



**EUROPEAN
SPALLATION
SOURCE**



Status of ESS cryomodule test in preparation for beam commissioning

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PRESENTED BY CECILIA MAIANO

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





Overview on ESS:

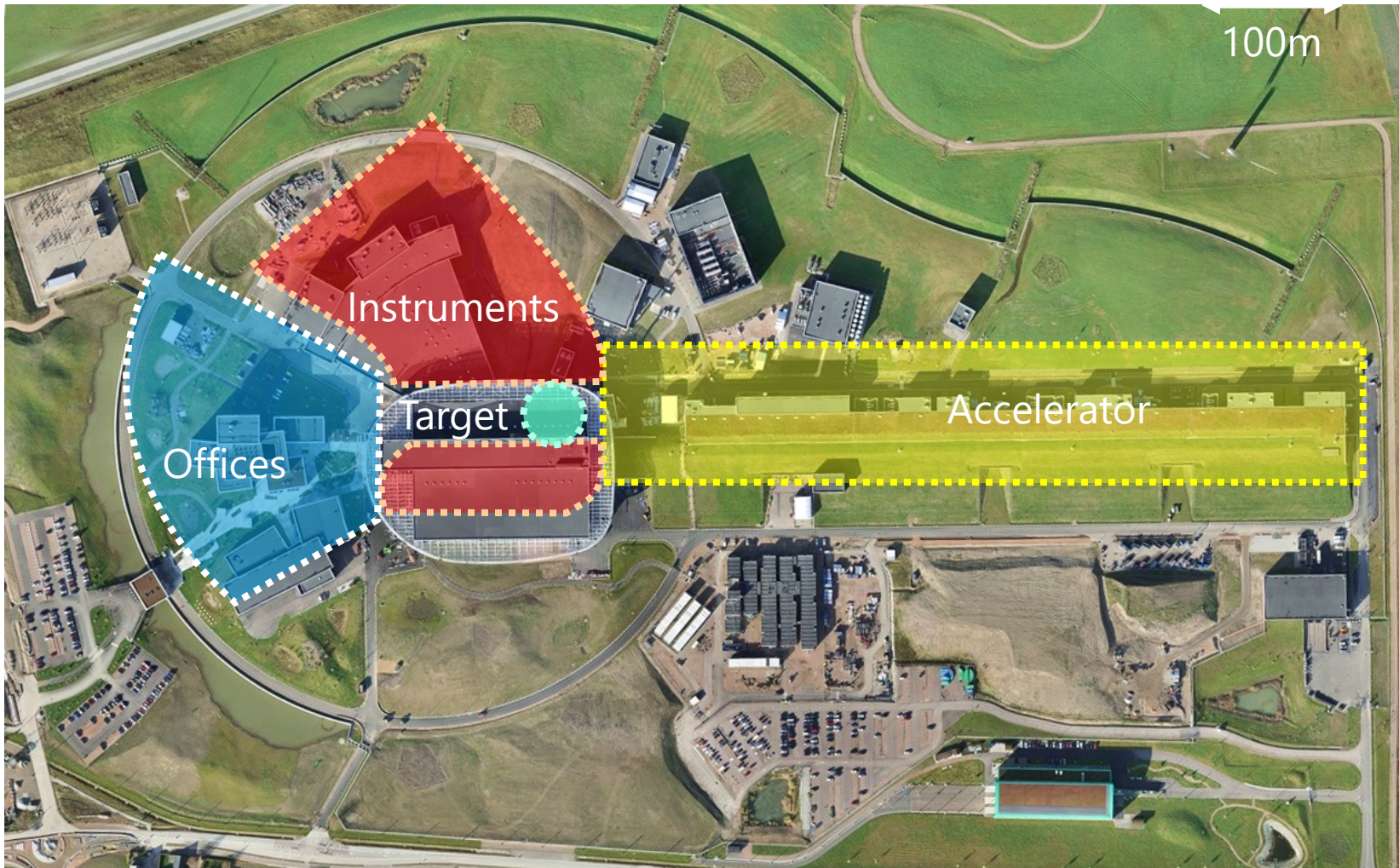
Accelerator, cryomodules, installation progress

