TECHNICAL NOTE IN RELATION WITH THE ITER NEUTRAL BEAM CRYOPUMPS - HEATING NEUTRAL BEAM CRYOPUMPS & DIAGNOSTIC NEUTRAL BEAM CRYOPUMP

Abstract

The experimental fusion reactor ITER will require 2 Heating Neutral Beam Cryopumps and 1 Diagnostic Neutral Beam Cryopump. The prototype of a Heating Neutral Beam Cryopump (Mitica Cryopump) was manufactured in 2023 and is pending to be installed in the Q4 of 2024. A Call for Tender for these 3 Cryopumping Systems will be published in 2025. This report outlines the design of these Heating & Diagnostic Neutral Beam Cryopumps.

idm@F4E Reference:	F4E_D_ 2Z245A	**Contract/GA**	**NA**
ITER PA/ITA Reference	**PA 3.1.P1.EU.04**		
Subject:	***ITER NEUTRAL BEAM CRYOPUMPS***		

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1. Introduction

The experimental fusion reactor ITER will require 2 Heating Neutral Beam Injectors (NBI) and 1 Diagnostic Neutral Beam Injector (DNB). Each NBI is equipped with 2 Heating Neutral Beam Cryopumps (HNB CP as described in Figure 2 below) and the DNB is equipped with 2 Diagnostic Neutral Beam Cryopumps (DNB CP). These 3 Cryopump systems pump gases by adsorption on charcoal coated cryopanels cooled to a temperature of about 4.5 K. The Cryopumps have only physical interfaces with the Beam Line Vessel (BLV), process interfaces with ITER Cryoplant & electrical interfaces with the Control system. The assembly/disassembly of the cryopump is compatible with the Remote Handling System.
The prototype of a Heating Neutral Beam Cryopump (Mitica Cryopump) was manufactured and delivered in 2023 and is pending to be installed in the Q4 of 2024. The build-to-print design of these cryopumps will be completed in Q4 of 2024. A Call for Tender for these 3 Cryopumping Systems will be launched in 2025.

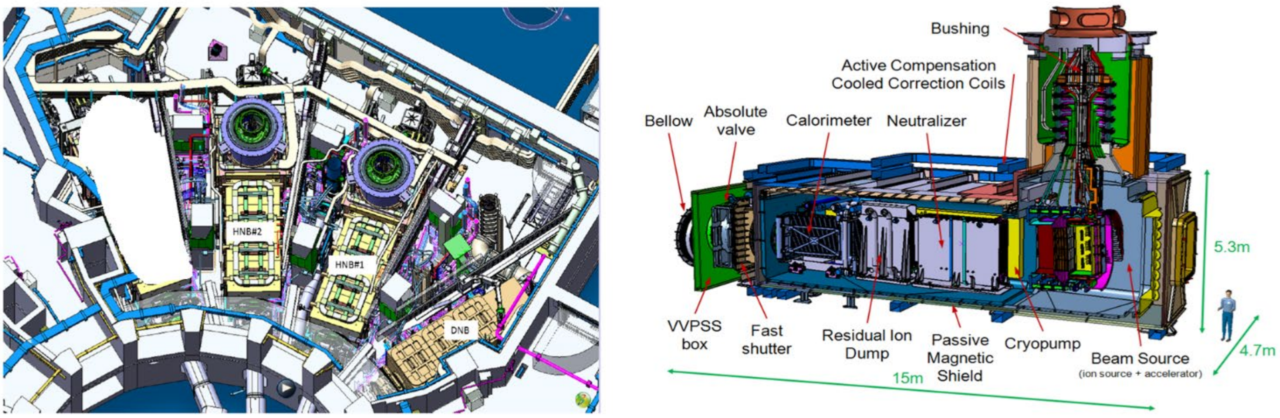


Figure 1 – 2 HNB systems, 1 DNB system, each containing a neutral beam cryopump system.

2. Design overview

2.1. Introduction

2.1.1. HNB CP

The 2 cryopumps are installed in the NBI BLV which is not part of the scope of supply. The cryopumps are about 8m long, 3m high and 1m wide. Each Cryopump is equipped with 32 pumping sections (64 for the whole cryopumping system). The overall weight of each pump is around 4 T.

The figures below show these components:

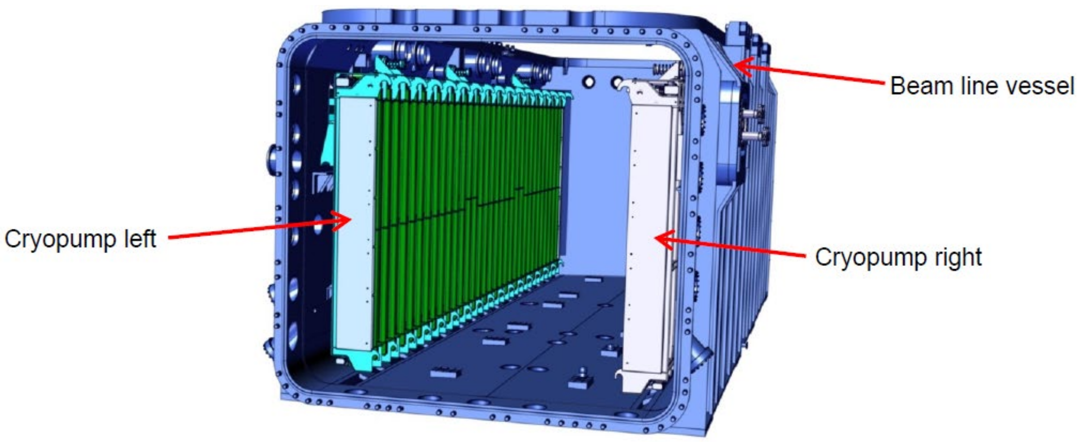


Figure 2 – HNB CP inside the BLV

Figure 3 – Mitica Cryopump (HNB CP prototype)

2.1.2. DNB CP

The 2 cryopumps are installed in the DNB BLV which is not part of the scope of supply. The cryopumps are about 5m long, 3m high and 1m wide. Each Cryopump is equipped with 20 pumping sections (40 for the whole cryopumping system).

