Collaring kinematics, mechanics, instrumentation, and mock-ups

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11T Dipole Collaring Task Force Meeting
15 January 2018
CERN

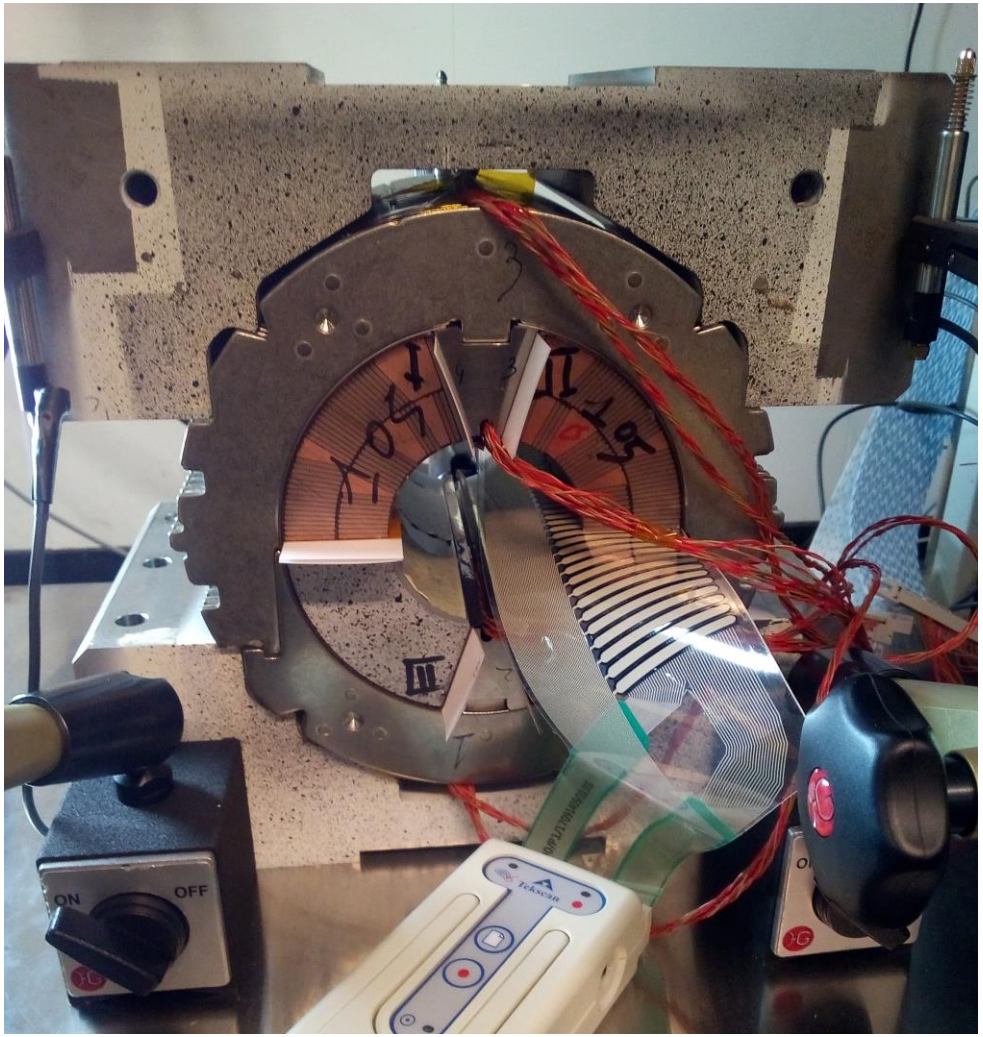
Aknowledgments

- Ten stack measurements
  - Michael Daly
- Coil size under pressure and modulus
  - Jose Luis Rudeiros Fernandez and Susana Izquierdo Bermudez
- Faro arm and CMM measurements
  - Salvador Ferradas Troitino
- Instrumentation and assembly of 150 mm mock-up
  - Michael Daly, Christian Hannes Loffler and Michael Guinchard, Phillip Grosclaude
- Capacitive gauges
  - Arnaud Foussat, Michel Parent, Francois-Olivier Pincot
- Fuji paper tests
  - Felix Josef Wolf
- Finite element models and data analysis
  - Christian Hannes Loffler, Emelie Kristina Nilsson, Susana Izquierdo Bermudez, Giorgio Vallone
- Collaring procedure and mock-up
  - Juan Carlos Perez, Nicolas Bourcey, Christian Hannes Loffler, Michael Daly
- …and
  - Jose Ferradas Troitino
  - Ezio Todesco
  - Giancarlo Spigo

Outline

- Status and plan of collaring test
- Status of the analysis

Collaring mock-up

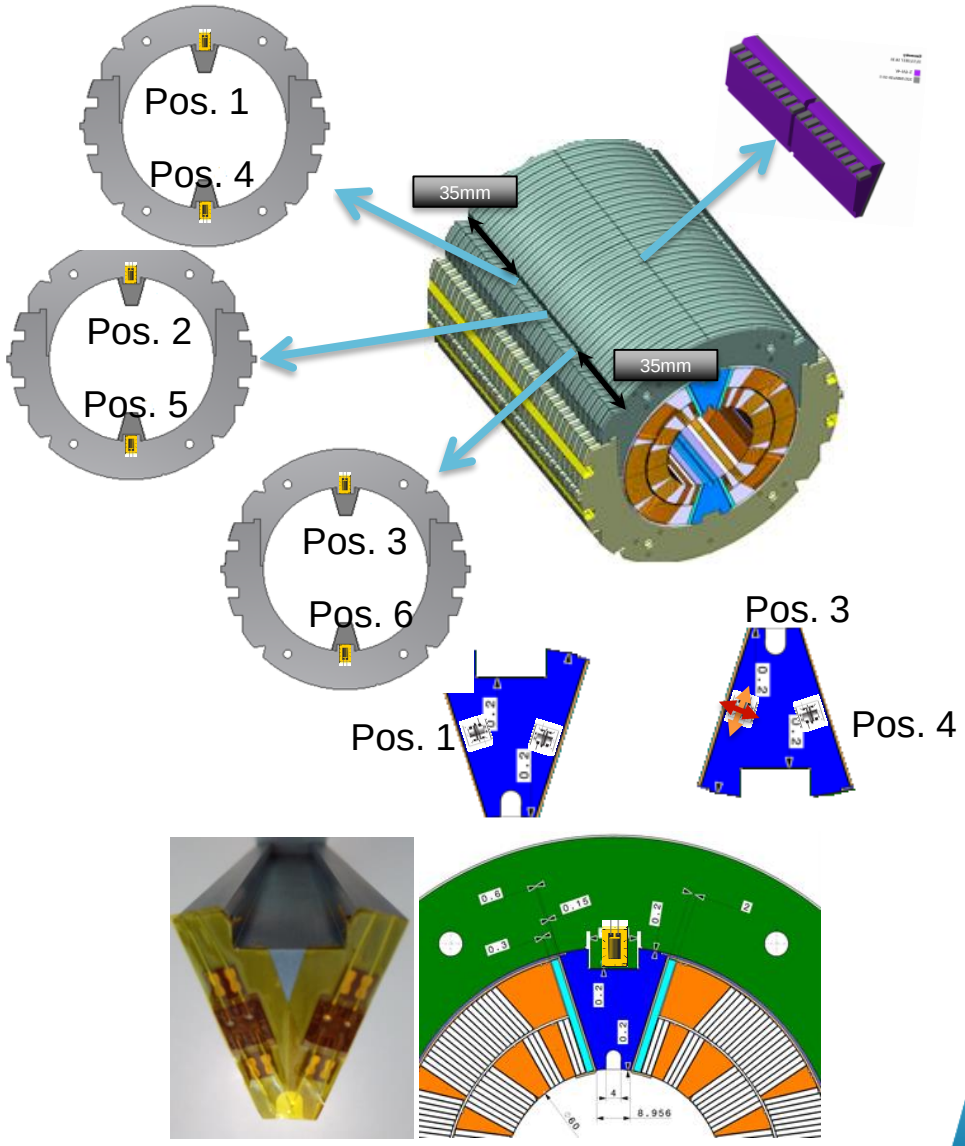


Plan: step 1
February 2018

- Goals
- Aluminum coils
  - Check 0.200, 0100, 0.050 mm excess
  - Validation of 927 press
  - Swap the coils in mechanical lab
- CR03
  - Cut and measure first segment and spare segments
  - Further practice with spare
  - Test with first segment

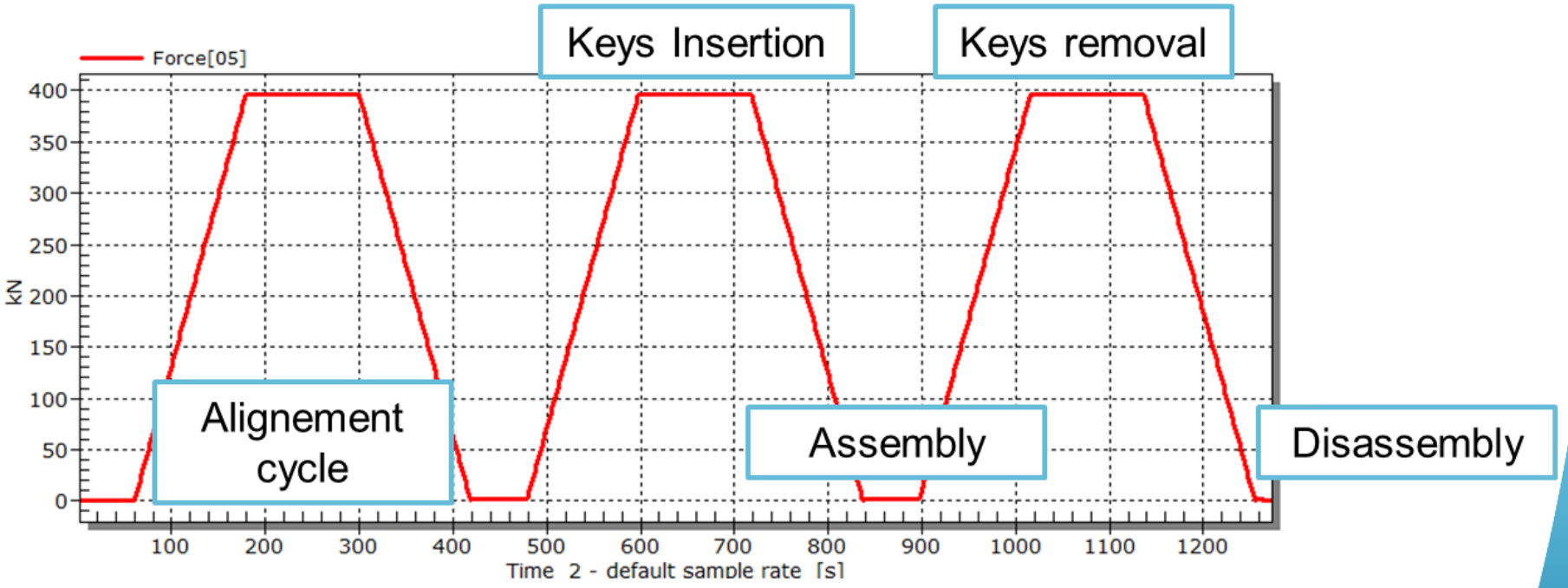
Status of instrumentation
From January 2018

- Both side of the 6 collars equipped with strain gauges in half-bridge configuration (Production)
- Bending and compression stress measurements for collars
- Slits with a gap of 500 µm between nose and pole
- Pole wedges equipped with biaxial strain gauges and angel wires



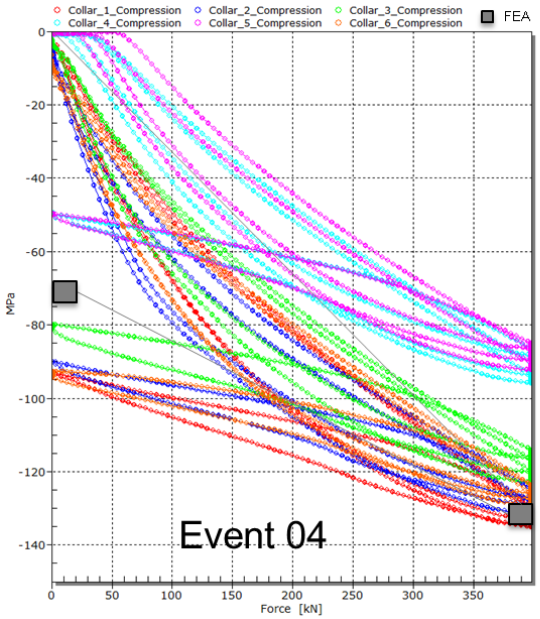
Test protocol

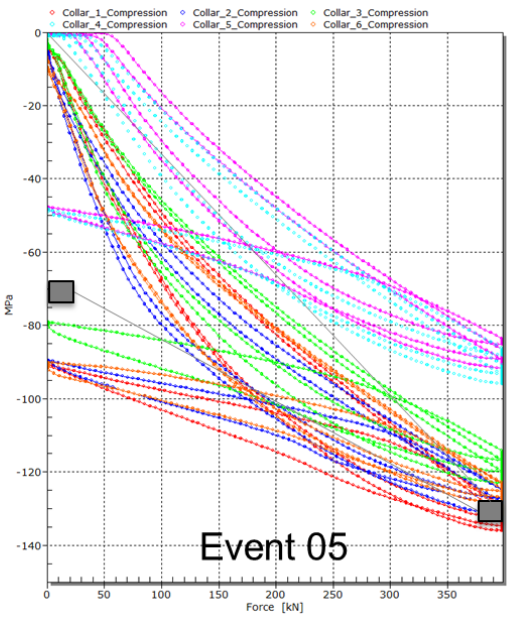
- 3 Cycles up to 400 kN (about 45 MPa on mid-plane in average)



