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ESS ELLIPTICAL CRYOMODULES TESTS AT LUND TEST STAND*

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Abstract

We present an overview and description of the elliptical cryomodules test activities at Lund Test Stand 2. During 2021 the test facility was commissioned with one prototype, and four series medium beta modules have now been successfully tested at ESS in Lund. This activity 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. incoming inspections, coupler conditioning, cooldown strategies, tuning to resonance and electromagnetic/cryogenic performance verification). During the initial test period techniques for diagnostics of limiting mechanisms have been developed and improved up to a consolidated and mature state for the rest of the test campaign. Tests results and the initial statistics is presented and commented.

INTRODUCTION

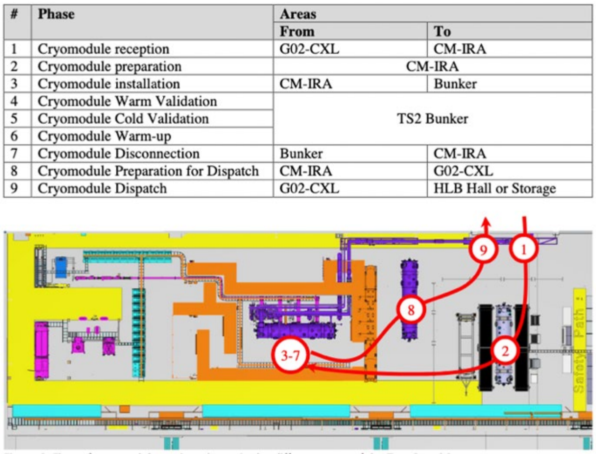
Cryomodules and cavities for the ESS linac [1] are in-kind contribution by several of the project partners (CEA, STFC, INFN, IJCLAB). The Lund Test Stand, TS2, is dedicated to medium and high beta elliptical cryomodules site acceptance tests, SAT. TS2 operation is made possible with the long-term presence of the IFJ PAN at Lund team for the whole duration of the elliptical cryomodule test activities. ESS and IFJ PAN act as a single team for everyday operation from cryomodule transport [2], incoming inspection, to definition and execution of tests protocols and finally to the preparation for installation in the ESS tunnel.

CRYOMODULE DOCUMENTATION

The design and individual component documentation packages, as received by the in-kind partners, are stored in the ESS central engineering documentation management system (CHESS), for the long-term maintenance needs of the facility. These include quality documentation and calibration data for instrumentation. The received documentation is further extended during the TS2 workflow, to document the ESS SAT activities for the component acceptance.

CRYOMODULE TEST CYCLE

The cryomodule testing workflow is split in phases and at each phase a number of test reports are produced. Phases and the flow of testing phases are illustrated in Fig. 1. Incoming inspections include: mechanical, electrical, vacuum and cavity frequencies surveys.

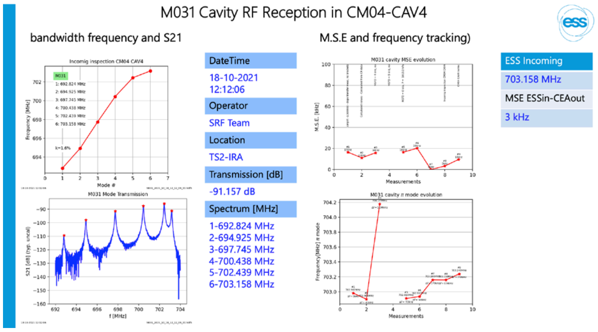


#	Phase	Areas	
		From	To
1	Cryomodule reception	G02-CXL	CM-IRA
2	Cryomodule preparation	CM-IRA	
3	Cryomodule installation	CM-IRA	Bunker
4	Cryomodule Warm Validation	TS2 Bunker	
5	Cryomodule Cold Validation		
6	Cryomodule Warm-up		
7	Cryomodule Disconnection	Bunker	CM-IRA
8	Cryomodule Preparation for Dispatch	CM-IRA	G02-CXL
9	Cryomodule Dispatch	G02-CXL	HLB Hall or Storage

Figure 1: Phases of the TS2 cryomodule test activities.

