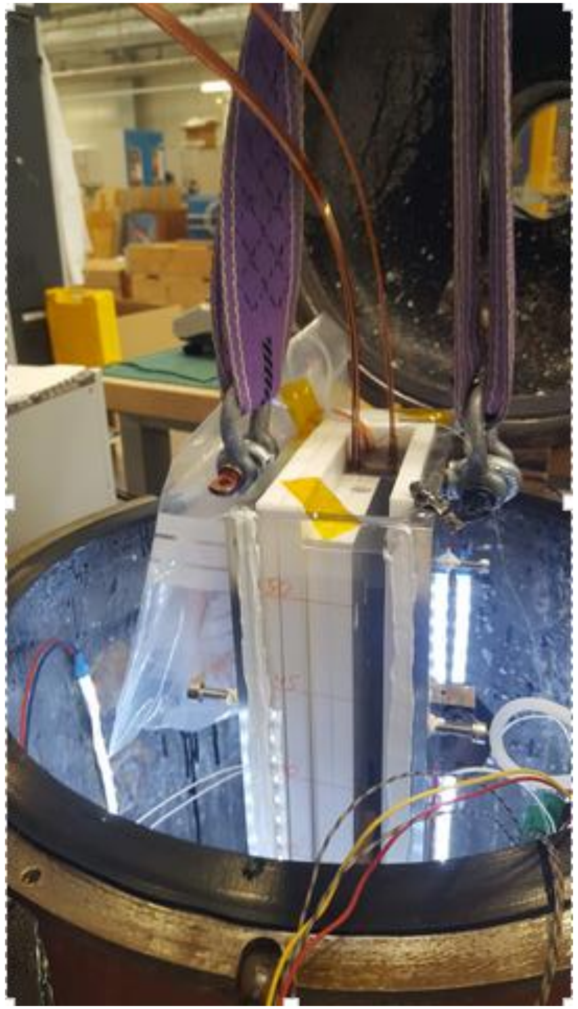




BigBOX winding

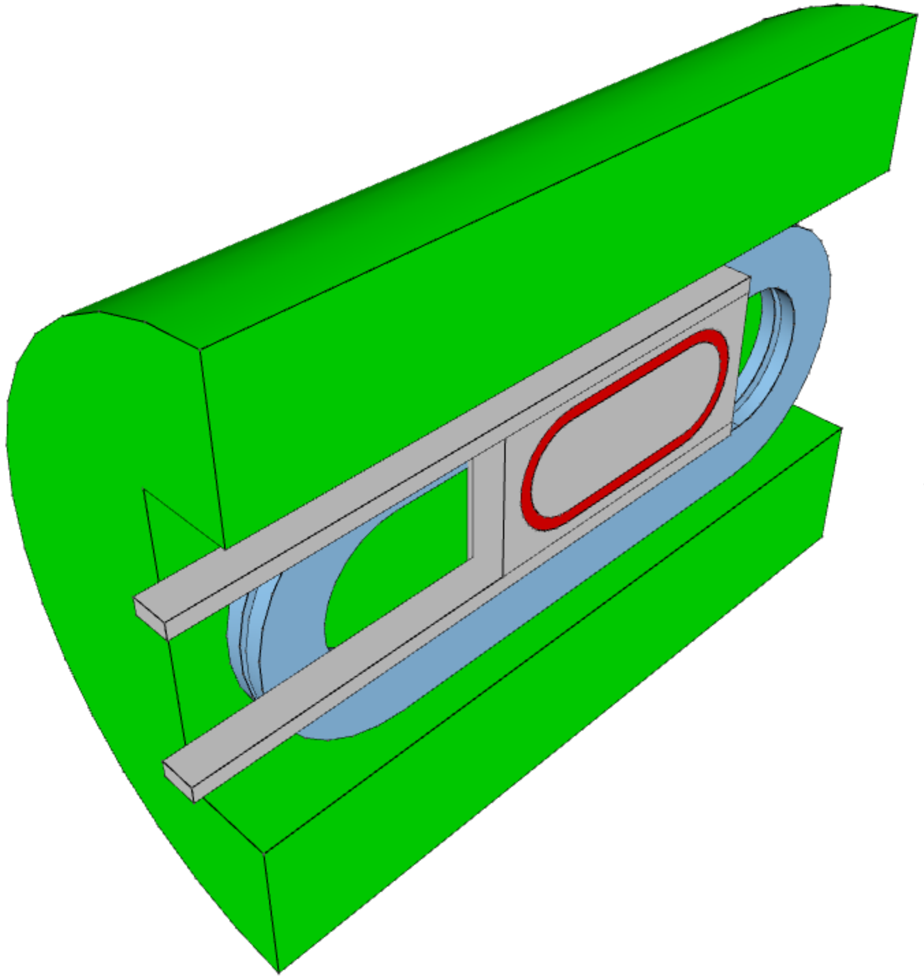


High temperature glass-ceramic coatings, A. Brem

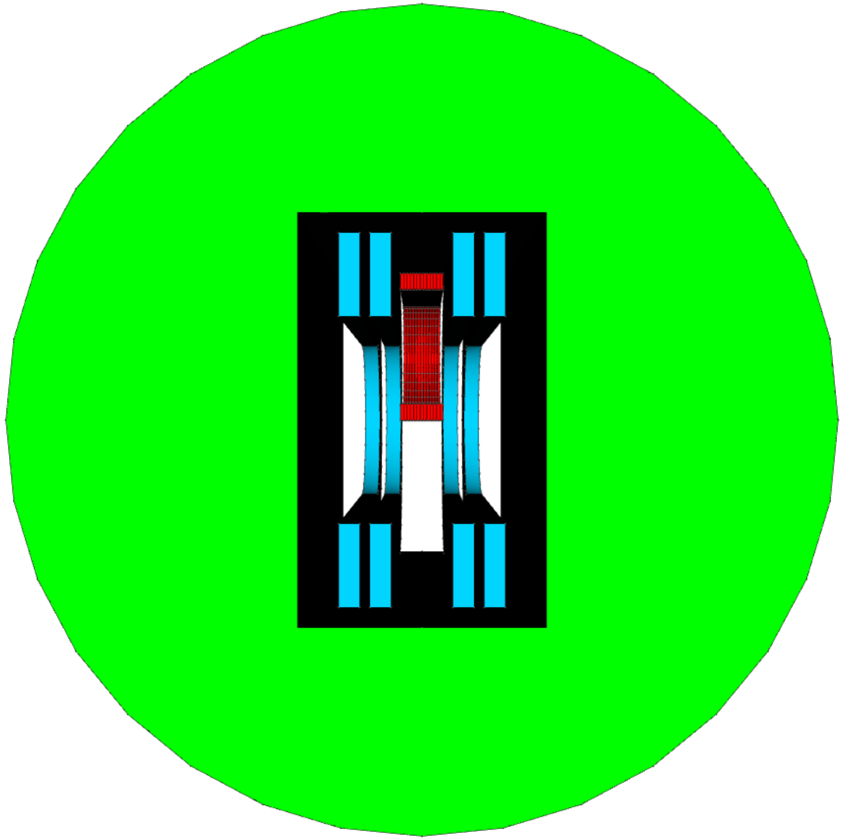


BigBOX impregnation, M. Daly and C. Hug

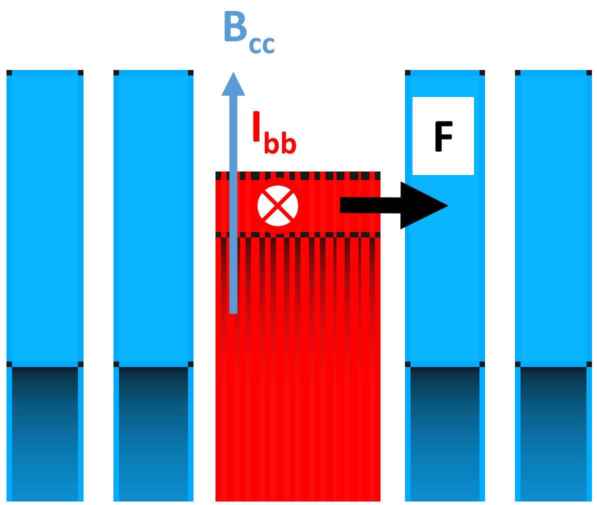
BigBOX and DCC17 Integration 1/2



BigBOX and DCC17 Integration

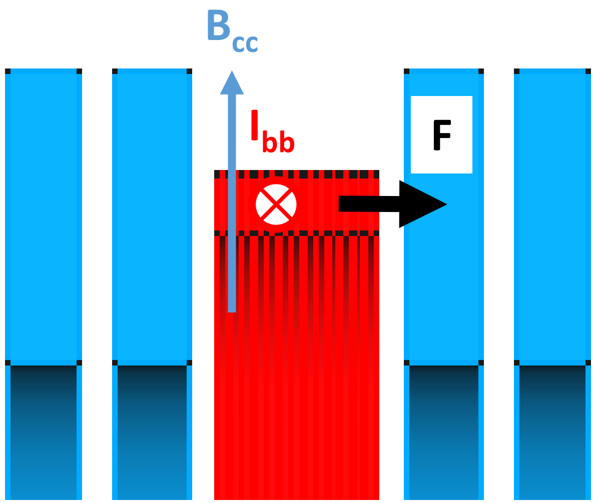


Coils and Yoke Cross-section

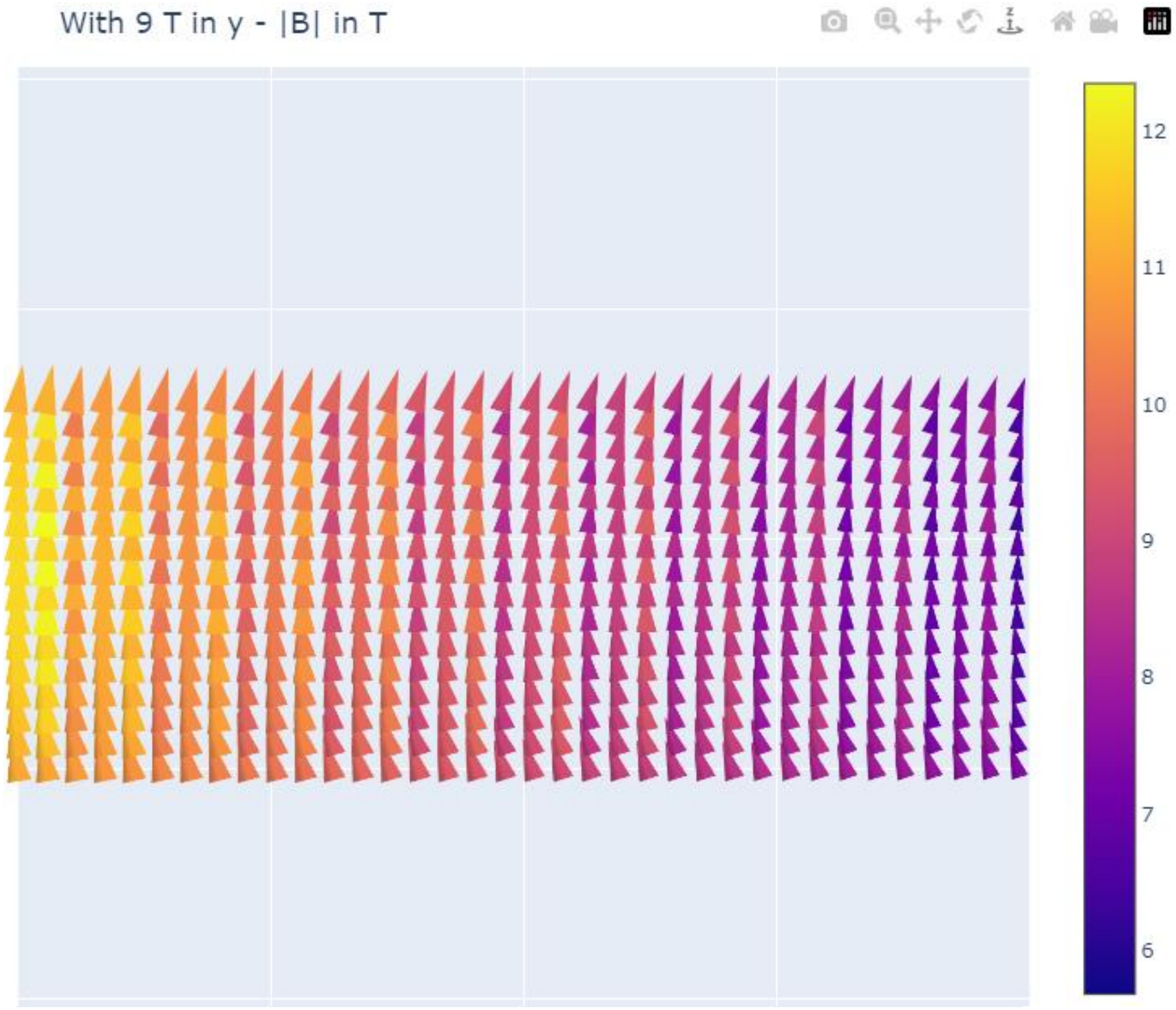


- Hard-way bending direction, otherwise the level of stress would be too low
- The coil block has 13 turns
- Bending radius is 30 mm
- Straight section of 100 mm
- LARP cable was used to produce BigBOX

BigBOX and DCC17 Integration 2/2



- The self-field contribution on the horizontal direction is small
- Due to the self-field contribution on the vertical direction, BigBOX field gradient is high
- The low-field turn is the one with high mechanical stress

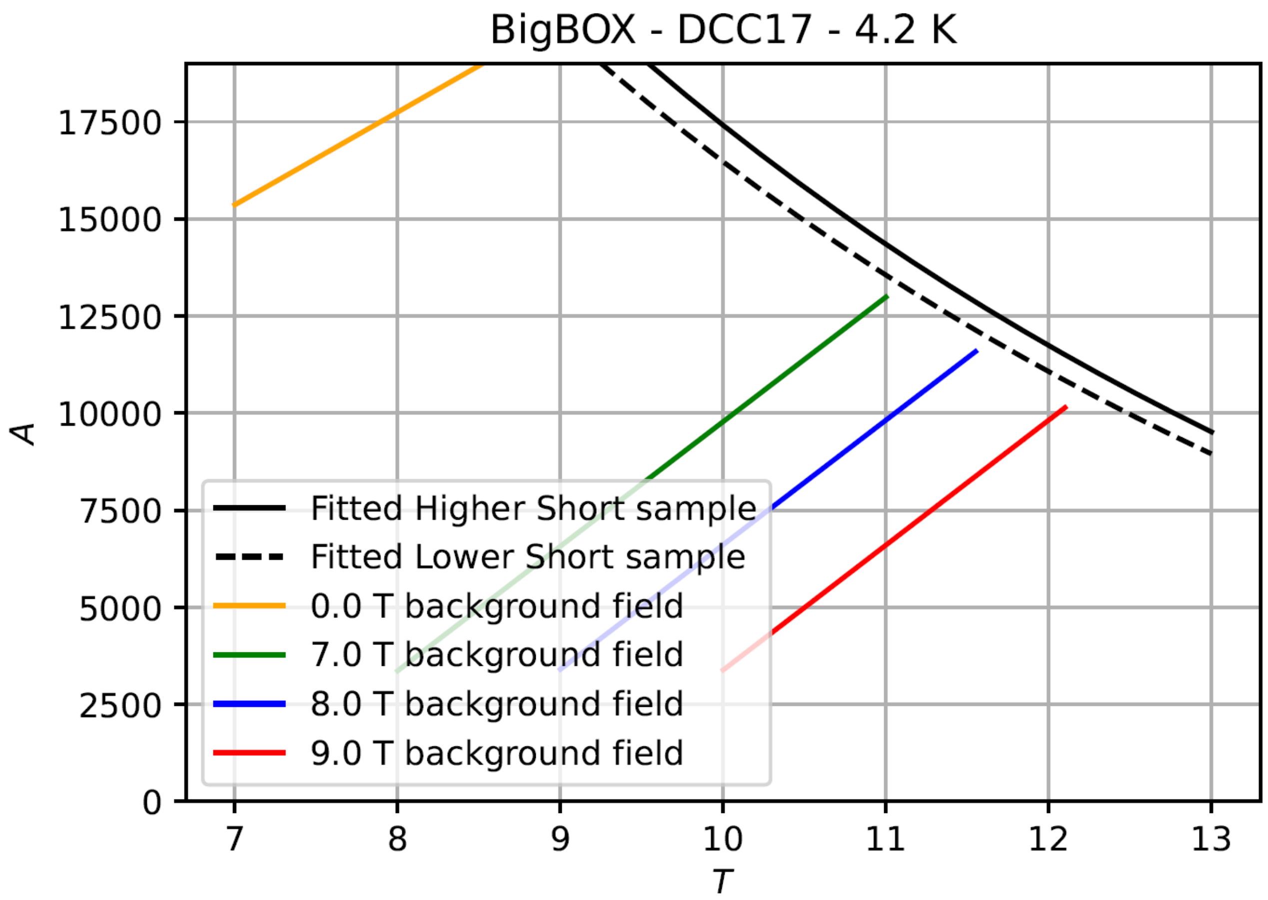


Ic fitting and BigBOX load lines

- Strand: 0.7 mm RRP OST 54/61
- Operational temperature: 4.2 K
- Cable bare width: 7.79 mm
- Cable bare thickness: 1.28 mm
- Insulation thickness: 155.0 µm

- Max current: 20 kA (after upgrade)
- Background field of 9 T on the vertical direction

Higher and Lower Short sample obtained from E. Barzi *et al.*, “RRP Nb3Sn strand studies for LARP,” *Applied Superconductivity, IEEE Transactions on*, vol. 17, pp. 2607–2610, Jul. 2007, doi: 10.1109/TASC.2007.899579.



By changing DCC17 background field the BigBOX load line changes, which allow us to change its stress level

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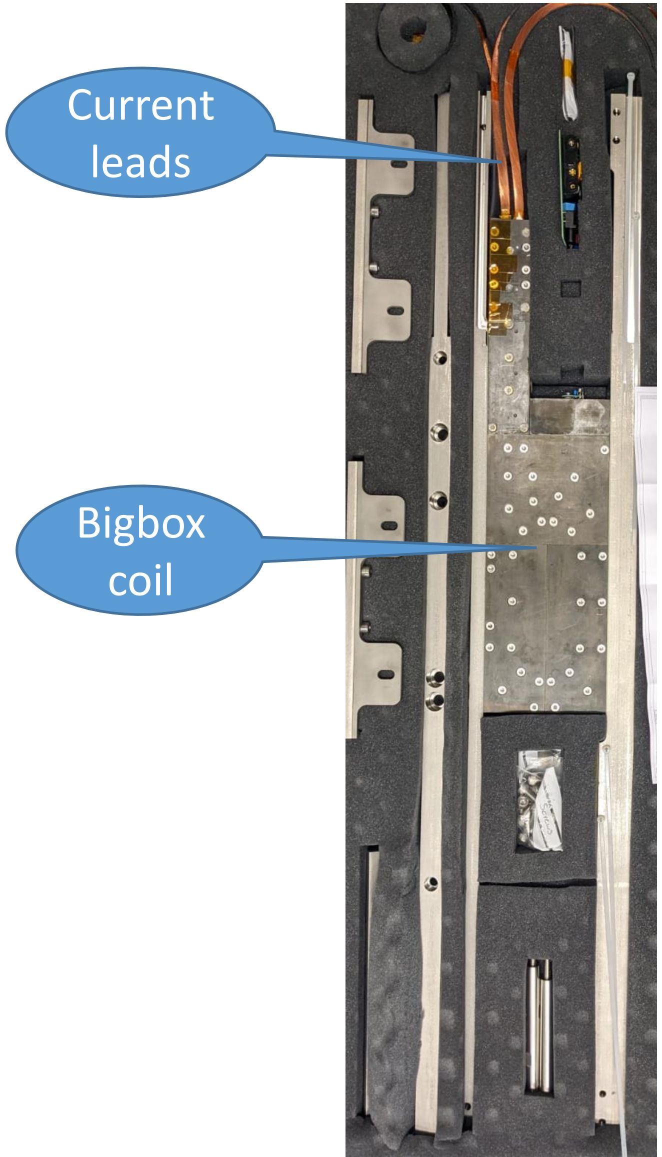
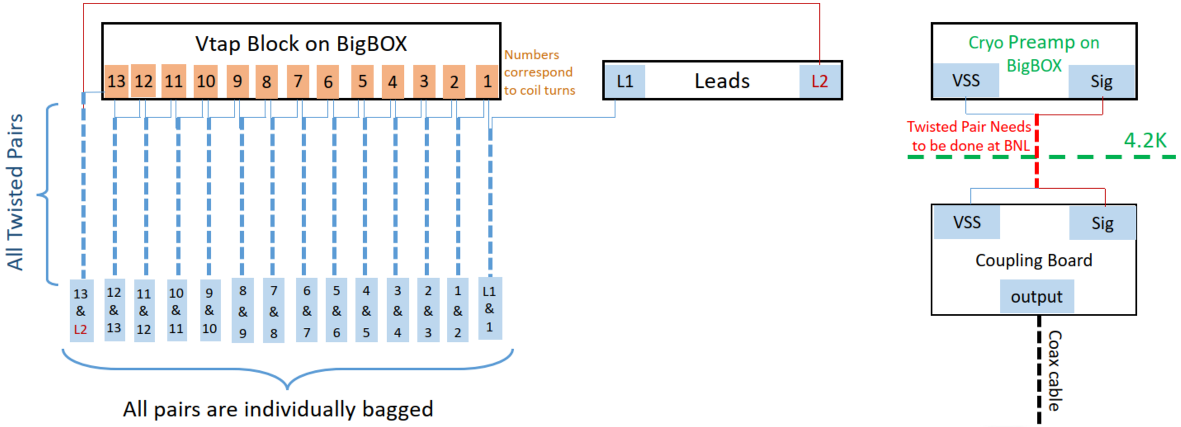
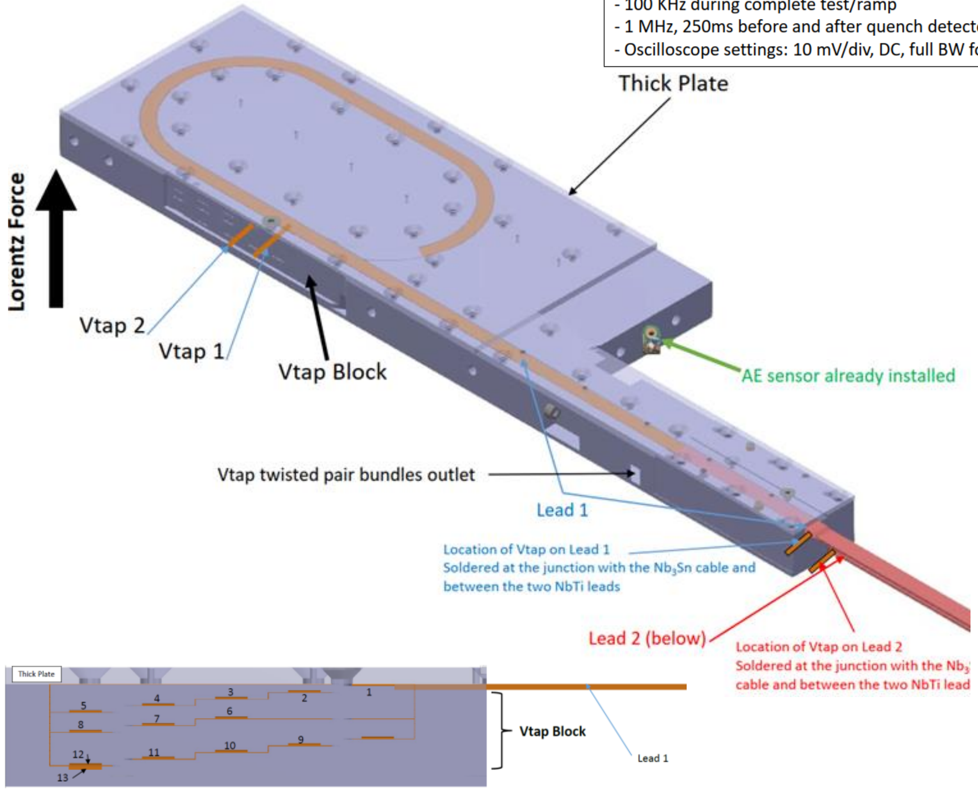
Test set up: Sample



