LQS01 Mechanical Analysis and LQS01b Assembly

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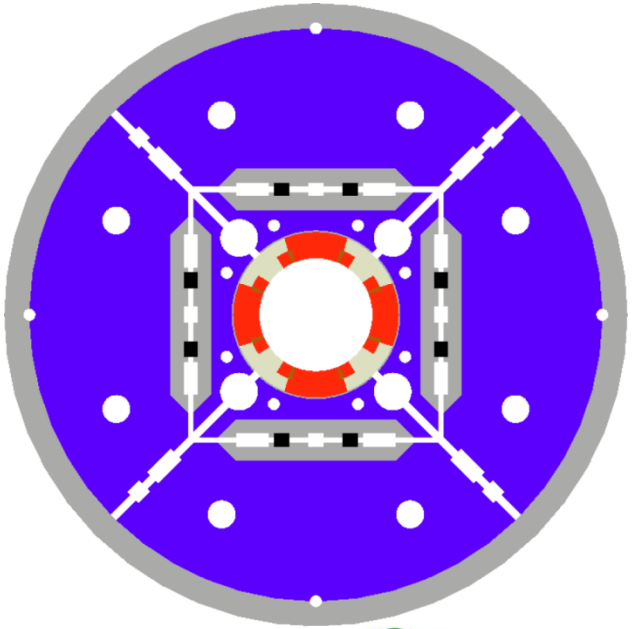
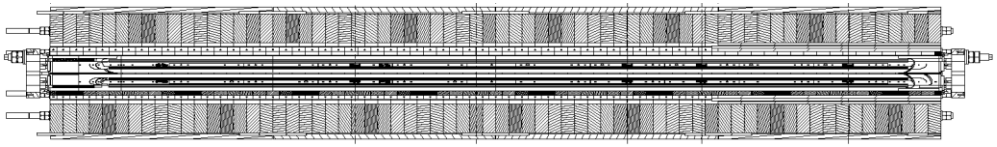
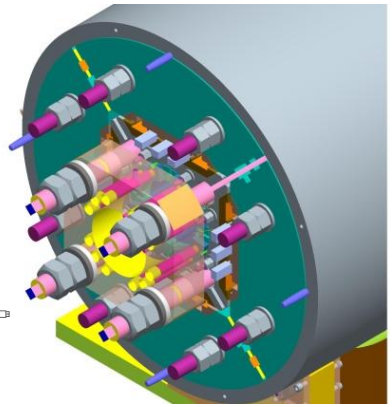
LQS01 magnet design

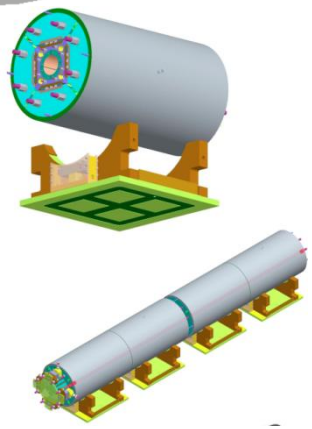
- Iron pads, masters and yokes
- 20 mm thick Al shell (500 mm OD)
- Pre-load with bladders and keys
- End support: plate and rods
- Assembly of short segments
- Connection of segments



- Coil length: 3.4 m
- Magnet length: 3.7

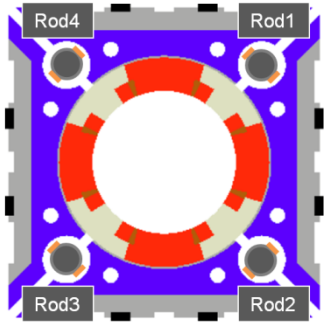


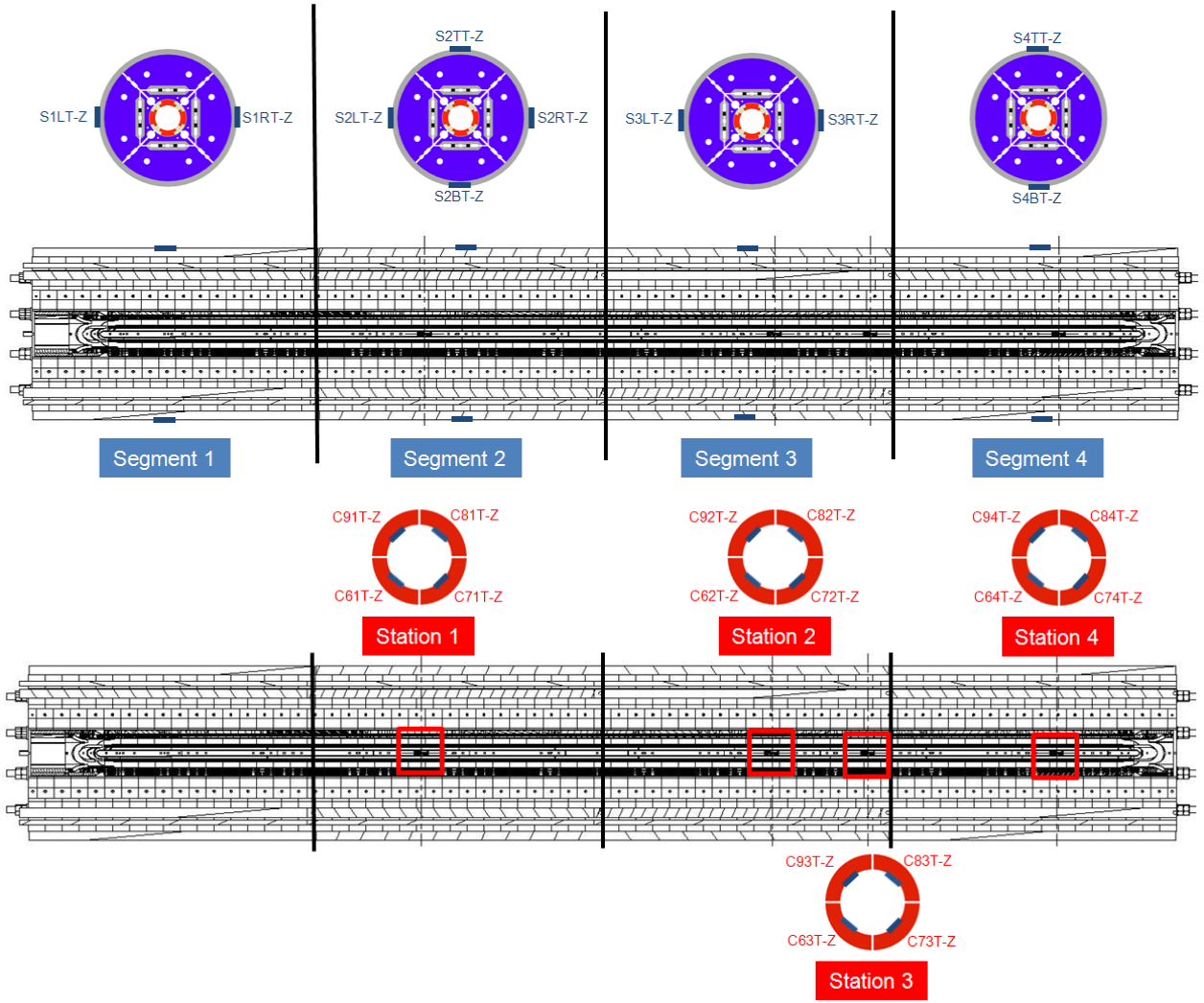




Strain gauge locations

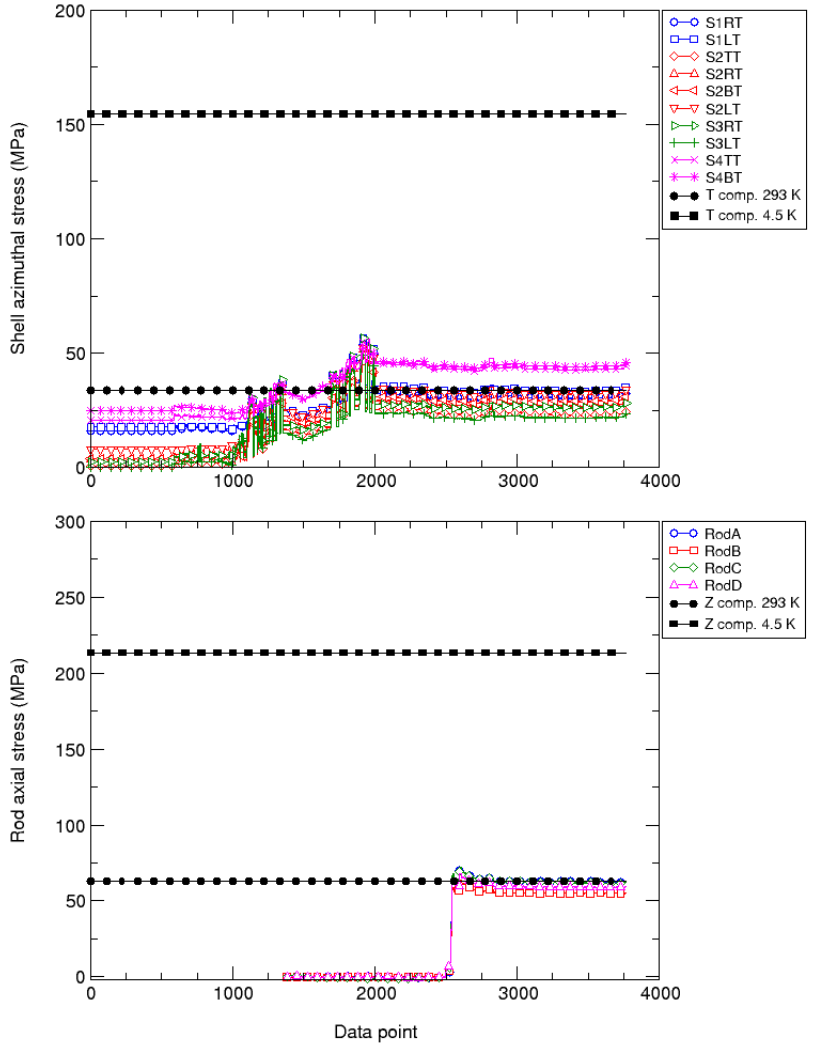
- Station
  - *y* and *z* gauges thermally compensated
- 10 shell stations
- 4 stations per coil
- 2 gauges per rod
- Total of 60 gauges





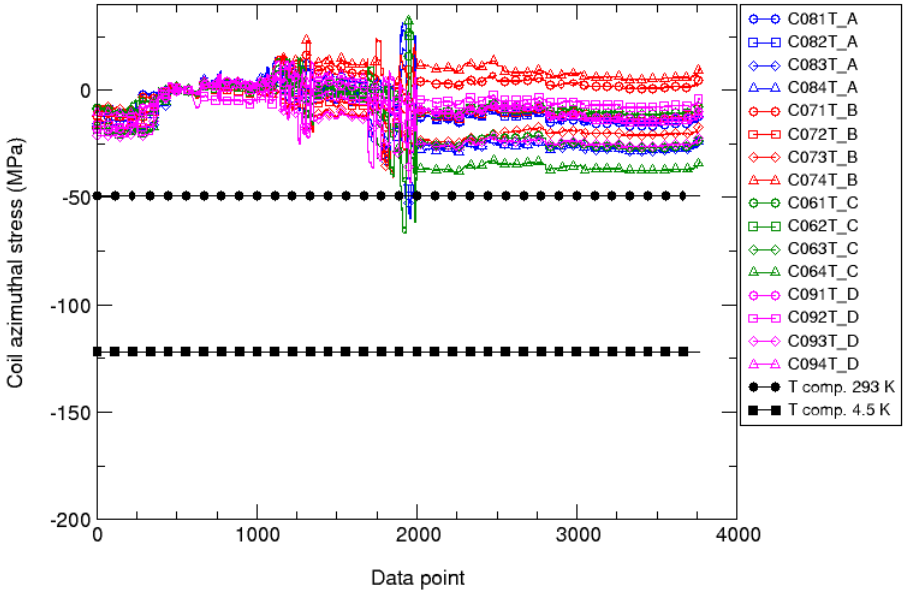
CM13
Loading of LQS01 completed

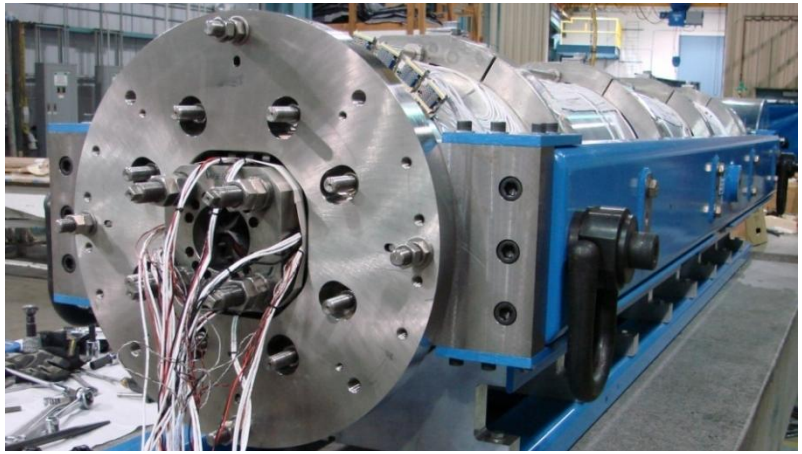
- Structure pre-loaded for a 230-240 T/m gradient
- Shell
  - Computed: +34 MPa
  - Measured: +33 ±8 MPa
- Rod
  - Computed: +63 MPa
  - Measured: +60 ±3 MPa

