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

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Abstract

The sophisticated large magnet system of the Wendelstein 7-X (W7-X) stellarator has been operated during first two experimental campaigns at the Max-Planck-Institute for Plasma Physics in Greifswald, Germany, for roughly 13 months. Its 70 superconducting coils (NbTi CCIC) are extraordinary not only due to complex 3D shapes of 50 non-planar coils, but also due to a non-linear support system. In addition, five big resistive coils with the aim to correct W7-X error fields are installed on the outer cryostat and use rubber pads in their supports to compensate thermal expansion of the coils. The structural behavior of the W7-X magnetic system is monitored and evaluated on the basis of the analysis of the signals from the extended set of mechanical and temperature sensors. Several cooldown/warming up and thousands of electromagnetic cycles with different loading patterns and with up to 70% design load magnitude have been performed by the system successfully. The focus of this paper is on the cyclic structural behavior of the W7-X magnet system and the comparison with finite element predictions. Several related issues such as bolts and rubber pads prestress degradation, support slippage development, evolution of mutual coil displacement, loading path dependence of stress levels, sliding weight support (cryoleg) adjustment, and sensor failure are addressed. Lessons learned so far are also briefly summarized.

Index Terms: Wendelstein 7-X, stellarator, magnet system, nonlinear, support system, monitoring, operation.

I. Introduction

Magnet systems (MS) of large experimental magnetic confinement fusion devices are able to produce considerable magnetic field strength in the plasma volume. As a result, considerable forces and significant moments are induced in the coils and their support structures [1], [2].

Nonlinear support systems with contact/sliding elements are very attractive for such highly loaded structures when the configuration space is not fully defined during design phase. Its ability to redistribute loads between components, if the support system for individual coil is overdetermined, allows for considerable reduction of required component space compared to fixed supports. Especially the experimental stellarators with narrow spaces between coils require special support design solutions.

The sophisticated MS of the largest modular stellarator Wendelstein 7-X (W7-X) is a great example of this approach. Several non-linear support elements have been introduced after refined finite element (FE) analyses due to strict space limitation.

The device has been successfully operated during the first two experimental campaigns (OP1.1 – with limiter only and OP1.2a/b – with passively cooled in-vessel components), for roughly 13 months with great physical achievements [3]. Its 70 superconducting coils (NbTi CCIC, AlMgSi (6063) jacket) arranged in the fivefold symmetric manner are extraordinary not only due to complex 3D shapes of 50 non-planar coils, but also due to the large set of structural and thermal sensors on the coils and their support structures to monitor the behavior of the non-linear support system (see Fig. 1 and [4]). All components of the magnet support system have been operated up to 70% of design loads to fulfill physics program with ~ 2.5 T of magnetic induction on the plasma axis. The search for optimized parameters for physics programs in steady-state operation phase OP2 (from2021) resulted in new magnetic configurations, which have to be carefully checked before their use [4], [5].
Successful compensation of main magnetic field errors [6] have been done by five normal conducting trim coils (TCs) installed on the cryostat and accessible for checking and maintenance.