Instrumentation Wiring of BigBOX

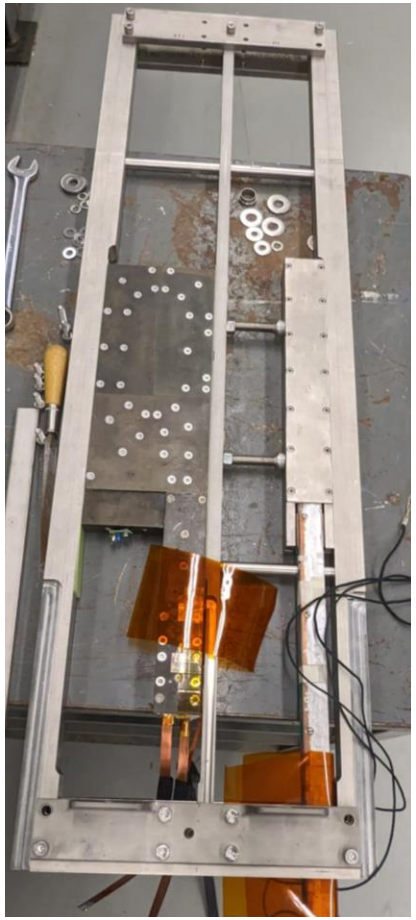


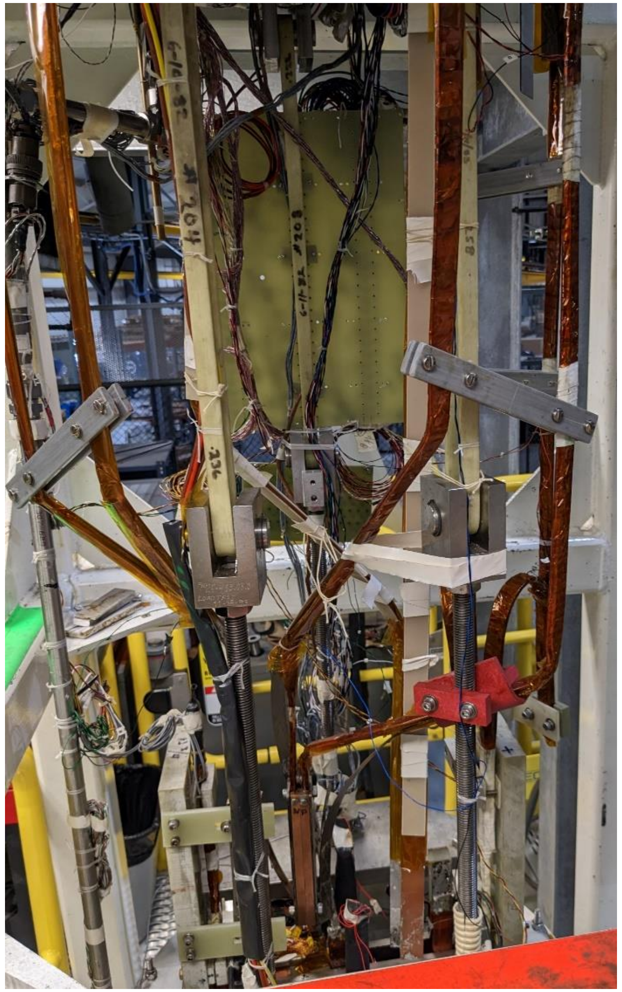
For testing the smaller BOX samples we record data using the following settings:
- Data acquisition of 16 bits
- 100 KHz during complete test/ramp
- 1 MHz, 250ms before and after quench detected
- Oscilloscope settings: 10 mV/div, DC, full BW for Vtaps and AE signals

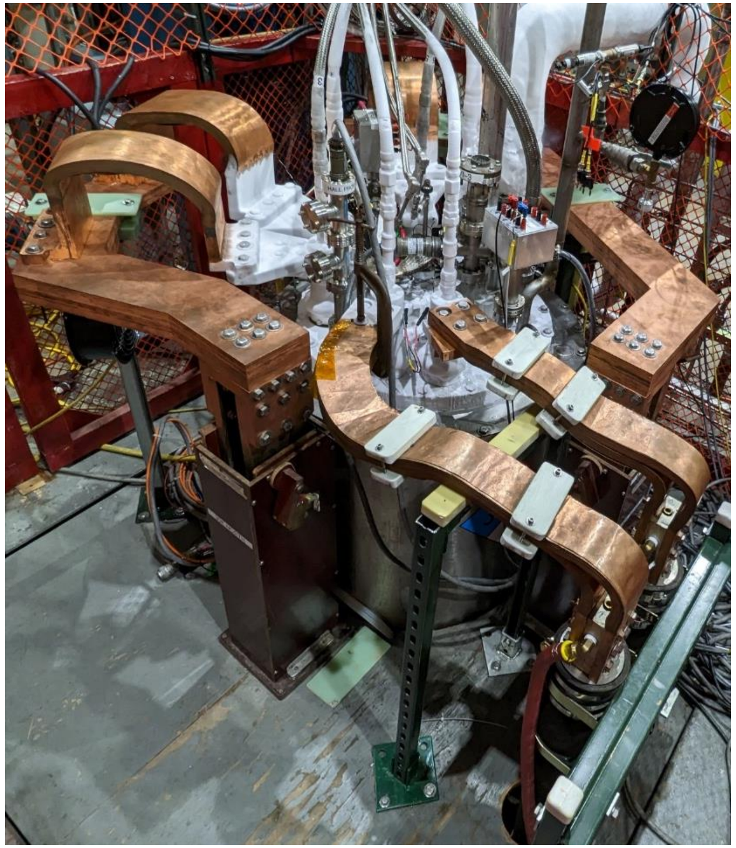


- The coil is made of Nb_3Sn conductor but the leads coming out of the magnet are made of NbTi.
- **Voltage taps:** There are 14 pairs (28 wires) of voltage taps coming out of the coil.
- **Acoustic sensor**

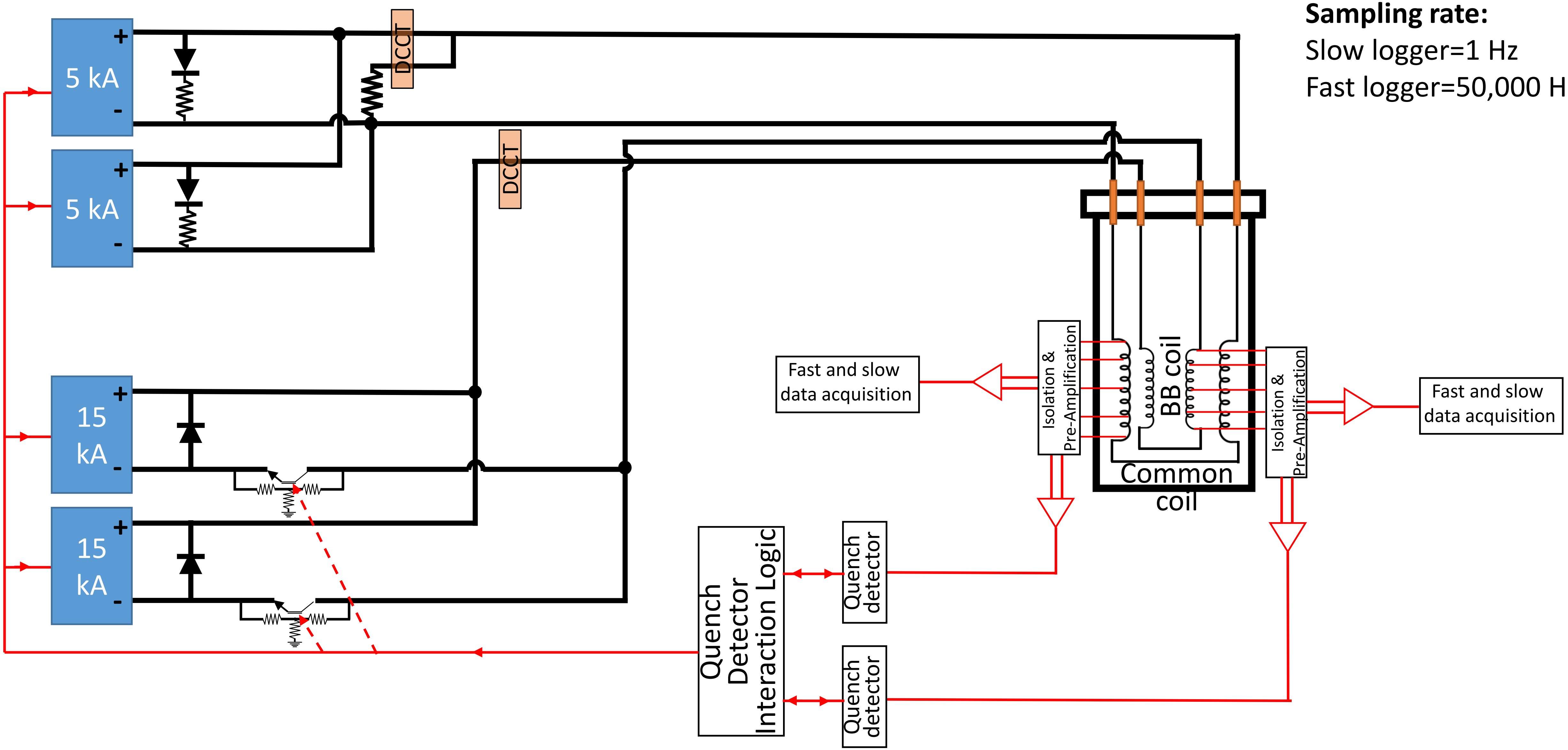
Test set up: Sample installation







Test set up: Power Circuit and DAQ



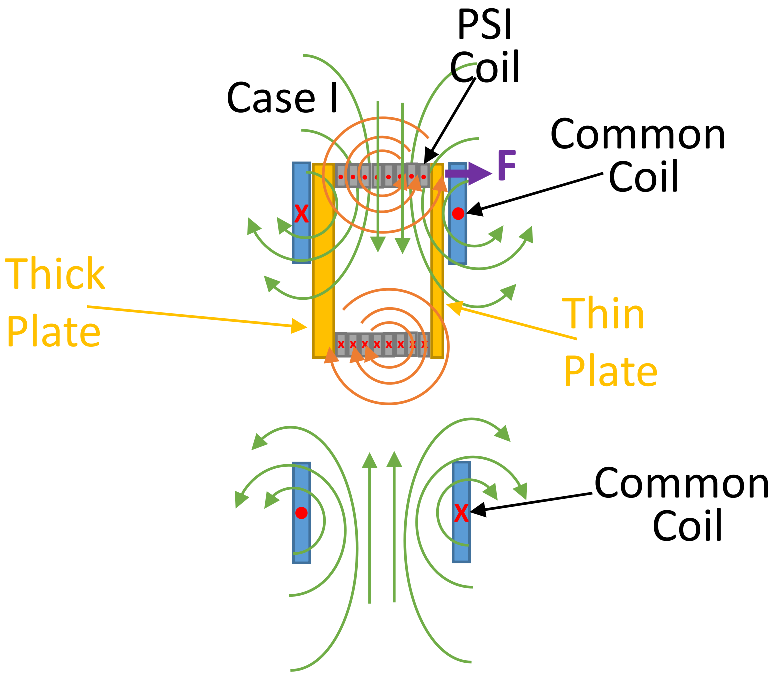
Sampling rate:

Slow logger=1 Hz

Fast logger=50,000 Hz

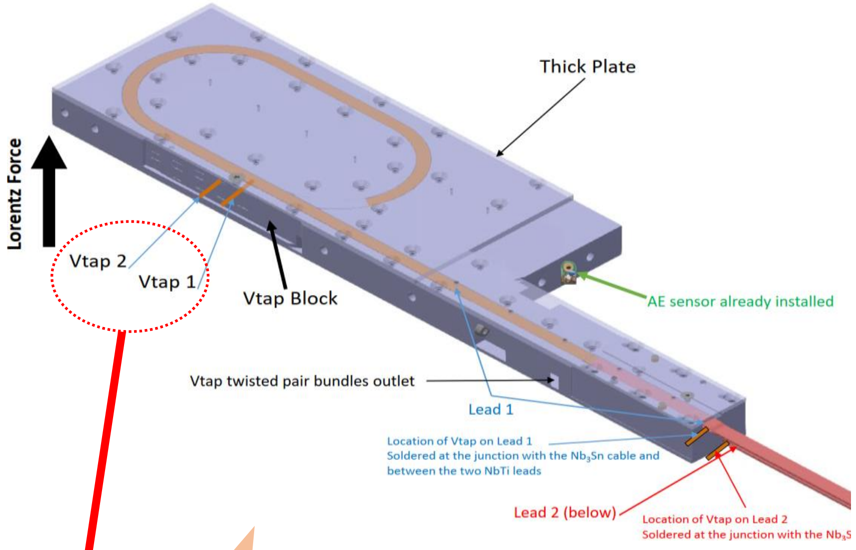
Coil energization

Top View



Common coil magnetic field

PSI coil magnetic field



The quenches always occurred in V-tap 1-2. The force was on the thin plate.

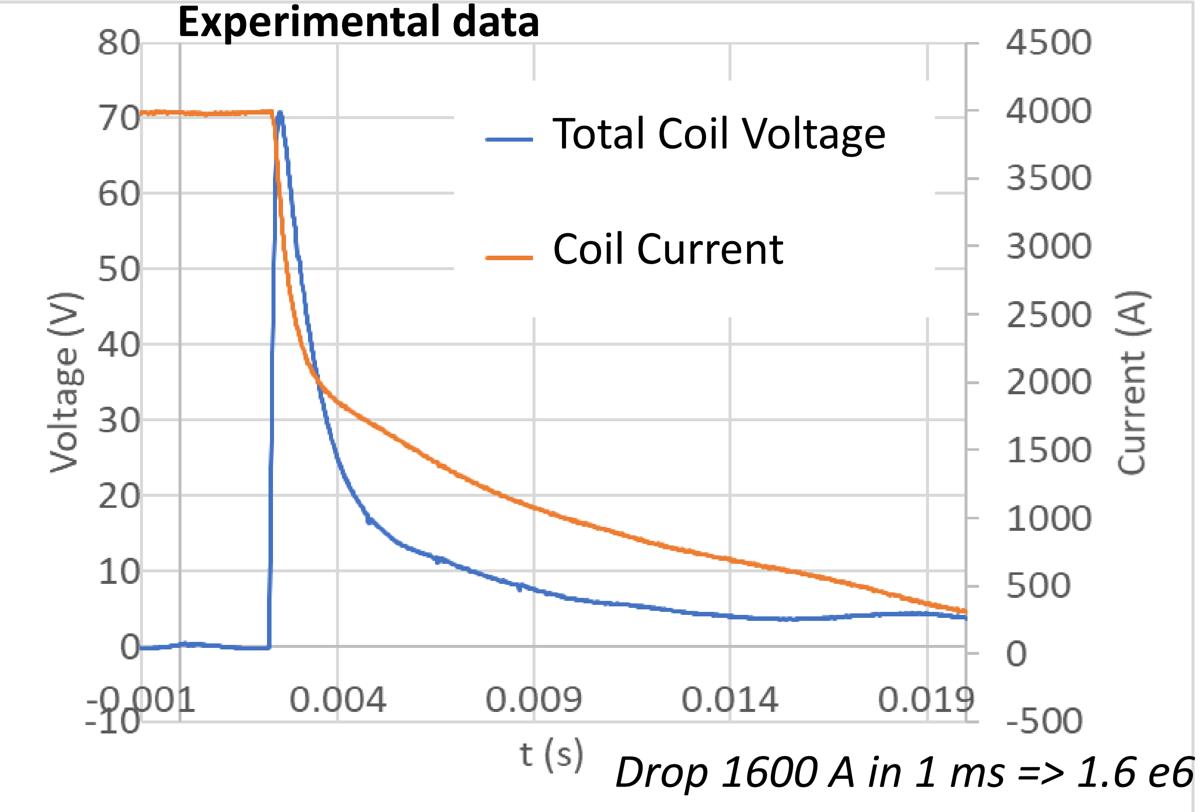
Test Sequence

- **Preliminary electrical checkout at room temperature in Test Dewar 6.**
  - Room temperature check of all resistances (coils, leads, splice, quench protection heaters) and to ground.
  - Hipot tests: 500 V.
  - 1 A voltage taps check.
- **Initial cold electrical checkout at 4.5 K.**
  - Same as room temperature.
- **Common coil checks**
  - Strip heater quench: half coil voltage trip at 2kA (20 A/s), strip heater voltage 450 V: check voltages etc => calculate MIITS
  - Strip heater #1 quench: half coil voltage trip at 4kA (20 A/s), strip heater voltage 450 V: check voltages etc => calculate MIITS
  - Strip heater #2 quench: half coil voltage trip at 4kA (20 A/s), strip heater voltage 450 V: check voltages etc => calculate MIITS
- **Insert coil tests**
  1. Set Big box to short. Ramp common coil to maximum stable current at 20 A/s. Monitor for stability.
  2. Set Common coil to short. Ramp big box to 10 kA at 20 A/s. Trip manually. Verify Quench detector operation.
  3. Ramp common coil to I_{CC} kA with 20 A/s. Ramp big box to max current I_{MDP} until quench.
     - If Big box quenches first, discharge Big box instantly, wait a few ms discharge common coil.
     - If common coil quenches first, discharge Big box instantly, wait a few ms discharge common coil.
  4. Repeat step 3 at common coil currents 7 kA, 8 kA, 9 kA, find I_Q. Repeat the same with CC current going down.
  5. If time permits, perform electromagnetic cycling of bigbox.
  6. Repeat test with I_{CC} 9 kA.

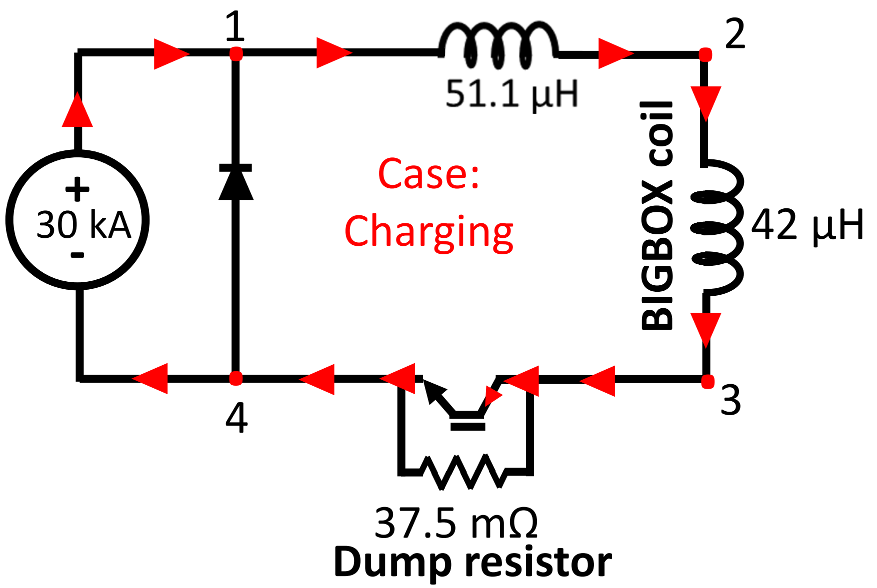
Simplified power circuit

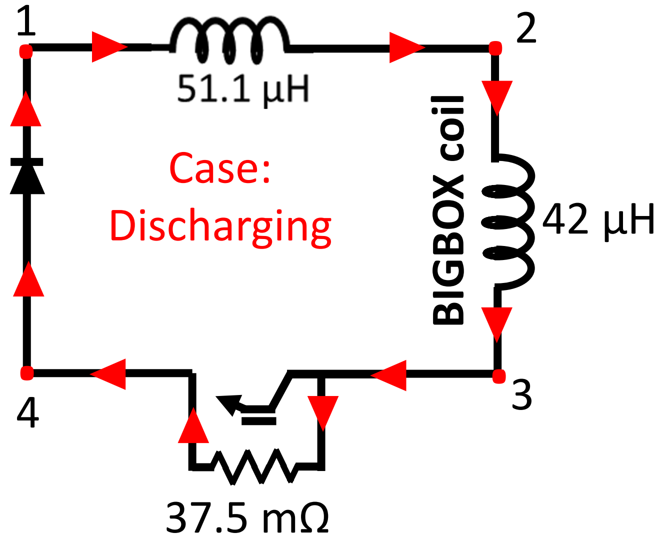
4 kA manual trip test on the BIGBOX coil

$$V_{PSI} = 37.5\ 10^{-3} \times 4\ 10^{3} \times \frac{42}{42+51.1} \approx 68\ V$$



Drop 1600 A in 1 ms => 1.6 e6 A/s

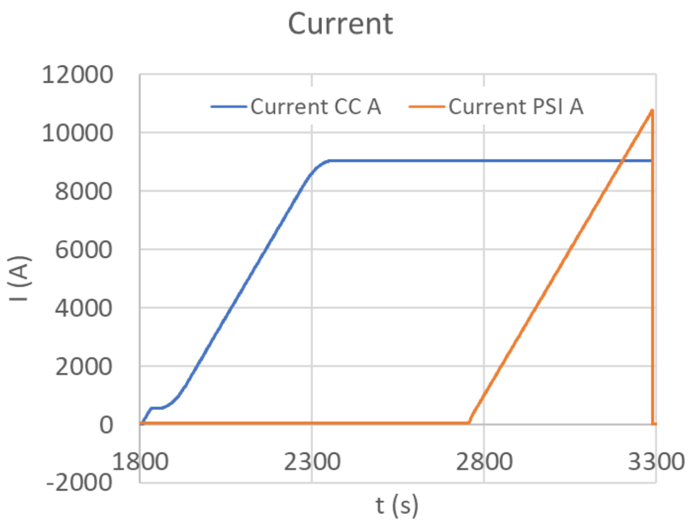


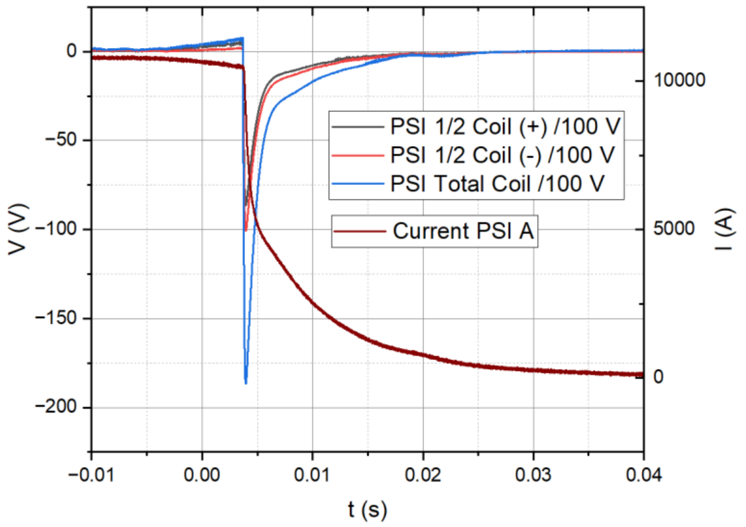


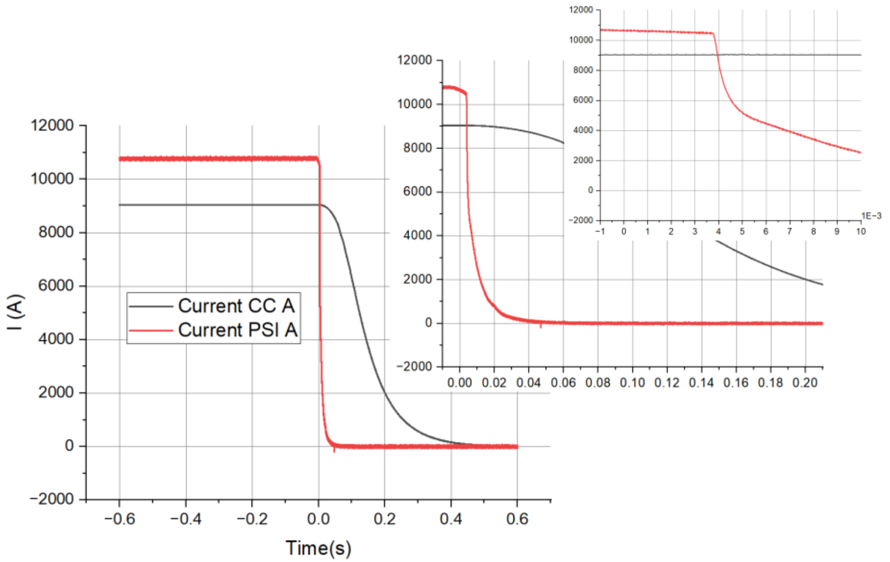
$$V_{PSI} = 37.5\ 10^{-3} \times 10.8\ 10^{3} \times \frac{42}{42 + 51.1} \approx 183\ V$$

