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PRODUCTION, TEST AND INSTALLATION OF ESS SPOKE, MEDIUM AND HIGH BETA CRYOMODULES

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Abstract

We present here an overview of the ESS cryomodule production, test and preparation to tunnel installation, covering both families of modules: spoke and elliptical. Cryomodules and cavities for the ESS linac are in-kind contribution by several of the project partners .

PRODUCTION AND DELIVERY STATUS

Spoke cryomodules (CM) are in-kind contributions [1, 2] by IJCLAB and they undergo their site acceptance test (SAT) at the FREIA Laboratory, in Uppsala.

ESS will have a total of 14 spoke cryomodules (13 in the linac and one spare): presently 8 modules have passed SAT at FREIA and are in Lund. Incoming inspection for all the 8 received modules have been completed for all the several disciplines (mechanical, vacuum, electrical and SRF) and modules are currently stored, ready for transport and tunnel installation as soon as the CDS (Cryo Distribution System) will end its commissioning and qualification at the beginning of 2023. The current forecast is to complete the spoke testing at FREIA by the beginning of 2023. All reports are stored in the ESS Enterprise Asset Management (EAM) system for long term stewardship of the facility.

Elliptical cryomodules, 9 medium-beta (MB) and 21 high beta (HB) cryomodules, are in-kind contributions [1, 2] of CEA Saclay: MB and HB cavities are provided by INFN and STFC. CEA is responsible for assembly and delivery, and for the high RF power test for the first three CM of each family (and prototypes). The industrial assembly is performed by the B&S International company using the CEA infrastructure, under CEA supervision. Presently 12 modules have been fully assembled: 7 medium beta and 2 high-beta are currently at ESS. At the arrival in Lund incoming inspection reports are produced and released in EAM. Currently 5 medium beta have been successfully tested at Lund Test Stand (TS2) and are ready for installation. By the end of 2022 the seven available medium beta CM will be tested and high beta testing will start. CM installation in the tunnel will start in 2023. ESS has the responsibility of CM transport to site [3].

The staged facility commissioning will perform beam operation on the permanent beam dump at 570 MeV after the installation of the 7 MB and 2 HB CM already available, before the finalization of the target system, which will be ready in 2025. After the initial commissioning on the beam dump the remaining HB CM for the 800 MeV goal of 2 MW operation on target.

SPOKE CM TEST STATUS

After SAT at FREIA the spoke CMs are shipped to ESS, inspected and stored before tunnel installation.

FREIA team developed competences in SRF projects from 2015 to 2019, testing the prototype components several times. The 6-week test procedure was optimized, in order to achieve a yearly throughput of 8/9 CM tests. Series modules testing started in Oct 2020 and proceeded without interruptions during the Covid-19 pandemic. A total of 14 cold tests were performed, 8 modules were accepted and other 6 tests are currently planned to reach a total of 14 modules. The spoke CM series testing completion is forecast by March 2023.

The test plan performed at FREIA can be factorized in four main sections:

- Reception test (2 weeks): incoming frequency measurements and mechanical preparation for bunker.
- Warm test (1 week): cable calibration and then warm coupler conditioning.
- Cold test (2 weeks): measurement of frequency shift vs temperature/pressure; tuner steps to resonance and tuner frequency sensitivity; assessment of accelerating field, Lorentz force detuning and heat loads.
- Warm up and departure to ESS (1 week)

Spoke Cryomodules Tests Statistics

The statistics collected for all modules tested to now at FREIA is presented in Figure 1, which shows that most of the module reached the administrative test limit of 12 MV/m and all of them fulfilled the 9 MV/m specification. Eight out the eleven modules tested have fulfilled SAT and some modules required actions to resolve non conformities and retesting. The present nonconformities under resolution regard cold tuner motor failures (CM10 and CM11 have been repaired and re-tested at Uppsala) and vacuum leaks (CM09), requiring a string reassembly at IJCLab. The statistics account for all tested modules.

