PROGRESS IN THE ELLIPTICAL CAVITIES AND CRYOMODULE DEMONSTRATORS FOR THE ESS LINAC

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Abstract

The European Spallation Source (ESS) accelerator is a large superconducting linac under construction in Lund, Sweden. A collaboration between CEA Saclay, IPN Orsay and ESS-AB is established to design the elliptical cavities cryomodule of the linac. It is foreseen to build and test two cryomodule demonstrators within the next two years.

We present the design evolution and the fabrication status of the cryomodule components housing four cavities. The latest test results of two prototype cavities are shown. The cryomodule assembly process and the on-going testing infrastructures at CEA Saclay are also described.

INTRODUCTION

ESS is a large scientific instrument under construction in Sweden aiming at producing the most powerful neutron source in the world [1]. This new facility is composed of a 5 MW proton linear accelerator, a tungsten target to produce neutrons by spallation reaction and experimental neutron beam lines for multidisciplinary users. The proton linac is a long pulse machine with 2.86 ms beam pulse length and 14 Hz pulse repetition rate giving a duty cycle of 4%. It accelerates a high intensity proton beam of 62.5 mA using a 50 meter long warm linac which increases the beam energy up to 90 MeV and a 312 meter long cold linac to reach the final energy of 2 GeV. This cold section works at a cryogenic temperature of 2 K in a saturated Helium bath and contains three families of superconducting resonators: 26 Spoke cavities working at 352.2 MHz, 36 medium beta elliptical cavities and 84 high beta elliptical cavities working at 704.4 MHz. The elliptical cavities are grouped four by four in 6.6 meter long cryomodules, designed to be similar for both cavity types. The fabrication and power testing of two Elliptical Cavities Cryomodule Technology Demonstrators (ECCTD) are planned before launching the series production of 30 cryomodules. The first one is equipped with medium beta cavities (M-ECCTD) and the second one with high beta cavities (H-ECCTD).

This paper describes the design evolution and fabrication status of the elliptical cavities and cryomodule demonstrators already presented in this workshop [2]. It also presents the cryomodule assembly strategy and the testing infrastructures being developed at CEA Saclay.

CRYOMODULE OVERVIEW

The design of the cavities, the cryomodule and its auxiliary components has been reported in [3] and [4]. Fig. 1 shows a 3D view of the cryomodule installed in the ESS tunnel and Fig. 2 gives a detailed description of the cryomodule composition.

The cavity package design and procurement are under the responsibility of CEA Saclay. It is composed of a bulk niobium multi-cell resonator welded to a titanium helium vessel, a vertical power coupler equipped with a single coaxial ceramic window and a WR1150 doorknob transition, a Cold Tuning System (CTS) with two piezo stacks allowing fast and slow adjustment of the resonant frequency, and a cold magnetic shield with high permeability. The four cavities are connected together by three 140 mm diameter hydroformed bellows and are ended by 100 mm diameter cold-warm transitions. This arrangement constitutes a cavity string and is connected to the focusing unit placed outside the vacuum vessel and at warm temperature. The connection is isolated by two DN 100 type Ultra-high vacuum gate valves at each extremity.

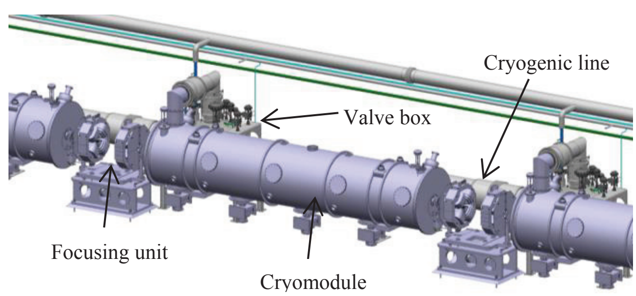

Figure 1: 3D view of the Elliptical cavities cryomodule installed inside the ESS linac tunnel.

