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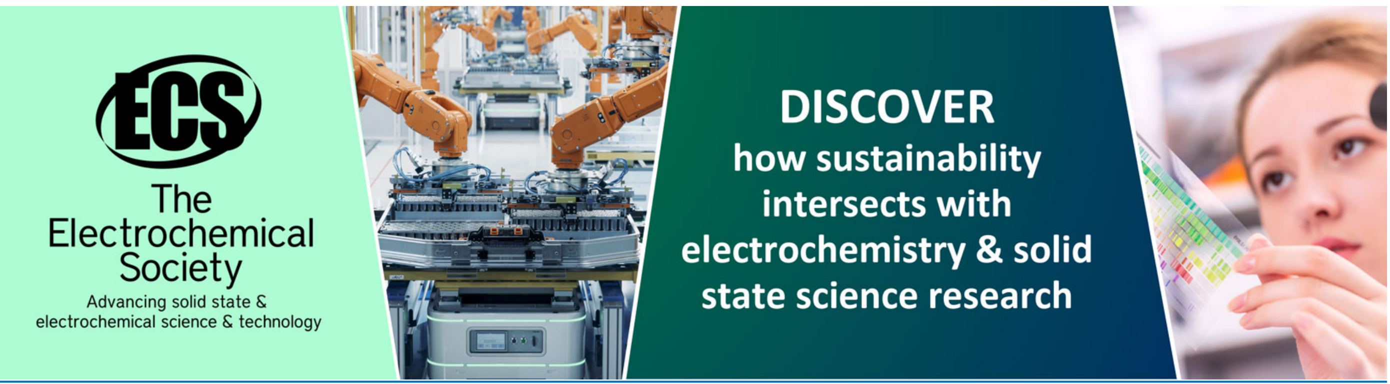

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Design of the helium gas transfer line for the Warm Regeneration System of the ITER fusion reactor

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Abstract. The Warm Regeneration Lines are a system of about 500 meters of flexible cryogenic transfer lines for the Warm Regeneration System of the ITER fusion reactor. The lines have been designed to transfer helium gas in a temperature range 100K/500K and a pressure range 1.2MPa/1.8MPa, for the regeneration of the cryopumps in the Torus Vacuum Vessel, Cryostat and Neutral Beam injector's vessel and for the cryopumps cool-down/warmup from/to room temperature.
The lines consist of an inner gas line in an outer vacuum jacket. In order to facilitate the installation in a congested plant environment, the WRL have been designed with custom flanged connections for the cryogenic process pipe and for the vacuum jacket. Many tests have been performed on the lines, among which a mechanical characterization for seismic qualification in nuclear environments, a pressure drop test and a pressure and temperature 100 cycles test to validate the leak tightness of the cryogenic flanged connections.

1. Introduction
The Warm Regeneration Lines (WRL) are a system of about 500 meters of flexible vacuum insulated transfer lines for the Warm Regeneration System (WRS) of the ITER fusion reactor.

The purpose of the system is to distribute gaseous helium to the cryopumps installed in the ITER vacuum vessel, cryostat and neutral beam injector, starting from the Warm Regeneration Box (WRB) placed at the ITER plant upper level L3. The purpose of the WRB is to warm up the supply helium from 300K to 500K, and to thermalize the return from cryopumps (between 100K and 500K) back to 300K.

2. The Warm Regeneration Lines design
Two concentric flexible pipes constitute the WRL. The lines must be built to withstand a full temperature range from 100K to 500K. The design pressure is reduced from 2.1 MPa to 1.4 MPa above 300K due to cryopump design pressure limitation.

Moreover, the lines must be designed with a fully dismountable coupling, to facilitate installation. The materials for the WRL, including the coupling seal and the MLI, must be chosen accordingly.

