Mechanical Monitoring Issues in Preparation to Next Step of W7-X Operation

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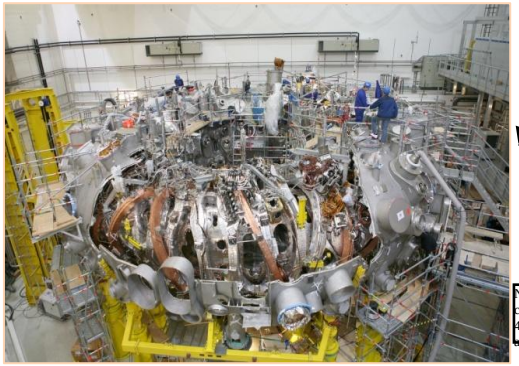
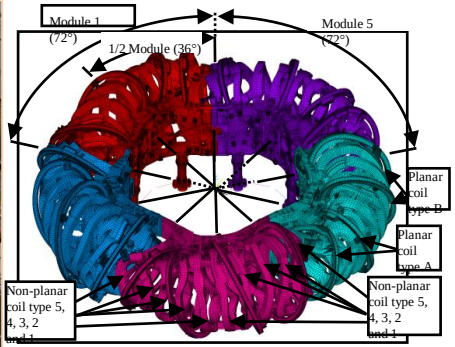
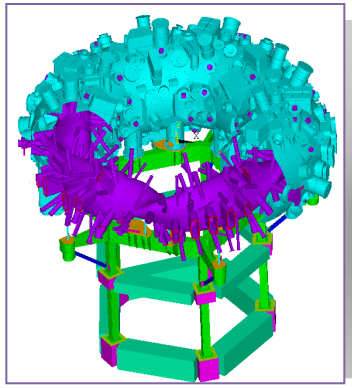
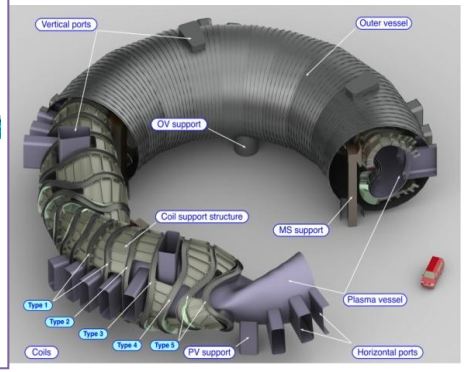
EUROfusion







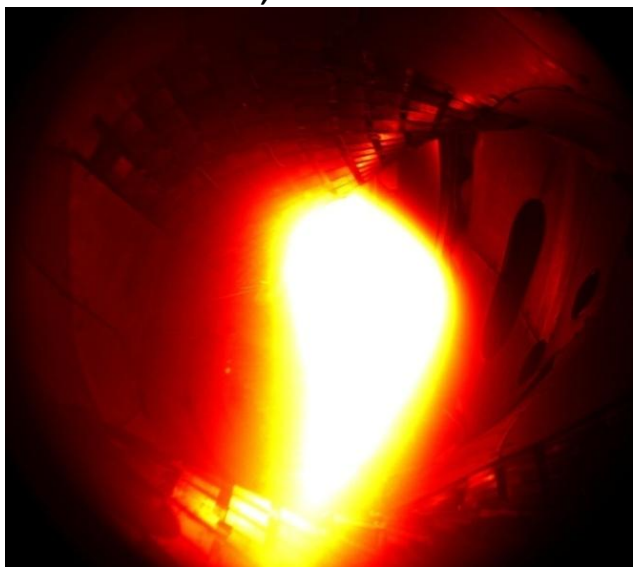


Outline

- Introduction
- Challenges of next step operation
- Filtering of new regimes
- Improvements of FE modeling and monitoring
- Agreement for next step operation
- Conclusions

Introduction: W7-X status

First helium plasma:
Dec. 10, 2015



(bean cross-section)

OP1.1
(limiter configuration plasma): Dec. 2015 – March 2016
~ 940 discharge programs;
pulse length up to 6 s; with up to 4 MJ

Prof. H-S. Bosch, Plenary talk, Thursday 08th .

Engineering: all systems are functioning properly,
More than 130 coil energizing.
95% of mechanical sensors are fine,
Two "main" 2.5 T load configurations are checked
(MN loads, up to 70% of maximum design values).
Many cycles with similar loadings

Next step of operation (OP1.2a)**:**
with an inertially cooled divertor: August – December 2017
up to 80 MJ, up to 60 s pulse

Commissioning is on-going: evacuation of cryostat and plasma vessel
trim coils with full current
magnet system cooldown

Introduction: The device W7-X

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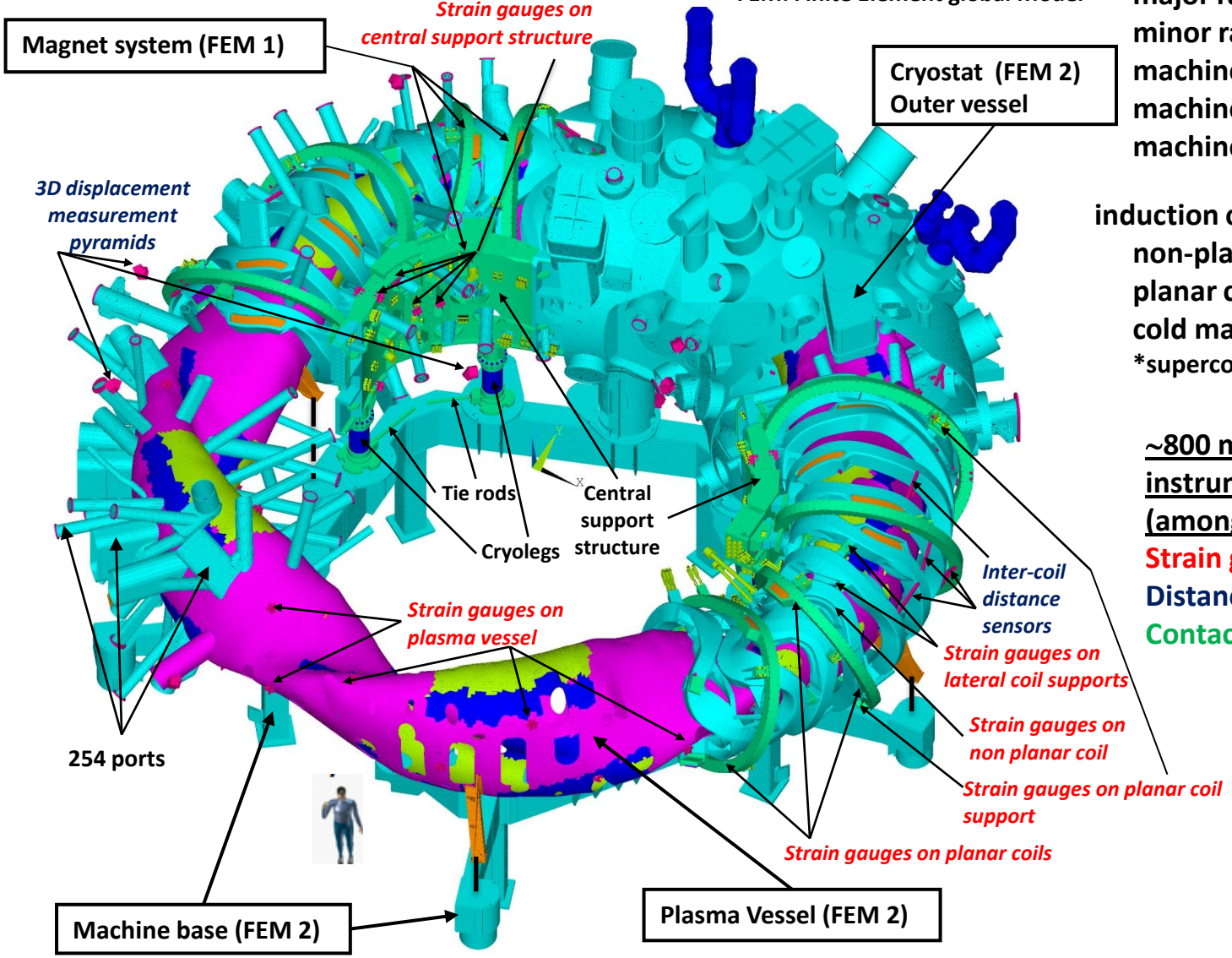


major radius	5.5 m
minor radius	0.53 m
machine height	4.5 m
machine diameter	16 m
machine mass	725 t
induction on axis	2.5 - 3 T
non-planar coils*	50
planar coils*	20
cold mass	425 t

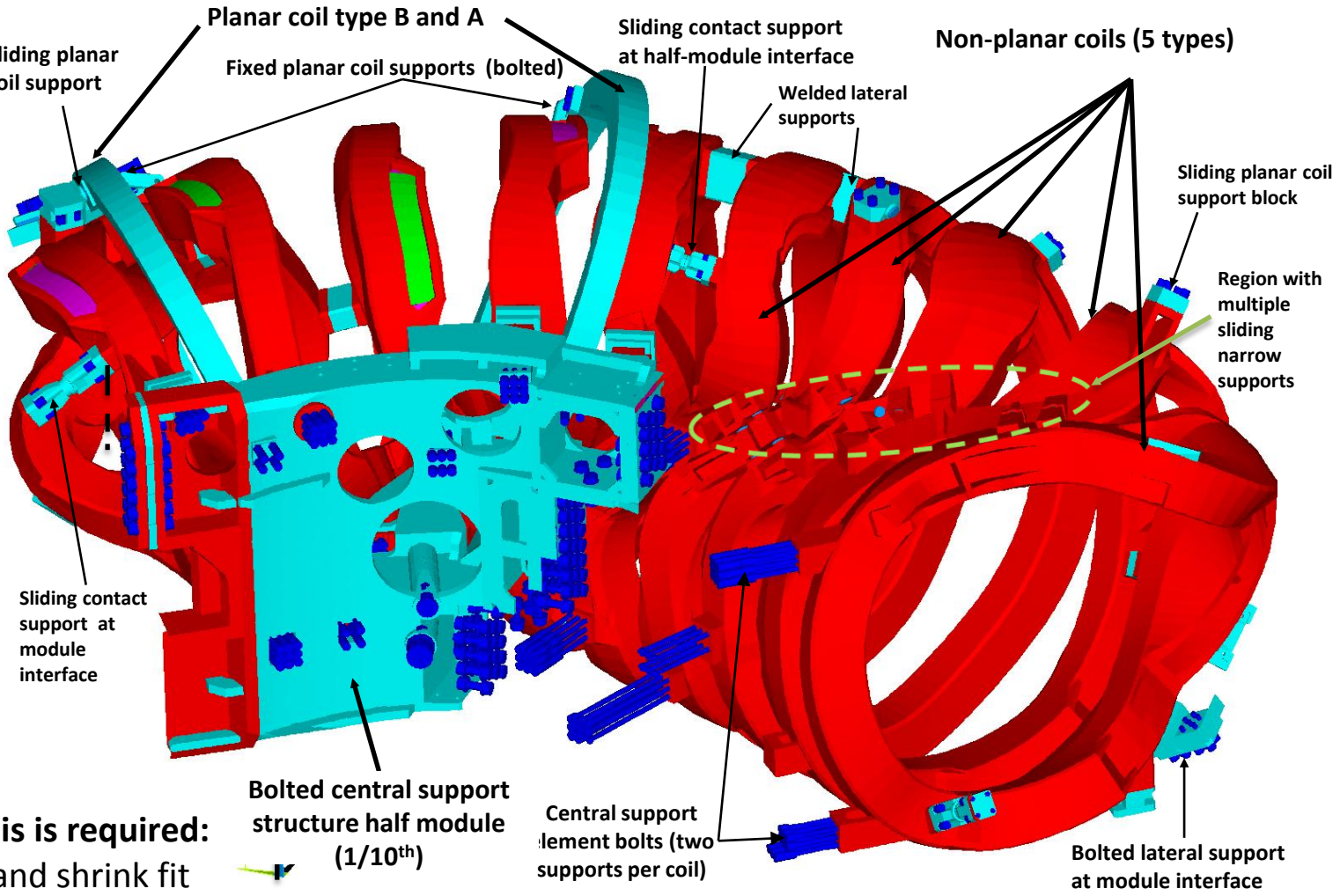
*superconducting coils

~800 mechanical instrumentation sensors [1] (among > 3000 in total):

- Strain gauges
- Distance
- Contact

Introduction: Magnet system supports

Fragment of magnet system 72° ANSYS Global Model



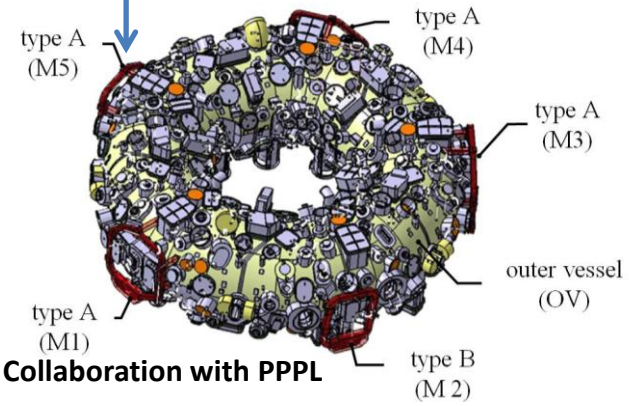
Five step analysis is required:

1) bolt preload and shrink fit
2) dead weight
3) cooldown
4) EM load application
5) EM unloading

- Multiple bolted connections with expected opening;
- Multiple contact elements with initial gap and gradual gap closing;
- Elements with different order of stiffness;
- Non-linear geometry option is to be activated to get reliable results.

