Collaring kinematics, mechanics, instrumentation, and mock-ups

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11T Dipole Collaring Task Force Meeting
21 February 2018
CERN

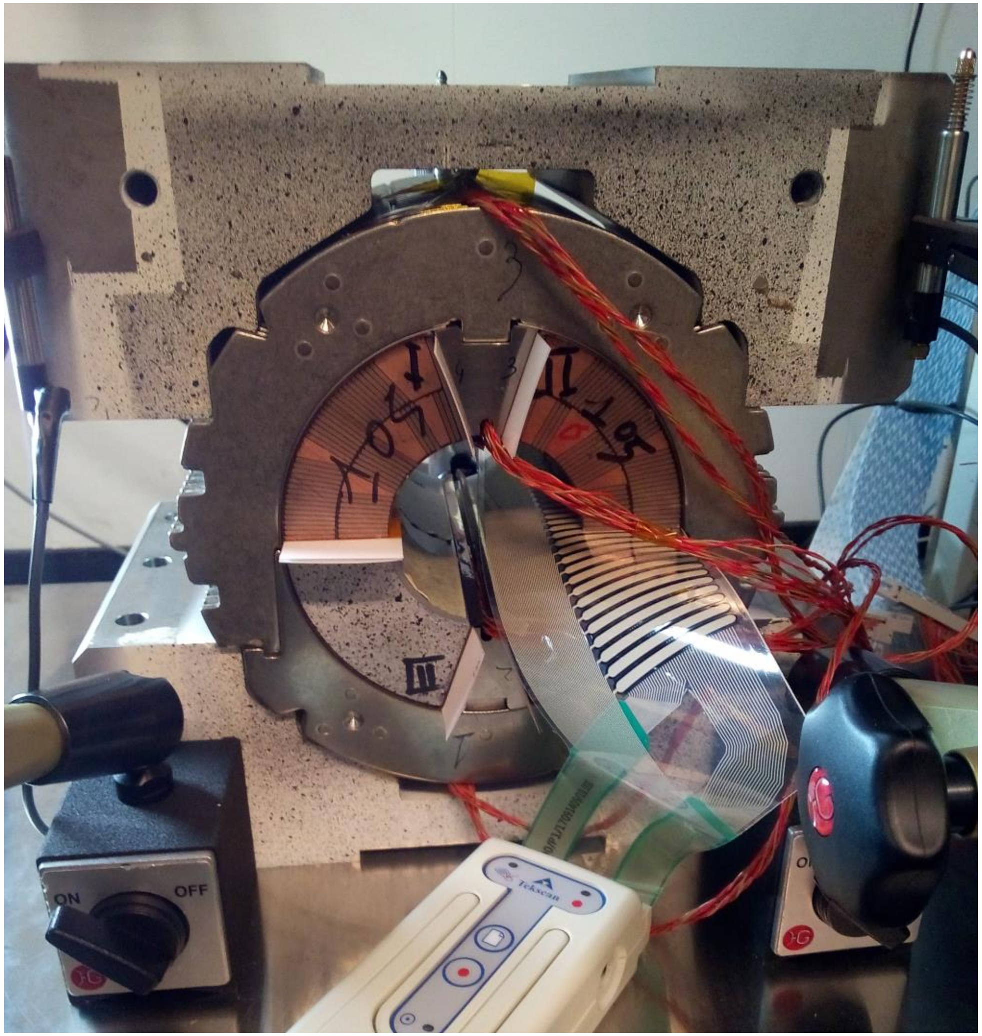
Aknowledgments

- 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

Plan: step 1
February 2018

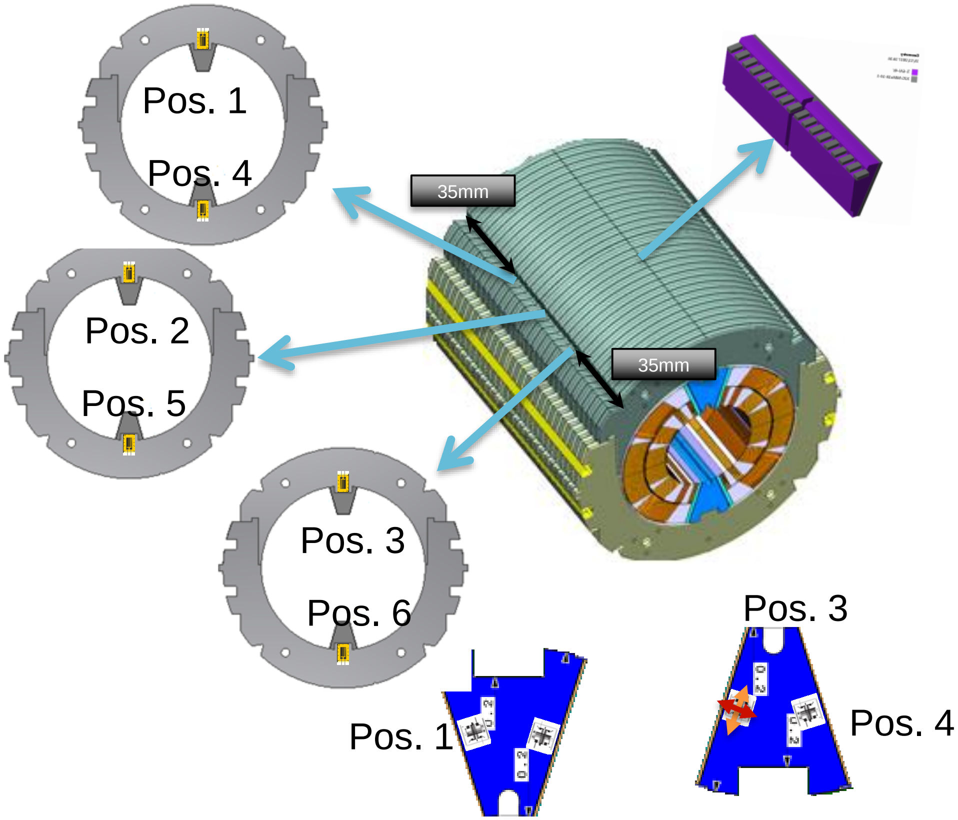
- Status
  - Test with aluminum coils
    - Loading with 0.150, 0100, 0.050 mm excess
    - Analysis data taken with digital image correlation
  - CR03
    - First segment and spare segments dimensions measured
  - 927 collaring press
    - “Recommissioning” in progress

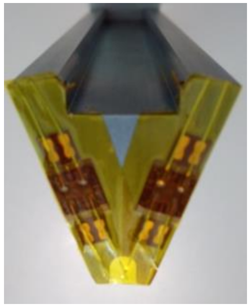
Collaring mock-up

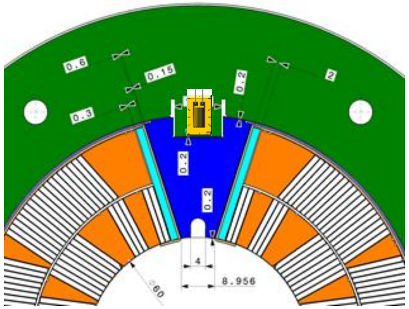


Status of instrumentation
From January 2018

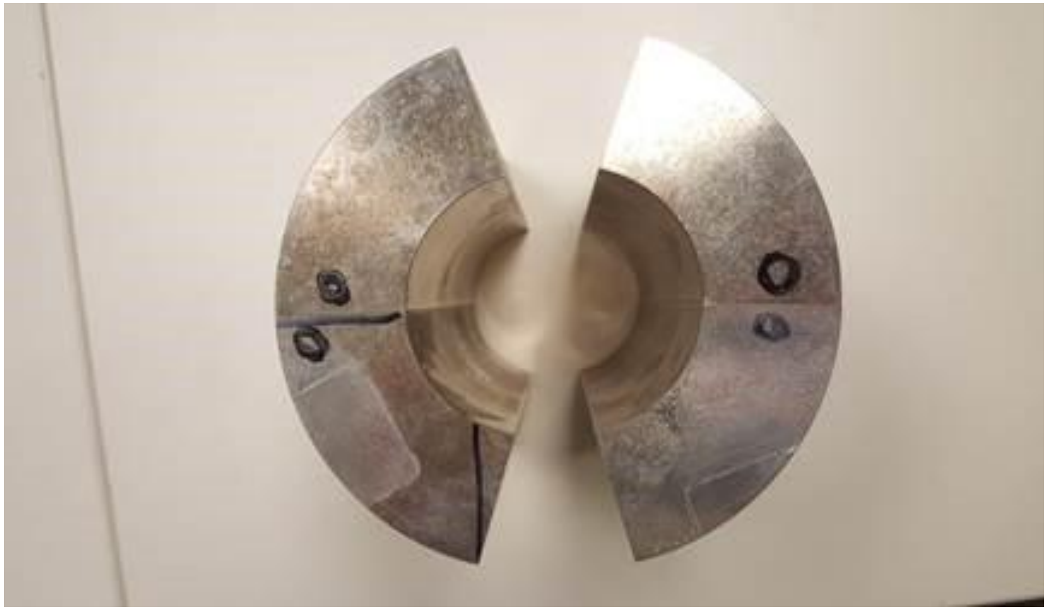
- Both side of the 6 collars equipped with strain gauges in half-bridge configuration (Production)
- Bending and compression stress measurements for collars
- Slits with a gap of 500 µm between nose and pole
- Pole wedges equipped with biaxial strain gauges and angel wires





