ESS SCL FAST TUNING SYSTEM CHARACTERIZATION DURING LINAC COMMISSIONING

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Abstract

In this paper we present the results of European Spallation Source (ESS) Superconducting Linac (SCL) cavities measurements which allowed us to determine crucial parameters for future SCL operation and Low-Level Radio Frequency (LLRF) systems tuning. The campaign of measurements was performed during the SCL commissioning for the second beam on dump campaign and prior to beam on target. All the measurements taken involved the usage of the cavity fast tuning system – the piezo tuner. Additionally, measurements of mechanical modes were done for all cavity types, which allowed to determine their longitudinal natural frequencies and prepare accordingly for optimal piezo tuners usage in the presence of the Lorentz Force Detuning (LFD). To confirm the frequency range of possible LFD, the LFD coefficient has been determined, and to ensure the piezo tuners are able to compensate for it, their characterisation has been carried out. SCL cavities passband modes were measured, in order to fine tune notch filter frequency position for all cavity types (expected π-mode neighbour position shows, as expected, a natural spread due to small variation in the cavity geometries). Piezo capacitance as function of temperature was measured, which can be used as a fault tuning tool in case of piezo aging effects, causing unexpected cavity detuning at high gradient. The described tools and measurement outcome are presented with their future implementation in the ESS Linac environment.

GENERAL OVERVIEW

For the current ESS operation phase at 2 MW on the beam dump (BOD2) 27 cryomodules can be powered with RF in the linac, 13 spoke cryomodules containing 26 spoke cavities, 9 medium beta cryomodules containing 36 medium beta cavities and 5 high beta cryomodules containing 20 high beta elliptical cavities, for a total of 82 RF systems. Additional 6 high beta cryomodules with another 24 high beta cavities have been installed in the tunnel but will be kept detuned in this phase while the RF systems installation is being completed for the next commissioning stages. During the first ESS linac commissioning on the beam dump in 2024/2025 the piezo tuners were not used, as the RF pulse length was only limited to 1 ms and the Lorentz Force Detuning (LFD) at the nominal field could be compensated with the LLRF feedback operation. For BOD2 the RF pulse length was increased to the nominal value 3.2 ms and to compensate for the LFD piezo tuners were applied.

For a complete characterization of the piezo action the following tests were done:

- Capacitance measurements during cool down and warm up (carried out also during BOD)
- Characterization of the cavity mechanical modes
- LFD compensation
- Piezo tuner identification
- Cavity bandpass-modes identification

Capacitance Versus Temperature

Electrical properties of the piezo components can change over time and are connected to possible degradation phenomena. This allows the possibility to detect degradation of the piezo components by continuous monitoring the capacitance of the piezoelectric stacks. The capacitance at room temperature (300K) is usually 3-4 times higher than the value in operating conditions at 2K [1, 2].

Table 1 lists the capacitance values for 300K for the piezo stacks chosen for the different cavity sections.

Table 1: Capacitance Value Versus Temperature for Spoke and MB/HB Elliptical Cavities

	Piezo	**Capacitance at 300K [nF]**
SPOKE	Noliac NAC2022-H72	13860
MB/HB	Noliac NAC2022-H30	5540

Figure 1 shows the variation of the piezo capacitance for a specific MBL system during the cool down transients, as a function of the temperature. Data is shown for both cooldown campaigns in March 2025 (BOD) and November 2025 (BOD2), showing a reproducible behaviour. The nominal room temperature capacitance as specified by the piezo stack vendor is shown in the plot with a star. Each tuner contains two piezo actuators stacks (indicated with A and B) for fault redundancy and voltage derating.

A full statistical analysis of the capacitance measurement of all the cold tuning piezo systems is being performed, in order to implement a continuous monitoring system allowing to monitor component degradation and plan maintenance intervention to exchange them when needed.

