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TESTING OF SRF CAVITIES AND CRYOMODULES FOR THE EUROPEAN SPALLATION SOURCE

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ABSTRACT

The European Spallation Source (ESS) is currently under construction in Lund, Sweden. The ESS linear accelerator aims to deliver a 62.5 mA, 2.86 ms long proton beam pulse onto a rotating tungsten target, at 14 Hz repetition rate, thus achieving an energy of 2 GeV and 5 MW power. Most of the beam acceleration happens in the superconducting fraction of the linac, which is composed of three sectors of cryomodules named after the cavities housed within. The first sector of the SRF linac is composed of 13 Spoke cryomodules containing 2 double spoke cavities with a geometric beta of 0.5, the second is composed of 9 medium beta cryomodules each housing four elliptical cavities (β=0.67) and finally 21 high beta cryomodules enclosing four elliptical cavities (β=0.86). ESS has strategically built up a SRF collaboration with other European institutions, these partners will deliver through in-kind agreements cavities and cryomodules performing within the ESS specification. This article describes the process leading to the acceptance of cavities and cryomodules received from the different partners and the necessary tests required prior to the final installation in the ESS tunnel.

INTRODUCTION

The European Spallation Source

The European Spallation Source (ESS) [1] is an accelerator based neutron source and aims at becoming the worlds most powerful by colliding a 2 GeV pulsed proton beam onto a rotating helium cooled tungsten target where neutrons are produced by spallation process.

The project is funded by a collaboration of 17 European countries and is currently under construction in Lund, Sweden.

The ESS Superconducting Linac

The linac will deliver 62.5 mA, 2.86 ms long proton beam pulses at 4 % duty cycle with a repetition rate of 14 Hz and 5 MW average beam power [2].

The superconducting part of the linac [3] is composed of different families of cryomodules organized in three sectors containing:

- 13 spoke cryomodules,
- 9 elliptical medium-β cryomodules,
- 21 elliptical high-β cryomodules.

Each of the aforementioned cryomodules will contain superconducting cavities with similar name.

A summary of the ESS specifications of the superconducting linac is given in Table 1:

Table 1: ESS Specifications for Each Sector of The ESS Superconducting Linac

	Spoke	**Medium-β**	**High-β**
Proton energy range, MeV	90 to 216	216 to 571	571 to 2000
Cryomodules/Sector	13	9	21
Cavities/Cryomodule	2	4	4
Cavities/Sector	26	36	84
Sector length, m	55.9	76.7	178.9
Operating freq., MHz	352.21	704.42	704.42
Operating temp., K	2	2	2
Cavities optimum β	0.5		
Cavities geometric β		0.67	0.86
E_{acc}, $MV \cdot m^{-1}$	9	16.7	19.9

The ESS SRF Collaboration

A large fraction of the ESS construction budget will be realised by means of in-kind contributions from European partners. On this basis, a strategic ESS SRF collaboration [4] is taking place to design, manufacture and test cavities and cryomodules [5] in agreement with the ESS specification.

The spoke cavities will be manufactured and tested as part of the IPN Orsay contribution, as well as the cryomodule design and production, furthermore the testing of the cryomodules will take place at FREIA laboratory as a contribution of the Uppsala University.

The medium-β cavities will be manufactured and tested as part of the INFN/LASA contribution, while the high-β cavities manufacturing and testing is part of the STFC/ASTeC contribution, moreover the cryomodule production is under CEA-Saclay responsibility.

The testing of the first 3 pre-series cryomodules for both medium-β and high-β sections is done at CEA to validate the assembly procedures. The final site acceptance test for all the elliptical cryomodules is done at the ESS Lund Test Stand 2 (TS2).

From production until final acceptance for installation, the ESS cavities and cryomodules will undergo a series of inspections and acceptance tests to assure conformance to the requirements. In the subsequent sections we will focus on the processes that take place during the lifecycle of the cavities and cryomodules in respect to testing.