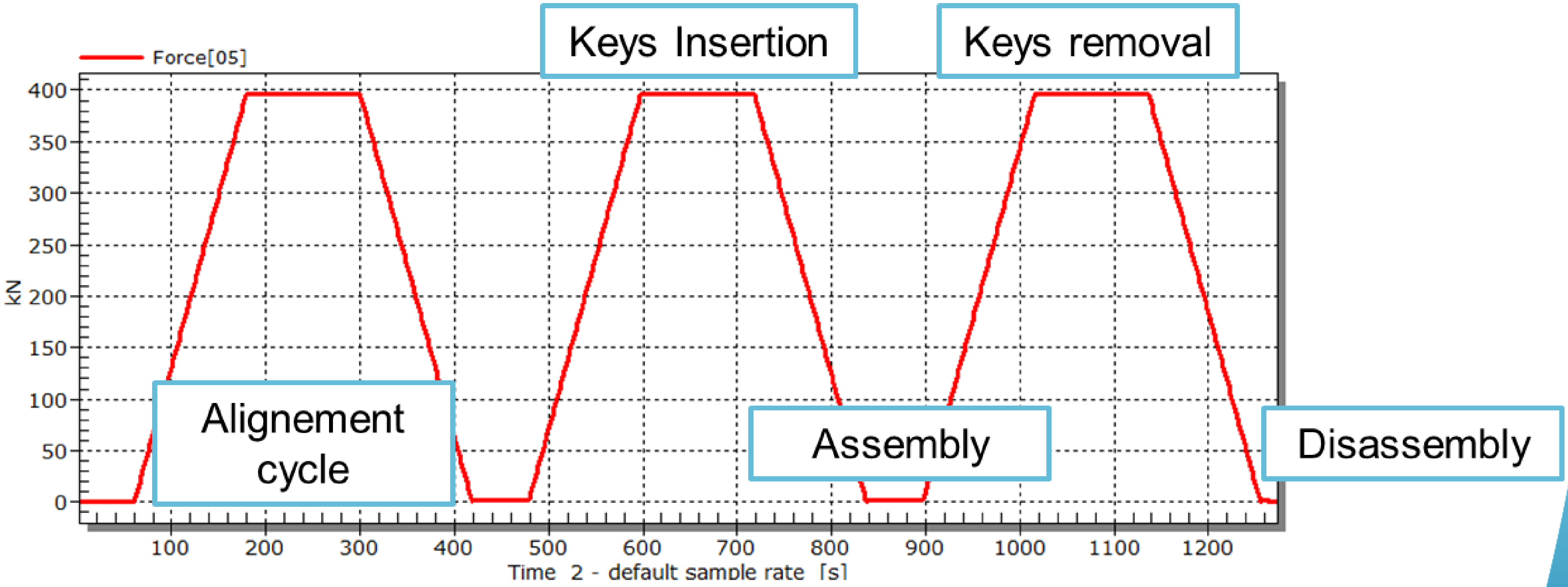


Aluminum dummy coils

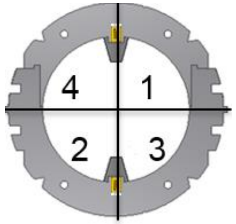


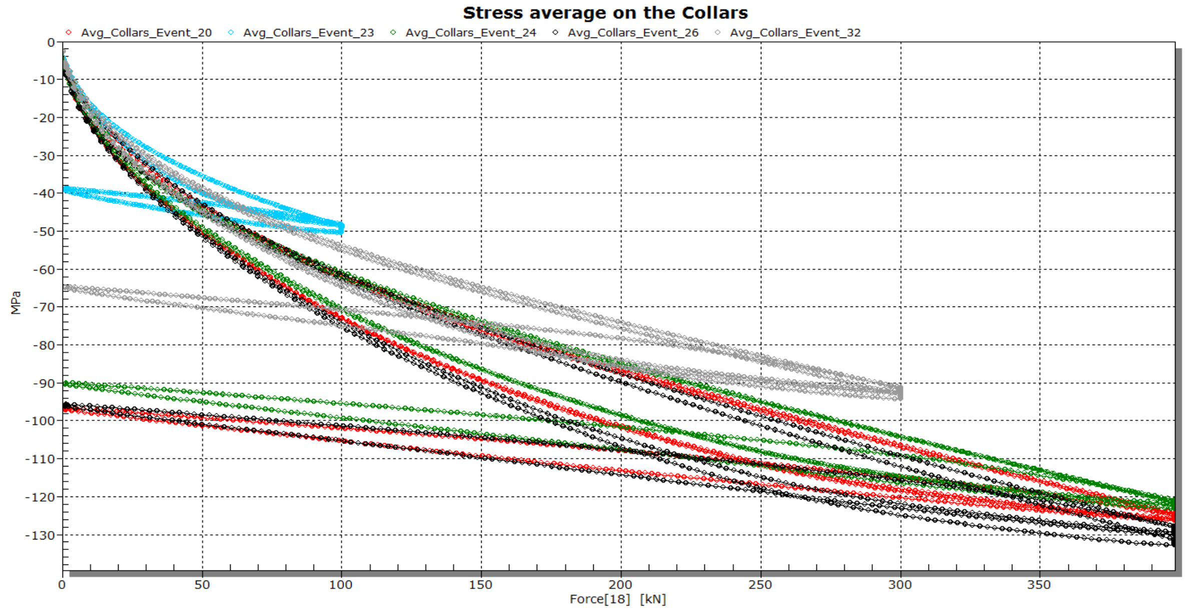
Test protocol

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



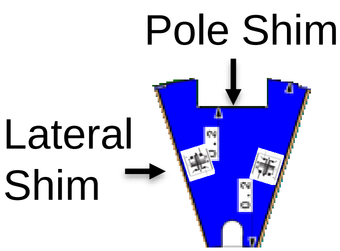
Result : Excess changing

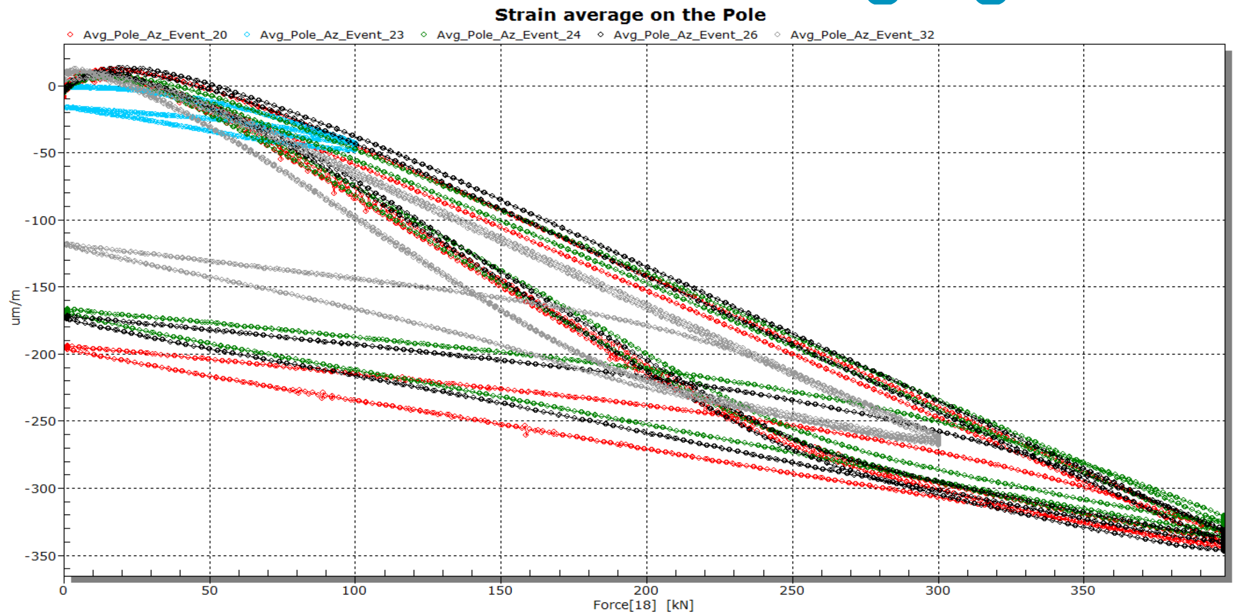




Curve	Pole Shim (µm)	Lateral Shim (µm)	Excess (µm)
red	200	200	150
light blue	200	100	50
grey	350	100	100
green	500	100	150
black	200	200	150

Result : Excess changing

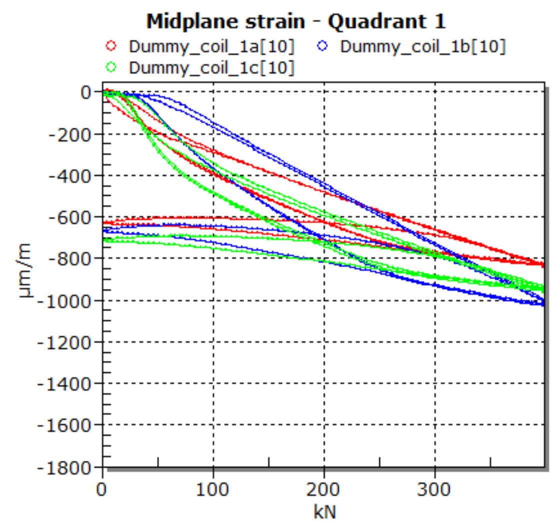


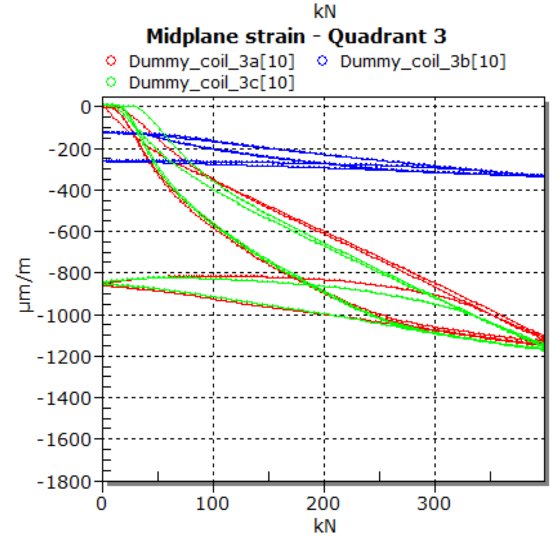


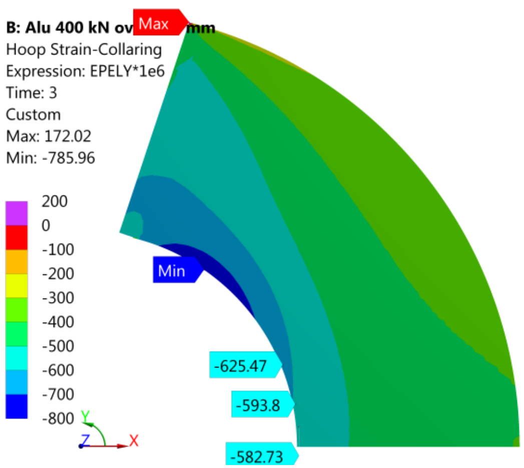
Curve	Pole Shim (µm)	Lateral Shim (µm)	Excess (µm)
red	200	200	150
light blue	200	100	50
grey	350	100	100
green	500	100	150
black	200	200	150

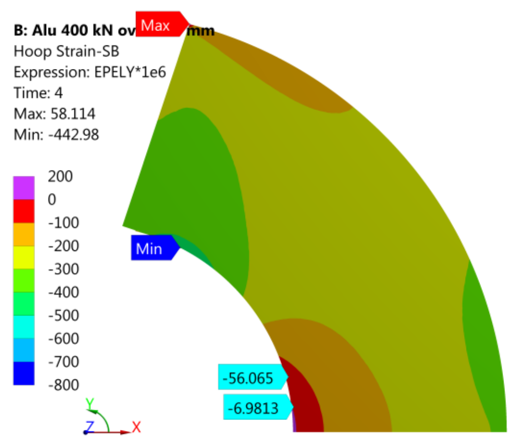
Dummy coil strain gauges

- Significant differences between coil measurements and computations
- Work in progress



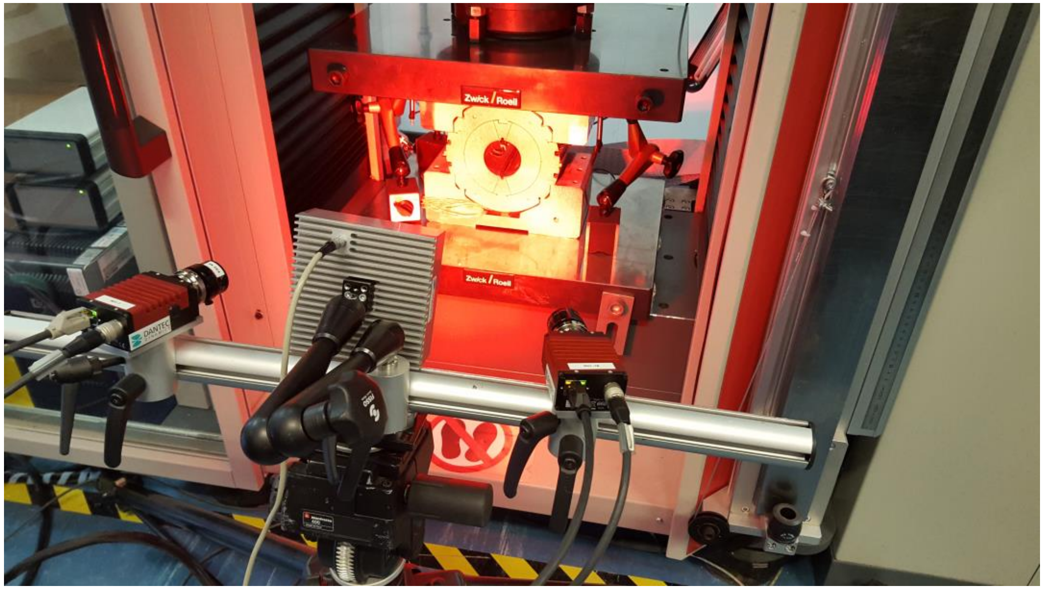




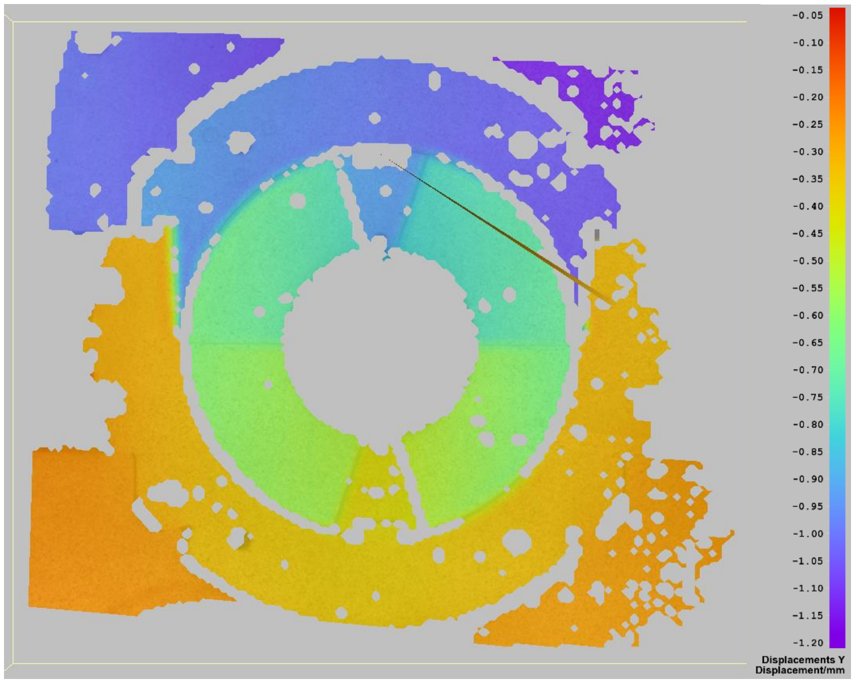


Digital Image Correlation (DIC)

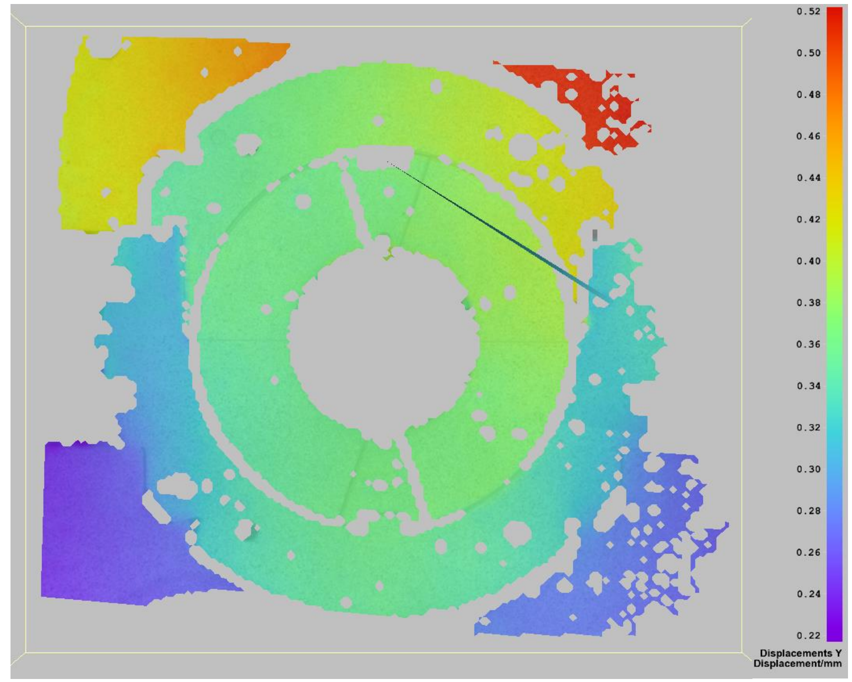
- **Digital image correlation** is an optical method that employs tracking and image registration techniques for accurate 2D and 3D strain measurements.
- A company will come to provide the equipment and do the data acquisition.



DIC results for baseline config.



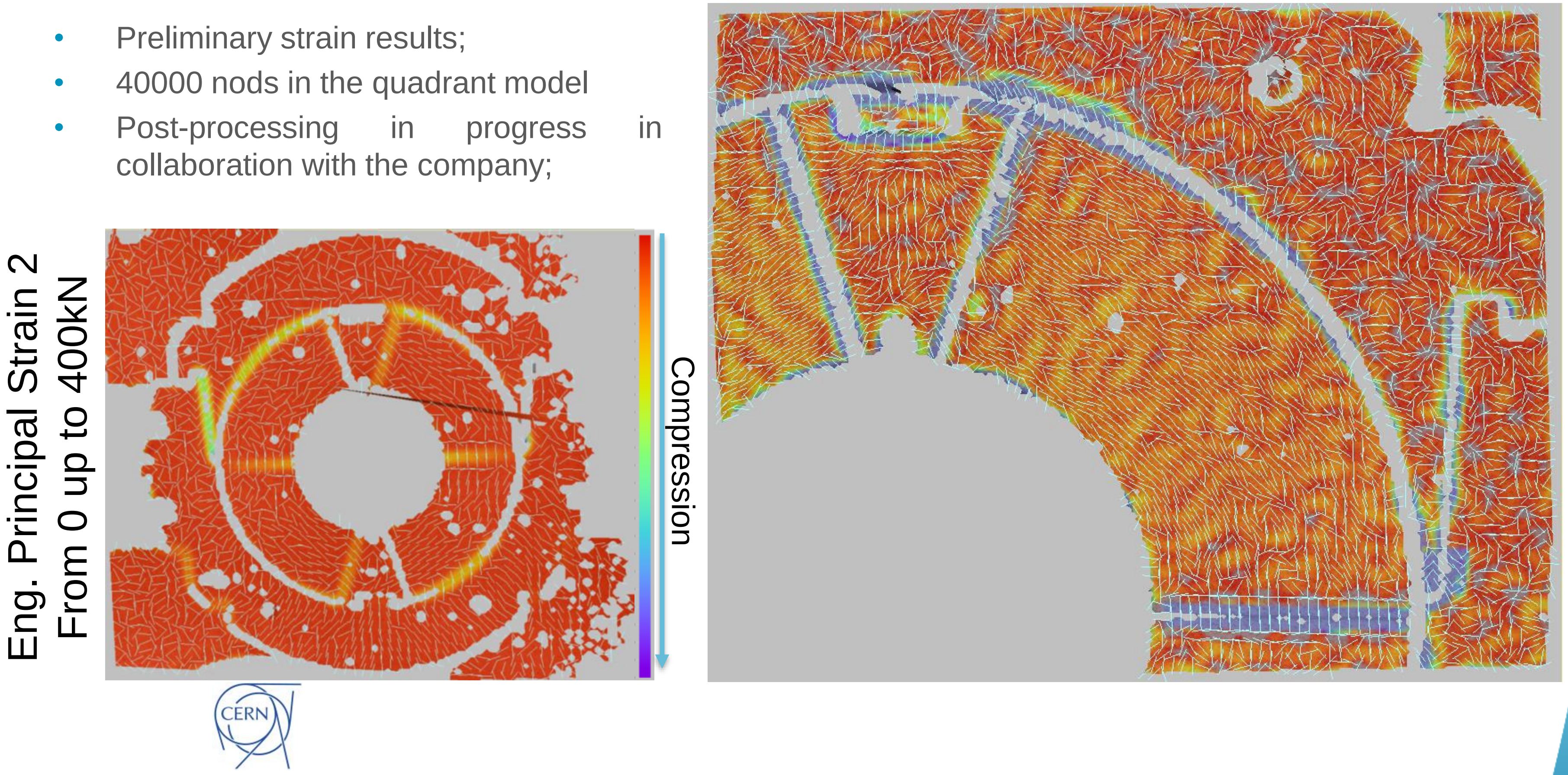
Vertical Displacement :
0 up to 400kN



Vertical Displacement :
From 400kN up to Keys inserted

DIC results for baseline config.