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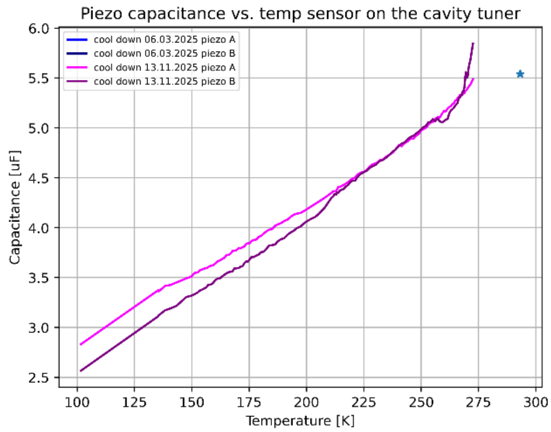

Figure 1: Example plot for Medium Beta Linac (MBL) cavity for piezo capacitance change during cool down

Mechanical Modes

Superconducting cavities are prone to mechanical vibration, due to their thin walls. Mechanical modes can be split to two types: transverse and longitudinal. Longitudinal modes that can lead to variations of the cavity length have a bigger impact on the cavity frequency. It is very important to localize these modes and to avoid their excitation during the piezo action for LFD compensation. Figure 2 shows the normalized detuning response of the spoke cavities to the frequency of the piezo excitation and illustrates the signature of the main mechanical modes for the spoke cavities. Most of the modes lie in the region between 280 and 330 Hz.

A measurement campaign is being performed during the current technical commissioning run in order to fully characterize the mechanical behaviour of all superconducting structures. Results for the elliptical sections require further analysis due to the much richer structure of possible mechanical modes in the multicell cavities.

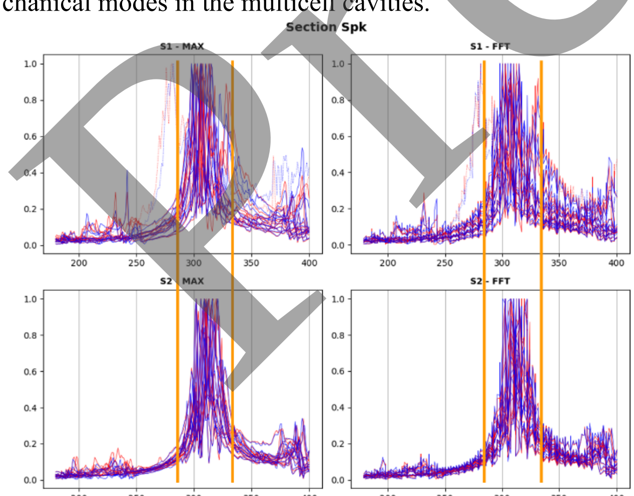

Figure 2: Mechanical modes for all spoke cavities

LFD Compensation

The mechanical pressure associated to the high field inside the cavity causes the deformation of the cavity wall and as a result, shifts the resonant frequency. The K_{LFD} (Lorentz Force Detuning Coefficient) depends on the design and construction of the cavity. To operate elliptical cavities at higher gradient and long RF pulses the LFD effect needs to be compensated with piezo to avoid excessive reactions of the feedback loop to the cavity detuning [3].

Table 2 presented the expected value for all types of cavities used at ESS Linac.

Table 2: Expected Values of the K_{LFD} Coefficients [4]

	$\mathbf{K_{LFD}}$ **[Hz/**$(\frac{MV}{m})^2$**]**
SPOKE	-5.1
MB	-1.8
HB	-1.0

It is worth noting that for the nominal accelerating fields of the three sections (respectively 9, 16.7 and 19.9 MV/m), the resulting static detuning corresponds to a considerable fraction of the cavity passband, thus needing a large power margin for its compensation with a pure feedback loop.

Figure 3 shows the comparison of the measurements in the high beta section with the expected value (shown in the red line). Variations of the measured LFD value can be attributed by small geometrical variation of the cavities (wall thickness reduction due to chemical preparation) and by the tuner preload (which depends to the final untuned cavity frequency at cold). A systematic analysis of the data gathered and correlation with the individual cavity frequency history is being performed.

Figure 3: Example of K_{LFD} for HB systems

Piezo Tuner Identification

To be sure that the piezo action will be sufficient to reduce the LFD for the minimization of the power needed for the LLRF stabilization with the feedback loop, a full characterization was performed in terms of: sensitivity, hysteresis, tuning range and polarity.

