Collaring kinematics, mechanics, instrumentation, and mock-ups

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11T Dipole Collaring Task Force Meeting
15 January 2018
CERN

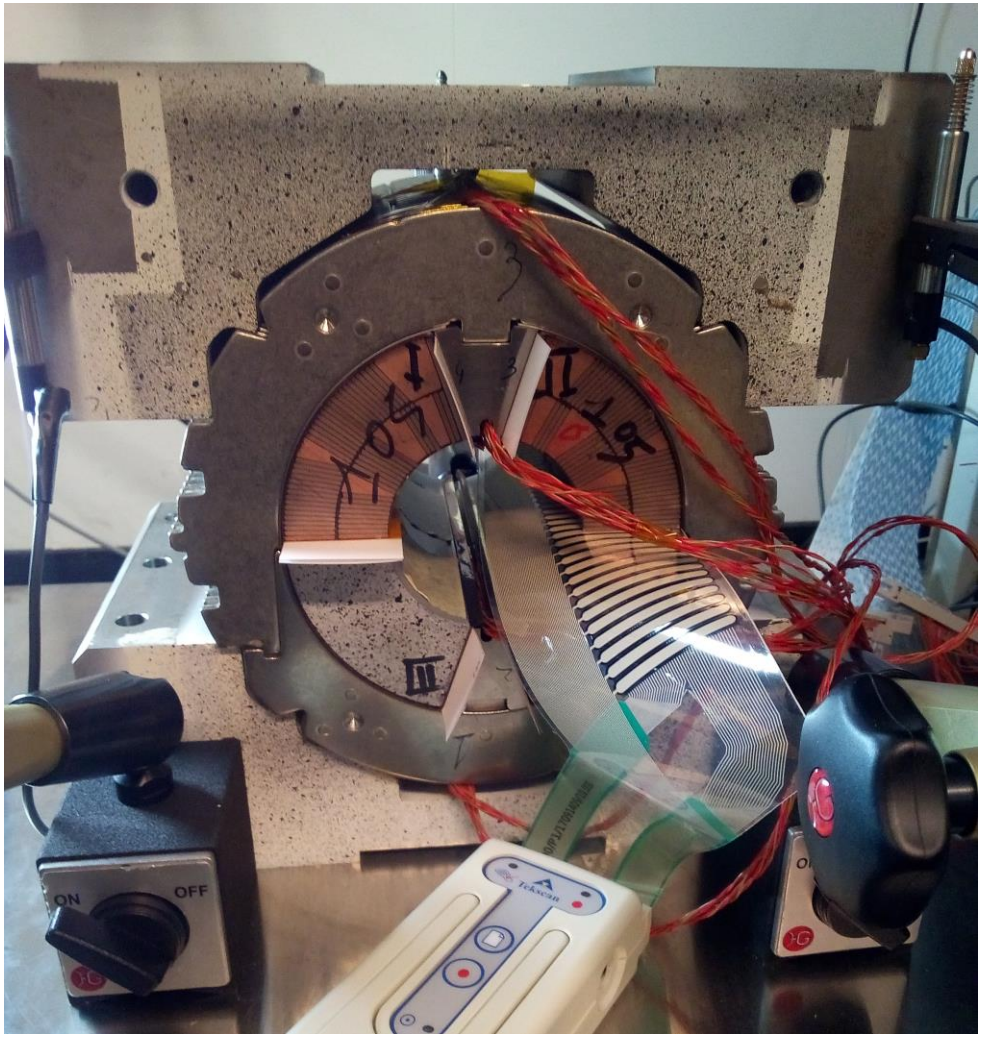
Aknowledgments

- 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
- 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



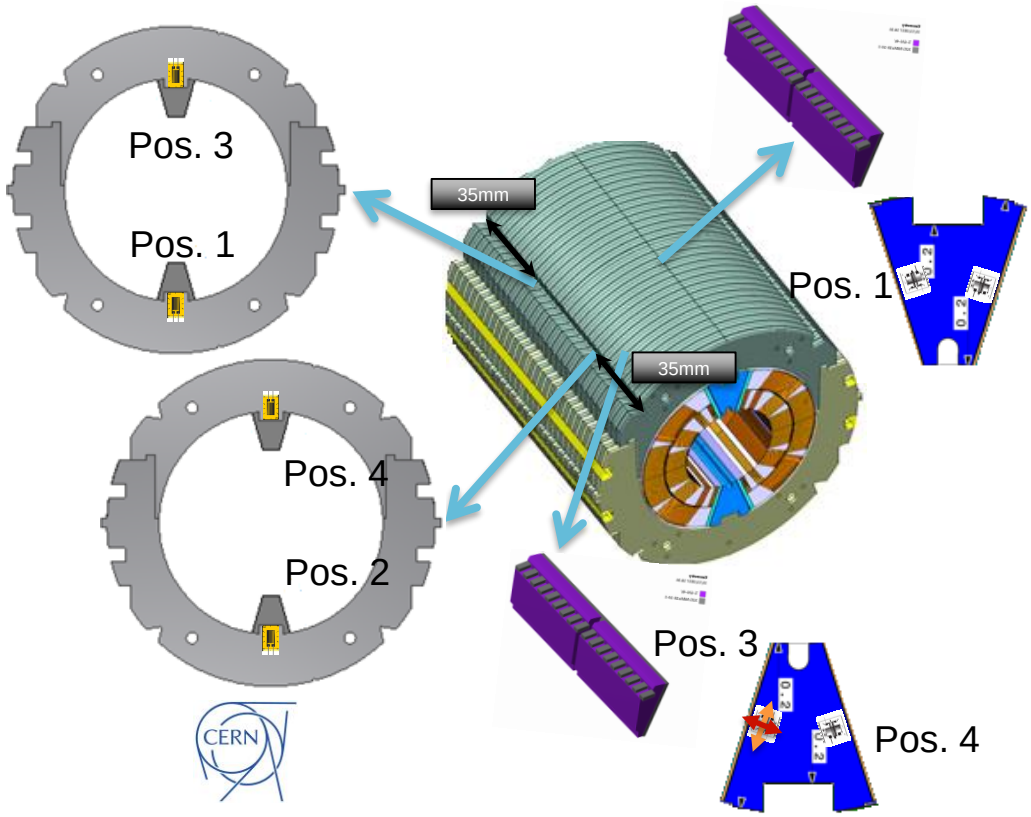
Plan: step 1
January – early February 2018

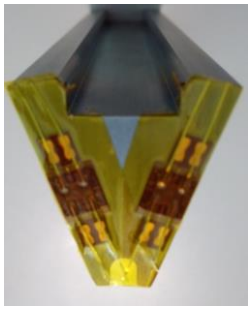
- Mechanical lab
  - Repeat 0.2 excess
    - Check if difference between collar and pole gauges results
  - Then 0.1 and 0.05
  - Measure collar deflection
  - Coils swap
  - Aluminum dummy coil tests
- 927
  - Reproducibility tests
  - High excess coils tests (0.3, 0.4, 0.5 per quadrant)

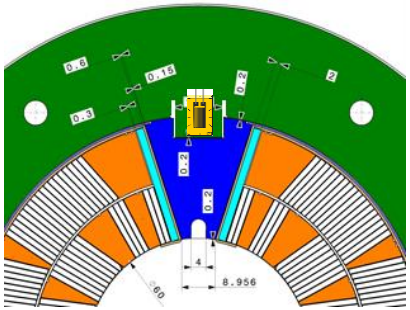
- Regarding Fuji paper test
  - MS+HS on the pole
  - MS+HS+HSS on the mid-plane
    - We may have to compensate the additional thickness on the mid-plane to keep the same excess

Status of instrumentation From…December 2017

- 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

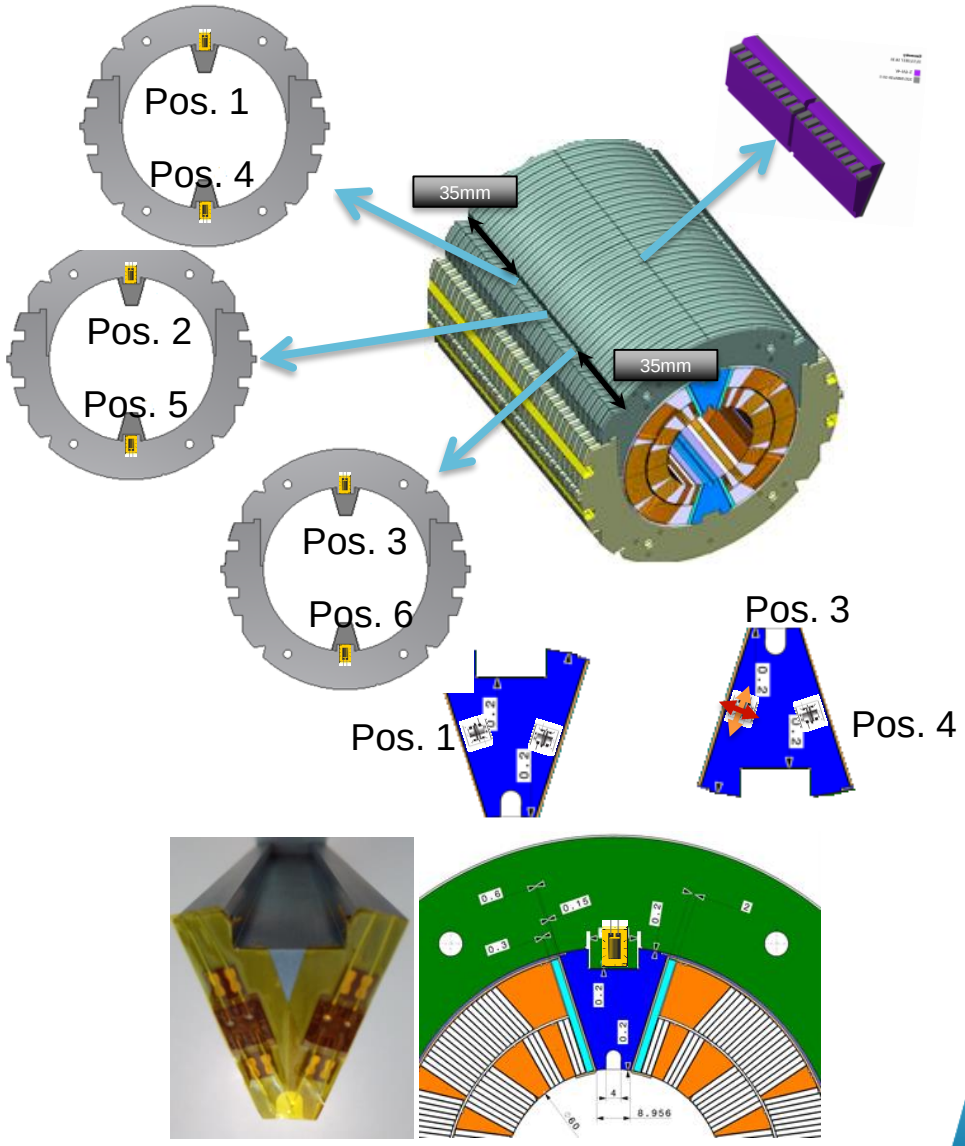






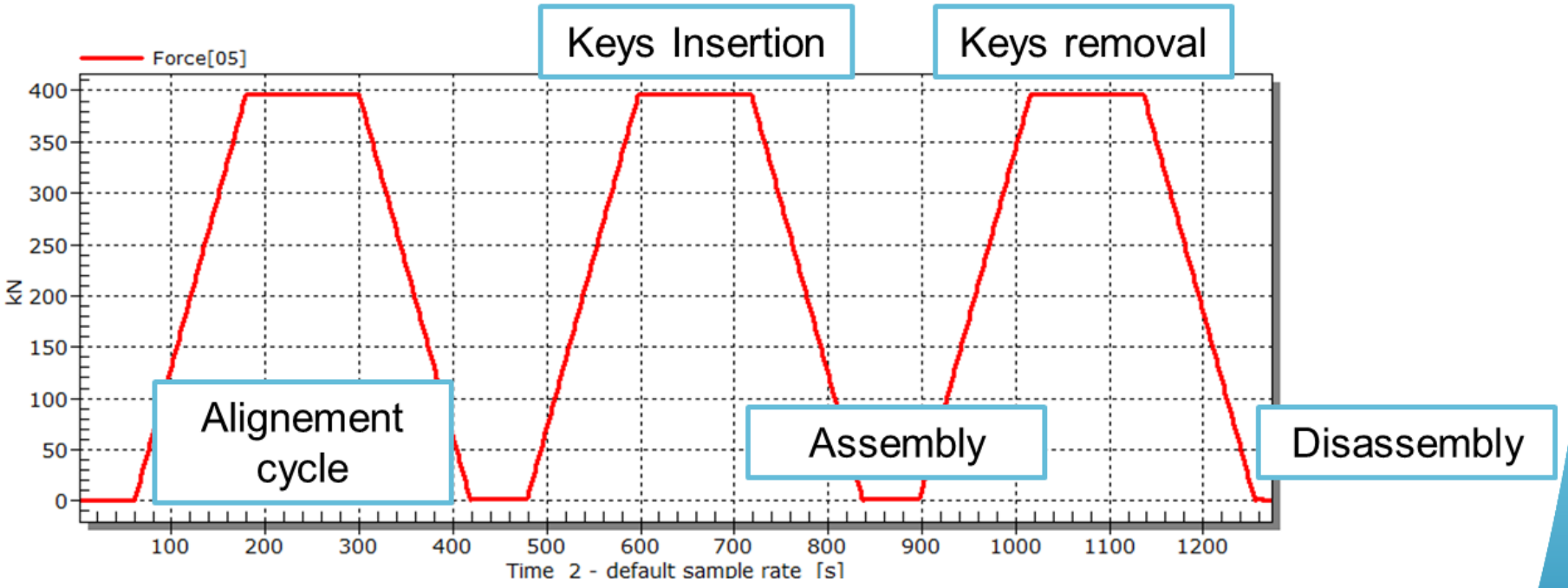
Status of instrumentation To…January 2018

