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TUNING OF SUPERCONDUCTING CAVITIES USING THE FFT OF TRANSMITTED POWER

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Abstract

We implemented a method to tune the ESS superconducting cavities based on the spectral analysis of the high resolution data available from the Low Level RF system (LLRF) for the transmitted power, without the need of connecting a network analyzer or any other dedicated instrumentation along the RF chain. A frequency peak up to 4 MHz off from the resonating frequency can be detected and used to control the stepper motor of the tuner until the cavity is stretched to the proper length to reach the correct operation frequency. Experience of its use at the ESS Test Stand 2 (TS2) facility at Lund during cryomodule acceptance testing is presented.

INTRODUCTION

The European Spallation Source superconducting linac is composed by 36 elliptical cavities with geometric β of 0.67 and 84 elliptical cavities with geometric β of 0.86. The cavities are assembled in groups of 4 per each cryogenic module as described in [1,2] and operate at the frequency of 704.42 MHz, accelerating the proton beam from 216 MeV up to the 2 GeV.

Superconducting cavities are fabricated with a lower frequency than the operational one and, once cooled down in a bath of helium at 2.0 K, the thermal contraction brings them close to the goal frequency, but not with the needed accuracy imposed by the small cavity bandwidth. The final adjustment needs to be done with a tuner that stretches the cavity through the action of a step motor. In order to follow the tuning process, one of the standard techniques consists in monitoring the S21 cavity transmission with a Vector Network Analyzer (VNA). The use of VNA S21 requires either to modify the high power RF wave-guide distribution system (RFDS) inserting matched transitions and disconnecting the pickup cables, or to inject the signals from the strongly attenuated ports in the directional couplers of the RFDS, with additional amplifier stages. Both methods introduce risks in the linac installation (RFDS leaks, missing cable re-connections) and is time consuming.

In all modern LLRF systems the cavity pick up (PU) for the transmitted signal is available with a high sampling rate (~10 mega samples per second) along the pulse. Its analysis in the spectral domain provides sufficient accuracy to identify the narrow cavity resonance in the noisy pattern of the highly detuned (~200 band widths) system. The pulsed klystron power, which has a carrier frequency of 704.42 MHz, has Fourier components that fall into the cavity resonance, and these appear with a clear signature peak in the spectral analysis of the transmitted signal. A similar approach was used to tune the 1.3 GHz SRF cavities at the European XFEL, DASY, Hambourg, Germany [3].

THE FFT TECHNIQUE FOR TUNING

The technique is illustrated in Fig. 1, where the FFT of the transmitted power signal is shown at three different positions during the motion of the tuner. The signature peak of the detuned frequency in the upper plot is shifted of 45 kHz with respect to the 704.42 MHz design frequency, and in the lower plots it moves towards the klystron frequency due to the tuner motion.