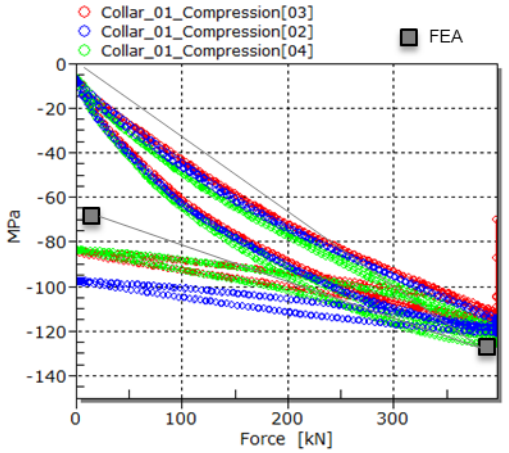
Comparison with January 2018

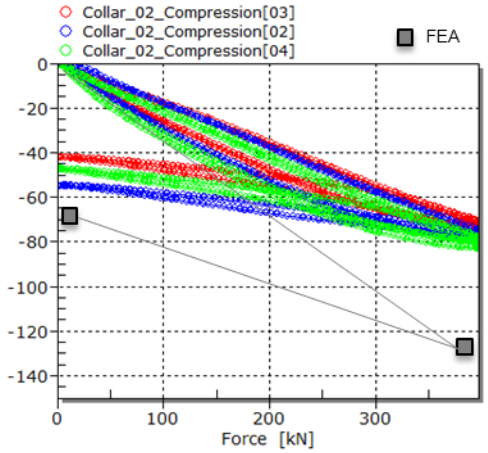
01/18

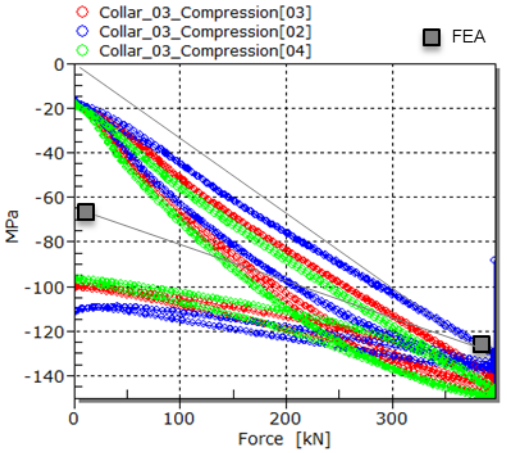




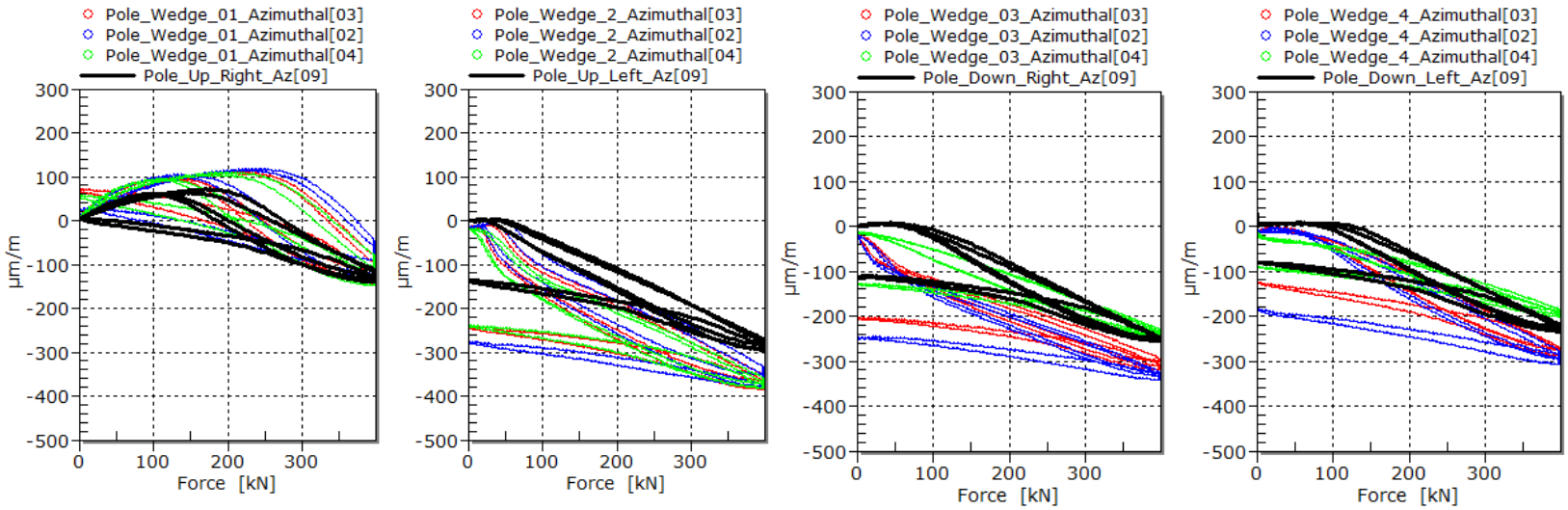
12/17



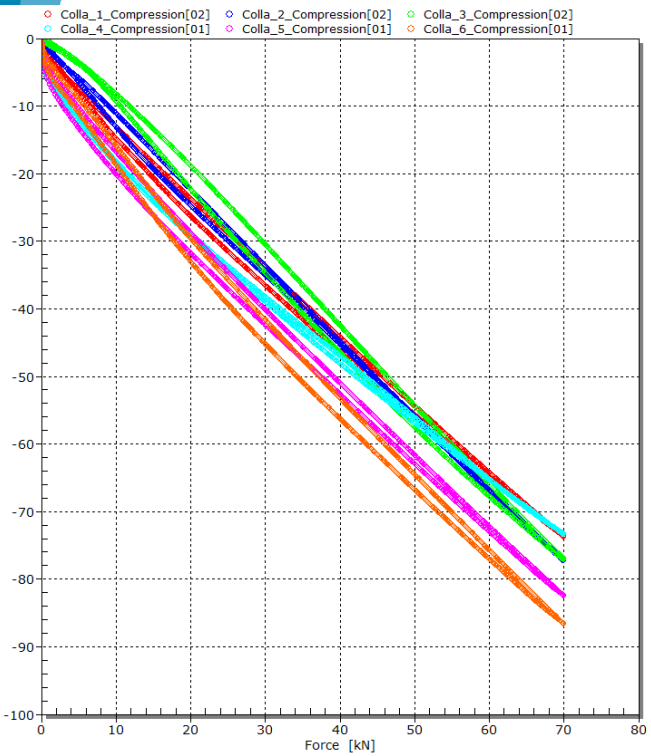


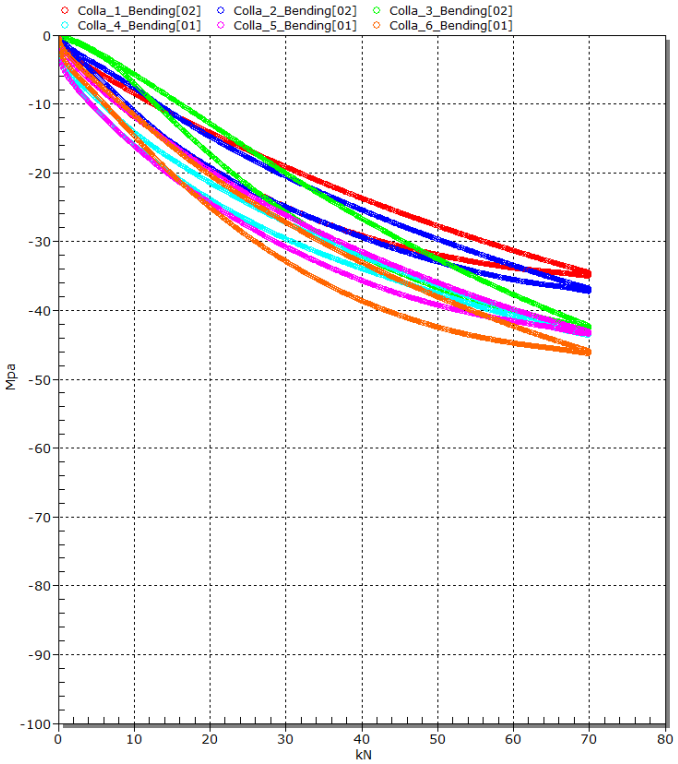


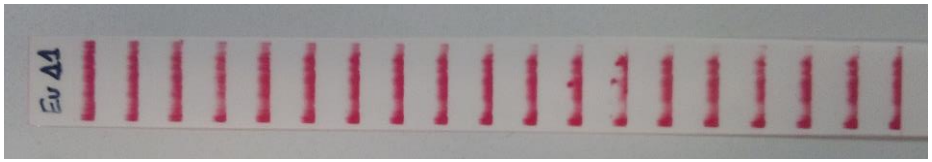
Comparison with December - January 2018



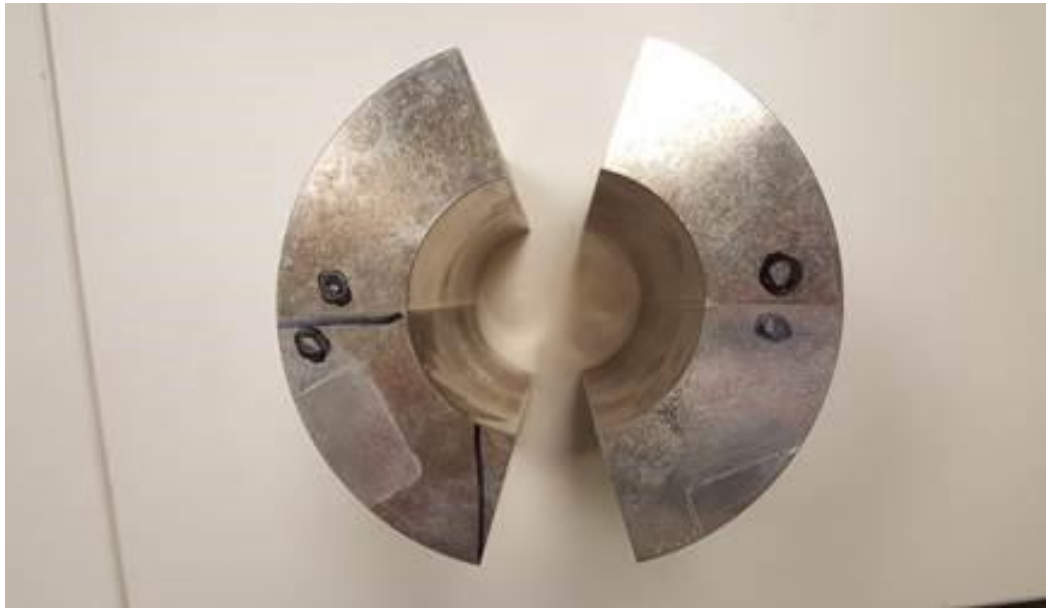
Collar noses calibration







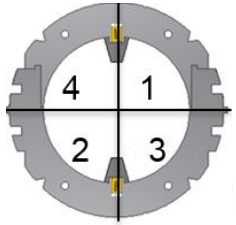
Aluminum dummy coils



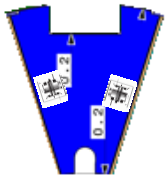
Result : Event 14/15 Test with Al dummy coil

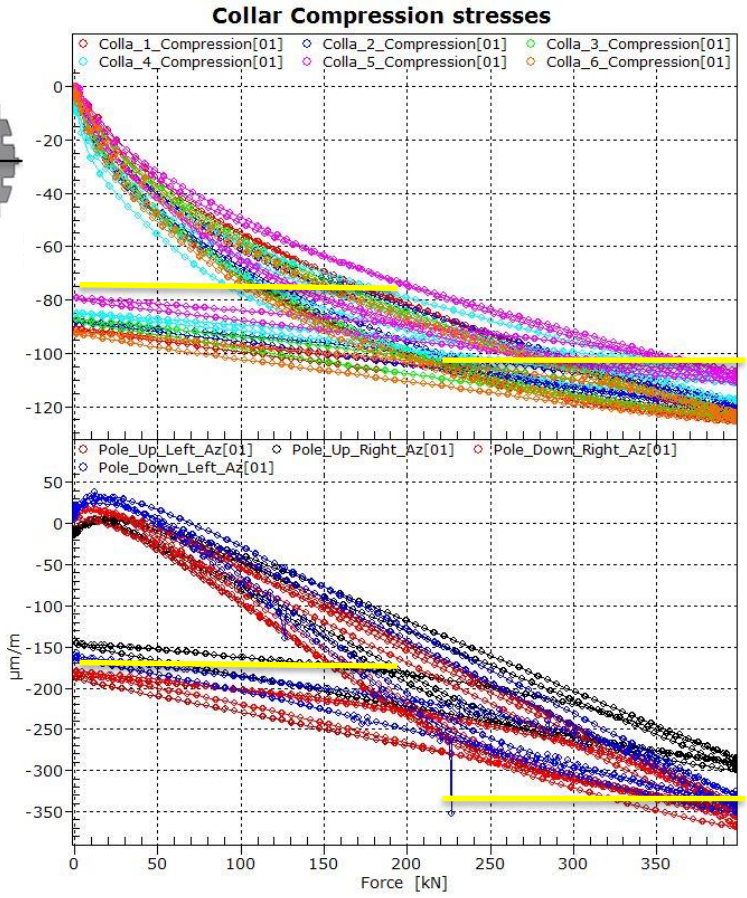
- Consistency among gauges
  - 6 collar locations
  - 4 pole locations
- No differences wrt case with real coils
- Overall, good agreement with computations

	400 kN	SB
Pole / µm/m	-338	-175
Collar Nose / MPa	-105	-72



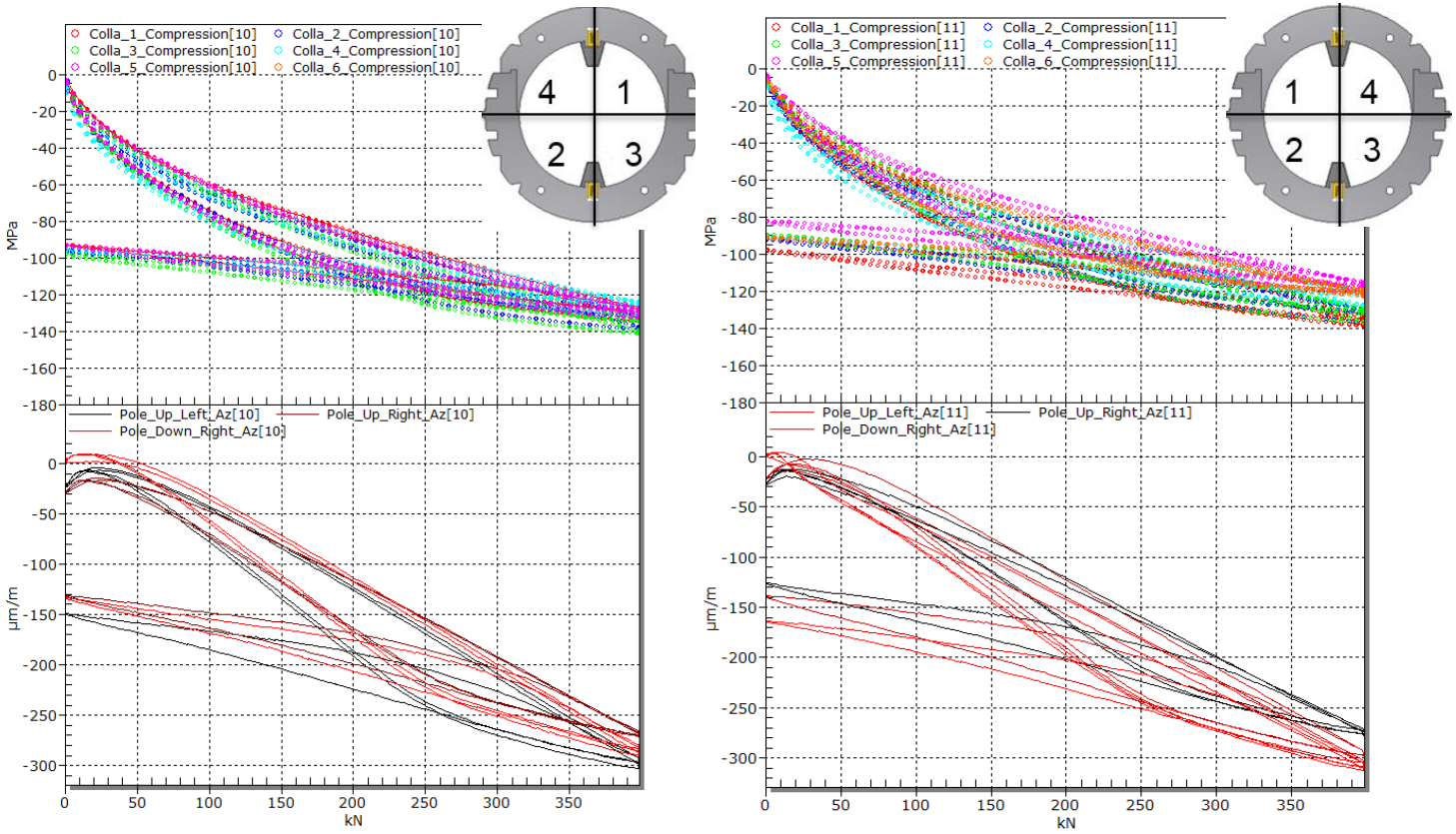
Coil excess per quadrant 0.184mm





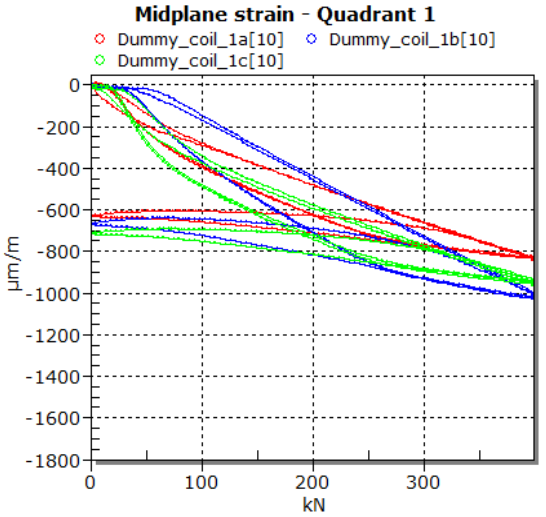
Result : Comparison Event 18/19 Coil swap

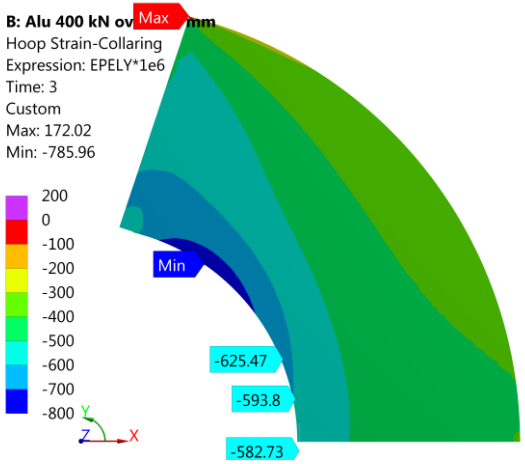
- Good agreement when coils are swapped

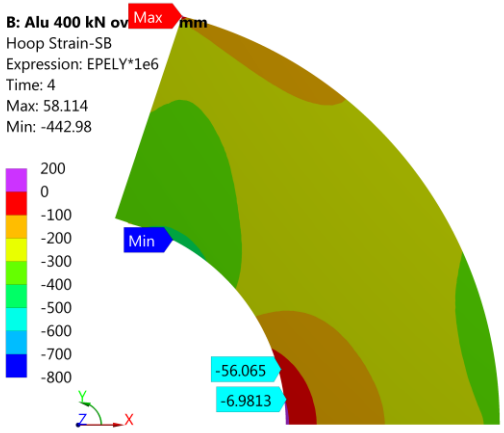


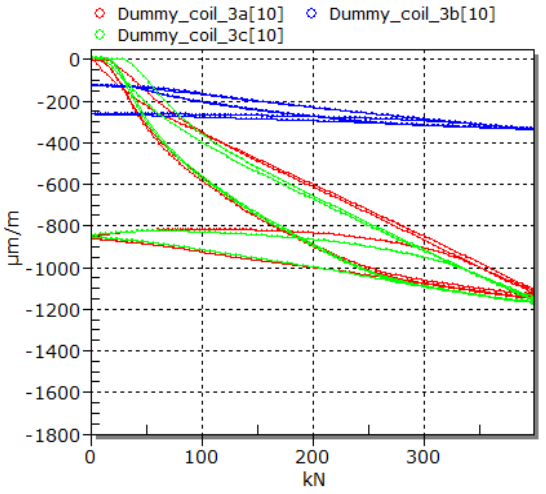
Dummy coil strain gauges

- Significant differences between coil measurements and computations









Next steps

- Change of excess with dummy coils
- Measure CR03 first segment and spare
- Test with spare
- Test with CR03 first segment

Plan for coil CR03
February-March 2018

- 1st collaring mock up (500-1100 mm)
  - Loading 1 (virgin coil)
    - No stoppers
    - Cycling at 25%, 50% and 75% of maximum collaring force
    - Key inserted with excess of 0.2 mm per quadrant
    - Full disassembly
  - Loading 2 (non virgin coil)
    - No stoppers
    - Cycling at 25%, 50% and 75% of maximum collaring force
    - Key inserted with excess of 0.3 mm per quadrant
    - Full disassembly
  - Loading 3-4 (non virgin coil)
    - No stoppers
    - Cycling at 25%, 50% and 75% of maximum collaring force
    - Key inserted with excess of 0.4-0.5 mm per quadrant
    - Full disassembly
  - Loading 5
    - With stoppers
    - Cycling at 25%, 50% and 75% of maximum collaring force
    - Key inserted with excess of 0.4 mm per quadrant
    - Full disassembly

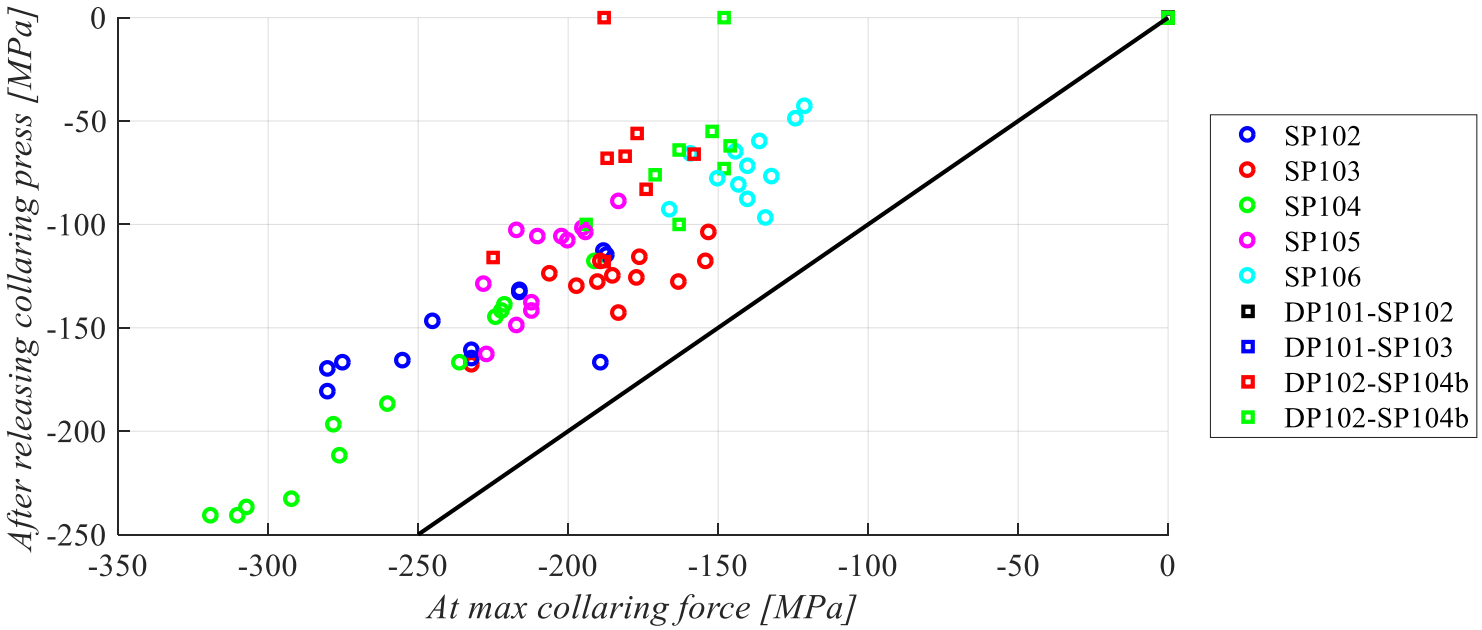
Plan for coil CR03
February-March 2018

- 2nd collaring mock up (2300-2900 mm)
  - Same as 1st collaring mock up
- 3rd collaring mock up (4300-4900 mm)
  - Loading 1 (virgin coil)
    - With stoppers
    - Cycling at 25%, 50% and 75% of maximum collaring force
    - Key inserted with excess of 0.2 mm per quadrant
    - Full disassembly
  - Loading 2-3-4 (non virgin coil)
    - With stoppers
    - Cycling at 25%, 50% and 75% of maximum collaring force
    - Key inserted with excess of 0.3-0.4-0.5 mm per quadrant
    - Full disassembly

