DESIGN OF THE ESS SPOKE CRYOMODULE

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Abstract

Part of the future European Spallation Source will consist in a superconducting linac containing a Spoke section. For prototyping purpose, a Spoke cryomodule is being designed and will be operated at nominal operation conditions by 2015. The current design of this device is presented.

INTRODUCTION

The European Spallation Source (ESS) project brings together 17 European countries to develop the world's most powerful neutron source feeding multidisplinary researches. The superconducting part of the linear accelerator consists in 59 cryomodules housing different superconducting radiofrequency (SRF) resonators among which 28 paired β = 0.5 352.2 MHz SRF niobium double Spoke cavities, held at 2K in a saturated helium bath. It will be the first section integrating double Spoke cavities in an operating linac. Parameters of the ESS layout are detailed in [1] and are now being optimized to meet the cost objectives. The prototyping phase of the project is under progress and will provide key elements to be tested under nominal operation conditions. A prototype Spoke cryomodule with two cavities [2] equipped with their cold tuning systems [3] and 300 kW RF power couplers [4] is hence being designed and will be constructed and tested at full power by the end of 2015 for the validation of all chosen technical solutions. Its assembly requires dedicated tooling and procedures in and out of an ISO 4 clean room. The design takes into account an industrial approach for the management of the fabrication costs. This prototype will have to guarantee an accelerating field of 8MV/m while optimizing the energy consumption and will intend to assess the maintenance operations issues.

For beam availability and mean time to repair (MTTR) considerations, the ESS superconducting linac is indeed a fully segmented machine: the beam pipe is the only connexion element between the independent cryostats which have their own insulation vacuum. They ended with two warm UHV gates valves delimiting the beam pipe and involving cold to warm transitions from the cold mass to the vacuum vessel. They require to be connected to an external cryogenic distribution or transfer line (CTL) by means of a jumpers and dedicated valve boxes.

CRYOGENIC OPERATION

SRF Spoke cavities are to be operating in a superfluid helium boiling bath at a 2 K temperature and a 31 mbar stable pressure. Taking into account the superconducting linac layout and the medium and high beta sections [5], the CTL provides a 4.5 K 3 bars helium distribution from the cryoplant for cool-down and nominal operations of the equipped cavities and of the RF power couplers. Two helium return lines, at 1.05 bar and 31 mbar, close the cold mass cooling circuit. For each cryomodule, a valve box ensures the distribution of the cryofluids. Connected on one side to the CTL and on the other to the cryomodule via a jumper, the valve box is equipped with a vacuum barrier placed on the tunnel side to enable the disconnection of the cryomodule without warming-up a long section of the linac. Superfuid helium is produced at each cryomodule location by use of a subcooler heat exchanger and an isenthalpic expansion Joule-Thomson valve placed within the jumper. It is then collected into a 63 mm i.d. biphasic pipe and redistributed through the top port of the cavity helium tank for its total filling. The total filling of the cavities tanks is ensured by the measure and the regulation of the level of the superfuid helium inside the biphasic pipe collector by use of a double wired superconductive gauge. In normal operation, the biphasic pipe also insures the collection of the pumped saturated vapours and, in the worst accident case of a beam vacuum break associated with an air entry into the beam pipe, the brutal evacuation of warmer vapours towards the burst disk. The single windowed coupler is connected to the cavity by use of a double-wall tube. Heat interception of the conductive heat from the ambient temperature and evacuation of the RF thermal dissipations is achieved by a supercritical helium circulation achieved within three parallel 1.5 x 2 mm² channels inserted helicoidally along the double-wall tube. They allow to distribute the required mass flow rate of about 0.015 g/s limiting the pressure drop induced by the laminar flow. The ceramic window and antenna of the coupler will be cooled at room temperature by use of two demineralised water circuits. They might be later connected into a single circuit for the serie Spoke cryomodules. It can be noted that for the Spoke prototype cryomodule, the magnetic shield will be actively cooled down, by use of the helium cooling line, before the transition of the SRF resonators into Meissner state.

