Final Design And Manufacturing Of The Cryolegs Of The W7-X-Superconducting Coil Support System

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Abstract **One of the most complicated tasks during the assembly of the WENDELSTEIN W7-X is the installation of the superconductive coil system.**

The entire magnet system is enclosed between the Outer Vessel and the plasma vessel in high vacuum at 4K.

The coils are supported by a support structure, the Central Support Structure (CSS).

The CSS carries all 70 coils, and it is designed as a closed ring made of 5 modules (10 half modules). The whole structure is supported by 10 Cryolegs which rest on the machine base.

This paper describes the final design and manufacture of these Cryolegs

Central Support Structure, Cryoleg, Wendelstein W7-X

1. Introduction

The Wendelstein W7-X is a fusion experiment which is currently under construction in the Greifswald branch of IPP. Its coil system with its CSS is within the cryostat at 4K and under high vacuum. Figure 1 shows a schematic cut through the Cryostat.

The CSS stands on 10 vertical supports that separate the CSS at cryogenic temperature from room temperature. These supports are called Cryolegs. The Cryolegs as vertical support elements of the whole magnet system are static highly loaded components and are located inside the cryostat supporting cylindrical legs. The Cryolegs are at cryogenic temperature at the connection with the CSS and at room temperature at the machine base. Stainless steel bellows are used between the Cryolegs and the cryostat supporting legs.

The Cryolegs fulfill five substantial tasks:

- Transmission of high vertical and horizontal forces (max Fv=1MN, max Fh=156kN)
- Compensation of different thermal expansions between the Central Support Structure (CSS) at 4K and the machine base at room temperature
- Thermal insulator between the cold parts (CSS / coil system) and the warm structure
- Compensation of manufacture and assembly tolerances between the CSS and the Outer Vessel (OV)
- Vertical and horizontal adjustment of the CSS on the machine-base

All components of the Cryolegs, except the insulator bush see Fig. 4, are made of stainless steel 1.4429 316LN (yield point Rp 0,2: >900MPa at 4K, elongation at fracture: >25%, Young's modulus : >190GPa at 4K, cobalt content < 500 ppm).

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Fig. 1: Schematic view of main Cryostat components of the WENDELSTEIN 7-X

2. Design of Cryolegs

Per module two Cryolegs ensure the support of the modular installed coils and its CSS.

One module is shown in fig. 2.

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Fig. 2: Module representation of CSS with Cryoleg-s

The Cryoleg is able to resist the bending moments. Its top part is bolted to a lower flange of the CSS.

Each connection is made with 3 M33 and 3 M30 Inconel studs, see table 1. The defined pre-loading is realized using superbolt-nuts at all screws.

The foot parts (bearing components) of the Cryolegs make possible the rotation and also the horizontal sliding on the machine basis.

For the toroidal restraining and the centring of the CSS tie rods are used at the base plate of the Cryolegs. The tie rods allow the radial displacements due to thermal expansion of the structures.

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Fig. 3: Sketch of the statical system

3. Function and structure of the Cryoleg components

The Cryoleg consists of 5 functional components:

Ring fitting
Insulator bush
Bearing components
Bellow
Tie rod, (centering component)

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Fig. 4: Structure of Cryolegs

The 10 Cryolegs are identically designed. Within a module there are only slight constructional deviations in the upper flange plate.

The upper parts of Cryolegs are computed and designed for the transmission of high vertical and horizontal forces.

The overall length of one Cryoleg is 1,54m. During the experiment time they have to withstand a maximum bending moment of Mb= 234kNm at the top of the Cryoleg, see table 2.

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Table 1: Bolt connection both Cryoleg upper flange to the CSS [5]

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Table 2: Forces and bending moments in Cryoleg parts [5]

3.1. Ring fitting design

The Ring fitting is a welded construction with 4 external stabilizing ribs. The connection between the pipe and the two flanges is achieved by EB-welding.

The connection of the external ribs is implemented by conventional welding.

3.2. Insulator bush function and design development

Prior to plasma operation time the coils and the CSS have to be cooled down to 4K with an active cooling system with liquid Helium (He). Therefore, during the operation, the upper parts of the Cryolegs are at 4K, but the lower parts are at room temperature (293K). For this reason the Cryolegs must have an intermediate element with enough strength, but with a very low thermal conductivity to withstand the loads and minimize the thermal losses. This intermediate element is the thermal insulator bush of the Cryolegs.

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Fig. 5: Structure of Insulator bush

The Insulator bush is a glass reinforced plastic (GRP) tube with two main stainless steel (1.4429) flanges in the upper and lower extremes.

