Summary on coil production and assembly for the 11 T short models

Susana Izquierdo Bermudez on behalf of the 11 T team

7th March 2018

\MDP-FCC-EuroCirCol coordination meeting 04

Acknowledgments

- Coil fabrication
  - Jacky Mazet, Dominique Cote, Carlos Fernandes, Gregory Maury, Remy Gauthier, Juan Carlos Perez
- Metrology and coil rigidity measurements
  - Jose Luis Rudeiros Fernandez, Jose Ferradas Troitino, Salvador Ferradas Troitino, Alejandro Carlon Zurita
- Electrical tests
  - Francois-Olivier Pincot
- Instrumentation and magnet assembly
  - Nicolas Bourcey, Christian Hannes Loffler, Phillip Grosclaude, Michael Guinchard, Juan Carlos Perez, Paolo Ferracin, Michael Daly, Herve Prin, Friedrich Lackner
- Finite element models and data analysis
  - Christian Hannes Loffler, Emelie Kristina Nilsson, Giorgio Vallone, Paolo Ferracin
- …and
  - Frederic Savary, Arnaud Devred, Luca Bottura, Ezio Todesco, Giancarlo Spigo
  - Mikko Karppinen, David Smekens, Bernhard Auchmann, Alexander Zlobin

Overview

- Coil fabrication
  - Overview on new features.
  - Winding
  - Curing
  - Reaction
  - Impregnation
  - Coil geometry
  - Coil stiffness
  - Electrical robustness
  - Remaining issues
- Magnet assembly
  - Collaring
  - Shell welding
  - Axial loading

Overview

- **Coil fabrication**
  - **Overview on new features.**
  - **Winding**
  - **Curing**
  - **Reaction**
  - **Impregnation**
  - **Coil geometry**
  - **Coil stiffness**
  - **Electrical robustness**
  - **Remaining issues**
- Magnet assembly
  - Collaring
  - Shell welding
  - Axial loading

In total we did:
- 4 x practice coils (101-104)
- 12 x RRP coils (105-109, 111-117)
- 2 x test coils (110, 201)

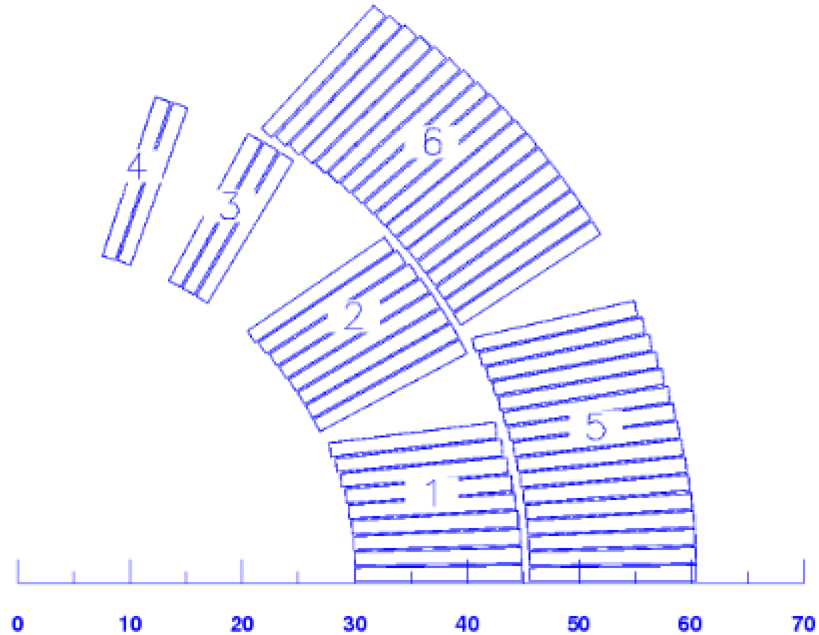
On going:
- 5 x RRP coils (118-122)

Material in stock to produce:
- 5 x PIT coils

[Juan Carlos Perez]

Reminder on coil design

- 56 turns coil
  - 22 Inner Layer, 34 Outer Layer
- Insulation layout: 80-µm-thick C-shaped Mica film and a braided sleeve made of S2-glass fibers
- Original target insulation thickness:
  - 100 µm at 30 MPa pressure
  - For the short models coils, the actual insulation thickness was 107 µm – 114 µm at 30 MPa (0.130-0.135 mm at 5 MPa) (14x2x34 µm = 0.95 mm of over-thickness in the outer layer!)
  - All short model coils produced up to the date and the prototype coils have been done using this insulation layout.
- Revised target insulation thickness (Nov. 2017):
  - 100 µm at 5 MPa pressure
  - Will be implemented in all the future short model coils (and the series magnets)
  - We gain 35x2x34 µm = 0.95 mm



Before Nov. 2017

25 mm Mica tape
6.9 mm gap

After Nov. 2017

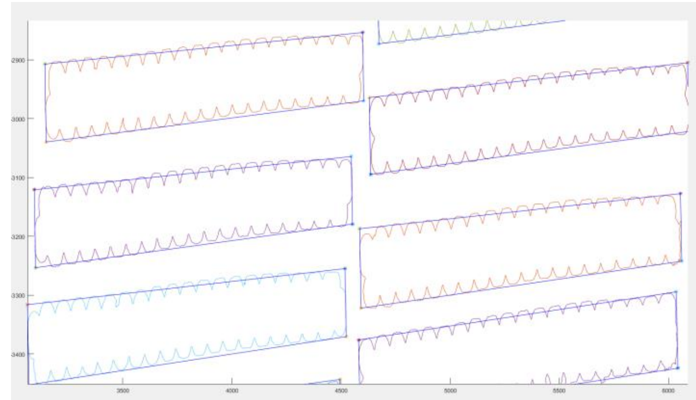
31 mm Mica tape
0.9 mm gap

[Christian Hannes Loffler, Emelie Nilsson]

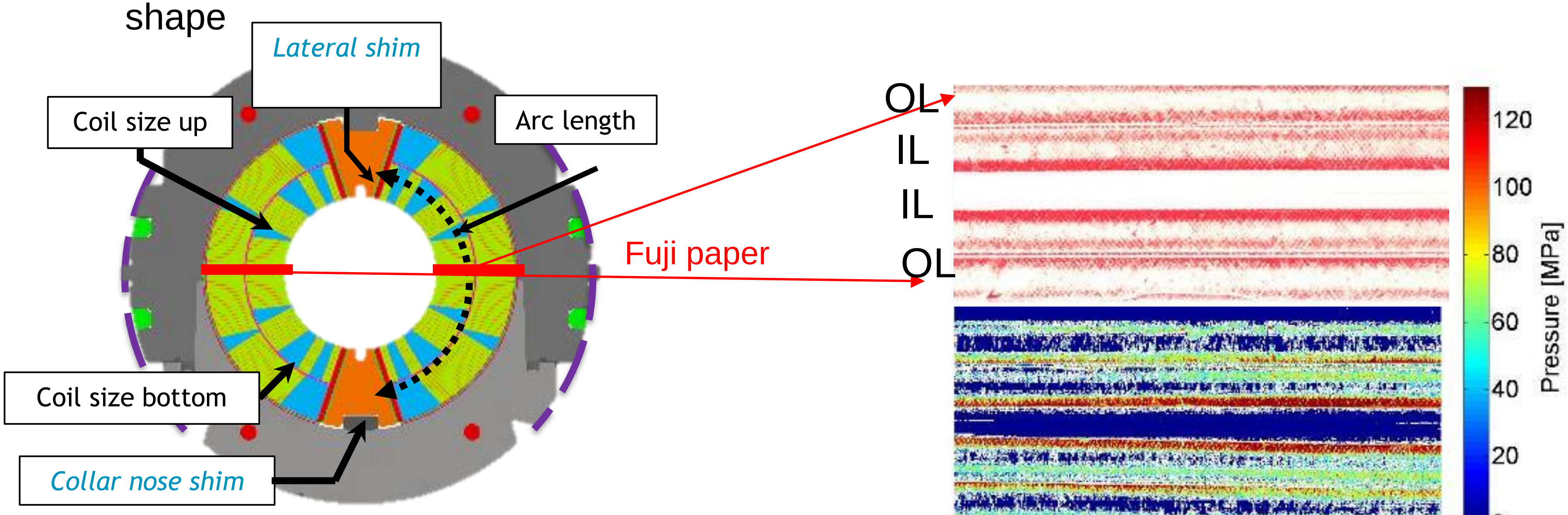
Overview on new features - Insulation

- Cables seem to be systematically 'bent', in the upward direction
- MICA is C-shaped with an opening on the top side (coincidence?)

https://indico.cern.ch/event/677887/



- Stress concentration on the cable edges, which seems to be related to the Mica C-shape



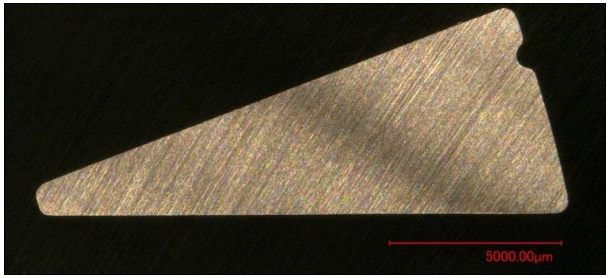
https://indico.cern.ch/event/641884/
https://indico.cern.ch/event/641886/

120 MPa stress gradient on the mid-plane in MBHSP105b

[Christian Hannes Loffler, David Smekens]

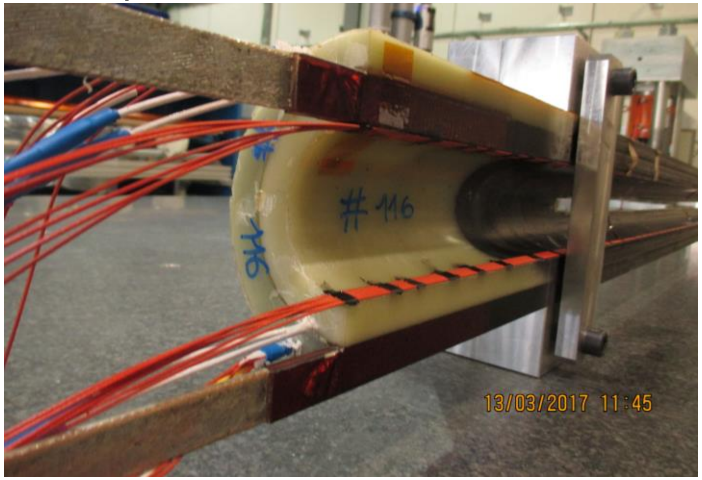
Overview on new features - Materials

ODS copper, adopted also for MQXF (nicest feature: thermal contraction closer to the coil so wedge gaps can be minimized)

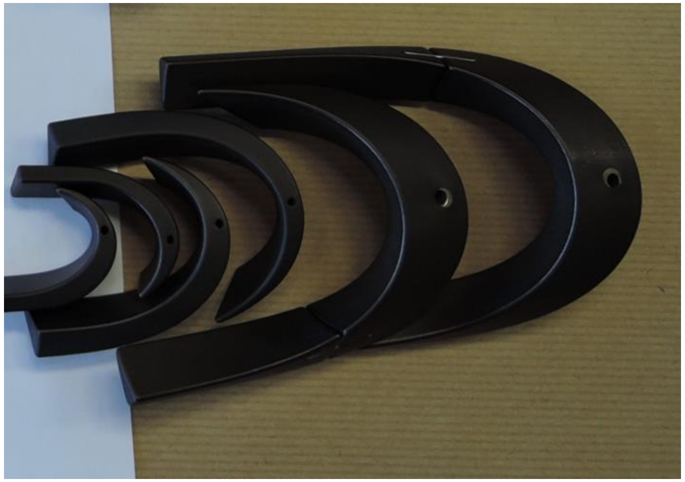


EDMS document 1216580

G11 end saddles. Simplifies significantly the insulation layout in the connection region. The material is softer (more displacements of the coil ends during powering), but did not show up as a performance limitation.



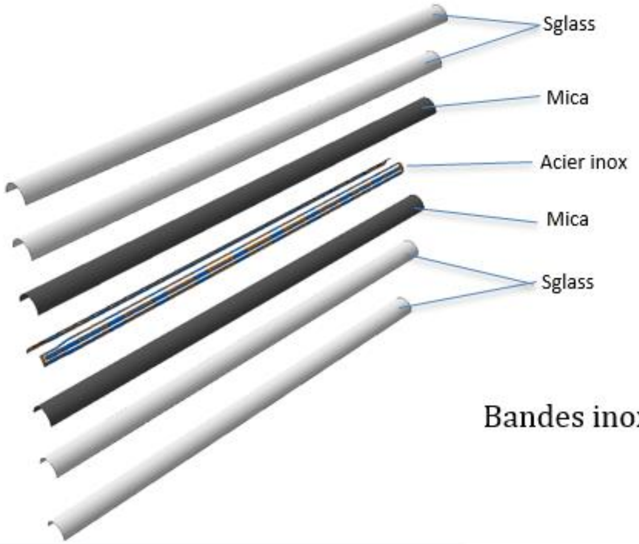
40 µm Al_2O_3 PVD coating
Not considered for the series production due to the very high cost.



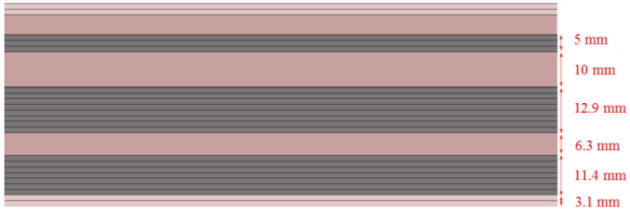
[Jacky Mazet]

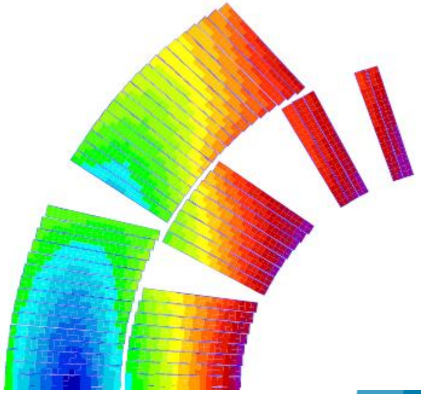
Overview on new features

- Inter-layer quench heaters were installed in 4 coils (2 tested at cold in MBHSP106)
- Electrically robust solution
- One out of the four circuits tested in MBHSP106 was lost after thermal cycle, and one more during a heater powering at “high” current.
  - Limited performance with the initial (conservative) powering parameters.



