THE SUPERCONDUCTING RADIO-FREQUENCY LINEAR ACCELERATOR COMPONENTS FOR THE EUROPEAN SPALLATION SOURCE: FIRST TEST RESULTS

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Abstract

The European Spallation Source requires a pulsed linac with an average beam power on the target of 5 MW, which is about five times higher than the most powerful spallation source in operation today. Over 97 % of the acceleration occurs in superconducting cavities. ESS will be the first accelerator to employ double spoke cavities to accelerate beam. Accelerating gradients of 9 MV/meter is required in the spoke section. The spoke section will be followed by 36 elliptical 704 MHz cavities with a geometrical β of 0.67 and elliptical 704 MHz cavities with a geometrical β of 0.86. Accelerating gradients of 16.7 and 20 MV/m are required in the medium and high-β elliptical cavities, respectively. Initial gradient test results will be presented in which results exceed expected requirements.

THE ESS LINEAR ACCELERATOR

The ESS new facility is composed of a 5 MW proton linear accelerator (linac), a tungsten target to produce neutrons by spallation reaction and experimental neutron beam lines [1]. The ESS Superconducting Radio-Frequency linac has been designed to deliver to the target a time averaged proton beam power of 5 MW at the completion with a nominal current of 62.5 mA with a stage at 1 MW in 2019. 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 %.

Figure 1 shows the layout of the ESS linac, Optimus + [2]. The superconducting linear accelerator lattice redesign has permitted to optimize the layout of the linear accelerator using a transition energy of 90 MeV with the normal conducting linac and reaching 2 GeV at the target. It accelerates a high intensity proton beam using a 50 m long warm linac, which increases the beam energy up to 90 MeV and a 312 m long cold linac to reach the final energy of 2 GeV.

The choice of Superconducting Radio-Frequency (SRF) technology is a key element in the development of the ESS accelerator. The SRF linac is composed of three families of cavity strings, which operate at 2 K [3-5].

In the framework of the ESS-CEA-CNRS cooperation agreement, signed in 2009, IPN Orsay and CEA Saclay are intensively involved in ESS project by leading the design of the whole spoke (WP04) and elliptical cryomodules (WP05) of the linac, respectively. Technology demonstrators are being designed, fabricated and tested for the spoke and the elliptical cavities and cryomodules. Those demonstrators will validate the technologies to be implemented for the ESS SRF linac series production.

According to the agreed In-Kind Contributions the series spoke cavities and cryomodules are fabricated and tested in IPN Orsay before being tested at high power in Uppsala University, then shipped to Lund.

The production of the elliptical cavities is distributed between LASA and STFC, who provide the medium- β and high- β elliptical cavities, respectively. Then, the elliptical cavities are assembled with their fundamental power couplers and cold tuning systems, before being assembled into cryomodules in CEA Saclay, using the experience learned from the X-FEL project. Finally, the cryomodules are shipped to Lund to be tested at high-power in collaboration with the IPJ Polish institute, before being installed in the ESS tunnel.

Since the main components are being fabricated by institutions located outside the Lund area, the integration and interfacing of each resulting components must be carefully planned. Hundreds of requirements have been identified to best integrate the SRF components in the ESS tunnel. The requirements are also used to define the interfaces with the conventional facilities, the control system and to define the operating modes for the ESS SRF linac [6-7].

