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EUROPEAN
SPALLATION
SOURCE

Status of ESS cryomodule test in preparation for beam commissioning

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LCWS 2024-07-10

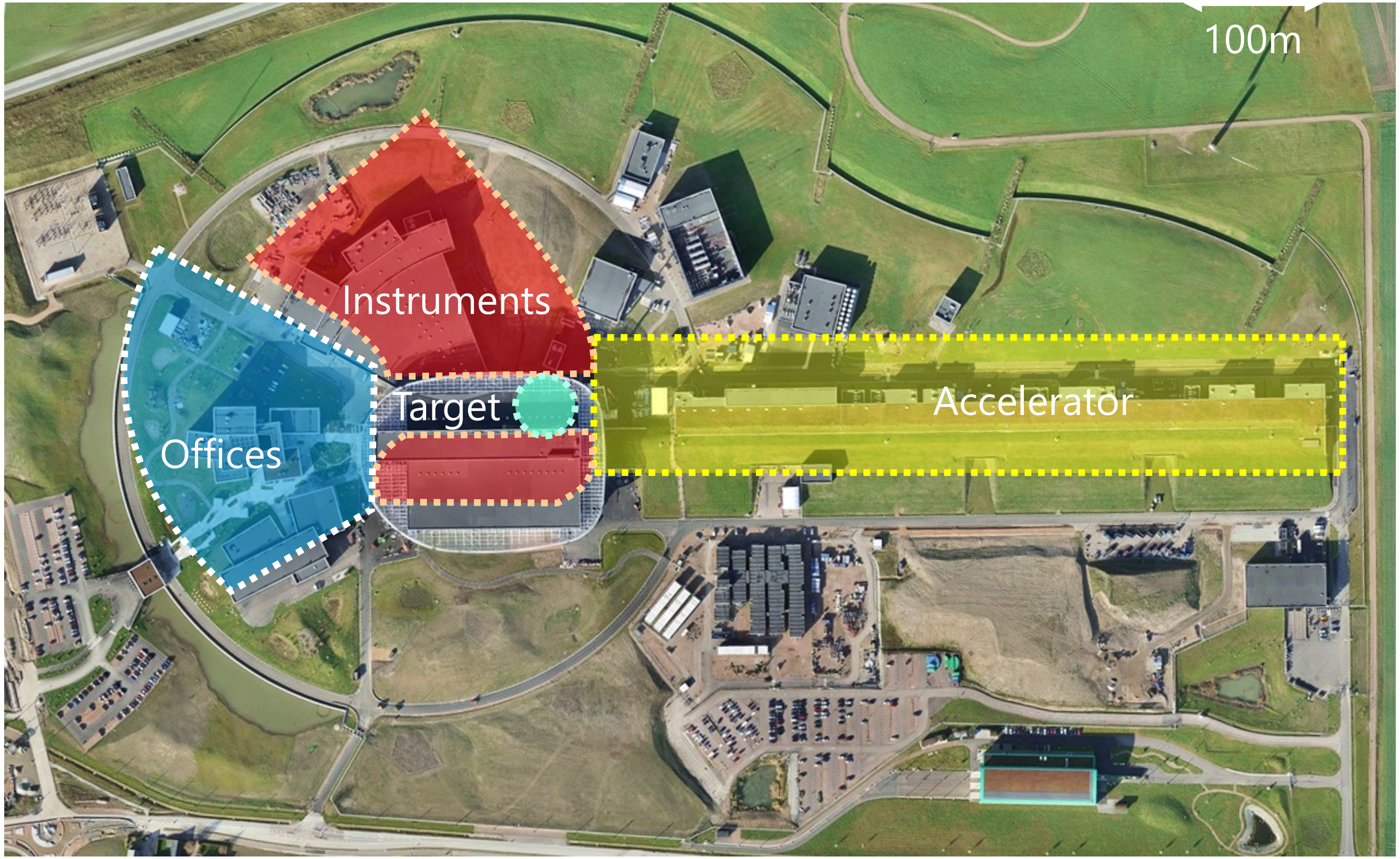
1. Overview on ESS
    - Accelerator, cryomodules, installation progress
2. Cryomodules:
    - Test workflow, performances and statistics
3. Operational challenges
4. Recent achievements

Overview on ESS:

Accelerator, cryomodules, installation progress

ESS: European Spallation Source, Lund , Sweden

World's most powerful neutron source
Enabling materials research: to advance energy, health and environment technologies



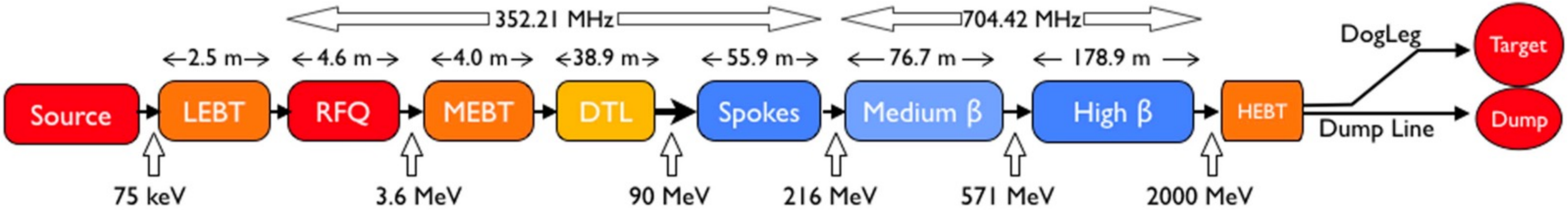
Proton Accelerator
- 2.86ms pulse length
- 14Hz repetition rate
- 62.5mA current

Target Station
- 2.5m Tungsten wheel (36 radial segments)
- Cooled by helium
- Neutron moderator cooled by hydrogen

Scientific Instruments
- 5; 15; 22 scientific experiments
- Diffractometers; Spectrometers, Reflectometers; etc..

The linear accelerator @ 5 MW

Overview

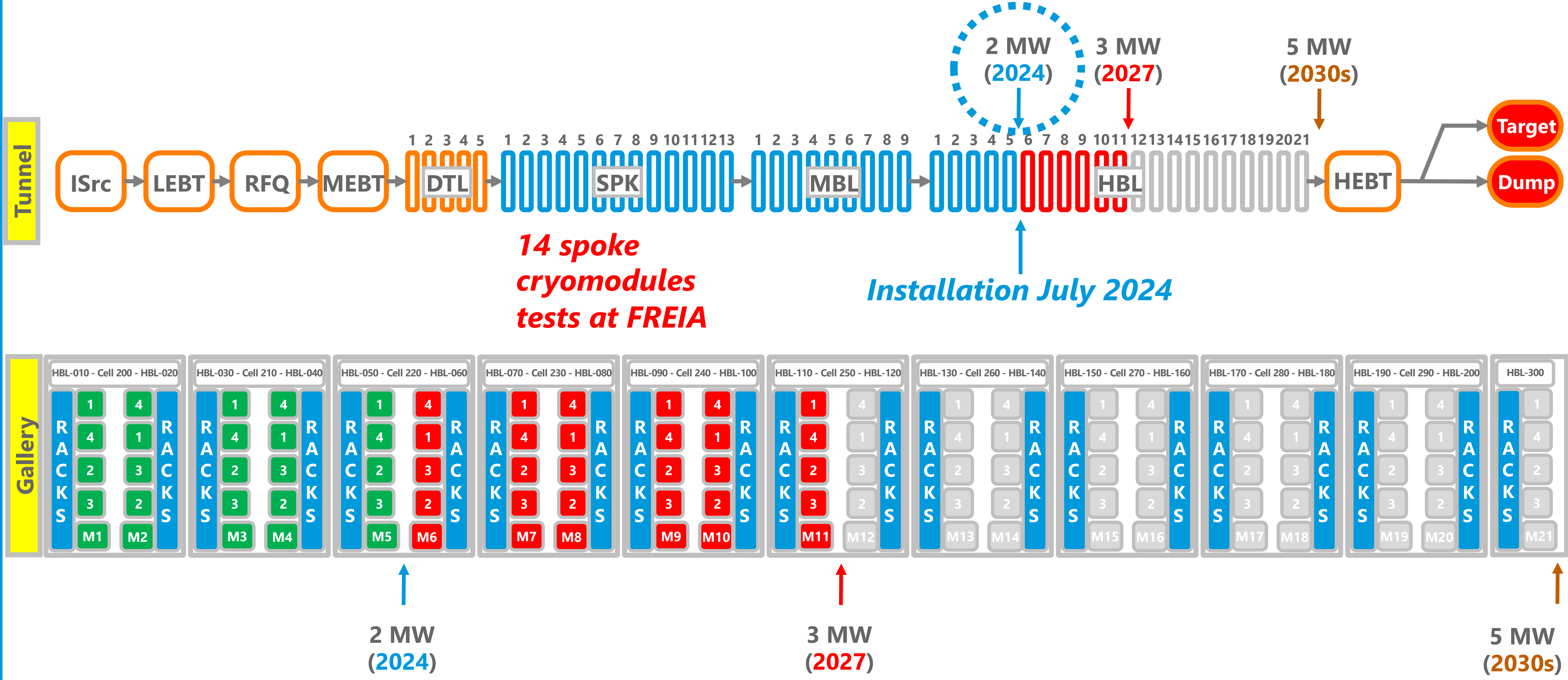


Parameter	Value
Ave power (design) [MW]	5
Max energy (design) [GeV]	2
Peak current [mA]	62.5
Pulse length [ms]	2.86
Rep rate [Hz]	14
Duty factor [%]	4
RF freq [MHz]	352.21/704.42

	Length	No. Magnet	#Cav x β_g/(Opt)	No. Sections	Power (kW)	IK partner
LEBT (from Plasma)	2.7	2 Solenoids	—	1	—	INFN-LNS
RFQ	4.5	—	1	1	1600	CEA Saclay
MEBT	4.0	11 Quads	3	1	15	ESS-Bilbao
DTL	38.9		5	5	2200	INFN-LNL
LEDP + Spoke	55.9	26 Quads	26 x (0.50)	13	330	IPNO
Medium Beta	76.7	18 Quads	36 x 0.67	9	870	LASA / CEA
High Beta I (~1.3 GeV)	93.7	22 Quads	44 x 0.86	11	1100	STFC / CEA
High Beta II	85.2	20 Quads	40 x 0.86	10	1100	STFC / CEA
Contingency + HEDP	132.3	32 Quads	—	15	—	Elettra
DogLeg	64.4	12 Quads + 2	—	1	—	Elettra
A2T	44.7	6 Quads + 8 Raster	—	1		Aarhus Uni
	603.0					

Overview: Increasing ACC Power Capability

From 2 MW (2024) to 3 MW (2027) to 5 MW

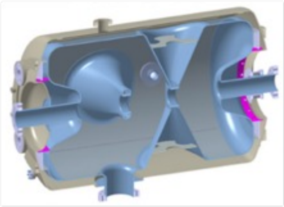


ESS SCL Cavities and Cryomodules

Cryomodules

13 x Spokes

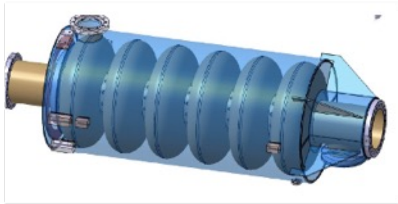
2 x



IJC-Lab (ZANON)

9 x Medium Beta

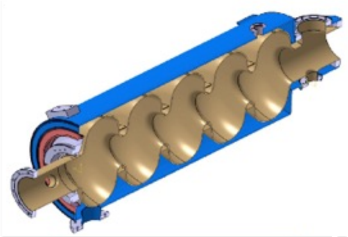
4 x



INFN-LASA (ZANON)

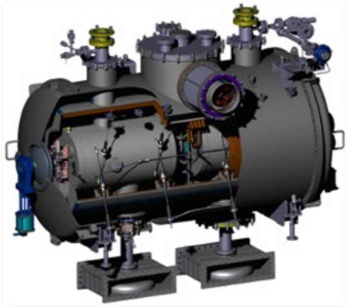
21 x High Beta

4 x



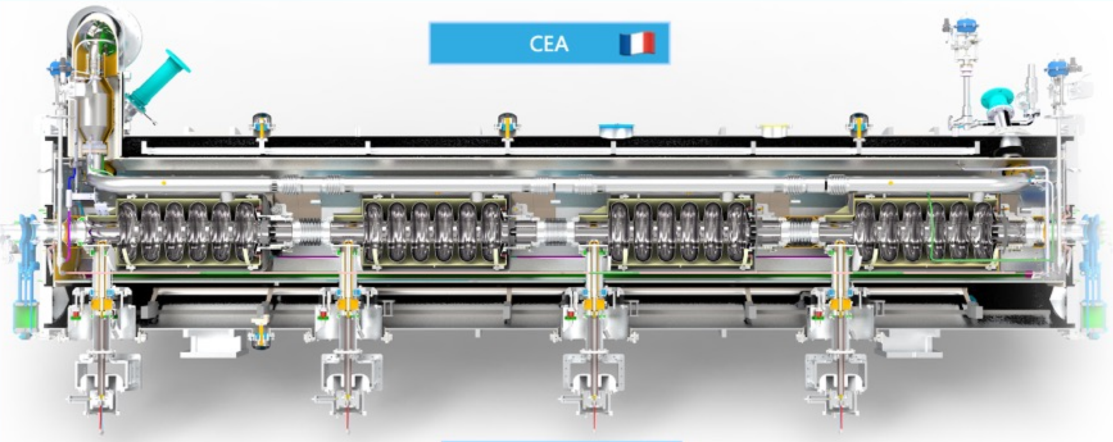
STCF (RI)

IJC-Lab



UU-Freia

CEA



ESS-TS2

Spokes

IJCLab Irène Joliot-Curie Laboratoire de Physique des 2 Infinis → UPPSALA UNIVERSITET

