Max-Planck-Institut für Plasmaphysik

Cyclic Behavior of Wendelstein 7-X Magnet System during First Two Phases of Operation

V. Bykov, J. Zhu, A. Carls, B. Hein, K. Risse, P. van Eeten, H-S. Bosch, L. Wegener and the W7-X Team

Max-Planck-Institut für Plasmaphysik, 17491 Greifswald, Germany

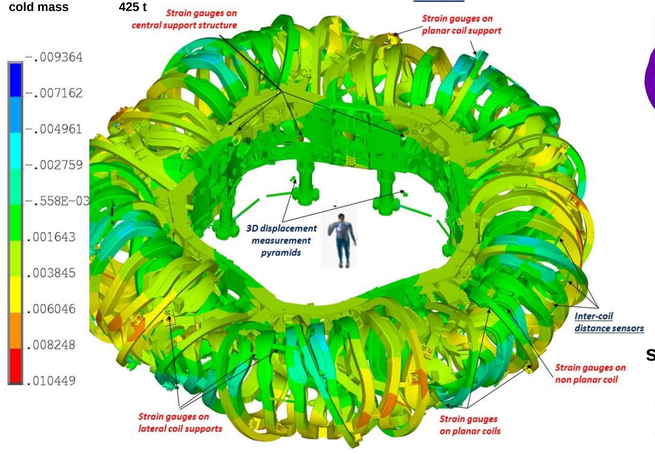
Abstract

- *Wendelstein 7-X (W7-X) largest modular stellarator;*
- *First two experimental campaigns (13 months);*
- *Sophisticated magnet system;*
- *70 superconducting coils (NbTi CCIC);*
- *Complex 3D shapes of 50 non-planar coils;*
- *Non-linear support system;*
- *Five big resistive coils to correct error fields;*
- *Rubber pads in their supports to compensate thermal expansion;*
- *Extended set of temperature and mechanical sensors to monitor;*
- *Comparison with finite element (FE) predictions;*
- *70% design load magnitude performed by the system successfully.;*
- *Cyclic structural behavior & related issues:*
  support bolts preload degradation,
  rubber pads prestress degradation,
  support slippage development,
  evolution of mutual coil displacement,
  loading path dependence of stress levels,
  sliding weight support adjustment….
- *Lessons learned so far*

Introduction

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

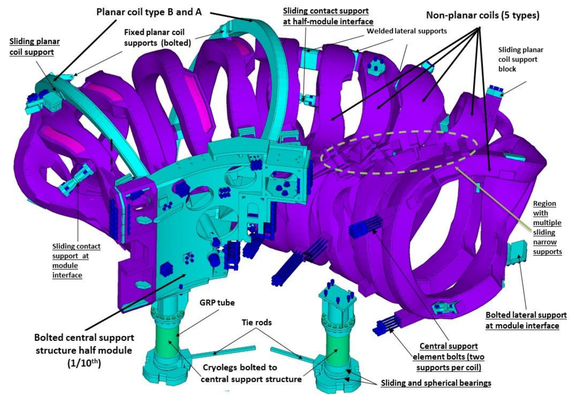
~800 mechanical instrumentation sensors (among > 3000 in total):
Strain gauges
Contact
Distance



Toroidal displacements under most used EJM+252 regime electromagnetic loads (m). 26 cycles from ~ 800 supervised cycles.

	Currents (kA)
Non-planar coils (type 1 ÷ 5)	13.1
Planar coils (type A & B)	0.7

Non-linear support system



Main non-linear support elements of W7-X magnet system (indicated on fragment of finite element model with underlined captures)

- 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 in FE analyses.

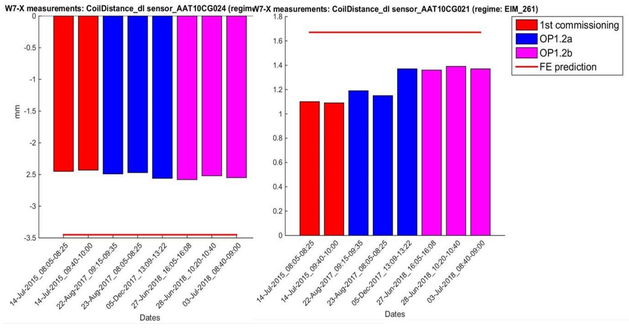
Cyclic loading and behavior

Evolution of the response during first loading cycles:
- settlement of the system;
- redistribution of internal residual stresses.

Minimization of full loading cycles/ operation time:
- transition from one configuration to another;
- scan through multiple configurations.

Bolt prestress degradation.
Bolted support slippage.

