DESIGN ASPECTS OF THE JOINTS FOR THE BUS BAR SYSTEM OF THE WENDELSTEIN 7-X STELLARATOR

G. Czymek*, B. Giesen, F.Harberts, A. Panin
Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, EURATOM Association D-52425 Jülich, Germany
M. Lennartz, U. Reisgen, W. Schuster, J. Wolters
Zentralabteilung Technologie, Forschungszentrum Jülich GmbH,
D-52425 Jülich, Germany

K. Rummel, M. Czerwinski, H. Lentz
Max-Planck-Institut für Plasmaphysik, EURATOM Association,
Teilinstitut Greifswald, D-17491 Greifswald, Germany
M. Ebner
Max-Planck-Institut für Plasmaphysik, EURATOM Association,
Teilinstitut Greifswald, D-85748 Garching, Germany

*Corresponding author. Tel.: +49-2461-61-3087
E-mail address: g.czymek@fz-juelich.de

Abstract

The superconducting magnet system of the WENDELSTEIN 7-X experiment consists of 50 non-planar and 20 planar coils. The coils are connected by 121 bus bars arranged in a serie of seven groups each of ten coils. The electrical and hydraulical interconnections of the bus bars will be provided by means of 184 joints each with the required resistance of less than 5 nOhm. The joint structure should withstand the internal pressure arising from the quench event. In order to permit joint replacement and repair after installation the joints have to be designed as demountable structures. Based on a conceptual design for an internal pressure of 30 bar and a current of 18 kA, the disconnectable joints have been redesigned for a pressure of 200 bar and a current of 20 kA. The report describes design, tests and stress analysis.

Keywords: Wendelstein 7-X, Joints, Bus Bar System, Superconductor

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1. Introduction

Within the framework of cooperation between the Max Planck Institute of Plasma Physics (IPP) and Forschungszentrum Jülich (FZJ), work is in progress on designing and manufacturing the joints for the bus bar system of the stellarator Wendelstein 7-X (presently under construction at Greifswald, Germany).

118 joints without and 66 joints with a helium inlet or outlet on top of the casing will be mounted in W7-X. Most joints without a helium inlet will be situated near the coils. In these joints a maximum pressure of 170 bar may occur in the case of quench, whereas the joints are laid out for an operating pressure of 30 bar.

The main functions of the joints are to connect the bus bars electrically and hydraulically. The main requirements are an electrical resistance lower than 5 nOhm at 4 K, helium tightness and the ability to withstand a maximum pressure of 170 bar in the case of quench.

The joints have a clamping system and a casing. The structure of the joint casing is shown in Fig.1. It consists of the cap and the base plate connected by a thread, which takes up the main pressure forces and welded lips to ensure vacuum tightness. The thread bearing length is 13.8 mm and the weld depth is 1.4 mm. The joint is equipped with two transition pieces welded to the base plate (weld depth is 1 mm) and also one He pipe screwed into the top of the cap (thread bearing length is 8.1 mm) and welded to its surface (weld width is 2 mm).

To meet these requirements three types of joints were developed: the first one with a helicoflex sealing, the second with a welding seam, and the third with a thread and a welding seam. Prototypes of all these joints have been manufactured and tested. After an evaluation, the type with the thread and welding seam was chosen and its design was improved as shown in Fig. 2.

2. Clamping system

The clamping system is shown in Fig. 3. The superconductors enter the joint at the transition pieces. Then their strands are guided by the former and its two pressure pieces made of aluminium alloy to the clamp, consisting of a copper and a stainless steel half, in which a gold-plated combination of steel and copper inlay is pressed onto the superconducting strands by screws. The functions of the inner parts of the joint are superconducting strand clamping, guiding the helium flow from the joint bottom to the top and back, heat transport and alignment to the inner wall of the casing.

Further information, also on the electrical qualification test of the complete joint, is given in the contribution by K. Rummel [2].

3. Welding seam of base plate and cap

The main points of interest were the thread and the welding seam of the base plate and cap. The requirement that the joint should be remountable and that it should also be pressure- and leakage-tested before being mounted in the W7-X stellarator means that the weld lip should have a height of 9 mm as well as a gold-coated thread. The cap will be screwed onto the base plate with a torque moment of 140 Nm and then the lip will be welded by laser in Jülich. After pressure and leakage tests, the joint casing will be disassembled and machined ready for assembly at the stellarator.

When it is mounted in the stellarator for the first time the lip will have a height of 7 mm. At the second time of mounting the height will be 5 mm and at the third and final time 3mm. Several tests were performed for this welding seam, first with 2 mm thick steel plates and different geometries of the lip. Later inert gas welding tests without welding wire were carried out at the base plates and caps. The results are 2 mm thick walls with a geometry as shown in Fig. 4 as well as in the Welding Procedure Specification (WPS). The cap could not be dismantled when a cylindrical lip or even a lip with a 2° angle was used because of shrinkage in diameter. Dismantling is possible with lips having an angle of about 8° as shown in (Fig. 4). Metallographic sections show the depth of the welding seam and were used to examine its inner material structure.