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

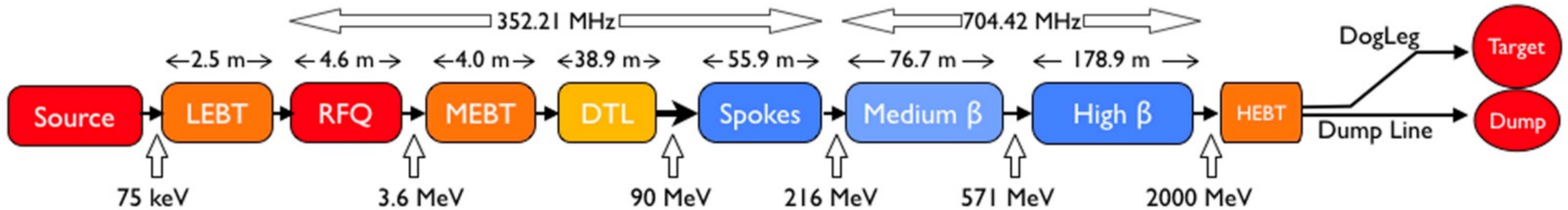
Scientific Instruments

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



The linear accelerator @ 5 MW

Overview



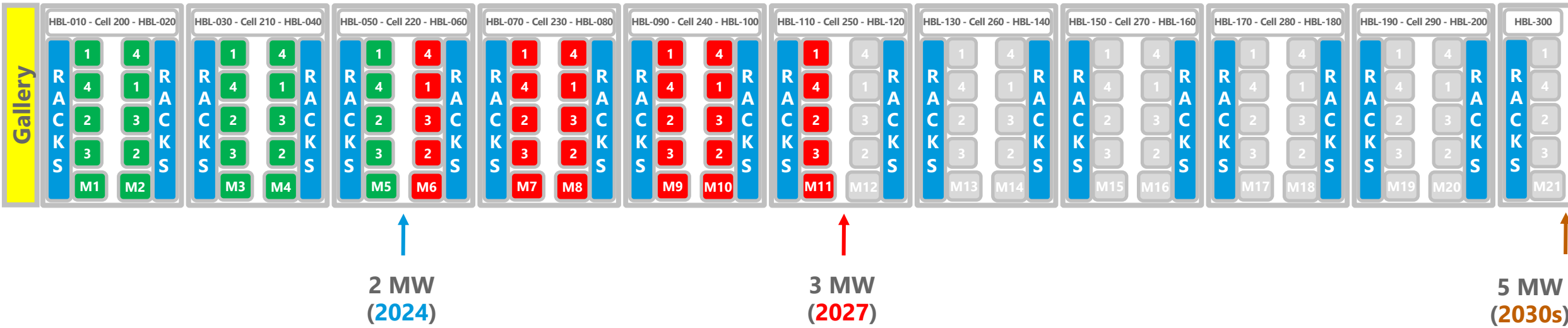
Parameter	Value
Ave power (design) [MW]	5
Max energy (design) [GeV]	2
Peak current [mA]	62.5
Pulse length [ms]	2.86
Rep rate [Hz]	14
Duty factor [%]	4
RF freq [MHz]	352.21/704.42

	Length	No. Magnet	#Cav \times 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 \times (0.50)	13	330	IPNO
Medium Beta	76.7	18 Quads	36 \times 0.67	9	870	LASA / CEA
High Beta I (~1.3 GeV)	93.7	22 Quads	44 \times 0.86	11	1100	STFC / CEA
High Beta II	85.2	20 Quads	40 \times 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



