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Physics Procedia 67 (2015) 1123 – 1128

Physics Procedia

25th International Cryogenic Engineering Conference and the International Cryogenic Materials Conference in 2014, ICEC 25–ICMC 2014

The ESS superconducting RF cavity and cryomodule cryogenic processes

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Abstract

The European Spallation Source (ESS) is one of Europe's largest research infrastructures, to bring new insights to the grand challenges of science and innovation in fields as diverse as material and life sciences, energy, environmental technology, cultural heritage, solid-state and fundamental physics by the end of the decade. The collaborative project is funded by a collaboration of 17 European countries and is under design and construction in Lund, Sweden.

A 5 MW, long pulse proton accelerator is used to reach this goal. The pulsed length is 2.86 ms and the repetition frequency is 14 Hz (4 % duty cycle). The choice of SRF technology is a key element in the development of the ESS linear accelerator (linac). The superconducting linac is composed of one section of spoke cavity cryomodules (352.21 MHz) and two sections of elliptical cavity cryomodules (704.42 MHz). These cryomodules contain niobium SRF cavities operating at 2 K, cooled by the accelerator cryoplant through the cryogenic distribution system.

This paper presents the superconducting RF cavity and cryomodule cryogenic processes, which are developed for the technology demonstrators and to be ultimately integrated for the ESS tunnel operation.

Keywords: Superconducting cavities; cryogenic process

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doi:10.1016/j.phpro.2015.06.174

1. Introduction to SRF linac

The European Spallation Source (ESS) superconducting Radio-Frequency (SRF) linac has been designed to deliver to the target a time averaged proton beam power of 5 MW at the completion, with a stage at 1 MW in 2019 [1]. The layout of the superconducting linac lattice has been optimized (Optimus+). The SRF linac is composed of twenty-six double spoke cavities (β=0.5), thirty-six 6-cell medium-β elliptical cavities (β=0.67) and eighty-four 5-cell high-β elliptical cavities (β=0.86). The spoke cavities and elliptical cavities are gathered two-by-two and four-by-four in their cryomodules, respectively. The SRF linac is designed, prototyped and tested in partnership with the ESS, CEA-IRFU, CNRS-IPNO and Uppsala University. Several other key scientific institutions will join this partnership for the SRF linac series fabrication, testing, installation and integration, as part of the ESS in-kind contribution.

The SRF proton acceleration in the intermediate energy section (90 to 216 MeV) of the linac will be performed by 352 MHz double spoke superconducting cavities. The IPN Orsay laboratory (CNRS/IN2P3) is designing the cavities, the power couplers, the cold tuning systems and the cryomodule for the ESS spoke section. The beta 0.5 double spoke cavities will be operated at 9 MV/m to accelerate the 62.5 mA pulsed proton beam.

The following acceleration is provided by 704 MHz elliptical cavities with an energy transition at 561 MeV for the two beta families, until the beam reaches 2 GeV [2]. The elliptical cavities will be operated at 16.7 and 19.9 MV/m for the medium-beta and high-beta cavity, respectively. The general cryomodule design is based on the SNS one using a space frame that supports the cold mass with 4 six-cell elliptical cavities. The power couplers will transfer a nominal RF power of 1.1 MW peak, with 3.5 ms pulse length at 14 Hz. A tuner with two piezo stacks is designed for Lorentz forces compensation. CEA/IRFU is designing the cavities, the power couplers, the cold tuning systems while the cryomodule is designed by CNRS/IPNO [3]. The two families of elliptical cavities are housed in the same type of cryomodules.

A similar cryogenic process will be used for the spoke and the elliptical cavities operating modes [4]. The cool-down phase, the normal operating phase and the failure scenarios are being studied.

The preliminary cryogenic processes of the ESS superconducting radio-frequency cavities and cryomodules will be tested using technology demonstrators, then implemented in the large-scale particle accelerator under construction in Lund, Sweden. Cryomodule prototypes are being realized and tested in collaboration between CEA and CNRS in the frame of the French-Swedish agreement for ESS.

This paper presents the preliminary cryogenic process to be used to operate these components.