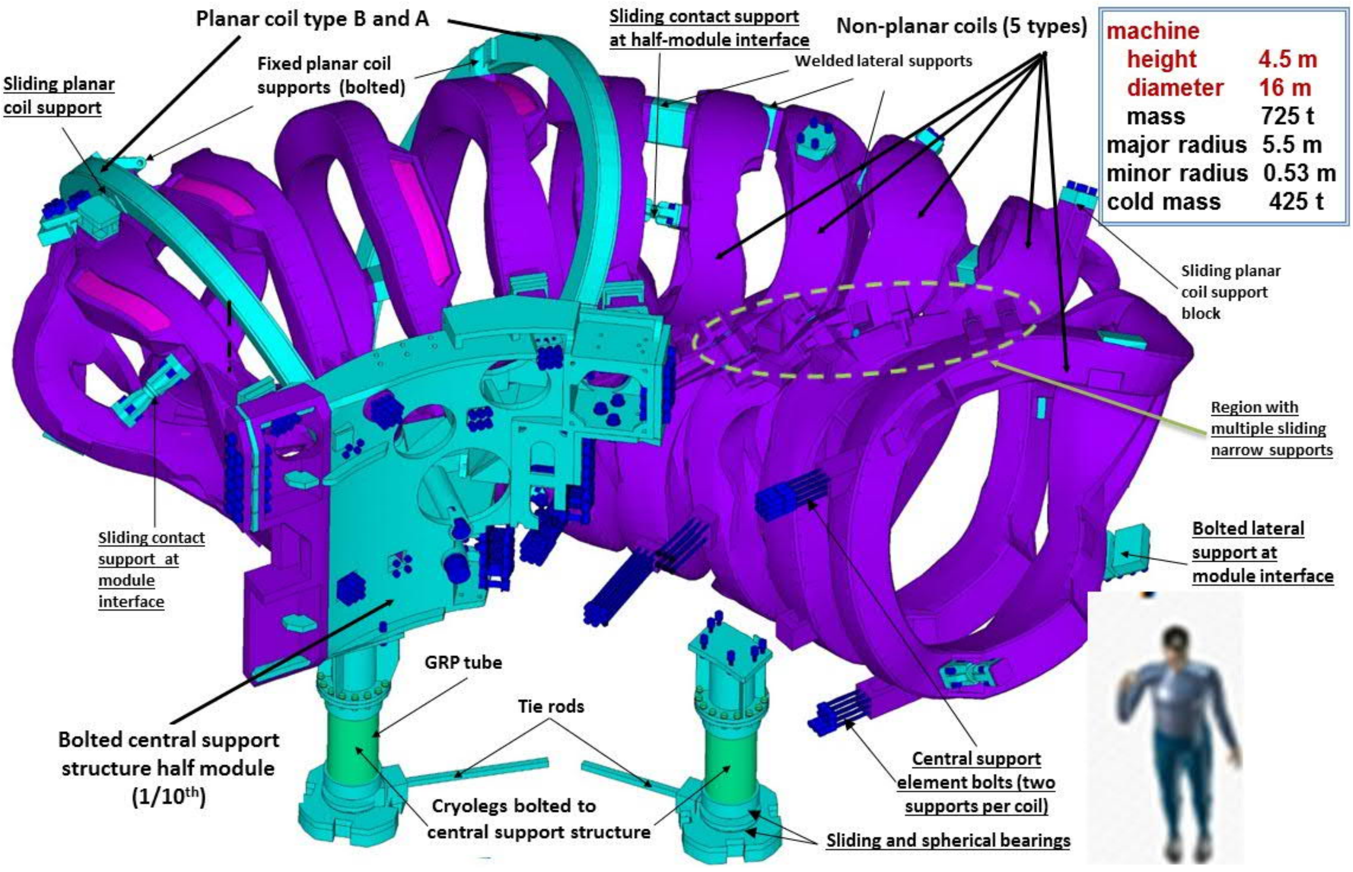

Fig. 1. Main parameters and non-linear support elements of W7-X magnet system (indicated on fragment of finite element model with underlined captures)

II. CYCLIC LOADING OF MAGNET SYSTEM

Due to the fact, that steady-state operation is an intrinsic feature of stellarators, the W7-X is a low cycle machine with structural criteria adjusted and partially relaxed to meet the goals with significant cost reductions [6]. In return, the structural margins against overloading are not significant and behavior of the complex system has to be closely monitored during gradually increasing operational loads. The first challenge was an

evolution of the system response during the first loading cycles due to settlement of the system and redistribution of internal residual stresses caused by complex manufacturing and assembly procedures [7].
Second challenge is a transition from one configuration to another or even a scan through multiple configurations [8] without full reduction of coil currents to zero. The approach allows to minimize the number of full loading cycles and operation time. The effect of loading path is discussed below in Chapter IV.C.