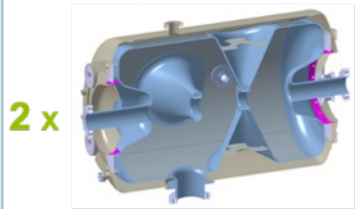
ESS SCL Cavities and Cryomodules

Cryomodules

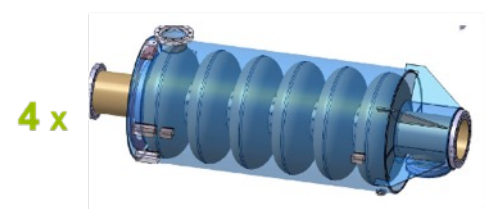
13 x Spokes

9 x Medium Beta

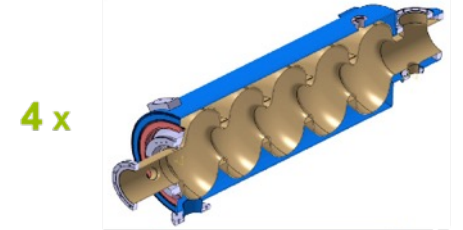
21 x High Beta



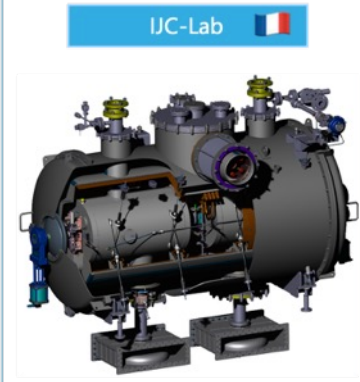
2 x IJC-Lab (ZANON)



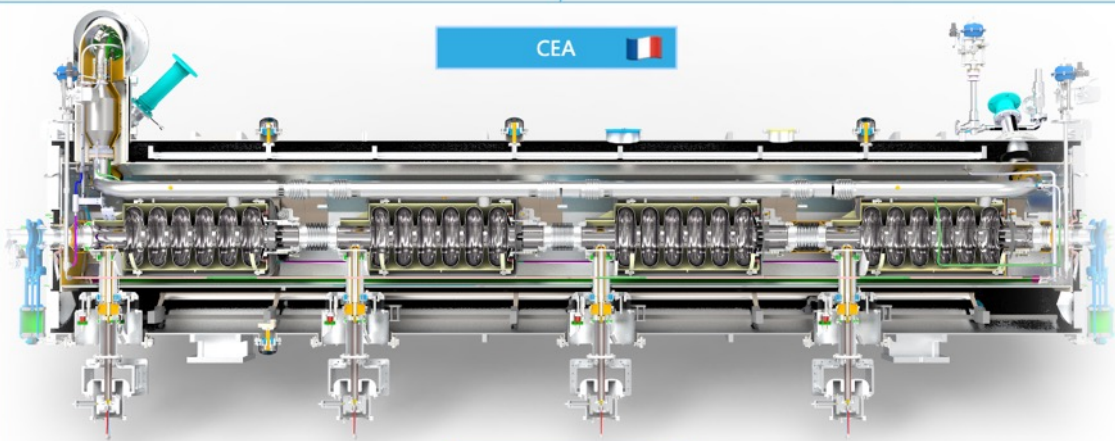
4 x INFN-LASA (ZANON)



4 x STCF (RI)



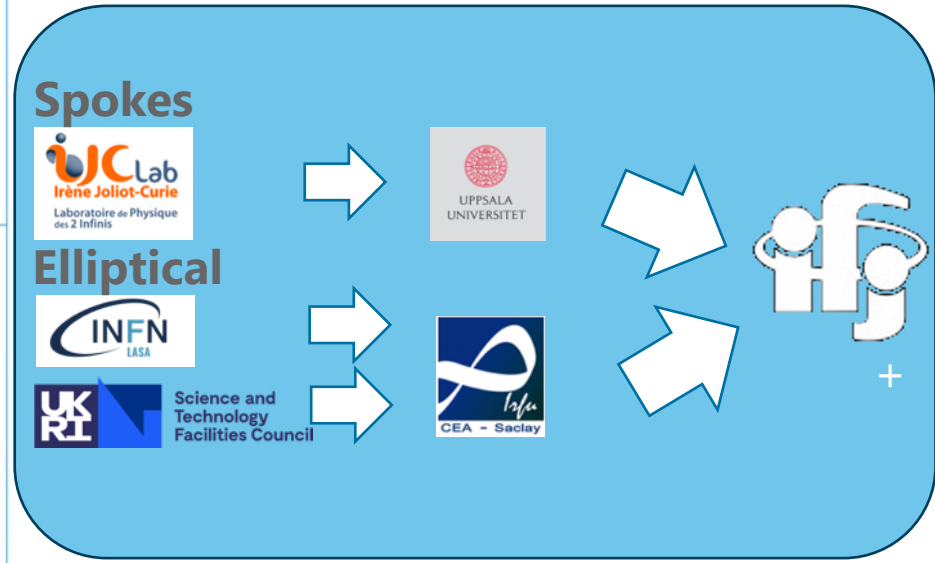
IJC-Lab



CEA

ESS-TS2

UU-Freia



Cavities

26

36

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

Cryomodules:

test workflow, performances and statistics



ELL CM: ESS Test Stand overview & workflow



The workflow and test is split in phases

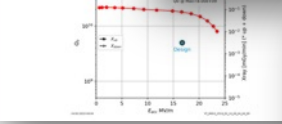
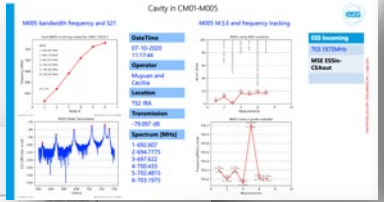
CM lifecycle is intensively documented

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

- CM Procedures
 - Step 1 Reception
 - Step 2 Incoming
 - Step 3 ToBunker
 - Step 4 WarmOps
 - Step 5 ColdOps
 - Step 6 Warmup
 - Step 7 Disconnect
 - Step 8 Outgoing
 - Step 9 Dispatch

SRF

CAV3-M003
Vertical Test Performance



Field Emission

CM36 FIELD EMISSION REPORT

Owner	Cecilia Malaino	Role/Title	SRF engineer, Linac Group, AD
Authors	Cecilia Malaino		SRF engineer, Linac Group, AD

1.4. Summary of results

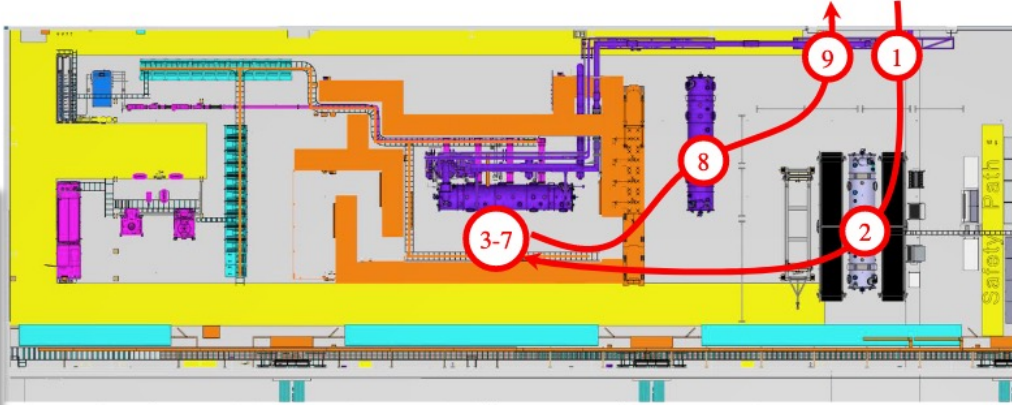
In table 1 a summary of measurements is provided:

- Cryomodule Field Emission (CFE) measurements were performed in accordance with the procedure of Radiation Protection.
- Measurements were performed during warm-up, conditioning and beam in closed loop operation.
- Cryomodule Field Emission (CFE) measurements were performed in accordance with the procedure of Radiation Protection.

Location	Energy [keV]	Counts	Rate [cts/s]
CAV3	10	100	10
CAV4	10	100	10
CAV5	10	100	10
CAV6	10	100	10
CAV7	10	100	10
CAV8	10	100	10
CAV9	10	100	10
CAV10	10	100	10
CAV11	10	100	10
CAV12	10	100	10
CAV13	10	100	10
CAV14	10	100	10
CAV15	10	100	10
CAV16	10	100	10
CAV17	10	100	10
CAV18	10	100	10
CAV19	10	100	10
CAV20	10	100	10
CAV21	10	100	10
CAV22	10	100	10
CAV23	10	100	10
CAV24	10	100	10
CAV25	10	100	10
CAV26	10	100	10
CAV27	10	100	10
CAV28	10	100	10
CAV29	10	100	10
CAV30	10	100	10

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		
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