2. SRF cryomodules production and cryogenic process

The SRF cavities and cryomodules are designed to comply with the SRF linac requirements [5-6]. The SRF performances of the spoke cavities are the critical path to obtain spallation neutrons for the first operation of the ESS accelerator [2]. In addition, stringent SRF requirements impose a peak field of 45 MV/m for the elliptical cavities and a maximum RF power of 1.1 MW transferred to the proton beam by each power coupler. Hence, each component life-cycle and its overall assembly sequence for the production of the series cryomodules are critical. Figure 1 shows the view of the two families of cryomodules: spoke and elliptical.

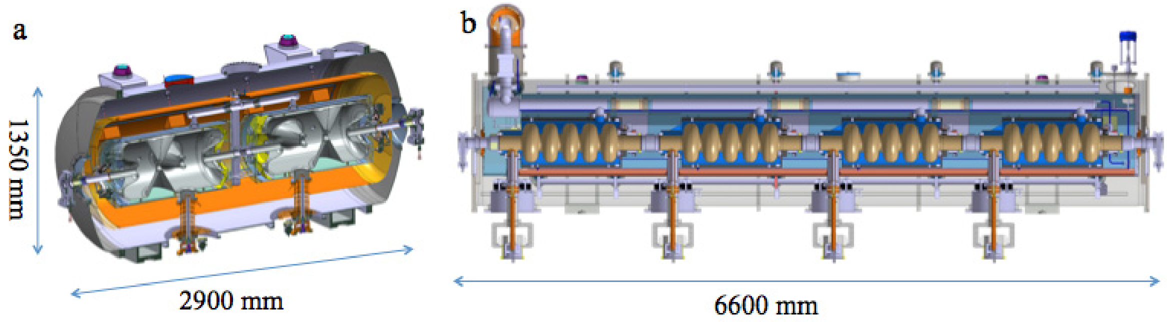

Fig. 1. Overview of the ESS (a) spoke cryomodule; (b) elliptical cryomodule.

The cryomodules are fed with cryogenic fluids by the Cryogenic Distribution System (CDS), which lies all along the linac and includes valve boxes [7-8]. The connection between a cryomodule and a valve box is achieved by a cryogenic jumper. Supercritical helium flow is supplied by the CDS (at a temperature of 5 K and a pressure of 3 bars) to the cryomodule. It is sub-cooled to a temperature of about 2.2 K within a heat-exchanger by using the enthalpy of the cold vapors leaving the cryomodule. It is then isenthalpically expanded within a cryogenic valve to produce LHe II [6]. The dedicated heat exchanger is a fin/fin heat exchanger, similar to the ones used in the LHC. These heat exchangers are designed for a helium mass flow rate of 1.5 g/s for the spoke cryomodules and 4 g/s for the elliptical cryomodules. The installation of cryo-valves and the heat-exchanger inside the cryomodule add a significant complexity and risks to the cryomodule assembly [9]. Hence, two different configurations have been adopted for the spoke and elliptical cryomodules cryo-distribution. For the case of the spoke cavities cryomodules, the Joule-Thomson valve (JT), the cool-down valve and the heat exchanger are located inside the valve box. On the other end, due to the larger size of the elliptical cryomodule heat-exchanger, those components are installed within the cryomodule. Figures 2 and 3 show the cryogenic distribution inside the spoke and elliptical cryomodules, respectively.

