ESS SRF CAVITY PREPARATION FOR BEAM ON DUMP 2/BEAM ON TARGET PHASE

A. Zwozniak†, N. Elias, A. Krawczyk, C. Maiano, M. Nabywaniec, P. Pierini, H. Przybilski, M. Skiba, M. Wang, European Spallation Source, Lund, Sweden

Abstract

The ESS (European Spallation Source) is presently configured as a 1.3 GeV linac, with three superconducting cavity sections starting from 90 MeV. For the moment in operation, we have 82 superconducting cavities: 26 double spoke resonators (β=0.5), 36 medium and 20 high beta elliptical cavities (respectively β=0.67 and 0.86). In this paper we would like to present the restart of the Linac after 4 months of summer break and further cryomodule installations. During this time all data from previous Beam on Dump (BOD) run at 870 MeV was collected to have a better overview before BOD2/BOT (Beam on Dump 2/ Beam on Target). The Warm Coupler Conditioning (WCC) started in the middle of October 2025. In November 2025 the first cryomodule was tuned and restored to the nominal gradient, after the off-resonant Cold Coupler Conditioning (CCC). During this process the key performance indicators are compared to those obtained during the Site Acceptance Test (SAT) and the 2025 BOD.

GENERAL OVERVIEW

During the first phase of the ESS project for beam operation on the temporary dump (BOD) at 800 MeV, 27 cryomodules were installed and commissioned (13 spoke containing two cavities each, 9 medium and 5 high beta elliptical, containing 4 cavities each). This configuration can provide 2 MW beam power capability at the nominal energy of 870 MeV and 62.5 mA of current. The first cooldown was performed in late November 2024 and cavity preparation, conditioning and testing for beam operation occurred in the period between January and April 2025. Beam operation on the dump was carried until July 2025 [1, 2].

To move to the second phase of the project additional 6 high beta elliptical cryomodules were installed during summer 2025 [3], pushing the energy reach to 1.3 GeV and the beam power capability to 3 MW. No RF power sources are however presently available for these cryomodules, so their tuning and RF operation is postponed to a later stage, after the completion of the RF infrastructure. In November 2025 the linac was cooled down again and a further "Beam on Dump 2" (BOD2) operation phase was started.

For each cavity the crucial parameters of their RF performances were followed from the first measurement in vertical test, up to the last beam commissioning phases – an example for MBL-010 S1 (CM08 cavity M021) can be found in Table 1.

† agnieszka.zwozniak@ess.eu

Table 1: Cavity Calibration and Performance Tracking

	Qt	Ql	Eacc [MV/m]
Vertical test	3.63E11	-	12.8
TS2	2.39E11	7.7E5	11.1
Linac BOD	2.21E11	7.14E5	
Linac BOD2	2.25E11	7.1E5	11.1

Warm and Cold Coupler Conditioning

For the Linac we followed the standard cavity test procedure usually performed at the test stands where the performances are verified prior to installation. The preparation starts from the warm coupler conditioning (WCC) at room temperature, followed by a second round of non-resonant cold coupler conditioning (CCC) after the linac cooldown. For both coupler conditionings the total time was compared with the times spent at the test facilities. Comparison between the Lund Test-Stand 2 (TS2), BOD and BOD2 conditioning times can be found in Fig. 1 (WCC) and Fig. 2 (CCC). Generally a shorter conditioning time was needed after the TS2 initial operation, but for some systems the time needed for coupler conditioning in the linac was substantially longer, as a possible hint of particulate redistribution during the installation or handling operation.

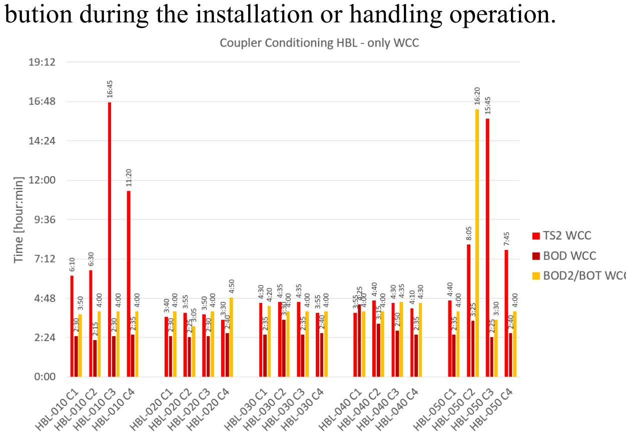

Figure 1: Comparison of the time needed for WCC between TS2, BOD and BOD2 (HB Section).

Cryogenic Operation

The cool down for the BOD2 started in November 2025 following an identical strategy to the one used during the first commissioning run [4, 5] where a distributed control architecture was used for the automated sequential process control, however this time with 6 additional cryomodules we integrated into the accelerator cryogenic system.