Significant increasing of coil currents

Coil type	Coil current, kA						
	OP1.1 / OP 1.2a ✓		*Planned (demanding) new 2.5T regimes during OP1.2a*				
	"J regime" Limiter (0)	*"A regime" Standard (2)*	High Iota (1)	High mirror (2)	Low mirror (2)	Inward shifted (3)	Low iota (4)
Non-planar coils							
Type 1	12.8	13.5	14.9	14.5	12.6	13.1	12.2
Type 2	12.8	13.5	14.9	14.1	13.2	13.0	12.2
Type 3	12.8	13.5	14.9	13.4	13.2	13.2	12.2
Type 4	12.8	13.5	14.9	12.8	14.2	14.6	12.2
Type 5	12.8	13.5	14.9	12.4	14.2	14.7	12.2
Planar coils							
Type A	0 ÷ 5	0	-10.3	0	0	4.1	9.2
Type B	0 ÷ 5	0	-10.3	0	0	-8.2	9.2
Outer warm Trim coils	1.1		1.8/1.95	1.8/1.95	1.8/1.95	1.8/1.95	1.8/1.95



Collaboration with PPPL

Next phase operation:
25% increasing of EM forces in non-planar coils
2-3 times increasing of EM forces in planar coils
2-3 times increasing of EM forces in trim coils

And many other proposals from physicists….

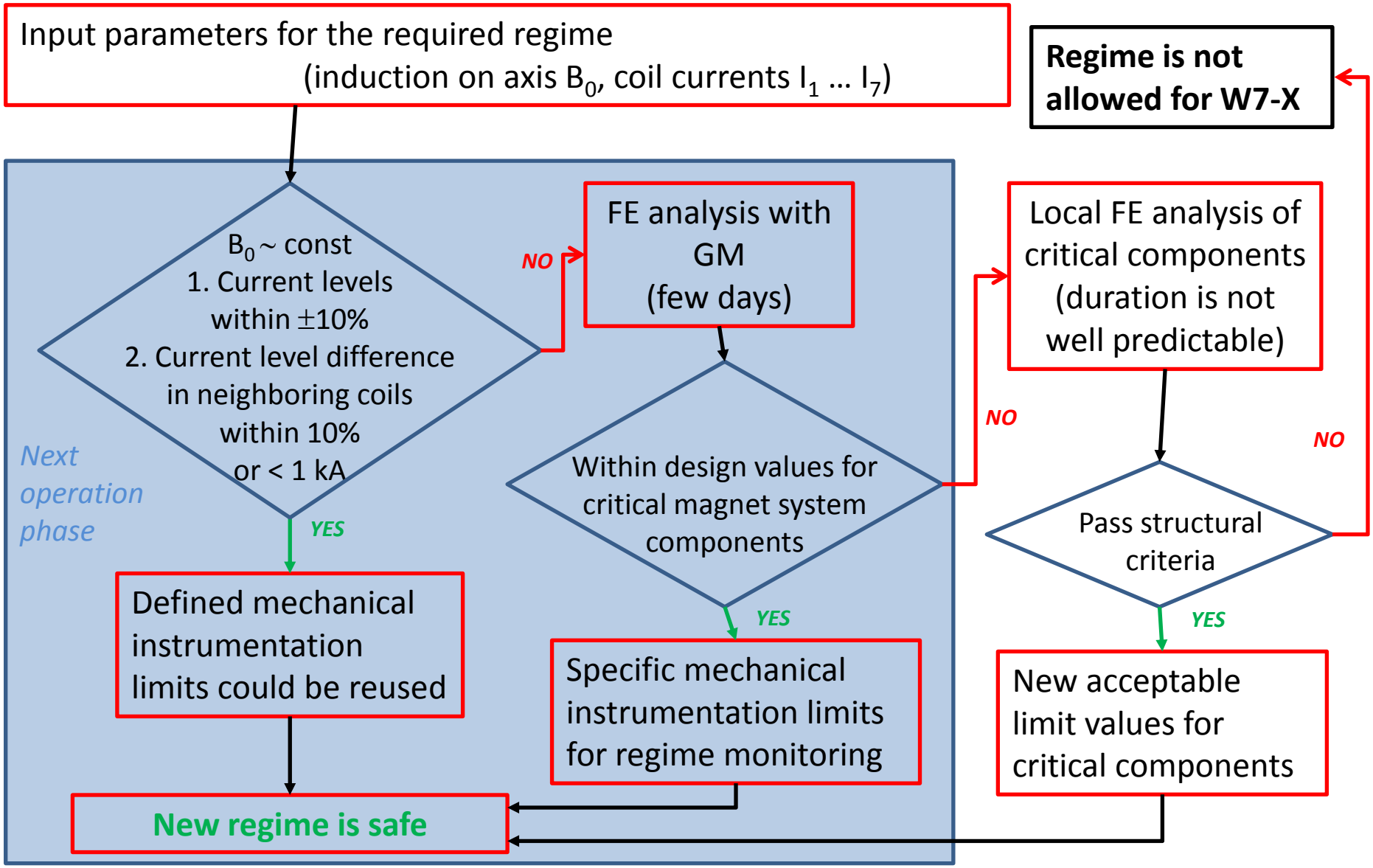
OP1.2: New regimes and regime variations

	coil currents	I_1 [kA]	I_2 [kA]	I_3 [kA]	I_4 [kA]	I_5 [kA]	I_A [kA]	I_B [kA]
J	Limiter OP1.1	12.78	12.78	12.78	12.78	12.78	4.98	4.98
B	Low iota	12.20	12.20	12.20	12.20	12.20	9.15	9.15
A	Standard case	13.47	13.47	13.47	13.47	13.47	0.00	0.00
D	Low mirror	12.63	13.17	13.17	14.24	14.24	0.00	0.00
E	High mirror	14.51	14.10	13.43	12.76	12.36	0.00	0.00
G	Inward shift	13.07	12.94	13.21	14.57	14.71	4.09	-8.17
C	High iota	14.88	14.88	14.88	14.88	14.88	-10.26	-10.26
I	Limiter case	14.15	14.55	13.49	12.17	11.77	-3.97	7.94
H	Outward shift	14.03	14.03	13.63	12.95	12.95	-5.67	5.67
F	Low shear	15.32	15.04	14.23	11.52	11.38	-9.76	10.16
EEM		12.3	12.3	12.3	12.3	12.3	4.8	4.8
GGP		12.3	12.3	12.3	12.3	12.3	4.8	0.0
IJM		13.0	12.8	12.4	12.0	11.8	0.0	0.0
MKM		13.2	12.7	11.9	11.1	10.6	0.0	0.0
KJN		13.0	12.7	12.2	11.7	11.4	1.1	-1.1
KKL		13.3	12.9	12.1	11.4	11.0	-1.1	1.1
KJM		12.9	12.6	14.0	11.3	11.0	0.0	0.0
KKM		13.3	12.9	10.1	11.8	11.4	0.0	0.0
ETM		13.9	14.6	13.3	14.6	14.4	-9.6	-9.6
UEM		12.6	10.8	8.8	6.8	6.4	9.5	9.5
PKM		13.3	12.7	11.5	10.4	9.8	0.0	0.0
AAM		11.8	11.4	12.7	12.9	12.8	8.8	8.8
ATM		13.6	15.5	13.5	16.0	15.9	-10.5	-10.5
-IM		12.5	13.3	13.4	14.7	15.0	0.0	0.0
-HM		12.3	13.5	13.7	15.9	16.5	0.0	0.0
TEH		14.1	9.7	9.7	9.4	5.3	3.3	13.2
EET		11.9	11.7	12.0	13.2	13.3	8.8	-2.8
EES		11.9	11.8	12.0	13.3	13.4	8.2	-3.0
EFS		12.0	11.9	12.2	13.4	13.5	7.3	-3.9
EGS		12.1	12.0	12.3	13.5	13.7	6.4	-4.9
EGS		12.3	12.1	12.4	13.7	13.8	5.6	-5.9
FHS		12.4	12.3	12.5	13.8	13.9	4.6	-7.0
QIT		12.4	12.0	11.5	10.9	10.5	6.9	-6.9
HFW		12.9	12.7	13.0	14.3	14.4	9.6	-9.6

Coil current for reference cases (B_0 = 2.5T), kA (Maximum structural Design Values at B_0 = 3T)

Many new regimes and/or coil current variations (just an example)

Filtering of proposals from physicists



To be corrected after further monitoring and FE analyses…

Fast filtering of new regimes

Results of fast acceptance with 10% -rule for neighboring coils i&j:

$$I_i^{new} \ within \ I_i^{reference\ k} \mp 10\%; \qquad I_j^{new} \ within \ I_j^{reference\ k} \mp 10\%;$$

$$\left(I_i - I_j\right)^{new} within \left(I_i - I_i\right)^{reference\ k} \mp (10\% \ or \ 1kA)$$

Short id	I2-I1 regime	I3-I2 regime	I4-I3 regime	I5-I4 regime	I2-IA regime	I3-IA regime	I4-IB regime	I5-IB regime
IJM	J	J	J	J	A	A	A	A
MKM	J	J	J	J	A	A	A	A
KJN	J	J	J	J	A	A	A	A
KKL	J	J	J	J	A	A	A	A
KJM	J	NaN	F	J	A	A	A	A
KKM	J	NaN	D	J	A	A	A	A
ETM	A	E	D	A	C	C	G	G
UEM	NaN	I	I	J	B	NaN	NaN	NaN
PKM	J	E	E	J	A	A	A	A
AAM	J	NaN	J	J	B	B	I	B
ATM	NaN	I	NaN	G	C	C	NaN	NaN
-IM	J	J	D	D	A	A	A	D
-HM	D	J	G	C	A	A	NaN	NaN
TEH	NaN	J	J	NaN	J	J	NaN	NaN
EET	J	J	D	J	B	B	NaN	NaN
EES	J	J	D	J	B	B	NaN	NaN
EFS	J	J	D	J	J	J	NaN	NaN
EGS	J	J	D	J	J	J	NaN	NaN
EGS	J	J	D	J	J	J	NaN	NaN
FHS	J	J	D	J	J	J	G	G
QIT	J	J	J	J	J	J	G	G
HFW	J	J	D	A	B	B	G	G

Reference configuration (k) covering new regime with mentioned margin

"NaN" – no reference regime to cover proposed new one with 10% (& 1.0 kA for delta) margin; additional consideration is necessary.

HFW regime is checked by FE global model analysis...

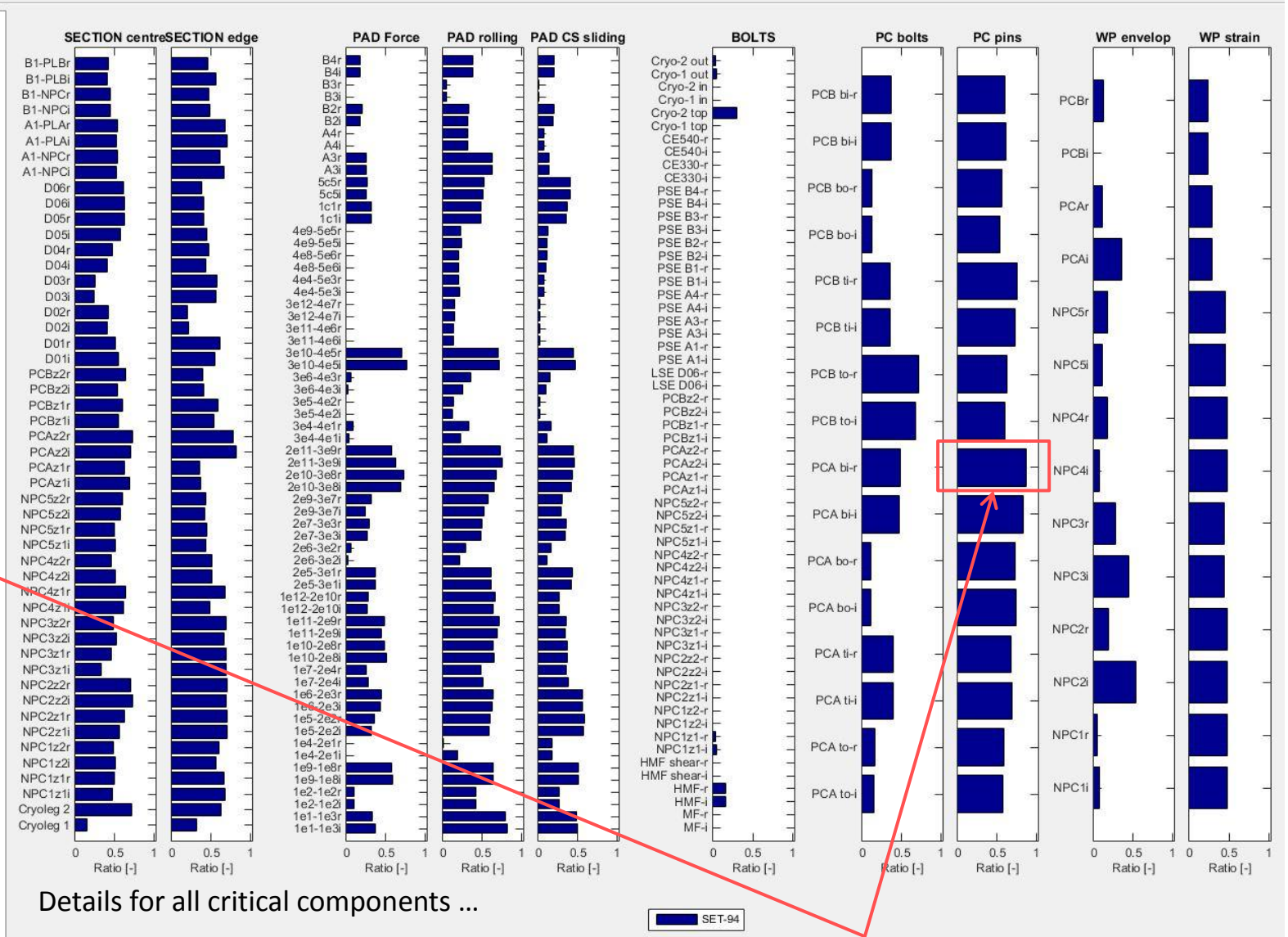
OP1.1: residual stress after unloading

Check of critical generalized forces and moments against Design Values at 3T

Plots

	SET-94
= SECTION =	----------
-- CENTRE --	----------
Cryoleg	0.71
CSE	0.73
LSE	0.62
PSE	0.53
-- EDGE --	----------
Cryoleg	0.63
CSE	0.82
LSE	0.61
PSE	0.70
== PAD ==	----------
Fnormal	0.77
Sliding	0.59
Rolling	0.82
== BOLT ==	----------
CSR	0.16
CSR shear	-0.09
CSE	0.05
LSE	-0.13
PSE	-0.02
CE	-0.16
Cryo	0.30
== PCs ==	----------
bolt	0.72
pin	0.88
== WP ==	----------
envelop	0.53
strain	0.48
=========	----------
ALL sig VM EDGE	0.82
+F PAD	0.82
+sig BOLTS	0.82
+eps WP	0.82
+F PC	0.88
+sig VM CENTRE	0.88
+u PADS	0.88
+u WP	0.88