Bandes inox

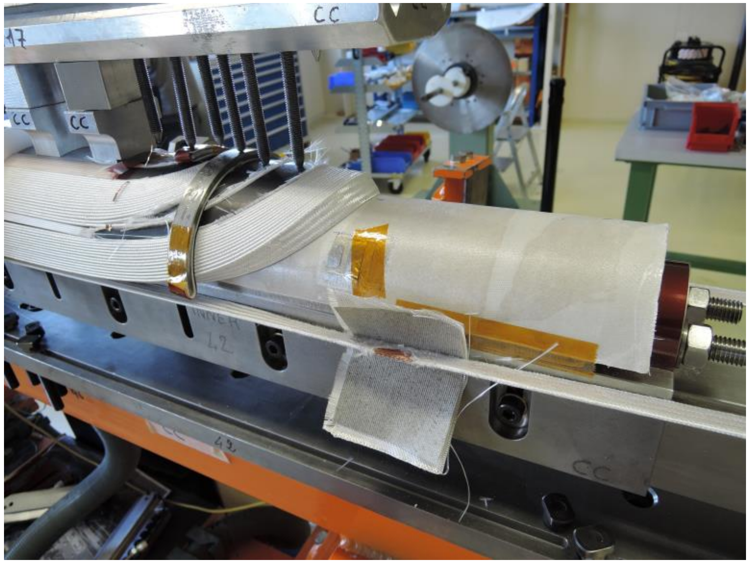


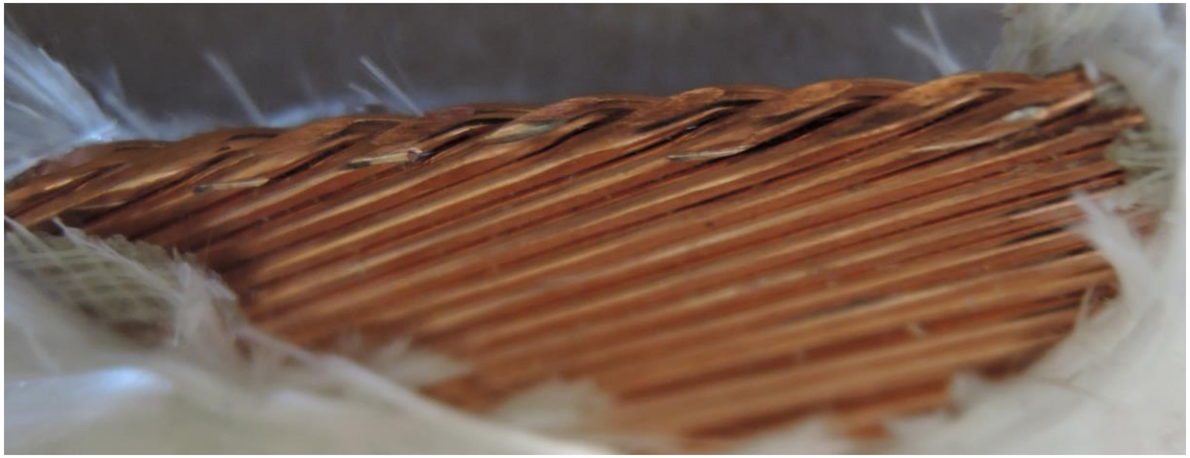


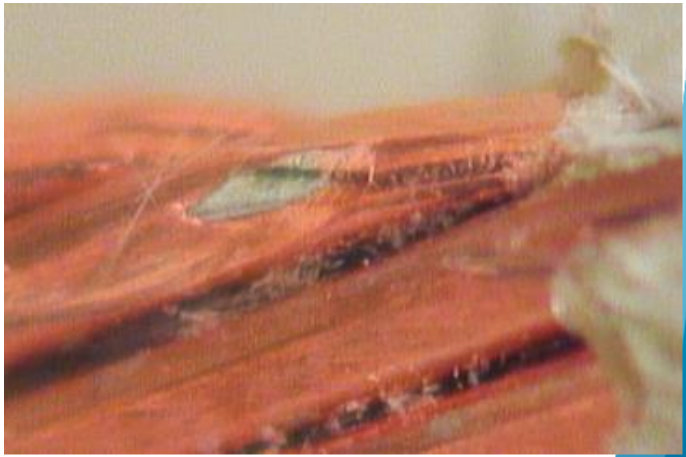
[Jacky Mazet, Carlos Fernandes]

Winding

- In general, winding OK
- Coil 117 was heavily damaged during winding, in the outer layer, last turn of the connection side.
  - The field is low there, but the damage was important, but we were not limited in that cold, we reached 13.2 kA! (third thermal cycle on-going)



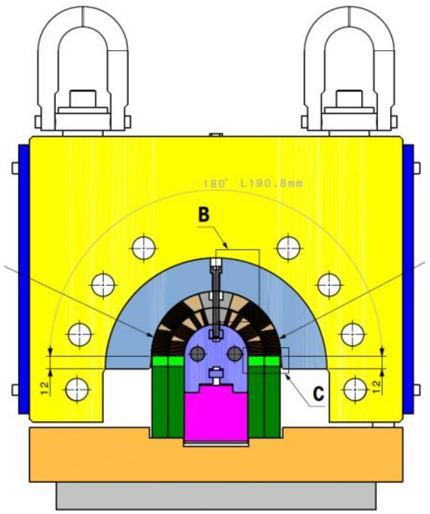




[Jacky Mazet, Carlos Fernandes]

Curing

- Nominal cavity size/turn
    - Reacted design cable thickness + 2*design insulation thickness
    - 1.306+2*0.1 = 1.506
- Size of unreacted turn
    - Un-reacted actual cable thickness + 2 * measured insulation thickness at 5 MPa
    - 1.25 + 2*0.135 = 1.520
- Missing free space in the reaction and curing cavity
    - 0.014 mm/turn → 0.476 mm missing in the OL!

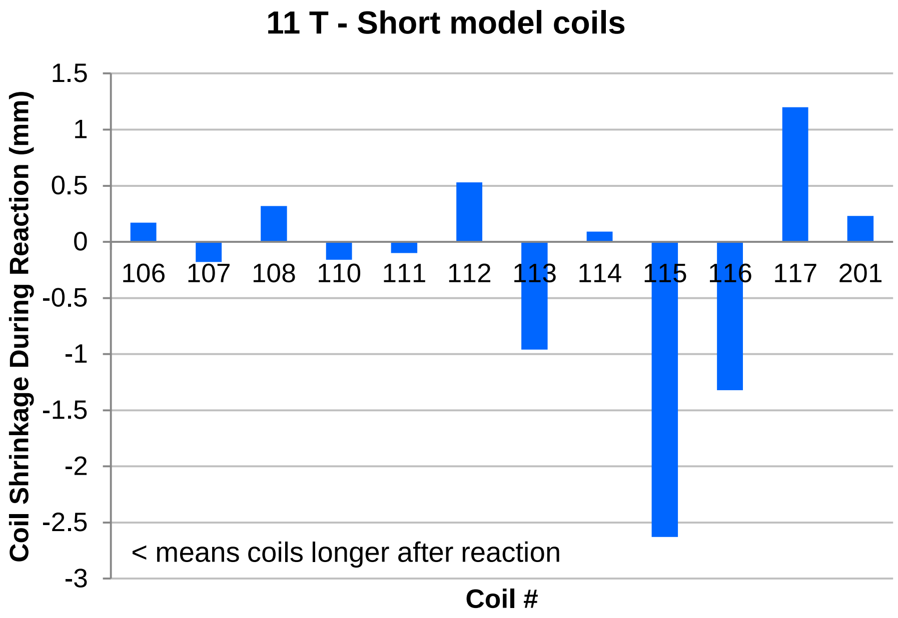


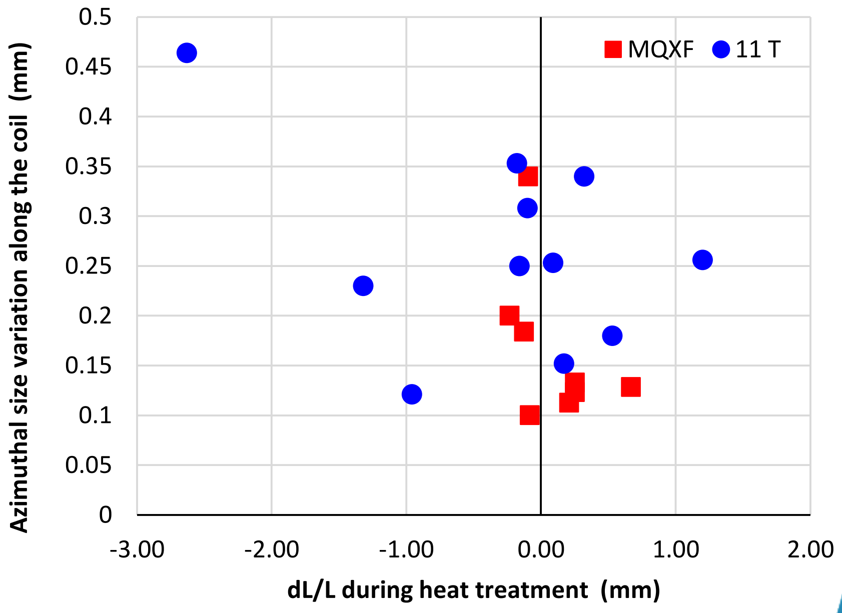
- Before coil 108, coils were cured in the nominal cavity
- From coil 108 (included), coils were cured in a cavity 0.5 mm smaller than nominal.
    - This was done following the big difficulties to close the reaction and impregnation moulds in the first coils!

HiLumi HL-LHC PROJECT CERN

Reation

- During heat treatment, short model 11 T coils some times get longer!
- Coil that get longer after reaction (for example 115) also show a large variation of the azimuthal size along the coil length.



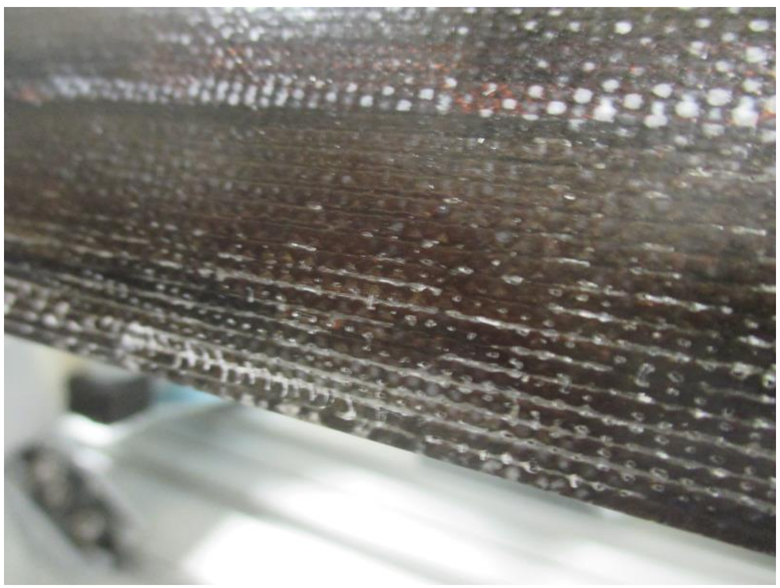


[Dominique Cote, Gregory Maury, Remy Gauthier]

Impregnation

- Only two coils (110 and 117) have been impregnated under pressure.
- Few coils show dry areas in the external and internal radius after impregnation, probably due to excessive radial compaction.

Coil 111, biggest coil in terms of azimuthal size that was tested

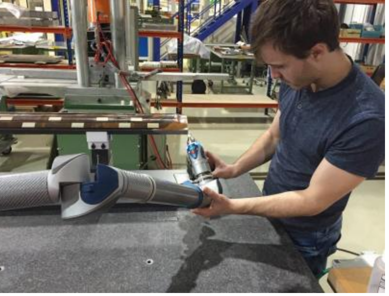


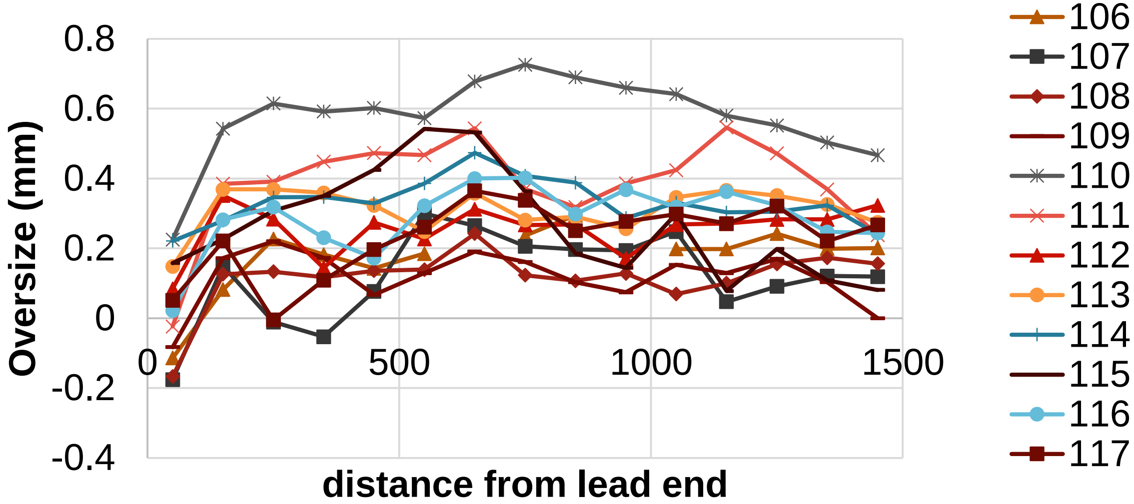
*Coil 114, coils with quite big defaults after impregnation which were repaired**

*From coil 114, “green paste” (OTOFORM) was replaced by silicon

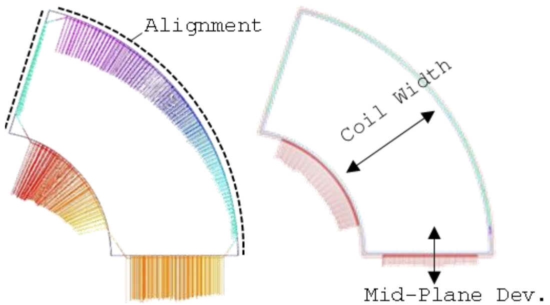
[Jose and Salvador Ferradas Troitino]

Coil size

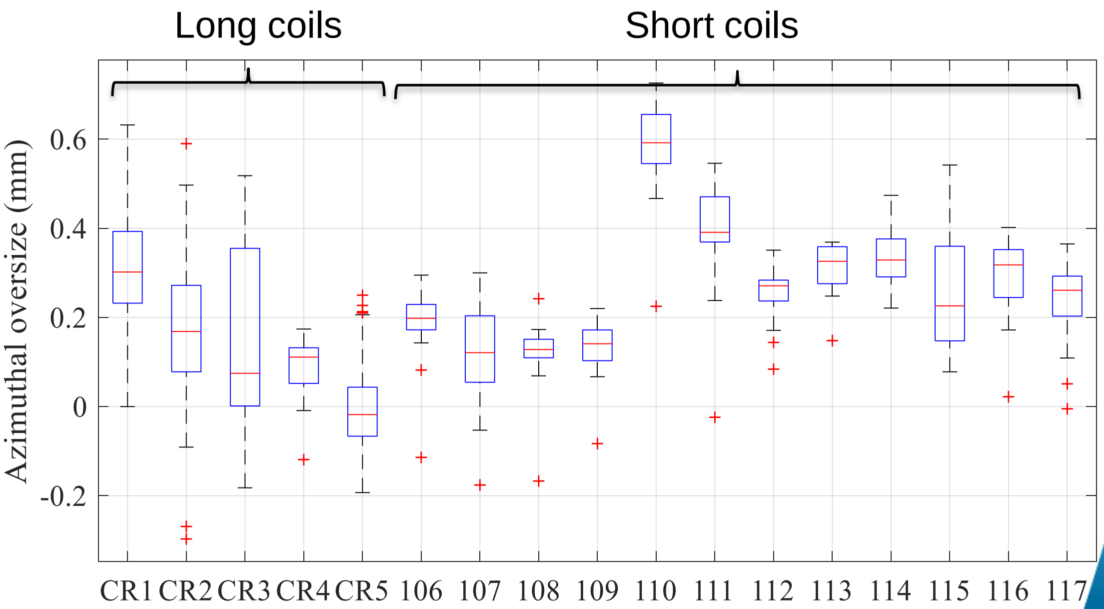




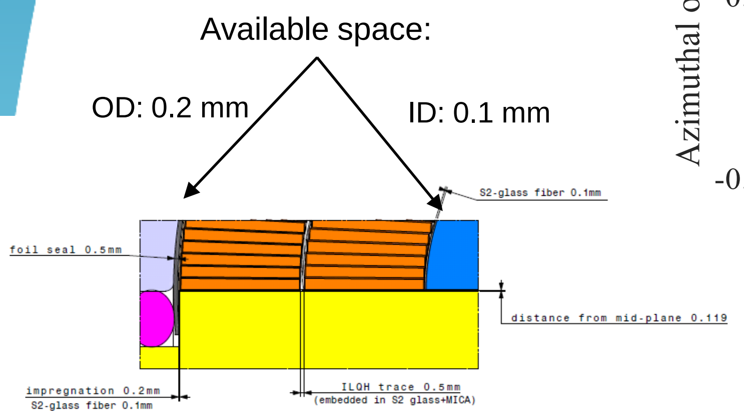
- Coil size quite not under control
- Difference among coils not critical (can be shimmed), but difference on size along the coil length is an issue.

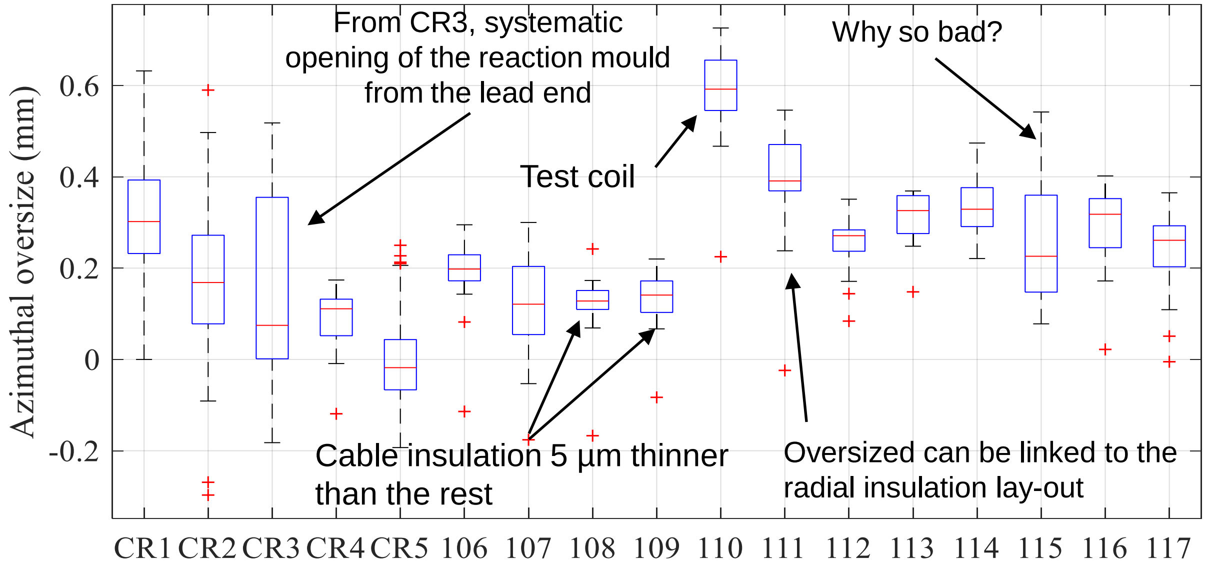


- We like to summarize coil size in this format:
  - Each box represents the eight cross sections measured per coil.
  - the central line corresponds to the median
  - the edges of the box are the 25th and the 75th percentiles
  - the whiskers extend to the most extreme data points.



