Production, tests and installation of the ESS spoke, medium and high beta cryomodules

For the ESS SRF Collaboration

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Agenda

1 Introduction
2 Cryomodule **production** status
3 Cryomodule **test** status
4 Preparation of **tunnel installation** activities
5 Conclusions

1

Cryomodule production and delivery status

MO1PA02 => Ryoichi Miyamoto for NCL Status

SPK

MBL

HBL

SPK CM: Scope and Status

13 cryomodules + 1 spare

Cavities & CM by ICJLAB
Tested at FREIA@Uppsala
Delivered to ESS

8 CM at ESS

Fixing NCRs to achieve RFI (Ready For Installation) status

Minor:
- LHe gauges
- Swapped sensors
- Fasteners

For followup:
- Loss of CTS action

Name	IJCLab name	Status	Location	ESS expected arrival	Comments
SM01	CM01	Incoming inspections compleeted and report released in CHESS	Lund - B02	21 September	Coupler accident at Orsay. Repair done.
SM02	CM02	Incoming inspections compleeted and report released in CHESS	Lund - B02	21 April 2021	Stepper motor problem at FREIA, returned to Orsay for repair, test OK at UU.
SM03	CM03	Incoming inspections compleeted and report released in CHESS	Lund - B02	16 Nov 2021*	Arrival in Uppsala 23rd of September. (history: Leak detected at Orsay, fixed. During tests at Uppsala, one motor stuck. Stepper motor repaired by IJCLab and assessed at UU.
SM04	CM04	Incoming inspections compleeted and report released in CHESS	Lund - B02	19 Oct 2021*	Helium leak in BV found during cold test at UU, was reprocessed at Orsay (ESS-3218927);
SM05	CM05	Incoming inspections compleeted and report released in CHESS	Lund - B02	25 May 2021	Test completed in Uppsala, test completed; minor doubt in field calibration.
SM06	CM06	Incoming inspections compleeted and report released in CHESS	Lund - B02	17 Dec 2021	Test completed
SM07	CM07	Incoming inspections compleeted and report released in CHESS	Lund - B02	08 Feb 2022	Test completed
SM08	CM08	Incoming inspections compleeted and report released in CHESS	Lund - B02	09 Mar 2022	Minor doubt in field calibration
SM09	CM09	2nd test planned for Dec 2022	Orsay	***End of Dec 2022***	Being fixed at IJCLab
SM10	CM10	2nd test planned for Nov 2022	Lund - B02	***Nov 2022***	at ESS for tuner motor repair: completed
SM11	CM11	under re-test	Uppsala	***September 2022***	-
SM12	CM12	Waiting for test	Uppsala	***October 2022***	-
SM13	CM13		Orsay	***Feb 2023 *****	planned UU delivery: Nov 2022
SM14	CM14		Orsay	***March 2023***	planned UU delivery: Jan 2022

Forecast: **All Spokes within Q1/23**, before start of installation effort

ELL CM: Scope

9 medium (+1 spare) and 21 high beta cryomodules

CEA: Delivery of **all components but cavities** + **assembly** + at **high power test of 3 MB + 3 HB cryomodules**.

Industrial assembly

B&S International Company

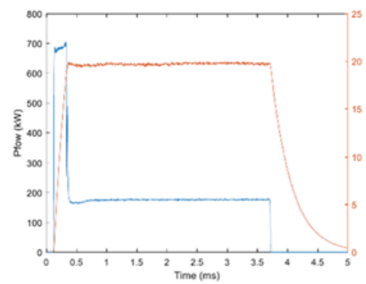
in the CEA Saclay infrastructure

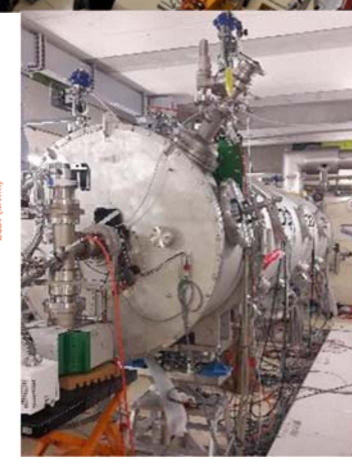
under the supervision of CEA

Presently **12 cryomodules fully assembled** (Throughput objective: 1 cryomodule/month).

<ins>Tests at high RF power performed at CEA :</ins>

- 2 prototypes (medium and high beta)
- 3 medium beta and 2 high beta cryomodules for checking the quality of the assembly and performances before delivery to ESS
- **Only 1 high beta cryomodule to test at CEA (before end 2022)**





<ins>Main ESS requirements reached:</ins>

- M-beta cavities: 17 MV/m, 3.6 ms, 14 Hz
- H-beta cavities: 20 MV/m, 3.6 ms, 14 Hz

ELL CM: Status

- All 9 cryomodules needed for ESS first beam are **already delivered to ESS**:
  7 Medium Beta + 2 High Beta
- **5** cryomodules (MB) so far successfully tested at ESS and ready for installation

MB	Status	ESS arrival *	Comments
CM01	**RFI**	25 SEP 2020	He Level changes not implemented.
CM02'	Waiting	01 JUL 2022	Assembly Accident/Reprocessed at CEA
CM03	**RFI**	02 JUL 2021	Tested at CEA OK. Cold Cathode Gauge damaged/exchanged at ESS venting the string. Tested two times.
CM04	**RFI**	01 OCT 2021	One cavity exchanged at CEA due to vacuum accident. **First CM to reach ESS untested.**
CM05	**RFI**	21 OCT 2021	Internal heater unfunctional. Used for tunnel installation test.
CM06	**RFI**	05 NOV 2021	
CM07	Waiting	11 MAR 2022	
CM08	Delayed	APR 2024	MB Cavity Production issues
CM09	Delayed	MAY 2024	