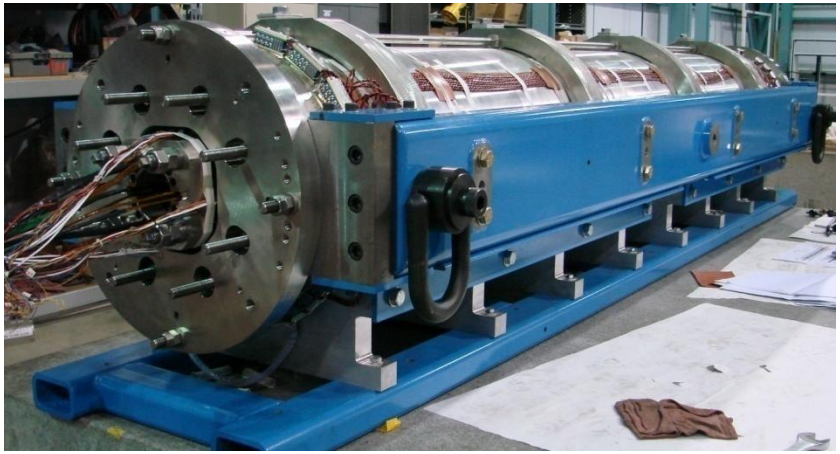


CM13
Loading of LQS01 completed

- Coil σ_ϑ to -12 ±11 MPa
  - Lower than comp. -49 MPa
    - Not observed in LQSD
    - Possibly related to coil dimens.
- Pre-loading strategy
  - Shell tension chosen as reference
    - Conservative approach for 1st test





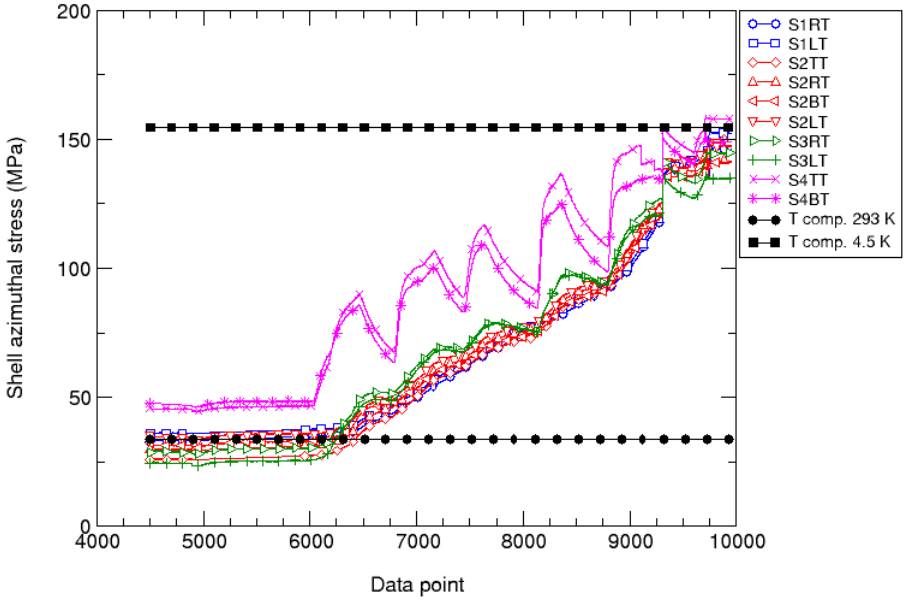


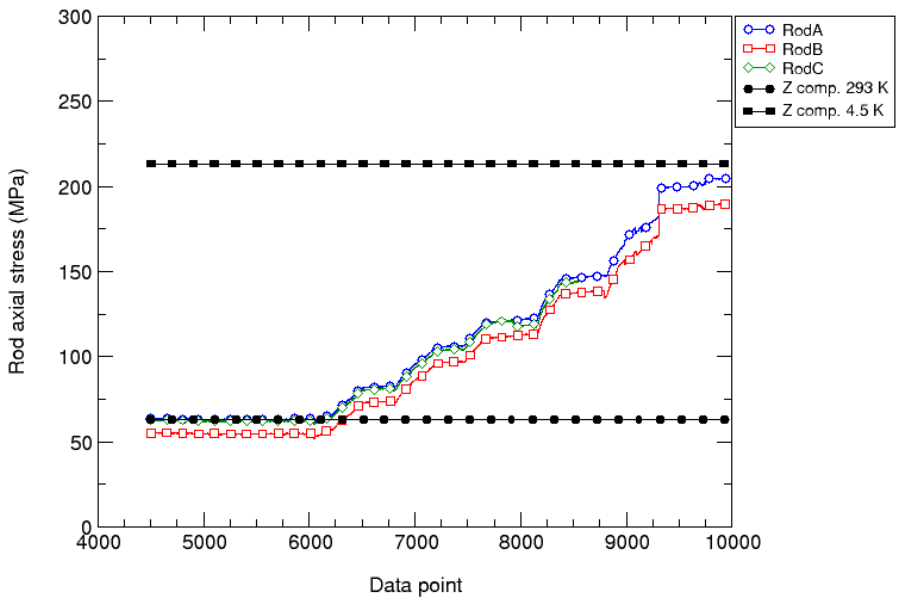
Outline

- LQS01 mech. behavior during cool-down and test
- Analysis with finite element model
- Post-test inspections: pressure sensitive film test
- LQS01b loading and expected coil stress

LQS01 mechanical behavior during cool-down

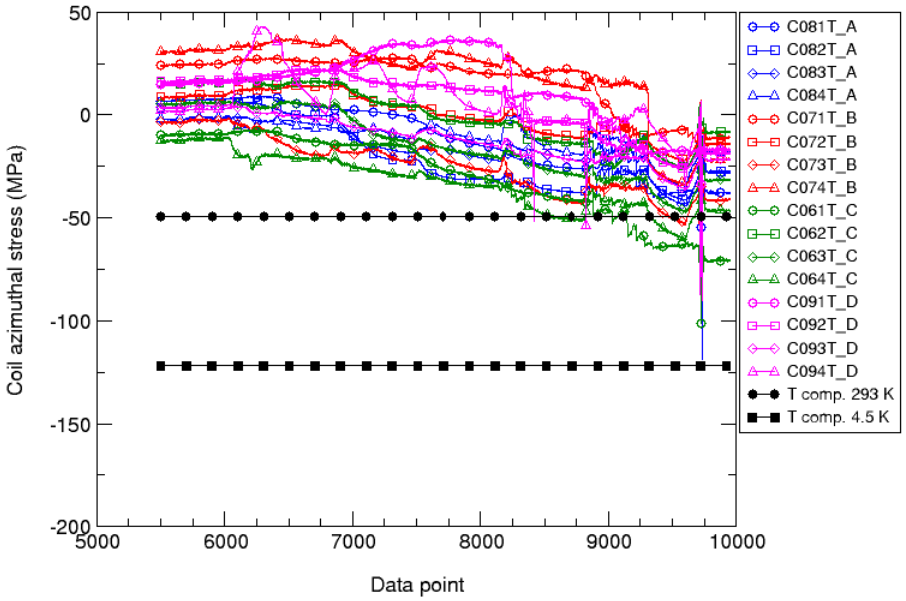
- Shell
  - Computed: +155 MPa
  - Measured: +146 ±6 MPa
- Rod
  - Computed: +213 MPa
  - Measured: +197 ±11 MPa





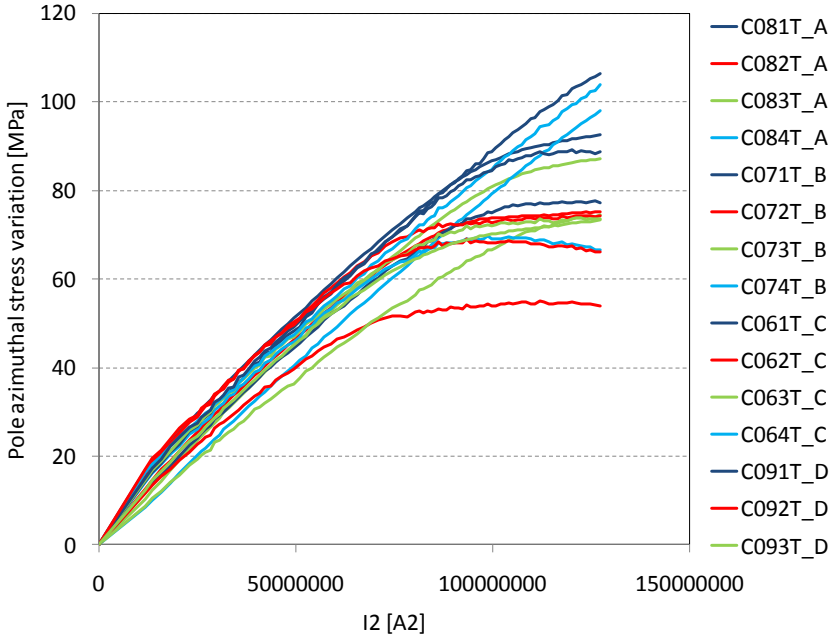
LQS01 mechanical behavior during cool-down

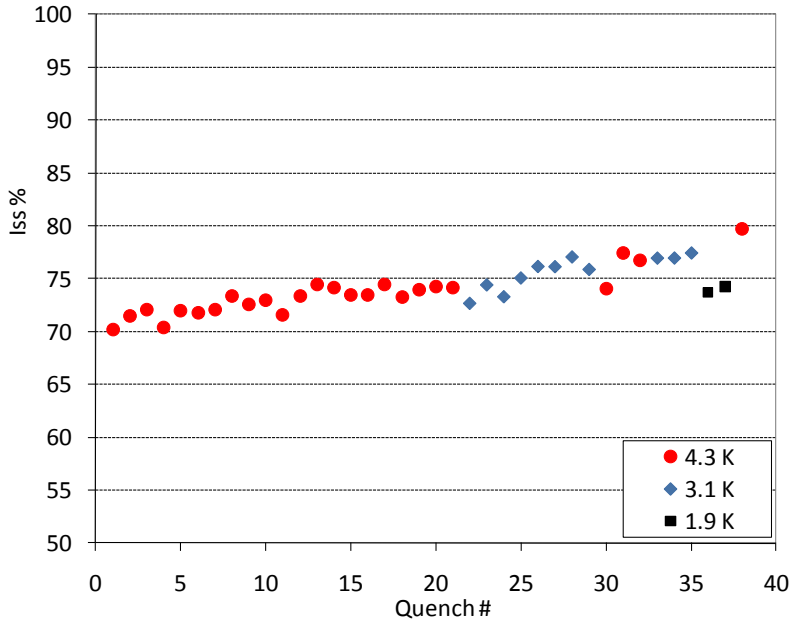
- Coil
  - Computed
    - From -49 MPa at 293 K
    - To -122 MPa at 4.5 K
  - Measured
    - From +5 ±12 MPa at 293 K
    - To -25 ±19 MPa at 4.5 K