4. Test campaign

Test campaign of the joint casing includes

- a pressure test at 200 bar for 10 min at room temperature
- a helium leakage test at 36 bar and room temperature
  (The leakage must not exceed 10^{-7} mbar · l ·s^{-1}.)
- 10 thermal cycles: room temperature – 77 K - room temperature
- a pressure test at 200 bar for 10 min at room temperature
- a helium leakage test at 36 bar and room temperature

Pressure tests were performed with air instead of water to make helium leakage tests more reliable. Additionally, a prototype was subjected to a bursting pressure test with water. It shows that the cap-base plate thread failed at 350 bar.

5. Material properties

The material used for the casing was forged stainless steel 304 LN of ESU quality, with a small grain size and a high purity to avoid leakage at cryogenic temperature. It has a relative permeability of max. 1.01 and a Co content of max. 500 ppm.

The mechanical properties of this steel (304 LN or 1.4311) are given in Table 1.

6. Stress analysis results at 4 K and room temperature

A stress analysis of the joint structure under an internal pressure of 170 bar due to quench was performed. Table 2 shows the allowable stresses used for analysis.

Analysis of the previous design shows that most stresses in the cap-base plate weld are the result of the shear load acting on the welding seam. The welded part is optimized for rated pressure of 200 bar and an additional goal of the present design is to make the cap-base plate welded part as flexible as possible so that more shear force is taken up by the thread.

On the other hand, it is desirable to make the structure demountable. This means that the welded portions (lips) could be cut off 3 times to dismantle the cap and the base-plate, which requires longer weld lips (up to 9 mm).

The elastic stress analysis of the joint structure was carried out using the material properties of 304 LN steel at 4 K. Under internal pressure, significant shear load arises in the welded and threaded connections.

The main analysis results are given in Tables 4 - 6. As an option, the cap-base plate weld depths of 1 mm and 1.5 mm are compared. The distribution of the von Mises stress in the structure is shown in Fig. 5.

Analysis shows that most of the body of the structure is not highly loaded. The primary membrane (S1) and the sum of the membrane and bending stresses (1.3 S1) in the structure body do not exceed those allowable for structural steel.

In the present contribution major attention is paid to the welded / threaded connections of the parts. The sharing of the shear load between the thread and welding seams is given in Table 3. The average shear stresses in the threaded connections are represented in Table 4 against the allowable stresses. The stresses in the threads are well below the allowable limits.

The stresses in the welds are given in Table 5 against the allowable ones. The stress static limits are satisfied. The increase in the cap-base plate weld depth from 1 mm to 1.5 mm enhances the structure safety margins.

An analytical stress analysis shows that the structure body works under an internal pressure of 200 bar in the elastic range at room temperature. Most of the shear load in the cap-base plate connection is taken up by the cap-base plate thread.

7. Conclusions

- A joint casing and a clamping system were developed and prototypes were manufactured.
- The test campaign for the prototypes was successfully performed.

- A stress analysis of the structure at 4 K under the quench pressure of 170 bar was carried out using the properties of the 304 LN steel. The results show that the static stresses in the structural parts and in their connections are within allowable limits.
- To confirm the validity of joint testing at RT under a pressure of 200 bar, an analytical calculation of the structure was performed. The results show that the structure does not break. The threaded connections work in elastic range.
- The qualification of the joints has been achieved and series production has started.

8. References

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[2] K. Rummel, M. Czerwinski, F. Hurd, A. John, H. Lentz, G. Czymek, B. Giesen, F. Harberts, S.A. Egorov, V. E. Korsunsky, I. Y. Rodin, P. Bruzzone, B. Stepanov, M. Vogel, Test results from the full size prototype test of W7-X joint, 24th Symposium on Fusion Technology, Warsaw, 2006, be published