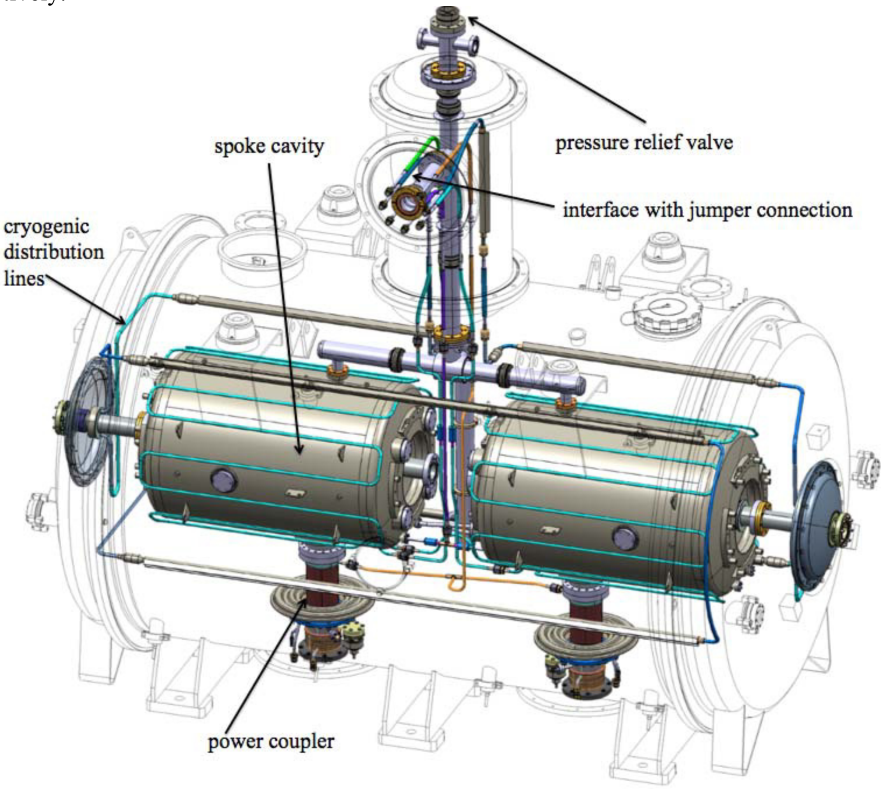

Fig. 2. Cryogenic piping of the spoke cryomodule.

Of primary importance is the location of the welds joining the cryolines to the valves, and the necessity to do the welding at the very end of the cryomodule assembly process if valves are placed within the cryomodule. Indeed, if an earlier assembly was considered, then the cryostating tooling could not be set up and inserting the string of cavities within the vacuum vessel would not be possible. It results that the two cryogenic valves, due to their large length, are assembled inside the cryomodule as a last step of the cryomodule assembly sequence. The cryogenic distribution within the cryomodule cannot thus be finalized before the very end of the assembly sequence by the welding of the cryolines onto the valves inside the cryomodule. This is a very complex and difficult procedure for the welding of this joint, and for the subsequent testing of the weld, especially for the spoke cryomodule. The partially mounted cryo-distribution requires additional tooling (or functions) to support the hanging cryogenic pipes during the cryostating. Although they will be maintained by the cryo-valves after the welding, they have indeed to be held before. If an additional tooling was required for this function, then it should be removed once the cryostating is completed in order to limit the heat load deposit to low temperature volumes. To finalize the cryo-distribution, welding operations and helium leak tests will be performed inside the cryomodule by taking into account the following constraints:

- very limited space for: the operating tools; the operator himself;
- narrowed visibility;
- presence of very delicate components: MLI, instrumentation.

Figure 3 shows the piping and cryo-distribution capable of cooling the four helium tanks and the four double-wall of the power couplers. The segmentation of the piping underlined on the left-hand-side is detailed for the analysis conducted with the notified body.

If there is no cryogenic valve in the cryomodule (Figure 2), then the cryogenic distribution of the cryomodule can be considered as a subsystem that can be manufactured, assembled and tested independently. It will then be mounted onto the string of cavities outside the cryomodule during the “dressing phase”; then inserted within the cryomodule, simultaneously with the string of cavities during the cryostating phase. The cryo-distribution will be finalized by connecting the jumper. Thus, dedicated tooling and protections will have to be designed and provided for those operations. An experienced welder will be required during the assembly phase. The choice of the location of the heat-exchanger inside the valve box of the spoke cryomodule is driven this arrangement. It would involve a doubling of the length of the vertical rise through which the 2 K helium must flow after the JT valve. The risk of this is that two-phase flow instabilities could arise, thus preventing successful operation of the cryomodule. These instabilities are very hard to model, and so standard practice is to minimize this risk during the design phase.

The heat load estimated for the whole linac has provided the basis to size the ESS accelerator cryo-plant [10]. The testing at high power of the series cryomodules will be performed in Saclay and in Lund test stands [11].

The spoke valve box and cryomodule operation will be validated in Uppsala test stand, while the elliptical cryomodule operation will be validated in Saclay.