LQS01 mechanical behavior during excitation

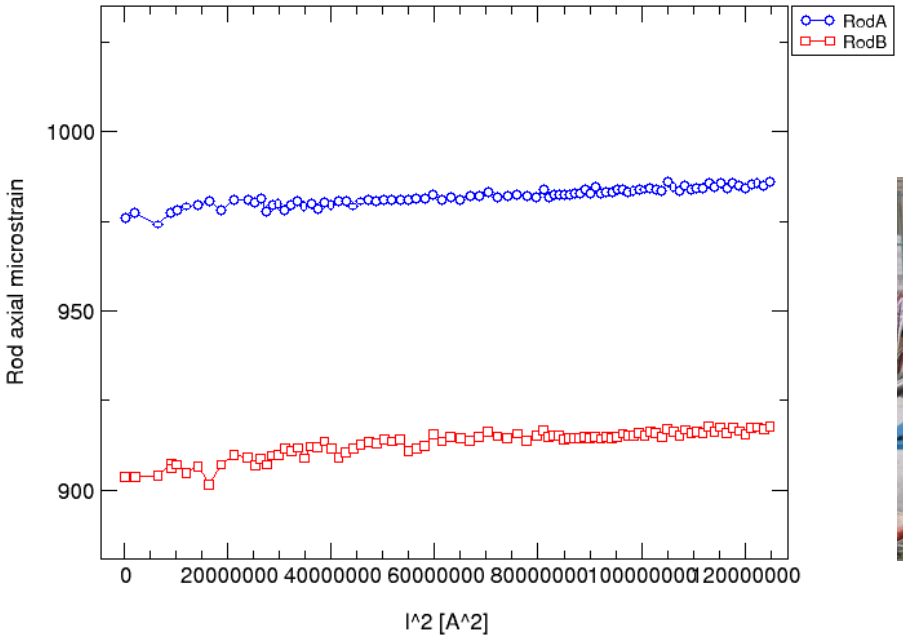
- Plateau (separation) observed in most of the *y* gauges
  - High tension (>50 MPa) measured at maximum field
    - Average pre-load after cool-down: 70-80 MPa?
    - Missing pre-load: 30-40 MPa?
- Training between 70% and 80% of I_{ss}

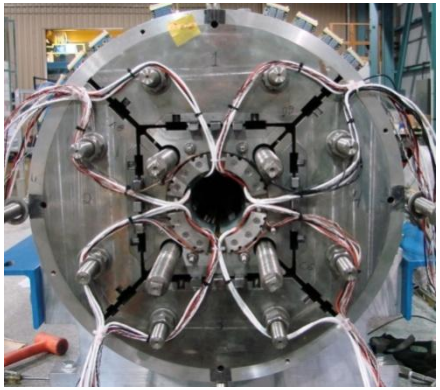


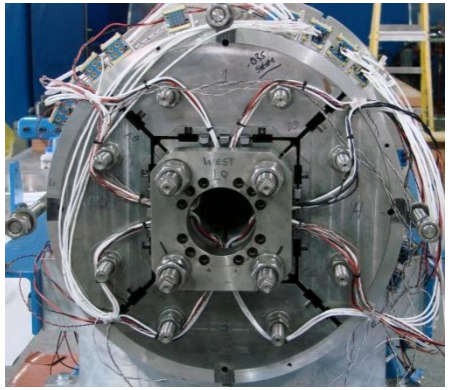


LQS01 mechanical behavior during excitation

- Variation of rod axial strain
  - +10 microstrain
- Elongation of the coil
  - 34 micron (with 330 kN, 33 t)

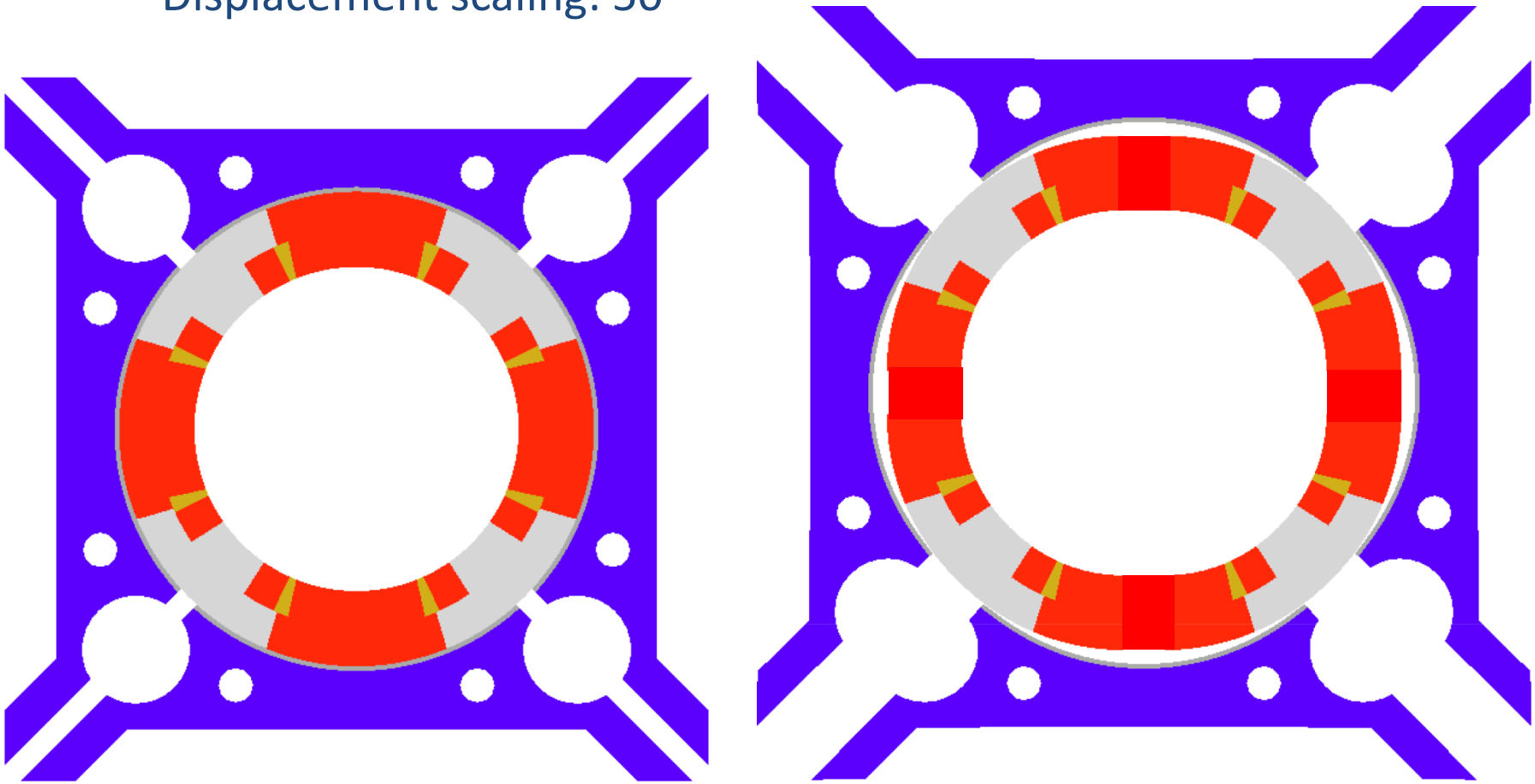






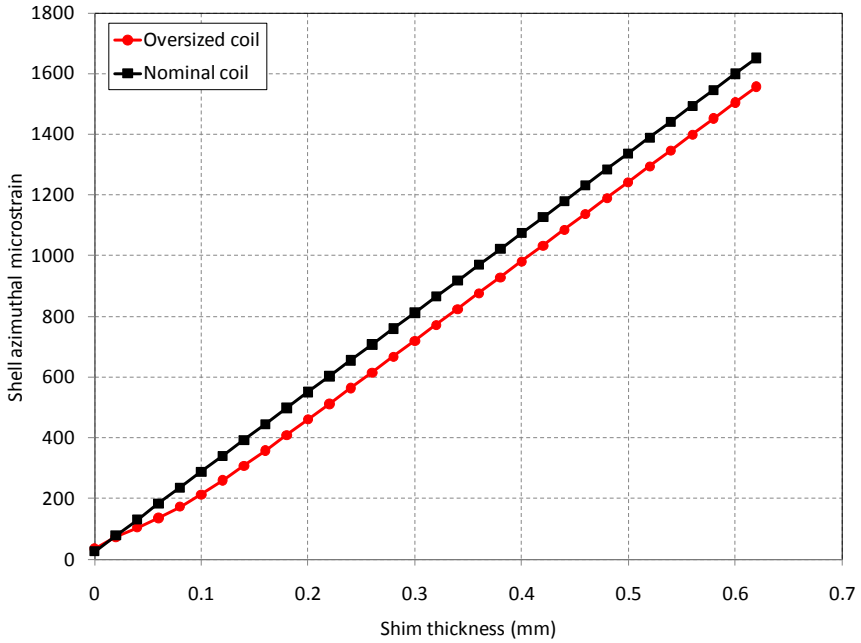
Analysis with finite element model

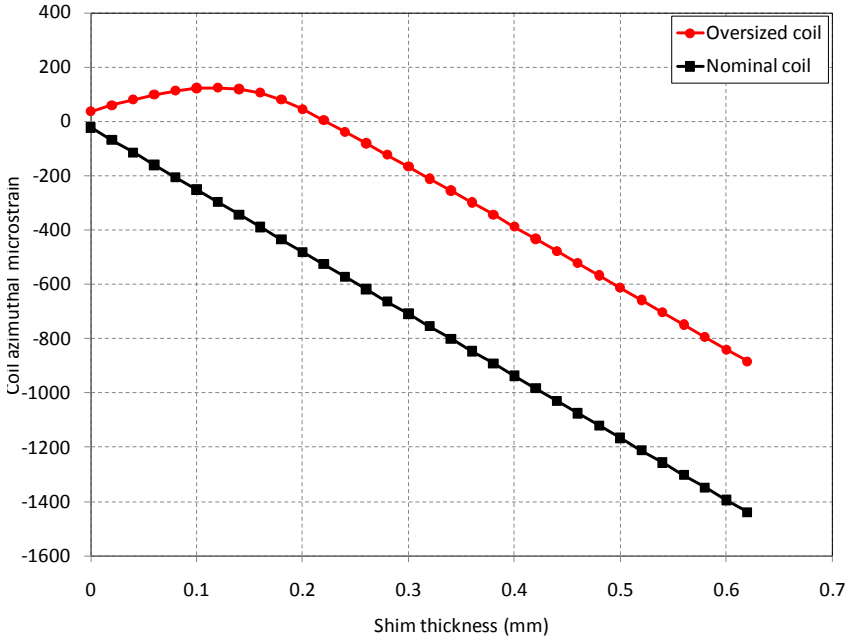
- Nominal coil and oversized coil (+120 μm on the mid-plane)
  - Displacement scaling: 50



Analysis with finite element model
Room temperature pre-load

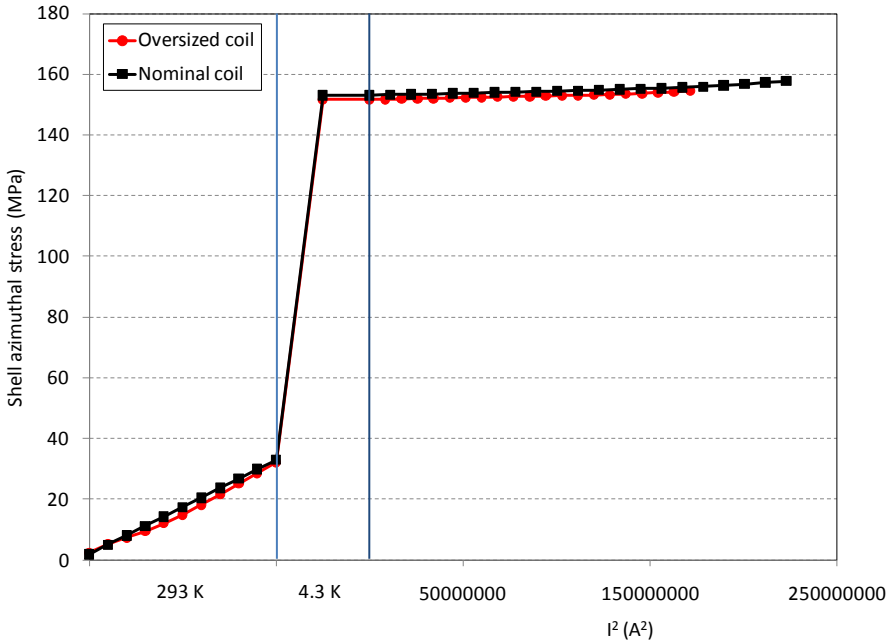
- Shell azimuthal strain
  - Similar increase with shim thickness
- Coil azimuthal strain
  - Oversized coil with initial plateau followed by same slope as nominal