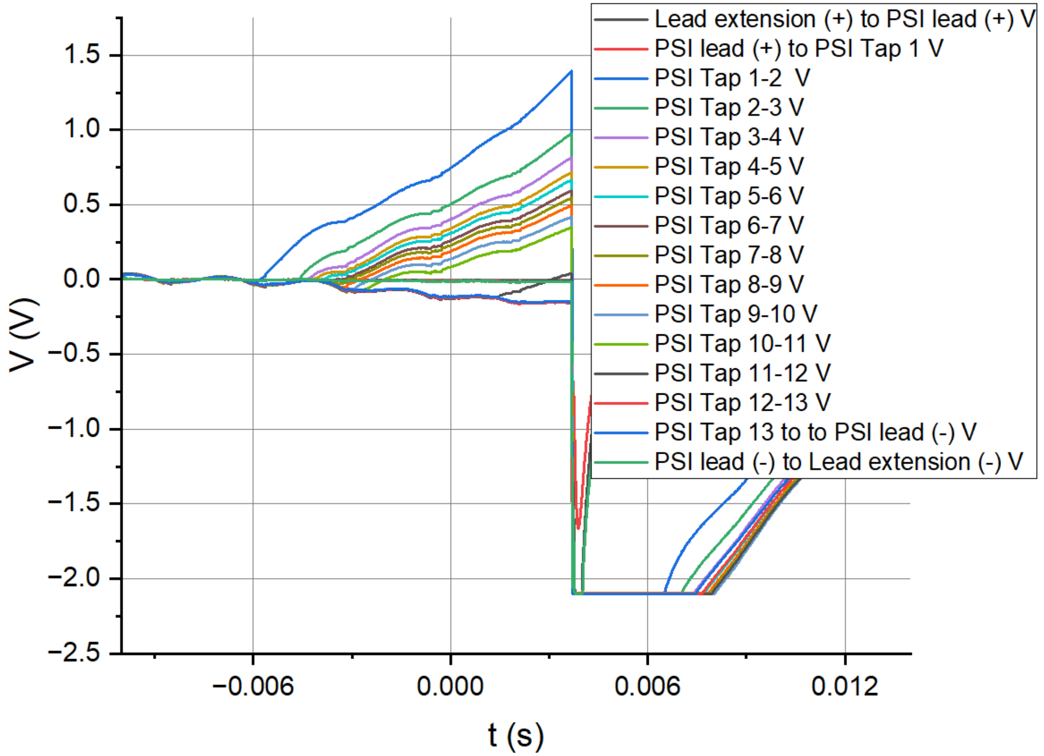
Experiment #6

I_{CC} = 9.04 kA
I_{PSI} = 10.77 kA
B_{CC} = 8.92 T (computed)
B_{PSI} = 3.28 T (computed)
B_{total} = 12.2 T









Main Results

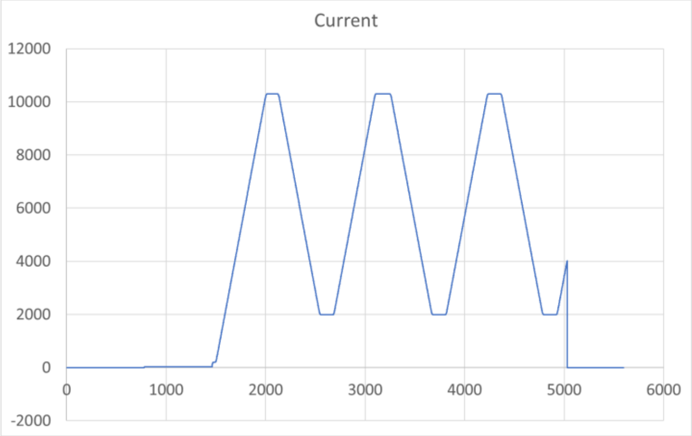
<u>Abbreviations</u>

I_{CC}= current in common coil, B_{CC}= magnetic field in common coil

I_{BB}= Quench current in bigbox coil

Run #	I_{CC} (kA)	I_{BB} (kA)	B_{CC} (T, estimated)
1	7.195	12.979	7.15
2	8.04	12.118	7.97
3	9.124	10.845	9.00
4	8.0393	12.06	7.96
5	7.0398	13.359	6.99
6 - 9	9.0	10.3	8.90
10	9.0395	10.769	8.92

EM cycling



There was a trip during the fourth electromagnetic cycle

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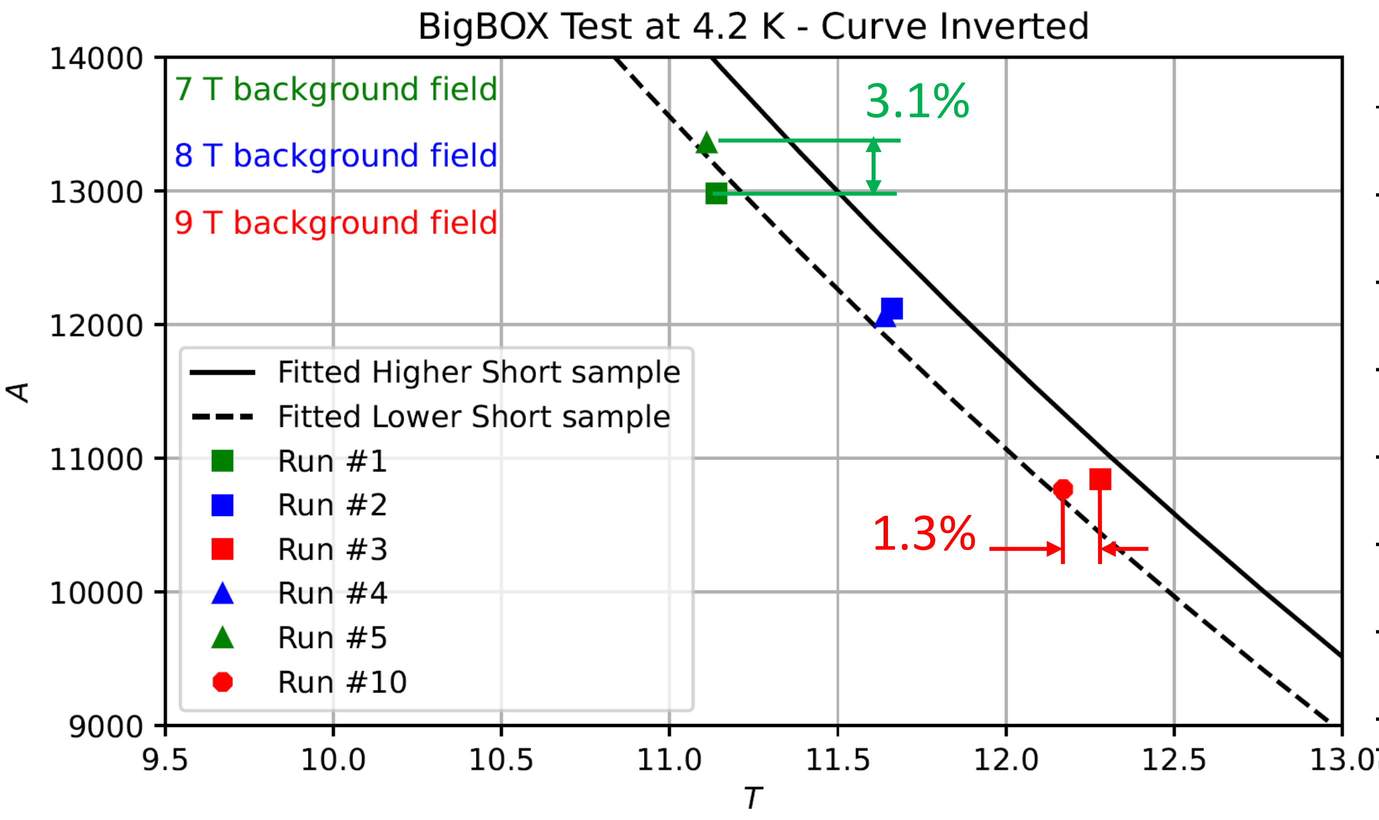
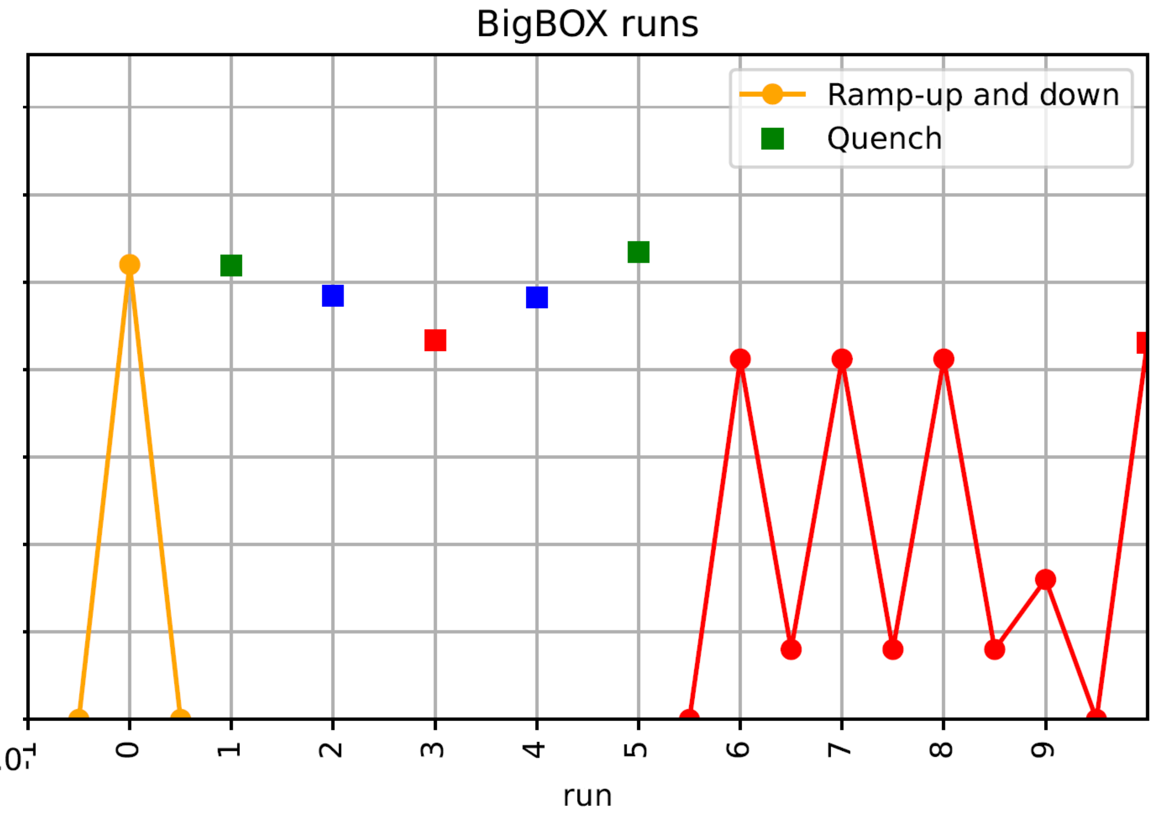
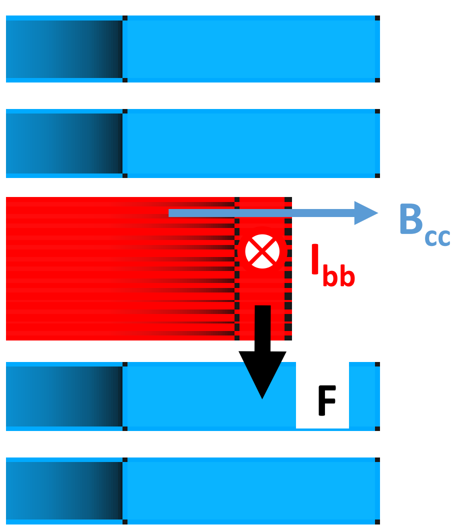
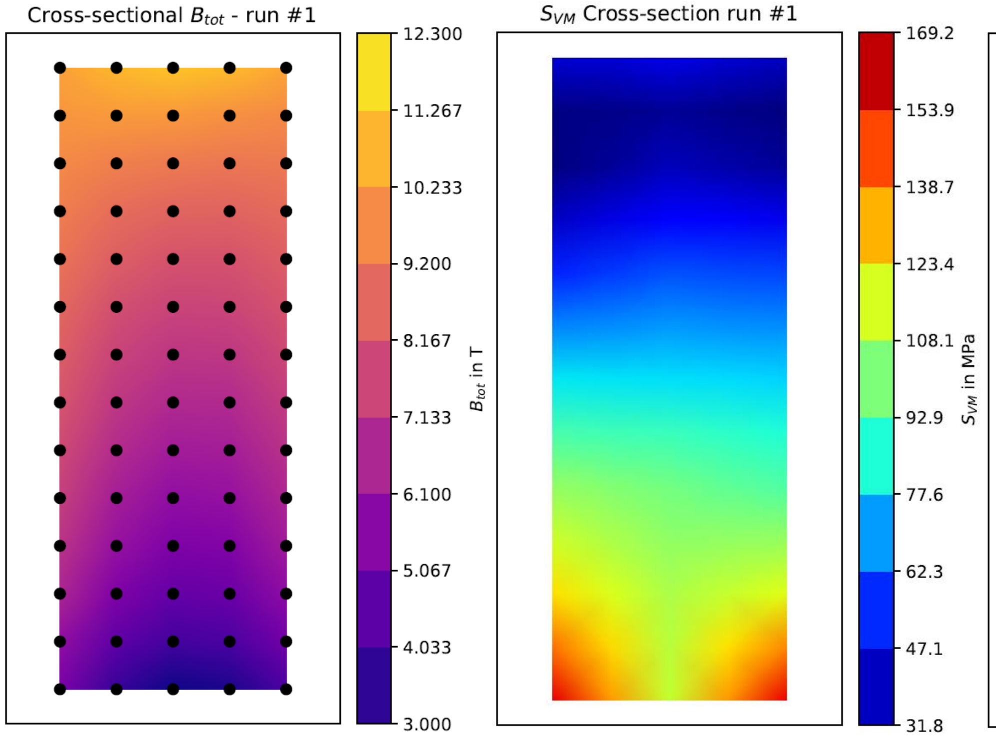
Training performance



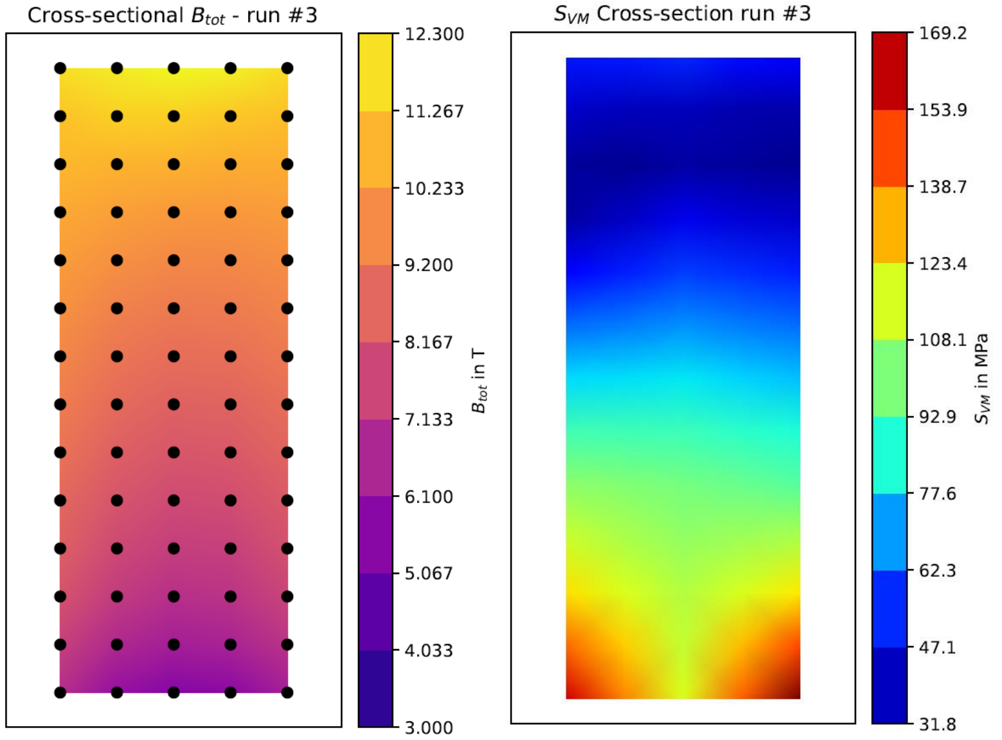


Stress and Field distributions





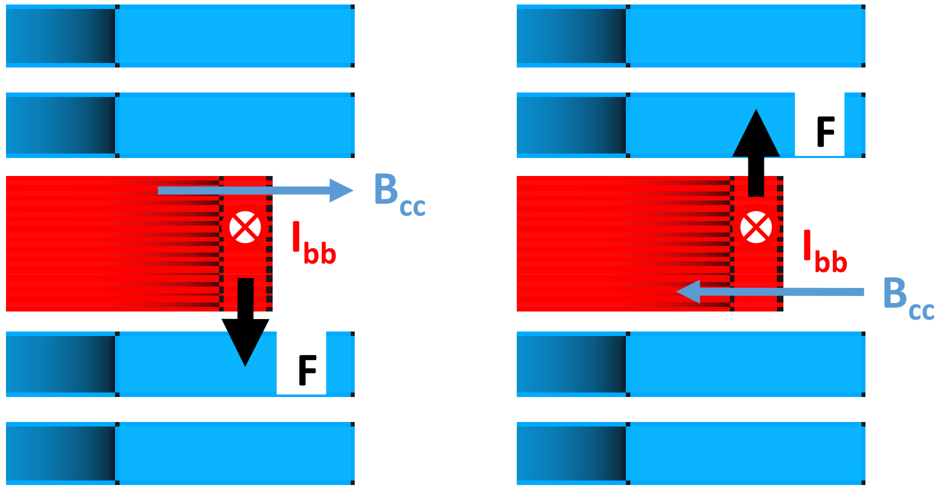
7 T background field

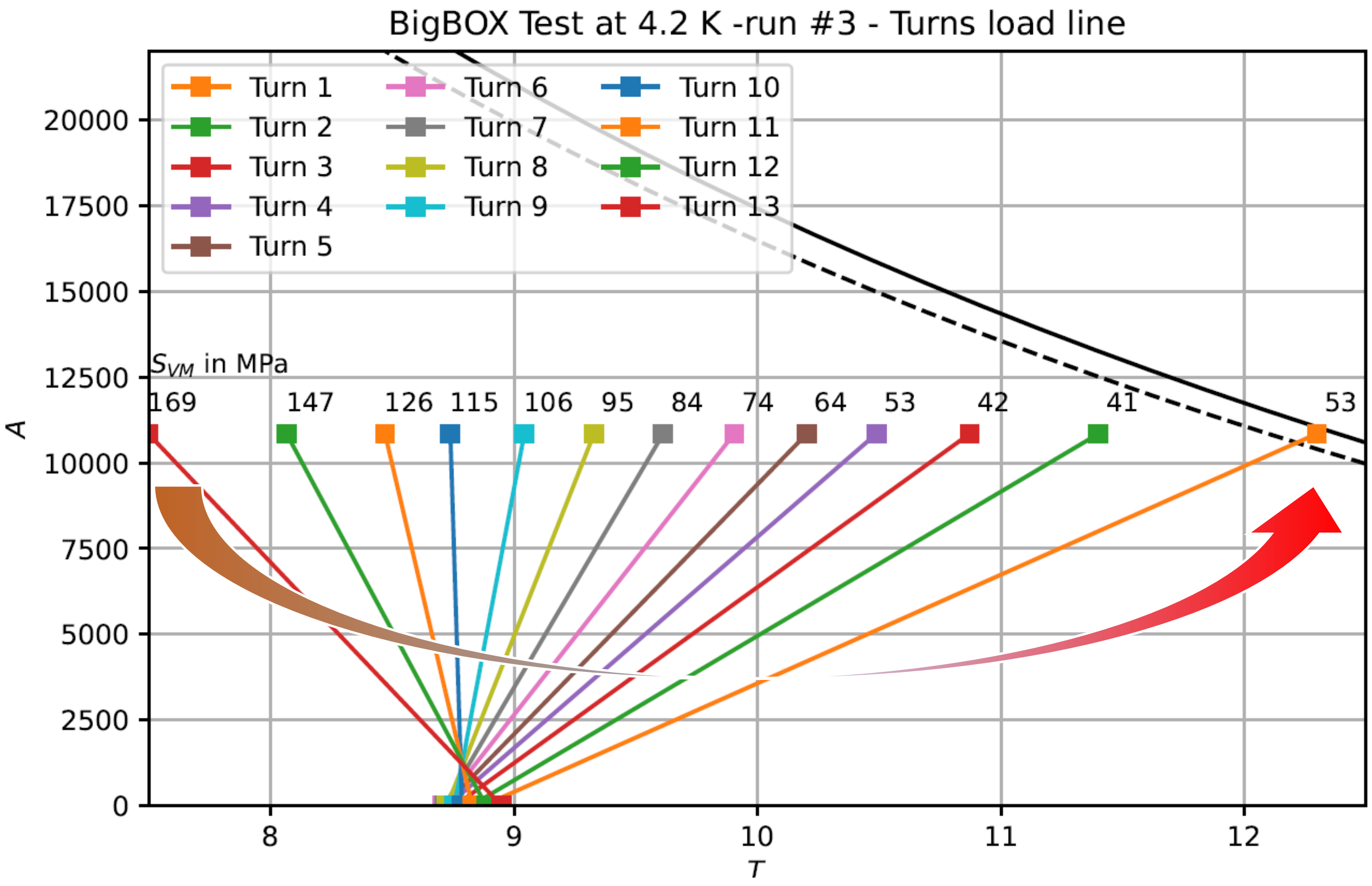


9 T background field

By increasing DCC17 background field, BigBOX stress increases and margin decreases.