The upper steel flange has two parts, the inner ring and the outer ring, connected with 12 bolts M20. The upper outer ring has to be connected to a flange with 16 bolts M20 to the Ring fitting lower flange of the Cryoleg. This connection has to transmit a bending moment of 144kNm.

At a defined height (with a level of 80K) the GRP bush of the Insulator bush has a heat conducting system made of an external fixed copper ring and internal fixed copper disk (material OFHC).

It has to transfer the heat from inside the Cryoleg to the thermal insulation shield.

For the realization of the stringent mechanical and heat conducting requirements in combination with high vacuum, the following characteristics were specified:

- Fiber material (R-Glass) and matrix material (epoxy resin) have to be free of Bromine and Boron, so a minimum radiation resistance of 1E7 rad (1E5 Gy) can be guaranteed.
- Thermal contraction from 293K to 4K (ΔT=289K) in several planes of the GRP bush, see table 3
- Mechanical properties at room temperature and at 80K like Young's modulus and strengths in several planes of the bush, see table 4, 5

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Table 3: Thermal contraction in several planes of the GRP bush [2]

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Table 4: Young's modulus several planes of the GRP bush [2]

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Table 5: Strengths in several planes of the GRP bush [2]

The Cryoleg design has been analysed using the code ANSYS. The Cryolegs have been inserted in the large global FEM model of the coil supporting structures.

The results of the analyses have shown the suitability of the design from the structural and thermal point of view.

An R&D task has been launched to develop and test this GRP material. After the manufacture of two prototypes a mechanical test shall examine the capability of the complete Insulator bush to withstand maximum loads. In figure 6 is shown a schematic experimental setup for load test.

Important data of the test:

Vertical load	1MN
Horizontal load	156kN
Number of load cycles	1250
Load duration	60s
Number of thermal cycles	50

- Load test will be performed at 77K
- Examination by force displacement diagram near the force point in horizontal and vertical direction

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Fig. 6: Schematic experimental setup for load test [3]

3.3 Bearing components - function and design

The Bearing component fulfills the function of a static floating bearing, whose degree of freedom in toroidal direction of the torus system is restrained by one tie rod, see fig. 2 and 3.

The Cryoleg bearing consists of one spherical and one plane sliding bearing component. The bearing should allows the radial thermal expansions/contractions and rotations due to deformations of the CSS but restricts toroidal movements.
The spherical bearing avoids bending moments of Cryolegs at the machine base.
This system also keeps the CSS centered.

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Fig. 7: Design of the bearing assembly

The material of all bearing components is stainless steel 1.4429.
A special coating - fiberslip - of the sliding surfaces on the components ensures a maintenance-free operation during the life span of 15 years with a friction factor ≤ 0,05 and a minimum radiation resistance of 1E7 rad (1E5 Gy). Fiberslip is a self-lubricating material.
An extensive test campaign with 2 prototypes has been launched. This should demonstrate that the bearings will function as designed for a life span of at least 15 years, see in table 6 and 7.

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Table 6: Cycles to reach the maximum loads for spherical bearing [4]

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Table 7: Cycles to reach the maximum loads for planar bearing [4]

3.4 Tie rods

The Tie rods are revolving attached at one side to the foundation of the machine and on the other side to a base plate between the spherical and the plane bearing components.
The horizontal fixation of the CSS on the machine base is achieved with the help of the Tie rods.
The length of the Tie rods is adjustable. The Tie rods consist of two M48 threaded rods with joint eyes of austenitic high-grade steel and an adjustable nut.

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Fig. 8: Design of Tie rods

3.5 Bellow

The Bellows are the flexible connecting link between Cryolegs and the OV-legs.
The maximum working ranges for the Bellows are:

- lateral: ± 40 mm
- axial: ± 25 mm

Their tasks are:

- Compensation of manufacture and assembly tolerances between the CSS and the OV
- Compensation of the relative movements between Cryoleg and OV-leg induced by the different operating conditions of the magnetic system and the thermal expansions of the CSS during the cool down.

4. Manufacture

All steel parts of Cryolegs are manufactured by steel plate 1.4429, except the tie rods. The machined parts of tie rods are made by round bar Ø90 and Ø52.
The ring fittings and the inner and outer rings of the Insulator bush are welded constructions. The pertinent tubes are manufactured by cold forming rolled

plates. The foot parts of Cryolegs, bearings and base plates are manufactured by jet cut and machined steelplate.
The bellows and the GRP bush are delivered by special companies.
The supplier of the Cryoleg steel parts has to deliver the complete assembled Cryolegs.