All components for First 9 HB CMs

HB	Status	ESS arrival	Comments
CM31	Waiting	03 JUN 2022	
CM32	Waiting	17 JUN 2022	
CM33	Assy	TBD	delayed due to leak
CM34	Assy	09 DEC 2022	3rd HB module to be tested at CEA
CM35	Assy	02 SEP 2022	
CM36	Assy	23 SEP 2022	
CM37		21 OCT 2022	
CM38		25 NOV 2022	
CM39		13 JAN 2023	STFC Cavities already at CEA
(...) Approximately one per month throughput, STFC cavities following			
CM50		JAN 2024	
CM51		MAR 2024	

2

Cryomodule test status

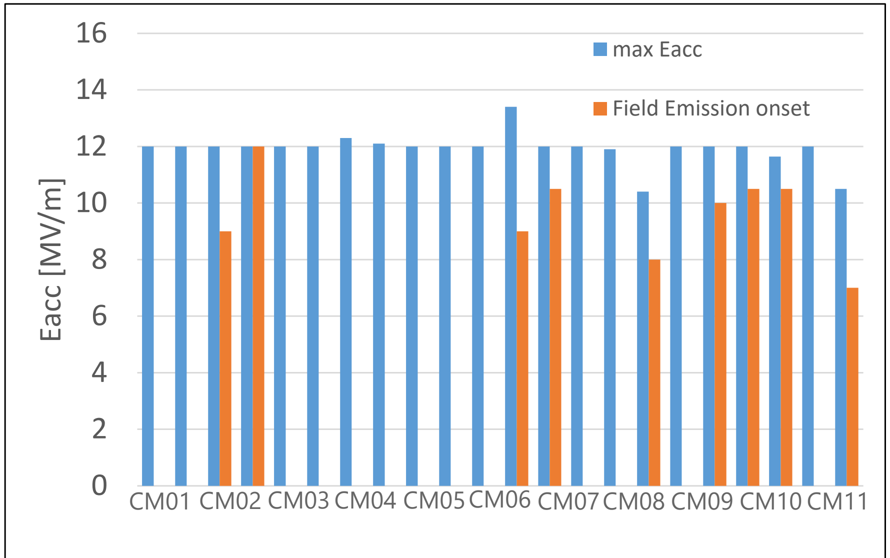
SPK CM: FREIA test summary

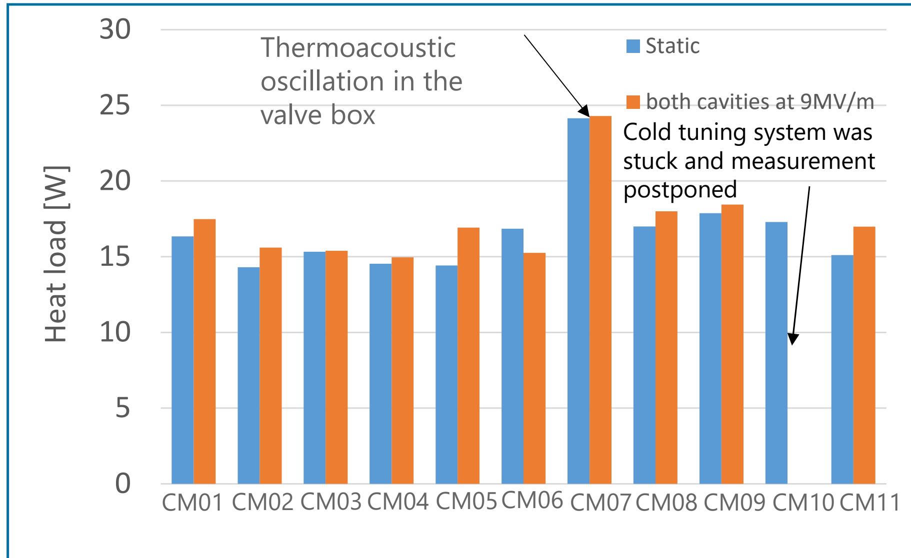
Accelerating field and heat loads

Started series module testing in **Oct 2020**, non-stop during Covid-19

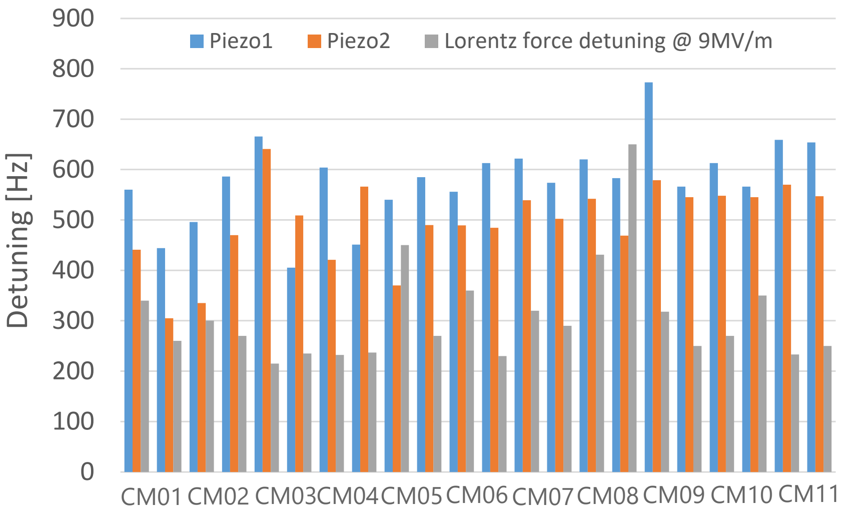
14 cold tests were performed, **8** modules were accepted, other **6** tests are planned to assess total **14 CMs.**
Aim is to finish series testing by March 2023

- ✓ RF power dissipation is almost always within fluctuation of helium gas flow for heat load estimation
- ✓ Q0 is above spec, lower field than elliptical cavities, and duty cycle is only 4.5%
- ✓ The static heat loads **might improve at** ESS because the thermal screen temperature is lower (**FREIA: 80K, ESS linac: 40K)**