Outline

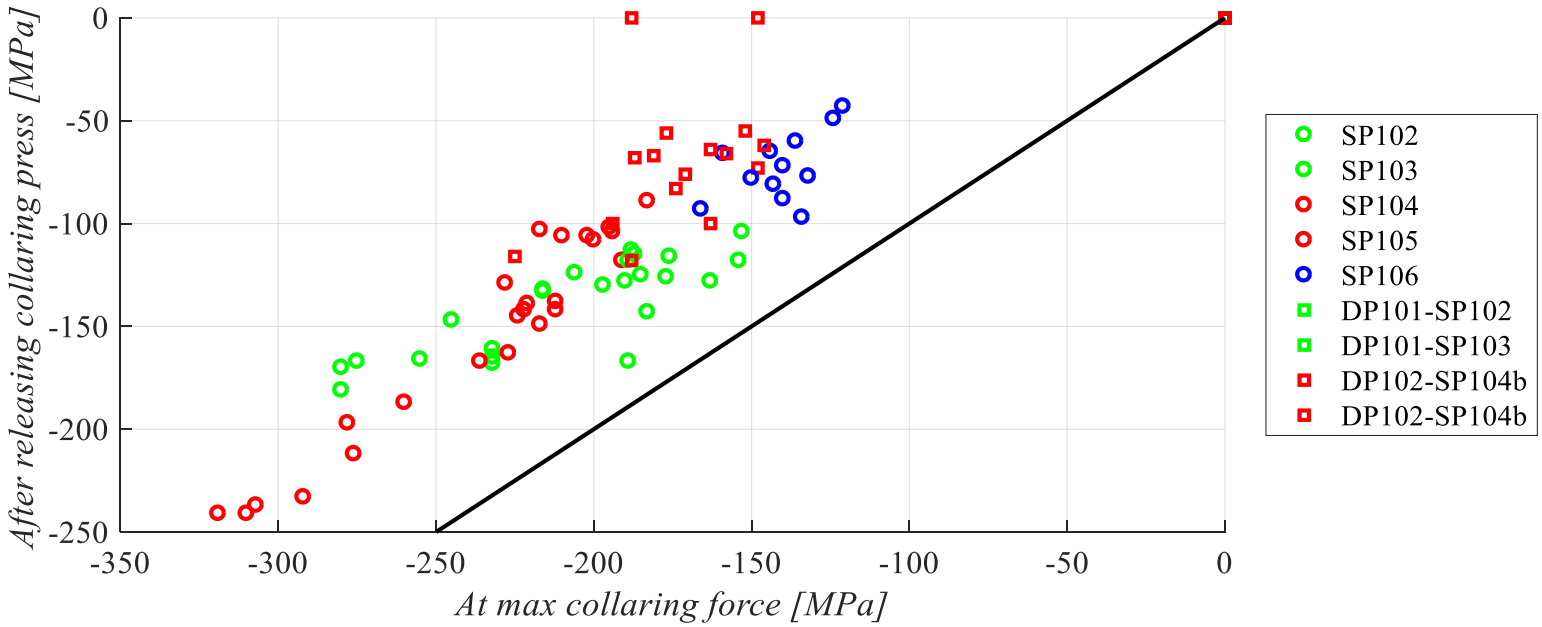
- Status and plan of collaring test
- Status of the analysis

Collaring



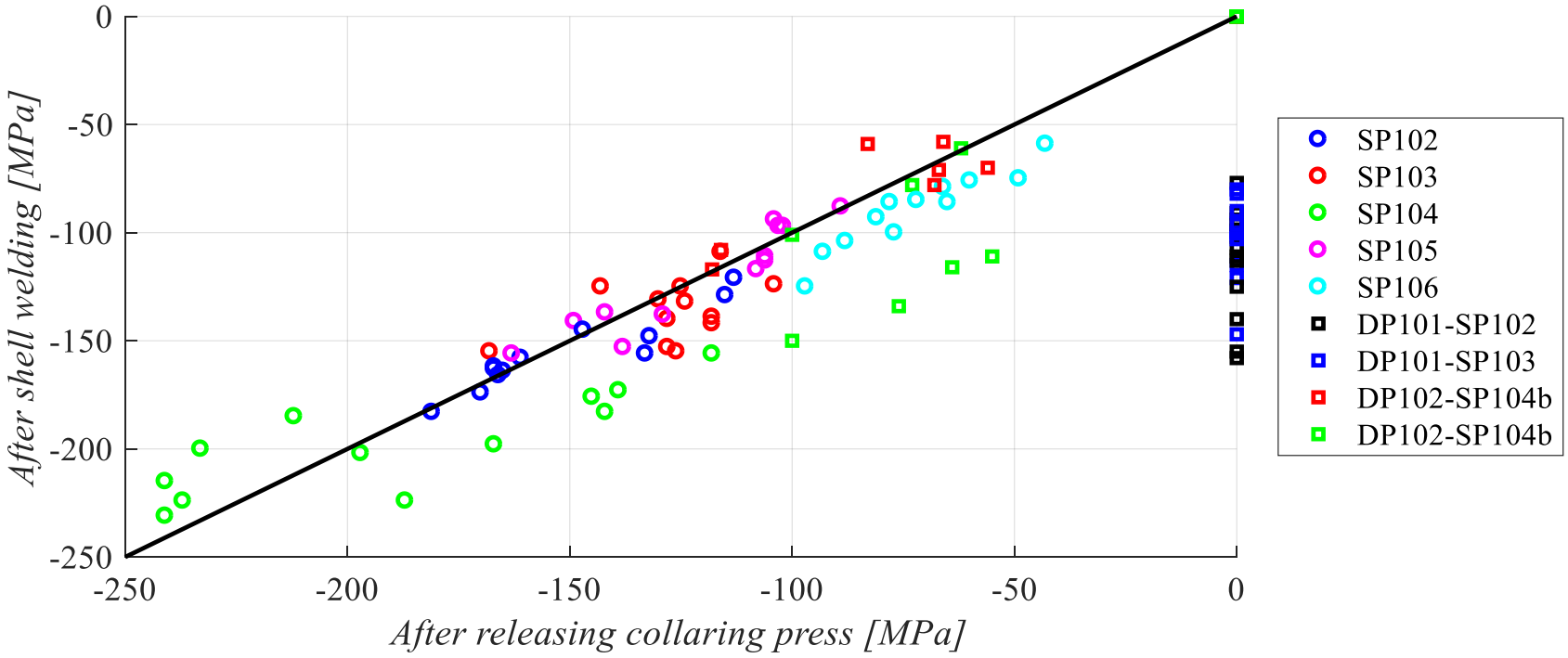
- $y = 0.9144x + 60.42$
  $R^2 = 0.823$

Collaring



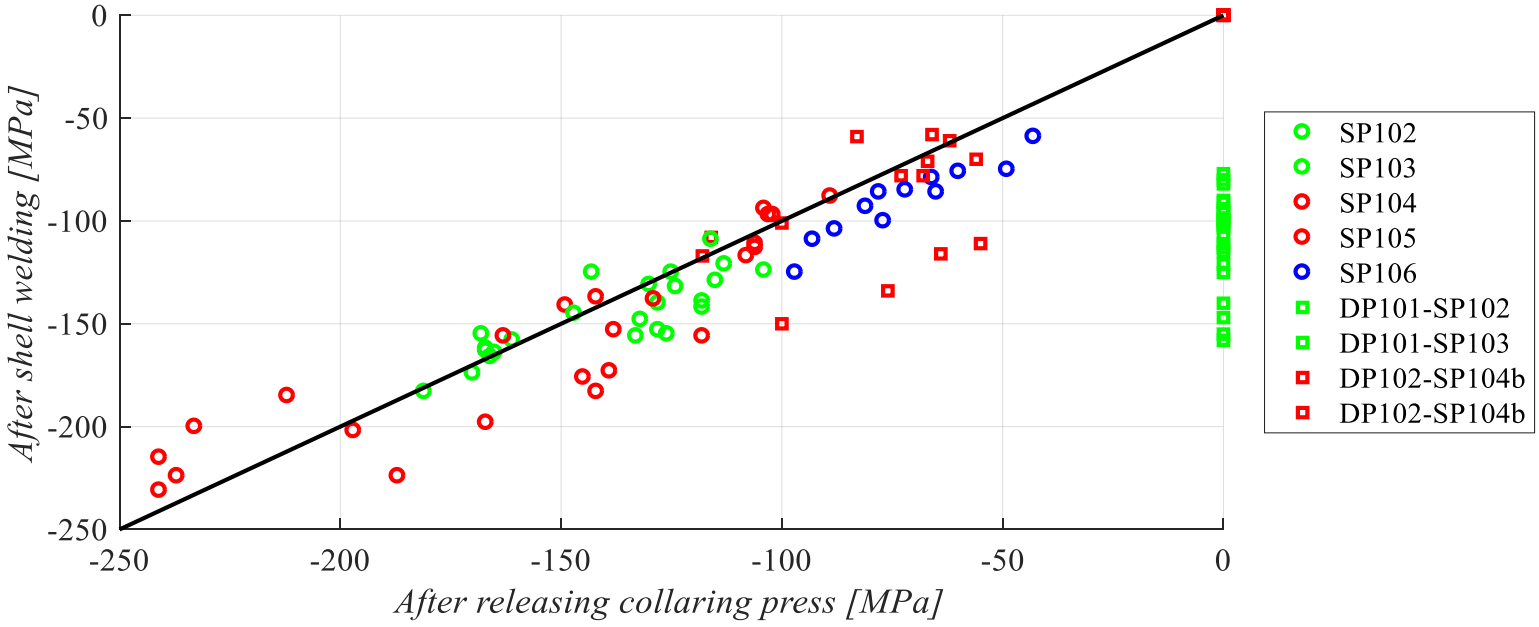
- $y = 0.9144x + 60.42$
  $R^2 = 0.823$

Shell welding



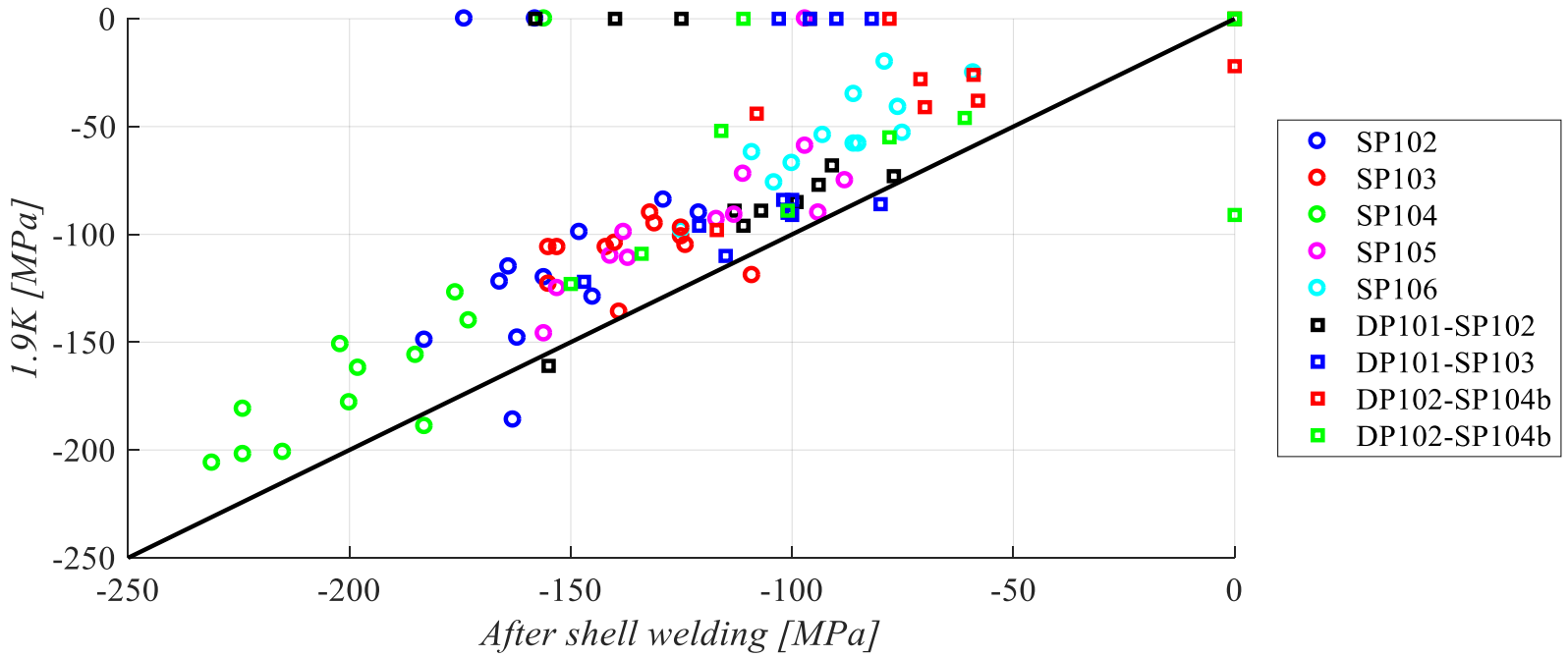
- y = 0.8283x - 30.124
  R^2 = 0.8403

Shell welding



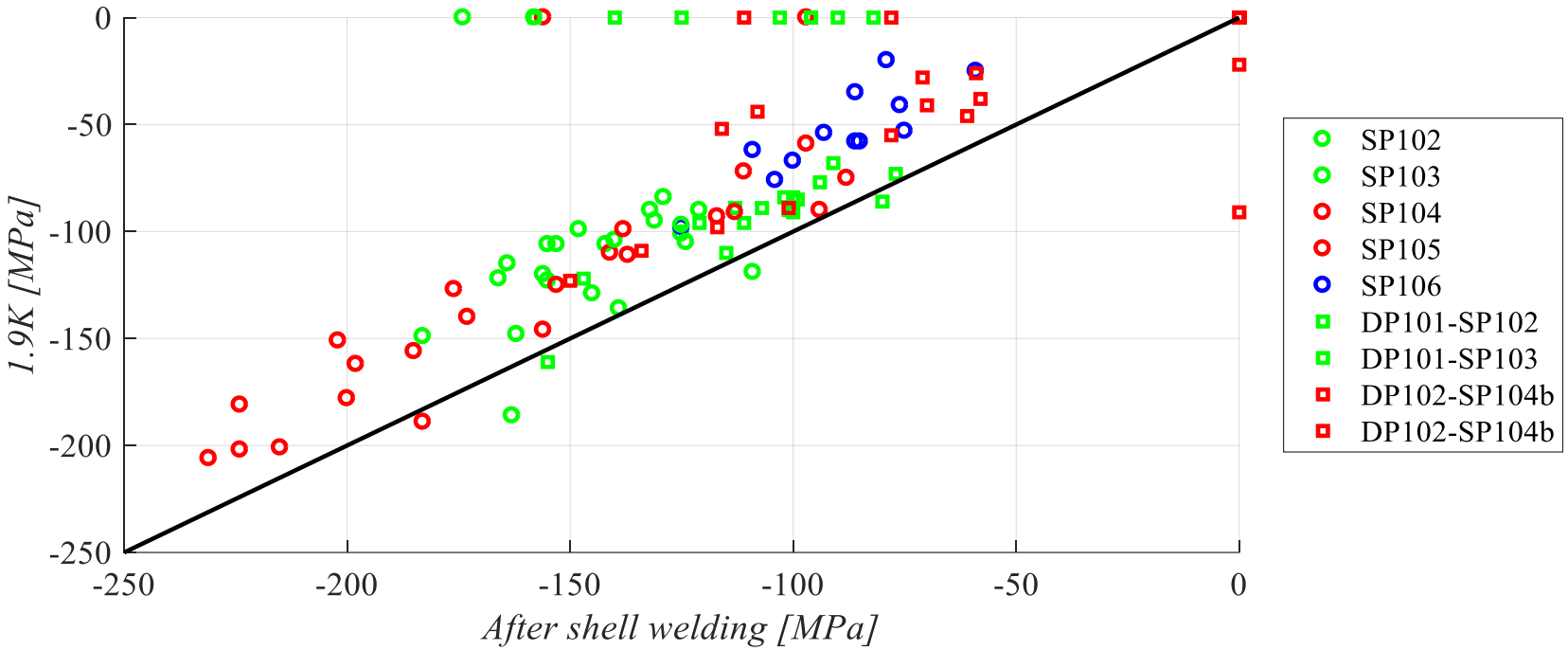
- $y = 0.8283x - 30.124$
  $R^2 = 0.8403$

Cool-down



- y= 0.9706x + 23.008
  R^2 = 0.8559

Cool-down

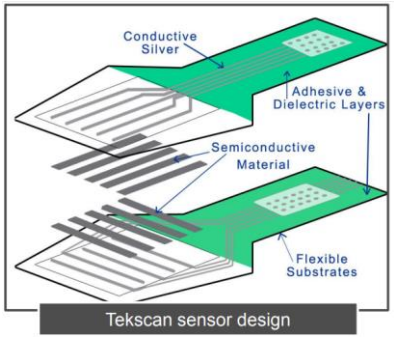


- y= 0.9706x + 23.008
  R^2 = 0.8559

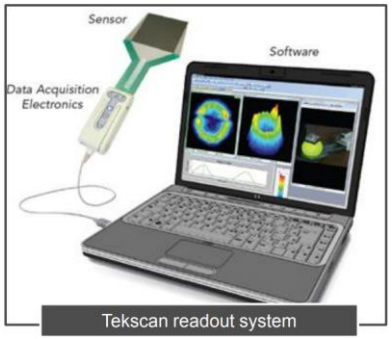
Appendix

Additional instrumentation

- Tekscan in 2-3 weeks

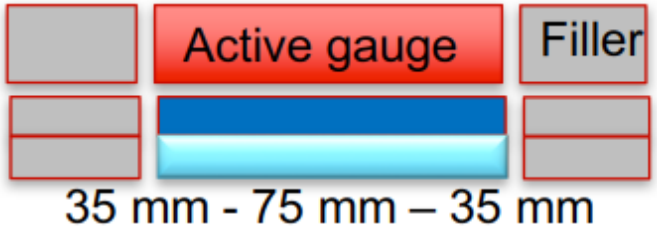


Tekscan sensor design



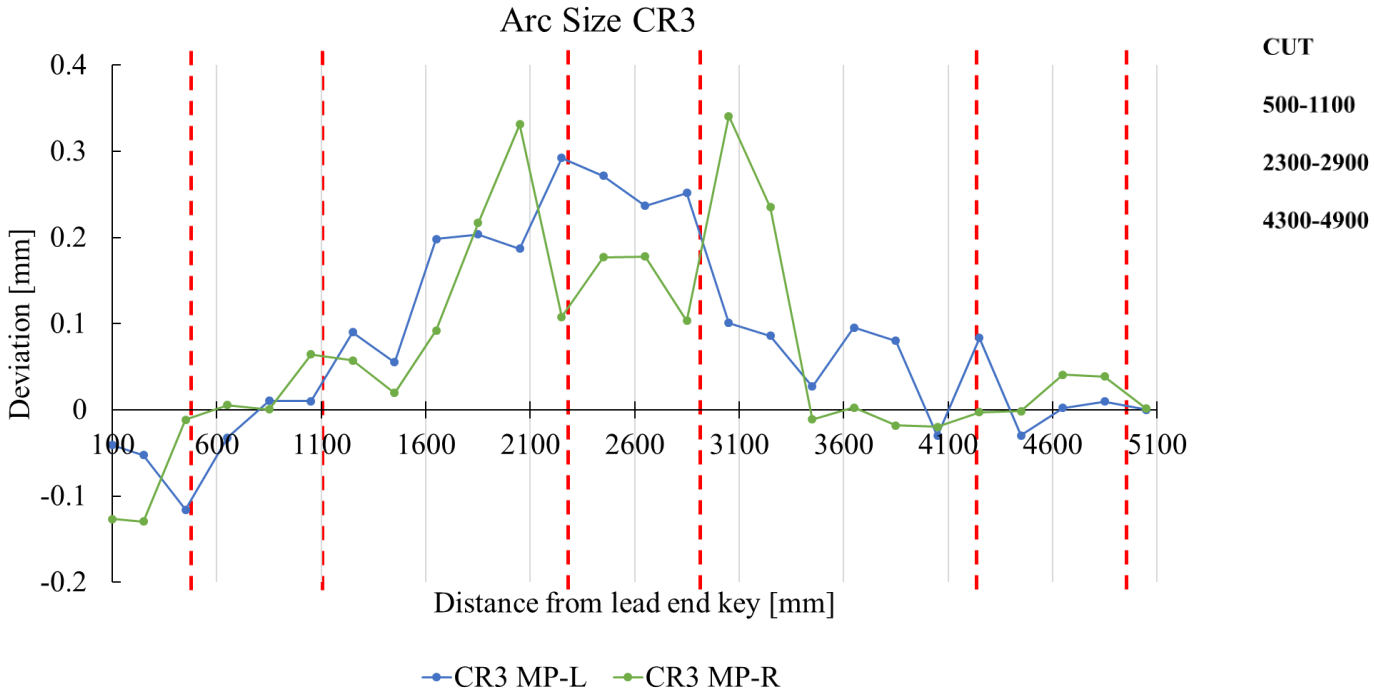
Tekscan readout system

- Capacitive gauges by mid-end February



Step 2

- Cut 6 sections from prototype coil CR03 in order to perform 3 collaring tests
  - In each segment, 2 sections for collaring and 1 for coil measurements → 150+150+300 mm
- In progress: first section by 29/01



