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# Monitoring of W7-X Cryostat Commissioning with Cryostat System FE Model

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The Wendelstein 7-X stellarator started its first operational phase in October 2015 at the Max-Planck-Institute for Plasma Physics in Greifswald with the goal to verify that a stellarator magnetic confinement concept is a viable option for a fusion power plant.

The main components of the W7-X cryostat system are the plasma vessel (PV), outer vessel (OV), 254 ports, thermal insulation, vessel supports and the machine base. The main task of the cryostat system is to provide an insulating vacuum for the cryogenic magnet system, UHV conditions within the PV and to provide external access to the PV through ports for diagnostic-, supply- and heating systems.

The updated finite element (FE) Global Model of the Cryostat System (GMCS) has continued to be used for predicting and assessing the behavior of W7-X as measured during its commissioning and operational phase. The measurements with strain, temperature and displacement sensors as positioned on the OV, Ports, PV and its supports form the basis of the cryostat system monitoring. After successful evacuation of the OV [1] commissioning continued and in 2015 the PV has been evacuated and baked for the first time. The measurements show good correspondence with the predictions of the GMCS and allowed for continuation of the commissioning. This paper gives an overview of analyses performed with the GMCS in support of cryostat commissioning and operation. In addition, the assessment performed for optional PV position adjustment is presented. A PV adjustment might be required in case plasma operation reveals problems with the plasma heat load distribution on critical in-vessel components.

Keywords: Wendelstein 7-X, Commissioning, Operation, Structural Monitoring, Instrumentation, Cryostat, Finite Element Analysis

## 1. Introduction

In 2014 the progress of the assembly of W7-X enabled the project to start the local and integral commissioning of the first systems [1] which was basically divided in the following steps:

1. Evacuation of the cryostat
2. Cool down of the cryostat
3. Cu-coil systems tests
4. Superconducting magnet tests
5. Evacuation and Baking of Plasma Vessel

For the commissioning steps 1 and 5 the updated finite element (FE) Global Model of the Cryostat System (GMCS) was used to predict and verify the behavior of the vessels during these activities. This model comprises of the components depicted in Fig. 1. As there is no direct mechanical interaction between the cryostat and the magnet system except for the bellows at the cryolegs it is possible to assess both systems in separate FE models.

Too verify the structural integrity of the cryostat during the commissioning process several accompanying measurements were prepared [2]:

- LT measurements of ~40 points on OV shell, domes and supply ports
- Monitoring of 90 PV strain gauges
- Monitoring of 15 PV vertical pendulum and 10 horizontal PV support loads
- 88 Contact Sensors between magnet structure and thermal insulation
- Displacement sensors on 15 supply ports (Fig. 2)
- PT100 Temperature sensors: 590 on ports / 80 on PV

The results for the evacuation of the cryostat have been presented in [1]. Since then the commissioning continued including evacuation and baking of the PV. This also required extensive monitoring of the cryostat behaviour.

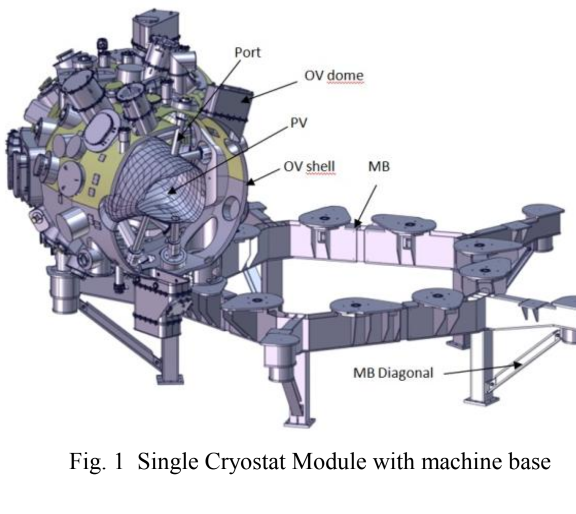


Fig. 1 Single Cryostat Module with machine base

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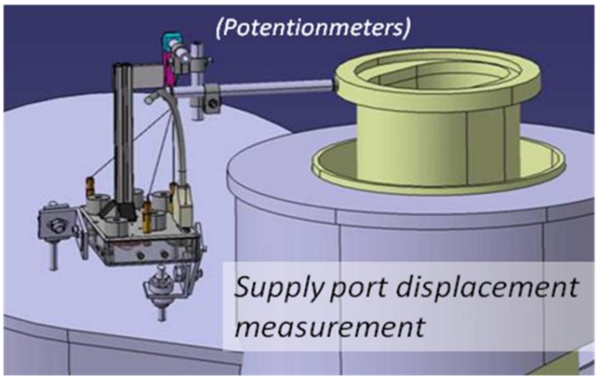