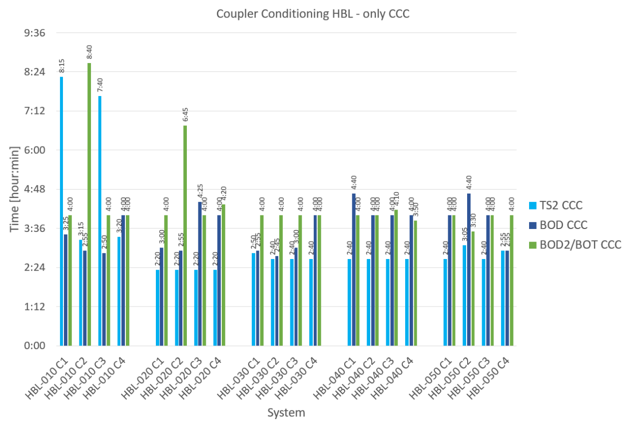

Figure 2: Comparison of the time needed for CCC between TS2, BOD and BOD2 (HB Section).

It took nearly 2 days for the initial cool-down from ambient temperature down to 4.2 K, followed liquid filling of the cavity tanks. Part of this time was used in parallel for the CCC. The cooldown to 2 K and subsequent stable operation was successful, taking advantage of independent pressure and level control within each cryomodule. Since during this run longer pulses and higher repetition rate are expected, a novel technique was introduced for compensation of dynamic heat loads using the cavity heaters. The cryogenic highlights and insights are presented in a dedicated paper [6].

Calibration and Cavity Conditioning

After coupler conditioning each cavity is tuned to resonance, using the ESS cavity tuning tools. More detailed description of tuning can be found in another paper [7]. After tuning the cavity gradient is calibrated in engineering units (MV/m) at low field with a rectangular RF pulse by use of the overcoupled cavity equations first computing the cavity Q_L from the field decay and then calculating the excited gradient from the forward power sent to the cavity. Then the PU calibration factor k_t is determined, to relate the accelerating field to the PU probe reading during the field rises. Comparison of k_t value for vertical test and both BOD and BOD2 phases can be found in Fig. 3.

The following relations are valid between the accelerating field E_{acc}, the calibration factor k_t, the cavity geometrical parameters R/Q and length L, the cavity frequency f, the cavity external coupling Q_L and the transmitted power level P_{trans} (equation 1 and 2).

$$E_{acc} = \frac{1}{L}\sqrt{4 \cdot P_{fwd} \cdot R/Q \cdot Q_L}\left(1 - e^{-\frac{\pi f t}{Q_L}}\right) \quad (1)$$

$$E_{acc} = k_t \cdot \sqrt{P_{trans}} \quad (2)$$

Finally, the $k_t$calibration factor is related to the cavity PU antenna $Q_t$by the relation (equation 3):

$$k_t = \frac{1}{L}\sqrt{\frac{R}{Q} Q_t} \quad (3)$$

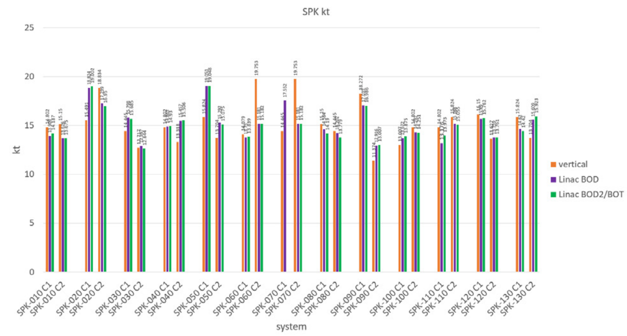

Figure 3: Comparison of the k_t values for Spoke section.

During the whole BOD phase all cavities have been operated with RF pulses of 1 ms length at the maximum repetition rate of 1 Hz, for the initial technical commissioning of the whole facility. For such RF pulse parameters the field stabilization with a LLRF feedback loop can be performed within the available power from the RF sources.

For the nominal ESS operation at the nominal RF pulse of 3.2 ms and 14 Hz Lorentz Force Detuning effects occur along the long pulse drive the power above the available levels provided by the RF sources.

The goal of the BOD2 phase is to establish the nominal operation with an RF pulse length of 3.2 ms and a repetition rate of 14 Hz, in order to commission the full LLRF including piezo Lorentz Force Detuning compensation and stabilization of long RF pulses up to the project specifications.

During the BOD and BOD2 technical commissioning stages the cavities were excited up to the maximum administrative power allowed by the coupler design and possible limiting mechanisms were compared with the experience at the test stands and the operational boundary of the cavities was determined. If necessary, proper actions are taken to avoid driving cavities towards breakdowns or quenches.

Handover to Operation

When all cavities were tuned and their operational envelope safeguarded, the system were handed over to the beam dynamics and operation teams to perform phase scan and accelerate the beam to one of the possible destinations along the linac, up to the Temporary Beam Dump (TBD).

Once the cavities were properly phased according to the ESS design, the nominal transmission of a 5 mA probe beam at 870 MeV out of the 27 cryomodules was obtained at the TBD.