Elliptical

INFN LASA

UKRI Science and Technology Facilities Council → CEA - Saclay Irfu

→ ifj +

Cavities

26

36

20 for 2 MW = 82
44 for 3 MW = 106
84 for 5 MW = 146

Cryomodules:

test workflow, performances and statistics

LCWS 2024-07-10

ELL CM: ESS Test Stand overview & workflow

The workflow and test is split in phases

CM lifecycle is intensively documented

- Cryomodule Assembly from (INFN/STFC) CEA
- Cryomodule testing phase (Mec/Vac/Cryo/SRF)

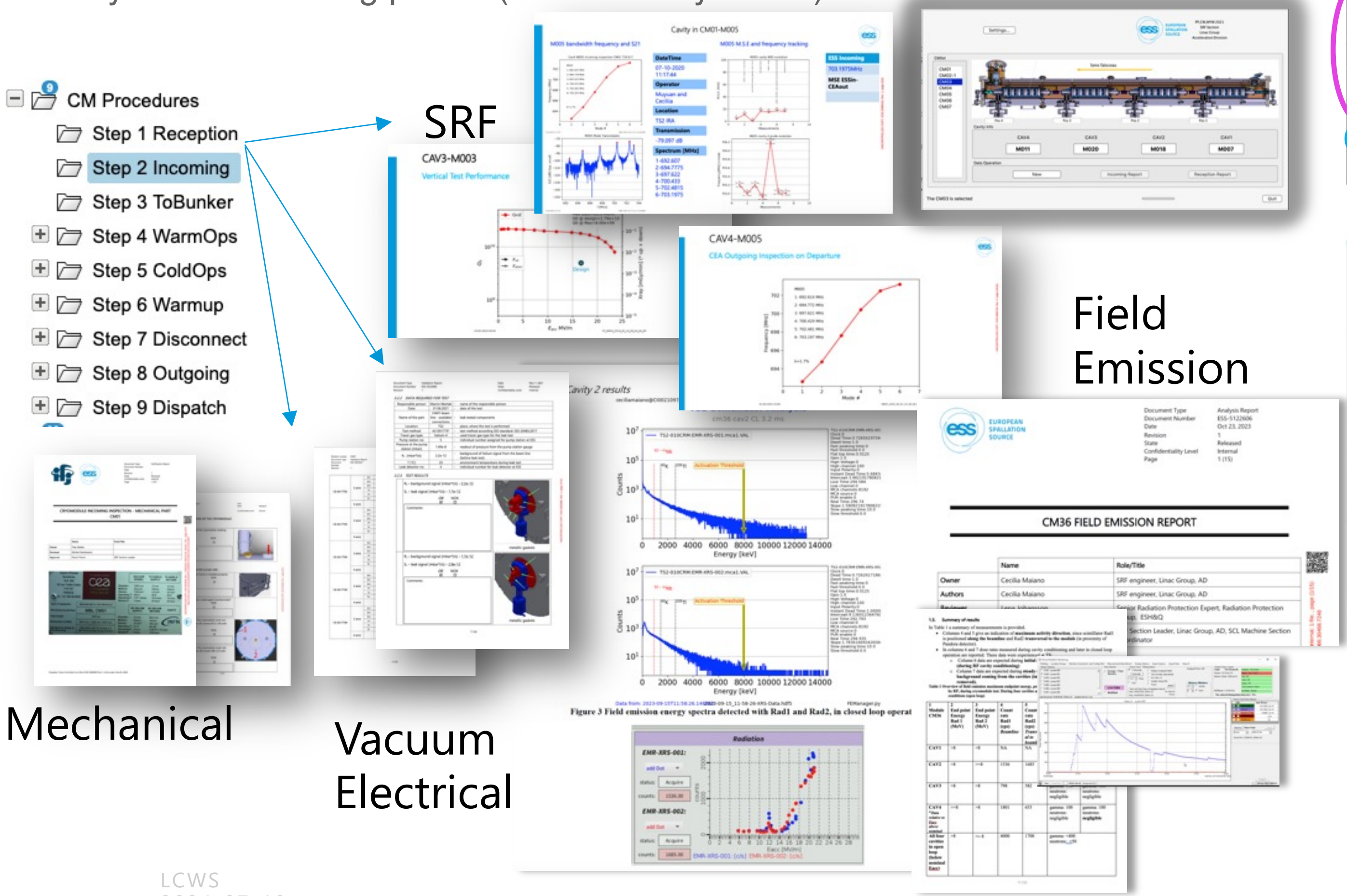


Table 1. Phases of the CM Workflow

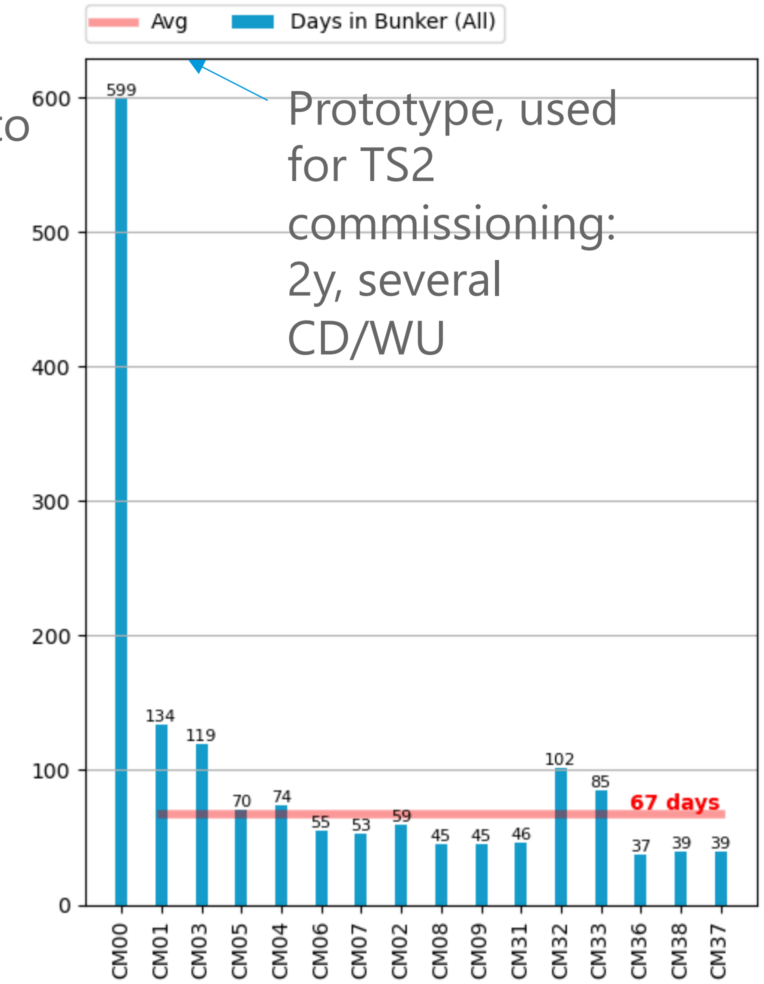
#	Phase	Areas From	Areas To
1	Cryomodule reception	G02-CXL	CM-IRA
2	Cryomodule preparation	CM-IRA	
3	Cryomodule installation	CM-IRA	Bunker
4	Cryomodule Warm Validation	TS2 Bunker	
5	Cryomodule Cold Validation		
6	Cryomodule Warm-up		
7	Cryomodule Disconnection	Bunker	CM-IRA
8	Cryomodule Preparation for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

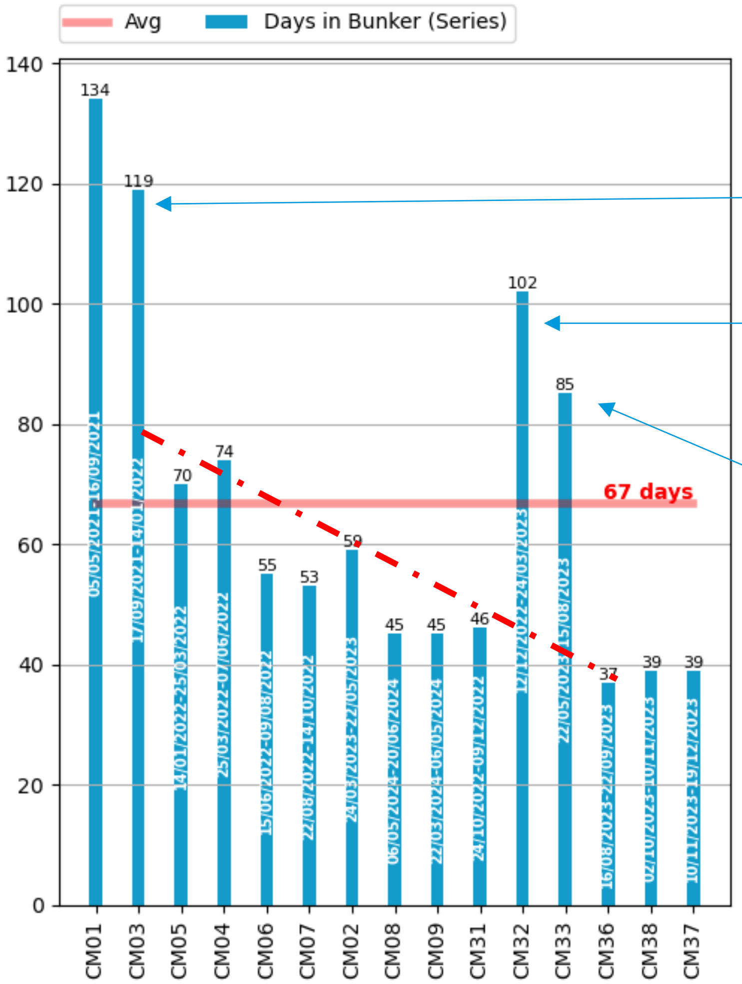
Site Acceptance Test of CM

TS2 **Statistics** – 15 CM tested

ELL: Number of days in TS2 bunker

1 proto
9 MB
6 HB





Trend improving over time, outliers:

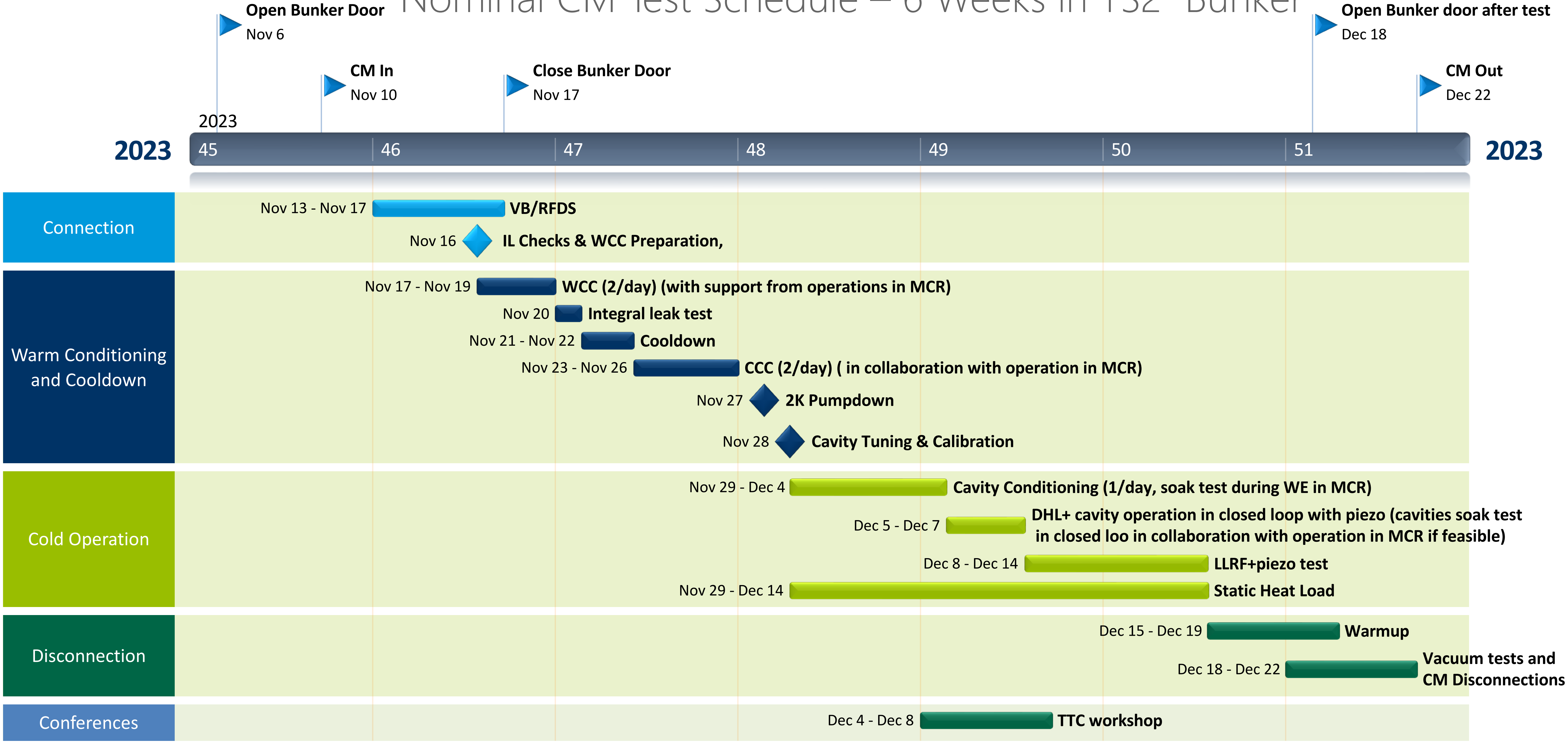
CM03:
Repair of gauge (2x test)