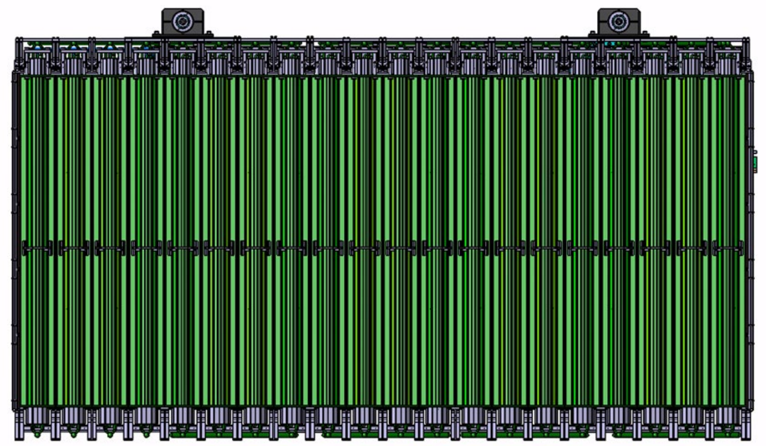
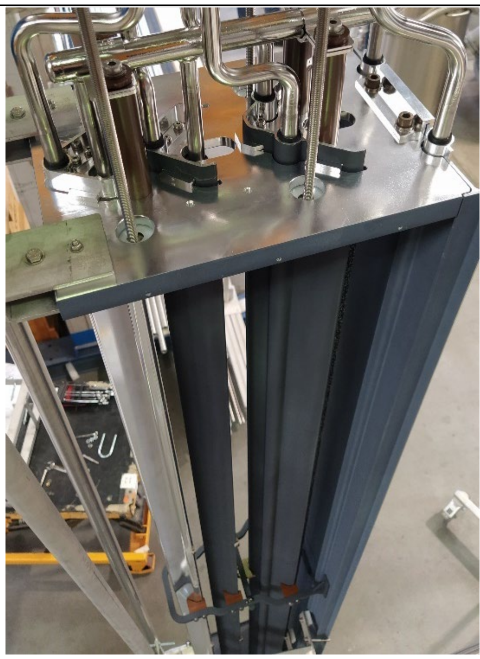
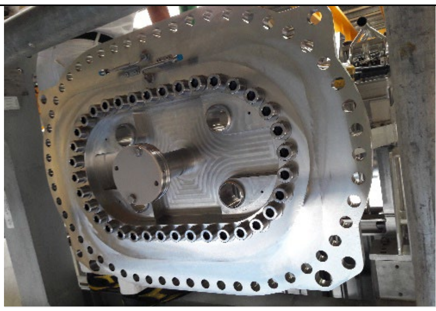
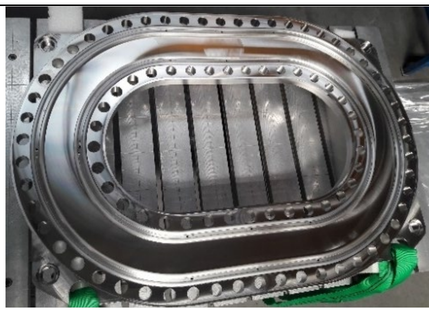
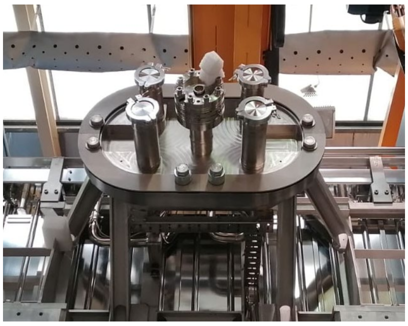


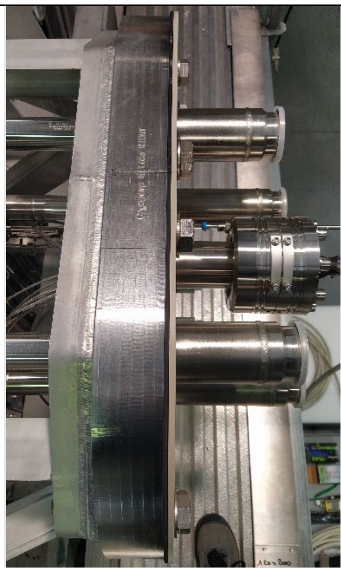
Figure 4 – DNB CP front view.

2.2. Subsystems

Each cryopump is composed of the following 6 subsystems listed in the table below:

FRAME One support frame, supporting all the components of the cryopump together. The frame includes supports that holds the Cryopump in the BLV (1.4429 Stainless steel structure).	

Pumping Sections Main components: three charcoal coated 4K cryopanels (CP), four 80K Thermal Radiation Shield (TRS) panels, top/ bottom plates and upper/bottom manifolds.	 
Passive shields Made by electro/chemical polished aluminium sheets to protect from heat radiation.	  
Vacuum Flange Assembly One vacuum flange assembly per cryopump. Main components: vacuum flange, connection flange, helicoflex seals, 4 Johnston Couplings (free issue item) female flanges & 1 electrical flange.	  

Temperature sensors assembly Main components: 10 Temperature sensors per cryopump, wires, cable tray, 1 electrical flange assembly and 1 electrical test cubicle for all the cryopumps (used to verify the correct functioning of the sub-system during the FAT & SAT).	 
Connection Manifold Piping arrange that connects the pumping sections to the Johnstons Couplings.	