Field Emission from Cavities

While some moderate field emission levels from cavities at the highest field levels were detected during the BOD phase, the higher RF duty cycle and pulse length used during the BOD2 phase led to a large increase of field emission level from the cavities, as shown in Fig. 4. During the cavity conditioning phases strong field emission burst can lead to multiple "global arc" interlocks detected by the plastic fibers monitoring the occurrence of arcs in the coupler region. The global arcs, tripping several dozens of cavities in a single event seem to be correlated to field emission burst that leads to Cherenkov radiation in the plastic fiber, triggering the photomultipliers in the gallery racks responsible for the protection to arc discharges in the coupler. Dedicated cavity processing time with increasing RF pulses and power levels is needed to condition these events.

One important mitigation factor to reduce the field emission buildup was to activate the high voltage bias of the couplers when multipacting (MP) activity was detected from the electron pickup of the couplers. Typically this occurs in the field decay portion of the pulse, when the field transition through the MP bands. Electrons emitted in the coupler region can be trapped by the cavity field lines and accelerated to higher energies, contributing to the increase of the field emission background.

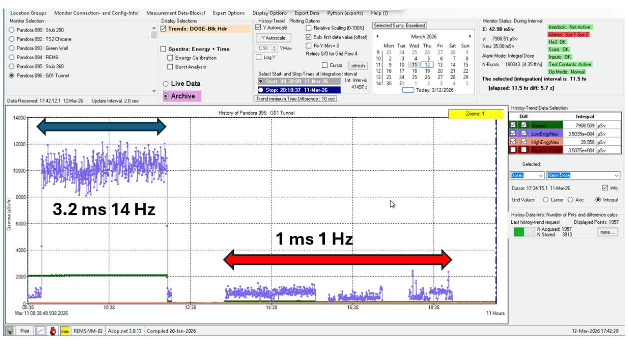

Figure 4: Comparison of the radiation level with the RF duty cycle.

SPOKE Slow Tuner Issue

Several slow tuner motors driving the cold tuning system of the spoke cavities failed during the acceptance tests of the cryomodules and were replaced before the module installation. An accelerated lifetime campaign performed at IJCLab confirmed that the chosen motor unit is possibly stressed above its capability by the stiff SPOKE cavities. While a long-term replacement is being explored at ESS, motor movement in the spoke section is administratively controlled to limit it to the minimum required. However, during the detuning and retuning operation needed by the thermal cycles between the BOD and BOD2 runs one motor unit failed, and for several others the drive current was increased above the nominal values (indicating a possible deterioration of the gearbox coating).

The standard procedure at ESS is to follow tuner sensitivity and frequency change (Fig. 5) during cavity tuning, in order to detect whether the system is behaving as it should, whether there are any deviations, e.g. loss of steps, large hysteresis and system thermal response to tuning and motor action.

Currently at ESS a dedicate liquid nitrogen cryostat is being set up to test a new slow tuner motor solution for the tuning system, based on the successive qualification of the LCLS-II HE motors [8]. The mechanical adaptation of the motor interfaces to the spoke motor interface has been agreed with the vendor and the first batch of units for starting an accelerated lifetime campaign is under production.

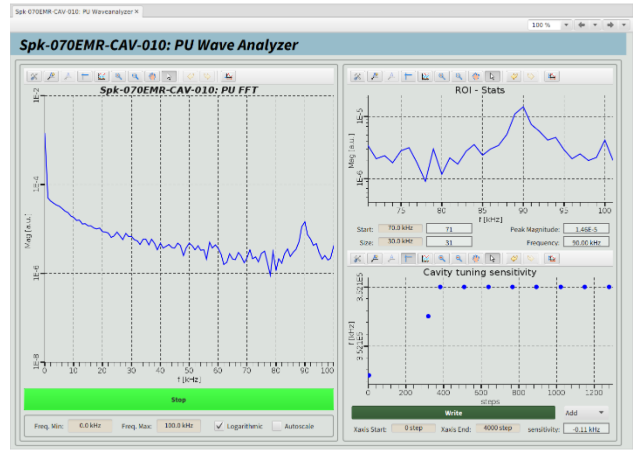

Figure 5: Sensitivity plot and FFT plots used during cavity tuning.

CONCLUSION

All 82 ESS SRF linac cavities have been conditioned to nominal RF pulse length of 3.2 ms with repetition rate of 14 Hz, with piezo to compensate the Lorentz Force Detuning and HV coupler bias to prevent occurrence of multipacting phenomena along the cavity decay.

During the Beam on Dump 2 phase the cavities performance was compared to those obtained during the previous Beam on Dump campaign and during the qualification at the test stand, to track the onset of possible degradation phenomena.

Additional test and analysis over the large amount of operational data are still ongoing, in parallel with normal Linac operation, to better understand future operational needs aimed at maintaining a high linac availability.

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