Plan: step 3
April 2018

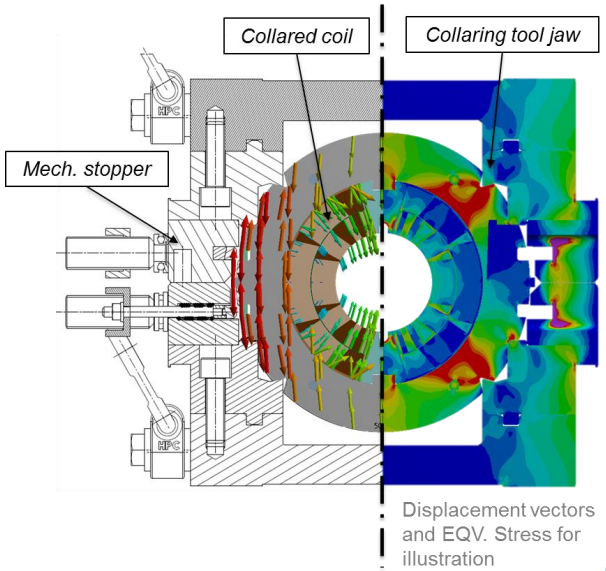
- Cut 4 sections the first short coil with RRP cable and new insulation scheme (coil 118)
- Perform 2 collaring tests to determine collar parameters for collaring of following short models and series magnets

Analysis of collaring "Old slide"

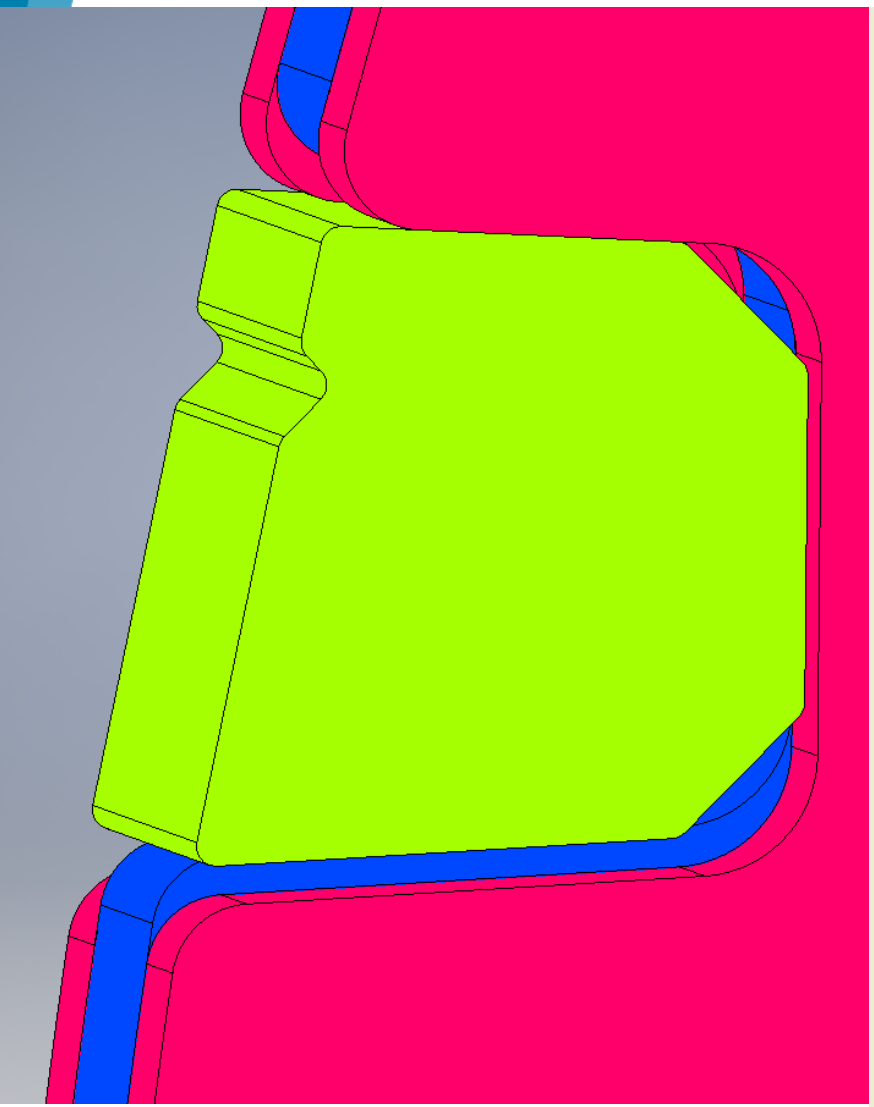
- Typical coil "excess" and force
  - 70 mm stopper equivalent to status when key inserted

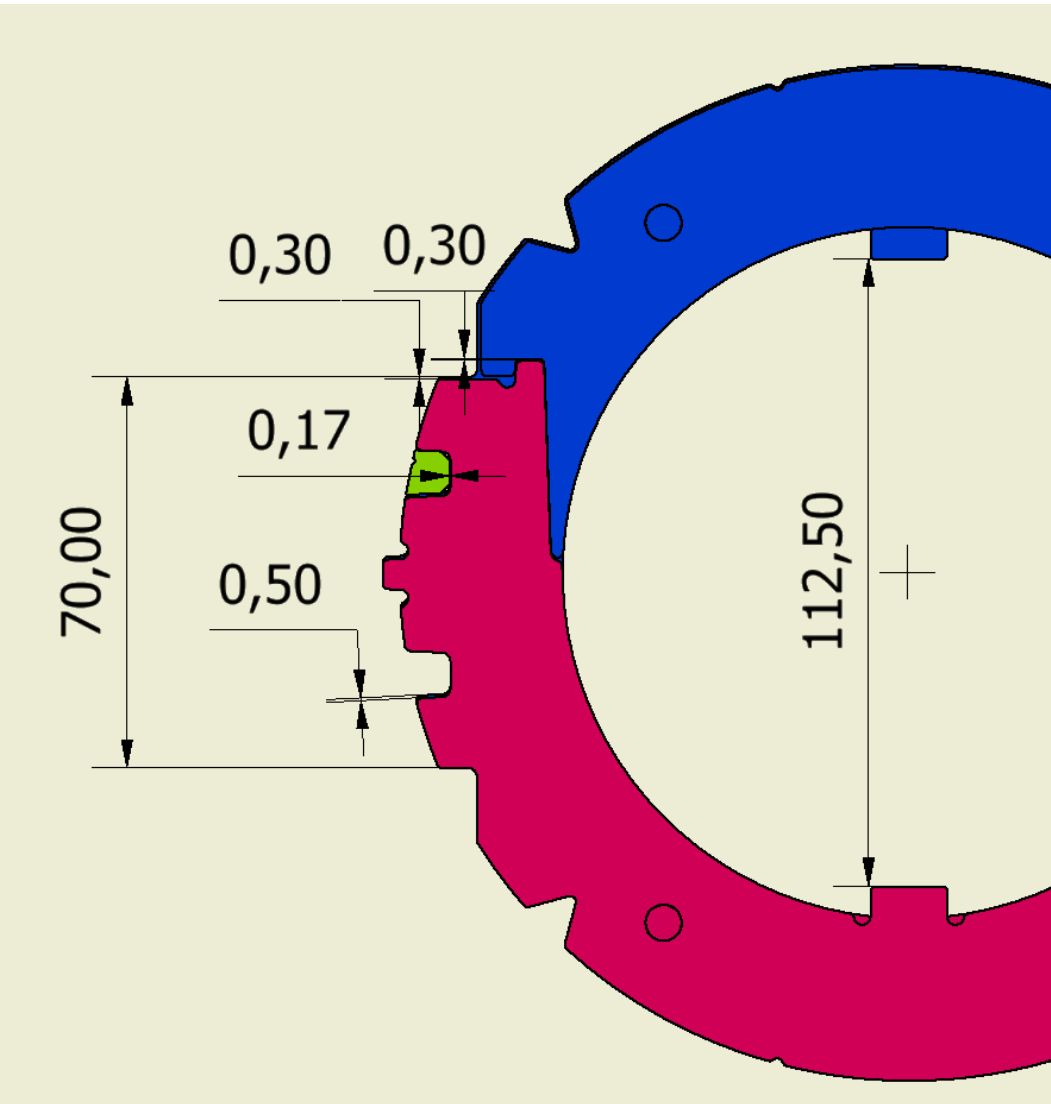
	Average Excess Quadrant	Applied Force / MN	70 mm stopper deviation / mm
CC101	0.31	32	+0.1
CC102	0.29	32	+0.1
CC103	0.38	32	+0.1
CC104	0.45	22	-0.15
CC104b	0.35	**20**	-0.15
CC105	0.35	16	-0.15
CC105b	0.30	**20**	-0.15
CC106	0.33	12	-0.15

- Deviation
  - Positive → interference
    - Tooling deformed
  - Negative→ clearance

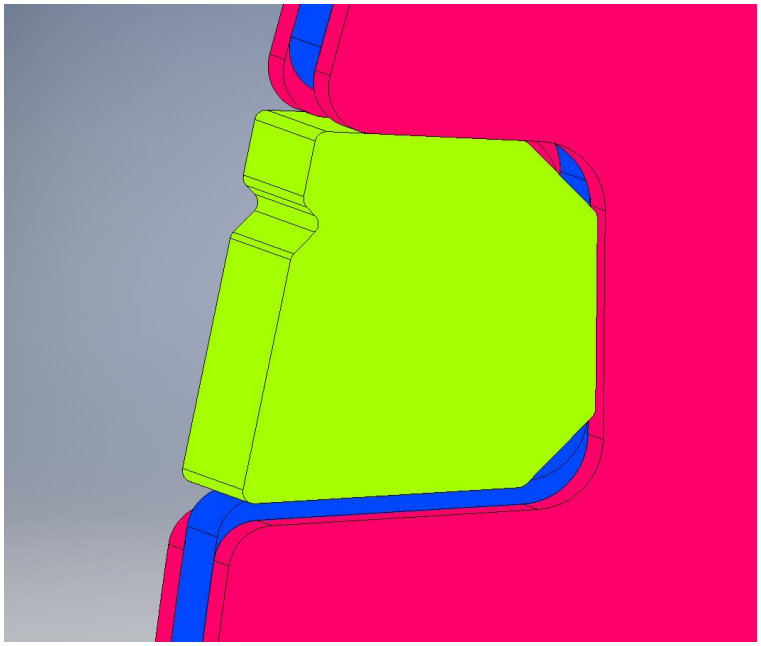


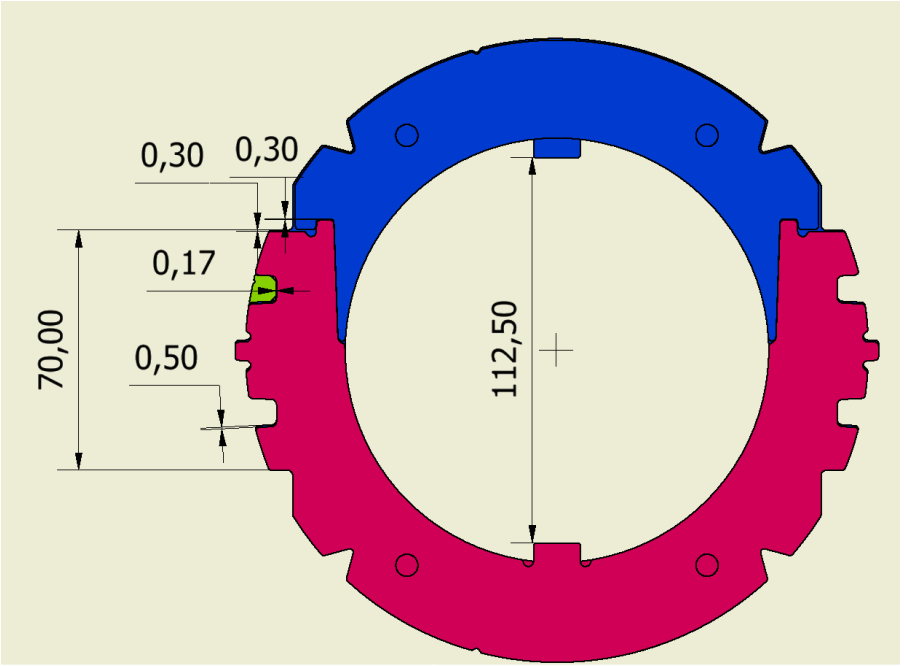
Key clearance vs stoppers shim





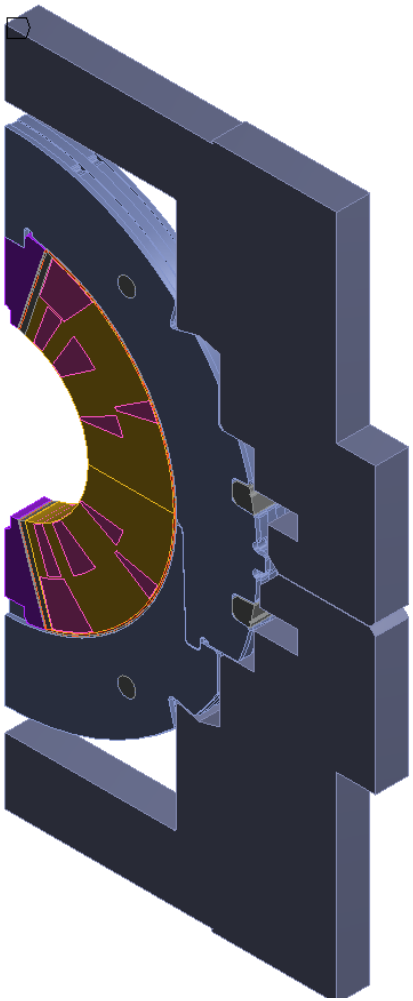
Key clearance vs stoppers shim

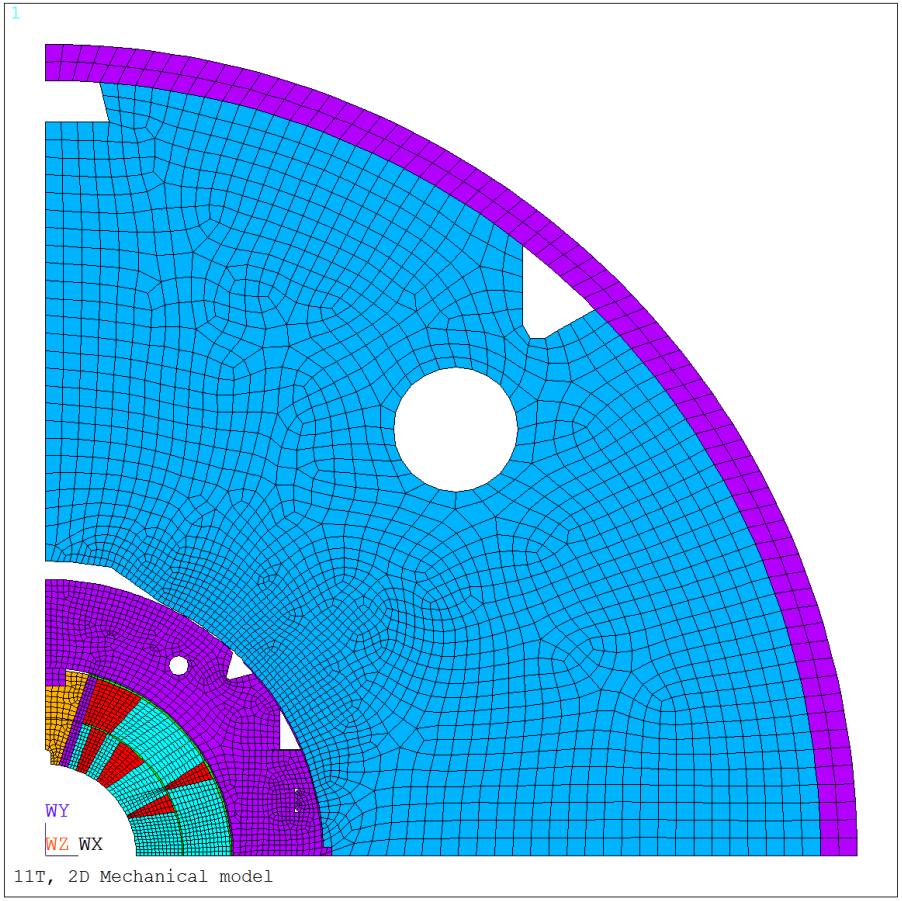




Magnet	Shim stoppers (μm)	Stopper height (mm)	Key clearance (μm)
	0	69.7	+300
	100	69.8	+200
	200	69.9	+100
	300	70.0	0
101,102,103	400	70.1	-100
104,105,106	150	69.85	+150

