DESIGN AND PROTOTYPING OF THE SPOKE CYROMODULE FOR ESS

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Abstract

A cryomodule integrating two superconducting radiofrequency double Spoke cavities and their power couplers is now being assembled at IPNO. It is the prototype version for the Spoke section which will be operated for the first time in a linear accelerator for the European Spallation Source. It will be the most powerful neutron source feeding multidisplinary researches. This cryomodule provides the environment for operating the two β = 0.5 cavities at full RF power in a saturated superfluid helium bath at a temperature of 2 K. For this operation, the prototype cryomodule includes all the interfaces with radiofrequency powering, cryogenics, vacuum systems, beam pipe and diagnostics. It will be tested by 2016 at IPNO by use of a test valve box which is also a prototype for the future cryogenic distribution system of the Spoke section, another contribution to ESS. Both prototypes will then be tested at full power in FREIA facilities at Uppsala University.

THE EUROPEAN SPALLATION SOURCE

The ESS Linac

The European Spallation Source (ESS) [1] is now designed to be the most powerful neutron source dedicated to multidisciplinary researches. It is an intergovernmental research project, carried out by 17 european countries, which started to be built in 2014 in Lund, Sweden, and will be fully operational by 2025.

The ESS machine is based on a linear particles accelerator (linac) placed in a tunnel and which accelerates protons from a source to a tungsten target located on the ground surface. From the collisions of the protons onto this target, fast neutrons are produced and then moderated before feeding multiple physics experiment lines.

The ESS linac operates in a pulsed mode with a pulse duration of 2.86 ms and a repetition frequency of 14 Hz. It shall accelerate protons up to an energy of 2 GeV to produce a 5 MW beam with a peak current of 62.5 mA. For that purpose, it benefits from a 312 m long section integrating superconducting radiofrequency (SRF) accelerating cavities. Electromagnetic waves are produced by klystrons and distributed into the tunnel along a network of waveguides to the RF power couplers which radiate this wave into each cavity. The cavity then acts as an electromagnetic resonator and produces an accelerating electrostatic field phased in time with the protons bunches traveling withinthe high vacuum of the beam pipe. All SRF cavities are made of bulk niobium and are operated in a superfluid helium bath at a temperature of about 2 K. This cryogenic environment is ensured by a surrounded dedicated horizontal cryostat, named cryomodule, and which also combines other functionalities and interfaces to run the cavities and transport the beam: magnetic shielding, support and alignment, RF powering, vacuum systems and beam interfaces.

Ordered by proton energy or by the ratio β of the speed of a particle (within the accelerating device) to the speed of light, this SRF linac section includes:

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

A cryogenic distribution system (CDS) runs all along the ESS linac tunnel to distribute or transform the needed cryofluids – helium at different thermodynamic states – produced by the cryoplant located at one end of the ESS machine. Consisting in a multichannel cryoline, this CDS also integrates 43 valve boxes aiming at managing the cryogenic distribution process of each cryomodule.

The Spoke Section

Between the Drifted Tube Linac (DTL) – which ends the warm section of the ESS linac – and the medium beta (elliptical cavities) linac (MBL), a 56 m long portion with 26 double Spoke SRF cavities shall increase the protons beam energy from 90 to 216 MeV. The Institut de Physique Nucléaire d'Orsay (IPNO) is responsible for the supply of most of this Spoke section pictured on Fig. 1: the 13 cryomodules and the cryodistribution system containing 13 valves boxes.

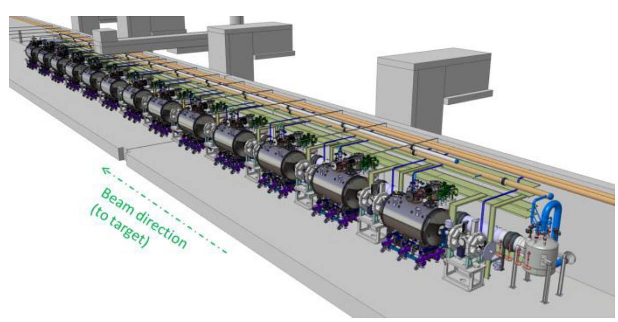

Figure 1: Spoke section of the ESS linac.