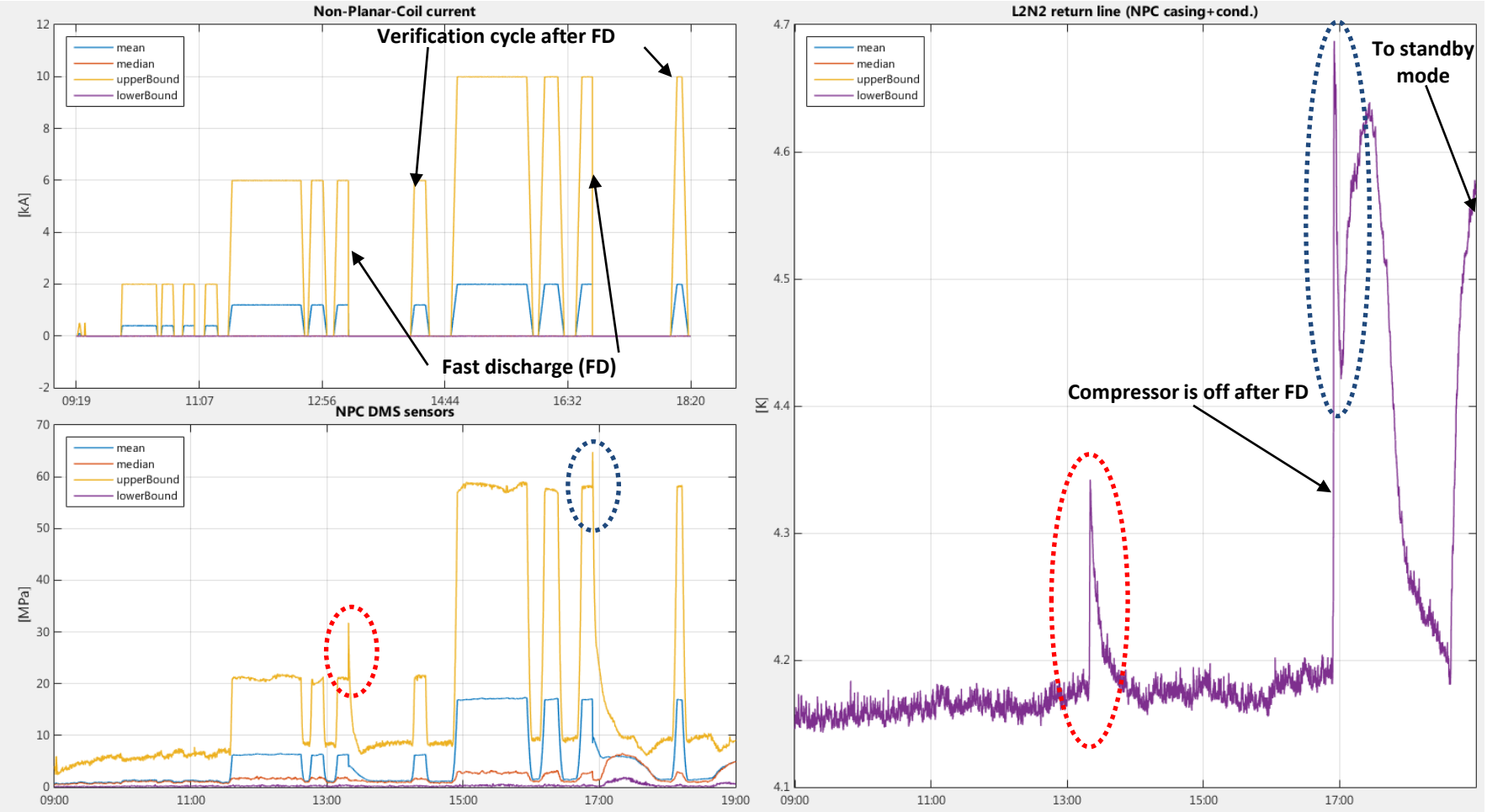
Summary (usage factor should be < 1)



Details for all critical components …

HFW regime above 2.5T design values (coefficient 1.13), but below 3T design values

Coil group commissioning: Type 5. Monitoring.

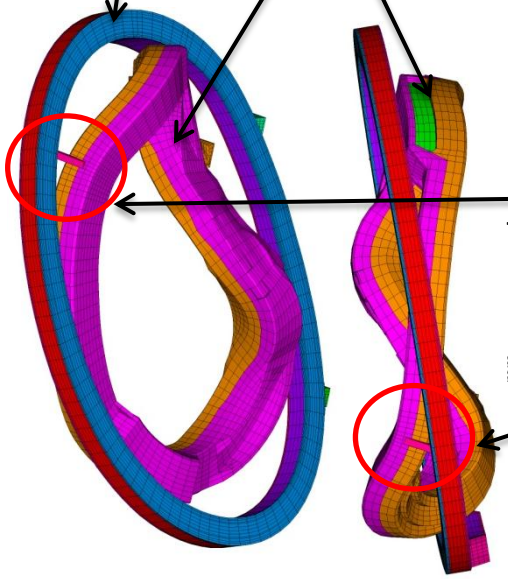


Commissioning of non-planar coil group 5 on 19 May 2015

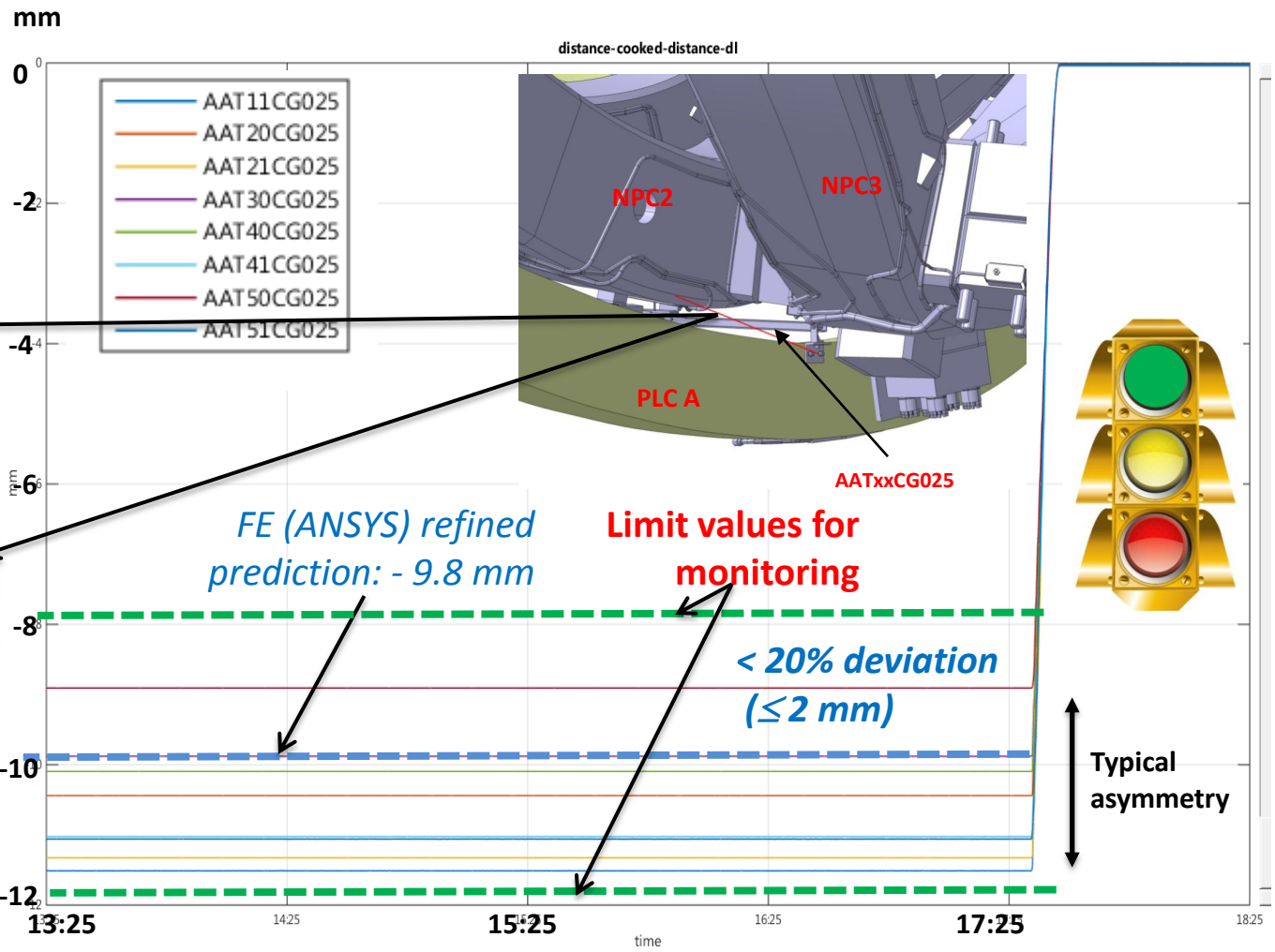
Overview graph from developed software MIViewer [3]
for mechanical instrumentation monitoring (in MATLAB).

OP1.1: FE/measurement typical asymmetry

Maximum measured relative displacements between PLC type A and NPC type 2



Fragment of ANSYS global model with indication of sensor locations in module 1



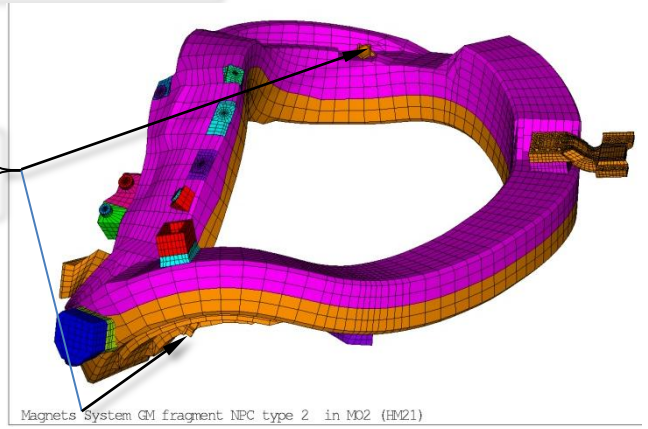
Fragment of measurements monitoring on 08 March 2016

OP1.1: FE/measurement cycles

Check of measurement cycle repetition and deviations from FE predictions.

Non planar coil type 2 case von-Mises equivalent stress levels, MPa. Comparison of FE prediction (GM 6.01) with measurements for cycles of Case A: Reliable, Questionable, NotReliable

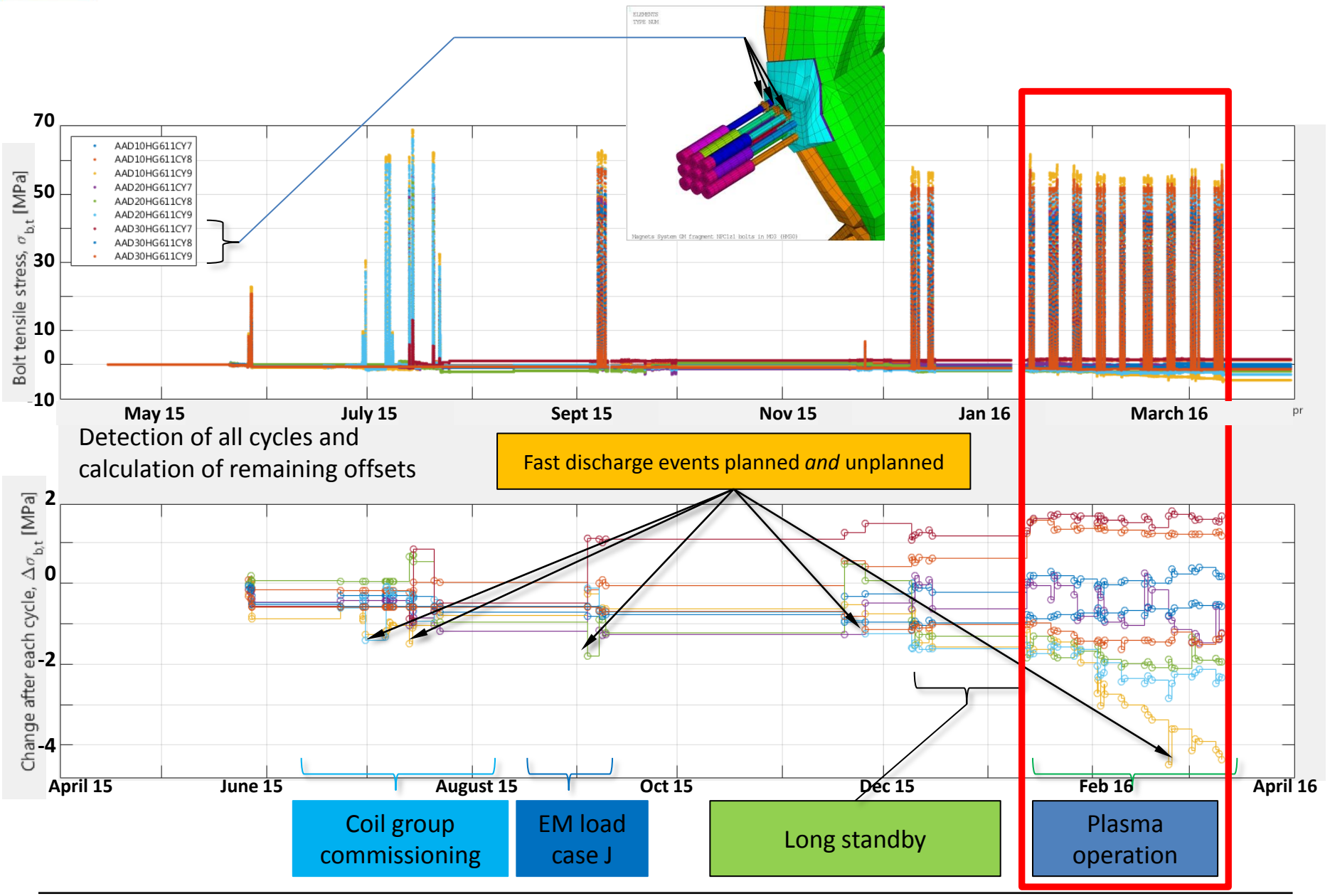
Name	FE results	14-Jul-2015 09:07-09:39			14-Jul-2015 10:36-13:40			Status		
KKS	pure	*pure*	Diff	%	*pure*	Diff	%	R	Q	NotR
AAB32CY001	**110**	***120***	10	9	***120***	10	9	X	.	.
AAB32CY002	**127**	***152***	24	19	***152***	25	19	X	.	.
AAB39CY001	**109**	***84***	-25	-23	***84***	-25	-23	.	X	.
AAB49CY001	**110**	***176***	66	60	***177***	67	61	.	.	X
AAB12CY001	**109**	***102***	-7	-6	***103***	-7	-6	X	.	.
AAB12CY002	**129**	***226***	97	75	***226***	97	75	.	.	X
AAB59CY001	**110**	***738***	628	571	***738.***	628	571	.	.	X