CM32:
Cryoplant trip/ cold leak investigations

CM33:
Needed to add pumping during conditioning due to severe vacuum activity

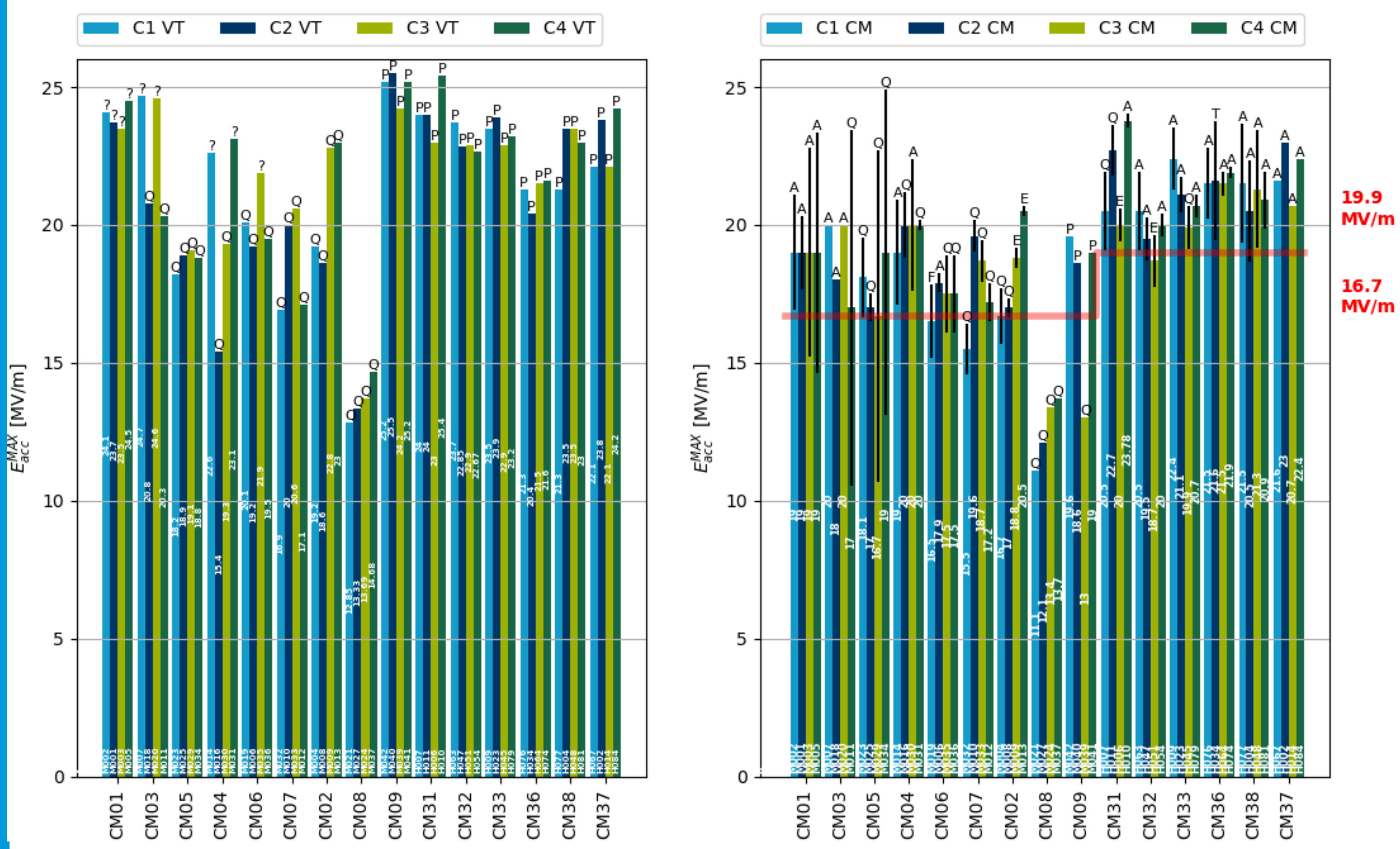
Steady State: **6 weeks in bunker (42 calendar days max)**

Nominal CM Test Schedule – 6 Weeks in TS2 Bunker



RF Performances: Gradient

ELL: VT/CM Gradient Performances

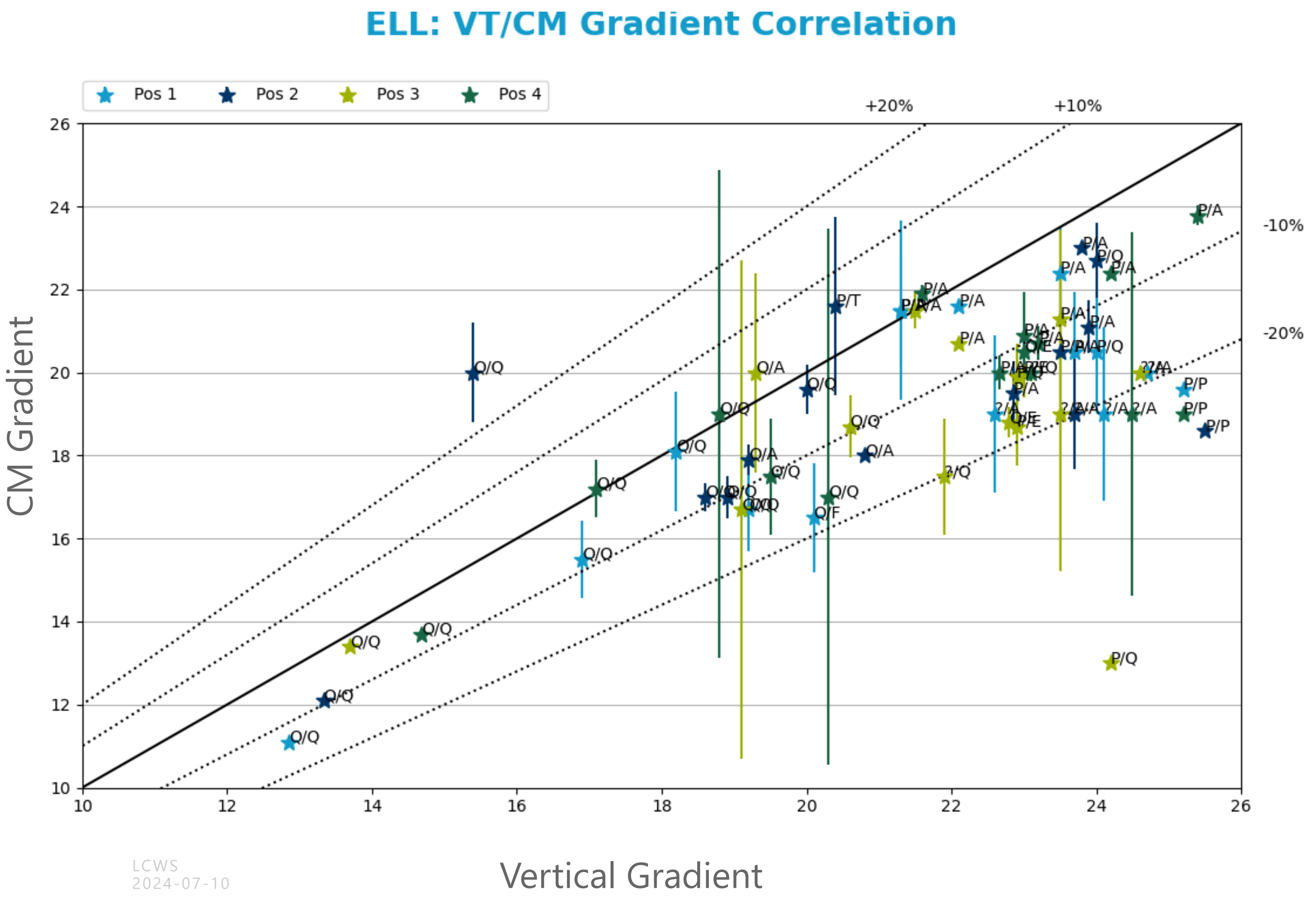


Nominal gradient is generally met

- Few marginal cav

Test uncertainties large at the start of TS2 commissioning, **improving with time**

Sanity Check: VT vs CM checks



As expected VT/CM results typically agree within 10-15%

The part at higher gradients suffers from the onset of the Admin limit (max coupler power in SW) in CM testing

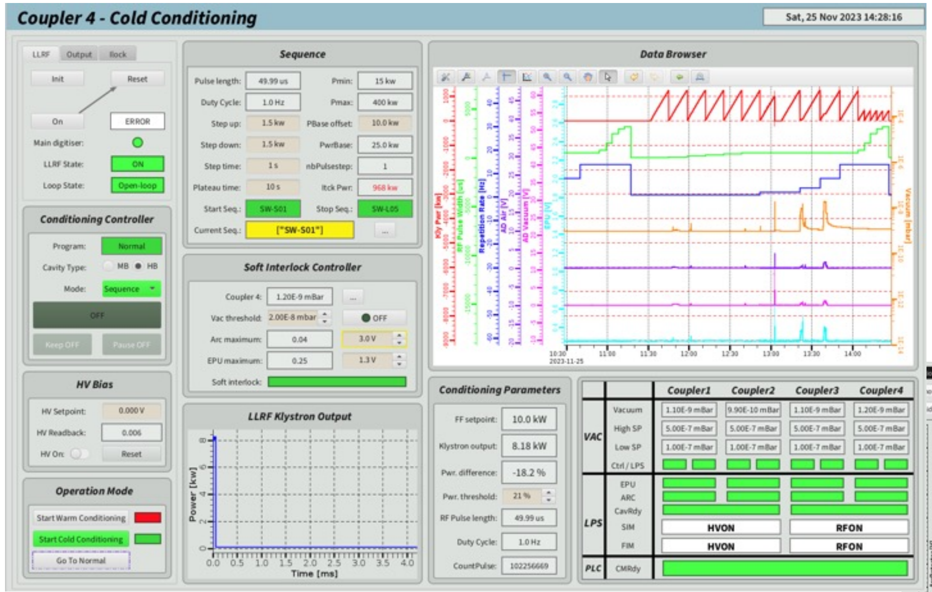
Coupler conditioning sequence

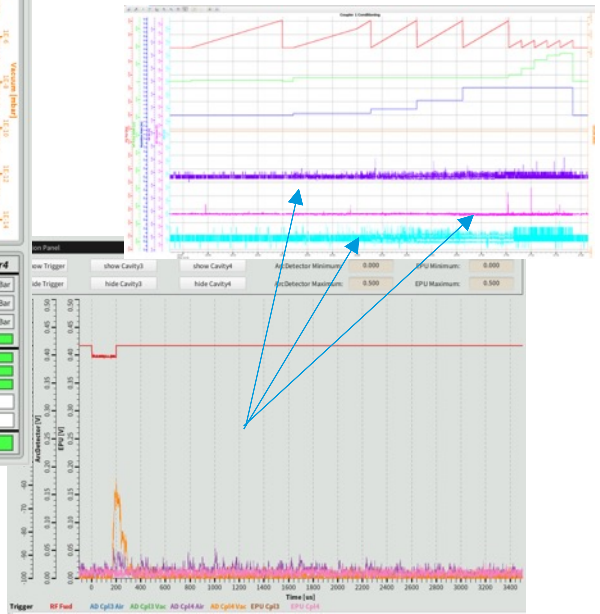
Warm and cold coupler conditioning

Automated sequencer script runs through the steps, and monitors vacuum, EPU and AD signals.

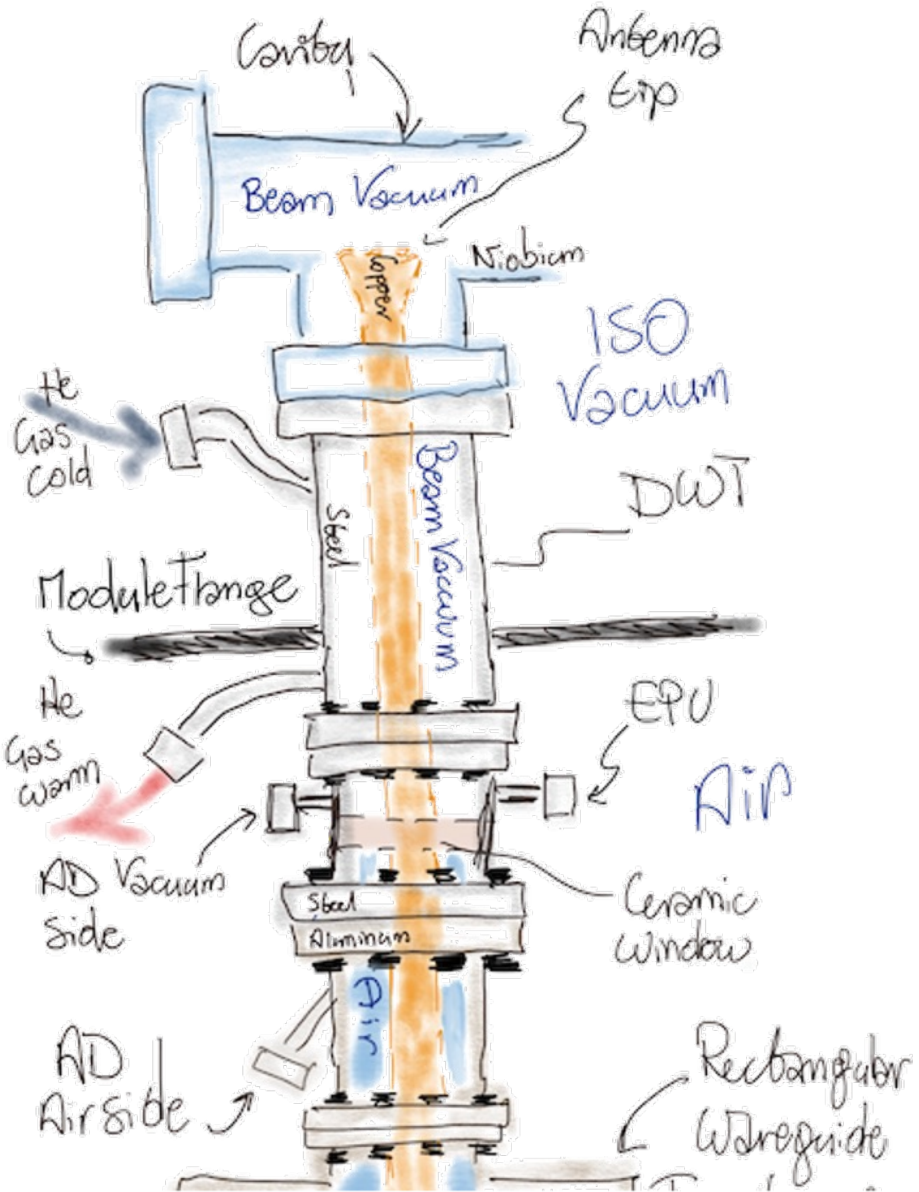
Admin limits in full reflection mode:

- Power cannot exceed **300/400 kW** for RF pulses (for medium and high beta couplers respectively) longer than **500 µs**.
- Peak power cannot exceed 1.1/1.2 MW for any pulse length



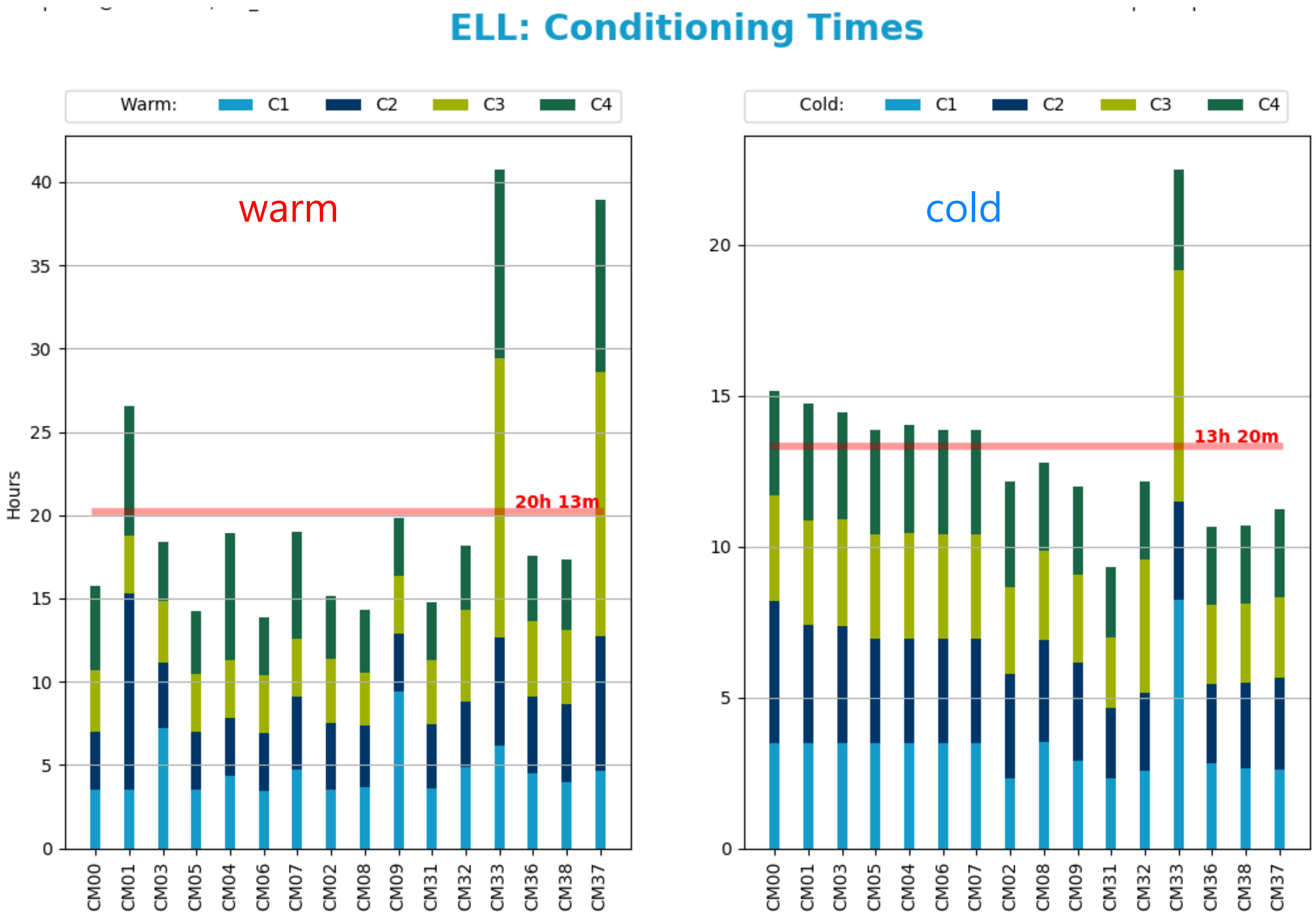


AD and EPU
Signal monitoring



Coupler Conditioning (off resonance)

Keeping track of experience, as it will be repeated in tunnel

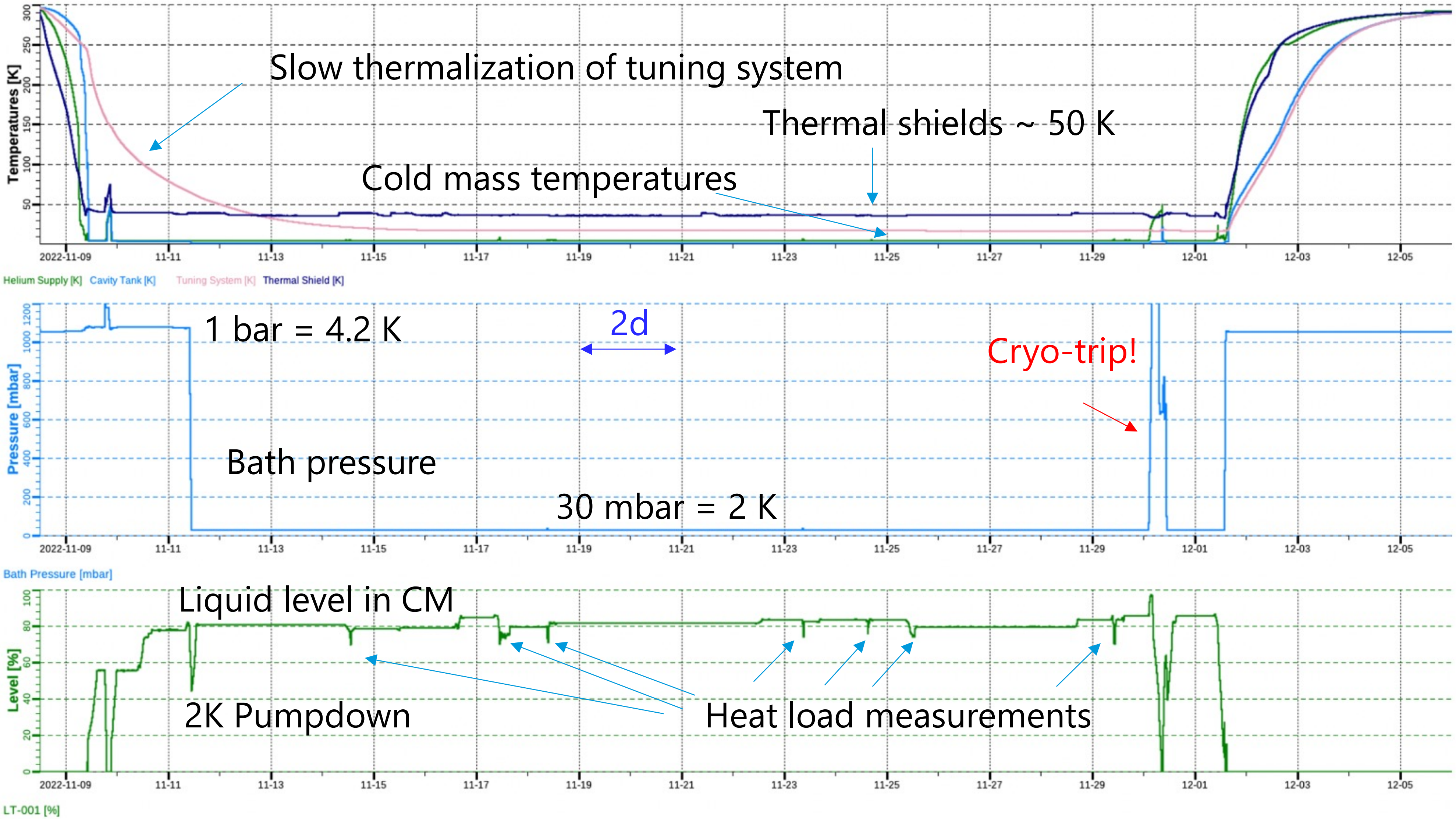


Conditioning times correlate with number of NCR registered during assembly

CM33 was extremely long, but we profited from the involvement of ESS OPS to run 24/7 conditioning through our automated scripts

- SRF experts may speed up the process, but the procedure is able proceed with no supervision.