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CAVITIES TESTING

The ESS superconducting cavities will have to meet strict design requirements allowing for the correct beam acceleration. In order for it to be achievable the cavities manufacturing process will have to follow well defined procedures. These should take in consideration lessons learnt during the prototyping phase, chemically and heat treated according to qualified and matured recipes and prepared in high class clean rooms by qualified personnel. Table 2 presents a summary of design requirements applied to each of the cavity types.

Table 2: Summary of Cavity Design Requirements

Design Requirements	Spokes	Medium-β	High-β
E_{acc}, MV·m^{-1}	9.0	16.7	19.9
Q_0 at E_{acc}	>1.5x10^9	>5x10^9	>5x10^9
Iris Diameter, mm	56	94	120
E_{pk}, MV·m^{-1}	39	40	44
B_{pk}/E_{acc}, mT·MV^{-1}·m	6.80	4.79	4.3
E_{pk}/E_{acc}	4.28	2.36	2.2
G (Ω)	130	196.6	241
R/Q max, Ω	425	367	435
RF peak power, kW	335	1100	1100

Spokes Cavities Testing

Three double-spoke prototype cavities (Figure 1) have been produced and have been tested in vertical cryostat at IPNO [6]. One of these cavities was installed with power coupler and was further tested last spring at the Uppsala University using the multifunction test cryostat, HNOSS [7].

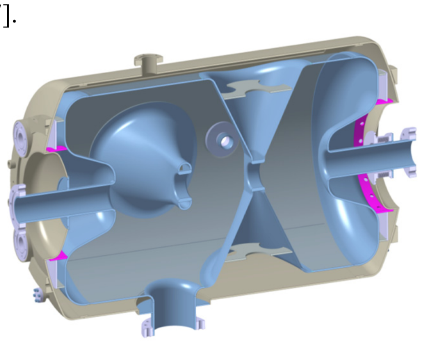

Figure 1: ESS double-spoke cavity cross-section and its helium tank (courtesy: IPNO).

The production of the 26 double-spoke cavities for the series cryomodules is responsibility of IPN-Orsay and has been awarded to the E. Zanon company in Italy, these will be produced using similar recipes as for the prototypes.

The double spokes cavities will be tested in vertical cryostat at IPNO assuring that the cavities perform within the ESS specification.

Medium-β Elliptical Cavities Testing

During 2016 six medium beta cavities prototypes have been manufactured and tested [8] using the CEA design (shown in Figure 2).

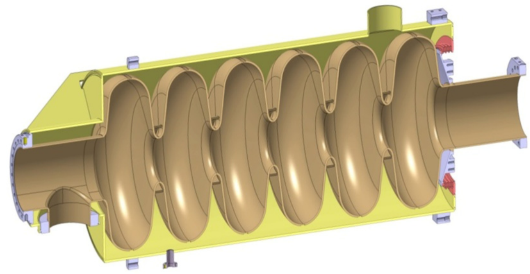

Figure 2: ESS medium-β elliptical cavity cross-section and its helium tank (courtesy: CEA).

Additionally, two prototype cavities with improved design have been procured by INFN/LASA, one was produced in fine grain niobium while the second was done in large grain for research purposes, both have been also tested in a vertical cryostat [9-10].

The production of the 36 medium-β cavities is part of INFN/LASA scope and the niobium contract has been placed while the cavity manufacturer is still being evaluated. The testing of the series cavities will be done in the AMTF facility [11] at DESY Hamburg and part of INFN/LASA scope.

High-β Elliptical Cavities Testing

Five high-β cavities prototypes (Figure 3) are currently under fabrication at RI Research Instruments as part of the scope of CEA Saclay in-kind contribution.

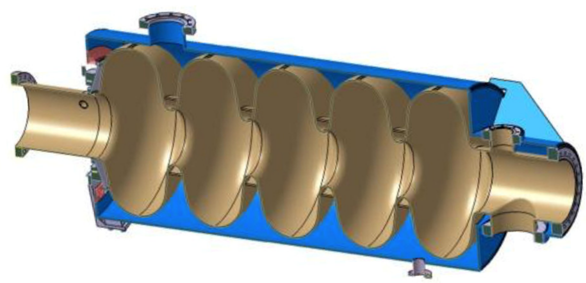

Figure 3: ESS high-β elliptical cavity cross-section and its helium tank (courtesy: CEA).