The development and procurement of the cryostat components for the M-ECCTD is under the responsibility of IPN Orsay. CEA Saclay will be in charge of this procurement for the H-ECCTD. A common module design for medium (6 cells) and high beta (5 cells) cavities has been possible thanks to the small difference in length (56 mm) between the two cavity types. This allows flexibility in the linac layout and a cost reduction of the cryomodule components manufacturing.

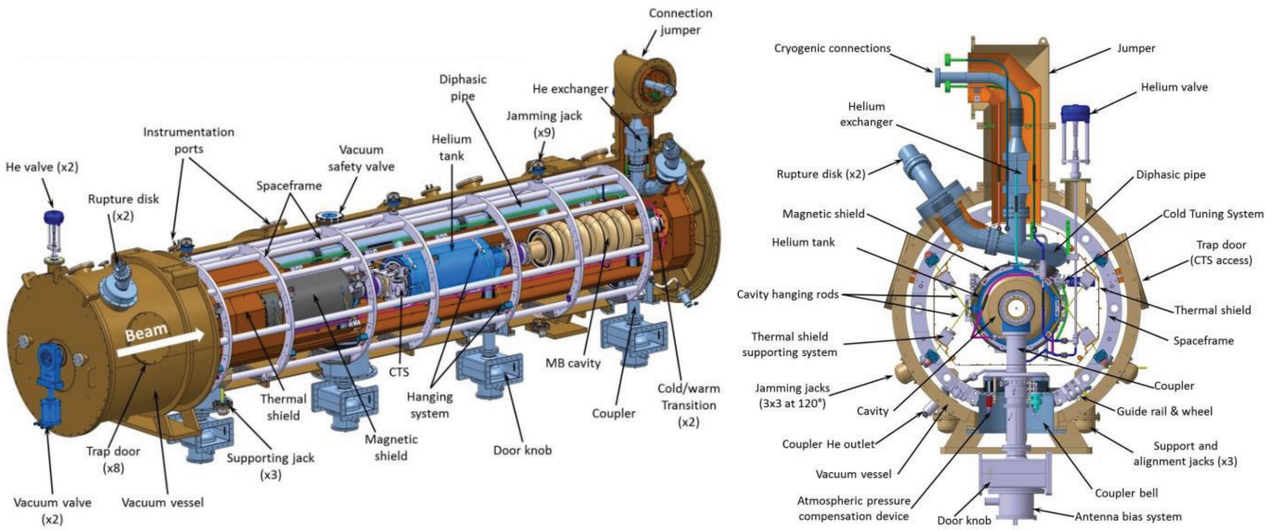

Figure 2: 3D view and transverse cross section of the ESS medium beta elliptical cavities cryomodule.

One important role of the cryomodule is to hold the cavity string while keeping it at cryogenic temperature. We opted for the JLAB/SNS approach [5] consisting in holding the cavities by tie rods in titanium alloy (TA6V) connected to a stiff structure called Spaceframe. The segmented design option was chosen to allow individual cryomodule warm-up and removal for maintenance, giving again enough flexibility during operation. The vacuum vessel is a 1344 mm diameter 304L stainless steel tube ended by two removable lids permitting the cavity string insertion.

The evaluation of the heat loads for the high beta cavities cryomodule is shown in Table 1. The cryogenic interfaces of the cryomodule consist in four helium circuits (inlet and outlet for cavities and thermal shielding cooling) integrated in a 90° jumper connection.

Table 1: Heat Loads for one HB Cryomodule (in W)

Components	**50 K**	**2/5 K**	**2 K**
	Stat.	Stat.	Dyn
Cavity string (when RF ON)			26
Beam losses (0.5W/m)			3.3
Cavity string radiations (14 m²)		0.7	
Thermal shield radiations (21 m²)	31.5		
Supporting system with thermalization at 50K	6	0.25	
Warm to cold transition (x2)	3	2	
Helium piping (including valves and bursting disks)	4.23	0.78	
Power coupler double wall tube (4x23 mg SHe at 5 K)		4	(4)
Instrumentation, heaters and actuators	1.5	2.7	
Radiation from coupler antenna to cavity		2.8	
TOTAL	**46.23**	**13.23**	**29.3**

The base of the jumper hosts the 2 K heat exchanger while most of the cryogenics valves are placed in the Cryogenics Distribution Line valve box.