- Is there a correlation of coil size with manufacturing parameters?





Coils limited close to the layer jump: 107 (11.9 kA), 113 (11.7 kA)

Coils limited in the mid-plane: 109 (11.4 kA),115 (12.4 kA)

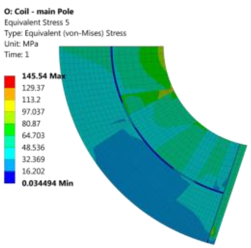
Coil limited in IL block 3: 116 (13.2 kA)

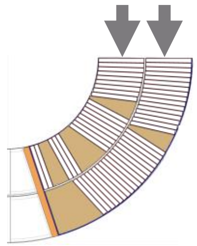
		106	107	108	109	110	111	112	113	114	115	116	117
OL	nothing	X			X								
	0.2 mm S2 glass						X						
	0.1 mm S2 glass		X	X									
	0.08 mm E glass							X	X				
	QH + 0.08 mm E glass					X				X	X	X	X
InL	0.5 S2 glass	X	X	X	X	X	X	X	X	X	X		
	0.5 mm S2 + Mica + QH											X	X
IL	nothing	X											
	0.15 mm S2 glass						X						
	0.1 mm S2 glass		X	X	X								
	0.08 mm E glass					X		X	X	X	X	X	X

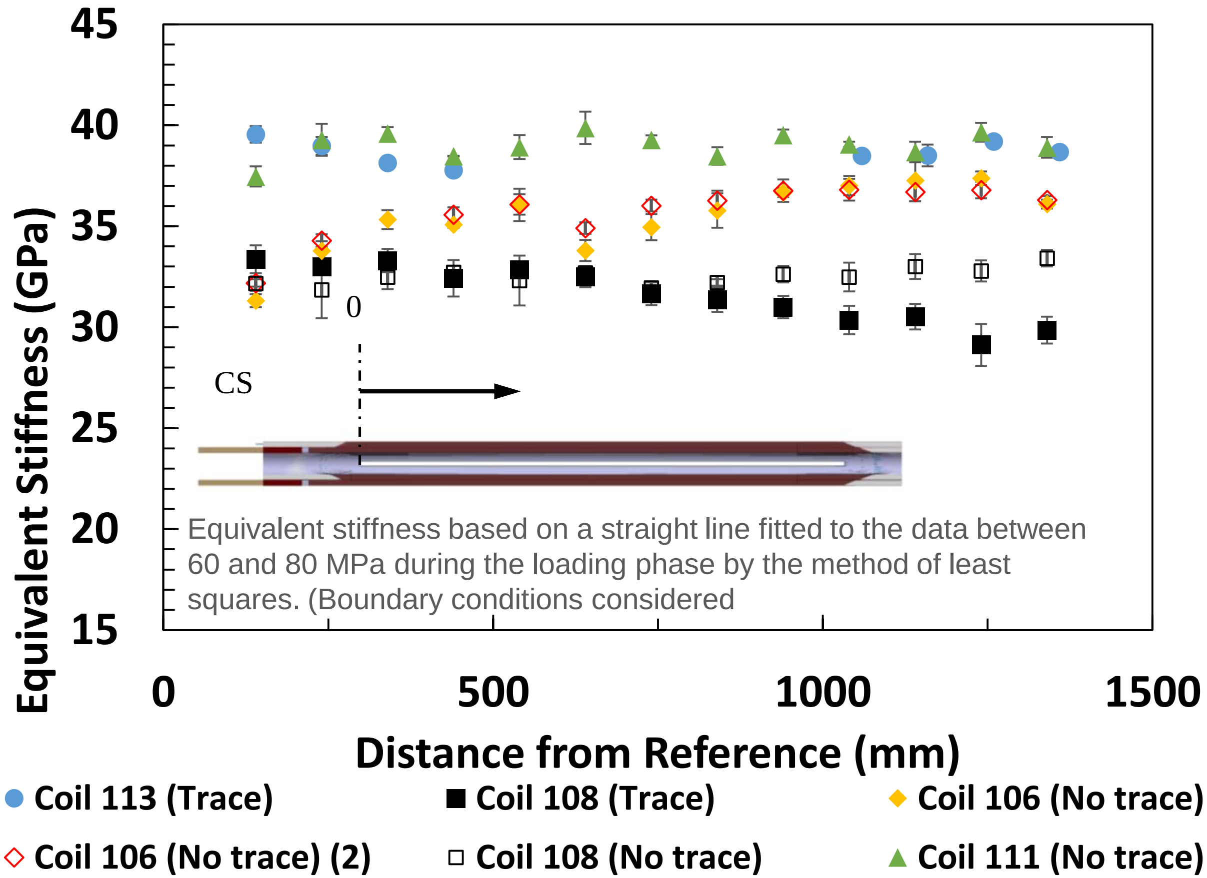
[Jose Luis Rudeiros Fernandez]

Coil stiffness

- Coil rigidity (including wedges) 33 – 39 GPa (~25 % lower when removing the contribution of the wedges)
- Some coils show a non-negligible variation of the coil rigidity along the length.
- Only coils after cold powering test have been measured (virgin coils will be measured soon).







[Francois Olivier Pincot]

Electrical robustness

- Rather low testing voltage for short model coils
  - All coils passed the 1 kV discharge test
  - All coils passed the 1 kV insulation coil to ground and quench heaters to ground, and quench heater to coil test.
  - In most of the coils, weak electrical insulation between coil and loading plate

- Coil 110 was pushed to the limit, to verify the electrical robustness:
  - Coil discharge test: ok up to 7kV (limit of the device)
  - Insulation:
    - Inter-layer quench heaters to coil: ok up to 8 kV
    - Outer layer quench heater to coil: ok up to 7 kV (connectors)
    - Loading plate to coil: ok up to 1.5 kV

https://indico.cern.ch/event/395351/

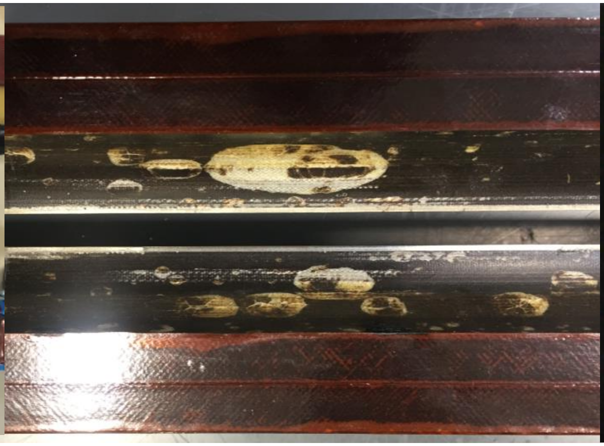
Remaining issues

- Coil size
  - Hopefully will be partially solved thanks to the thinner insulation, i.e., less compacted coils.

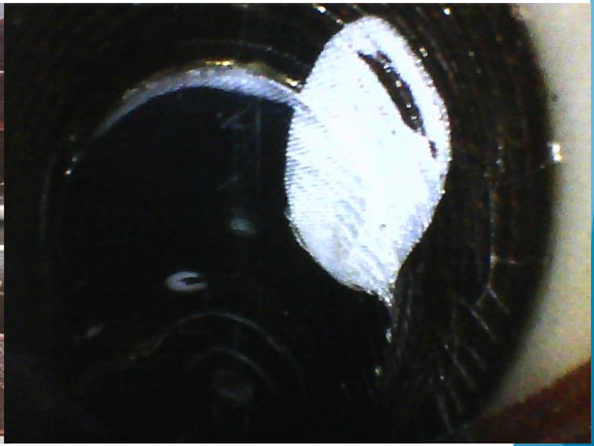
- Glass to coil delamination, mainly starting on the metal to resin surfaces.
  - Main concern: damage on the electrical insulation.
  - Original explanation: trapped superfluid helium trying to get out from the coils after quench is not the source of the bubbles.

Typical bubbles on 11 T coil ends after cold powering test

Defects also observed in the straight section
(mainly 111, biggest coil we tested, see additional slides)



Detachment observed in SP106 after test at 4.5 K



https://indico.cern.ch/event/693840/
https://indico.cern.ch/event/664529/

Overview

- Coil fabrication
  - Overview on new features.
  - Winding
  - Curing
  - Reaction
  - Impregnation
  - Coil geometry
  - Coil stiffness
  - Electrical robustness
  - Remaining issues
- **Magnet assembly**
  - Collaring
  - Shell welding
  - Axial loading

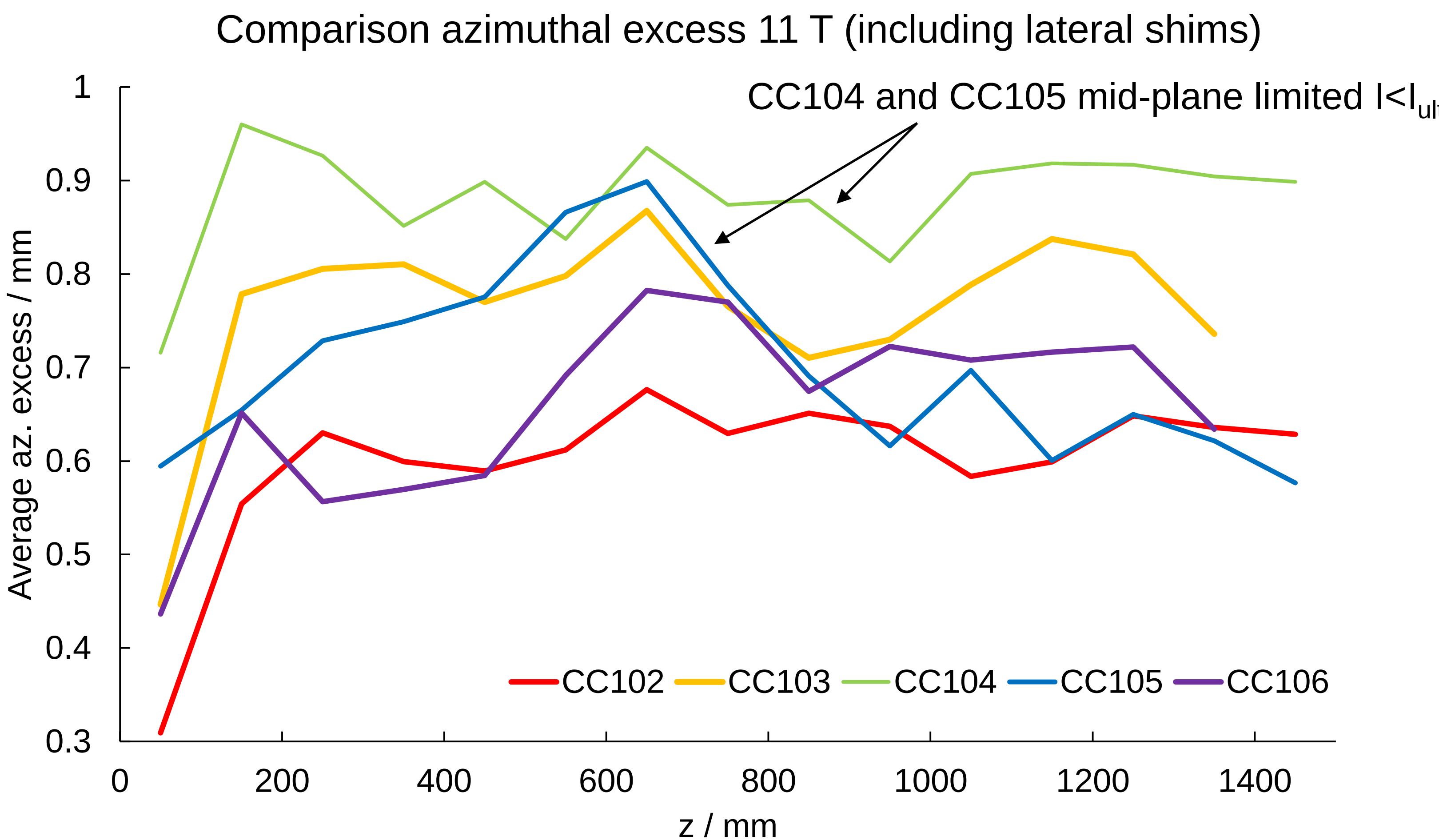
[Juan Carlos Perez]

In total we did:
- Six single aperture models
- Two double aperture

Coming soon:
- Two single aperture models

[Christian Hannes Loffler and Emelie Nilsson]

Average excess in the tested assemblies



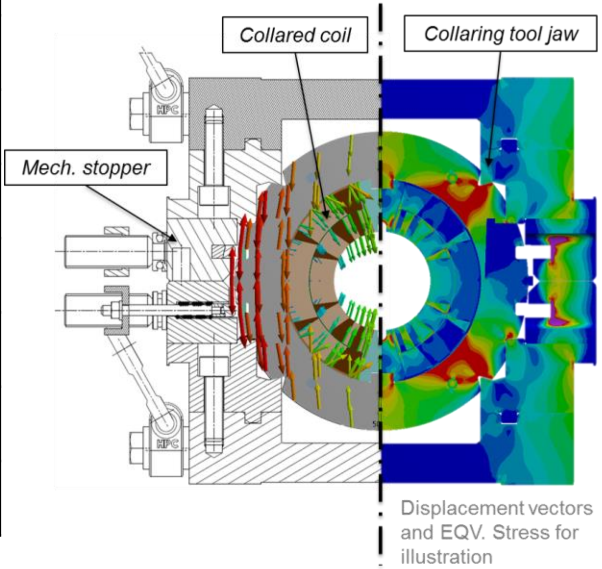
[Nicolas Bourcey, Christian Hannes Loffler, Juan Carlos Perez]

Collaring

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

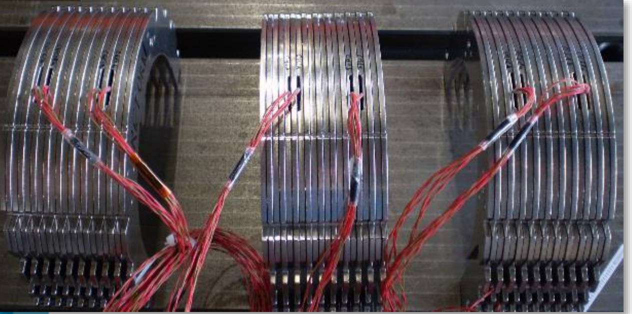
	Average Excess Quadrant	Applied Force / MN	70 mm stopper deviation / mm
CC101	0.31	32	+0.1
CC102	0.29	32	+0.1
CC103	0.38	32	+0.1
CC104	0.45	22	-0.15
CC104b	0.35	20	-0.15
CC105	0.35	16	-0.15
CC105b	0.30	20	-0.15
CC106	0.33	12	-0.15

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

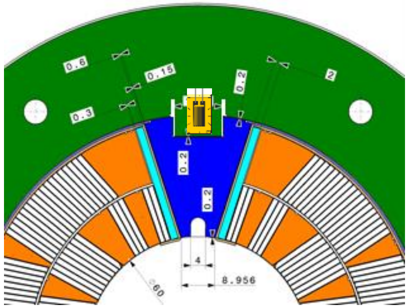


Displacement vectors and EQV. Stress for illustration

Collaring

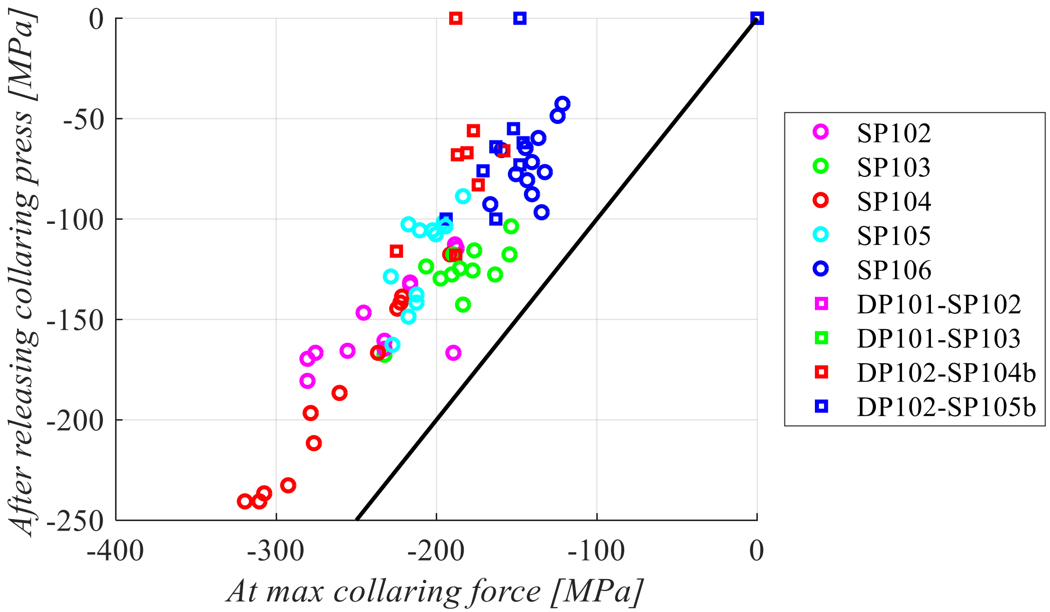


[Phillip Grosclaude, Michael Guinchard]



Strain gauge measurements on the collar nose

- In total, 24 instrumented collars per collared coil (3 instrumented sections: connection side, centre of the magnet, non connection side, with eight instrumented collars per section)
- Clearance needed for keys insertion during collaring ≅ 0.150 mm
- Spring-back is around 60MPa in the collar nose, which corresponds to around 20MPa on the coil
- Large dispersion of the data!

