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RF CM TEST PROGRAM AT ESS TS2

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Abstract

We present here the RF test program of the ESS TS2. Several tools have been prepared at TS2 for the later stages of the technical commissioning in the Linac. Automated tools for tuning the cavities to resonance using spectral analysis or cavity gradient calibration have been deployed and tested to assist the later stages of commissioning.

INTRODUCTION

The Test Stand 2 (TS2) in Lund is dedicated to the site acceptance testing (SAT) of the medium and high beta elliptical cryomodules (CMs) for the ESS superconducting accelerator. Until now one prototype, seven series medium beta modules, and two series high beta modules have been successfully tested. This allowed the joint ESS and IFJ PAN team to develop all the procedures and the necessary automated tools for the different phases of the site acceptance test campaign (e.g., coupler conditioning, cavity tuning, calibration and cavity conditioning). The main components for the RF operation are here presented and described.

MODULE TEST AND RF OPERATION

RF operation of the module is performed after the installation in the TS2 bunker, which is a short replica of the ESS tunnel and linac RF environments. Differently than in the tunnel, the CM is attached to the Valve Box (VB) of the He distribution system by means of flanged connections, and two klystrons allow the powering of the four CM cavities. Each of the klystron can distribute power to two cavities, by means of a variable power divider.

Warm and cold coupler conditioning

RF operation on the module starts with the non-resonant coupler conditioning at warm to process possible coupler multipacting levels before cooldown and operation. Coupler conditioning is performed using an automated EPICS sequencer which uses the LLRF system in open loop to run through a cycle of steps as defined by CEA for the medium beta (MB) and high beta sequences (HB), while monitoring vacuum and other multipacting diagnostic signals provided by a biased electron pick-up by the arc detectors. Typically, vacuum level is used as a control loop parameter to determine the increase or decrease of the RF fields. In case of need the control loop parameters can extend to the multipacting diagnostic signals. The maximum power sent to the cavity in full reflection conditions (no beam) is limited to 300 kW for MB and 400 kW for HB for any RF pulse width longer than 500 us. Shorter RF pulse lengths are limited to 1.2 MW of peak power.

The conditioning sequence is also repeated after cooldown and prior to complete thermalization, before tuning the cavities. The resonant frequency of the cold cavities before tuning is sufficiently far from the klystron output to avoid cavity excitation.

The sequencer completes a full conditioning cycle in approximately 3.5 h/4 h (MB/HB), and thus 14 h/16 h of RF operation per module in each of the warm and cold conditioning stages are required before tuning the cavity to the operating frequency. Vacuum evolution and the occurrence of interlocks, or severe multipacting activity can increase the time needed for the conditioning of the RF surfaces [1].

The coupler conditioning sequence and operator user interface (OPI), shown in Fig. 1, allows to affect several parameters of the conditioning process, in order to speed up uneventful conditioning operations or to slow down during significant activity in the coupler region. The most frequently used are the power increase/decrease steps that can be, for example, changed to speed the cold coupler conditioning faster when warm coupler conditioning has led to no significant vacuum evolution.

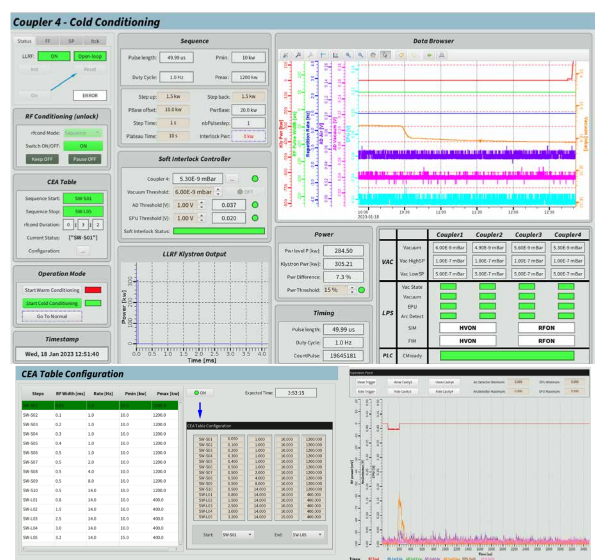

Figure 1: Coupler conditioning tools and steps. On the top the conditioning main OPI.At the bottom left : CEA predefined sequence for the high beta cryomodule conditioning in standing wave mode. At the bottom right: scope waveforms (available in EPICS) for the electron pick-up and the signals from the arc detectors placed at both sides of the coupler RF window.

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Figure 2 shows the evolution of a few key scalar values during an uneventful power coupler conditioning.

Figure 2: Coupler conditioning overview from top to bottom: magnitude of the forward power (red), duty cycle (green), RF pulse width (blue), vacuum (orange), arc detection (vacuum in magenta and air side in violet) and electron pick-up signals (cyan).

Cavity tuning

After the successful power coupler conditioning operations in warm and cold conditions and the establishment of the 2K operating environment, the cavities are tuned from resonance from their parking position.