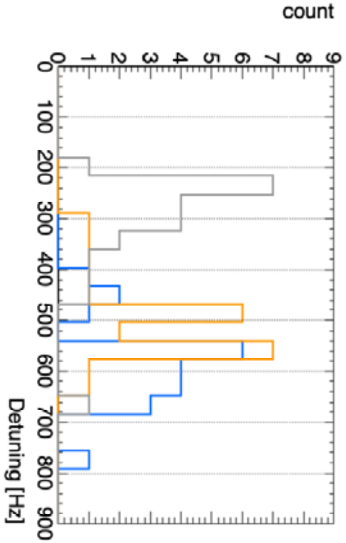


SPK CM: LFD Characterization



projection

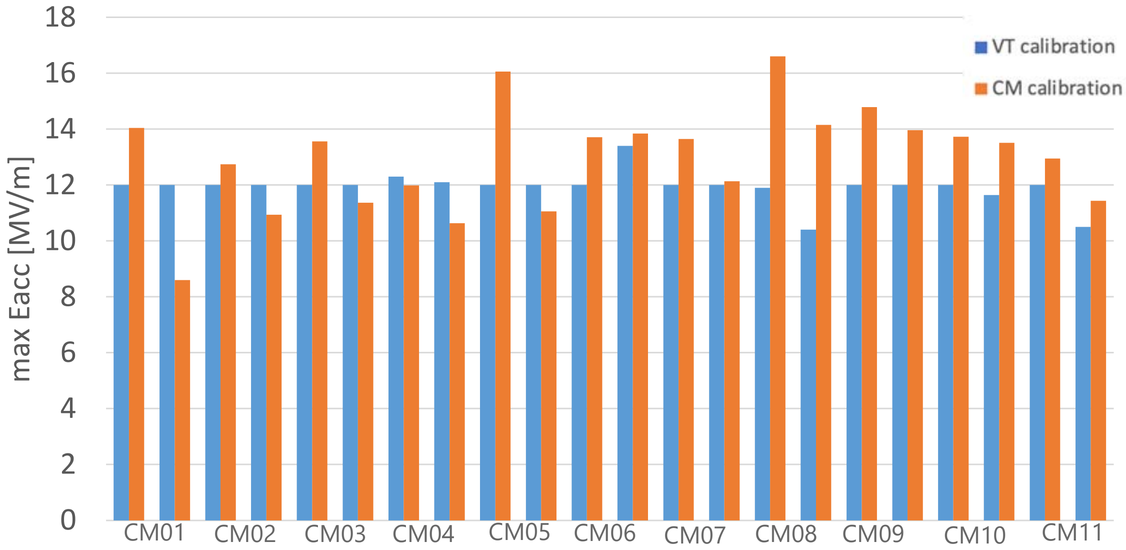
Corresponding histogram



- ✓ Piezo tuning performed with **unipolar bias (0-200V) in quasi-static condition** slower than 50V/1min
- ✓ **LFD < (single) piezo tuning range is generally true**, if both used ample margin
- ✓ Note: FREIA tests are performed in **open loop** conditions.

SPK CM: VT/CM Cross-Calibration

- ✓ **Several methods implemented**: most satisfactory is stored energy computation from reflected power (cfr Tom Powers) **was deployed only after CM09**
  - ✓ Old data was estimated manually by looking at waveform structure
- ✓ Systematic trend of learning process of the FREIA team must be taken into account
- ✓ **Calibration uncertain** of power measurement was estimated to be maximum **0.5 dB (12%)**
  - ✓ Standing-wave effect, standard deviation of statistics (twice calibration for all modules), etc



ELL CM: ESS Test Stand

The workflow is split in phases

At each phase test reports are produced
=> Cryomodule operation
(+ incoming package from CEA)
=> Cryomodule Assembly

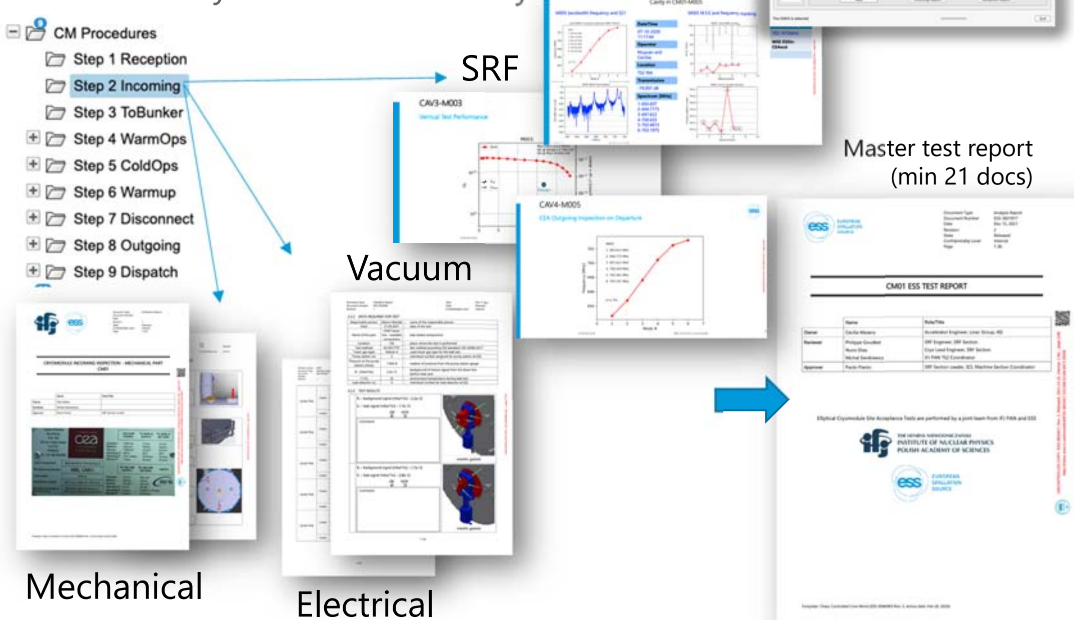


Table 1. Phases of the CM Workflow

#	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	TS2 Bunker	
6	Cryomodule Warm-up	TS2 Bunker	
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 2. Flow of cryomodule testing phases in the different areas of the Test Stand 2

