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Structural analysis of the W7-X cryopump during the superconducting coil fast discharge event

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The cryopump will be installed for the high power and long pulse operation up to 30 minutes of Wendelstein 7-X (W7-X). In total there are 10 independent and identical cryopumps, one cryopump for each of the 10 discrete divertor units. The cryopump is located along the pumping gap in the toroidal direction below the divertor target modules and close to the location where field lines hit the divertor target surface. Each pump has a design envelop of ~400mm diameter and ~4m length. During a fast discharge event of the W7-X superconducting coils, the changing magnetic field will induce eddy currents on the metallic cryopump components, especially on the low resistance copper parts. The combination of the eddy current and the background magnetic field will generate mechanical forces and moments on the cryopump structure. The electromagnetic analysis provided the eddy current and Lorentz force distribution as an input for the mechanical analysis. These analyses showed no possible resulting damages on the structure of the cryopump.

Keywords: Stellarator, Wendelstein 7-X, cryopump, fast discharge event, electromagnetic analysis, eddy current

1. Introduction

The stellarator Wendelstein 7-X (W7-X) is a superconducting fusion device with five-fold magnetic field periodicity. Each of the 5 similar machine modules are made of two-flip symmetric half modules with 5 different non-planar coils (NPCs) and 2 different planar coils (PLCs) each. The NPCs provide the confining magnetic configuration, which presents a strong variation in the toroidal direction from an indented elongated shape or ‘bean shape’ to triangular shape in one half-module; the planar ones are inclined to the horizontal plane, generating a vertical magnetic field to shift the magnetic axis [1].

For the second operation phase (OP2) with high power and pulse duration up to 30 min. an actively-cooled divertor system with cryo vacuum pumps (CVPs) will be installed. The divertor system is made of ten discrete divertor units installed, above and below the helical axis [2]. In total there are 10 independent and identical CVPs, one CVP for each of the 10 divertor units.

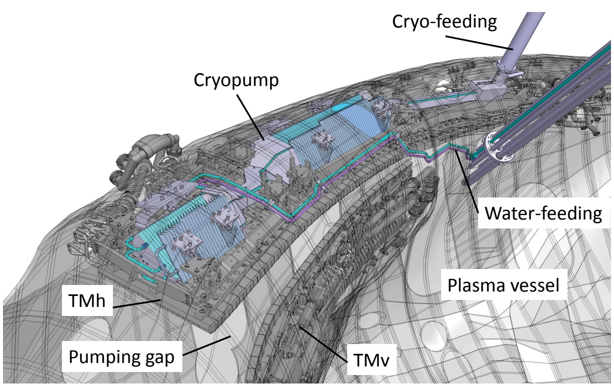

Fig. 1. CVP location in W7-X plasma vessel

The CVP is located along the pumping gap in the toroidal direction below the divertor target modules and close to the location where field lines hit the divertor target surface as shown in Fig.1. The CVP plays a critical role for capturing ash particles from the plasma, including hydrogen and deuterium. Each pump has a design envelop of ~400mm diameter and ~4m length, and is fixed to the wall of the plasma vessel by 8 supports. The CVP is divided in two units named DCU1 and DCU2 (DCU: Divertor Cryopump Unit). This division has been made to allow the integration of diagnostics such as the Langmuir probe in the divertor surface. Three independent cooling loops of water, LN_2 and ScHe, respectively, supply the cooling requirements at different conditions for its operation.

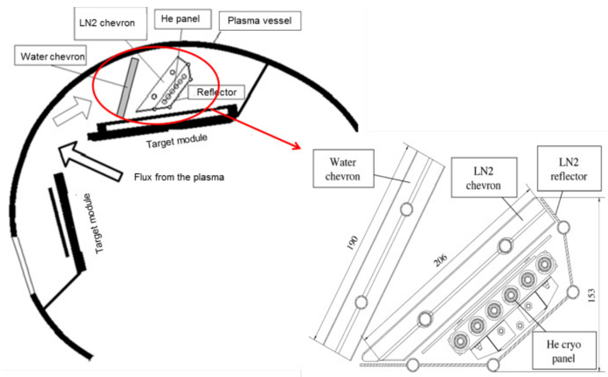

Fig. 2. Main components of CVP

Discharge gases will be pumped with He-panel (Fig. 2), which is cooled by supercritical He between 3.4K and 3.9K depending on operation mode. This panel is surrounded by a reflector and a series of chevrons which is cooled by liquid N_2 at 80K; in front of the LN_2 chevron, another series of room temperature water cooled chevrons protects the cryogenic parts against plasma radiation.