Cryogenic operation: full Cooldown Cycle

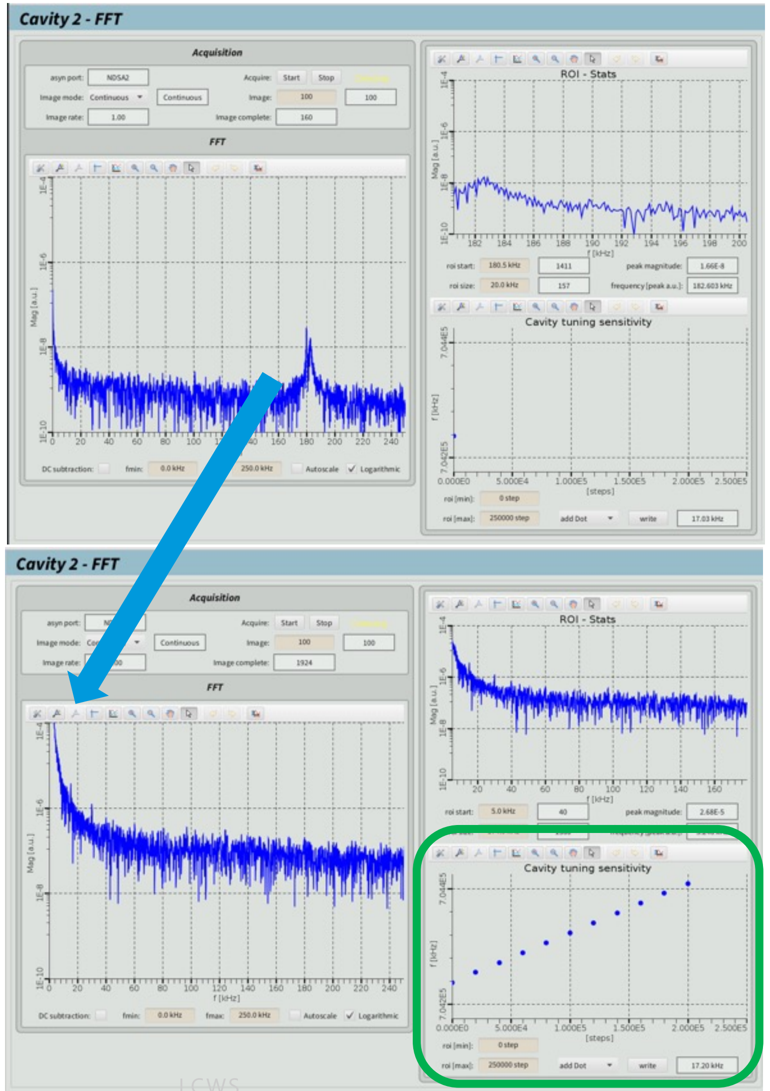


~20 d cold

Credits, N. Elias, ESS

Tuning tool

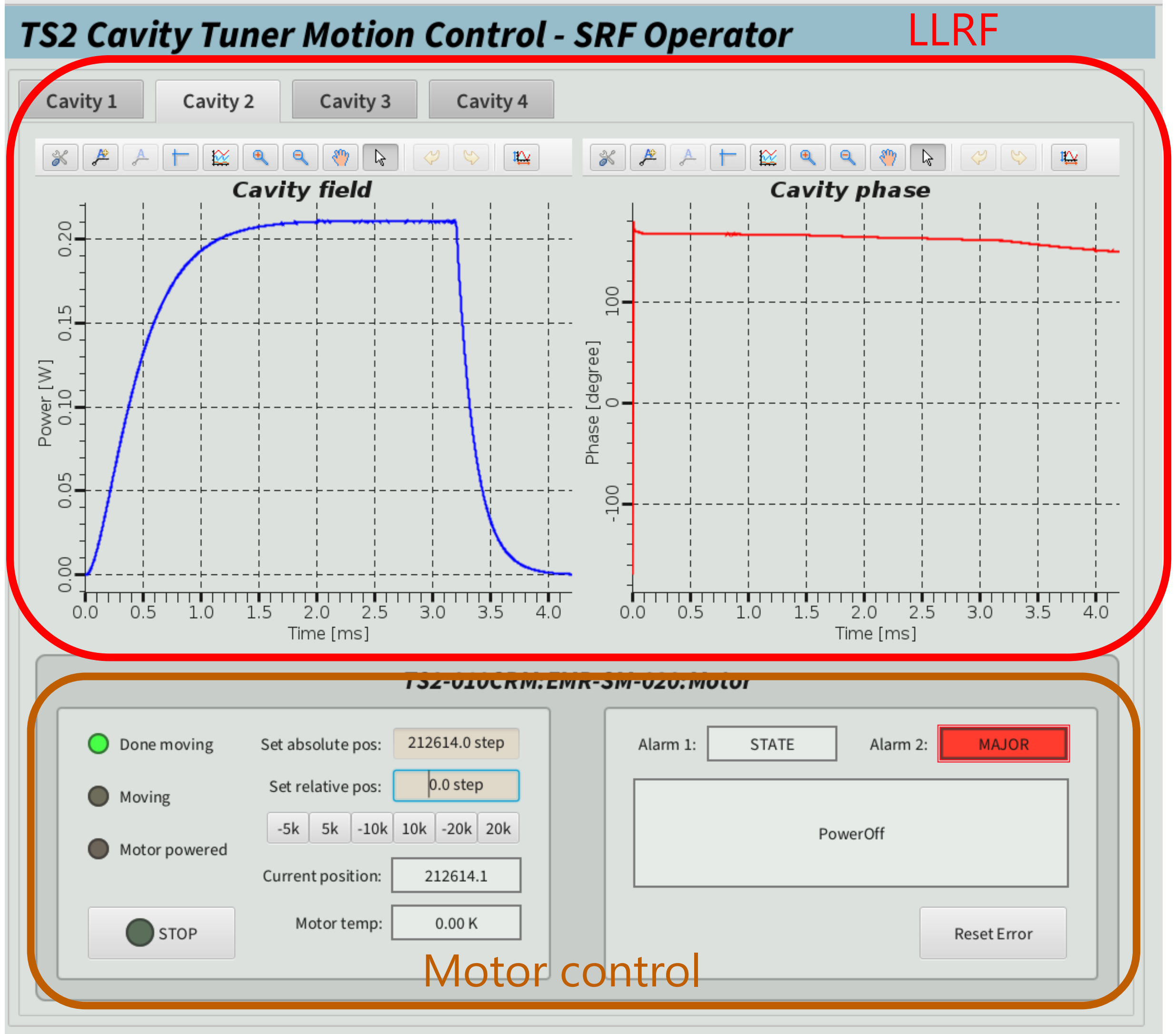
Far and Fine tuning tools



Far tuning with calculations from LLRF Waveforms

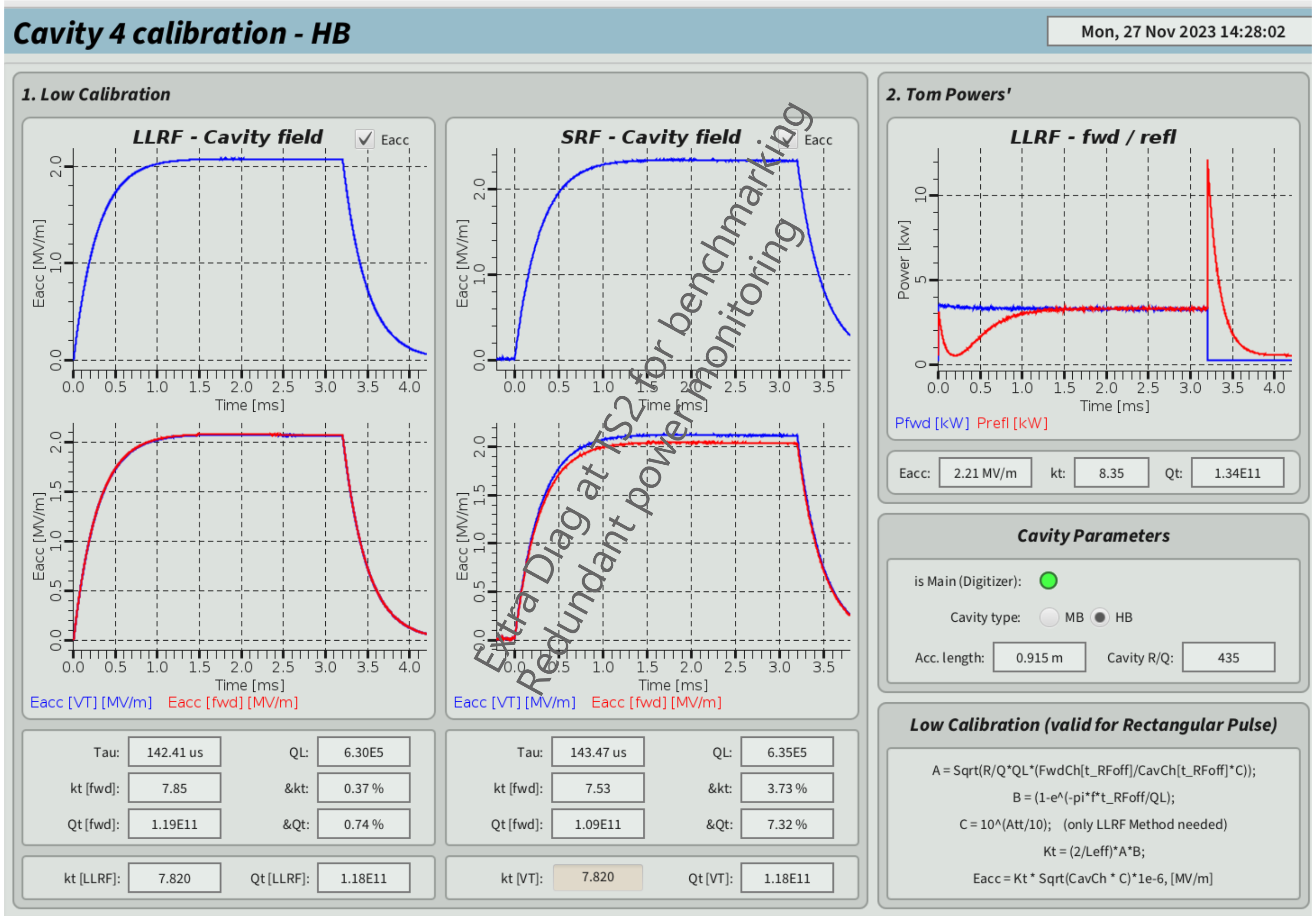
Tuning sensitivity (health check)

Fine tuning with power increase and phase flattening



Calibration tool

Convert from power sent from Klystron to E_{acc} (or V…)



Using cavity parameters and calibration factors

PU antenna recalibrated using forward power, as VT calibration factors lead frequenctly to overestimation of cavity field

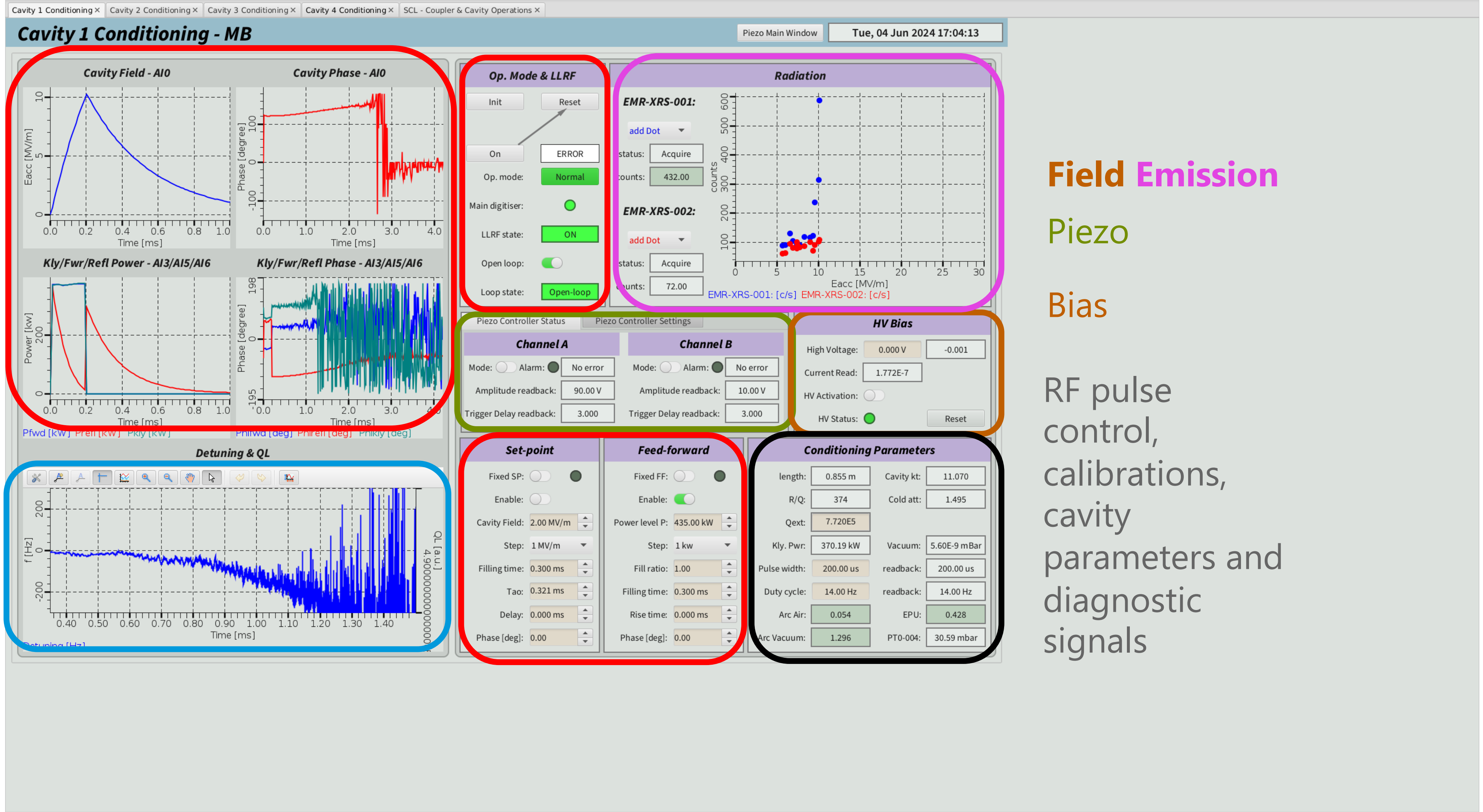
By using different methods and **power readings (redundant power monitoring**) we estimate uncertainty of gradient calibration

Cavity Conditioning/Operation tool (TS2)

Getting PV from several subsystems, still manual process

LLRF
Open loop at low field, then Closed loop to cope with LFD

Cavity IOC, providing in-pulse detuning calculation



Field Emission

Piezo

Bias

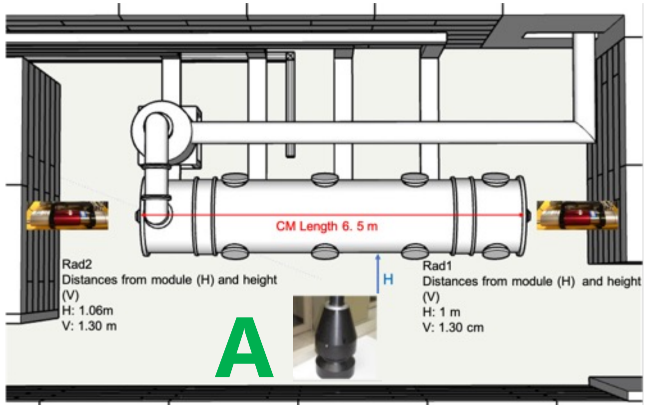
RF pulse control, calibrations, cavity parameters and diagnostic signals

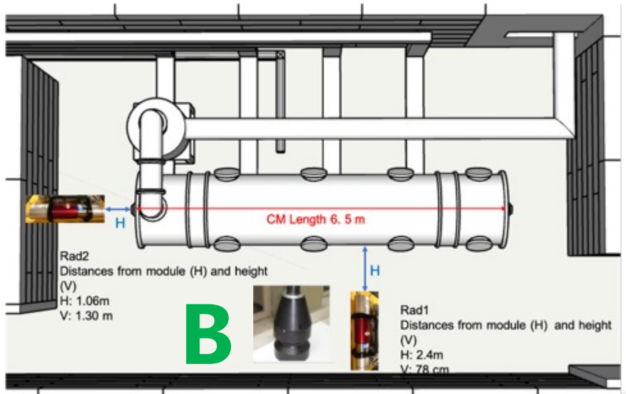
Operational challenges

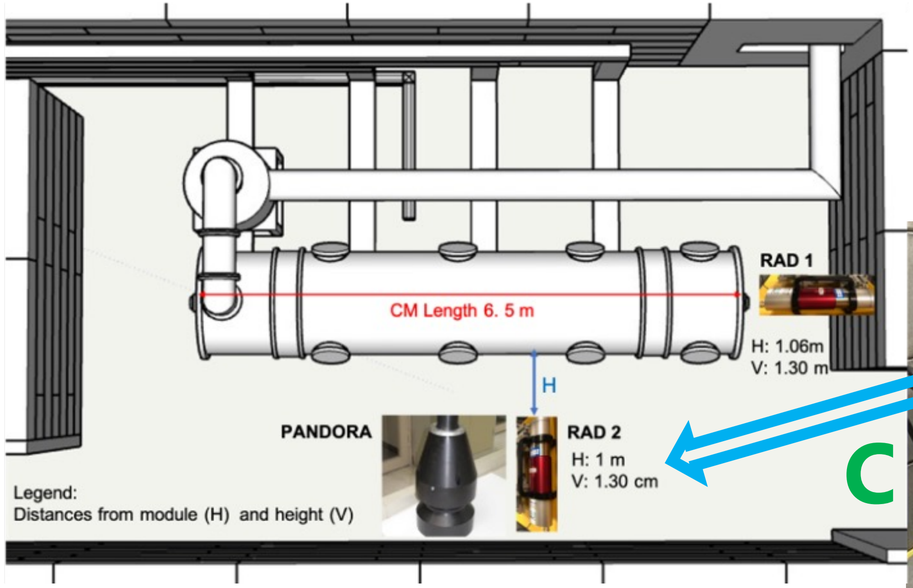
Equipment description for field emission

NaI(tl) detectors with Pb shielding (AMPTEK Gammarad5 76x76mm)

https://www.amptek.com/-/media/ametekamptek/documents/resources/products/user-manuals/gammarad5-user-manual-b0.pdf?la=en&revision=afb7309f-7ab0-4490-8e10-db886b022bfc