ELLIPTICAL CAVITIES

The two families of 704.42 MHz elliptical cavities have a geometrical beta of 0.67 and 0.86 (Fig. 3). They have to reach the challenging accelerating gradients of 16.7 and 19.9 MV/m respectively with a Q_0 above 5E9 at 2 K.

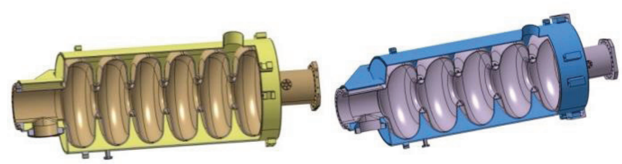

Figure 3: Medium and high beta cavity 3D models.

Medium Beta Cavities

Six medium beta cavities are under manufacturing. Four of them will be integrated in the first cryomodule demonstrator M-ECCTD. The fabrication status is reported in [6]. The first bare cavity is foreseen to be delivered in October 2015 and the first vertical test is planned at CEA Saclay before the end of 2015.

High Beta Cavities

The manufacturing of two high beta prototype cavities was anticipated at the beginning of the ESS project. They were built in two different European companies for qualification purpose. The vertical test results of the two bare cavities (before helium tank welding) shown in Fig. 4 demonstrate that the cavity can achieve the ESS specifications with a factor of 2 of margin on the Q_0. The first cavity P01 could even reach the accelerating gradient of 24 MV/m without significant Q_0 degradation. The test was limited by the RF power at 330 W in CW mode. A gradient of 22 MV/m was achieved with the second

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cavity P02, limited by quench. The heat treatment performed after the test induced a degradation of the performances, possibly due to an accidental surface pollution during the thermal cycle.

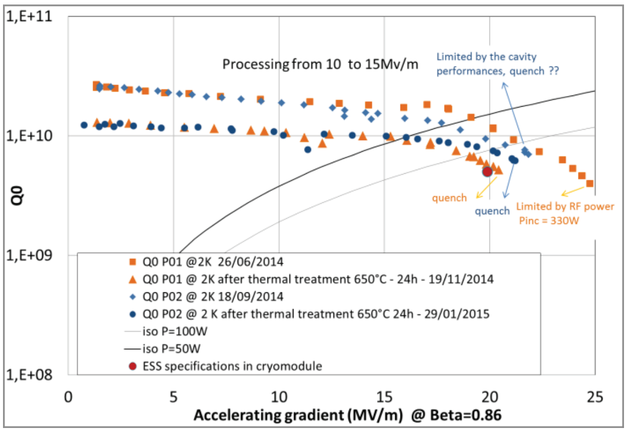

Figure 4: Vertical test results of the two prototype ESS 704.4 MHz high beta cavities before helium tank integration (tested in CW mode).

The π-mode resonant frequency was monitored during the cavity preparation and tests. Results are given in Table 2 and are in good agreement with the predictions.

Table 2: Frequency Monitoring of the High Beta Cavity

Parameter	Simulated	Measured
Tuning sensitivity [kHz/mm]	197	190
Stiffness [kN/mm]	3.3	3
Effect of BCP [kHz/μm]	-3.2	-3.08
Frequency shift from 300 K in air to 2K under vacuum [MHz] (free ends)	+ 1.21	+1.25
Static Lorentz Force Detuning coefficient [Hz/(MV/m)²] (free ends)	-8.9	-7.65

Both prototype cavities were tuned very close to the target accelerating π-mode frequency with reasonable field flatness. However, they were not compliant with the ESS Higher Order Mode (HOM) requirement stating that all HOM mode frequencies shall be at more than 5 MHz from beamline frequencies. This is to avoid beam emittance degradation [7]. On the first cavity P01, 3D measurements of the cavity shape were performed followed by a shape reconstruction using the electromagnetic software HFSS. A strong internal shape deviation exceeding 1 mm was highlighted, thus explaining clearly the frequency decrease of the two dangerous HOM (Table 3). The analysis is in progress for the second cavity P02. As said in [2], great care will be taken to control the shape and correct it by both mechanical and RF measurements at each fabrication step.