Non planar coil type 2 case von-Mises equivalent stress levels, MPa.
Comparison of FE prediction (GM 6.01) with measurements for cycles of Case J: Reliable, Questionable, NotReliable

Name	FE results	06-Jul-2015 11:13-11:50			07-Sep-2015 09:55-16:29			13-Jan-2016 12:45-18:22			10-Mar-2016 12:10-17:40			Status		
KKS	pure	*pure*	Diff	%	*pure*	Diff	%	*pure*	Diff	%	*pure*	Diff	%	R	Q	NotR
AAB32CY001	**98**	***108.***	10	11	***108***	10.3	11	***104***	6	6	***103***	5	5	X	.	.
AAB32CY002	**133**	***161***	28	21	***157***	23.8	18	***153***	20	15	***153***	20	15	.	X	.
AAB39CY001	**98**	***75***	-23	-24	***75***	-22.8	-23	***72***	-27	-27	***71***	-27	-28	.	X	.
AAB49CY001	**98**	***158***	59	61	***157***	58.9	60	***151***	53	54	***150***	52	53	.	.	X
AAB12CY001	**98**	***92***	-6	-6	***91***	-7.15	-7	***88***	-10	-10	***86***	-12	-12	X	.	.
AAB12CY002	**135**	***242***	107	80	***233***	98.1	73	***229***	94	69	***228***	93	69	.	.	X
AAB59CY001	**98**	***118***	20	21	*727*	629.0	642	***722***	625	637	***723***	625	638	.	.	X

Detailed analysis of bolt-preload loss



Detailed analysis of bolt-preload loss

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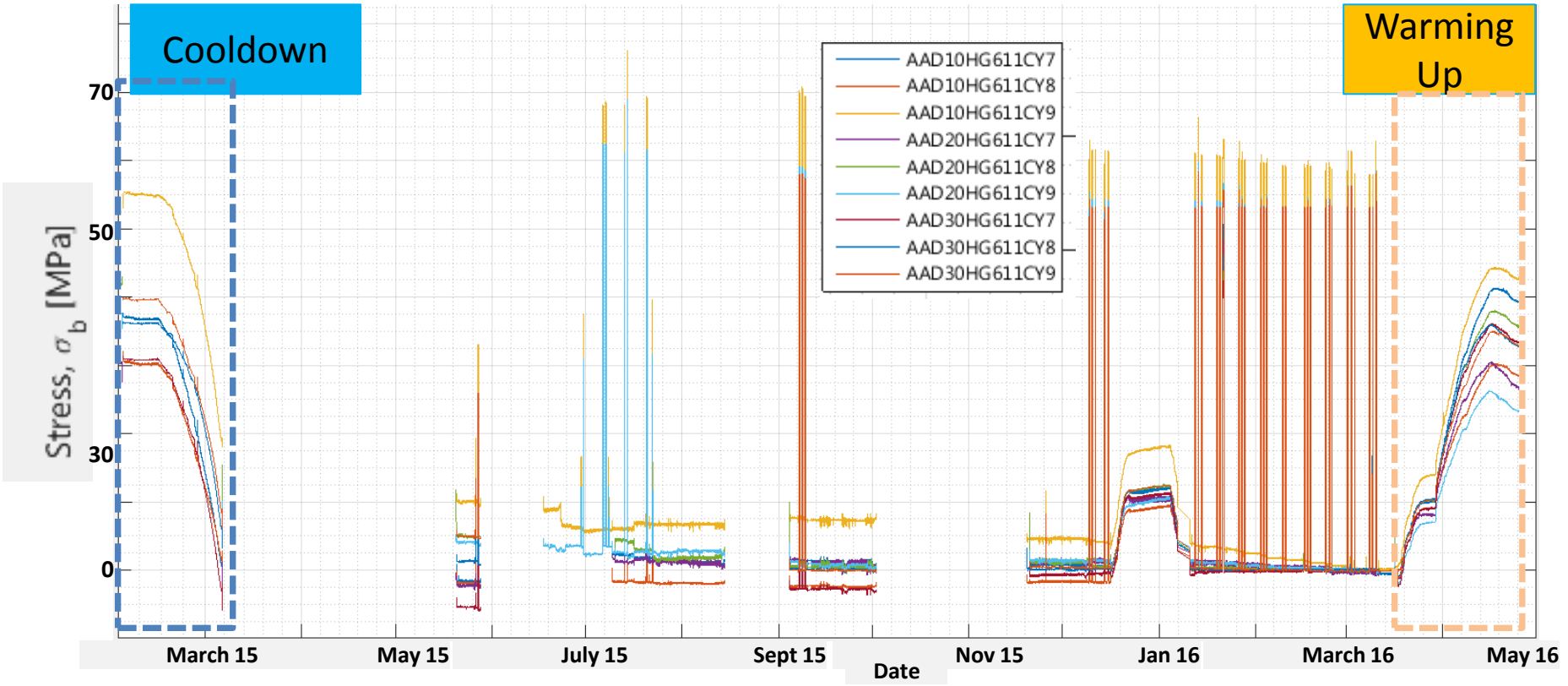


Bolt	Avg. loss over all cycles DPL , MPa	Avg. loss over last 10 cycles DPL_{10},MPa
AAD10HG611CY7	0.0019	0.0197
AAD10HG611CY8	0.0205	-0.0058
AAD10HG611CY9	-0.0713	**-0.1097**
AAD20HG611CY7	-0.0109	**-0.1192**
AAD20HG611CY8	-0.0312	0.0155
AAD20HG611CY9	-0.0455	0.0068
AAD30HG611CY7	0.0247	**0.0321**
AAD30HG611CY8	-0.0085	0.0077
AAD30HG611CY9	-0.0208	0.0234

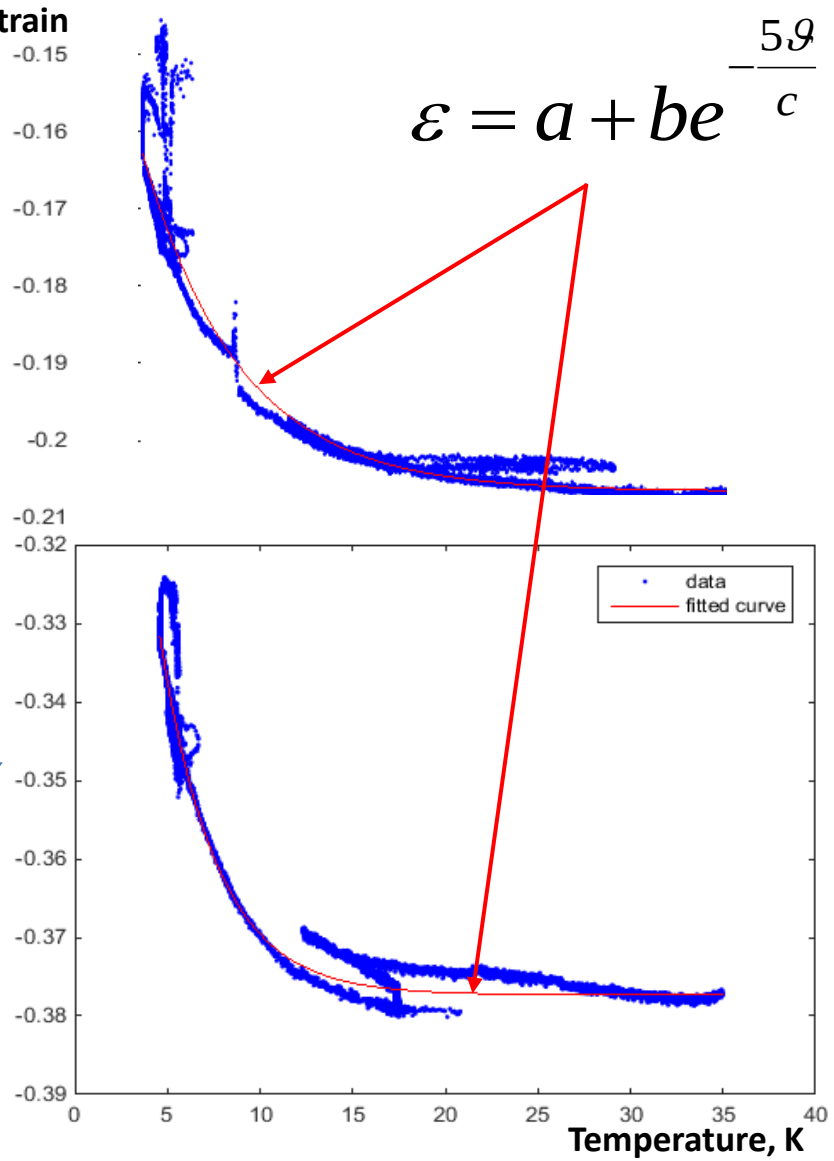
Expected max. loss for OP1.2a ~ 13 Mpa + Cooldown/ Warming up

Bolt	$D_{PL\ Temp}$, Mpa
AAD10HG611CY7	1.66
AAD10HG611CY8	-3.65
AAD10HG611CY9	**-9.97**
AAD20HG611CY7	-3.89
AAD20HG611CY8	-6.04
AAD20HG611CY9	**-14.19**
AAD30HG611CY7	1.99
AAD30HG611CY8	-3.41
AAD30HG611CY9	-6.96

MIVeiwer monitoring improvements

To be faster and user-friendly…

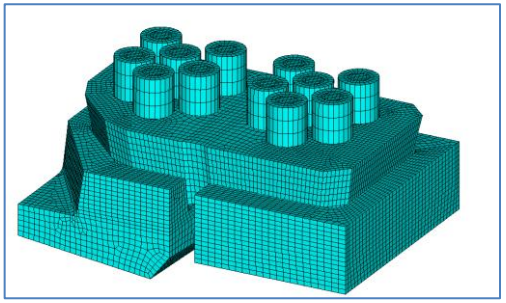
- Change of strategy for storage; post-processing of raw data on request;
- Zeroing stream
  with possibility to have required offset;
- Easy review on selected sensor locations;
- Additional sensors to monitor in parallel (mainly temperature: in-vessel components, thermal insulations, etc);
- Ramping up with simultaneous monitoring and structural assessment;
- Temperature compensation
  with Kalman filter prediction.



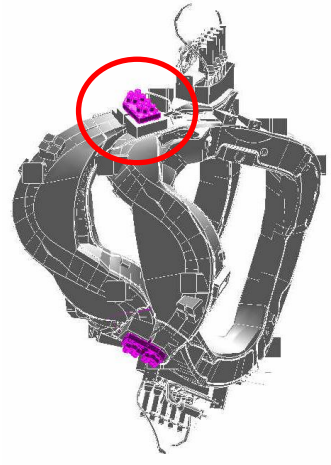
Data collected during first operation phase, coefficients (a,b,c) defined for all strain gauges. Introduction of the compensation in monitoring software is being implemented.