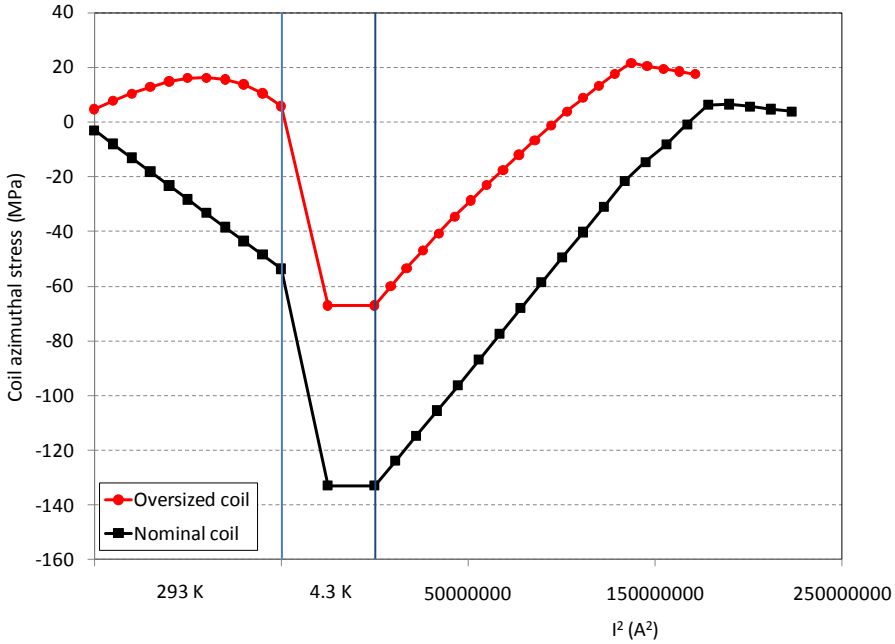




Analysis with finite element model
Assembly, cool-down, excitation

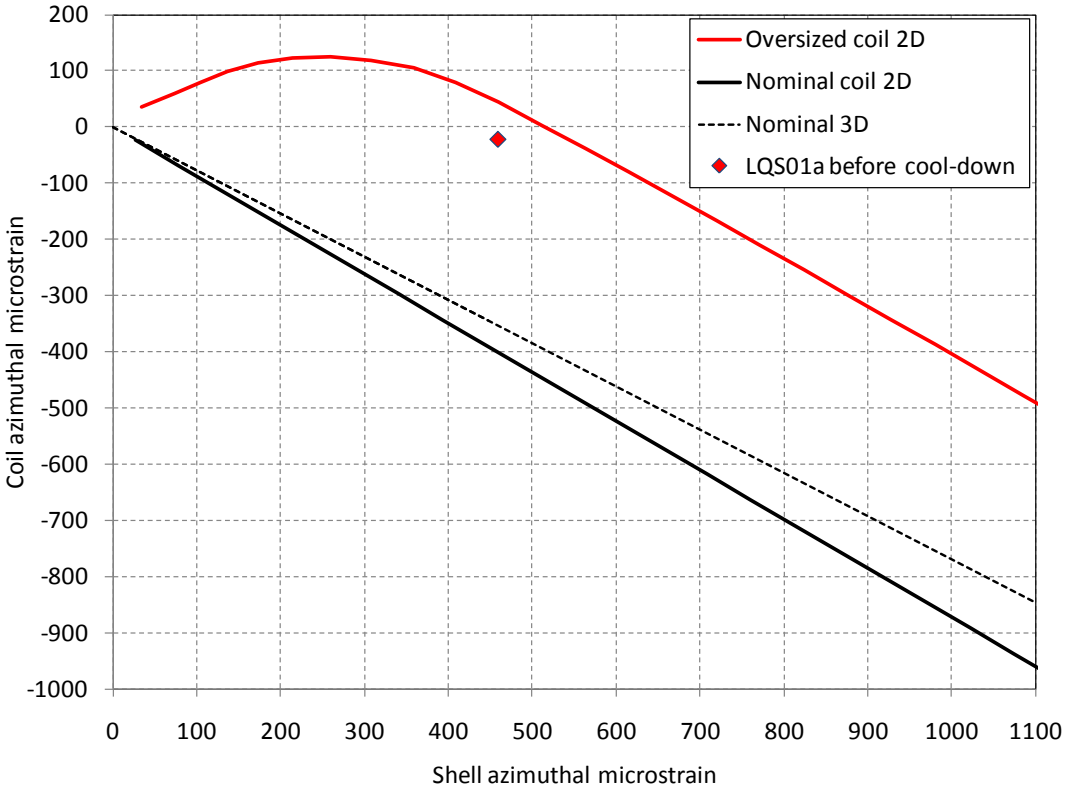
- Shell azimuthal stress
  - Similar variations during cool-down and excitation
- Coil azimuthal strain
  - Oversized coil with lower compression at 4.5 K
    - Still higher pre-load than measurements





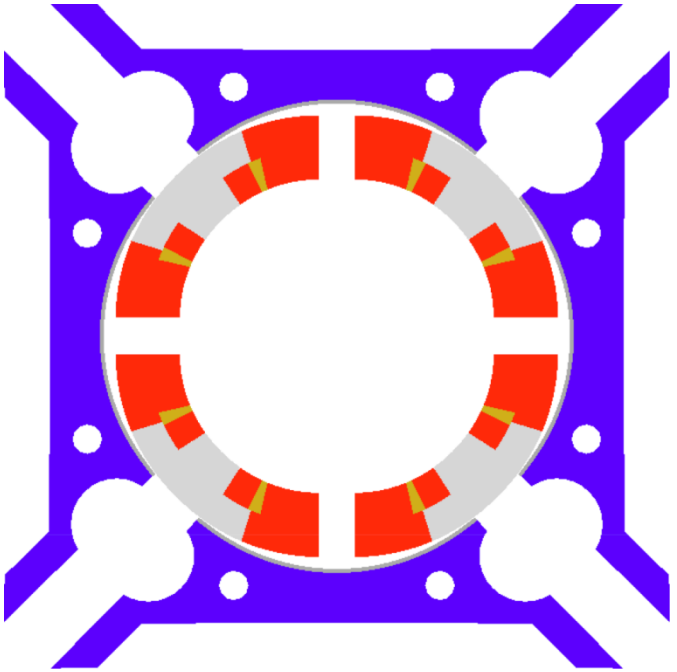
Analysis with finite element model
Room temperature pre-load

- After LQS01 pre-load
  - Coil vs. shell strain consistent with oversized behavior

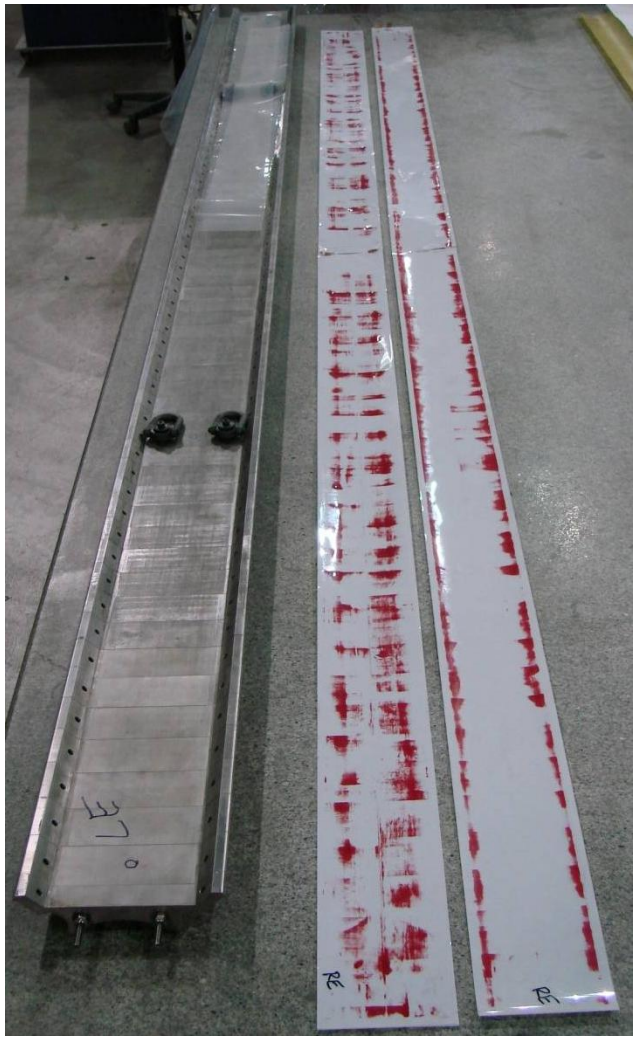


Pressure sensitive film test
LQS01 conditions

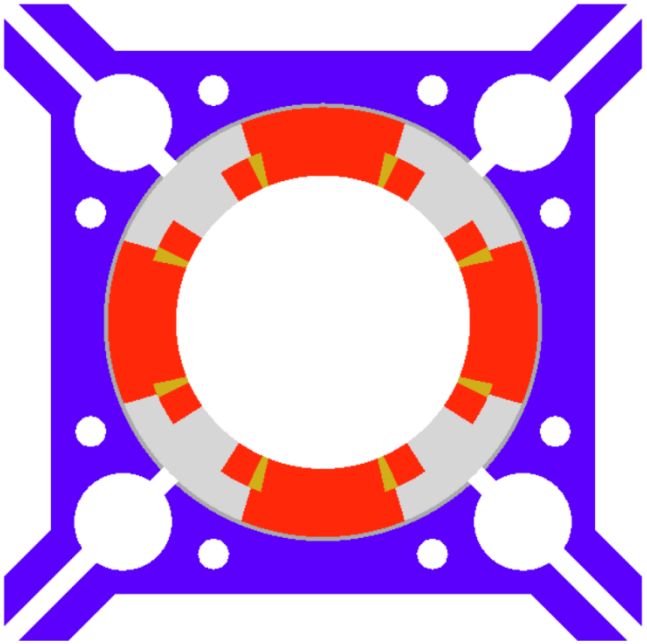
- G10 coil-pad shim
  - 30 mils (0.765 mm) thickness



