The ESS Spoke cryomodule and its test valve box

P. Duthil1, M. Pierens1, D. Reynet1, S. Brault1, F. Chatelet1, P. Duchesne1, G. Olry1, N. Gandolfo1, S. Bousson1, C. Darve2, N. Ellias2, F. Fydrych2.
1 Institut de Physique Nucléaire d'Orsay, IPNO CNRS/IN2P3–Univ. Paris Sud, France
2 European Spallation Source, Lund, Sweden
duthil@ipno.in2p3.fr

Abstract. The European Spallation Source project aims at being the most powerful neutron source feeding multidisplinary researches. Based on superconducting radiofrequency technologies, the linear accelerator will operate for the first time a 56 meter long section of niobium double Spoke cavities. Paired in 13 cryomodules, each cavity will generate an accelerating pulsed field of 9MV/m. A prototype cryomodule housing two superconducting Spoke cavities and their RF power couplers is now being fabricated and assembled. It provides the cryogenic environment for their operation in a 2K saturated superfluid helium bath: a 50 K thermal shield, a cold magnetic shield, and integrates all the interfaces necessary to be operational within the linac machine. This prototype will be tested in 2016 at IPNO site and then at Uppsala university FREIA facilities. A valve box was designed to take into account the specific features of this prototype cryomodule and of both test sites. This valve box is also considered as a prototype of the cryogenic distribution of the linac Spoke section. This element will then be used for the tests of the series cryomodules.

1. Introduction

1.1. ESS context
The European Spallation Source (ESS) will be a multidisciplinary research laboratory taking advantage of the most powerful neutrons source. This machine can be compared to a large microscope for which neutrons instead of photons are used to study the structure and behaviour of matter. Under nominal operations, ESS will be 30 times more powerful than present apparatus giving new opportunities to researchers in several fields such as health, biology, environment, climate, energy, transportation and cultural patrimony. ESS is also an intergovernmental research project which building started in 2014 in Lund, a city located in South of Sweden. 17 european countries contribute to the design and the future exploitation of this large instrument that will be fully operational by 2025.

1.2. The ESS machine
The ESS machine [1] includes a source producing protons which are then accelerated in a linear particles accelerator (LINAC). Once having gained enough energy, protons hit a tungsten target to produce fast neutrons which are moderated before feeding multiple physics experiment lines. The LINAC will accelerate protons up to an energy of 2 GeV. It operates in a pulsed mode with a pulse length of 2.86 ms and a pulse repetition frequency of 14 Hz. Having a peak current of 62.5 mA, the average power of the beam is 5 MW. Specifically, the acceleration chain integrates a 312 m long
section based on superconducting radiofrequency (SRF) cavities: the superconducting LINAC which allows to save 95% of energy compared with normal conducting solutions. It contains (ordered by proton energy):

- 26 double Spoke type cavities with $\beta = 0.50$ and paired in 13 cryomodules;
- 36 elliptical 6-cell type cavities with $\beta = 0.67$ and grouped by 4 within 9 cryomodules;
- 84 elliptical 5-cell type cavities with $\beta = 0.86$ and grouped by 4 within 21 cryomodules.

$\beta$ is the ratio of the speed of a particle (within the accelerating device) to the speed of light. Those cavities are supplied with an electromagnetic wave by means of RF power couplers and act as electromagnetic resonators to provide a sufficient accelerating electrostatic field phased in time with the particles bunches traveling within the high vacuum of the beam pipe.

The accelerator cryoplant (ACCP) produces pressurized liquid or supercritical helium which is distributed all along the LINAC via the Cryogenic Distribution System (CDS) to cool the SRF cavities and maintain them in an efficient cryogenic environment. Part of this CDS is the Cryogenic Distribution Line (CDL) which runs aside the LINAC. It is a multichannel cryoline which includes two cold circuits: a circuit dedicated to the cold mass, with a temperature ranging from 4.0 to 5.2 K; another one for the thermal shields with $40 < T < 53$ K. Each of the CDL 43 valve boxes is connected to one cryomodule and manages the cryogenic processes [2]. From the ACCP, cold helium flows from the high beta cryomodules to the lower beta ones. An end-box is placed at the end of the CDS, near the first Spoke cryomodule which is located at the opposite side of the accelerator cryoplant. It aims at reversing the exceeding helium flows and to partially smooth heat loads fluctuations on the cryoplant.