Table 3: Frequency analysis on high beta prototype P01 of the two dangerous HOM close to the 4th beamline frequency at 1408.84 MHz

Design frequency at 300 K [MHz]	Measured frequency [MHz]	Calculated frequency with measured shape (HFSS) [MHz]
1418.18	1402.25	1403.80
1418.67	1404.67	1406.80

The first prototype P01 was recently delivered to CEA Saclay after helium tank welding (Fig. 5). No significant variation of the field flatness and resonant frequency was observed. Surface preparation using a newly developed High Pressure Rinsing system is planned in autumn 2015.

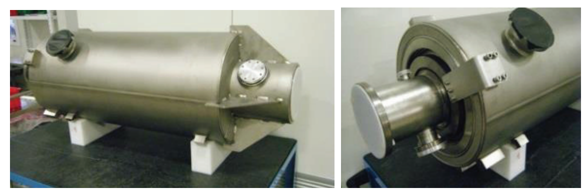

Figure 5: First high beta prototype cavity after helium tank welding.

All the lessons learnt from these two prototypes (Q_0 degradation and HOM issue) will be taken into account in the manufacturing of the six medium beta cavities under manufacturing and also of the five high beta cavities foreseen to equip the second prototype cryomodule H-ECCTD. For these five new cavities, contracts for the high purity (RRR>250) Niobium material and cavity manufacturing will be placed before the end of 2015.

CRYOMODULE COMPONENTS

The design of the power coupler, the cold tuning system and the magnetic shield has been described in [4]. Since then only minor changes have been done.

The power coupler activity is presented in detail in [8]. The manufacturing of the main coupler parts will be completed at the end of 2015. We plan to start the conditioning of the first coupler pair at the beginning of 2016. The magnetic shielding thickness has been enlarged from 1.5 to 2 mm in order to increase the margins on the material permeability at cold temperature (15000 instead of 20000) while achieving the same shielding efficiency of 35 (B_{ext} = 1.4 µT max.). For the cold tuning system, the piezo frame design was simplified and its stiffness was optimized. A piezo frame stiffness of 14.7 kN/mm was adopted which should be compatible for both cavity types. We expect to start the manufacturing of the magnetic shieldings and the cold tuners next October and foresee to receive first elements in the first semester of 2016.

The manufacturing of the vacuum vessel (Fig. 6) and thermal shield is in progress. The Spaceframe is already finished (Fig. 7) and has already been delivered to CEA Saclay.

Figure 6: Picture of the vacuum vessel tube (left) and lid (right) under manufacturing.

Figure 7: Picture of the Spaceframe.

The cryomodule instrumentation has been widely discussed with ESS-AB and with the Spoke cavity cryomodule development team in order to be as similar as possible. For the ECCTD, the list of instrumentation elements is the following:

- 24 temperature sensors 2/5K (Cernox 1050 CU)
- 37 temperature sensors 50/300K (PT100)
- 2 helium level gauges (American magnetics)
- 18 heaters (Vulcanic and Omega)
- 4 CTS motorizations (Phytron) and 8 CTS piezo systems (Noliac)
- 2 helium valves (Weka)
- 4 helium pressure transmitters (MKS)
- 4 helium flow meters + control valves (Brooks)
- 4 water flow meters (Eletta)
- 4 coupler HV bias power supplies
- 4 electron detectors and 8 arc detectors
- 4 RF pick-ups (Coorstek)
- 6 penning vacuum gauges and 2 pirani vacuum gauges (Pfeiffer)
- 9 vacuum valves (VAT) and 2 pumping groups
- 2 helium Safety relief valves
- 2 helium rupture disks and 1 vacuum rupture disk

The number of instruments will be reduced significantly for the series cryomodules.

