

ESS SPOKE CRYOMODULE AND TEST VALVE BOX

Denis Reynet, Sylvain Brault, Patxi Duthil, Matthieu Pierens, Patricia Duchesne, Guillaume Olry, Nicolas Gandolfo, Emmanuel Rampoux, Sébastien Bousson, IPNO, UMR 8608 CNRS/IN2P3 - Université de Paris Sud 15, rue G. Clémenceau, BP1, 91406 ORSAY cedex, France
Christine Darve, ESS Lund, Sweden

Abstract

The future European Spallation Source is based on a superconducting linac which includes a Spoke section. For prototyping purpose, a Spoke cryomodule and a valve box are being built and will be assembled by the end of 2015 and tested at full power. Design, fabrication and procurement of those components provide an insight of the series phases. The valve box will also be used for the test of the 13 series cryomodules.

INTRODUCTION

17 European countries are involved in the development of the European Spallation Source (ESS), a project for building the world's most powerful neutron source feeding multidisciplinary researches. This machine includes a linear accelerator based on superconducting radiofrequency (SRF) technologies [1]. Among 146 SRF resonators housed in 43 cryomodules, 26 paired $\beta = 0.5$ 352.2 MHz SRF niobium double Spoke cavities will be used for the first time in an operating linac. They will function at a temperature of about 2 K in a saturated superfluid helium bath within 13 cryomodules.

A prototype cryomodule containing two cavities, fully equipped, was designed [2] at IPNO and will be tested by the end of 2015 by use of a dedicated prototype valve box. All components of this cryomodule, among which the SRF cavities and the RF power couplers, were procured during the last two years. They were received at IPNO and tested. Among others, those test phases included assembly tasks, alignment using dedicated tooling, cryogenic tests in vertical cryostat, RF tests, etc. Beyond the consecutive validation or eventual modification of the pieces design, experience was gained concerning the procurement phase and the relating technical specifications and will be useful for the series.

The prototype valve box is now being constructed to achieve two main objectives. On the one hand it is thought as a prototype valve box: it must validate the cryogenic operation of the prototype cryomodule as it would be on the linac; it might prove the legitimacy of the mechanical and thermal designs and, consecutively, the assembly procedure. This will be preliminary done at IPNO test stand. On the other hand, this valve box will be used for the tests of all the series cryomodules at the FREIA test stand in Uppsala University. Those environments differ one from each other and are far from the linac cryogenic installations. The valve box hence requires a very versatile configuration.

THE SPOKE CRYOMODULE PROTOTYPE



Figure 1: The Spoke cryomodule prototype.

The Spoke cryomodule (cf. Figure 1) holds two SRF double Spoke cavities equipped with two RF power couplers, positioned vertically with the antennas standing up and two cold tuning systems. This cold mass is covered by MLI blankets manufactured by Jehier and made of 10 layers of reflective aluminised PET films (Mylar) separated by polyesters. The direct contact between the cold mass and the MLI blankets might be useful in case of loss of insulation vacuum by preventing the air condensation directly on the metallic surfaces of the cavities liquid helium tanks, smoothing the consecutive pressure increase within the cryogenic distribution. Each cavity is entirely enclosed in a double shield consisting in an inner and an outer shell made of Cryophy® and manufactured by Mecamagnetic. A copper serpentine allows for the cooling down of the magnetic shield expecting therefore to reach a large magnetic permeability before the Meissner transition of the cavity. To complete the tests of the Spoke cavities [3], they were equipped with their MLI blankets and their cold magnetic shield on a specific handling tool (cf. Figure 2).



Figure 2: Left: MLI on the cavity. Centre and right: actively cooled magnetic shield.

By use of a set of 22 rods, the cavities are positioned within the 1.288 m i.d. vacuum vessel manufactured by SDMS. Alignment corrections can be performed under vacuum and cryogenic conditions (i.e. when the cavities are cold). The alignment diagnostic is accomplished by use of 8 internal fiducials which can be optically targeted through a set of four windows installed on the vacuum vessel. 4 fiducials are mounted on each cavity and remain visible outside the thermal shield. Tests were achieved to verify the ability of determining the cavity axis from the fiducial measurements (cf. Figure 3).