- 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



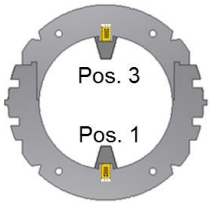
Test protocol

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

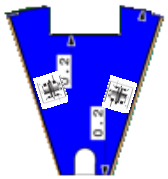


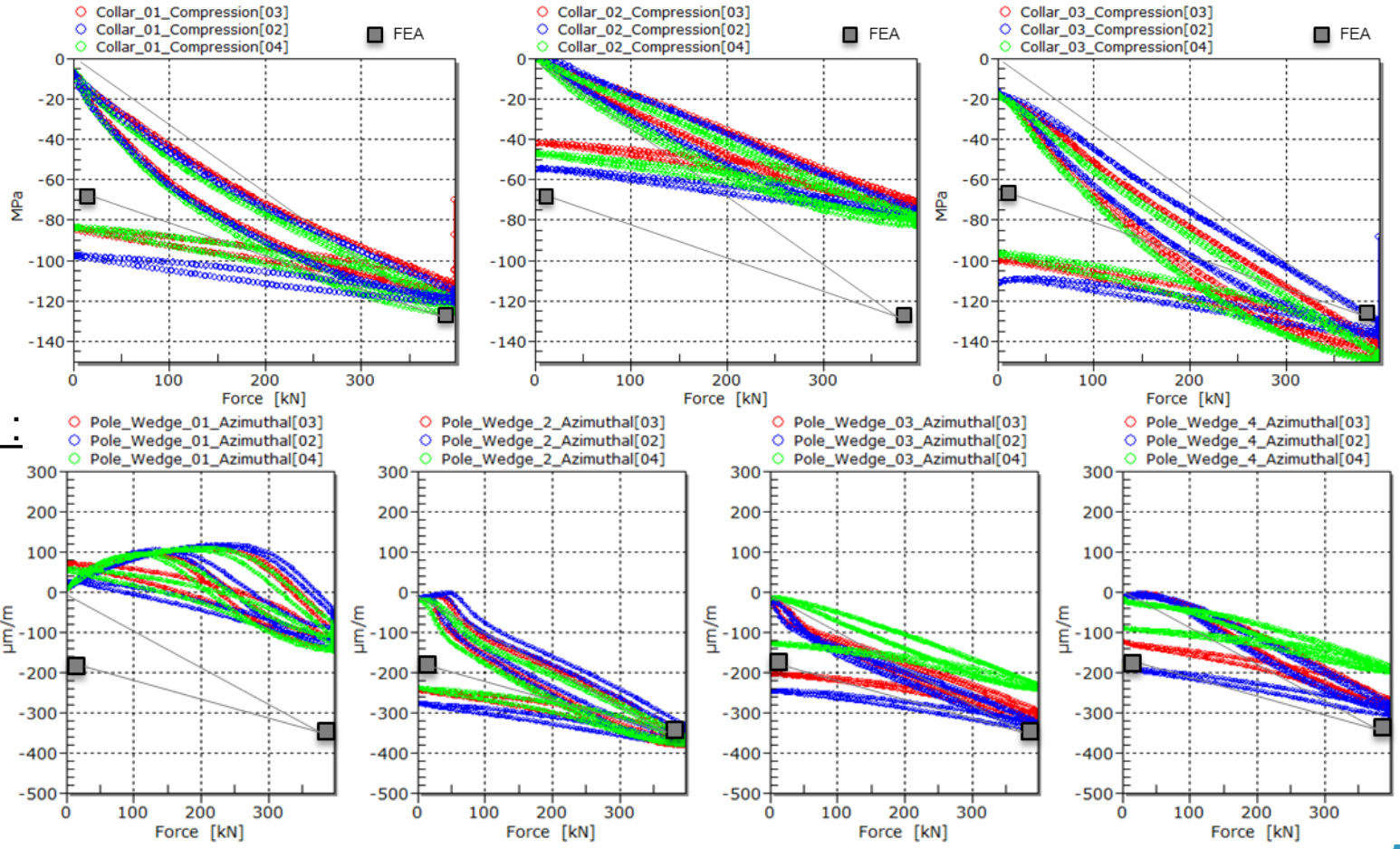
Results in December 2017

- Reproducibility and in 5 out of 7 consistency with FEM



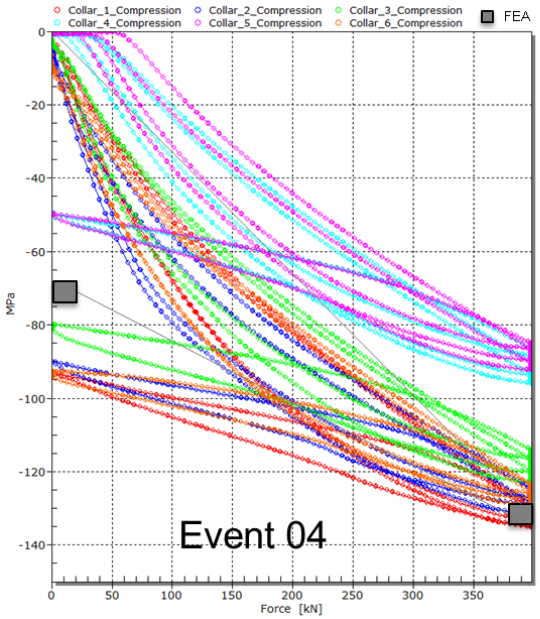
Coil excess per quadrant : 0.184mm

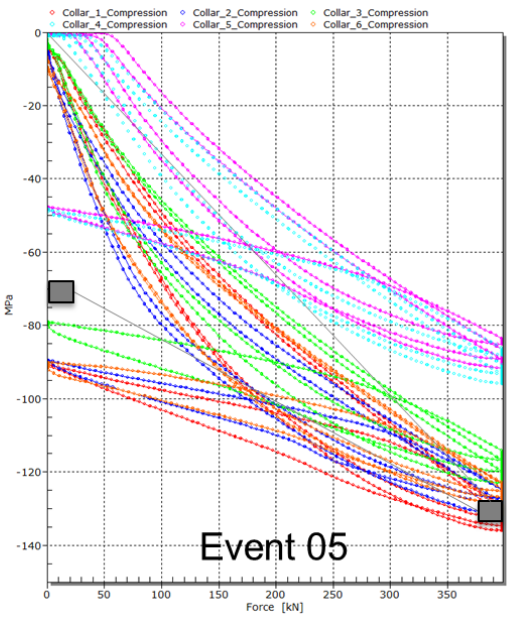




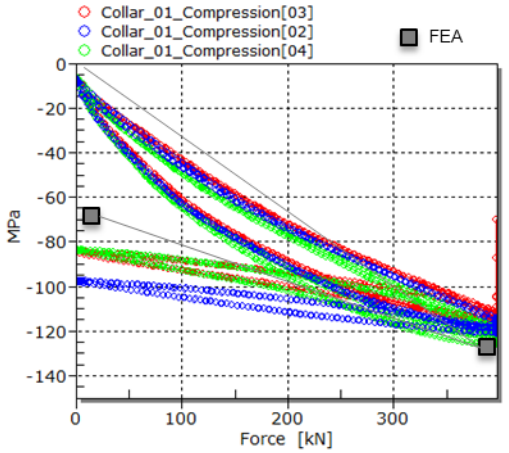
Comparison with January 2018

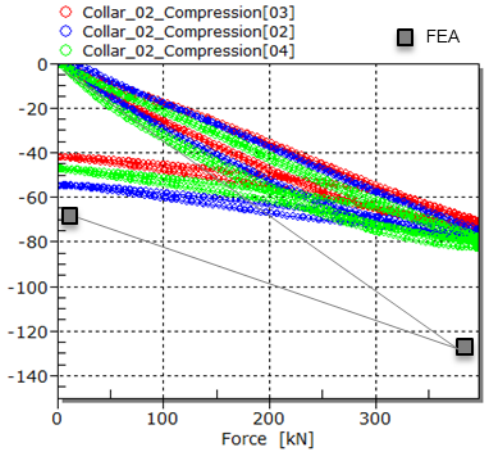
01/18

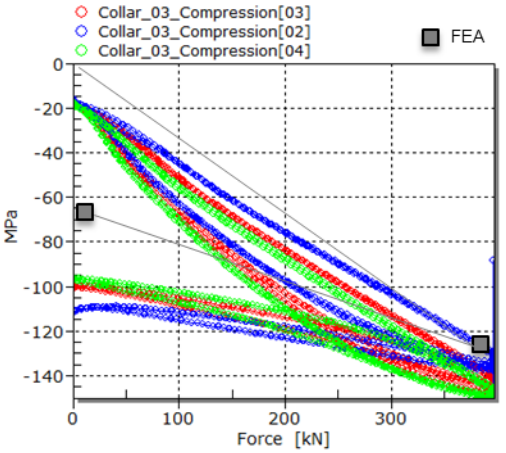




12/17

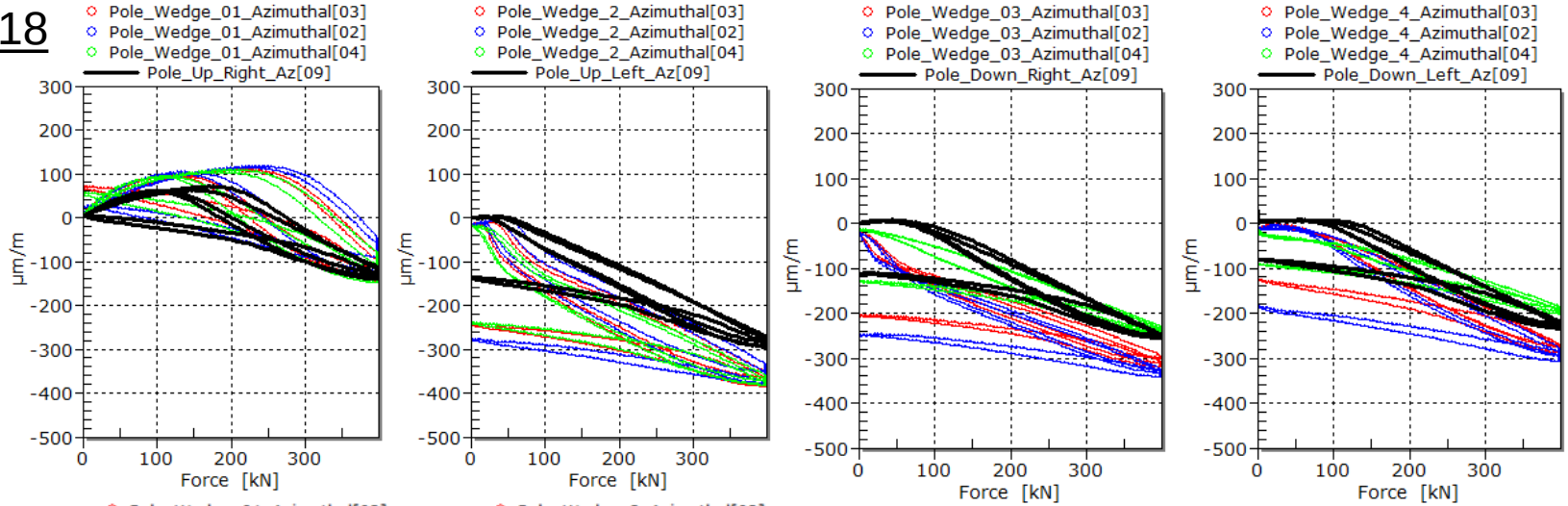






Comparison with January 2018

01/18



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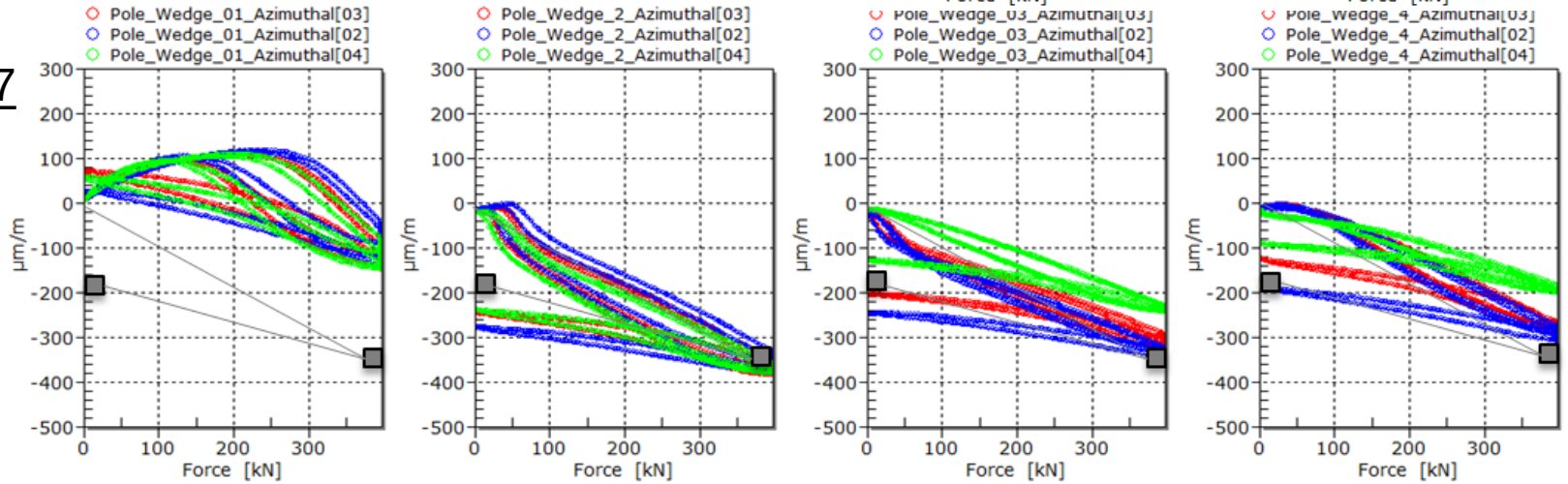
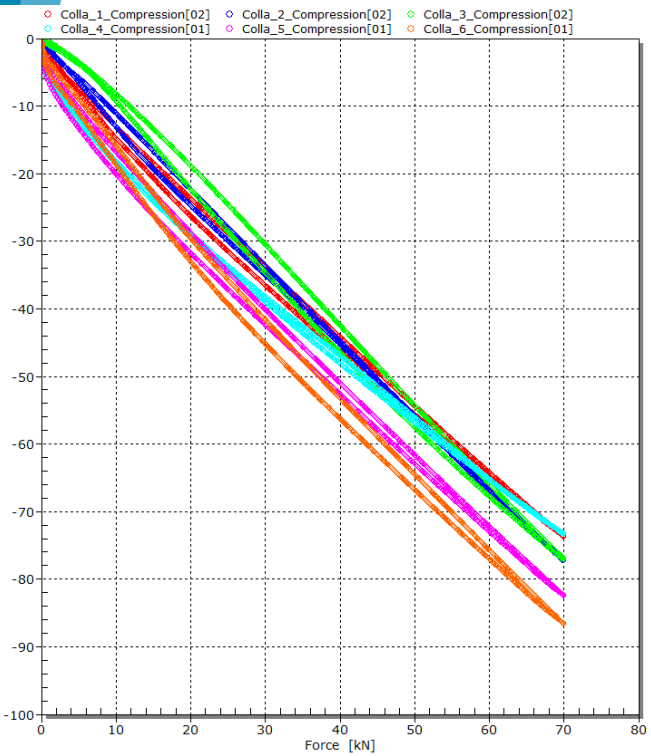
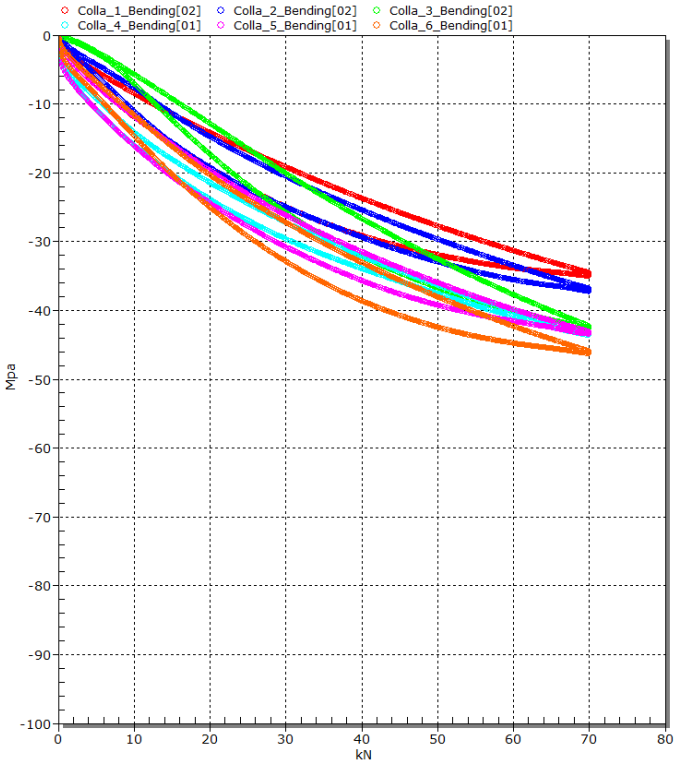
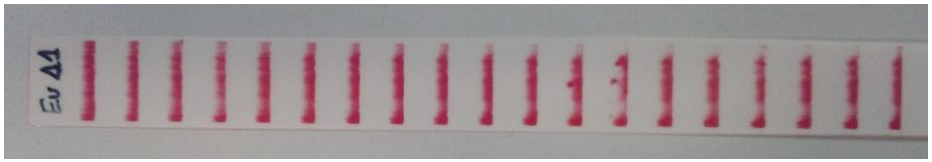


Collar noses calibration

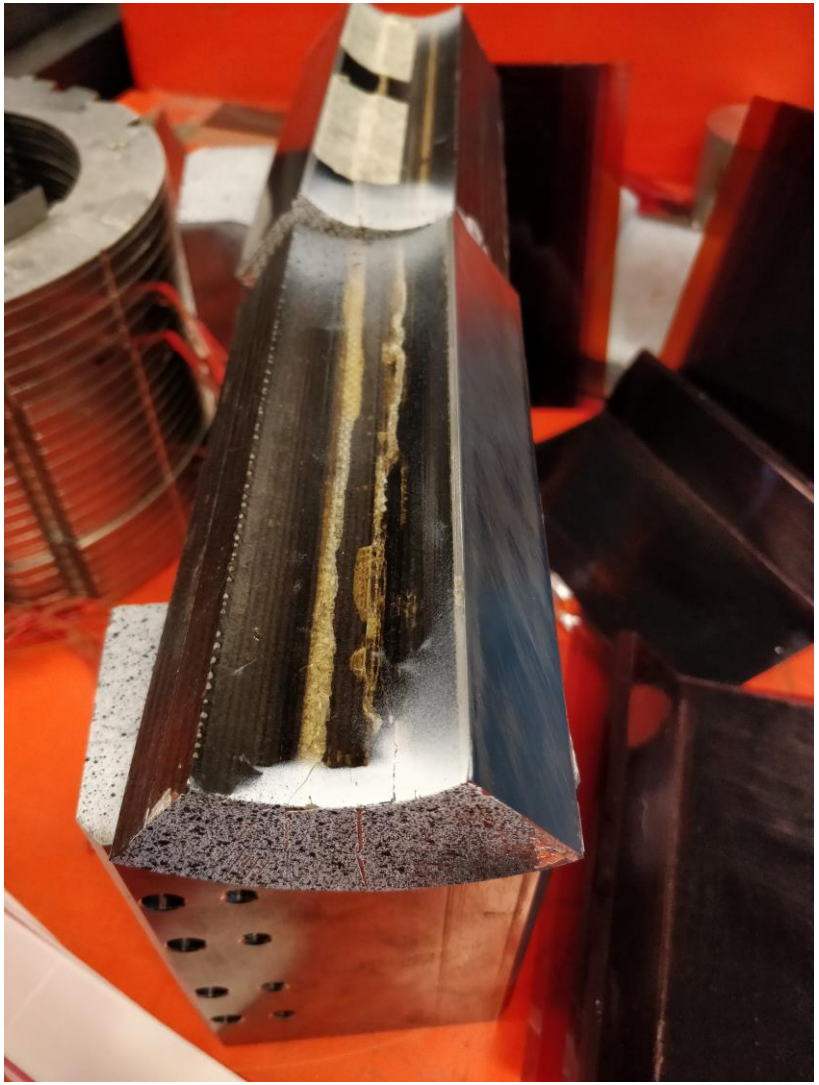






Assembly fault

- Coil misplaced during assembly and damaged during loading

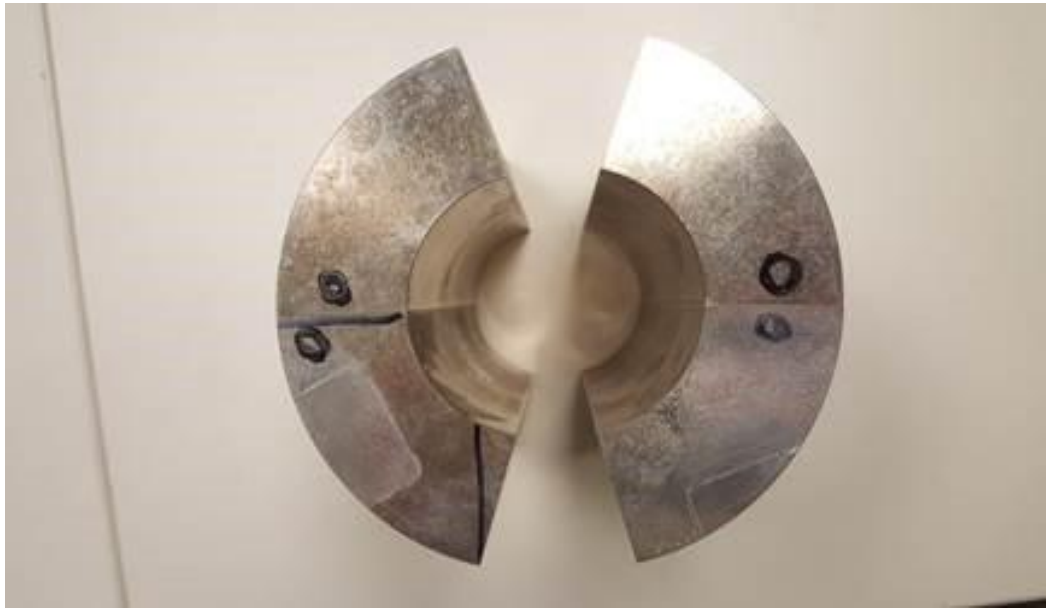


Plan: step 1
22/01-29/01

- Mechanical lab
  - Instrument Aluminum dummy coils
  - Aluminum dummy coil tests with 0.15 and 0.05 excess
  - Measure collar deflection
- 927
  - Reproducibility tests

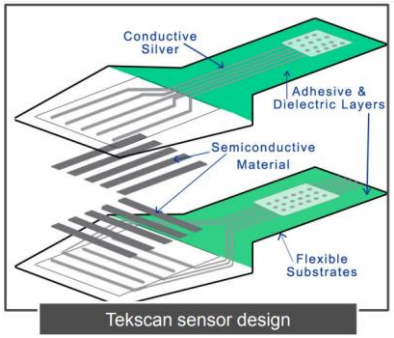
- Regarding Fuji paper test
  - MS+HS on the pole
  - MS+HS+HSS on the mid-plane
    - We may have to compensate the additional thickness on the mid-plane to keep the same excess

Aluminum dummy coils

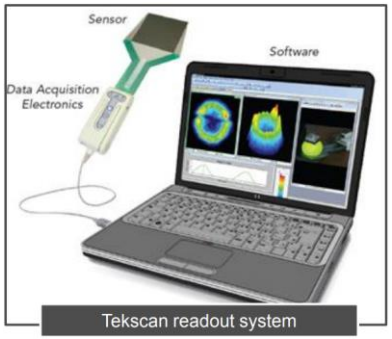


Additional instrumentation

- Tekscan in 2-3 weeks

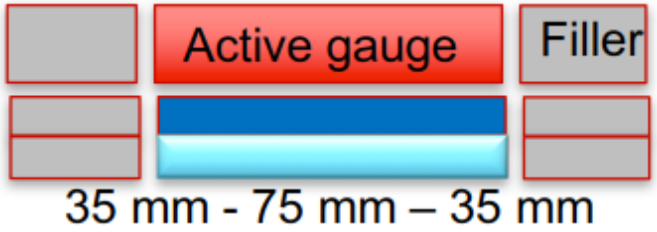


Tekscan sensor design



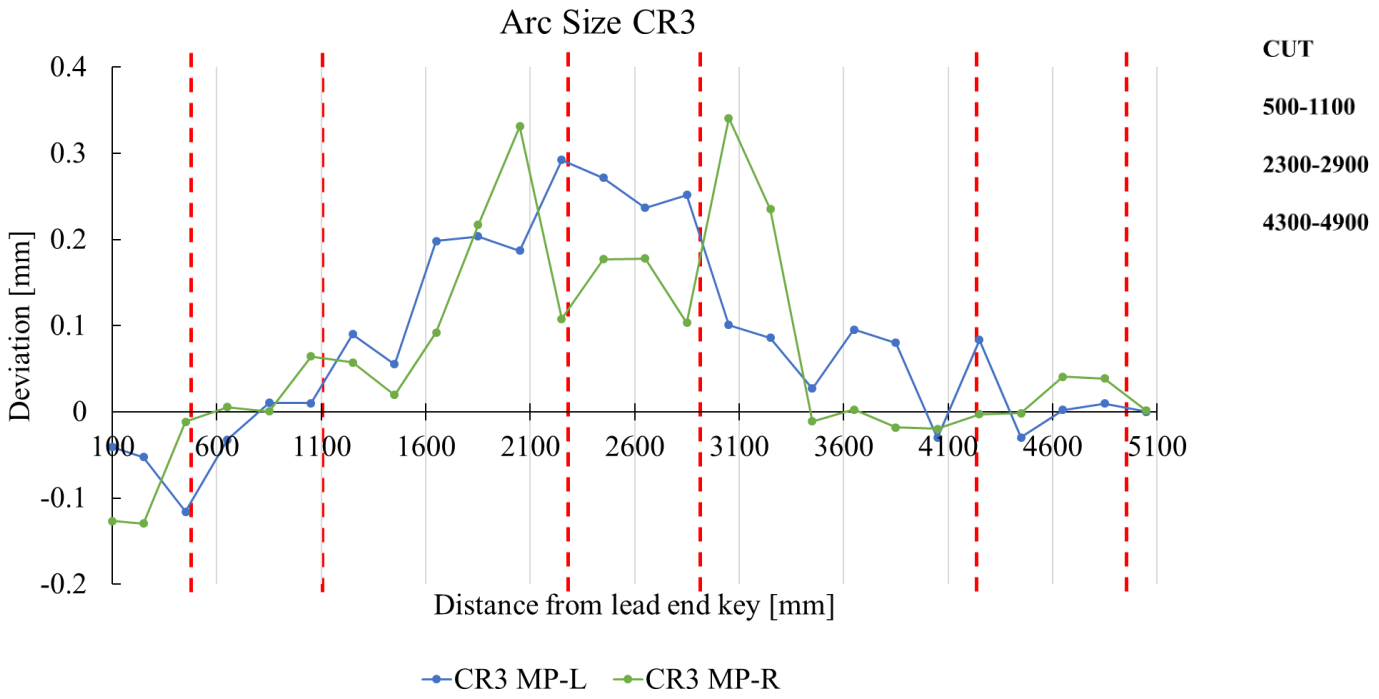
Tekscan readout system

- 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 for coil CR03
February-March 2018

- 1st collaring mock up (500-1100 mm)
  - Loading 1 (virgin coil)
    - No stoppers
    - Massages 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
    - Massages 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
    - Massages 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
    - Massages 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
    - Massages 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
    - Massages 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

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

Outline

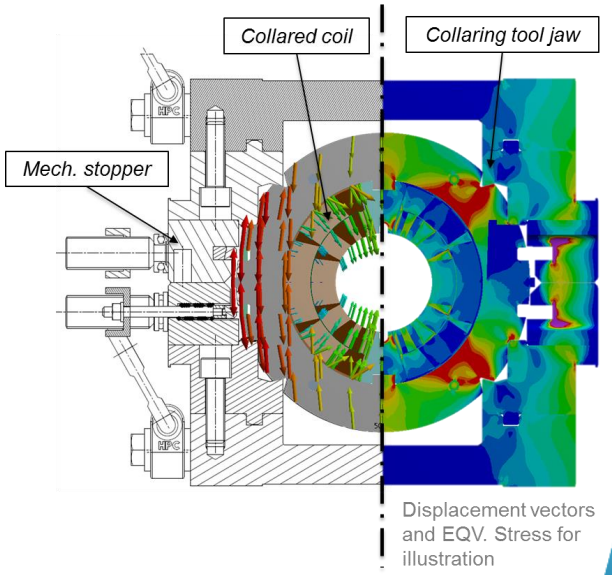
- Status and plan of collaring test
- Status of the analysis

Analysis of collaring "Old slide"

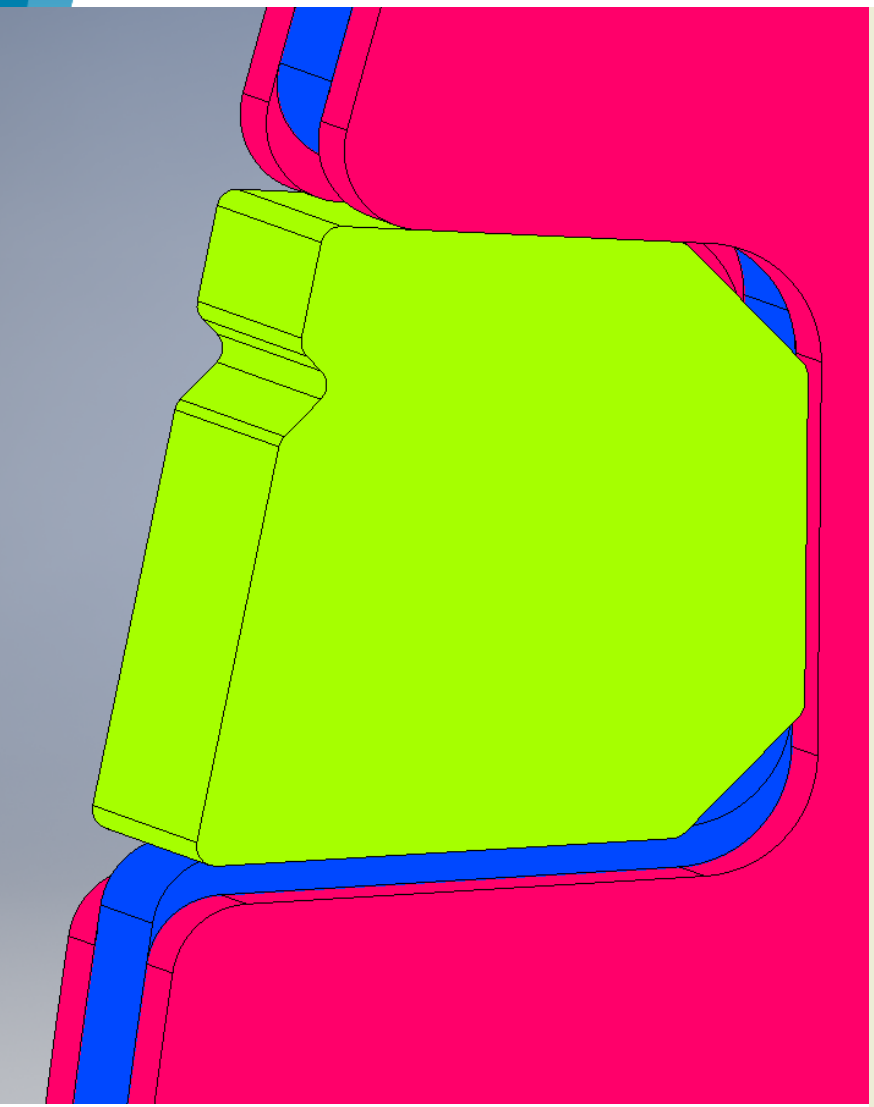
- Typical coil "excess" and force
  - 70 mm stopper equivalent to status when key inserted