CRYOMODULE ASSEMBLY

The assembly of the cryomodule is performed in two main sequences:

- assembly of the cavity string in an ISO5 clean room
- assembly of the remaining cryomodule elements inside the vacuum vessel outside the clean room

Cavity String Assembly in Clean Room

The cavity string assembly is highly critical. Pollution might occur when removing the cavity flanges or the coupler conditioning box. Slow venting of the cavity inside through the beam tube is envisaged as performed in the XFEL project. Two supporting tools have been developed to handle the cavity/bellow and the cold-warm transition/vacuum valve sub-assemblies. They can adjust the pitch, roll, yaw defaults by about ± 5 degrees. The supports are fixed on a double rail system to approach the cavities on a common axis. The coupler verticality will be prioritized while a pre-alignment of the cavity axis will be performed inside the clean room. Fig. 8 shows the cavity string configuration after clean room assembly. It is foreseen to store the cavities under vacuum.

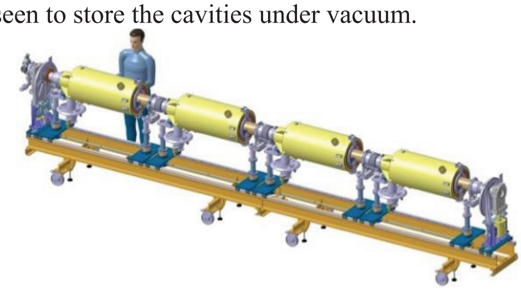

Figure 8: Assembly configuration of the cavity string in ISO5 clean room.

Cryomodule Assembly in the Vacuum Vessel

The cavity string will be transferred to an identical rails system and will be carefully transported towards a new dedicated assembly area. The first step will consist in welding the helium diphasic piping. Then the magnetic shields and the tuners will be mount on each cavity. Final alignment of the cavities and the coupler will be done and accurate fiducialization will be performed using dedicated toolings attached to the cavity. In parallel, the thermal shield and Multi Layer Insulation will be prepared and assembled inside the spaceframe. Two successive phases of cavity string insertion in the spaceframe and the vacuum vessel will follow as illustrated in Fig. 9.

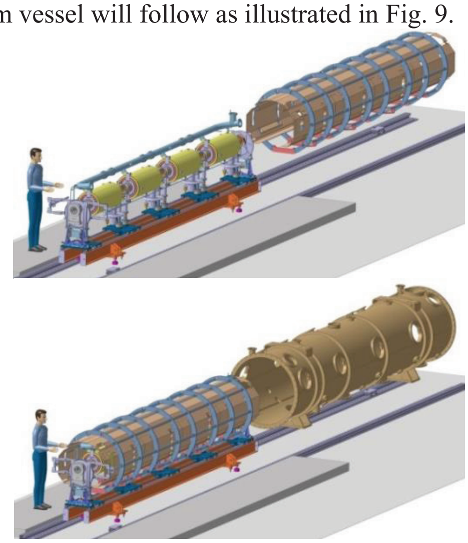

Figure 9: Cavity string insertion inside the spaceframe (up) and the vacuum vessel (down).

The last operation will consist in closing the vacuum vessel with the end lids. Dedicated tools have been developed to transfer the mass of the cold-warm transition/vacuum valve assembly into the vessel lids.