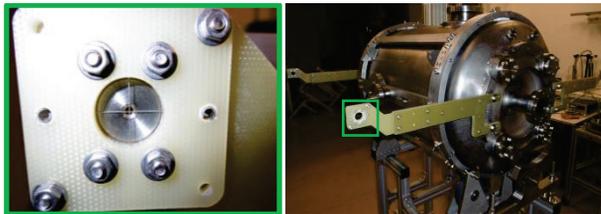


Figure 3: Optical fiducials mounted on the cavity.

The cryogenic bi-phase pipe is mounted on the top of the cavities to feed them with liquid HeII and to collect helium vapour resulting from the RF and the static heating. For assembly (and disassembly) reasons, not any cryogenic valve is implanted in this cryomodule but all are set into the valve box. The thermal shield was made of aluminium alloy 6082 by Sominex. When operated on the ESS linac, it is supplied by supercritical helium at a pressure of 19.5 bars and a temperature of 40 K. However, for the tests of this prototype, saturated nitrogen around the atmospheric pressure will instead be used. A thermal analysis was thus carried out to size and position the hydraulic cooling circuit, to determine the heat loads and the consecutive thermal field on the thermal shield for the use of both cryofluids (cf. Figure 4).

The design of this prototype Spoke cryomodule was hence achieved this year and all components were procured. Design and technical specifications of the components of this prototype cryomodule were established as originals for the coming phase of providing 13 series cryomodules, a task IPNO is in charge of. In that sense they might be fully compatible with the procurement of the series elements. Specifically, standards components were favoured when available; materials grades were chosen to comply easily with the European market; fabrication controls such as welding controls were defined and proposed as to be compliant with the ESS requirements.

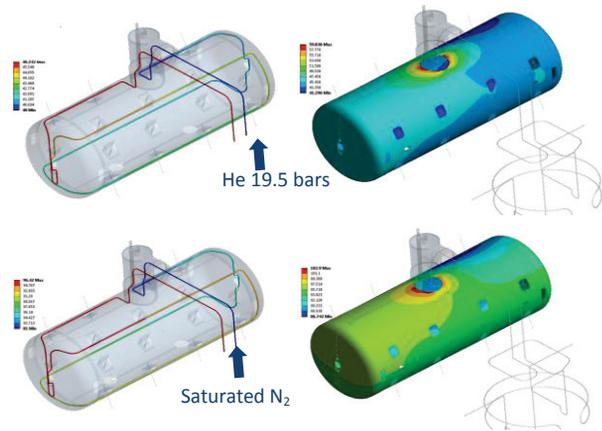


Figure 4: Thermal analysis of the cryomodule thermal shield. Top: ESS nominal operation; Bottom: prototype configuration.

Quality management was also settled during this prototyping phase. It obviously includes the management of engineering data (drawings, calculations, technical specifications, etc.) but also the life cycle analyses of each subpart of the cryomodule: SRF cavity, RF power coupler, cold tuning system and cryomodule. From those analyses, control, preparation or assembly procedures were identified, established, referenced, as were their corresponding reporting records. Assembly tests were accomplished to validate some dedicated tooling and procedures. As an example, a mock-up of the coupler was 3D printed to be used for the tests of the clean room tooling and for the validation of the vacuum vessel RF interface (cf. Figure 5).



Figure 5: 3D mock-up of the coupler mounted on the vacuum vessel interface.