As for the high-β cavities for the series cryomodules, STFC Daresbury is responsible for the production and testing of 84 cavities. The tendering process for the niobium material and cavities production is ongoing and acceptance tests will take place at STFC.

A complete new test facility including cryoplant and vertical cryostat capable of testing 3 cavities in horizontal position has been procured and is currently under commissioning [12]. Additionally, the RF test setup is under development and first tests have been carried out [13].

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CRYOMODULES TESTING

Spokes Cryomodule Testing

All the 13 series spokes cryomodules (Figure 4) will have their Site Acceptance Test (SAT) at the FREIA test stand located at the FREIA Laboratory of Uppsala University [14].

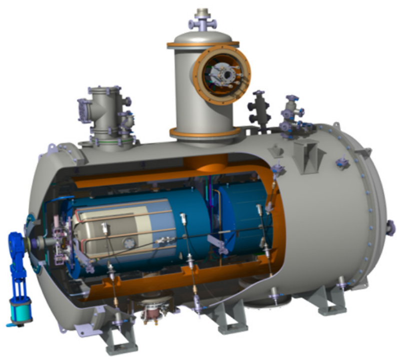

Figure 4: Cut-view of the model of a spokes cryomodule equipped with 2 double-spokes cavities (courtesy IPNO).

The test stand consists of a radio-protection bunker a test stand cryoplant with a capacity of 140 l/h [15] and a high-power RF system consisting of 2 tetrodes based 352 MHZ RF sources and 400 kW amplifier stations [16] and RF distribution system.

Elliptical Cryomodules Testing

The SAT of all elliptical cryomodules (Figure 5), medium beta and high beta, will take place at ESS Lund Test Stand 2 (TS2) in Lund [16].

The medium-β and high-β cryomodules share the same design and have the same external interfaces, albeit housing cavities with different design properties and slightly different dimensions. This design solution carries multiple advantages, worth highlighting here is the sharing of assembly tooling, common assembly and installation procedures, but also common testing and commissioning procedures.

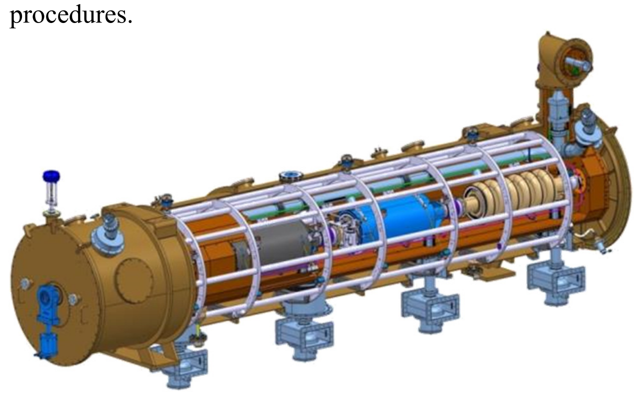

Figure 5: Cut view of the model of an elliptical cryomodule containing 4 medium-β cavities (courtesy CEA).

The TS2 (Figure 6) consists of a radio-protection bunker made out of 1200 t of heavy magnetite loaded concrete with 1m thick walls with the same cross section as the accelerator tunnel. The test stand cryoplant will provide 2 K and 40 K helium with a liquefaction rate of 6 l/h.

The RF system consists of 2 klystrons powered by one modulator and each of the klystrons supplying 2 cavities at 1.1 MW.