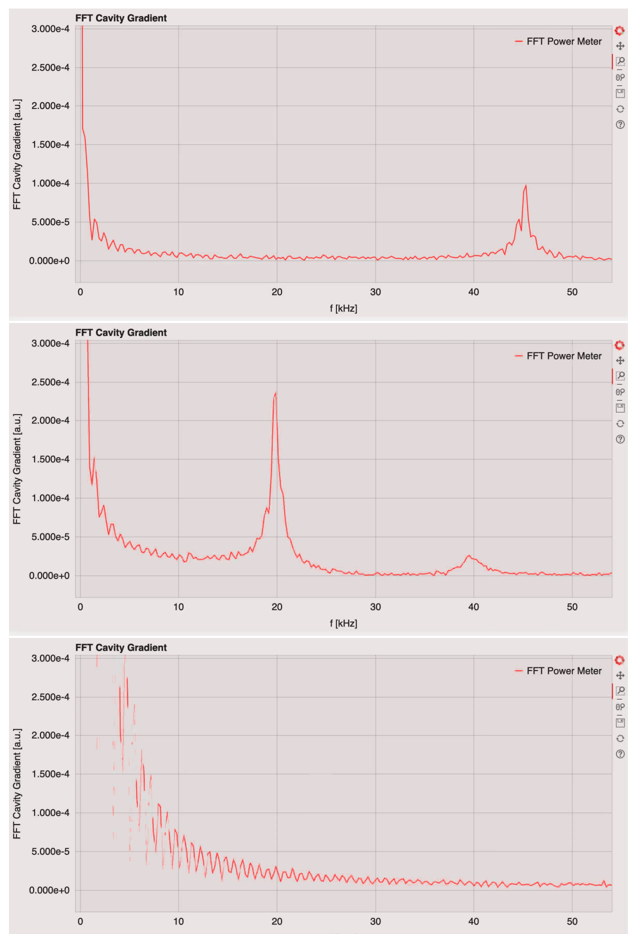

Figure 1: Fast Fourier Transform of the transmitted power in three moments of the tuning process for the 3rd cavity in the cryomodule CM01. The peak moves toward the zero (carrier RF frequency) when the cavity is approaching the driver frequency of the klystron, and in the last step it is no longer visible.

The method has been initially implemented at the ESS TS2 as a high level application that acquires (here at 1 Hz)

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the down-sampled transmitted power amplitude from the LLRF system, digitized in an array of 35000 samples with a sampling rate of 8.386 MHz in a 4.174 ms time window. The data is then subjected to an FFT transformation that has an un-aliased reach of approximately 4 MHz from the carrier frequency. DC component minimization is performed by subtraction of the mean value of the signal.

The analysis of the FFT data can isolate the cavity frequency signature that can be followed during the process and correlated to the motor position information to derive and verify the design frequency tuning coefficient.

Far Tuning

The cavity frequency depends on the tuner motor position, which is available in the control system as an EPICS Process Variable (PV). We are then able to evaluate the correlation of the frequency versus the number of steps and verify the linearity of the system over almost the full range [4], as shown in Fig. 2. The position of the stepper motor is indicated by

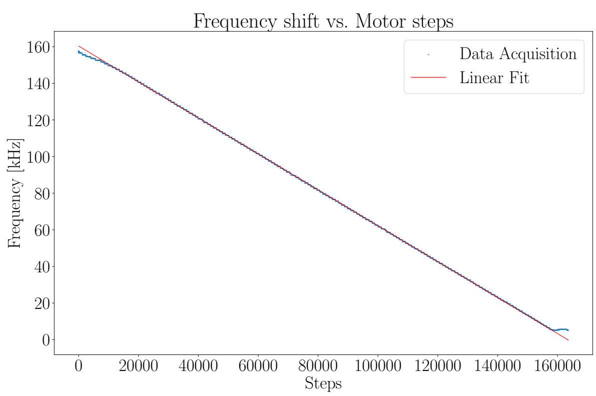

Figure 2: Frequency versus motor steps.

the number of full steps performed by the motor controller. A full turn of the motor axis corresponds to 200 full steps. The motor is equipped with a 1:100 gearbox to rotate the main tuner screw with a 1.5 mm pitch that actuates a double leverage system with ratio 1:17 which produces the cavity elongation. The combined effect of the cavity frequency sensitivity (217 kHz/mm) and the mechanical reduction results in a nominal design sensitivity of 190 Hz/motor turn (200 full steps), that is 0.95 Hz/full step.

The function that relates the frequency to the steps fits very well with an RMS error on the frequency of ± 10 Hz except for the two regions at the opposite extremes. At the beginning, when the tuning range is between 0 and 10000, the tuner did not establish a full mechanical coupling between the cavity and the tuner. At the ending of the range during the final tuning process between 158000 and 164000, the data can deviate from the linear behaviour due to the small mechanical hysteresis shown by the tuning leverage upon inversion of motion and due to the loss of accuracy in the peak identification when it reaches the carrier DC component.

