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THE SUPERCONDUCTING ACCELERATOR FOR THE ESS PROJECT

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Abstract

The European Spallation Source, ESS, is under construction in Lund since 2014. While the installation of the source and the normal conducting part will start in this autumn, the production and testing of cryomodules and cavities for the superconducting accelerator is in full swing at the partner laboratories. The spoke cavities and cryomodules will be provided by IPN Orsay and the testing of those modules will take place at Uppsala University. Prototyping and assembly of the elliptical cryomodules series is occurring at CEA Saclay, and the modules will be tested at a new test stand at ESS. The fabrication and test of the medium beta cavities is provided by INFN Milan and STFC Daresbury for the high beta cavities respectively. An overview of the current activities and test results will be presented in this paper.

INTRODUCTION

The proton accelerator of the European Spallation Source (ESS) [1] consists of several sections as depicted in Fig. 1, beginning with the so-called warm front end. It consists of the proton source, low energy beam transport, radio frequency quadrupole, medium energy beam transport as well as the drift tube linac. The cold section will contain spoke cryomodules, medium-beta cavity cryomodules and high-beta cavity cryomodules to provide an optimised energy gain pattern [2]. The performance of the linac will be 5 MW average proton beam power with 62.5 mA current at 4 % duty cycle with a repetition rate of 14 Hz. This beam will be led to a tungsten target to generate neutrons for various experiments. To achieve these parameters, there are demanding requirements on the accelerator and its components. An overview of the requirements on the superconducting cavities is given in Table 1.

As the ESS is a European project, a large share of the components to be installed are provided by partner laboratories all around Europe via in-kind contributions. In-kind contributions are not limited to the provision of hardware, they also include the use of equipment at partner labs and installation/commissioning work force at the ESS site. This includes the three types of cryomodules, where an overview of the activities during the design and particularly the prototyping phase can be found in [3, 4]. The current status and recent test results will be described in the subsequent sections.

Table 1: Requirements on Superconducting Cavities

Requirement	**Spoke**	**medium-β**	**high-β**
Frequency / MHz	352.21	704.42	704.42
Optimum β	0.5		
Geometric β		0.67	0.86
E_{acc} / MV m^{-1}	9.0	16.7	19.9
E_{Pk} / MV m^{-1}	39	45	45
$B_{\mathrm{Pk}}/E_{\mathrm{Acc}}$ / mT/(MV/m)	6.80	4.79	4.3
$E_{\mathrm{Pk}}/E_{\mathrm{Acc}}$	4.28	2.36	2.2
Iris diameter / mm	56	94	120
RF peak power / kW	335	1100	1100
G / Ω	130	196.63	241
maximum R/Q / Ω	425	394	477
Q_{ext} / 10^5	1.75-2.85	7.5	7.6
min $Q_0(E_{\mathrm{acc}})$ / 10^9	1.5	5	5

SPOKE CRYOMODULES

The first part of the superconducting linac consists of 13 spoke cryomodules, housing two double spoke cavities each with an optimal beta of $\beta = 0.5$, whose main requirements are shown in Table 1. This section of the linac allows to increase the energy of the proton beam from 90 MeV to 216 MeV. A 3D model of the cryomodule is shown in Fig. 2.

The design of the cavities [5] and cryomodules [6] as well as testing the cavities of the series is in the hands of IPN-Orsay. In addition, the cryogenic tests to qualify the prototype valve box and prototype cryomodule are also carried out at IPN-Orsay. Nevertheless, cryogenic and high power RF tests of the cryomodule prototype and series will take place at the FREIA laboratory at the University of Uppsala [7].