BigBOX as a tool for degradation studies



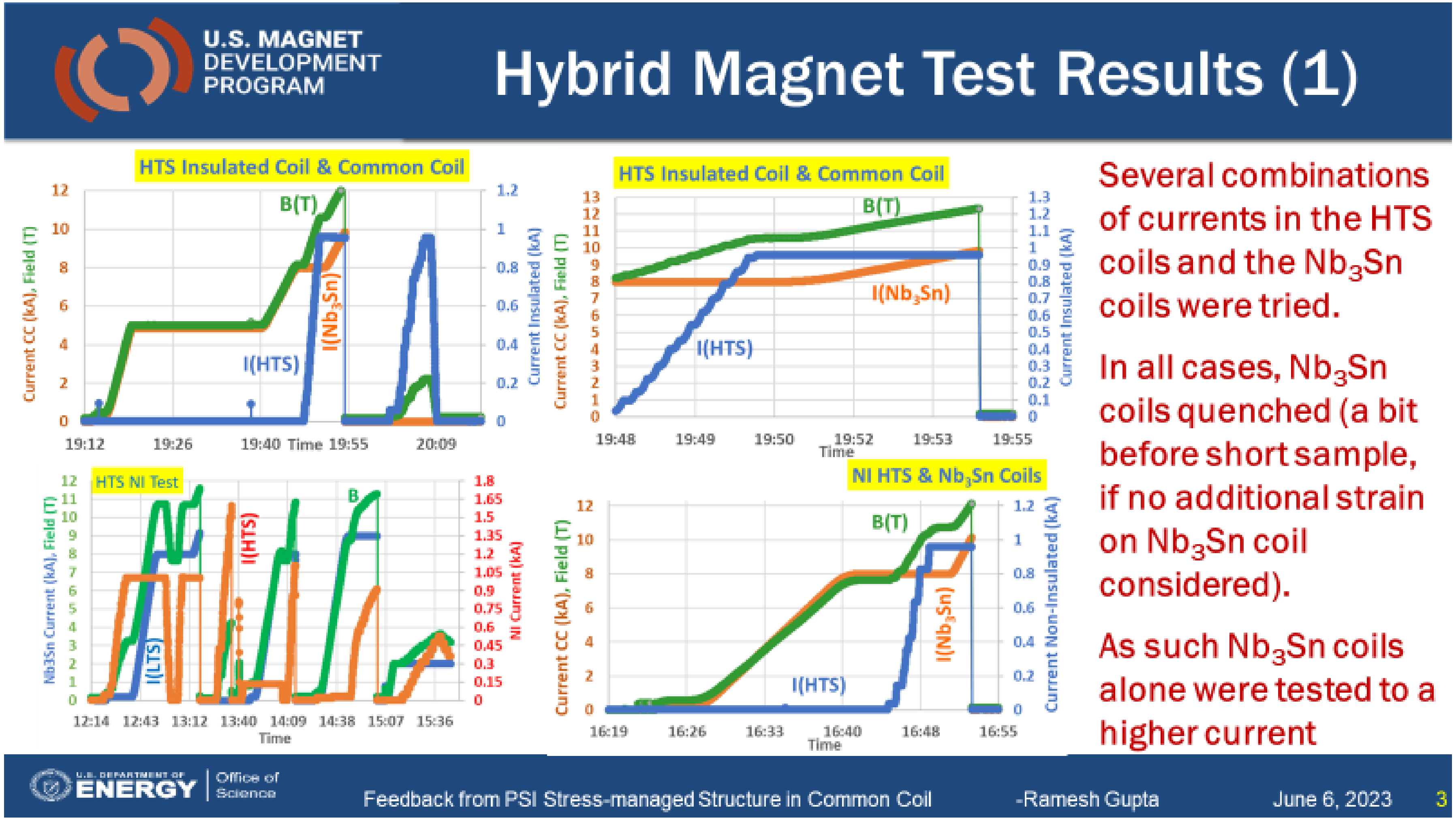


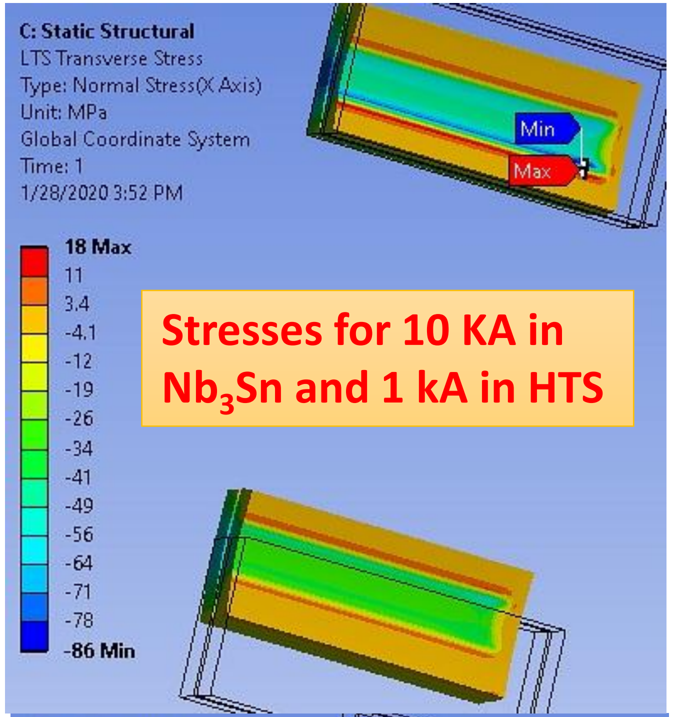
- First, the coil is powered and the distribution of stress is the one given in the plot.
- After a number of cycle, the background field or BigBOX current direction is inverted.
- Now, the new high-field turn has a historic of high stress. Is the coil be able to go to short-sample again?

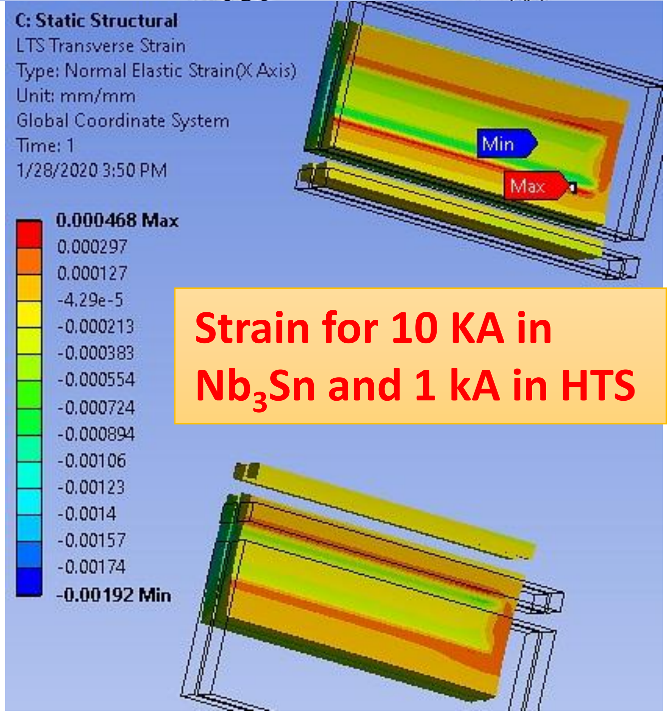
Agenda

- Magnet R&D Approach for High Field Magnets (R. Gupta)
- Nb_3Sn Coil (BigBOX) integration into DCC17 Magnet (D. M. Araujo)
- Test Setup, Quench Detection and Results (M. Kumar)
- Analysis of Results and Conclusions (D. M. Araujo)
- DCC17 Performance with Stress-management Structure (R. Gupta)

Need for Stress Management with Insert in DCC017





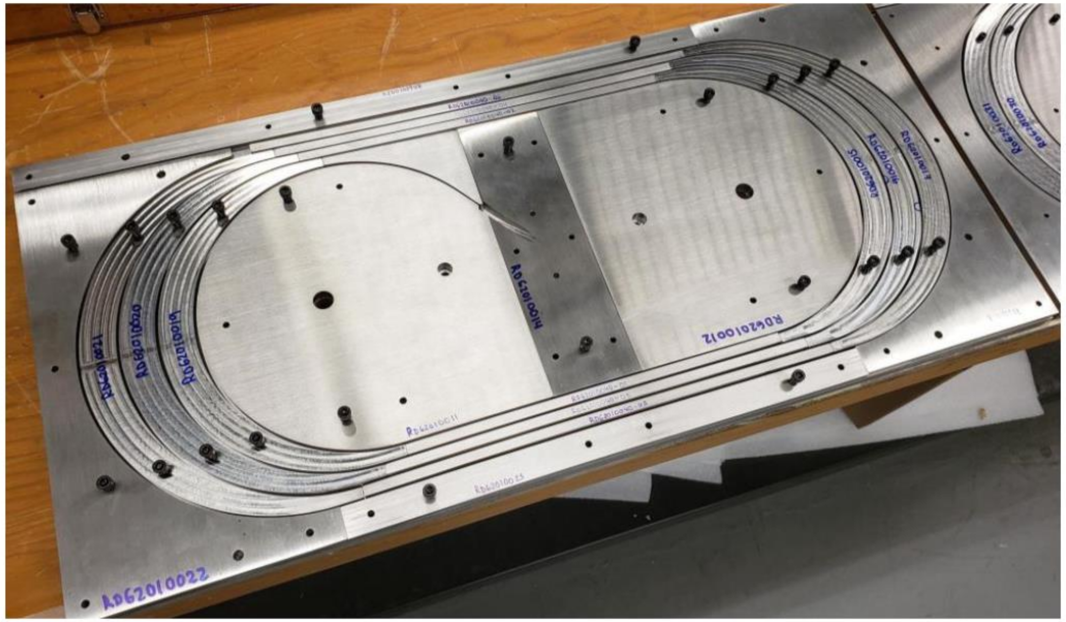


Theory: Local stresses/strain in Nb_3Sn coil limited the performance of Nb_3Sn coil (and hence of HTS/LTS hybrid dipole test in 2020 to 12.3 T)

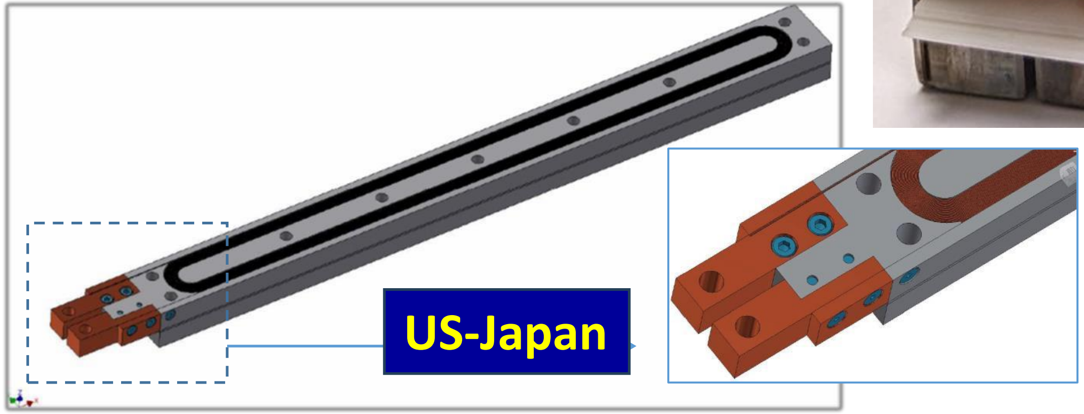
Solution and test: reduce/diffuse local strain with intermediate structure on insert or pads in between (stress management) – incorporated in future tests

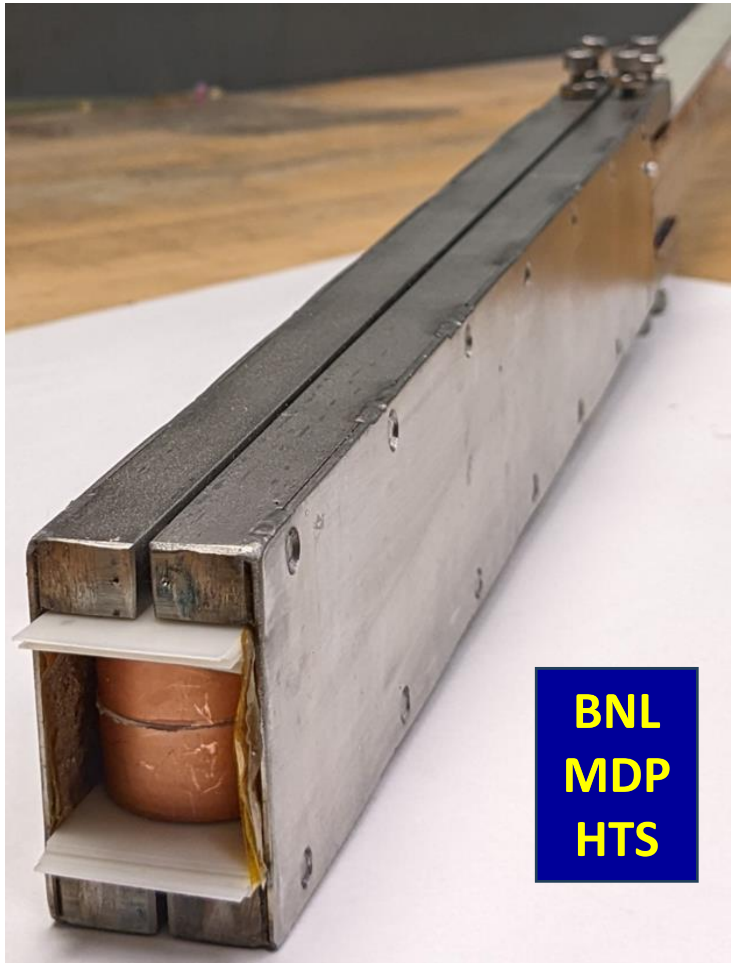
Stress-managed Inserts in the Common Coil Dipole

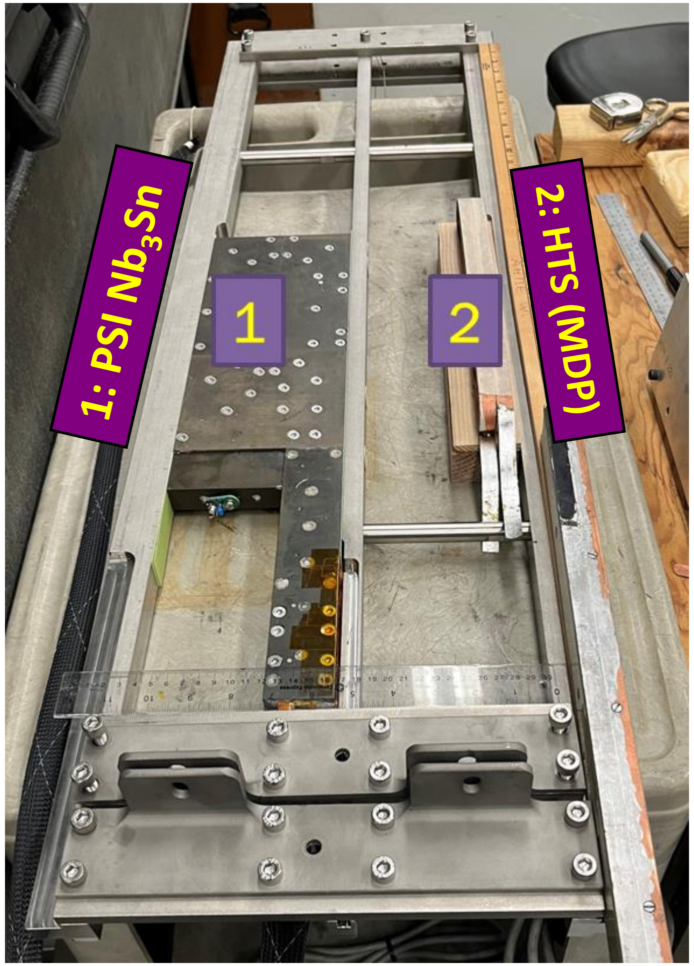
All inserts in DCC017 now have a structure around the coil



CORC



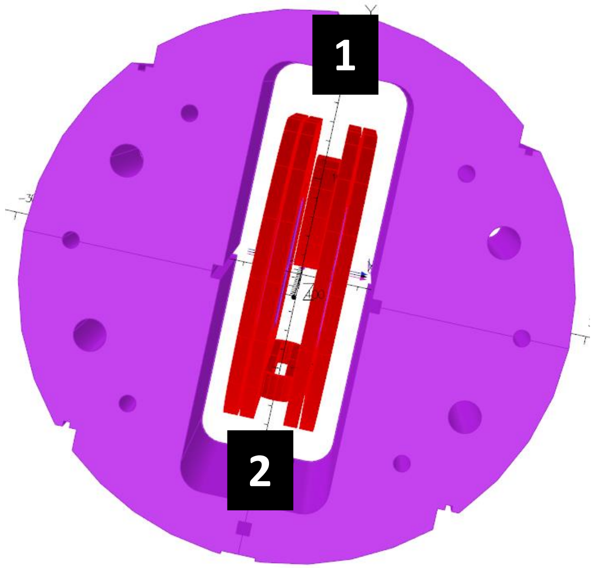


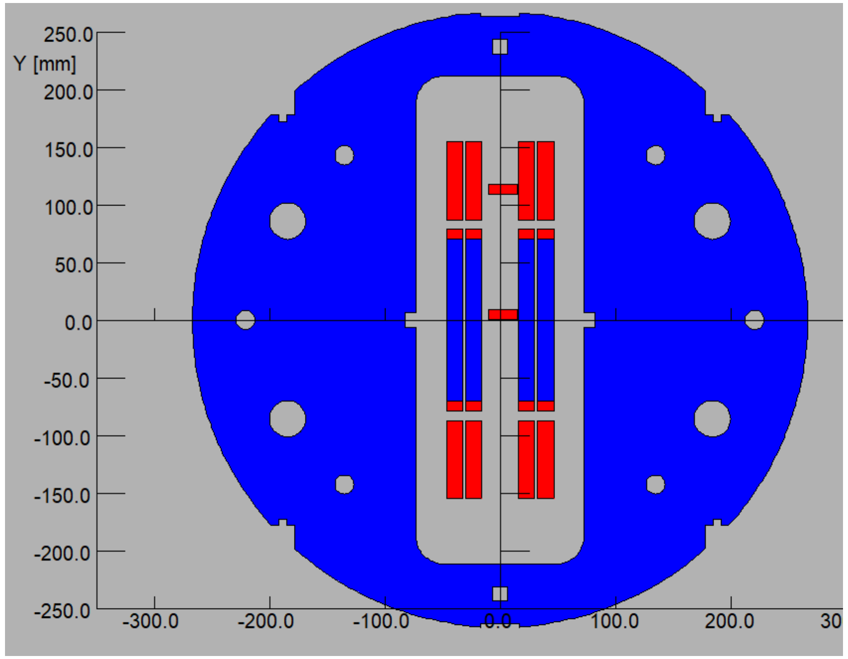


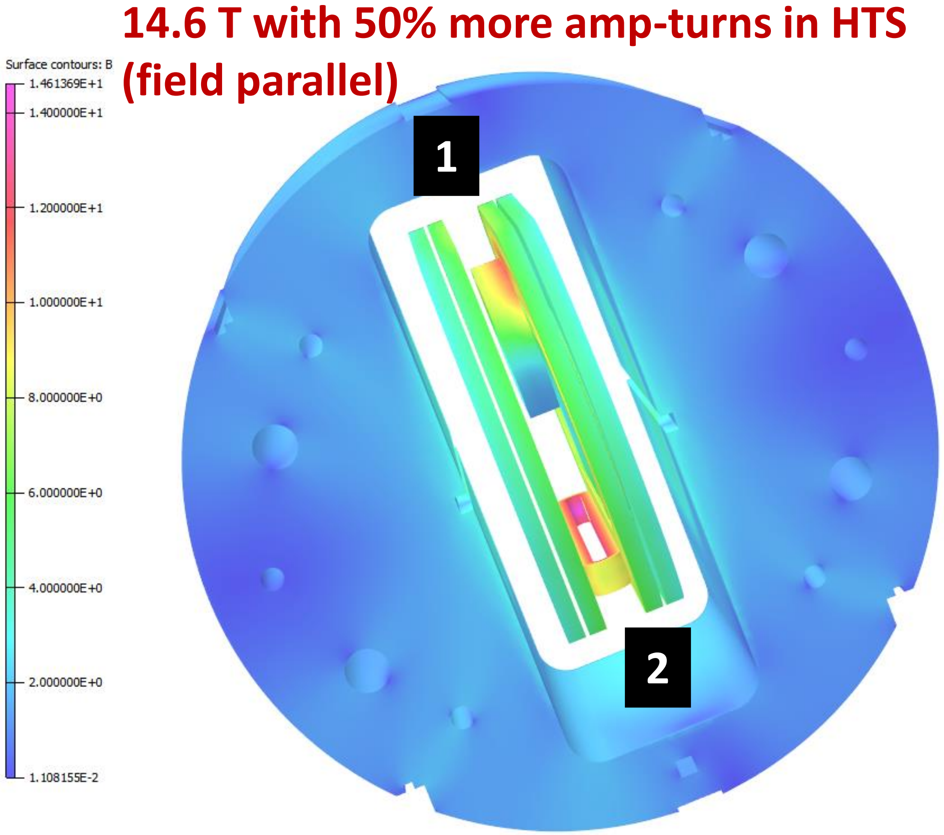
PSI (Nb_3Sn) and MDP (HTS)

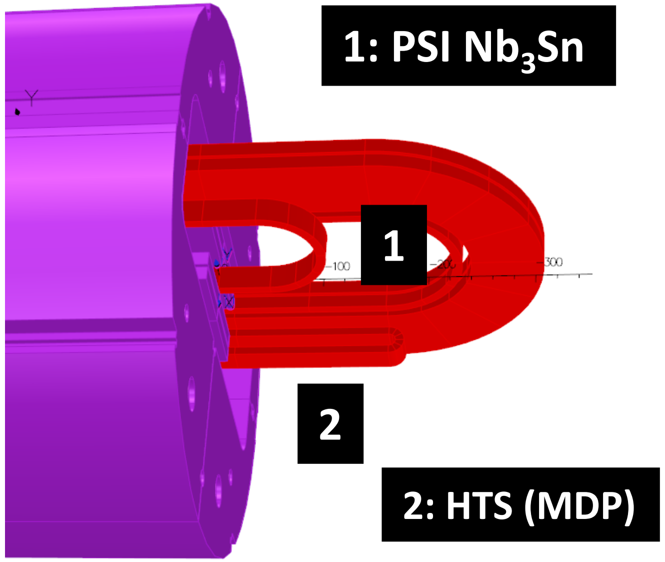
~2 mm plate on one side and ~4 mm on the other side

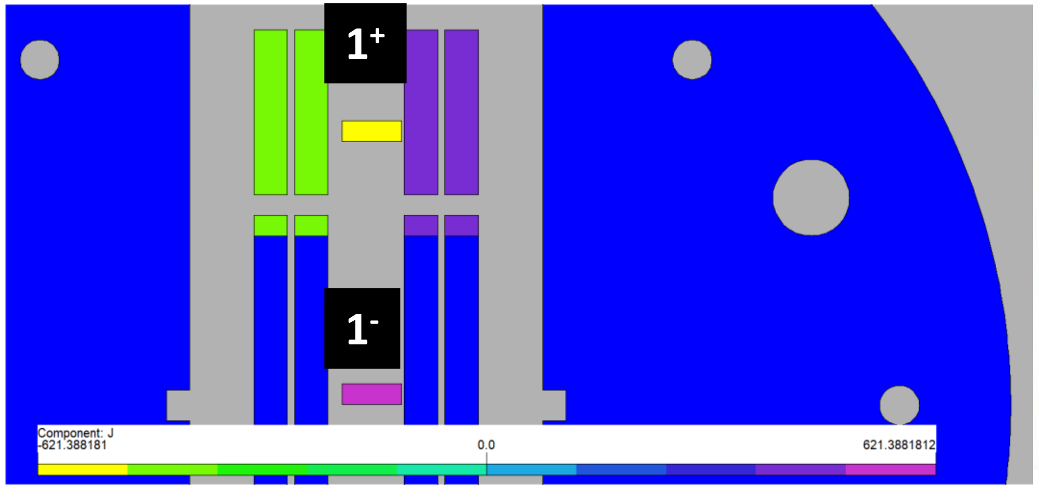
OPERA Models of Nb_3Sn PSI Coil and HTS MDP Coil in Common Coil Dipole DCC017

