OPERATIONAL EXPERIENCE WITH THE COLD TUNING SYSTEM FOR ESS SUPERCONDUCTING CAVITIES

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Abstract

The European Spallation Source (ESS) is undergoing its next technical commissioning run, with the goal of achieving first Beam On Target (BOT). This milestone requires the full superconducting linac—27 cryomodules consisting of 26 Spoke, 36 Medium-Beta, and 20 High-Beta cavities—to achieve nominal parameters. This paper presents a statistical study of the Cold Tuning System (CTS) based on data from repeated tuning and detuning operations. The analysis focuses on tuning methodology and key parameters, assessing its repeatability and stability. The results provide a detailed characterisation of each CTS, ensuring stable cavity fields.

INTRODUCTION

The European Spallation Source (ESS) [1] is constructing a 5 MW superconducting proton linac that will comprise in future 43 cryomodules to accelerate the beam to 2.0 GeV. Between December 2024 and June 2025, ESS completed a major commissioning run that delivered the first beam on dump (BOD) at energies above 800 MeV. This campaign demonstrated stable operation of the cryogenic plant, RF systems, and superconducting cavities under integrated conditions [2] [3].

The next commissioning phase (BOD2) begins in November 2025 and will focus on achieving nominal RF pulse parameters (14 Hz, 3.2 ms). This phase will prepare the facility for the first beam on target (BOT), planned for January 2027, marking the transition toward high-power operations [3].

COLD TUNING SYSTEM

The cold tuning system (CTS) for the ESS superconducting cavities is based on proven CEA tuner design. For slow mechanical tuning, it uses a stepper motor, gearbox, and main screw assembly to drive lever arms and eccentric shafts to alter the cavity frequency. Additionally, two piezo actuators provide fast tuning to actively counteract dynamic Lorentz force detuning - essential for pulsed operations (Fig. 1) [4].

A key mechanical difference in CTS design exists between the Spoke and Elliptical cavities. The MBL and HBL cavities are pre-tuned and operate with all mechanical play removed. In this configuration, the tuner must apply a positive frequency shift of 120–220 kHz to bring the cavity to its nominal operating frequency.

In contrast, the CTS Spoke cavities operate from a mechanically free state, without initial pre-tensioning or closed mechanical play.

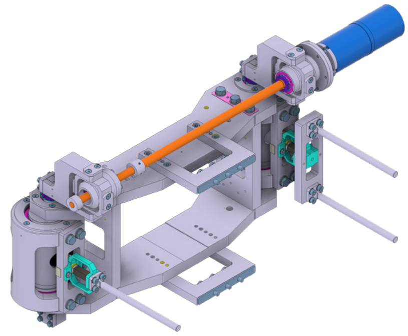

Figure 1: CTS CAD model of elliptical cavities with coloured stepper motor (blue), drive screw (orange) and piezo actuator (turquoise).

The CTS works under vacuum at cryogenic temperature, thermalizing near 18 K for MBL/HBL and 60 K for the Spoke cavities. The system converts motor rotation into cavity elongation through a sequence of reduction stages - gearbox, drive screw, and lever mechanism - which together define the tuning resolution, as listed in Table 1.

Table 1: Cold Tuning System Parameters

Parameters	**Spk**	**MBL**	**HBL**
CTS sensitivity [kHz/mm]	135	217	197
Motor steps per turn	200	200	200
Gearbox ratio	256	100	100
Leverage ratio	20	17	17
Screw pitch [mm]	2	1.5	1.5
Resolution [Hz/step]	0.26	0.96	0.87

TUNING METHODOLOGY

ESS uses an FFT-based tuning method that analyses transmitted-power signals from the LLRF system, integrated into the EPICS control system. The procedure has three stages [5]:

- Far Tuning
  FFT identifies the detuned cavity as a distinct peak, and initial motor steps confirm the tuning direction.
- Signal Beating
  As the cavity approaches the drive frequency, the peak merges with the carrier, and time-domain beating provides a visual measure of the remaining detuning.