IPNO is also in charge of prototyping this section by designing, constructing one prototype cryomodule and one prototype valve box and testing them at IPNO. This valve box is also part of the facilities which will be

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ISBN 978-3-95450-178-6

used to qualify the prototype and the 13 series Spoke cryomodules at full RF power at Uppsala University (Sweden) [2].

PROTOTYPING THE RF COMPONENTS

Double Spoke Cavities

The double Spoke cavity [3] is 994 mm long with an internal diameter of 481 mm. It contains n = 3 accelerating gaps and its accelerating length is Lacc = β × n × λ / 2 = 0.639 m, where λ = c / f is the wavelength of the 352.21 MHz electromagnetic wave. One advantage of this type of cavity is a stiff geometric configuration: it can achieve low Lorentz detuning factor and is less sensitive to pressure fluctuations. Because it has frequency modes well separated, High Order Modes (HOM) are intrinsically filtered making it robust to beam instabilities. With an expected quality factor of $1.5{\cdot}10^9$, those double Spoke cavities shall produce the ESS nominal accelerating field of 9 MV/m, which was very challenging in 2009 at the time of the accelerator design update. Their design was performed by IPNO taking care of optimizing the shape of the cavity (e.g. Spoke bars, coupler location) for RF/mechanical purposes as well as for cost consideration. The nominal thickness of the bulk niobium was chosen to be 4.2 mm and stiffeners were added at each cavity end cups as well as inside the Spoke bars. The helium tank is made of 4 mm thick titanium grade 2 sheets and standard dish ends. It is linked to the cavity by two welded rings to improve the mechanical behaviour of the assembly limiting local stress and reducing the Lorentz factor to K_L = -5.5 Hz/MV²/m². The tuning sensitivity (along the beam axis) is 130 kHz/mm.

Three prototypes were manufactured: 2 by the Italian company Zanon and one by the French SDMS. They were all prepared at IPNO facilities and different procedures tested. The preparation baseline includes an ultrasonic degreasing for the first cleaning following the manufacturing. Then a chemical etching of the inner cavity surface is achieved to remove a layer of niobium of about 200 µm (3.4 kg). During this 8 hours etching, position of the cavity is changed. The mix of hydrofluoric, nitric and phosphoric acids is maintained at a temperature below 15 °C by use of a cooling system placed on the acid storage vessel and by a water flow circulating within the helium tank. Cavity is then rinsed inside an ISO 4 class clean room with a high pressure ultra-pure water jet moving up and down and rotating within the cavity. Each cavity and each preparation procedure were evaluated by testing the performances of the cavity in a vertical cryostat. All cavities were equipped with their helium tank allowing the possibility of mounting their cold tuning system. It can be noted that IPNO also designed a new vertical cryostat for the simultaneous test of two SRF cavities. It will be constructed by 2017 and will be used to qualify the ESS series double Spoke cavities.

During the tests in vertical cryostat, performances of all prototype cavities were measured to exceed the ESS nominal specifications as shown on Fig. 2 where the quality factor Q_0 of the three (named) cavities is plotted versus the accelerating field.

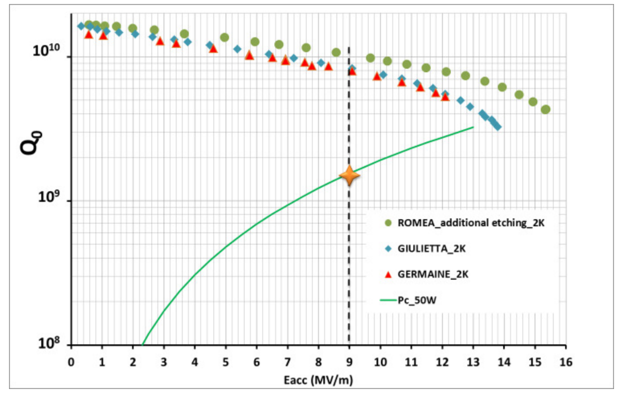

Figure 2: Prototypes of the double Spoke cavities: measured performances in vertical cryostat.