The assessment of the accelerating field during tests, E_{acc}, is performed in two different ways and comparison with VT (Vertical Test) results is systematically performed. The field k_t calibration factor is either computed using the forward power over-coupled relation or from the stored energy method. Calibration uncertain in power measurements was estimated in 0.5 dB (12%). For spokes the difference between VT and cryomodule, CM, calibration is not systematic (see Figure 2), while for elliptical medium the VT estimation leads to higher fields than the CM test.

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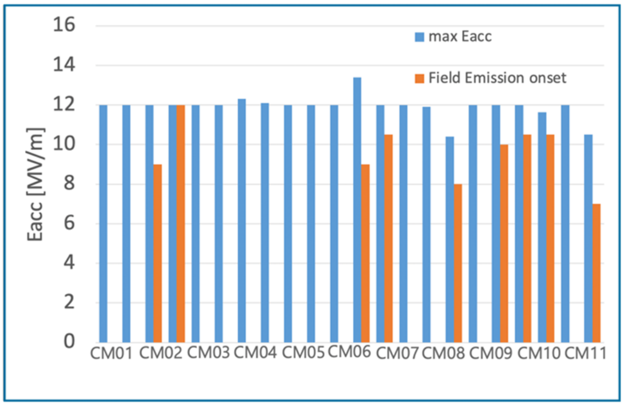

Figure 1: Maximum accelerating gradient reached during spoke modules test and field emission onset

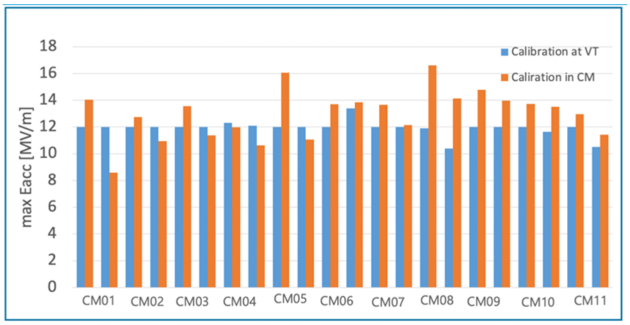

Figure 2: VT and cryomodule calibration comparison.

Figure 3 shows the static and total heat loads measured for the modules, which are almost always dominated by static loads. The dynamic (RF power) dissipation is almost always within fluctuation of helium gas flow, and below the facility measurement sensitivity. The static heat load might improve in ESS linac, because of the lower thermal screen temperature during operation (FREIA uses LN, while in the linac a dedicated cooling circuit at 40 K is provided by the accelerator cryoplant).

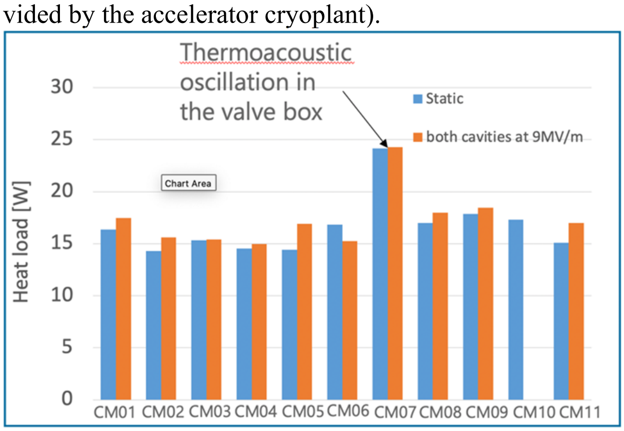

Figure 3: Heat load statistics. The CM10 dynamic heat load measurements will be performed at the next test after the motor repair.

FREIA tests are performed in open loop condition, and the nominal Lorenz Force Detuning (LFD) and the piezo tuning action in quasi static conditions is measured for all cavities (see Figure 4). Unipolar excitation of a single piezo is generally sufficient to provide the LFD range.