Polarity verification allows us to confirm that the piezoelectric actuators are connected correctly and respond in the expected direction. Hysteresis measurements provide information about the mechanical behaviour of the cavity–tuner system and may reveal differences in the mechanical structures or mounting conditions. The sensitivity, expressed as the achievable tuning range per applied voltage, determines the capability of the piezo system to compensate for the cavity detuning caused by Lorentz Force Detuning (LFD). For superconducting elliptical cavities, the expected compensation range should cover at least the cavity bandwidth, i.e., approximately 1 kHz. Table 3 summarizes the expected sensitivity values for spoke and elliptical cavities (when 2 piezos are running at the same time).

Table 3: Piezo Sensitivity

	Sensitivity [Hz/V]
SPOKE	5-6
MB/HB	7.5

Figure 4 presents the results of the piezo actuators characterization. For each change of the excitation voltage applied to the piezo element, the corresponding cavity detuning was measured. A hysteresis of approximately 20–30 V can be observed between the increasing and decreasing voltage characteristics. For the presented example, the achieved tuning range is 1165 Hz, corresponding to a sensitivity of approximately 7.4 Hz/V. The average sensitivity and hysteresis behaviour of the piezo stack is clearly visible in the butterfly diagram of Fig. 4.

Nominal piezo sensitivity has been verified across all the tested cavities.

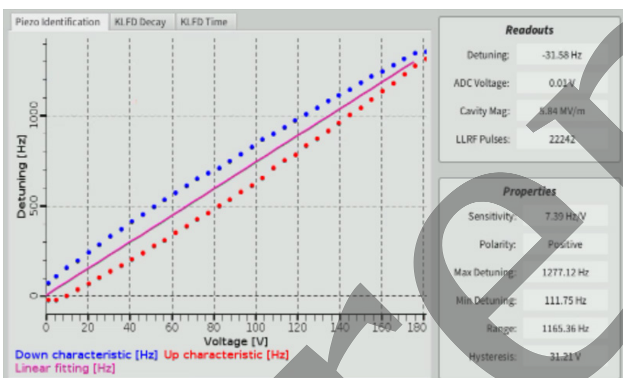

Figure 4: Example of piezo tuner identification

Cavity π-Mode Identification

While the multi-cell cavities operate at the frequency of the fundamental mode (π-mode), the frequency of the neighbouring mode in the bandpass ((N-1)π/N) lies typically within the bandwidth of the LLRF system and can be spuriously excited by it. This will cause high frequency ripples in the cavity field profile, caused by this spurious excitation. One common way to avoid this excitation is to apply a narrow-band notch filter which was applied into the LLRF system feedback loop, to avoid the harsh penalization of a low-pass filter.

Table 4 lists the nominal mode separation of the nearest neighbour for the elliptical cavities. Its precise value however varies for each cavity and for the notching to be efficient without limiting the LLRF performance the value of this mode needs to be determined individually for each cavity.

Cavity π-mode identification measurements allow us to determine the position of the nearest mode and for the configuration of the notch filter properties to avoid this spurious excitation [1,2] (Fig. 5).

Table 4: (N-1)π/N Mode for Elliptical Cavities

		Modes separation [MHz]
MB	5π/6	0.7
HB	4π/5	1.2

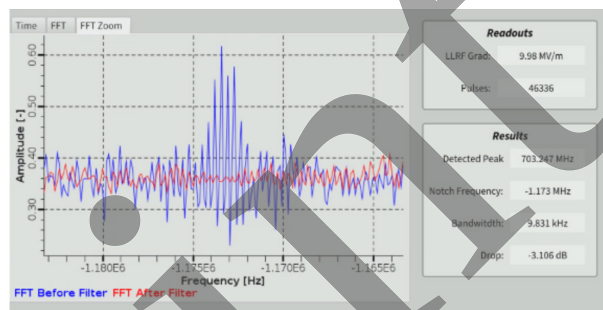

Figure 5: Example of the filtering 4π/5 mode for HB cavity, the peak of the mode was detected at -1.173 MHz from the carrier frequency (blue plot), after filtration (red plot), its amplitude has been reduced

CONCLUSION

A number of tools have been performed to characterize cavity and piezo performances for all 82 cavities currently available for the ESS operation at 2 MW. Most of the tools were developed at the TS2 test stand to check the correctness of the software and to verify the test procedures.

The results showed a solid consistency, but still some tests and simulations are ongoing to fully understand the operation needs.

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