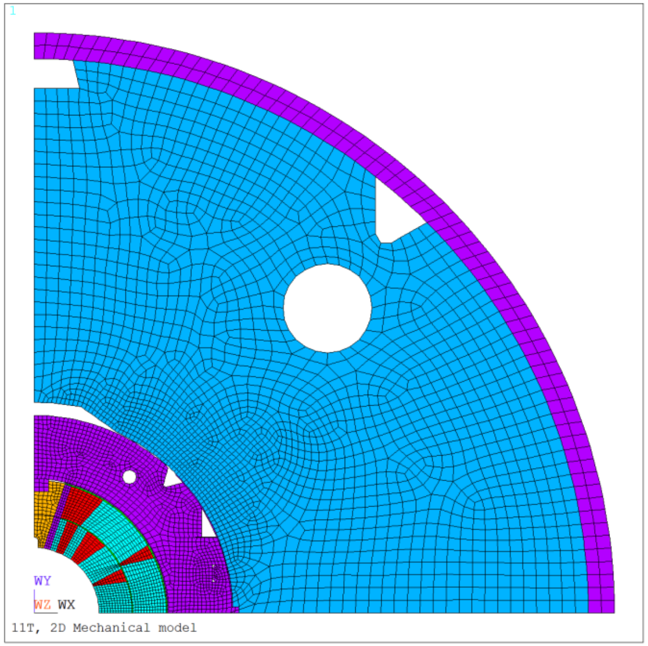


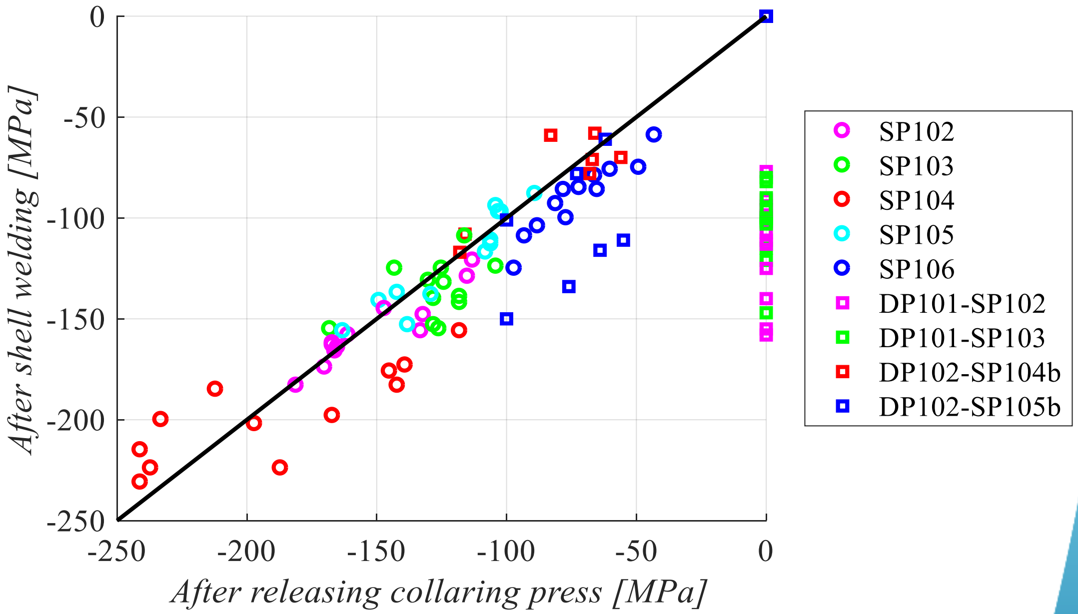
$y = 0.9144x + 60.42$; $R^2 = 0.823$

Forcing the slope to 1: $y = x + 77$;

Shell welding

- Yoke gap closes during welding
- Small increase on the stress on the coil (<10 MPa) during welding



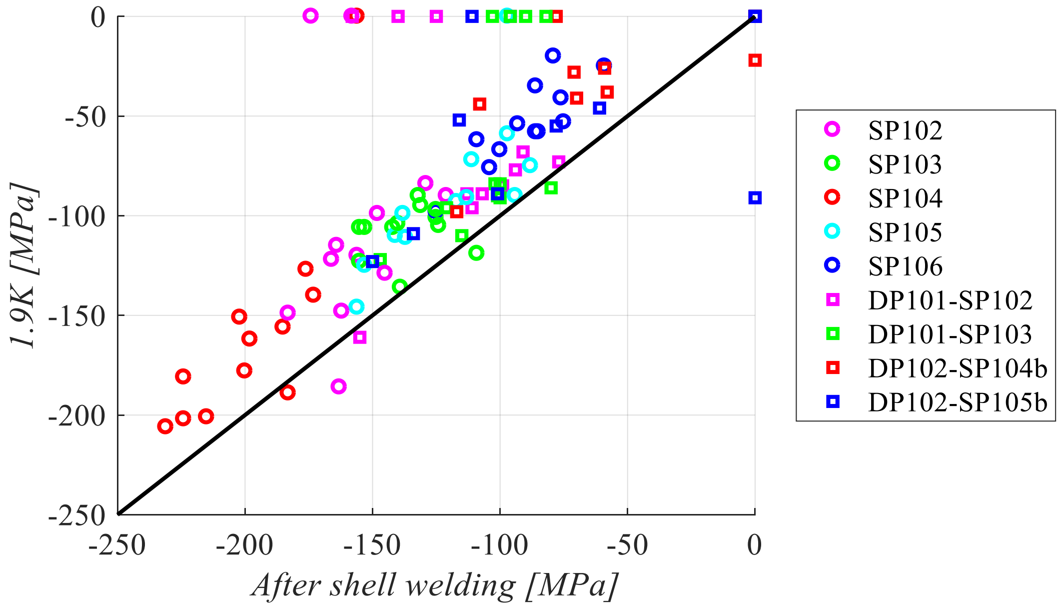


y = 0.8283x - 30.124; R^2 = 0.8403

Forcing the slope to 1: y = x -10;

Cool down

- Slight loss (≅ 25 MPa in the collars, i.e., less than 10 MPa in the coil) of pre-stress due to cool down.



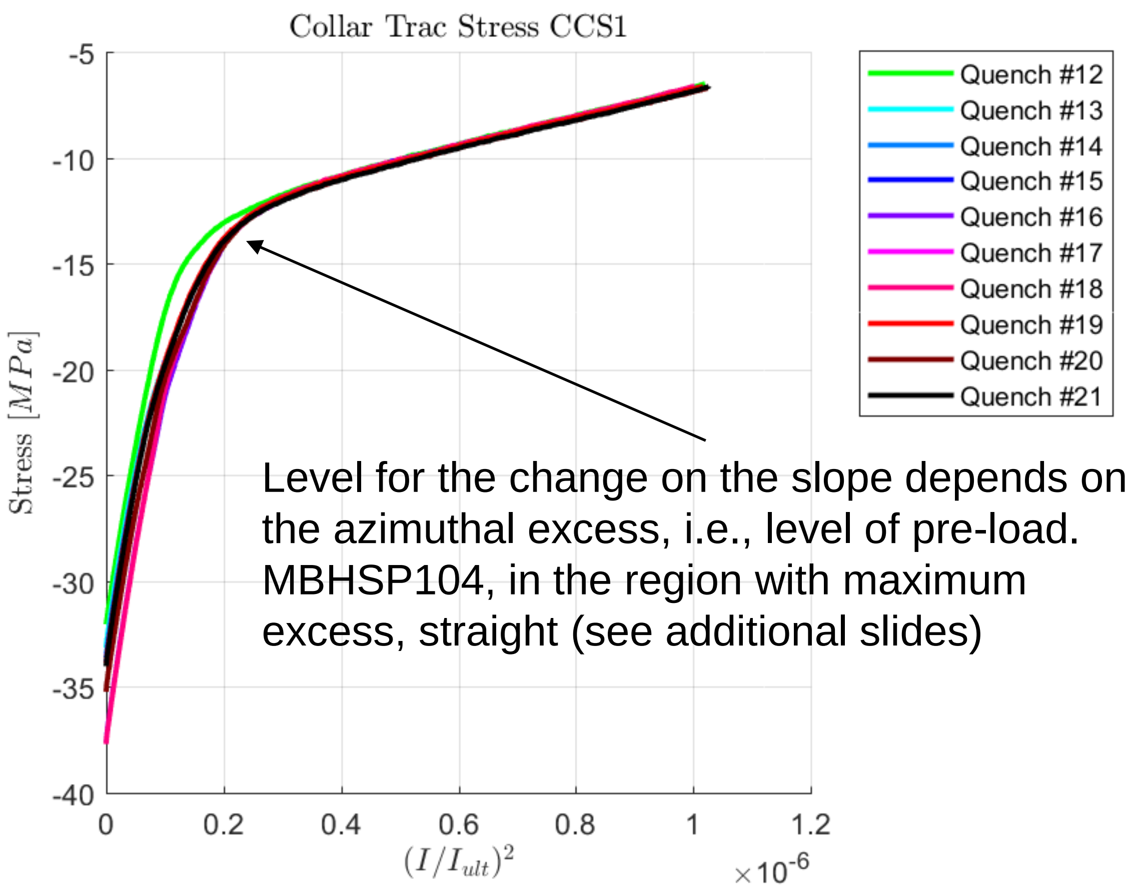
y= 0.9706x + 23.008; R^2 = 0.8559

Forcing the slope to 1: y = x + 26;

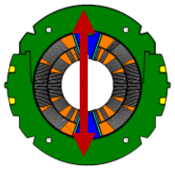
Powering

MBHSP106

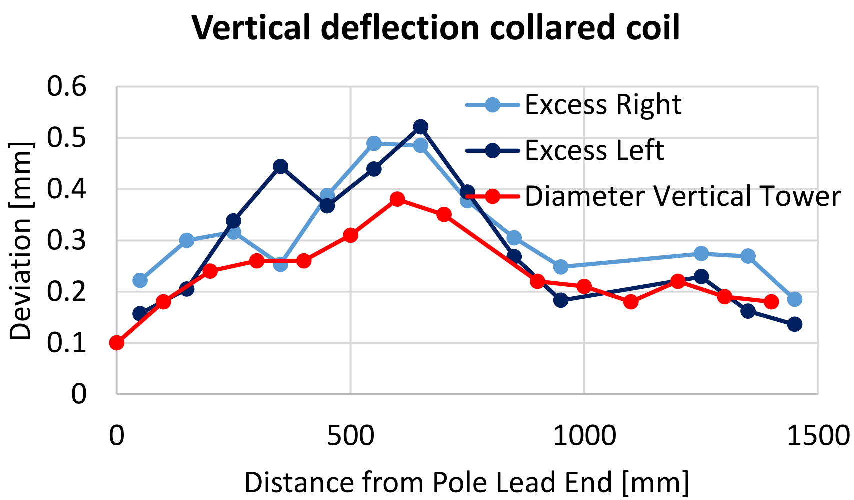
(magnet with lower pre-stress, I_{max} = 13.2 kA)

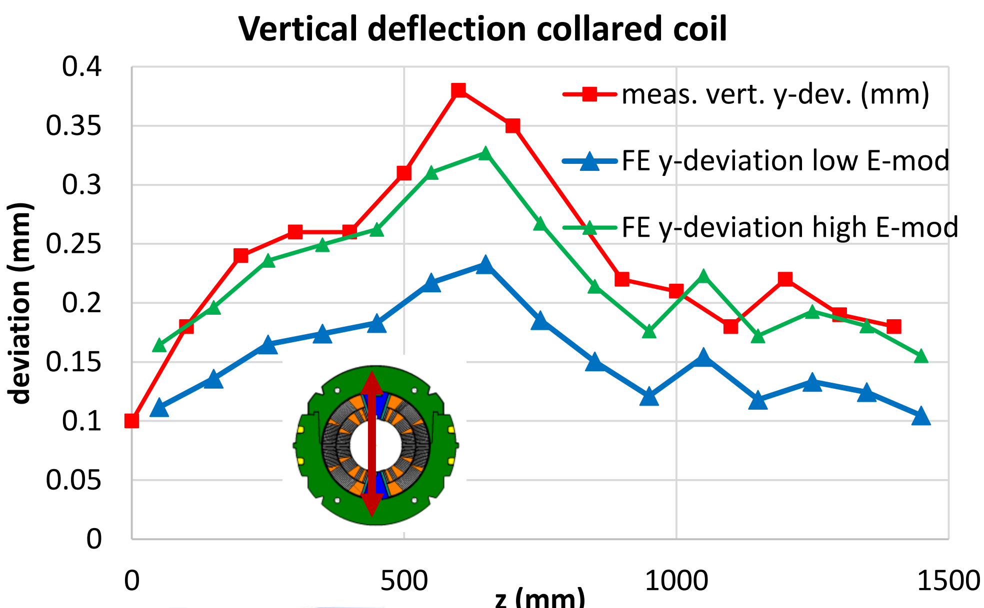


Collared coil vertical deflection – SP105 case

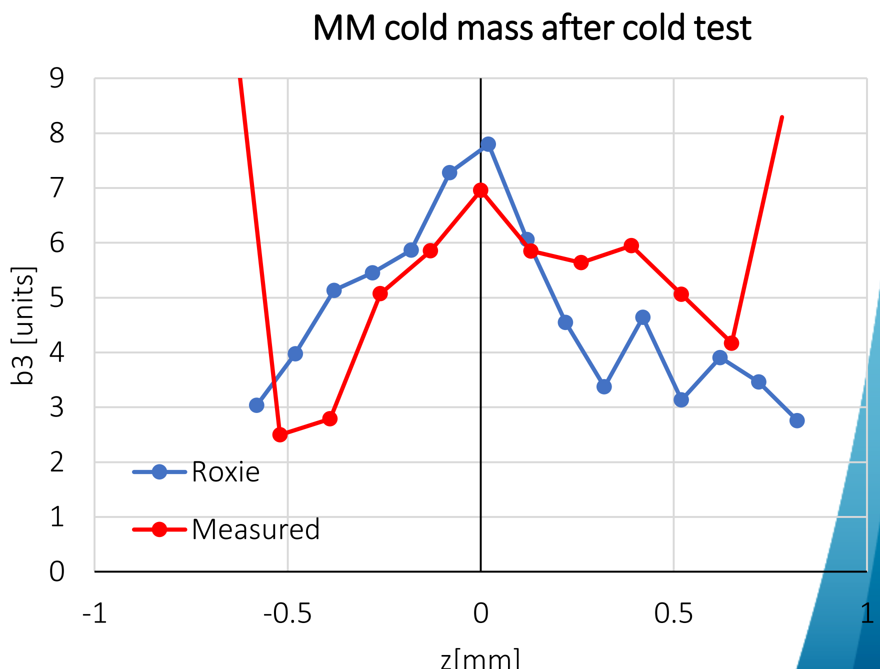


- Measured vertical of the collard coil consistent with the coil azimuthal size.
- Effect on field quality (sextupole) consistent with expectations.
- The derived rigidity of the coil with these measurements is around 40 GPa