Mechanical

Vacuum
Electrical

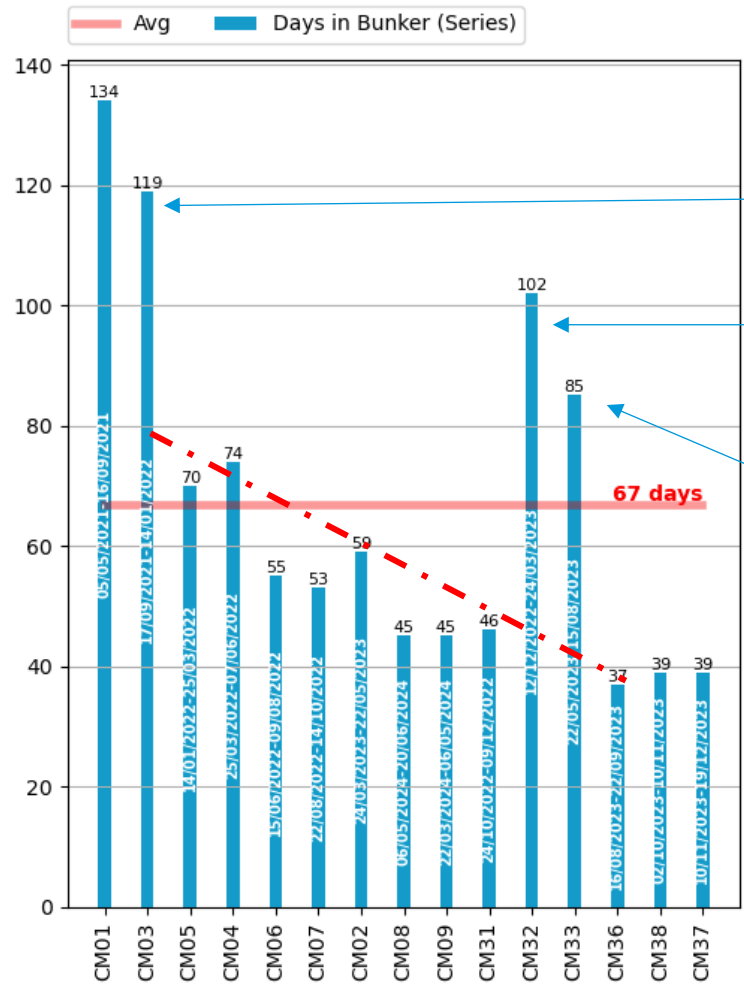
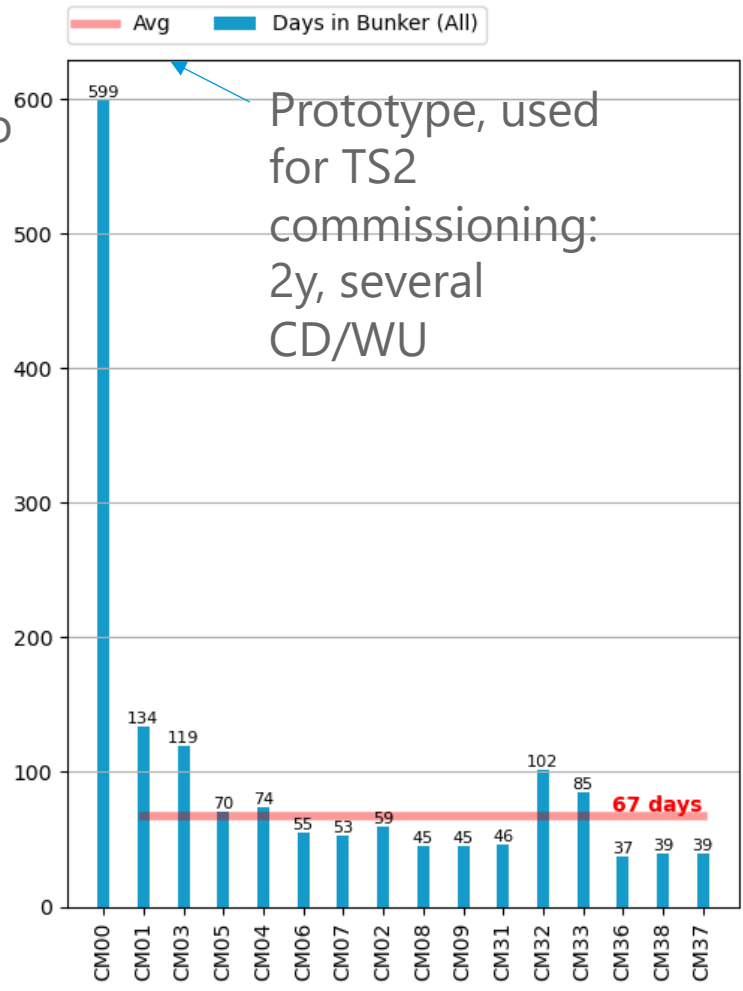