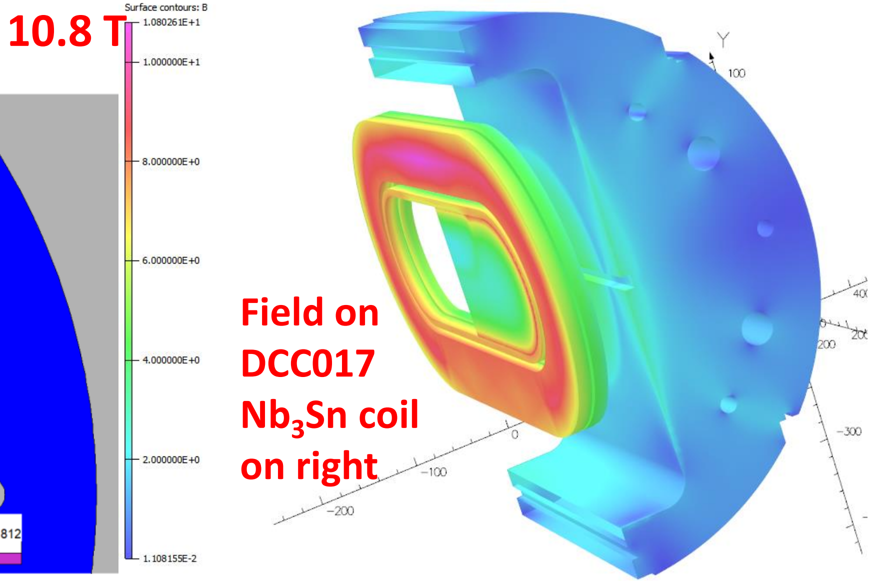






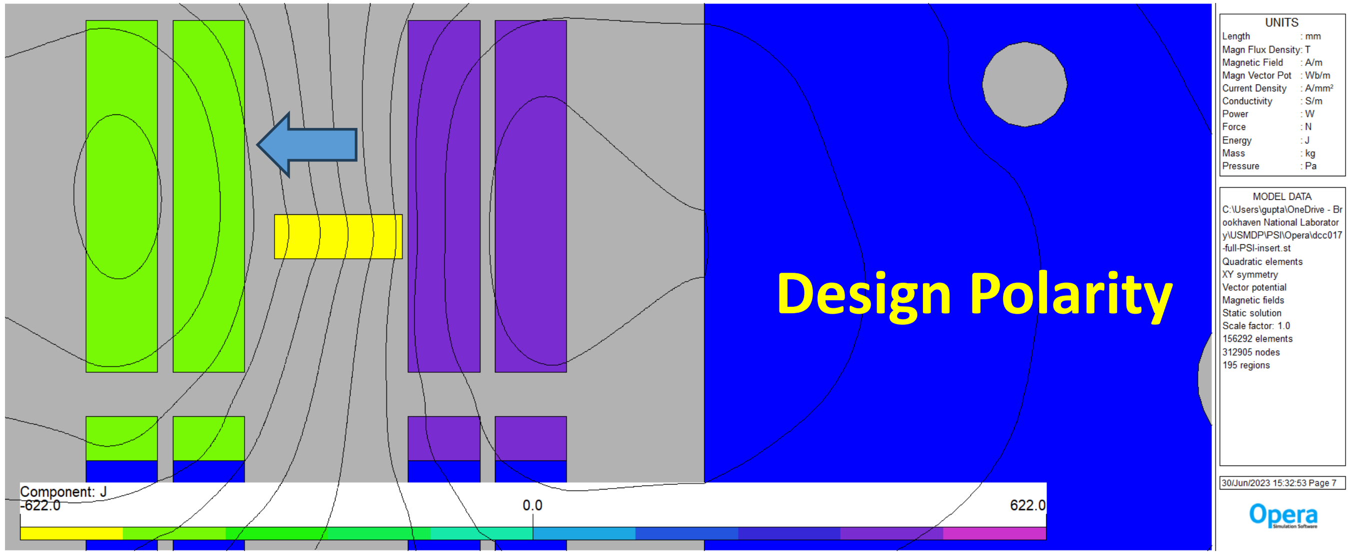


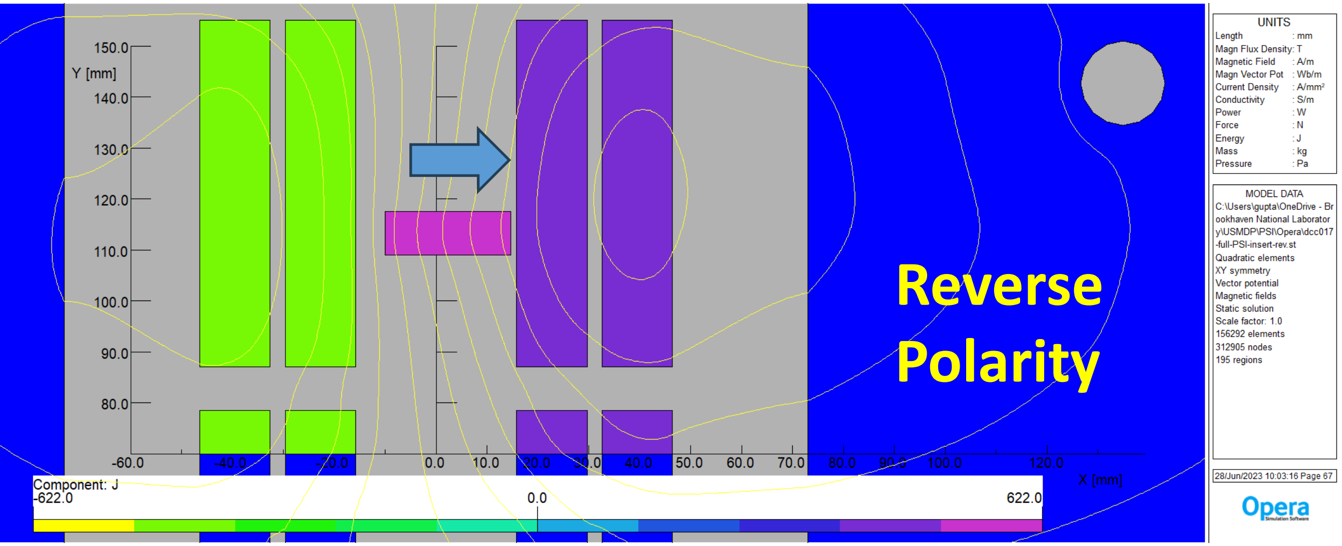




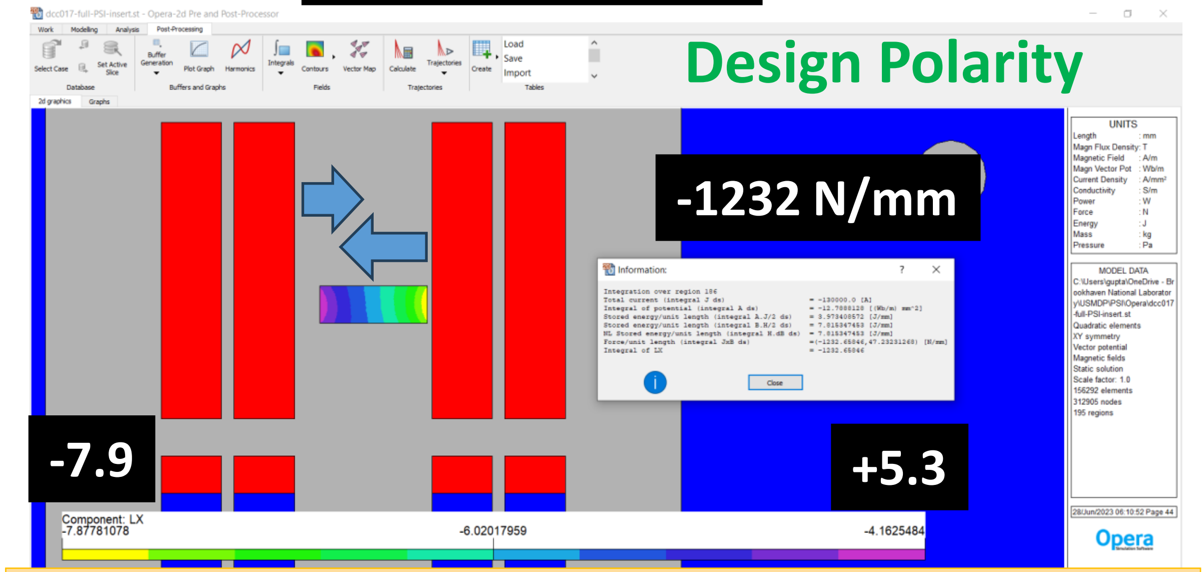
Lorentz Forces on PSI Insert Coil (with design & reversed polarity)

Current density

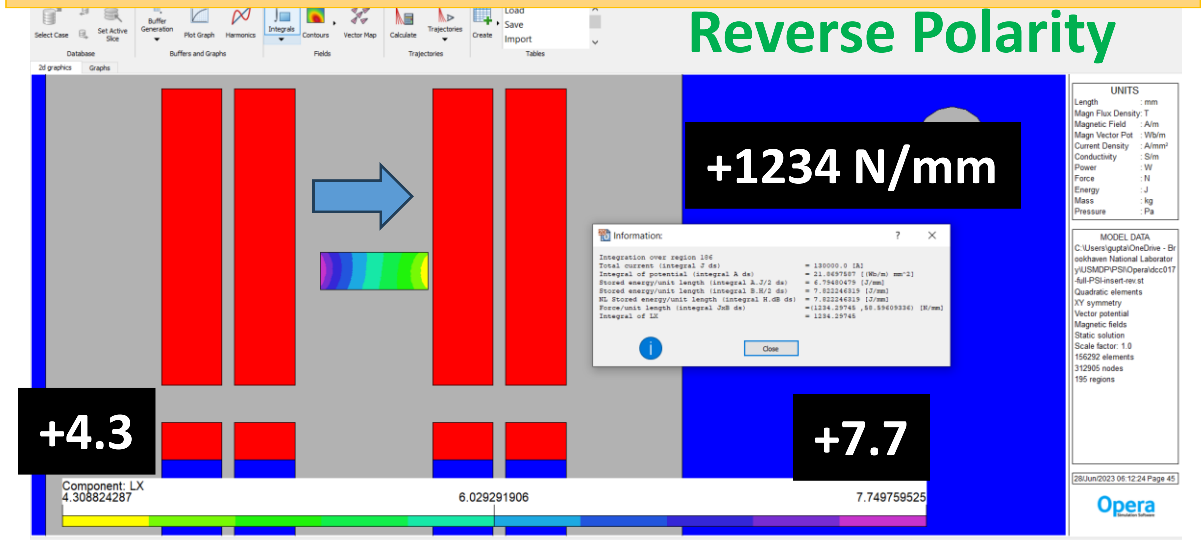




Lorentz force density

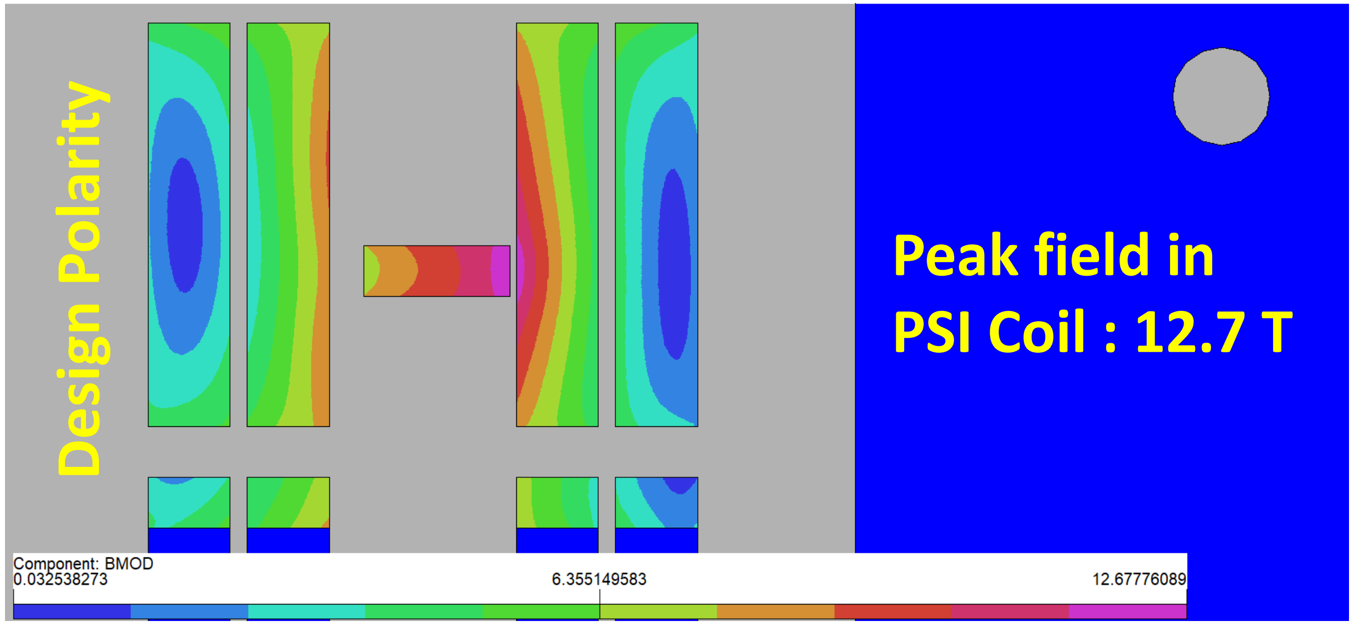


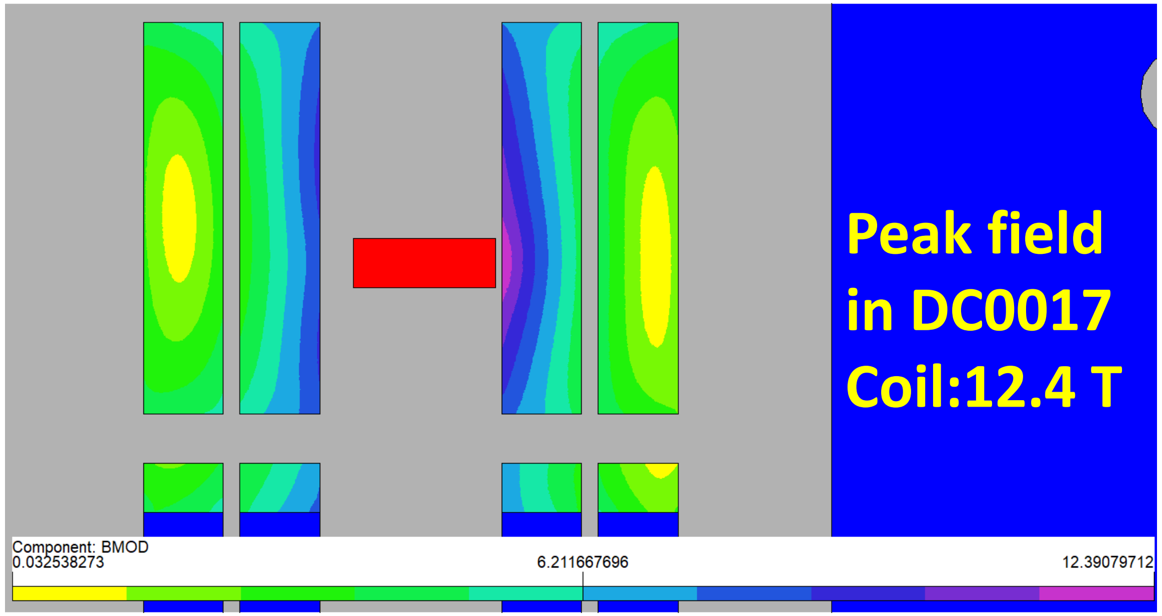
Note: Net forces are about the same in both cases, but PSI coil gets squeezed (stressed) more in the design case

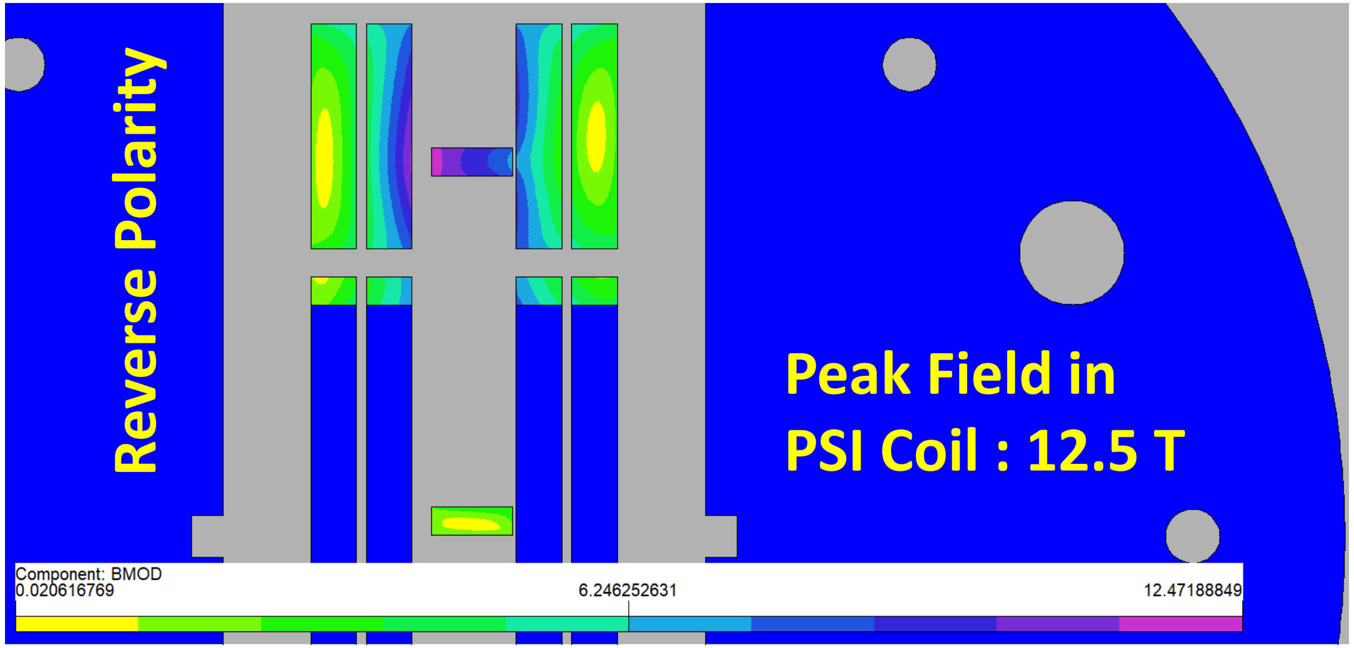


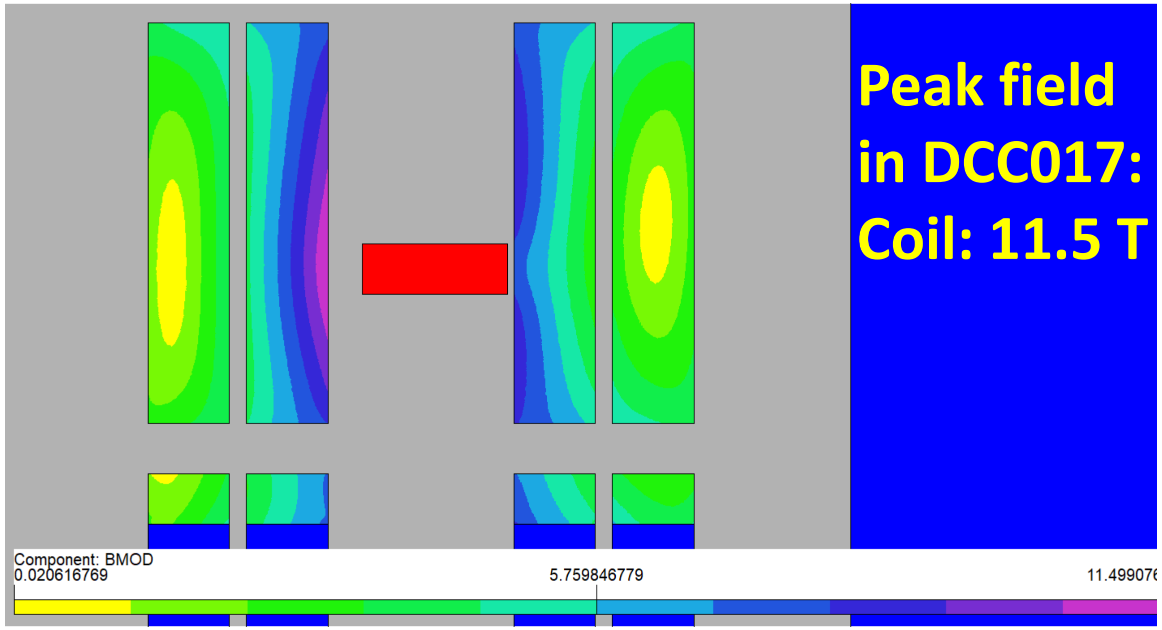
Run 3: DCC017@9.124kA, PSI@10.845

Field on PSI Coil & DCC017 Coil (with design & reversed polarity)









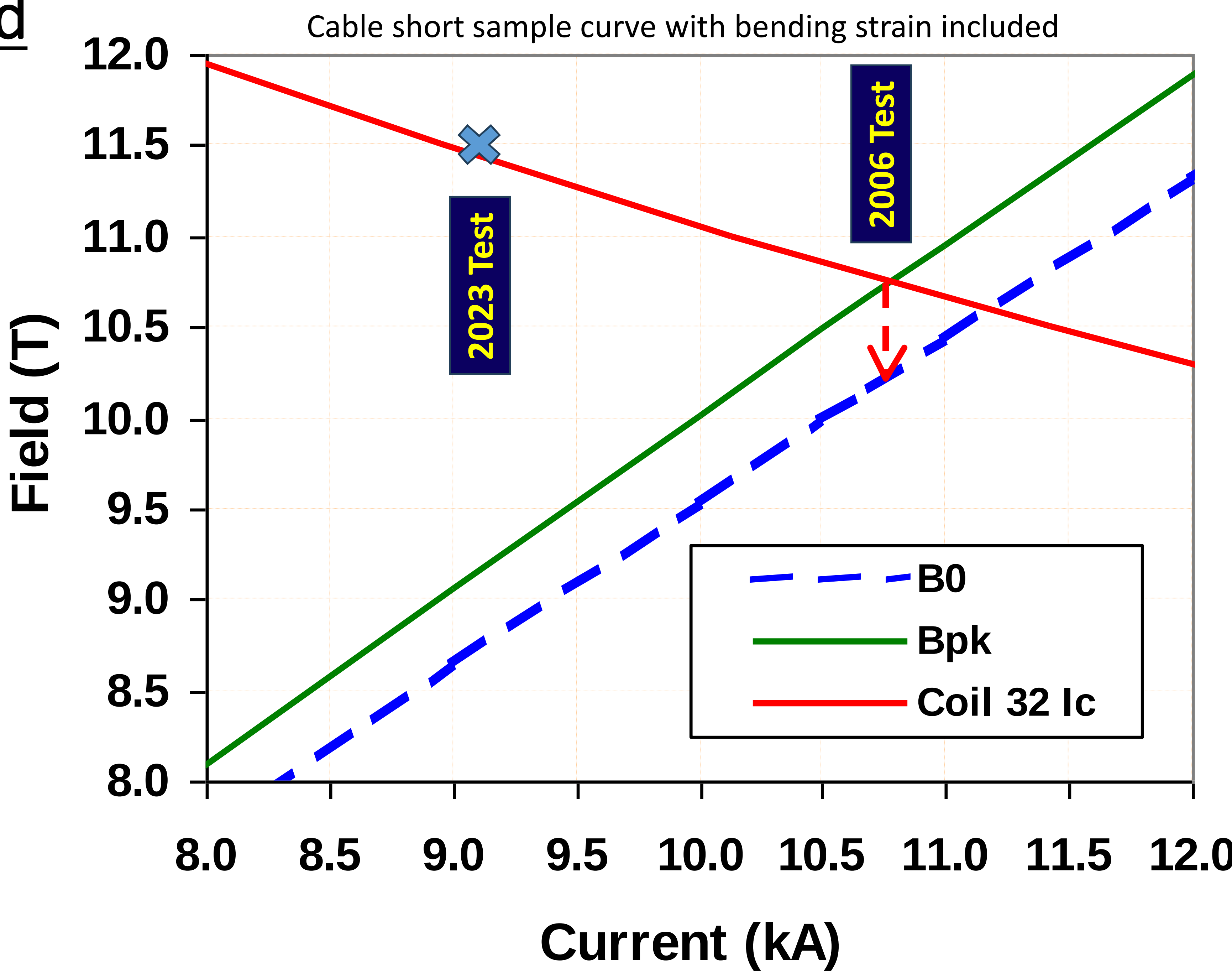
Short Sample Reached

DCC017 Short Sample Calculations with PSI Insert

I=9.1 kA
B_{pk}=11.5 T

DCC017 reached 11.5 T (earlier was 10.8 T)