Pressure sensitive film test
LQS01b vs LQS01 conditions

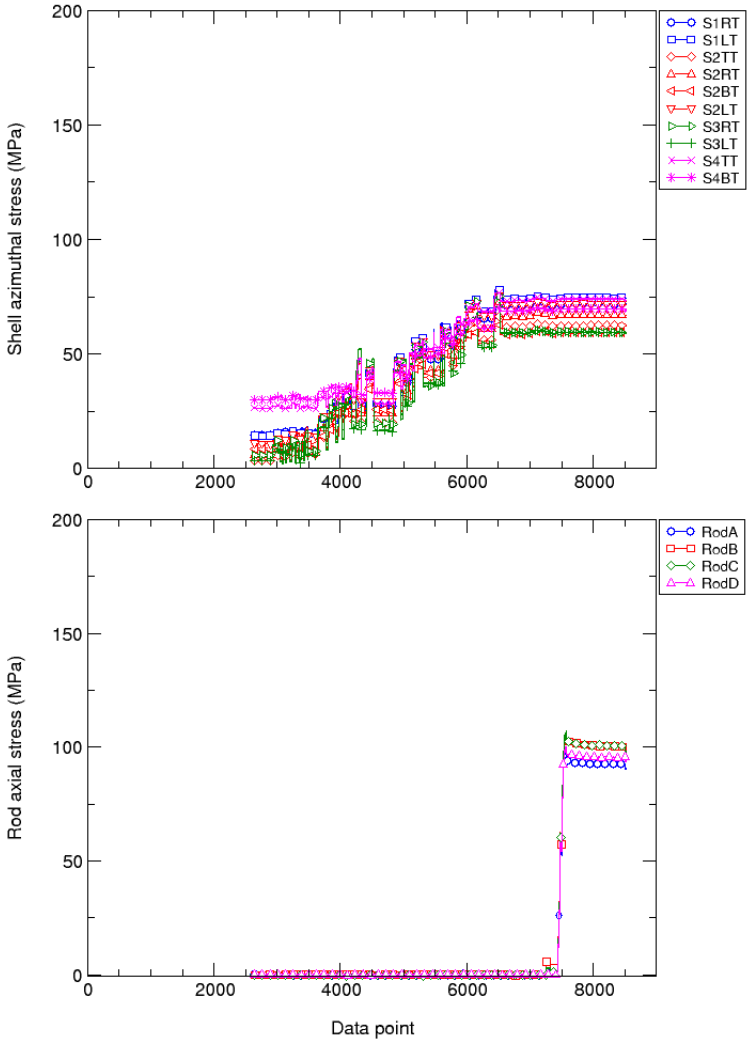


- G10 coil-pad shim
  - From 30 mils (0.765 mm) to 15 mils (0.380 mm) thickness



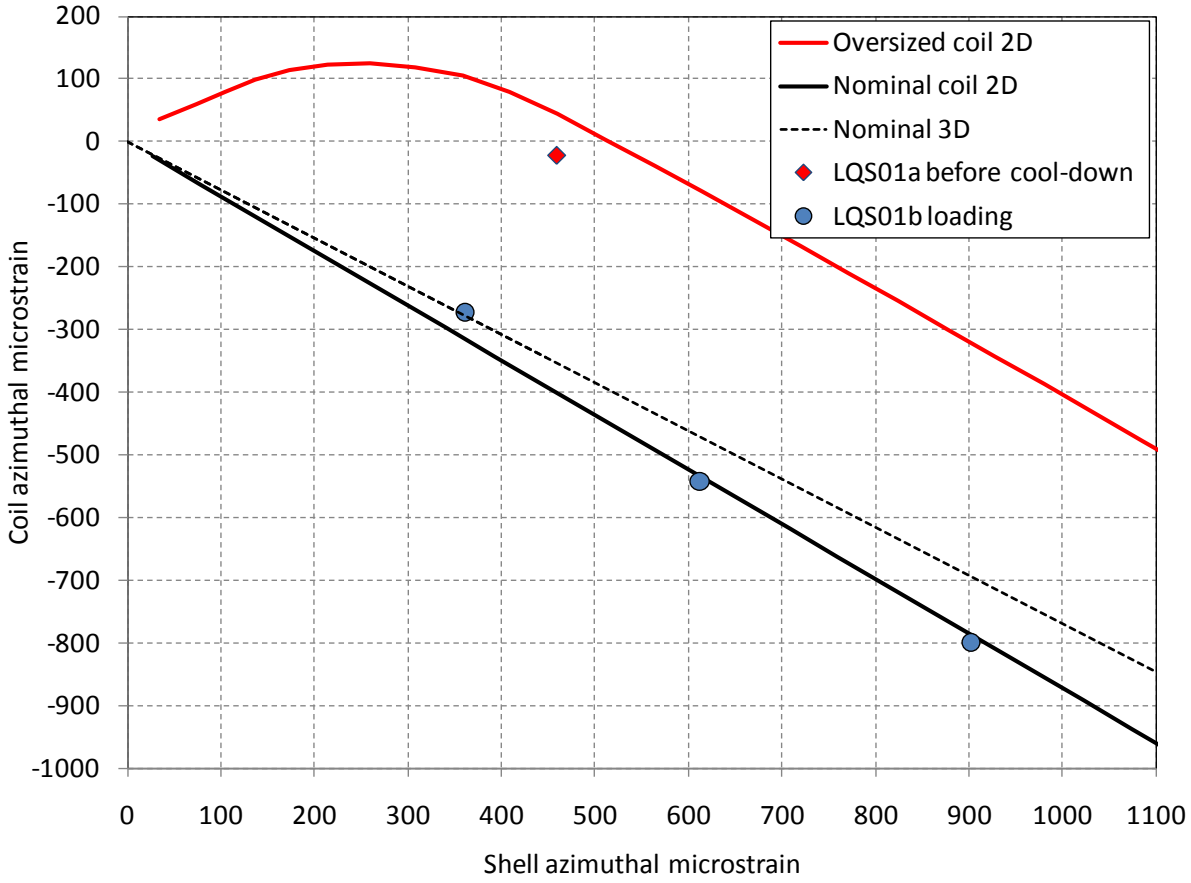
LQS01b loading

- Choice of pre-load increase based on LQS01 measured variations during cool-down
- Shell
  - From (LQS01) +34 ±8 MPa
  - To (LQS01b) +67 ±6 MPa
- Rods
  - From (LQS01) +76 ±7 MPa
  - To (LQS01b) +94 ±5 MPa



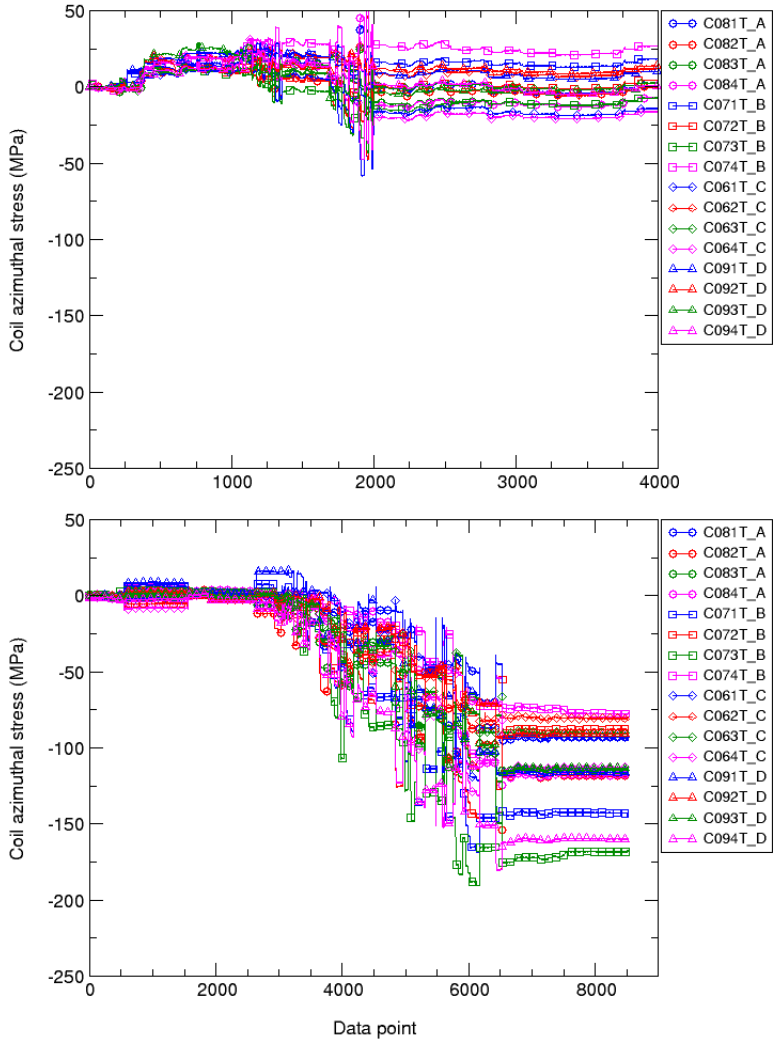
LQS01b loading
Meas. vs. analysis with finite element model

- Coil strain consistent with nominal coil model



LQS01b loading
Coil azimuthal strain/stress

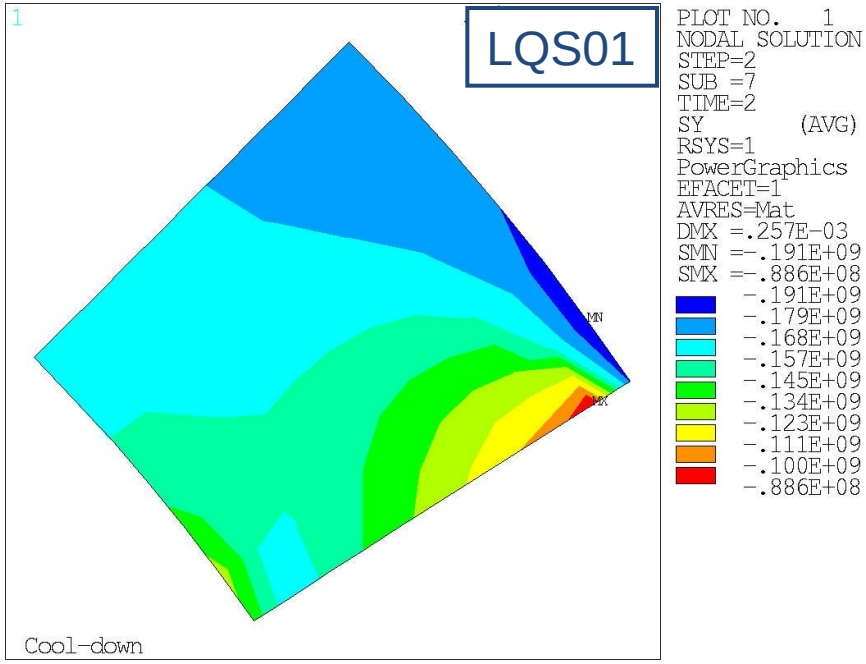
- LQS01a
  - No compression measured on the pole gauges at the end of loading
  - Ave. stress: +5 ±12 MPa
- LQS01b
  - All the coil gauges indicate compression at the end of the loading
  - Ave. stress : -107 ±26 MPa

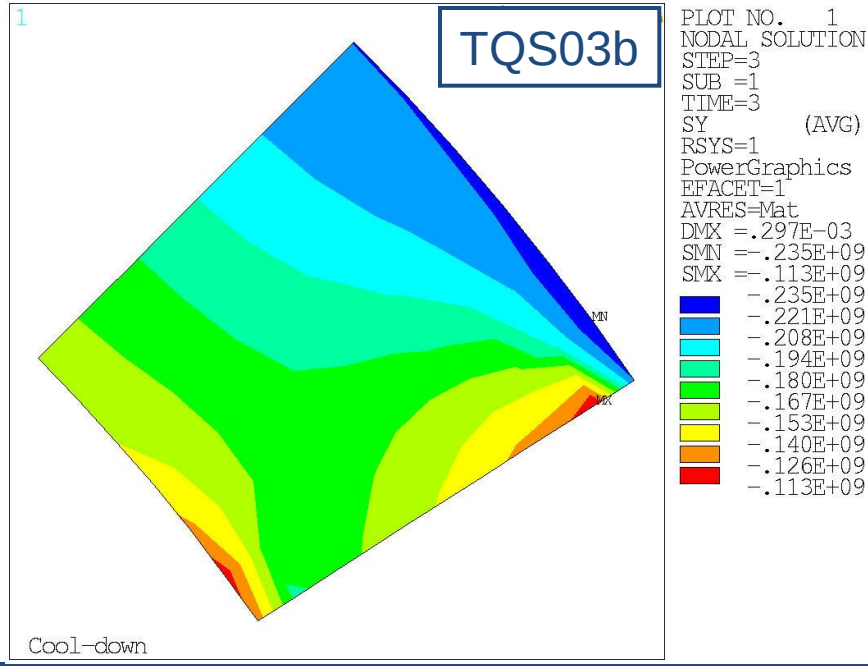


Expected LQS01b pre-load after cool-down (Variations based on sensitivity analysis)

- Shell azimuthal stress
  - +180 MPa
- Ti pole azimuthal stress
  - -160 ±30 MPa