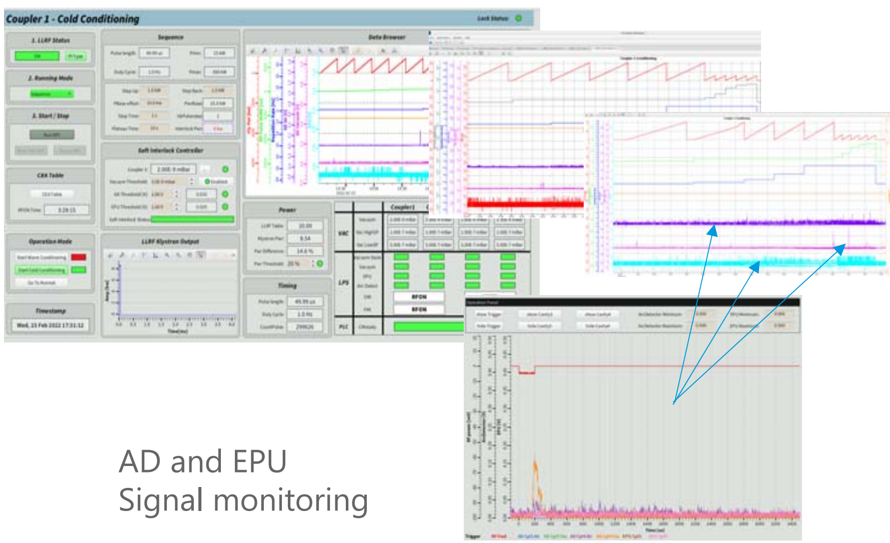
Non-stop operation during Covid-19

ELL CM: Coupler Conditioning

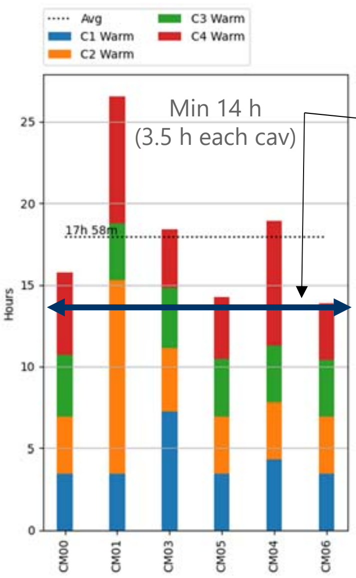
(1) Warm and cold coupler conditioning

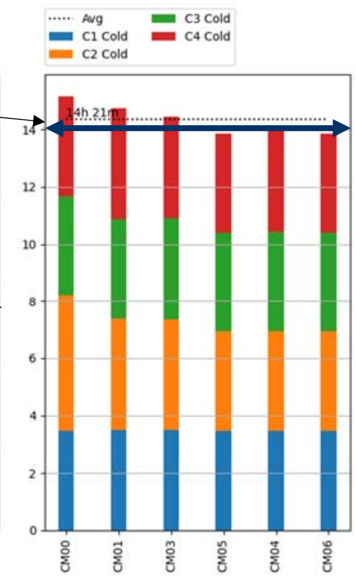
Automated EPICS sequencer script runs through a cycle of steps, as defined at CEA, and monitors vacuum, EPU and AD signals.
Power cannot exceed **300 kW in full reflection** for RF pulses longer than **500 µs**. Peak power cannot exceed 1.2 MW for any pulse length

Gradual improvements of processing times for each successive module.
Conditioning reports are produced for each CM (**14 h** is the cumulative duration of the uneventful power sweeps of the nominal cycle)



AD and EPU
Signal monitoring

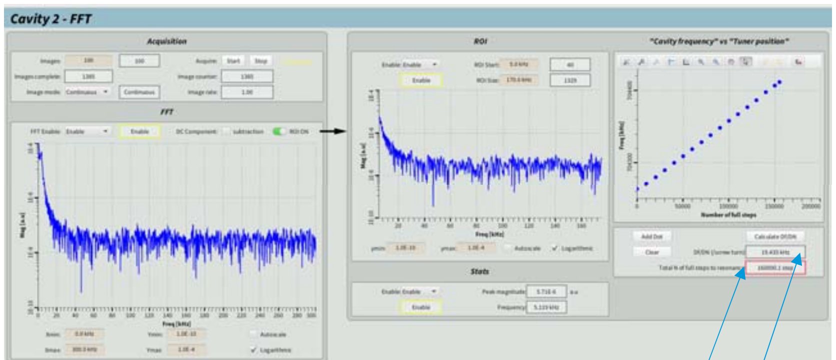


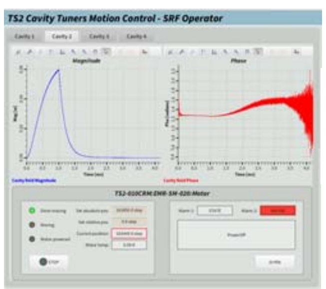


ELL CM: Tuning and Calibration

(2) Cavity tuning & cavity calibration (kt and Qt)

TS2 allows us to build the High Level Tools and OPIs that are needed later into T&C phase in the Linac





1 Hz/step
200 steps/turn
~ 0.8 turns/sec

Getting ready for future linac commissioning and operation

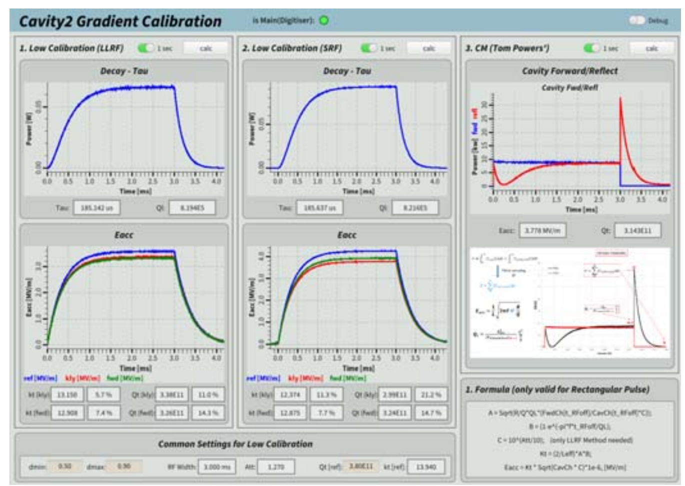
- **Df/Dsteps**
- **Total Nsteps to resonance**