SRF Incoming Reception and Cavity Data

Cavity data is collected from in-kind partners during the follow-up of the component handover, from fabrication at vendors, installation in the modules, and to the shipment to ESS. This data is collected and consolidated in the ESS cavity database, ESSCDB[3]. The ESCSDB is used after the module reception to store all incoming and verification measurements. This allows to follow cavities history, collect in-kind calibration coefficients (e.g. the field calibration constant k_t and the transmitted power antenna quality factor Q_t from vertical tests), create incoming reports and manage cryomodules configurations. The reports are constantly used in the receiving station and in the control room during tests to cross check the measured performance with the experience reported during the activities at the in-kind partners laboratories. Figure 2 shows an example.



M031 Cavity RF Reception in CM04-CAV4

bandwidth frequency and S21

M.S.E and frequency tracking)

DateTime
18-10-2021 12:12:06

Operator
SRF Team

Location
TS2-IRA

Transmission [dB]
-91.157 dB

Spectrum [MHz]
1-692.824 MHz
2-694.925 MHz
3-697.745 MHz
4-700.438 MHz
5-702.439 MHz
6-703.158 MHz

ESS Incoming
703.158 MHz

MSE ESSin-CEAout
3 kHz

Figure 2: The ESSCDB allows to summarize the main cavity data (bandwidth, frequency evolution and deviations).

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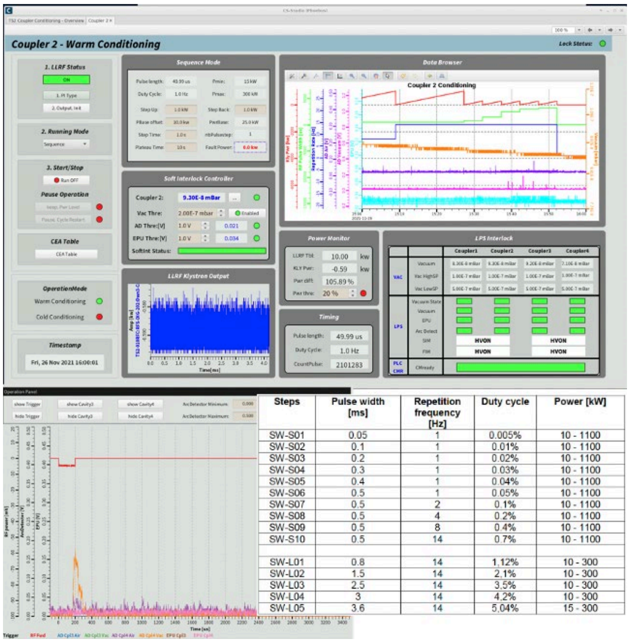
MODULE TEST AND OPERATION

Warm and Cold Coupler Conditioning

Coupler conditioning is needed to reach the nominal coupler power levels, both at warm and after cooldown. This phase has been automated using an EPICS procedure which runs through a cycle of steps defined at CEA (with different forward power, pulse length, repetition rate, and amplitudes) using vacuum as control variable and monitoring EPU (electron pick up) and AD (arc detector) waveforms. In standing wave mode (as it is during CM test with no beam), the full power sent to the coupler must not exceed 300 kW for pulse lengths above 0.5 ms, at any repetition rate, whereas peak power can extend to 1.2 MW for shorter pulse lengths, at any repetition rate.

The full coupler conditioning sequence and the operator interfaces are shown in Fig. 3. The sequence runs in a nominal time of 3 h and 30 m, for a minimum of 14 h of RF operation per module in each of the warm conditioning and cold conditioning stages before tuning the cavity to the operating frequency. Vacuum evolution and the occurrence of interlocks or severe multipacting activity can increase the nominal time for the conditioning of the RF surfaces.