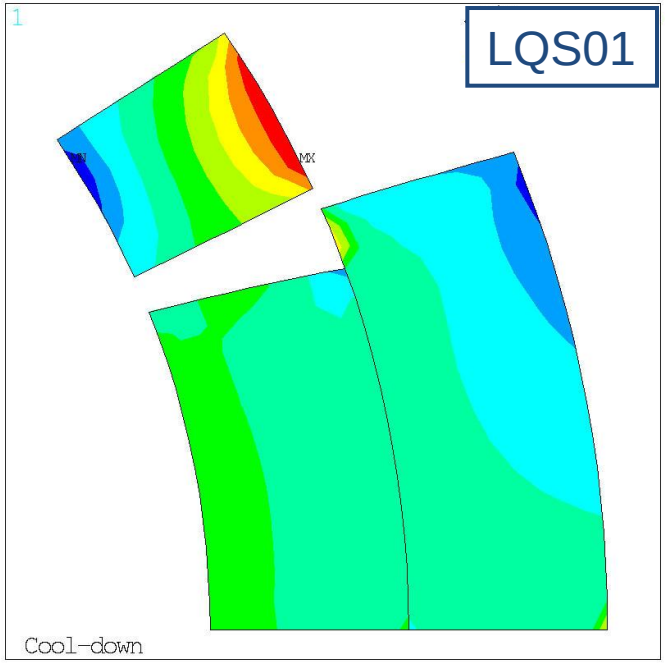
- Same pole stress as TQS03b
  - No pole turn separation
  - 91% Iss

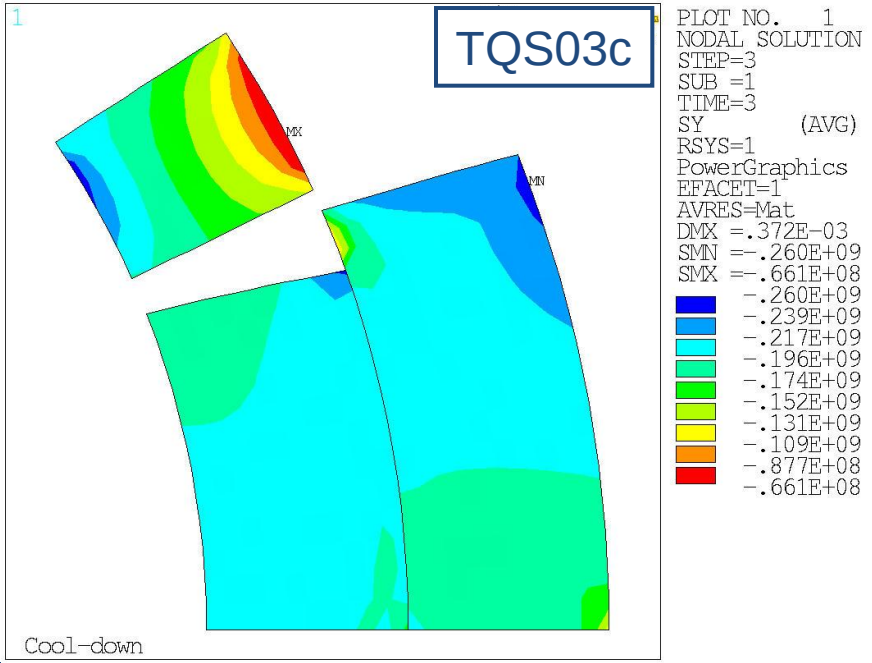




Expected LQS01b pre-load after cool-down (Variations based on sensitivity analysis)

- Coil peak stress
  - Layer 1: -193 ±30 MPa
  - Layer 2: -186 ±30 MPa
- Less than TQS03c (88% I_{ss})
  - Layer 1: -240 MPa
  - Layer 2: -260 MPa



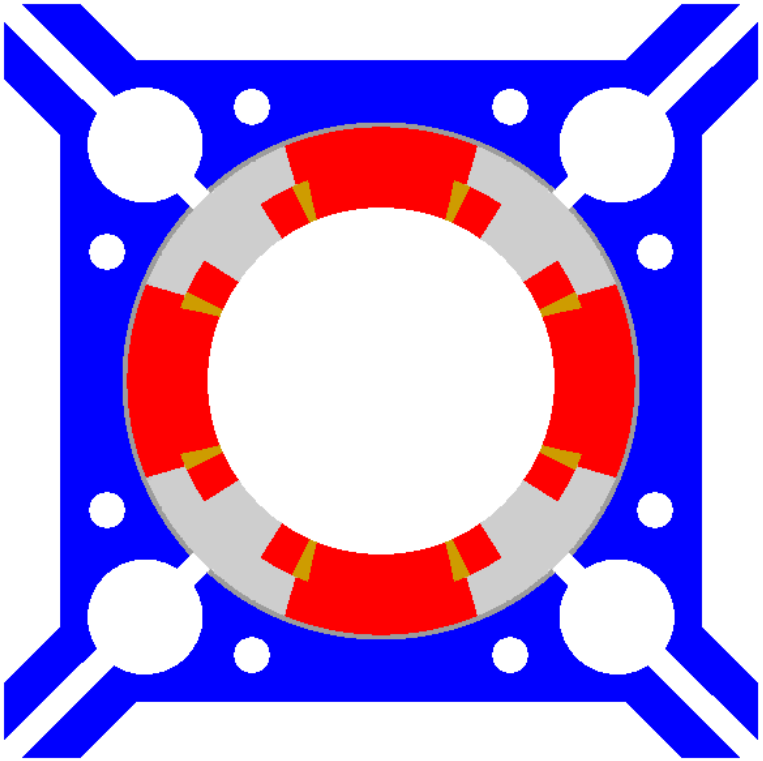


Conclusions

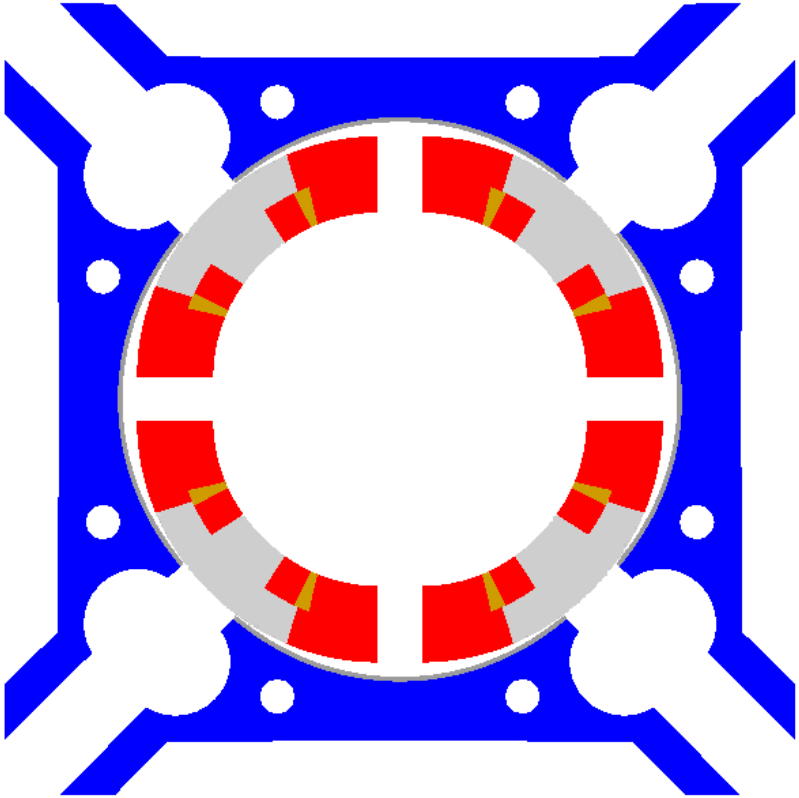
- LQS01 mech. behavior at 4.5 K similar to 293 K conditions
  - Low pre-load in coil inner layer
- Pole strain plateau, indicating separation, observed during test
  - Magnet trained between 70% and 80% of I_{ss}
- Mismatch between coil OD and pad ID pointed out by finite element models and pressure sensitive films
- Target coil pre-load achieved in LQS01b with optimized pad ID
  - Average and peak stresses similar to TQS03b-c tests
  - Spread consistent with sensitivity analysis

Appendix

Analysis with finite element model
Nominal coil

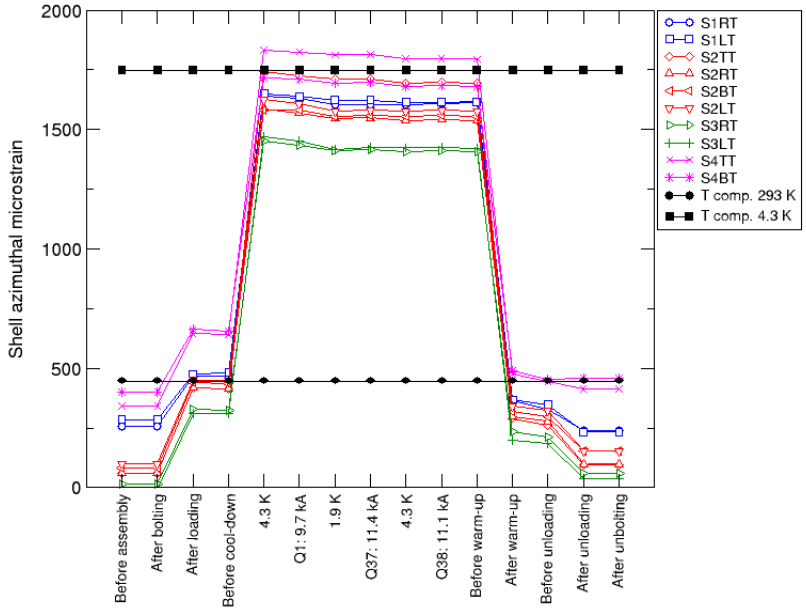


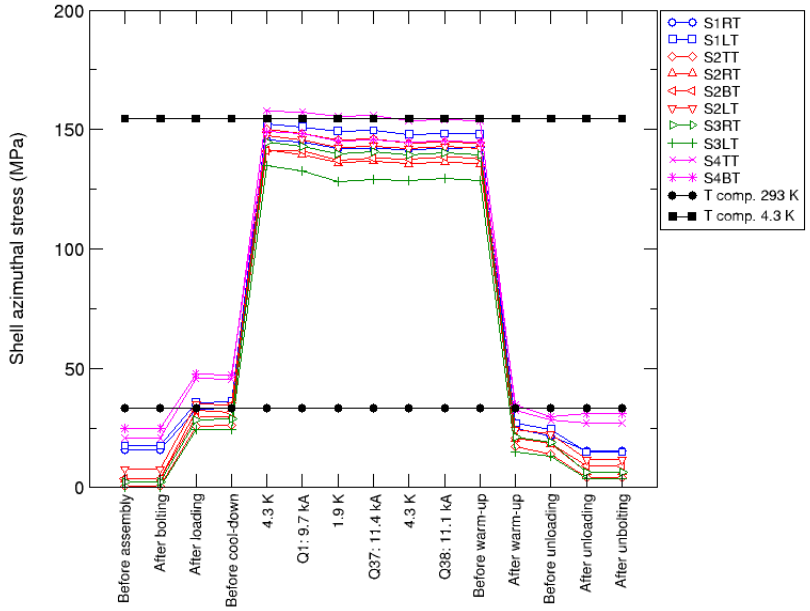
Analysis with finite element model
Oversized coil



LQS01a shell azimuthal strain – stress (Computed target: pre-load for 230 T/m)

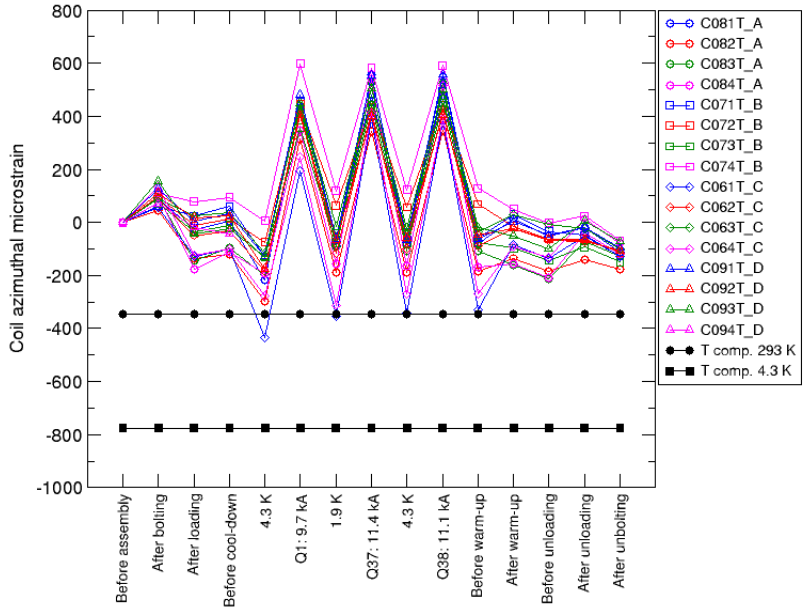
- 293 K before loading: +159 ±146 με +10 ±9 MPa
- 293 K before cool-down +459 ±114 με +34 ±8 MPa
- 4.3 K before test +1630 ±117 με +146 ±6 MPa
- 4.3 K after test +1589 ±119 με +142 ±7 MPa
- 293 K after warm-up: +338 ±93 με +24 ±6 Mpa
- 293 K after unloading: +194 ±143 με +13 ±9 MPa