1.3. A major component of the linear accelerator: the cryomodule and its valve box

A cryomodule is an elementary brick of the ESS superconducting LINAC [3]. It contains several accelerating radiofrequency resonators (cavities) made of bulk niobium. 43 cryomodules are laid and assembled end to end to compose a long string: the ESS superconducting LINAC.

The first function of a cryomodule is to provide the cryogenic environment required to operate those resonators with a large quality factor. For ESS, they are thus maintained at a temperature of about 2 K in a saturated superfluid helium bath. Advantages of this direct cooling method is (i) the large heat transfer coefficient helping to keep a constant temperature on the cavity surface and (ii) the fine control of pressure limiting fluctuations which might affect the performances of the resonators by inducing slight mechanical deformations. Preventing heat flowing to the cavities is also inherent to this functionality and the cryomodule consecutively acts as a horizontal cryostat. The SRF cavities are protected by one or several heat shields, protecting them from thermal radiation, and placed inside the vacuum vessel preventing from convection and gas conduction. To provide this cryogenic environment, the cryomodule implements an internal cryogenic distribution handling several cryofluids at different temperatures, pressures and states.

The cryomodule provides the support of several SRF cavities, their alignment with respect to the beam axis and ensures the conservation of this alignment during the temperature and pressure cycles of the machine. This mechanical functionality extends to the support and the alignment of the cryomodule itself with respect to other cryomodules forming the LINAC, to the tunnel it is placed in and to other components such as beam diagnostics, etc.

To obtain a large quality factor ($>10^5$), SRF resonators must be sheltered from any magnetic field: from the Earth magnetic field and from possible local sources. Hence, the cryomodule integrates one or several magnetic shields operating at room or at colder temperature, depending on the magnetic permeability of the shield material.

Lastly, the cryomodule integrates all interfaces to the RF distribution, the cryogenic distribution, the tunnel infrastructures, the vacuum pumping systems and the diagnostics (instrumentation).

The cryogenic process of the cryomodule is managed by the valve box. It contains all process equipment (valves...) necessary for the control and regulation of the cryofluids flowing into or out of the cryomodule. It takes into account the process variables measured within the cryomodule (helium level, pressure) [4]. It might also integrate additional components to change cryofluids temperature
(heat exchanger), pressure (throttle valve) and phase state (combination of both). The cryogenic connection between the valve box and the cryomodule is done with a cryogenic jumper. For ESS, a vacuum barrier is located within this connection, on the valve box side, and it is thus possible to disconnect the cryomodule without affecting the vacuum inside the valve box and the cryodistribution. The cryomodule might also be disconnected while the valve box being cold.

2. The Spoke section of the ESS linac

Considering the protons travelling from the source to the target, the Spoke section (see figure 1) is the first superconducting part of the ESS LINAC. It consists in 13 cryomodules containing 26 paired cavities and the Spoke Cryogenic Distribution System (CDS): the cryogenic distribution line with 13 valve boxes and four auxiliary process lines. Two are for helium recovery purposes during partial cool-downs or from safety valves; two are for purging, flushing or warming-up the cryomodules. Considering cold helium flowing from the ACCP, the Spoke CDS is placed after the CDS for the elliptical cryomodules section. The end box (termination box) is hence part of the Spoke section. IPNO is in charge of the design, supply and installation of the Spoke section within the ESS tunnel. Specifically, installation of the CDS for the Spoke section shall begin by mid 2017.