The high-level far tuning tool is based on a Fourier analysis of the cavity pick-up signal to identify the cavity resonance when driving LLRF in open loop at the fixed machine frequency [2]. The user panel is shown in Fig. 3 and allows controlling the cavity tuning process without requiring the use of additional RF instrumentation (e.g., VNA) or the need to setup special frequency tracking modes in LLRF by PLL or SEL configurations. This provision greatly simplifies the technical commissioning and operation procedures in the accelerator. The tools only relies on the analysis of the cavity field signal and its postprocessing (by Fast Fourier Transform FFT), to detect the cavity signature from the broad frequency contents of the incoming RF pulse trains. The steps from parking frequency to resonance and tuning sensitivity are tracked and record during testing (as shown in Fig. 3), to be kept as reference for the Linac commissioning activities.

The ESS MB cavities have an approximate sensitivity of 1 Hz per full motor step, whereas the HB show 0.8 Hz per full motor step. The motor is a vacuum and cryogenic grade stepper motor equipped with a gearbox at 1:100 ratio. Motor speed is limited to 1.0 motor axis turn per second.

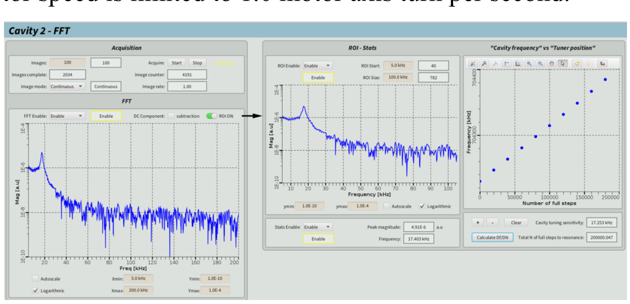

Figure 3: Cavity Far tuning interface. From left to right is FFT for cavity field signal, region of interest for peak detection, cavity sensitivity calculation by linear regression method.

Cavity Calibration

When the cavity has been brought to resonance the cavity signals are used to calibrate the cavity gradient in significant units for operation in the linac (i.e., accelerating field in MV/m), by using a calibration tool.

TS2 calibration relies both on the LLRF wide dynamic band RF receivers and off-the-shelf RF power monitoring to allow us make assessment of systematic calibration uncertainties. All power readings (P_f, P_r and P_t) are taken from the ports of several directional couplers along the RF path, both close to the RF sources and in front of the cavities. The cavity gradient E_{acc}, in the Engineering Units (EGU) of MV/m, is assessed through the implementation of several methods as shown below, which generally agree within 10~15%, as expected.

The calibration procedure starts with using the cold cable attenuation values and the vertical test (VT) pickup calibration as reported by the IK partners providing cavities to the project (INFN from MB and STFC for HB). The pickup power measured at the cavity from the LLRF system and the commercial power meters is used to derive the accelerating field in MV/m via the VT calibration coefficient and the Q_{ext} is computed from the cavity decay. New cavity calibration constants are evaluated:

- using the overcoupled calculations from a rectangular RF pulse of amplitude P_f;
- calculating the stored energy from the emitted power trace [5].

Figure 4 shows the calibration OPI, where the lower plots illustrate the discrepancies obtained from the VT and the CM estimations and the differences in the calibration constants. Typically, the VT values tend to overestimate the cavity gradients by ~10%.

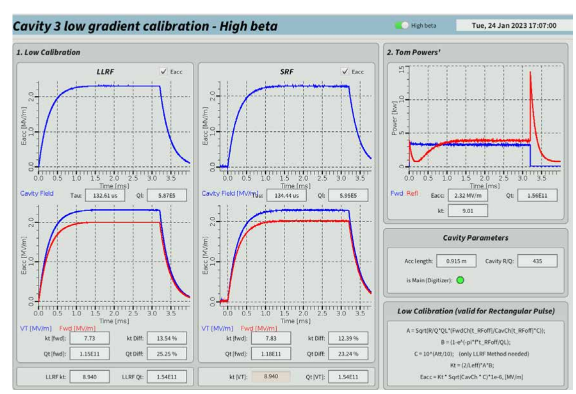

Figure 4: Initial cavity calibration using VT coefficients and computation of recalibration factors.

At this point the values obtained from the recalibration using the LLRF channels are then pushed to the control system to be used as new calibration values to convert all power readings in accelerating voltages in MV/m.

Once these new calibration coefficients are being used the operator can verify the alignment of the different estimations, using the different available channels. The remaining uncertainty of the different estimations at this point is typically in the range 2-7%.

