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THE INTEGRATION AND RF CONDITIONING OF THE ESS DOUBLE-SPOKE PROTOTYPE CRYOMODULE AT FREIA

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Abstract

The European Spallation Source (ESS), will adopt a single family of double-spoke cavities for accelerating the proton beam from 90 to 216 MeV between the normal conducting section and the elliptical superconducting cavities. They will be the first double-spoke cavities in the world to be commissioned for a high power proton accelerator. The first double-spoke cavity cryomodule for the ESS project is under high power test at Uppsala University. This paper presents the experience with the prototype cryomodule including integration and RF conditioning.

INTRODUCTION

Superconducting spoke cavities have some unique advantages and are considered to be used in worldwide proton accelerators such as ESS, PIP-II and CiADS [1][2][3][4]. However, as a new resonator structure, the knowledge of the spoke cavity is not as extensive as for the elliptical cavity technology.

ESS will be the first accelerator to be equipped with double-spoke cavities in the world. The superconducting double-spoke section of the ESS linac increases the proton beam energy from 90 to 216 MeV, β = 0.41 to 0.58, from the normal conducting section to the elliptical superconducting cavities. This section adopts bulk niobium double-spoke cavities, a total of 26 cavities, grouped by 2 in 13 cryomodules (CMs) [5].

The ESS double-spoke CM is designed and fabricated by IPN Orsay, France. The testing of the prototype and series CMs is performed at Uppsala University, Sweden, where the Facility for Research Instrumentation and Accelerator development (FREIA) was established for the development of instrumentation and accelerator technology [6]. This test represents an important verification milestone before the ESS tunnel assembly.

The high power test-stand at FREIA for the ESS double-spoke prototype CM consists of two high power RF stations running with tetrode tubes, two high power circulator protection devices, a water cooling system, a load, a cryo-plant and two low level radio frequency (LLRF) systems based on either self-excited loop (SEL) or open loop. The object of this test thus becomes the validation of the complete RF-cavity chain consisting of high power RF amplifier, high power RF distribution, fundamental power coupler (FPC), double-spoke cavity CM, cold tuning system (CTS), and LLRF system.

SUPERCONDUCTING CAVITIES

The basic design parameters for the ESS double-spoke cavity are listed in Table 1[3]:

Table 1: Main Parameters of Double-spoke Cavities

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

Two double-spoke cavities have been fabricated and installed in the prototype CM. Both cavities completed their own vertical test at IPN Orsay with an excellent performance. Both cavities showed promising quality factors of about 8×109 and a maximum Eacc above 12 MV/m [7]. One cavity was previously tested at FREIA with its power coupler [8].

SYSTEM INTEGRATION

A prototype valve box was installed and was connected to the FREIA cryo-plant where it will be permanently located for the coming 13 series CM acceptance testing [7]. The prototype valve box is slightly modified from the final series to adapt it to the FREIA infrastructure using a buffer helium tank and using liquid nitrogen for the thermal shield cooling. Several cryogenic experiments of this valve box were accomplished at FREIA in order to check the performance of the instrumentation and equipment inside after the long distance shipping as well as the leak-tightness of all piping. However, while working at 4 K, the presence of thermo-acoustic oscillations was found. In order to reduce this effect, a small volume with a needle valve was added to an existing pipe. The prototype CM equipped with the FPC and cold tuning system was shipped to FREIA, where it 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 FREIA and ESS. A vacuum pumping cart provided by ESS was then connected to the CM beam vacuum in a portable clean room.

Figure 1 shows the prototype CM and valve box installed at FREIA.

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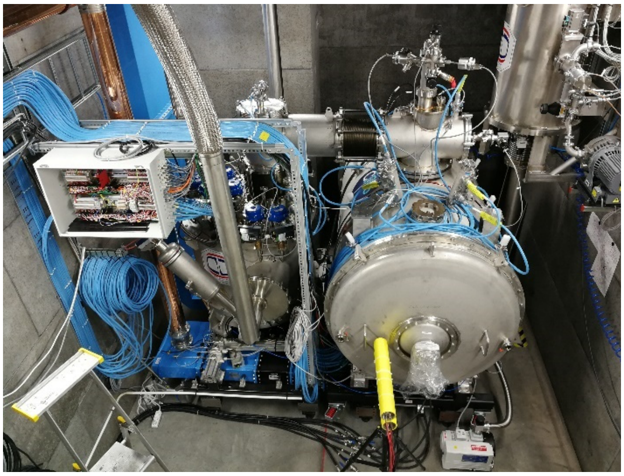

Figure 1: The ESS prototype double-spoke CM at FREIA.

FPC CONDITIONING

FPC Conditioning Algorithm

The FPC RF power processing both at room temperature and 4K were thoroughly completed before the high power RF test. Limited by the pumping capacity and availability of the RF power stations, the FPC conditioning of each cavity inside the CM was conducted one after the other. The FPC conditioning at FREIA is done in an open loop with standing wave regime at 14 Hz repetition rate. In order to avoid electromagnetic field build in the cavity, RF frequencies of 353 MHz, way outside the cavity bandwidth, were chosen for at warm temperature and 4 K. In addition, the cavity field level was always monitored to prevent accidental powering to the cavity.