TS2 Statistics – 15 CM tested

ELL: Number of days in TS2 bunker

1 proto
9 MB
6 HB

Prototype, used for TS2 commissioning: 2y, several CD/WU



Trend improving over time, outliers:

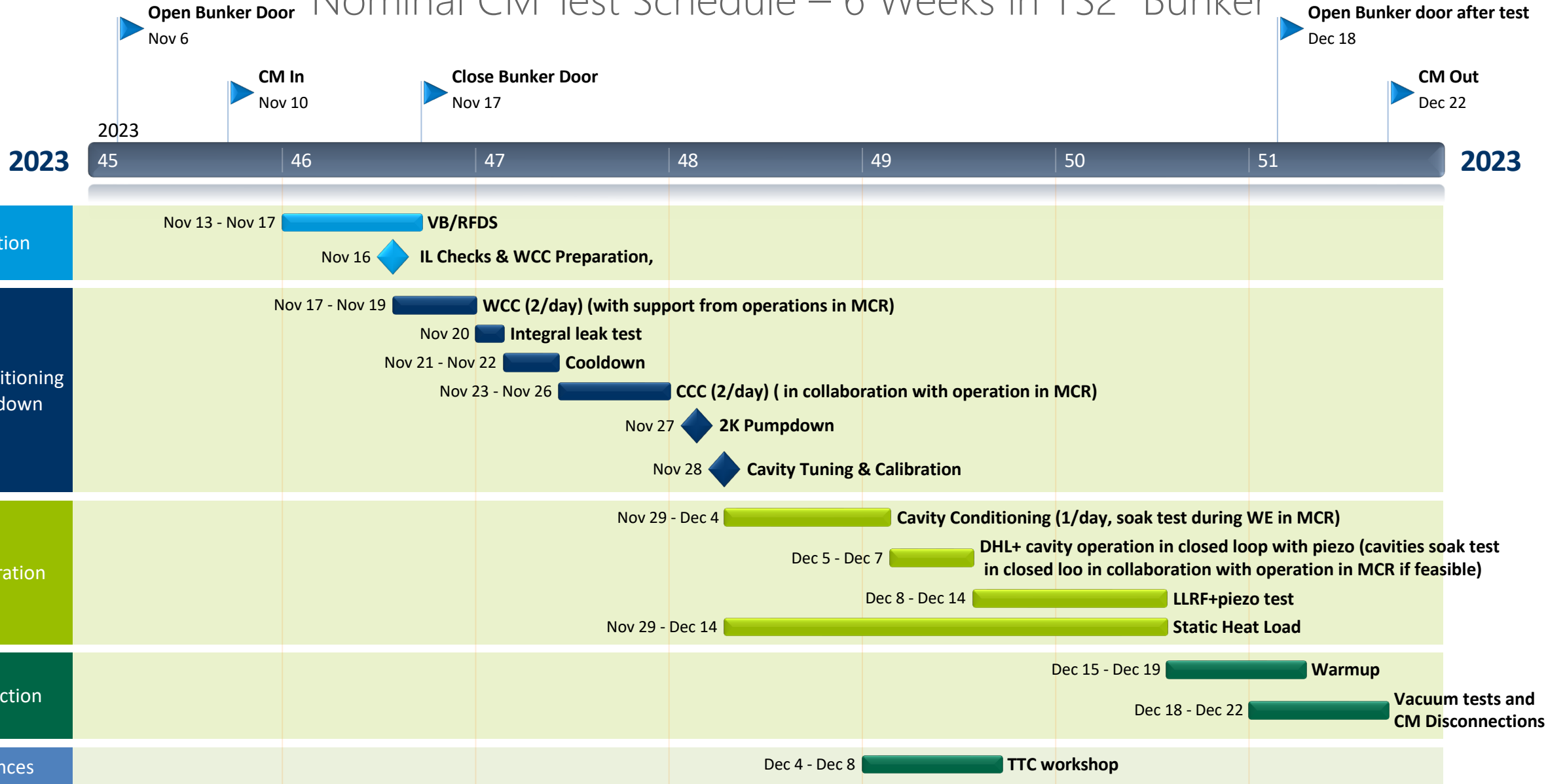
CM03: Repair of gauge (2x test)