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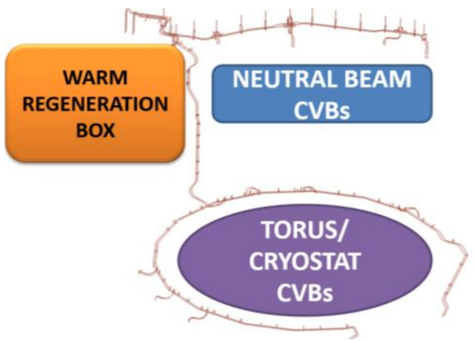

Figure 1. The Warm Regeneration System, supplying Torus, Cryostat and Neutral Beam Cold Valve Boxes (CVBs).

2.1. Technical data

Table 1. Technical data

Requirement	Values
Design temperature and pressure	100 K to 300K at 2.1 MPa 300K to 500 K at 1.4 MPa
Required leak rate	<1*10^{-9} Pa*m^3/s for the inner process line <1*10^{-7} Pa*m^3/s for the outer vacuum jacket
Pressure drop requirement	300 Pa/m @ 500 K , 1.2 MPa, 150 g/s
Thermal requirement	< 6 W/m @ Room temperature to 100 K
Quality class	QC1 (ITER highest quality class)
Safety category	Not Safety Relevant
Cumulated radiation dose	500 kGy

2.2. Structure of the lines

The WRL consist of a main distribution line, with smaller lines branching from it to the cold valve boxes (CVB) supplying the cryopumps (figure 1). The branch lines are smaller in diameter due to the lower mass flow rate.
The lines are therefore divided in two types:

- Main lines: inner DN80/outer DN125, lengths going from 2 to 35 meters (about 400 meters total)
- Branch lines: inner DN65/outer DN100, lengths going from 2 to 5 meters (about 100 meters total)

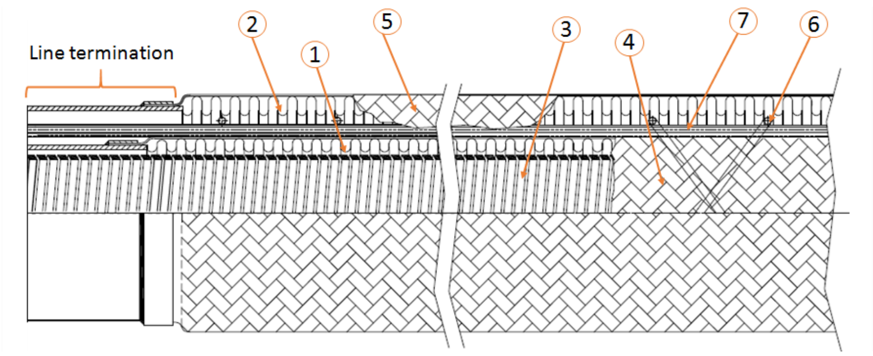

Figure 2. Structure of the line

The internal structure of each line is shown in longitudinal cross section in figure 2. The inner and outer lines are made of hydro-formed flexible pipe (1/2). Both have an external braid (4/5), mainly for vacuum and pressure requirement, but also for protection purposes on the external one. Moreover, the inner line has an internal interlocked pipe (3) to reduce the friction factor and the pressure drop, after the test described in Section 3.5. For thermal insulation purpose the inner line has been wrapped with

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multi-layer insulation (MLI) (7) and a metallic-spring spacer (6), tested with a setup described in Section 3.1.

2.3. *The coupling*

The coupling between the lines has been designed to be completely dismountable; no welding is required in the construction site. A mounting procedure is shown in figure 3.

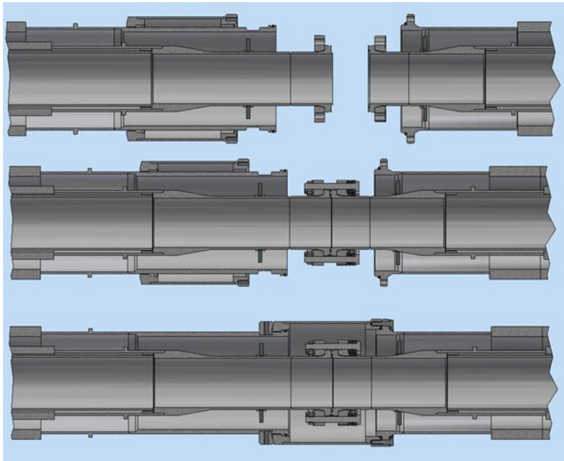

Figure 3. Coupling mounting procedure.