Fig. 2 Potentiometers in Pyramid-Setup for displacement measurements

## 2. Plasma Vessel Evacuation

After the cryostat evacuation and magnet system cool down [3] the plasma vessel was evacuated for leak search and subsequent baking with the goal to achieve a pressure of <$10^{-8}$mbar before start of plasma operation.

The PV evacuation corresponds to GMCS load case 3a as shown in Table 1. The mechanical observation focused mainly on the PV shell stresses, PV vertical and horizontal support loads and supply port movement.

Fig. 3 shows the evolution of the vertical loads between the three pendulums within one module due to the deformation of the PV during evacuation. The predicted load redistribution vs. the measured load (hydraulic pressure on jack up cylinders) shows good correspondence for the outer AEA41 and the AFF40 pendulum. The AEX41 shows less reduction than predicted. Since all AEXx1 pendulums are close to the neighboring AFFx0 (x=1..5) the load distribution on this pendulum pair is very sensitive. Important was to check that the overall pendulum load stays constant as the weight of the PV and its components supported by the pendulums should remain constant. This was confirmed by the measurements performed between April 2014 and July 2015 stayed at roughly 100 Tons. The installed in-vessel components in this time frame can be neglected and is within the hydraulics measurement accuracy.

Table 1 Main six cryostat load cases

| LC# | Pressure (bar) | | PV °C | OV °C | Explanation |
|---|---|---|---|---|---|
| | in PV | in OV | | | |
| 1 | 1 | 1 | RT* | RT | Assembly phase |
| 2 | 0 | 0 | 150 | Gradient* | Baking |
| 3a | 0 | 0 | RT** | RT | Normal operation |
| 3b | 0 | 0 | 80** | RT*** | Normal operation / warm PV |
| 4 | 1 | 0 | RT | RT | Maintenance in PV |
| 5 | 0 | 1 | RT | RT | Maintenance in OV |

*16 abnormal load cases not shown here*

*: For baking the outer vessel will have a temperature gradient between the hot components (150degC at port dome plate interface) and the OV components at RT.

**: For long pulse operation it still needs a detailed assessment on the expected PV temperature.

***: It is assumed that the transfer of heat from the warmer PV in LC3b is not resulting in an increased temperature for the OV, thus OV at RT. This is different for the baking cases where the whole PV + Ports are heated to 150degC.