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- Fine Tuning

In the final stage, micro tuner movements flatten the phase across the RF pulse to achieve klystron synchronisation.

CTS CHARACTERISATION

Following cooldown to the nominal 2 K operating temperature, systematic tuning and detuning campaigns were carried out across the linac. CTS performance was evaluated using data from linac commissioning (BOD and BOD2) and from Site Acceptance Tests at ESS and FREIA. The analysis focuses on initial parking frequencies, the motor steps/turns needed, and the measured tuner sensitivity.

Motor Steps/Turns to Tune

The CTS showed high mechanical stability across repeated tuning cycles. Spoke cavities required a median of 3,400 screw turns to reach resonance, while the elliptical sections operated in step-based mode with medians of 170,085 steps for MBL and 217,250 steps for HBL (Fig. 2).

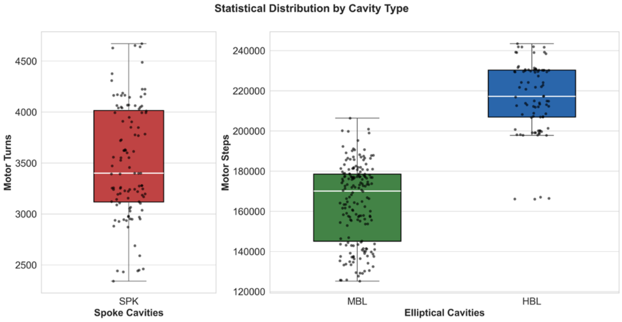

Figure 2: Comparison of tuning distributions for SPK (turns), MBL, and HBL (steps). Boxplots show medians and IQRs; strip plots show individual measurements.

These results confirm distinct but highly repeatable operational envelopes for each cavity type, as shown in Figure 3 for HBL cavities.

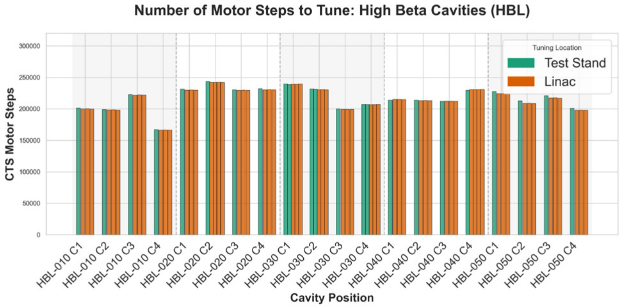

Figure 3: Tuning history for HBL cavities, comparing Test Stand (green) and linac installation (orange). Cavities grouped by cryomodule.

Parking Frequency

The CTS demonstrated good mechanical precision, with local repeatability better than 2 kHz for most SPK and many HBL cavities for tuning and detuning operations. Median parking frequencies are 83.0 kHz (SPK), 159.0 kHz (MBL), and 188.0 kHz (HBL) (Fig. 4).

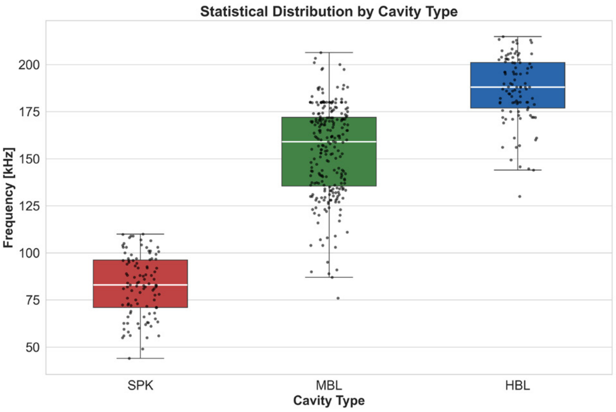

Figure 4: Parking frequency shift distributions for SPK, MBL, and HBL. Boxplots show medians and IQRs; strip plots show individual measurements.