2.3.1. The inner coupling. The inner coupling consists of a pair of stub flanges, each with rotatable ring. Each coupling is closed by 12 A4-80 M8 bolts. The gasket is a metallic spring-energized C-ring, chosen for its wide temperature resistance and high vacuum sealing and reliability.

The inner line is subject to Pressure Equipment Directive (PED) and the coupling has been designed accordingly, making use of a specialized software – Sant'Ambrogio Nextgen [2] – for main stresses calculations and its safety factors. Beyond that, an extensive test campaign has been run to determine the optimal seal configuration and seismic resistance (see Section 3.3).

In order to compensate for the difference in thermal expansion during the frequent heating and cool-down transients of the inner line, the bolts have been complemented with a set of Belleville spring washers. These allow a minimum load to be kept during the cooldown – when expansion of the bolts is higher than the flanges – and to reduce the load on the flanges during heating – when expansion of the bolts is lower than the flanges.

Beyond the inner coupling bolting system, a backup welding lip has been added in case the seal should leak. This additional feature should be used only if a leak is found after proper installation, during the lifetime of the machine.

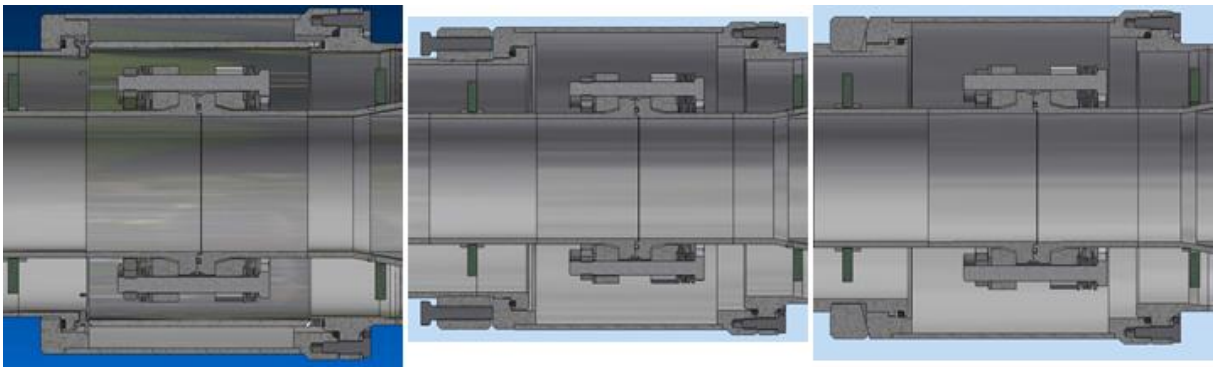

Figure 4. Outer line design iteration: a) with spacer ring; b) with pusher bolt; c) with tapered clamps.

2.3.2. The outer coupling. The outer coupling consists of a sliding ring with two EPDM O-ring seals. This allows reaching the inner line easily without having to move the flexible lines.

The main challenge for the outer coupling was driven by the need of having a double stable seal, the front one (right) being an angular seal with bolted axial compression, the back one (left) requiring mechanical investigation. The problem has been faced with different strategies and improved by design iterations (see Figure 4, left to right):

a. In the first design, a spacer ring was placed between the stub flanges to allow axial compression of the back O-ring. This option was later discarded because of the high requirements in tolerances and poor stiffness in seismic conditions.
b. In the second design, the spacer ring has been replaced by an outer clamp with pusher bolts to axially compress the back O-ring. This way, each O-ring had a set of bolts to ensure correct sealing, thus making the coupling more resistant and reliable. The configuration was then manufactured and successfully tested against the most stressful seismic condition of 6g, simulated by an equivalent bending moment of 750N*m.
c. In the third design, the back axial O-ring was replaced by a piston O-ring, and outer tapered clamps were coupled with tapered grooves.