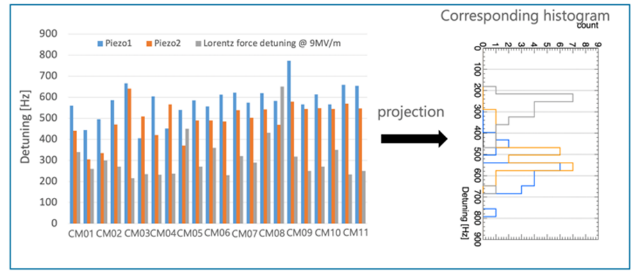

Figure 4: Piezo statistics in unipolar bias (0-200 V): in quasi-static condition slower than 50 V/1 min. LFD frequency offset is generally lower than piezo tuning range.

Coupling, Q_{ext}, statistic (Figure 5) shows a distribution which lays in the lower edge of design spoke values (1.75E5-2.85E5), implying the need of a 10 kW overhead to recover the mismatch. To avoid this overhead the outliers could be placed at the beginning of the spoke section, where lower gradients are needed in the linac design for the phase advance matching.

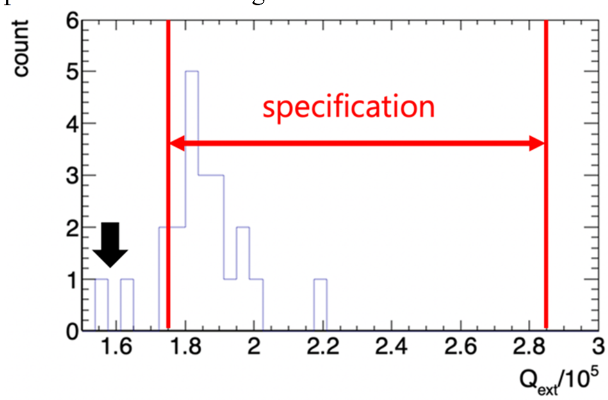

Figure 5: External Q, Qext, distribution for all spoke modules tested until now. Nominal Qext range for spoke modules is 1.75E5 to 2.85E5.

ELLIPTICAL CM TEST STATUS

Elliptical cryomodules are tested at ESS Test Stand, TS2, in Lund. The prototype modules, both for MB and HB, and first three series module of each family are also tested at CEA, Saclay [4] and ESS, in order to:

- Provide rapid test feedback to the CEA module assembly process at its starting phase
- Verify that the main ESS requirements on accelerating field and RF pulse structure is achieved
- Validate the ESS test facility and cross check results with those obtained at CEA

The TS2 has been commissioned in 2020 with the prototype CM0 and RF operation started in 2021. Until now only MB have been tested at TS2 (the prototype CM0 and the series modules CM01, CM03, CM05, CM04, CM06). CM07 is approaching test as we write this paper and CM02 is being prepared for test; HB tests will start at the end of this year with the available CM031 and CM32. The total of 9 modules presently at ESS will allow to have the first beam through the superconducting linac section at 570 MeV, for the operation on the permanent beam dump.

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Operations at CEA are performed in open loop with manual LFD compensation with piezo. The closed loop operation and LFD LLRF algorithms are in the TS2 scope.

TS2 Cryomodule Test 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: 1) Cryomodules assembly documentation (quality) and 2) Cryomodules operation documentation (calibration data for instrumentation, like thermal sensors and accelerating field calibration constant *kt)*. The received documentation is further extended during the TS2 workflow, to document the ESS SAT activities for the component acceptance.

The CM documentation test package includes all incoming inspections, RF and cryogenic measurements reports, and a final master report for documenting the overall SAT findings and resolution for possible non-conformities.

Cryomodule Test Cycle

The cryomodule testing workflow is split in phases, and properly documented in CHESS. Phases and the flow of testing phases are illustrated in Figure 6.