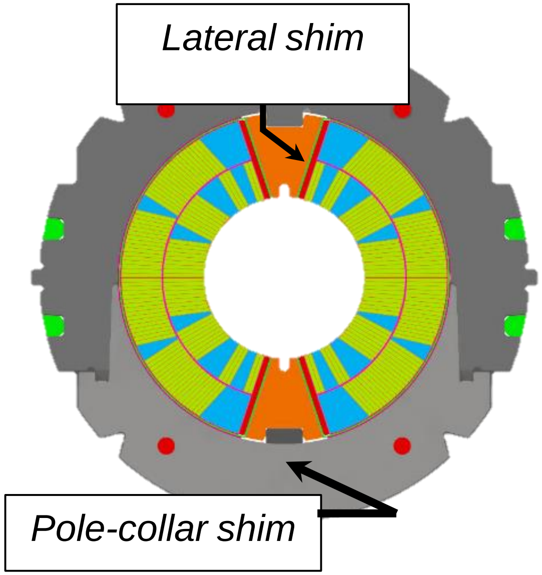


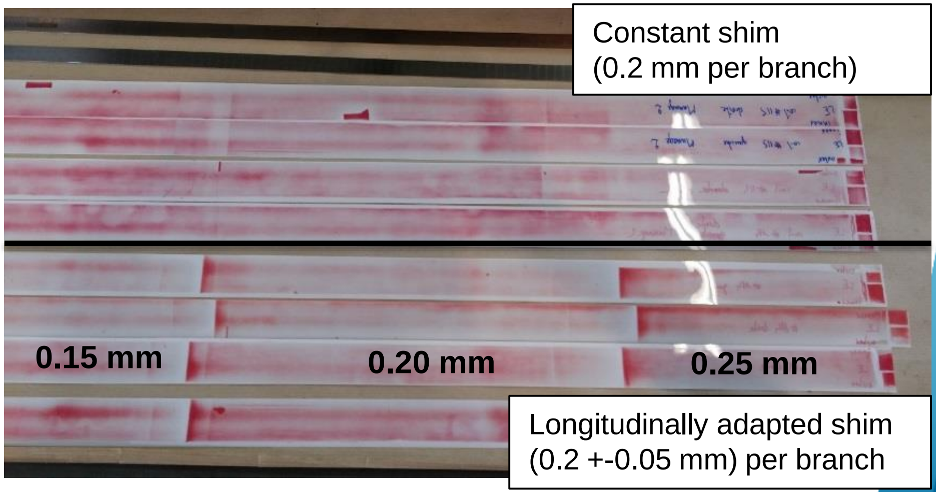
Low E-mod = 20 Gpa
High E-mod = 40 GPa



Lessons form Fuji assemblies

- Stress concentration on the edges of the mid-plane turns.
- Radial contact coil to collar is rather uniform.
- Attempt to adjust variation of pre stress with graded pole-collar shim in SP106, but discarded due to elevated strain gauge stresses in collar nose at collaring in the enhanced area (connection side) and Fuji paper imprints.





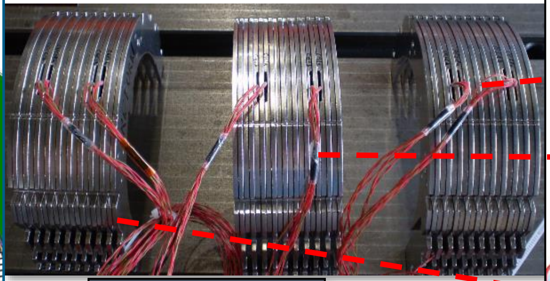
Conclusions and final remarks

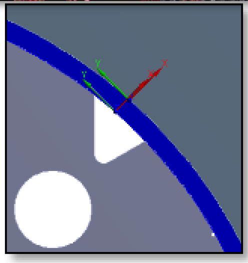
- The high compaction of the 11 T coils have been addressed by reducing the thickness of the insulation.
  - Hopefully this will solve most of our coil-manufacturing problems.
- The layer jump – transition to coil ends remains a delicate region (several coils limited at cold).
- Some coils with large manufacturing defects did were not limited at cold.
- Detailed analysis on assembly on-going to optimize parameters.

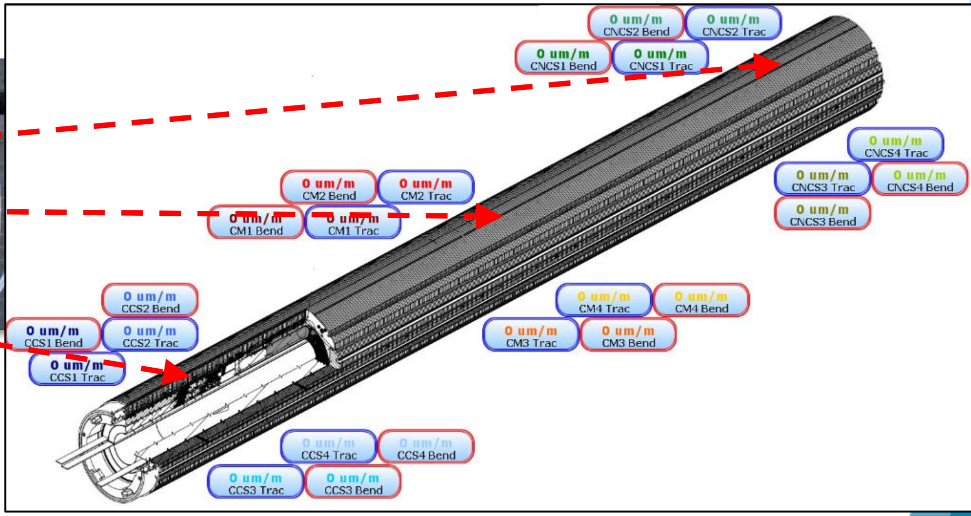
Additional slides

Instrumentation

- The short model magnets are instrumented with strain-gauges
  - Instrumented collar packs on each extremity and center equipped with 8 gauges each
  - Shells on inner and outer radius
  - Magnet extremities with 4 bullet gauges per side
- Pressure sensitive film (FUJI) provides insight on stress distribution across the pole wedge, outer diameter of coil, and midplane during collaring at room temperature





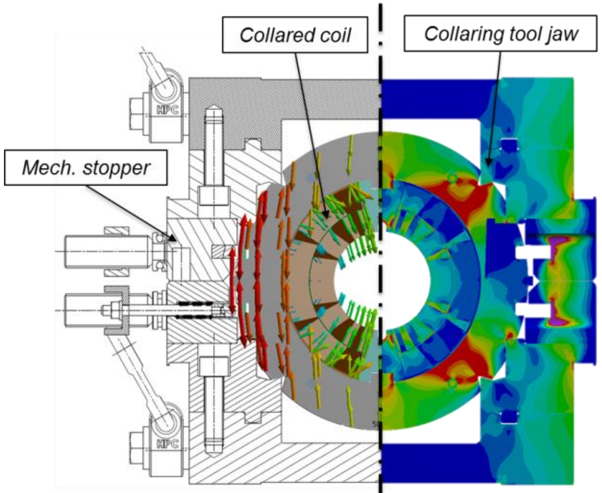


Analysis of collaring
"Old slide"

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

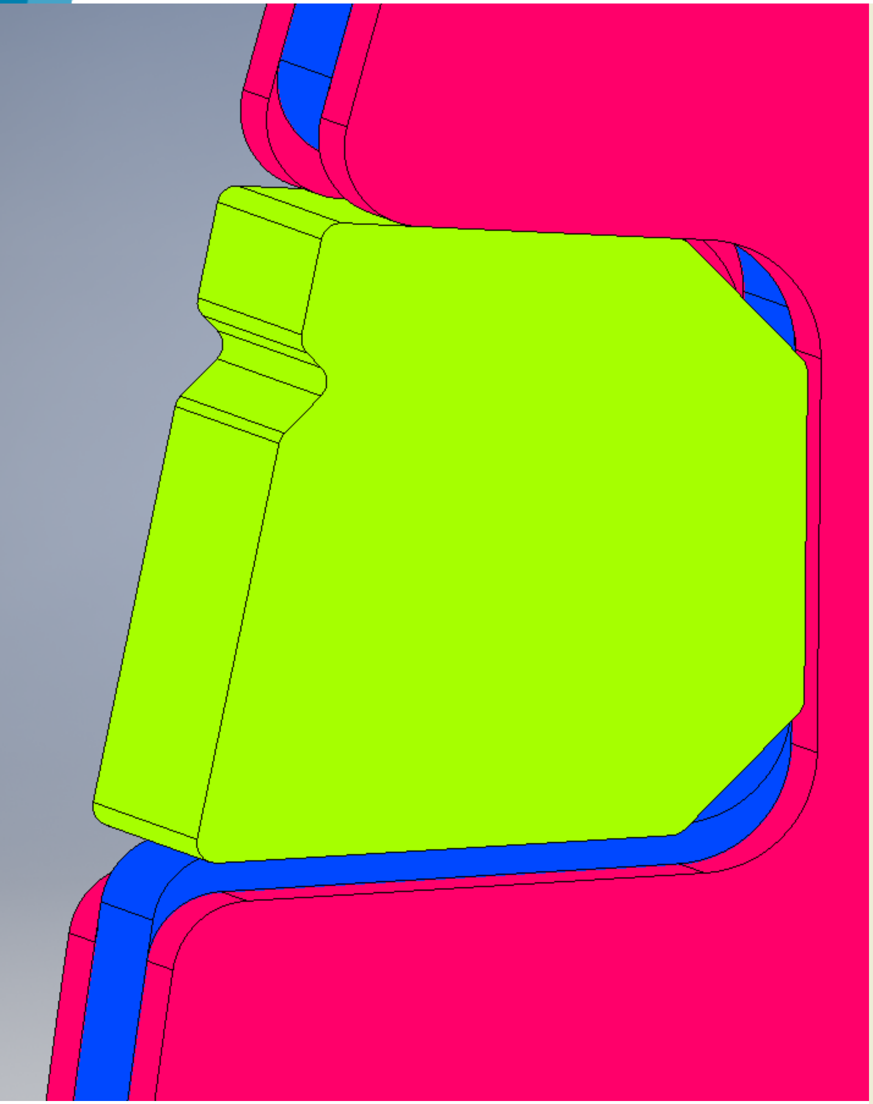
	Average Excess Quadrant	Applied Force / MN	70 mm stopper deviation / mm
CC101	0.31	32	+0.1
CC102	0.29	32	+0.1
CC103	0.38	32	+0.1
CC104	0.45	22	-0.15
CC104b	0.35	**20**	-0.15
CC105	0.35	16	-0.15
CC105b	0.30	**20**	-0.15
CC106	0.33	12	-0.15

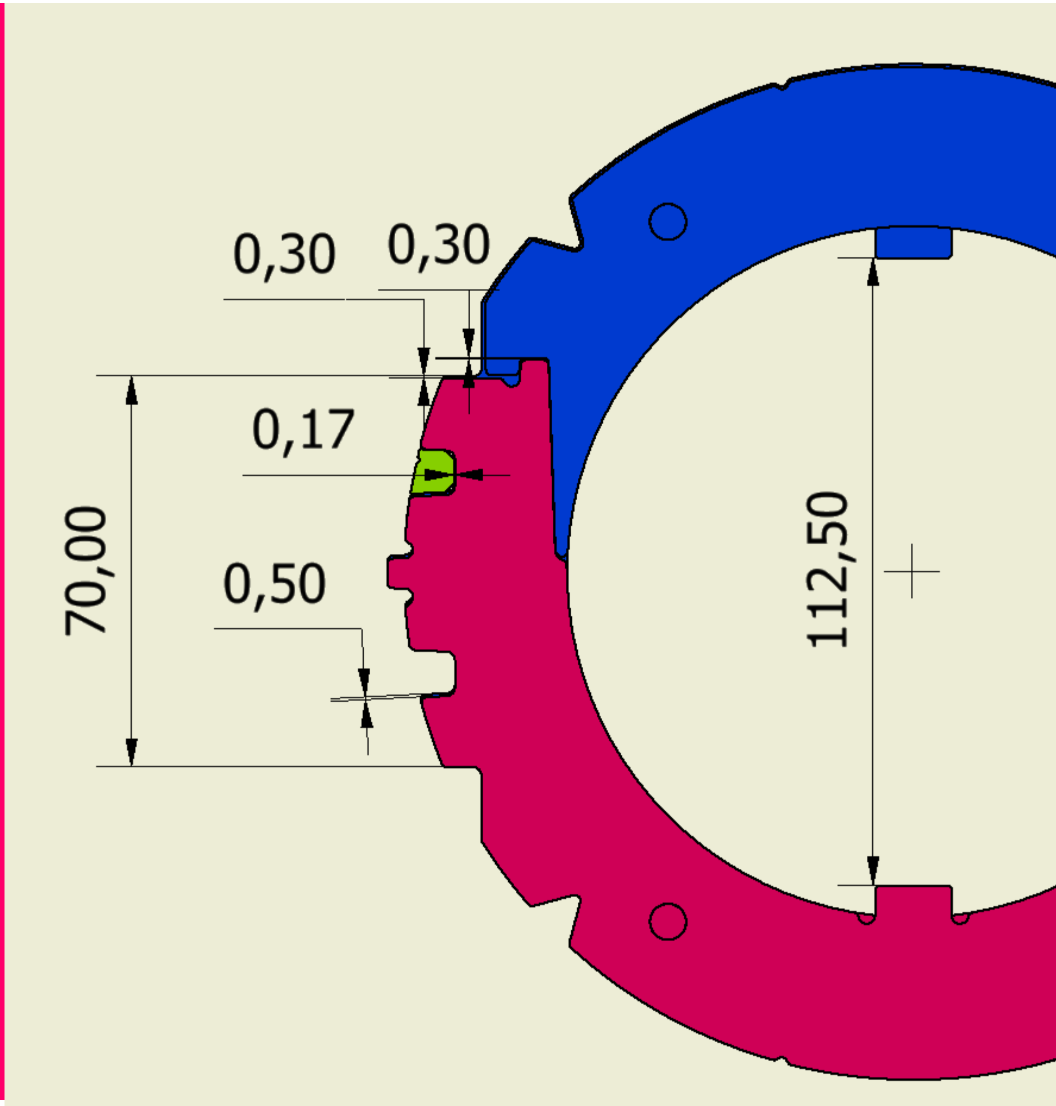
- Deviation
  - Positive → interference
    - Tooling deformed
  - Negative→ clearance



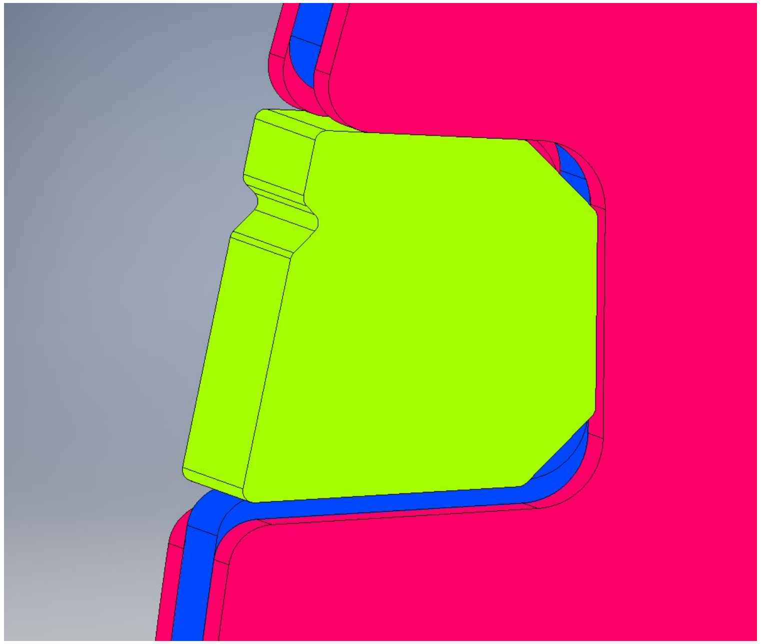
Displacement vectors and EQV. Stress for illustration