3. R&D

As per IO requirements, the lines design had to be validated against a series of parameters such as those shown in Section 2.1. More than 20 tests were performed on the lines' samples for the approval of the Final Design Review (FDR) and Manufacturing Readiness Review (MRR).

3.1. Thermal test

A thermal test was required by the technical specification to prove a thermal loss specification within 6W/m between room temperature vacuum jacket and 100K process pipe.

A sample of the line was flushed with warm air or liquid nitrogen to simulate all temperature conditions. The rate of nitrogen evaporation was used to determine the thermal loss of the line.

Three different configurations of MLI have been tested:

- 22 layers of fiberglass tissue + 22 aluminum foils
- 22 layers of fiberglass tissue + 22 aluminum foil + 3 final layers of RUAG COOLCAT 2NW [3].
- 1 layer of fiberglass tissue + 22 layers of Lydall CRS-wrap [4].

All configurations had an additional metallic-spring spacer on top, to reduce contact spots between the two concentric lines. The third option was chosen, being the thermal performance considered acceptable for the WRL: 6.5W/m for the main line and 6.0W/m for the branch lines. Moreover, Lydall CRS-wrap, made of glass fiber and aluminum foils is fully compatible with the temperature range of the lines and the radiation environment. It is more adaptable to the flexible surface of the line, thus more performing with bended lines.

Figure 5. The MLI wrapping machine.

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3.2. MLI Wrapping machine
A MLI wrapping machine has been developed for the automatic and repetitive wrapping of more than 5000m^2 of MLI (figure 5).

The wrapping machine is designed to wrap up to 6 layers of MLI at once, built on wheels to move along the line, laid horizontally. Each reel of MLI has independently adjustable tensioning for the optimal coverage of the line based on the gap available. It was custom-studied for the WRL and it can be adapted to any cryogenic line.

3.3. 100-cycled gasket thermal test
The inner line has a leak test requirement to be <1*10^{-9} Pa*m^3/s. Because of the large operating temperature range, a metallic spring energized C-ring was chosen as the optimal sealing solution.

A test campaign of 100 thermal cycles was performed to prove the coupling leak tightness stability over time. The cycle definition simulates the operation temperature change rate, and consists of:

- 22.5min heating from 300K/1.75MPa to 500K/1.4MPa with two 150W heaters
- 45min stationary at 500K/1.4MPa
- 45min cooldown from 500K/1.4MPa to 100K/2.1MPa with liquid nitrogen
- 45min stationary at 100K/2.1MPa
- 22.5min heating from 100K/2.1MPa to 300K/1.75MPa with two 150W heaters

Other than the performance of the metallic gasket (leak tightness), the test also allowed to determine a thermal distribution in the inner flange: there is an expected heating/cooling delay between the stub flanges, the rotatable flanges and the bolts, given by the thermal conduction in the metal. A maximum temperature difference of 200K has been measured, justifying the use of the Belleville spring washers in the inner coupling, to compensate for differential thermal expansion.

At the end of the test, the leak rate value always stayed below the required level, so the seal was validated.