Spoke Cavities

Three double spoke prototype cavities have been manufactured in 2014 and have been tested succesfully in the vertical cryostat at IPNO in 2015 [3]. The cavities were treated by BCP in three steps using different cavity orientations with the goal of a minimum removal of 200 µm, followed by four high pressure rinsing cycles taking three hours each. With-

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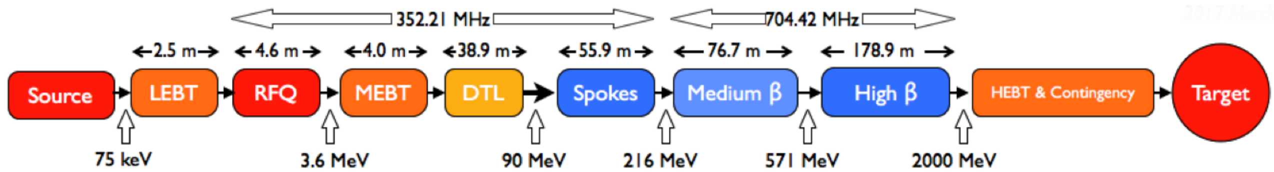

Figure 1: Schematic of the ESS linac: The proton source, radio frequency quadrupole (RFQ) and the drift tube linac (DTL) accelerate the protons to an energy of 90 MeV. The superconducting part consists of the spoke-, medium-β and high-β sections, resulting in a final beam energy of 2000 MeV.

Figure 2: Picture of the spoke prototype cryomodule with the prototype valve box in the test pit at IPN-Orsay.

out any heat treatment (neither high nor low temperature), the cavities exceeded the ESS requirements.

During spring this year, the prototype spoke cavities equipped with their titanium helium vessel have been successfully heat treated at 650 °C. This reduced the cryogenic losses by a factor of 2 at 9 MV m^{-1}. The spoke prototype cavity Romea equipped with its power coupler was tested successfully up to 9 MV m^{-1} in HNOSS, the horizontal cryostat at FREIA. more details about the test can be found in [8]. It is planned to test the prototype cryomodule towards the end of 2017.

The production of the cavities for the cryomodule series has recently started at E. Zanon in Italy, and a first delivery of cavities is anticipated in January 2018. In parallel, the acquisition of the further cryomodule parts is ongoing.

Spoke Cavity Tuning

Each ESS double-spoke cavity will be tuned with a double-lever arm-type tuner with eccentric shaft actuated by a cold motor and equipped with 2 piezo stacks as shown in Fig. 3.

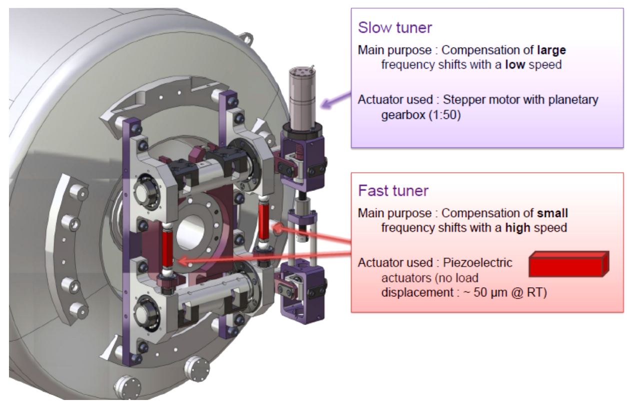

Figure 3: Schematics of the spoke cavity tuning system.

The coarse tuning range is about 160 kHz with a maximum stroke of 1.28 mm, while the required fast tuning range required is minimum 675 Hz for dynamic Lorentz force compensation. Details and results of first measurements performed in various configurations at room temperature are presented in [9].

ELLIPTICAL CRYOMODULES

The largest section of the cold linac consists of 30 elliptical cryomodules. It is to be noted that, even if the cryomodules are identical from the exterior, the first 9 cryomodules contain four medium-beta cavities with $\beta = 0.67$ (see following section), while four high-beta cavities each with $\beta = 0.83$ reside in the remaining 21 cryomodules. The high-beta cavities are 6 centimeters longer compared to the medium-beta, which is compensated with shorter bellows in-between the cavities. Hence, the medium- and high-beta vacuum vessels use the same fabrication design. This design has been chosen to optimise the effort on assembly procedures by having the same setup for both cavity types. A model of the cryomodule is shown in Fig. 4. More details about the developments and current status of the ESS elliptical cryomodules is given in [10].