The CTS showed high mechanical stability across repeated tuning, although systematic downward shift was observed in the MBL section, where transitions from Test Stand qualification to final linac installation produced frequency drops of up to 50 kHz, as illustrated in Fig. 5.

The higher MBL median relative to its mean, together with the large spread, suggest reduced mechanical stiffness within these cavities.

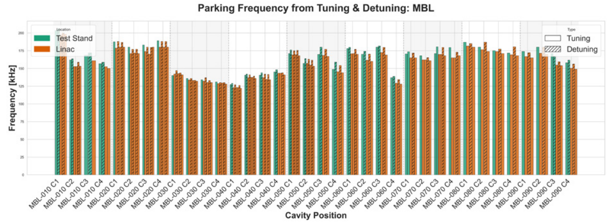

Figure 5: MBL tuning history comparing Test Stand (green) and linac installation (orange). Hatched markers indicate detuning measurements.

Tuning Sensitivity

Median sensitivity values for MBL, HBL, and SPK are 19.6, 17.5, and 7.5 kHz/turn, respectively. SPK shows the largest operational spread, while HBL demonstrates the highest consistency with the tightest distribution (Fig. 6).

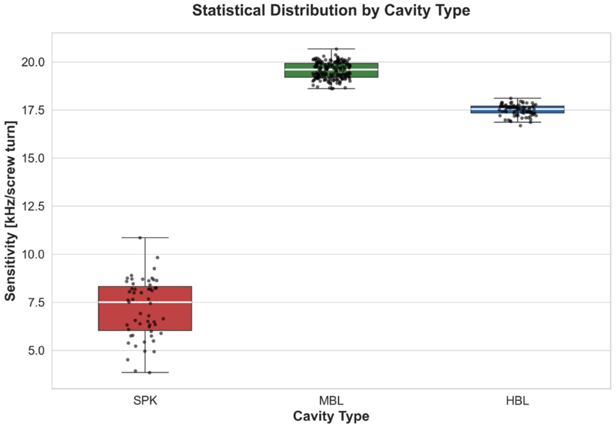

Figure 6: Tuning-sensitivity distributions for SPK, MBL, and HBL. Boxplots show medians and IQRs; strip plots show individual measurements.

OPERATIONAL PERFORMANCES

During linac commissioning, the CTS were subjected to cryogenic fluctuations and prolonged mechanical cycling, highlighting critical insights into their pressure sensitivities and mechanical stability. This section examines the CTS response to transient helium bath pressure variations, followed by an analysis of the mechanical reliability challenges encountered with the Spoke cavity tuning motors.

Pressure sensitivity

For superconducting cavities, the pressure sensitivity K_P characterizes how the cavity resonance frequency shifts in response to changes in the surrounding helium bath pressure. Variations in the liquid helium pressure elastically deform the cavity walls, altering the internal RF volume and shifting the resonance frequency [6].

From experimental measurements, K_P is determined by calculating the ratio of the resonant frequency shift Δf to the change in helium bath pressure ΔP:

$$K_p = \frac{\Delta f}{\Delta P} \quad . \tag{2}$$

During the pump-down of the cold linac to 2 K, an FFT analysis was performed to track the peak resonance frequency as a function of helium-bath pressure. Figures 7 and 8 show calculated pressure sensitivity coefficients K_p.

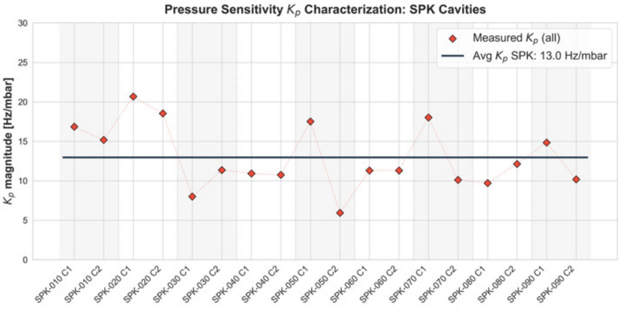

Figure 7: Pressure sensitivity K_p for Spoke cavities.