- ➢ TS2 has **redundant RF power monitoring** to allow assessment of systematic calibration uncertainties:
  - Readings from several DC along the RF path

Several methods implemented:

- Stored energy from reflection (à la Tom Powers)
- VT calibration coefficients from IK
- Overcoupled calculations from Forward power

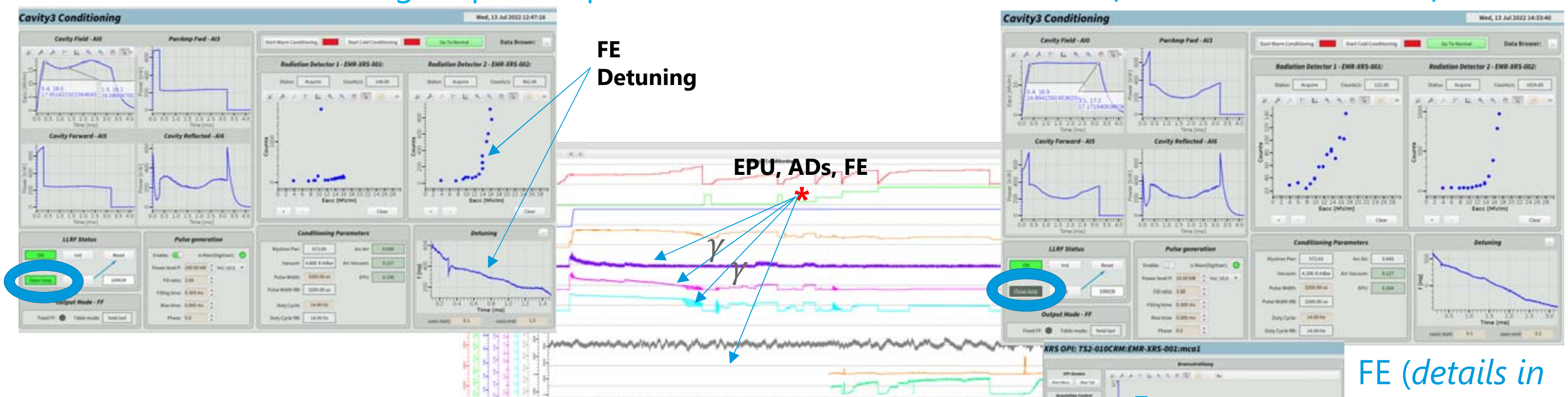
- ➢ Power reading using LLRF and off-the-shelf SRF Power Meters
- ➢ **Agreement generally within10-15%**, as expected



ELL CM: Ramp up to nominal field

(3) Cavity conditioning – operation & and field emission measurements

Conditioning – open loop- | Operation – closed loop-



This process is currently manual, in open loop. Pulse length is set manually and the power is then ramped to the maximum achievable.

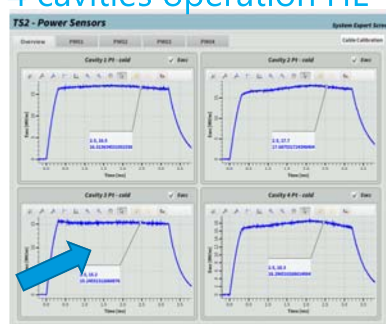
Beam vacuum, arc detector and electron pick-up (*) provide interlock capabilities and are monitored during the process. Field emission is also monitored during conditioning.

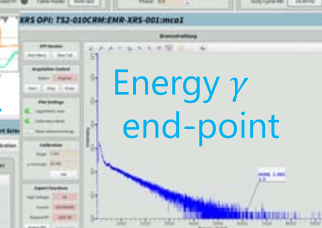
Cavities so far have mainly been power limited (300 kW coupler limit)

RF pulse width is gradually increased until the operation pulse length of 3.2 ms is reached.

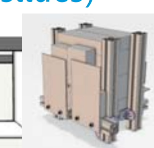
Cavities can then be run simultaneously by splitting the power evenly from each klystron.

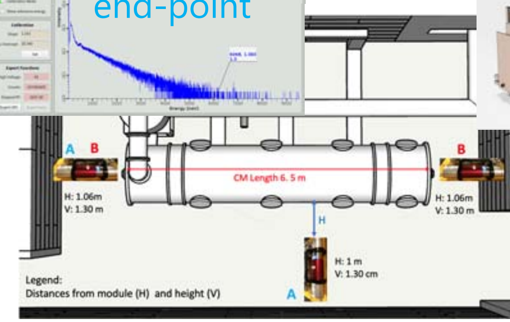
4 cavities operation HL





FE (*details in back-up slides*)



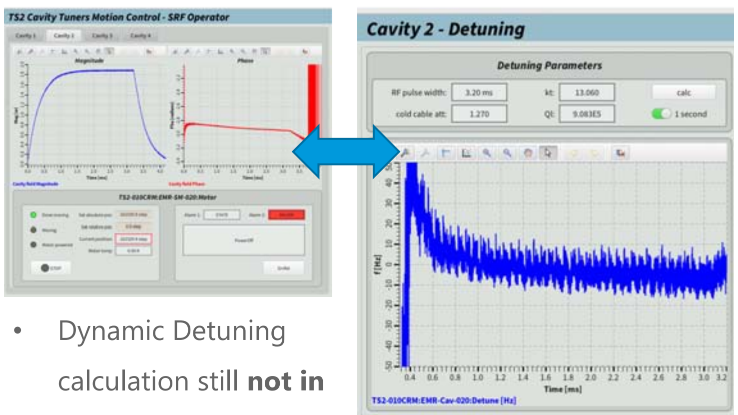


ELL CM: Cavity Studies

(4) Miscellaneous:, detuning calculations, simulated beam loading

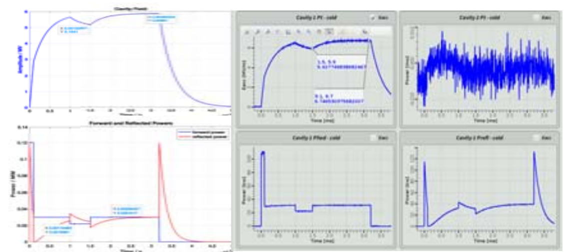
Detuning general (*details in back-up slides*)

$$\text{Detune[Hz]} = \frac{1e6 * (V_{cavI} * \frac{dV_{cavQ}}{dt} - V_{cavQ} * \frac{dV_{cavI}}{dt} + 2 * \omega_{1/2} * (V_{forI} * V_{cavQ} - V_{forQ} * V_{cavI}))/2\pi}{{V_{cavI}}^2 + {V_{cavQ}}^2}$$