Complete assembly of the Spoke cryomodule will be achieved by the end of this year 2015. The dressing and cryostating tooling was designed (cf. Figure 6) and is now being procured. It is used to dress the cavities at the exit of the clean room by mounting the magnetic and thermal shields and the cold tuning systems. To that purpose, full access to and around the cavities is provided. It also performs the insertion of the dressed cold mass into the vacuum vessel. One highlight of this tooling is that it avoids transferring the mass load of the string of cavities during cryostating in order to protect sensible elements from mechanical stresses, such as the bellow between the two cavities. Hence, during the cryostating phase, the vacuum vessel is translated around the dressed string of cavities which remains static. Final load transfer is achieved by interfacing the support rods onto the vacuum vessel and controlling their tensile loading.

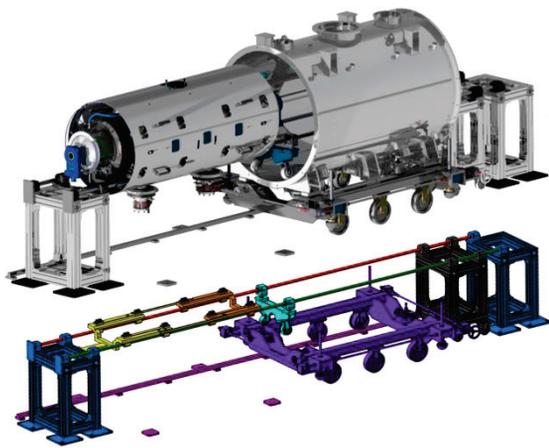


Figure 6: Spoke cryostating tooling. Top: cold mass and vacuum vessel ready for cryostating. Bottom: cinematically coloured assembly tooling.

CRYOGENIC ENVIRONMENT AND TEST VALVE BOX

A cryogenic jumper, mounted on the top of the vacuum vessel of the cryomodule, connects the cryogenic distribution to the valve box which manages the cryofluids. On the ESS machine, each cryomodule is fed by a dedicated valve box which is part of the Cryogenic Distribution System (CDS) that runs all along the linac. IPNO is responsible for the provision of 13 Spoke cryomodules for ESS and the CDS for the Spoke section which includes specifically 13 valve boxes. For the tests and qualifications of the prototype and series Spoke

cryomodules, a test valve box was designed this year and is now being manufactured. The prototype Spoke cryomodule will be assembled at IPNO, connected to its test valve box and cryogenic and low RF power tests will be performed. Those components will then be sent to Uppsala University in Sweden to be tested at full RF power within the new FREIA facility. All series Spoke cryomodules will then be qualified at Uppsala. Two objectives were considered for the design of the test valve box. First, it is seen as a prototype for the 13 series valves boxes. All linac cryogenic operating modes thus shall be integrated and the functionality of the cryogenic distribution will have to be validated. On a mechanical (or thermal) point of view, the test valve box shall validate the chosen technical solutions during the assembly phase and the cryogenic operations. Secondly, this test valve box will be connected to two cryogenic infrastructures, at Orsay and Uppsala, differing from the cryogenic distribution system of the ESS linac, which provides pressurized helium (at 3 bars and 4,5 K for the cold mass and 19.5 bars and 40 K for the thermal shields) from a cryoplant. Saturated helium and nitrogen at pressure ranging from 1.2 to 1.5 bars will instead be distributed from dewars for the initial tests at Orsay (the helium liquefier of the laboratory will also be involved) and from the FREIA liquefier via an interconnection cold box. The process and instrumentation diagram (PID) of the prototype Spoke cryomodule and its test valve box is shown on Figure 7. To comply with the availability of the linac and the radiation environment, all cryogenic valves are control valves and are all placed within the valve box.