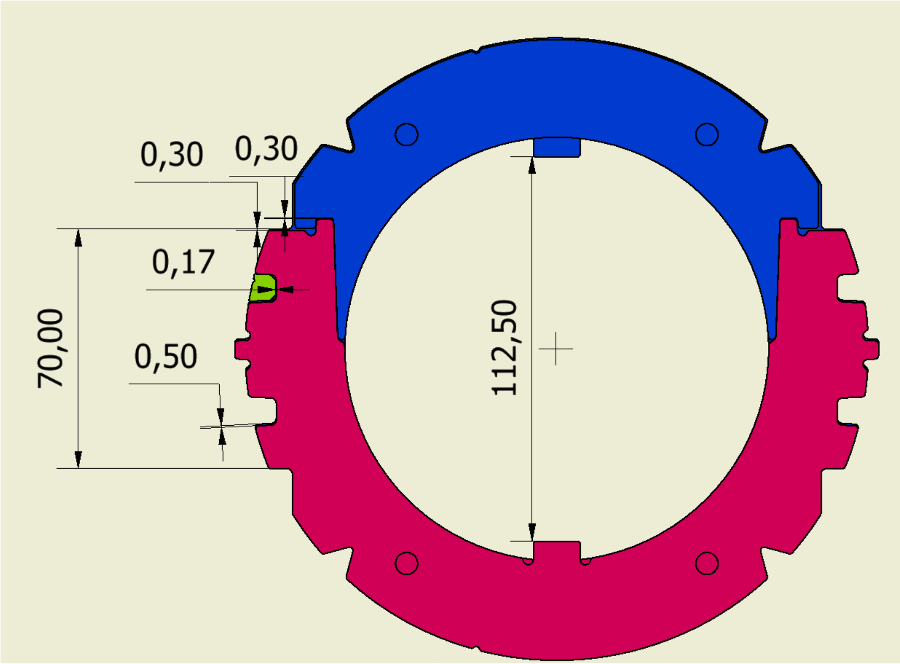
Key clearance vs stoppers shim





Key clearance vs stoppers shim





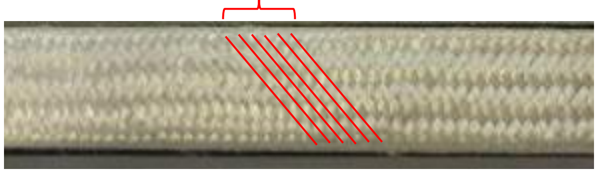
Magnet	Shim stoppers (μm)	Stopper height (mm)	Key clearance (μm)
	0	69.7	+300
	100	69.8	+200
	200	69.9	+100
	300	70.0	0
101,102,103	400	70.1	-100
104,105,106	150	69.85	+150

S2-Glass braiding parameters

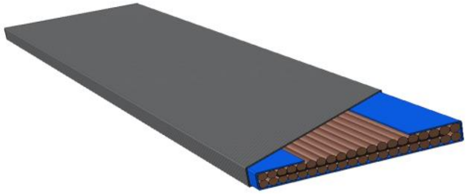
Basic parameters of the insulation:

Speed

Picks per cm



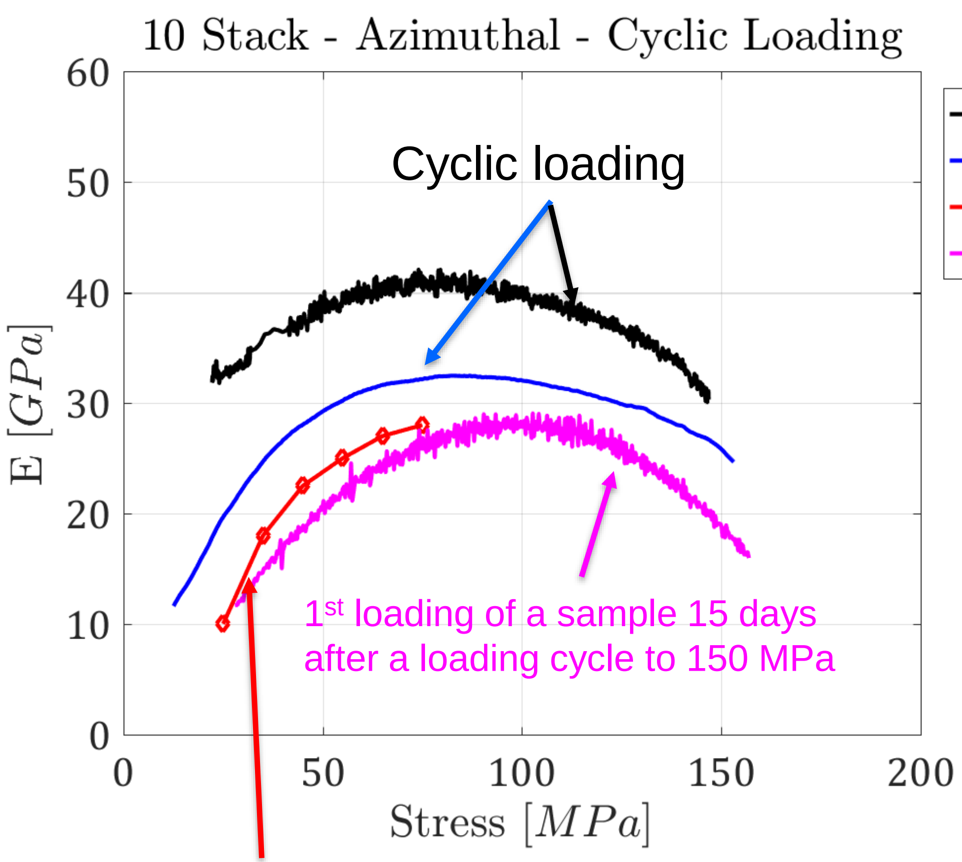
Nb_3Sn Cable, Mica insulation, Glass Sleeved

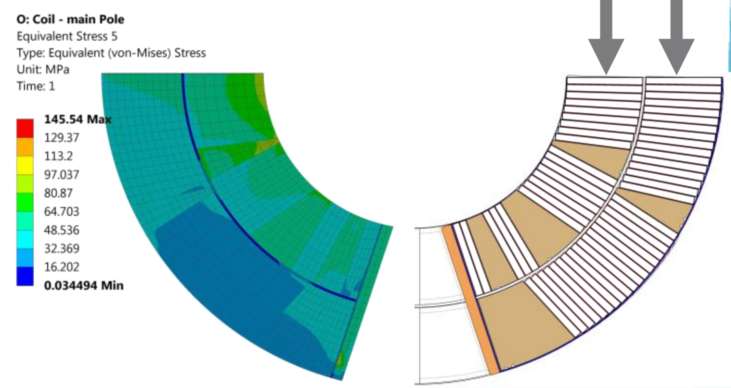


	Coils 105-107 and 110	Coil 108-110 and 111-117	11 T After Mid-2017
Strand (also called Yarn)	11 TEX (636)	11 TEX (636)	11 TEX (636)
# Carriers	32	32	32
Picks per cm	7	6	9
Insulation thickness at 5 MPa, µm	130	130	100
# Plies/Strand	9	9	4

Ten Stacks vs Coil Measurements

- Results on coil measurements need further thinking. We will have a better view once we measure a virgin coil segment.





Coil (cold powered tested), shows similar rigidity in the first loading than ten stacks cyclic reloading (but loading goes only to 70 MPa)

Coil summary data

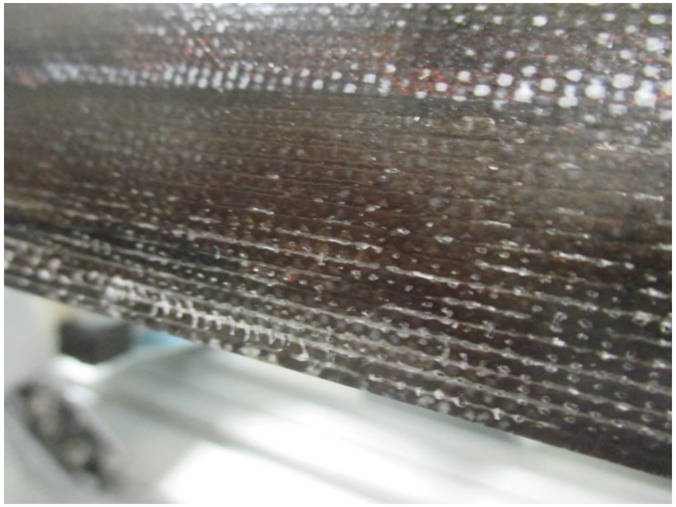
	Magnet	Strand lay out	cu/sc	Coil R at 300 K mΩ	Glass heater-coil mm	Azimuthal oversize* L, mm	Azimuthal oversize* R, mm	Interlayer Quench Heater	End Saddles	Wedges Type	End Spacers	Impregnation	E-modulus** [GPa] w.o. trace	E-modulus** [GPa] w. trace
Coil 105	MBHSM101	RRP 108/127	1.22	426	0.1	-0.282	-0.319	no	SLS 316LN	ODS Cu 2 segments	SLS 316LN		35	34
Coil 106	MBHSP101 MBHSP102 MBHDP101	RRP 108/127	1.22	423	0	-0.059	-0.138	no	G11	ODS Cu 2 segments	SLS 316LN		36	
Coil 107	MBHSP101	RRP 108/127	1.22	426	0.1	-0.053	-0.105	no	G11	ODS Cu 2 segments	SLS 316LN			
Coil 108	MBHSP102 MBHDP101	RRP 132/169	1.22	407	0.1	-0.076	-0.040	no	G11	ODS Cu 2 segments	SLS 316LN		33	32
Coil 109	MBHSP103 MBHDP101 MBHDP102 (ap SP104b)	RRP 132/169	1.27	400	0	-0.041	-0.085	no	G11	ODS Cu 2 segments	SLS 316LN			
Coil 111	MBHSP103 MBHDP101	RRP 132/169	1.27	401	0.1	-0.216	-0.171	no	G11	ODS Cu 2 segments	SLS 316LN		39	
Coil 112	MBHSP104 MBHDP102 (ap SP104b)	RRP 132/169	1.27	403	0.08	-0.148	-0.141	no	G11	ODS Cu full length	SLS 316LN			
Coil 113	MBHSP104	RRP 132/169	1.27	403	0.08	-0.053	-0.258	no	G11	ODS Cu full length	SLS 316LN			39
Coil 114	MBHSP105 MBHDP102 (ap SP105b)	RRP 150/169	0.98	432	0 (heaters imprg)	-0.108	-0.222	no	G11	ODS Cu full length	SLS 316LN			
Coil 115	MBHSP105 MBHDP102 (ap SP105b)	RRP 150/169	0.97	436	0 (heaters imprg)	-0.097	-0.174	no	G11	ODS Cu full length	SLS 316LN			
Coil 116	MBHSP106	RRP 150/169	0.97	449	0 (heaters imprg)	-0.191	-0.094	yes	G11	ODS Cu full length	SLS 316LN			
Coil 117	MBHSP106	RRP 150/169	0.97	450	0 (heaters imprg)	-0.096	-0.136	yes	G11	ODS Cu full length	SLS 316LN coated	With pressure		
Coil 110	Test coil	RRP 132/169			0 (heaters imprg)	-0.274	-0.303	yes	G11	ODS Cu full length	SLS 316LN	With pressure		
Coil 201	Test coil	PIT			0 (heaters imprg)	-0.096	-0.136	tes	G11	ODS Cu full length				

*Negative means bigger than nominal

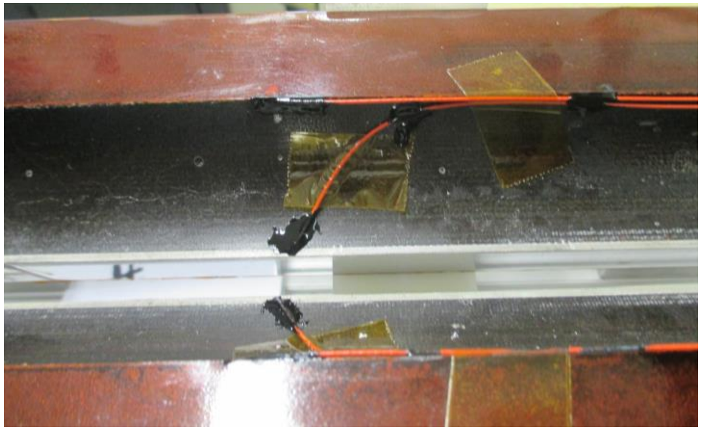
** Equivalent stiffness based on a straight line fitted to the data between 60 and 80 MPa during the loading phase by the method of least squares. (Boundary conditions considered as $\mu = 0.2$)