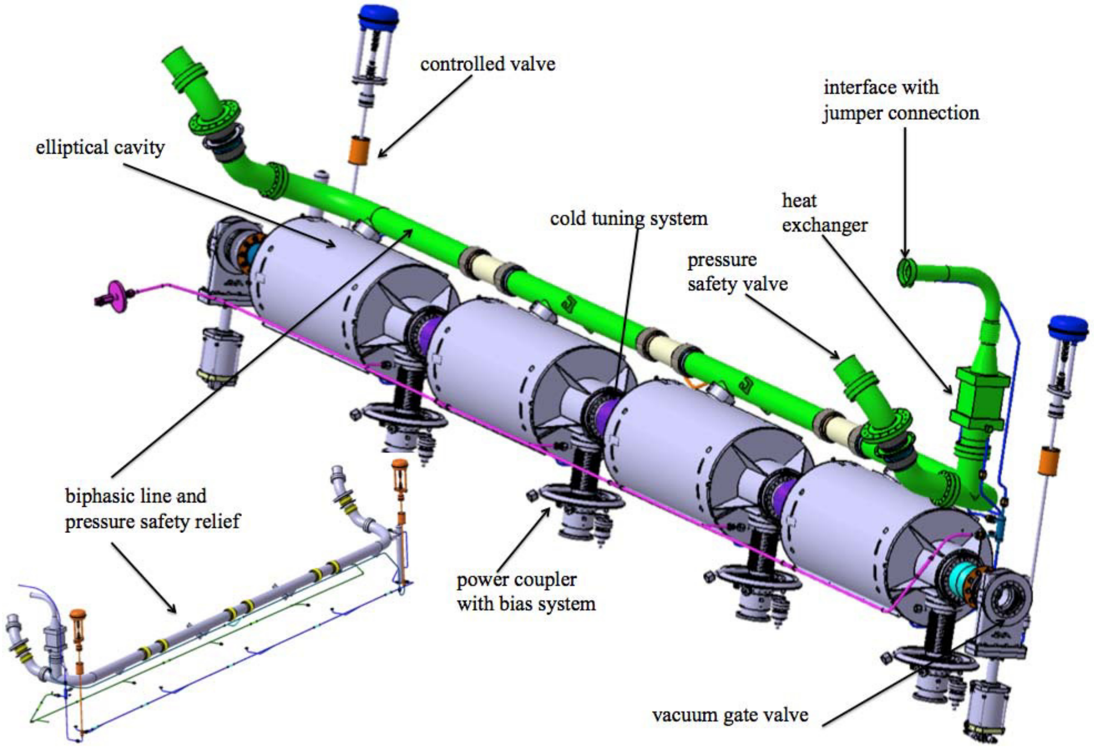

Fig. 3. Cryogenic piping of the elliptical cryomodule.

2.1. Approach to size the cryomodule cryo-distribution

The functional analysis of the operational modes permit to size the cryo-valves and cryo-distribution line for the proper operation of the SRF cavities [12-14]. For instance, during the cool-down phase of a solid S of mass m_s from an initial temperature T_I to a final temperature T_F the enthalpy to be transferred to the fluid is defined as follows (1):

$$H_{S_F} - H_{S_I} = m_s \int_{T_I}^{T_F} cp_s(T)\,dT, \tag{1}$$

where cp_S (unit: J/kg/K) is the specific heat of the solid.

Two cool-down scenarios are been investigated: complete linac cool-down with a variable CDS temperature, and an individual cryomodule cool-down with a constant nominal CDS temperature of 5 K at a pressure of 3 bar. This helium will be expanded into the cool-down valve in order to reduce the pressure to the maximum working pressure. This pressure shall match the requested CDS requirement of a pressure no larger than 1.431 bar(a) at the exhaust of the cryomodule pressure [15]. Helium temperature and pressure conditions at the inlet of the cold mass are 5 K and 1.35 bar. Since the helium enthalpy change is negligible between 1.3 to 3 bar, results would not change if the pressure was slightly adjusted. The thermal shield will be cooled by use of supercritical helium flowing in at a temperature of 40 K and a pressure of 19.5 bar or less.

The cavity cryomodules are designed in accordance to the European Pressure Directives 97/23 EC in order to be integrated and operated in the ESS accelerator. The segmented cryomodule string configurations and the low helium operating pressure allow a safe operation of the cryomodule helium vessels. Microphonics are ruled unimportant to design and size the cryogenic systems, due to the large bandwidth necessary to operate the ESS SRF cavities [2].