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)**

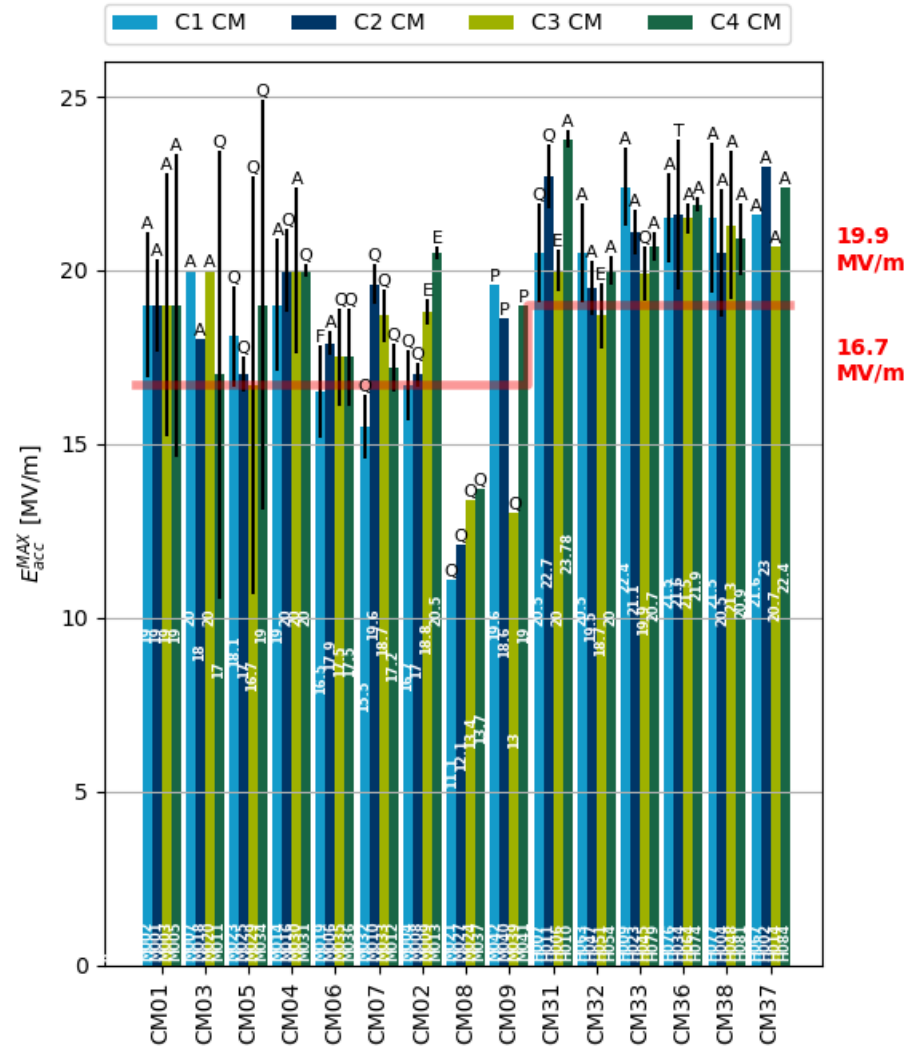
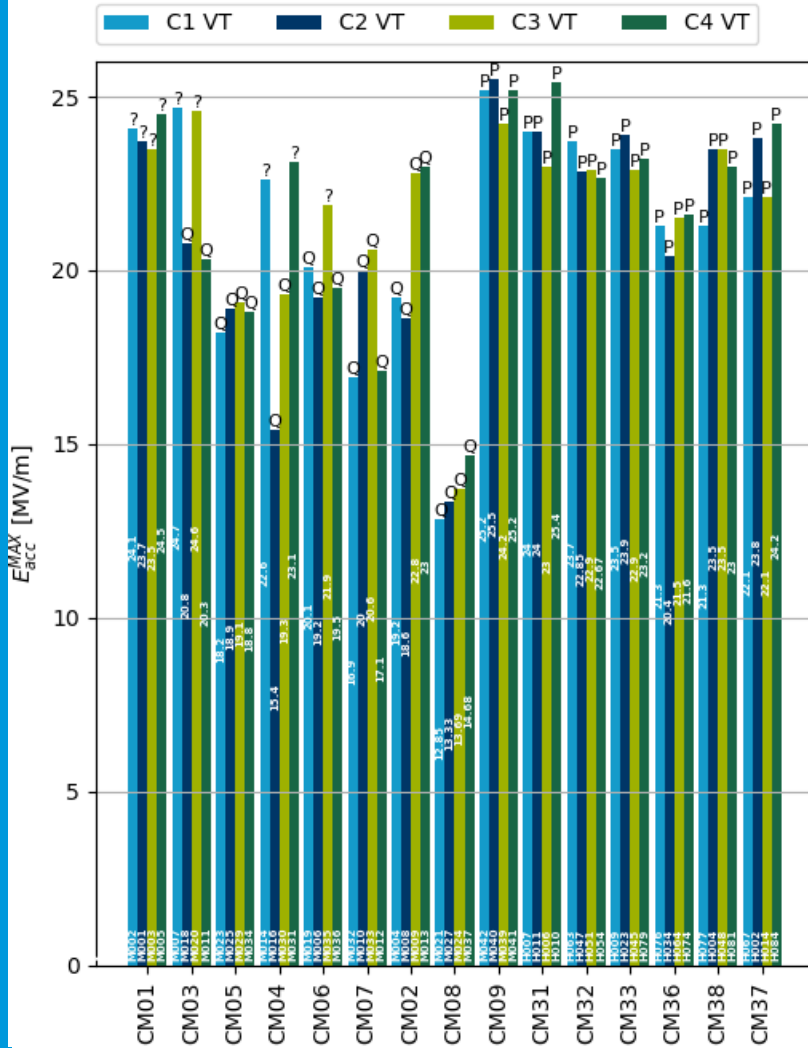
Nominal CM Test Schedule – 6 Weeks in TS2 Bunker