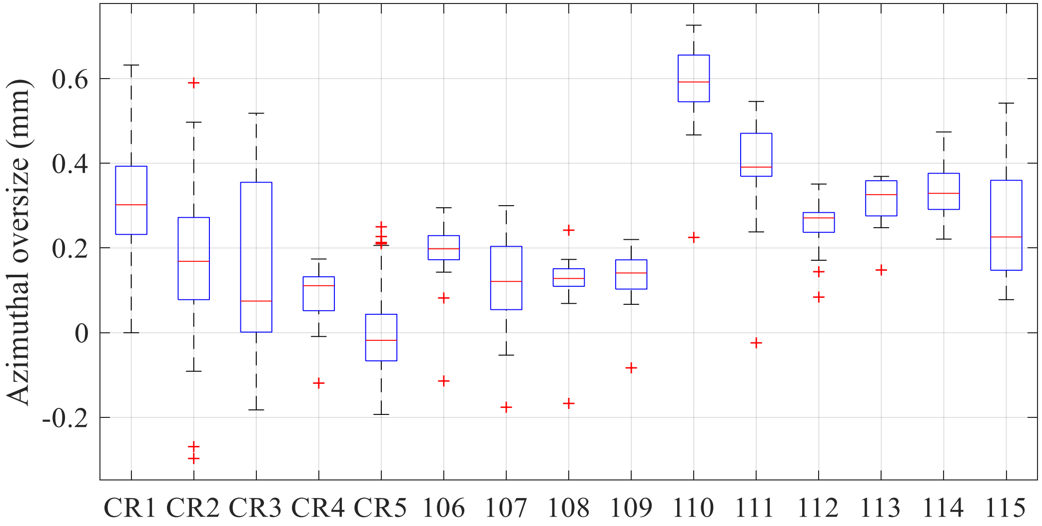
Coil 111

Before test

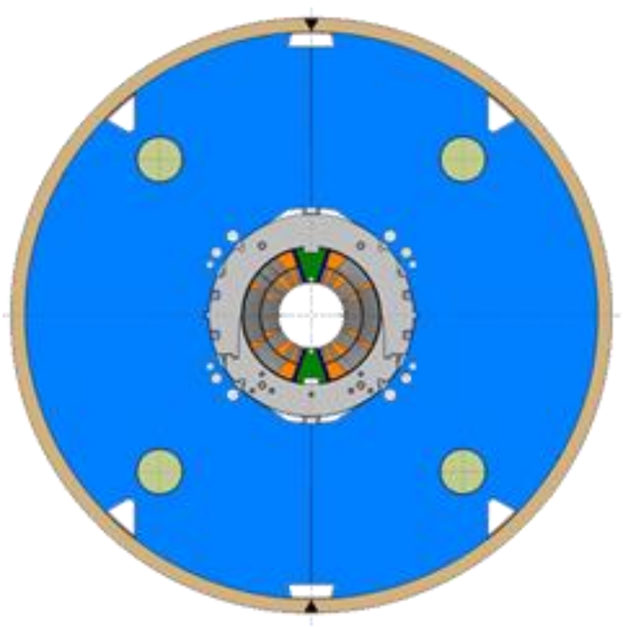


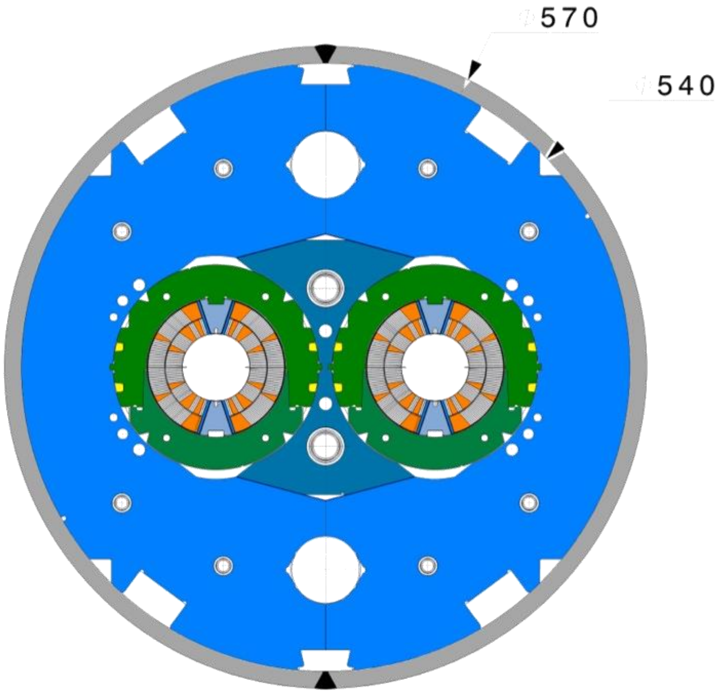
Before test

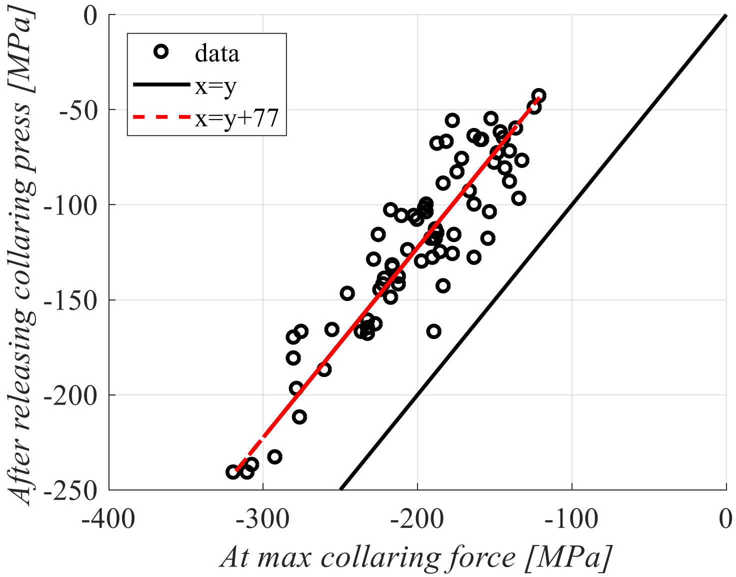




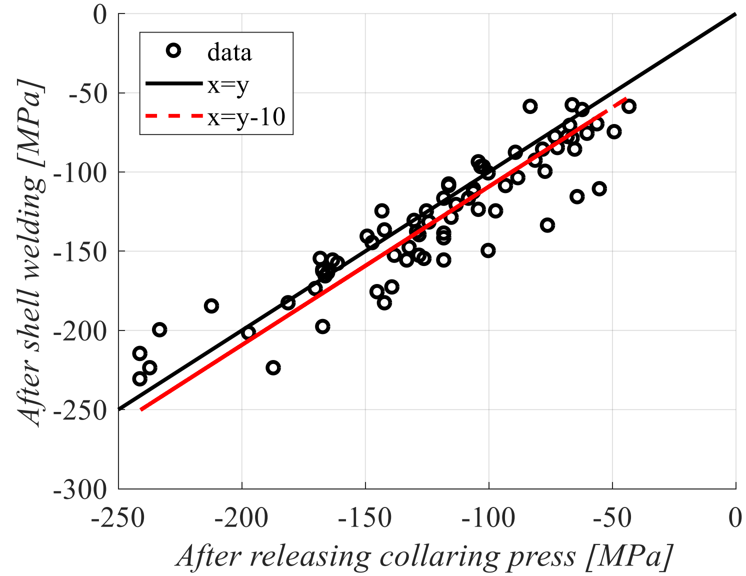
After test



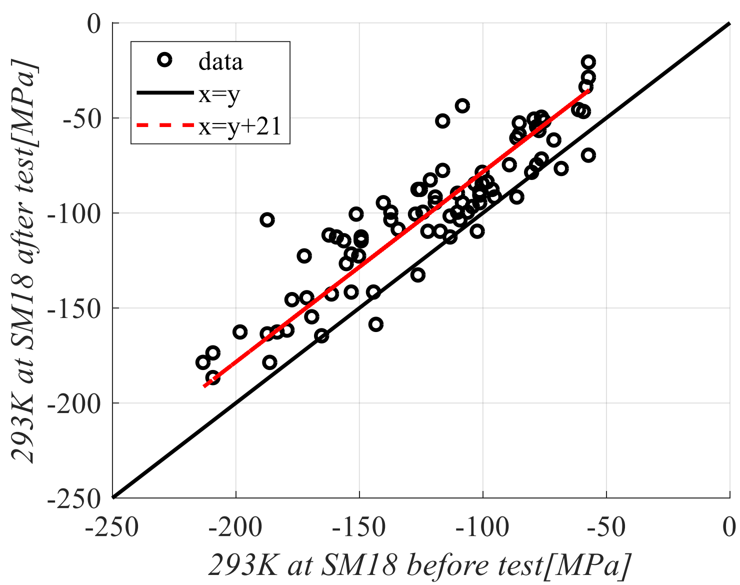

570
540



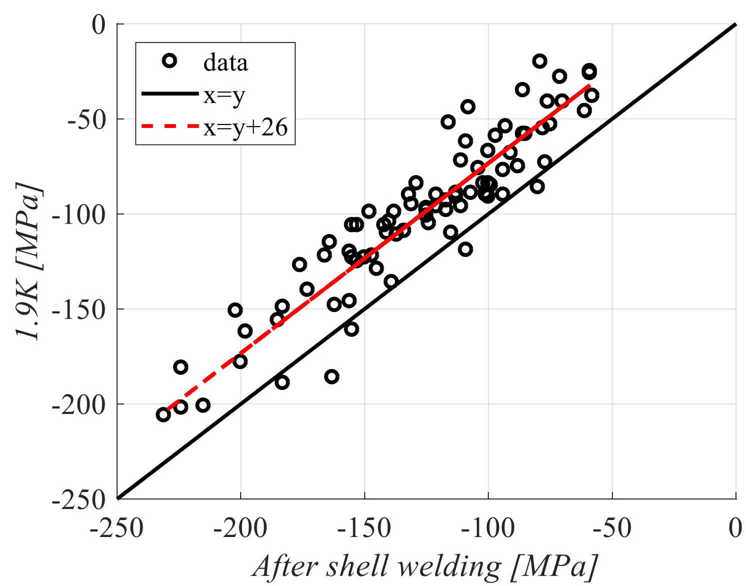
data
x=y
x=y+77
0
-50
-100
-150
-200
-250
-400
-300
-200
-100
0
After releasing collaring press [MPa]
At max collaring force [MPa]



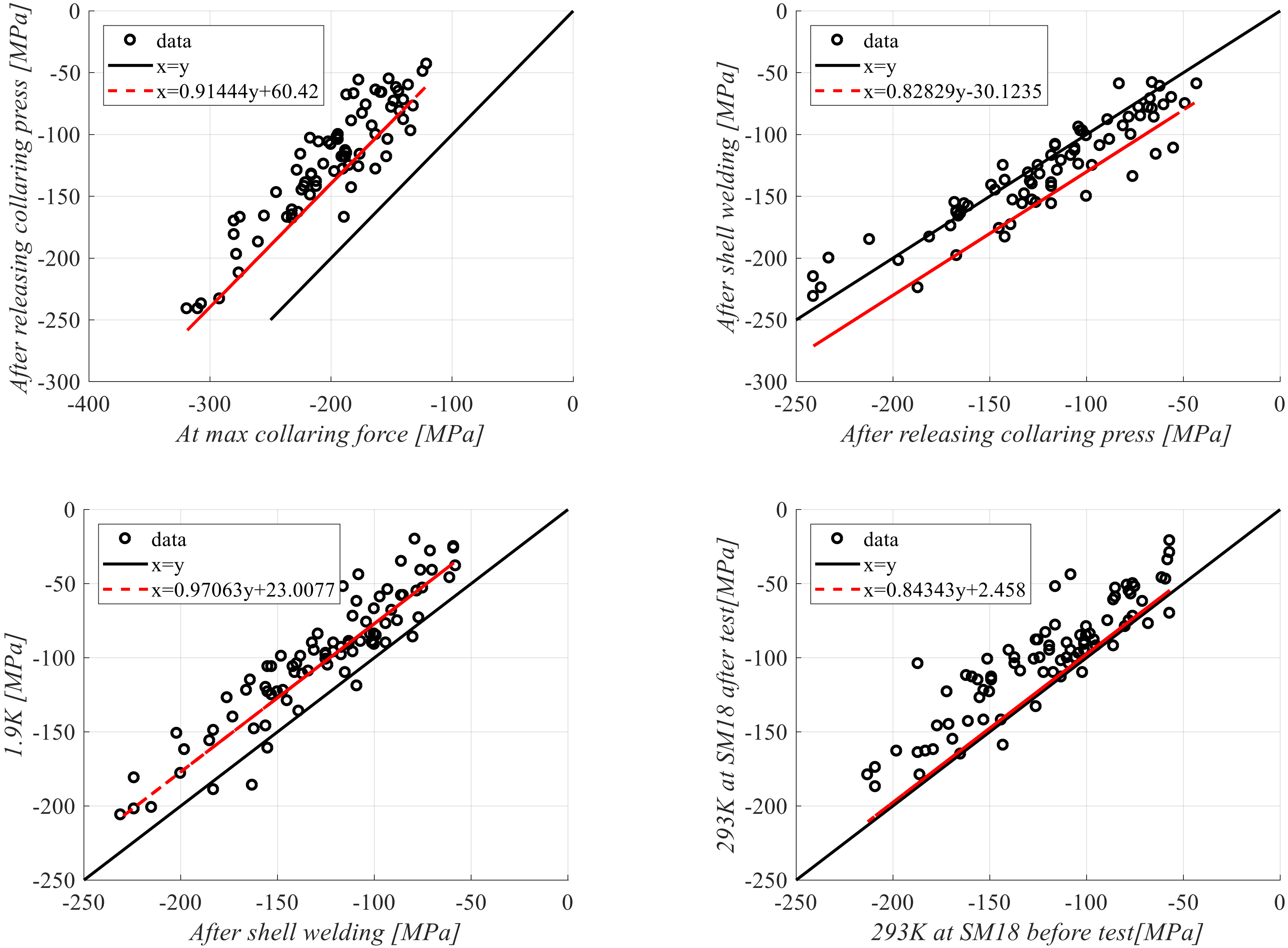
data
x=y
x=y-10
0
-50
-100
-150
-200
-250
-300
-250
-200
-150
-100
-50
0
After shell welding [MPa]
After releasing collaring press [MPa]

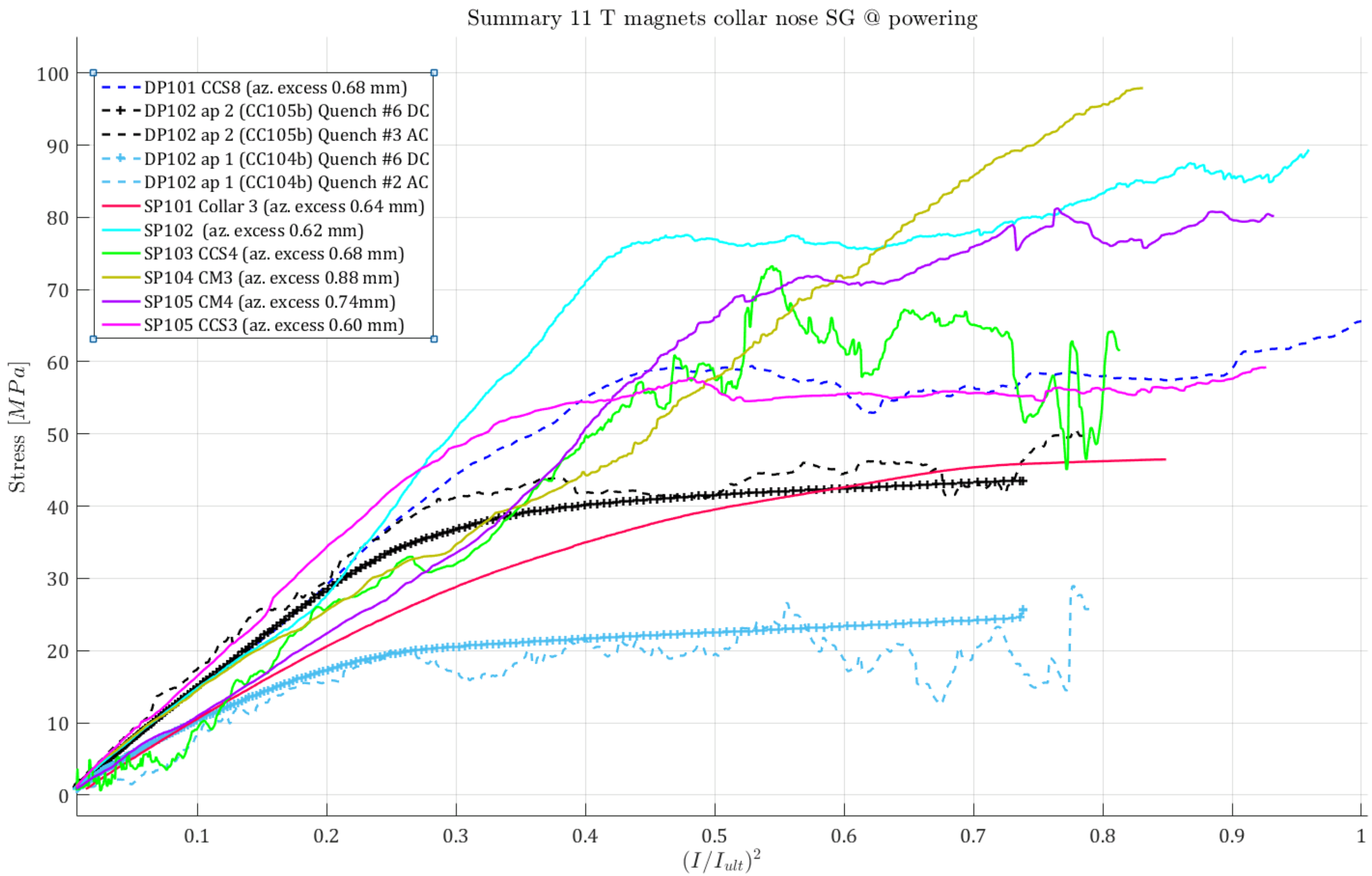


data
x=y
x=y+21
0
-50
-100
-150
-200
-250
-250
-200
-150
-100
-50
0
293K at SM18 after test[MPa]
293K at SM18 before test[MPa]



data
x=y
x=y+26
0
-50
-100
-150
-200
-250
-250
-200
-150
-100
-50
0
1.9K [MPa]
After shell welding [MPa]


data
x=y
x=0.91444y+60.42
After releasing collaring press [MPa]
At max collaring force [MPa]
data
x=y
x=0.82829y-30.1235
After shell welding [MPa]
After releasing collaring press [MPa]
data
x=y
x=0.97063y+23.0077
1.9K [MPa]
After shell welding [MPa]
data
x=y
x=0.84343y+2.458
293K at SM18 after test[MPa]
293K at SM18 before test[MPa]

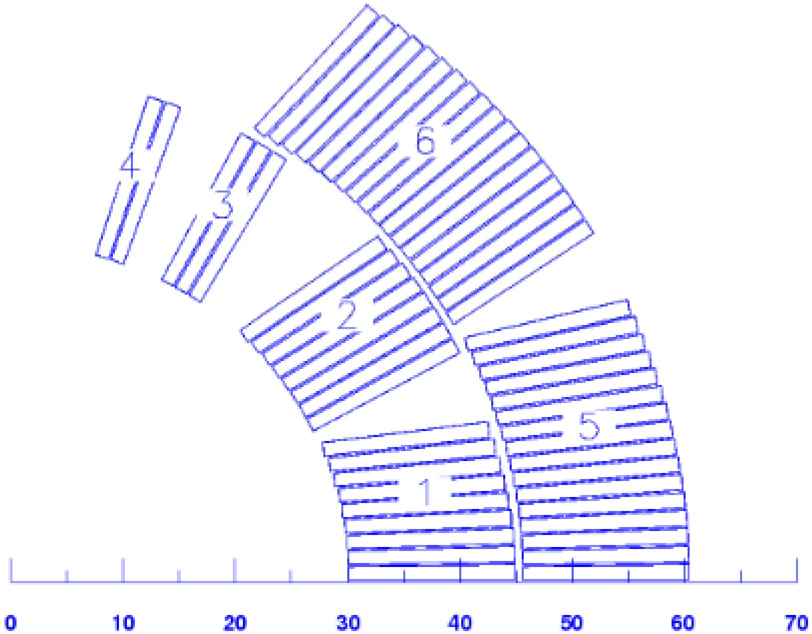


(Signals shifted to zero)