Model improvements part 1 [5]

Bolted lateral support element at module separation between each coil pair NPC5 / NPC5



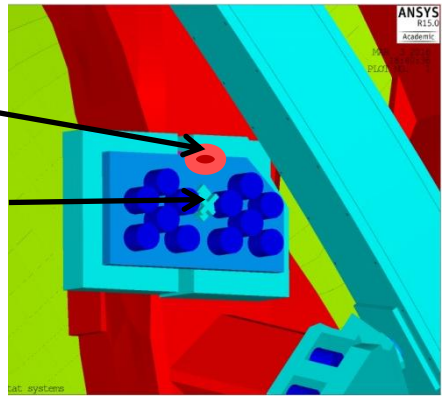
Refined support model incorporated now in Global Model



Solder terminals

Wrong assumption

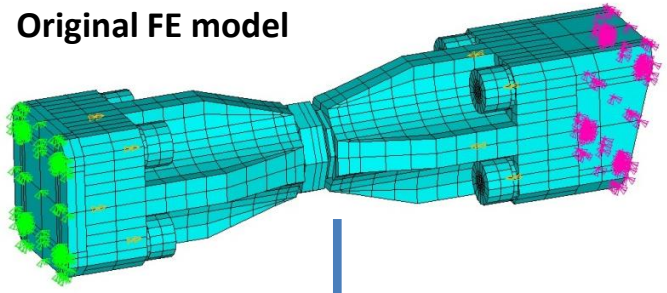
Active grid as glued



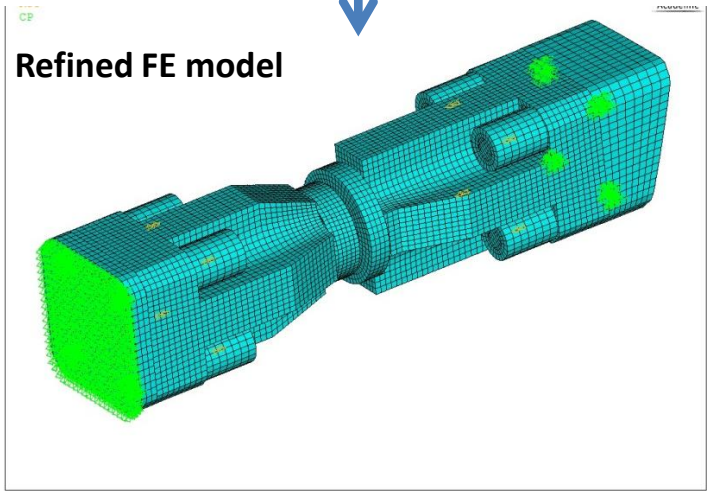
Fragment of global model

Contact support at module interface

Original FE model



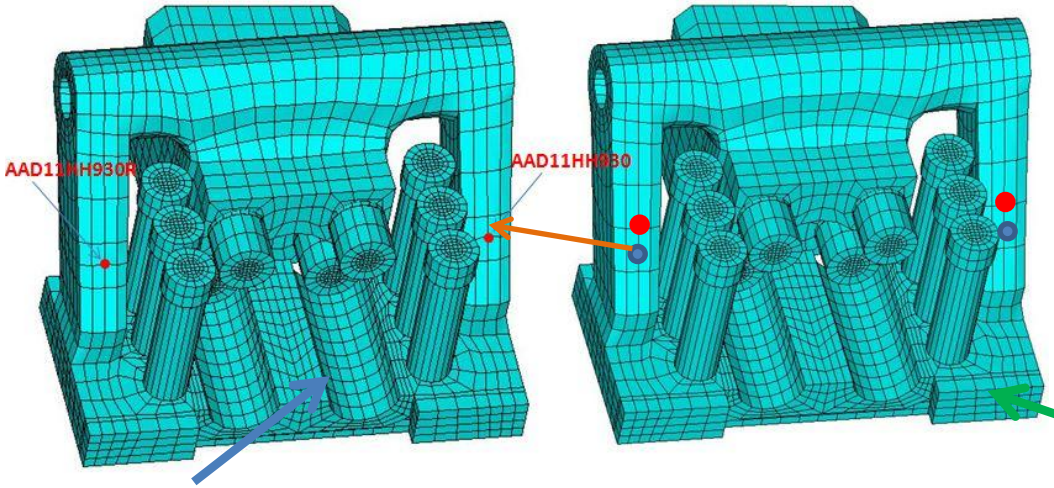
Refined FE model



Model improvements part 2 (local)

Step 2: refinement of ANSYS global model at sensor locations

FE representation of bolted planar coil support B1

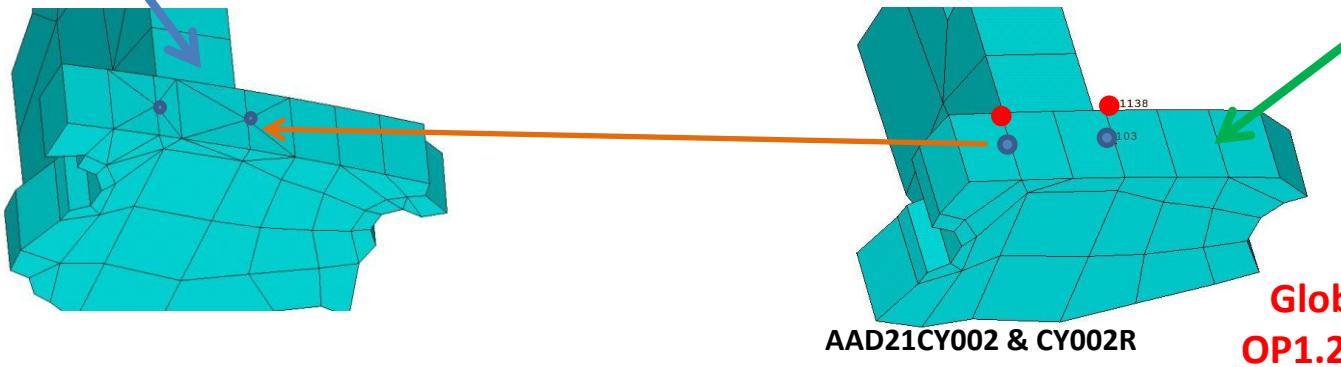


Sensors	Case J (2.5T), MPa		
	Original GM 6.01	*Measure-ments*	Refined GM 6.02
AAC52CY002	**18.0**	*22 - 24;*	**20.0**
AAD30HH930R	**12.0**	*24.2*	**30.0**
	Case A (2.5T), MPa		
AAD10HH930	**20.0**	*62.0*	**40.0**
AAD11HH930	**24.0**	*46.6*	**35.0**
AAD31HH930	**24.0**	*51.8*	**35.0**

Refined FE model

FE representation of central support ring (fragment)

Original FE mesh



AAD21CY002 & CY002R

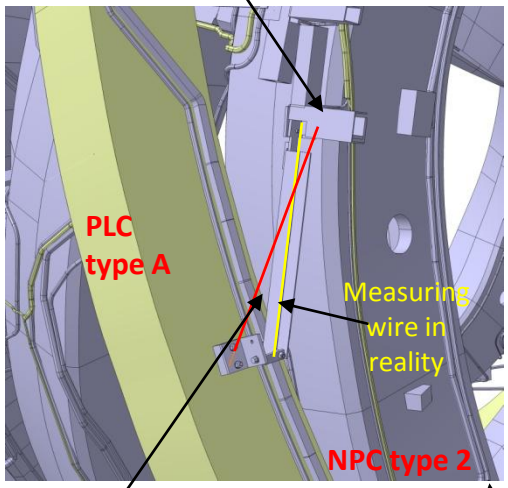
- Extraction node
- Strain gauge position

Global model for OP1.2a monitoring: distance < 20 mm for all sensors

Post-processing improvements

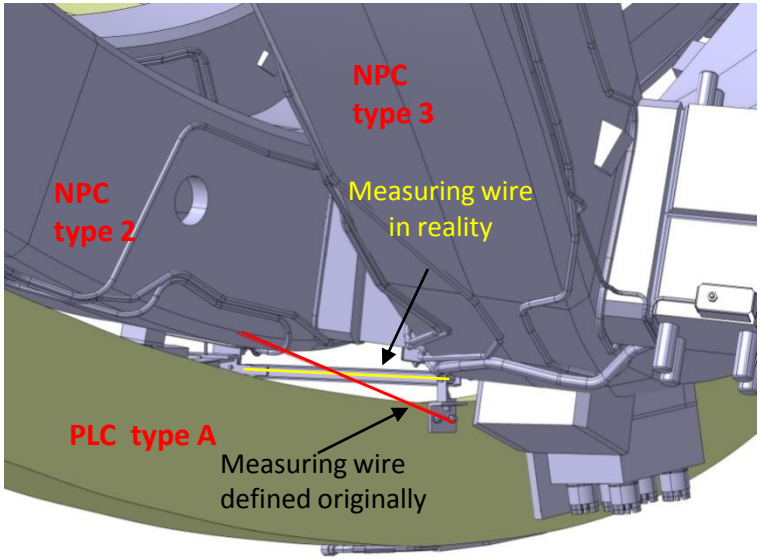
Correction of inclination and extraction for mutual displacement prediction

AATxxCG025r (significant influence)

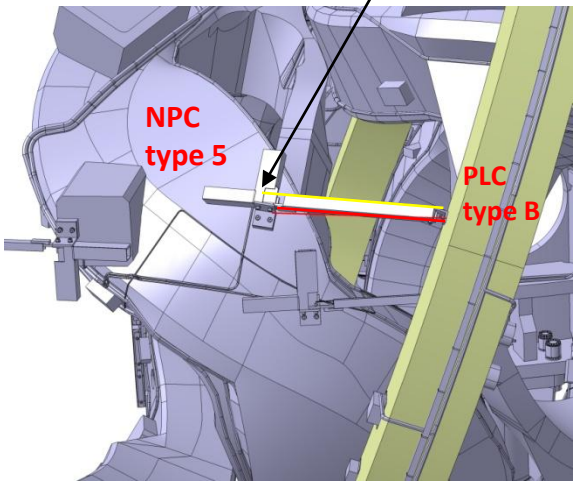


Measuring wire defined originally

AATxxCG025 (moderate influence)



AATxxCG026 (small influence)



Mutual coil displacements, Case J (2.5T), mm

Name	FE results GM 6.01	*Measurement* 1	2	3	4	FE results GM 6.02
AAT10CG021	**-1,67**	*-2,48*	*-1,62*	*-2,16*	*-2,64*	**-1,59**
AAT10CG022	**8,14**	*8,42*	*7,94*	*8,14*	*8,06*	**8,1**
AAT10CG023	**-1,6**	*-1,63*	*-1,76*	*-1,62*	*-1,39*	**-1,88**
AAT10CG024	**-3,41**	*-2,42*	*-2,57*	*-2,61*	*-2,52*	**-2,57**
AAT20CG025	**-10,81**	*-11,12*	*-10,33*	*-10,55*	*-10,59*	**-9,77**
AAT10CG025r	**-6**	*-3,96*	*-3,73*	*-3,86*	*-3,88*	**-4,04**
AAT10CG026	**-0,57**	*-1,27*	*-1,61*	*-1,24*	*-1,26*	**-0,52**

> 2 mm (30%) difference

< 1.1 mm difference

Agreement for next phase operation

1. Slow current ramping up to test monitoring procedure with simultaneous assessment.

2. Only EM regimes satisfying criteria without FE local analysis.

3. Temperature compensation for strain gauges is to be introduced and checked.

4. Level of current and number of fast discharges for test purposes are to be reduced.

5. Regular assessment of the bolt preload degradation.

Conclusions

- **Results of comparison between numerical modeling and mechanical instrumentation measurements show good agreement after introduced modification;**

- **Areas of most attention are defined;**

- **Temperature compensation procedure is developed and is to be tested in order to be fully functioning during most demanding operation phases;**

- **Approach for fast approval of an extension of physics program is developed.**

Further technical challenges are ahead, BUT we are confident to face them and resolve.

References

[1] V. Bykov et al, WENDELSTEIN 7-X MECHANICAL INSTRUMENTATION SYSTEM FOR COMMISSIONING AND OPERATION, Fusion Sci. Technol., vol. 68, no. 2, pp. 267–271, 2015.

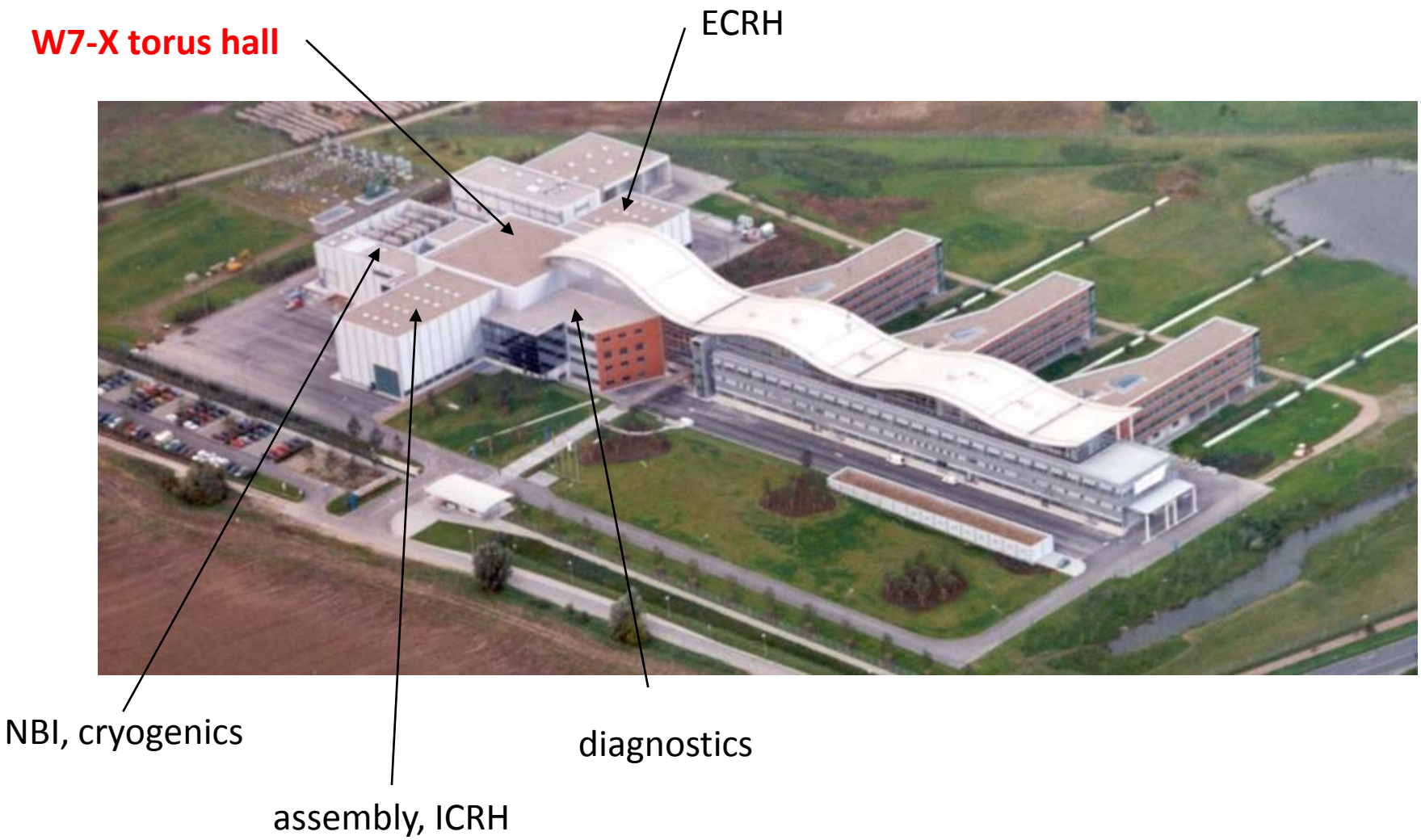
[2] V.Bykov et al., and "Structural Analysis at the Transition from W7-X Construction to Operation", Trans. on Plasma Science, vol. 44, no. 9, pp. 1722-1730, 2016.