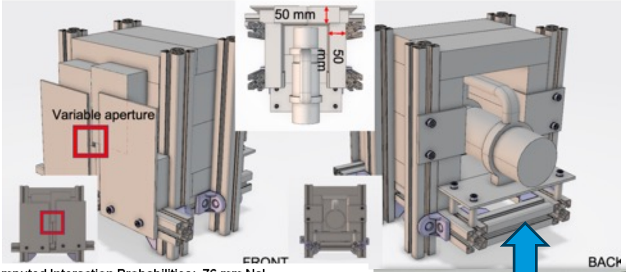


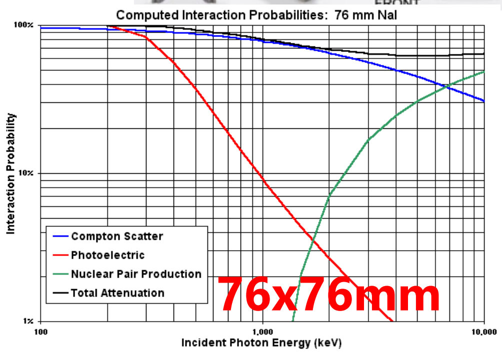


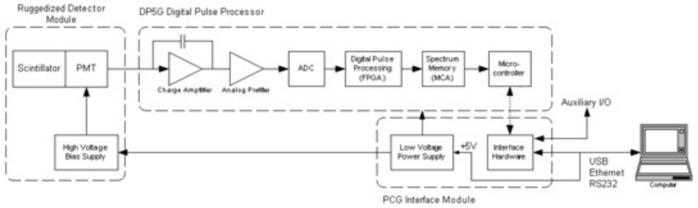
C

RP Pandora

Dose rate:
Neutrons
and gamma

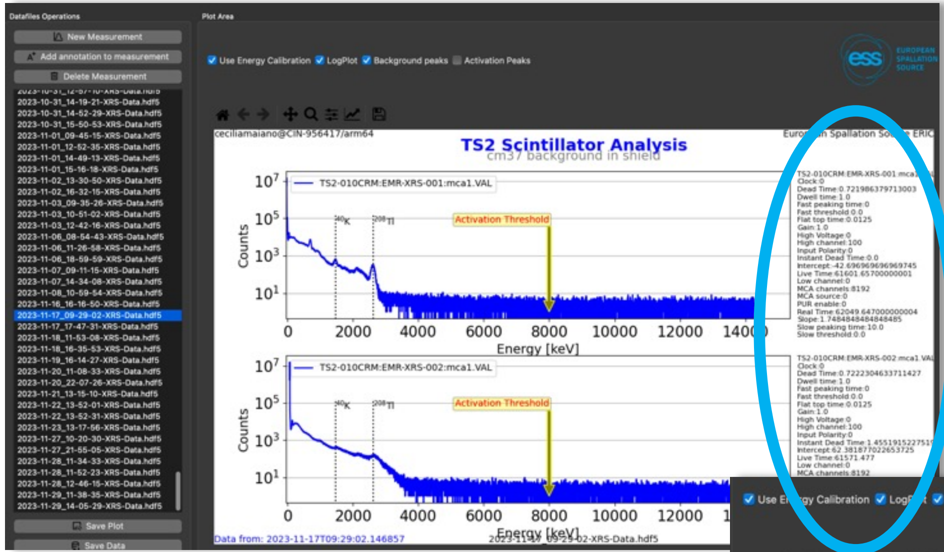


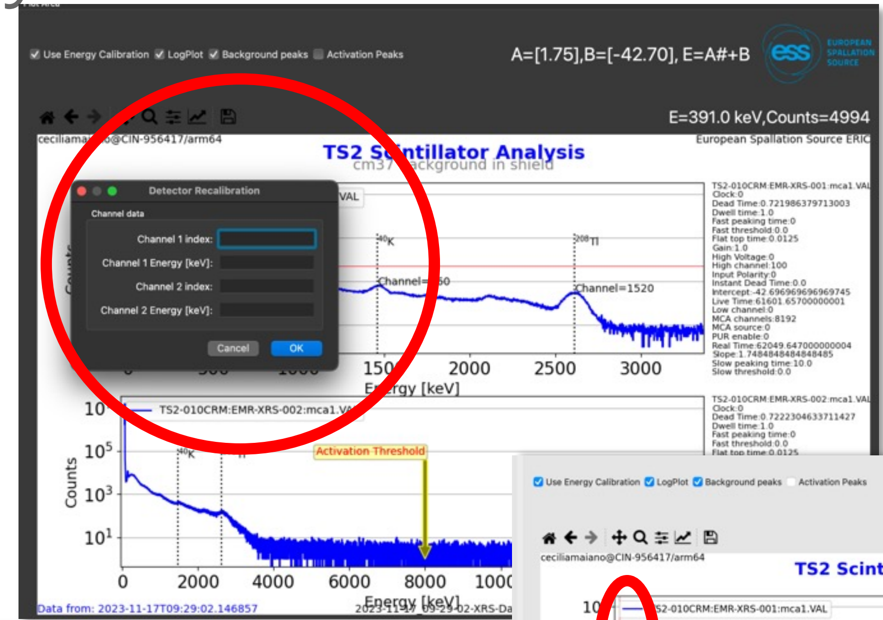




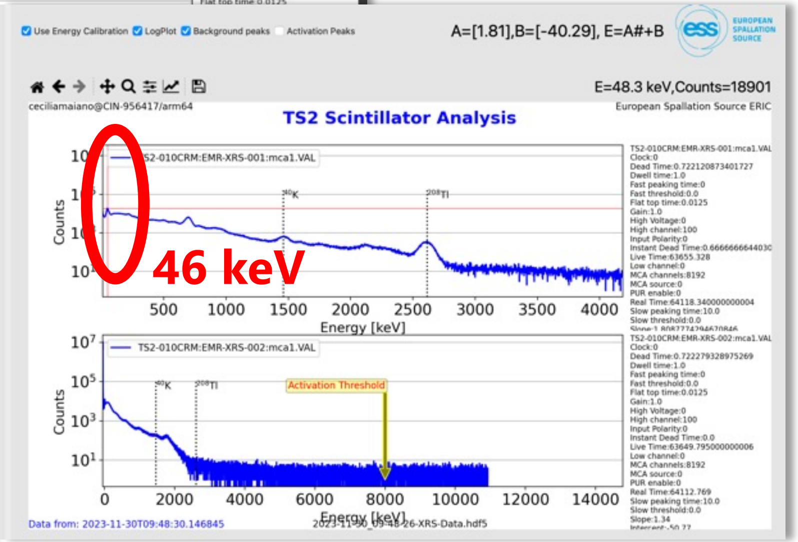
Acquisition and Analysis tool

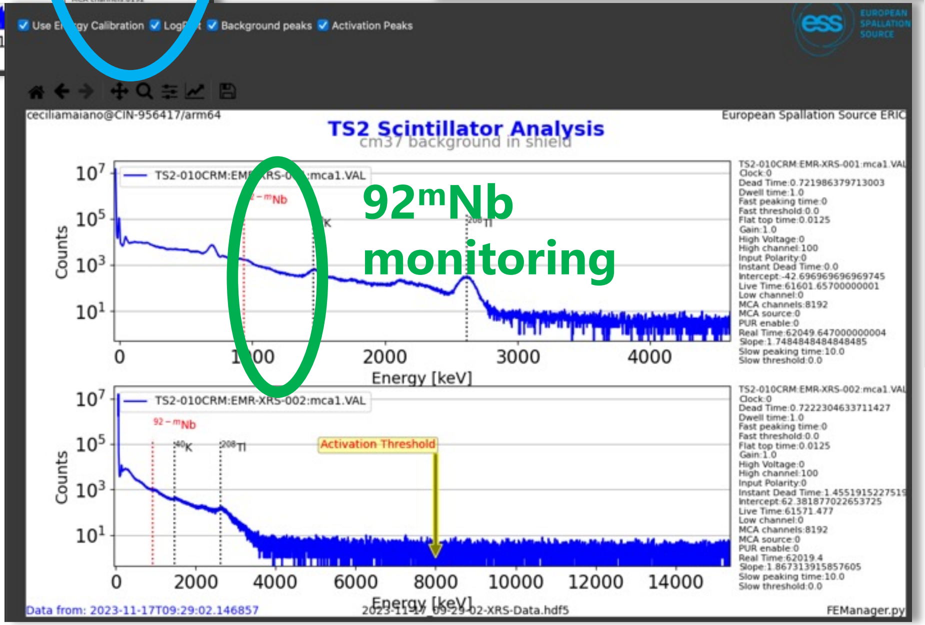
- NaI(Tl) integrated in EPICS
- Tools with python scripts





Recalibration, using
- 208Tl
- 40K
- Pb x-ray 46 keV

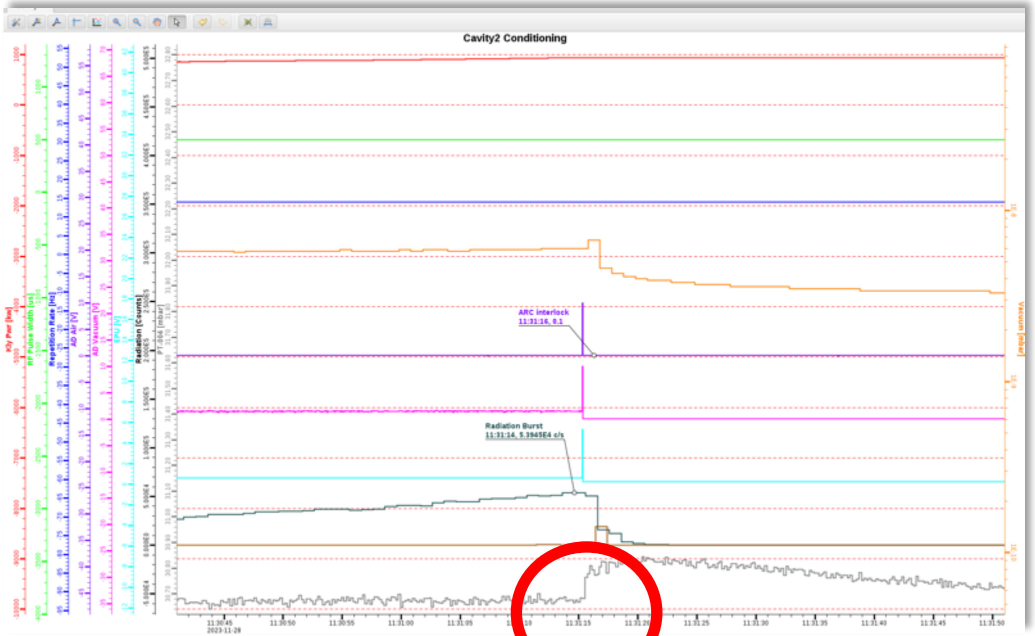


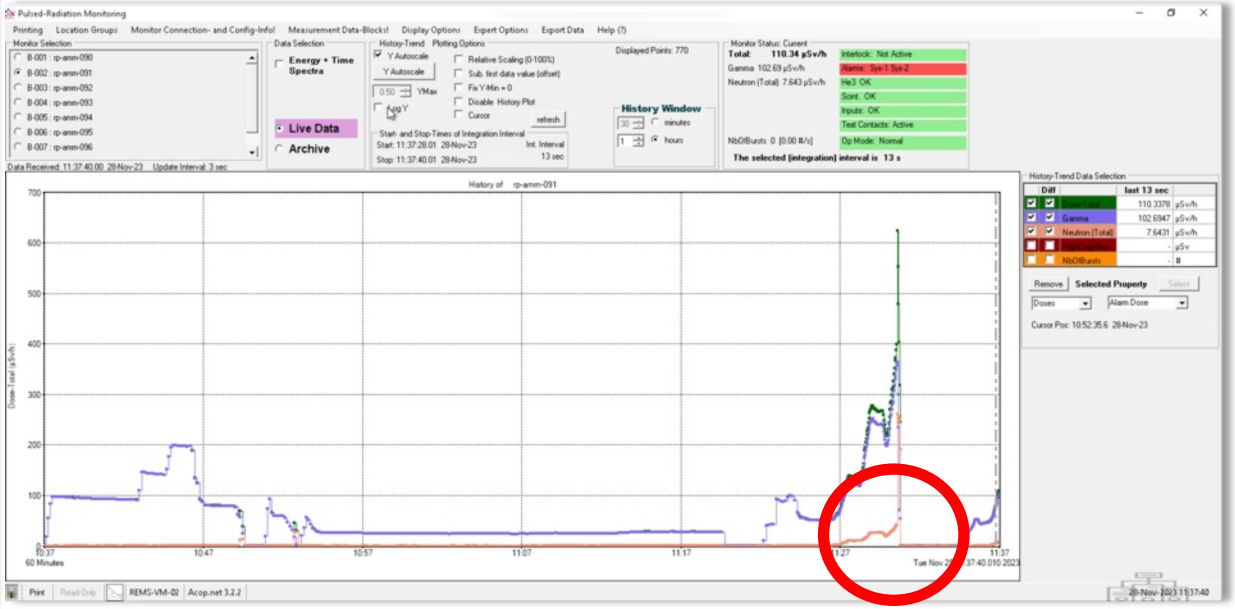


Regular measurements
- BKG
- FE meas
- **Configuration parameters**

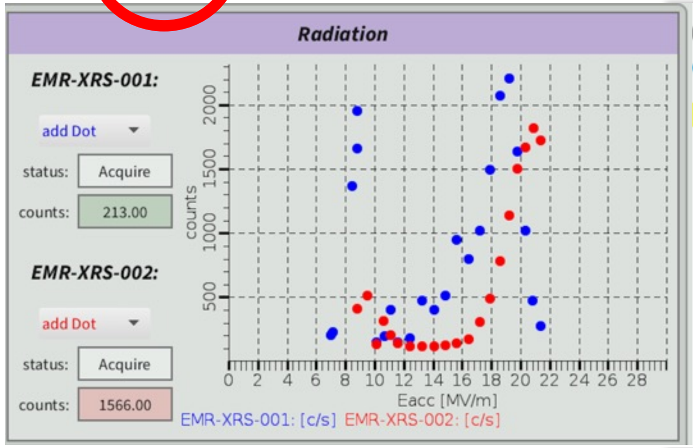
Activation check
- mainly **^{92m}Nb** due to giant resonance (y,n) activation