5. Conclusion

The design of the Cryolegs has been developed for a variety of different functions.
The main function - statically highly loaded supporting element of the Coil System and the CSS - requires a bending resistance construction of all components of the Cryolegs.
The further tasks, like balancing of bending moments, relative movements to adjacent W7-X components and the interruption of the thermal conduction of the machine base to the CSS, affected the design of the bearing components and the Insulator bush.
The material development of the Insulator bush requires extensive thermal and load tests by the supplier.
In addition a proof of the life span for at least 15 years is to be performed by the suppliers of the bearing components and the Insulator bush.
These tests are to be implemented by the suppliers according to technical specifications of the IPP.
Only after successful examination of 2 prototypes of the Cryolegs all other Cryolegs will be delivered to IPP.

6. References

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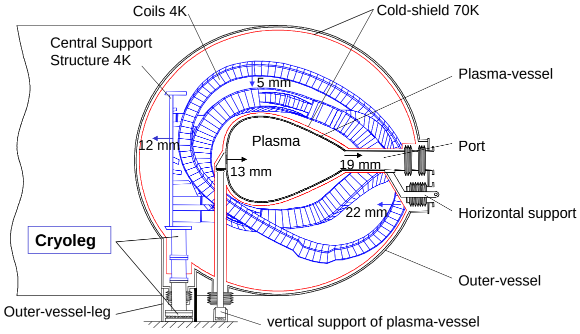

Fig. 1: Schematic view of main cryostat components of WENDELSTEIN 7-X

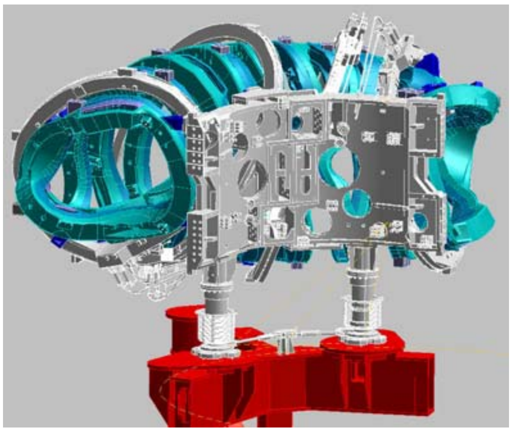

Fig. 2: Module representation of CSS with Cryolegs

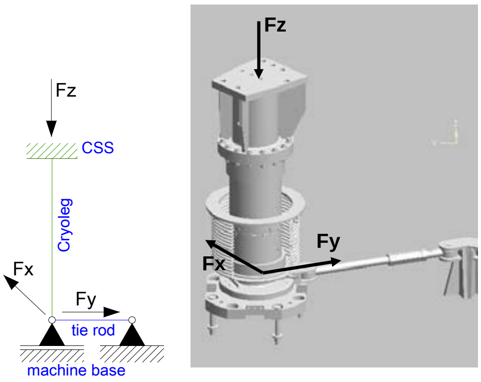

Fig. 3: Scetch of the statical system

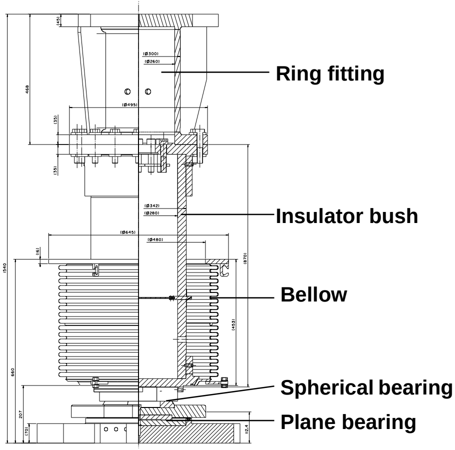

Fig. 4: Structure of Cryolegs

	Cryoleg upper flange N1		Cryoleg upper flange N2		GRP tube upper flange
Flange bolt layout	3xM33 + 3xM30 Inconel 718		3xM33 + 3xM30 Inconel 718		Circular ∅395. 16xM20 A4-80
Bolt size	M33	M30	M33	M30	M20
Maximum force per bolt, kN	**540**	**380**	480	305	**100**
Maximum stress in bolt, MPa	**780**	**670**	690	505	**440**

Table 1: Bolt connection both Cryoleg upper flange to the CSS [5]

			Cryoleg upper flange	GRP tube upper flange
Axial (vertical) force	Fz	kN	1000	1000
Radial force	FX	kN	100	100
Toroidal force	FY	kN	120	120
Transversal force	F	kN	156	156
Radial Bending moment	Mx	kNm	180	111
Toroidal Bending moment	My	kNm	150	92
Bending moment	M	kNm	234	144

Table 2: Forces and bending moments in Cryoleg parts [5]