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During the W7-X operation, coil fast-discharge event could possibly happen. The fast changing magnetic flux will induce eddy current on surrounding metallic conductors such as the CVP. Combined with the background magnetic field, the eddy current produces Lorentz forces on the conductors, which may damage the structure. In this paper, two analyses are presented: (1) the electromagnetic analysis to define the eddy currents and the Lorentz forces, (2) the resulting mechanical analysis of the CVP.

2. Analysis procedure

The complete workflow of the analysis procedure is presented in Fig. 3. At first, the fast discharge process of the superconducting coils is simulated in the electromagnetic analysis. All NPCs & PLCs are charged with the maximum working currents. The currents decrease following a preset profile, which produces eddy currents in the CVP. Together with the background field, Lorentz forces are generated on the metallic structure. The resulting forces on the CVP are transferred to the mechanical model and finally corresponding structural stress are calculated in the mechanical analysis taking the mechanical boundary conditions into account. This procedure is realized with the multi-physics analysis software ANSYS [3].

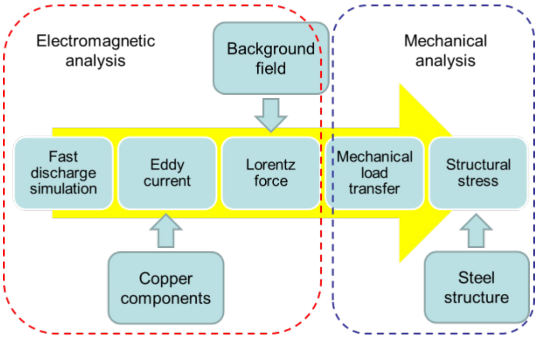

Fig. 3. Workflow of the cryopump analysis

Following assumptions and simplifications are made in this analysis:

1) Only the CVP components made of copper are considered in the eddy current calculation (marked as 1 to 4 in Fig.4), the eddy current and electromagnetic load on the stainless steel components are considered as negligible.

2) The local magnetic field influence of the plasma vessel as a shield for the CVP from the coils is considered as negligible.

3) The five trim coils and the ten control coils are not included in this approach; the trim coils are located outside the cryostat and the control coils are close to the cryopump, the working current of both of them are lower than the superconducting coils.

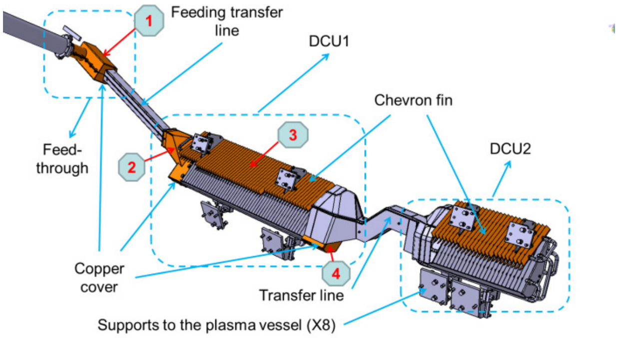

Fig. 4. CVP mechanical design (Cu: orange; stainless steel: grey) and the 4 copper components: 3 copper cover made of thin plates, chevron fins.

3. Electromagnetic analysis

Due to the W7-X symmetry, only one machine module (72°out of the 360°) is modeled: 10 NPCs and 4 PLCs, the position of the 4 copper CVP components for an upper positioned CVP is shown in Fig.5.

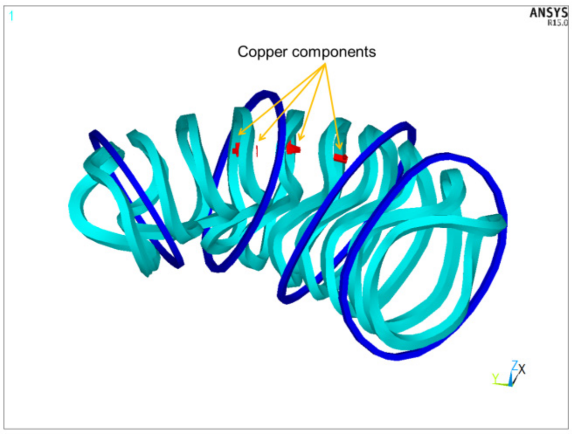

Fig. 5. The 10 NPCs (purple) and 4 PLCs (blue) in one W7-X module

The magnets are charged with the maximum working current to simulate the operation status, a NPC contains 108 turns, each turn carries 12.8 kA, and a PLC carries 36x5 kA. The fast discharge process is shown in Fig. 6. In 3 seconds, the current in all coils drops to 0 linearly.