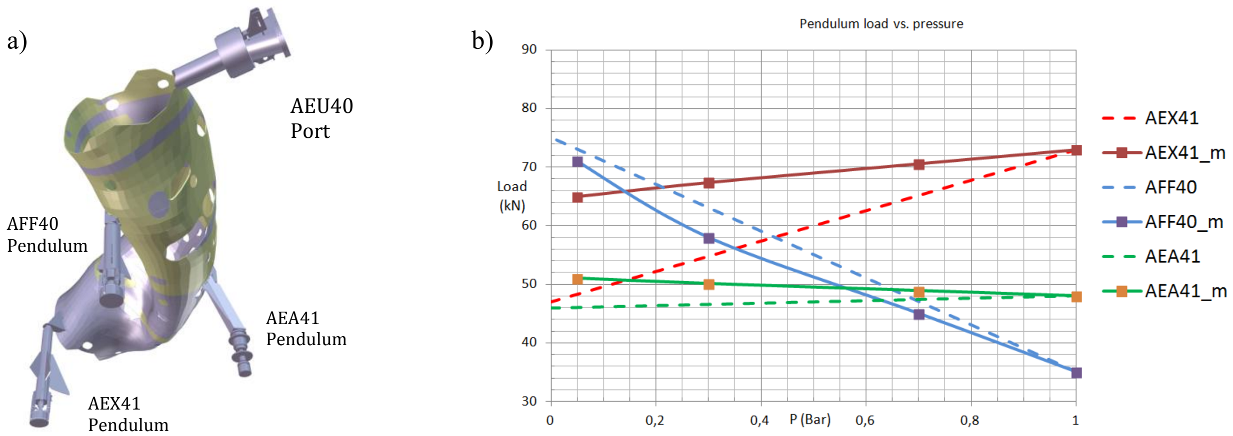


Fig. 3 Pendulum Support positions (a) and support loads (b) for single PV module: measured (_m) vs. prediction

The evaluation of the stresses during the PV evacuation did not show any structural issues at hand. Fig. 4 shows the stress evolution of five typical strain gauge rosettes during evacuation of the cryostat, with PV still flooded.

Three months later the PV was evacuated causing the pressure delta over the PV shell to disappear and stresses to reduce. The jump in the steady state stress levels over the three month pause between evacuation activities is most probably caused by the in-vessel assembly activities incl. welding of stud bolts on the inside of the PV shell. The overall stress levels remain very moderate.

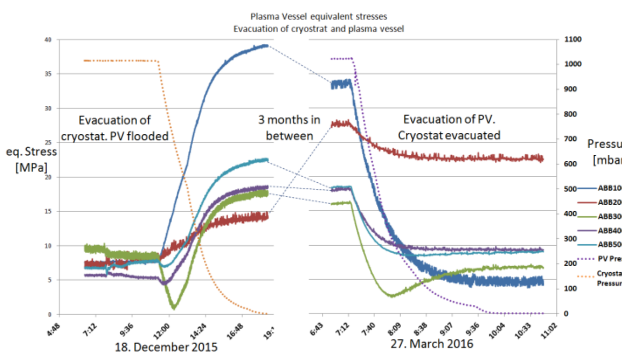


Fig. 4 Stress development during cryostat and PV evacuation

## 3. Plasma Vessel Baking

After successful evacuation and leak check the PV and ports were baked at ~150°C. The baking temperature was achieved by the following systems:

1. Plasma Vessel, Ports and control coils heated by water @ 150°C
2. ~90 electrical heating mats for diagnostic port heating up to 160°C.
3. Insulation mats for ~150 ports and ~60 extensions (see Fig. 5 for an example).

Fig. 5 Typical insulation and baking mats at port flanges

The PV support system (Fig. 3 and Fig. 11) enables free expansion of the PV and ports during baking. The GMCS predicts the expansion of the PV and ports assuming a uniform 150°C temperature distribution on these components (Fig. 6). The radial displacement of the 5 horizontal AEU-Ports as measured by the pyramids (Fig. 7) is ~30% lower than the prediction.

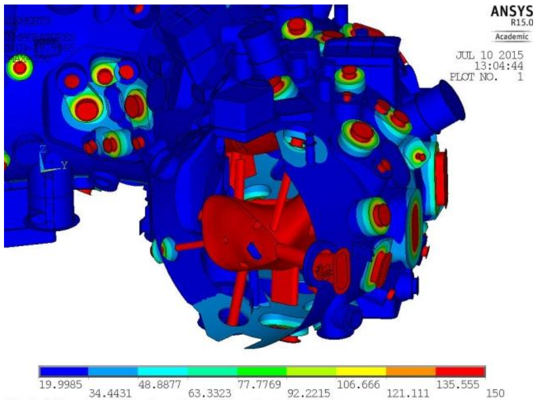


Fig. 6 Temperature (°C) on cryostat in GMCS during baking

The lower measured value is most probably due to the non-uniform temperature of the PV and the cooler ports with temperatures between 100 and 150°C.