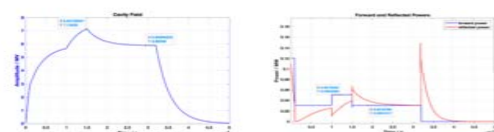
- Dynamic Detuning calculation still **not in core LLRF functionality**. IOC has been developed in TS2
- Assist in cavity tuning.

"Simulated" beam (3mA) in Test Stand vs Theoretical Model

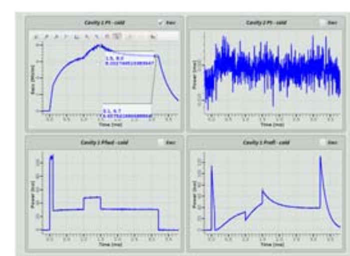


"beam" injected directly into feedforward table

"Beam"(6mA) off but FF table still on



Feedback performance with beam loading,: the **simulation** shows a reasonable feedback loop should **suppress beam loading to ±1%,** but so far in **TS2** only get **±4~5%**

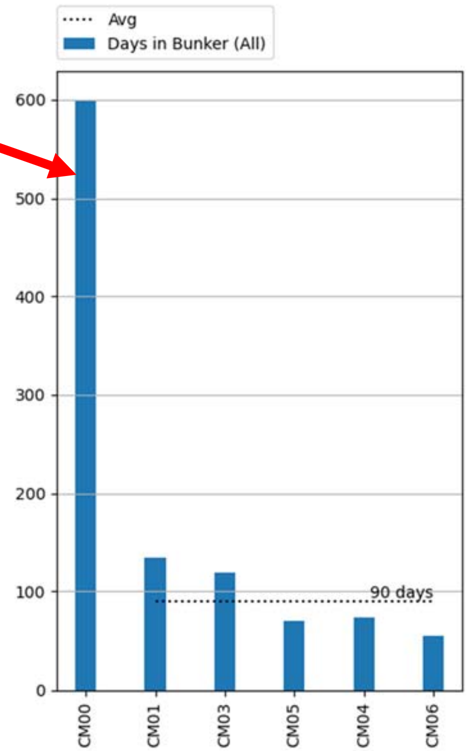


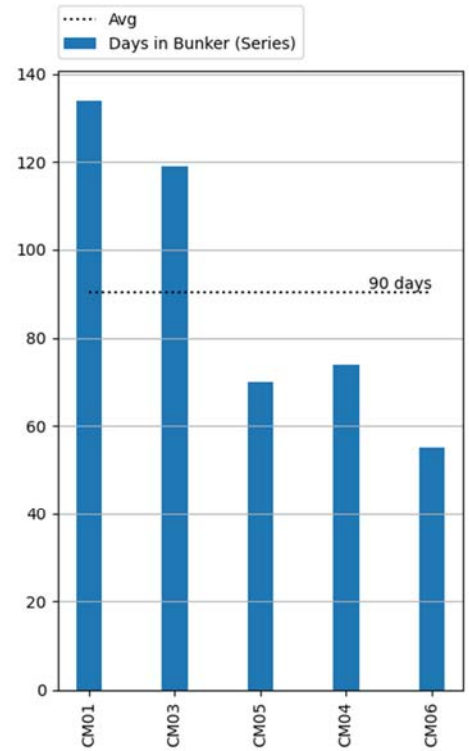
ELL CM: Testing times

Medium Beta testing time

The **prototype CM00 was used to commission the testing facility** and the ESS testing procedures in a staged fashion, with several cooldowns and RF test campaign

The module was kept in the test bunker for nearly two years before starting the series test campaign

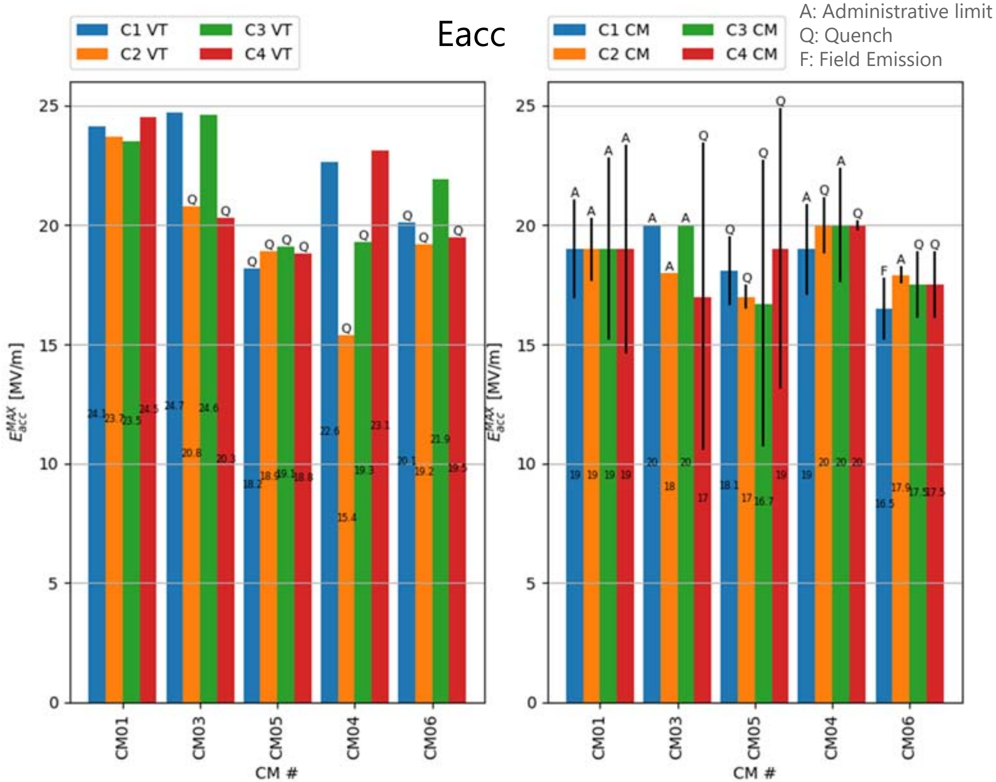




The goal testing time is of **5-6 full weeks** in the test bunker (~40 days).