[3] A.Carls et al., "A structural integrity monitoring tool for Wendelstein 7-X," presented during SOFT 2016.

[4] V. Bykov and e. al., "Specific Features of Wendelstein 7-X Structural Analyses," IEEE Trans. on Plasma Science, vol. 42, no. 3, pp. 690-697, 2014

[5] V. BYKOV et al., " Engineering Challenges of W7-X: Improvement of Numerical Modelling and Mechanical Monitoring after Commissioning and First Phase of Operation," Fusion Science and Technology (to be published in 2017)

Thank you for you attention!



Q&A

Additional slides

Strategy

Prioritization, simplification [2]…

Experience gained during intensive parametric analyses of critical components…
Monitoring of mechanical instrumentation during commissioning and first operation…

Benchmarking with mechanical instrumentation measurement results ✓

Reliable sensors
Areas for modeling improvements ✓

Software tools [4] for
- easy signal monitoring
- new regime approval
- automatic report generation ✓…

Identification of features to be neglected/ omitted …

Fast analysis of new effects/issues …

Confidence:
modeling is **mostly** reliable
next more demanding step of **OP1.2** is safe

Mostly implemented…

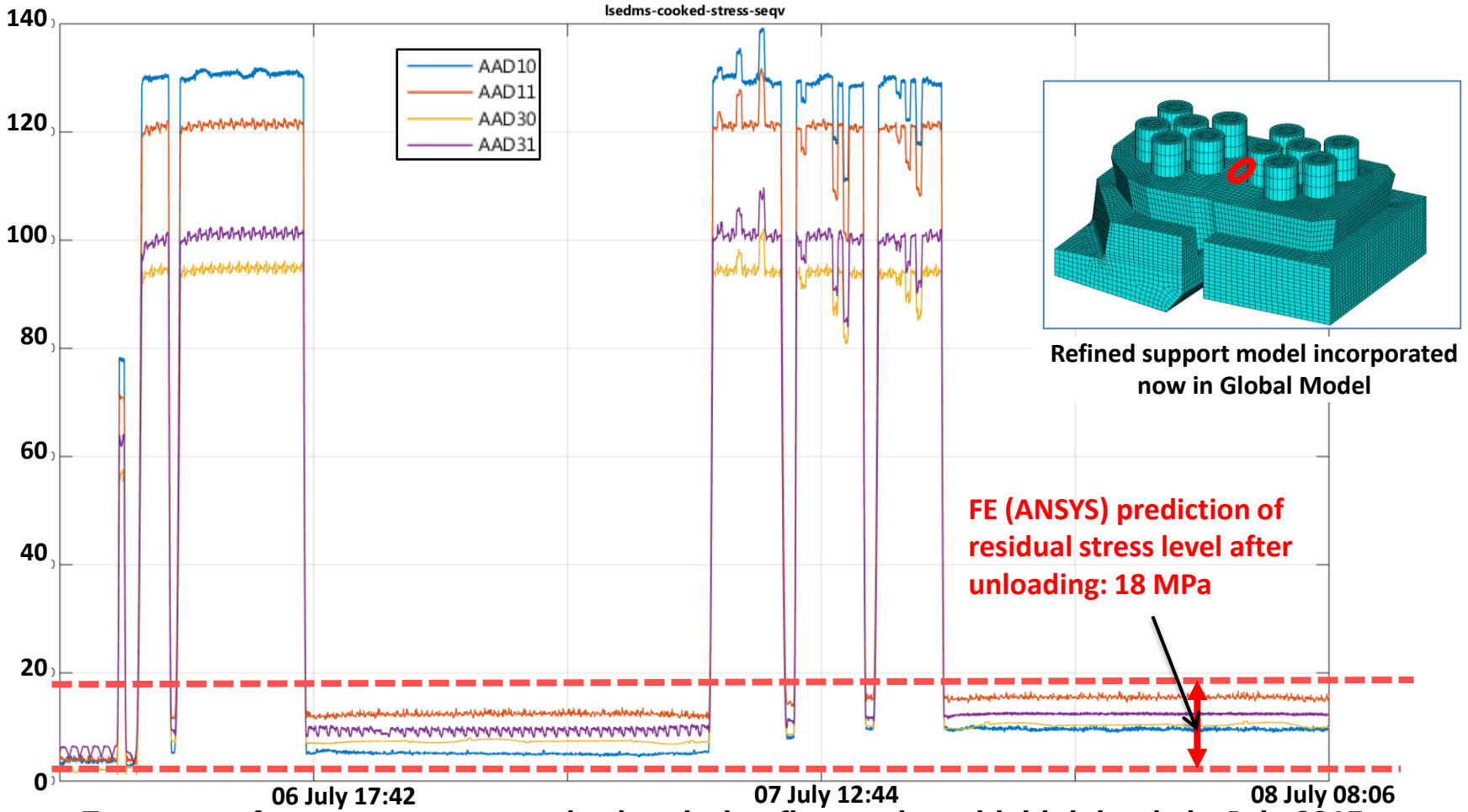
OP1.1: residual stress after unloading

Max-Planck-Institut für Plasmaphysik

Bolted lateral support element at module separation between each coil pair NPC5 / NPC5

Few months of intensive analysis work:

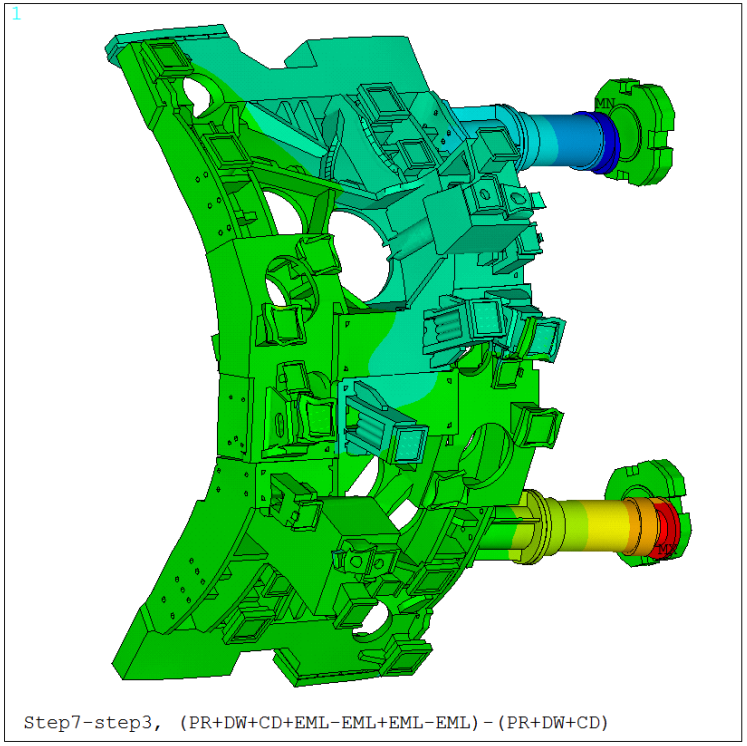
unloading residual stress levels are important and to be including in modeling



Fragment of measurements monitoring during first cycles with high loads in July 2015

EM unloading is added in standard operation FE model analysis

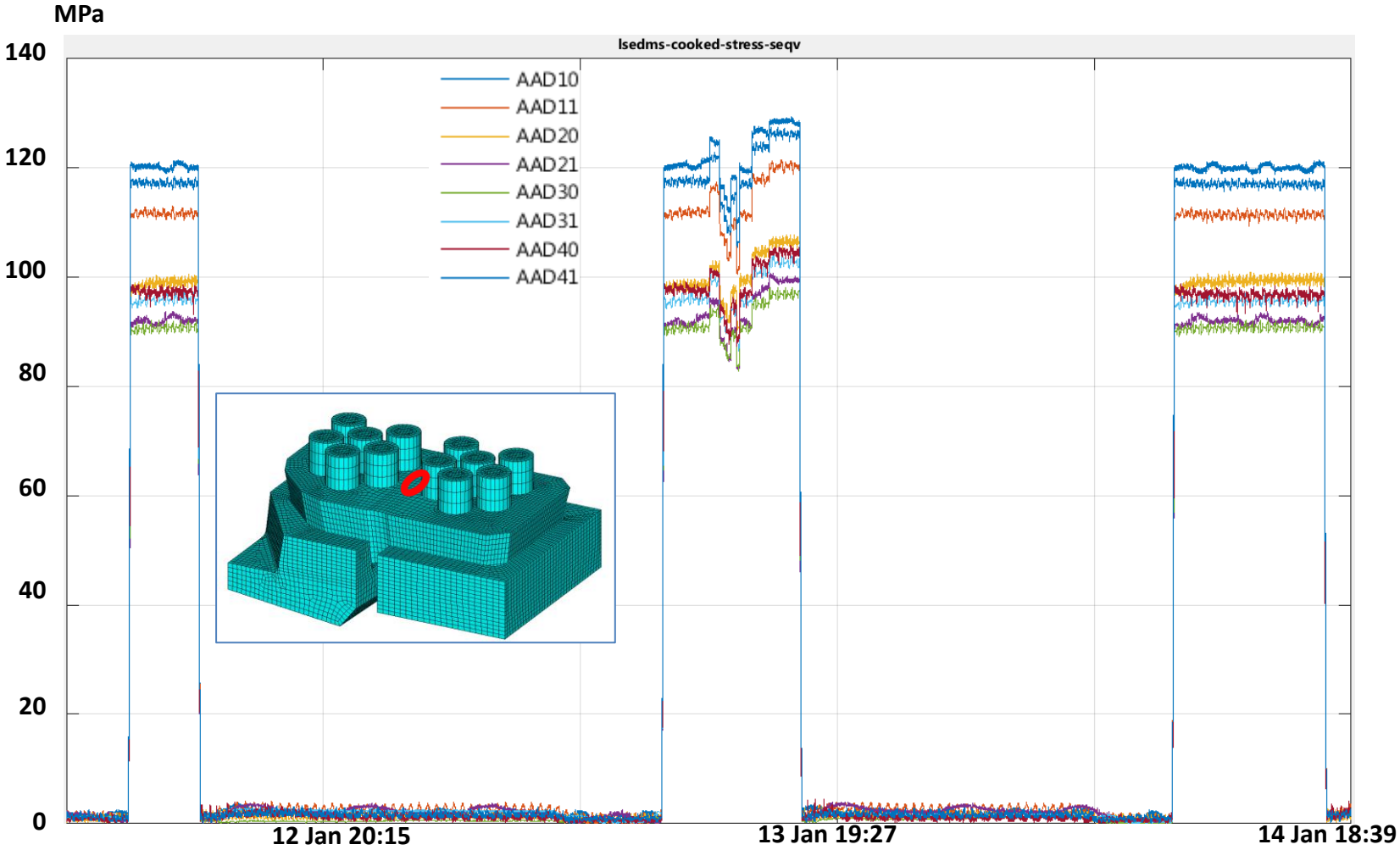
Residual displacements after unloading



Outwards movements of cryolegs after second unloading, m.

OP1.1: stable behavior

Bolted lateral support element at module separation between each coil pair NPC5 / NPC5