The medium beta cryomodule prototype (M-ECCTD) is currently under final assembly in the test bunker at CEA

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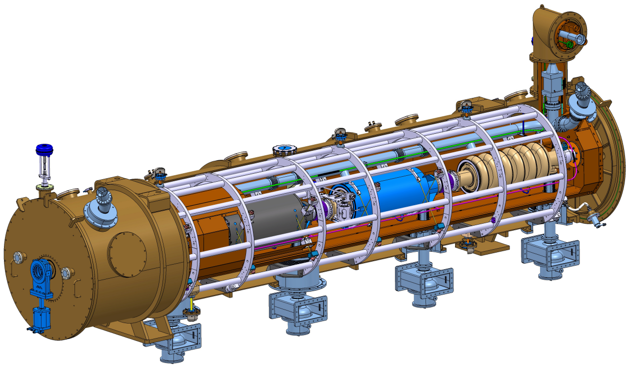

Figure 4: Model of the ESS elliptical cryomodule - in this case equipped with medium-beta cavities.

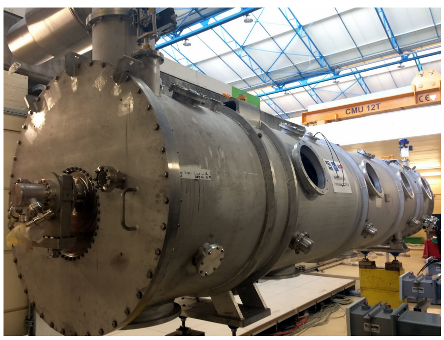

Figure 5: Medium-beta demonstrator cryomodule after completed cavity string insertion and closing of the end flanges in the CEA Saclay test bunker, beginning of July 2017.

Saclay and it is scheduled to perform the first cool down shortly. A recent picture (end of June 2017) of the cryomodule is shown in Fig. 5, right after both end flanges were closed. It is important to note that the first test of this prototype and further cryomodule tests that will be carried out at CEA Saclay is closely followed by ESS personnel and the Polish in-kind team in charge of the high power test in Lund, in order to set up the appropriate infrastructure and test routines for the test stand (TS2) on the ESS site [11, 12].

The fabrication and testing of the series cavities will be carried out by INFN/LASA for the medium beta cavities and STFC Daresbury for the high beta cavities respectively. It is to be noted that for risk reduction purposes, the niobium sheet material for the fabrication of the cells will receive eddy-current scanning and - if needed - subsequent analysis of inclusions/defects at DESY [13]. Scratches and inclusions of foreign materials in the niobium sheets may lead to a poor cavity performance due to a quench limitation at a lower field than required for the accelerator operation. In comparison to the niobium sheets for the European XFEL [14], the eddy-current scanning machines need adaptations to allow the reception of the larger niobium sheets (XFEL with approx. 260x260 mm compared to ESS sheets of 460x460 mm or more). These adaptations have been made and a first successful scan of a test sheet has been carried out.

A summary of the main elliptical cavity parameters is given in Table 1, and the subsequent sections present the recent results and status.

Medium-Beta Cavities

Within the last year, the medium beta cavity prototypes manufactured by E. Zanon under contract from CEA Saclay have been tested successfully without helium tank, and further after tank integration.

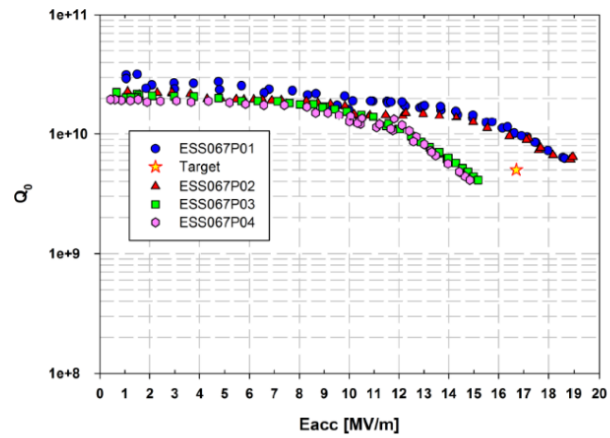

Figure 6: Q vs. E curves of vertical tests for the dressed CEA Saclay medium-beta cavity prototypes [15].