Modelling





Analysis

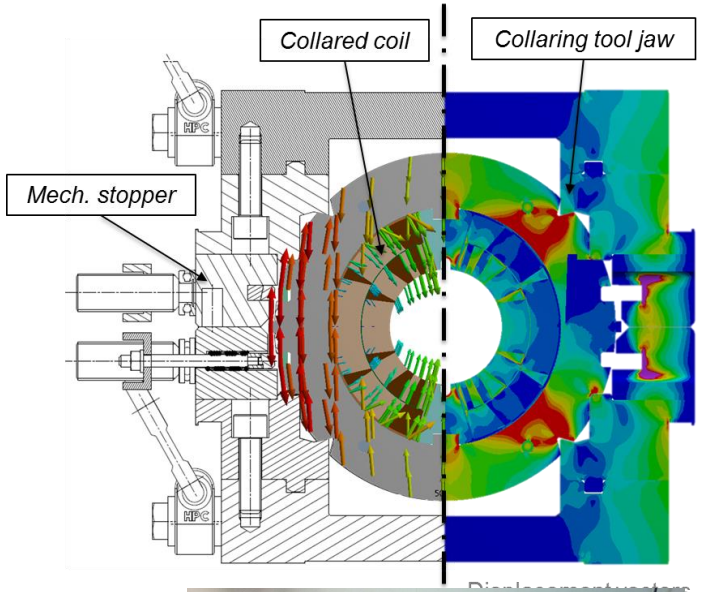
- Output from ANSYS model
  - For each of the 4 excesses
    - Steps
      - Collaring maximum force
      - After collaring (key inserted)
      - After welding
      - After cool-down
      - During powering: 10%,20%....100% of the nominal force
    - Collar vertical and horizontal deflection
    - Collaring force and clearance
    - Vertical and horizontal stress/strain collar nose
    - Radial and azimuthal stress/strain in pole SG location
    - Contact pressure pole/loading plated in
      - inner layer: r_{in}, r_{mid}, r_{out}
      - outer layer: r_{in}, r_{mid}, r_{out}
    - Radial, azimuthal and VM stress/strain in pole turn and mid-plane turn
      - inner layer: r_{in}, r_{mid}, r_{out}
      - outer layer: r_{in}, r_{mid}, r_{out}
    - SS Shell azimuthal strain/stress in SG locations
    - Total force from shell and between the 2 yokes, collars coil

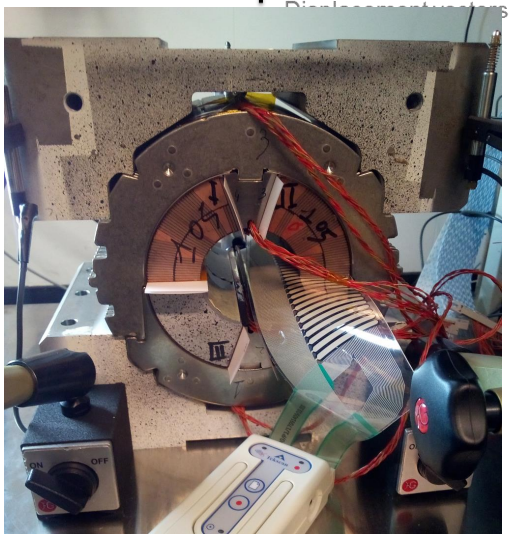
Analysis: open points

- Strain gauge summary
  - Include all collar gauges
- Measure/analyze collar deflection
- Collaring: impact of stopper shimming on coil stress
  - Is it possible that the deformation of the tooling has positive impact on the coil stress
- Evaluate key insertion clearance according to strain gauge data→ it seems 150 micron
- Plot peak stress considering maximum excess
- Produce ANSYS output, in particular transfer function and unloading
- Pole/nose shim and collar-yoke shim

Goals

- By using a 150 mm long collaring mock-up
  - Study collaring kinematics and mechanics
    - In particular coil peak stress during collaring
  - Define type and location of the instrumentation
  - Define shimming and loading scenarios (algorithm) to
    - Reduce coil peak stress during collaring in the next models
    - Achieve target pre-load after collaring

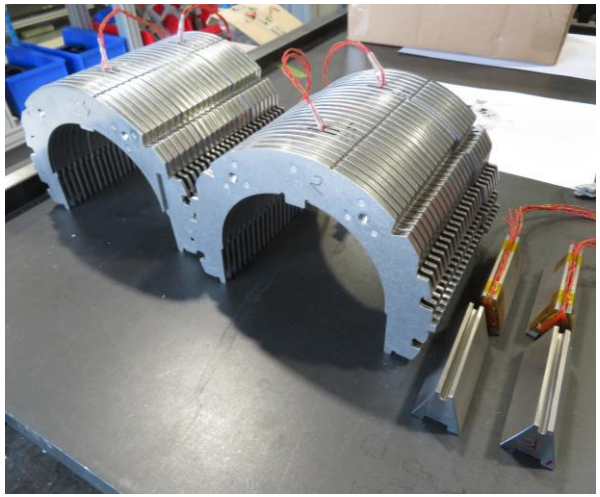


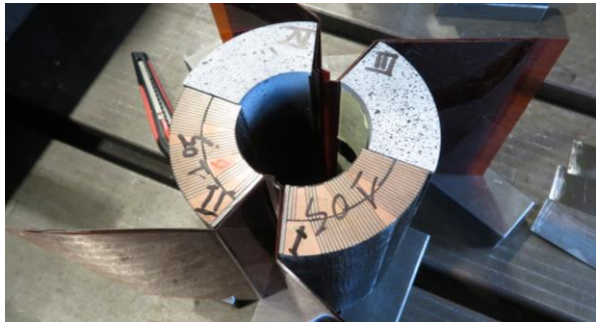


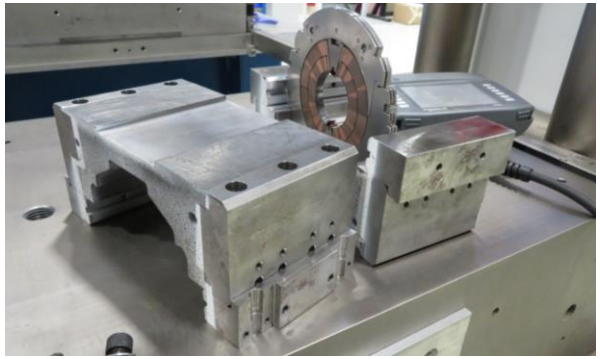
Status of components

- Collar packs
- Two piece poles
- 2 pieces from coil 107
  - Tested in SP101 and limited in the layer jump
- 2 pieces from coil 105
  - Tested in the mirror

- All parts measured with Faro arm and CMM

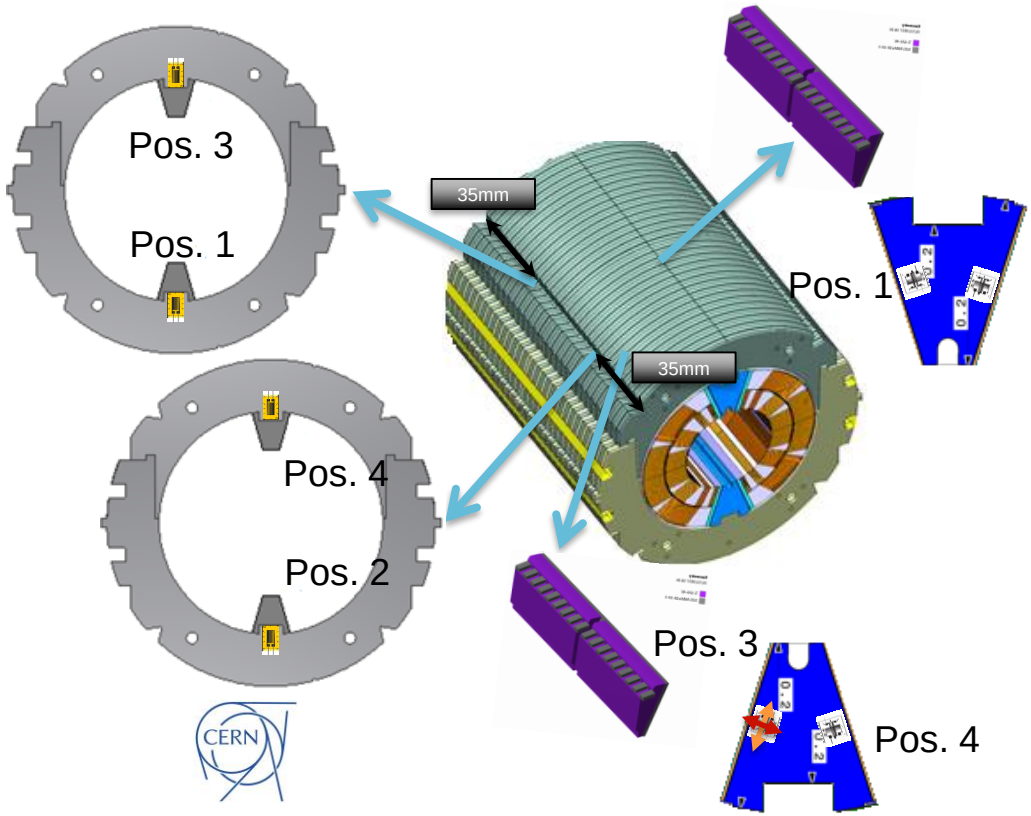


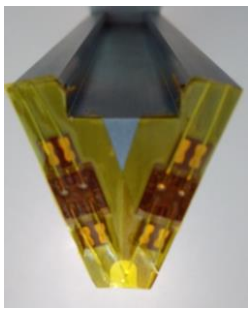


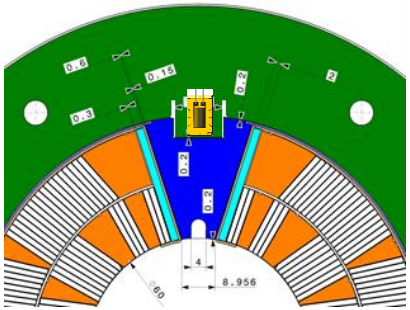


Status of instrumentation

- Both side of the collars equipped with strain gauges
  - Quarter bridge configuration
  - Bending and compression stress measurements
  - Slits with a gap of 500µm between nose and pole
- One face of the pole, in the center, instrumented

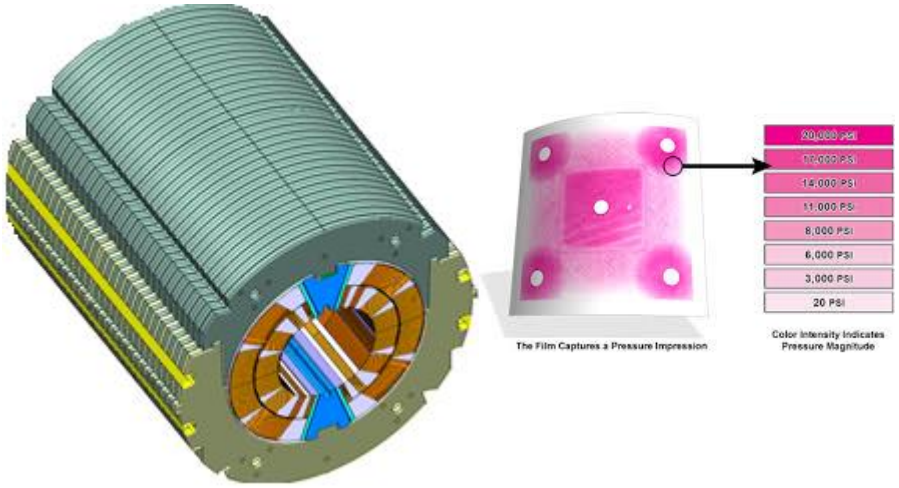


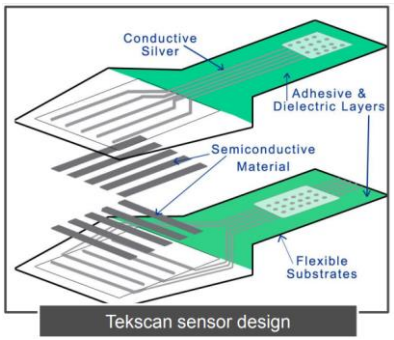




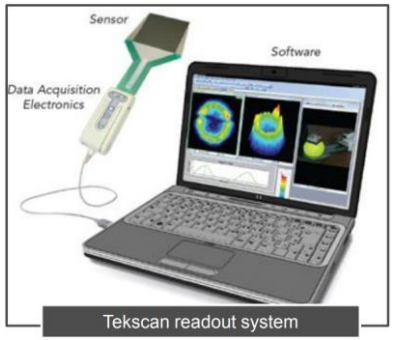
Status of instrumentation

- FUJI paper on mid-plane and pole
  - Ranges
    - MS: 10-50 MPa
    - HS: 50-130 MPa
    - HSS: 130-300 MPa
- Tekscan
  - Live read-outs of pressure throughout the collaring process.
  - Range 0 to 150 MPa





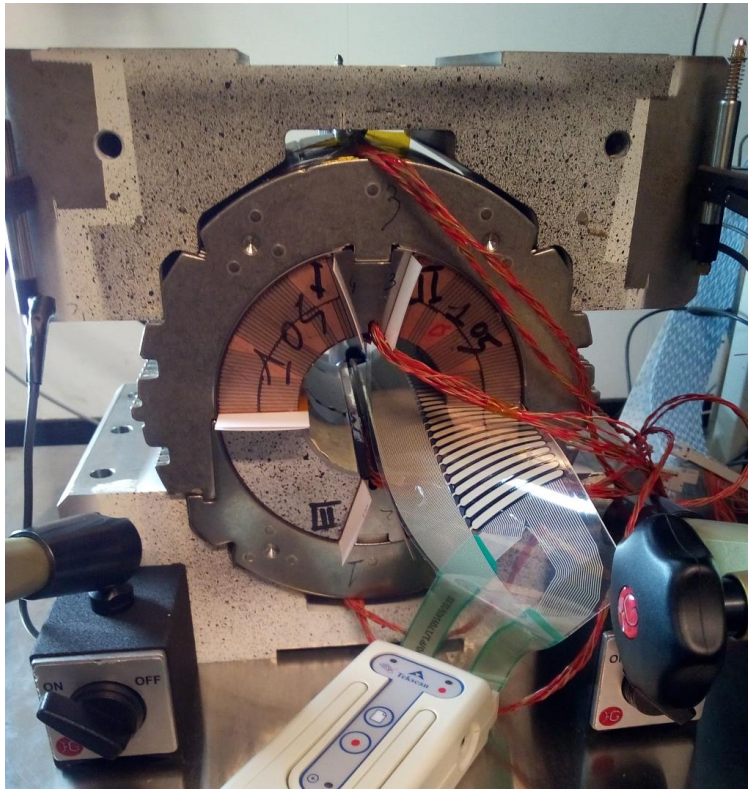
Tekscan sensor design



Tekscan readout system

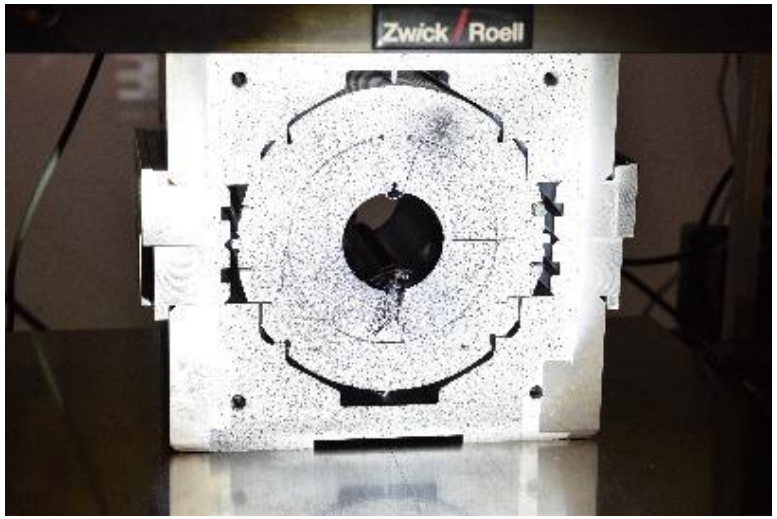
Status of instrumentation

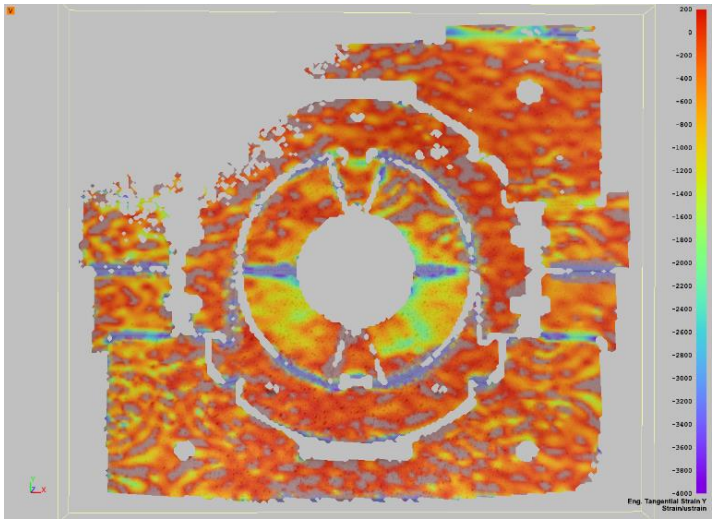
- Setup and displacement sensors
  - Z400 Universal Testing Machine
  - 400 kN max load
  - 3 LVDT's in vertical position's
  - 1 LVDT in Z position

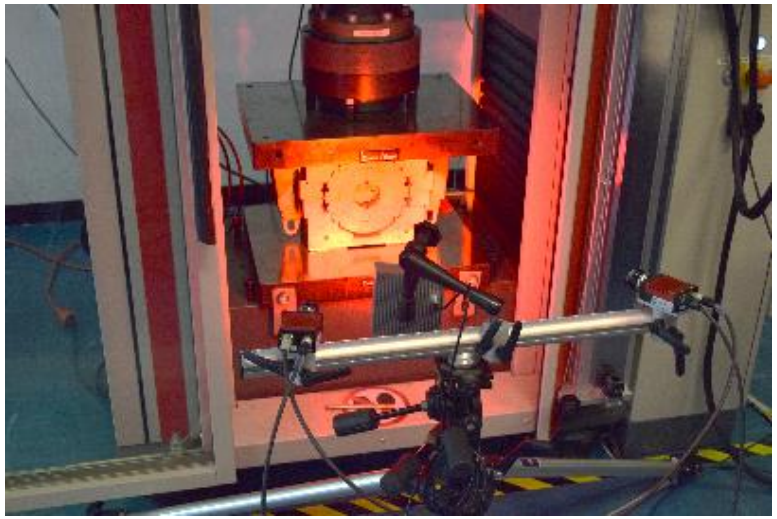


Status of instrumentation

- In progress
  - Digital image correlation
    - optical method that employs tracking and image registration techniques for accurate 2D and 3D strain measurements.
    - A company will come to provide the equipment and do the data acquisition.