2.2.1. Frame

The frame, supports and aligns all the components of the cryopump. The Frame is composed of 3 different types of subframes, flange supports, cryopump top and bottom supports, top lock and top stiffener.
The cryopump top and bottom supports and top lock are the physical interfaces with the BLV (together with the flange). The top stiffener enhances the rigidity of the cryopump.

H profiles with non-standard geometries are used to manufacture the frame. The material for the whole frame is 1.4429 stainless steel.
The main manufacturing and testing processes involved are welding and redressing, machining, pickling and passivation and dimensional control.

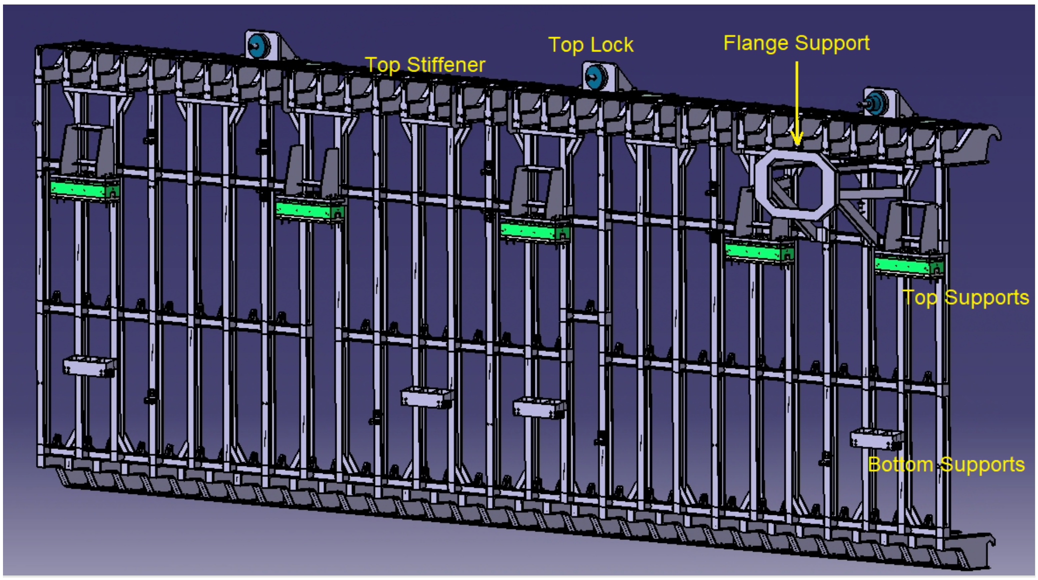


Figure 5 – The main components of the HNB CP Frame

2.2.2. Pumping Sections

The pumping sections are the active parts of the pump. They include the 4 K charcoal coated cryopanels that trap the gases. To minimize heat loads, the 4 K cryopanels are protected by thermal radiation shields (TRS), cooled to about 80 K, and the top and bottom plates. Both 4 K and 80 K panels are cooled down by helium, this helium is distributed by the Upper and Bottom 4 K / 80 K manifolds. In order to limit the transversal movement of the panels during cool down and warm up a TRS Brace Assembly is installed.

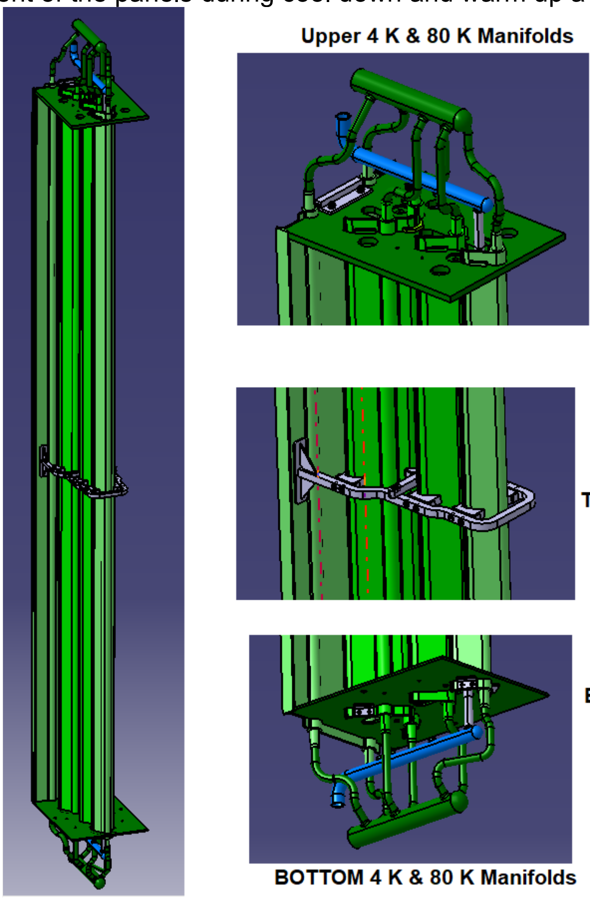


Figure 6 – Pumping section overview

Profiles

The 4 K cryopanels and the 80 K TRS have a profiled shape and are about 2.8m long. They are obtained from AW 6082-T6 aluminium extruded profiles and ESR (Electro-Slag-Remelted) or VAR (Vacuum-Arc-Remelted), low impurities (<%Co,Ta,Nb: 0,05%, 0,01%, 0,01%), stainless steel 1.4306 or 1.4307 (EN 10216-5) pipes. The stainless-steel pipe is inserted inside the aluminium profile then expanded in order to achieve a good contact between the aluminium profile and the pipe. The expansion process is made by applying high hydraulic pressure inside the pipes. The pictures below show the result of this expansion process:

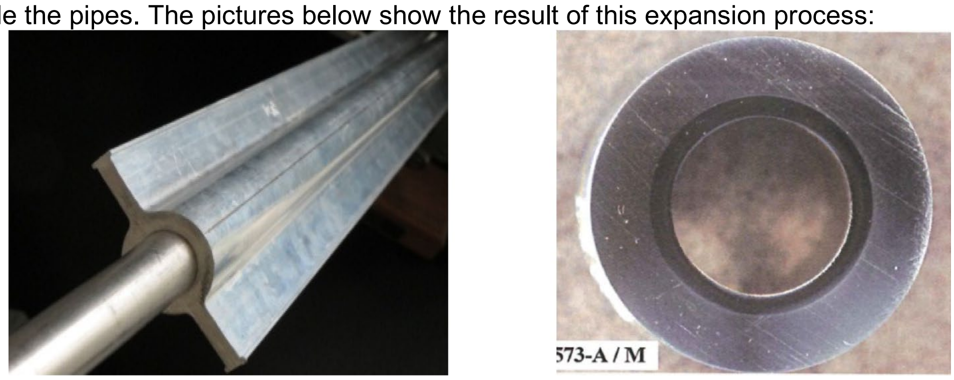


Figure 7 – General view of the 4 K cryopanels, before charcoal coating and polishing, and its cross section

Surface treatments

The surfaces of the profiles described above will be subject to the following treatments:

Charcoal coating: The 4 K cryopanels are charcoal coated. This needs to be done with a qualified process that ensures an optimum charcoal density on the panels. The coating is done by means of ceramic glue. The panels are baked after the coating. The charcoal is free issued by F4E.

Electro/Chemical polishing: Both 4 K and 80 K panel among other pumping sections components (such as top and bottom plates, manifolds, etc) will be polished. This process needs to be qualified to assure an optimum roughness (around 1 µm), emissivity and homogeneity.

Blackening: The blackening shall be done by plasma spray coating using Al_2TiO_5 (Al_2O_3 + TiO_2, 87%/13%) unsealed. The emissivity of the surfaces after blackening shall be greater than 0.9.

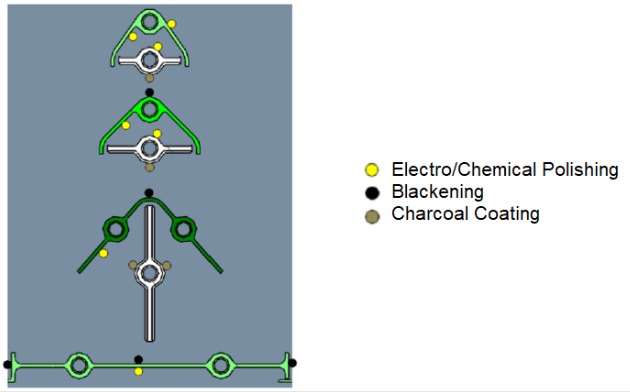


Figure 8 – Pumping section surface treatment .

The main manufacturing and testing processes involved are the extrusion of the aluminium profile, the expansion of the stainless-steel panels pipes, blackening, charcoal coating of the 4 K cryopanel, machining, electro/chemical polishing and welding of the manifold into the panels pipes.

The main tests involved in the manufacturing of the pumping sections are the pressure test, cold leak test, thermal cycle test, roughness test, 100% welds Radiographic Test (RT), charcoal coating adherence test and dimensional control.

2.2.3. Passive Shields

The passive shielding protects all parts of the 4 K circuit from thermal radiation.

It consists of two main sub-systems:

- Cover shields, pumping sections & temperature sensors passive shields – Aluminium sheets fastened to the pumping sections and connection manifolds during final assembly to protect the 4K CP circuit from 300K radiation.
- Side walls – Assemblies that close both sides of the cryopump.

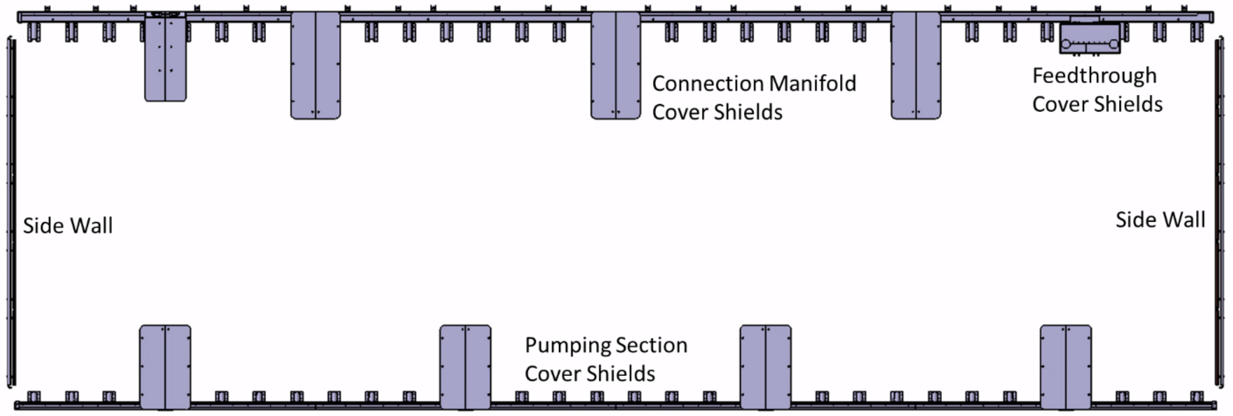


Figure 9 – Cover shields and Side walls (pumping sections & temperature sensors passive shields are not represented).

The cover shields are formed from 2 mm thick electropolished aluminium 1050 sheet, and due to the complex geometries, are optimised and installed during final assembly.

The main manufacturing and testing processes involved are welding, forming and electro/chemical polishing.

2.2.4. Vacuum Flange Assembly

The cryopump flange is welded to the cryopump frame and it gets connected to the beamline vessel flange via an intermediate connection flange. The required leak tightness is achieved with two Helicoflex seals fixed to the connection flange. Both the cryopump flange and the connection flange are within the scope of this supply.