For both the CDS for the Spoke and the Elliptical sections, helium pressurized at 3 bara and supplied by the ACCP flows via the CDL to all valve boxes at a temperature ranging from 4.0 to 5.2 K. This supplied helium is destined to cool down the cold mass (SRF cavities) within the cryomodules and to fill-in the cavities helium tanks with saturated helium at about atmospheric pressure for the initial filling or for a 4 K stand-by operating mode of the LINAC. Part of this helium is also used in the heat interception from 5 to 300 K along the RF power couplers which connect the cavities to the room environment. Supercritical helium at a pressure ranging from 10 bara to 20 bara also flows from the ACCP via the CDL at a temperature ranging from 40 to 53 K for the cool down and maintain of a unique level of thermal shields (TS) within the cryomodules and CDS. Those two circuits are the main cold process lines (so-called headers). At the valve boxes locations, branches lines connect the main lines to the cryomodule circuitry. Superfluid helium is produced locally by isobaric subcooling down to 2.2 K and isenthalpic expansion down to about 30 mbar: inside the valve boxes for the Spoke CDS, or inside the cryomodules for the Elliptical section. Because cavities are cooled in a saturated superfluid helium bath, cold vapours produced in the cryomodules (or during isenthalpic expansion) are pumped out into the vapour low-pressure (VLP) line of the CDL and directed to the cold compressors of the ACCP. The VLP line is the largest of the CDS with a diameter ranging from 160 mm for the Spoke section to 250 mm for the Elliptical section.

Table 1. Estimated maximum flow rates in the CDS of the Spoke LINAC.

| Line                          | At the interface with the CDS for the Elliptical section (g/s) | In the end box (g/s) | In the valve box (g/s) |
|-------------------------------|---------------------------------------------------------------|----------------------|-----------------------|
| Helium supply line            | 27.1                                                          | 12.3                 | 1.14 (0.98 for cavities and 0.16 for couplers) |
| VLP line                      | 25.0                                                          | 12.3                 | 0.98                  |
| TS supply line                | 20.0                                                          | 2.9                  | 1.32                  |
| TS return line                | 20.0                                                          | 2.9                  | 1.32                  |
In nominal operation condition, the linac requires a cooling capacity of 2.5 kW at 2 K and 8.1 kW at 50 K. 6.8 g/s of liquefaction power is also required for the cooling of all RF power couplers. The needed mass flow rate for the helium supply line is estimated to be of 14.8 g/s for the 13 Spoke cryomodules and valves boxes (see Table 1). 12.3 g/s will flow to the end box and will be reversed to the ACCP. 17.2 g/s is needed for the thermal shields cooling of the 13 cryomodules and valves boxes. The maximum allowable heat loads budget for the CDS of the Spoke section is indicated in Table 2.

Table 2. Maximum allowable heat loads for the CDS of the Spoke linac section.

| Component        | Power (W) |
|------------------|-----------|
| Helium supply line | 33.1      |
| VLP line         | 68.8      |
| Total for cold He circuit | 102 |
| TS supply line   | 78.7      |
| TS return line   | 581       |
| Total for TS circuit | 660 |

Prototyping the Spoke linac section involves constructing a prototype Spoke cryomodule and its prototype valve box. IPNO is in charge of the design, construction and part of the tests of those prototypes. RF tests will be performed at low power at IPNO site. Then, the prototype cryomodule and prototype valve box will be installed at Uppsala university (in Sweden) to be tested at full RF power in the FREIA facility [5]. Cryogenic operations will be fully tested at both sites. All parts of the prototype Spoke cryomodule are already fabricated and it is now being assembled. Preliminary tests were carried out on different components. Those experiments are dedicated to verify the functionalities of the components (mechanical, RF, cryogenic, etc) but also the peripheral components (tooling) and the procedures (cleaning, assembly, etc).