Value with the design polarity ~12.3 T



Acknowledgment

- BNL testing and magnet design teams
- BNL for providing LARP cable for the produced coil
- LBNL colleagues for the useful discussion on the cable HT
- PSI Magnet section for supporting the realization and initial tests of the demonstrator

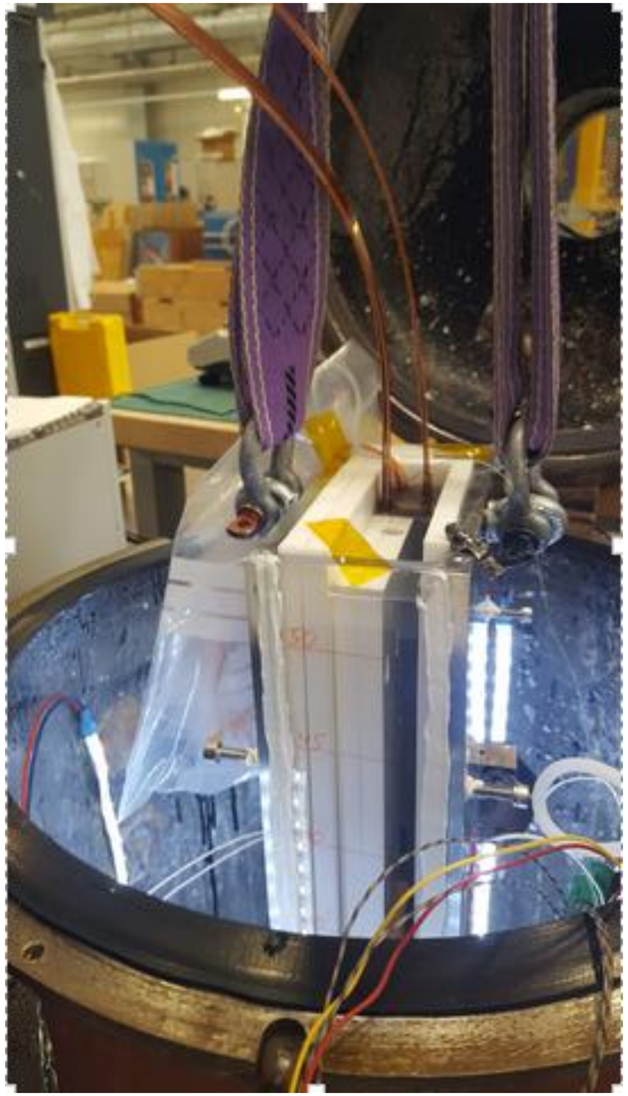
- Funding for this collaboration came from PSI, CHART, CERN-HFM Program and US-MDP

Additional Slides

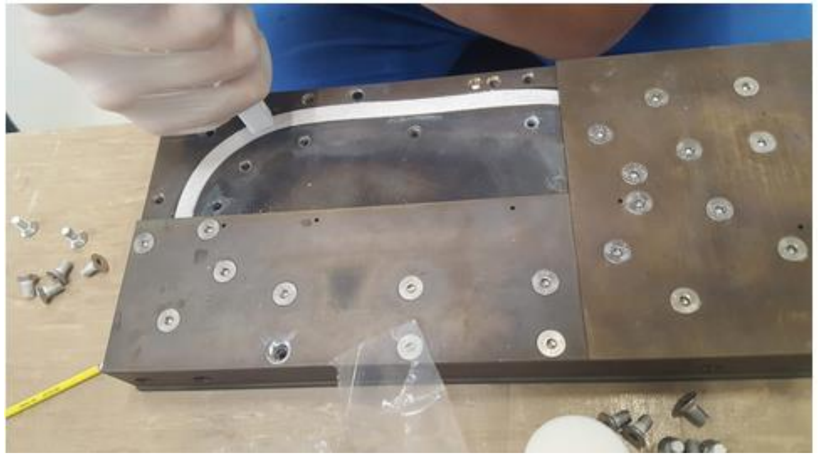
Some pictures of the manufacturing process

- Winding

- impregnation

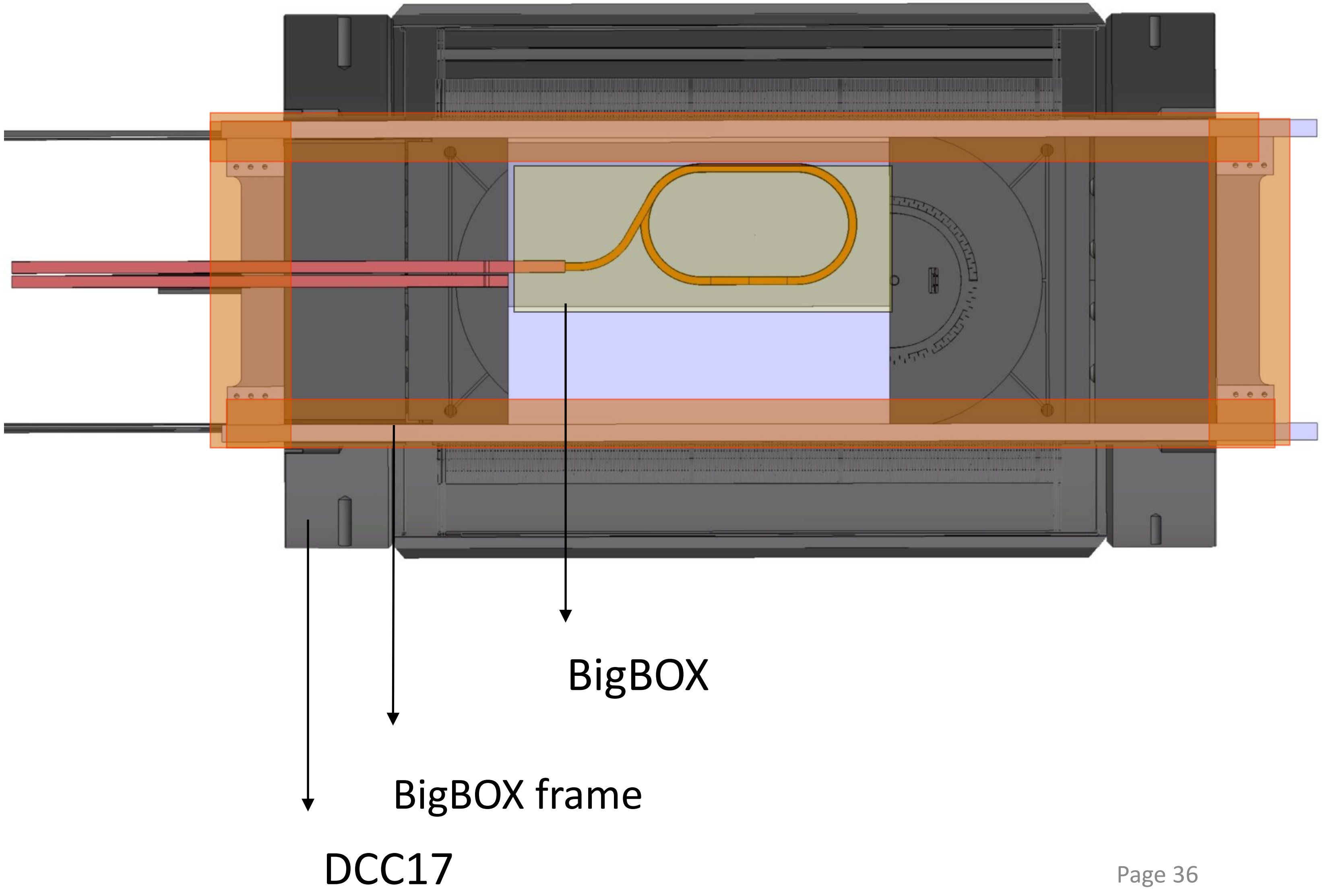


- Closing the thin cover



Scheme during the tests…

- **BigBOX insulated in respect to the Frame**
- Frame could, therefore be in contact with DCC017 structure
- **BigBOX will be insulated from the Common coils**
- **Highpot test box and the Frame (750 V) successfully achieved**



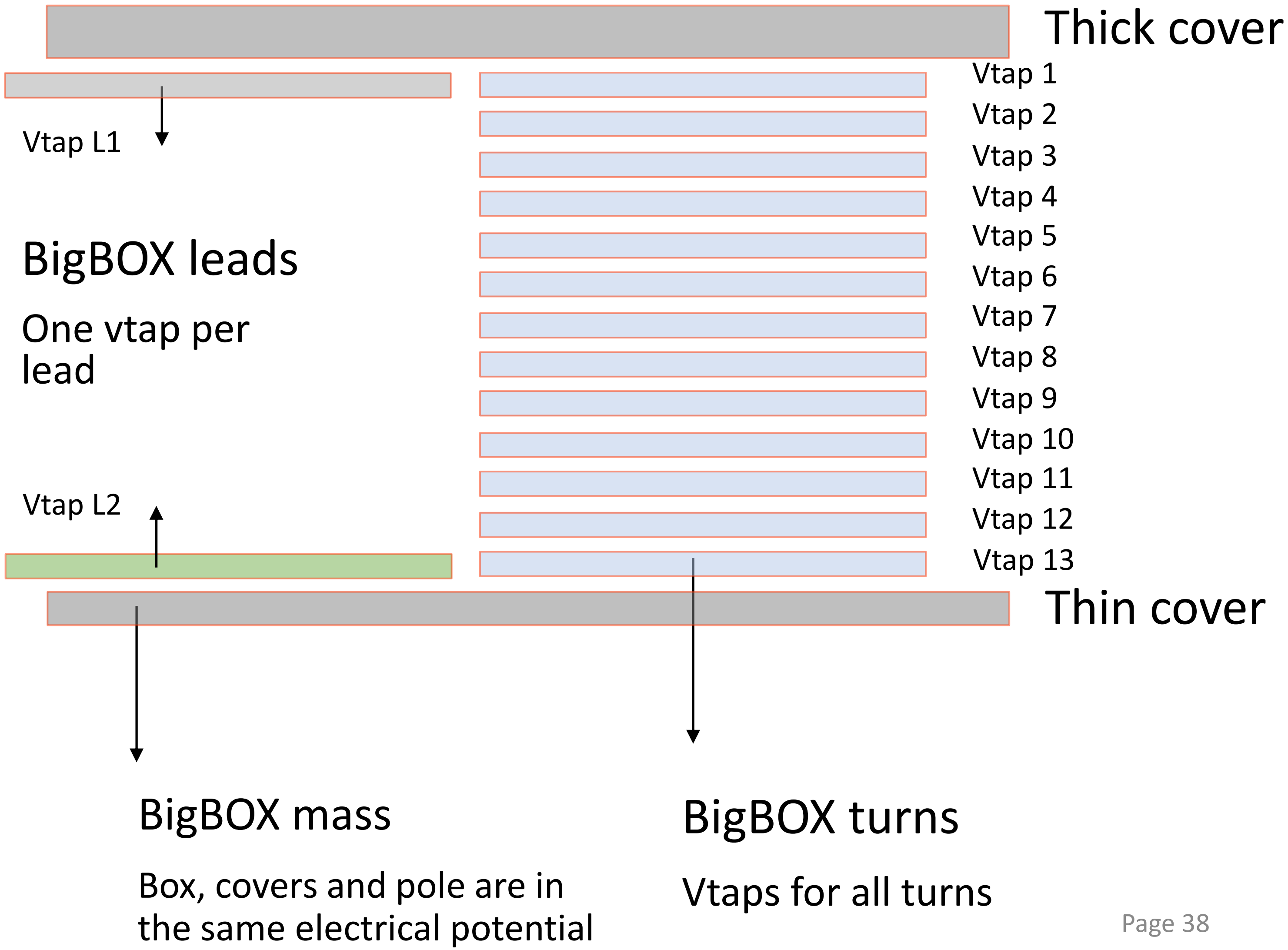
High-pot tests

- Box to Frame

- 100 V: > 100 Gohm
- 250 V: 260 GOhm
- 500 V: 235 GOhm
- 750 V: 233 GOhm

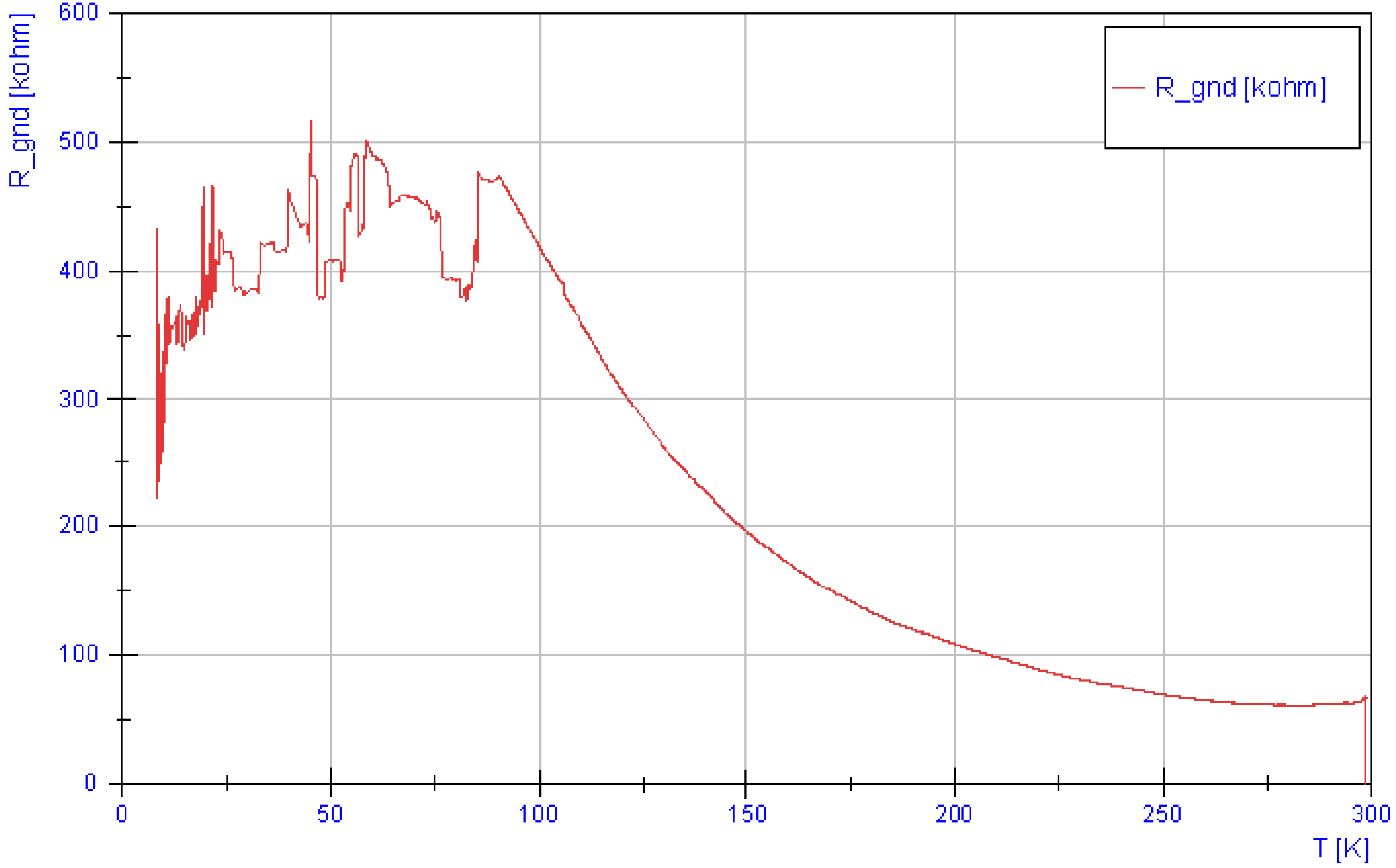
Scheme during the electrical tests and tests

- Latest resistance between coil and box ~57 kOhm
- All boxes components are at the same electrical potential (convers, box and pole)
- Feeding current between L1 or L2 and the mass
- Measuring the voltage drop between vtaps and a reference



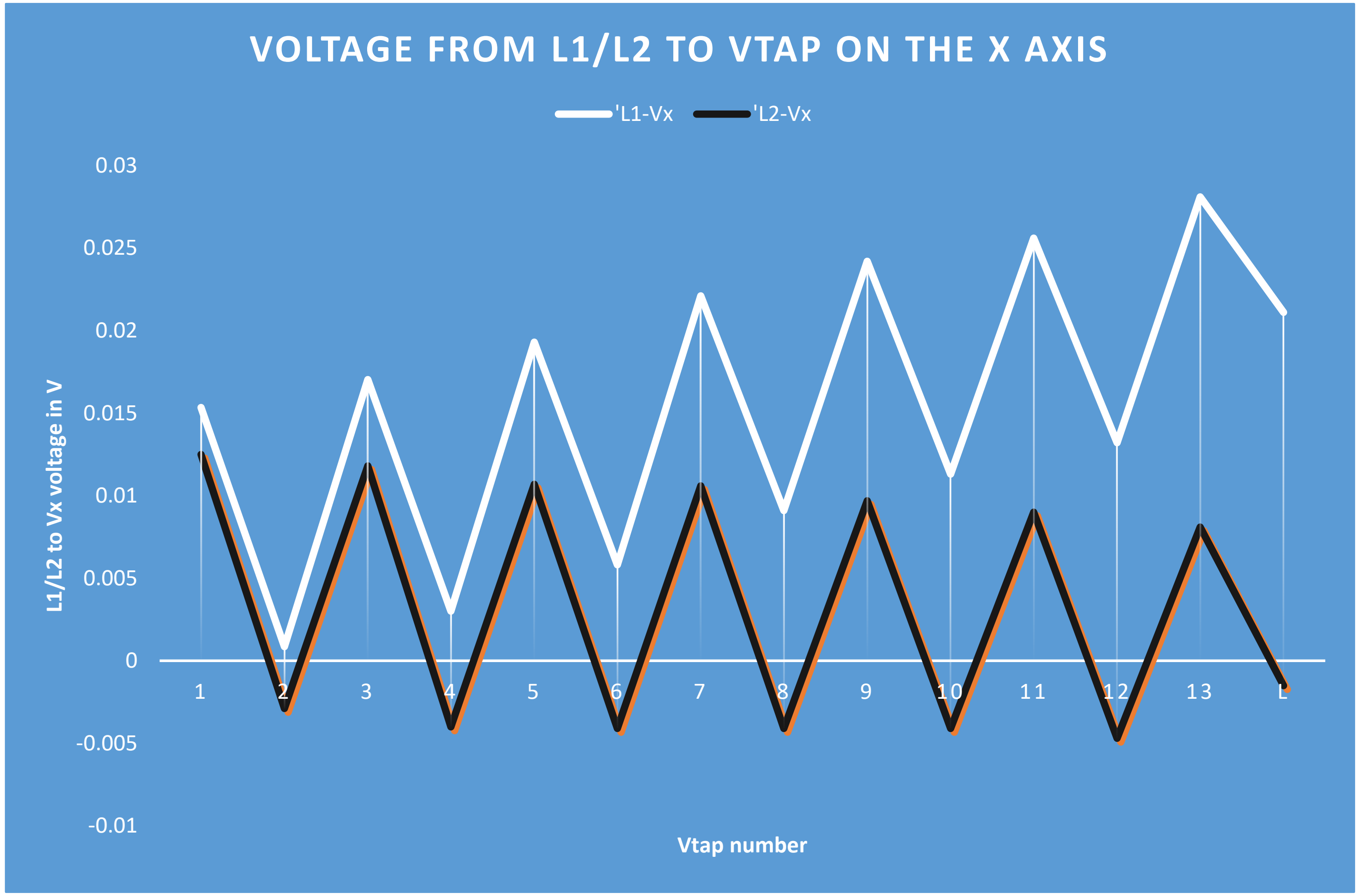
Evolution of resistance during cooling down

- Resistance measured from the coil to the mass
- From about 60 kOhm to 350 kOhm



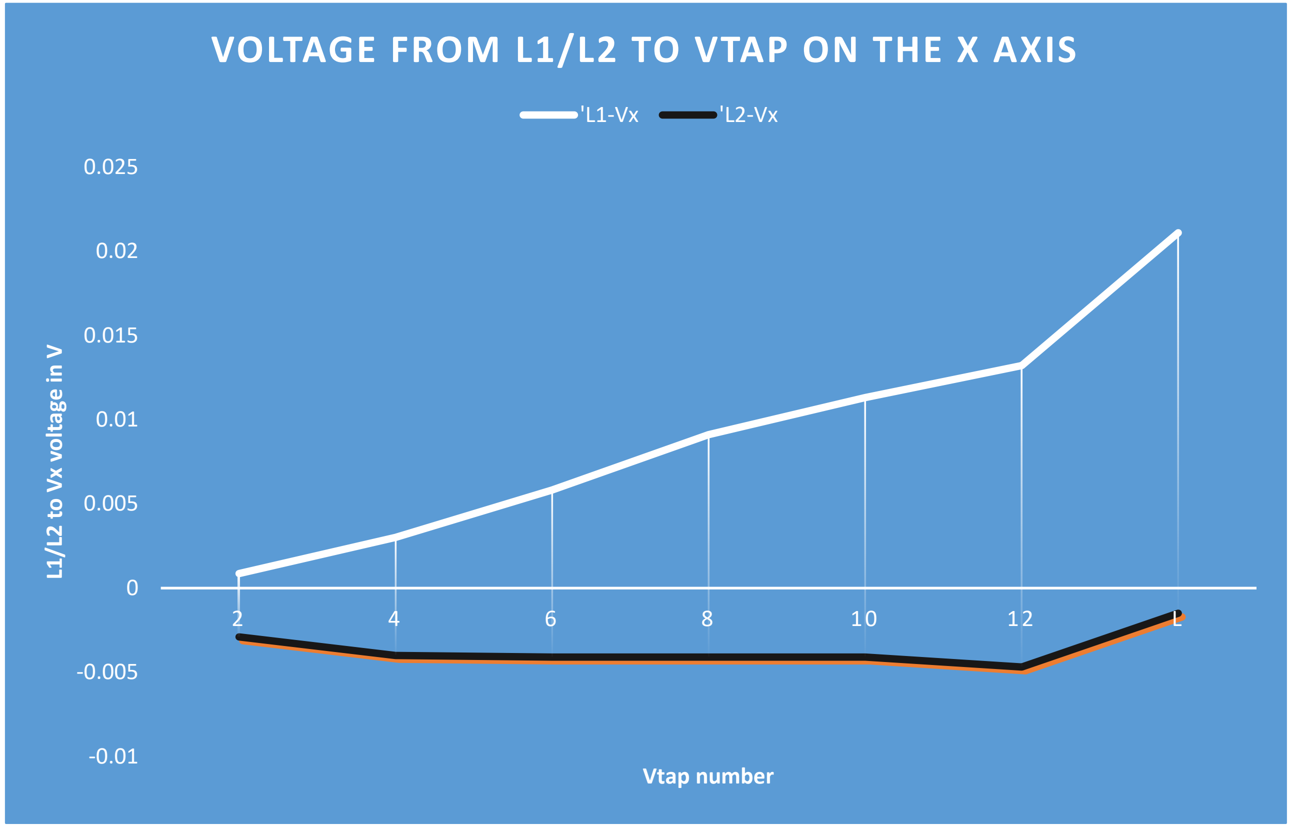
First set of measurements

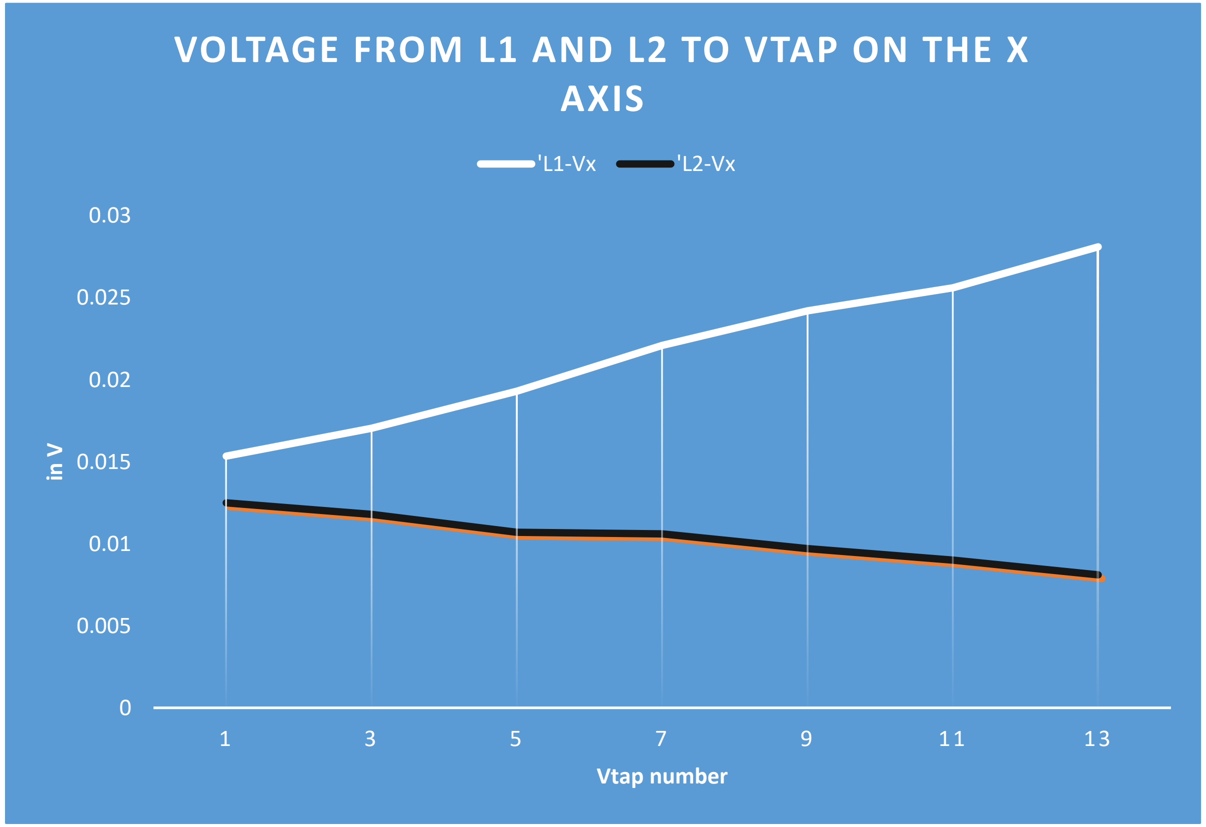
- Current from L1 or L2 and mass: 0.276 mA
- Voltage across the power supply: 13.78 V
- Oscillation between even and odds vtaps
- Let’s look to the vtaps separately