#	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

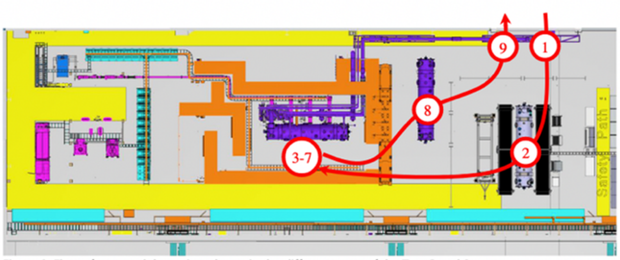

Figure 6: Phases of TS2 module test activities

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 [5]. The ESSCDB is used after the module reception to handle all incoming and verification measurements. This allows to follow cavities frequency history, collect in-kind calibration coefficients (e.g. 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 during the incoming reception phase and control room operations to cross check the measured performance with the experience reported during the activities at the in-kind partners laboratories. Figure 7 shows an example.

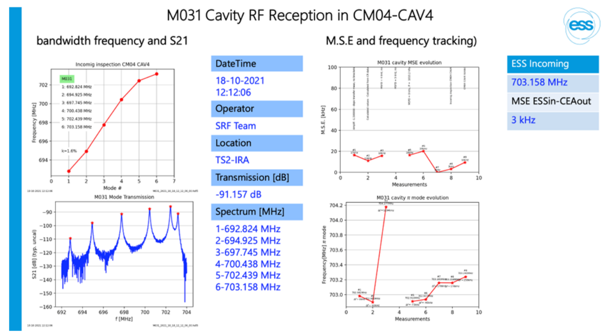

Figure 7: ESSCDB example, the ESSCDB allows to summarize the main cavity data (bandwidth, frequency evolution and deviations).

TS2 Module Test and Operation

Warm and cold coupler conditioning

Both warm and cold coupler conditioning operations are performed through an automated EPICS sequencer script which runs through a cycle of steps (with different forward power sweeps, at increasing pulse length and repetition rate) as defined by CEA in order to condition couplers to the operation power levels. The procedure use as control variable vacuum level and monitors EPU (Electron Pick Up) and AD (Arc Detectors) waveforms. The main constraint during conditioning (in standing wave mode, as it is while testing at test stand, without any beam) is that power sent to power couplers must not exceed 300 kW for pulse lengths above 0.5 ms at any repetition rate. Peak power cannot exceed 1.2 MW at any pulse length. The conditioning graphical interface is shown in Figure 8, and the statistics of conditioning times reported in Figure 9.

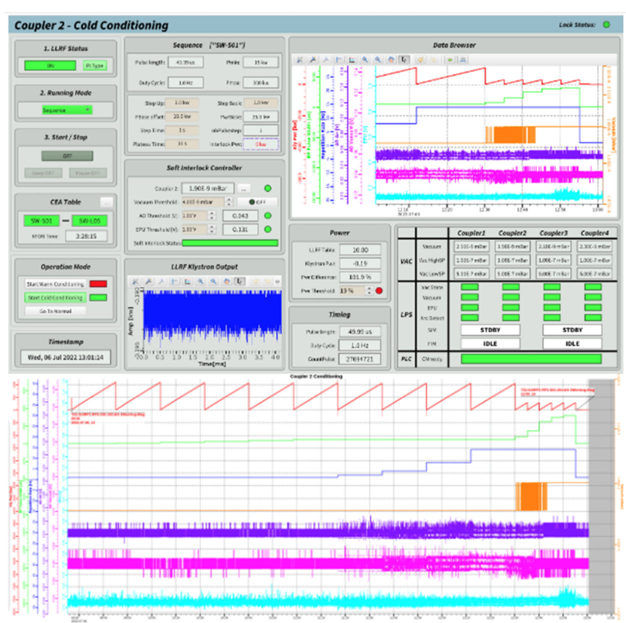

Figure 8: Example of cold coupler conditioning overview: operator interface on top and trends for the full cycle on bottom. Vacuum is control parameter, and AD and EPU activity are monitored during the process