- Preliminary strain results;
- 40000 nods in the quadrant model
- Post-processing in progress in collaboration with the company;



Plan: step 1
February 2018

- Next steps
  - Test CR03 spare in 376
    - Loading 1 (virgin coil)
      - No stoppers
      - Cycling at 25%-50% and 75% of maximum collaring force
        - 1-100-1-200-1-300-1-400 kN
      - Key inserted with excess of 0.2 mm per quadrant
      - Full disassembly and replace GI and protection sheet
    - Repeat
  - Validation set-up in 927
    - Repeat test with aluminium dummy
    - Repeat test with CR03 spare

Plan step 2 (coil CR03) 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 step 2 (coil CR03) 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

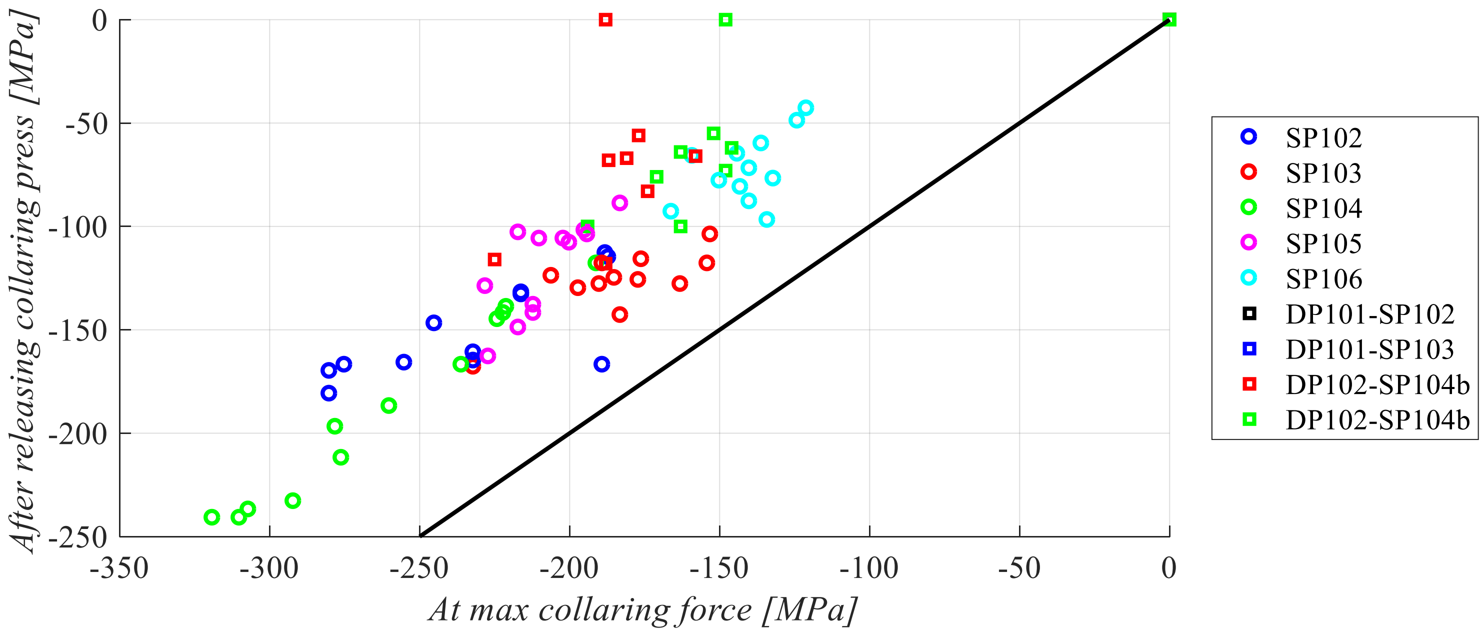
Plan step 3 (coil 118)
April 2018

- 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

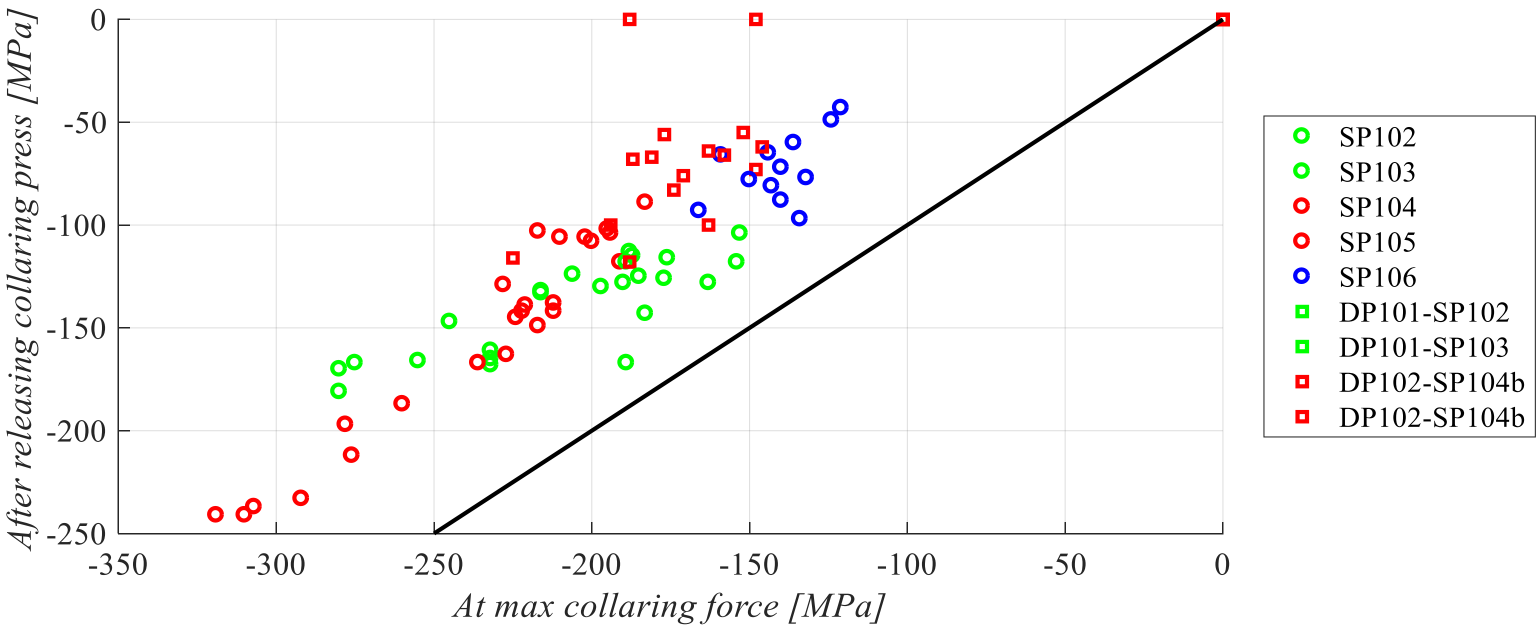
Appendix

Collaring



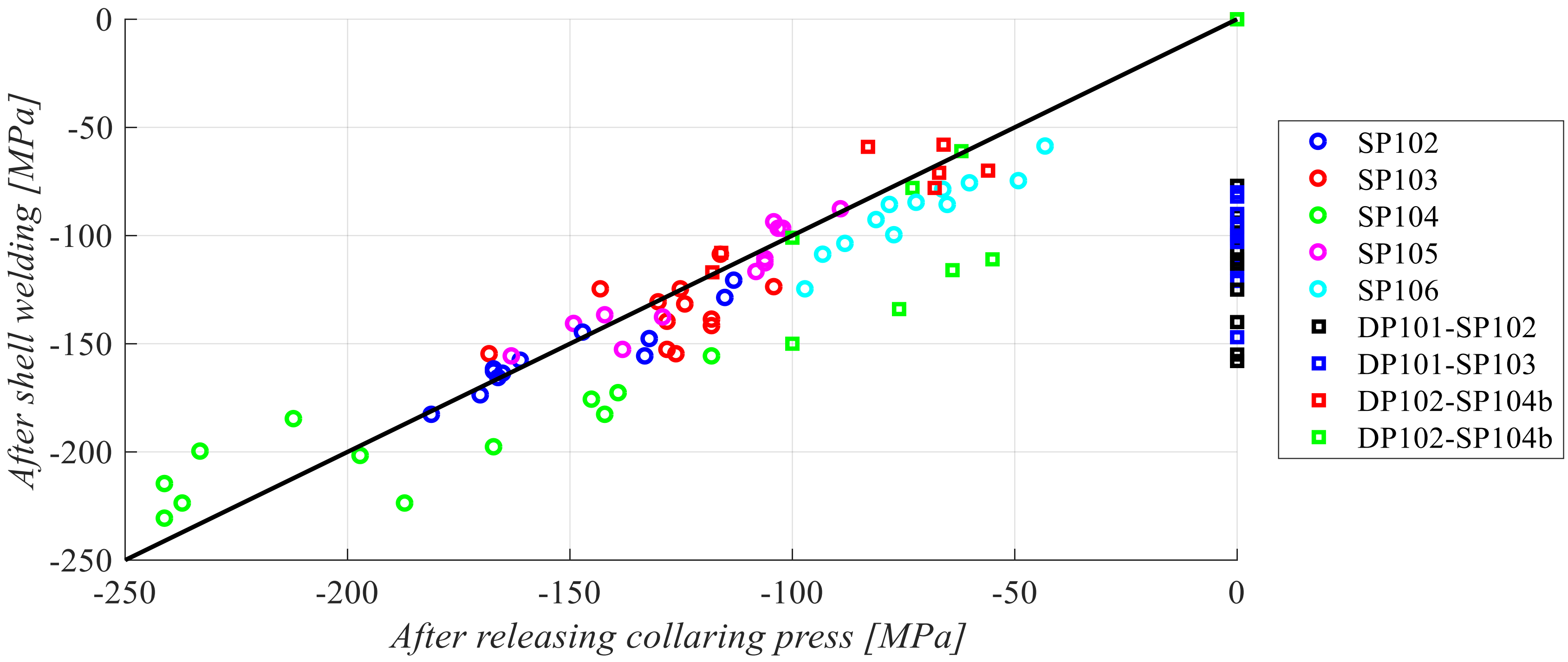
- $y = 0.9144x + 60.42$