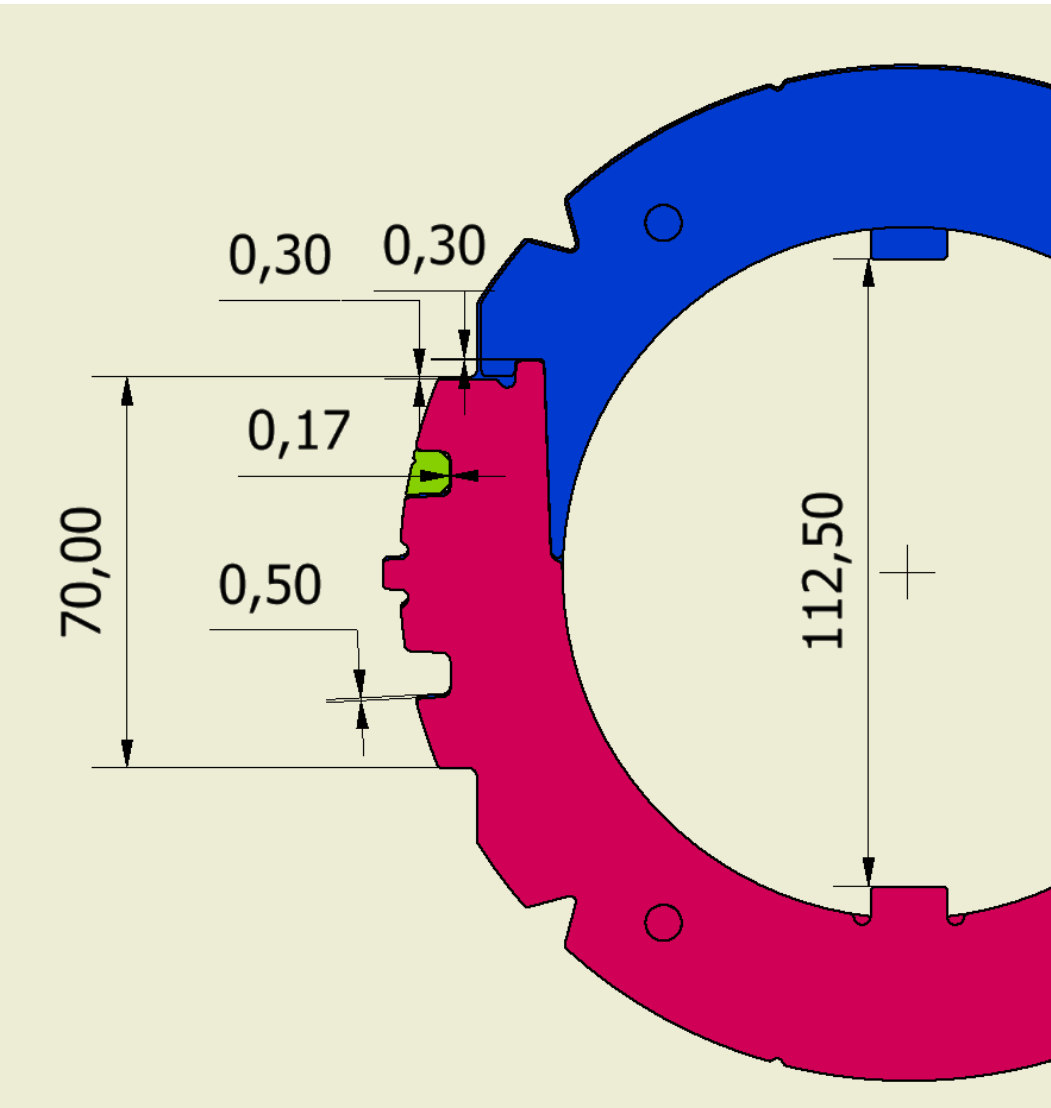
	Average Excess Quadrant	Applied Force / MN	70 mm stopper deviation / mm
CC101	0.31	32	+0.1
CC102	0.29	32	+0.1
CC103	0.38	32	+0.1
CC104	0.45	22	-0.15
CC104b	0.35	**20**	-0.15
CC105	0.35	16	-0.15
CC105b	0.30	**20**	-0.15
CC106	0.33	12	-0.15

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

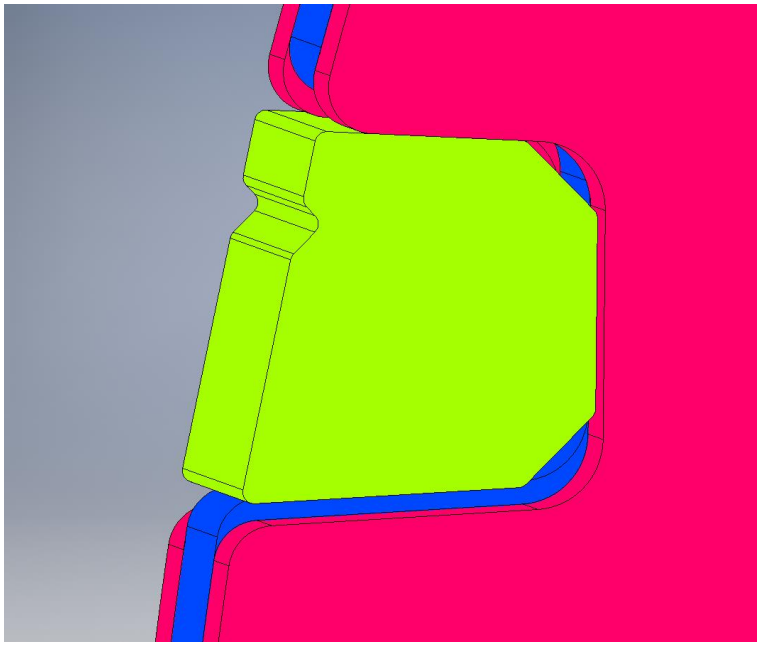


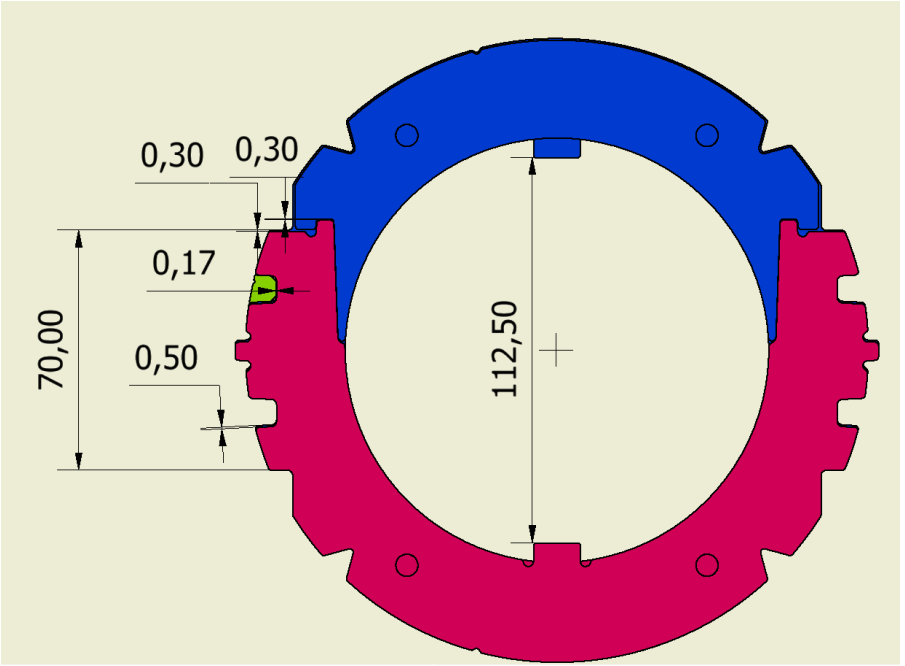
Key clearance vs stoppers shim





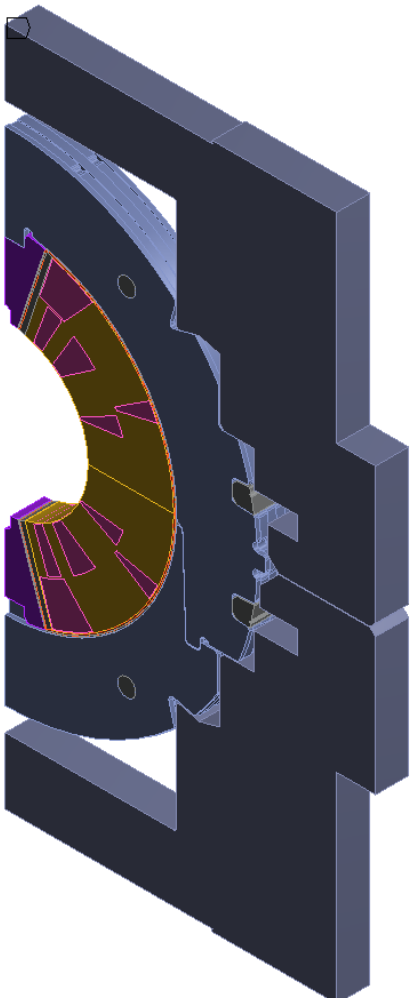
Key clearance vs stoppers shim

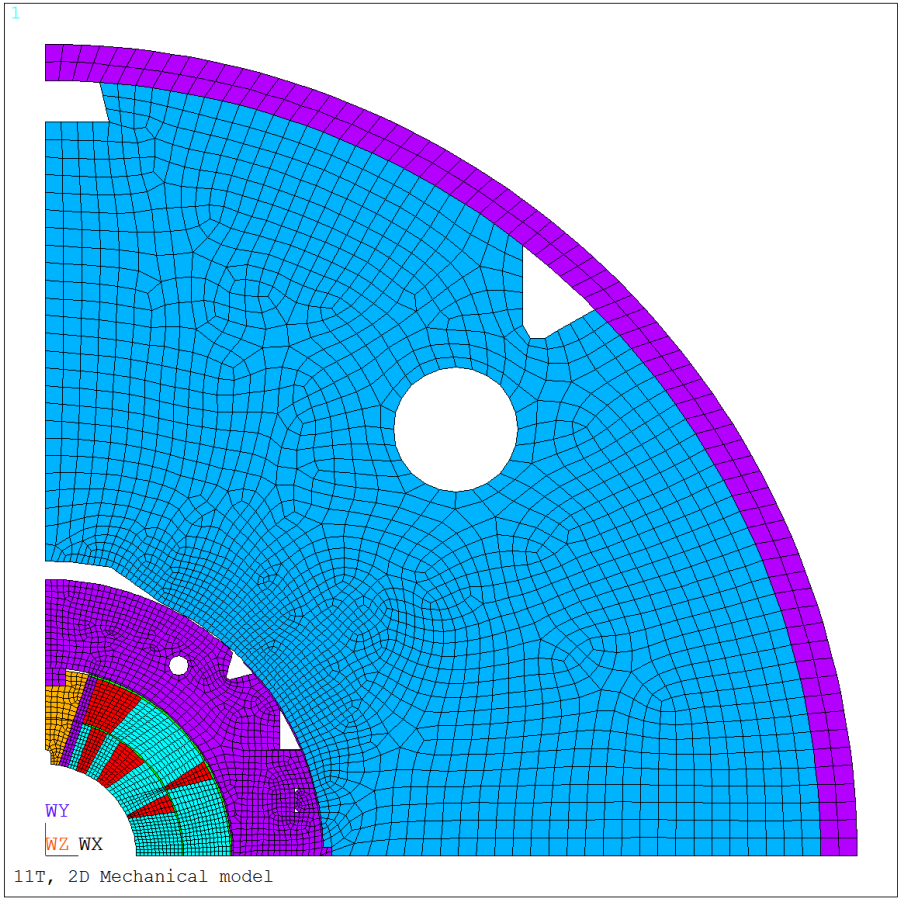




Magnet	Shim stoppers (μm)	Stopper height (mm)	Key clearance (μm)
	0	69.7	+300
	100	69.8	+200
	200	69.9	+100
	300	70.0	0
101,102,103	400	70.1	-100
104,105,106	150	69.85	+150

Modelling



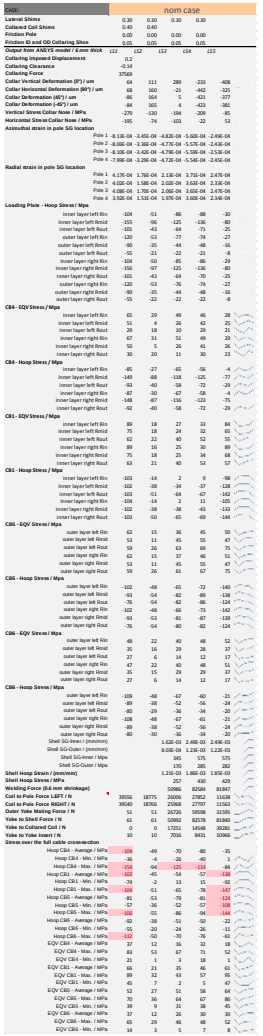


Analysis

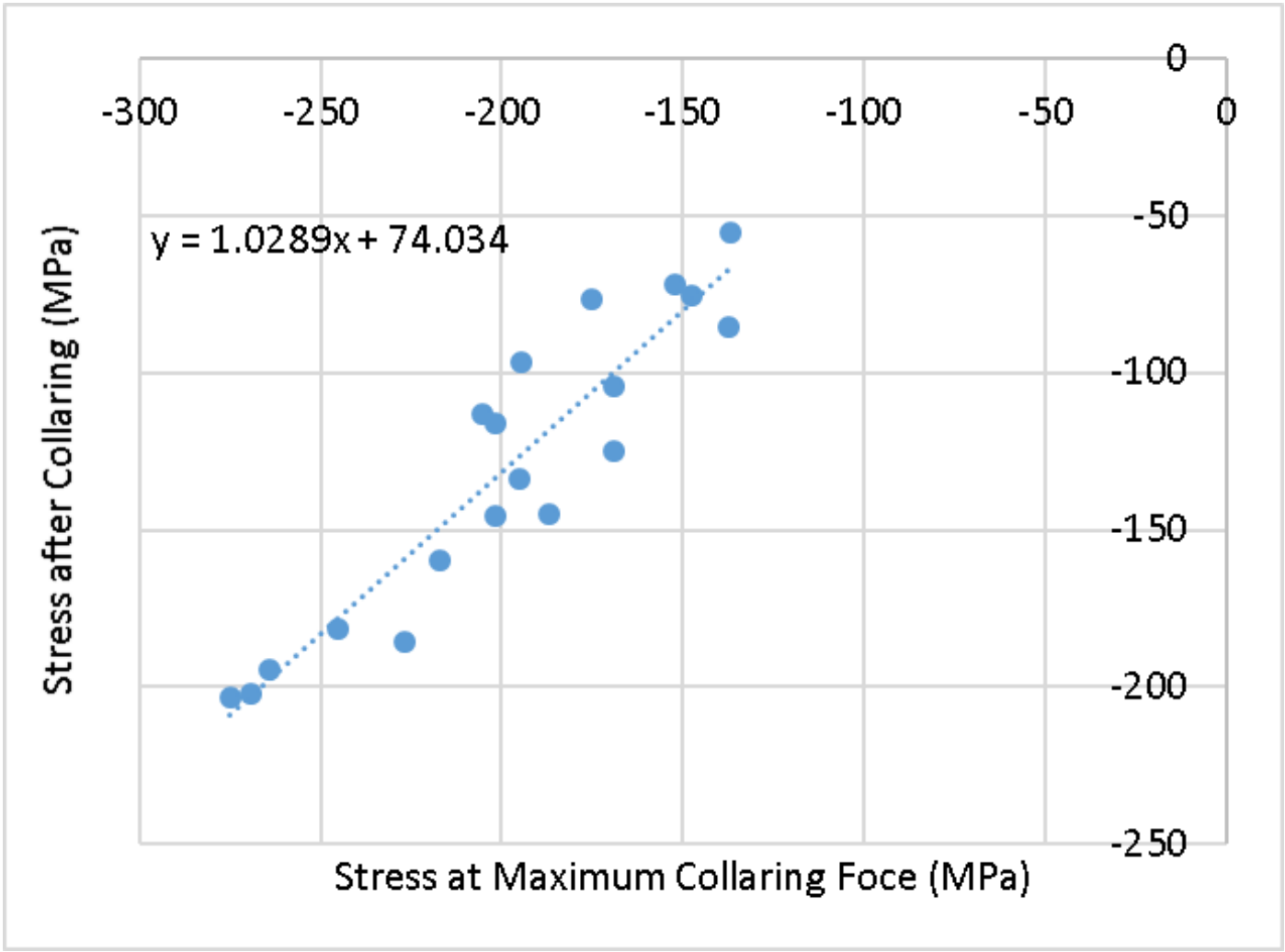
- Output from ANSYS model
  - For each of the 4 excesses
    - Steps
      - Collaring maximum force
      - After collaring (key inserted)
      - After welding
      - After cool-down
      - During powering: 10%,20%....100% of the nominal force
    - Collar vertical and horizontal deflection
    - 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

“Transfer function”

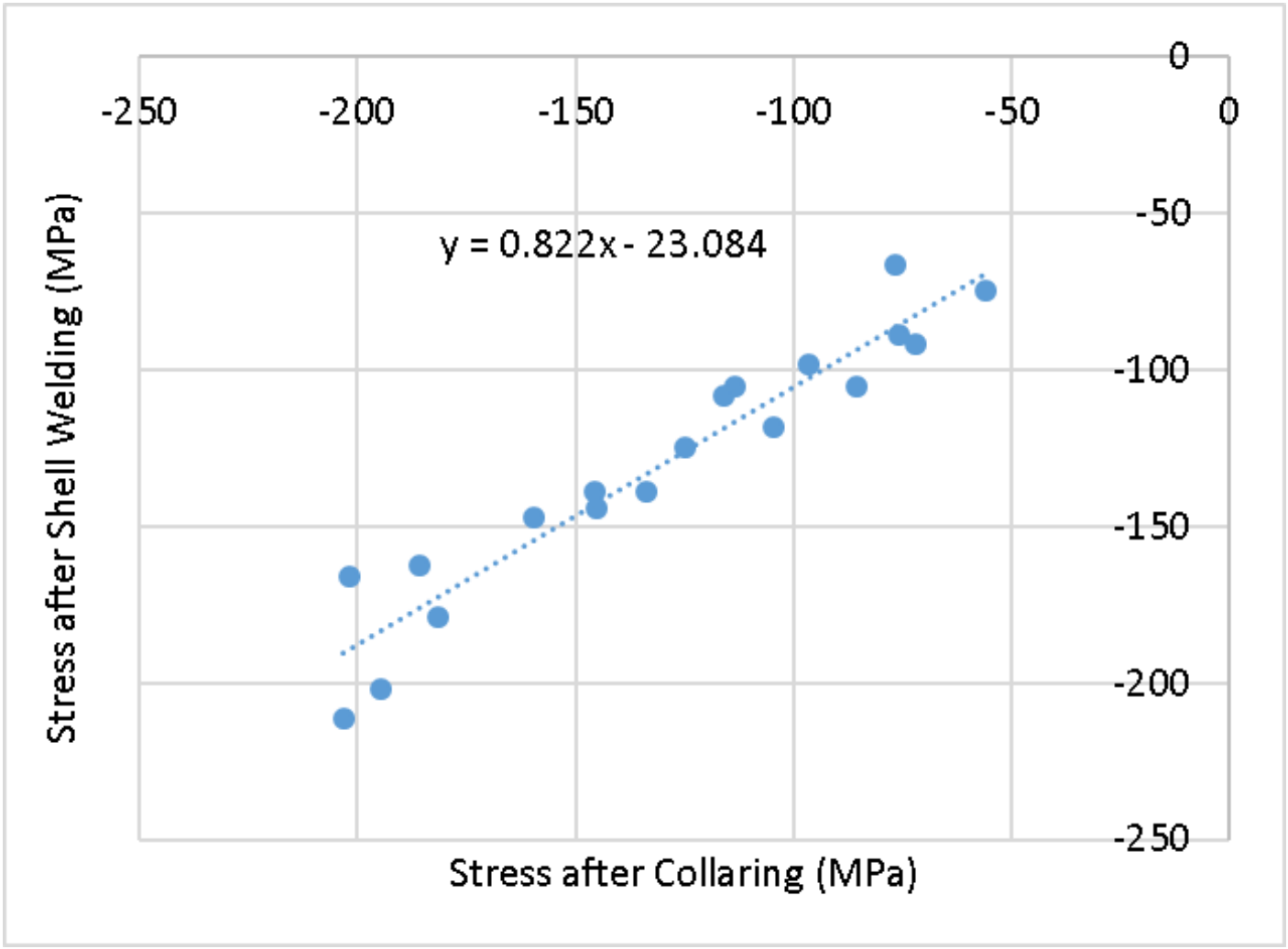
CASE:	nom case				
Lateral Shims	0.30	0.30	0.30	0.30	
Collared Coil Shims	0.40	0.40			
Friction Pole	0.00	0.00	0.00	0.00	
Friction ID and OD Collaring Shoe	0.05	0.05	0.05	0.05	
Output from ANSYS model / 6 mm thick	*LS1*	*LS2*	*LS3*	*LS4*	*LS5*
Collaring Imposed Displacement	0.2				
Collaring Clearance	-0.14				
Collaring Force	37569				
Collar Vertical Deformation (0°) / um	64	111	289	-233	-408
Collar Horizontal Deformation (90°) / um	68	160	-21	-442	-325
Collar Deformation (45°) / um	-86	164	5	-421	-377
Collar Deformation (-45°) / um	-84	165	4	-423	-381
Vertical Stress Collar Nose / MPa	-279	-130	-194	-209	-85
Horizontal Stress Collar Nose / MPa	-195	-74	-103	-22	53
Azimuthal strain in pole SG location					
Pole 1	-8.13E-04	-3.45E-04	-4.82E-04	-5.60E-04	-2.49E-04
Pole 2	-8.06E-04	-3.36E-04	-4.77E-04	-5.57E-04	-2.43E-04
Pole 3	-8.10E-04	-3.42E-04	-4.79E-04	-5.59E-04	-2.53E-04
Pole 4	-7.99E-04	-3.29E-04	-4.72E-04	-5.54E-04	-2.45E-04
Radial strain in pole SG location					
Pole 1	4.17E-04	1.76E-04	2.13E-04	3.71E-04	2.47E-04
Pole 2	4.02E-04	1.58E-04	2.02E-04	3.63E-04	2.33E-04
Pole 3	4.08E-04	1.70E-04	2.06E-04	3.65E-04	2.47E-04
Pole 4	3.92E-04	1.51E-04	1.97E-04	3.60E-04	2.34E-04
Loading Plate - Hoop Stress / Mpa					
inner layer left Rin	-104	-51	-86	-88	-30
inner layer left Rmid	-155	-96	-125	-136	-80
inner layer left Rout	-101	-43	-64	-71	-25
outer layer left Rin	-120	-53	-77	-74	-27
outer layer left Rmid	-90	-35	-44	-48	-16
outer layer left Rout	-55	-21	-22	-21	-8
inner layer right Rin	-104	-50	-85	-86	-29



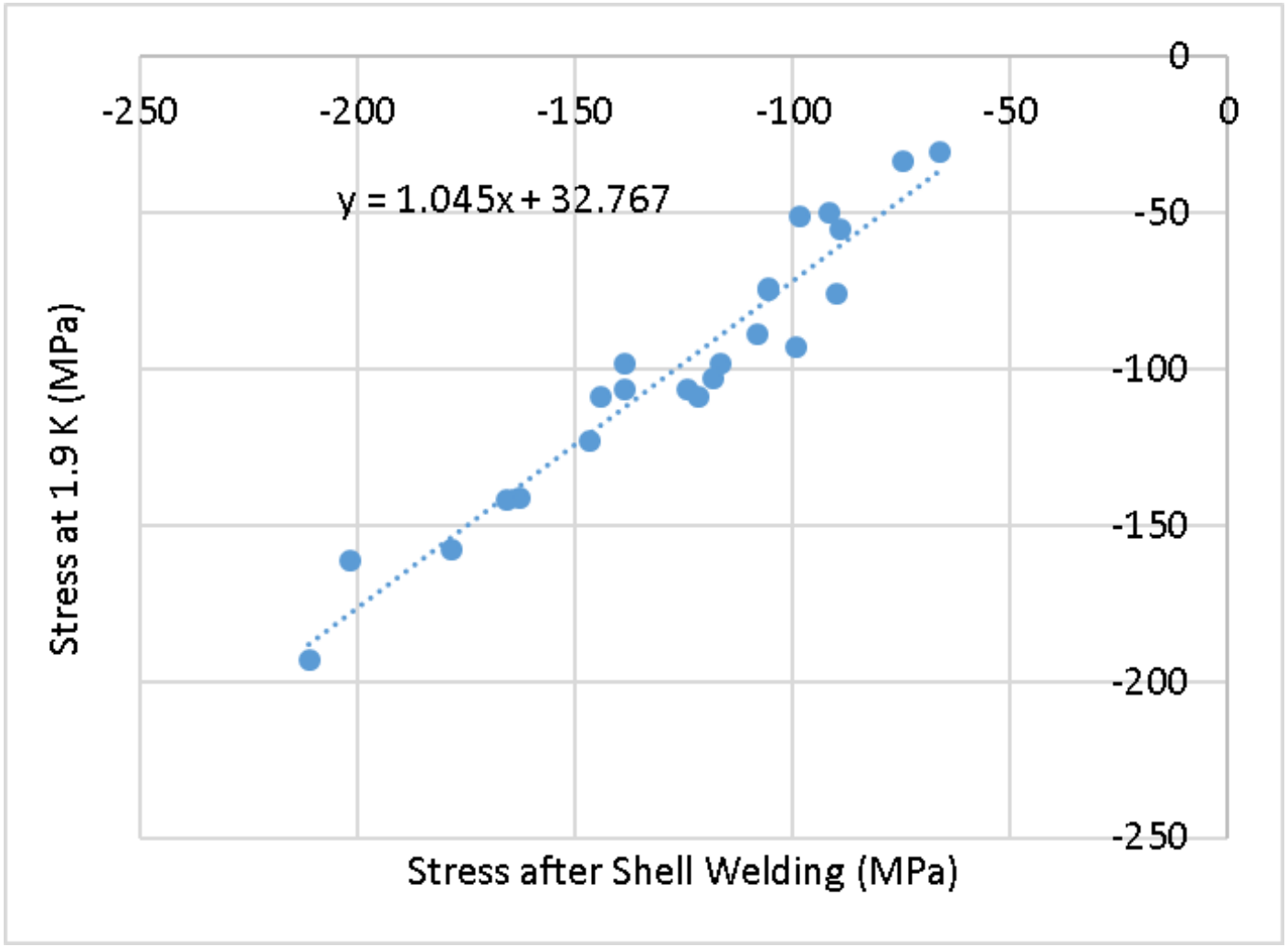
Analysis


y = 1.0289x + 74.034
Stress after Collaring (MPa)
Stress at Maximum Collaring Foce (MPa)
-300
-250
-200
-150
-100
-50
0
0
-50
-100
-150
-200
-250