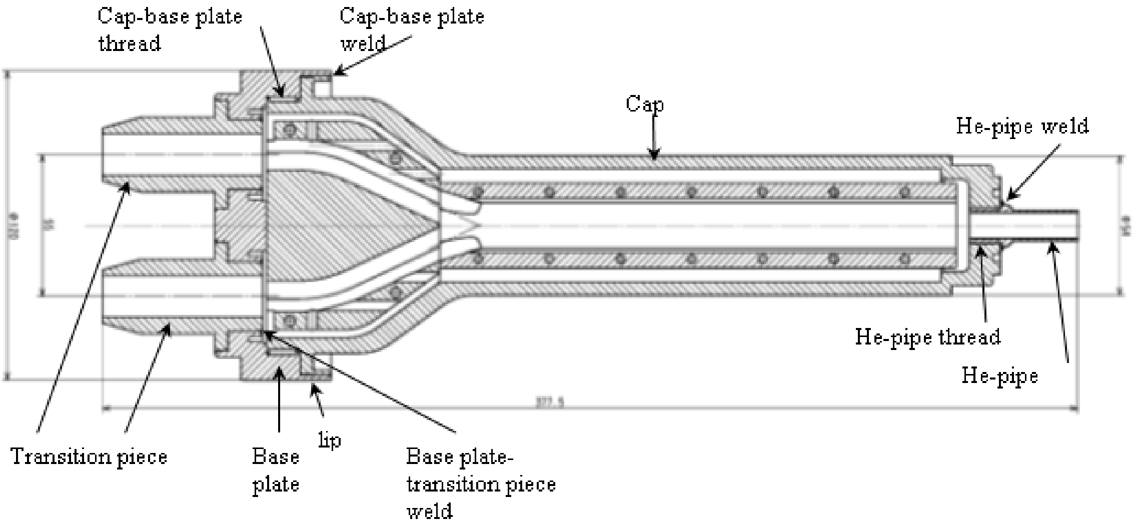

Fig. 1. Joint structure cross-section

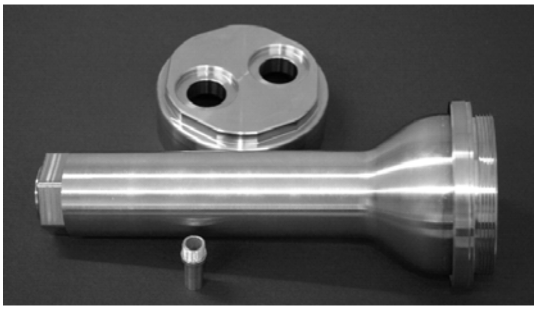

Fig. 2. Joint casing – final design

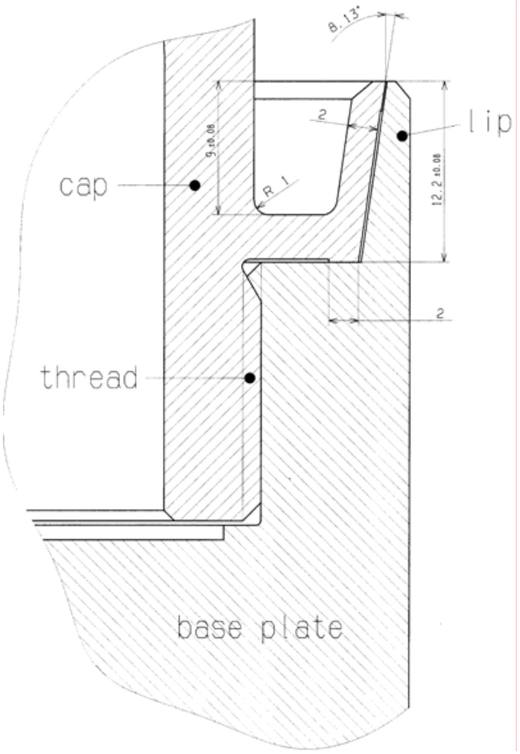

Fig. 4. welding seam at base plate and cap

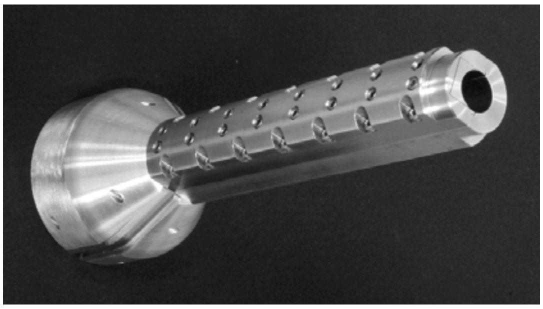

Fig. 3. Joint clamping system – final design

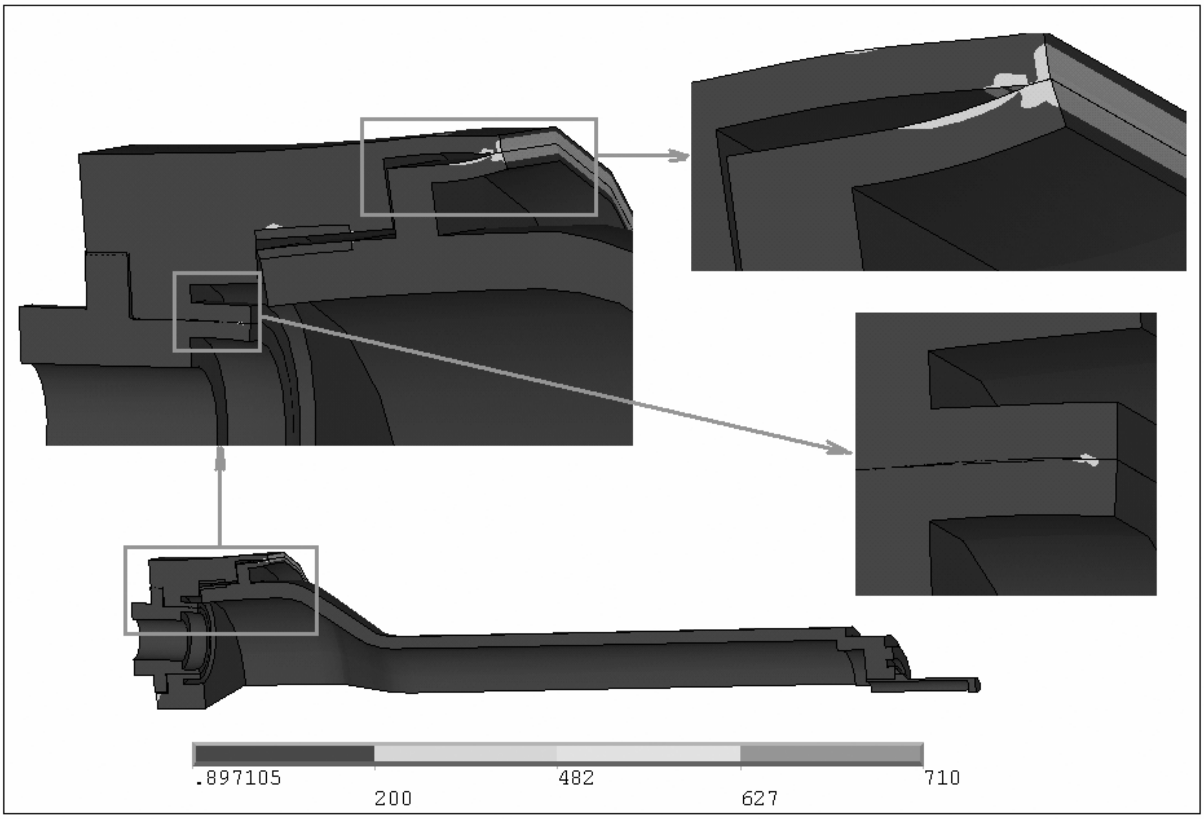

Fig. 5. Von Mises stress (MPa) in the joint structure under internal pressure of 170 bar at 4 K

Steel	T, K	E, Gpa	ν	$\sigma_{0.2}$, MPa	σ_{ult}, MPa	δ, %
304 LN	293	195	0.3	270	550-750	40
	4	205	0.3	724-1000	1650-1860	≈ 20

Table 1. Mechanical properties of steel 304 LN at RT and 4 K

Steel	T, K	$\sigma_{0.2}$, MPa	σ_{ult}, MPa	S1, MPa	1.3 S1, MPa	τ, MPa
304 LN	293	270	550	180	234	108*/54**
	4	724	1650	482	627	288*/144**

*) all types of threaded joints

**) leak-tight threaded joints

Table 2. Allowable stresses used for analysis

Weld / thread location	Weld or thread	Weld thickness/ thread length, mm	Force on connection, kN	Net force, kN