3. Cryogenics of the Spoke cryomodule

3.1. Cold mass

The Spoke cryomodule [6] is pictured on figure 2. It contains two double-Spoke bulk niobium cavities contained in titanium grade 2 helium tanks. Advantages of this type of cavities are: a stiff geometric configuration making those cavities less sensitive to pressure fluctuations; they can achieve low Lorentz detuning factor, are less sensitive to High Order Mode (HOM) trapping because they have frequency modes well separated, making them robust to beam instabilities. Those cavities have to produce the ESS nominal accelerating field of 9 MV/m, which was very challenging in 2009 at the time of the accelerator design update but since then repeatedly obtained with the first three prototypes [3]. With a quality factor target of $2 \cdot 10^9$, the averaged heat power dissipated by one cavity in the 2 K helium bath is estimated to be 2.5 W. Adding the conservative assumption retained by ESS of 0.5 W/m of beam losses, the dynamic (induced by RF) heat loads budget for the 2.86 m long ESS Spoke cryomodule is 6.5 W.

Figure 2. The prototype ESS Spoke cryomodule.
The power couplers, that feed the cavities with electromagnetic wave, thermally link them to the room temperature environment. RF dissipations along this coaxial line might also add additional dynamic heat loads. If not intercepted, those extra heat loads are received by the superfluid helium baths of the cavities. Hence, part of the 3 bar 5 K helium supply flow is deducted to circulate along the external conductors of the RF couplers intercepting heat while warming up to 300 K. A 3D FEM analysis was carried out to determine the heat load at 2 K and the needed mass flow rate of helium that relates to the Spoke cryomodule requirements for the cryoplant liquefaction power. The model takes into account:

- heat diffusion into all solid / surface elements taking into account temperature dependant thermal conductivities;
- surface to surface heat radiation inside the coupler double-wall pipe taking into account temperature dependant emissivity (when required);
- the helium cooling flow with temperature dependant thermal fluid properties;
- the heat power dissipated along the outer conductor by the RF electromagnetic field and due to the temperature dependant surface resistance of the 30 μm thick copper layer covering the stainless steel outer conductor.

![Figure 3](image_url). FEM analysis of the RF power couplers. Left: temperature field. Right: Diffusive and radiant heat powers received on the helium bath for different helium mass flow rates and different emissivities of the coupler antenna (ε\_ant) or outer conductor (ε\_out).

This analysis shows (cf. figure 3) that with a mass flow rate of 46 mg/s, when RF is ON (dynamic regime), the heat diffused to the 2 K cavity port is estimated to 1 W and the heat radiated to the cavity port to about 0.75 W. Optimization of the cooling would confront the cost of the helium mass flow rate production to the one of the resulting diffused heat at 2 K. When the RF power is not supplied (static regime), the mass-flow rate of helium is reduced by about 6 mg/s but the heat load at 2 K (diffused and radiated) remains unchanged. Hence, for the RF power couplers, the dynamic regime induces a (slight) change in the liquefaction power of the CDS for the Spoke section.

Each double Spoke cavities is entirely enclosed in a magnetic shield made of a double layer of Cryophy®. During cool-down, a flow of helium is diverted from the helium supply line and circulates inside a cooper serpentine placed between the two shield layers to cool it quicker than the cavity. It is thus expected that the magnetic shield reaches a large magnetic permeability before the Meissner transition of the cavity, avoiding trapping magnetic field. After the cavity is superconducting, the magnetic shield is no longer actively cooled and left thermally anchored to the cavity helium tank.