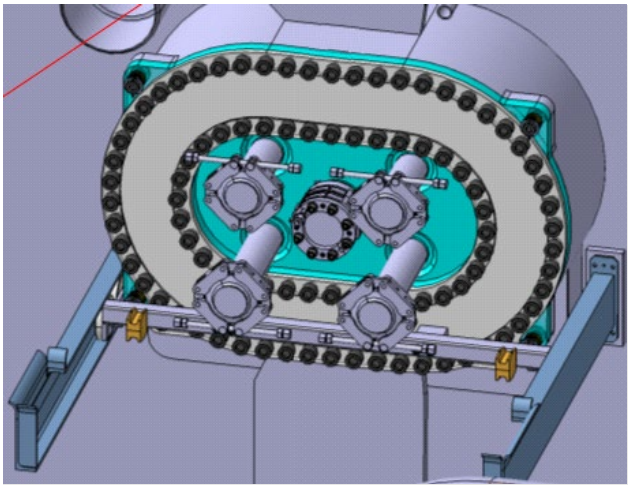


Figure 10 – Flange assembly mounted in the BLV.

The female of four Johnston Couplings and one electrical flange assembly are welded to the cryopump flange. The Johnston couplings are free issued by F4E to the supplier.

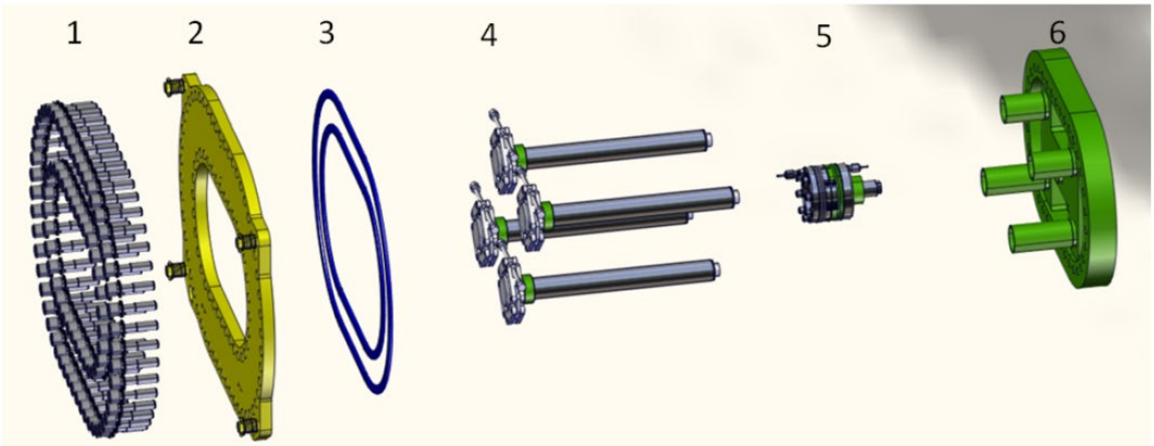


Figure 11 - Exploded view of vacuum flange assembly, [1] fasteners, [2] connection flange, [3] Helicoflex seals, [4] Johnston couplings, [5] electrical feedthrough, [6] cryopump vacuum flange.

The connection and vacuum flange are made of cross forged/upset forged, ESR/VAR, low impurities (<%Co,Ta,Nb: 0,03%, 0,01%, 0,01%), 1.4306 or 1.4307 or 1.4429 (EN 10222-5) stainless steel.

The main manufacturing and testing processes involved are welding, machining, dimensional control, manual polishing of sealing surfaces, RT, sealing surface examination, and leak test.

2.2.5. Temperature Sensors Assembly

The connection manifold will include a total of 10 temperature sensors (5 in the 4 K Manifolds and 5 in the 80 K Manifolds) for each cryopump distribute it in 5 different areas.

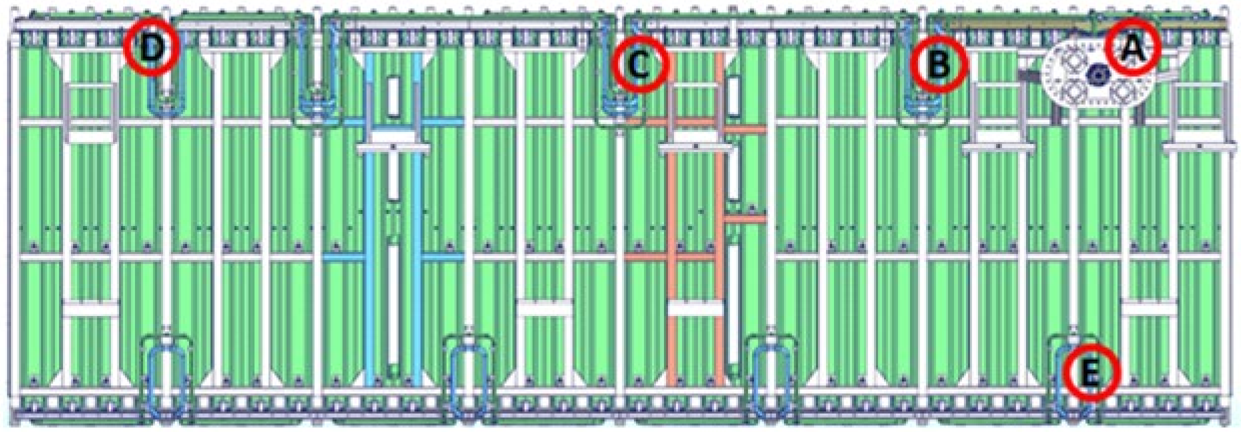


Figure 12 – Location of the temperature sensors on a cryopump in the HNB CP.

Cable trays are placed in the Frame to protect the wires that go from the temperature sensors to the electrical feedthrough.