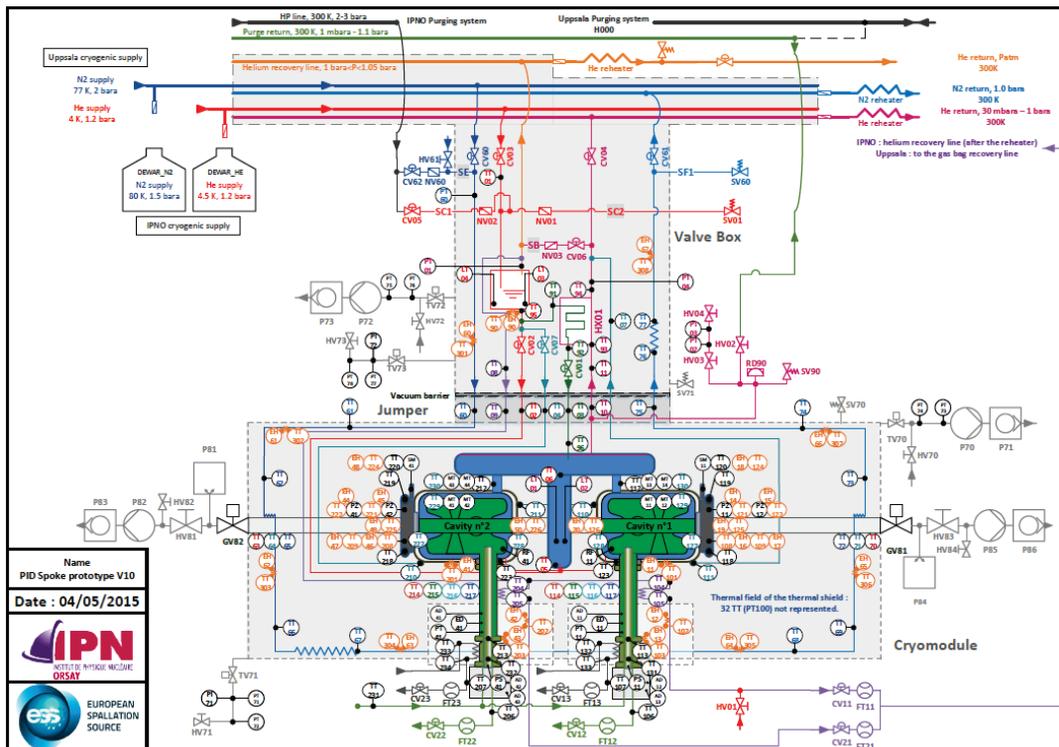


Figure 7: PID of the prototype Spoke cryomodule.

The use of saturated liquid helium in this test valve box involves integrating a phase separator. Superfluid helium is then produced from the saturated liquid helium as it would be from the pressurized liquid helium. Within a subcooler (He-He heat exchanger), it is isobarically cooled down to a maximum temperature of 2.2 K, benefiting from the enthalpy of the cold vapours circulating in a low pressure line which is used to pump the saturated helium bath of the cavities. Then it is isenthalpically expanded through a JT valve. The heat exchanger is now being fabricated by DATE. Pressure drop with the low pressure circuit is critical for the Spoke valve boxes as the Spoke section is far from the cryoplant of the ESS machine. IPNO being also responsible for the design of the elliptical cryomodule of the linac (see [3]), it is strongly involved in the cryogenic design of this section. It was hence decided to have a unique heat exchanger on both the Spoke and elliptical cryomodules. This heat exchanger is thus compliant with the maximum mass flow rates of both types of cryomodules (2.5 and 4.5 g/s respectively for the Spoke and elliptical cryomodules) and with the use of saturated or pressurized helium (prototype and series cases). Consequences of this choice are the use of a unique type of component for the whole linac and the reduction of the pressure drops by oversizing the heat exchanger for the Spoke section: about 20 Pa are thus expected for both the prototype and series cases.