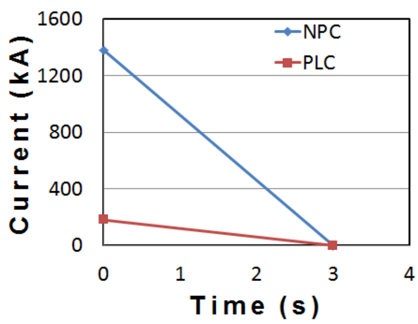

Fig. 6. The current profile

Table 1 summarizes the peak magnetic flux density (B) on the 4 copper CVP components. The vector directions are defined in a cylindrical coordinate system located in the center of the W7-X machine. The vertical axis of the coordinate system is consistent with the machine, the radial axis points to the outside, and the toroidal axis is in the clockwise direction from the top view.

Table 1. Magnetic flux density (B) on the copper components

Part	B-radial (T)	B-toroidal (T)	B-vertical (T)
1	-0.660~-0.504	2.256~2.671	0.195~0.490
2	-0.521~-0.287	2.463~2.686	0.132~0.508
3	-0.620~-0.508	2.458~2.508	-0.021~0.100
4	-0.644~-0.512	2.128~2.460	0.145~0.467

This table show that the toroidal field is dominant compared to the radial and vertical directions.

The eddy current is distributed in the poloidal section because the magnetic field is mostly in the toroidal direction. The CVP structure has quite the same toroidal direction. The cover Cu part of the CVP is made of thin plates inducing in-plane distributed eddy current (Fig. 6). The total current through this plane on the side plate is ~0.4 kA. The other copper CVP parts have similar eddy current and Lorentz force distributions.

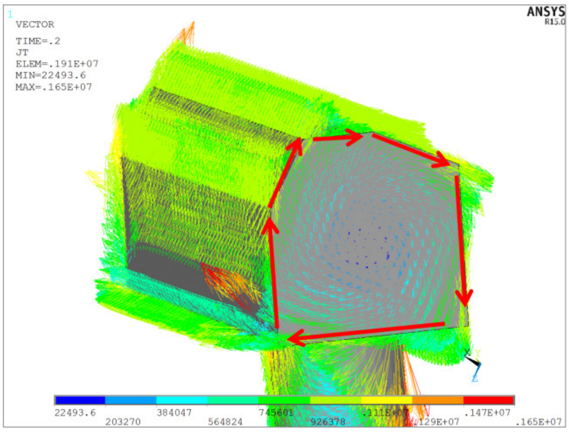

Fig. 6. Peak eddy current distribution on the CVP copper component #1. Red lines outline the current direction.

The combination of the poloidal in-plane eddy current and the toroidal background field generates Lorentz forces perpendicular to the plates, as shown in Fig.7. The magnetic field changing rate stays in steady-state conditions as well as the eddy current due to the linear fast discharge process. The peak electromagnetic load occurs in the beginning of the fast discharge because the background field is decreasing. A simple calculation gives a 900 N/m Lorentz force on the copper component #1 side plates, which points out of the plate.

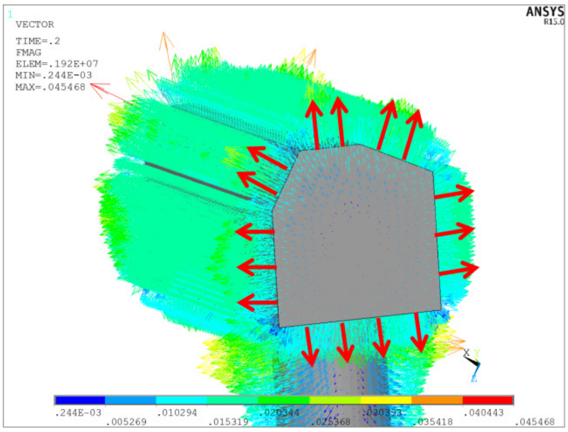

Fig. 7. Lorentz force on the copper component #1

To quantitatively check the electromagnetic loads, and transfer the Lorentz forces from the electromagnetic analysis to the mechanical one, the distributed forces on each copper component are accumulated to a total force and a total moment. The moment takes the center of the component as a reference point. Table 2 gives the force and moment results for the 4 copper CVP components. Table 2 shows that the loads are quite low.