The summary of the vertical test results is shown in Fig. 6, while more details about the fabrication and testing is given in [16]. INFN/LASA chose to make slight modifications to the RF design, and produced two prototype cavities (one made of fine grain material as expected for the series, one large grain cavity for research purposes [17]).The fine grain cavity showed excellent results (see Fig. 7, [18]), and it was decided to integrate this cavity with three of the CEA prototypes into the cavity string for the M-ECCTD (see before).

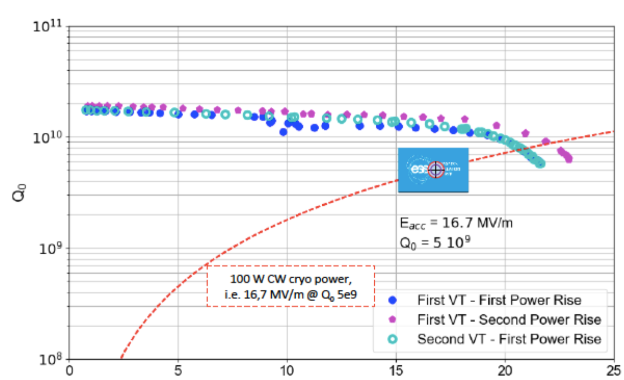

Figure 7: Q vs. E curve of the vertical test of the dressed LASA medium-beta cavity prototype.

The niobium material for the manufacturing of the 36 medium-beta cavities at INFN/LASA has been ordered, and

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the evaluation of the call-for-tender of the cavity manufacturing is ongoing. The chemical and heat treatment will be based on the lessons learned from CEA and the experience of LASA during the XFEL 3.9 GHz cavity production. The testing of the series cavities will be done in the AMTF [19] at DESY Hamburg. Possible additional high pressure rinsing (HPR) to cure field emission and additional BCP treatments will be performed by industry. It is expected to have the first set of four cavities for the assembly in the first medium beta series cryomodule ready mid 2018.

High-Beta Cavities

For the high beta cavity technology demonstrator cryomodule, five cavities are currently under fabrication at RI Research Instruments under the supervision of CEA Saclay.

At STFC Daresbury, the preparation for the testing of the cavity series (84 for 21 cryomodules plus 4 spare cavities) are well underway. STFC will conduct the cavity performance tests in their own laboratory. For this reason, a complete setup including cryoplant and vertical cryostat has been acquired and is currently completing installation for commissioning to start late 2017 [20]. STFC will have the capacity to HPR up to 30% of the cavities, if they do not reach the required $Q_0(E_{acc})$ performances during the first test. Furthermore, the radio frequency test setup is under development and first tests have been carried out [21].

The procurement process for the niobium material and for the fabrication of the cavities in industry is underway.

Elliptical Cavity Tuning

In comparison to spoke cavities, the elliptical cavities are more sensitive to deformation resulting in a frequency shift. To reduce the deformations induced by electromagnetic force (Lorentz force detuning) or helium pressure fluctuation, stiffening rings are placed between the cavity cells [1]. The corresponding coefficients K_L for the static Lorentz force detuning and K_P for frequency change due to pressure fluctuation of the high-beta cavity are summarised in Table 2.

Table 2: Mechanical Sensitivity of the High-beta Cavity

Parameter	Unit	Value
K_L fixed ends	Hz/(MV/m)^2	-0.36
K_L free ends	Hz/(MV/m)^2	-8.9
K_P fixed ends	Hz/(mbar)	4.85
K_P free ends	Hz/(mbar)	-150
$\Delta f/\Delta l$	kHz/(mm)	197

The cold tuning system is based on the proven mechanical design principles of Saclay tuners. The Saclay V tuner is working at cryogenic temperature inside the vacuum tank. All the surfaces exposed to friction are treated with a dry lubricant coating efficient at cryogenic temperatures. It combines a slow and a fast tuner. The slow tuner is, like for the spoke cavity, a double lever system. It consists of eccentric shafts actuated by a motor gear box and a screw. The fast tuner is made by two piezo actuators that can act simultaneously (or not) to compensate Lorentz force detuning. A model is shown in Fig. 8.