The CTL also provides an additional 19.5 bars helium circuit for the operation of one thermal shield at an intermediate temperature range of 40 to 50 K. This coolant is also used efficiently at both ends of the cryomodule to achieve a heat interception on the cold to warm transitions linking the cold beam pipe to the warm UHV gate valves. It limits the static conductive heat load. The process and instrumentation diagram (PID) of the Spoke cryomodule is shown on Figure 1.

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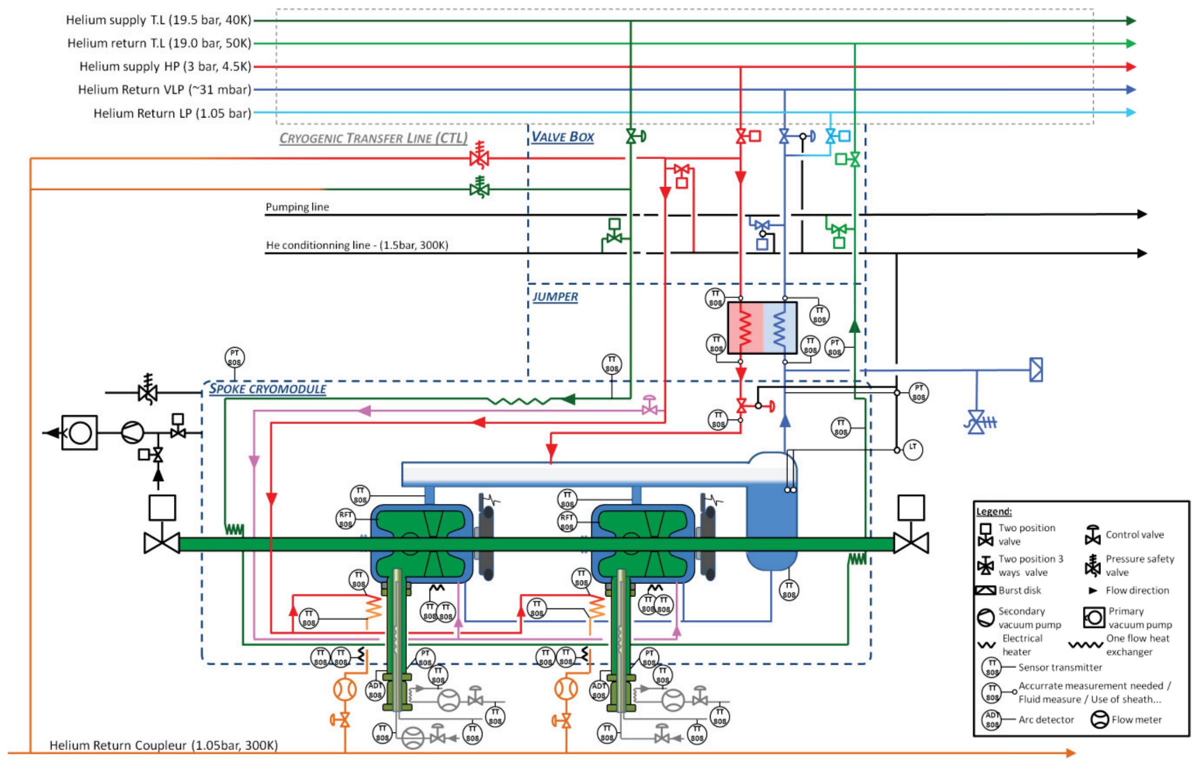

Figure 1: PID of the Spoke cryomodule.

The cryogenic distribution has been sized using the heat loads estimated for the static (cryostat and cold mass at nominal temperatures) and dynamic conditions (nominal temperatures, beam and RF additional dissipations). The cool-down times considered are of 4 hours for the thermal and magnetic shields, and 8 hours for the cold mass. This ensure sufficient margin for a full day time cooling. The estimates have been updated and refined along the design progress. As an example, Figure 2 shows a numerical simulation of the conducto-radiative heat transfer in one cold to warm transition for the design of the active heat interception yielding the involved heat loads on the 40 and 2 K levels.