The main component of the electrical flange assembly is the electrical double feed-through which is integrated on a DN65 ITER-style flange.

The electrical double feedthrough contains a standard multipin vacuum feedthrough into an interspace and a second ITER multipin feedthrough from the interspace to the primary vacuum of the machine.

The proper functioning of the temperature sensor assembly is verified during Factory Acceptance Testing (FAT) and Site Acceptance Testing (SAT) by connecting the electrical flange assembly to the electrical cubicle.

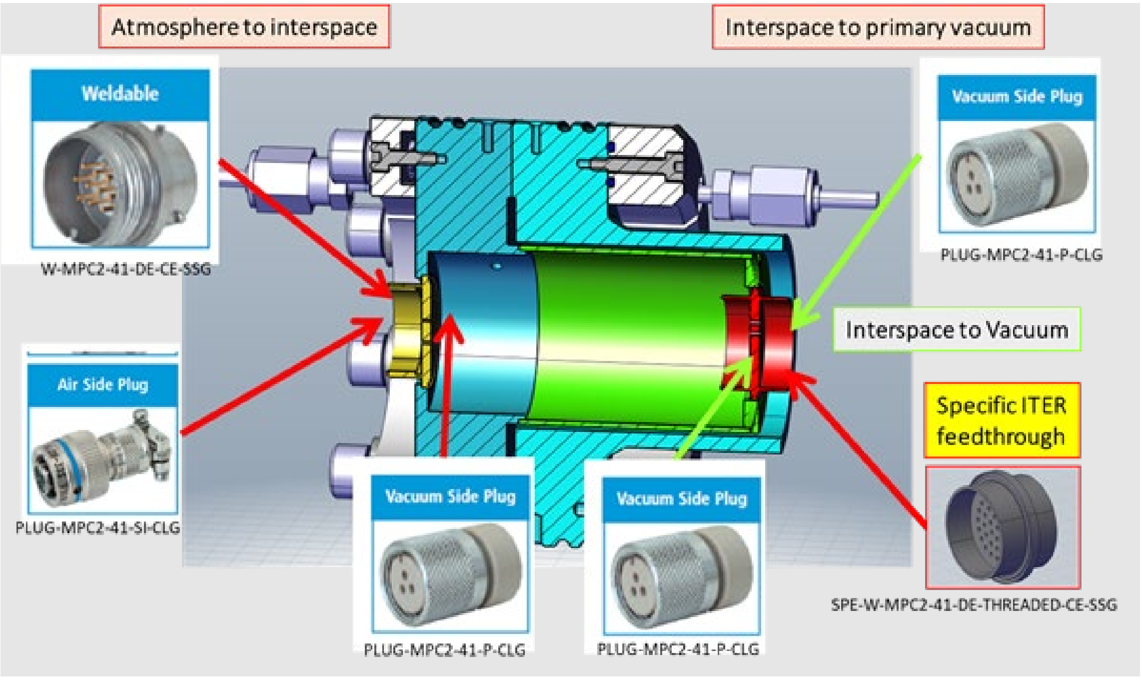


Figure 13 – Overview of the electrical flange assembly

The main manufacturing and testing processes involved are soldering, wiring, crimping, electrodeposition, electrical isolation test and temperature sensor functional test.

2.2.6. Connection Manifolds

Connection manifolds are the ESR or VAR stainless steel 1.4306 or 1.4307 (EN 10216-5) seamless pipes that connect the pumping sections together to the vacuum flange.

They are split into three families:

- Module connectors – these route the flow from the upper or lower pumping sections manifolds of one pumping section module (a module is composed by four pumping sections) and connect it to the next pumping sections module.
- Return lines – these route the flow from the last pumping section module back to the cryopump flange feedthroughs.
- Inlet/outlets – these are the four spools that are finally welded to the Johnston couplings located on the cryopump flange.

Expansion loops and bends provide sufficient flexibility to accommodate the thermal cycles of the pump.