  $R^2 = 0.823$

Collaring



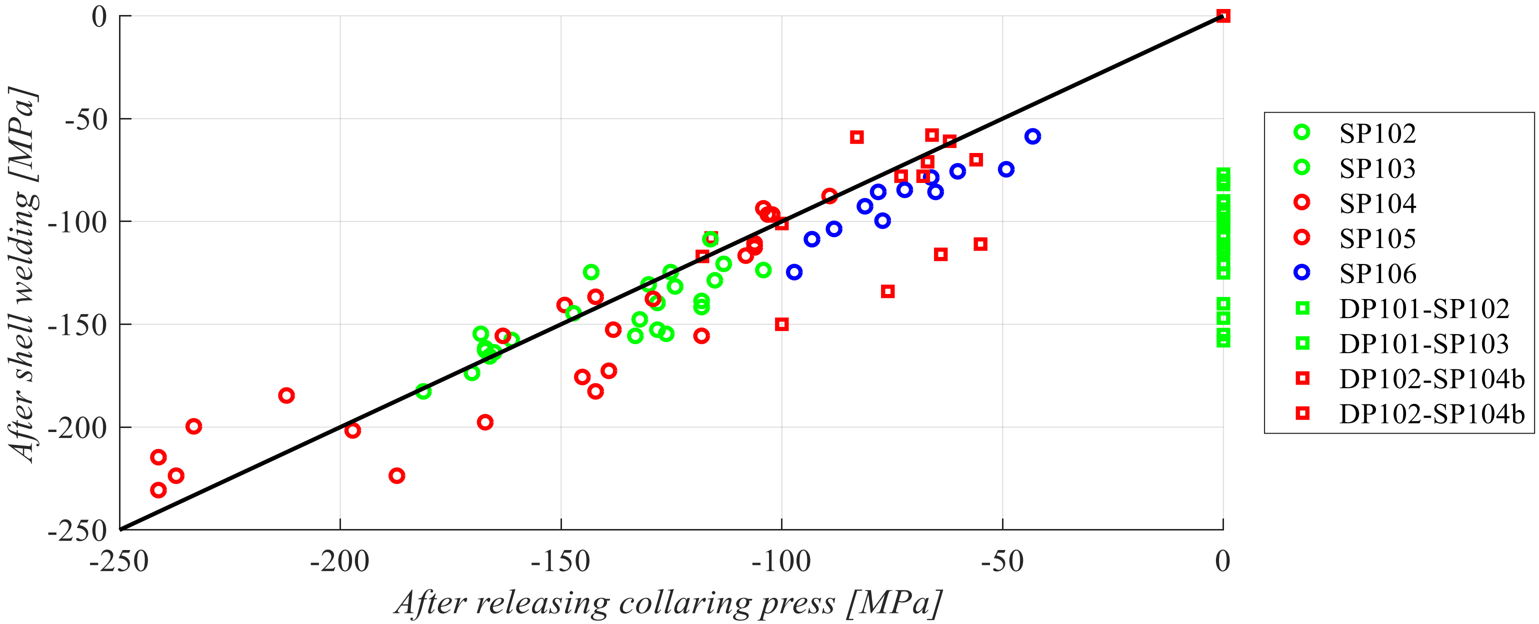
- $y = 0.9144x + 60.42$
  $R^2 = 0.823$

Shell welding



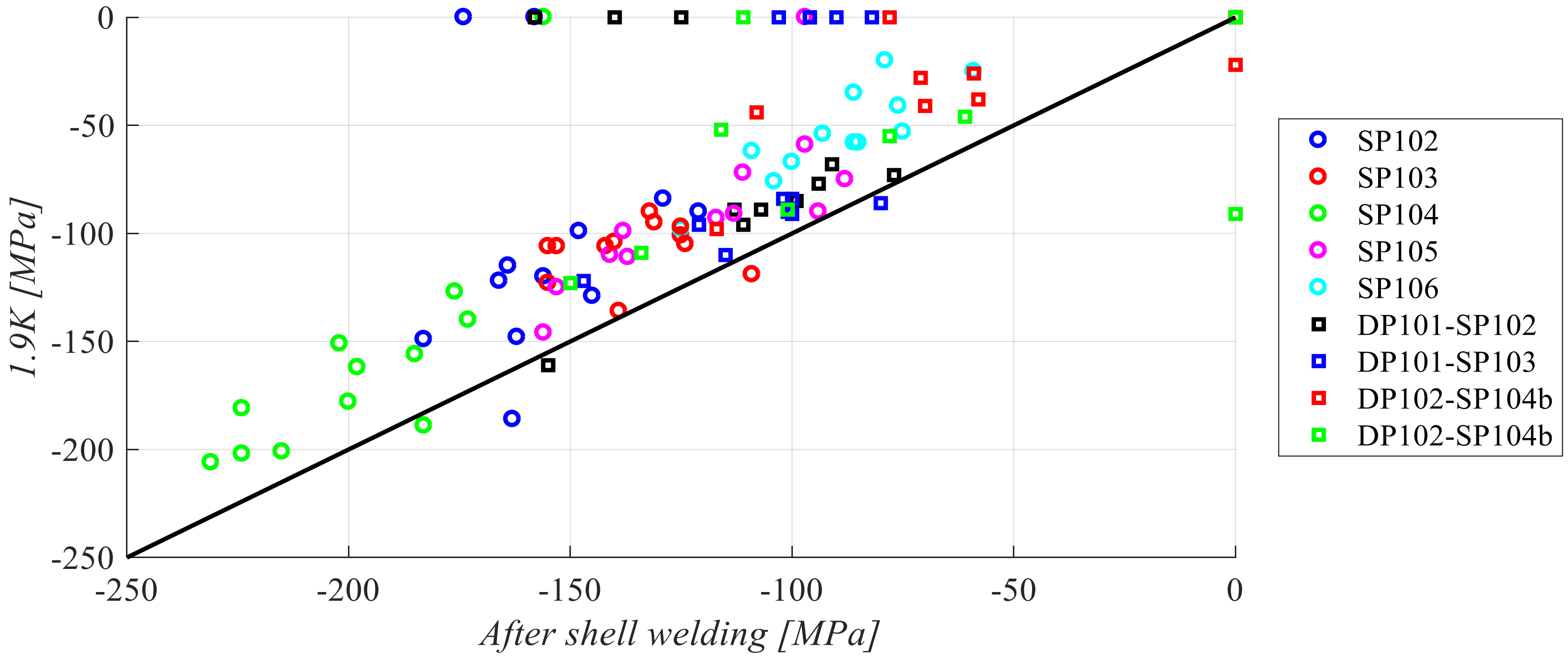
- y = 0.8283x - 30.124
  R^2 = 0.8403

Shell welding



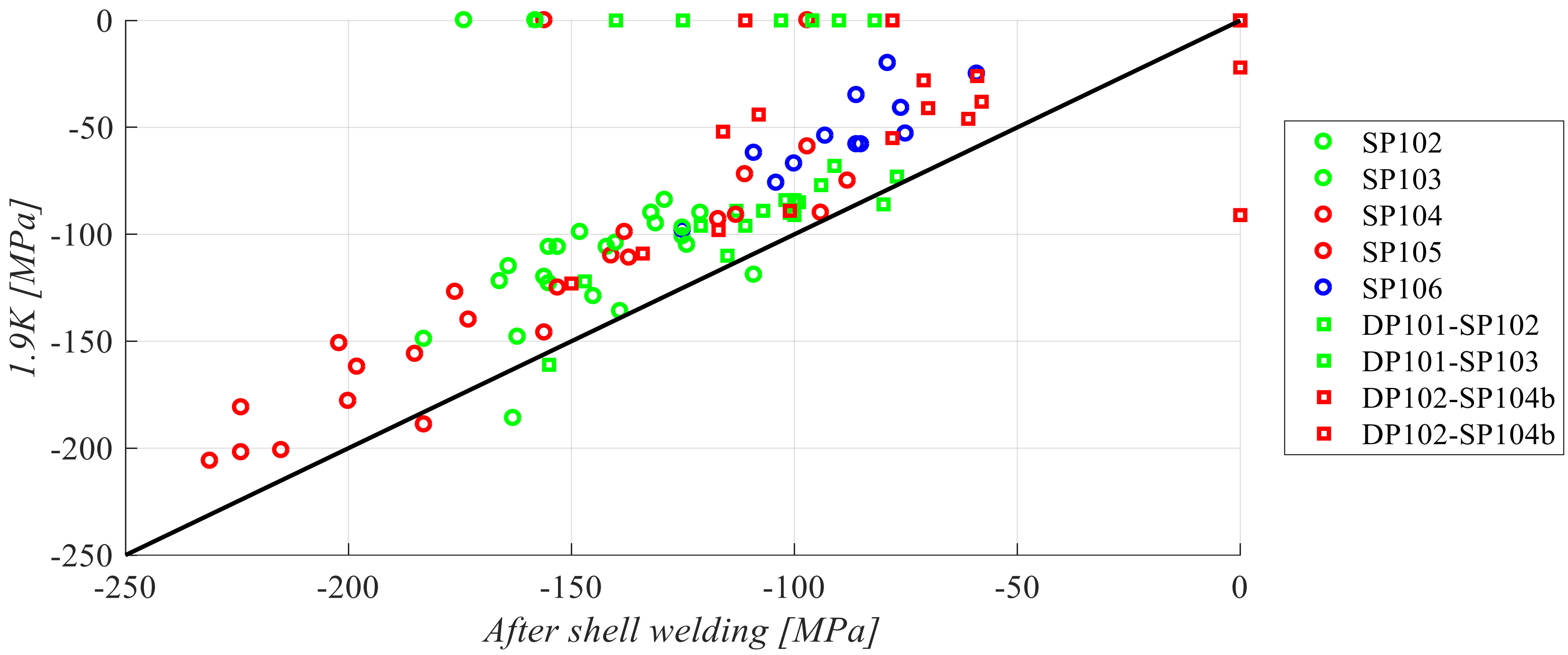
- $y = 0.8283x - 30.124$
  $R^2 = 0.8403$

Cool-down



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

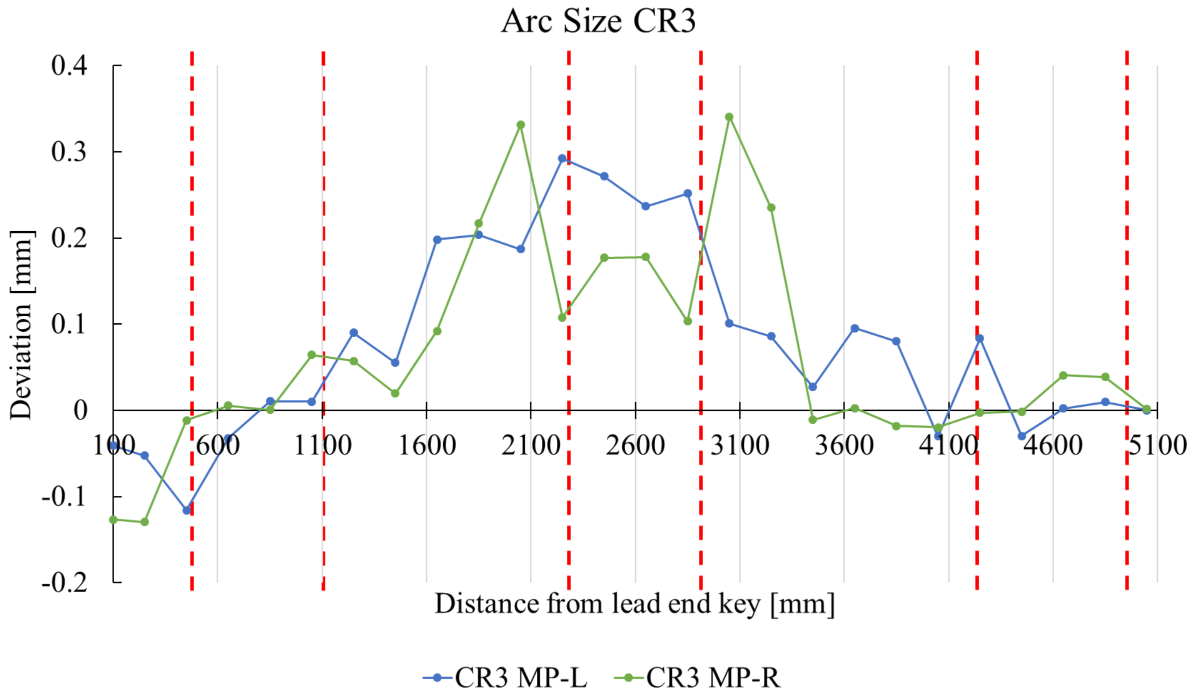
Cool-down



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

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



CUT

500-1100

2300-2900

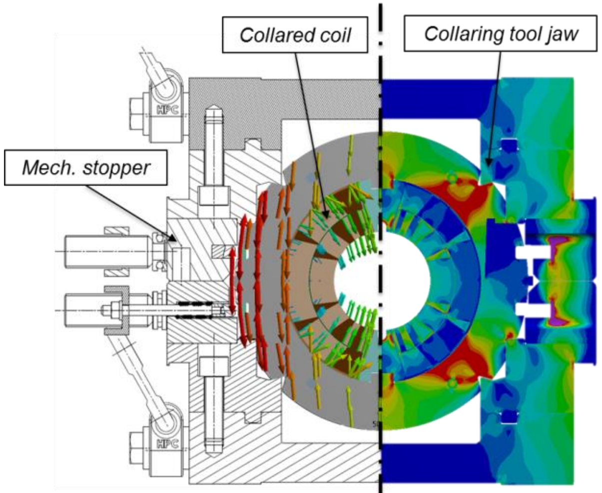
4300-4900

Analysis of collaring
"Old slide"

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

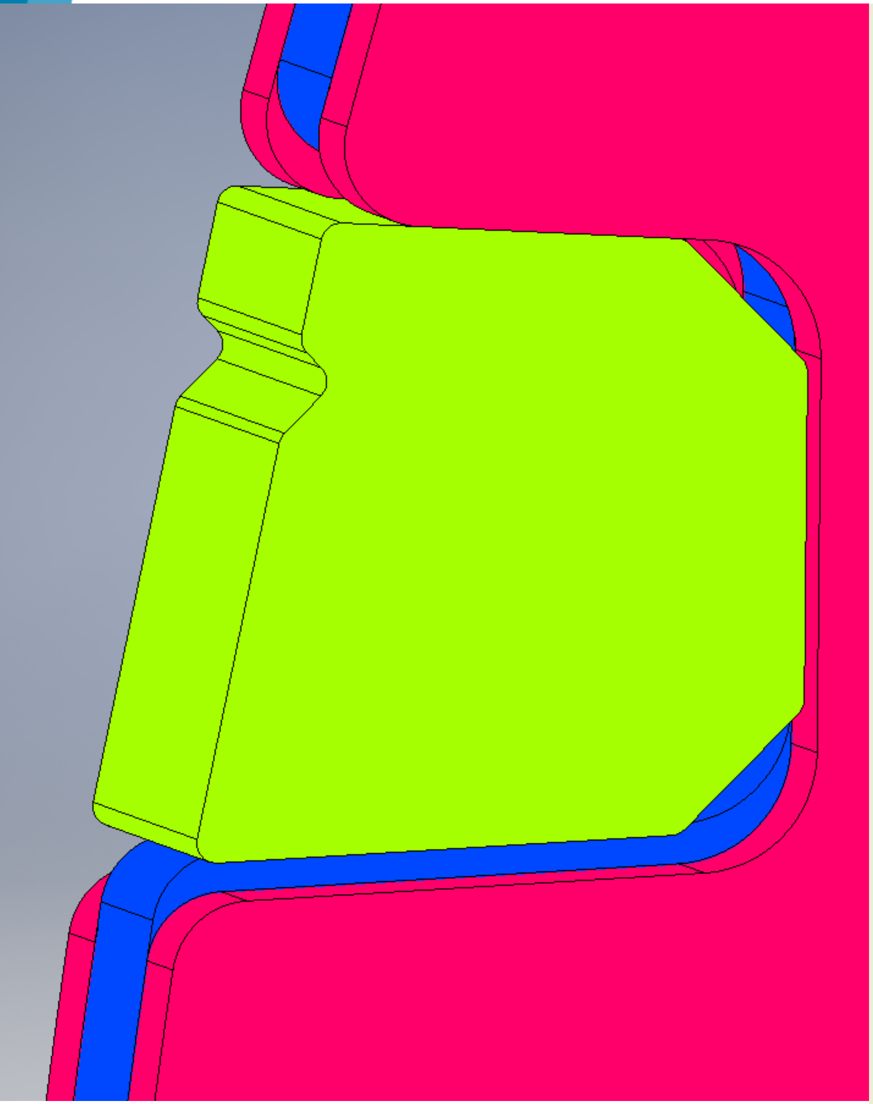
	Average Excess Quadrant	Applied Force / MN	70 mm stopper deviation / mm
CC101	0.31	32	+0.1
CC102	0.29	32	+0.1
CC103	0.38	32	+0.1
CC104	0.45	22	-0.15
CC104b	0.35	**20**	-0.15
CC105	0.35	16	-0.15
CC105b	0.30	**20**	-0.15
CC106	0.33	12	-0.15