However the thermal cycling of the cavities during this intensive experimental campaign induced a degradation of the quality factor. It is considered that this effect is due to the hydrides formation on the inner surface of the cavities during cool-down. Hydrides formation also induces defects on the surface that remain even after a warm-up at room temperature. Those generated defects then create favoured sites stimulating new hydrides formation during the successive cool-downs. Surface recovery induces a heat treatment at high temperature. An ultra-high vacuum furnace was hence installed at IPNO and was qualified up to 1400 °C by measuring the residual pressure levels and the temperatures at several locations during different thermal cycles. Prototype cavities (with their helium tank) will hence be heat treated at 600 °C to degas hydrogen responsible for hydrides occurrence. This temperature is indeed limited by the brazing of stainless steel flanges onto the niobium cavity. Until now, preliminary annealed heating tests were carried out on samples: niobium rectangular or disk samples and a 1.3 GHz niobium cavity with titanium supports. For one sample having a Residual Resistivity Ratio (RRR) of 320 before being annealed, a RRR of 300 was obtained afterward.

352 MHz RF Power Couplers

The power coupler [4] feeds each cavity with the 400 kW RF electromagnetic wave. It is a coaxial waveguide which links the cavity to the ambient environment: air at room temperature. The outer conductor is attached to the cavity and the inner conductor, made of copper, ends as an antenna inside the cavity. Its design includes a single ceramic window made of high purity alumina. It separates the ultra-high vacuum of the cavity from the ambient air. To limit the heat flowing from the room temperature environment to the cavity operated at 2 K, the outer conductor of this coupler is made of stainless steel with an inner coating of 30 µm thick copper layer. It also consists in a double wall tube within which supercritical helium flows at a temperature ranging from 5 to 300 K. A mass flow of 40 mg/s reduces most of the diffusing and radiating heat flowing to each cavity at 2 K to 1.75 W. When

ISBN 978-3-95450-178-6

the RF is operated, the penetration of the magnetic field into the copper layer induces substantial additional heat loads that are evacuated by increasing the helium flow by 6 mg/s.

Four power couplers were manufactured by two French companies: PMB and SCT. The qualification of those couplers to the ESS nominal operating conditions involved the design and construction of a dedicated conditioning bench. It consists in a RF resonant cavity made of stainless steel whose inner surface is coated with copper. The outer surface is equipped with a brazed water channel to maintain the cavity at a controlled temperature when RF power is dissipated onto the inner surface. In clean room, two couplers are mounted onto the top of this cavity. After baking, ultra-high vacuum of 10^{-9} mbar is achieved inside the cavity at room temperature by use of a turbomolecular pump. Mass flow rates and temperatures of the different water circuits cooling the cavity, the couplers antennas and ceramic windows are controlled. The RF wave is produced by a 352.21 MHz klystron and its power and time pulse is controlled. The wave propagates via waveguides, into the RF cavity via the upstream coupler and out from it via the second coupler. Downstream, a sliding RF short-circuit is used inducing full RF reflection at its location. This place is then changed to modify the position of wave anti-nodes along the couplers. Directional couplers are used at the inlet and outlet of the cavity to measure the RF power. Each power coupler is equipped with an arc detector and with an electron pickup to evaluate multipacing. 3D multipactor effect within the Spoke power coupler (and within the Spoke cavity) was previously assessed by use of a new software developed at IPNO and named MUSICC 3D [5]. By identifying several multipacting barriers with the numerical analysis, TiN coating of the inner surface of the ceramic window of the ESS Spoke couplers was realised. Until now, suppression of multipactoring by use of a high voltage bias is not implemented on those prototypes.

Different conditioning tests were carried out at CEA Saclay where a 352.21 Hz klystron was available and where the IPNO test bench was installed (see Fig. 3). During a test at 250 kW, one ceramic window was broken and analyses are now carried out to understand the origins of this failure. One coupler is conditioned at the ESS nominal operating conditions. It will now be mounted onto a prototype SRF Spoke cavity and tested in a horizontal cryostat, named HNOSS, in the FREIA facilities at Uppsala University. Coupling factor between the cavity and the RF coupler will be measured and the efficiency of the supercritical helium heat intercept evaluated.

A new power test station was installed at IPNO, in the Supratech technical infrastructure, and commissioned. Named SPARE, it is able to deliver RF power up to 2.8 MW (1.5 ms, 50 Hz or 3 ms, 14 Hz) at 352 MHz for the needs of several accelerator projects. It will be used for the conditioning of the series ESS Spoke couplers.

Figure 3: IPNO conditioning bench for the Spoke RF power couplers installed at CEA Saclay.