Pulse length: 49.99 us
Duty Cycle: 1.0 Hz
CountPulse: 2101283
Pwr thre: 20 %

Steps	Pulse width [ms]	Repetition frequency [Hz]	Duty cycle	Power [kW]
SW-S01	0.05	1	0.005%	10 - 1100
SW-S02	0.1	1	0.01%	10 - 1100
SW-S03	0.2	1	0.02%	10 - 1100
SW-S04	0.3	1	0.03%	10 - 1100
SW-S05	0.4	1	0.04%	10 - 1100
SW-S06	0.5	1	0.05%	10 - 1100
SW-S07	0.5	2	0.1%	10 - 1100
SW-S08	0.5	4	0.2%	10 - 1100
SW-S09	0.5	8	0.4%	10 - 1100
SW-S10	0.5	14	0.7%	10 - 1100
SW-L01	0.8	14	1,12%	10 - 300
SW-L02	1.5	14	2,1%	10 - 300
SW-L03	2.5	14	3,5%	10 - 300
SW-L04	3	14	4,2%	10 - 300
SW-L05	3.6	14	5,04%	15 - 300

Figure 3: Power coupler conditioning tools and steps. On the top the conditioning user interface. From bottom left to bottom right: AD and EPU waveforms and the CEA sequence for coupler conditioning in standing wave mode.

Figure 4 reports the current ESS conditioning experience from the prototype CM00 to the first four series CM. It is to be noted that the prototype and three series modules were tested at CEA, and were therefore subjected already to a conditioning process in the Saclay test bunker [4]. CM04 was the first CM reaching ESS with no prior testing at CEA and did not show a substantial increase of the conditioning time with respect to the minimal nominal time needed by the process. Some moderate evolution occurred during a few of the couplers, mainly for CM01.

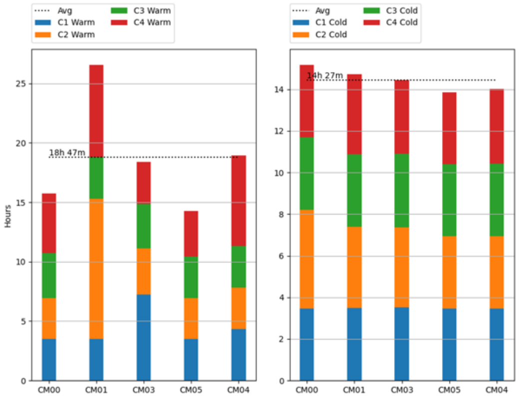


Figure 4: Power coupler conditioning statistics for the modules tested at ESS. CM04 was the first CM that reached ESS with no prior exposure to RF at Saclay.

Cavity Tuning

During cavity tuning to resonance, it is crucial to determine the initial cavity parking frequency, to compute the expected pi-mode shift and to verify that the tuner frequency sensitivity matches the expected nominal value of ~20 kHz per tuner shaft turn. The high-level tool [5] shown in Fig. 5 (which will also be used later during the commissioning of the linac) allows controlling the tuner process without requiring the use of additional RF instrumentation (e.g. VNA) or the need to setup frequency tracking by PLL or SEL configurations. The tool relies only the analysis of the cavity field pick up data and its postprocessing (by Fast Fourier Transform FFT). The needed steps to resonance and the parking frequency are stored for the future linac commissioning activities.