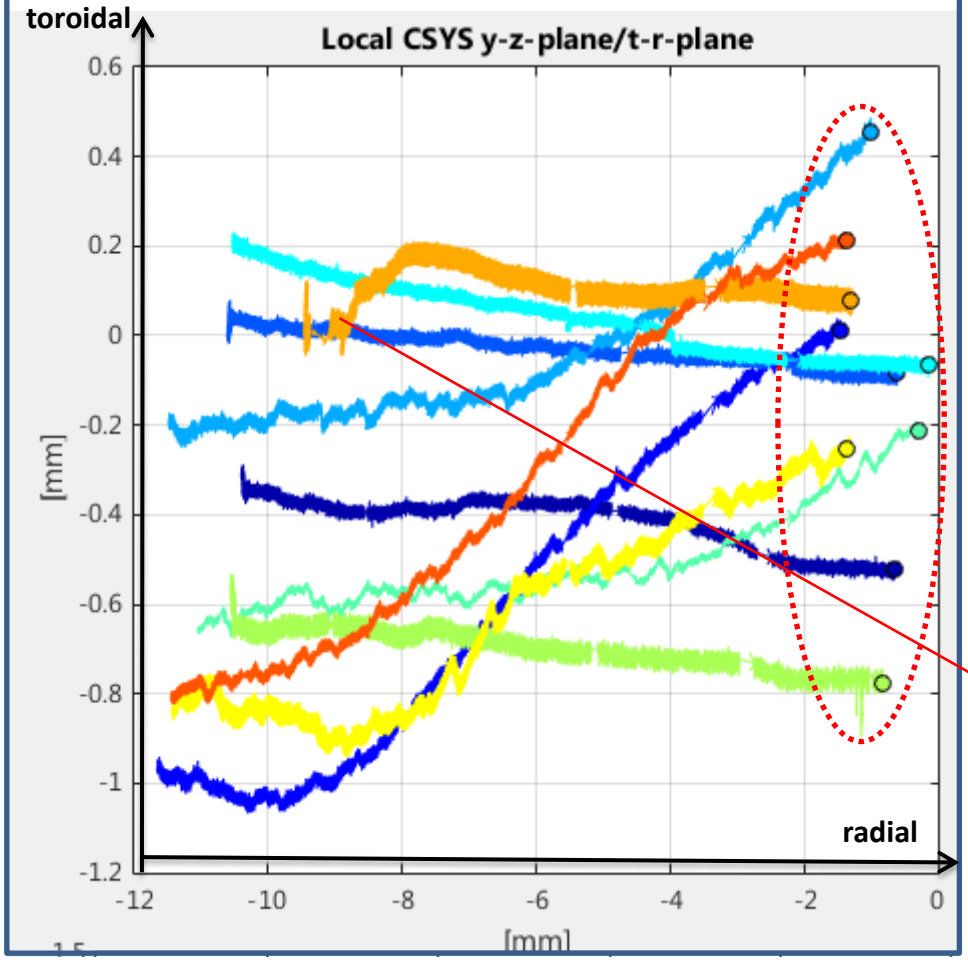


Fragment of measurements monitoring during plasma campaign in January 2016

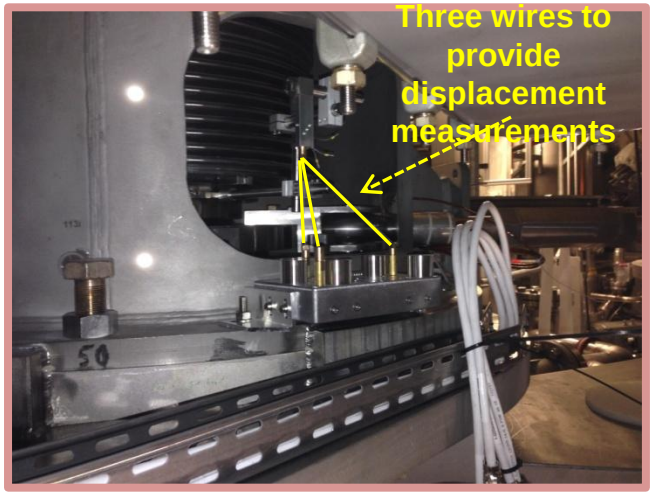
Warming up: Cryoleg sliding

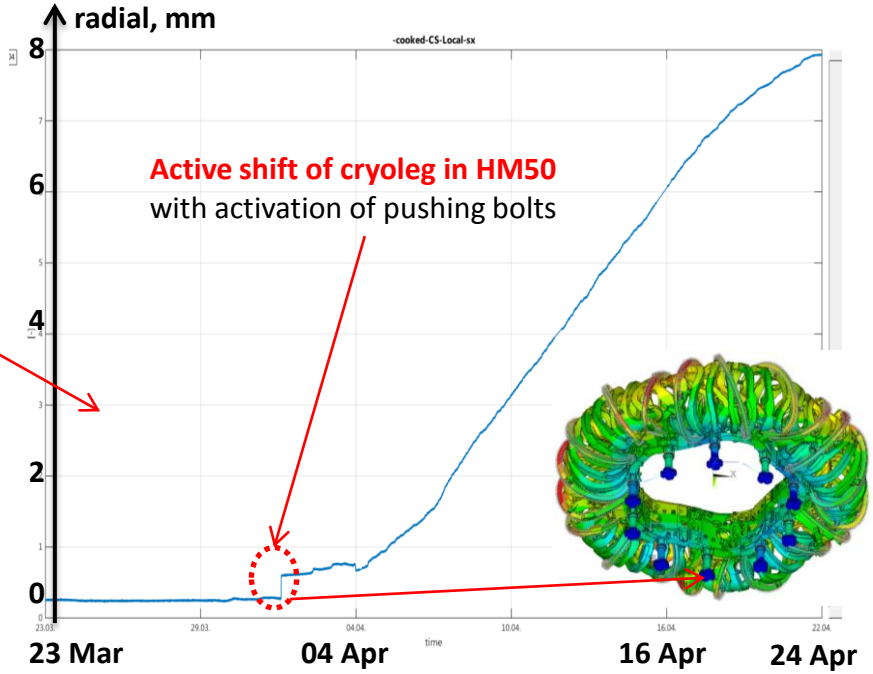
Max-Planck-Institut für Plasmaphysik

Warming up: March – April 2016
(calibration file - before cooldown in Feb 2015)



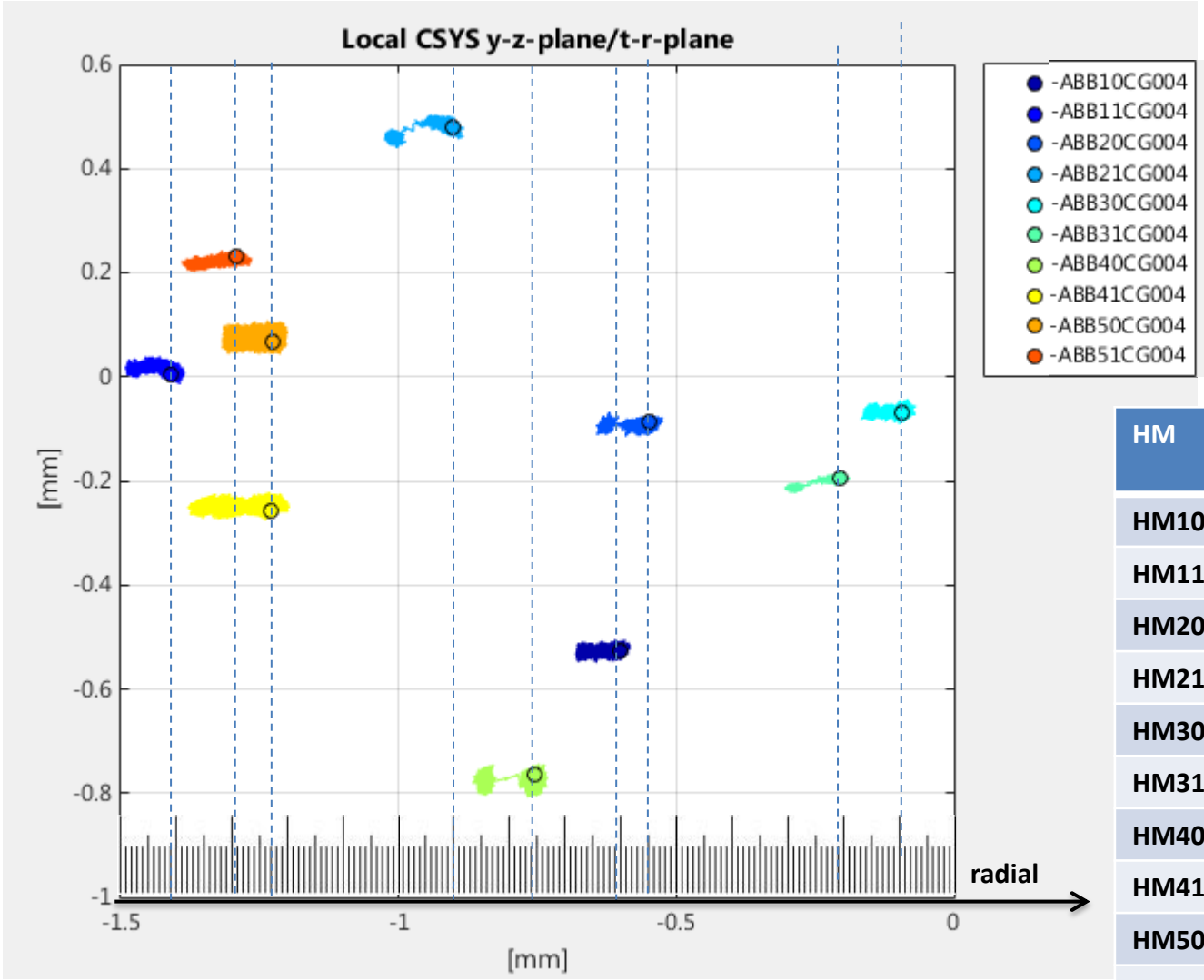
HM10
HM11
HM20
HM21
HM30
HM31
HM40
HM41
HM50
HM51





Positions of cryolegs were not uniform before start of warming up. Final position is with some inclination.

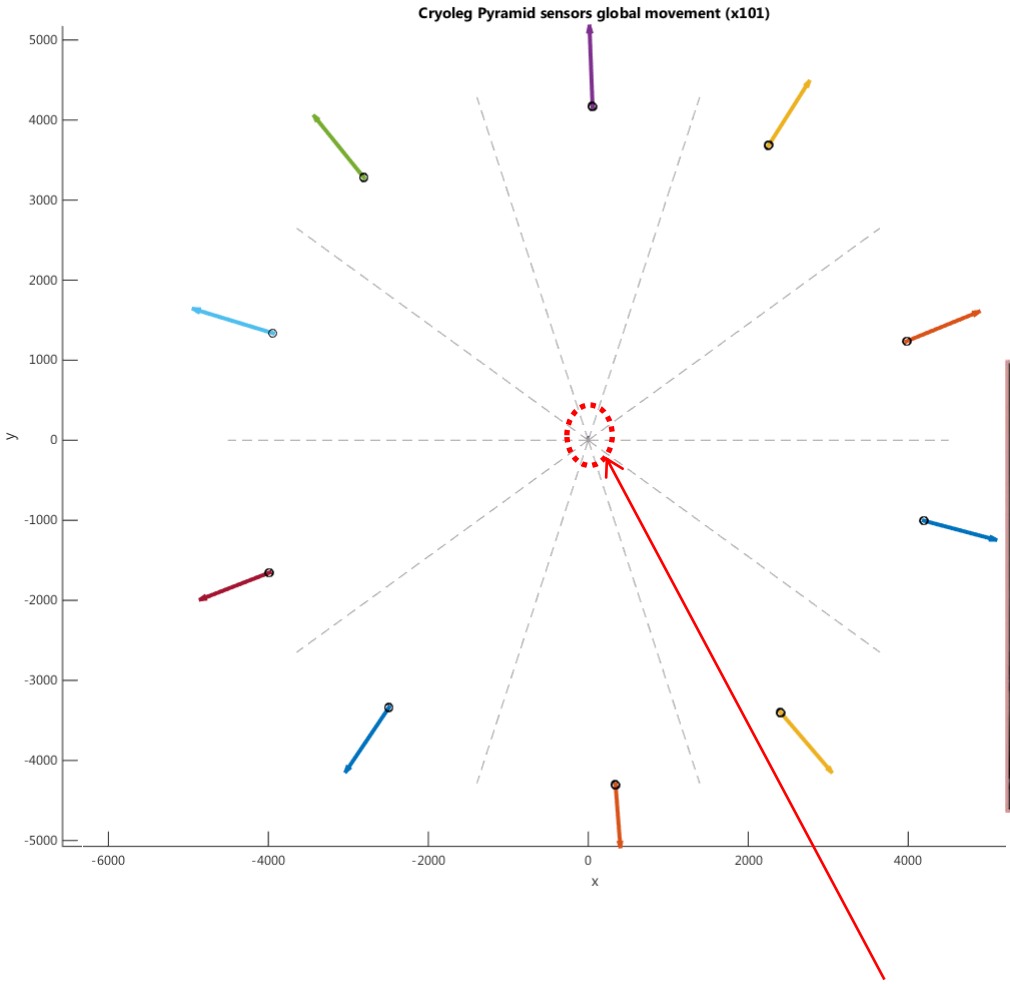
Position of cryolegs after warming up

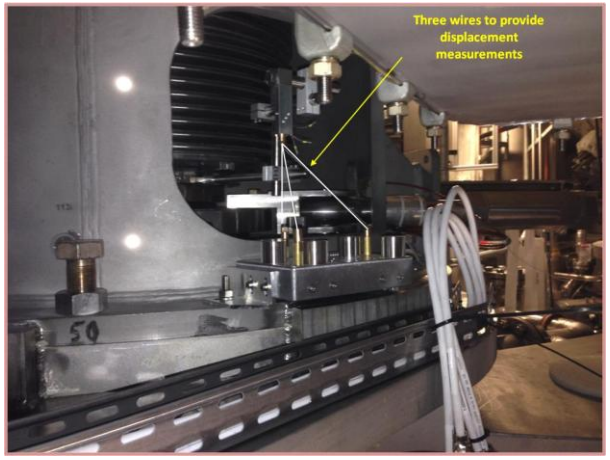


HM	Position	Offset from average -0.82
HM10	-0.61	0.21
HM11	-1.41	-0.59
HM20	-0.55	0.27
HM21	-0.90	-0.08
HM30	-0.09	0.73
HM31	-0.11	0.71
HM40	-0.76	0.06
HM41	-1.23	-0.41
HM50	-1.23	-0.41
HM51	-1.29	-0.47

Position of cryolegs after warming up, mm.