Analysis


y = 0.822x - 23.084
Stress after Shell Welding (MPa)
Stress after Collaring (MPa)
-250
-200
-150
-100
-50
0
0
-50
-100
-150
-200
-250

Analysis


y = 1.045x + 32.767
Stress at 1.9 K (MPa)
Stress after Shell Welding (MPa)
-250
-200
-150
-100
-50
0
0
-50
-100
-150
-200
-250

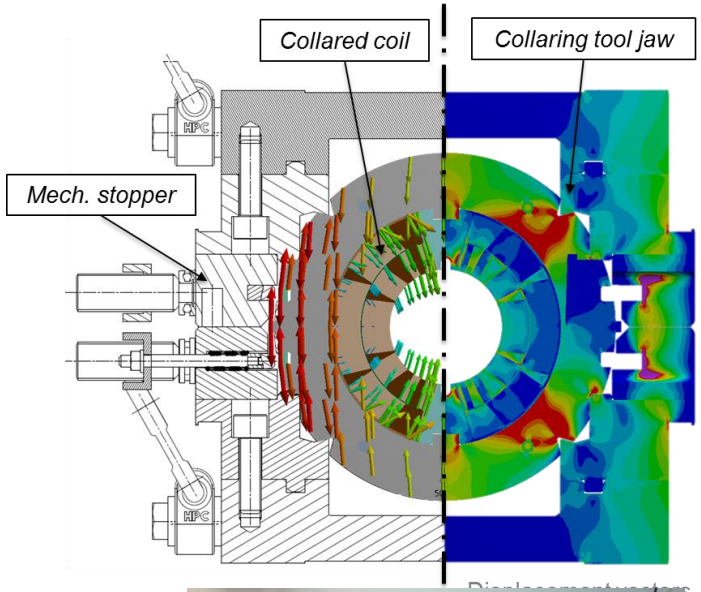
Analysis: open points

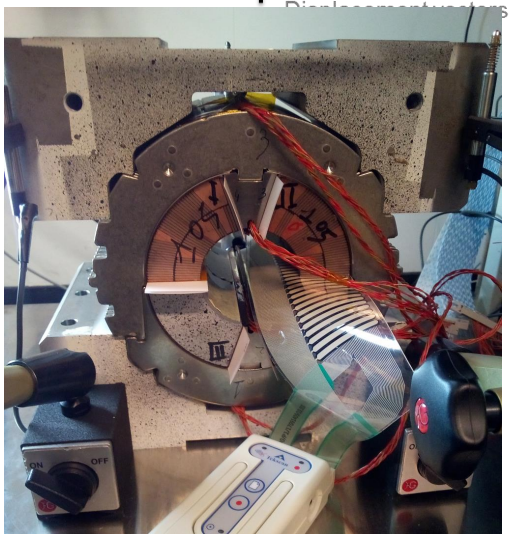
- Strain gauge summary
  - Include all collar gauges
- Measure/analyze collar deflection
- Collaring: impact of stopper shimming on coil stress
  - Is it possible that the deformation of the tooling has positive impact on the coil stress
- Evaluate key insertion clearance according to strain gauge data→ 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

Appendix

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

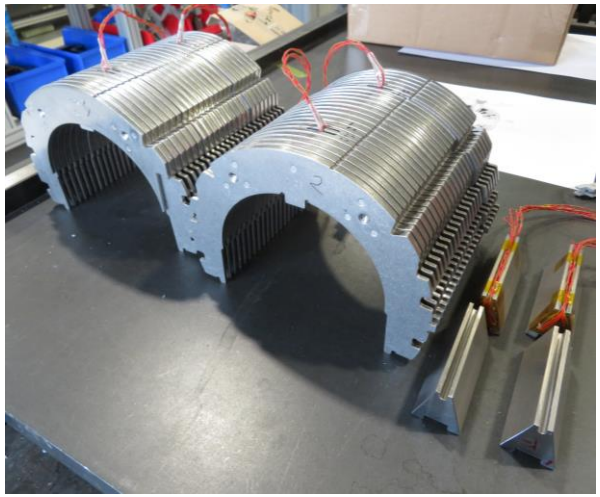


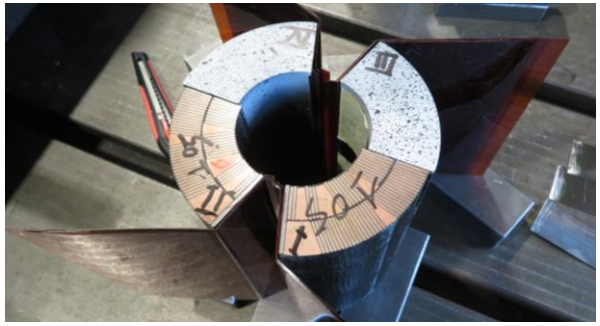


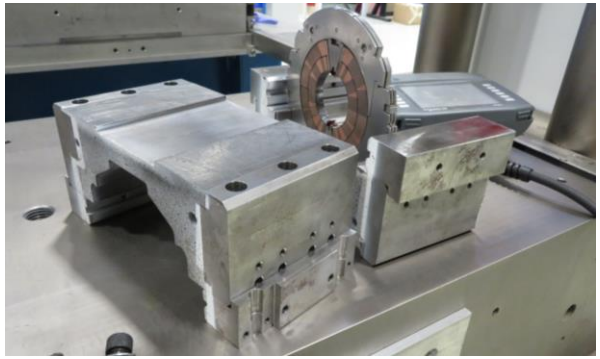
Status of components

- 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

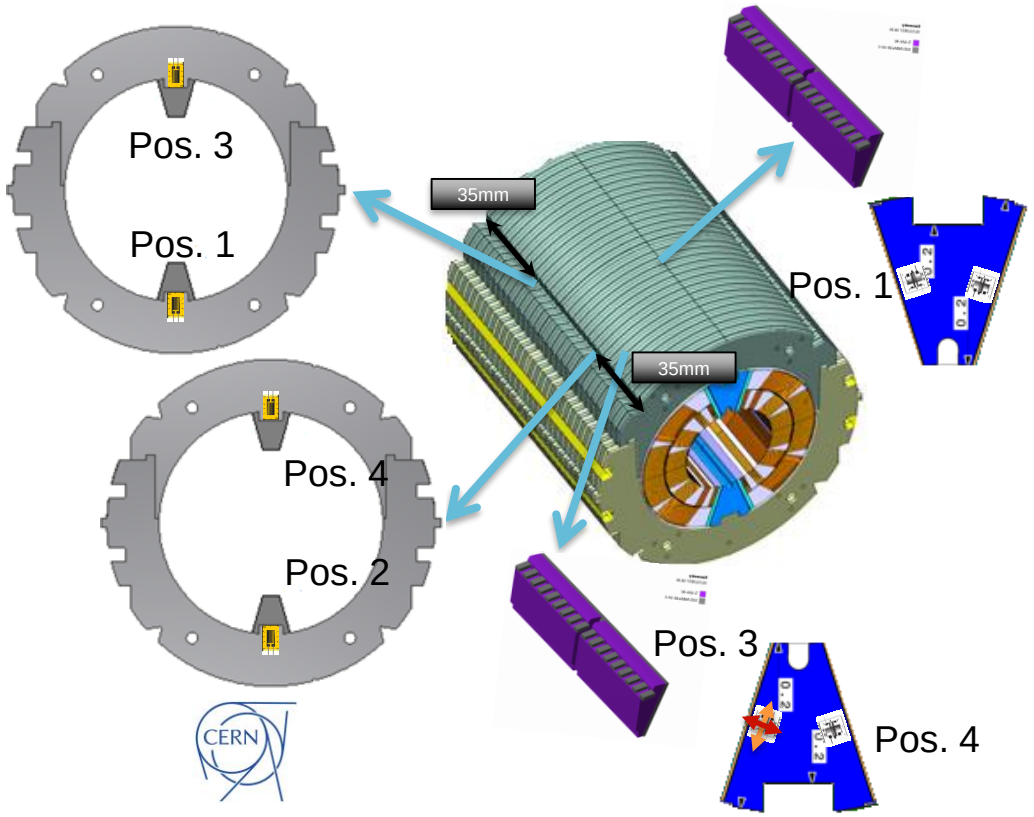


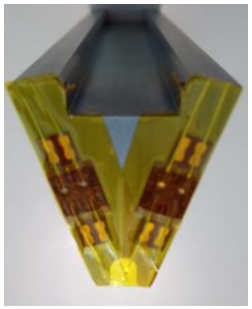


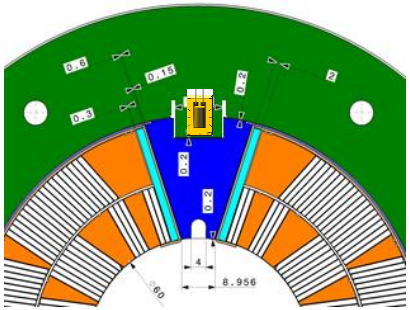


Status of instrumentation

- 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

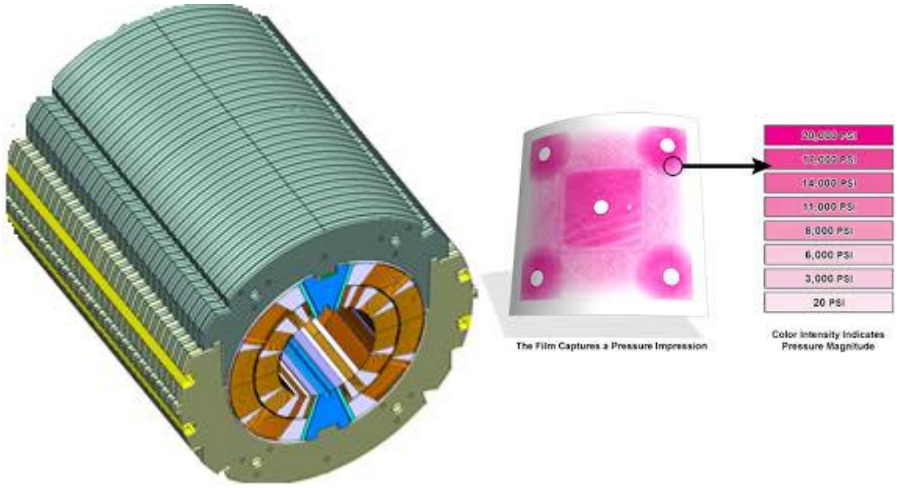


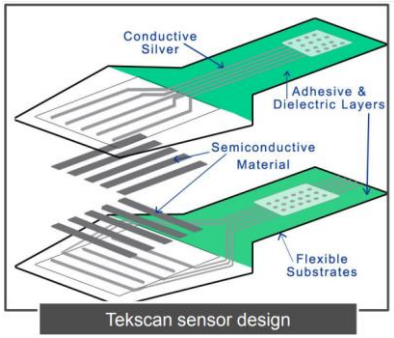




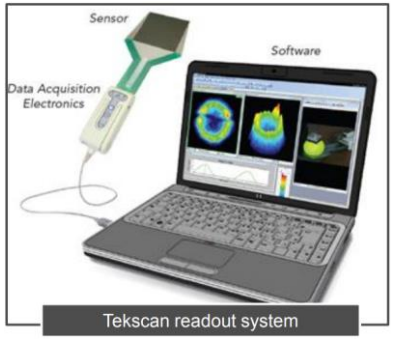
Status of instrumentation

- 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





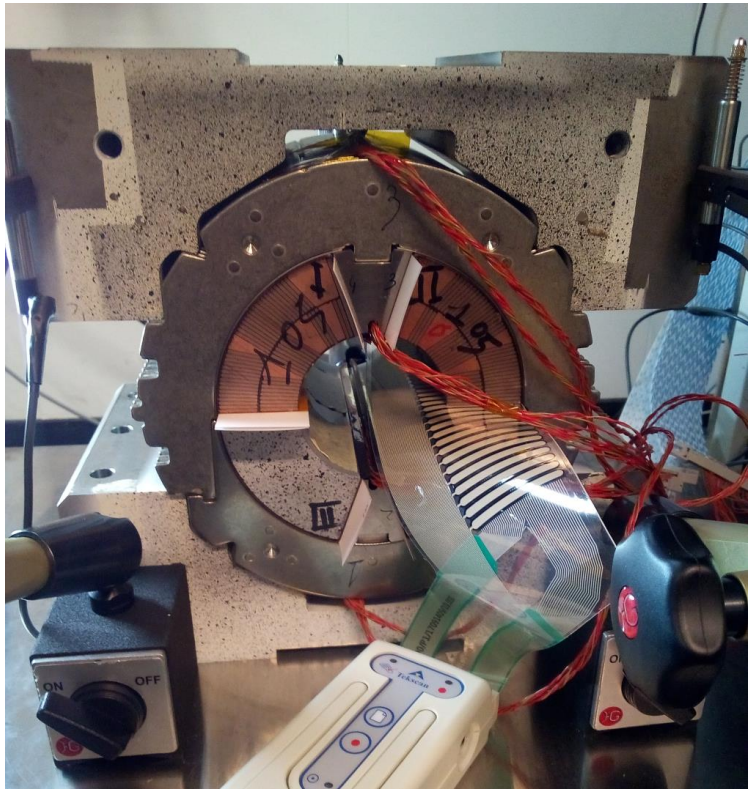
Tekscan sensor design



Tekscan readout system

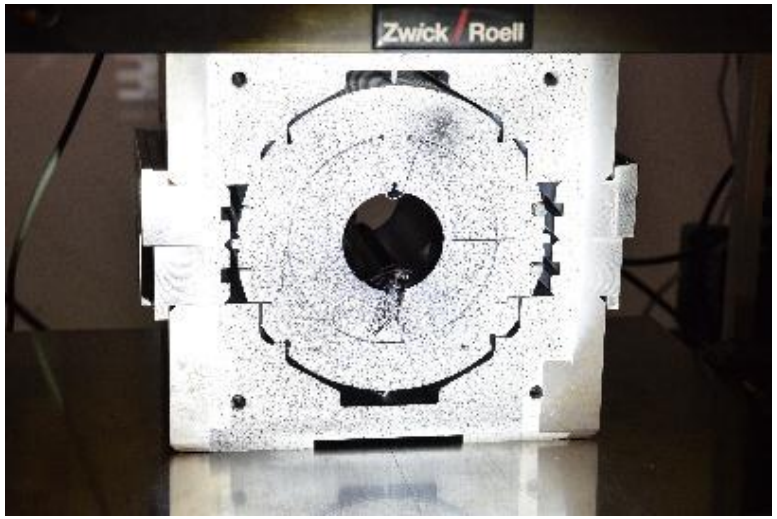
Status of instrumentation

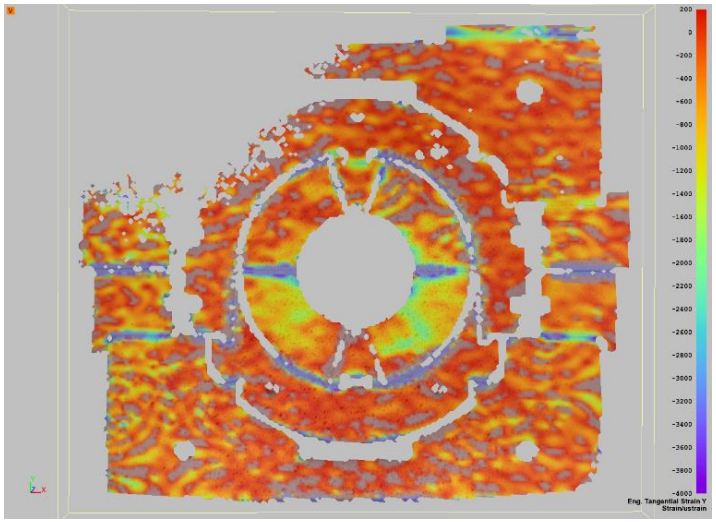
- Setup and displacement sensors
  - Z400 Universal Testing Machine
  - 400 kN max load
  - 3 LVDT's in vertical position's
  - 1 LVDT in Z position

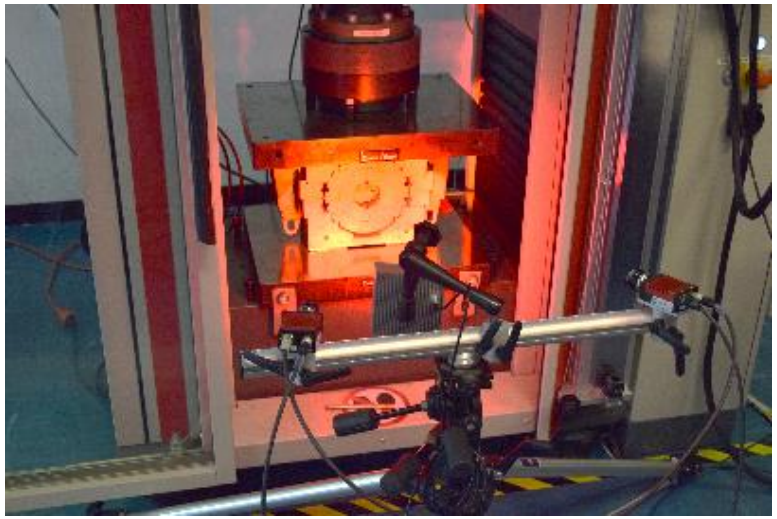


Status of instrumentation

- 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.

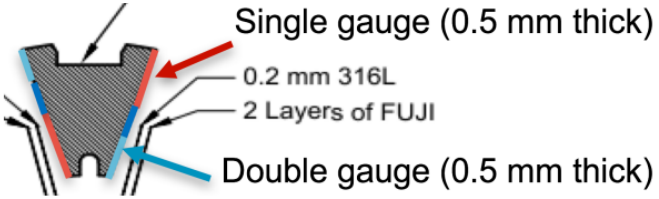


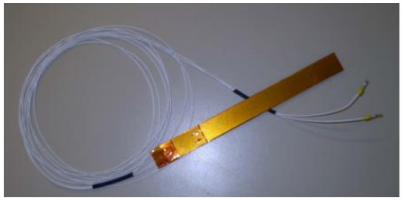


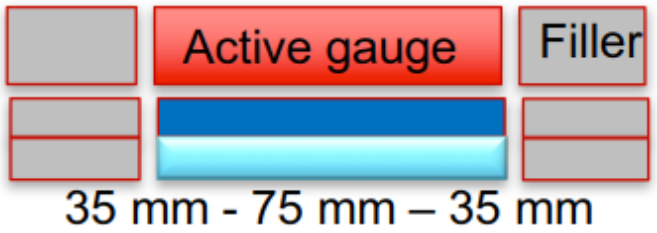


Status of instrumentation

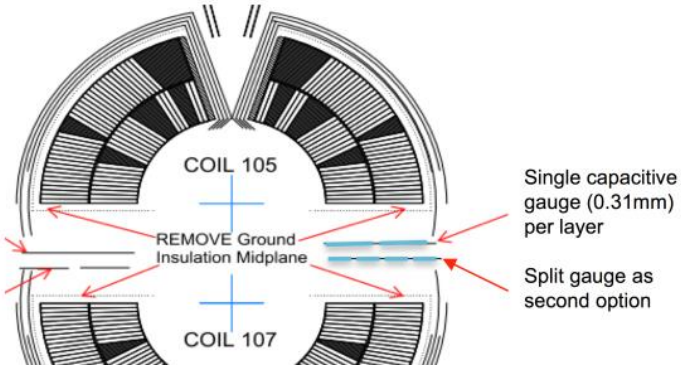
- By mid-February
  - “Resurrection” of capacitive gauges





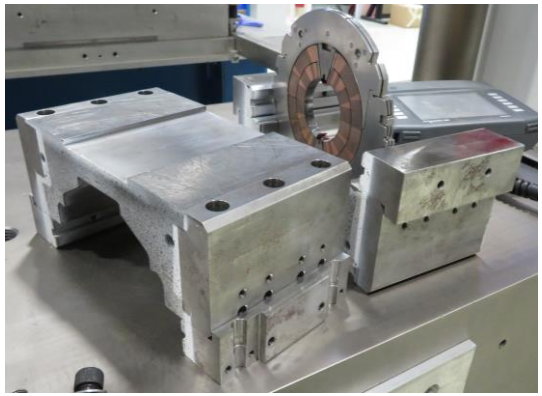


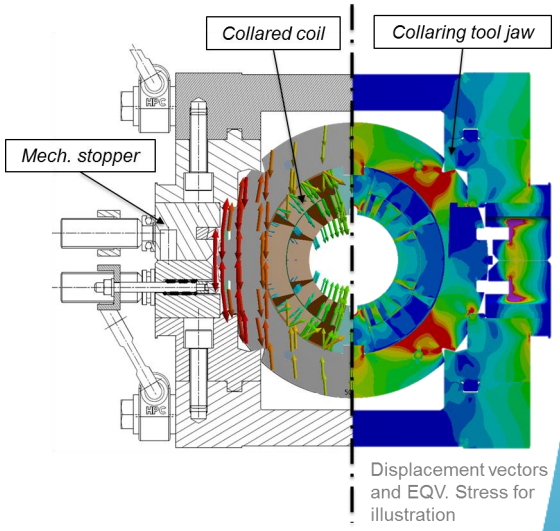
  - Gauge thickness: 0.31-0.5 mm
  - Pole
    - 150 mm long pole machined by - 0.5 mm on both face
  - Mid plane
    - first use of 150 mm long, 0.31 mm thick single gauge per layer then split gauge as an option