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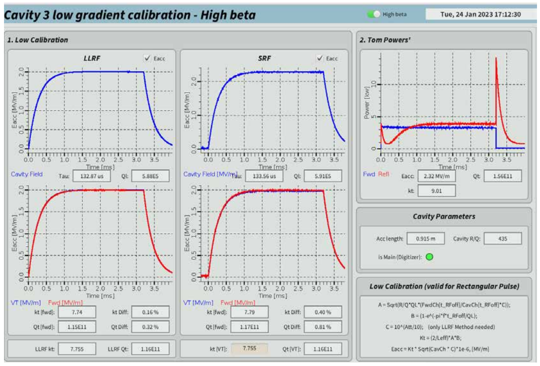

Figure 5: Traces after recalibration in cryomodule, both on the left and centre shown E_{acc} calibration using P_t read from LLRF and off-the-shelf SRF power meters. The loaded Q_L is computed from the decay and E_{acc} is assessed by the overcoupled relations. On the right the emitted power method, which relies on calculation of the stored energy, from the reflected power trace.

Cavity Conditioning

After performing the cavity calibration at low power, the cavities are usually conditioned one by one, up to nominal gradient in open loop, by increasing pulse length, duty cycle and ramping up RF forward power (feed-forward output method). The analog signals of the arc detector and electron pickups are acquired through a scope and the traces are available through a scope OPI in the control room, triggered synchronously with the RF pulses. For all the cavities the conditioning has been extended to the coupler administrative limit of 300 kW for medium beta cavities and 400 kW for high beta cavities at long RF pulses (>0.5 ms). Possible multipacting levels are slowly conditioned before increasing RF parameters.

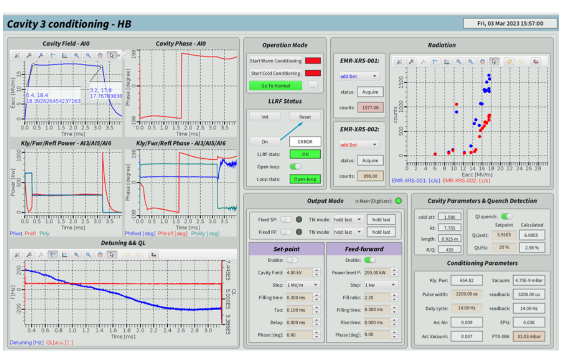

Figure 6: Cavity conditioning interface which shows the LLRF traces (e.g., both amplitude and phase for cavity field, forward and reflected power) and configuration. Then conditioning parameters and cavity diagnostics (dynamic detuning, loaded Q calculation and cavity field emission measurement).

After the cavity has been conditioned in open loop, the test plan proceeds with setting the LLRF system in closed loop operation by enabling feedback mode, and the final cavity performances are assessed.

Detuning and Q_L Calculation

During all stages of cavity conditioning and operation, the dynamic detuning is calculated along the RF pulse, to assist with cavity tuning and so perform LFD coefficient computation [3]. The following formulas express the detuning and half-bandwidth general equations along the pulse, after the necessary signal calibration procedure to eliminate cross-talk introduced by directional coupler.

The first step is to calibrate the real components of the forward and reflected voltage waveforms (U_{for} and U_{ref}) by eliminating the crosstalk in the measurements from the directional coupler (U^*_{for} and U^*_{ref})

$$U_{for} = aU^*_{for} + bU^*_{ref}$$
$$U_{ref} = cU^*_{for} + dU^*_{ref}$$
$$\text{with } U = U_{for} + U_{ref}$$

The voltage waveforms are then transformed in I/Q values. The general dynamic detuning and half-bandwidth equations are evaluated, along the RF pulse according to:

$$\omega_{1/2} = \frac{I_c \cdot \left(2 \cdot K \cdot I_{ForCal} - \frac{dI_c}{dt}\right)}{I_c^2 + Q_c^2} + \frac{Q_c \cdot \left(2 \cdot K \cdot Q_{ForCal} - \frac{dQ_c}{dt}\right)}{I_c^2 + Q_c^2}$$

$$\Delta\omega = \frac{I_c \cdot \left(\frac{dQ_c}{dt} - 2 \cdot K \cdot Q_{ForCal}\right)}{I_c^2 + Q_c^2} + \frac{Q_c \cdot \left(2 \cdot K \cdot I_{ForCal} - \frac{dI_c}{dt}\right)}{I_c^2 + Q_c^2}$$

With $K = f_0/Q_{ext}$, where the Q_{ext} is evaluated at the low power calibration point, and the following expression relates finally the Q_L to the half-bandwidth $\omega_{1/2}$ and the operational frequency f_0:

$$Q_L = \frac{f_0 \cdot \pi}{\omega_{1/2}}$$

Field emission

Cavity field emission is monitored during the cavity conditioning and at the operation E_{acc}, using two scintillator detectors: both energy endpoint spectra and count rate trend are recorded while ramping cavities to nominal gradient and at operating gradient (16.7 MV/m and 19.9 MV/m respectively for medium and high beta cavities) [4].

CONCLUSIONS

TS2 is in operation for the ESS elliptical cryomodules testing. One prototype, seven series medium beta modules and two series high beta modules have been jointly tested by ESS and IFJ PAN, who set the entire test workflow from cryomodule transport, incoming inspection, execution of tests protocols, and finally to the preparation for installation in the ESS tunnel. High level conditioning and operation tools are being developed, and will be used for the upcoming linac conditioning after CM installation.

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