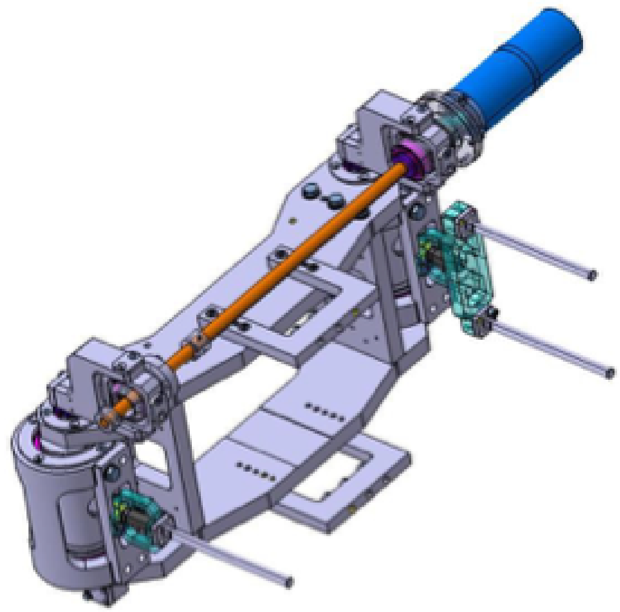

Figure 8: Model of the Saclay tuner in use for the ESS elliptical cryomodules [22].

SUMMARY

The ESS SRF Collaboration [23] is working hard towards the goal of providing and installing cryomodules for the ESS linear accelerator. First cavities of various types have been tested, the medium beta cryomodule prototype is under final assembly in the test bunker at CEA Saclay and is scheduled to undergo the first cool down soon. This overview can only serve as a snapshot of all the ongoing activities at the contributing with the aim to a successful operation of the European Spallation Source.

ACKNOWLEDGEMENT

The fabrication, testing and installation of the cavities and cryomodules within the ESS SRF Collaboration is a huge effort and would not be possible without our partners at CEA-IRFU Saclay, CNRS-IPN Orsay, Uppsala University, INFN-LASA and STFC Daresbury.

REFERENCES

[1] S. Peggs (ed.), *ESS Technical Design Report*. 2013.
[2] D. McGinnis, "New Design Approaches for High Intensity Superconducting Linacs - The New ESS Linac Design", in *Proc. of International Particle Accelerator Conference (IPAC'14), Dresden, Germany*, 2014.

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[3] C. Darve *et al.*, "The Superconducting Radio-Frequency Linear Accelerator Components for the European Spallation Source: First Test Results", in *Proc. of Linear Accelerator Conference (LINAC'16), East Lansing, MI, USA, 25-30 September 2016*, JACoW, May 2017, pp. 651–656. DOI: https://doi.org/10.18429/JACoW-LINAC2016-WE1A03.

[4] C. Darve *et al.*, "ESS SRF Linear Accelerator Components Preliminary Results and Integration", in *Proc. of International Particle Accelerator Conference (IPAC'17), Copenhagen, Denmark, 14–19 May, 2017*, JACoW, May 2017, pp. 3666–3669. DOI: https://doi.org/10.18429/JACoW-IPAC2017-THOBB3.

[5] P. Duchesne *et al.*, "Design of the 352 MHz, Beta 0.50, Double-Spoke Cavity for ESS", in *Proc. of International Conference on RF Superconductivity (SRF2013), Paris, France*, 2013.

[6] D. Reynet *et al.*, "Design of the ESS Spoke Cryomodule", in *Proc. of International Conference on RF Superconductivity (SRF2013), Paris, France*, 2013.

[7] R. Ruber *et al.*, "The New FREIA Laboratory for Accelerator Development", in *Proc. of International Particle Accelerator Conference (IPAC'14), Dresden, Germany*, 2014.