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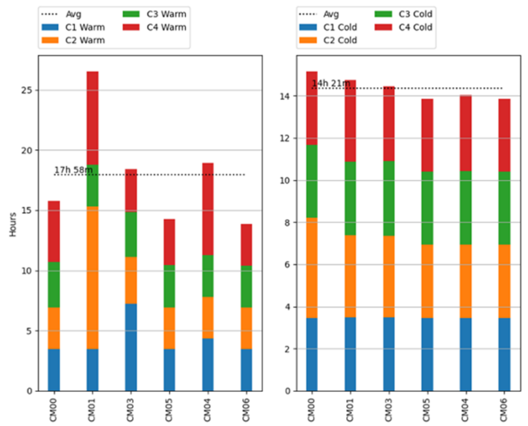

Figure 9:Warm (left) and cold (right) conditioning times collected until now, from left to right. All couplers are conditioned in travelling and standing wave mode at a dedicated coupler test stand in Saclay.

Cavity tuning & calibration

The starting point for the cavity's acceptance is the tuning to resonance. The tuning operation is performed from the control room detecting the cavity frequency signature from the Fourier Transform analysis of the transmitted power *Pt* [6]: from the assessment of the parking frequency and the nominal sensitivity the expected number of steps is calculated and then recorded, once the cavity is on resonance. A high-level EPICS program allows to run the tuning process and determine the actual frequency sensitivity. The measured sensitivity and the steps to tune are recorded in the test documentation as necessary parameters for the future LINAC commissioning phase and will help in saving commissioning time (see Figure 10).

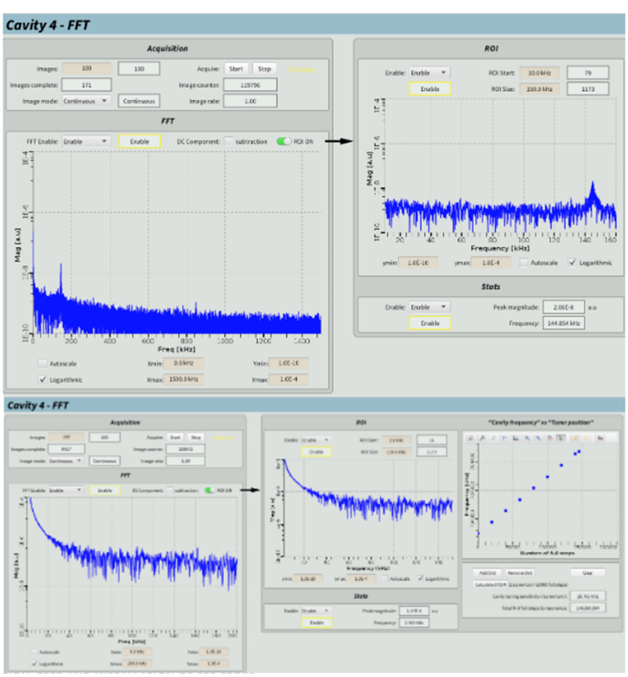

Figure 10: The panel for tuning cavities from the parking position. On the top the signature of the cavity *parking* frequency, when the slow tuner is disengaged. On the bottom the tuning history to resonance is shown.

Once the cavity is tuned the calibration coefficient *kt* is calculated from the RF traces and compared with VT reported values. At TS2 redundant power monitoring is present to allow assessment of systematic calibration uncertainties, power reading is performed from several directional coupler along the RF path. Several methods are implemented by using: 1) Stored energy from reflection (à la Tom Powers 2) Overcoupled calculations from forward power and 3) power reading using LLRF and off-the shelf power meters belonging to the SRF section (see Figure 11). The agreement with different estimation methods is generally within 20%.

After calibration at low power the cavity conditioning process starts in open loop. Forward power and pulse length are gradually incremented manually (typically at the maximum nominal repetition rate of 14 Hz to speed up the processing) until the nominal design field of ~17 MV/m is reached with the nominal pulse parameter, and then to maximum achievable level (according to the power coupler power handling administrative limit), see Figure 12. While power is incremented the AD and EPU activity and beam vacuum level provide interlock capabilities. Most cavities have so far been tested up to the coupler administrative limit of 300 kW in full reflection mode.