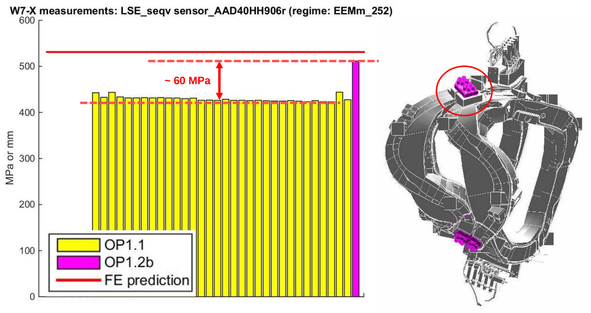
V. Bykov et al, Engineering Challenges of Wendelstein 7-X Mechanical Monitoring during Second Phase of Operation, Fusion Science and Technology, , DOI: 10.1080/15361055.2019.1623568

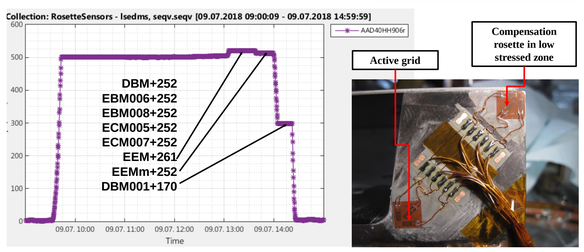


Stable and evolutionary behavior of mutual coil displacements (mm) during standard regime (EIM261) loadings 2015 - 2018. Between coils of type 5 (module interface, (left) and between coil types 1-2 (right)

Specific issues

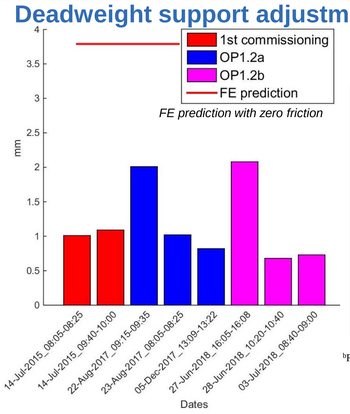
Loading path dependence





Difference in stress levels (corner of bolted lateral support shoulder) depending on loading path:
loading from zero current in OP1.1 campaign (yellow, top) vs transition from EEM+261 during OP1.2b (magenta, top) and bottom figure

Deadweight support adjustment

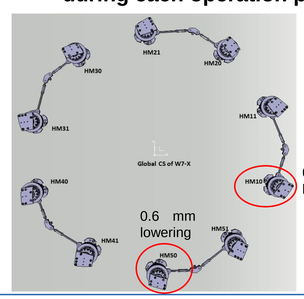


Cryoleg load asymmetry correction

Module	HALF MOULE	FRICTION FACTOR[a] %	Measurements		
			Force before action, kN	After action, kN	Stiffness[b], kN/m m
1	10	1.77	366	550	240
	11	3.66	-	-	-
2	20	2.99	-	-	-
	21	2.90	-	-	-
3	30	2.64	-	-	-
	31	3.98	-	-	-
4	40	5.32	-	-	-
	41	2.58	-	-	-
5	50	6.79	640	350	230
	51	4.65	-	-	-

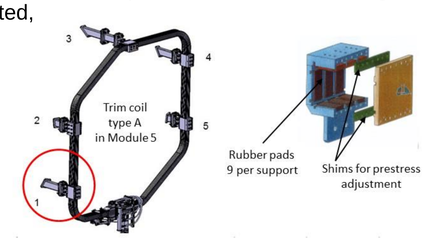
[a]FE estimation (equal distribution of DW between supports)
[b]FE estimation is 280 kN/mm without machine base

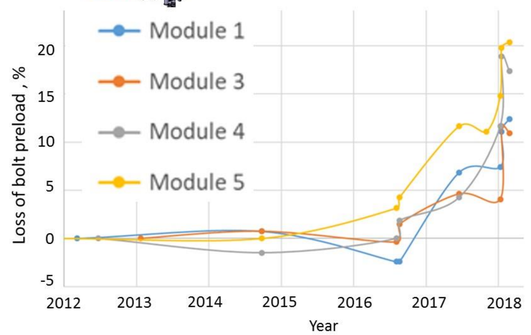
Degradation of HM50 cryoleg sliding for standard configuration loading (EIM261) during each operation phase



Rubber pads in resistive coil supports

Degradation is exponential rather than logarithmic as expected,





Typical degradation of rubber pad prestress

does not exceed predicted values.
Increasing of the rubber pad prestress: before next operation campaign.

Conclusions

- Detail analysis of cyclic behavior is ongoing process. Conclusions after two W7-X operation phases:

+ Stable cyclic behavior in general.

+ Non-linear supports system proved its ability to withstand high loads in different new regimes.

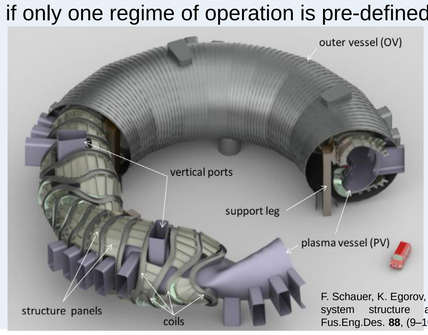
- Several corrective measures are necessary. (cryolegs adjustment successfully completed).

- Close monitoring is strongly required; safety margins included in the design are reduced by unexpected deviations with no clear explanation.

- The global FE model prepared is to be subjected to benchmarking and refinement.

Non-linear support system is attractive for systems with not fully defined loading patterns,

It could be easily dropped for a future stellarator reactor, if only one regime of operation is pre-defined:



F. Schauer, K. Egorov, V. Bykov, HELIAS 5-B magnet system structure and maintenance concept, Fus.Eng.Des. **88**, (9–10) 1619-1622, 2013

*Corresponding author: victor.bykov@ipp.mpg.de

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