Cold Tuning Systems

Each cavity is equipped with a double lever type fast / slow cold tuning system (CTS) which uses a push pull action on the beam pipe to deform the cavity along the beam axis. This aims at accurately tuning the resonance frequency of the cavity after cool-down and to compensate microphonics (pressure waves) and Lorentz force detuning. Slow and large displacements up to 1.28 mm are achieved by a stepper motor yielding a tuning range of about 170 kHz with a resolution of 1.1 Hz. Fast tuning over a range of about 800 Hz involves two piezo-actuators. Two pairs of CTS prototypes were constructed in order to test different piezo-actuator stack lengths. Several bearings (with or without dry lubricant) were also implemented. A dedicated test bench is now being designed at IPNO to qualify the 26 series ESS Spoke CTS and to operate CTS over long-time periods for reliability analysis of their components.

A PROTOTYPE SPOKE CRYOMODULE

A prototype Spoke cryomodule is now assembled at IPNO [6]. It will contain a string of two (among the three) double-Spoke prototype cavities contained in their helium tanks. This cryomodule is dedicated to provide the cryogenic environment needed to operate the cavities at 2 K in a saturated helium bath and all needed interfaced.

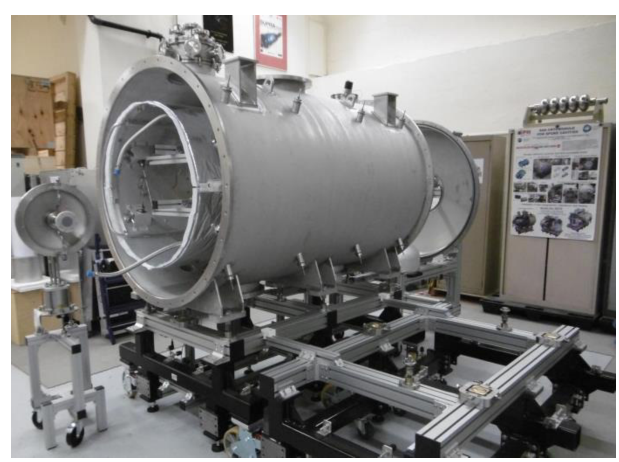

Figure 4: Vacuum vessel of the prototype Spoke cryomodule with the thermal shield.

Its cryostat functionality implicates the use of a vacuum vessel made of stainless steel (304 L) having a diameter of 1.288 m (see Fig. 4). From one UHV gate valve to the

ISBN 978-3-95450-178-6

other one closing the beam pipe, the cryomodule is 2.86 m long. A unique thermal shield made of 2 mm thick aluminium alloy 6082 sheets and covered with 30 layers of MLI protects the string of cavities form the radiant heat. On the ESS machine it will be operated at a temperature between 37 and 53 K with supercritical helium at a pressure ranging from 10 to 19.5 bara. However, for the tests of this prototype at IPNO as well as at Uppsala University, saturated nitrogen at a pressure of about 1.2 bara will be used. This thermal shield was hence designed to cope with both cryofluids. It was already operated twice inside the cryomodule vacuum vessel to verify the mechanical behaviour and to measure the liquid nitrogen consumption which was in agreement with the expected heat load of about 25 W. The distribution of the different cryofluids – saturated normal and superfluid helium; saturated nitrogen – for the test and qualifying operations is done by a piping network inside the cryomodule. However it is managed by the valve box connected to the cryomodule by a branch multichannel cryoline named the cryogenic jumper. To simplify the assembly of the Spoke cryomodule, all cryogenic control valves needed for the cryogenic process were indeed moved into the valve box. Hence the cryomodule contains only cryogenic control transmitters such as thermometers, pressure transmitters, superconducting liquid level sensors and vacuum gauges.

The support of the string of cavities involves 16 antagonist radial rods and 4 longitudinal rods, all made of Ti6Al4V titanium alloy. Their interfaces, out of the vacuum vessel, shall allow for the alignment correction of the cavities even if vacuum is achieved within the cryomodule or if the cavities are cold. 8 fiducials, mounted onto the two cavities, can be optically targeted from 4 windows placed on the vacuum vessel dish ends to diagnostic and control the alignment.

Each cavity will be entirely enclosed in a magnetic shield made of a double layer of Cryophy® and actively cooled. During cool-down, a flow of helium will indeed be diverted from the helium supply line and will flow 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 a cavity, avoiding trapping magnetic field. After the cavity is superconducting, the magnetic shield will no longer be actively cooled and left thermally anchored to the cavity helium tank.