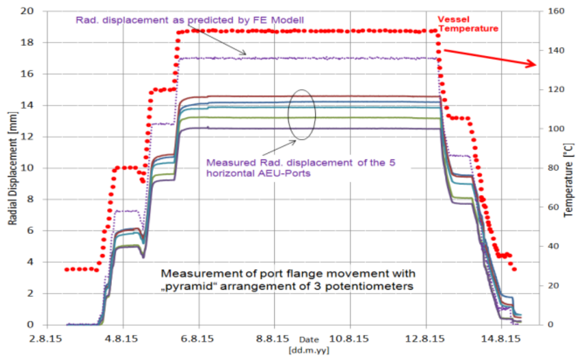


Fig. 7 Radial displacement of AEU ports during baking

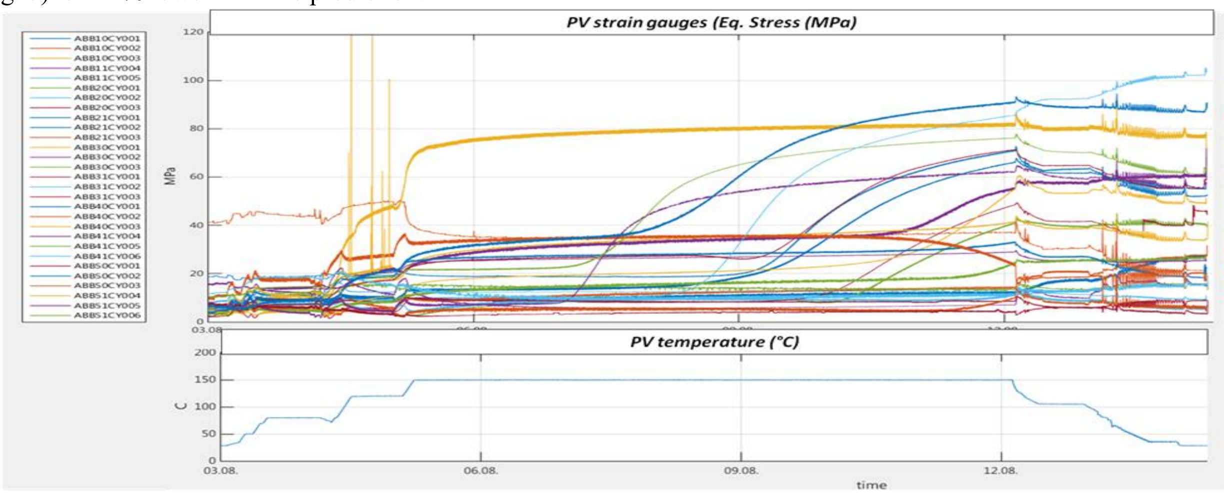


Fig. 8 Evolution of PV strain gauges during baking cycle caused by outgassing of NP-50 adhesive

Roughly one day into steady state baking at 150°C the PV strain gauge rosettes one by one started to show rising stress levels continuing until the end of the baking process (Fig. 8). This behavior was assessed and it was found that the out gassing of the NP-50 adhesive was causing these signals to occur. As the strain gauges have been applied relatively late in the manufacturing and assembly process of the PV no baking of adhesive was performed at an earlier stage. The signals needed to be zeroed again to enable monitoring future stress changes due to flooding/evacuation cycles and other vessel activities.

## 4. Plasma Vessel Adjustment

At the five evenly distributed horizontal AEU ports radial and toroidal adjustment of the PV is possible (Fig. 11). (Cylinder Ø10mm, h=10mm). This allows for additional correction of the divertor modules position in case of heat load asymmetries.

A MATLAB® routine by Rostock University [4] provides optimal adjustment (in minimising loads on AEU port weld to PV) of the five radial and five toroidal adjustment points for any given solid body motion in the x-y plane.

**Definition of vectors:**

- $l_i$ strut length increment ($l=[l_1,...,l_5]^T$).
- $s_i$ relative changing of displacement between screws and contact plates in screw direction ($s=[s_1,...,s_5]^T$).
- $x_i$ radial displacement of five rotational symmetric measurement ($x=[x_1,...,x_5]^T$).
- $y_i$ tangential displacement of five rotational symmetric measurement points ($y=[y_1,...,y_5]^T$).
- $Q_i$ normal strut forces ($Q=[Q_1,...,Q_5]^T$)
- $R_i$ normal contact forces of the screws ($R=[R_1,...,R_5]^T$)
- $S_i$ applied auxiliary force in direction of $x_i$ ($S=[S_1,...,S_5]^T$)
- $T_i$ applied auxiliary force in direction of $y_i$ $T=[T_1,...,T_5]^T$)

$$[\bar{A}]\begin{bmatrix} l \\ s \\ x \\ y \end{bmatrix} = \begin{bmatrix} Q \\ R \\ S \\ T \end{bmatrix} \quad with [\bar{A}]\ being\ stiffnes\ matrix\ as\ deduced\ by\ GMCS$$