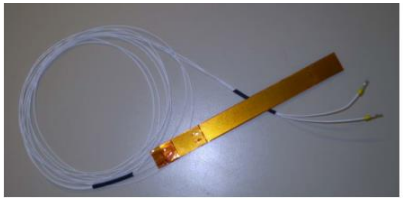


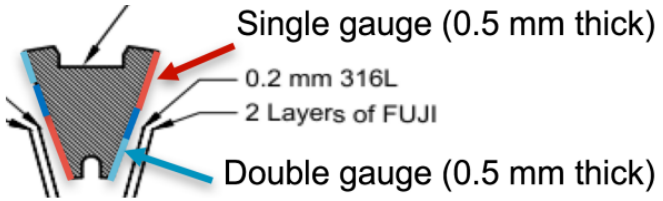


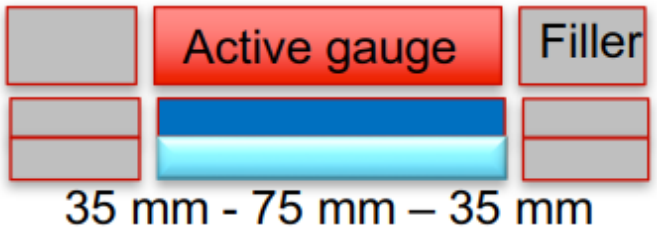


Status of instrumentation

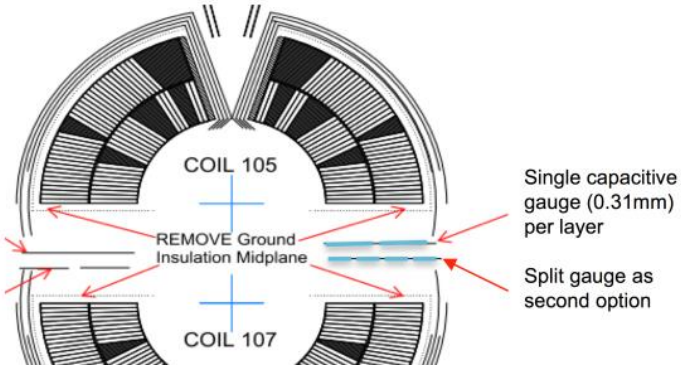
- By mid-February
  - “Resurrection” of capacitive gauges





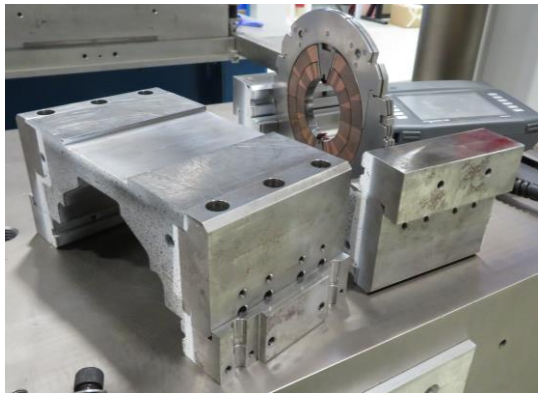


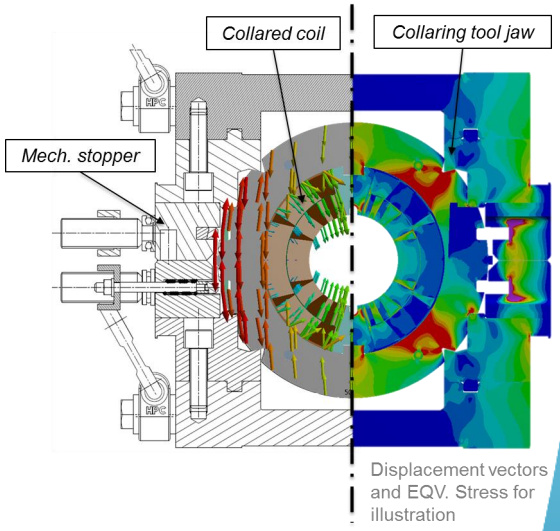
  - Gauge thickness: 0.31-0.5 mm
  - Pole
    - 150 mm long pole machined by - 0.5 mm on both face
  - Mid plane
    - first use of 150 mm long, 0.31 mm thick single gauge per layer then split gauge as an option



Analysis of collaring

- 6 degree tapered key and collar slot
- The collaring tooling does not allow to apply a large force to insert the key
  - In the short model with screws and in the prototype with a system of springs
- When all the collar laminations are aligned (long collar in contact with the short collar)
  - 280 micron of maximum clearance between key and collar slot
- In the finite element model we assume a clearance of 150-200 micron to insert the key



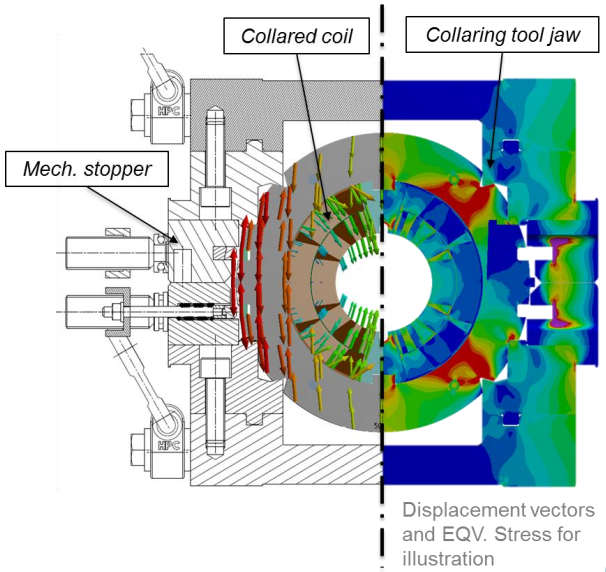


Analysis of collaring

- Typical coil "excess" and force
  - 70 mm stopper equivalent to status when key inserted

	Average Excess Quadrant	Applied Force / MN	70 mm stopper deviation / mm
CC101	0.31	32	+0.1
CC102	0.29	32	+0.1
CC103	0.38	32	+0.1
CC104	0.45	22	-0.15
CC104b	0.35	**20**	-0.15
CC105	0.35	16	-0.15
CC105b	0.30	**20**	-0.15
CC106	0.33	12	-0.15

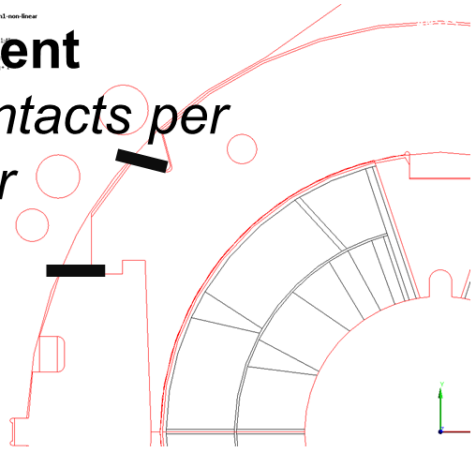
- Deviation
  - Positive → interference
    - Tooling deformed
  - Negative→ clearance



Analysis of collaring by FEM

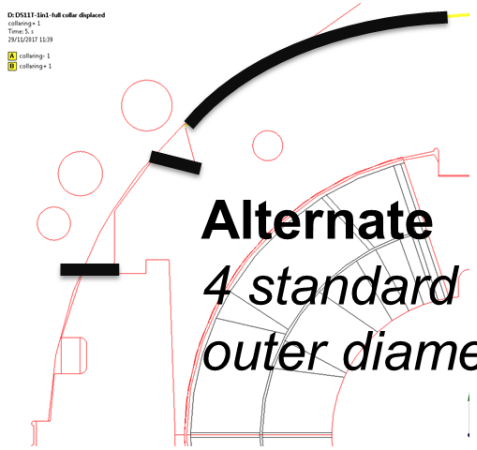
- Different scenarios considered

Current
4 contacts per collar

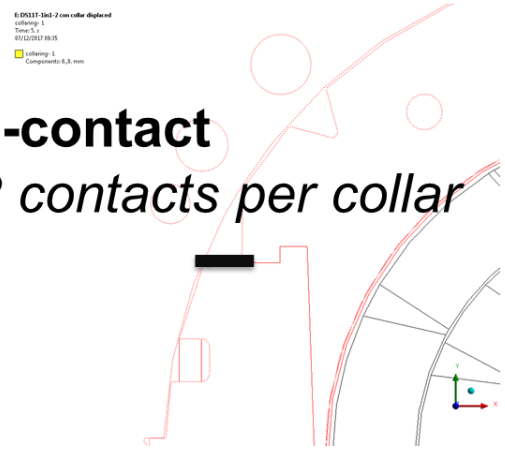


Fixed displacement by 0.1 mm

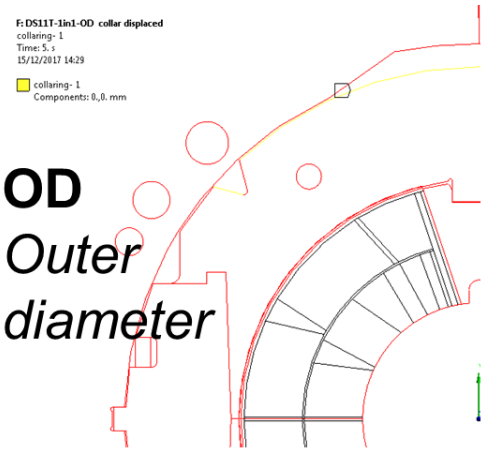
Alternate
4 standard contacts + outer diameter



2-contact
2 contacts per collar

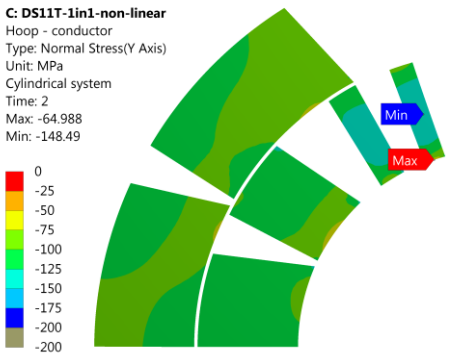


OD
Outer diameter



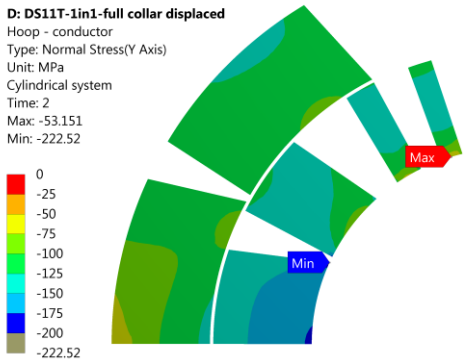
Analysis of collaring by FEM

- Different scenarios considered



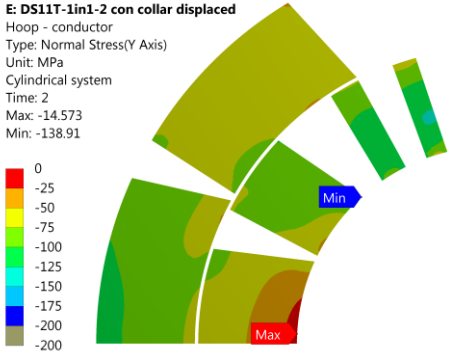
Current

4 contacts per collar



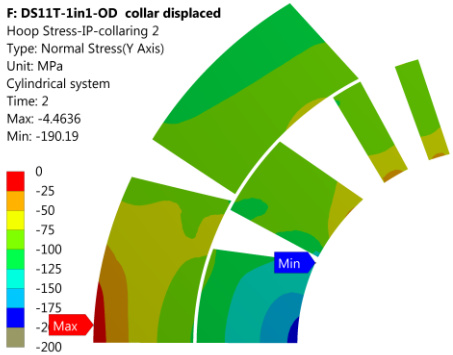
Alternate

4 standard contacts + outer diameter



2-contact

2 contacts per collar

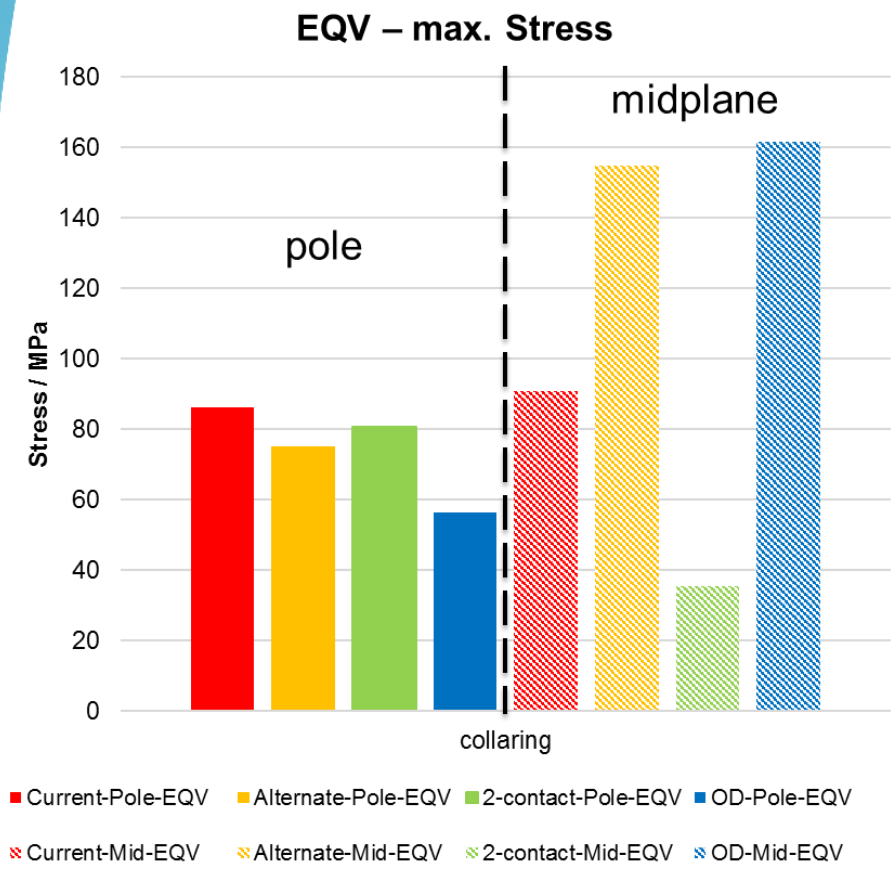


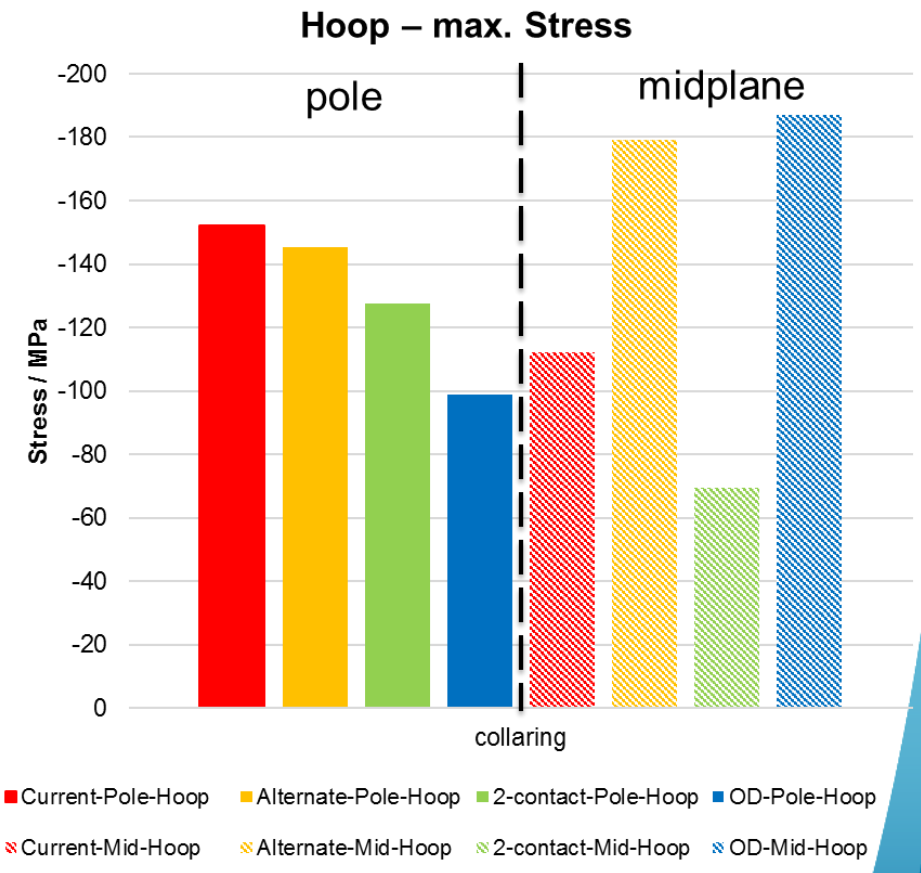
OD

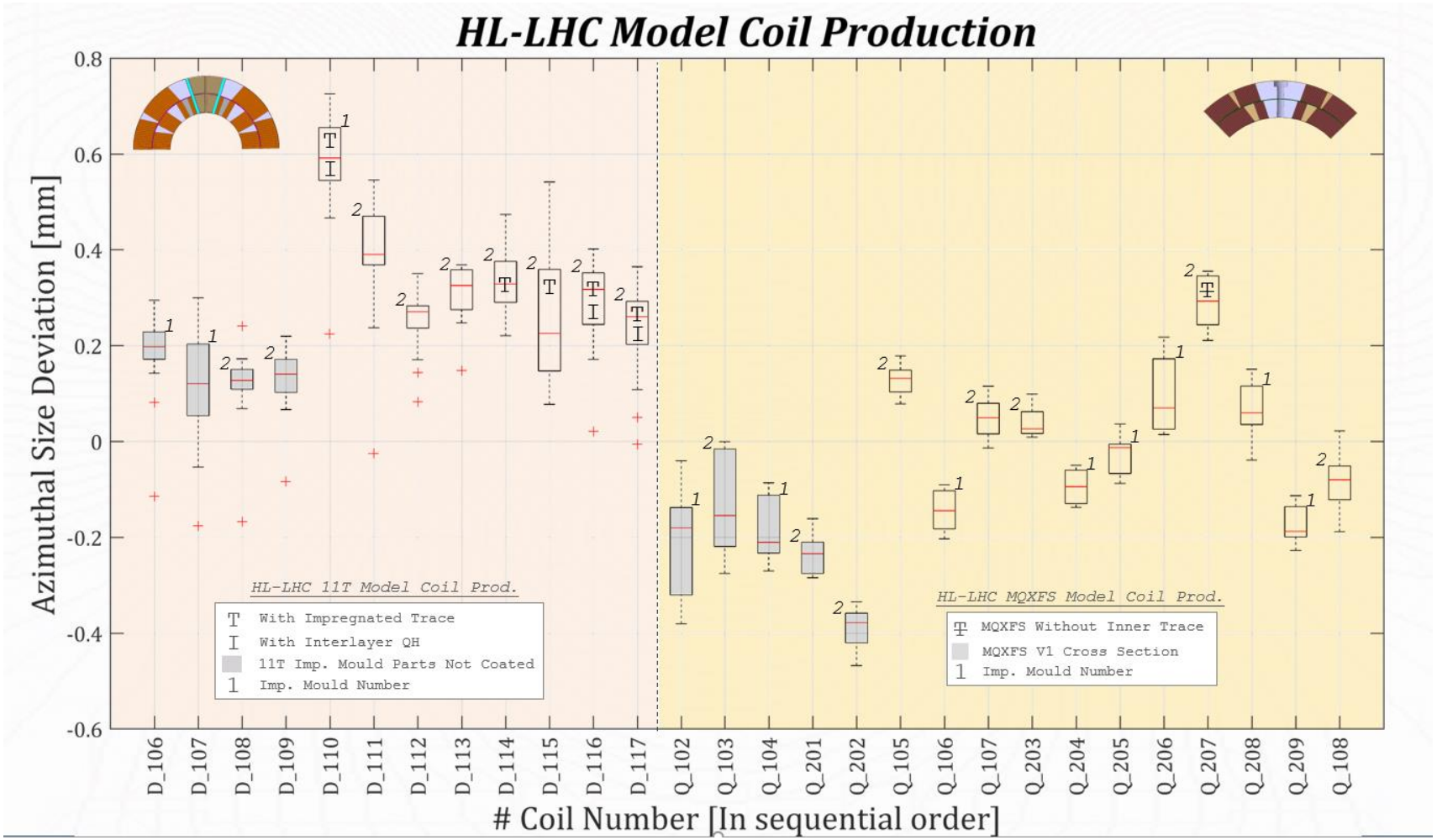
Outer diameter

Analysis of collaring by FEM

- Different scenarios considered



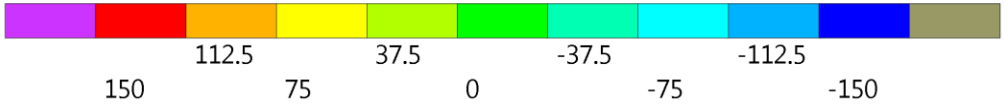


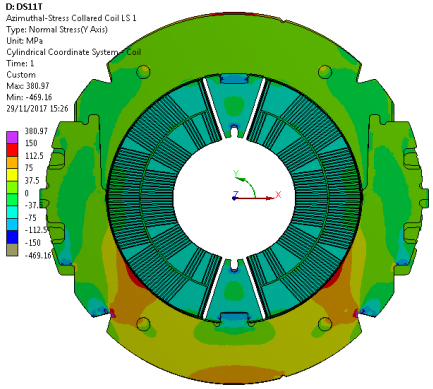

HL-LHC Model Coil Production
Azimuthal Size Deviation [mm]
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
HL-LHC 11T Model Coil Prod.
With Impregnated Trace
With Interlayer QH
11T Imp. Mould Parts Not Coated
Imp. Mould Number
HL-LHC MQXFS Model Coil Prod.
MQXFS Without Inner Trace
MQXFS V1 Cross Section
Imp. Mould Number
D_106
D_107
D_108
D_109
D_110
D_111
D_112
D_113
D_114
D_115
D_116
D_117
Q_102
Q_103
Q_104
Q_201
Q_202
Q_105
Q_106
Q_107
Q_203
Q_204
Q_205
Q_206
Q_207
Q_208
Q_209
Q_108
Coil Number [In sequential order]