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CRYOMODULE POWER TEST STAND

A new power test stand is under construction at CEA Saclay in order to test the prototype and pre-series cryomodules at nominal gradient. The layout is shown in Fig. 10. This new infrastructure uses the RF power system developed during the CARE/HIPPI European program. It is composed of a pulsed 704 MHz klystron from CPI delivering 1.1 MW peak, a hard-tube High Voltage (HV) 95 kV modulator developed at CEA Saclay and a circulator from Ferrite Inc. The HV modulator has been upgraded by changing a set of capacitors to enlarge the pulse length from 2.1 ms to 4.1 ms. The waveguide network is designed to feed either the coupler conditioning stand or the cryomodule installed inside a concrete bunker located 60 meters away from the klystron. Only one cavity will be supplied at the same time. Typically, a peak power of 400 kW is required to reach a gradient of 25 MV/m on a high beta cavity coupled at a Qx of 7.6E8.

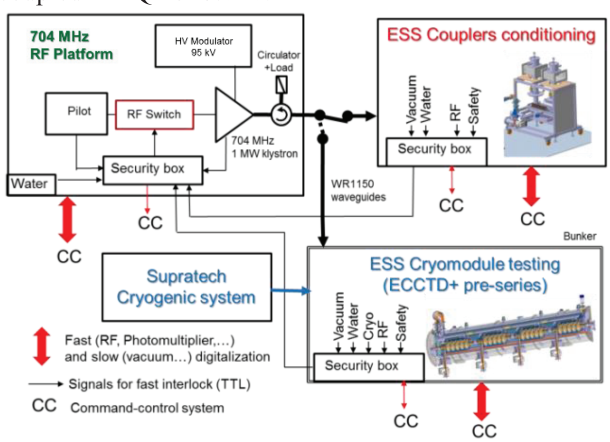

Figure 10: Power test stand layout.

An extension of the existing cryogenic system of the Supratech platform is being constructed to cooldown the the cavities at 2K and the thermal shield at 50 K. This upgrade consists mainly in integrating a new 90 meters long cryogenic line connected to the Supratech valve box which feeds a 2000 L dewar installed near the bunker. The testing conditions of the cryomodule will be slightly different from the nominal operating conditions as detailed in Table 4.

Table 4: Cryomodule Testing Conditions

Parameters	ESS operation	ECCTD tests at CEA
Acc. gradient	16.7 and 19.9 MV/m	
Peak RF power	1.1 MW max	400 kW max
RF pulse length	2.86 ms	3 ms
RF pulse rate	14 Hz	16.7 Hz
Cavity cooling	LHe at 2K	
Coupler cooling	SHe at 4.5 K & 3 bara	GHe at about 4.64 K & 1.2 bara
Thermal shield temperature	GHe at 50 K & 19 bara	LN_2 at 77 K

A total of nine electronic cabinets will be developed for the complete test stand. Six cabinets will be implemented near the bunker to control and acquire the cryomodule instrumentation. It is decomposed as follows:

- control of the Supratech cryogenic extension (x1)
- fast signals acquisition and digitalization for RF signals, electron pick-ups and arc detectors (x2)
- Cold tuning systems control (x1)
- Slow signal acquisition for vacuum and cryogenic diagnostics of the cryomodule (x2)

Three other cabinets will be integrated near the klystron and the coupler test stand area for the renovation of the control and acquisition system. The control system will be based on EPICS. The fast signals will be associated to new acquisition cards under development at CEA Saclay to convert the signals into a 0-10V format. The signals will then be digitalized using IOxOS ADC_3111 cards integrated in the VME64X ESS control-box. The cryogenic system will be controlled by MUSCADE® Embedded SCADA system combined with a modular sensor conditioner crate BoraNet for the cryogenics temperature conditioners. The control of the LLRF system and cold tuning systems is not fully defined yet.

CONCLUSION

The design evolution and fabrication status of the ESS elliptical cavities cryomodule demonstrator have been reported. Few elements of the first ECCTD have already been received and we expect all the components for the first prototype cryomodule M-ECCTD delivered in June 2016. The new assembly and testing capabilities under construction at CEA Saclay have been presented. First assembly sequences of the cavity string are planned in the second semester of 2016 and first high power tests in the end of 2016 or beginning of 2017.

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