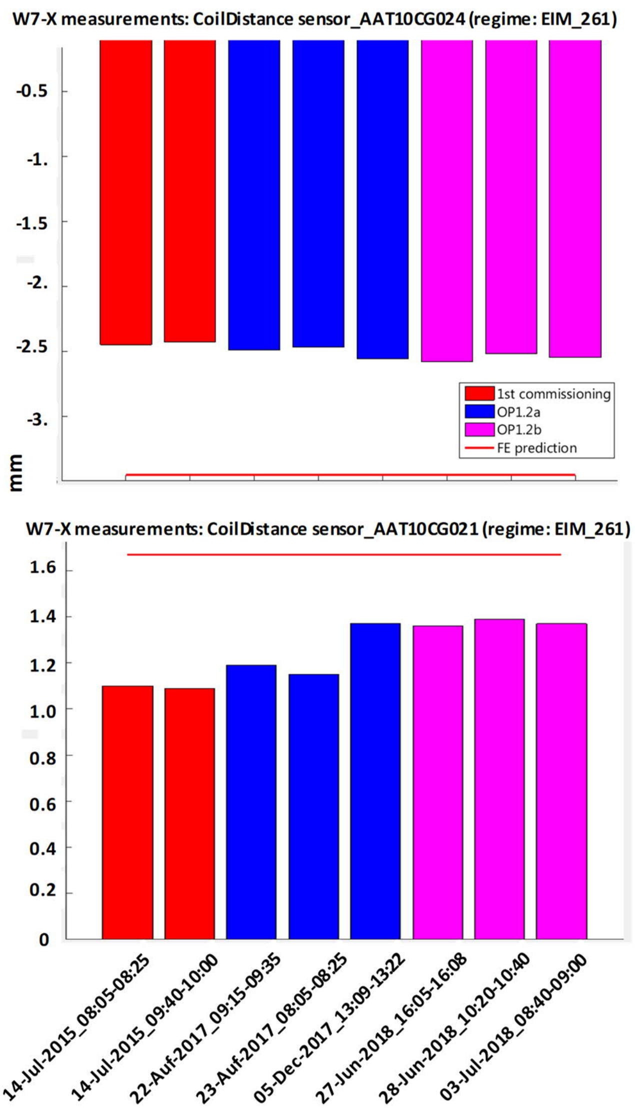

Fig. 2. Stable and evolutionary behavior of mutual coil displacements (mm) during standard regime (coil currents in NPCs: 13.47kA, PLCs: zero) loadings 2015 - 2018. Between coils of type 5 (module interface, top figure) and between coil types 1-2 (bottom).

III. MAIN COMPONENTS OF NONLINEAR SUPPORT SYSTEM

There are multiple sources of non-linear behavior in the W7-X MS (see Fig. 1) starting from the fact that winding packs of five types of non-planar coils (NPCs, 9 × 12 conductor arrangement, maximum current up to 18.2 kA) and two types of planar coils (PLCs, 6 × 6, 12.25 kA) could slide against welded stainless steel (SS) case and bolted/pinned case respectively.

The intercoil support system comprises sliding narrow support elements (NSEs) and sliding planar support elements (PSEs) with predefined initial gaps carefully defined for nine reference configurations (region of NSEs is indicated by dashed line in Fig. 1). Moreover, NSE bronze pads coated with MoS_2 could be plastically deformed in case of overloading [9]. Each coil is fastened to the central support structure with two central support elements (CSEs). Due to limited space and very high forces/moments to be transferred (up to 4 MN per support [17]), the CSEs comprise long Inconel bolts with high preload and are designed to withstand intended opening of the bolted connection flanges [10]. In case of overloading the threading in the casted SS coil case blocks could be locally plastified and cause a loss of bolt preload.

Lateral supports (LSEs) at the module interfaces are shrink-fitted wedge shaped bridges pressed against coil support block shoulders by multiple high prestressed bolts. Local sliding under high loads is unavoidable for the connections [11]. Fixed PSEs, central support structure (CSS) flanges, etc. are additional highly loaded bolted connections in the system.

Finally ten deadweight supports, so called cryolegs, with sliding/rotating at the bottom bearings are attached to the bottom of the CSS (see Fig. 1). With such design, only toroidal tie-rods fix the MS position without restrictions for the shrinkage during cooldown to 4 K [12].

IV. SPECIFIC ISSUES

A. Evolution of displacements

The displacement sensors are a small sub-set of the mechanical instrumentation (MI) system with roughly 750 sensors [13].

They provide the most important and reliable data to judge MS behavior.

The MS has three types of displacement sensors:

1) one directional sensor to measure mutual coil displacements,
2) pyramids to measure cryoleg movements and
3) sensors to measure opening and shift of bolted flanges.

The third group of displacement sensors is still out of serious consideration due to relatively small signal levels. Typical examples of stable and evolutionary behavior of mutual coil displacements are presented in Fig. 2.

B. Highly Loaded Bolted Supports and Support Slippage

The FE parametric analysis confirms that MS could still be operated in case of 30% bolt preload loss [14]. Despite this margin, the judgement of corresponding signals has highest priority during operation. Accessibility issues make it very difficult to retighten the bolts in case of significant loss of bolt preload.