[8] H. Li, K. Gajewski, L. Hermansson, M. Jobs, R. Ruber, and R. Santiago Kern, "High Power Testing of the First Dressed ESS RF Cavity", in *Proc. of International Conference on RF Superconductivity (SRF2017), Lanzhou, China*, 2017.

[9] N. Gandolfo *et al.*, "Fast Tuner Performance for a Double Spoke Cavity", in *Proc. of Linear Accelerator Conference (LINAC'14), Geneva, Switzerland*, 2014.

[10] F. Peauger, "Developments and progress with ESS Elliptical Cryomodules at CEA-Saclay and IPN-Orsay", in *Proc. of International Conference on RF Superconductivity (SRF2017), Lanzhou, China*, 2017.

[11] N. Elias *et al.*, "Testing of SRF Cavities and cryomodules for the European Spallation Source", in *Proc. of International Conference on RF Superconductivity (SRF2017), Lanzhou, China*, 2017.

[12] R. Zeng, E. Asensi Conejero, C. Maiano, and H. Li, "An Optimal Procedure for Coupler Conditioning for ESS Superconducting Linac", in *Proc. of International Conference on RF Superconductivity (SRF2017), Lanzhou, China*, 2017.

[13] A. Brinkmann, M. Lengkeit, X. Singer, and W. Singer, "Testing of Niobium Material for the European XFEL Pre-Series Production", in *Proceedings of Linear Accelerator Conference LINAC2010*, 2010.

[14] M. Altarelli *et al.*, "The European X-Ray Free Electron Laser Technical Design Report", Tech. Rep. DESY 06-97, 2007.

[15] E. Cenni *et al.*, "Vertical Test Results on ESS Medium and High Beta Elliptical Cavity Prototypes Equipped with Helium Tank", in *Proc. of International Particle Accelerator Conference (IPAC'17), Copenhagen, Denmark, 14–19 May, 2017*, JACoW, May 2017, pp. 948–950. DOI: https://doi.org/10.18429/JACoW-IPAC2017-MOPVA041.

[16] E. Cenni, "Vertical Test Results on ESS Medium and High Beta Elliptical Cavity Prototypes Equipped with Helium Tank", in *Proc. of International Conference on RF Superconductivity (SRF2017), Lanzhou, China*, 2017.

[17] M. Bertucci *et al.*, "Experience on large-grain multi-cell cavity besed on infn-lasa medium beta design for the ess", in *Proc. of International Conference on RF Superconductivity (SRF2017), Lanzhou, China*, 2017.

[18] D. Sertore *et al.*, "INFN-LASA Medium Beta Cavity Prototypes for ESS Linac", in *Proc. of International Conference on RF Superconductivity (SRF2017), Lanzhou, China*, 2017.

[19] J. Swierblewski, "Large Scale Testing of SRF Cavities and Modules", in *Proc. of Linear Accelerator Conference (LINAC'14), Geneva, Switzerland*, 2014.

[20] L. Bizel-Bizellot, M. Ellis, S. Pattalwar, M. Pendleton, P. Smith, and A. Wheelhouse, "Innovative Cryogenic Test Facility for Testing SRF Cavity Series Production", in *Proc. of International Conference on RF Superconductivity (SRF2017), Lanzhou, China*, 2017.

[21] P. Smith *et al.*, "ESS High Beta Cavity Test Preparations at Daresbury Laboratory", in *Proc. of International Conference on RF Superconductivity (SRF2017), Lanzhou, China*, 2017.

[22] G. Devanz *et al.*, "ESS Elliptical Cavities and Cryomodules", in *Proc. of International Conference on RF Superconductivity (SRF2013), Paris, France*, 2013.

[23] C. Darve *et al.*, "ESS Superconducting RF Collaboration", in *Proc. of International Particle Accelerator Conference (IPAC'17), Copenhagen, Denmark, 14–19 May, 2017*, JACoW, May 2017, pp. 1068–1070. DOI: https://doi.org/10.18429/JACoW-IPAC2017-MOPVA090.