ELL CM: VT vs CM Performances

Vertical test VS Cryomodule Test



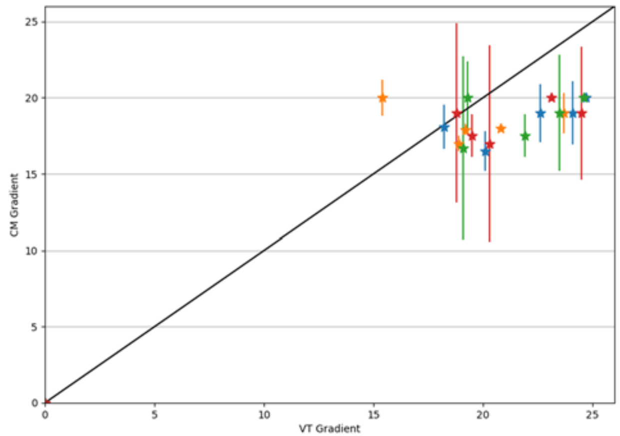
Calibration constants of the **VT** are typically more (up to 20%) **optimistic** than those determined during the CM tests (through forward power or stored energy)

We use recalibrated values from CM tests to assess gradient performances.

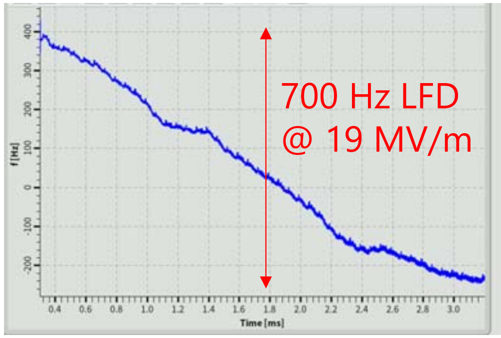
MOPOGE25 Rf Measurement and Characterisation of ESS Cavities at UKRI-STFC Daresbury Laboratory and DESY
TUPOJO15 Commissioning of UKRI-STFC SRF Vertical Test and HPR Reprocessing Facility
THPOGE05 Some Interesting Observations Seen During Vertical Tests on ESS-HB-704 SRF Cavities at UKRI-STFC Daresbury Laboratory

ELL CM: Administrative CM test limits

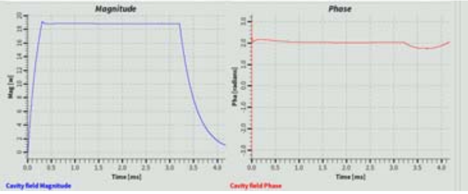
VT-CM Correlation



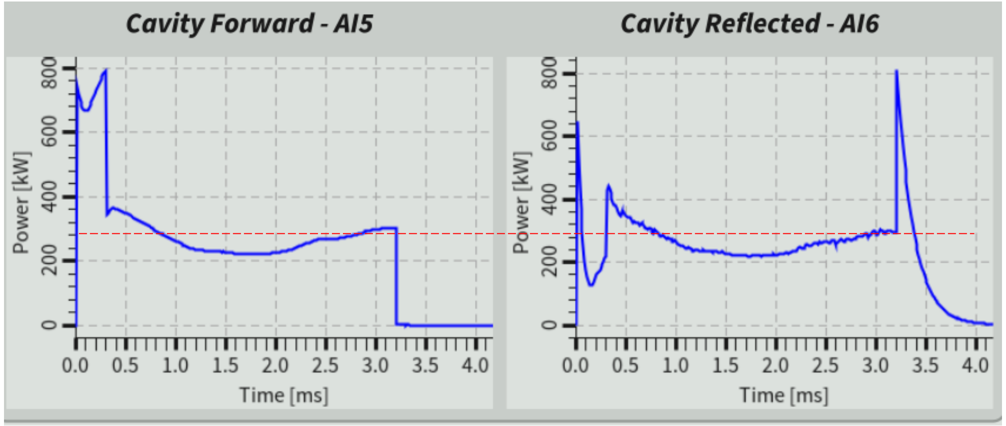
CM Testing frequently stops at the administrative limit of ~300 kW for long pulses in full reflection, set by the coupler design (and conditioning history)



Piezo hardware and its integration within the ESS LLRF is not yet ready, so this limit is reached at approximately **18-20 MV/m** due to the large LFD along **the 3.2 ms RF pulse length** and the FB operation



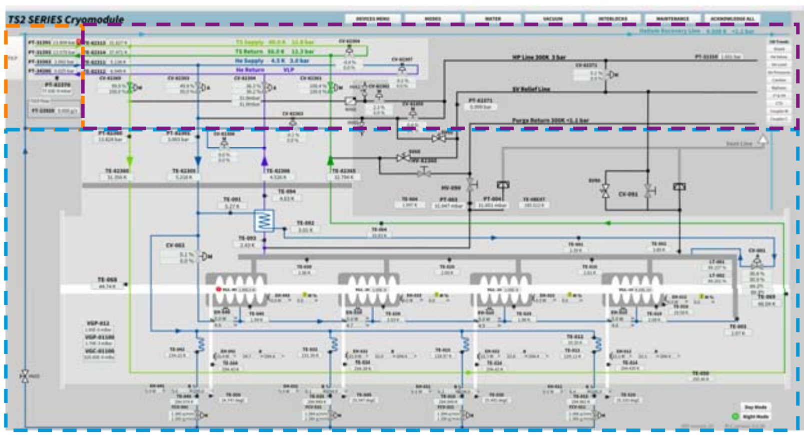
Even predetuning statically, there is a large power overhead required at beg. and end for closed loop ops