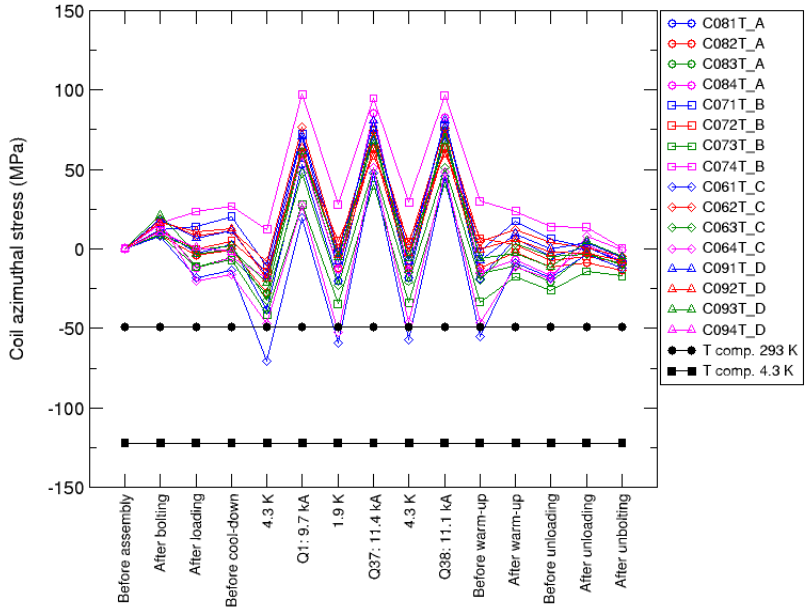




LQS01a pole azimuthal strain – stress (Computed target: pre-load for 230 T/m)

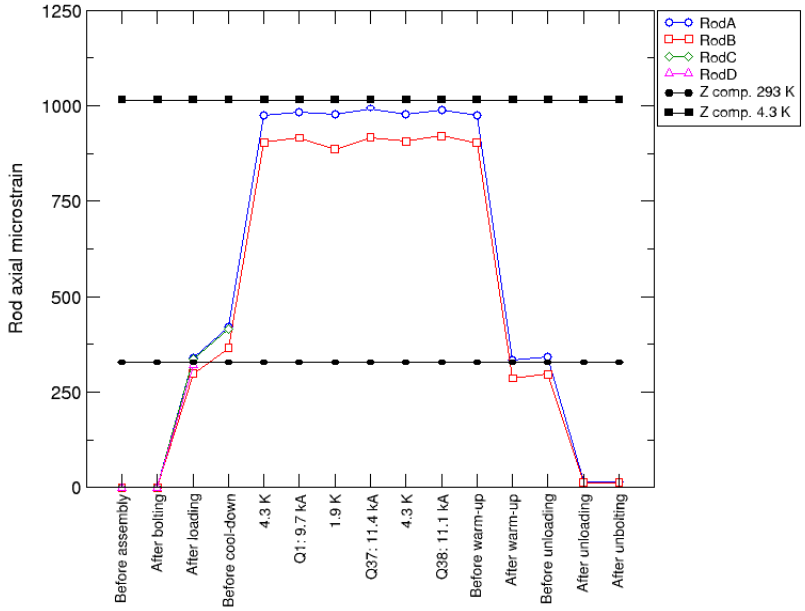
- 293 K before loading: +95 ±30 με +14 ±4 MPa
- 293 K before cool-down: -22 ±69 με +5 ±12 MPa
- 4.3 K before test -179 ±104 με -25 ±19 MPa
- 4.3 K after test –89 ±116 με -13 ±21 MPa
- 293 K after warm-up -47 ±70 με +1 ±12 MPa
- 293 K after unloading: -44 ±43 με +0 ±7 MPa

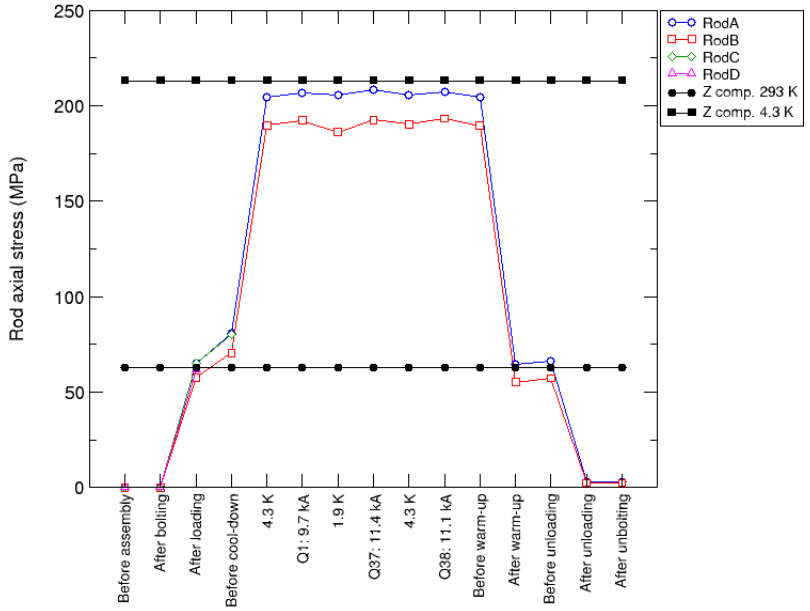


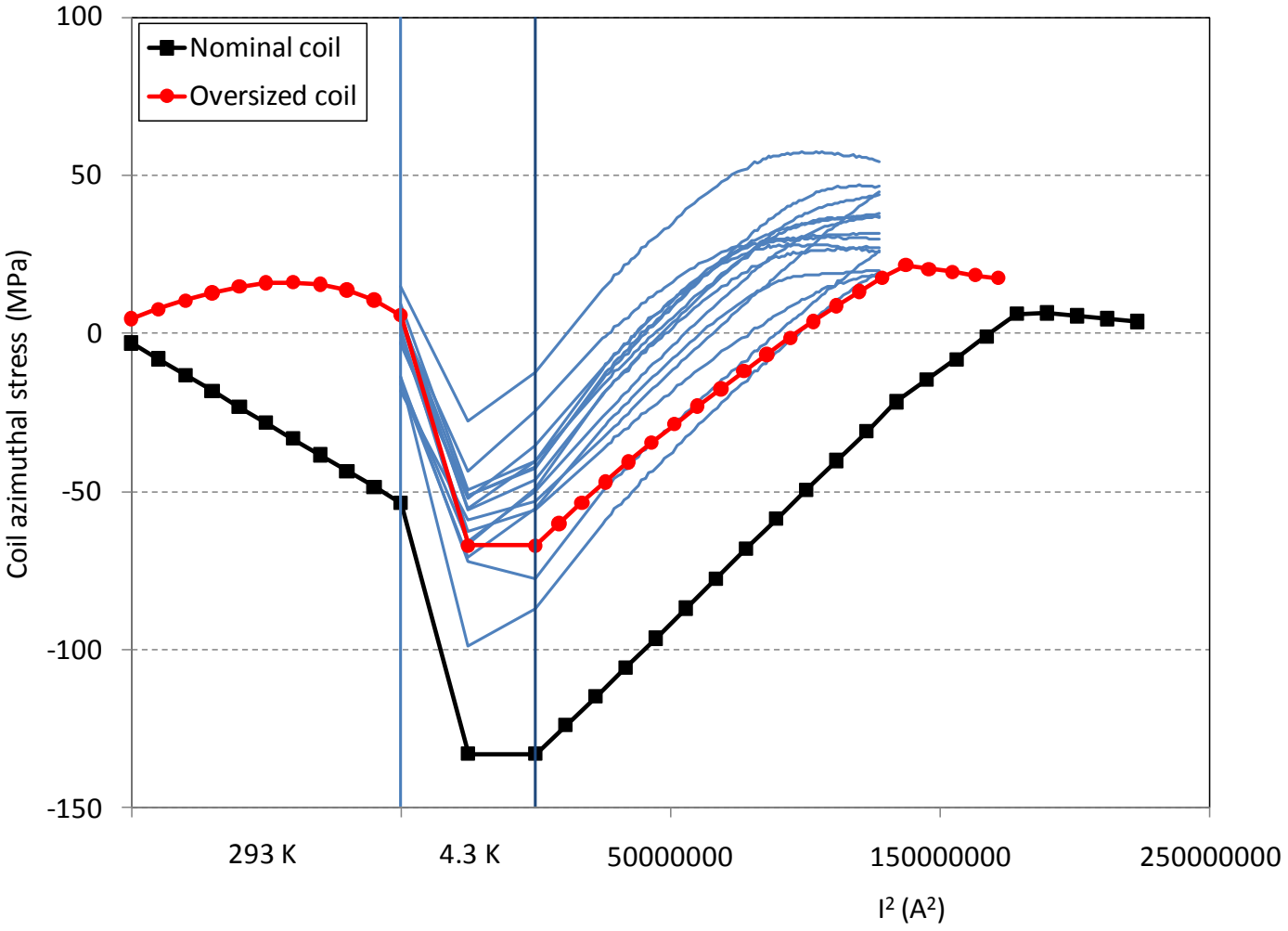


LQS01a rod axial strain – stress (Computed target: pre-load for 230 T/m)

- 293 K before loading: +0 ±0 με +0 ±0 MPa
- 293 K before cool-down +393 ±38 με +76 ±7 MPa
- 4.3 K before test +939 ±50 με +197 ±11 MPa
- 4.3 K after test +939 ±51 με +197 ±11 MPa
- 293 K after warm-up: +311 ±34 με +60 ±7 MPa
- 293 K after unloading: +0 ±0 με +0 ±0 MPa






Nominal coil
Oversized coil
100
50
0
-50
-100
-150
Coil azimuthal stress (MPa)
293 K
4.3 K
50000000
150000000
250000000
I² (A²)