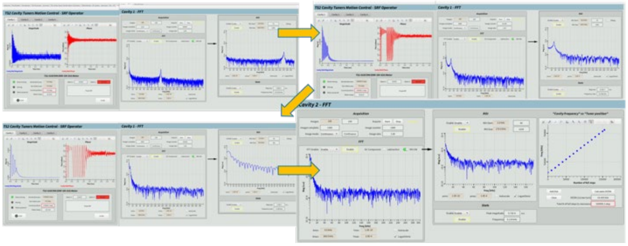
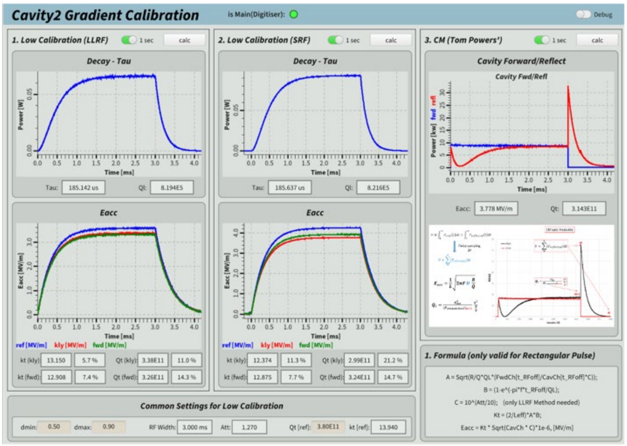


Figure 5: Cavity tuning tools. The picture shows the evolution of the frequency shift, monitored using the FFT of transmitted power P_t, during the cavity tuning (following arrows flow). Frequency sensitivity is monitored for every system (last step on bottom right) to check the design parameters are met.

Cavity Calibration

One important asset of TS2 is the redundant RF power monitoring capabilities for the assessment of systematic calibration uncertainties. The power reading (Pf, P_r and P_t) is done from several directional couplers along the RF path and using different sensors. Cavity gradient, E_{acc}, is evaluated through the implementation of several methods: computing stored energy from the reflection trace, from the vertical test calibration coefficient and from the overcoupled calculations from forward power P_f, as shown in Fig. 6.

The power is read both by the LLRF receivers and by off-the-shelf power meters (to mitigate uncertainties). Agreement within different E_{acc} calculations is generally within 10-15%, but further analysis is under development.



1. Low Calibration (LLRF): Tau: 185.142 us; Ql: 8.194E5; kt (kly): 13.150, 5.7 %; Qt (kly): 3.38E11, 11.0 %; kt (fwd): 12.908, 7.4 %; Qt (fwd): 3.26E11, 14.3 %

2. Low Calibration (SRF): Tau: 185.637 us; Ql: 8.216E5; kt (kly): 12.374, 11.3 %; Qt (kly): 2.99E11, 21.2 %; kt (fwd): 12.875, 7.7 %; Qt (fwd): 3.24E11, 14.7 %

3. CM (Tom Powers'): Eacc: 3.778 MV/m; Qt: 3.143E11

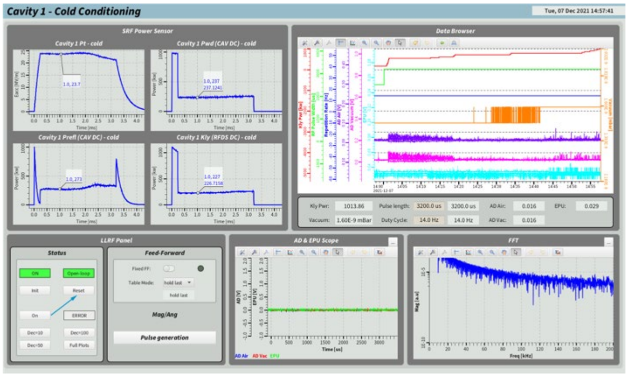
Common Settings for Low Calibration: dmin: 0.50; dmax: 0.90; RF Width: 3.000 ms; Att: 1.270; Qt (ref): 3.80E11; kt (ref): 13.940

A = Sqrt(R/Q*QL*(FwdCh[t_RFoff]/CavCh[t_RFoff]*C));
B = (1-e^(-pi*f*t_RFoff/QL);
C = 10^(Att/10); (only LLRF Method needed)
Kt = (2/Leff)*A*B;
Eacc = Kt * Sqrt(CavCh * C)*1e-6, [MV/m]

Figure 6: On the left and center insets: E_{acc} calibration using P_t read from LLRF and off-the-shelf power meters. The loaded Q, Q_l, is computed from the decay and E_{acc} is assessed by the overcoupled relations. On the right the reflected power method, which relies on calculation of the stored energy, from the reflected power trace.