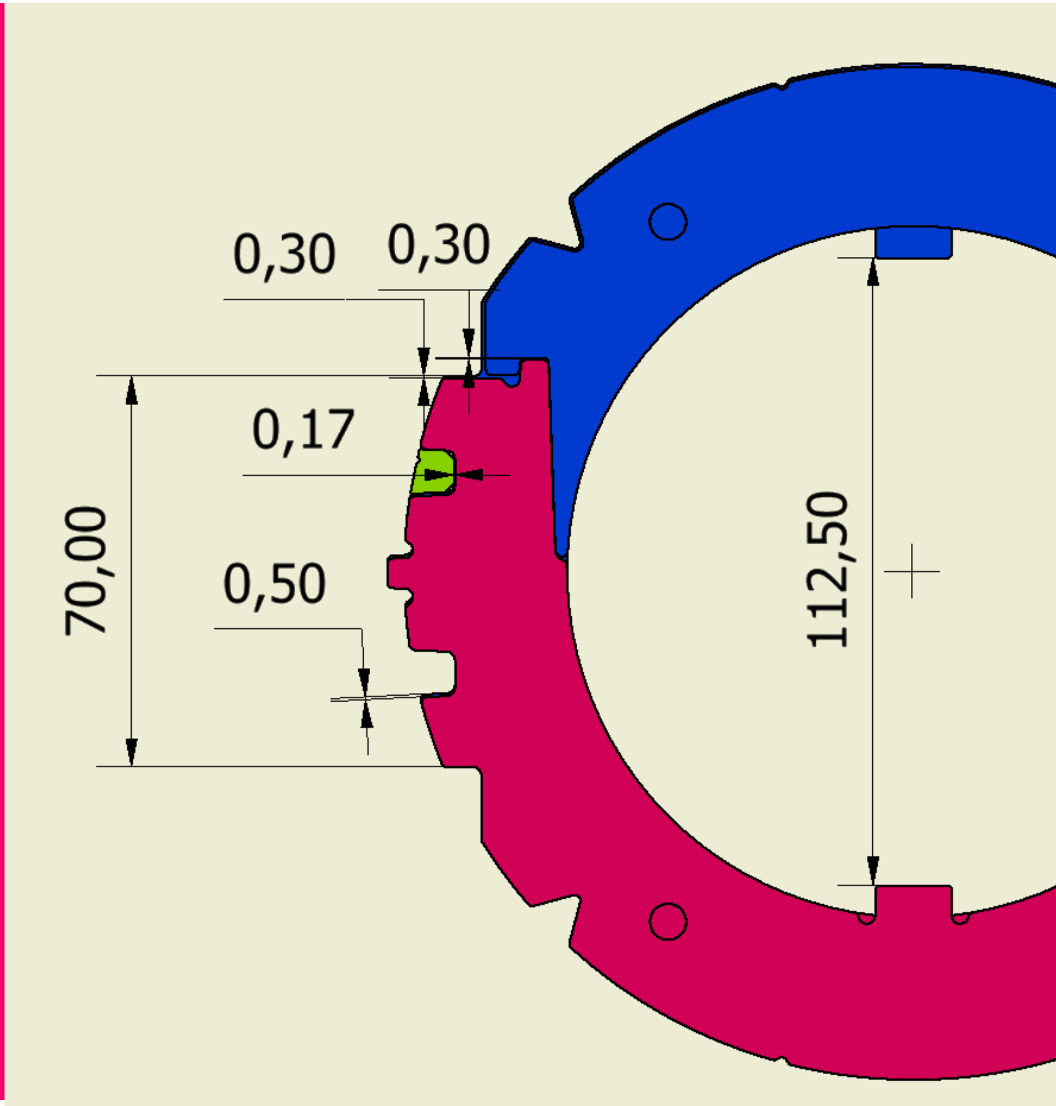
- Deviation
  - Positive → interference
    - Tooling deformed
  - Negative→ clearance



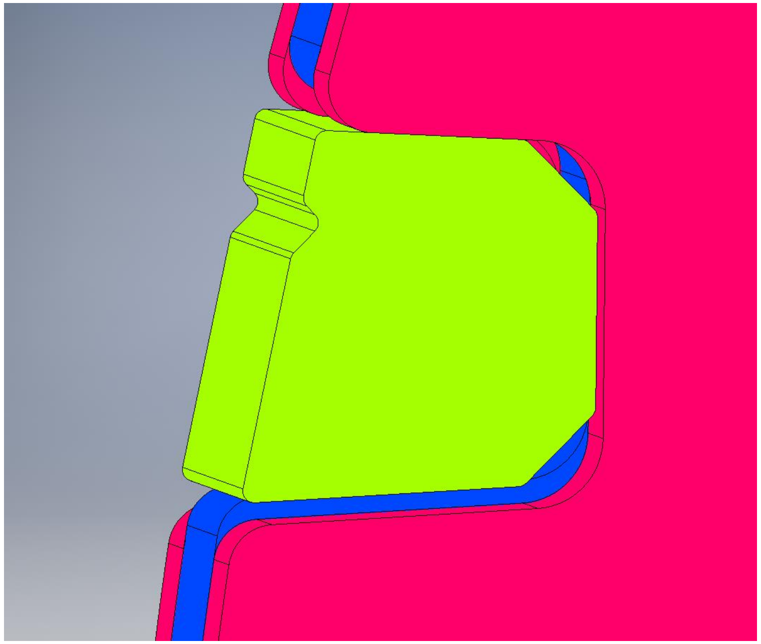
Displacement vectors and EQV. Stress for illustration

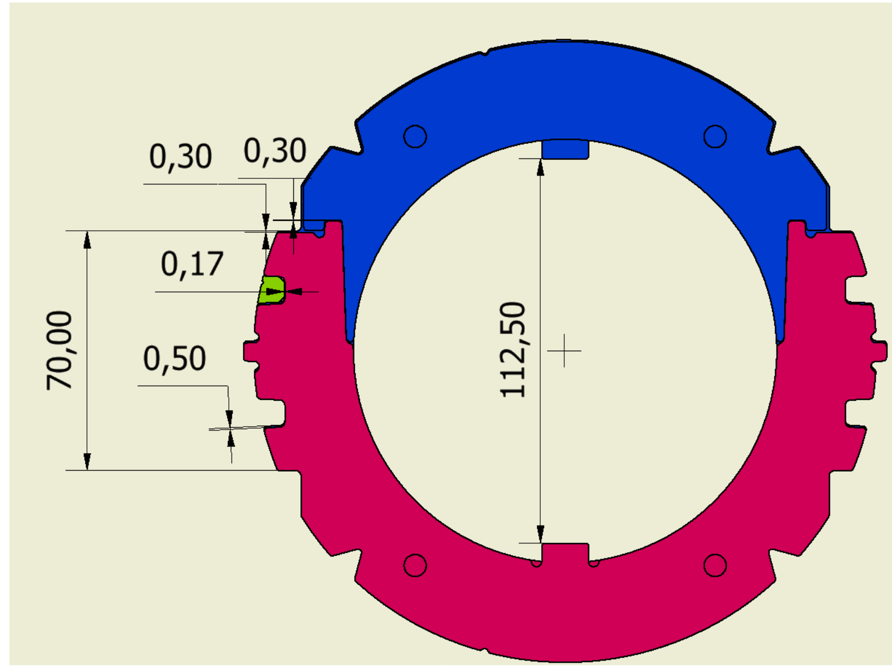
Key clearance vs stoppers shim





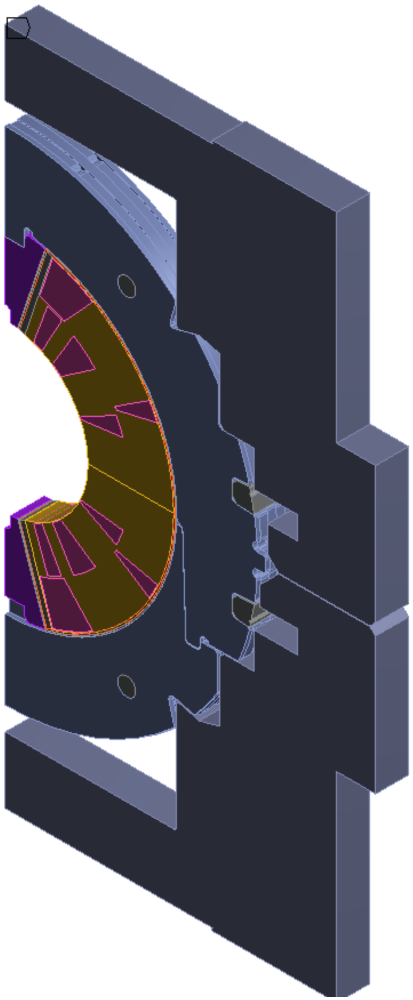
Key clearance vs stoppers shim

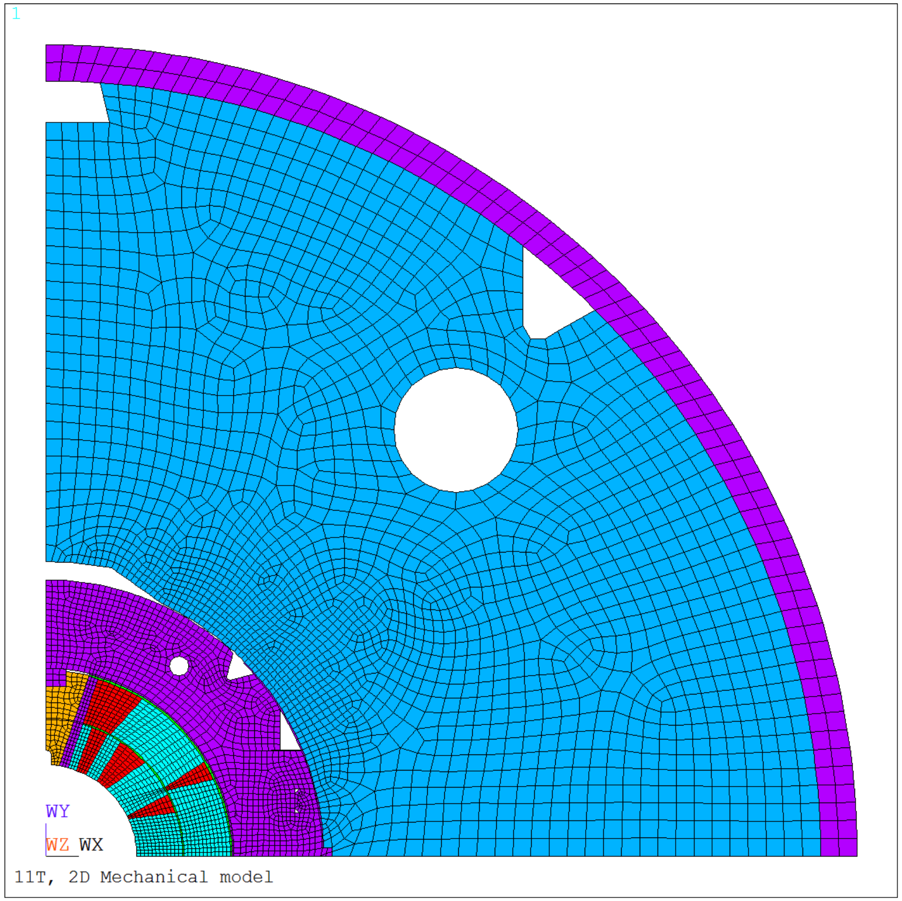




Magnet	Shim stoppers (μm)	Stopper height (mm)	Key clearance (μm)
	0	69.7	+300
	100	69.8	+200
	200	69.9	+100
	300	70.0	0
101,102,103	400	70.1	-100
104,105,106	150	69.85	+150

Modelling





11T, 2D Mechanical model

Analysis

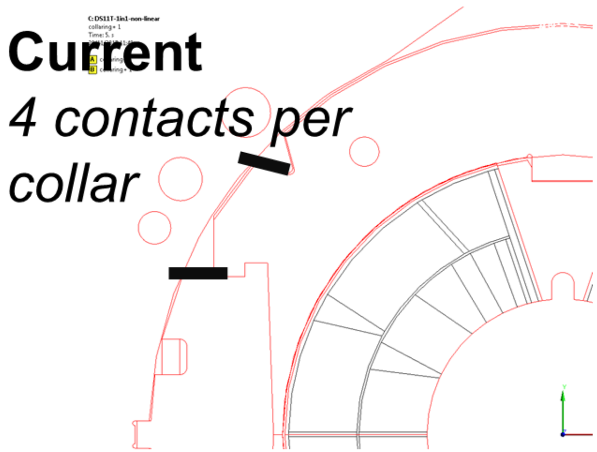
- Output from ANSYS model
  - For each of the 4 excesses
    - Steps
      - Collaring maximum force
      - After collaring (key inserted)
      - After welding
      - After cool-down
      - During powering: 10%,20%....100% of the nominal force
    - Collar vertical and horizontal deflection
    -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

