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PROGRESS AND PRELIMINARY STATISTICS FOR THE ESS SERIES SPOKE CRYOMODULE TEST

H. Li, A. Miyazaki, M. Zhovner, L. Hermansson,
R. Santiago Kern, K. Fransson, K. Gajewski, R. Ruber
Uppsala University, Sweden

Abstract

The European spallation source (ESS), as a world-class high power proton accelerator facility, will be the first one to adopt 26 double spoke resonators (DSR) at its low energy section. As a new superconducting accelerating structure, these DSRs are therefore considered key technology and a challenge for the whole project. They will be the first DSRs in the world to be commissioned for a high power proton accelerator. Since 2019, FREIA Laboratory, Uppsala university, has successfully tested the first DSR prototype cryomodule and is now in charge of the acceptance tests of the ESS series cryomodules prior to installation in the tunnel. The cryomodule test, including cryogenic and RF testing, verifies operation of the cavities, couplers and cold tuning systems. This poster will present the test results for the ESS series spoke cryomodules, including preliminary statistics, experience in general.

INTRODUCTION

The European Spallation Source (ESS) is an accelerator-driven neutron spallation source built in Sweden whose layout is shown in Figure 1. Unique capabilities of high brightness and long pulses help to ESS forward as frontiers of the neutron science [1]. ESS is also facing challenges such as high efficiency and high availability demand in cavity control and operation, wide cavity and RF parameters spread in system operation, and enormous data collection from variety of test stands. Therefore, it requires strict quality control for each critical sub-system by an acceptance test before tunnel installation.

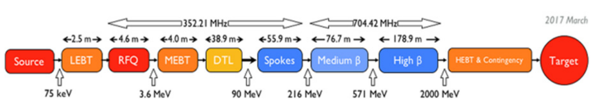

Figure 1: The layout of ESS accelerator.

The superconducting spoke section of the ESS linac accelerates the beam from the normal conducting section to the first family of the elliptical superconducting cavities. This spoke section includes a single family of β=0.5 bulk niobium double spoke resonator (DSR), as shown in Table 1, operating at a temperature of 2 K, and at a frequency of 352.21 MHz. A total of 26 spoke cavities are designed at IJCLab Orsay and will be grouped by 2 in 13 cryomodules [2]. From 2015, low power test of a dressed spoke cavity (Germain) had been done to verify the hardware and test procedure at Uppsala University, Sweden, where the Facility for Research Instrumentation and Accelerator development (FREIA) has been equipped with superconducting cavity test facility [3, 4]. Afterward the qualification of a cavity package, a DSR (Romea) with its fundamental power coupler (FPC) was tested with low level radio frequency (LLRF) system and radio frequency (RF) station, which represented an important verification before the module assembly [5]. As a milestone, the first DSR prototype cryomodule for ESS project has been successfully high power tested in 2019 and the series DSR CM acceptance has been official launched in 2020. In this qualification test of the cryomodule, including cryogenic and RF testing, fundamental power coupler (FPC), DSRs, cold tuning system (CTS) are verified.

Table 1: Main Parameters of Spoke Cavities

Parameter	ESS Spoke cavity
Frequency (MHz)	352.21
Temperature (K)	2
Pulse beam mode duty factor (%)	4
Repetition rate (Hz)	14
Nominal gradient (MV/m)	9
Beta (optimal)	0.5

FREIA TEST STAND

The FREIA laboratory at Uppsala University is established in order to support the development of instrumentation and accelerator technology [6, 7]. In a total 1000 m^2 area, FREIA developed a test stand infrastructure consists of a horizontal cryostat and a vertical cryostat, three concrete bunkers for radiation protection purposes, a helium liquefaction and recovery plant, RF station and affiliated equipment and, LLRF control system [8].

The high power test stand at FREIA for the ESS DSR prototype CM consists of two high power RF stations running with tetrode tubes, two high power circulator protection devices, a water cooling system, two loads, and two LLRF systems based on either self-excited loop (SEL), open loop or closed loop with proportional integrate (PI) feedback (FB) function. In order to maximize safety and to minimize interference, the FB mode based on the ESS LLRF system is the first choice for RF measurements and, the open loop using ESS LLRF system as a signal source is applied for FPC conditioning while the SEL will be used as a backup system for ESS series CM test. The interlock system integrates all interlock signals from the FPC/cavity/loop through NI compact RIO system and sends out an overall interlock control during RF on. A valve box was installed and connected to the FREIA cryo-plant where it is permanently located for all 13 series CMs acceptance testing [9]. This valve box is slightly modified from the final series to adapt it to the FREIA cryogenic infrastructure using a buffer helium tank and using liquid nitrogen for the thermal shield cooling.