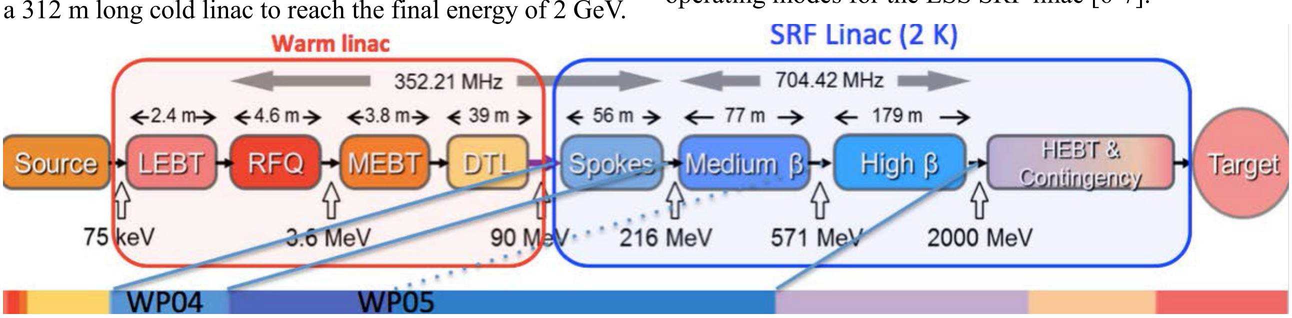

Figure 1: Block diagram of the Optimus+.

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SPOKE CAVITIES AND CRYOMODULES

The ESS spoke superconducting linac consists of twenty-six double-spoke cavities (β=0.5) to accelerate the beam from the Drift Tube Linac (DTL) at 90 MeV up to the 216 MeV at the entrance of the elliptical cryomodule section. Like the elliptical cavities, the spoke cavities provide 1) the capacity to transfer energy from RF system to the beam, 2) the capacity to confine the protons longitudinally, and 3) the capacity to steer the protons longitudinally [8].

Figure 2 shows the spoke cryomodule, which contains a cavity string, mainly composed of two SRF spoke cavities inside their helium tanks, two RF power couplers, two cold tuners and vacuum, cryogenic, RF equipment and instrumentation for the cryomodule operations.

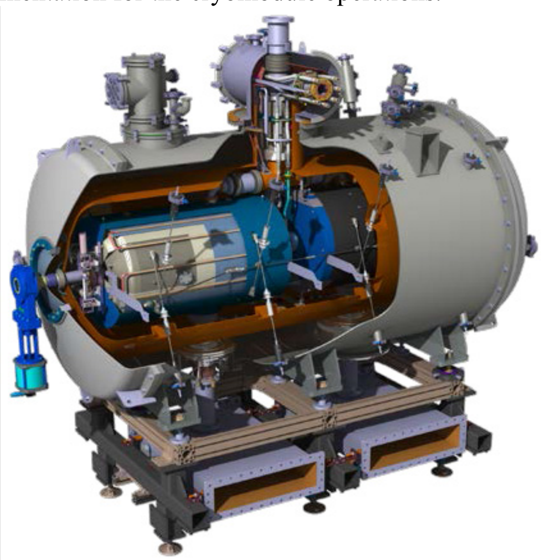

Figure 2. View of spoke cavity cryomodule.

The spoke cavity electromagnetic design is driven by the frequency, the optimum β and then the optimization of the peak fields [1]. Whereas the most important parameter for the beam is the accelerating field or the voltage seen by the particle, the most important optimization criteria is the ratio surface fields to peak fields, that is to minimize the peak fields while keeping constant the accelerating field. Another important factor to optimize is the cavity overall length: a spoke cavity has a re-entrant shape, and the size of the re-entrant part can be increased to give more volume to store the energy, thus resulting in a peak field decrease. The RF and mechanical designs have been presented in [8]. The optimal ratio 4.28 for Epk/Eacc and 6.80 mT/(MV/m) for Bpk/Eacc have been calculated numerically.

Following the beam dynamics simulations, a set of parameters was established in order to fulfill the requirements and is summarized in Table 1.

Three double-spoke prototypes have been fabricated and delivered at the end of 2014: two prototypes (ZA-01 and ZA-02) by E.Zanon and one prototype (SD-01) by SDMS.