The degradation of bolt preload is discussed in [4, Chapter VI, and 14] with an indication that fast discharges from a high current level is a possible source of the process. So far, the estimated loss is in the order of 20 MPa, which is well below 10% and fully covered by initial safety margin for both the MS system and for possible increasing of MS displacements and requirements for the clash analysis [15].

Slippage of the bridge of the bolted LSE [11] is another important monitoring area. It is clearly indicated during energizing of the MS by significant delay of that sensor responses.

C. Loading Path Dependence

Non-linear behavior of the MS requires careful definition of operational limits to avoid false alarms and subsequent interruption of operation. Typical cyclic behavior for the signal of strain gauge sensor located in vicinity of bolted LSE bridge is presented in Fig. 3. It shows that a direct transition from one magnetic configuration regime to another (magenta, OP1.2b) results in a different stress compared to approaching that regime from zero current. The difference is approximately 15%, reaches 60 MPa for the location, not yet critical and correlate well with FE predictions.

D. Deadweight Support Adjustment

During each cooldown/warming up cycle and during operation phase, one of the two cryolegs in the module 5, installed first in the pit during assembly [7], showed some visible delay in its flat bearing sliding (see Fig. 5 in [19]). Therefore pushing of the cryoleg was implemented several times to overcome static friction and minimize the bending moment on the cryoleg.

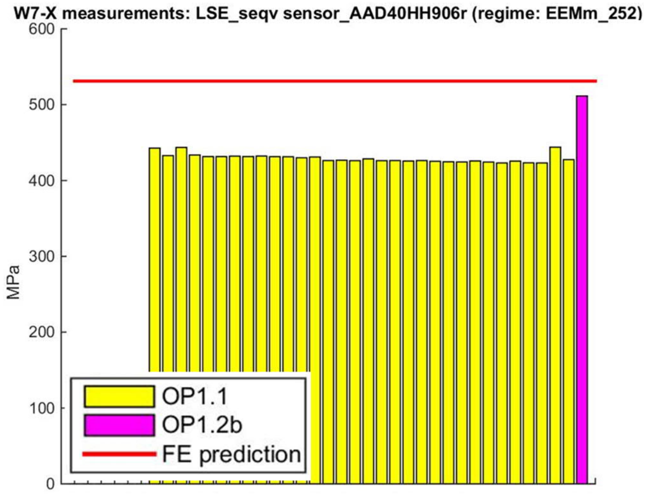

Fig. 3. Difference in stress levels (in the corner of bolted lateral support shoulder) depending on loading path for standard configuration (coil currents in NPCs: 13.0kA, PLCs: zero): loading from zero current in OP1.1 campaign (yellow) and transition from limiter configuration (coil currents in NPCs: 12.8kA, PLCs: 5kA) during OP1.2b on 9th of July 2018 (magenta).

Moreover, degradation of sliding stroke for the most critical cryoleg has been observed during each phase of operation (see Fig. 4). It was clear that friction force in the cryoleg was much higher in comparison with others. Intensive review of measurement results for the cryoleg sliding with support of parametric FE analyses allowed to conclude that friction forces are quite different between each of the ten cryolegs and could reach the ration of 1.8/6.8. The results of estimation are summarized in Table I.

The access to the cryoleg hydraulic cylinder and fixation bolts was a quite challenge already after OP1.2 and would be even more difficult after installation of periphery for actively cooled in-vessel components and additional diagnostics [7].
To minimize the impact on the tight construction schedule, it was decided to measure and to adjust vertically only two cryolegs highlighted in Table I: lowering/lifting in HM50/HM10 by 0.6/0.4 mm respectively.

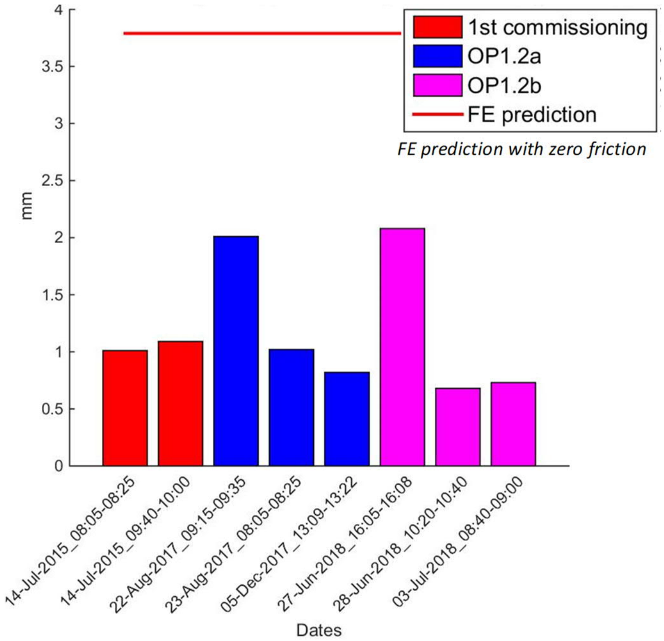

Fig. 4. Degradation of HM50 cryoleg sliding for standard configuration loading during each operation phase.