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



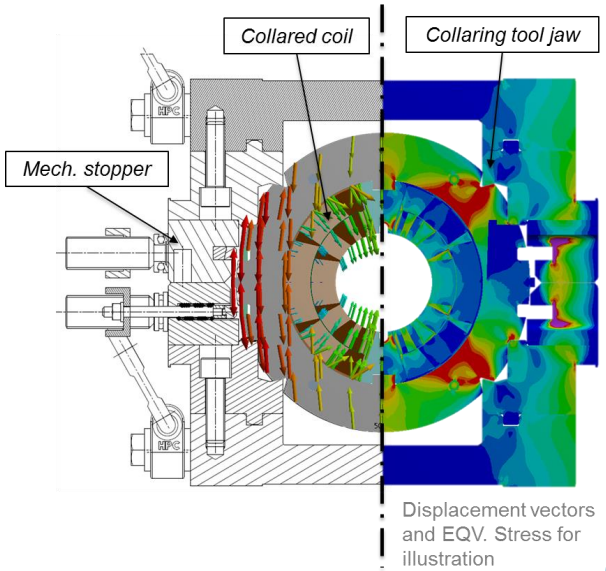


Analysis of collaring

- 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

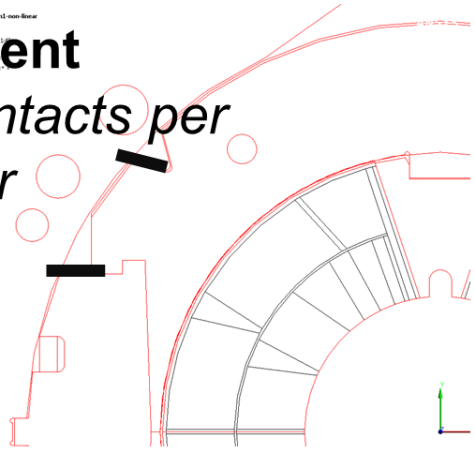
- Deviation
  - Positive → interference
    - Tooling deformed
  - Negative→ clearance



Analysis of collaring by FEM

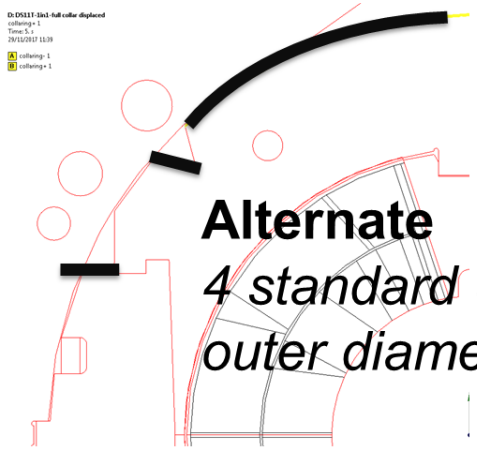
- Different scenarios considered

Current
4 contacts per collar

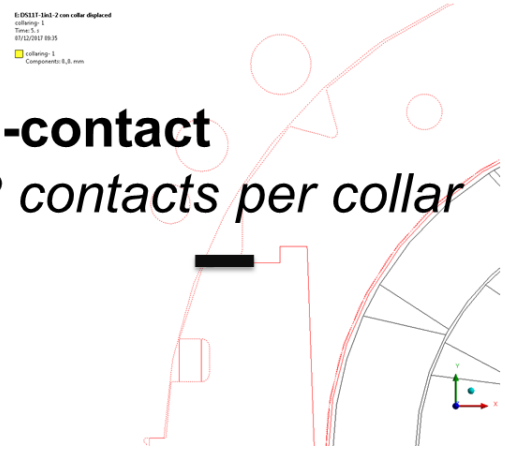


Fixed displacement by 0.1 mm

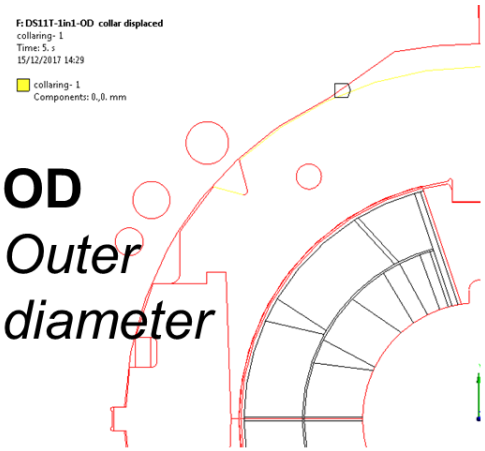
Alternate
4 standard contacts + outer diameter



2-contact
2 contacts per collar

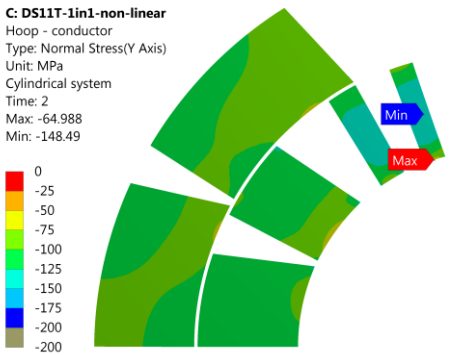


OD
Outer diameter



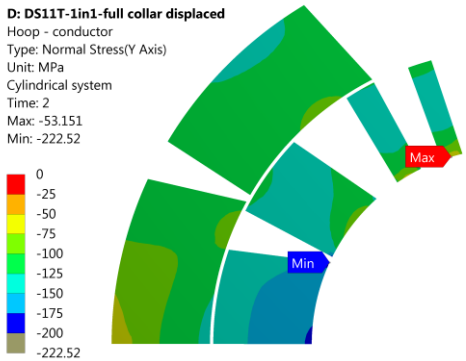
Analysis of collaring by FEM

- Different scenarios considered



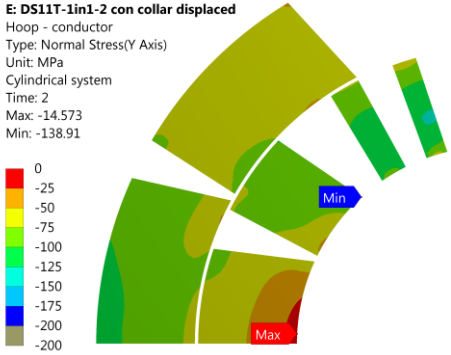
Current

4 contacts per collar



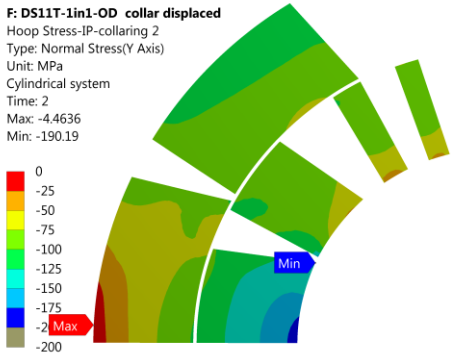
Alternate

4 standard contacts + outer diameter



2-contact

2 contacts per collar

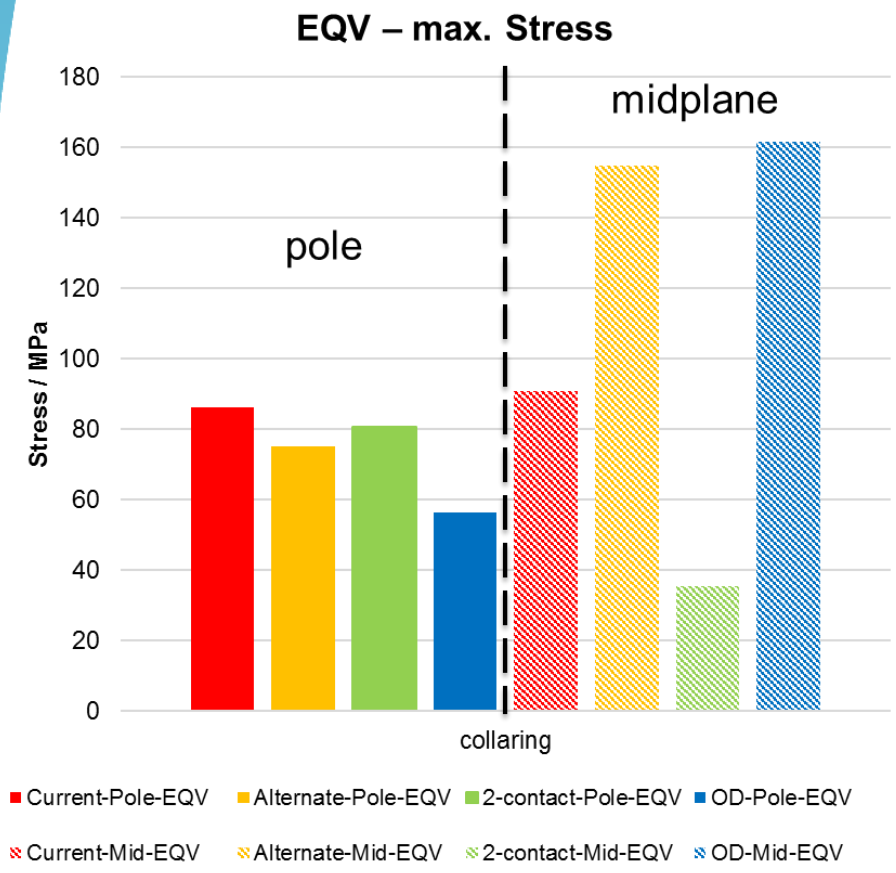


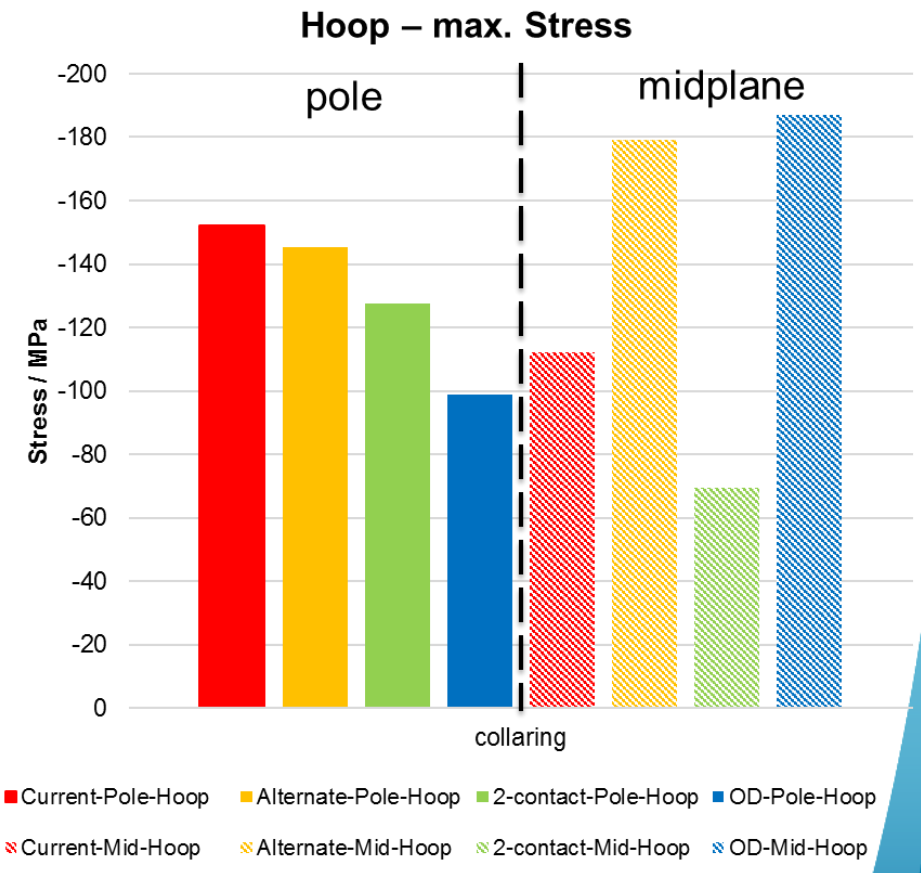
OD

Outer diameter

Analysis of collaring by FEM

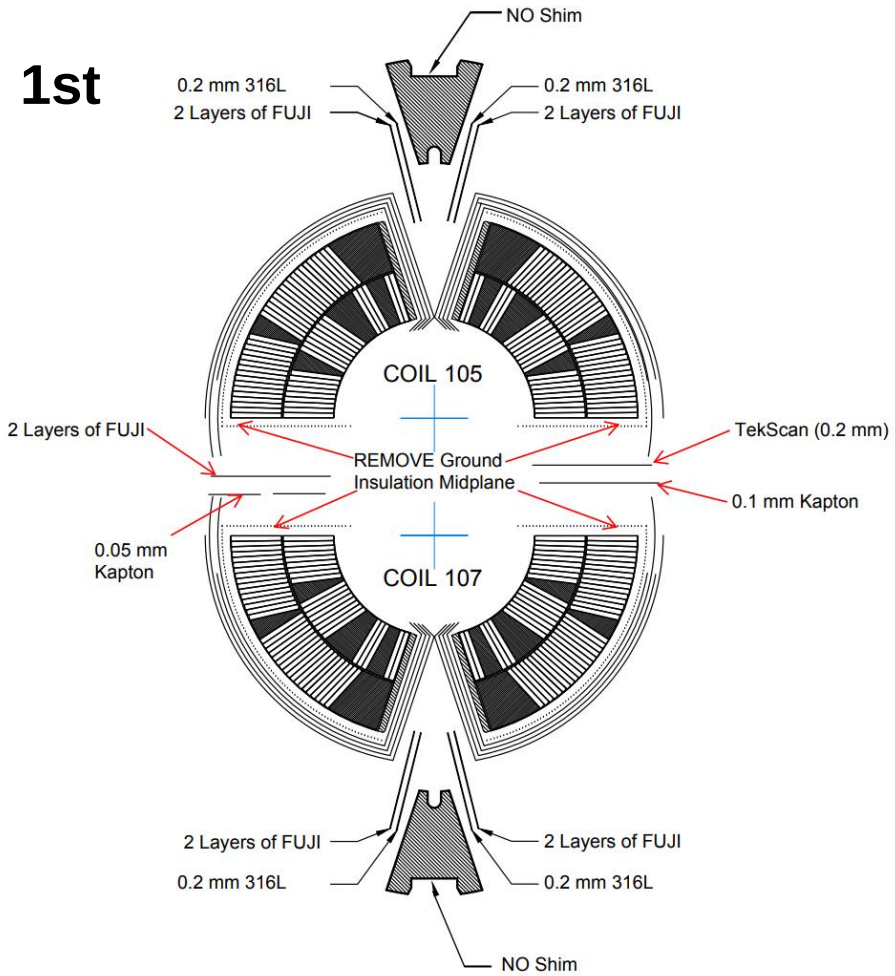
- Different scenarios considered



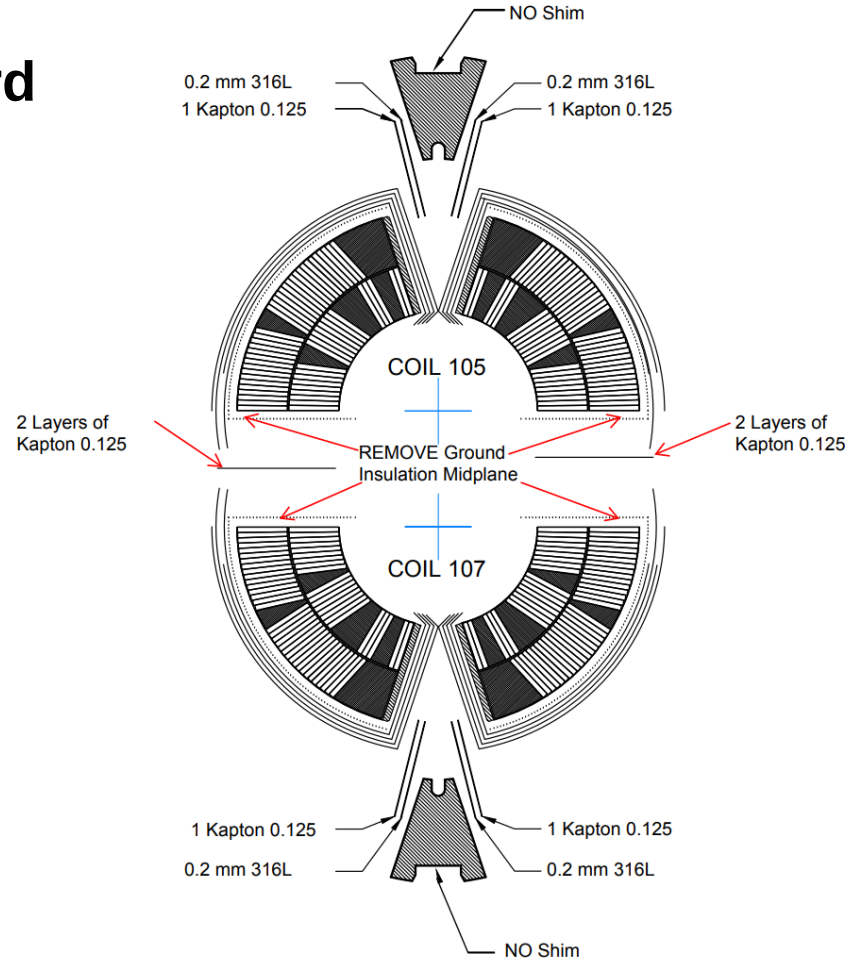


Preliminary results from mock-up

1st

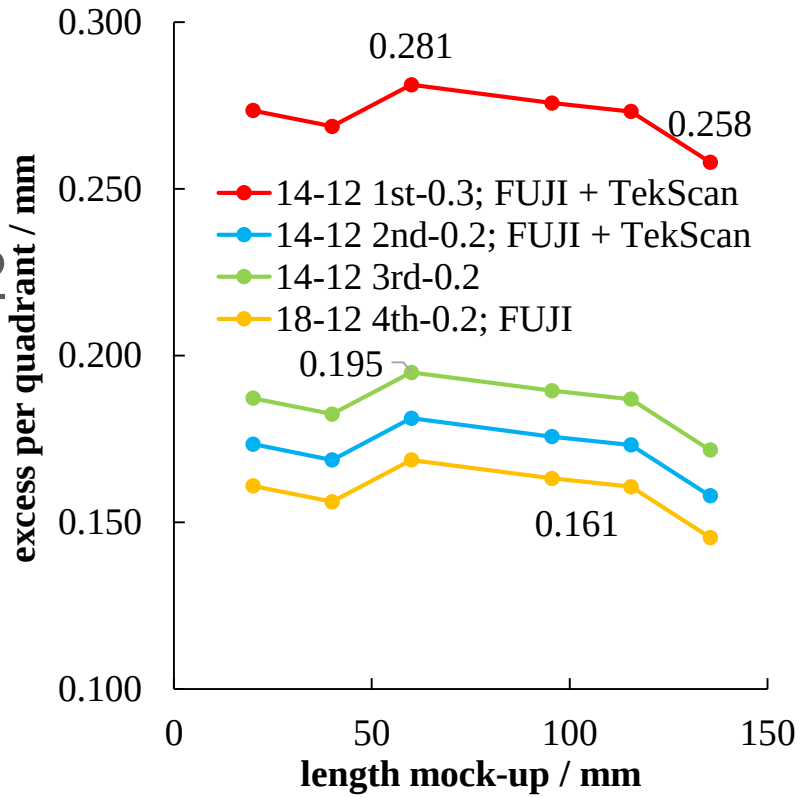


3rd



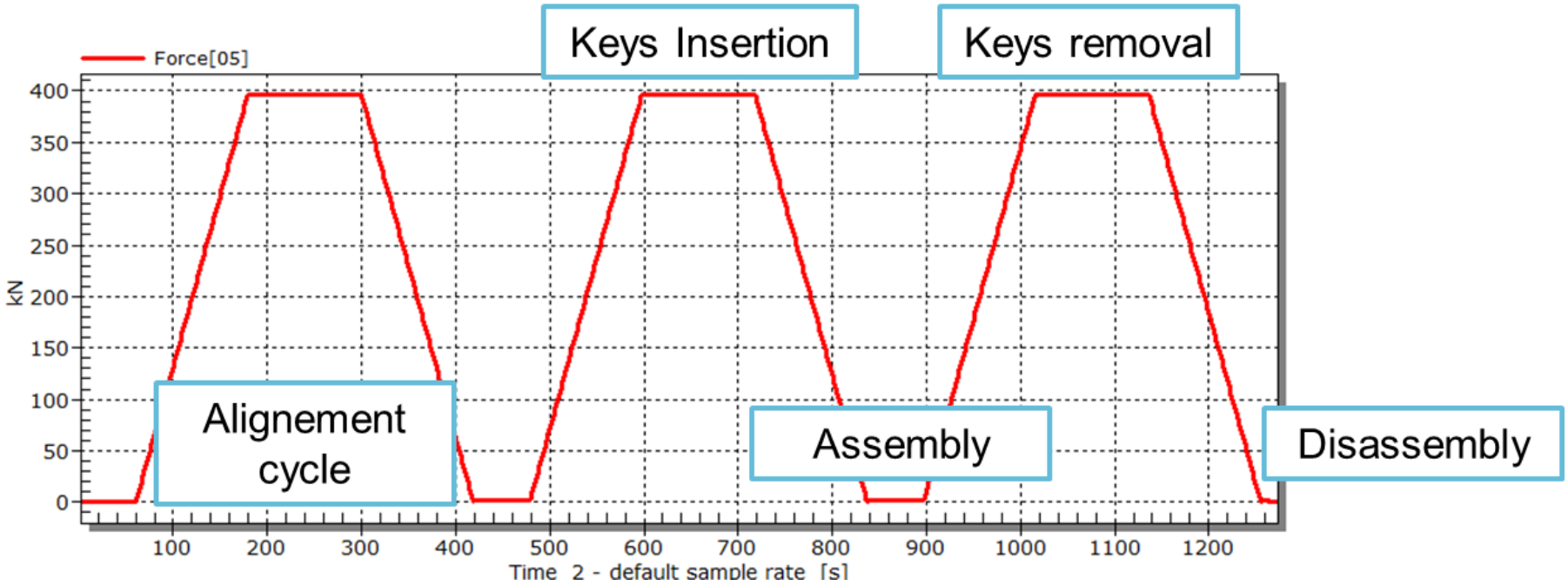
Preliminary results from mock-up

- On the 14th and 18th of December four different shimming's were performed
- Per quadrant: 0.3 and 0.2 mm excess
- NO mechanical stoppers
- It was not possible to collar the 1st excess with 400 kN
  - 44 MPa mid-plane average