Table 1: Double Spoke Main Parameters and Requirements

Item	Values	Unit
Beam mode	Pulsed (4 % duty cycle)	
Frequency	352.21	MHz
Optimal β	0.50	
Temperature	2	K
Bpk	70 (max)	mT
Epk	39 (max)	MV/m
Eacc	9	MV/m
Lacc	0.639	m
Bpk/Eacc	6.80	mT/(MV/m)
Epk/Eacc	4.28	
Beam tube dia.	56	mm
Pmax	335	kW

From the same detailed technical drawings provided by IPN Orsay, the two companies have developed different techniques for the forming of the end-cups and the spoke bars. E.Zanon built the spoke bars in 2 pieces while SDMS chose to split the bars into 4 parts. For the end-cup fabrication, E.Zanon spun this cavity part from one sheet whereas SDMS spun two discs and welded them together. Likewise, for the frequency-tuning phase (before completion of the bare cavity with the welding of the two end-cups), the two companies chose not to trim the same part: the cavity body for E.Zanon and the end-cups for SDMS.

All cavities were delivered fully jacketed with their 4-mm thick titanium helium vessel. The integration of the helium vessel around the bare cavity was one of the most critical steps of the fabrication and had a non-negligible impact on the cavity frequency (between 200 and 500 kHz). All three cavities have been etched by BCP. The goal was set to 200-μm minimum removal. The double-spoke cavities have been etched in 3 phases:

- Phase 1 (120 min): horizontal position.
- Phase 2 (120 min): horizontal position, turned 180°.
- Phase 3 (240 min): vertical position.

These three positions provided a better homogeneity of the chemical etching and nearly cancel the frequency shift caused by the BCP process.

Then, the cavities were high-pressure rinsed 4 times at 100 bar, through all ports in vertical position. Each HPR pass has lasted 3 hours. A total of 6,000 litres of ultra-pure water was necessary for the whole process. Finally, the cavities were dried for a minimum of 48 hours.

The cavities have been tested at 2 K in vertical cryostat. No 120 °C baking nor 600 °C heat treatment have been done before those tests. As shown on Figure 3, all cavities exceeded the ESS requirements (i.e. Q_o>1.5 10^9 at 9 MV/m). Multipacting barriers have been observed at 1 MV/m (narrow and soft) and between 6 and 8.5 MV/m (wide and harder). Processing time for the hardest barriers lasted about one hour. Similar results have been reproduced to validate Uppsala high power test stand capacity as shown in Figure 4 [9-10].

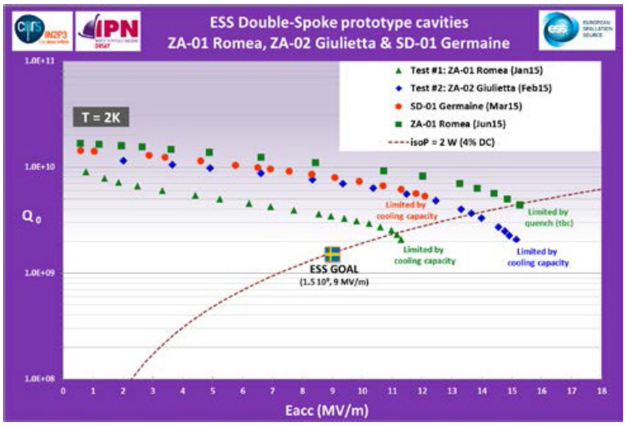

Figure 3: Double spoke cavity first results in IPNO.

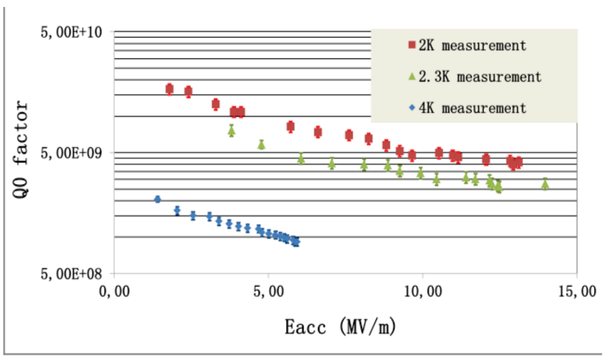

Figure 4: Double spoke cavity first results in UU.