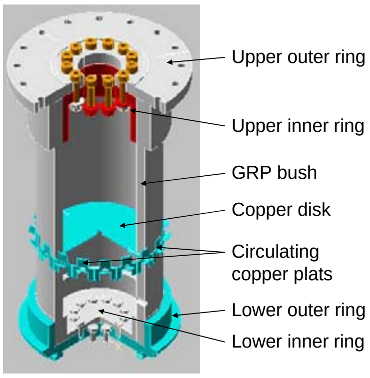

Fig. 5: Structure of insulator bush

Thermal contraction from 293K to 4K (ΔT=289K)	
vertical direction (vertical in plane)	2,8 •10-3 m/m < α1 ‖ *ΔT< 3,2 •10-3 m/m
hoop direction (horizontal in plane)	2,8 ·10-3 m/m < α2 ‖ *ΔT< 3,2 ·10-3 m/m
radial direction (through thickness)	α⊥ *ΔT < 7,6 ·10-3 m/m

Table 3: Thermal contraction in several planes of the GRP bush [2]

	Directions		**RT**	**80K**
Young's modulus (GPa) (minimum values)	Vertical	Ez	25	32
	Hoop (toroidal)	Ey	25	32
	Radial (through thickness)	Ex	11	20

Table 4: Young's modulus several planes of the GRP bush [2]

	Directions	Option A, RT	Option B, 80K
Strength (MPa)	Vertical tensile (σ_1 ||t)	300	400
	Vertical compression (σ_1 ||c)	300	450
	Hoop tensile (σ_2 ||t)	300	120
	Hoop compression (σ_2 ||c)	300	100
	Radial tensile (σ_3 ⊥t)	30	30
	Radial compression (σ_3 ⊥c)	100	50
	Shear inter laminar (τ⊥)	30	30
	Shear in-plane (τ||)	55	55

Table 5: Strengths in several planes of the GRP bush [2]

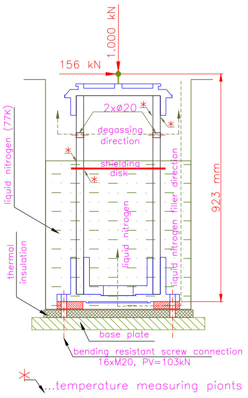

Fig. 6: Schematic experimental setup - load test [3]

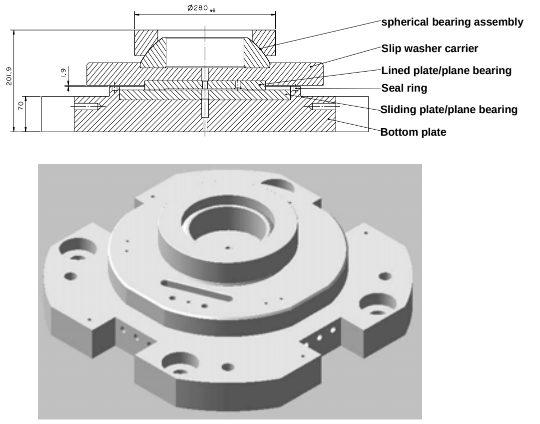

Fig. 7: Design of the bearing assembly

Test step	Number of cycles	Load vertical (kN)	Motion (deg)	Sliding velocity
1	50	200	+/-2°	1 mm/s
2	800	500	+/-2°	1 mm/s
3	850	750	+/-2°	1 mm/s
4	250	1000	+/-2°	1 mm/s
5	15	500	+/-2°	30 cm/h

Table 6: Cycles to reach the maximum loads for spherical bearing [4]

Test steps	Number of cycles	Load vertical (kN)	Motion (mm)	Sliding velocity
1	50	200	+/-30	1 mm/s
2	800	500	+/-30	1 mm/s
3	850	750	+/-30	1 mm/s
4	250	1000	+/-30	1 mm/s
5	15	500	+/-30	30 cm/h

Table 7: Cycles to reach the maximum loads for planar bearing [4]

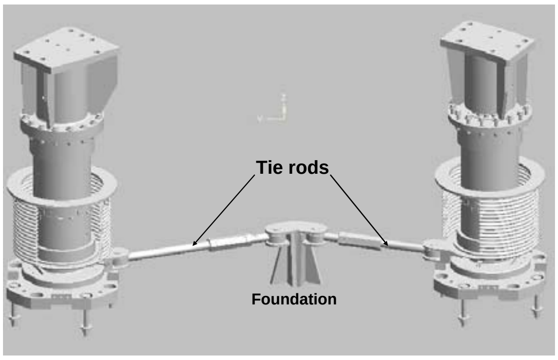

Fig. 8: Design of tie rods