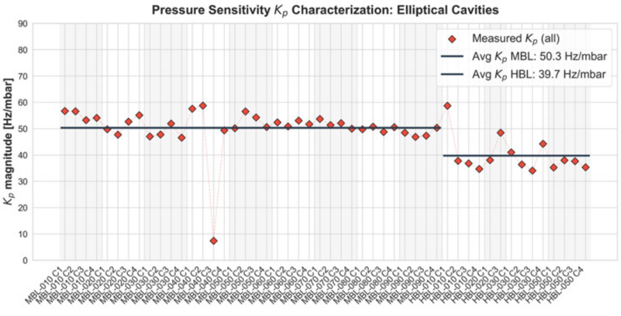

Figure 8: Pressure sensitivity K_p for MBL/HBL cavities.

The measurements show clear differences in pressure sensitivity across the cavity types: the MBL and HBL cavities have mean values of 50.3 Hz/mbar and 39.7 Hz/mbar, while the Spoke cavities show a lower sensitivity of 13.0 Hz/mbar.

Response to Pressure Transients

During commissioning, temporary 4 K warmups from unplanned cryoplant trips to scheduled maintenance caused large helium bath pressure swings (from 31 to over 1000 mbar). During these 4 K excursions, cavities stayed tuned but pressure fluctuations induce mechanical hysteresis in the CTS assembly.

As a result, returning to nominal 2 K operations requires systematic verification and fine-tuning (Fig. 9). Elliptical cavities (MBL and HBL) typically experience positive detuning, requiring negative motor step corrections. Planned warmups cause less detuning than abrupt cryoplant trips; for example, a planned warmup required corrections in only 17 of 36 MBL cavities, whereas an abrupt trip required adjustments across all of them.

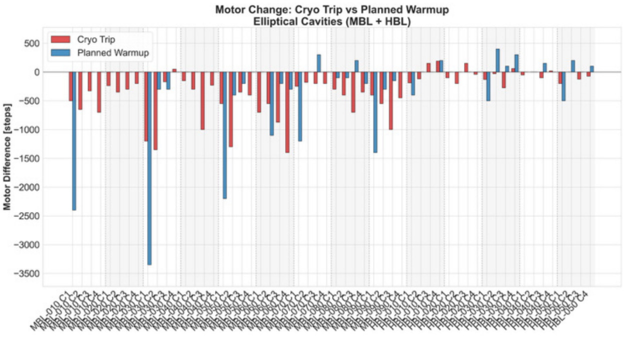

Figure 9: Motor step adjustments following a 4 K pressure transient. Negative step values indicate positive frequency detuning at RF restart.

Spoke Motor Failures

Reliability issues with spoke cavity tuning motors were first identified in late 2021 at Freia, primarily caused by thermal contraction issues from temperature sensor copper collars. As an immediate mitigation before Spoke cryomodule installation in the tunnel, the copper collars were removed, and sensors were mounted directly to motor wires.

Despite these interventions, motor failures continued during the BOD2 commissioning. The motor for cavity Spk-070-1 failed completely, leaving it untuned and excluded from beam operations. A second motor, Spk-100-2, shows similar pre-failure symptoms, stalling during fine-tuning until drive current was increased from 0.6 A to 0.9 A. To resolve these ongoing issues, ESS is currently developing a dedicated test stand to design and validate long-term hardware solutions.

CONCLUSION

The commissioning of the ESS superconducting linac has confirmed the mechanical repeatability of the CTS. Although extensive characterization has already been completed, further data collection and analysis remain possible. The main engineering effort is currently directed toward resolving the Spoke motor failures to ensure long term system reliability.

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