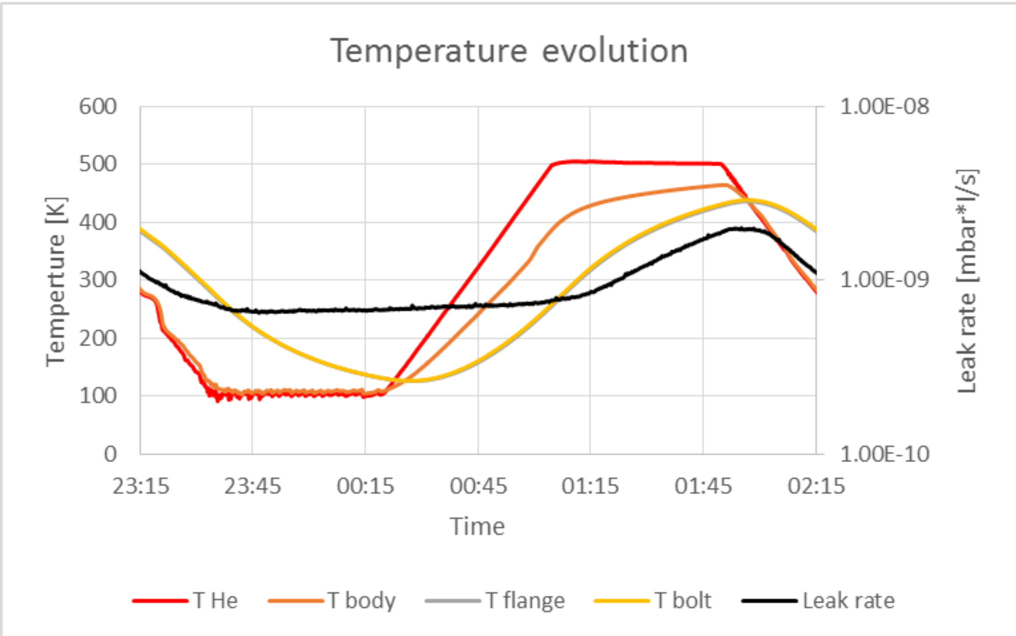

Figure 6. Thermal cycle on the inner coupling.

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3.4. Seismic analysis
Three seismic events have been taken as a reference for validation:
- Seismic Level 1 event (SL1, event category II): normal operation without shutdown
- Maximum Historically Probable Earthquake (SMHV, event category III): normal operation, allowable stresses within the elastic limits
- Seismic Level 2 (SL2, event category IV): safe shutdown, plastic deformation can occur but no fracture

A full mechanical characterization was performed on a sample of the line to give the input parameter of a global beam model, such as equivalent beam area, moment of inertia and moment of torsional inertia. Given the complexity of modelling flexible multi-layer pipes, the seismic analysis was performed by two independent specialized companies, and the envelope of loads/displacements used for dimensioning the supports.

3.5. Pressure drop test
The line has been tested for its pressure drop with a special setup. Three configurations were considered: corrugated line, corrugated line with inner braid and corrugated line with inner interlocked pipe. As a final result, the third option was chosen, having the lowest pressure drop of 350Pa/m (500 K, 1.2 MPa, 150 g/s).

3.6. Factory acceptance test (FAT)
A FAT will be performed at Criotec on each line at the end of the manufacturing phase, consisting of:
- Visual, dimensional and cleanliness test
- Pneumatic pressure test as per (PED) requirements.
- 1st Helium Leak into the vacuum insulation (from inner line and from outer vacuum jacket)
- Cryogenic test
- 2nd Helium Leak into the vacuum insulation (from inner line and from outer vacuum jacket)

4. Conclusions
The WRLs have been developed in close collaboration between Criotec, F4E and IO. The project has been approved during FDR and MRR and the lines are currently under manufacturing. The lines will be delivered to IO between end of 2018 and the beginning of 2019.

The main challenges of the project have been the operative temperature range and the critical seismic condition, that heavily influenced the design process and the choice of materials. The WRL have been engineered and its design has been iterated to guarantee the best performances under any design requirement.

References
[1] Kouzmenko G 2014 *Technical specification for the supply of helium gas transfer lines for the warm regeneration system of the ITER vacuum system* (Fusion for Energy, internal document), F4E_D_26JM76 v.2.3
[2] Sant'Ambrogio NextGen, https://www.sant-ambrogio.it/
[3] RUAG COOLCAT 2NW product datasheet, https://www.ruag.com/sites/default/files/2016-12/150622_Broschuere_Thermal_Jun2015_single-low.pdf, page 9
[4] Lydall CRS-wrap product datasheet, http://communications.lydallpm.com/acton/ppform/15386/001f/f-0173