Static heat loads are given in Table 1. Dynamic loading induces by RF and beam dissipations brings additional 4 W onto the superfluid helium bath and about 0.015 g/s of liquefaction power for one coupler cooling.

Table 1: Static Heat Loads

Component	**Heat loads**	**@ 40 K (W)**	**@ 2 K (W)**
Thermal radiation		10.0	0.5
Supporting system (rods)		4.0	0.2
Cold to warm transitions (2 items)		0.8	0.9
RF power couplers (2 items)		-	2.0
Cryogenic distribution		3.0	1
Safety equipment		4.1	0.75
Instrumentation		8.0	0.2
Total of the static heat loads		**30.0**	**5.6**

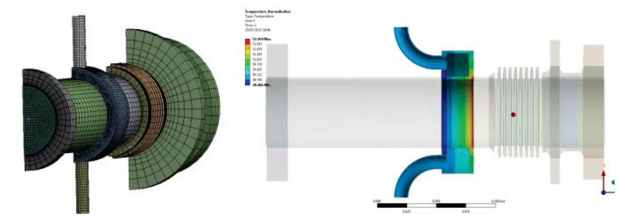

Figure 2: Numerical simulation of the conducto-radiative heat transfer in the cold to warm transition.

MECHANICAL DESIGN

A cut view of the Spoke cryomodule is shown on Figure 3. The two Spoke cavities are positioned along the axis of the vacuum vessel. Their cold tuning systems face towards the end caps of the cryomodule to facilitate the maintenance operations. Cold magnetic shields cover the cavities. The RF power couplers are positioned vertically, the antenna of the inner conductor standing up. The bi-phase pipe is positioned horizontally on the top of the cavities. The cold mass is surrounded by the thermal shield. Two control valves required for the cryogenic process are positioned vertically: the cooling valve and the JT valve.

From one UHV gate valve to the other, the total length of the cryomodule is of 2.86 m. The internal diameter of the vacuum vessel is 1.288 m and results from the consideration of the coupler length imposed by the RF power propagation in nominal operations and during the conditioning phase. The vacuum vessel is thus a rigid cylinder with a 6 mm thickness, ending with two removable dish caps and withstanding the static and buckling loading from the ambient pressure. Inducing small deformations during the vacuum-pressure cycles, it is used to support directly the cold mass expecting small misalignment.

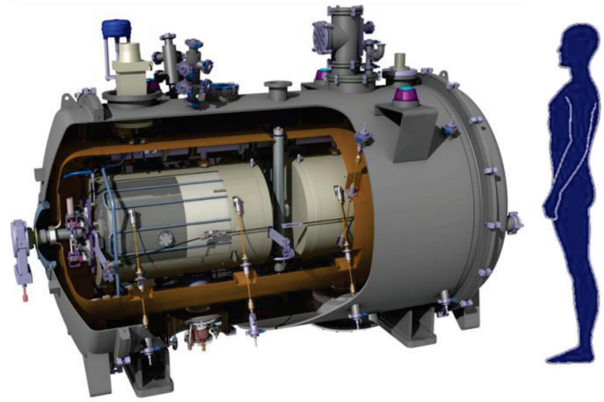

Figure 3: The Spoke cryomodule.

This support is ensured by means of antagonist rods fixed on the helium tank of the cavity. Rods antagonism increases the length of the conductive thermal path and reduces the stress generated by the helium tank thermal contraction by converting the tensile force into a deflexion moment. 8 radial rods are positioned in two vertical planes at both ends of each cavity. Within the horizontal plane of the cryomodule, 4 rods link the cavities to the vacuum vessel and two invar rods connect them mutually. This set of rods enables: (i) the positioning of the two equipped Spoke cavities one from each other and relatively to the vacuum vessel; (ii) blocks all freedom degrees of the cold mass keeping the connection of the RF power couplers to the cavities as two fixed points. The 8 radial rods are each originally designed in an assembly of two parts (see Fig. 4): an inner rod links the cavity helium tank to the thermal shield maintaining the shield during the cryostating phase; the outer rod is connected after cryostating to the inner one and positions the cold mass and the shield into the vacuum vessel. Connection of this outer threaded rod to the vacuum vessel is carried out by use of a bolt supporting on spherical washers. This experienced connection [6] allows the correction of the positioning of the cold mass at any time: under effective vacuum in the vessel or/and at cryogenic conditions.