Table 2. Total force and moment on each copper component

Part	F (N)	M (Nm)
1	5	0.7
2	2	3
3	0.07	0.02
4	8	2

4. Mechanical analysis

The maximum electromagnetic loads during the fast discharge process are applied as static loads. The analysis has to take the connections between the different parts of the CVP into account:

1) There are flexible connections between the feed-through, DCU1 and DCU2. These 3 parts are independent to each other, and can be analyzed separately.

2) The two water baffles in DCU1 and DCU2 are independently supported by the plasma vessel; they can be analyzed separately.

3) The DCU1 water baffle is larger, and the electromagnetic loads are higher.

Therefore, 3 independent models are used for the mechanical calculation as shown in Fig. 8 considering only DCU1: feed through, cryogenic part and water baffle (see also Fig. 2). Applied mechanical loads and boundary conditions for the 3 models are

1) Feed-through: the total resulting force and moment of the electromagnetic analysis are applied as distributed loads (see component#1 of Table 2). The flexible connection to DCU1 is set free. The other end to the plug-in is welded to the cryogenic tubes.

2) DCU1 cryogenic part: the total resulting force and moment of the electromagnetic analysis are applied as distributed loads (Fig. 9). The flexible connections to the feed-through and DCU2 are set free, and the supports to the plasma vessel are bolted.

3) The DCU1 water baffle: all the 44 fins are supposed to be identically loaded. The flexible connection to the DCU2 water baffle is set free, and the supports to the plasma vessel are bolted.

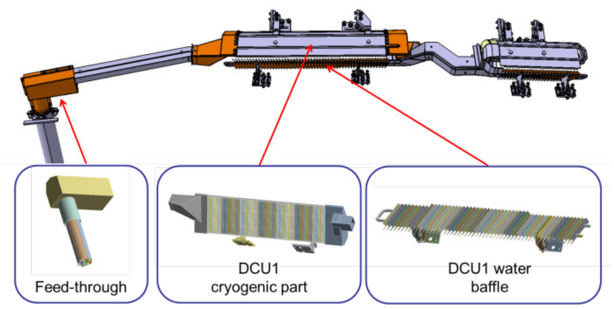

Fig. 8. The 3 mechanical models (left: feed-through; middle: DCU1 cryogenic part; right: DCU1 water baffle)

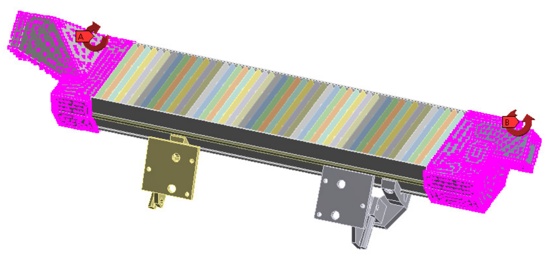

Fig. 9. Forces and moments applied as distributed loads (pink region) on the DCU1 cryogenic part

The results of the mechanical analysis performed at room temperature are listed in Table 3. The stress on the CVP structure is very low.

Table 3. Mechanical analysis results

Component	Material	Equivalent stress (MPa)	Allowable stress (MPa)	Outcome
Cu part	Cu	2.5	>69 (20 ℃)	Pass
Feed-through	Stainless steel	4.6	>172 (20 ℃)	Pass
DCU1 cryogenic part	Stainless steel	0.6	>172 (20 ℃)	Pass
DCU1 water baffle	Stainless steel	0.6	172 (20 ℃)	Pass

The fatigue issue is not considered because the fast discharge does not happen frequently.

5. Conclusions

The electromagnetic and mechanical analyses on the W7-X cryopump have been performed to check the impact of a superconducting coils fast discharge event on its structure, and in particular the Cu parts. The changing toroidal dominant magnetic flux induces poloidal eddy currents on the metallic conductors, especially the low resistance Cu covering and baffle fins. The generated Lorentz force is perpendicular to the cryopump plates in the poloidal plane, and the resulting total loads are low. The mechanical analysis showed that the structural stresses are also low. The results of these analyses showed no possible resulting damages on the structure of the cryopump.

Acknowledgements

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