First set of measurements

- Looking to evens and odds vtaps separately

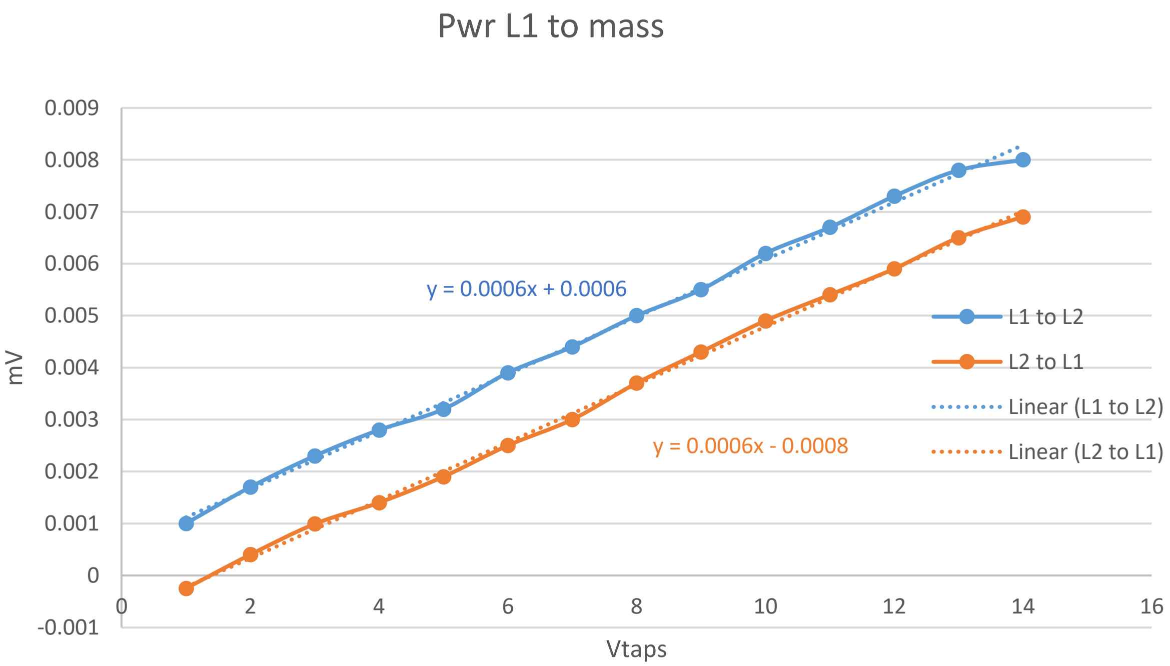


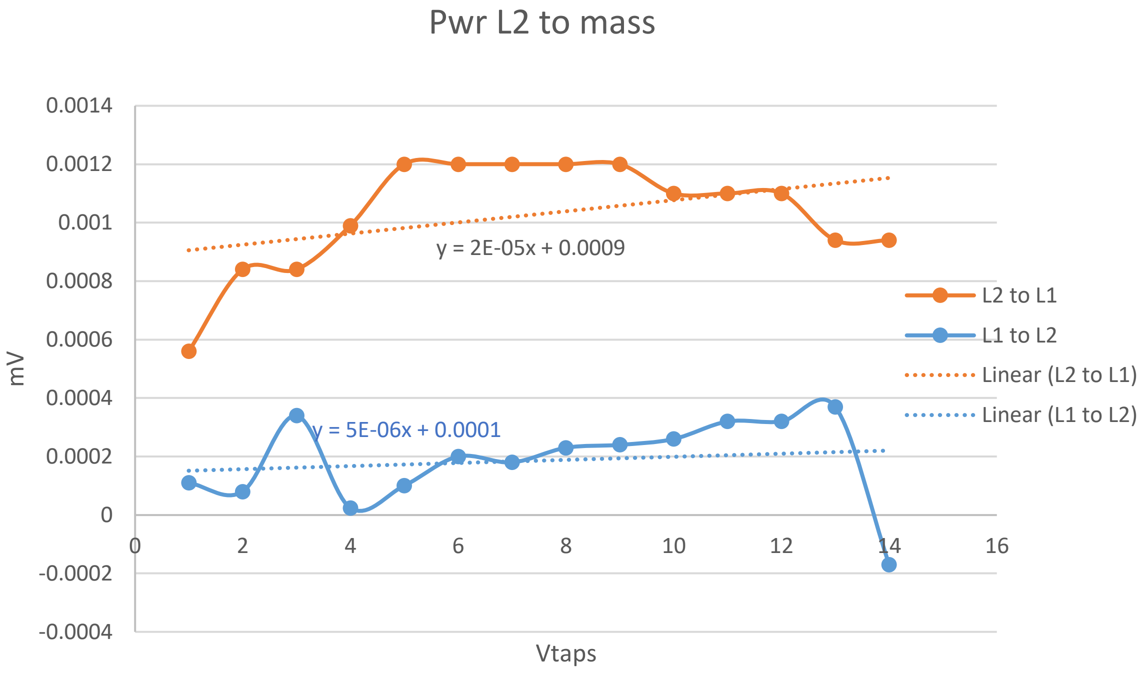


- Current leaking at L2

Measurements

- Oscillation when changing the reference from L1 to L2





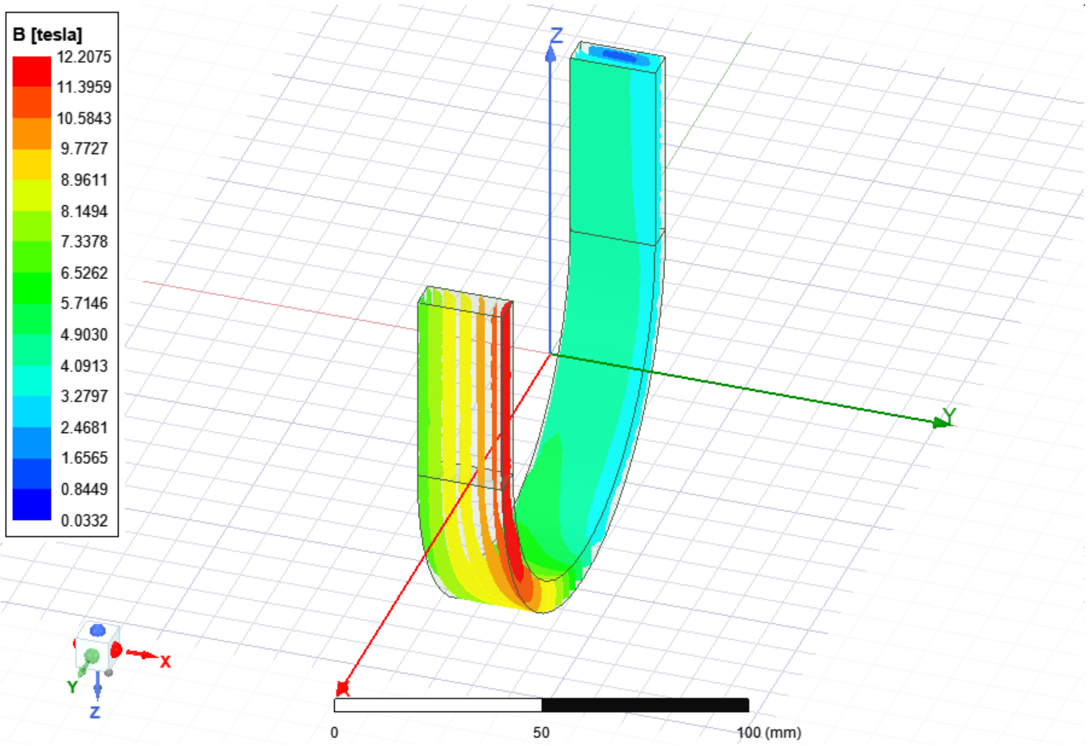
M. Duda, M. Daly

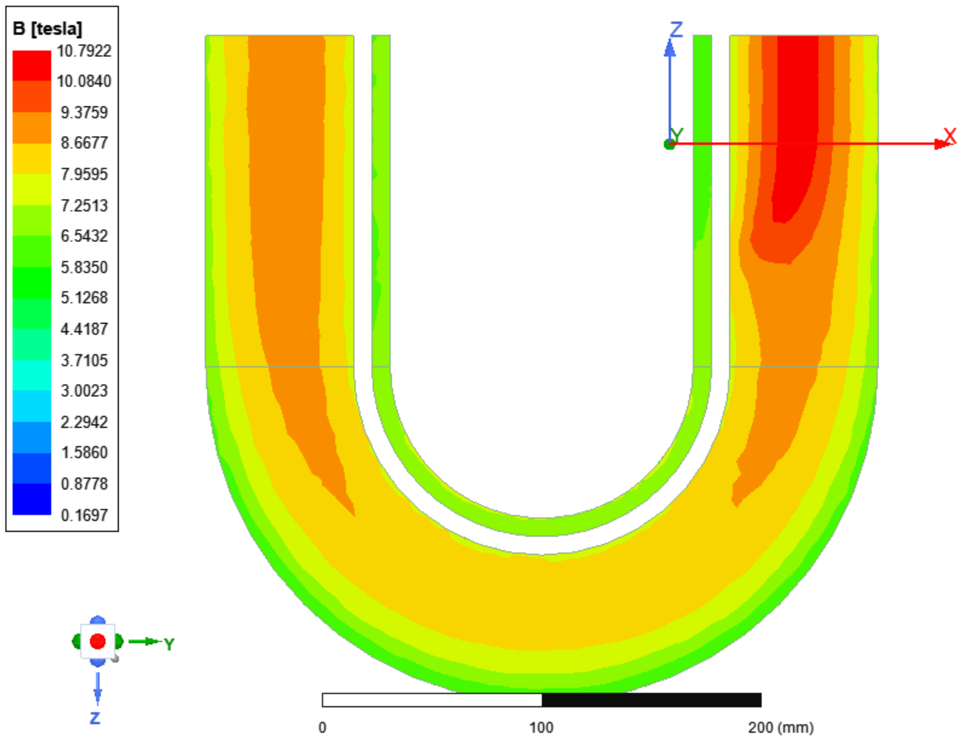
- Current leaking at L2

Run 10

3D magnetic and mechanical analysis

3D Magnetic Analysis

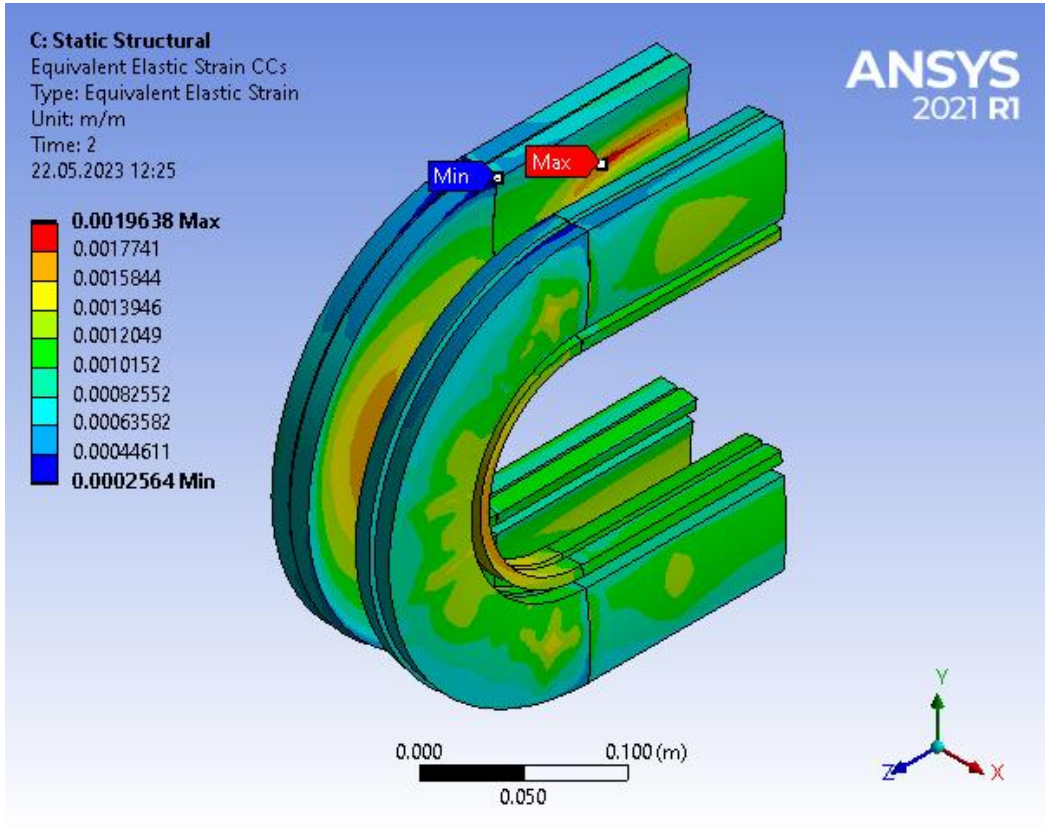


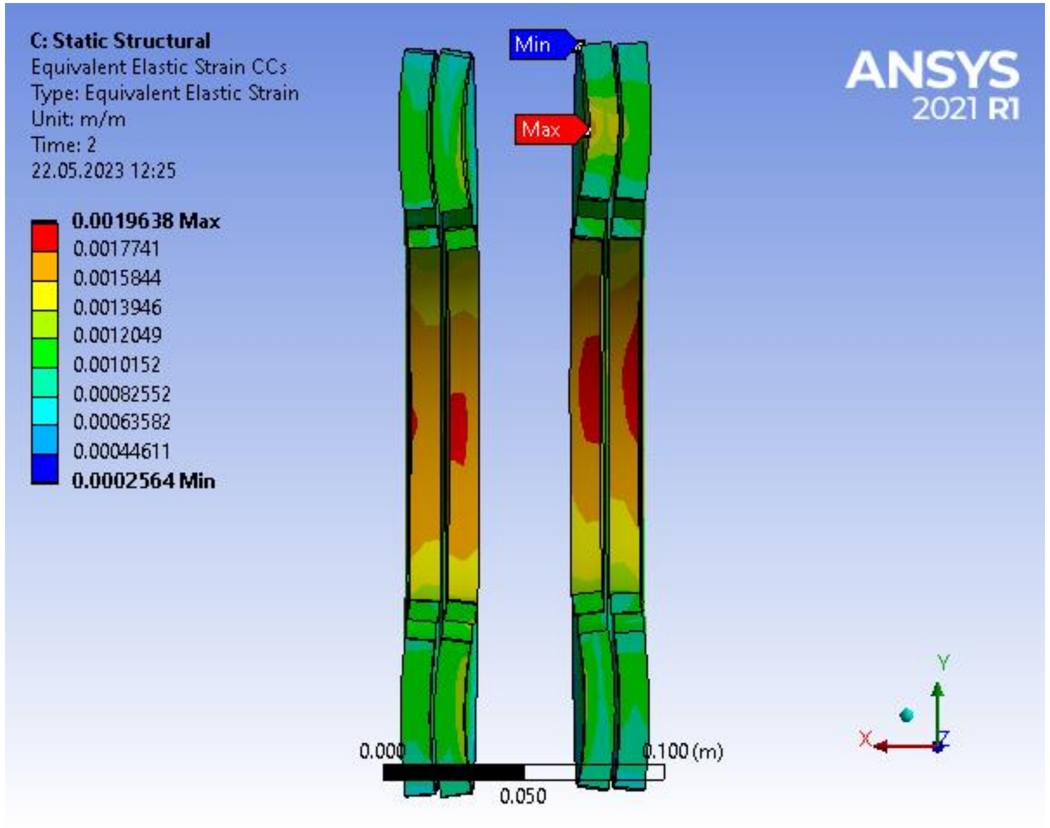


B_{peak} on BigBOX = 12.21 T
BigBOX I_{run10} = 10.77 kA

B_{peak} on DCC17 = 10.79 T
DCC17 I_{run10} = 9.04 kA

3D Mechanical Analysis: DCC17 LTS Coils

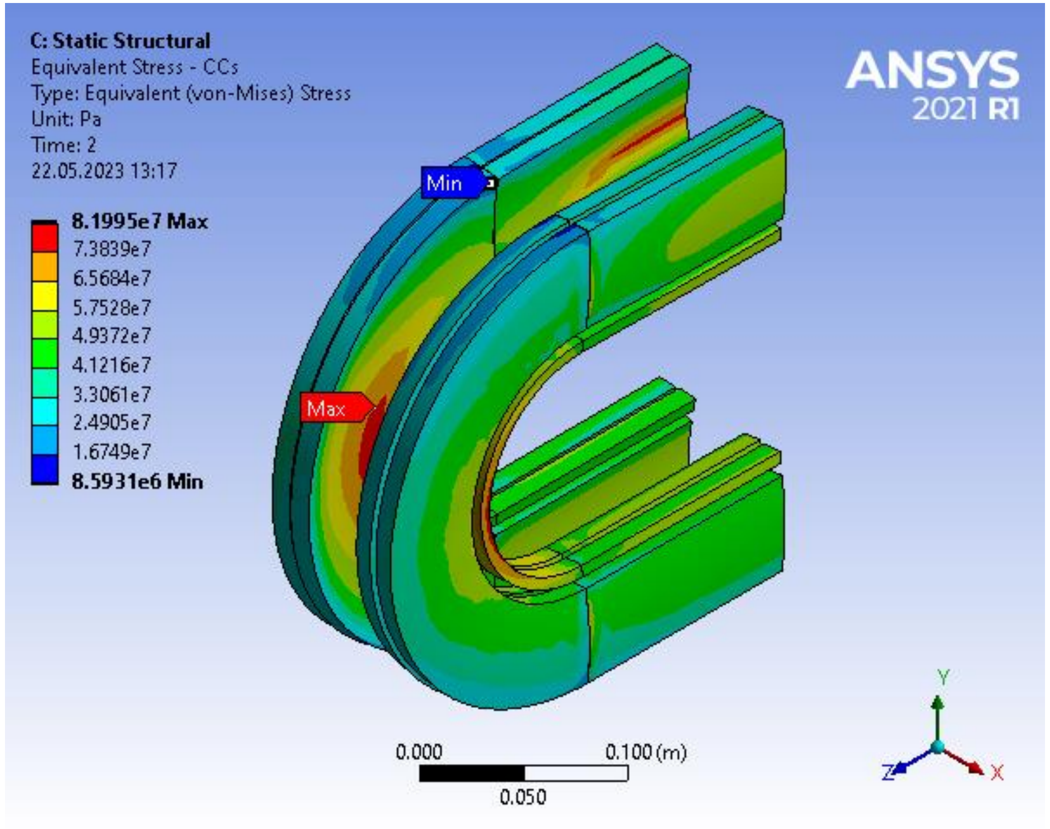


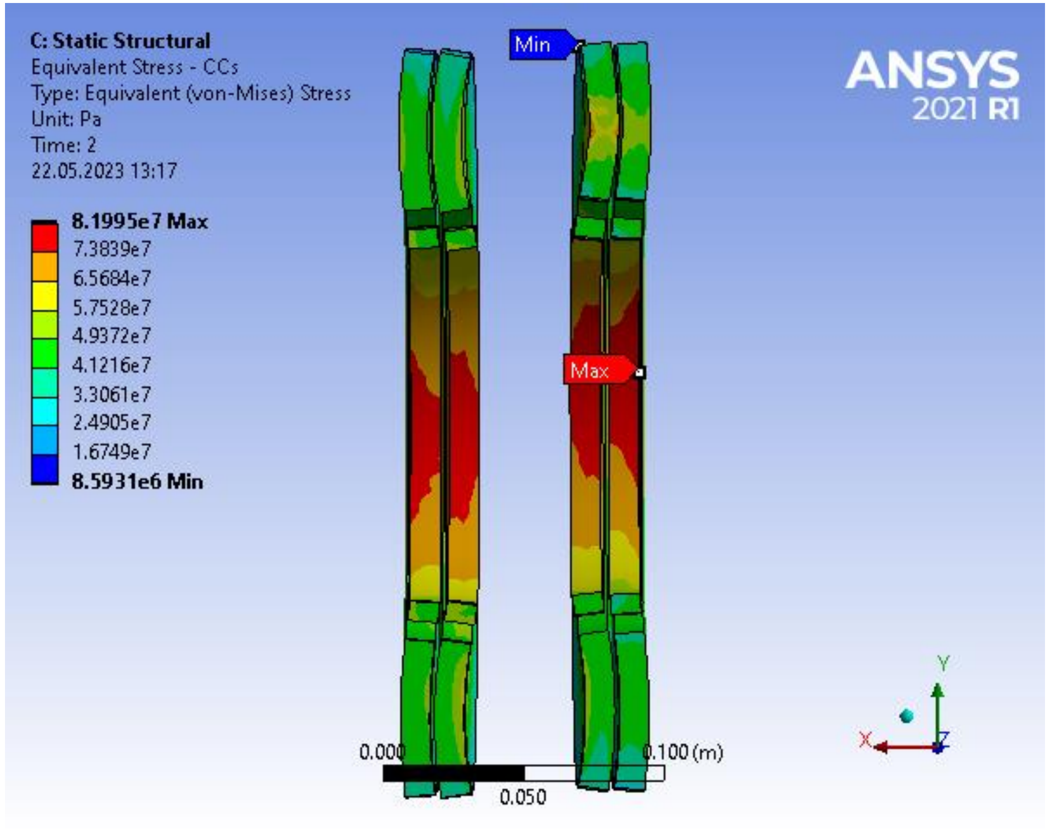


ε_{peak} on DCC17 = 0.00196
Due to BigBOX forces

This peak of strain has a value close to the on DCC17 coil ends

3D Mechanical Analysis: DCC17 LTS Coils

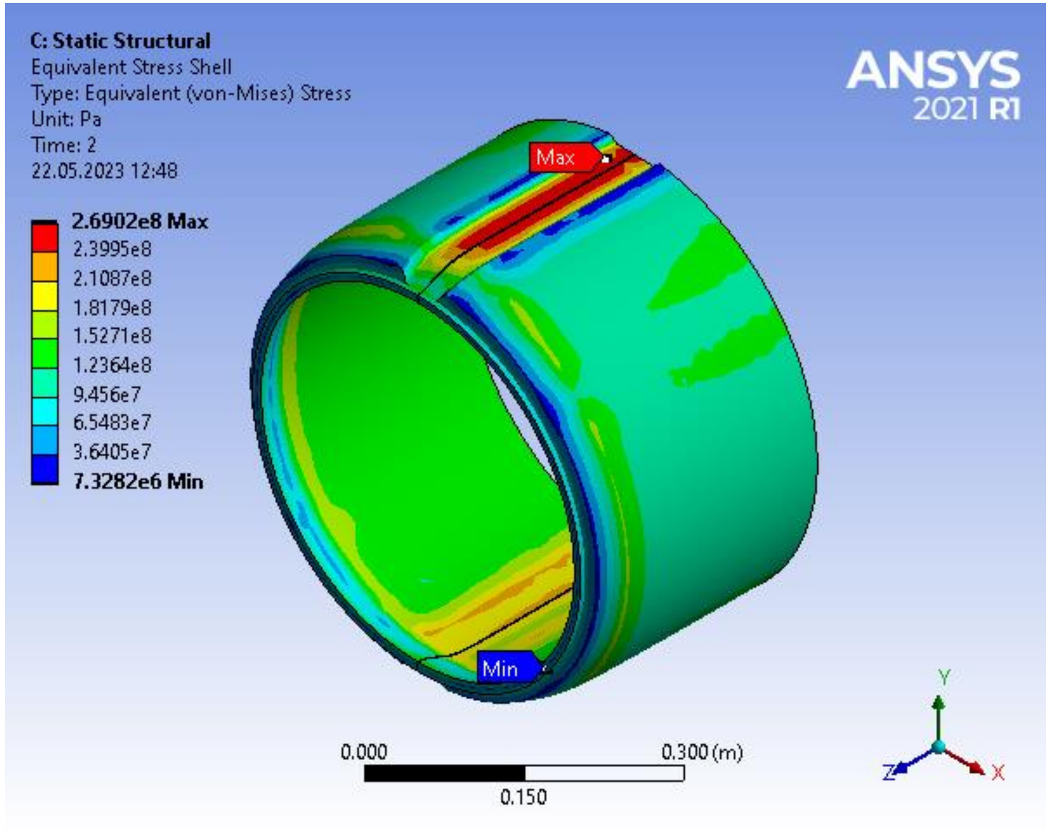