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INTEGRATION AND CM ASSEMBLY

The prototype DSR CM as well as later the series CMs equipped with the FPC and cold tuning system are shipped to FREIA, where each of them was then connected to the doorknob, the valve box, the cryo-plant and the high power system. The doorknob is located at a compact space right below the CM and therefore was installed on-site before moving the CM into the bunker. Its successful installation proves the feasibility of mechanical construction design and gives a standard procedure for future CM installations at ESS. Two vacuum pumping carts provided by ESS were then connected to the CM beam vacuum on both sides in a portable clean room which give the test a possibility of better pumping capacity during FPC conditioning. A residual gas analyser (RGA) device also connect to the CM beam vacuum in order to help with the leak diagnosis and outgassing monitor during FPC conditioning as well as warm-up.

Figure 2 shows one example of a DSR cryomodule installed at FREIA.

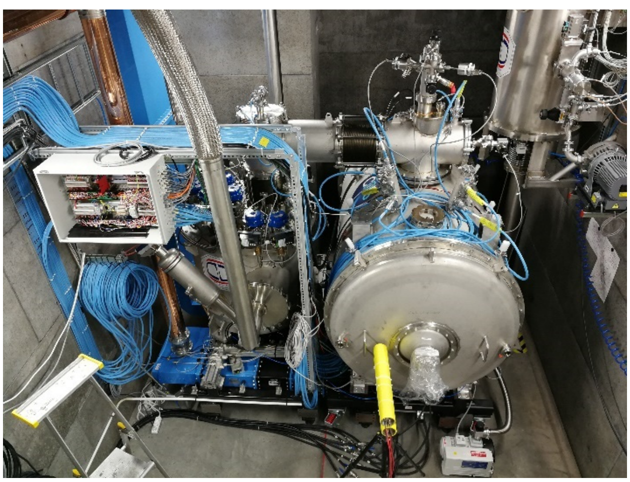

Figure 2: One ESS DSR spoke cryomodule at FREIA.

Statistics of cryomodule assembly is studied for both the prototype CM and 5 series CMs tested at FREIA. As a critical part for the CM acceptance test, CM installation and disconnection require well-planned schedules both in logistic and human source in advance. The CM installation itself requires a 4-day fulltime workload. However, in the case of ESS DSR series CM test at FREIA, the CM installation procedure usually takes more than a week in total and has become a limiting factor due to many reasons such as pandemic, overlap of two CMs' mechanical work and lack of man power.

HIGH POWER PERFORMANCE

A total of 26 DSRs, grouped in pairs in 13 cryomodules, aim for accelerating the proton beam from 90 to 216 MeV between the normal conducting section and the elliptical superconducting cavities. According to the cryogenic design, this DSR should have a dynamic heat load less than 2.5 W at 2 K with respect to a goal of quality factor of 1.5×10^9 at a nominal gradient of 9 MV/m. Since 2019, FREIA has been undergoing of the acceptance tests of 6 ESS cryomodules, including the prototype cryomodule. The statistics study of CM test time study is shown in Figure 3. According to the testing experience, the average overall testing time for a CM is around 7.1 weeks (actual time), which is slightly longer than the expectation of 6 weeks. However, longer spare and waist time is inevitable especially during the beginning of CM mass production. The major reasons for extra time are due to overlap of two CMs' test, repair of malfunctional components and extra investigation for unexpected situations.

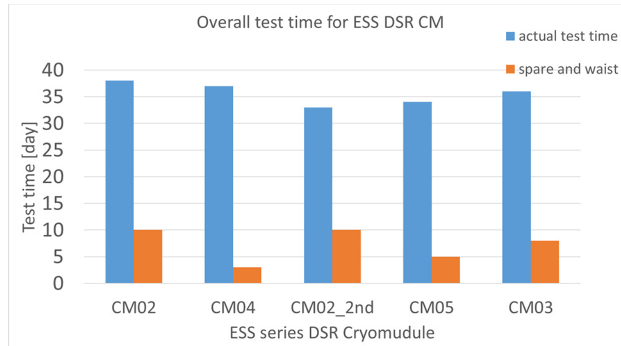

Figure 3: Statistics study of overall test time for ESS DSR CM.