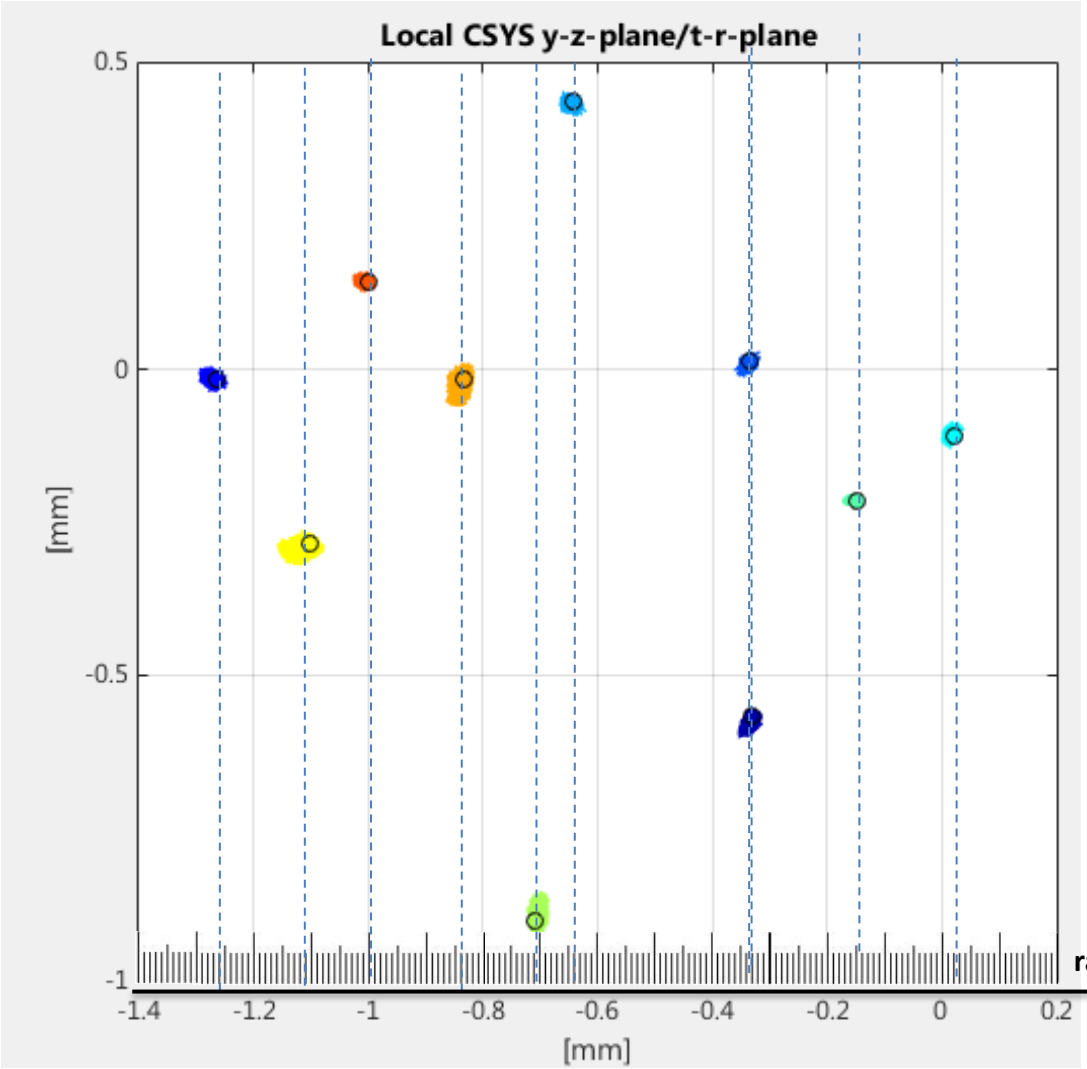
Residual displacement of magnet system





Magnet system is back with < 0.5 mm accuracy

Position of cryolegs after warming up

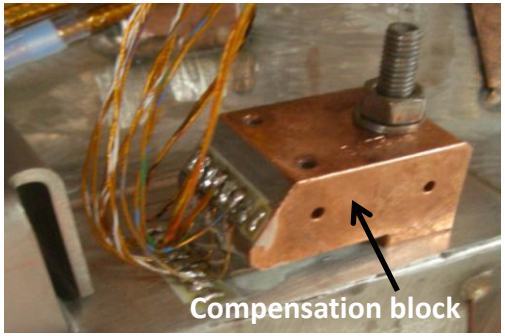


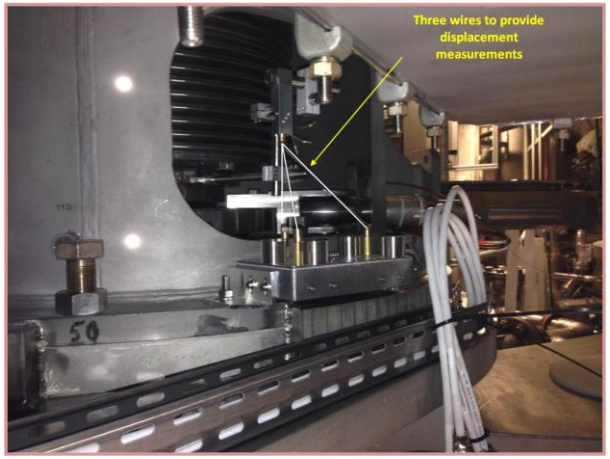
HM	Position After Warming Up	Position After CP 1.2a
HM10	-0.61	-0.34
HM11	-1.41	-1.26
HM20	-0.55	-0.33
HM21**	-0.90	-0.64
HM30	-0.09	+0.03
HM31	-0.11	-0.14
HM40	-0.76	-0.71
HM41	-1.23	-1.11
HM50	-1.23	-0.84
HM51	-1.29	-1.00

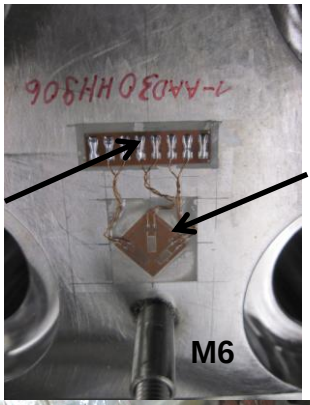
**** re-adjusted on 20 February 2007**

Position of cryolegs after CP1.2 at the beginning of cooldown up, mm.

Sensors

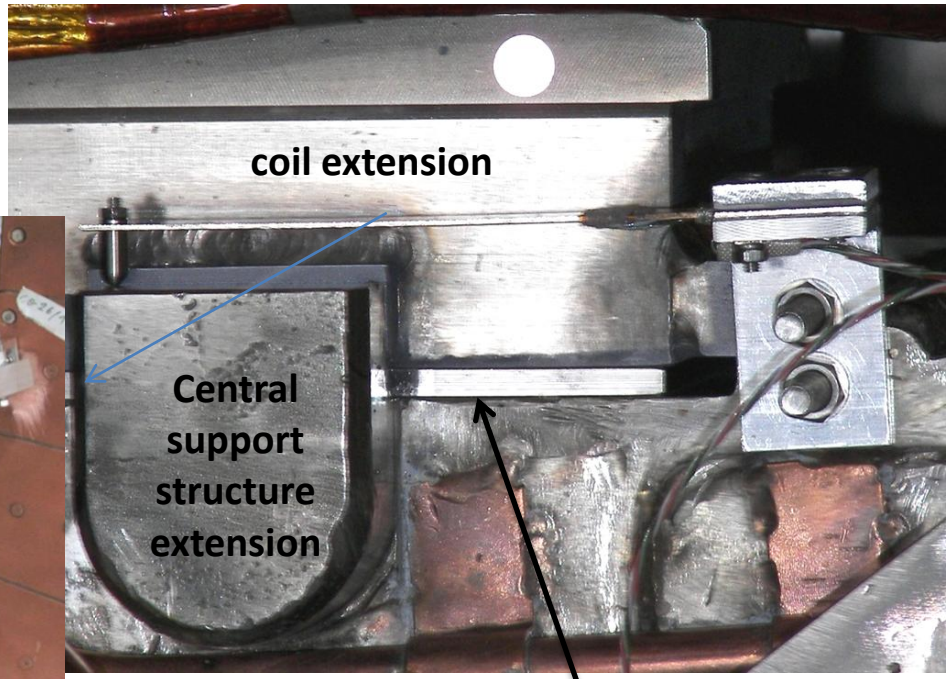


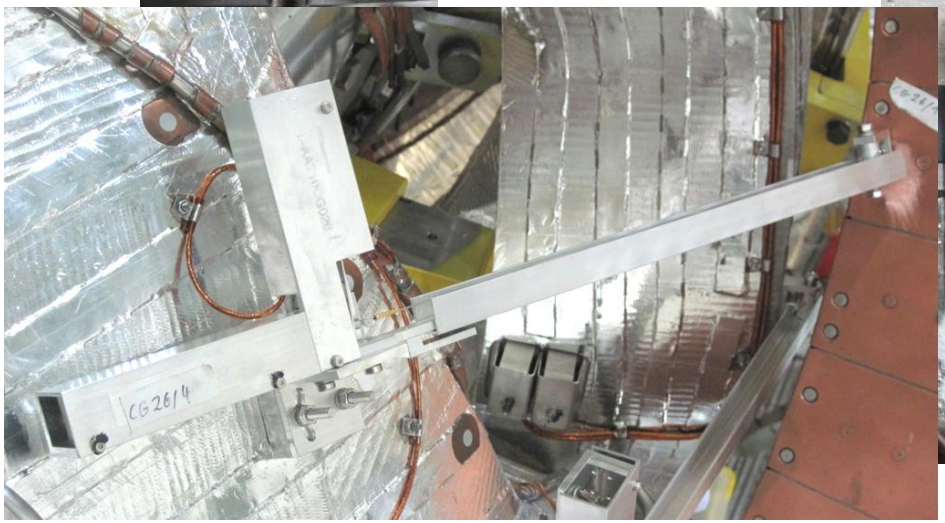




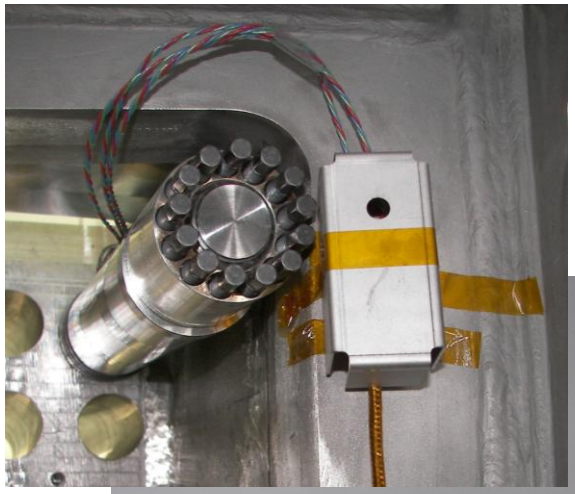
Solder terminals

Active grid as glued

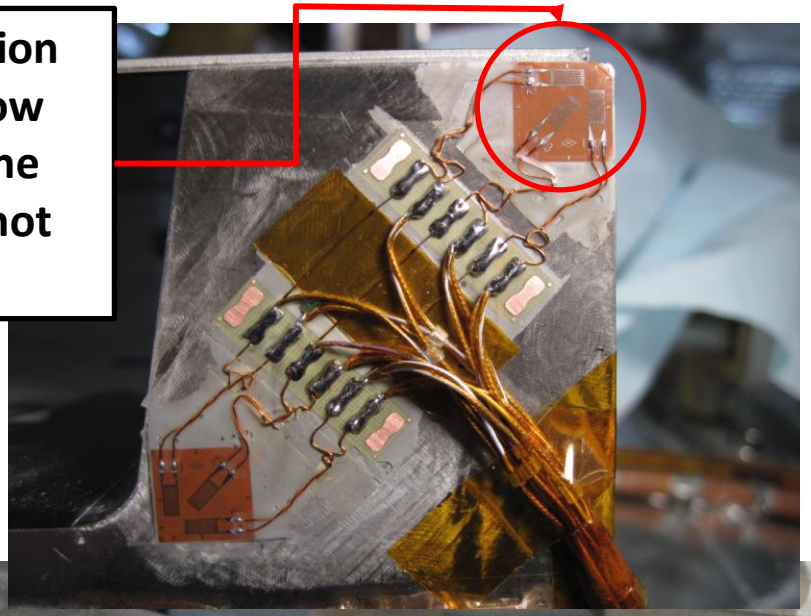




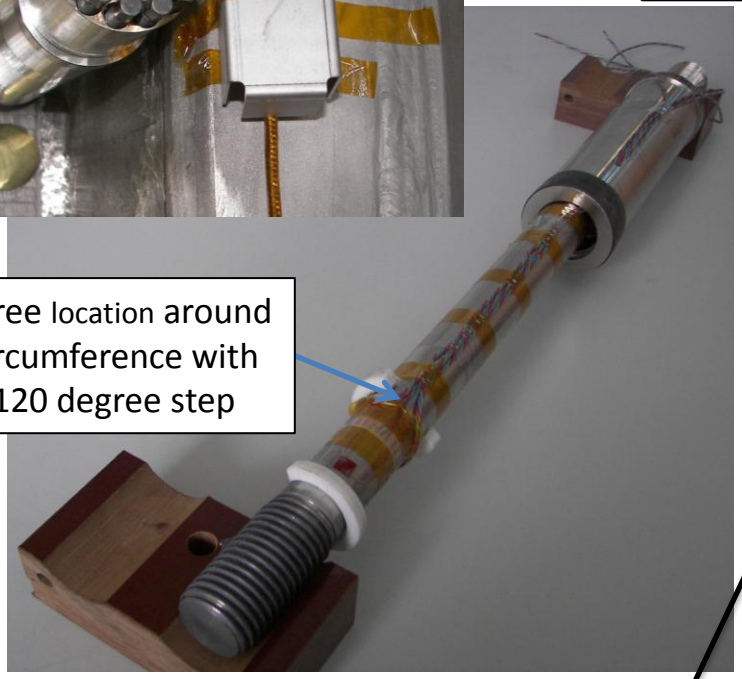
Sensors 2

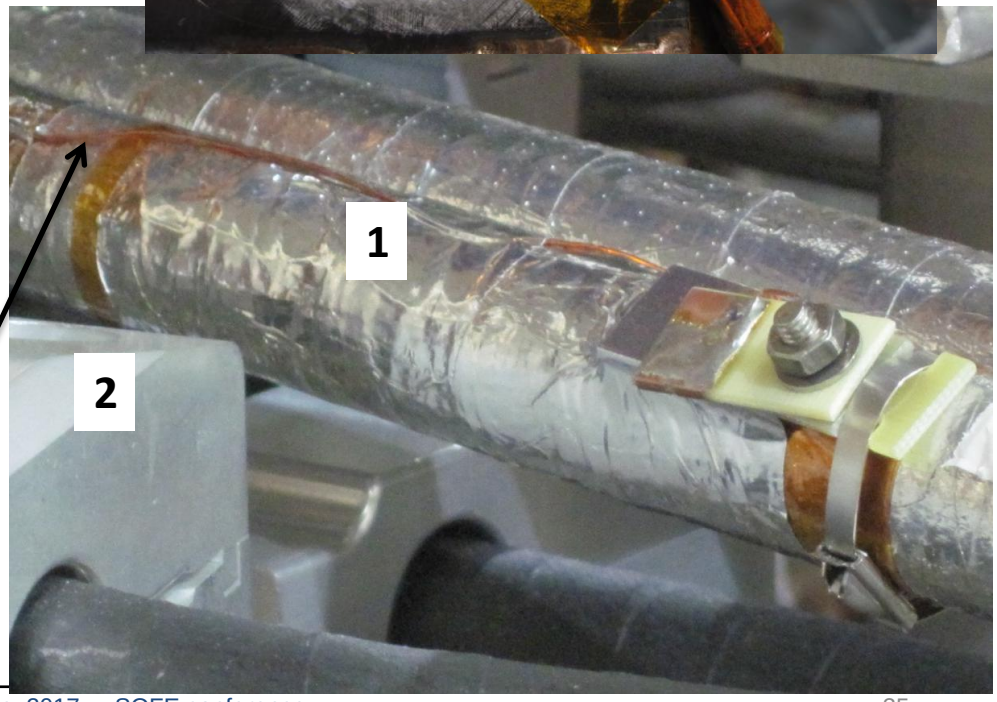


Compensation rosette in low stressed zone Housing is not possible



Three location around circumference with 120 degree step





wire