In order to reduce damage from destructive factors, the FPC's vacuum is chosen as a leading preventive indicator. A corresponding automatic conditioning system based on LabView software was developed and validated at FREIA [9]. The conditioning procedure started from pulse lengths of 20 µs and followed by ramping up to full pulse length of to 3200 µs. During each phase of selected pulse length, the power is started from a low value and then ramped up step by step depending on various operating parameters. Finally, the maximum power of 400 kW is reached to keep a margin from the ESS design maximum power of 360 kW.

Two software vacuum thresholds were adopted in this conditioning procedure. As long as the coupler vacuum kept below the first software threshold of 5E-7 mbar, RF power increased with a power increment of 0.1 dB. Once above the first software threshold, the controller held the RF output until the vacuum was recovered. Otherwise, RF power was decreased by 3 dB if the vacuum got worse, down to the second threshold at 5E-6 mbar. In this way, vacuum limits avoid local overheating or electrical arcing within the vacuum side, which otherwise would damage the fragile ceramic window in the coupler. The next phase should not be executed until the vacuum recovers below the first threshold. In parallel, an interlock system protected the RF components independently. Essential detective activities employed in the interlocks were electronic events, maximum forward power and vacuum. An arc detector on the ceramic window is under development and therefore was not adopted in this prototype test but will be integrated in the series CM test. The main FPC conditioning control parameters are shown in Table 2 .

Table 2: Main Parameters Of Double-spoke Cavity Conditioning

Parameter	Value
Pulse repeat rate (Hz)	14
Vacuum upper limit (mbar)	5e-6
Vacuum lower limit (mbar)	5e-7
pulse length step (µs)	20, 50, 100, 250, 500, 1000, 2000, 3200

FPC Conditioning Experience

The FPC conditioning of the prototype CM provides important guidance for the CM commissioning at the LINAC tunnel.

The FPCs warm conditioning was performed over a period of a few weeks, as shown in Figure 2. RF powering was only done during working hours, and technical interventions to the bunker and system troubleshooting caused additional down time. The effective time of warm RF processing for each FPC was about 70 hours, including one main conditioning and two re-conditionings.

The re-conditionings were necessary because individual FPC conditioning caused a significant cross-contamination between the two FPCs. The limited pumping capacity of only one pumping cart connected to one side of the CM is considered to be the major reason for this cross-contamination, the offline coupler is easily polluted by the outgassing produced by the one under conditioning. This outgassing was up to 5E-6 mbar and slowly recovered.

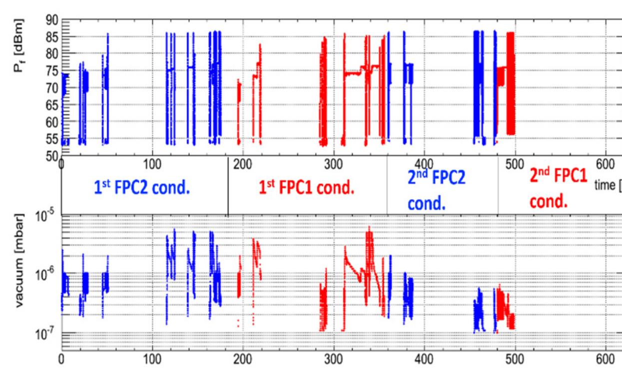

Figure 2: Time plot of the warm conditioning of the two FPCs of double-spoke CM

Figure 3 shows the warm conditioning history of one of the FPCs. Both in main conditioning and re-conditioning procedure, lots of outgassing occurred through the forward power region of 20-30kW at short pulses and 40-50kW at long pulses. These multipacting regions are consistent with those in the first high power test of the ESS double-spoke

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cavity at the FREIA test stand in 2017 [8]. The FPC processing at cold did not show substantial outgassing and took about 3 hours thanks to a thorough processing at warm.