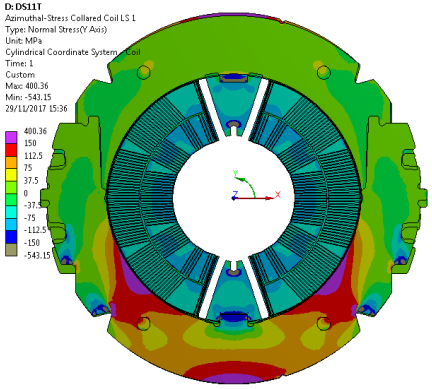
LS1 – collaring
LS2 – collared coil
LS3 – shell welding
LS4 – 1.9 K
LS5 – 12T

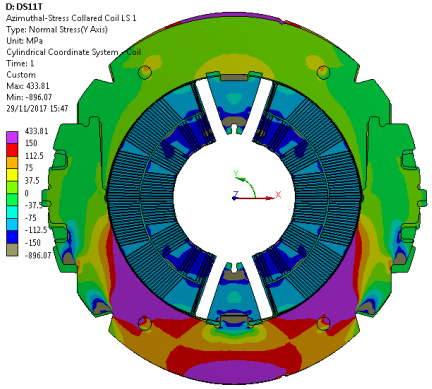
Azimuthal-Stress LS1

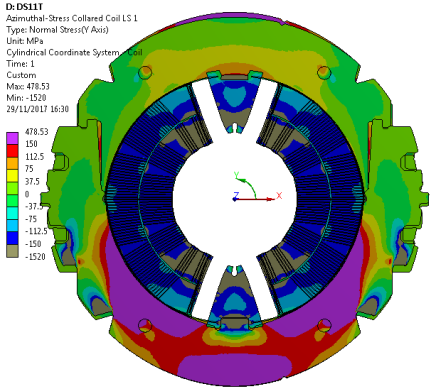
X.X lateral pole shim
0.0 collared coil shim











0.2 mm arc excess

0.4 mm arc excess

0.6 mm arc excess

0.8 mm arc excess

	pole			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Pole AV.	**19**	**29**	**39**	**50**
EQV-Pole Min.	17	24	28	36
EQV-Pole Max.	31	56	83	103
Hoop-Pole AV.	**-43**	**-72**	**-106**	**-141**
Hoop-Pole Min.	-50	-91	-154	-191
Hoop-Pole Max.	-28	-48	-62	-79

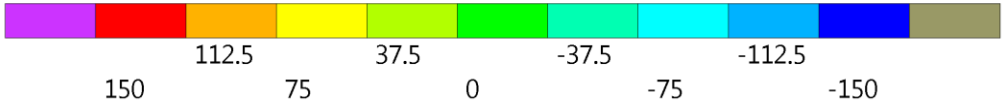
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**29**	**45**	**62**	**77**
EQV-Mid Min.	28	44	59	74
EQV-Mid Max.	61	80	101	121
Hoop-Mid AV.	**-44**	**-70**	**-98**	**-123**
Hoop-Mid Min.	-69	-91	-117	-147
Hoop-Mid Max.	-45	-70	-98	-119

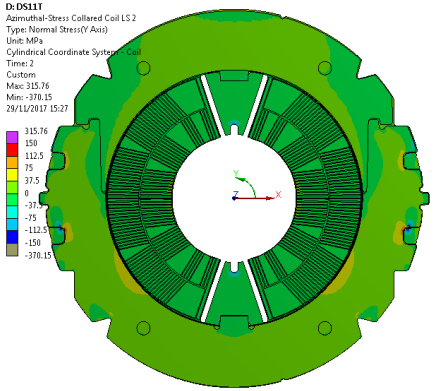
Scaling x25

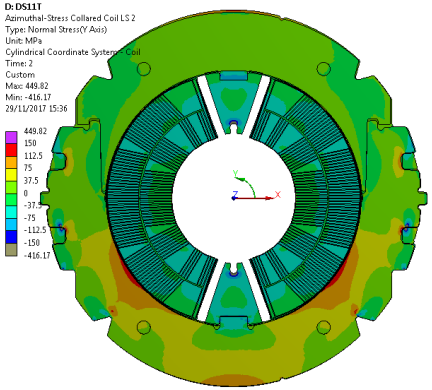
LS1 – collaring
LS2 – collared coil
LS3 – shell welding
LS4 – 1.9 K
LS5 – 12T

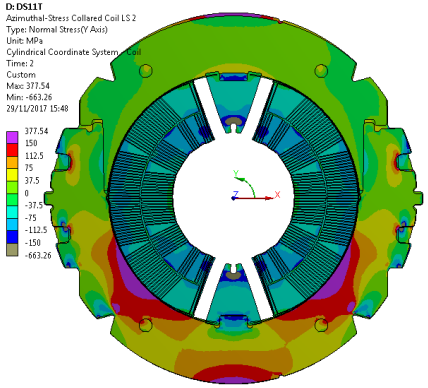
Azimuthal-Stress LS2

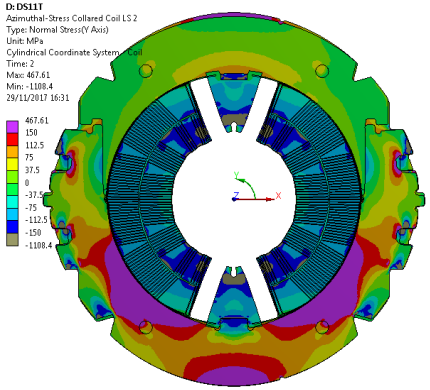
X.X lateral pole shim
0.0 collared coil shim











0.2 mm arc excess

0.4 mm arc excess

0.6 mm arc excess

0.8 mm arc excess

	pole			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Pole AV.	**4**	**10**	**19**	**29**
EQV-Pole Min.	1	1	5	10
EQV-Pole Max.	17	37	60	79
Hoop-Pole AV.	**-17**	**-43**	**-76**	**-110**
Hoop-Pole Min.	-25	-62	-126	-161
Hoop-Pole Max.	-3	-21	-36	-52

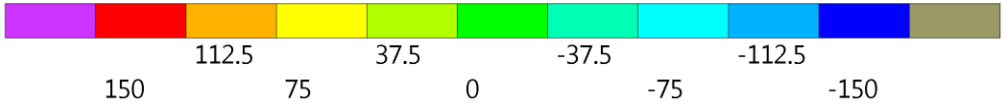
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**12**	**24**	**40**	**54**
EQV-Mid Min.	4	5	7	14
EQV-Mid Max.	61	69	53	56
Hoop-Mid AV.	**-17**	**-40**	**-68**	**-93**
Hoop-Mid Min.	-20	-44	-73	-101
Hoop-Mid Max.	34	32	10	-6

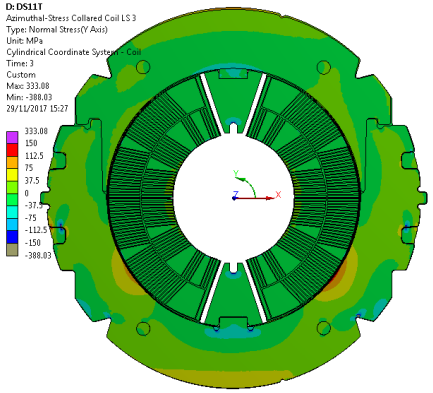
Scaling x25

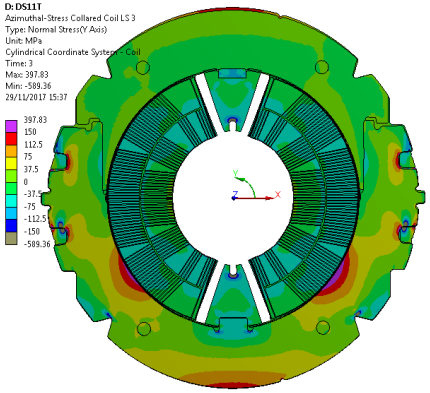
LS1 – collaring
LS2 – collared coil
LS3 – shell welding
LS4 – 1.9 K
LS5 – 12T

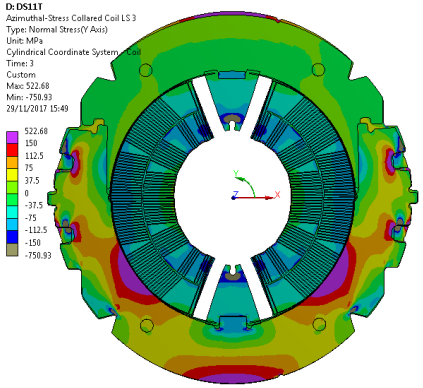
Azimuthal-Stress LS3

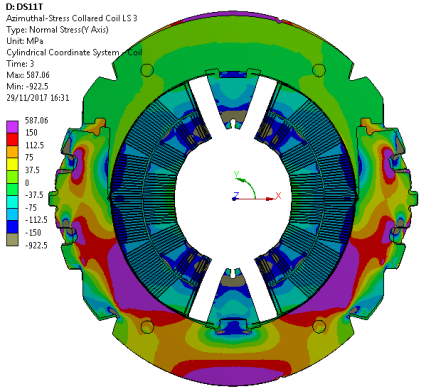
X.X lateral pole shim
0.0 collared coil shim











0.2 mm arc excess

0.4 mm arc excess

0.6 mm arc excess

0.8 mm arc excess

	pole			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Pole AV.	**5**	**11**	**18**	**29**
EQV-Pole Min.	1	2	4	11
EQV-Pole Max.	18	39	65	91
Hoop-Pole AV.	**-20**	**-44**	**-74**	**-109**
Hoop-Pole Min.	-31	-67	-127	-170
Hoop-Pole Max.	-7	-24	-42	-70

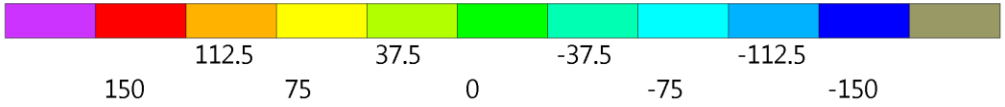
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**16**	**26**	**39**	**53**
EQV-Mid Min.	5	6	7	8
EQV-Mid Max.	61	81	103	123
Hoop-Mid AV.	**-18**	**-40**	**-64**	**-88**
Hoop-Mid Min.	-21	-43	-69	-95
Hoop-Mid Max.	34	46	60	73

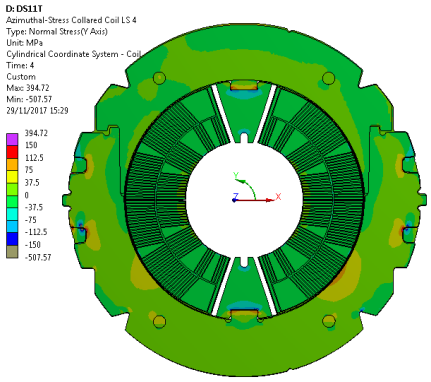
Scaling x25

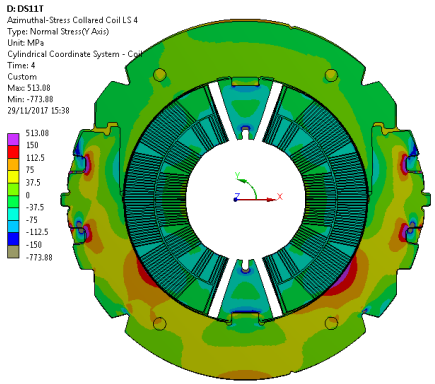
LS1 – collaring
LS2 – collared coil
LS3 – shell welding
LS4 – 1.9 K
LS5 – 12T

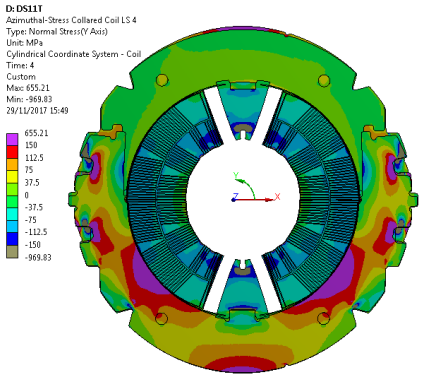
Azimuthal-Stress LS4

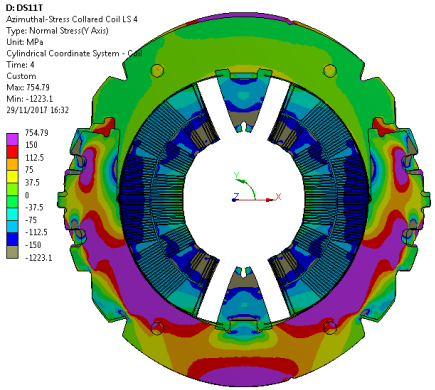
X.X lateral pole shim
0.0 collared coil shim











0.2 mm arc excess

0.4 mm arc excess

0.6 mm arc excess

0.8 mm arc excess

	pole			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Pole AV.	**14**	**23**	**35**	**50**
EQV-Pole Min.	4	4	11	22
EQV-Pole Max.	29	40	72	104
Hoop-Pole AV.	**-23**	**-49**	**-85**	**-127**
Hoop-Pole Min.	-28	-67	-136	-188
Hoop-Pole Max.	13	-7	-24	-58

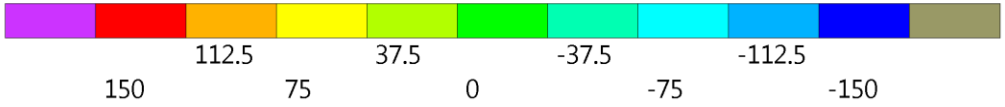
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**22**	**34**	**49**	**66**
EQV-Mid Min.	4	5	2	1
EQV-Mid Max.	62	84	106	128
Hoop-Mid AV.	**-16**	**-39**	**-67**	**-96**
Hoop-Mid Min.	-25	-52	-81	-112
Hoop-Mid Max.	50	66	83	100

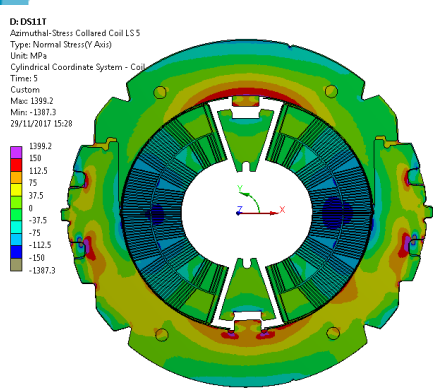
Scaling x25

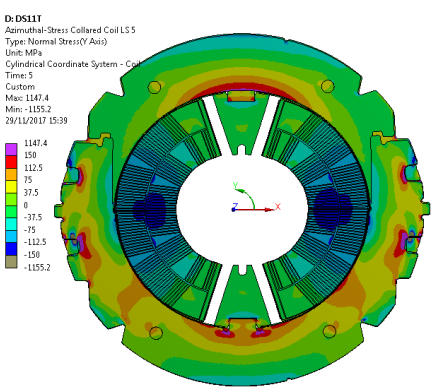
LS1 – collaring
LS2 – collared coil
LS3 – shell welding
LS4 – 1.9 K
LS5 – 12T

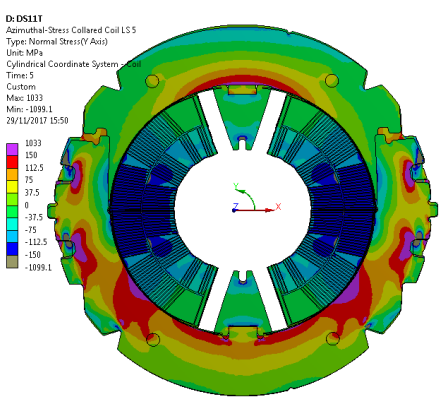
Azimuthal-Stress LS5

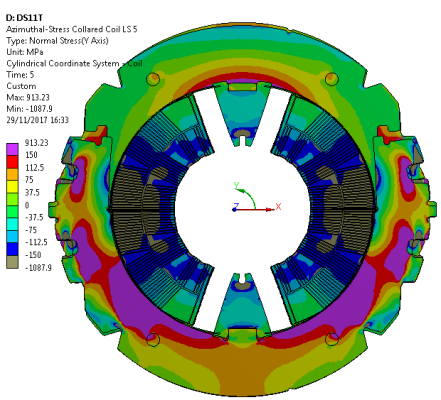
X.X lateral pole shim
0.0 collared coil shim











0.2 mm arc excess

0.4 mm arc excess

0.6 mm arc excess

0.8 mm arc excess

	pole			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Pole AV.	**7**	**17**	**16**	**19**
EQV-Pole Min.	1	7	4	3
EQV-Pole Max.	31	52	53	67
Hoop-Pole AV.	**-5**	**-8**	**-39**	**-80**
Hoop-Pole Min.	-12	-22	-82	-134
Hoop-Pole Max.	35	49	36	6

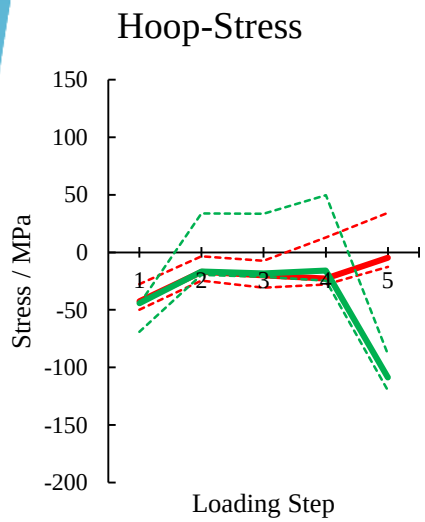
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**41**	**50**	**64**	**80**
EQV-Mid Min.	35	36	41	49
EQV-Mid Max.	92	98	101	94
Hoop-Mid AV.	**-109**	**-114**	**-138**	**-167**
Hoop-Mid Min.	-120	-125	-149	-179
Hoop-Mid Max.	-89	-94	-88	-69