The design, construction and operation of the Spoke section have to comply with the European Pressure Equipment Directive (PED 97/23/EC) and with Swedish national requirements (ordinance AFS 2005:2). The cryodistribution of the Spoke cryomodule of the cold mass is made of stainless steel pipes and material transition with the titanium helium tanks of the cavities is done by the use of...
niobium-titanium and stainless steel flanges. To simplify the commissioning of the cryomodules of the LINAC, decision was taken to classify helium tanks in the article 3.3 of the PED. The volume of each cavity tank is hence reduced to 48 L yielding a maximum allowable pressure, $p_s$ (cf. EN13445), of 1.04 barg. Moreover, as the maximum permitted pressure in the VLP return line shall not be lower than 1.43 bara at the inlet of the cold compressors of the ACCP (specifically during cool down), safety devices protecting the cavities and the cryogenic distribution shall work between those two pressure levels (see figure 4). In case of a major incident (beam vacuum break-up), a DN 100 burst disk is devoted to be the main protection device of the cryodistribution. A safety relief valve avoids the bursting of this disk in case of minor incidents, e.g. overpressure during cool-down. As helium flowing out of this safety valve is recovered, the valve outlet pressure might fluctuate from the atmospheric pressure (which also varies) to a maximum of 1.1 bara. Hence, to keep sufficient margins, it is foreseen to add a safety valve in the form of a PLC controlled valve, mounted in parallel with the safety valve and opening at an absolute pressure of 1.5 bara.

3.2. Thermal shield

The thermal shield of the Spoke cryomodule is made of 2 mm thick aluminium alloy 6082 sheets and covered with 30 layers of MLI. It consists in two half cylinders and four half dish ends. 4 extruded aluminium profiles are welded along the half cylinders and connected together to form a continuous circuit in which cryofluids flow. At each side of the cryomodule, two cold to warm transitions link the string of cavities to the room temperature ultra-high vacuum gate valves forming the beam pipe. To limit conductive heat loads to the cavities helium bath, heat interceptions are performed on those two heat transitions by making the thermal shield cryofluid circulating into a small exchanger box welded around each transition. Each cold to warm transition is thus part of the thermal shield. The heat radiating and diffusing along each cold and warm transition was estimated using a FEM analysis. For one cold to warm transition, it is found that the heat load at 2 K is 0.41 W, among which the net radiated (absorbed) heat is about $6.75 \times 10^{-2} W$. The heat intercepted at 50 K by supercritical helium is 0.39 W. If supercritical helium circulation is switched off, then the heat load at 2 K becomes 1.09 W. Taking into account an ideal Carnot Coefficient Of Performance (COP) for the refrigerating process that will remove heat from the 2 K and 50 K levels, we find that the required ideal work to be provided is: 160 W without heat interception and 62 W with heat interception i.e. an ideal efficiency gain of about 2.6.

When operated on the ESS linac, the thermal shield is supplied by supercritical helium at a pressure ranging between 10 and 19.5 bara and a temperature of 40 K. However, for the tests of this prototype, saturated nitrogen will be used: at IPNO site from a dewar at about 1.5 bara; at Uppsala site, from a cold box at a pressure of about 2.5 bara. Thus, a thermal analysis [6] was carried out to size and
position the hydraulic cooling circuit, to determine the heat loads and the consecutive thermal field on
the thermal shield when using one or the other of the two cryofluids. Temperature fields are shown on
figure 5. The total heat load on the thermal shield of the prototype Spoke cryomodule is estimated to
be of about 25 W. This value is comparable with the series Spoke cryomodule: the heat load excess
induced by the lower temperature of the shield is balanced by the having less instrumentation.

Figure 5. Temperature fields of the thermal shield obtained by FEM analysis. Helium and
nitrogen are considered as cryofluids in this design analysis to take into account tests and machine
operating conditions.

4. The Spoke valve box

The prototype Spoke valve box aims at validating the cryogenic process for operating the Spoke
cryomodule in the machine configuration. Hence, this valve box is a demonstrator to validate the
 technological choices (sizing, manufacturing and assembly), the cryogenic functionalities and it
 includes the suitable instrumentation and diagnostics for this purpose. This valve box will also be used
 at Uppsala facilities to test and validate all the 13 series Spoke cryomodules and thus being intensively
 used during 3 years. It results in a more complex test valve box and in a prototype valve box which
 will not be as thermally efficient as the series ones. Moreover, instead of being supplied with
 pressurized helium produced from the ESS ACCP, this prototype valve box will be fed with cryofluids
 available at both experimental sites - IPNO and Uppsala facilities – i.e. saturated nitrogen for the
 cooling of the thermal shields; saturated helium for the cold mass.