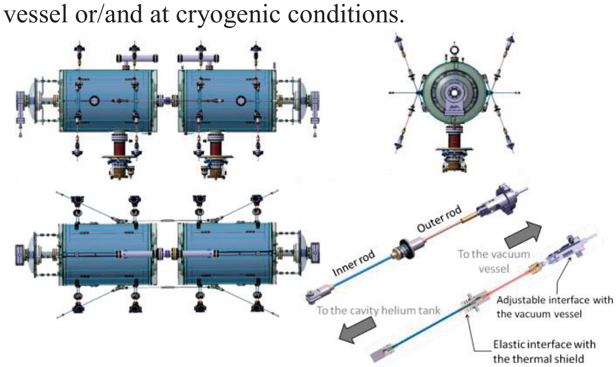

Figure 4: Cavities supporting and positioning system. Detail of a radial rod is given.

The thermal shield is made of a 2.35 m long cylinder with a 0.924 m diameter and ending with two dish caps, all covered with 30 layers of MLI. The supercritical helium, at a mean pressure of 19.5 bars, flows into a 10 mm i.d. aluminium pipe going back and forth two times along the cylinder. Its specific cross-section profile enables a continuous welding onto the 2 mm thick aluminium sheets of the cylinder. The consequential thermal contact length of about 11 m smoothes the temperature field of the thin shield. On Figure 5 is shown the temperature field resulting from the numerical simulation of the shield at a nominal stationary state. Radiant and conductive heat transfers are taken into account and the helium flow is modelled with one-dimensional elements computing the convective heat transfer coefficient at the fluid solid interface. This model will be use to assess the thermal gradients during transient states and the resulting mechanical stresses.

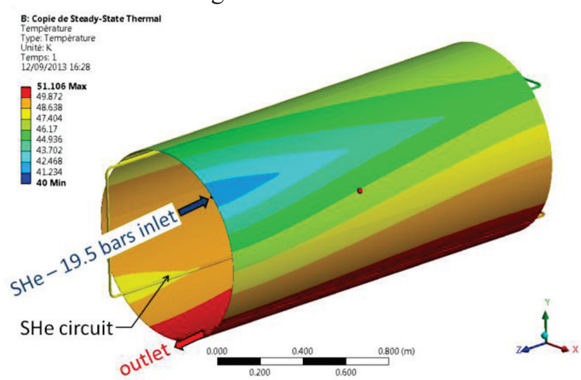

Figure 5: Numerical simulation of the temperature field of the thermal shield. Supercritical helium circulation is thermodynamically modelled.

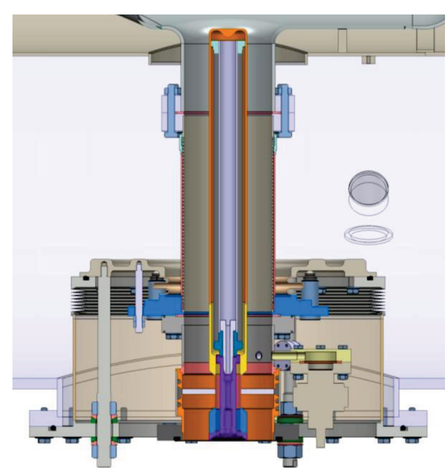

Figure 6: Interface between the coupler double-wall tube and the vacuum vessel.