RF Conditioning

At FREIA the FPC conditioning is done in an open loop with standing wave regime at 14 Hz repetition rate. In order to avoid electromagnetic field building in the cavity, RF frequencies of 353 MHz, way outside the cavity bandwidth, were chose for room temperature and 2 K. In addition, the cavity field level was always monitored to prevent accidental powering in the cavity. Both arc detector and electron pickups are equipped as interlock protection and found to be sufficient during the FPC conditioning.

The FPC conditioning of each cavity inside the CM was conducted one after the other for the prototype CM due to the limited pumping capacity and availability of the RF power stations. Unfortunately, severe cross-contamination has been found and the total conditioning period is about 4 weeks (real time) [10]. We realize that FPC conditioning has become the most time-consuming part throughout the whole CM test. To accomplish the test within schedule, shortening the FPC conditioning with high efficiency is obviously the biggest challenge. Therefore, for the series CM, a strategy of simultaneous FPC conditioning has been applied. Following 4 major actions have been carried out:

1) Two pumping carts are installed on both side of the CM in order to improve the pumping.
2) In order to minimize the time for FPC conditioning, some embedded safety program was implemented in the current conditioning system, such as a watchdog program which can cut the RF whenever the software is non-responsive. This upgrade version allows for a reliable automatic conditioning running 24 hours without supervision.

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3) Most of the system issues, like blocked flow meters, trouble shooting of the high power station, and communication or hardware issues in LLRF were localized and solved.
4) Better coordination to minimize technical intervention.

Thanks to above improvement, the overall FPC warm conditioning time is shortened to around 4 days, as shown in Figure 4.

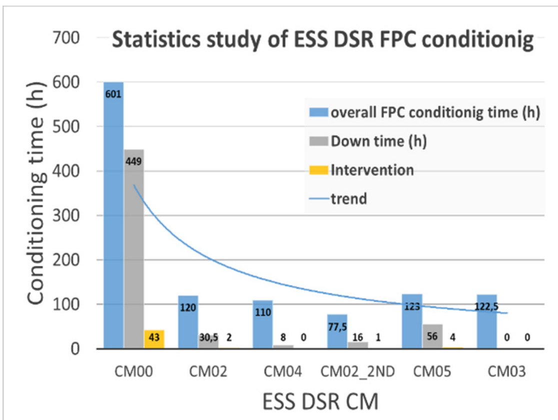

Figure 4: FPC Conditioning study at FREIA.

Cooldown

The DSR CM cooldown from room temperature normally takes 2 days. Before the LHe cooldown of the cavity, the LN2 shield is cooled from room temperature to 80 K within 3-4 hr. After that, the system takes about 24 hr in average to reach stabilization at 4 K with LHe and takes another 3 hr on the second day for the whole system fully cooldown to 2K. To avoid risk of Q-disease, a cooling rate greater than 1 K/min is achieved around 100 K region.

High Power Measurement

The quality factor measurement of the ESS DSR cryomodule is based on the calorimetrical method, where the liquid helium evaporation is measured via the flowmeter placed after the sub-atmospheric pumps. Both cavities in a CM were having the CTS engaged then operated with 14 Hz pulse repetition rate and 3.2 ms duration.

The preliminary statistics study of ESS DSR CM performance are shown in Figure 5 and Figure 6. In general, the dynamic heat load measurement showed that the cavity power consumption is less than 1W at the nominal gradient and is way better than the ESS target of 2.5 W. It proves the success of cavity post-processing procedure and cryomodule assembly. Therefore, the static heat load becomes the dominating part to be considered for ESS DSR CM section. Please note that the LN_2 thermal shield applied at FREIA is 80 K which differs from the ESS tunnel operation of 40 K. The real static heat load presenting during ESS commissioning is expected to be 1-2 W lower than the observed value at FREIA test stand. It is concluded that Q_0 estimation by the mass flow cannot provide an enough resolution if the dynamic heat load is below 1 W. It is not possible to see a difference among the heat loads when at low gradients and only a few points within the potential operating gradient range from 8 to 12 MV/m are chose for the quality factor measurement.