Figure 6. Prototype Spoke valve box: CAD views and photograph of internal piping.

The prototype valve box is pictured on figure 6. The four horizontal main lines of the CTL are
implemented. They will be used for liquids feeding and vapours recovery. The jumper connection to
the cryomodule is placed at the top, on a vacuum barrier [4]. In order to facilitate the tightness controls on the cryomodule cryodistribution before its integration into the cryomodule, to avoid welds and control operations in narrow spaces and thus to simplify the cryomodule assembly, all the cryogenic valves needed for the cryomodule operation are placed in the valve box. Therefore, the seven cryogenic valves mainly size the diameter of the vacuum vessel. Hence, superfluid helium is produced within the valve box from the saturated helium provided by the test facilities. The subcooler is a plate heat exchanger of the same DATE type as used in the LHC [7]. The subcooler was designed to operate for the test conditions and machine conditions, i.e. with saturated liquid and pressurized helium in the high pressure (H.P.) circuit. For this circuit and for the low pressure (L.P.) circuit, operating parameters used for the design of this subcooler are sum-up in Table 3. Because of the saturated helium supply, a phase separator is also placed inside the prototype valve box. Liquid is subcooled and then expanded to produce superfluid. Vapours are used to accomplish the heat interception along the RF power couplers outer conductors.

| Table 3. Operating parameters for the helium subcooler. |
|----------------------------------------------------------|
| H.P. circuit    | B.P circuit |
|-----------------|-------------|
| Mass flow rate (g/s) | 1.2 – 2.5     | 12.3         |
| Inlet temperature (K) | 4.4 – 5.5    | 2.0          |
| Outlet maximum temperature (K) | 2.2 | -           |
| Inlet pressure (mbar) | 1200 - 3000 | 20 - 30      |
| Allowable pressure drop (mbar) | 100 | 0.5         |

5. Conclusion
The design of the Spoke section of the ESS LINAC is still under progress but prototypes of a Spoke cryomodule and valve box are now being assembled. Preliminary tests of components were and are still carried out to check some functionalities and procedures. Complete cryogenic tests of those prototypes will be done this spring at IPNO facilities. If validated, the two Spoke components will be transported to Uppsala to perform the experiences at full RF power. Meanwhile, the construction of the cryogenic distribution system for the Spoke section of the linac might start this autumn to begin installation in the tunnel in 2017.

References
[1] ESS Technical Design Report, (2013), http://europeanspallationsource.se/accelerator-documents
[2] Fydrych J, Arnold P, Hees W, Tereszkowski P, Wang X L and Weisend II J G 2014 Cryogenic distribution system for the ESS superconducting proton linac, Proceedings of ICEC 25, Eschede, The Netherlands pp 828-33
[3] G. Olry et al. 2015 Recent progress of ESS Spoke and elliptical cryomodules, SRF 2015, Whistler, Canada
[4] Reynet D, Brault S, Duthil P, Pierens M, Duchesne P, Olry G, Gandolfo N, Rampnoux E, Bousson S and Darve C 2015 ESS Spoke cryomodule and test valve box, SRF 2015, Whistler, Canada
[5] Ruber E et al. 2014 The new FREIA laboratory for accelerator development, Proceedings of IPAC 2014, Dresden, Germany pp 3059-61
[6] Reynet D, Brault S, Duthil P, Duchesne P, Olry G, Gandolfo N, Rampnoux E and Bousson S 2013 Design of the ESS Spoke cryomodule, Proceedings of SRF 2013, Paris, France pp 357-60
[7] Roussel P, Bézaguet A, Bieri H, Devidal R, Jager B, Moracchioli R, Seyfert P and Tavian L 2002 Performance tests of industrial prototype subcooling helium heat exchangers for the Large Hadron Collider, AIP Conf. Proc.