The double-wall tubes of the RF power couplers are interfaced onto the bottom of the vacuum vessel. This interface (see Figure 6) is designed on the one hand to alleviate the offset and/or deviation of the coupler double-wall tube in regard of the vacuum vessel port. It is induced by the set of tolerances of the cavity-coupler

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assembly of the vacuum vessel and of the cavity positioning inside the vessel. The misalignment alleviation is done by the integration of an edge welded bellow and a set of screws mounted on spherical washers. On the other hand, it lightens the mechanical forces applied on the coupler port of the cavity along the assembly process of the cryomodule or due to the thermal contraction of the double-wall tube when cooled-down. This is achieved by use of an hydrodynamically formed bellow and a set of adjustable compressed springs.

CRYOMODULE ASSEMBLY

The string of cavities will be assembled inside the clean room of IPNO. At the exit of this facility, it might consist in two cavities linked together by a bellow and equipped with their RF power couplers. The two cold to warm transitions are mounted and the beam pipe is closed by the two UHV gate valves. Two small dish caps are put onto the string of cavities and take part in the vacuum vessel closure: they enable to escape the gate valves.

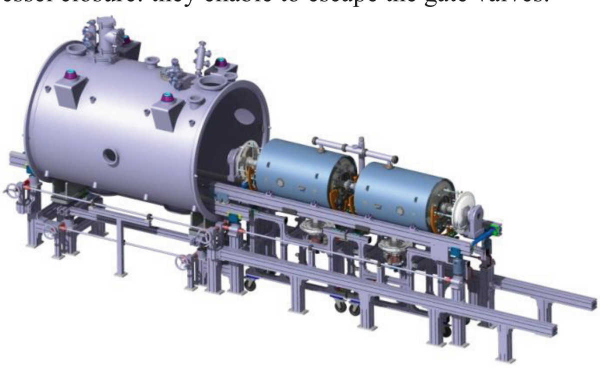

Figure 7: Assembly and cryostating tooling.

The cavities are equipped with their magnetic shied. The vacuum vessel and the string of cavities are then positioned onto the cryostating tooling (see Figure 7). The string of cavities is fully dressed before its insertion into the vacuum vessel. The mounting of all critical components is made easier by benefiting from the possible space around the tooling. Thus, cold tuning systems, instrumentation (including the positioning diagnostics or the heat intercept blocks), and cryogenic distribution are assembled. The thermal shield is positioned onto the string of cavities by use of the inner part of the supporting rods. When the string of cavities is dressed, it is translated into the vacuum vessel. The outer part of the supporting rods are fixed onto the inner part and connected to the vacuum vessel. The weight of the dressed string of cavities is then transferred onto the vacuum vessel. Two control valves are mounted and soldered to the cryogenic distribution. The two coupler double-wall tubes are sealed onto the vacuum vessel by use of the dedicated interface.

The alignment of the cavities is then carried out. Each cavity is equipped with four referenced spherical targets, offsetting the mechanical axis of the cavity. Theodolites, or laser tracker are positioned outside the vacuum vessel for the measurement of the cavities positions. The small aspect ratio of the vacuum vessel eases this measure. The adjustment of the cavities positions is performed by use of the supporting rods at their vacuum vessel interface. Once the alignment is done, the cryomodule is closed. Positions of the cavities might slightly be affected by the pressure and temperature changes within the vacuum vessel. Those changes are being now estimated to be taken into account in the alignment procedure. Nevertheless, the prototype Spoke cryomodule is equipped with an optical diagnostic to measure the position of each cavity at nominal operation conditions (cavities at cryogenic temperature; vacuum in the cryomodule). It relies on the two optical targets lenses mounted onto each cavity. Four windows are integrated onto the two dish caps of the vacuum vessel allowing the fiducial alignment diagnostic by pointing to the cavities lenses. Then, corrections might be made by use of the supporting and positioning system without warming-up the cryomodule.

CONCLUSIVE PERSPECTIVES

A Spoke cryomodule is being designed as a prototype for the future ESS superconducting linac. Mechanical studies will be finalized by the end of this year. Some components have already been ordered and will be tested by the beginning of 2014. Assembly and first test at low RF power of the complete cryomodule will be achieved by the end of 2014.

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