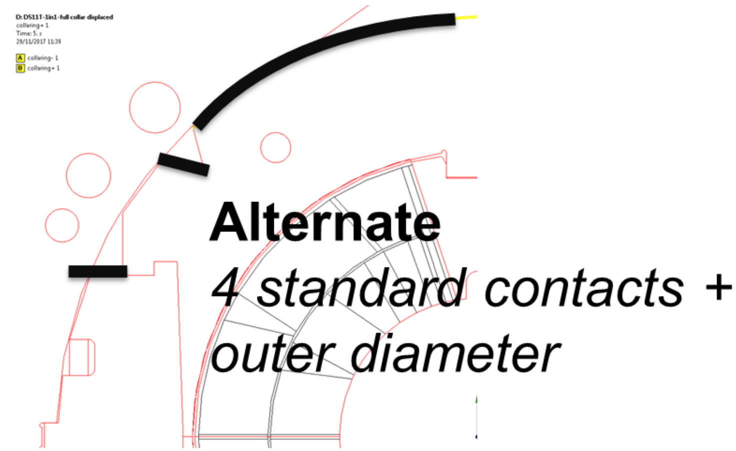
Analysis: open points

- 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

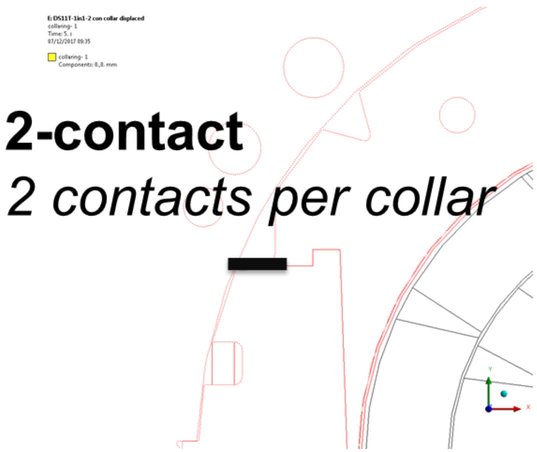
Analysis of collaring by FEM

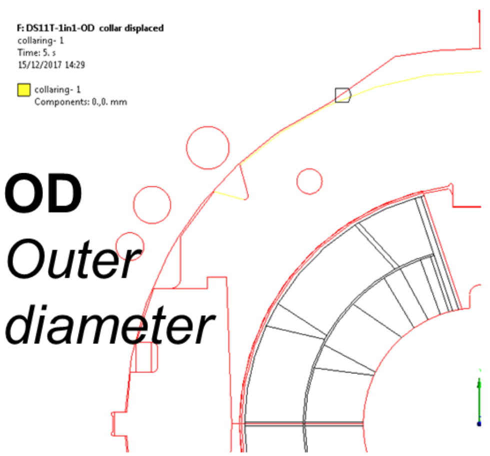
- Different scenarios considered





Fixed displacement by 0.1 mm

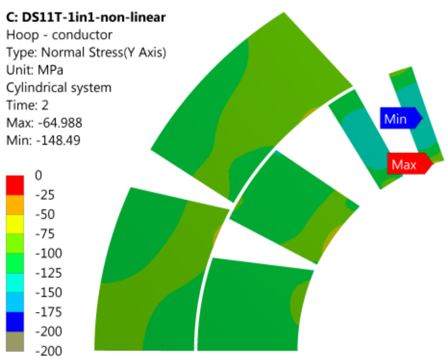




2

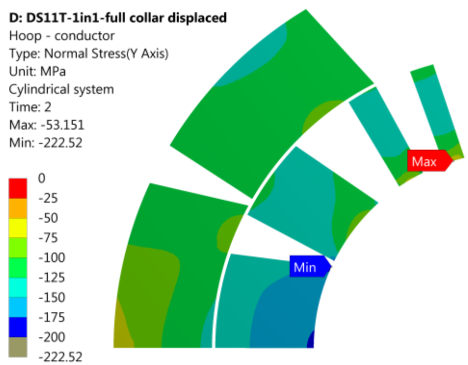
Analysis of collaring by FEM

- Different scenarios considered



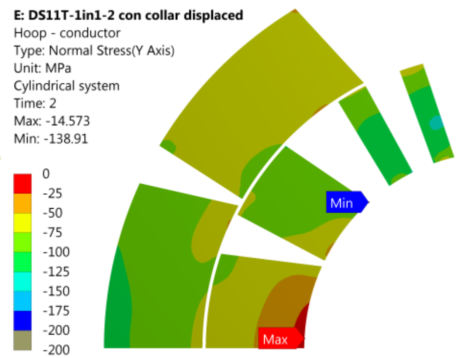
Current

4 contacts per collar



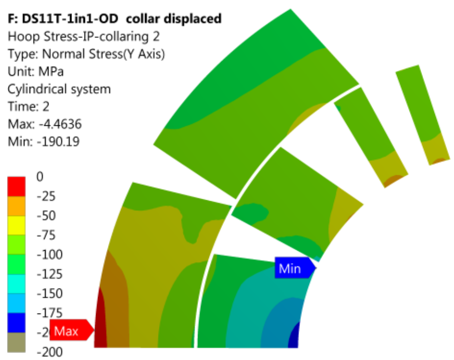
Alternate

4 standard contacts + outer diameter



2-contact

2 contacts per collar

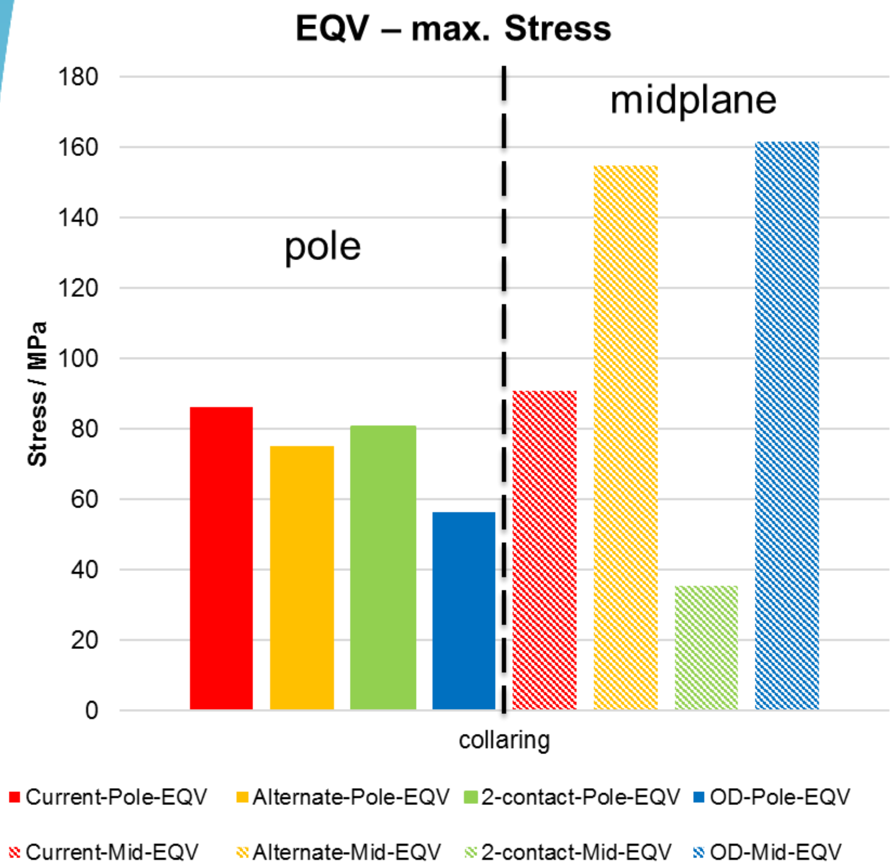


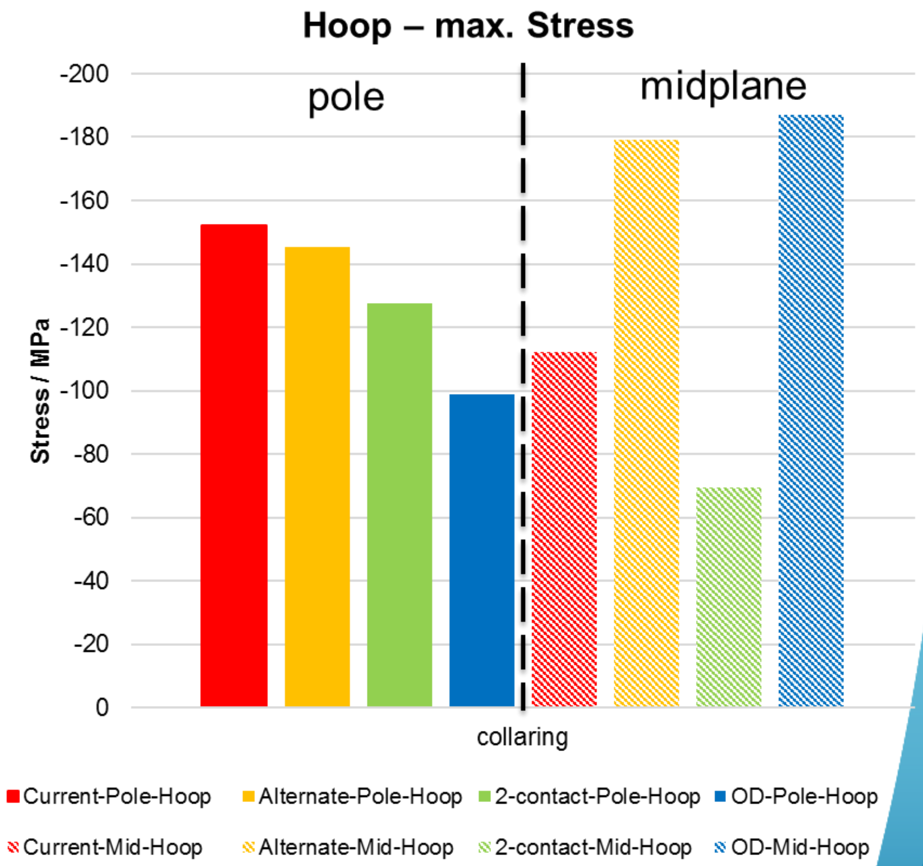
OD

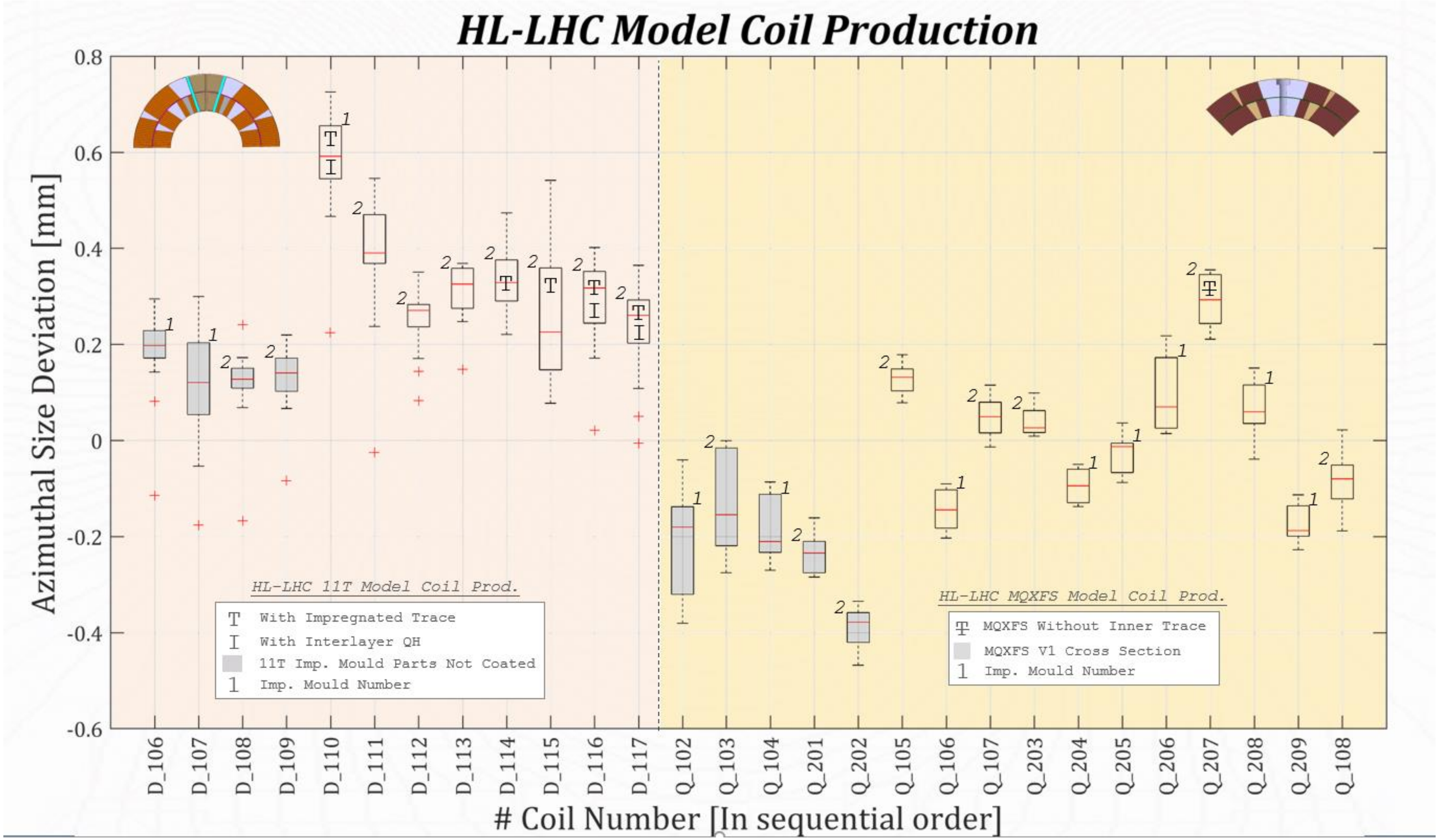
Outer diameter

Analysis of collaring by FEM

- Different scenarios considered



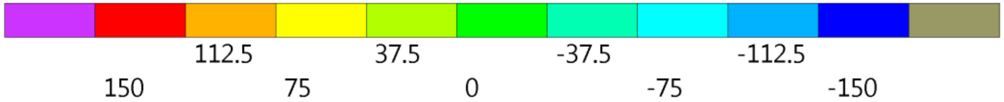


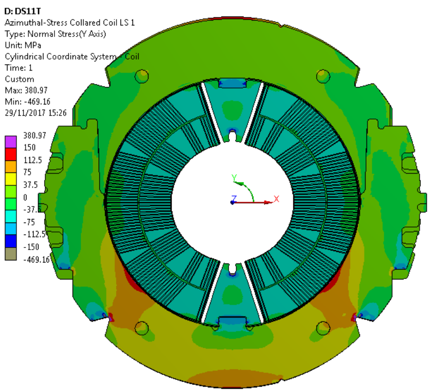

HL-LHC Model Coil Production
Azimuthal Size Deviation [mm]
Coil Number [In sequential order]
HL-LHC 11T Model Coil Prod.
With Impregnated Trace
With Interlayer QH
11T Imp. Mould Parts Not Coated
Imp. Mould Number
HL-LHC MQXFS Model Coil Prod.
MQXFS Without Inner Trace
MQXFS V1 Cross Section
Imp. Mould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

Azimuthal-Stress LS1

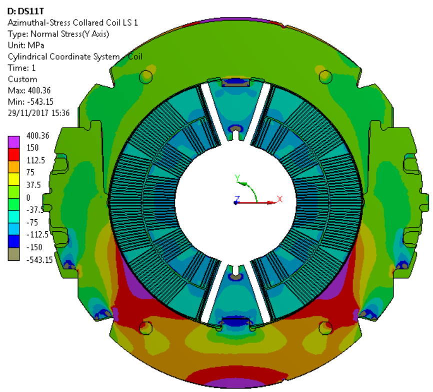
LS1 – collaring
LS2 – collared coil
LS3 – shell welding
LS4 – 1.9 K
LS5 – 12T

X.X lateral pole shim
0.0 collared coil shim

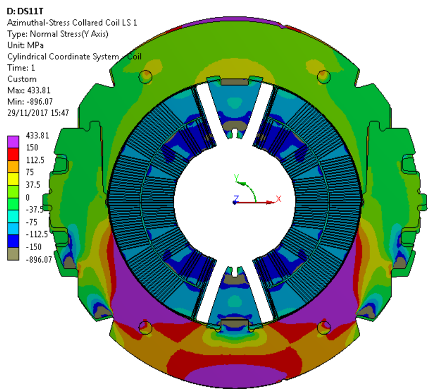




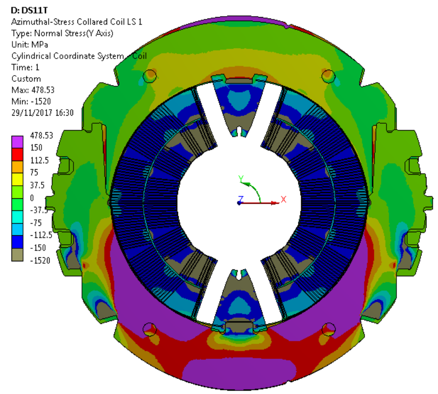
0.2 mm arc excess



0.4 mm arc excess



0.6 mm arc excess



0.8 mm arc excess

	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

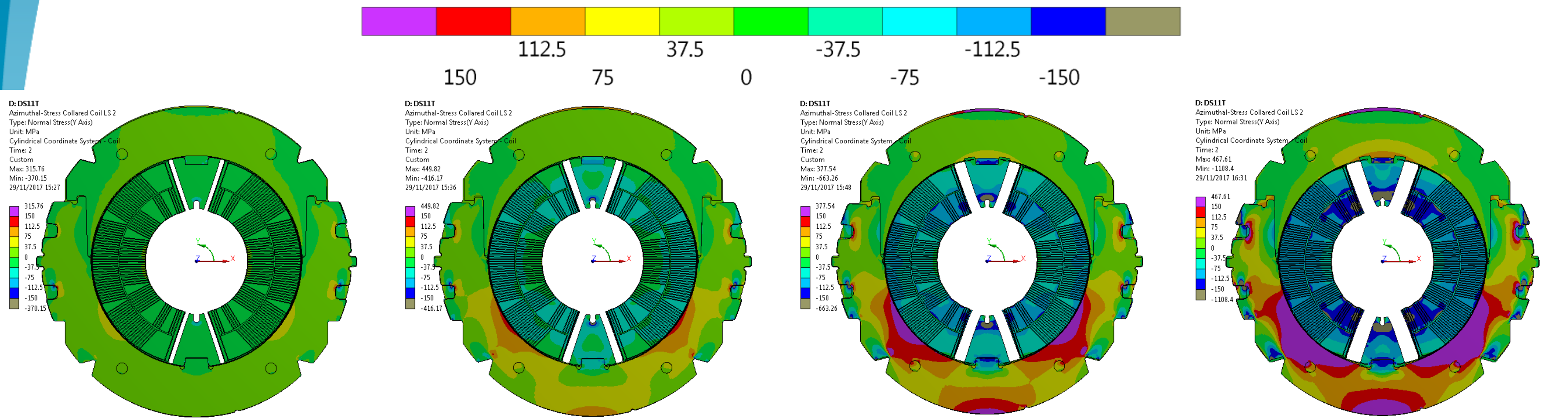
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**29**	**45**	**62**	**77**
EQV-Mid Min.	28	44	59	74
EQV-Mid Max.	61	80	101	121
Hoop-Mid AV.	**-44**	**-70**	**-98**	**-123**
Hoop-Mid Min.	-69	-91	-117	-147
Hoop-Mid Max.	-45	-70	-98	-119