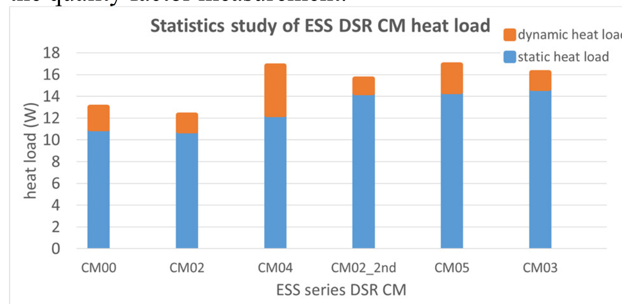

Figure 5: Preliminary statistics study of ESS DSR CM heat load.

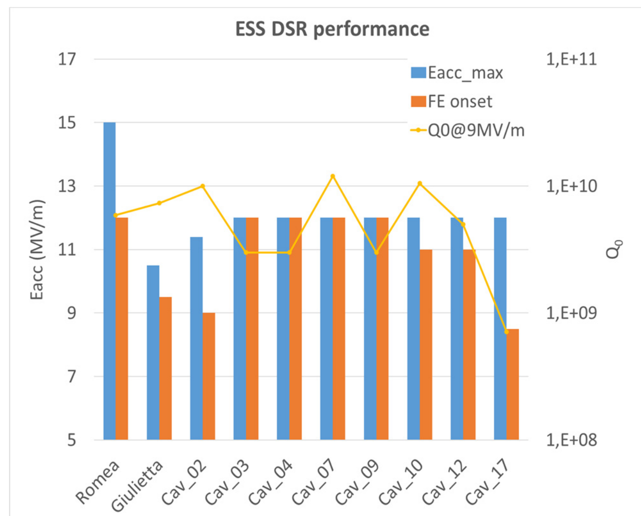

Figure 6: ESS DSR performance.

ISSUES AND RISK

CTS

The CTS function with cavity is fully studied [11]. Throughout the tests of the DSR CM at 2 K, the CTS is tuned to the target frequency every day before RF measurements and then is fully released during work-off time for safety. The repeatability of the stepper tuner is therefore studied via VNA and a crucial issue of CTS malfunction is found. So far, 3 out of 12 CTSs showed strange behaviour. One requires double driving current while the other two suffered with stuck motor. In this case, disengage system is activated in order to release the slow tuner from the stuck point. Two CMs were returned back to IJClab Orsay for further study and repair due to the stuck tuner. On the other hand, all the turning range of working stepper motor is sufficient for frequency pre-tuning, which obviously provides an easy operation in the ESS tunnel.

External Quality Factor

The specification for ESS DSR Q_{ext} is within the range of $1.75–2.85\cdot10^5$ adapted to the optimal beam current of

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62.5 mA. The External quality factor (Q_{ext}) of the FPC is monitored via S parameter method by VNA at room temperature. After cold down this value is double checked both by VNA and cavity field decay measurement. All Q_{ext} measurement results at room temperature show consistent with those from the outgoing test at Orsay and within the specification. However, several FPCs showed unexpected low Qext value (about 20% lower the measured value at warm) after cooldown which caused about 20-30% more power consumption. The reason is still unknown and the corresponding investigation is ongoing.

Beam Vacuum Leakage

A leak issue has been addressed during the ESS DRS CM test. One DRS CM (CM03) was identified a leakage during the CM assembly before shipping to Uppsala. Another CM (CM04) was found leaky at cold test at FREIA. So far, the reason has been localized at the double-wall tube of the FPC. This FPC is designed with a double-wall structure within which space will be filled with He gas for FPC cooling purpose. However, this complicate structure lead to a welding challenge at the conjoint area between double-wall and flange. Helium leak might happen if the inner-wall-to-flange connection part is not welded thoroughly. More careful welding procedure and strict quality control is then necessary to be developed for future FPC production.

CONCLUSION

FREIA has successfully tested the first DSR prototype cryomodule and is now busy with the series CM acceptance tests. Many experience and fruitful results are obtained from the prototype CM and the first 5 CMs test.

The average overall test time for each CM is around 7.1 weeks and can be improved by stressed on the mechanical installation/disconnection. All CMs show an excellent performance with a max accelerating gradience higher than nominal value of 9 MV/m and most reach 12 MV/m. The plausible dynamic heat load lower than 1 W at nominal gradient is way better than the ESS target of 2.5 W. The static heat load of about 14 W at FREIA with an 80 K thermal shielding and is the major consideration for heat load for ESS.

However, some issues are found, such as malfunctional CTS, unexpected lower Q_{ext} of FPC and the risk of leakage of the FPC double-wall structure. All these issues have addressed and under investigation.

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