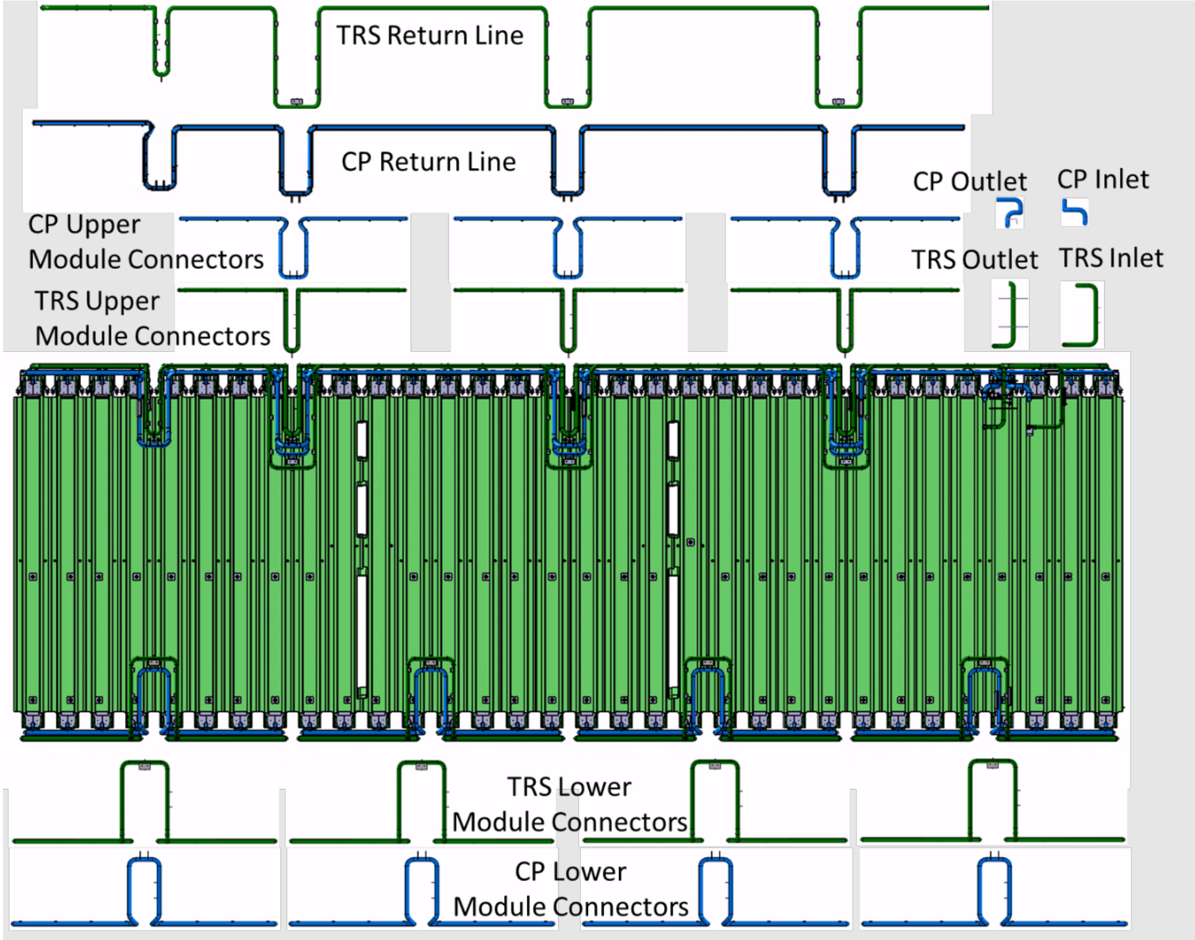


Figure 14 - Breakdown of individual connection manifolds for HNBCP_L

The main manufacturing and testing processes involved are welding, electro/chemical polishing, bending of the pipes, roughness test, pressure test, cold shock test, 100% radiographic test and leak test.

2.3. **Manufacturing and Assembly**

The manufacturing and assembly of the cryopumps will have to be done following cleanliness requirements for high vacuum components as well as the Quality Assurance requirements for Quality Class 1 components and Protection Important Components according to the French Order of 2012.

Most components of the cryopumps will have manufacturing tolerances which can be considered standard in industry (DIN ISO 2768 - mK and EN ISO 13920 - BF for welded parts). Some components such as vacuum flanges, Frame or the position of the Cryopanels and TRS will have stringer tolerances.

2.4. **Auxiliary components**

Manufacturing, assembly, testing and transportation tools will be required during the different steps of the project. Some examples used in Mitica Cryopump below. All the tools developed during the Mitica Cryopump (like the ones below) will be free issued by F4E.

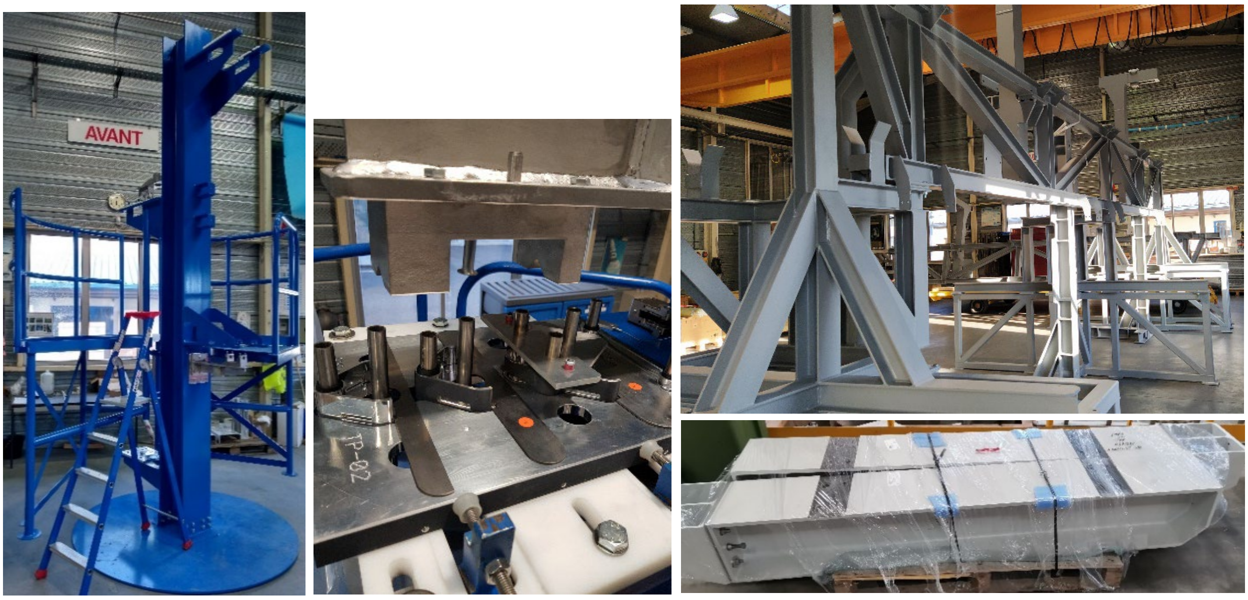


Figure 15 – Some of the tooling used during the assembly, testing and transportation of the Mitica Cryopump. On the left side: the pumping sections assembly tool; on the middle: the cryopanels-TRS centring tools; on the right side: the subframes and cryopump assembly tools.