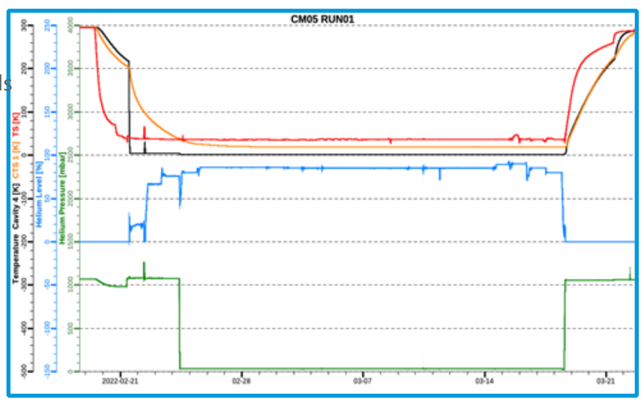
Cryogenic Operations

OPI overview

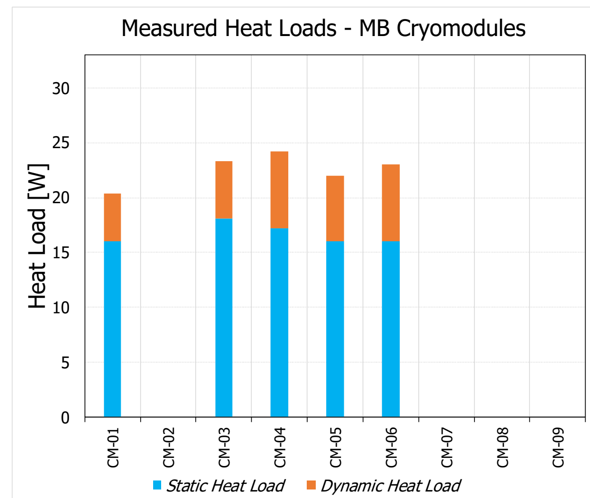
- TS supply
- TS return
- HSL
  - JT circuit
  - Filling
- PCDW cooling
- VLP return
- Purge return
- Safety relief
- Vent line



- Installation/Interconnections
- Verification of signals +cryo-controls
- Purge circuits, Leak Checks
- **Cool-down of Thermal Shield to 35K**
- **Cool-down to 4.2K**
- **Cool-down to 2K**
- **Stable conditions for SRF operation**
- **Heat load measurements**
- **Studies of cryo-performance**
- **Warm-up to 4K**
- **Warm-up to Ambient**
- Disconnection



Heat Loads statistic ~
DHL 5/7 W
SHL 16/18 W



Test cycle, cool down & warm up

3

Cryomodule test installation

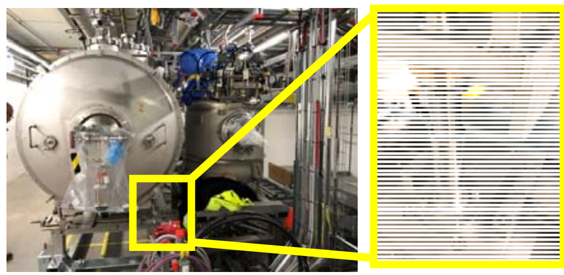
Due to delays in the finalization of the Cryogenic Distribution System, CM installation will start only in Q1 2023

Several CMs are RFI now, so we performed dummy installation tests during finalization of CDS

SPK CM: Installation test

(1)Transport

(2)Alignment



(3)Wave guide test installation

(4)Doorknob RF transition test assembly

(5) Cabling connection test

(6) Connection to cryogenic distribution system

ELL CM: Installation test

(1) Transport & Alignment

(2) Wave guide test installation

(3) Cabling connection test

(4) Connection to cryogenic distribution system

Summary

Preparing for the RBOT (Ready for Beam on Target) Milestone

All CM for the initial linac configuration at ESS by Q1/2023, when installation starts

- 13 SPK, 7 MB ELL and 2 HB ELL to reach > 570 MeV

Linac will be commissioned for the Beam On Dump phase

9/13 SPK CM tested to specs at FREIA

5/30 ELL CM tested at Lund TS2 (only 9 ELL CM necessary for RBOT, 5 MB + 2 HB)

The start of the beam commissioning to the beam dump is foreseen 2024-07

Thanks

LINAC papers

MO1PA02 Beam Commissioning of Normal Conducting Part and Status of ESS Project
MOPOGE25 Rf Measurement and Characterisation of European Spallation Source Cavities at UKRI-STFC Daresbury Laboratory and DESY
TUPOJO13 Wire Scanner Systems at the European Spallation Source (ESS): Tests and First Beam Commissioning
TUPOPA04 First Beam Matching and Transmission Studies on the ESS RFQ
TUPOJO14 Status of Testing and Commissioning of the Medium Energy Beam Transport Line of the ESS Normal Conducting Linac
TUPOJO20-TUOPA02 Progress of the ESS Target Proton Beam Imaging System
TUPORI29, TUOPA08
Space Charge and Electron Confinement in High Current Low Energy Transport Lines: Experience and Simulations From IFMIF/EVEDA and ESS Commissioning
TUPOPA05 RFQ Performance During RF Conditioning and Beam Commissioning at ESS
TUPOJO15 Commissioning of UKRI-STFC SRF Vertical Test and HPR Reprocessing Facility
THPOGE05 Some Interesting Observations Seen During Vertical Tests on ESS-HB-704 SRF Cavities at UKRI-STFC Daresbury Laboratory
MOPORI17 The ESS Fast Beam Interlock System: First Experience of Operating With Proton Beam
THPORI19, THOPA10 HSMDIS Performance on the ESS Ion Source
TUPOJO10, TUOPA01 Beam Commissioning to 21.3 MeV at the European Spallation Source