ELLIPTICAL CAVITIES AND CRYOMODULES

The two types of medium and high-β cryomodules have the same general design with minor differences to adapt the medium and high-β cavities [11]. Figure 5 shows the view of the elliptical cryomodules. The layout is based on the SNS/CEBAF concept with an aluminium space-frame and titanium alloy (TA6V) tie rods holding the cavity string and the thermal shield inside the vacuum tank. Each cryomodule houses 4 cavities operating at 2 K. The ESS coupler and tuner designs are based on the ones that have been developed within the European program CARE/HIPPI and have been successfully tested on a superconducting cavity at 704 MHz up to 1.1 MW, with a duty cycle of 10 % at 50 Hz and pulse length of 2 ms. The cavities are not equipped with any higher order modes (HOM) coupler and they must fulfil the requirement on the HOM frequency that shall be at least 5 MHz away from any multiples of the beam bunching frequency 352.21 MHz. The magnetic shield is 2 mm thick. The shielding efficiency is estimated at 35 (Bext =1.4 µT max.) taking into account some spread on the material permeability at cold temperature (15,000 instead of 20,000). The thermal shield in aluminium is cooled by helium gas at 50 K and 19 bar.

The 100 mm diameter bi-phase cryogenic pipe above the cavities ends at its two extremities by 2 burst discs, ensuring the security against accidental events.

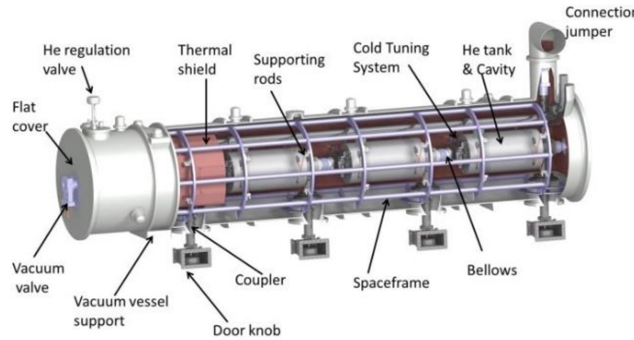

Figure 5: View of the ESS elliptical cryomodule.

The geometry of this pipe has been optimized to limit the pressure increase in the worst case of a beam vacuum rupture accident at the maximum pressure of 0.99 ± 0.05 barg. This value fixes the service pressure of the cryomodule at Ps=1.04 barg allowing these cryomodules to be compliant with the article 3.3 of European Pressure Equipment Directive (PED 97/23/EC).

The Prototype Cryomodules

Two prototype cryomodules, so-called Elliptical Cavity Cryomodule Technology Demonstrators: M-ECCTD (for the medium-β section at geometrical beta, β=0.67) and H-ECCTD (for the high section at β=0.86) are being developed in order to qualify the technology. This paper describes the first prototype M-ECCTD. The cryomodule design is a collaboration of CNRS-IPNO and CEA-Irfu. IPNO is in charge of the cryostat design and procurement of the components and Irfu is in charge of the cavity package (i.e. cavity, power coupler, tuner, magnetic shield) design, procurement, tests, RF processing of the couplers, cryomodule assembly, and RF power tests of the cryomodule at Saclay. Lund University provided the medium-β cavity design.

The "INFN" type is a new RF design proposed by LASA/INFN for the series of medium-β cavities. Parameters of both cavities types are summarized in Table 2.

Table 2: Medium-β cavity parameters.