Cap - base plate	Weld	7 / 1	36.44	176
	Thread	12.8	139.56	
	Weld	3 / 1	27.32	175.1
	Thread	12.8	147.76	
	Weld	3 / 1.8	29.2	173.6
	Thread	12.8	144.4	
Base plate - transition piece	Weld	1	9.58	9.57
Cap – He pipe	Weld	2	2.07	3.38
	Thread	8.1	1.3	

Table 3. Shear load sharing in the weld/thread connections. Pressure 170 bar at 4 K

Thread location	Lip length / weld depth, mm	Calculated average shear stress MPa	Allowable shear for threads, MPa	
			All types	**Leak-tight**
Cap - base plate	7 / 1	69.4	**288**	**144**
	3 / 1	73.5		
	3 / 1.8	71.8		
Cap – He pipe	1	8.2		

Table 4. Shear stresses in the threads. Pressure 170 bar at 4 K

Weld location	**Lip length / weld depth, mm**	**Primary von Mises stress, MPa**			
		Membrane		**Membrane and bending**	
		Calculated	**Allowable**	**Calculated**	**Allowable**
Cap - base plate	7 / 1	271	**482**	400	**627**
	3 / 1	198		364	
	3 / 1.8	139		214	
Base plate - transition piece	1	208		364	
Cap – He pipe	2	31		37	

Table 5. Von Mises stress in the welding seams. Pressure 170 bar at 4 K