Cavity Conditioning

After calibration the cavities are usually conditioned, one by one, up to the nominal gradient in open loop, by increasing pulse length and ramping the power. Cavity multipacting levels are processed by monitoring arc and electron signals. For most of the cavities the conditioning has been extended to higher fields until reaching the coupler administrative limit of 300 kW at long pulses. Figure 7 shows the cavity conditioning interface.



Kly Pwr: 1013.86; Pulse length: 3200.0 us, 3200.0 us; AD Air: 0.016; EPU: 0.029
Vacuum: 1.60E-9 mBar; Duty Cycle: 14.0 Hz, 14.0 Hz; AD Vac: 0.016

Figure 7: The cavity conditioning interface, showing the LLRF power traces and the trends of the conditioning process (e.g. power levels, vacuum, arc and electron activity).

Four Cavity Operation

The RF system at TS2 consist of two klystrons feeding each two of the cavities in the module by means of a variable power divider. After conditioning each cavity to the nominal operation pulse, all cavities are run simultaneously for the dynamic heat load measurement, by acting on the power distribution system, as shown in Fig. 8.

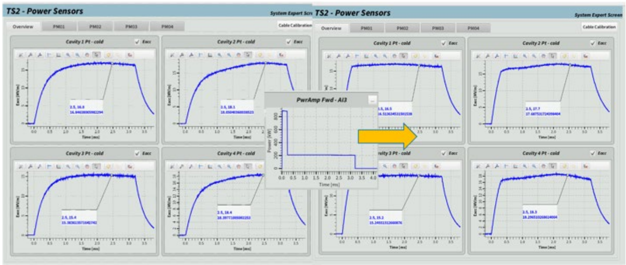


Figure 8: Four cavity operation in open loop. Left: natural filling time. Right: filling time for nominal ESS RF pulse.

Field Emission

Cavity field emission is monitored during the conditioning and at the operating E_{acc}, using scintillator detectors [6].

Closed Loop Operations

The ESS LLRF system [7] is being developed in parallel with the commissioning of the TS2. Closed loop operation became available only during CM04 test and will be reported in future publications.

Cryogenic Operations

Once moved in the test bunker, the cryomodule is connected to the permanent valve box and auxiliary circuits. All cryogenic circuits are checked for leaks to ambient, insulation vacuum and beam vacuum. The circuits are then conditioned by successive pump and purge cycles.

Before cool down, the proper functioning of each device and diagnostics instrumentation is verified with the control system. The cool down of the cryomodule is then started by first initiating cooling the thermal shield to 35 K and then the accelerating cavities to 4.5 K providing also a steady flow supply to the power couplers double wall cooling. Once a He-I bath liquid is established, the cool down to a superfluid He-II bath at 2 K is engaged by reducing the pressure of the helium bath to 31 mbar. The control system takes care of maintaining stable level and temperature conditions for the cavity tests.

Static and dynamic heat load measurements [8] take place towards the end of the tests, when the cryomodule has reached a steady state condition. A survey for systematic errors on temperature, level and pressure is performed.

Test Throughput

Table 1 shows the test duration and the goal. The prototype CM was extensively used to qualify the cryogenic and RF infrastructure prior to the series.

Table 1: Test Duration (Days in Bunker)

Goal	CM00	CM01	CM03	CM05	CM04
40	597	133	119	70	71

CONCLUSIONS

TS2 is in operation for the testing of the ESS elliptical cryomodules. One prototype and four series medium beta modules have been tested and the facility is ramping to its nominal throughput to deliver one module per month.

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