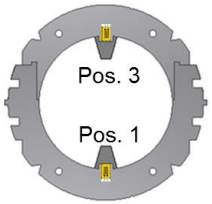
Preliminary results from mock-up

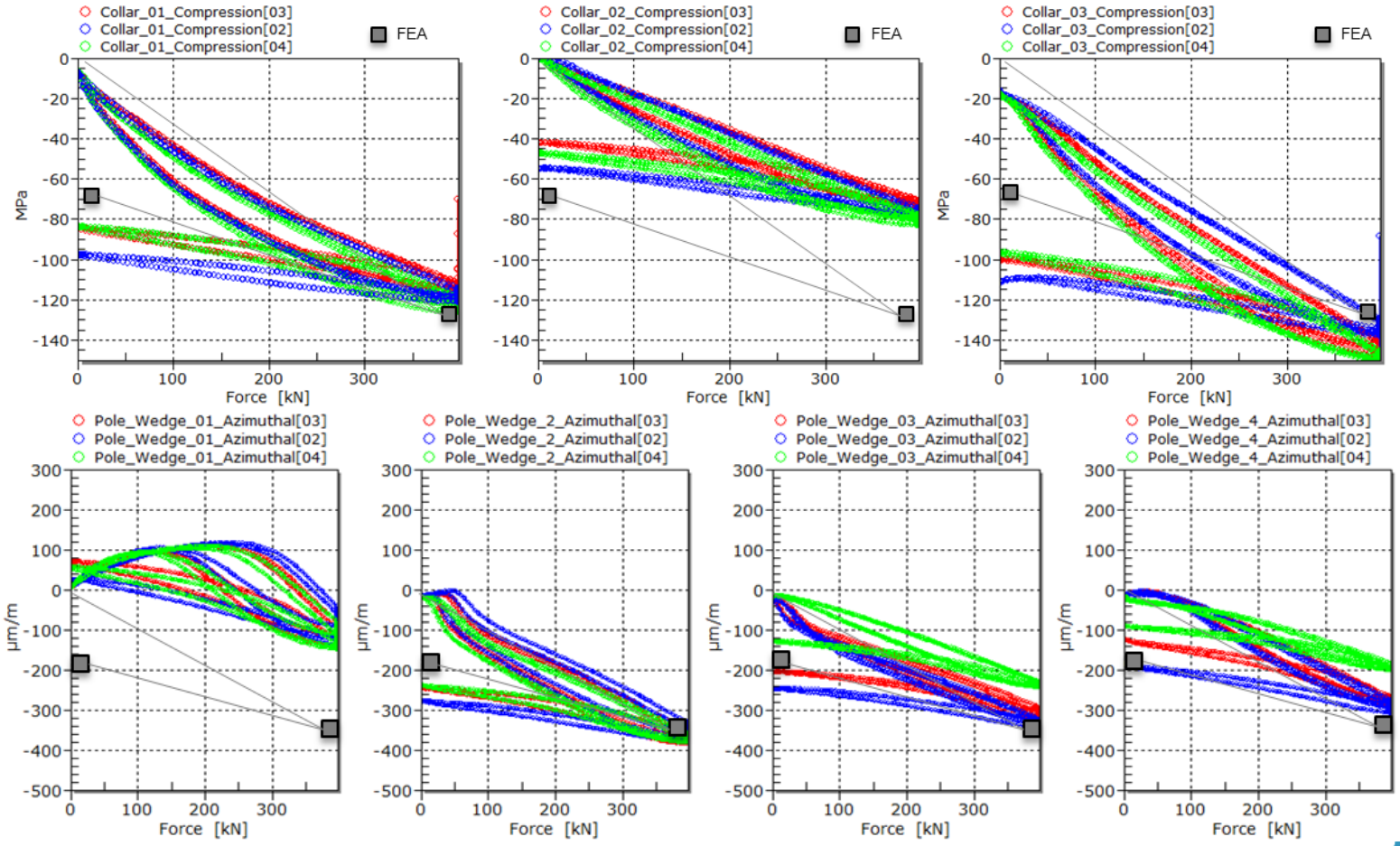
- Test protocol

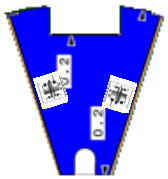


Preliminary results from mock-up

- Reproducibility and in 5 out of 7 consistency with FEM

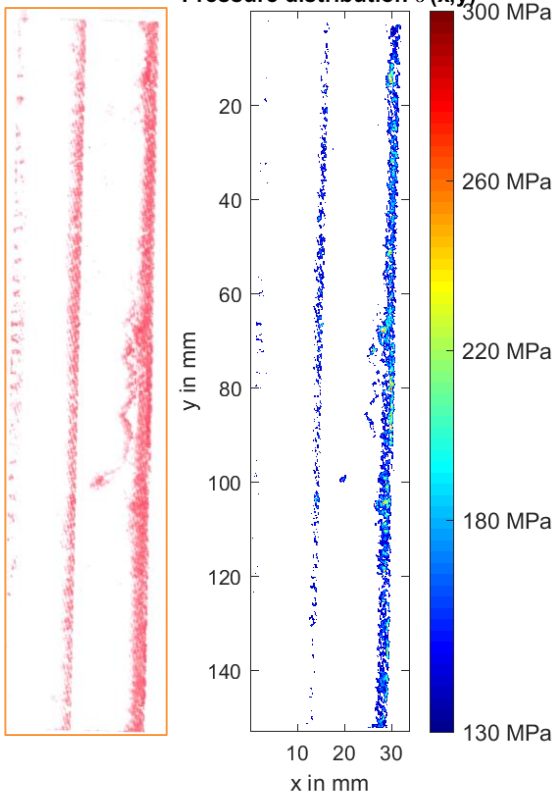


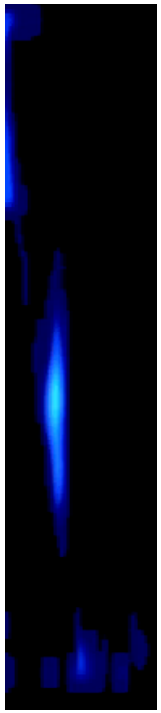


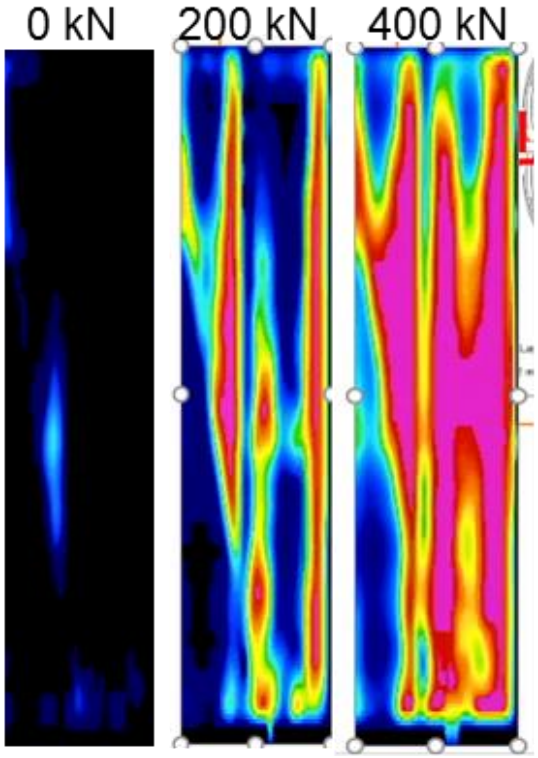


Preliminary results from mock-up

- Fuji vs. Tekscan results

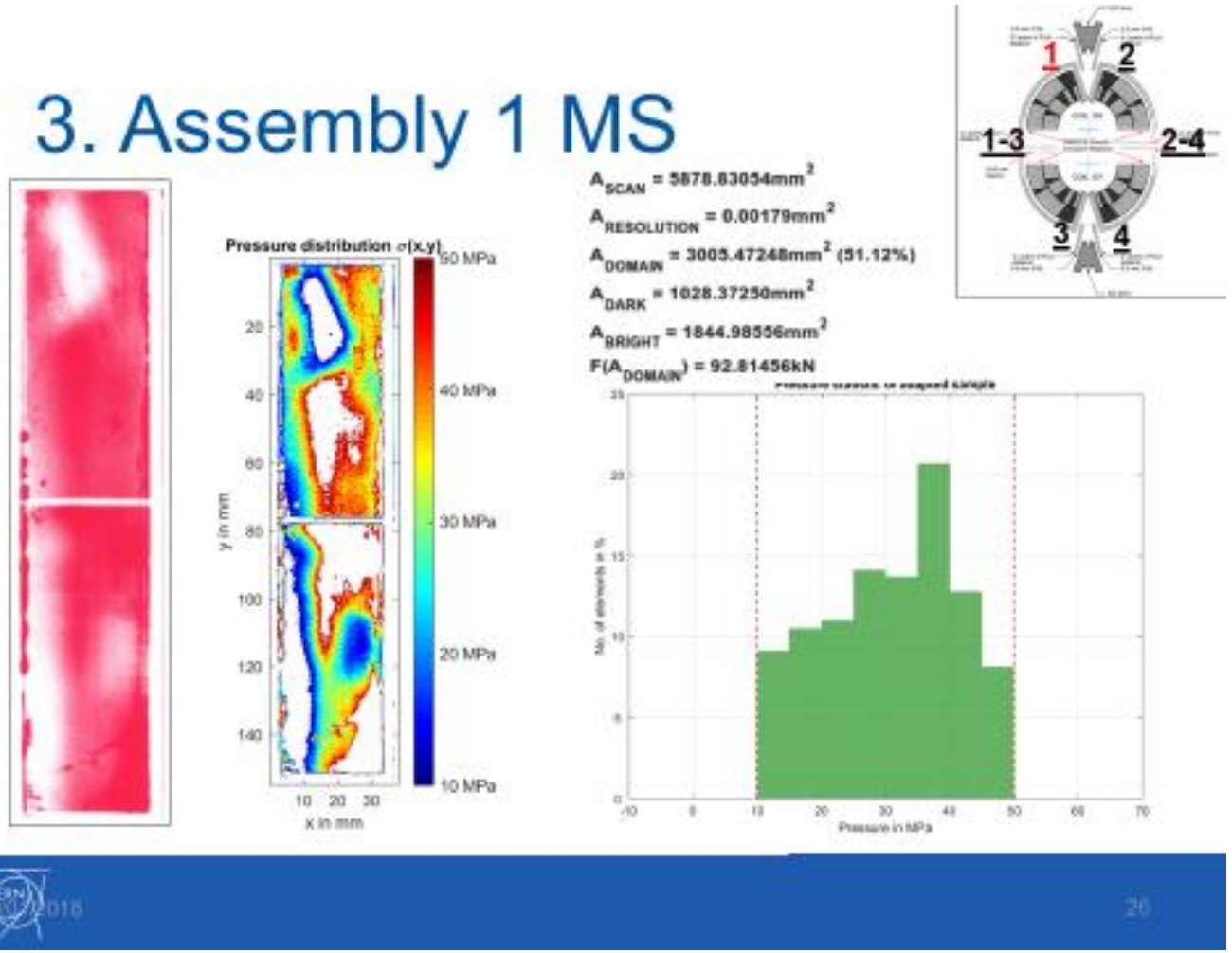






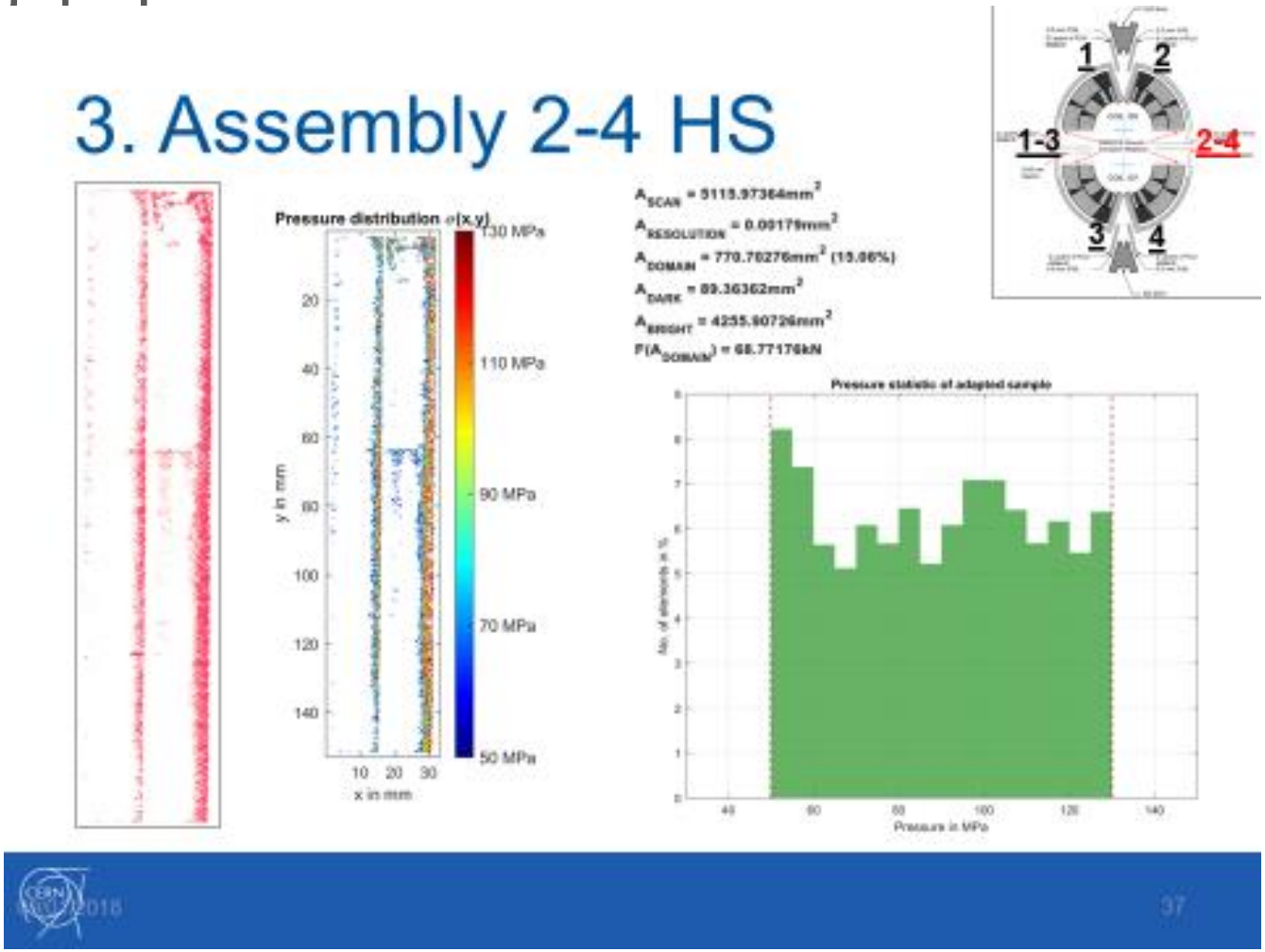
Preliminary results from mock-up

- Fuji paper



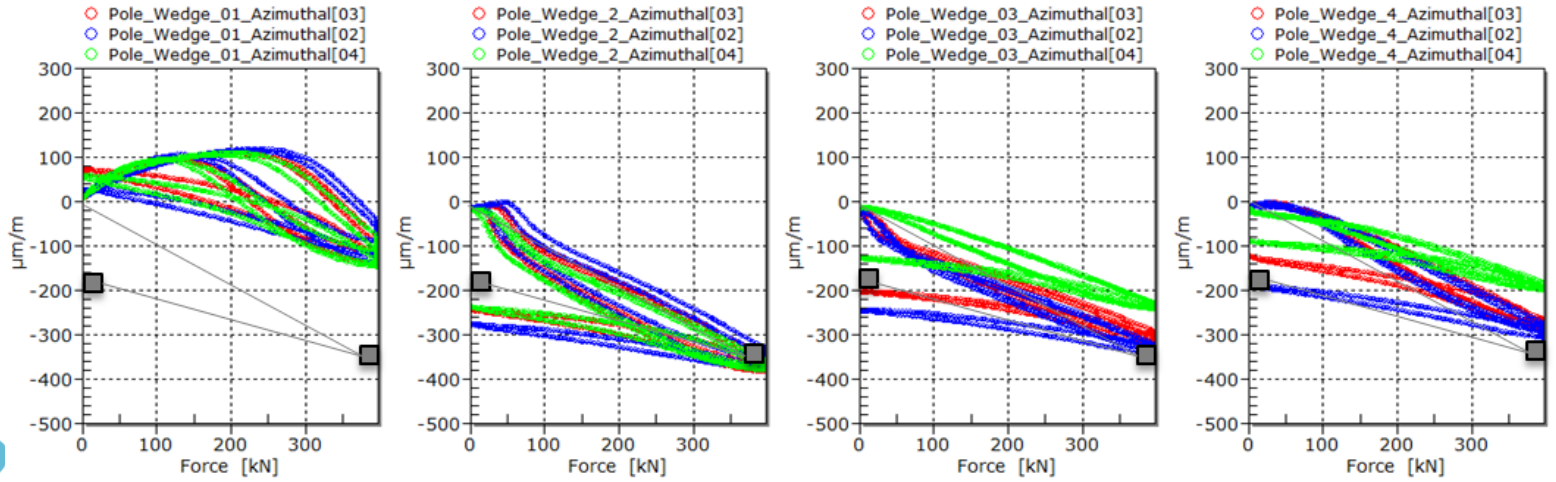
Preliminary results from mock-up

- Fuji paper



Preliminary results from mock-up

- Fuji paper conclusions
  - On the mid-plane
    - 60-70% of the area > 10 MPa
    - 20-30% of the area > 50 MPa
    - 5% of the area > 130 MPa
      - So it looks like the amplification factor is more than 2 (average is 44 MPa)
  - On the pole
    - 80% of the area > 10 MPa and less than 50 MPa
    - 20% of the area > 10 MPa
      - It looks relatively uniform, close to the analytical value and not far from the strain gauges (300 microstrain * 120 GPa = 40 Mpa)



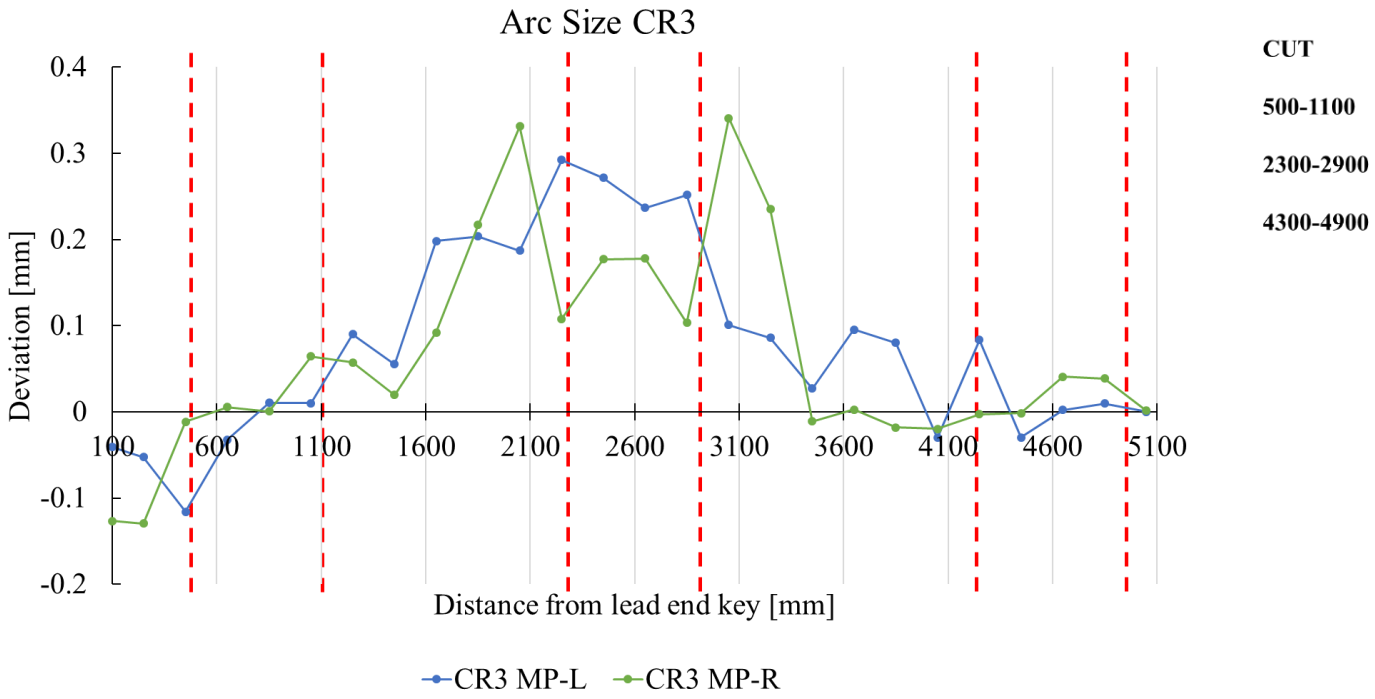
Plan: step 1
January – early February 2018

- Mechanical lab
  - Friction coefficient effects on the pole wedge
  - Low excess coil tests (0.1, 0.05 per quadrant)
  - Coils swap
  - Aluminum dummy coil tests
  - Thermal cycle at 77K
- 927
  - Reproducibility tests
  - High excess coils tests (0.3, 0.4, 0.5 per quadrant)

- Regarding Fuji paper test
  - MS+HS on the pole
  - MS+HS+HSS on the mid-plane
    - We may have to compensate the additional thickness on the mid-plane to keep the same excess

Plan: step 2
February – April 2018

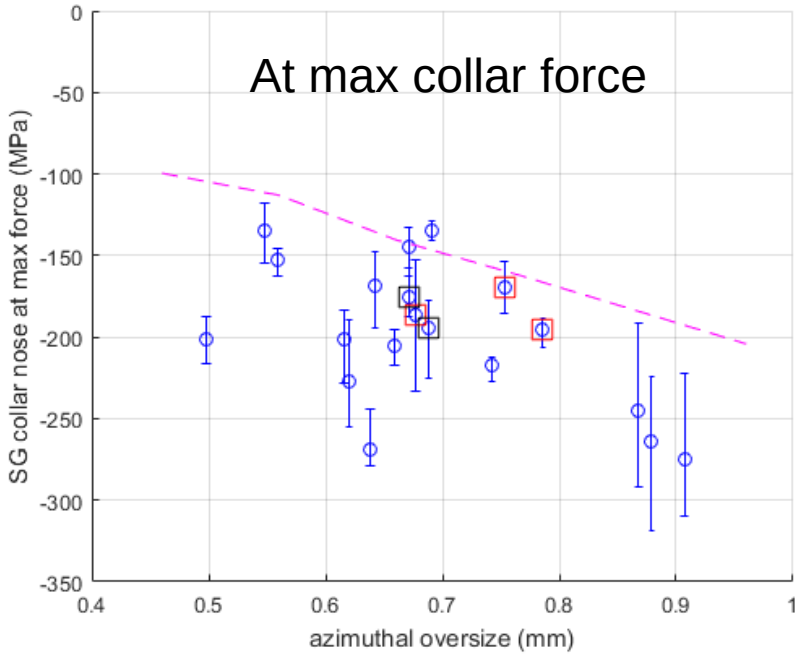
- Cut 6 sections from prototype coil CR03 in order to perform 3 collaring tests
  - In each segment, 2 sections for collaring and 1 for coil measurements → 150+150+300 mm