The slope of the linear interpolation gives -0.98 Hz per full motor step that is comparable with the expected design value for the tuner of 0.95 Hz per full motor step [4].

Approach to Resonance

Once the detuning frequency is below 10 kHz the FFT analysis becomes unreliable because the detuned peak is too close to the DC component and the mechanical position may be affected by a small hysteresis if inversion occurs in the last steps of the tuning process.

When the cavity frequency is close to the drive klystron, the transmitted power starts to build up in the cavity and the small frequency difference between the cavity frequency and the driver frequency appears as a "beating" modulation over the transmitted power.

The number of beating peaks present in the transmitted power in 1 ms gives a visual indication of the approximate detuning frequency and allows a further adjustment with the sensitivity of 1 Hz/step. An example of three moments of this tuning process is represented in Fig. 3.

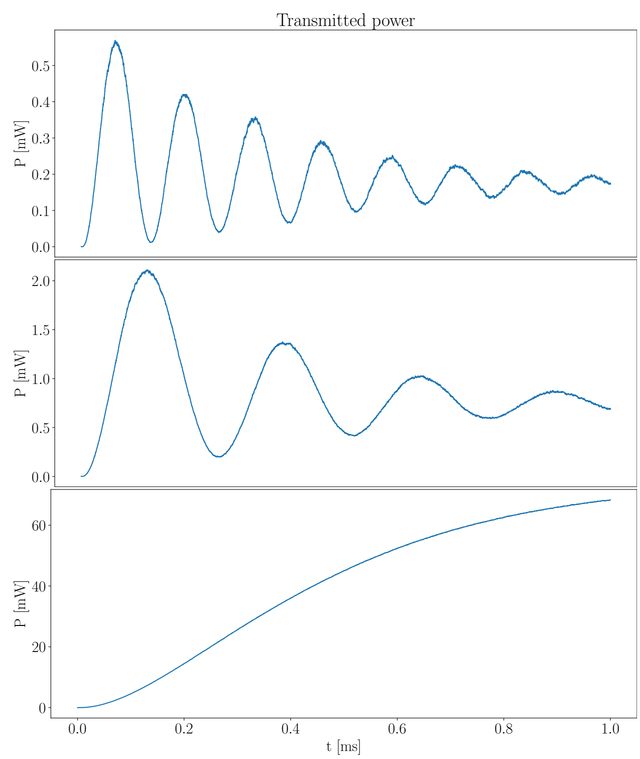

Figure 3: Amplitude of the transmitted power close to the resonance, in the first ms of the RF pulse. Top: the 8 peaks indicate a 8 kHz detuning. Middle: After correction of approximately 4000 steps the cavity has a remaining detuning of 4 kHz. Bottom: After a further tuning of 4000 steps the cavity is on resonance and the signal does not show oscillation, but the usual filling characteristic of an SRF cavity, with a long fill time.

Fine Tuning

When the cavity frequency approaches the klystron frequency within a fraction of its bandwidth (~1 kHz), the last

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tuning action can be performed by flattening the transmitted power phase. When the input and the transmitted power are at the same frequency the phase is flat, as it can be seen in Fig. 4.

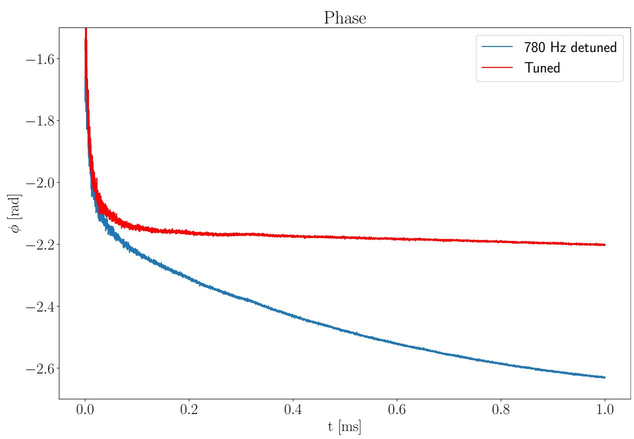

Figure 4: Fine tuning of the cavity in the last bandwidth fraction from the resonance. In blue the phase is not flat, it means that the input and the transmitted frequencies are not the same and the motor can be adjusted until the phase is flat as in the red plot. The detuning from the blue and the red plots was of 780 Hz.