Pressure drop along the lines and enthalpy of the cold mass transferred to the cryofluid are used to size the cryo-system of the elliptical and spoke cryomodules [12-13]. The minimum mass flow rate of helium for the cool down of the cold mass is estimated to be 1.30 g/s for the spoke cryomodule and 3.5 g/s for the elliptical cryomodule. The maximum helium mass-flow rate during cool-down corresponds to the maximum aperture of the valve (maximum flow coefficient Kv) depending on the pressure drop within the circuit. Pressure drops are estimated taking into account the temperature dependant thermo-physical properties of the fluid and the temperature dependant heat exchange between the fluid and the solid.

In addition, due to the geometry and materials of the cold mass and of the thermal shield, the characteristic time of the thermal diffusion (depending on the temperature) within their components is much smaller than the cool down time. Thus the cool-down time is directed by the mass-flow rate of the cryo-fluids and by the convective heat transfer between inside the cryo-fluids circuits and not by the thermo-mechanical stresses. However, it has to be noted that the diffusion time cannot be estimated for the cold tuning system (CTS) of the cavity as it consists in several movable components linked together by sliding contacts, gaps, etc. Thus, although no thermo-mechanical stress is expected for this system (due to its intrinsic stiffness range ability), its cool-down time is not evaluated. Using spoke CTS earlier operation, CTS should reach thermal stationary state within 24 hours. Hence, it seems reasonable to consider a cool-down time of about 8 hours. This cool-down time is the time needed to cool the cold mass down to 5 K and to fill in the tanks of the cavities with liquid helium. The CTS increase the thermal load to the liquid helium bath until they reach stationary state. Additional heat loads will also be observed until the thermal insulation (MLI) reach a stationary state.

3. Control of the cryomodule operation

The cryogenic instrumentation is used to monitor the operating variables, to control the valves and to interlock systems. A functional analysis describes the cryogenic process of the SRF cryomodules and defines the operational modes for cool-down, warm-up, emptying, cold stand-by and cold floating [4,12,14].

It also defines the instrumentation, the regulations, alarms and interlocks required for the operation of the installation as well as the interface with the RF source, the cryogenic valve box, the vacuum system and the antenna water cooling system. The control system and safety equipment ensure a high degree of reliability during the different operating modes. The monitoring and control of the cryogenic instrumentation implemented on the elliptical and spoke cavity cryomodules are transmitted from the measuring elements to the control system. More than 100 field objects are available for each cryomodule and valve box subsystem. Signal conditioning and Programmable Logic Controller (PLC) are used for the control of the cryogenic valves and instrumentation located in the cryomodules and valve box. The control system is distributed and uses Profibus for commercial IOs and intelligent valve positioners. Cables link the field objects in the tunnel to the electronic hardware located in the gallery. The electronics are installed in q protected area because of the high radiation dose expected inside the tunnel in the cryomodule area. Profibus is the preferred protocol used for the control command. The ESS control system is based on EPICS (Experimental Physics and Industrial Control System). The EPICS platform is set of Open Source software tools, libraries and applications developed collaboratively and used worldwide to create distributed soft real-time control systems for scientific instruments such as a particle accelerators [4]. The selected process variables will ensure the proper performance of the SRF cavities and the safe interlock system using the Machine Protection System and relative interlocks.

The control system is identified in accordance with the ESS naming convention [16]. The naming convention ensures meaningful, short and yet consistently structured names of signals and devices. Given the millions of signals to control and thousands of devices to operate, clear communication is essential among operators, physicists and engineers. The names shall be used on operator screens, in the inventory system, drawings, design schematics, computer software, project databases, equipment nametags, test procedures, and other sources of technical information at ESS. The ESS Naming Convention is based on a standard originally developed for the Super Superconducting Collider (SSC) and later adopted by other large research facilities, for example the Spallation Neutron Source (SNS), Facility for Rare Isotope Beams (FRIB), International Thermonuclear Experimental Reactor (ITER), and the Continuous Electron Beam Accelerator Facility (CEBAF).

4. Conclusion

The design of the ESS SRF components has been completed to achieve stringent SRF performances while studying carefully the requested life-cycles of the cavities and cryomodules series production. The cryogenic process and functional analysis of the SRF linac permit us to define the operational modes. The signal conditioning and control system will be tested during the prototyping phase. Large risks for the cavities and cryomodules tunnel integration have been identified and mitigated during the design phase.

The fabrication of the spoke and elliptical cavities and cryomodules enhance the feasibility and the challenges of collaborative effort in big science.

Acknowledgement

The authors want to thanks P. Duthil for his constructive comments and advices in the whole process.

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