Medium β cavity type	**CEA**	**INFN**
Optimum β, βopt	0.705	
Accelerating length [m]	0.855	
Qo at nominal gradient	$> 5\ 10^9$	
G [ohm]	196.6	198.8
Qext	$7.5\ 10^5$	$7.6\ 10^5$
Dynamic RF load [W]	4.9	5.13
Iris diameter [mm]	94	100
Cell to cell coupling [%]	1.22	1.55
π and 5π/6 mode separation	0.54	0.7
Epk/Eacc at βopt	2.36	2.55
Bpk/Eacc [mT/(MV/m)] at βopt	4.79	4.95
Maximum r/Q [ohm] at βopt	394	374

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The development plan of the M-ECCTD has been modified at the beginning of 2016 in order to test three cavities "CEA" type and one "INFN" type.

Six "CEA" medium- β cavities have been ordered to one manufacturer. All treatments are being completed at CEA laboratory: BCP, field flatness tuning, high pressure rinsing and tests in vertical cryostat. The heat treatment for hydrogen degassing is performed in industry.

The first MBP01 cavity has followed all process of BCP, field flatness tuning, heat treatment, and tests in vertical cryostat before helium tank welding. Results of the RF tests at different steps of the process are presented in Figure 6 [12-13].

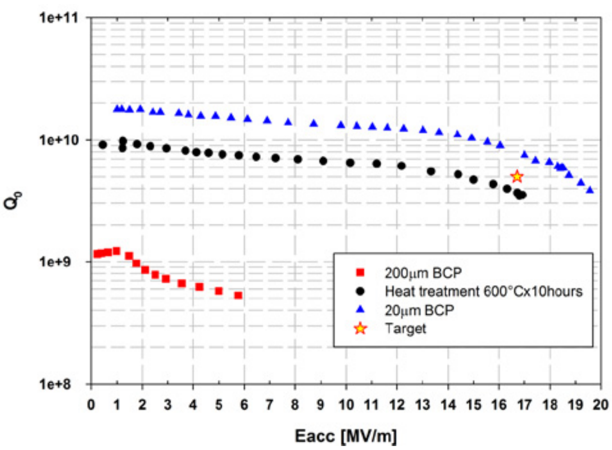


Figure 6: Q curves of the cavity MBP01.

MBP01 bare cavity showed performances above the ESS nominal point after heat treatment and 20 µm BCP. No baking at 120 °C and no N2 doping has been applied. The Q disease has been observed before heat treatment and with a fast cooling rate of 4 K/min. This is explained by a large quantity of hydrogen that was contained in the niobium. Fortunately, this cavity could be cured by the standard heat treatment of 600 °C during 10 hr. The MBP01 cavity has been tested directly after the heat treatment without any BCP. Only a HPR rinsing has been performed and the performances were quite high, even if they are lower than the ESS requirements. The last 20 µm BCP helped to increase the Q0 and the maximum gradient above the ESS nominal point.

Currently, MBP01 cavity has been sent to industry for welding of its helium tank. The dressed MBP01 cavity will be tested again in vertical cryostat before its assembly in the M-ECCTD. The preparation of the five other cavities is in progress and three cavities will be ready to be assembled in the M-ECCTD before the end of December 2016.

The "INFN" cavity is being fully processed in industry. The first BCP treatments are starting with several steps of adjustments and controls. The RF test in vertical cryostat of the bare cavity will be completed at LASA and the cavity with its helium tank will be sent to CEA for assembly in the M-ECCTD by the end of December 2016.

The RF Power Couplers

The design of the HIPPI type couplers has been adapted to the ESS cavities and cryomodule [14]. Different manufacturers have fabricated two types of power couplers. The first pair of couplers is presently being processed at Saclay using an RF power source of 1.1 MW max composed of a CPI Klystron and a homemade modulator. The coupling box is in stainless steel without inside copper coating, and the air fan evacuates the power dissipated in the box.

The first phase of the coupler conditioning performed at CEA has been completed in traveling wave (TW) with low power, short pulses and low repetition rate. An interlock system using an electron pickup, a pressure gauge and 2 arc detectors protects the ceramic windows and the process is handled by an automated control system. The RF power, the pulse length and the repetition rate are increased respectively up to 1.1 MW, 3.6 ms and 14Hz. Figure 7 shows the pressure evolution during the different RF cycles for a pulse frequency of 14 Hz and up to a maximum pulse length of 2.5 ms. The RF power ramps were not stopped by the interlock system because the degassing was quite limited and could be maintained below the threshold value of 5. 10^{-7} mbar.