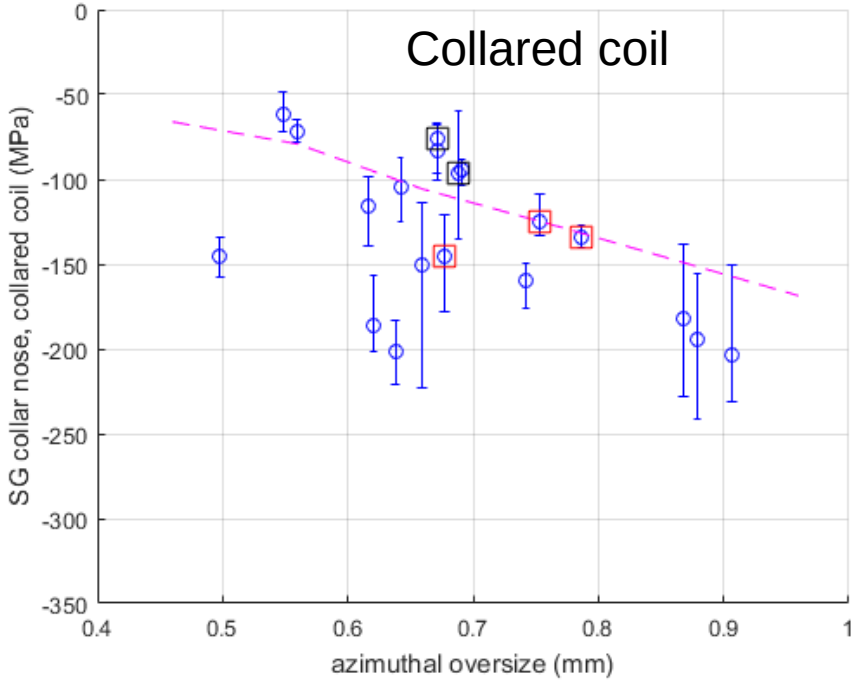


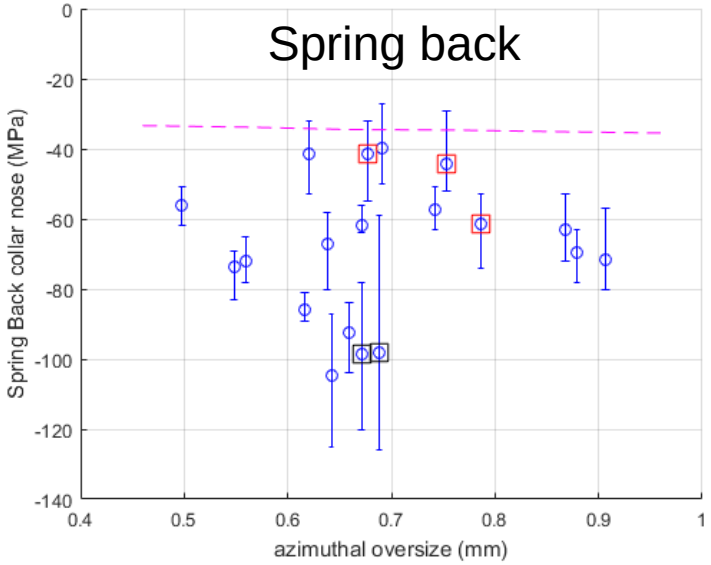
Plan: step 3
May – June 2018

- 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

Plot collaring - assemblies coil 109 diff color

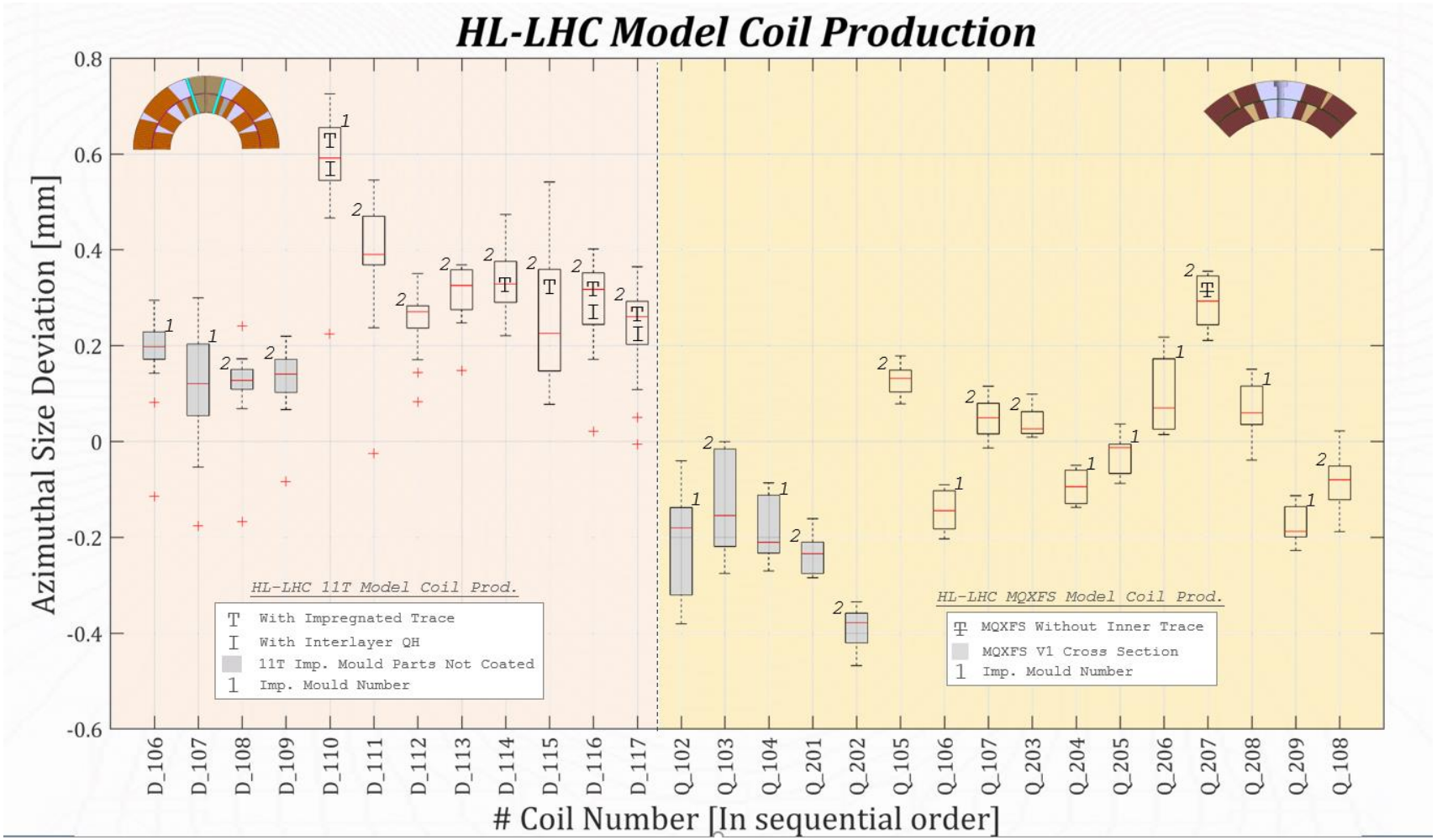






Black square: CC104b

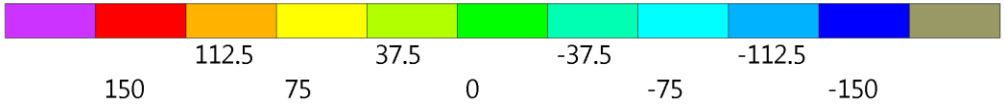
Red square: CC103

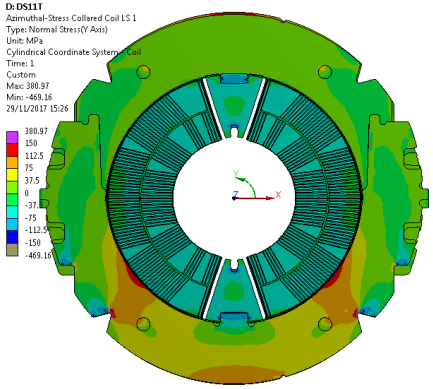

HL-LHC Model Coil Production
Azimuthal Size Deviation [mm]
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
HL-LHC 11T Model Coil Prod.
With Impregnated Trace
With Interlayer QH
11T Imp. Mould Parts Not Coated
Imp. Mould Number
HL-LHC MQXFS Model Coil Prod.
MQXFS Without Inner Trace
MQXFS V1 Cross Section
Imp. Mould 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]

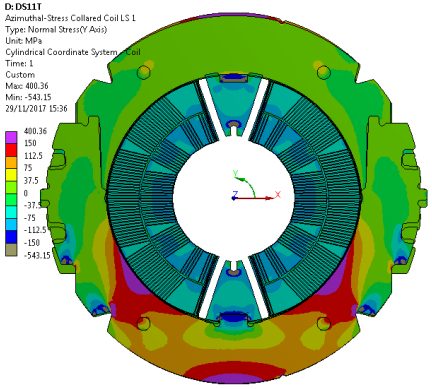
LS1 – collaring
LS2 – collared coil
LS3 – shell welding
LS4 – 1.9 K
LS5 – 12T

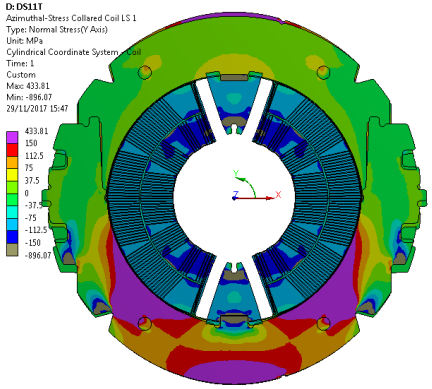
Azimuthal-Stress LS1

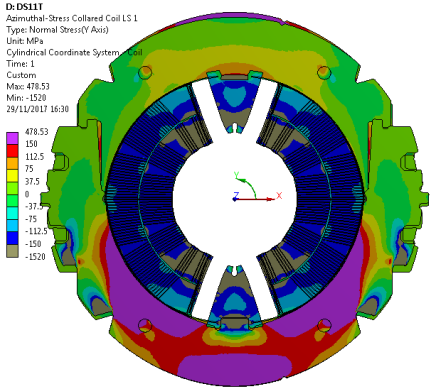
X.X lateral pole shim
0.0 collared coil shim











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

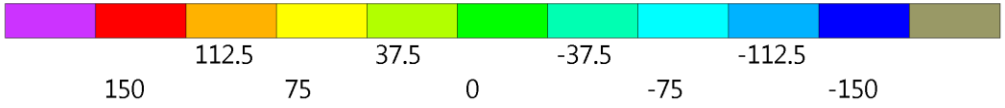
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**29**	**45**	**62**	**77**
EQV-Mid Min.	28	44	59	74
EQV-Mid Max.	61	80	101	121
Hoop-Mid AV.	**-44**	**-70**	**-98**	**-123**
Hoop-Mid Min.	-69	-91	-117	-147
Hoop-Mid Max.	-45	-70	-98	-119

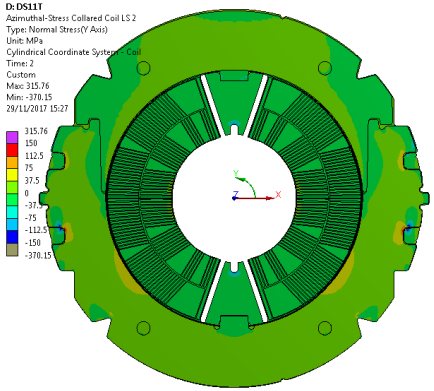
Scaling x25

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

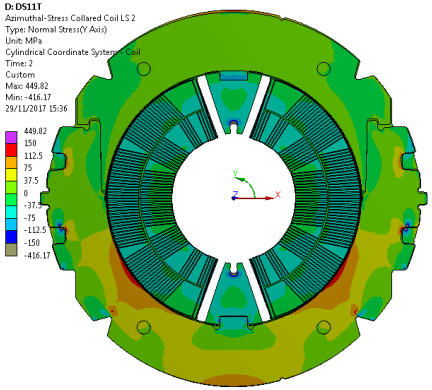
Azimuthal-Stress LS2

X.X lateral pole shim
0.0 collared coil shim

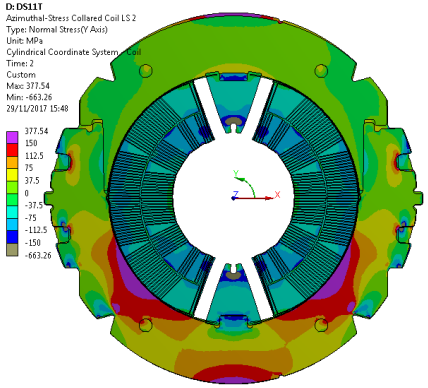




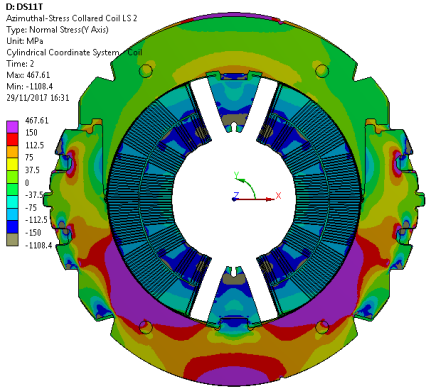
0.2 mm arc excess



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

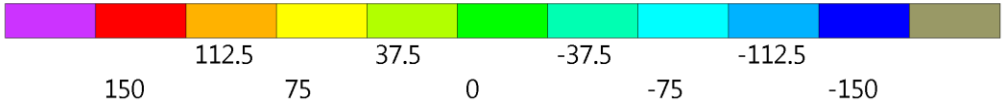
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**12**	**24**	**40**	**54**
EQV-Mid Min.	4	5	7	14
EQV-Mid Max.	61	69	53	56
Hoop-Mid AV.	**-17**	**-40**	**-68**	**-93**
Hoop-Mid Min.	-20	-44	-73	-101
Hoop-Mid Max.	34	32	10	-6

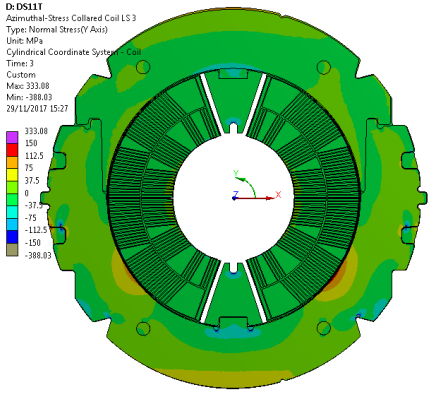
Scaling x25

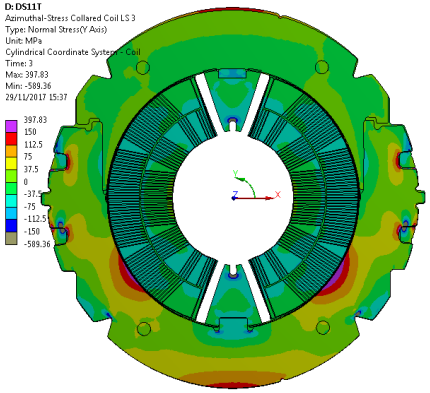
LS1 – collaring
LS2 – collared coil
LS3 – shell welding
LS4 – 1.9 K
LS5 – 12T

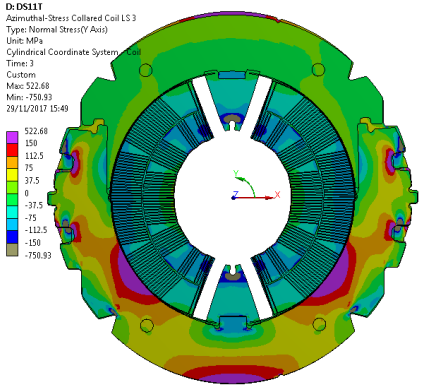
Azimuthal-Stress LS3

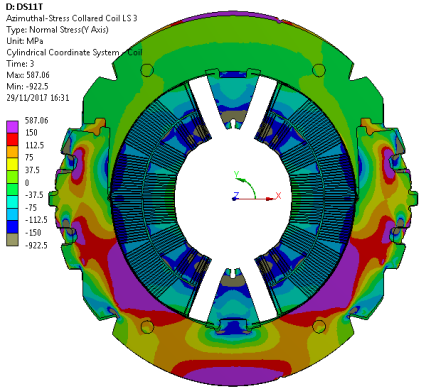
X.X lateral pole shim
0.0 collared coil shim











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

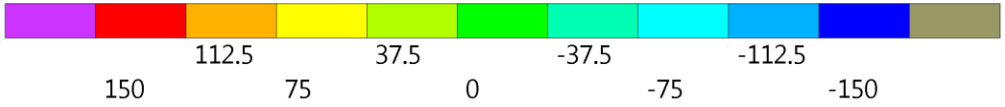
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**16**	**26**	**39**	**53**
EQV-Mid Min.	5	6	7	8
EQV-Mid Max.	61	81	103	123
Hoop-Mid AV.	**-18**	**-40**	**-64**	**-88**
Hoop-Mid Min.	-21	-43	-69	-95
Hoop-Mid Max.	34	46	60	73

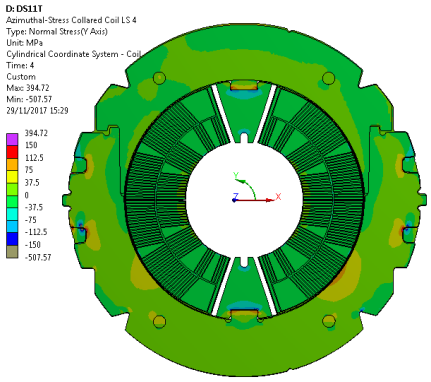
Scaling x25

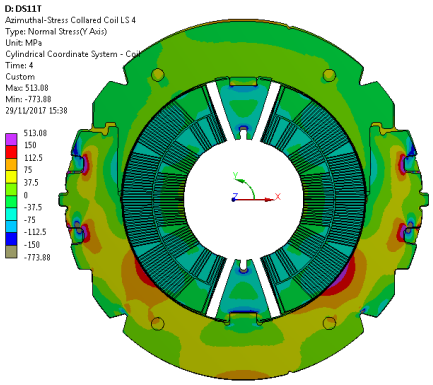
LS1 – collaring
LS2 – collared coil
LS3 – shell welding
LS4 – 1.9 K
LS5 – 12T

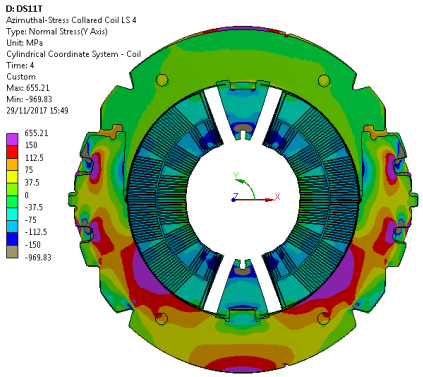
Azimuthal-Stress LS4

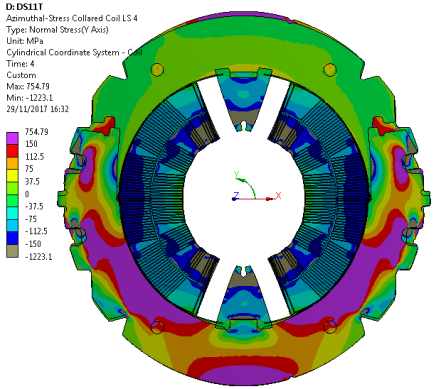
X.X lateral pole shim
0.0 collared coil shim











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

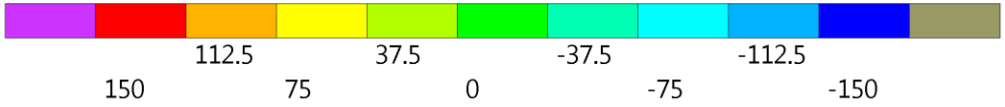
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**22**	**34**	**49**	**66**
EQV-Mid Min.	4	5	2	1
EQV-Mid Max.	62	84	106	128
Hoop-Mid AV.	**-16**	**-39**	**-67**	**-96**
Hoop-Mid Min.	-25	-52	-81	-112
Hoop-Mid Max.	50	66	83	100

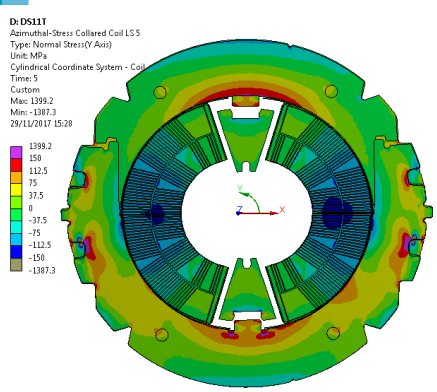
Scaling x25

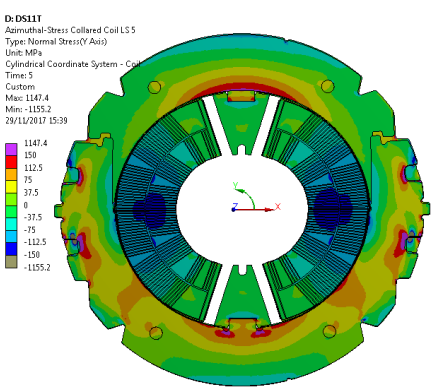
LS1 – collaring
LS2 – collared coil
LS3 – shell welding
LS4 – 1.9 K
LS5 – 12T

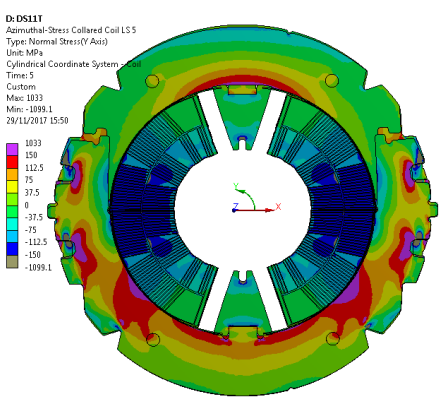
Azimuthal-Stress LS5

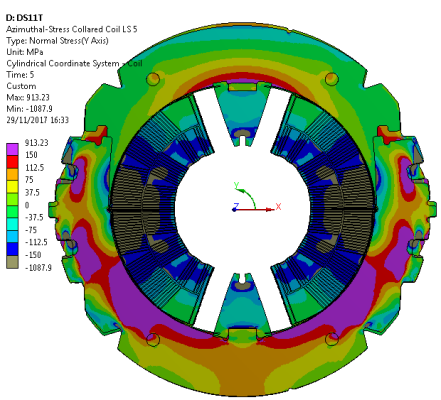
X.X lateral pole shim
0.0 collared coil shim











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

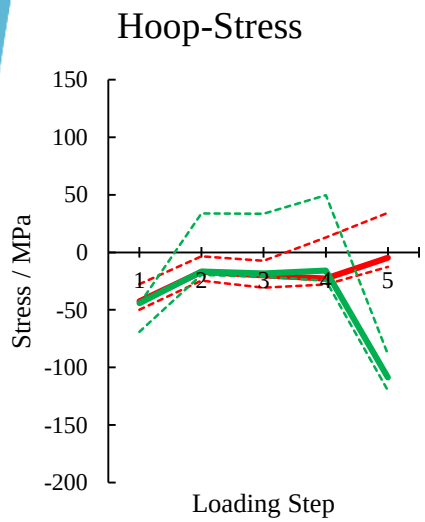
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**41**	**50**	**64**	**80**
EQV-Mid Min.	35	36	41	49
EQV-Mid Max.	92	98	101	94
Hoop-Mid AV.	**-109**	**-114**	**-138**	**-167**
Hoop-Mid Min.	-120	-125	-149	-179
Hoop-Mid Max.	-89	-94	-88	-69

Scaling x25

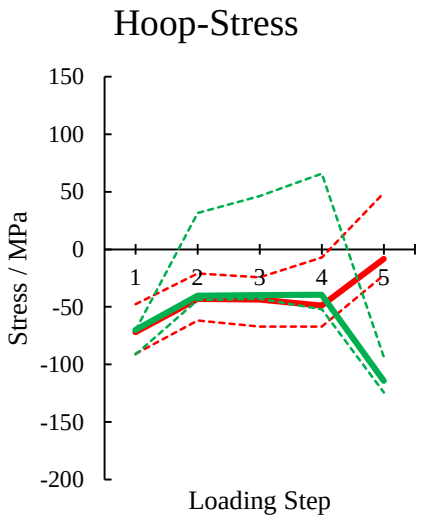
Azimuthal-Stress

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

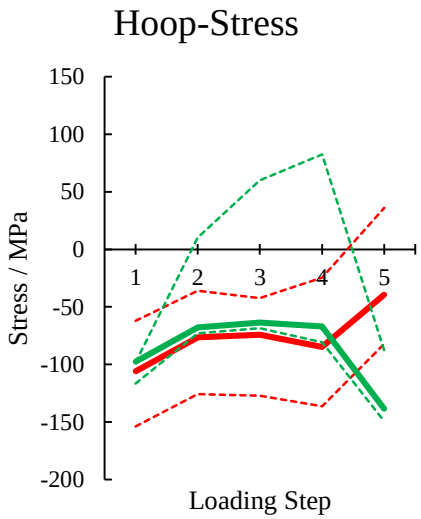
X.X lateral pole shim
0.0 collared coil shim