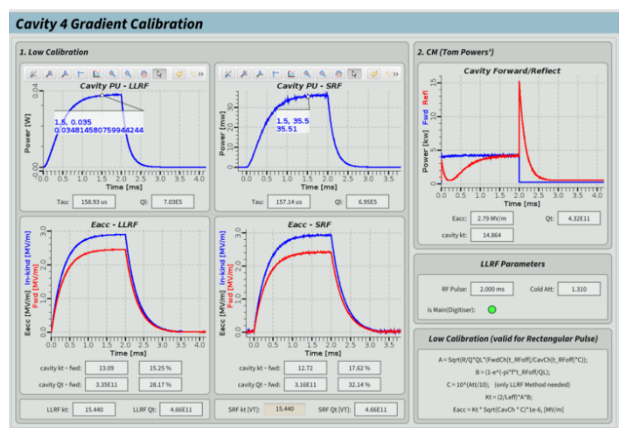

Figure 11: Calibration of cavity pickup coefficient, using different methods.

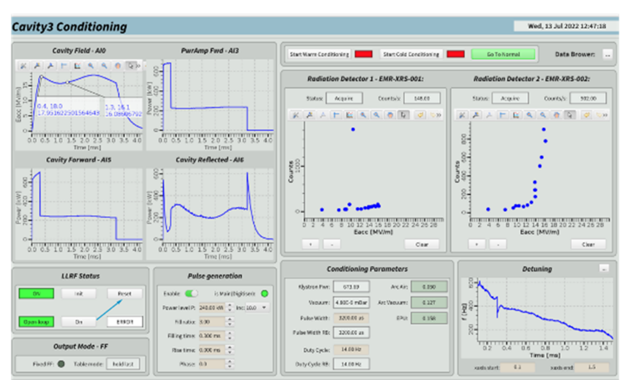

Figure 12: Cavity conditioning panel, open loop. From the top left the several power readings *Pt*, *Pf* (in different points along RF path) and *Pr*. Pulse generation parameters on the bottom. On the top-right the scintillator radiation count rate, and on the bottom-right the dynamic detuning.

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Possible multipacting activity is fully processed during the cavity conditioning process. TS2 is equipped with two 1.5 MW klystron connected each to a Variable Power Divider to split the power from 0 to 100% on two cavities. When all cavities have been individually characterized, they are all run simultaneously in open loop by splitting the power in order to achieve nominal gradients on all structures, in order to perform the CM dynamic RF heat loads.

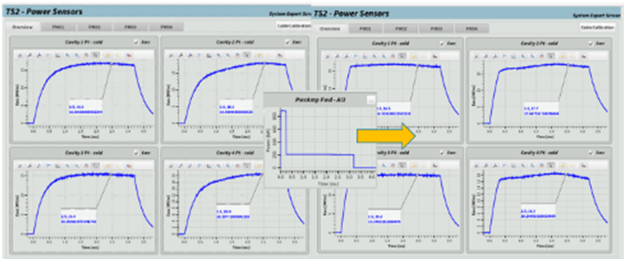

Figure 13: Four cavities operation for dynamic heat load estimations, in open loop, using bi-square pulse

During cavity operation field emission (FE) measurements are taken with two spectrometers (NaI(Tl) scintillators) to determine the stop energy of the emitted radiation and detect the possibility of activation during tests [7].

After open loop conditioning is finished, the cavities are operated in closed loop with LLRF FB. The E_{acc} set-point is ramped up in closed loop manually (Figure 13) and, since the piezo control is not yet integrated in the ESS LLRF system, above ~8 MV/m cavities are pre-detuned in order to avoid that the LFD drives forward power in closed loop beyond the coupler administrative power limits.