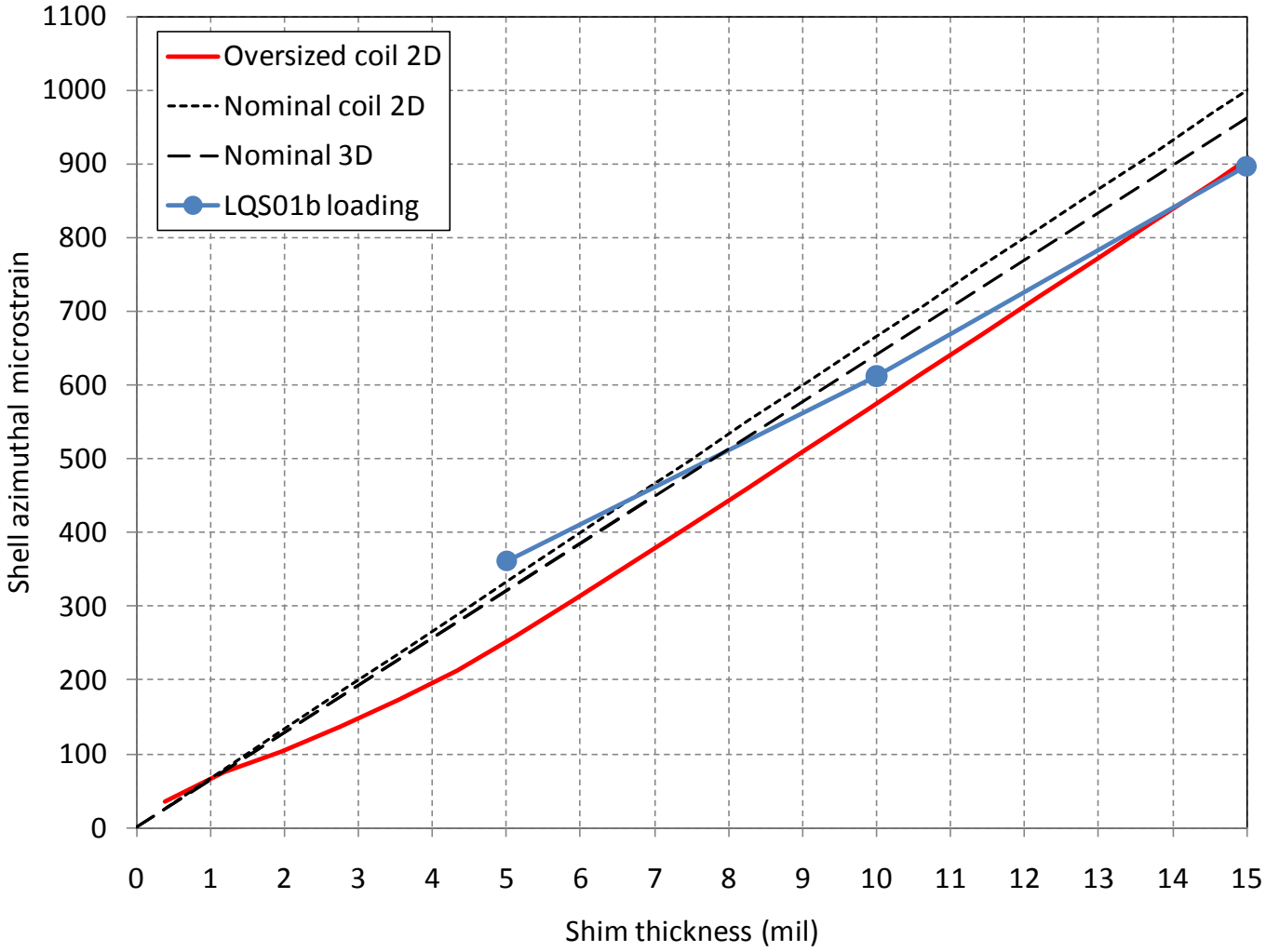
Coil-pack dimensions
LQS01a vs. LQS01b

From LE	2”	33”	66”	99”	132”	Av. end	Av. center
LQSD before cool-down (torque: 100 inch*pound)							
Width							**6.543”**
Height							**6.545”**
LQS01a before test (torque: 100 inch*pound)							
Width	6.549”	6.583”	6.584”	6.582”	6.566”	6.558”	**6.583”**
Height	6.552”	6.574”	6.564”	6.569”	6.543”	6.548”	**6.569”**
LQS01a after test (torque: 35 inch*pound)							
Width	6.560”	6.579”	6.581”	6.582”	6.560”	6.560”	**6.581”**
Height	6.549”	6.587”	6.586”	6.581”	6.556”	6.553”	**6.585”**
LQS01b before test (torque: 100 inch*pound)							
Width	6.512”	6.530”	6.531”	6.533”	6.516”	6.514”	**6.531”**
Height	6.510”	6.541	6.533”	6.536”	6.514”	6.512”	**6.537”**

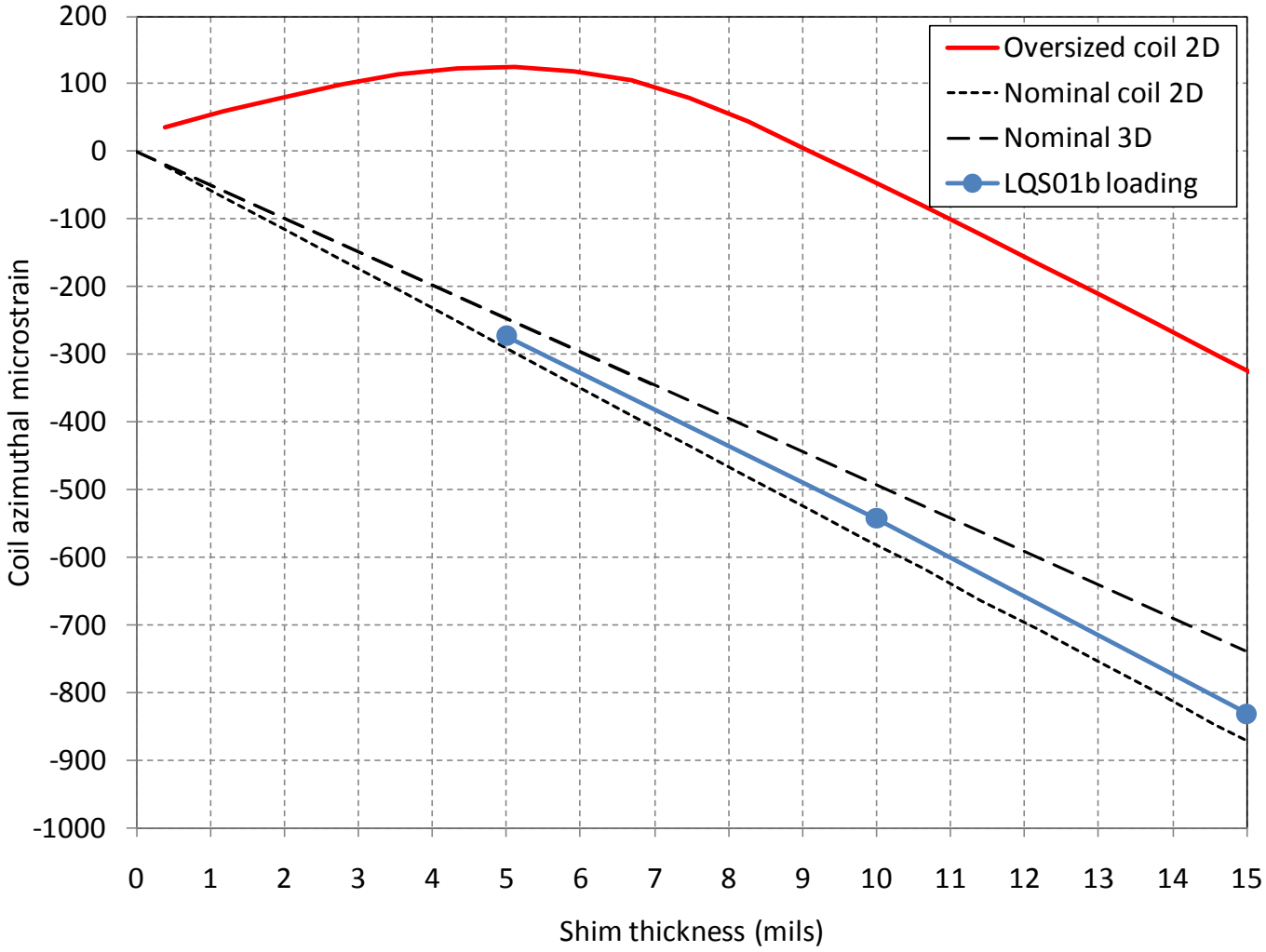
Coil-pack dimensions
LQS01a vs. LQS01b

- After bladder operation
  - LQSD
    - Shell azimuthal microstrain: 535
    - Load shim stack: 0.070”
      - 0.069” for 460 microstrain
  - LQS01
    - Shell azimuthal microstrain: 460
    - Load shim stack: 0.050”
  - LQS01 coil-pack width at full load 0.040” bigger than LQSD
- After LQS01a test
  - After removal of top-pad
    - Some misalignment between adjacent coils towards the ends
    - 3 mil (filler gauges) between mid-planes in the central region

Shell strain vs. shim thickness

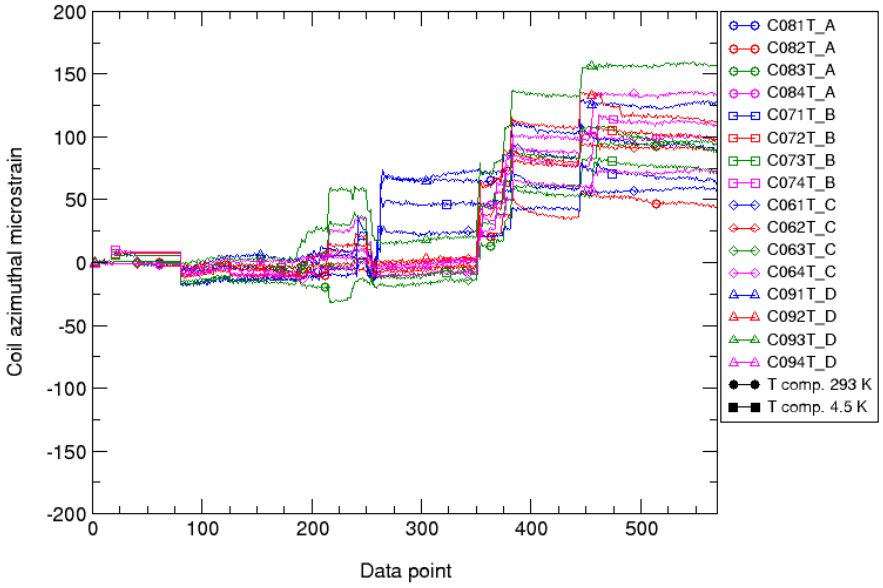


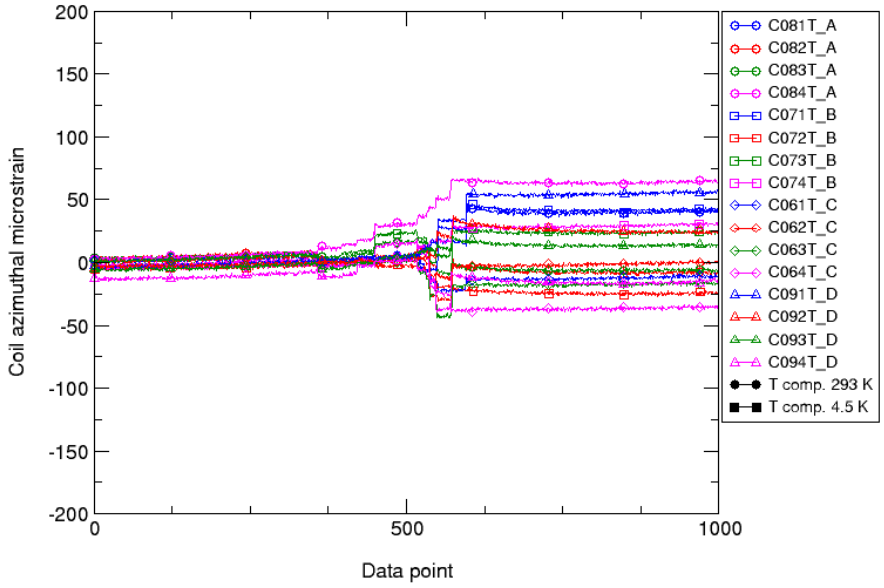
Coil strain vs. shim thickness



Coil-pack assembly
Pad bolting

- LQS01 pole gauges
  - Tension after bolting
    - Bending
- LQS01b pole gauges
  - Minimum strain (bending) after bolting





Sensitivity analysis

- Variation of coil mid-plane:
  - ±2 mils (±50 μm)
    - The variation is simulated by shifting vertically the coil mid-plane by ±50 μm
- Variation of shell inner radius :
  - ±2.5 mils (±65 μm)
    - The variation is simulated by changing the shim of the interference key by ±65μm

Computed sensitivity

Coil mid-plane	Shell	Pole σ_y at 293 K	Pole σ_y at 4.3 K	Coil σ_{y_peak} at 293 K	Coil σ_{y_peak} at 4.3 K	Shell σ_y at 293 K	Shell σ_y at 4.3 K
		MPa	MPa	MPa	MPa	MPa	MPa
LQS01 target	LQS01 target	-51	-128	-48/-36	-164/-162	+32	+151
LQS01b target	LQS01b target	-87	-163	-82/-61	-193/-186	+54	+180
+50 μm	Nominal	-92	-50	-90/-76	-189/-205	+65	+196
-50 μm	Nominal	-96	-176	-86/-58	-197/-169	+41	+164
Nominal	+65 μm	-106	-182	-100/-74	-209/-200	+66	+195
Nominal	-65 μm	-68	-144	-64/-47	-167/-173	+42	+164
-50 μm	+65 μm	-116	-193	-105/-68	-212/-182	+53	+179
+50 μm	-65 μm	-84	-131	-80/-68	-173/-191	+52	+180
+50 μm	+65 μm	-107	-169	-104/-85	-205/-218	+77	+211
-50 μm	-65 μm	-75	-156	-68/-48	-181/-155	+29	+148