Scaling x25

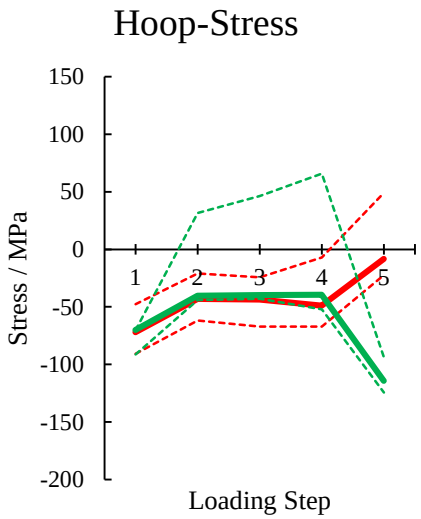
Azimuthal-Stress

LS1 – collaring
LS2 – collared coil
LS3 – shell welding
LS4 – 1.9 K
LS5 – 12T

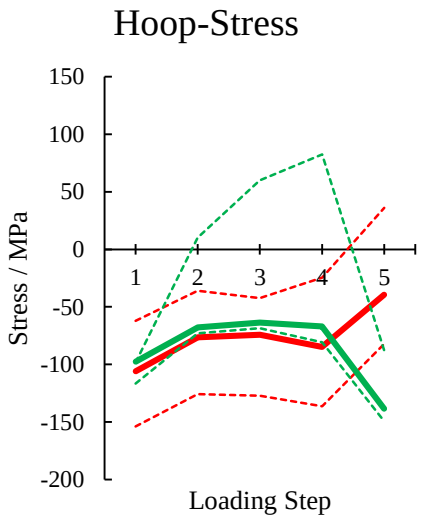
X.X lateral pole shim
0.0 collared coil shim



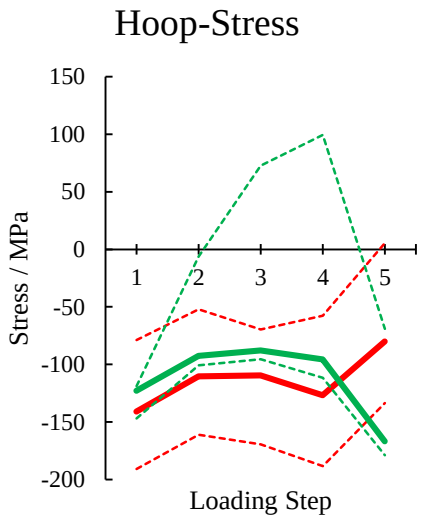
0.2 mm arc excess



0.4 mm arc excess



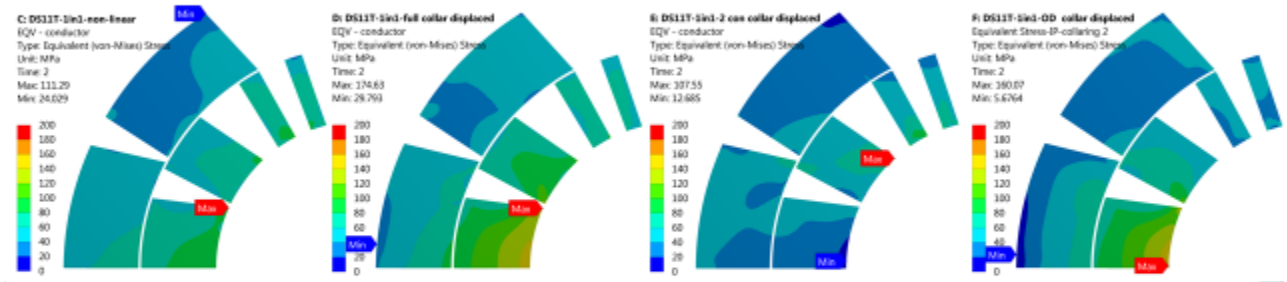
0.6 mm arc excess



0.8 mm arc excess

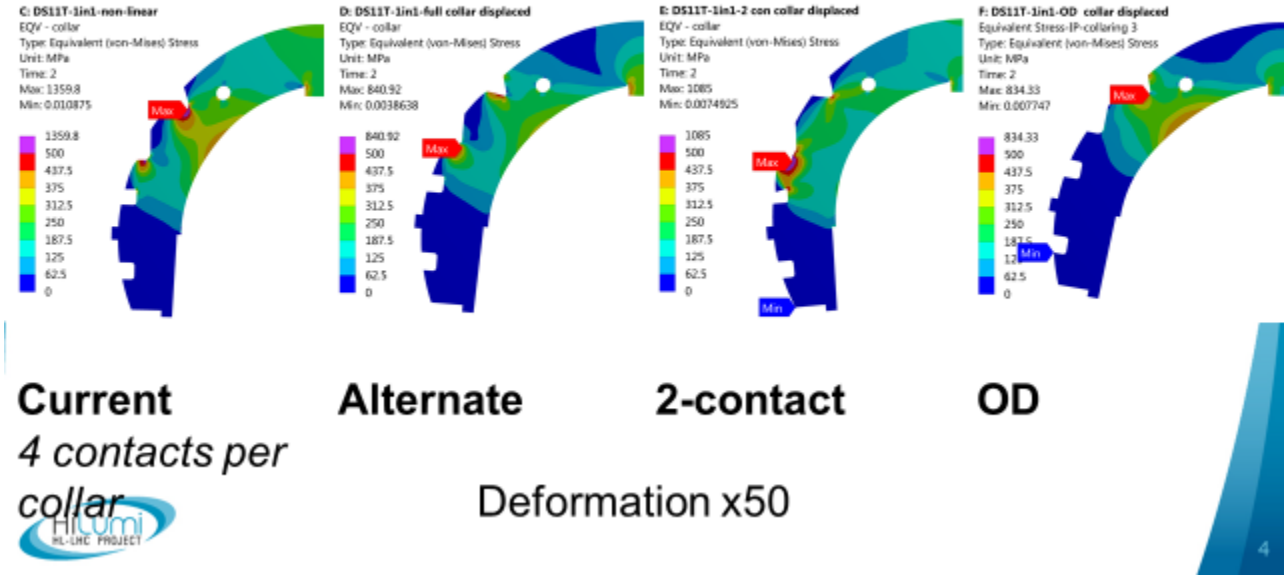
Hoop-Pole AV. Hoop-Pole Min. Hoop-Pole Max.
Hoop-Mid AV. Hoop-Mid Min. Hoop-Mid Max.

Collaring comparison-
EQV Stress during collaring - conductor



Current **Alternate** **2-contact** **OD**

Collaring comparison-
EQV Stress during collaring - collars



Current
4 contacts per collar

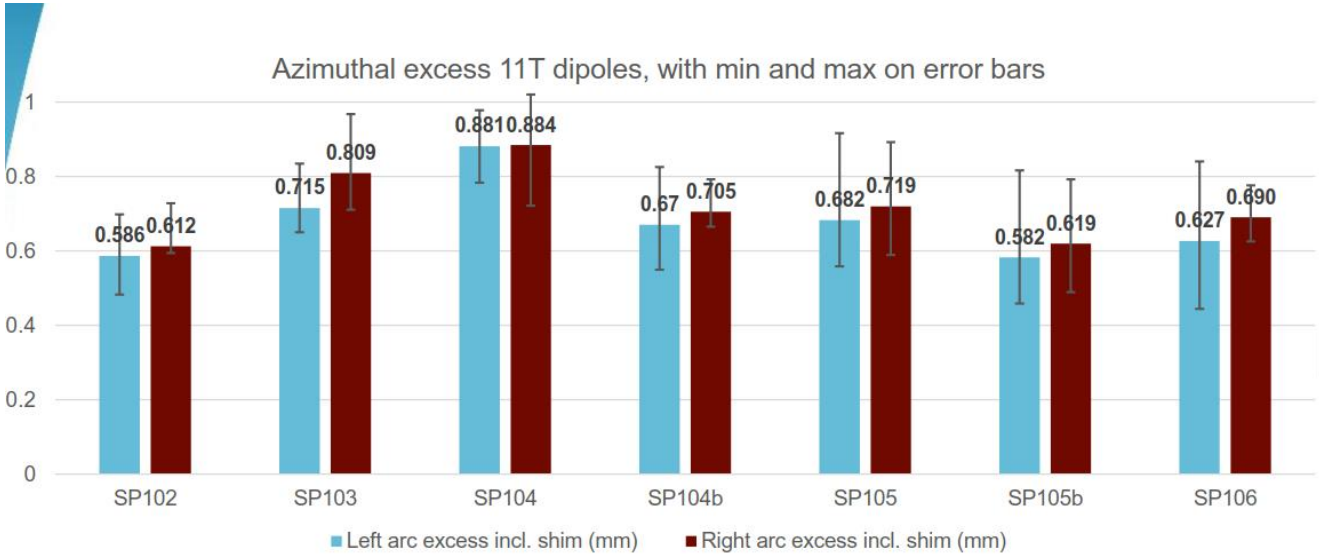
Alternate

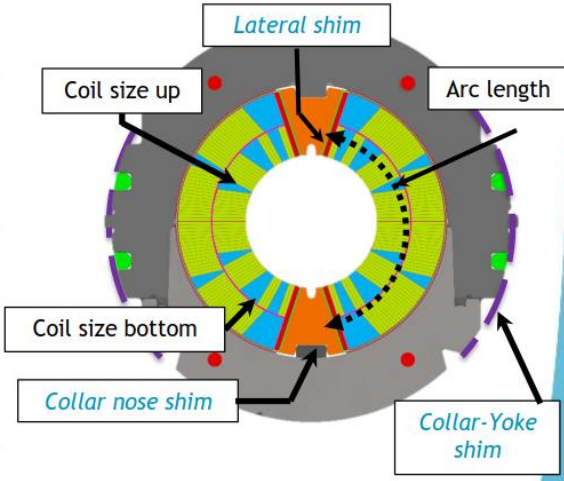
2-contact

OD

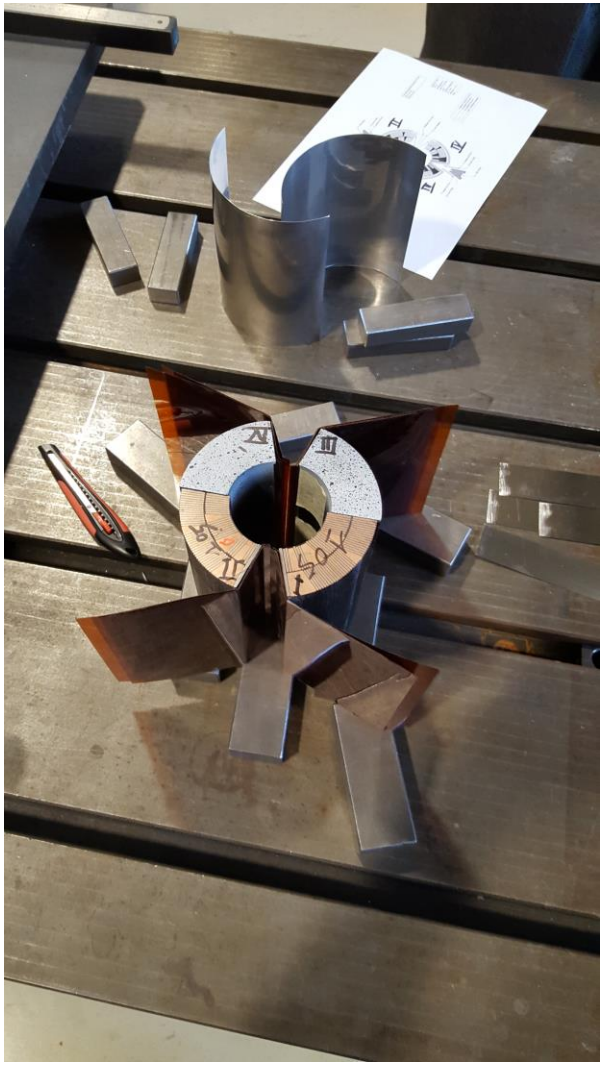
Deformation x50

Excess per half

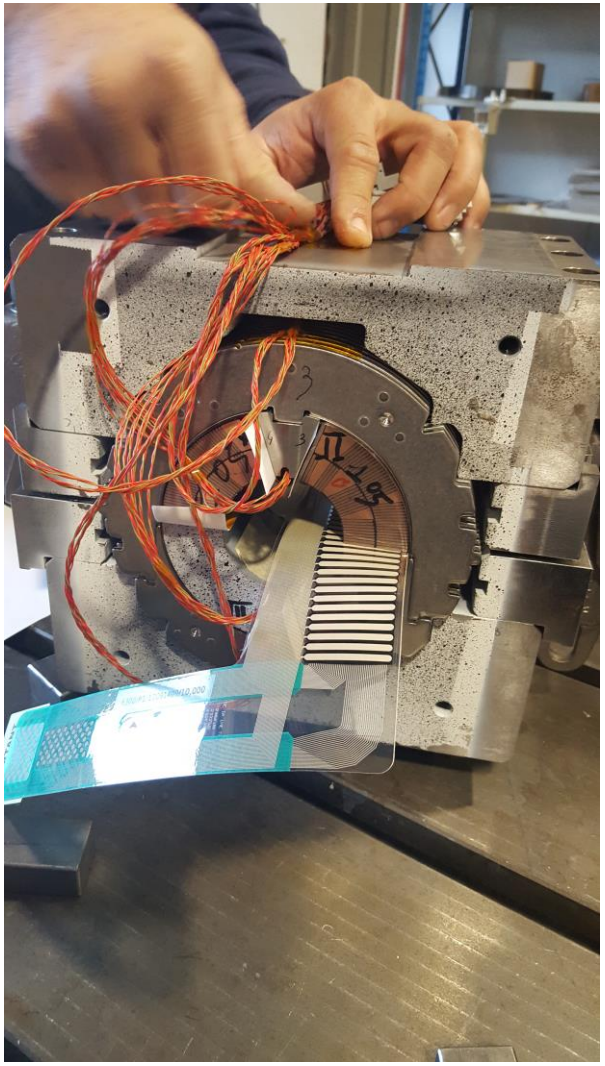


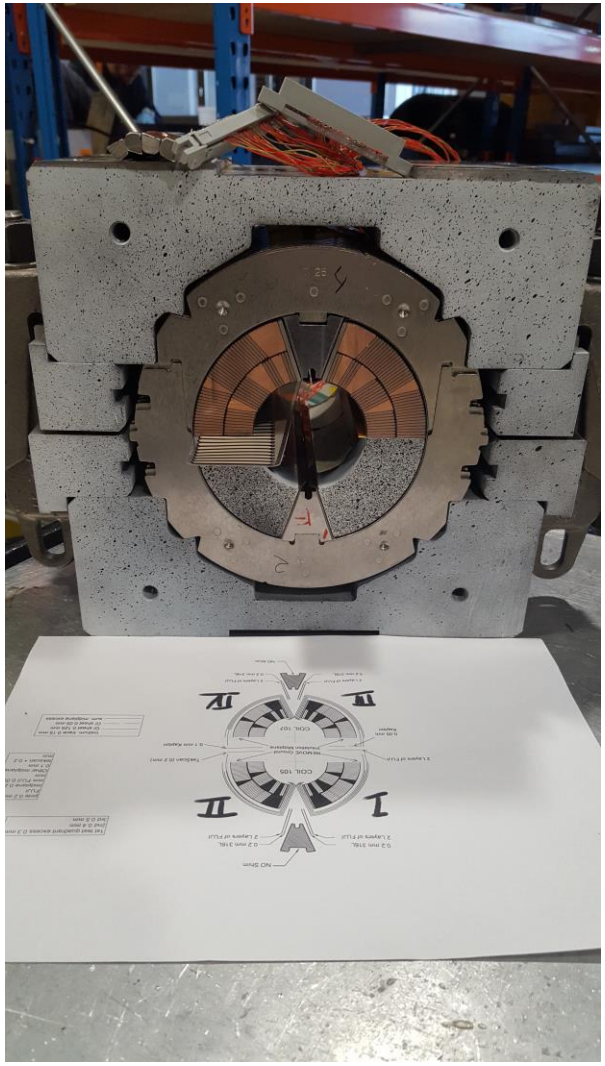


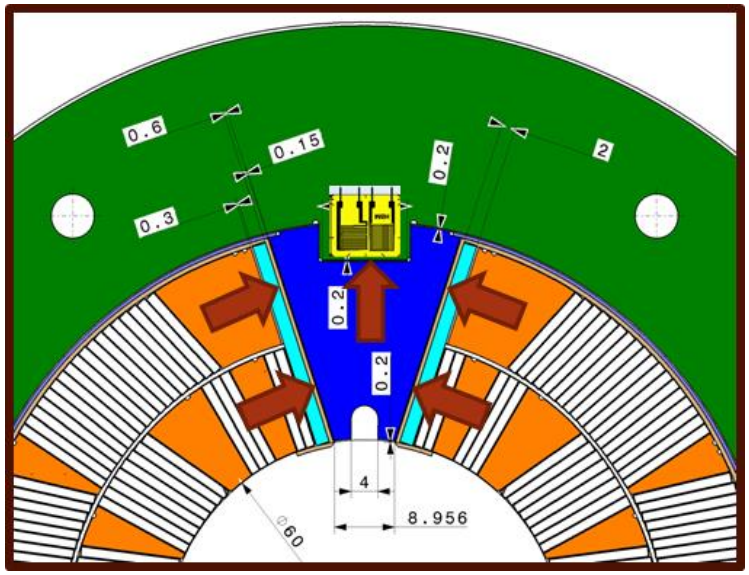
Collaring mock-up step 1

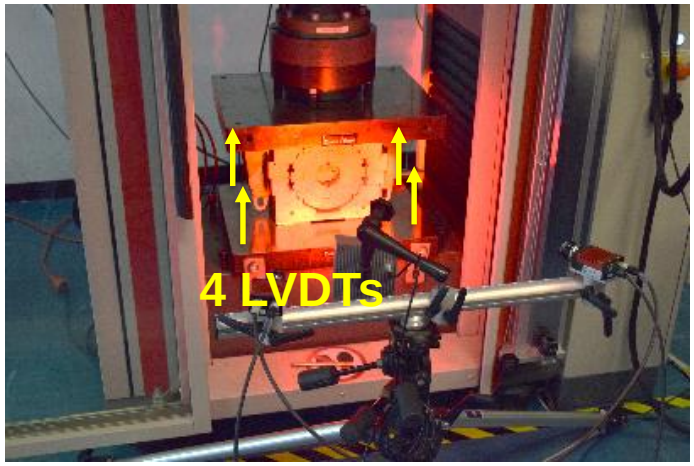


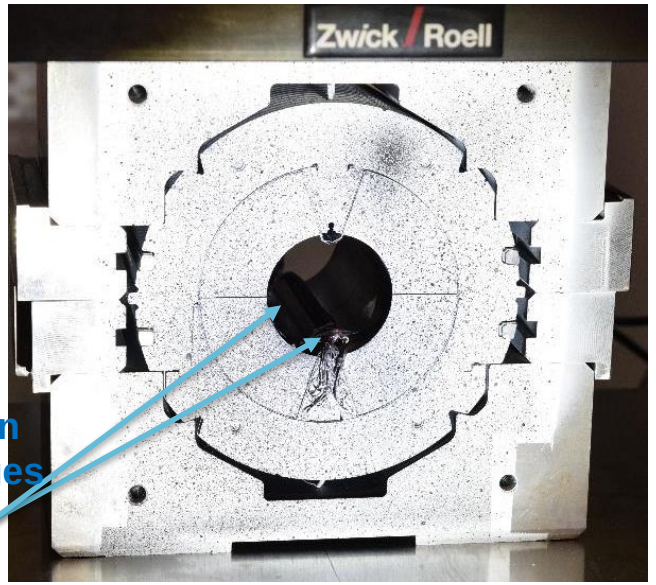
Collaring mock-up step 1






0.6
0.15
0.2
2
0.3
0.2
0.2
4
8.956
Ø60


4 LVDTs


Zwick / Roell
Strain gauges