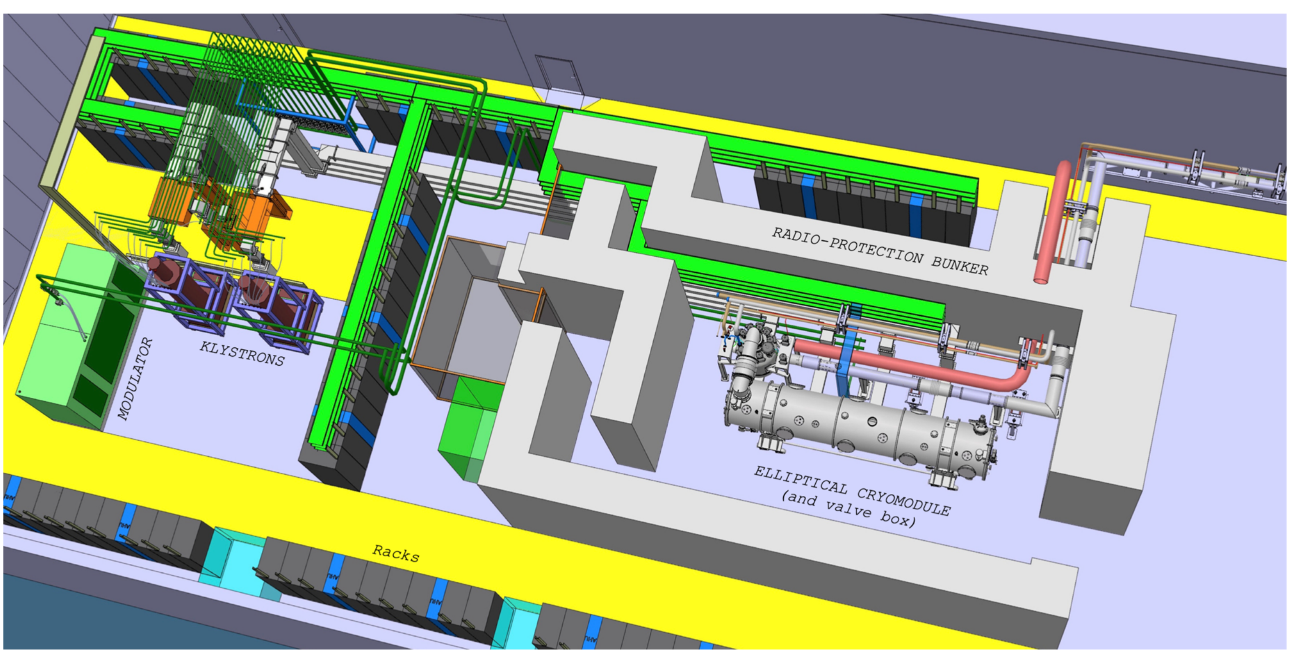

Figure 6: Layout of the ESS Lund Test Stand 2 (TS2). The RF sources shown on left side and bunker with cryomodule under test on the right side.

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COMPONENTS LIFECYCLE

As a result of the complex nature of the project and due to the vast distribution of responsibilities over a multitude stakeholders throughout the project lifecycle, well-defined acceptance criteria have to be set as well as efficient ways for information exchange.

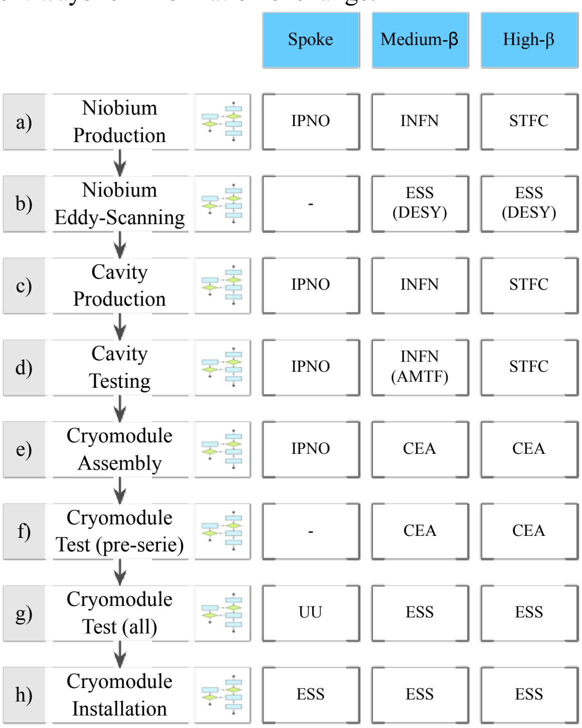

Figure 7: Simplified cavities and cryomodules life-cycle and responsibilities of each institute.