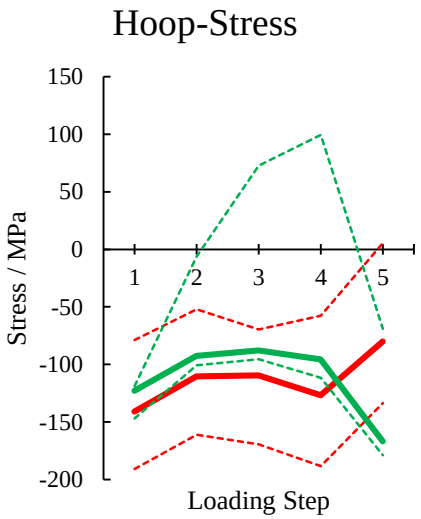
0.2 mm arc excess



0.4 mm arc excess



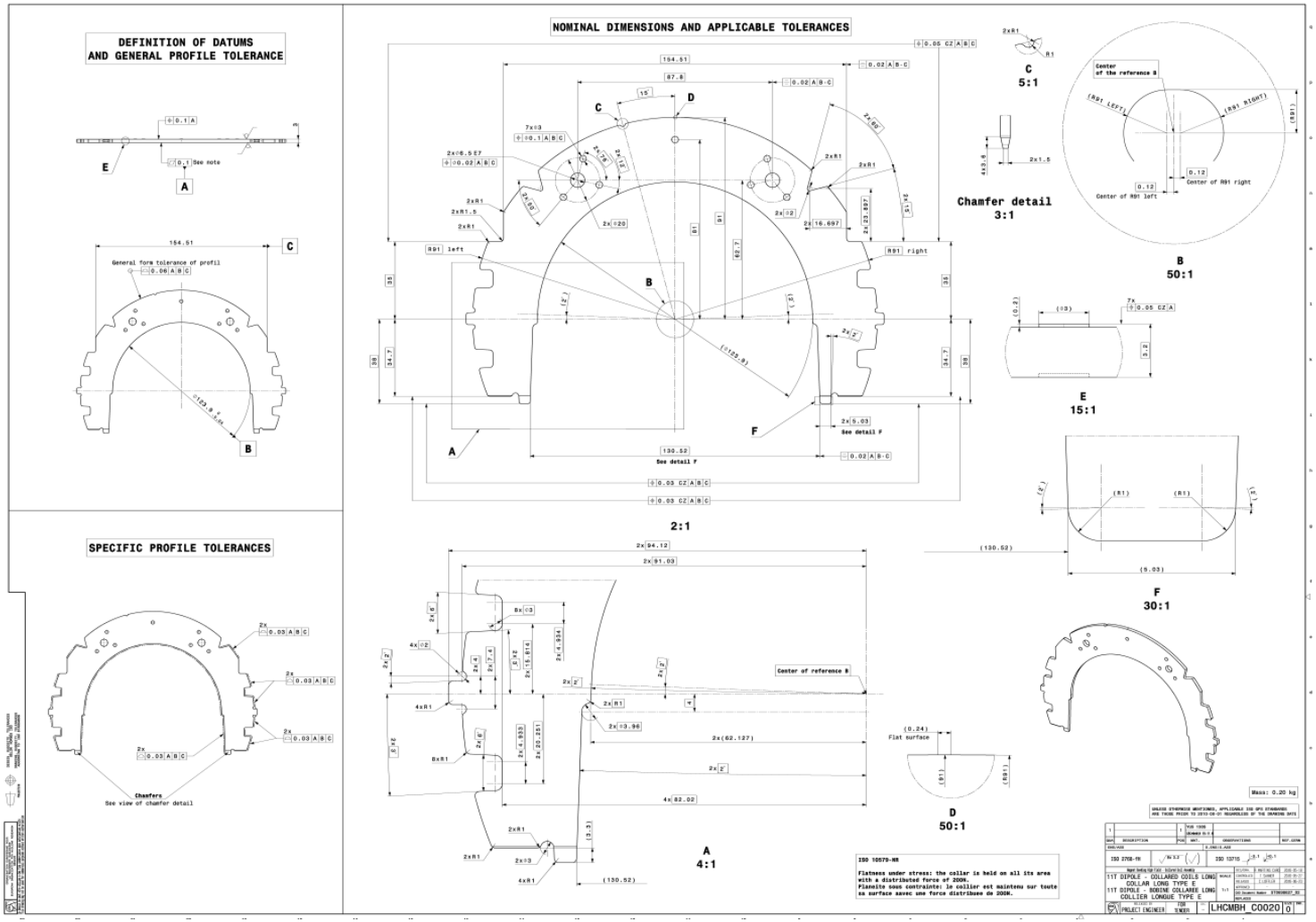
0.6 mm arc excess



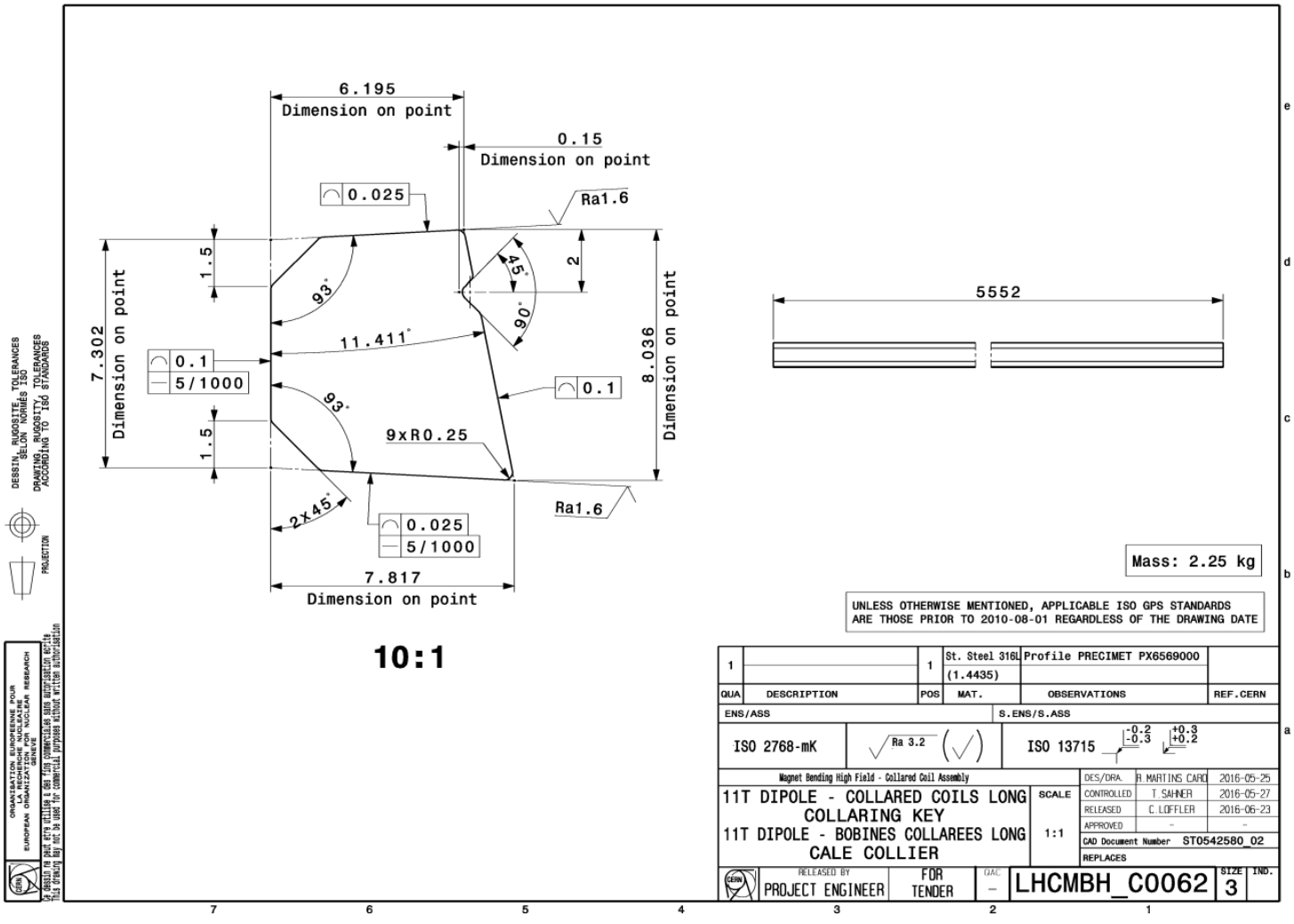
0.8 mm arc excess

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

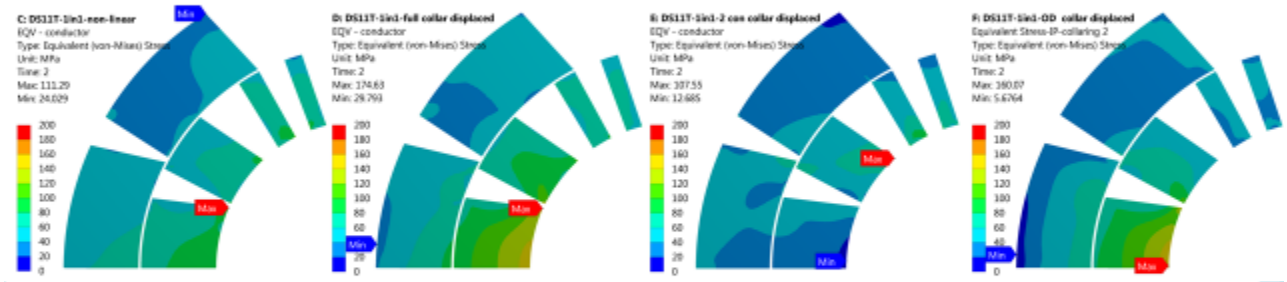
Analysis of collaring



Analysis of collaring



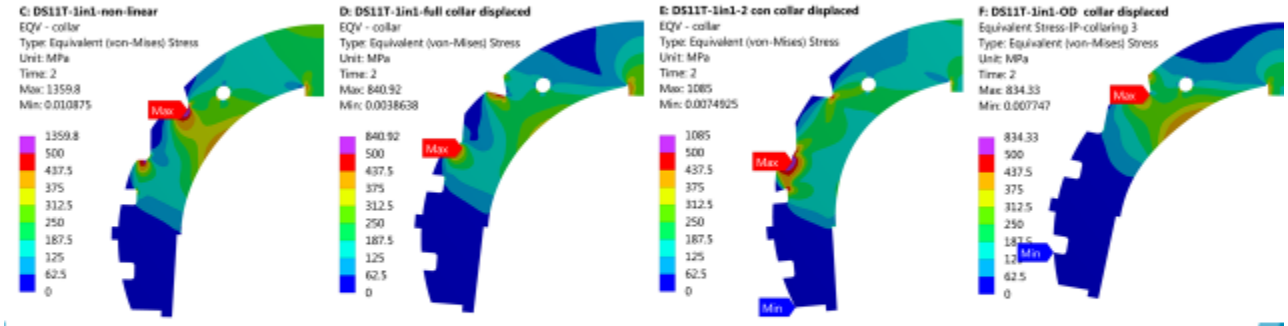
Collaring comparison-
EQV Stress during collaring - conductor



Current Alternate 2-contact OD

5

Collaring comparison-
EQV Stress during collaring - collars



Current
4 contacts per collar

Alternate

2-contact

OD

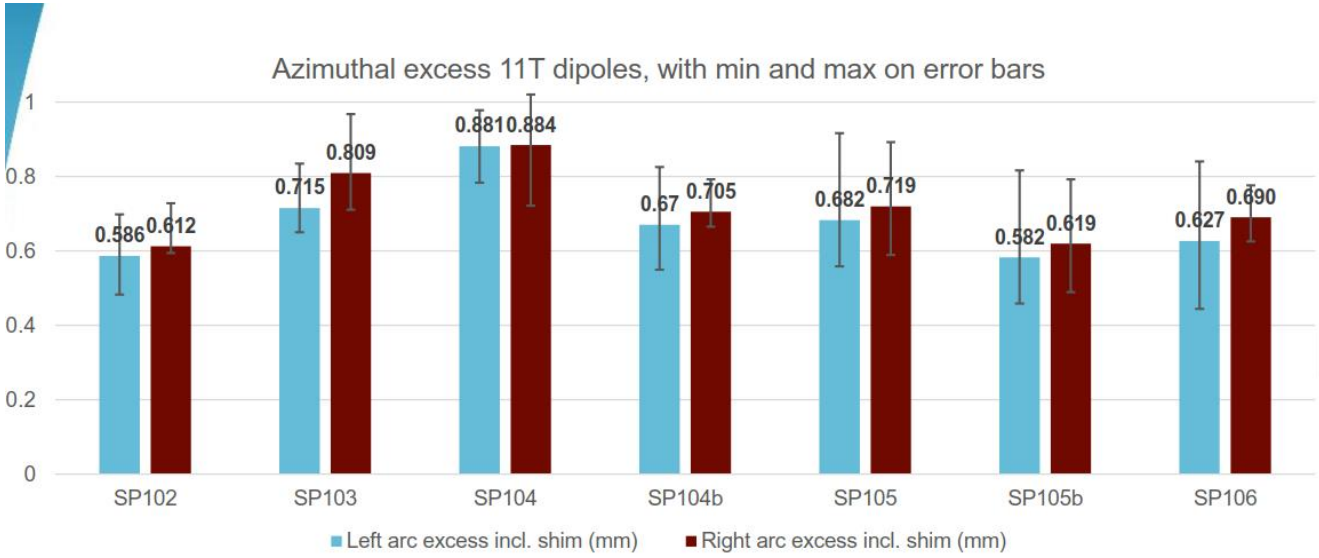
Deformation x50

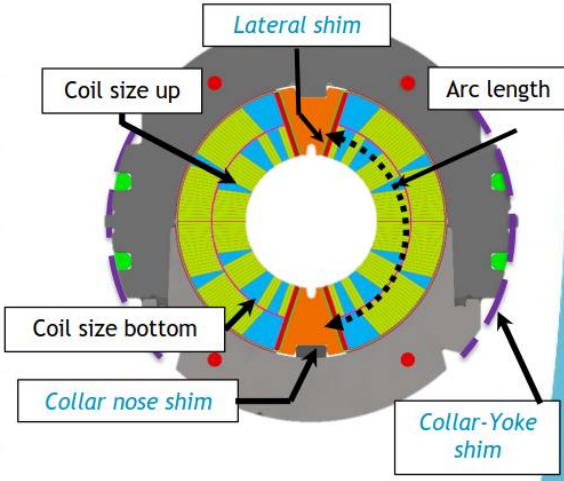
Fuji paper surface data

- The total area is 4600 mm2
- The Ascan is larger because it includes the part at the edges
- The Adomain is the area where we have signal
- The Adark is the area where we have saturation (above max)
- The Abright is the area where we are below min

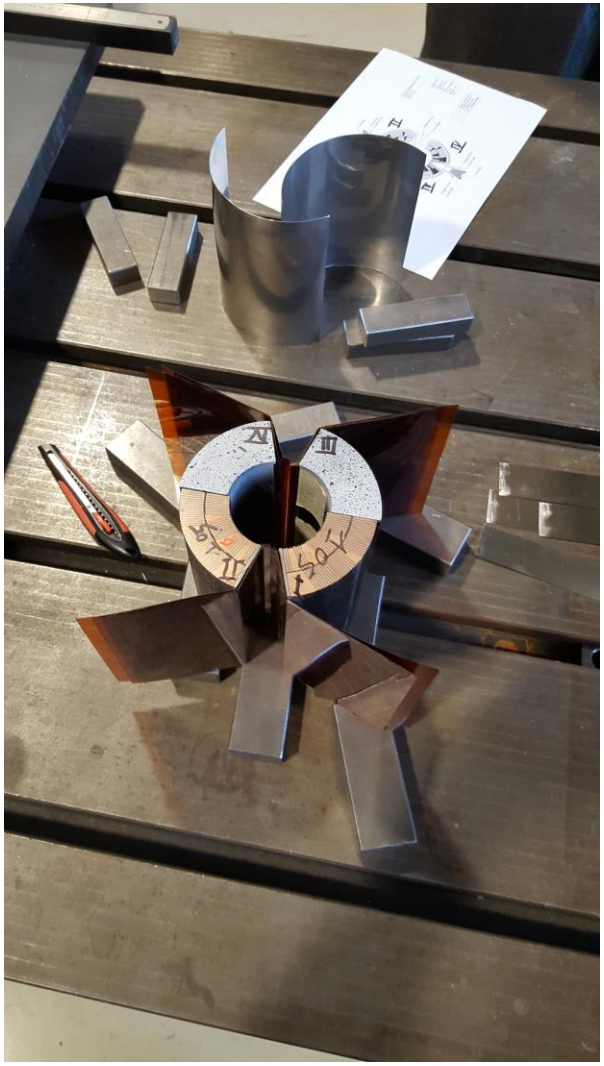
- The average peak stress should be 44 MPa

Excess per half

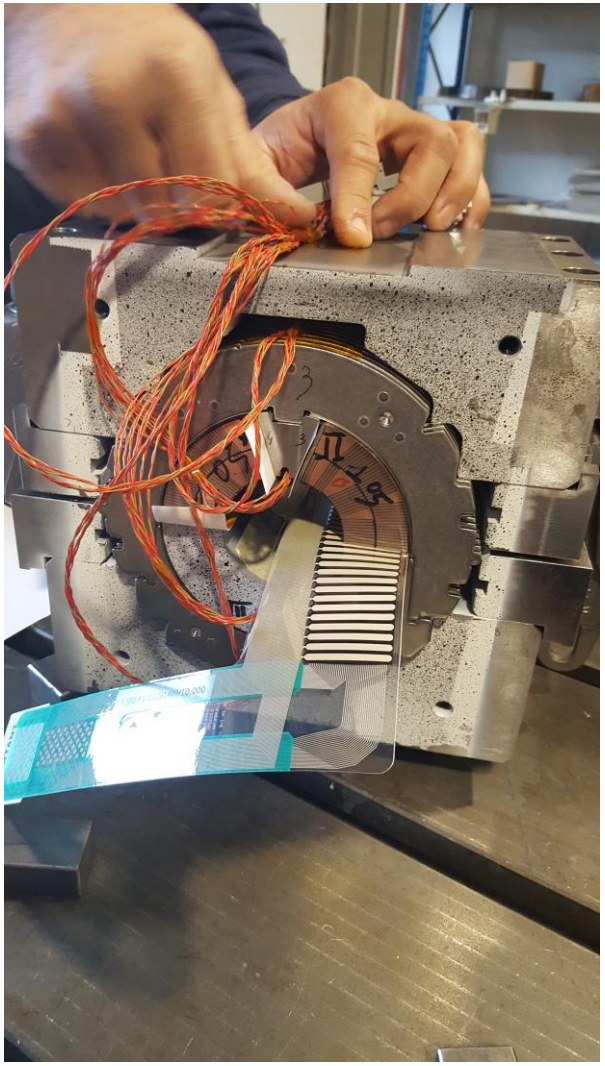


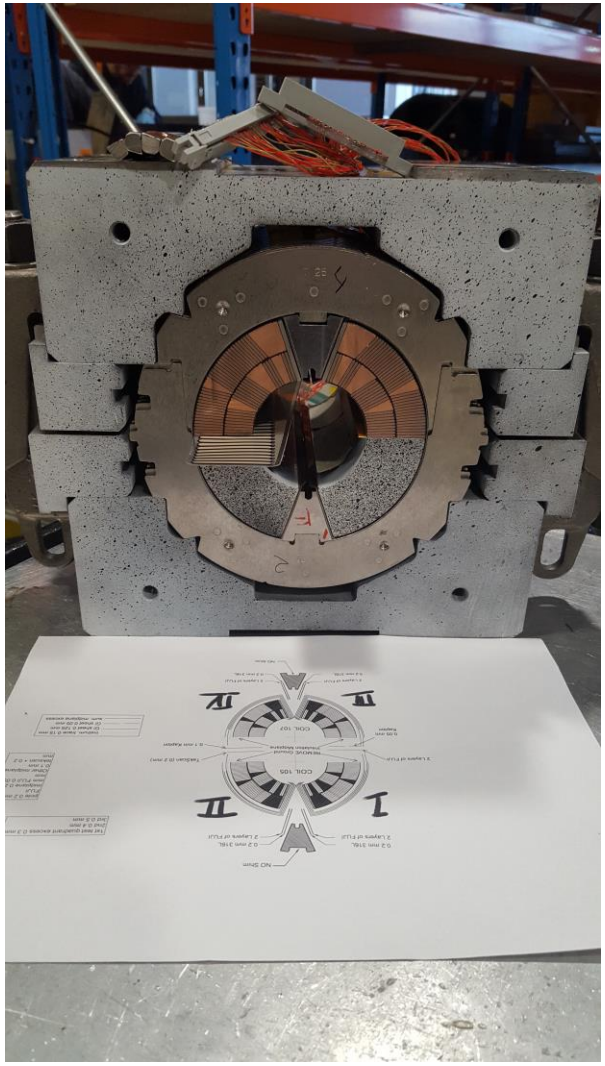


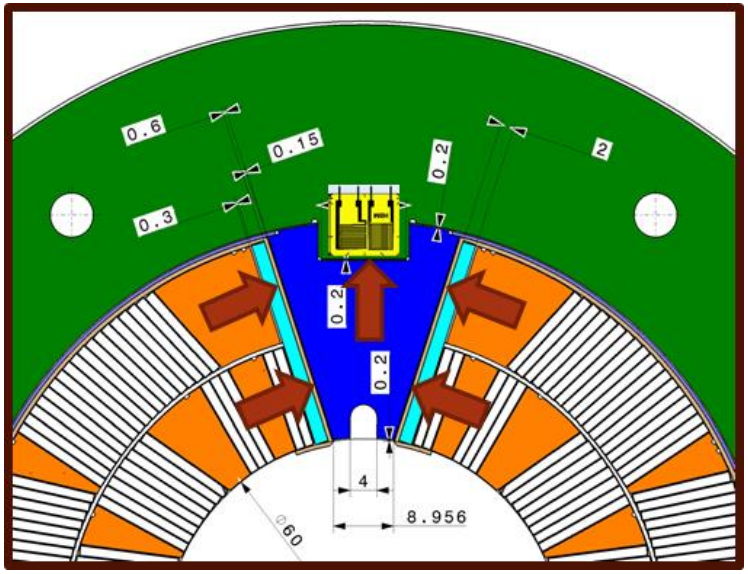
Collaring mock-up step 1

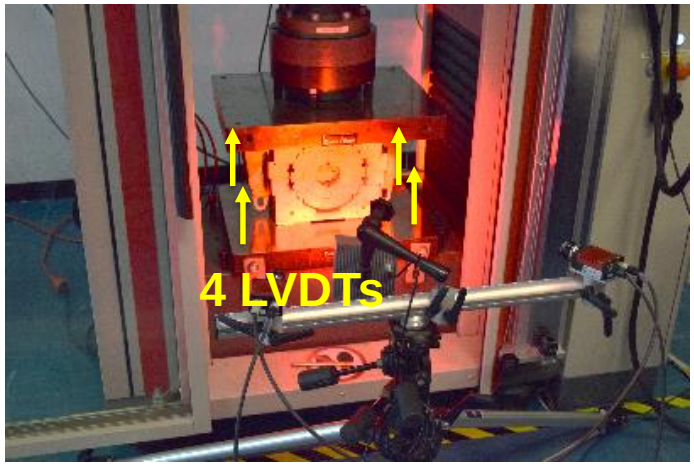


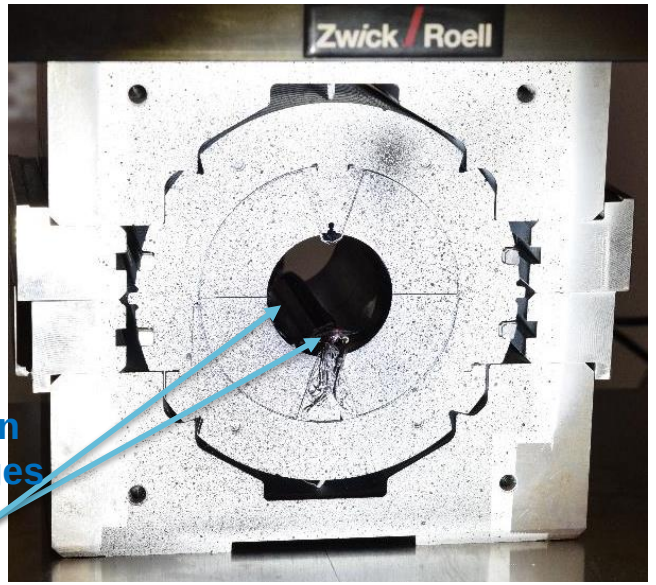
Collaring mock-up step 1






0.6
0.15
0.2
2
0.3
0.2
0.2
4
8.956
Ø60


4 LVDTs


Zwick / Roell
Strain gauges