CM performances

Figure 14 shows the current statistics of the cavity performances during VT at INFN and as measured at TS2, with indication of the limiting mechanisms in the tests. Figure 15 shows the VT/CM correlation plot.

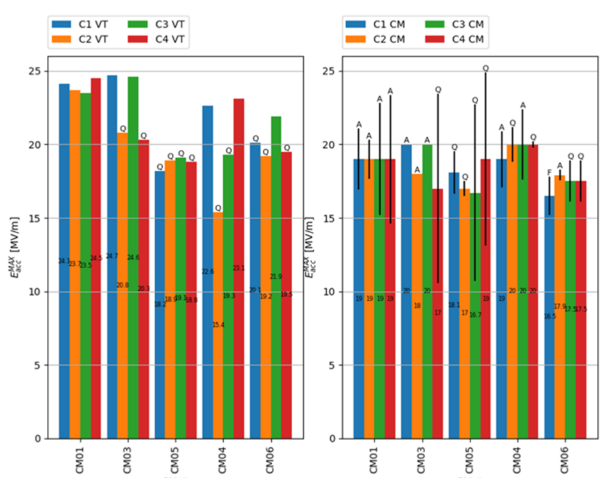

Figure 14: Statistics of the cavities during the VT at INFN (left) and during the TS2 CM tests (right). VT calibration constants are typically more (up to 20%) optimistic than those determined during the CM tests. Limiting mechanisms are indicated (Q=Quench, A=Administrative power limit, F=strong FE heating)

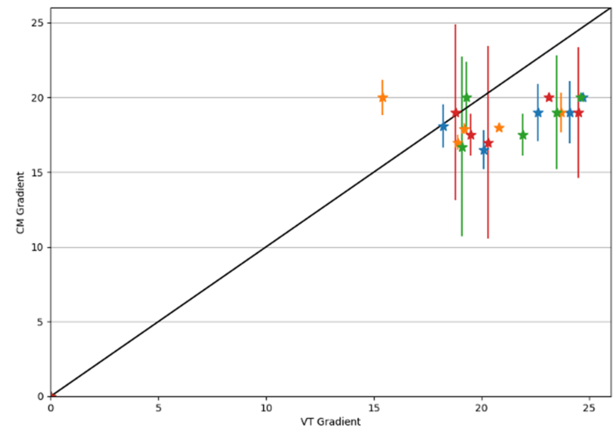

Figure 15: CM Testing frequently stops at the administrative limit of ~300 kW for long pulses in full reflection, set by the coupler design (and conditioning history).

Cryogenics operations

After the cryomodule reception, the cryogenic equipment goes through initial visual inspection and electrical checks are performed to all internal instrumentation. The cryomodule is then moved inside the test bunker, where it is connected to the permanent valve box and auxiliary circuits, part of the cryogenic distribution system.

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 together with the control system.

The cool down of the cryomodule is started by first cooling the thermal shield to 35K followed by the cooling and filling of the helium tanks surrounding the cavities to 4.5K.

Once a He-I bath liquid is established, the cool down to a superfluid He-II bath at 2K is engaged by reducing the pressure of the helium bath to 31mbar. A carefully defined control system takes care of maintaining a stable level and temperature conditions for the cavity tests.

Heat loads to the cryogenic system are measured according to a set of defined methods [8]. Static and dynamic heat load measurements take place towards the end of the tests, when the cryomodule has reached a steady state condition. Finally, a survey for systematic errors on temperature, level and pressure measurements is performed and documented for future linac operation.

The cryogenic operation is complete by safely warming up the cryomodule to ambient temperature.

CONCLUSION

We presented the status of the assembly and test of the spoke and elliptical cavity cryomodules for the ESS linac. A large portion (17/22) of the CM needed for the first phase of the project with 570 MeV operation on the beam dump are already available in Lund, either at the Ready-For-Installation state or awaiting test at TS2 and Uppsala. Installation of CMs in the tunnel will start in Q1 2023 after the cold commissioning of the cryogenic distribution system.

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