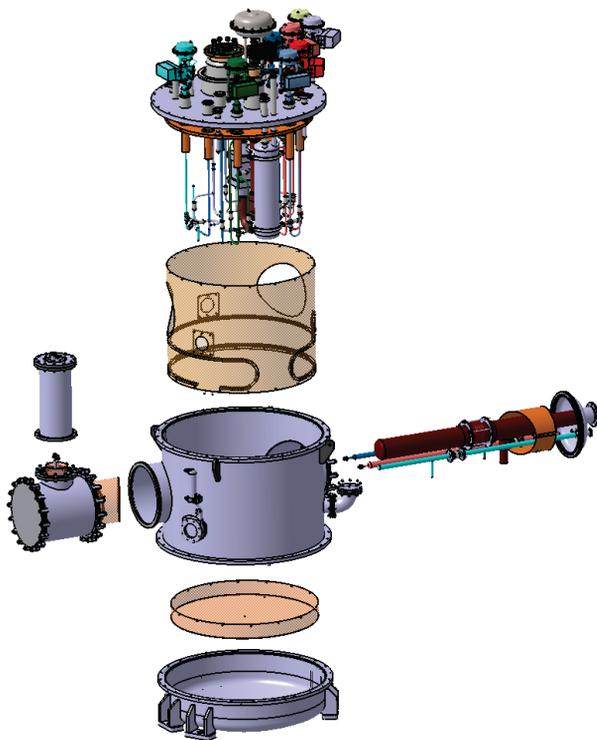


Figure 8: The test valve box for the Spoke cryomodule.

Figure 8 presents the prototype valve box and its conceptual assembly. All cryogenic components such as control valves, phase separator, helium heat exchanger, and circuitries are assembled to the top dish of the valve

box. For prototyping reasons, cryogenic interfaces to the test facilities for the supply of liquids and collection of exhaust vapours are implemented into a horizontal circuitry simulating the cryogenic distribution line which connects the valve boxes into the linac tunnel. It will be assembled onto the valve box once the central parts of the thermal shield and of the vacuum vessel will be mounted. All welds connecting this horizontal circuitry to the rest of the pipes will be assessable from the bottom of the valve box.

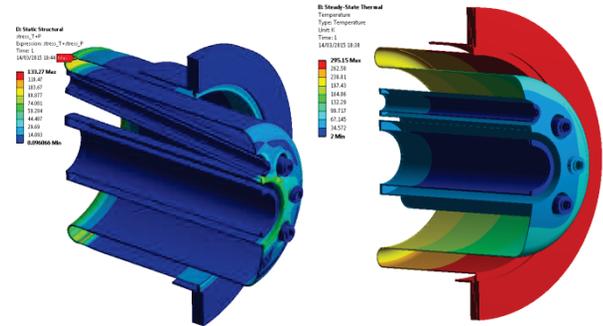


Figure 9: Vacuum barrier integrated onto the valve box.

Table 1: Static Heat Loads

Component	Prototype		Series	
	@80 K (W)	@2 K (W)	@50 K (W)	@2 K (W)
C Thermal radiation	14.7	0.4	14.7	0.4
R Supporting system	5.7	2.3	6.2	2.3
Y 2 cold-warm transitions	0.1	2.0	1.0	1.0
M 2 RF power couplers	-	3.5	-	3.5
O Cryo distribution	-	0.6	-	0.6
U Instrumentation	2.0	1.4	1.0	1.0
L Total	22.5	10.2	22.9	8.8
V Thermal radiation	14.3	0.1	14.3	0.1
A Supporting system	29.2	1.0	30.8	1
L Cryogenic valves	4.8	2.2	5.4	1.9
V Vacuum barrier	7	1.0	7.4	0.5
E Cryo distribution	0.5	0.2	0.5	0.2
B Instrumentation	0.8	1.0	0.8	0.6
O Total	56.6	5.5	59.2	4.3

Insulation vacuum of the cryomodule is separated from the one of the valve box (and from the cryogenic distribution system of the ESS linac) by use of a vacuum barrier. It allows for disconnecting one cryomodule from the linac while maintaining the other cryomodules and the cryogenic distribution system in a cryogenic environment. This vacuum barrier is placed at the basis of the cryogenic

jumper. It is fully integrated to the top dish of the valve box. This vacuum barrier is a fixed point for all the cryogenic pipes going into the cryogenic jumper. It was thus designed as a rigid structure, made of shell and tubes, withstanding a pressure difference of 2 bars across its sides that may result from an overpressure caused by the break of a cryogenic pipe, whether in the cryomodule or in the valve box (cf. Figure 9). Thermal aspects were also considered to minimize the heat loads, specifically onto the low pressure line which returns the pumped cold vapours to the helium subcooler. By adding a delicate heat intercept with the thermal shield circuit, 0.25 W at 2 K and 7.5 W at 50 K are foreseen for the series case.