Two mock-up cavities, made of stainless steel were built in order to validate different concepts of the prototype cryomodule. The external envelope of those cavities is very similar to the helium tank of the real Spoke cavities including interfaces for the magnetic shields, cold tuning system and coupler. The inner envelope is simplified although it includes two cylinders featuring the Spoke bars. The inner and outer envelopes constitute the helium tank which has the same volume as the one of the prototypes: 48 L. The inner cavity volume is not subjected to ultra-high vacuum as for the Spoke cavities but is connected to the insulation vacuum of the cryomodule. First, those mock-up cavities are now used to qualify the tooling which was designed and constructed for the assembly phases of all the components of the cryomodule outside the clean room. Secondly, by being equipped with the double magnetic shield of the Spoke cavities, they help characterizing the shielding at room and cryogenic temperature. To that end, three flux gates magnetometers are used to measure the Earth's magnetic field components inside the mock-up cavity. A support made of peek is used to translate those sensors allowing an accurate measurement at different locations inside the cavity and comparison with our numerical simulations. This field mapping will be performed at liquid nitrogen temperature using several flux gates by the end of summer 2016. Then, we expect to have additional measurements at liquid helium temperature. Thirdly, they will be used to check the conformity of the cryogenic process to the ESS requirements. They will act as cryogenic reservoirs, being cooled-down, filled with liquid normal and superfluid helium. They will also be equipped with electrical heaters, consisting of etched-foil resistive heating elements laminated between layers of flexible polyimide insulation, to quantify the cooling capacity of the valve box and the cryomodule and to check the regulation loops of the cryogenic control and command system.

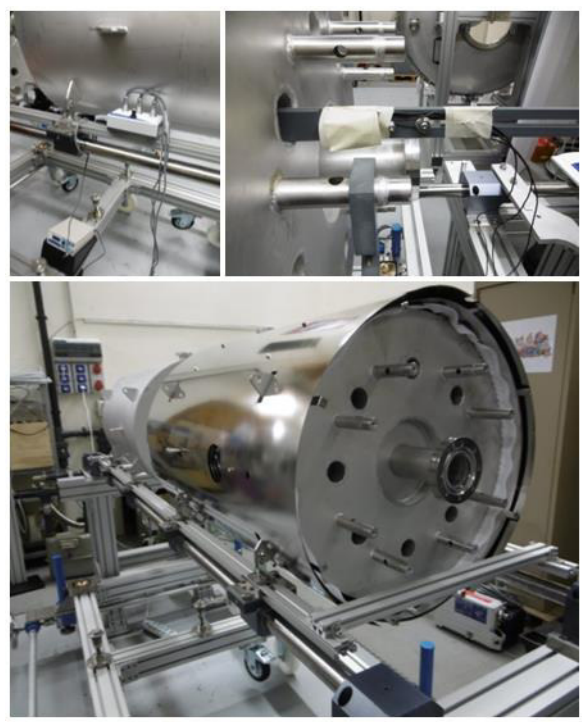

Figure 5: String of two mock-up cavities being assembled on the cryostating tooling and equipped with the Spoke double magnetic shield (bottom). Measurement, by use of fluxgates magnetometers, of the residual Earth's magnetic field within the mock-up cavities (top).

A PROTOTYPE/TEST VALVE BOX

IPNO is in charge of the supply of the cryogenic distribution system for the Spoke section of the ESS linac [7]. It includes the construction of 13 valve boxes for managing the cryofluids distribution into each Spoke cryomod-

ISBN 978-3-95450-178-6

ule. Specifically for the Spoke section, part of the cryogenic diagnostics belongs to the cryomodule whereas all programmable logic controller driven devices such as cryogenic valves are part of the valve boxes only. The consequence is that the production of saturated superfluid helium from the pressurized liquid delivered by the ESS cryoplant is accomplished locally inside each Spoke valve box by isobaric subcooling in a heat exchanger and isenthalpic expansion within a Joule-Thomson valve.