Each major step of the component production and assembly is accompanied by verification checks, where a pre-defined logic for helping decision makers in dealing with non-conformities is followed.

Moreover, whenever an exchange between stakeholder is necessary, outgoing inspections take place at the departure facility and are matched by incoming inspections at the receiving facility.

A set of documentation containing results of test reports and other pertinent data is accompanying the different components throughout the lifecycle.

Components Acceptance

A non-exhaustive list of the quality controls and acceptance tests in respect to the cavities and cryomodules lifecycle is described below and is presented in Figure 7:

a) During the niobium production samples are taken to assure the correct characteristics and documented prior to shipment (e.g. chemical composition, RRR, mechanical properties, absence of surface defects).
b) The selection of the correct RF side for the niobium sheets will done by conjunction visual inspection, dimensional controls and eddy current scanning (elliptical cavities only).
c) The different cavity parts (e.g.: hall cells, dumb-bells and end-groups), will also be subject to quality controls in order to achieve the correct final frequency and overall dimensions. Once the cavities have been produced, surface treatments will take place (chemical and heat treatments), here at each step of the way strict quality controls (e.g.: acid temperature, flow, oven temperature, gas analysis) and reports are created. The cavities are then tuned to achieve the correct field flatness and fundamental mode frequency and integrated with helium tank followed by pressure tests and leak tests.
d) Cavity tests will be performed at 2 K, in vertical cryostats, nevertheless some important checks are done at incoming inspection. Here fundamental mode frequency and bandwidth is re-measured and compared as well as checks for completeness and damages. At cold, the fundamental frequency is re-measured, cold leak checks are done and the power rise curves are derived (Q vs. E) as well as the maximum achievable gradient (quench limit).
e) The accepted cavities are then sent for string assembly where again they undergo incoming inspections which should match the previous outgoing inspections. After that, ready for cryomodule installation is granted and sorting is done if possible. String assembly is done in a clean room where fundamental power couplers are mounted. In addition, the full cryomodule is assembled encompassing, cold tuning system, magnetic and thermal shields, cryogenic circuitry, instrumentation, cabling and cryostating in the vacuum vessel. Warm checks are done (electrical, pressure and leak checks), and quality documentation is gathered.
f) The first 3 elliptical cryomodules of each series (pre-series) will undergo cold a test at CEA-Saclay in slightly different conditions than that of ESS (both in terms of cryogenic operation as well as RF conditions) to validate the assembly procedure.
g) The final site acceptance tests will allow for the determination of the readiness for installation of all cryomodules, a thorough inspection protocol will be followed to access that all requirements are met. This will allow for the correct validation of previously measured parameters as well as to validate the correct functioning of other systems (e.g.: dimensional control and final integration of components, absence of damage during transport, cold tuning system operation associated with tuning sensitivity measurements, power coupler conditioning, cryogenic heat loads, absence of leaks).
h) Once the final site acceptance is granted the cryomodules status becomes ready for installation (RFI) and will follow ESS installation, testing and commissioning plan.

SUMMARY

The ESS SRF Collaboration was put in place with the goal of providing cavities and cryomodules performing

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within the ESS specification, while sharing vital knowledge and experiences enabling project progress and success. Prototype cavities of the various types have now been tested, the medium beta technology demonstrator cryomodule prototype is under preparation for first cold tests at CEA.

The cavities and cryomodules lifecycle is rather complex, taking place at different facilities and under responsibility of a multitude of institutions. At critical steps of the lifecycle, acceptance tests are necessary to determine product conformity. We presented the process leading to the acceptance of cavities and cryomodules received from the different partners and a succinct description of the necessary testing required prior to the final installation in the ESS tunnel.

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