EPICS IMPLEMENTATION

The method described above was developed during the TS2 testing of the first cryomodule (CM01) of the ESS series, after a direct frequency check with a VNA. The procedure was firstly implemented as a high level scripting application in Python.

After this successful test the method was ported to a full EPICS IOC module (based on the AreaDetector generic module) and a full EPICS graphic interface developed for the operations.

This version is now routinely used in the test facility to tune the 36 medium β and 84 high β cavities with the same conceptual procedure described in this paper, integrated in the operational screens as shown in Fig. 5. A further version is being developed for the regular commissioning of the superconducting linac.

CONCLUSIONS

We presented a procedure to tune the superconducting cavities of the ESS linac based on the FFT analysis of the transmitted power. The FFT is used during the far tuning to bring the system within reach of the klystron frequency from the parking position starting the cavity excitation. The frequency beating between the two systems is then used to approach the cavity bandwidth to the klystron frequency. Finally, the phase of the cavity is finely flattened in order to have the cavity to resonate exactly at the klystron frequency.

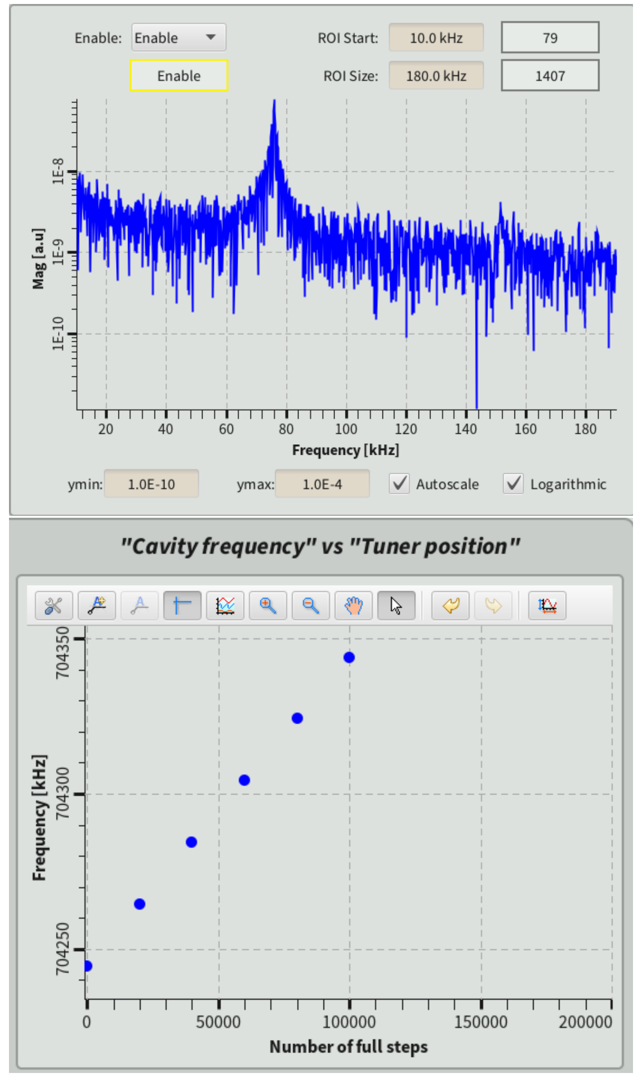

Figure 5: The FFT method implemented in the OPI for normal operations. Top: the frequency spectrum. Bottom: Frequency versus motor steps.

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