Static heat loads for the cryomodule and the valve box are given in Table 1 for both the prototype and series cases. Dynamic loading induced by RF and beam dissipations brings additional 4 W and 1.5 W onto the superfluid helium bath. 0.15 g/s of liquefaction power is needed to cool the outer conductor of the two couplers.

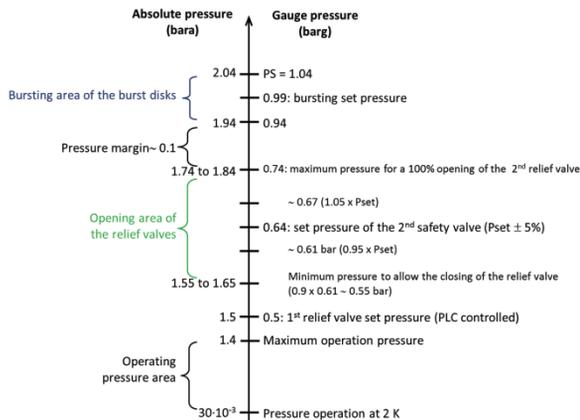


Figure 10: Operating pressure scale of the ESS cavities.

Design, construction and operation of the Spoke cryomodule and valve box will comply with the safety regulation of the European Pressure Equipment Directive (PED 97/23/EC) and with Swedish national requirements (ordinance AFS 2005:2). To simplify the commissioning of the cryomodules of the linac, it was decided that the cavities and their helium tanks will be classified in the article 3.3 of the PED. Based on the nature, on the pressure and volume of the contained fluid, this is the lowest category of pressure equipment, inducing less restricting controls and tests. The consequence is that the Service Pressure PS of the cavities (their maximum permanent allowable internal pressure) is limited to 1.04 barg. Safety devices protecting the cryogenic distribution (and the cavities) from overpressure include: a DN 100 burst disk in the case of a major incident (e.g. the loss of beam vacuum); a safety valve which protects the burst disk in case of operational faults. During the operation of the ESS linac and specifically when cooling down, the pressure at the inlet of the compressors of the cryoplant can reach a maximum of 1.4 bara. It then states the maximum pressure within the low pressure line used to pump the helium bath of the cavities. All safety devices thus should work between this pressure and PS, letting

slight margins for their safe operation. Moreover, as the safety valve is connected to a helium recovery line, its outlet pressure ranges from the (fluctuating) atmospheric pressure to 1.1 bara. To be conservative and keep sufficient working pressure margin, an additional safety valve is added in the form of a PLC controlled valve. In parallel with the passive safety valve, it will open at an absolute pressure of 1.5 bara. The pressure scale for the operation of the safety devices of the Spoke cryomodules (as well as for the elliptical cryomodules) is presented on Figure 10.

CONCLUSIVE PERSPECTIVES

A Spoke cryomodule was designed as a prototype for the future ESS superconducting linac. All components were procured according to quality insurance procedures which will also be used for the series. Control procedures and preliminary assembly or preparation phases were identified with life cycle analyses of cryomodules sub-parts and then experienced. A test valve box was also designed and is now manufactured. Foreseen as a prototype of the 13 series valve boxes, it will be installed at IPNO as well as in FREIA facilities at Uppsala. Although connected to cryogenic environments differing from the linac one, it will process similar cryogenic conditions for the Spoke cryomodules operations. Assembly of the Spoke cryomodule and valve box prototypes (cf. Figure 11) will be achieved by the end of this year 2015 for performing the first tests at Orsay.



Figure 11: Prototype Spoke cryomodule and its test valve box.

REFERENCES

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