TABLE I
CRYOLEG LOAD ASYMMETRY CORRECTION IN 2018

Module	Half module	Friction factor[a] %	Measurements: Force before action, kN	Force after action, kN	Stiffness[b], kN/mm
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 on the basis of measured cryoleg radial displacements with assumption of equal distribution of deadweight between supports
[b]FE estimation is 280 kN/mm without taking into account flexibility of machine base. Presented values is average of all steps up to full stroke of ~1 mm.

Contrary to the stiffness measurements in 2015 (not published), the approach was to have lifting/lowering with higher stroke (up to 1 mm) in order to minimize an influence of the nonlinear system settlement on stiffness measurement results. The approach fully proves its value. Main results of measurements and adjustments are summarized in Table I.

E. Rubber Pads in Warm Coil Supports

Five big resistive trim coils [16] with the aim to correct W7-X error fields are installed on the outer cryostat and use rubber pads in their supports to allow for thermal expansion of the coils.The supports are quite compact in comparison with flexible support types and relatively simple due to absence of sliding components, but rubber degradation is to be monitored.

Pad prestress degradation does not exceed predicted values for the period from their assembly in 2012 – 2013, but degradation during last operation period is exponential rather than logarithmic as it was expected (see Fig. 5). Increasing of the rubber pad prestress is planned before start of OP2 by removal of dedicated shims and re-tightening of the bolts in the supports.

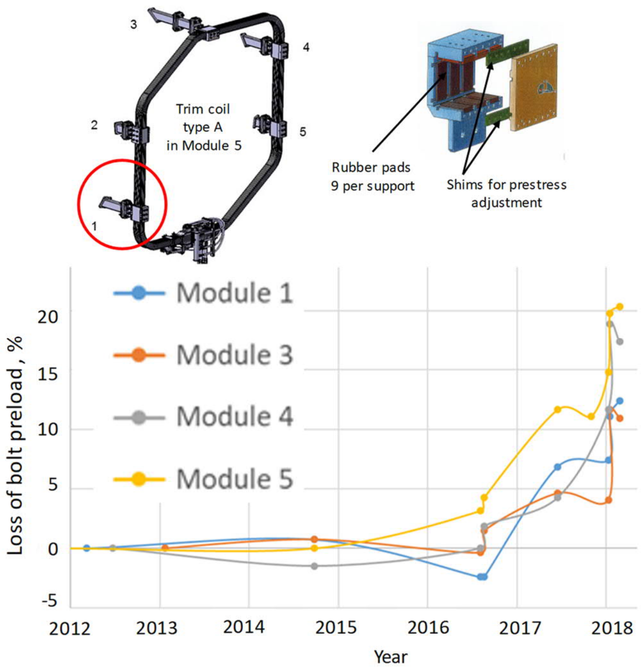

Fig. 5. Typical degradation of rubber pad prestress.

V. CONCLUSIONS AND LESSONS LEARNED

In spite of the fact that detail analysis of cyclic behavior is ongoing process, the following conclusions can be drawn from the brief risk assessment after two W7-X operation phases (+ - positive; - - negative):

+ The W7-X MS so far shows a stable cyclic behavior in general. The non-linear supports system proved its ability to withstand high loads in different new regimes.

– Several corrective measures are necessary to guarantee safe operation during more demanding phases in the future. One of them (cryolegs adjustment) has been successfully completed.

– Close monitoring is strongly required; safety margins included in the design are reduced by unexpected deviations with no clear explanation [4].

– The global FE model prepared to support the operation of the MS [17] is to be subjected to benchmarking and refinement [14], [4]. The process is extremely important if nonlinear effects are pronounced and evolve during operation.

In spite of the fact that non-linear support system is very attractive for experimental magnet systems with not fully defined loading patterns, it is worth to mention that the approach could be easily dropped for a future stellarator reactor, if only one regime of operation is pre-defined [18].

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