Scaling x25

Azimuthal-Stress LS2

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

	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

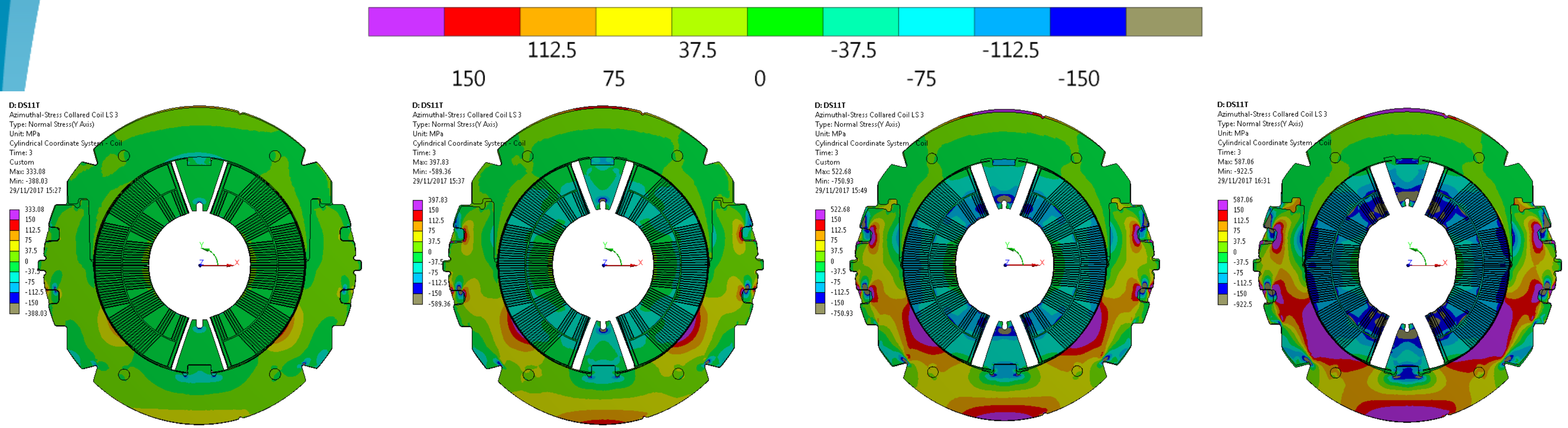
Scaling x25

HiLumi HL-LHC PROJECT

Azimuthal-Stress LS3

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

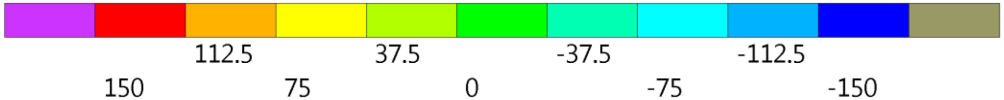
	pole			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Pole AV.	**5**	**11**	**18**	**29**
EQV-Pole Min.	1	2	4	11
EQV-Pole Max.	18	39	65	91
Hoop-Pole AV.	**-20**	**-44**	**-74**	**-109**
Hoop-Pole Min.	-31	-67	-127	-170
Hoop-Pole Max.	-7	-24	-42	-70

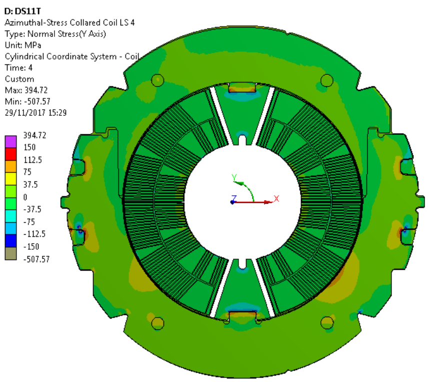
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**16**	**26**	**39**	**53**
EQV-Mid Min.	5	6	7	8
EQV-Mid Max.	61	81	103	123
Hoop-Mid AV.	**-18**	**-40**	**-64**	**-88**
Hoop-Mid Min.	-21	-43	-69	-95
Hoop-Mid Max.	34	46	60	73

Scaling x25

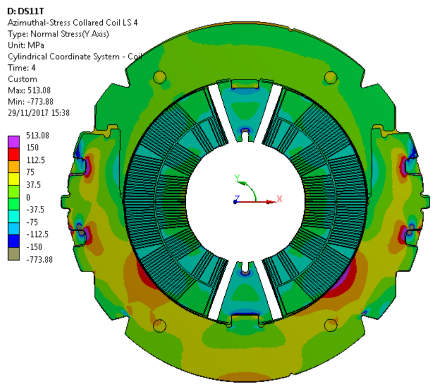
Azimuthal-Stress LS4

X.X lateral pole shim
0.0 collared coil shim

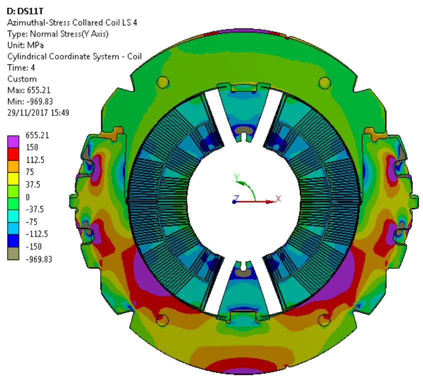




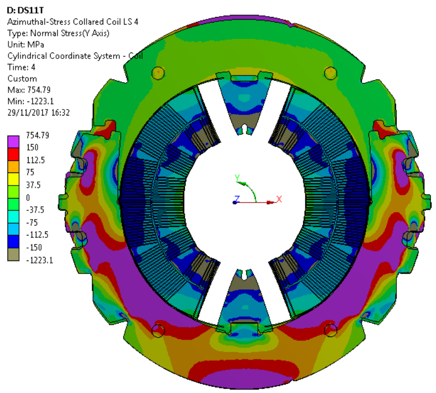
0.2 mm arc excess



0.4 mm arc excess



0.6 mm arc excess



0.8 mm arc excess

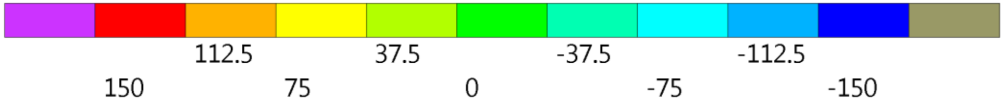
	pole			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Pole AV.	**14**	**23**	**35**	**50**
EQV-Pole Min.	4	4	11	22
EQV-Pole Max.	29	40	72	104
Hoop-Pole AV.	**-23**	**-49**	**-85**	**-127**
Hoop-Pole Min.	-28	-67	-136	-188
Hoop-Pole Max.	13	-7	-24	-58

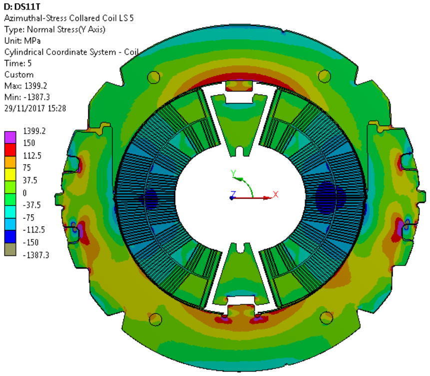
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**22**	**34**	**49**	**66**
EQV-Mid Min.	4	5	2	1
EQV-Mid Max.	62	84	106	128
Hoop-Mid AV.	**-16**	**-39**	**-67**	**-96**
Hoop-Mid Min.	-25	-52	-81	-112
Hoop-Mid Max.	50	66	83	100

Scaling x25

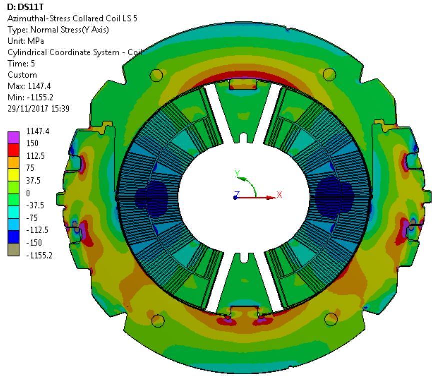
Azimuthal-Stress LS5

X.X lateral pole shim
0.0 collared coil shim

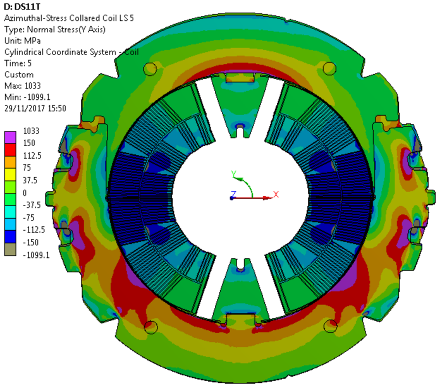




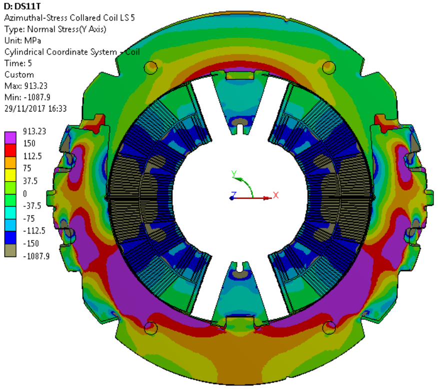
0.2 mm arc excess



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

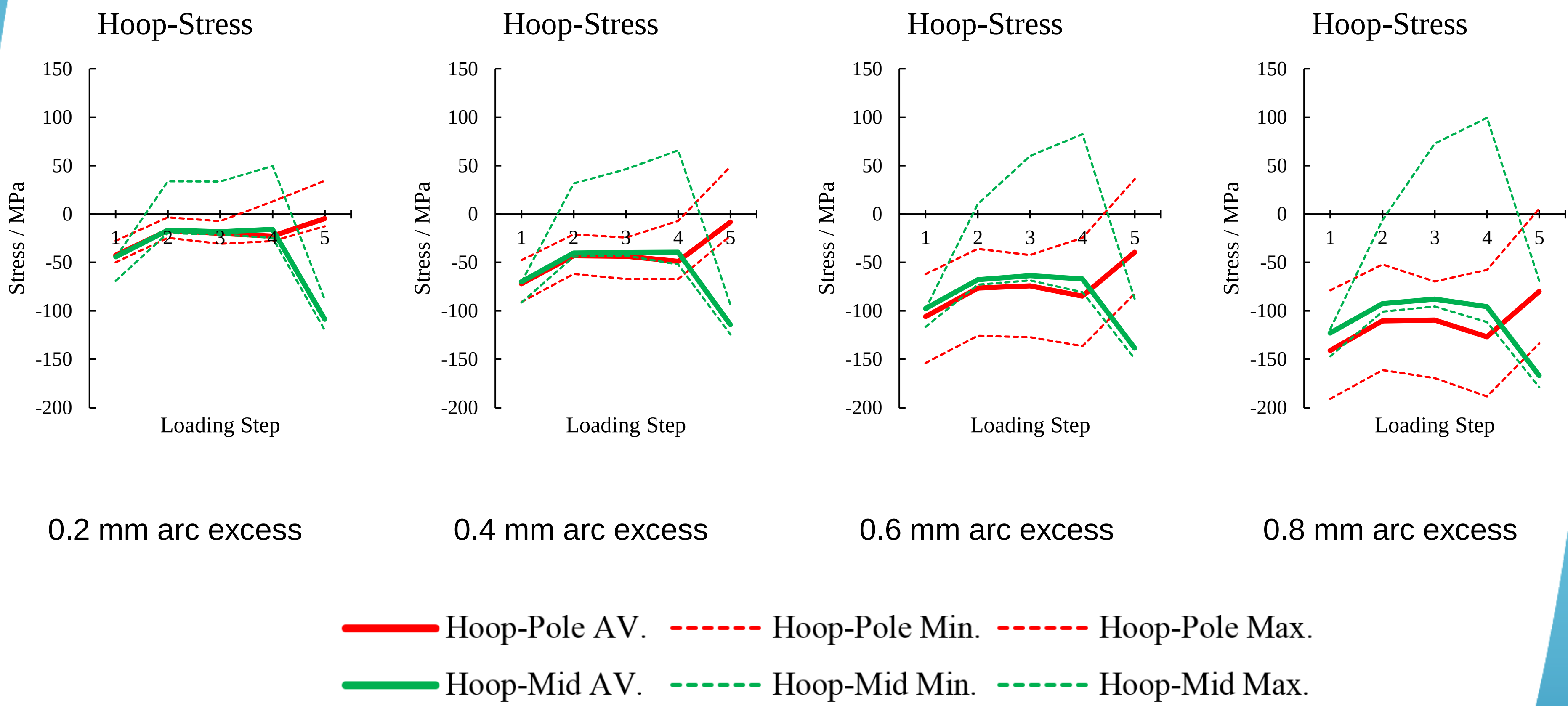
	midplane			
arc excess	*0.2*	*0.4*	*0.6*	*0.8*
EQV-Mid AV.	**41**	**50**	**64**	**80**
EQV-Mid Min.	35	36	41	49
EQV-Mid Max.	92	98	101	94
Hoop-Mid AV.	**-109**	**-114**	**-138**	**-167**
Hoop-Mid Min.	-120	-125	-149	-179
Hoop-Mid Max.	-89	-94	-88	-69

Scaling x25

Azimuthal-Stress

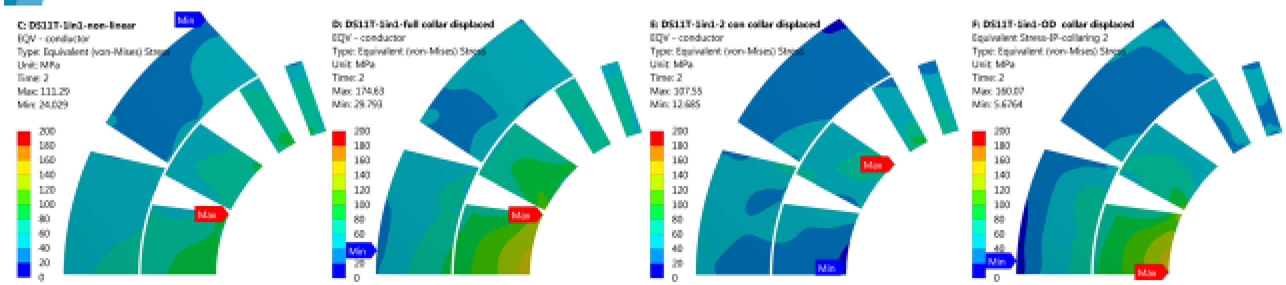
LS1 – collaring
LS2 – collared coil
LS3 – shell welding
LS4 – 1.9 K
LS5 – 12T