Fig. 9 Force-Displacement Equation for whole cryostat system

The aim of the positioning tool is to minimize the difference between the actual and desired position of the plasma vessel whilst minimizing the loads on the horizontal supports. The full adjustment procedure has been documented in a work instruction that can be used for adjustment of the PV as soon as required.

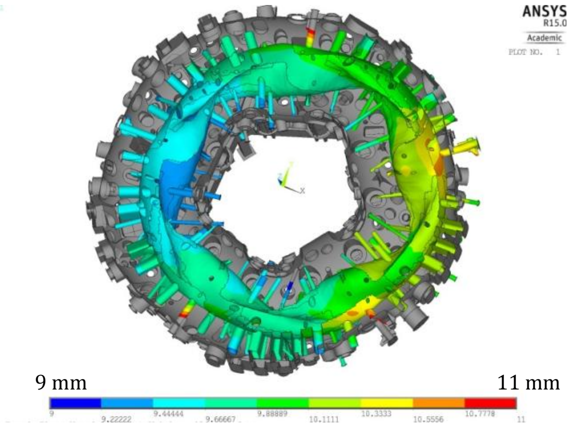


Fig. 10 Example: PV moved 10 mm in global x direction

A pure toroidal (rotational) movement is also possible solely adjusting the toriodal struts. A vertical adjustment can be done with the pendulums and is straight forward. Fig. 10 shows a typical example of applying the outcome of the MATLAB®-Tool to the GMCS for a 10 mm movement in global x direction.

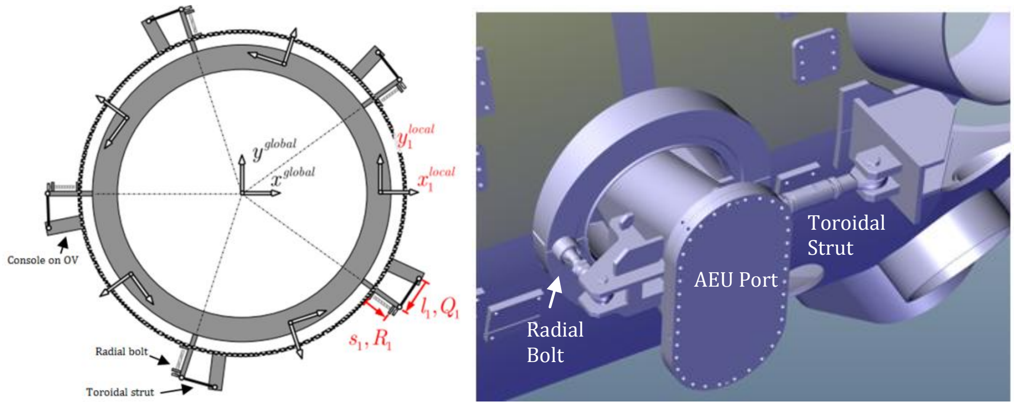


Fig. 11 PV horizontal supports at AEU-Ports.

## 5. Conclusion and outlook

The monitoring activities during commissioning of W7-X did not reveal any major structural issues with the plasma vessel and cryostat and their respective supports. The FE global model was used intensively and the instrumentation in form of PV strain gauges, port displacement sensors and temperature sensors provided a solid basis for assessing the behaviour of the cryostat.

For the next operational phase OP1.2 (starting mid 2017) the GMCS and the structural sensors will be used again to support commissioning. Of special interest will be the more energetic plasma pulses (from 4 MJ in OP1.1 to 80 MJ in OP1.2) inducing higher heat loads onto the in-vessel components incl. the plasma vessel and ports. When adjustment of the PV is required to repositioning the divertor modules a procedure is available to do this.


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