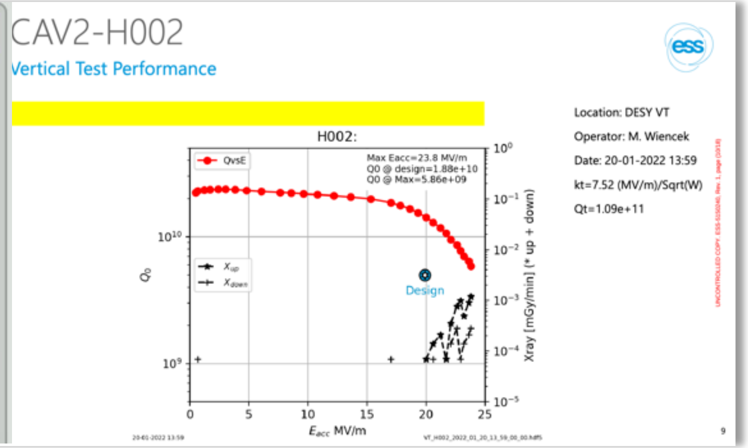
FE as limiting mechanism





Cryomodule test CM

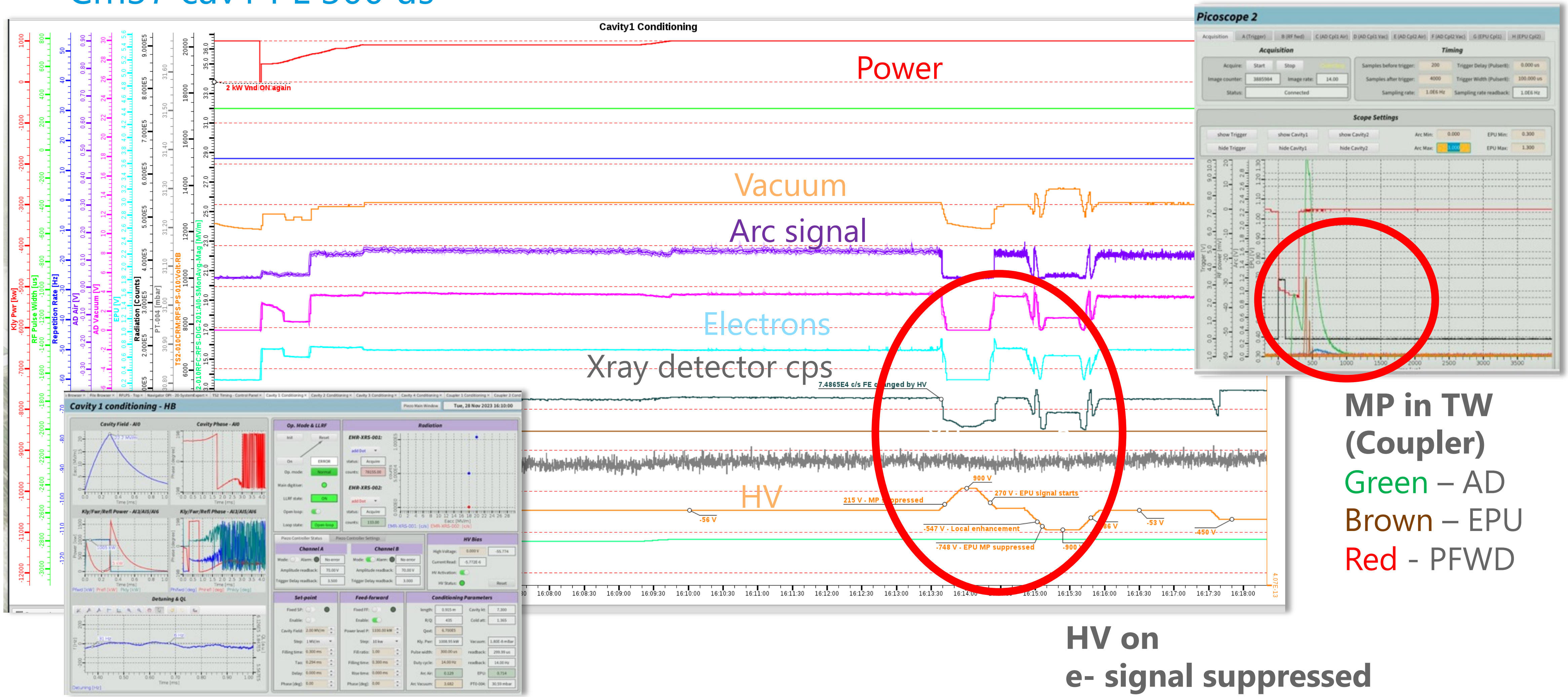




VT Vertical Test

FE as limiting mechanism fed by coupler MP: HV suppression

Cm37 cav1 PL 300 us

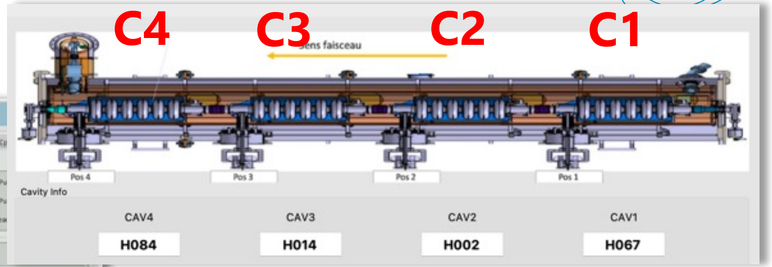


MP in TW (Coupler)
Green – AD
Brown – EPU
Red - PFWD

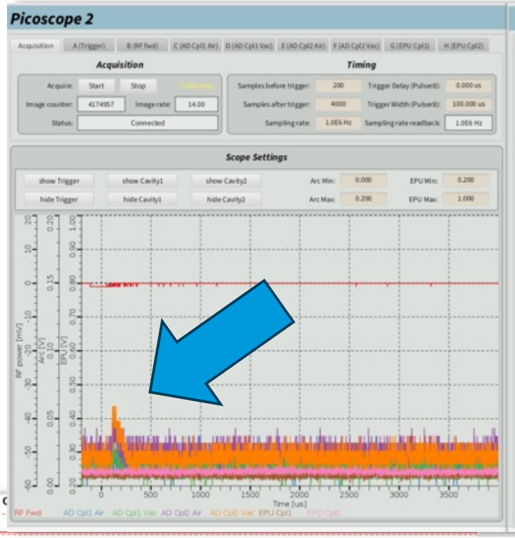
HV on
e- signal suppressed
Radiation suppressed

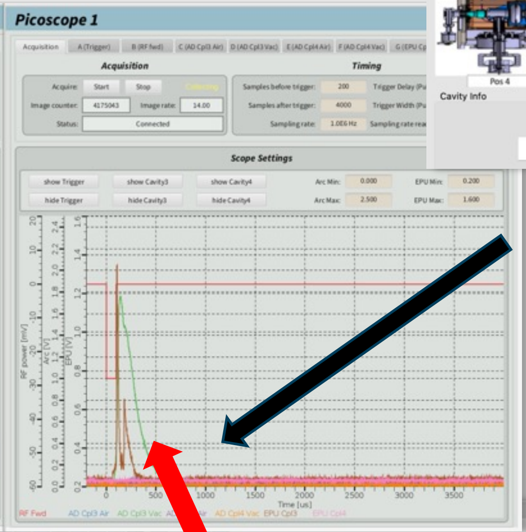
FE as limiting mechanism: cherenkov in fibers

Experience with HB cm37 – cav3 -



AD cav 1and cav 2 detect radiation coming from cavity 3 downstream

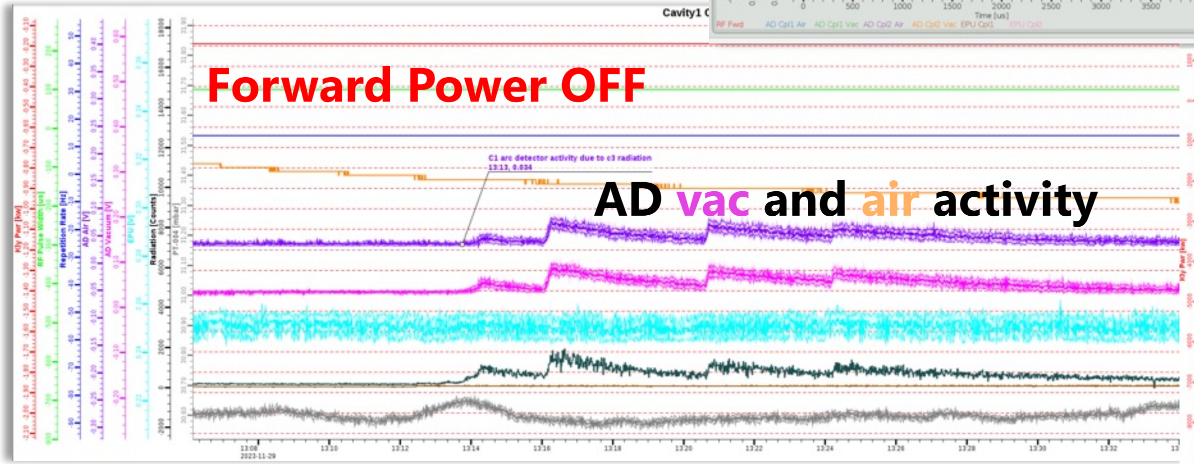


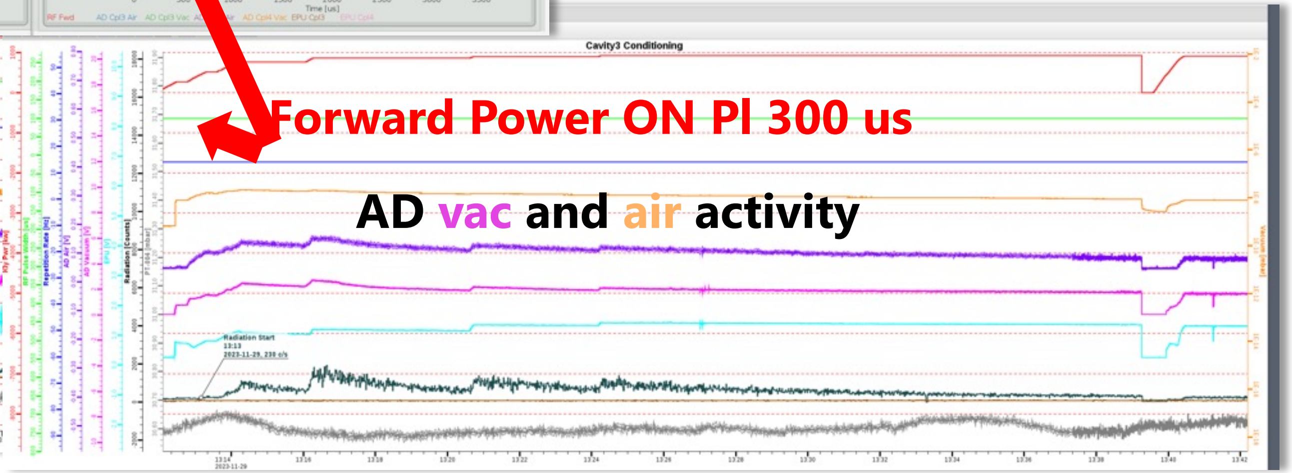


AD and e- pu signal Outside RF pulse (TW – coupler)

C1/C2 off

C3 on



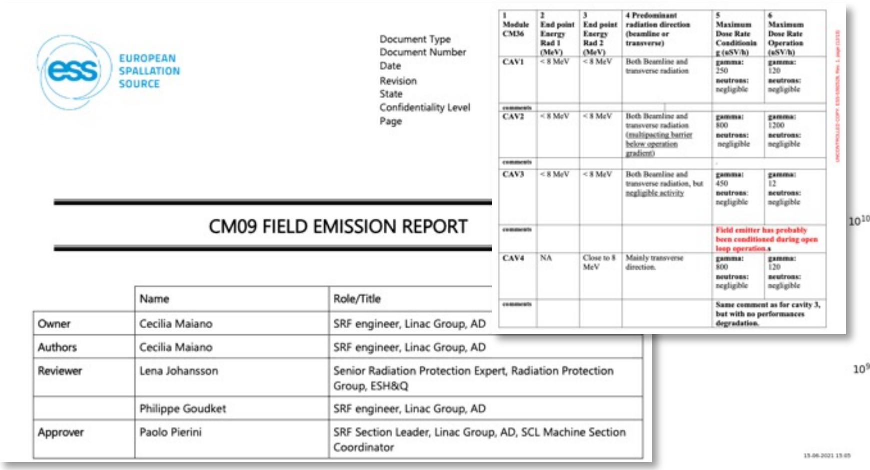


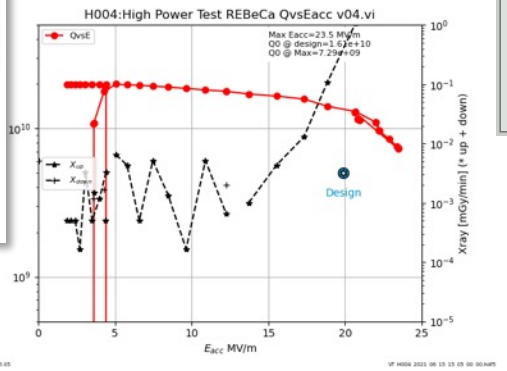
Measurement results collection

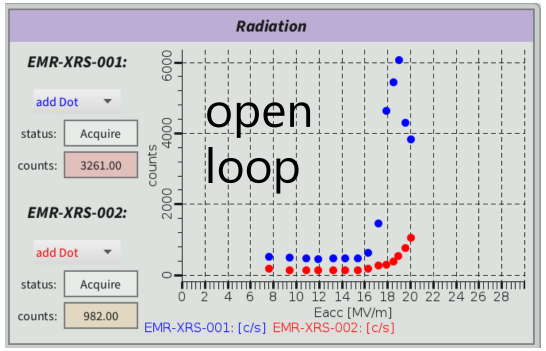
Detector technical documentation/calibration and configuration files stored in ESS intranet

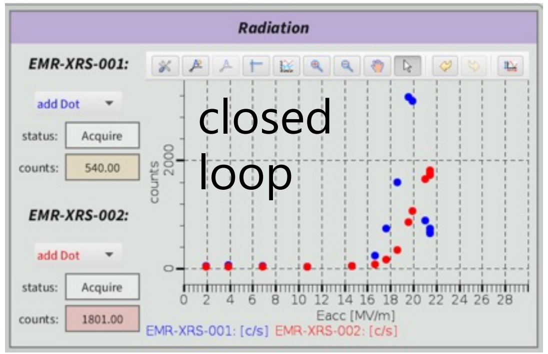
Data collection (dose rate, max FE energy, direction of emission) stored in ESS management system:

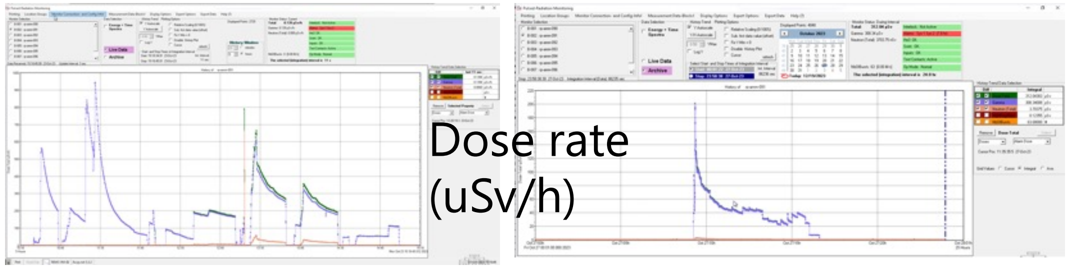
CM	Accelerating gradient				Dose Rate (uSv/h)				NaI count rate (cps) Radiation direction				NaI endpoint energy (MeV)			
Medium Beta	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4	C1	C2	C3	C4
CM04 Configuration B	20	19	15	18	y 30	Y 1200	Y 1900	Y 1800	AC	bck	AL-D	AL-D	Rad1: 4 Rad2: 4	Rad1 <3 Rad2 <3	NA	Rad1: 3 Rad2: 6
High Beta																
CM37 Configuration C	20	21	19	22	OL y 250 n <50 CL Y 30 n <10	OL y 500 n <200 CL Y 250 n <25	OL Y 1000 n <100 CL Y 800 n <50	OL y 600 n <50 CL Y 100 n <10	AL-U	AL-U	Both AL-U AC	AL-U	Rad1 >>8 Rad2 <8	Rad1 >8 Rad2 <8	Rad1 >8 Rad2: 8	Rad1 >8 Rad2: 8





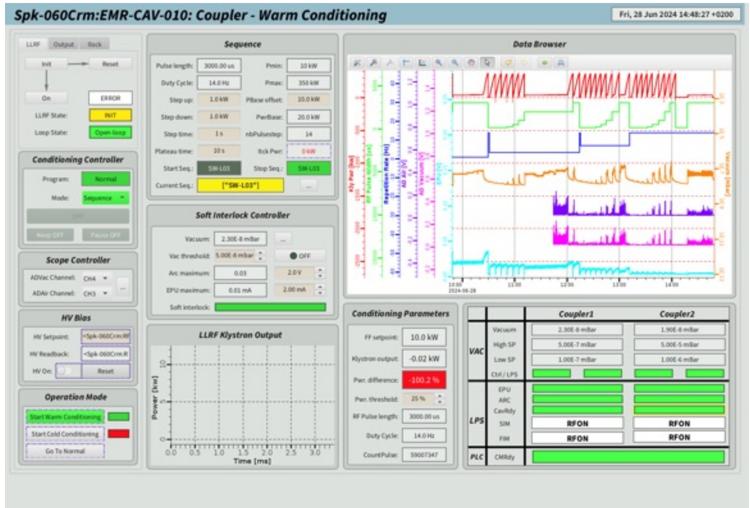


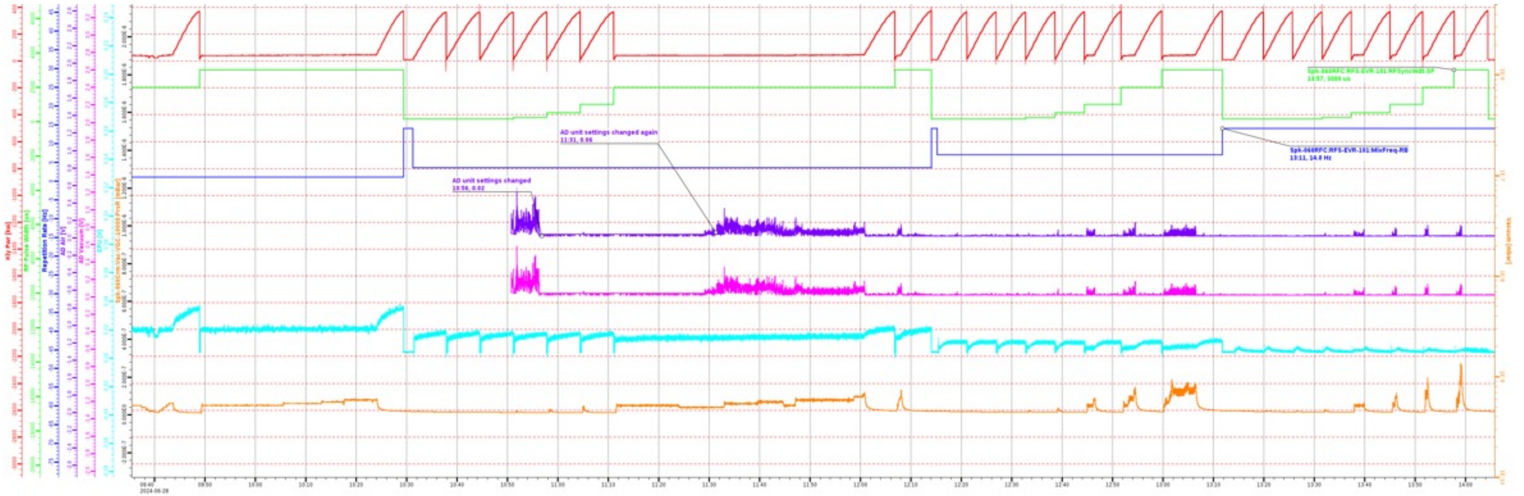




Recent achievements

Start and completion of SPK060 Warm Coupler 1 and 2 Conditioning





Sequence Table Spoke ×

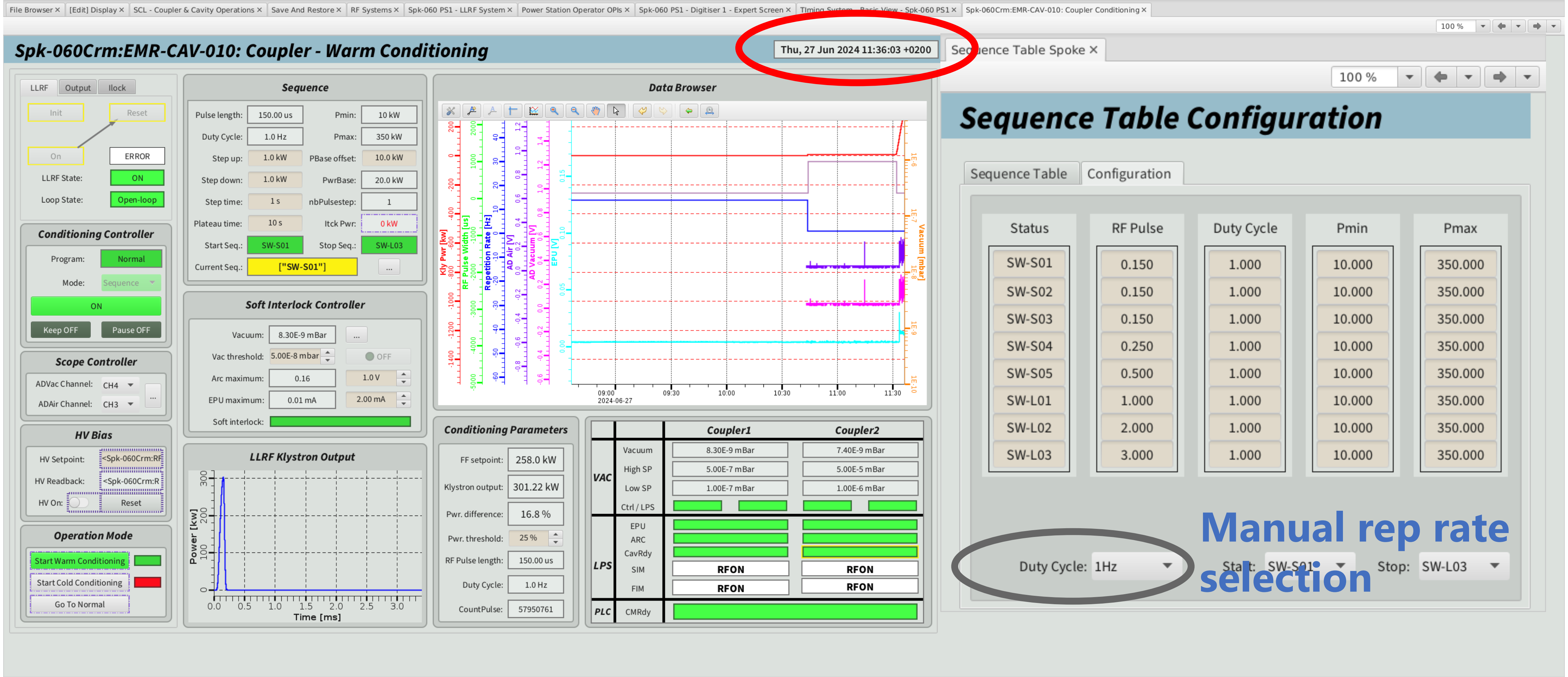
100 %

Sequence Table Configuration

Sequence Table | Configuration

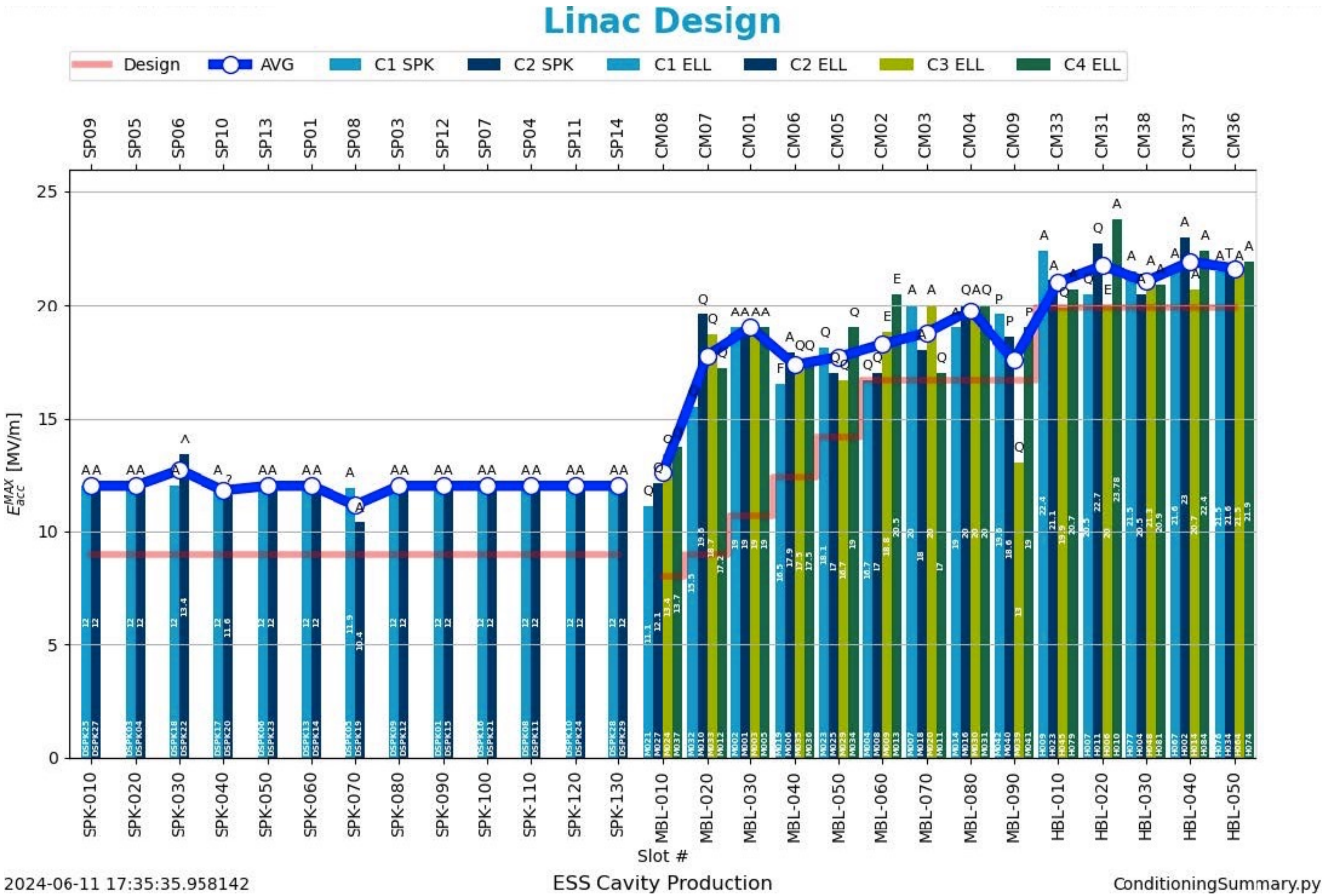
Steps	RF Width [ms]	Rate [Hz]	Pmin [kw]	Pmax [kw]
SW-S01	0.15000000596	14.0	10.0	350.0
SW-S02	0.15000000596	14.0	10.0	350.0
SW-S03	0.15000000596	14.0	10.0	350.0
SW-S04	0.25	14.0	10.0	350.0
SW-S05	0.5	14.0	10.0	350.0
SW-L01	1.0	14.0	10.0	350.0
SW-L02	2.0	14.0	10.0	350.0
SW-L03	3.0	14.0	10.0	350.0

SPK-060 coupler wcc 1



Our First spoke operation at ESS SCL tunnel

Linac Configuration



ESS Cavity DB used to generate linac configuration, to match performance with gradient requirements of the nominal design

Thanks

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* CEA/INFN/STFC in-kinds