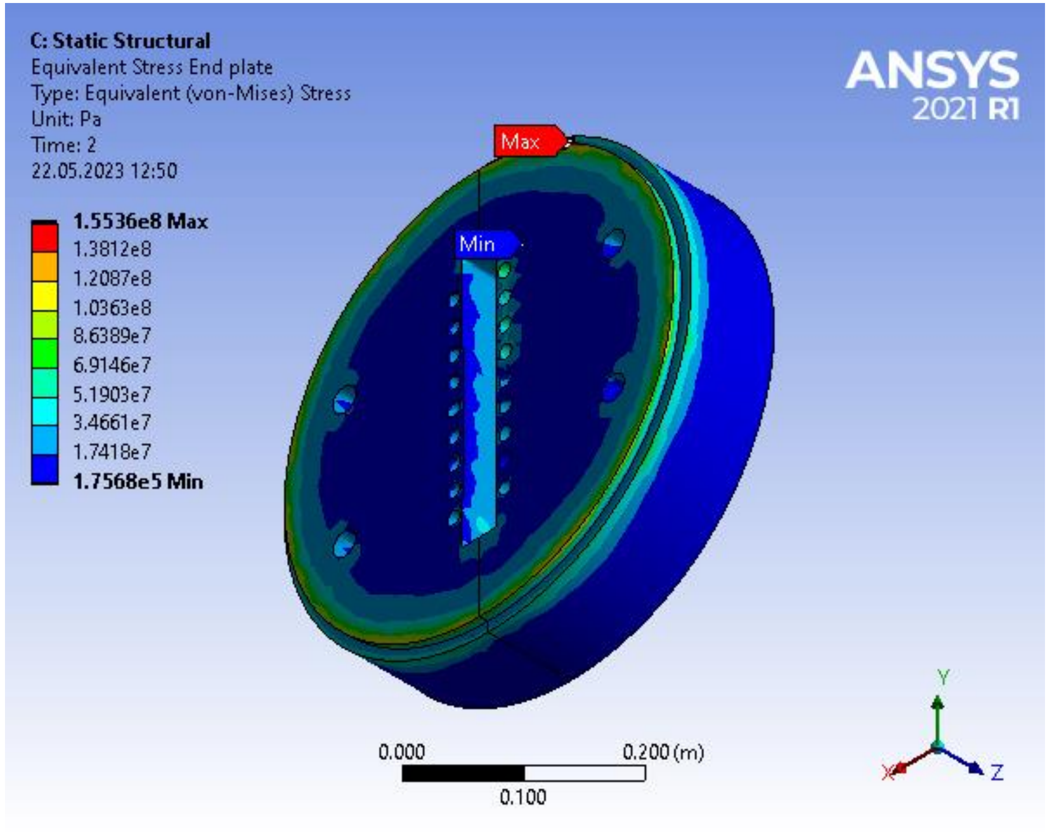


Max S_{VM} = 82 MPa
On the ends

Similar peak of VM stress on the ends and BigBOX region

3D Mechanical Analysis: DCC17 Shell and End-plate (both made of stainless steel)

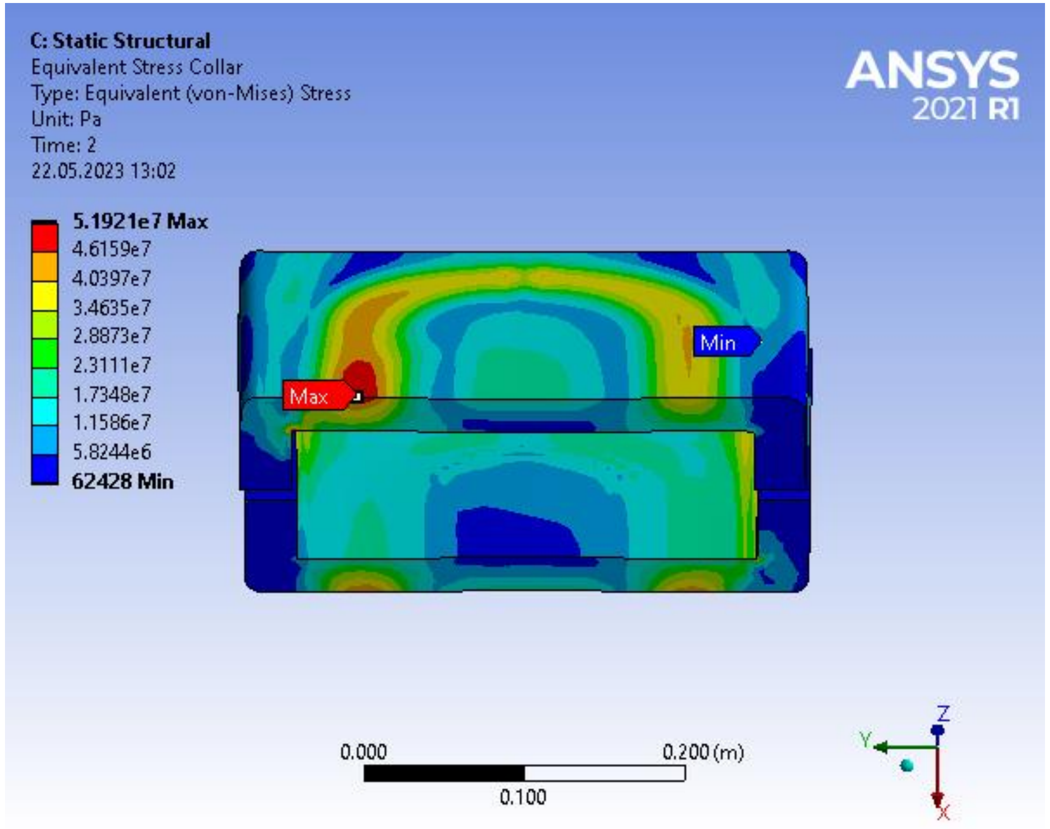




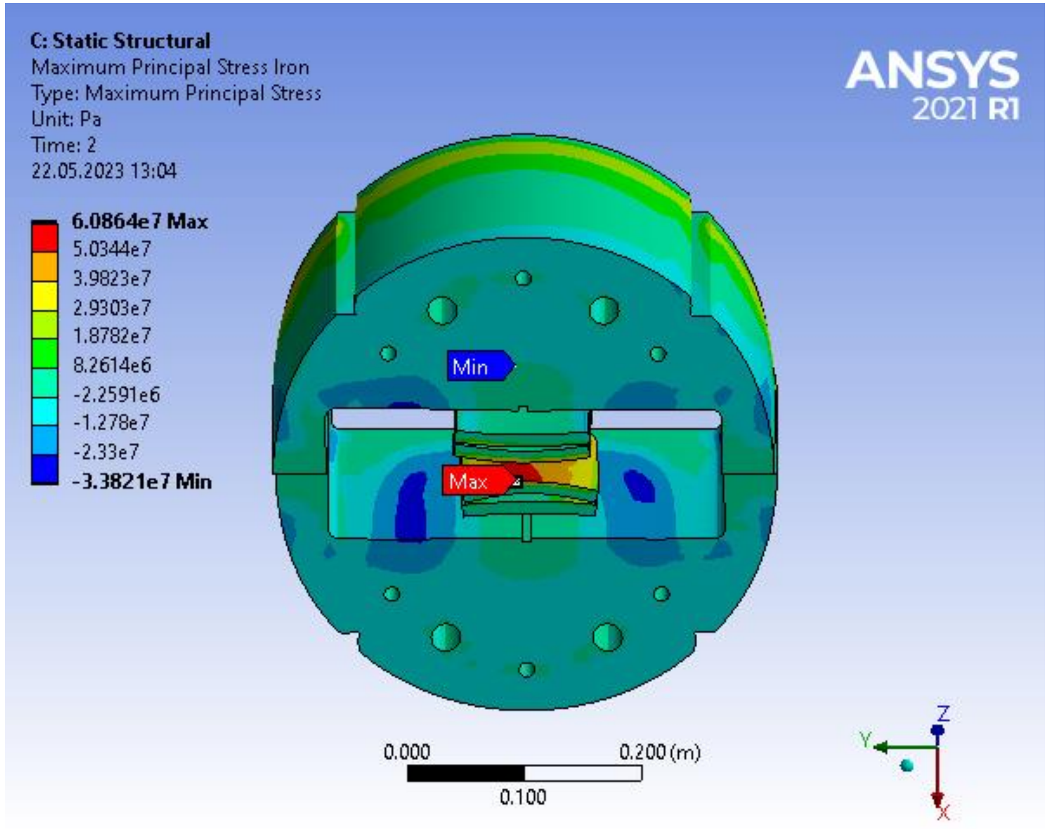
Max S_{eqv} on DCC17 Shell = 269 MPa

Max S_{eqv} on DCC17 End-plate = 155 MPa

3D Mechanical Analysis: DCC17 Collar (stainless steel) and Iron

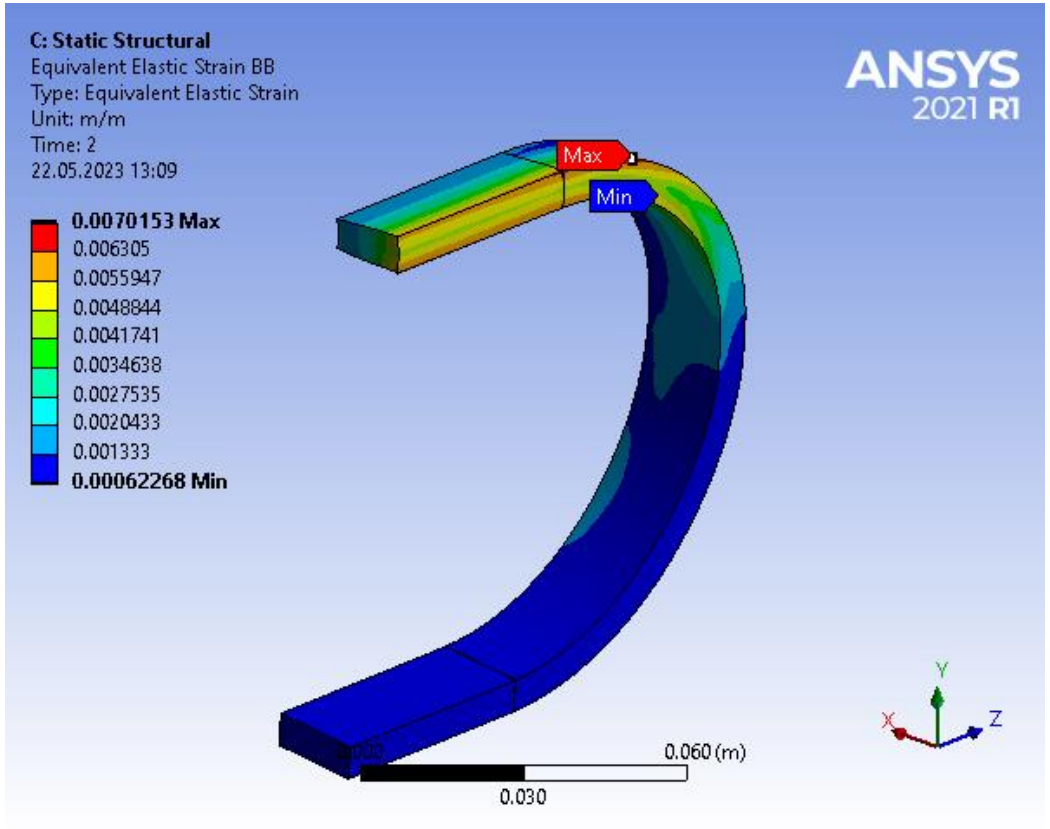


Max S_{eqv} on DCC17 Collar = 52 MPa

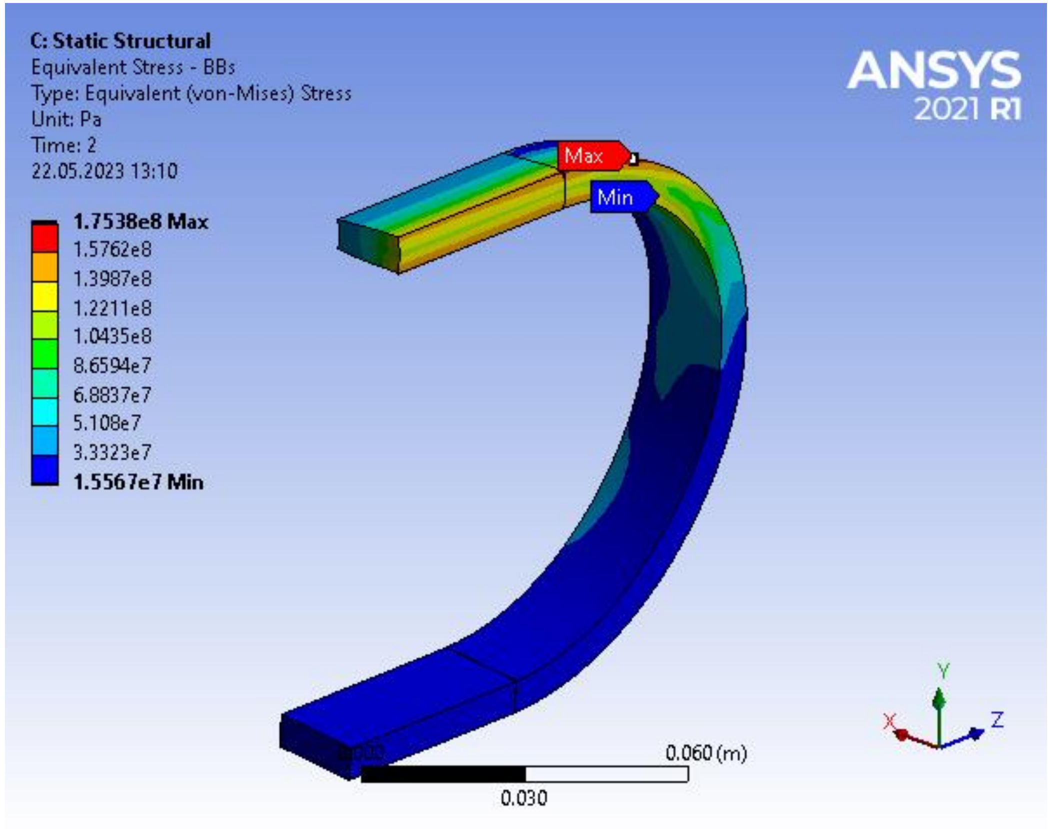


Max S_{MPS} on DCC17 Iron = 61 MPa

3D Mechanical Analysis: BigBOX LTS Coil

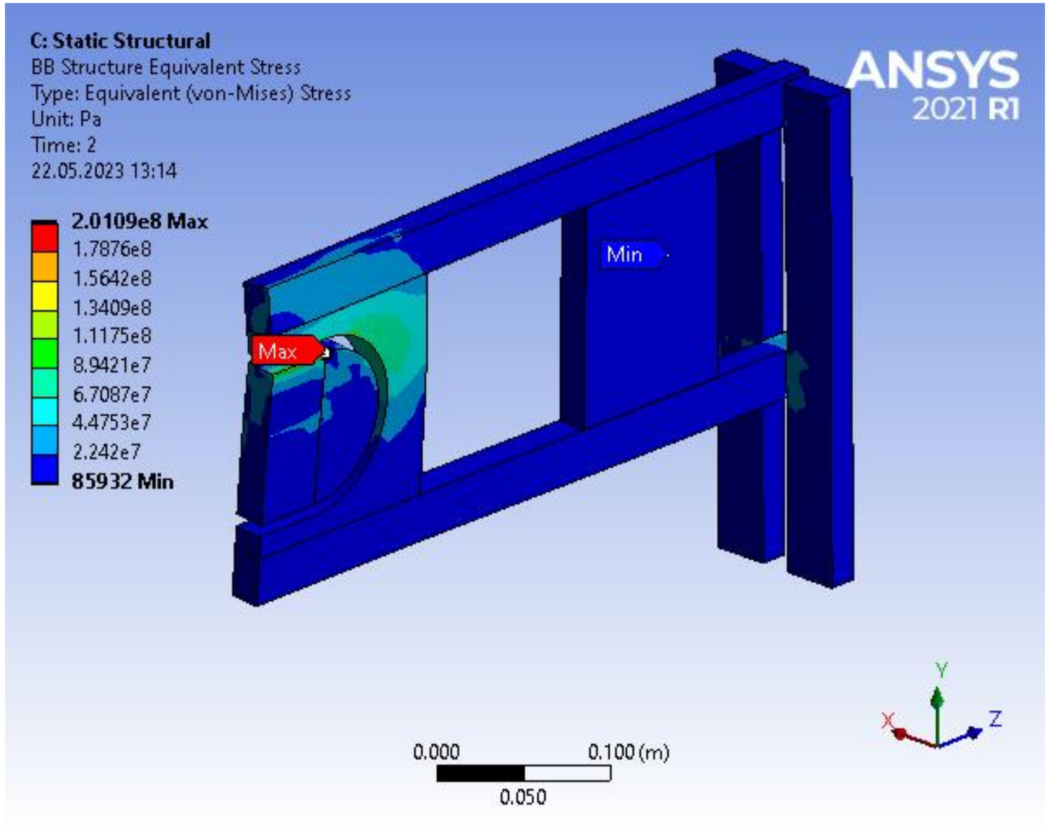


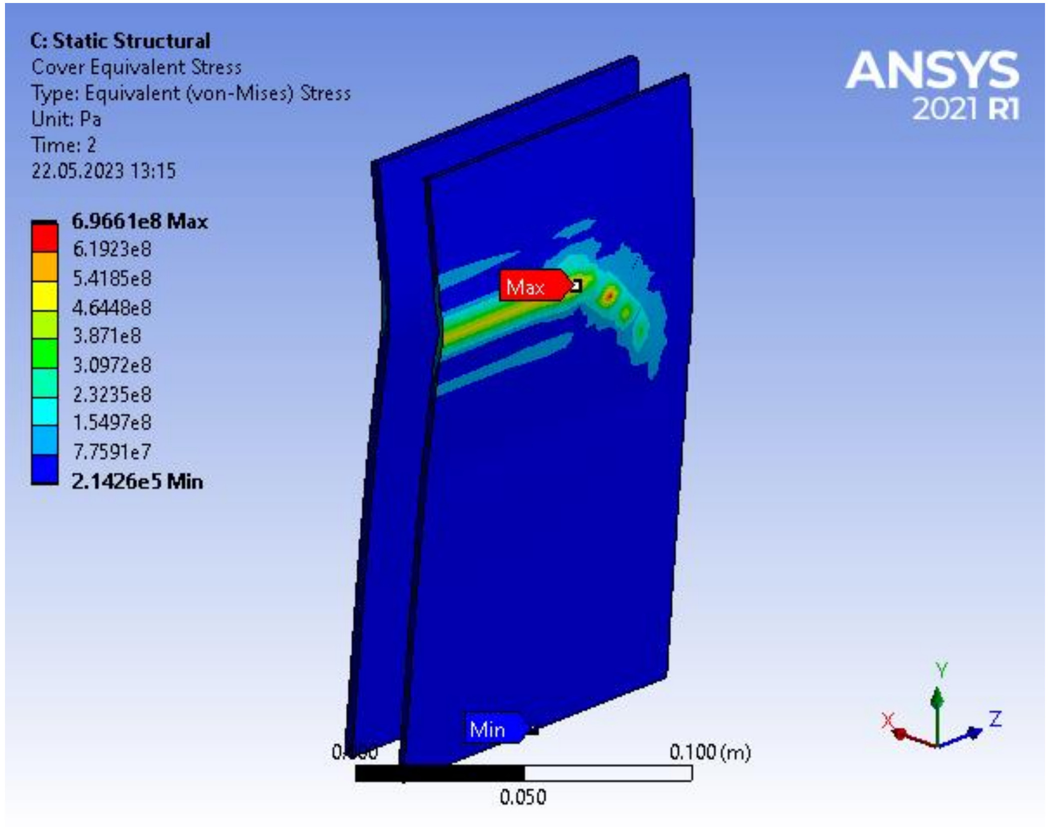
ε_{peak} on BigBOX = 0.007



Max S_{VM} = 175 MPa

3D Mechanical Analysis: BigBOX Structure and Covers





Max S_{eqv} on BigBOX structure = 201 MPa

Max S_{eqv} on Covers = 697 MPa

Due to the inverted current