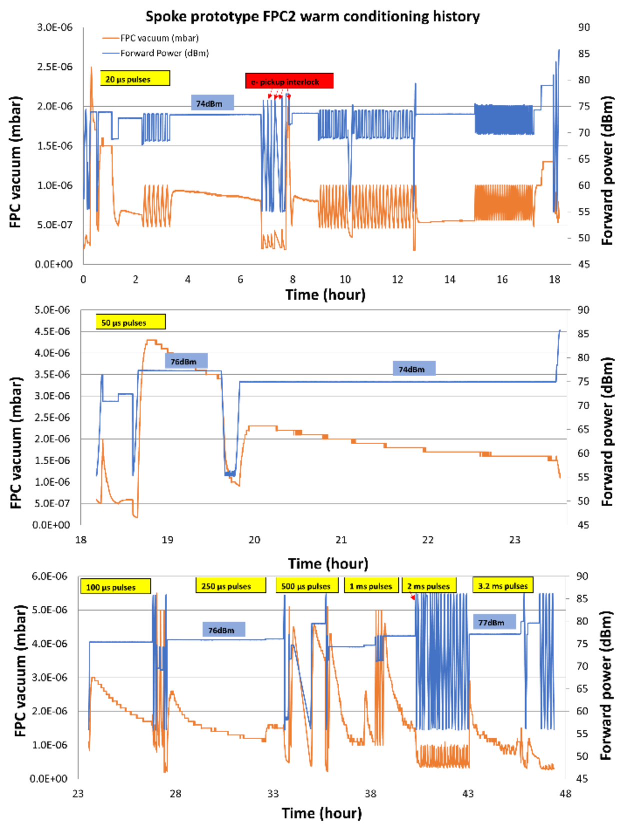

Figure 3: Main conditioning of FPC2 at warm temperature.

In order to minimize the time for FPC conditioning, some embedded safety program was implemented in the current conditioning software, such as a watchdog program which will cut the RF whenever the software is non-responsive for any reason. This upgrade version allows a reliable automatic conditioning running 24 hrs without supervision. On the other hand, several approaches are considered to further reduce the time: 1) Install a second pumping cart on the other side of the CM in order to condition two couplers simultaneously, 2) optimize the vacuum threshold and 3) pre-baking of the FPC up to 120 °C. Due to the consideration of preventing a degradation of cavity performance, the pre-baking option has been ruled out.

CAVITY CONDITIONING

The cavities RF conditioning used a SEL to lock the cavity resonant frequency without requiring a CTS feedback which was not yet available when starting the conditioning. In order to control different pulse duration in a pulse-mode operation in the SEL, a RF switch controlled by a programmable trigger signal is integrated into the circuit.

The first run of cavity conditioning was aiming for the cavity multipacting bands study which is independent of the operational temperature. Therefore, it was carried out at 4 K because of the easier operation mode of the cryogenic system. During the multipacting conditioning, a quench happened at a forward power around 24 kW and the quality factor of the cavity dropped down to critically coupled to the FPC. The SEL followed the cavity frequency and fed RF regardless of the frequency shift caused by the quench. Since a quench detection system was not included in the specification, the RF power was not cut by the interlock and continuous power of the order of 1 kW went into the cavity. Consequently, a helium pressure burst occurred which caused the safety valve to open and eventually the rupture disc to brake. This incident forced a warm up of the CM to room temperature and the broken rupture disk was replaced.

A quench detector system will be implemented into the FREIA high power test stand, especially when using the SEL. A slow interlock of helium pressure rise and a fast interlock of anomaly detection of the transmitted signal during a pulse has already been implemented. A more complete quench detector by monitoring the pulse-by-pulse loaded Q through the decay time is now under development and will be adopted for the series test [10].

The cavity conditioning is now ongoing at FREIA and after that related RF experiments will be done in the coming month.

CONCLUSION

The ESS double-spoke prototype CM is integrated with its all necessary ancillaries and is now under test at the FREIA Laboratory. Warm and cold RF conditioning up to full power levels for the FPCs have been demonstrated. Cross-contamination was observed during the individual FPC warm conditioning in sequence, which required a reconditioning. Several approaches to improve the FPC conditioning process are under study. A cavity quench occurred during the cavity multipacting conditioning causing a helium pressure rise and a rupture disc to burst. Several quench detection methods are being implemented in the test stand to prevent similar events in the future.

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REFERENCES

[1] J. R. Delayen, "Application of RF Superconductors to Linacs for High-Brightness Proton Beams", Nucl. Inst. Meth. B40/41 892-895 (1989).

[2] K. W. Shepard et al., "High-energy ion Linacs Based on Superconducting Spoke Cavities", Phys. Rev. ST-AB 6, 080101 (2003).

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[3] P. Duchesne et al., “Design of the 352 MHz, beta 0.50, double-spoke cavity for ESS”, in *Proc. SRF2013*, FRIOC01

[4] H.Li et al., ‘‘Development of a 325 MHz β=0.12 superconducting single spoke cavity for China-ADS’’, *Chinese Physics C* Vol. 38, No. 7 (2014) 077008

[5] ESS Technical Design Report, (2013); https://europeanspallationsource.se/accelerator-documents

[6] M. Olvegård et al., “Progress at the FREIA laboratory”, in *Proc. IPAC*2015, THPF081.

[7] P. Duthil et al., “Design And Prototyping Of The Spoke Cyromodule For Ess”, HB2016, WEAM4Y01

[8] H. Li et al., “High power testing of the first ESS spoke cavity package”, SRF2017,THPB035

[9] H. Li et al., “ESS Spoke Cavity Conditioning at FREIA”, in *Proc. IPAC2017*, MOPVA094.

[10] J. Branlard et al., “Superconducting cavity quench detection and prevention for the European XFEL”, in *Proc. ICALEPCS2013*, THPPC072