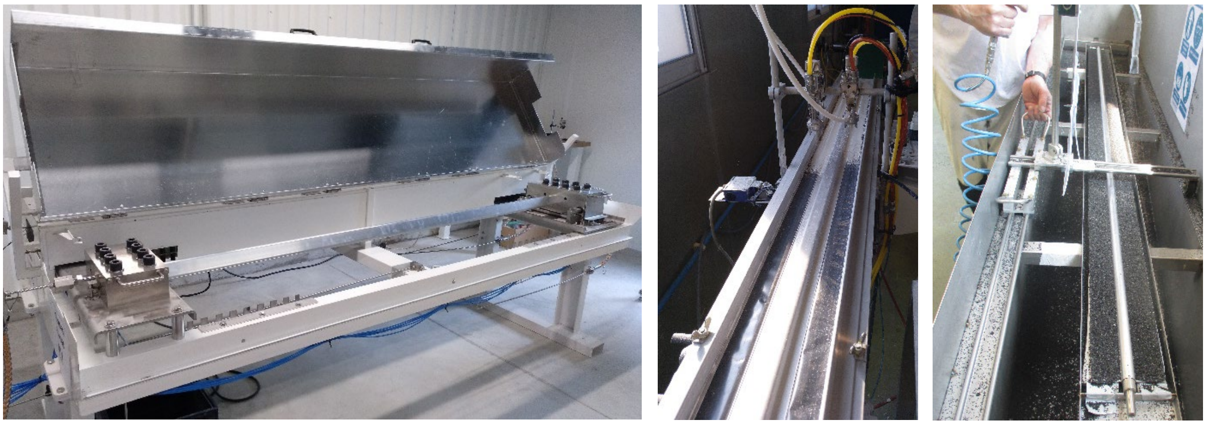


Figure 16 – Some of the tooling used during the expansion and charcoal coating of the panels. On the left side: the pipe expansion station; on the middle: the glue spray station; on the right side: the charcoal coating station.

2.5. **Applicable codes and standards**

The cryogenic circuit of the cryopanels and manifolds are classified as an assembly of pressure equipment under the Pressure Equipment Directive 2014/68/EU (PED) and the classification of the assembly is SEP (Sound Engineering Practice) according to Article 4 paragraph 3 of the PED.
The complete cryopumps were designed according to EN 13445 and shall be manufactured according to this standard.
These Cryopumps are PIC-1 components following the definition of the French Order of 2012 because they provide a first confinement barrier.

3. Scope of work

The company will be responsible for the preparation of the manufacturing design (starting from Build-to-print input provided by F4E/IO), manufacturing, assembly, testing and delivery of the 3 cryopump systems (= 6 cryopumps in total).

The following activities will be part of the scope of work of the selected supplier:

- Setting up a Quality System under which all activities will be performed;
- Preparation of a Project and Quality Management Plan including all sub-contractors working on PIC;

- Manufacturing Design from the supplied build-to-print package and production of manufacturing drawings;
- Preparation of Manufacturing and Inspection Plans or Control Plans for each part;
- Preparation of all the required documentation, such as but not limited to drawings, Welding Documentation, material lists, dimensional controls, qualification reports and other manufacturing and testing documentation;
- Preparation of technical specifications for all components and subcomponents to be procured, contract management, subcontractors supervision, binding and contracting;
- Qualification of manufacturing and testing processes;
- Preparation of test plans, material lists and clean work plans;
- Performance of technical reviews, such as Manufacturing Readiness Reviews (MRR);
- Procurement of raw material and off-the-shelf components (except for those free issued by F4E);
- Preparation of all material certificates with full traceability;
- Manufacturing and testing of single parts and components of the cryopumps;
- Performance of quality assurance and qualification of processes, such as but not limited to electro and chemical polishing, blackening, pipe expansion, charcoal coating;
- Assembly of the cryopumps;
- Inspection and testing of the cryopumps and their components, such as but not limited to visual and dimensional checks, pressure tests, leak tests, thermal cycling tests, cold tests;
- All the necessary tooling, equipment and personnel qualifications for inspection and testing;
- Follow up and tracing of all manufacturing and welding activities in the Manufacturing and Inspection Plans;
- Management and supervision of all sub-contractors and suppliers;
- Supply, testing and integration of temperature sensors assembly;
- Supervision and reporting of all tests to be performed, including drafting and review of test reports;
- Follow up, management and supervision of all subcontractors and suppliers;
- Design, manufacture and testing of the manufacturing and assembly tools;
- Design, manufacture and testing of transport frames for each cryopump;
- Cleaning, inerting, packing, transport and delivery of the 3 cryopump systems and all other associated components, spare parts and tools to the ITER site in Cadarache, France;
- Production of a complete Manufacturing File for each cryopump ;
- Activities for certification and qualification of procedures and processes;
- Project management activities such as planning, reporting, configuration management, risk management, documentation management, sub-contractors management, organizing, attending and minuting proceedings of meetings;
- Any necessary travel and visits;

The supplier shall deliver the following:

- 4 HNB CP, each on their own transport frame with connection flanges.
- 2 DNB CP, on its own transport frame. Each half cryopump shall include its own connection flange.
- 6 Helicoflex seals for the cryopump flange (S/N);
- 6 Helicoflex seals for the BLV flange (S/N);
- 6 Helicoflex seals for the electrical feedthrough (S/N);

- The necessary screws for the flanges described above, including the screws needed for installing the connection flange to the vacuum flange and to the BLV;
- 1 electrical cubicle;
- 2 spare pumping sections:
- Spare 4 K cryopanels, 80 K TRS and Helicoflex seals.
- Manufacturing and assembly tools required.

4. F4E MARKET SURVEY

To establish an optimum contract strategy, F4E needs to develop its understanding of the market with a comprehensive list of possible EU suppliers interested in the cryopumps manufacturing.

In the frame of the market survey, interested suppliers are invited to submit information. This information will be used by F4E and IO and will not be communicated to other parties.
Further exchanges with the survey respondents will be organized (video-conference or face-to-face).

Interested entities can answer to the survey here:
https://ec.europa.eu/eusurvey/runner/ITER_NEUTRAL_BEAM_CRYOPUMPS