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

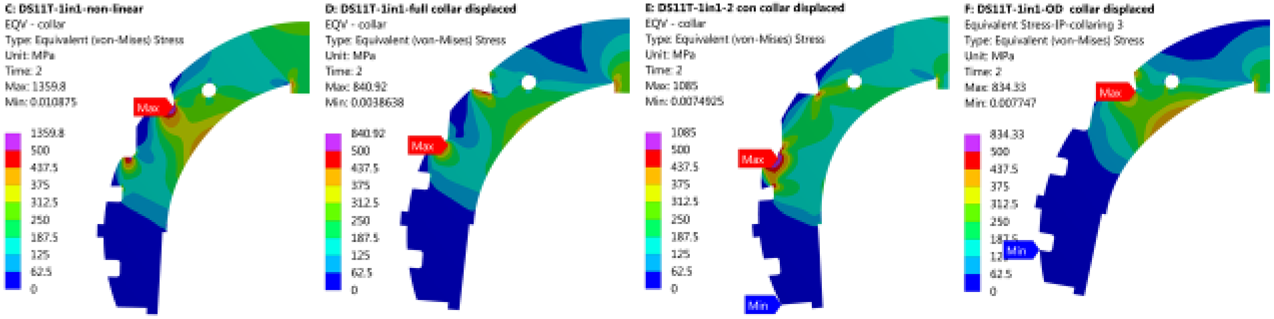
Collaring comparison-
EQV Stress during collaring - conductor



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

5

Collaring comparison-
EQV Stress during collaring - collars



Current — *4 contacts per collar*

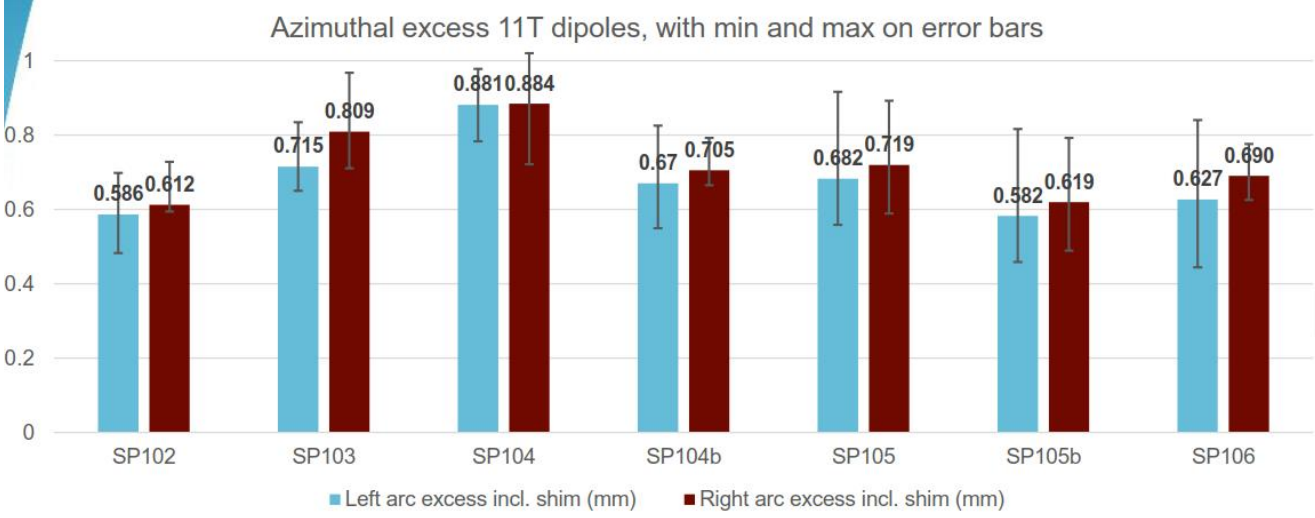
Alternate

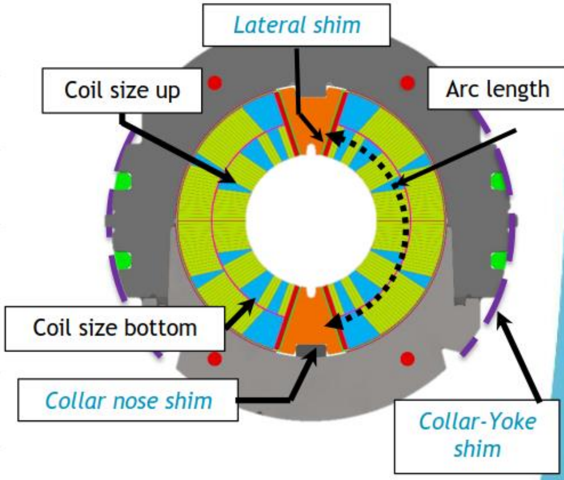
2-contact

OD

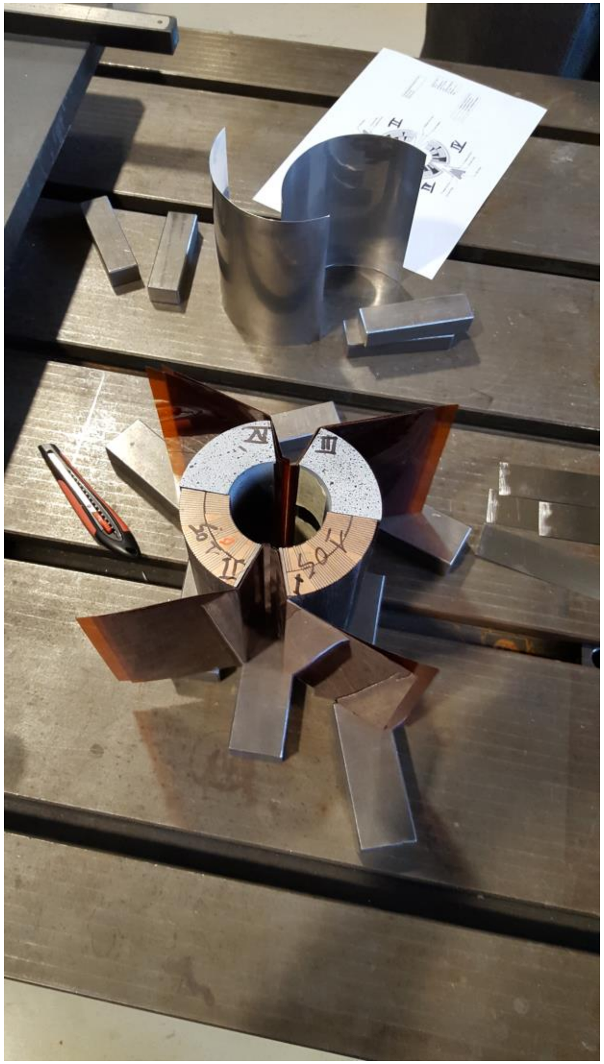
Deformation x50

Excess per half

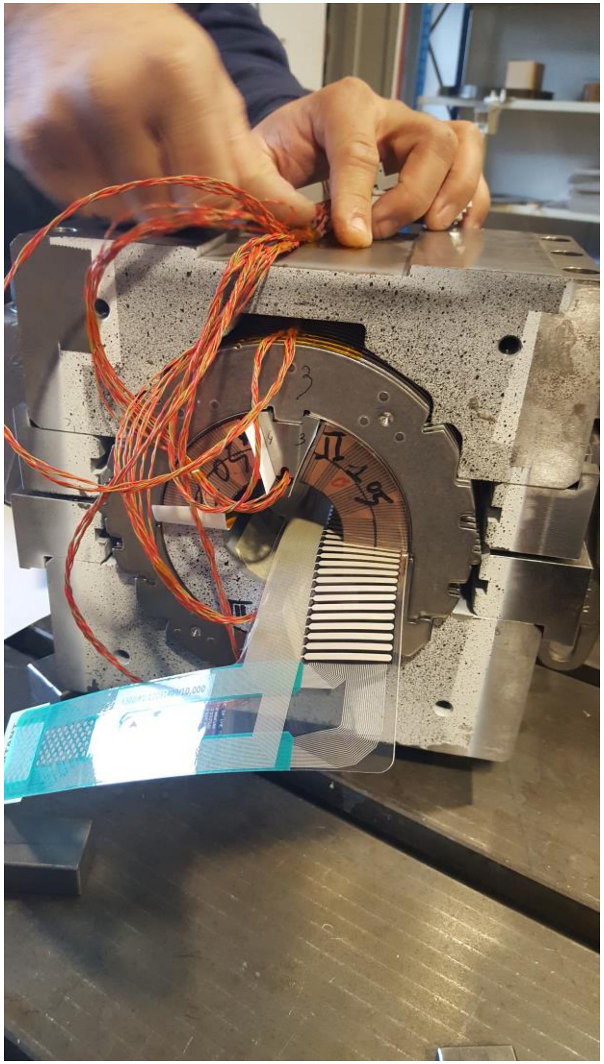


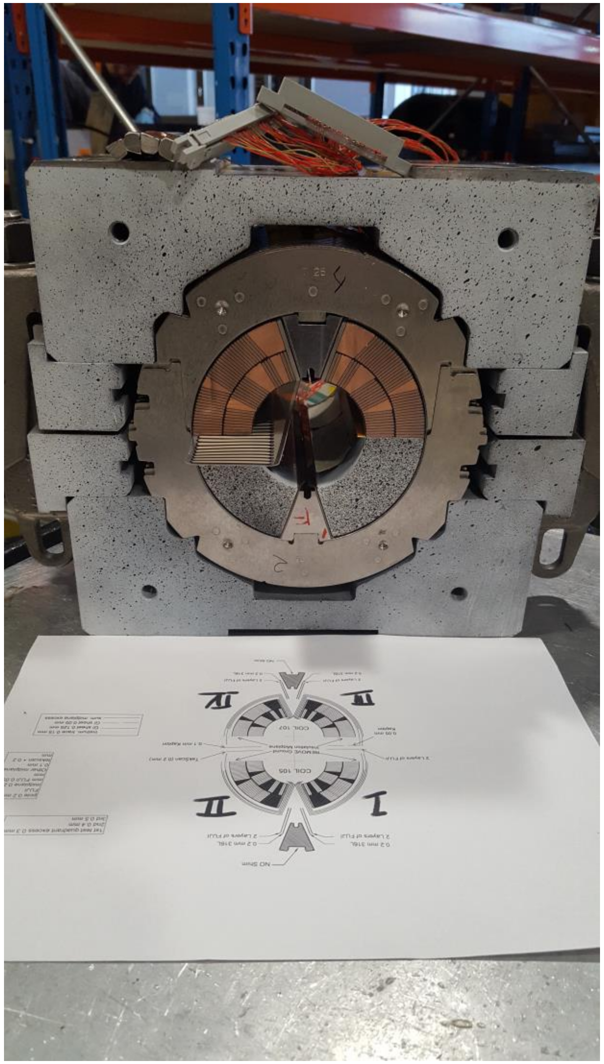


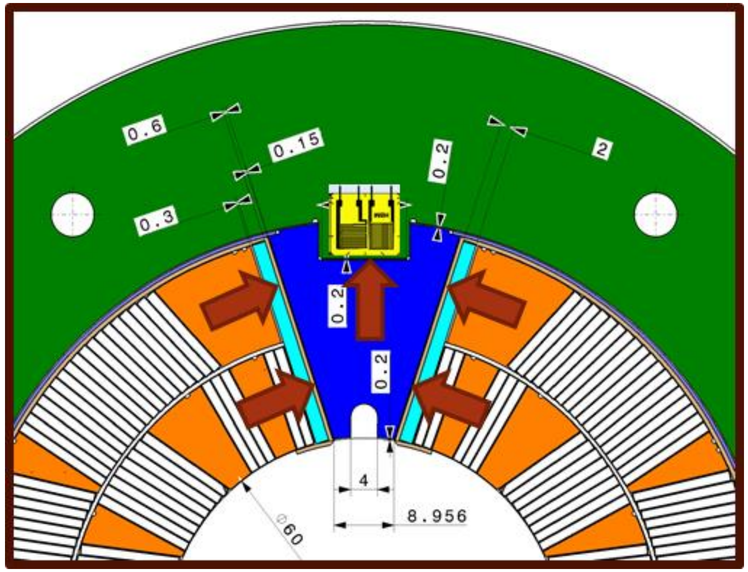
Collaring mock-up step 1

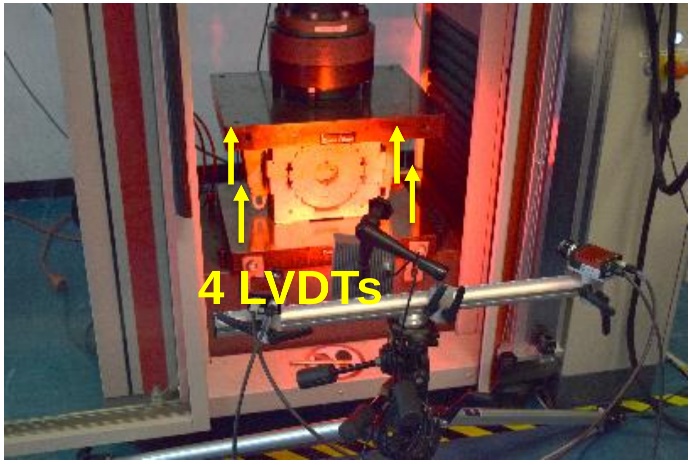


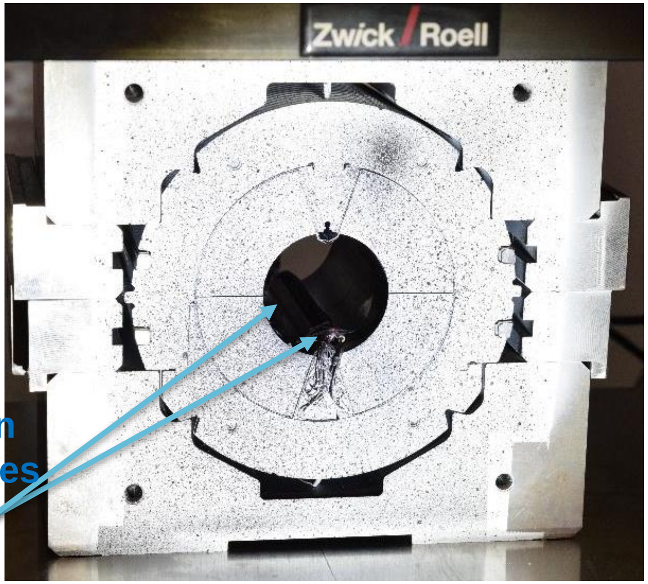
Collaring mock-up step 1











HiLumi HL-LHC PROJECT