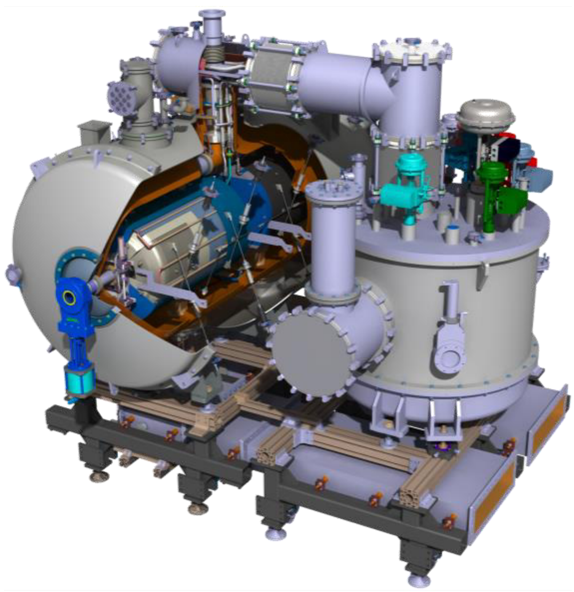

Figure 6: Prototype Spoke cryomodule and valve box.

A prototype valve box was designed by IPNO and is being built. It aims at validating the cryogenic design, the construction, as well as qualifying the prototype Spoke cryomodule (see Fig. 6). The cryogenic tests of those prototype Spoke cryomodule and valve box will be carried out at IPNO. Then, tests at full RF power will be performed in the FREIA facilities of the Uppsala University. But this valve box will also be used for the tests of the 13 series Spoke cryomodules at Uppsala. Hence, it is a complex compromise between a demonstrator and a test bench. It shall integrate the cryogenic operating modes of the ESS linac while functioning with laboratory infrastructures delivering cryofluids differing – by nature or by thermodynamic state – from those supplied by the ESS cryoplant.

The test valve box will hence be feed with saturated helium instead of pressurized subcooled liquid as for the series. It thus integrates a phase separator. The liquid phase will be used to cool-down the cold mass of the cryomodule (magnetic shields, string of cavities and piping) and to produce superfluid helium for 2 K operations. Part of the saturated vapour phase will be used to flow and intercept heat along the couplers double wall tubes instead of using supercritical helium as it will be done on the ESS Spoke section. However this supercritical helium cooling will be tested separately at Uppsala during the RF tests of a single prototype Spoke cavity equipped with a prototype RF power coupler and mounted into the HNOSS horizontal cryostat.

The saturated superfluid helium surrounding the cavities is set at a temperature of 2 K by maintaining and rigorously controlling the bath pressure to 31 mbar. The helium vapours resulting from the vaporization of helium due to heat loads are pumped through the very low pressure line (VLP) of the cryomodule and valve box by use of the laboratory infrastructure vacuum pumping roots. For the prototypes, this VLP ranges from a DN 50 to 63. It is oversized to allow for extra cooling power during the tests and to get the possibility of operating the prototype cryomodule below 2 K for RF tests purposes. The test valve box will be installed at IPNO by this summer to perform the first cryogenic tests.

CONCLUSION

A prototype ESS Spoke cryomodule containing two double-Spoke cavities $\beta = 0.5$ was designed and is now assembled at IPNO. Most of the components of this cryomodule were qualified separately, by use of dedicated test benches, procedures and tooling. Three prototype cavities passed successfully the vertical cryostat tests by being operated above the ESS requirements. Hydrogen degasing operation is now foreseen by heat treatment in a vacuum furnace which was recently installed and qualified at IPNO. One prototype RF power coupler was conditioned at nominal operating conditions and will be installed on a prototype Spoke cavity for RF tests in a horizontal cryostat at Uppsala University. In the meantime, the cryomodule is assembled at IPNO with a string of two mock-up cavities which will be used for the validation of the assembly tooling and procedure, the magnetic shielding concept and the cryogenic process. A valve box was also designed and is constructed to be the prototype of the future cryogenic distribution system of the ESS Spoke section. It will be used at IPNO for the cryogenic experimental campaign of the prototype Spoke cryomodule and then at Uppsala University for the runs at full RF power. This test valve box will also be part of the qualifying bench of the 13 series cryomodules. A preliminary control and command system for managing the cryogenic process is now being implemented at IPNO facilities for the first cryomodule test. It is the basement of the one needed to operate the Uppsala test bench which is also designed by IPNO in collaboration with Uppsala University. This control and command system is built on an EPICS/PLC architecture and includes all the instrumentation controllers for cryogenic processing. It is foreseen as a prototype for the future control and command system of the whole ESS linac which could be supplied by IPNO.

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ISBN 978-3-95450-178-6