Az. Excess on connection side: 0.56 mm for CC105b and 0.67 mm for CC104b

Reminder on design criteria

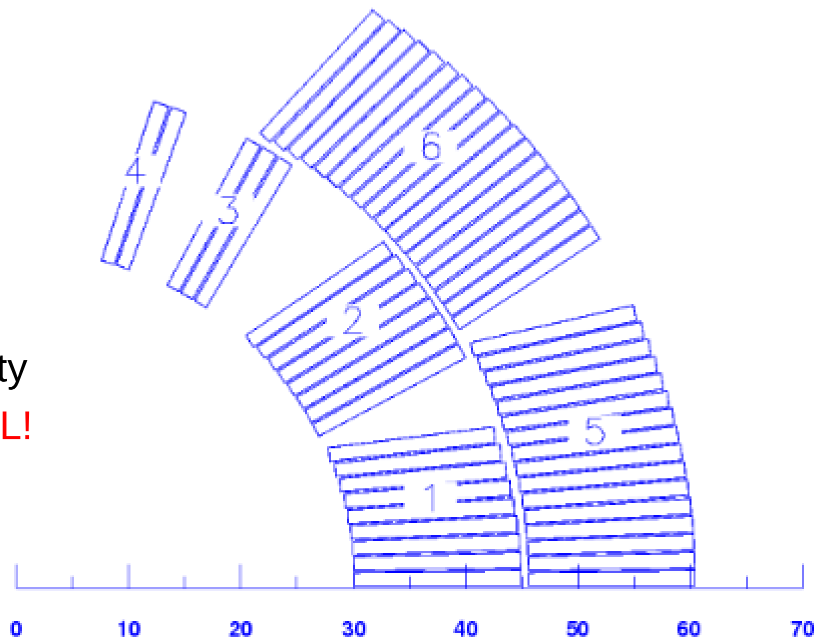
- 56 turns coil
  - 22 Inner Layer, 34 Outer Layer
- Assumptions at the early design to define the cavity (with FNAL):
  - Un-reacted cable: 14.7 mm x 1.269 mm
  - 3 % growth in thickness, 1% growth in width
  - Insulation thickness: 100 µm
- Design evolution at CERN (1st Generation)
  - Un-reacted cable: 14.7 mm x 1.25 mm
  - Cavity was not updated, meaning that CERN short models and prototype have slightly more room for increase on thickness during heat treatment (4.5 % instead of 3 %)
  - Insulation thickness: 100 µm at 30 MPa
- CERN 2nd Generation
  - Un-reacted cable: 14.7 mm x 1.25 mm
  - 3 % growth in thickness, 1% growth in width
  - Insulation thickness: 100 µm at 5 MPa
- CERN 1st Generation
  - Un-reacted cable: 14.7 mm x 1.25 mm
  - 4.5 % growth in thickness, 1% growth in width
  - Insulation thickness: 100 µm) at 5 MPa



Reminder on design criteria

- Let us define:
  - Nominal cavity size/turn (from the design)
    - Reacted design cable thickness + 2 * design insulation thickness
  - Size of unreacted turn (from accurate measurements performed on each coil)
    - Un-reacted actual cable thickness + 2 * measured insulation thickness at 5 MPa
  - The free available space in the reaction cavity when closing the mold is:
    - Nominal cavity size/turn - Size of unreacted turn

- Example (CERN-11 T, first generation):
  - Nominal cavity size/turn
    - 1.306+2*0.1 = 1.506
  - Size of unreacted turn
    - 1.25 + 2*0.135 = 1.520
  - Missing free space in the reaction and curing cavity
    - 0.014 mm/turn → 0.476 mm missing in the OL!



Reminder on design criteria

- Free available azimuthal space in the reaction cavity
  - 11T first generation design is missing 0.014 mm/turn (-0.014*34=-0.476 mm in the OL)
  - 11T first* generation design (coils wound after November 2017) has 0.056 mm/turn of free space (0.056*34=1.904 mm in the OL)
  - 11T second generation design has 0.038 mm/turn of free space (0.038*34=1.292 mm in the OL)
  - MQXF first generation design has 0.079 mm/turn of free space (0.079*28 =2.212 mm in the OL)
  - MQXF second generation design has 0.069 mm/turn (0.069*28=1.932 mm in the OL)

	11 T FNAL[1]	11 T CERN 1st gen. des.	11 T 1st gen. des., from Nov. 2017	11 T 2nd gen. des.	MQXF 1st gen. des.	MQXF 2nd gen. des.
Bare mid-thickness before/after HT, mm	1.269 /1.306 ($\Delta = 3$ %)	1.250 /1.306 ($\Delta = 4.5$ %)	1.250 /1.306 ($\Delta = 4.5$ %)	1.250 /1.288 ($\Delta = 3$ %)	1.525/1.594 ($\Delta = 4.5$ %)	1.525/1.594 ($\Delta = 4.5$ %)
Bare width before/after HT, mm	14.70 /14.85 ($\Delta = 1$%)	14.70 /14.85 ($\Delta = 1$%)	14.70 /14.85 ($\Delta = 1$%)	14.70 /14.85 ($\Delta = 1$%)	18.150/18.513 ($\Delta = 2$ %)	18.150/18.313 ($\Delta = 1.2$ %)
Keystone angle before/after HT, mm	0.79/0.81	0.79/0.81	0.79/0.81	0.5/0.5	0.55/0.55	0.40/0.40
Measured insulation thickness at 5 MPa, mm	n.a.	0.135	0.100	0.100	0.145	0.145
Design insulation thickness, mm	0.100	0.100	0.100	0.100	0.150	0.145

Azimuthal cavity size

- By design, we leave 0.3 mm or radial space for conductor expansion during reaction.
  - All molds (curing, reaction and impregnation) are designed (in principle) to have this free space with respect to the non reacted cable dimensions

	Insulated conductor, Reacted*	Impregnated Coil
Inner radius	30.0	29.9
Outer radius	60.6	60.8

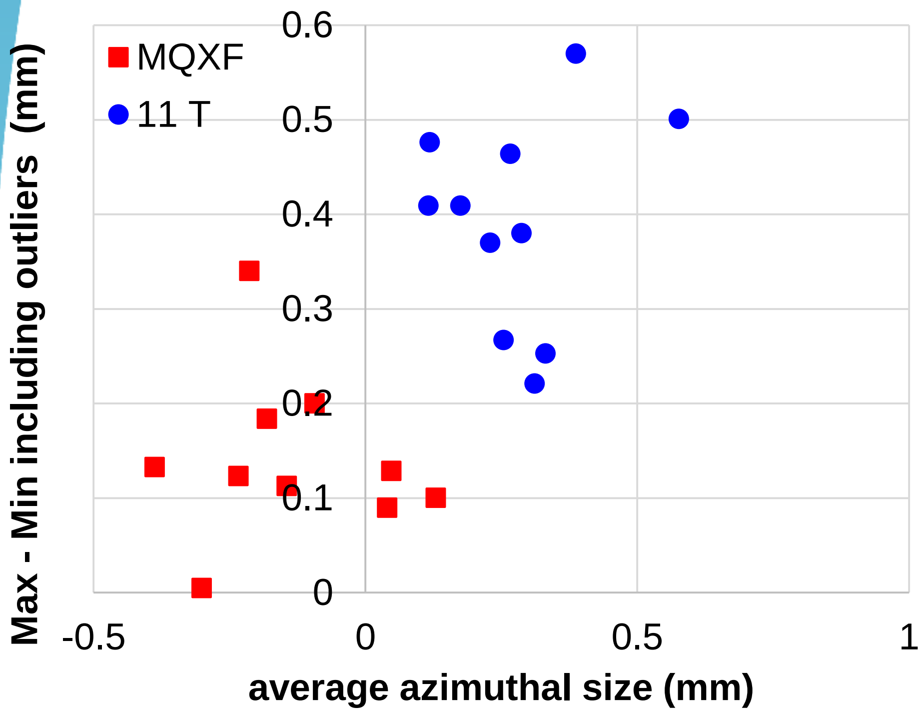
***includes 0.3 mm radial free space (0.15 mm per layer) with respect to the non reacted cable geometry**

HiLumi HL-LHC PROJECT CERN

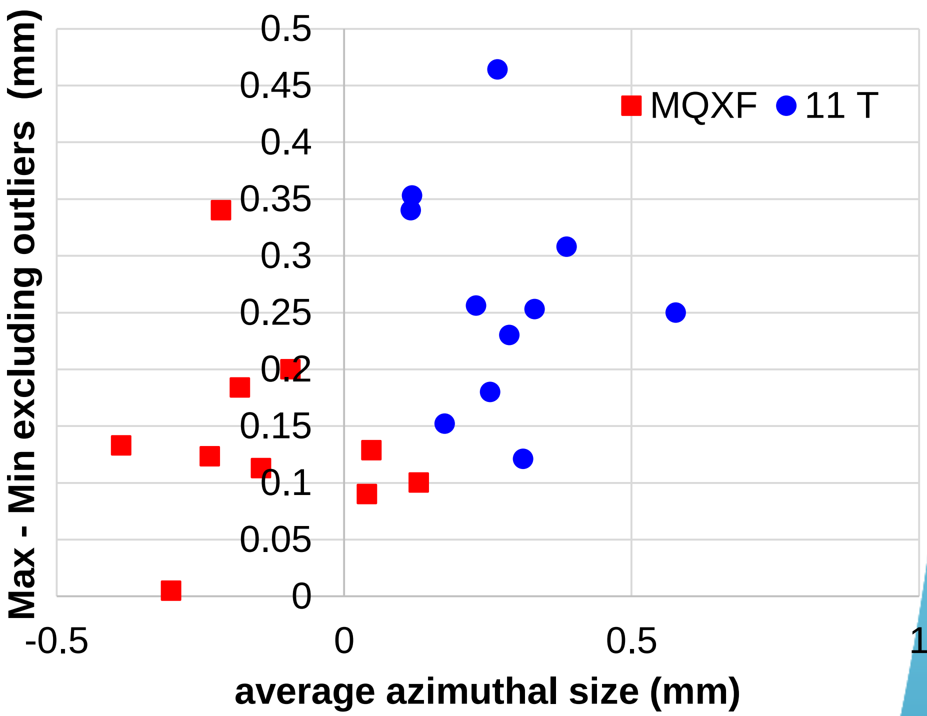
Reference drawings for 2nd generation tooling

- For the second generation design, work done to verify all dimensions match (Emelie, Thomas, Jacky, Carlos, Greg…)
  - LHCMBHST0845
  - LHCMBHST0846
  - LHCMBHST0847
- In the radial dimension, first and second generation are identical, so it should be OK, but Jacky to verify the details (again)

Coil size



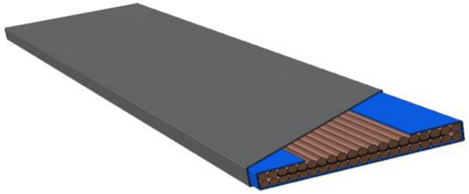
MQXF
11 T
Max - Min including outliers (mm)
average azimuthal size (mm)
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.5
0
0.5
1



MQXF
11 T
Max - Min excluding outliers (mm)
average azimuthal size (mm)
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-0.5
0
0.5
1

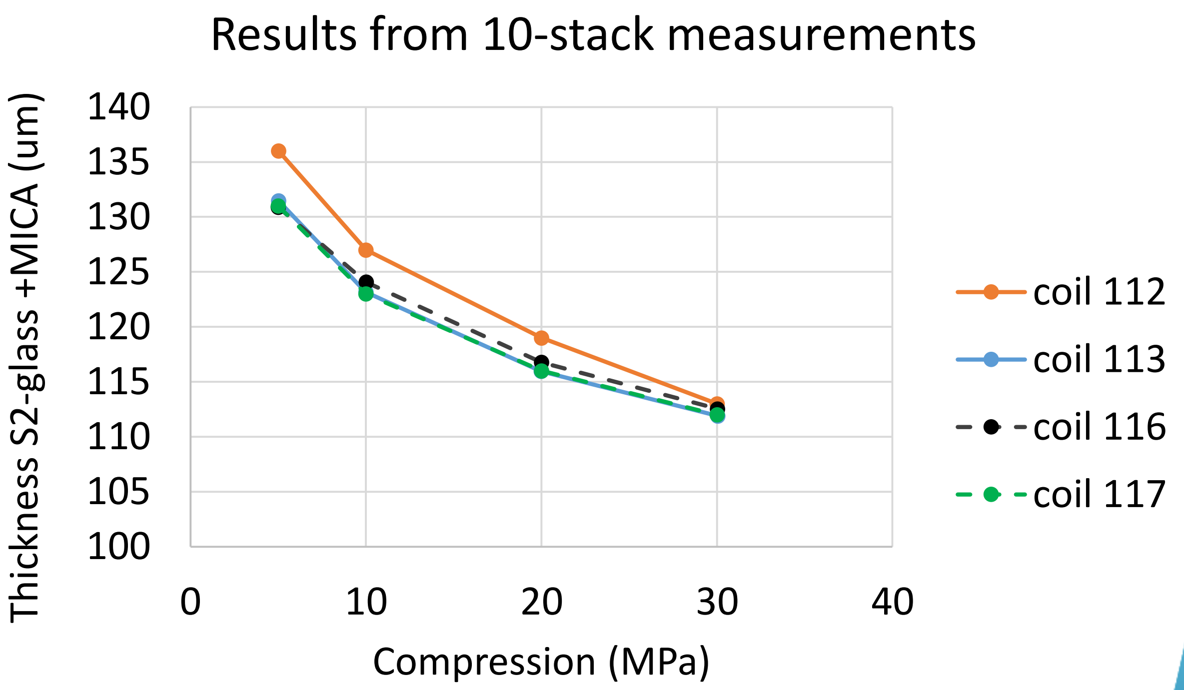
11 T insulation lay-out

Nb$_3$Sn Cable, Mica insulation, Glass Sleeved

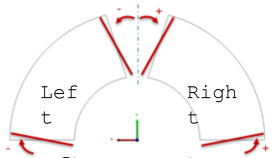


- Cavity design assuming 0.1 mm of insulation at 30 MPa.
- Even after a small adjustment on the braiding parameters, the insulation thickness was larger than the design value.
  - Original braiding: yarn count 14/2 cm (Coil 105-107, 110).
  - Updated braiding: yarn count 12/2 cm.

coil	Ins thickness @ 30 Mpa (μm)
105	114
106	114
107	114
108	107
109	107
110	113
111	106
112	114
113	112
114	114
115	112
116	113
117	112

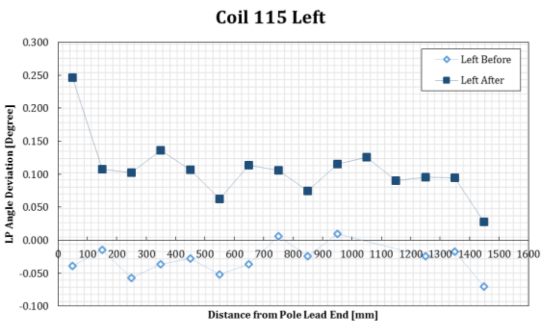


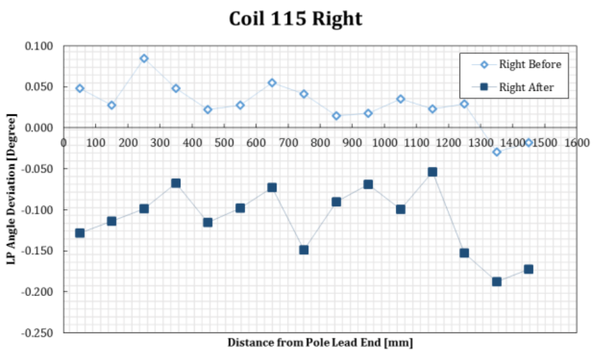
Comparison before and after test of coil #115

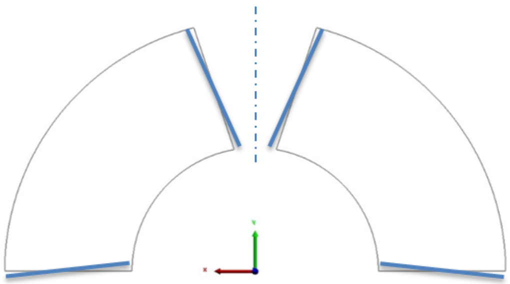


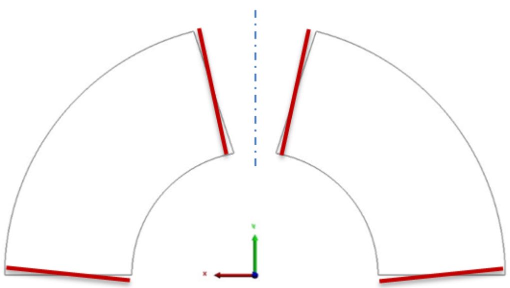
Sign convention

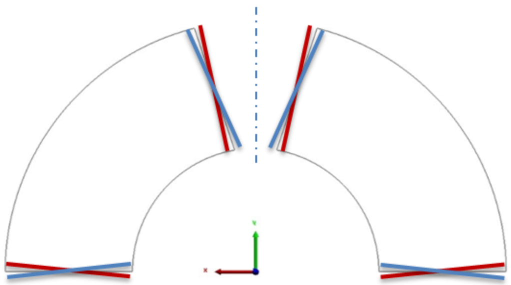
- Loading plate changes both in direction and magnitude.






Before test


After test


115

Before test

After test

<u>Loading plate angle:</u> 0.1 degree = 50µm azimuthal difference in length over the loading plate (50µm=25MPa difference during powering) [1]

[1] From C.H. Loffler