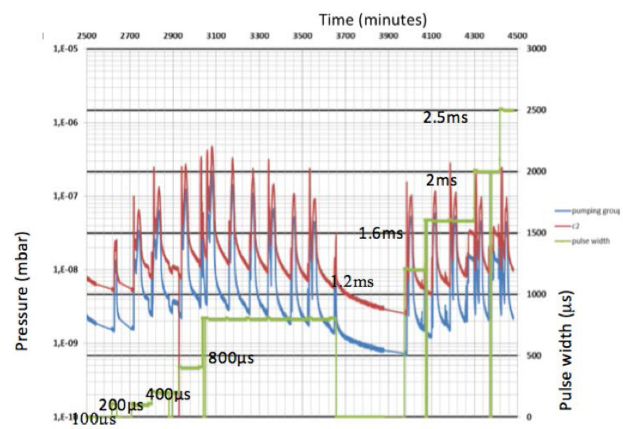


Figure 7: Pressure evolution during RF power cycles.

The conditioning of the couplers is progressing without issue and at the time of this paper drafting the first phase of the RF processing in TW is complete and the second phase with the standing wave (SW) is starting. The SW process is similar to the TW one, however, the RF is totally reflected by a movable short circuit allowing the maximum field position sweeping along the coupler and particularly near the ceramic.

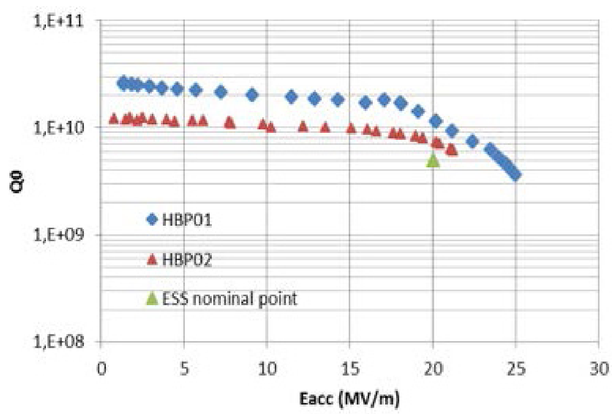
A second pair of couplers manufactured by other factories is being prepared for RF conditioning. The objective is to have four couplers ready to be mounted on cavities by the end of year 2016.

High−β Prototype Cavities

Two high-β prototype cavities have been manufactured by two European companies, prepared and tested by CEA

Saclay. The Q curves of these two cavities measured before heat treatment for hydrogen degassing are shown on Figure 8. Both cavities show performances above the ESS requirements. They were not subjected to Q disease using a cooling rate of about 4 K/min, as it was the case for the first two medium-β prototype cavities.

Figure 8: Q curves of the cavities HBP01 and HBP02.



The H-ECCTD will be assembled at CEA following the test of the M-ECCTD and is expecting to provide results by mid 2018.

CONCLUSION

The development of the SRF components for the European Spallation Source proton accelerator has been summarized [15] and is available thanks to the collaboration platform [16]. This report is not exhaustive, since large quantity of results are being processed and analysed by each SRF collaboration team. Such challenging progresses are possible thanks to the ESS SRF Collaboration team composed of the most competent European institutes and using lessons learned from existing high power proton beam and electron accelerators. Communication and coordination of each interface are keys to the success of the project and require continuous effort.

Technology demonstrators are being designed, fabricated and tested for the spoke and the elliptical cavities and cryomodules. Those demonstrators will verify the selected concepts and will validate the technologies to be implemented for the ESS SRF linac series production by the end of the decade.

ACKNOWLEDGEMENT

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