RF Performances: Gradient

ELL: VT/CM Gradient Performances



Nominal gradient is generally met

- Few marginal cav

19.9
MV/m

16.7
MV/m

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



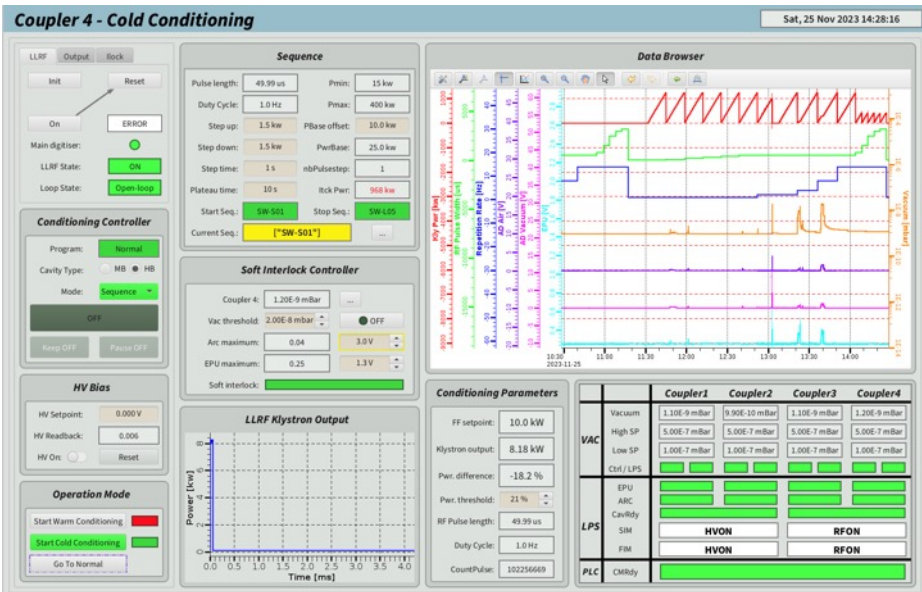
Coupler conditioning sequence

Warm and cold coupler conditioning

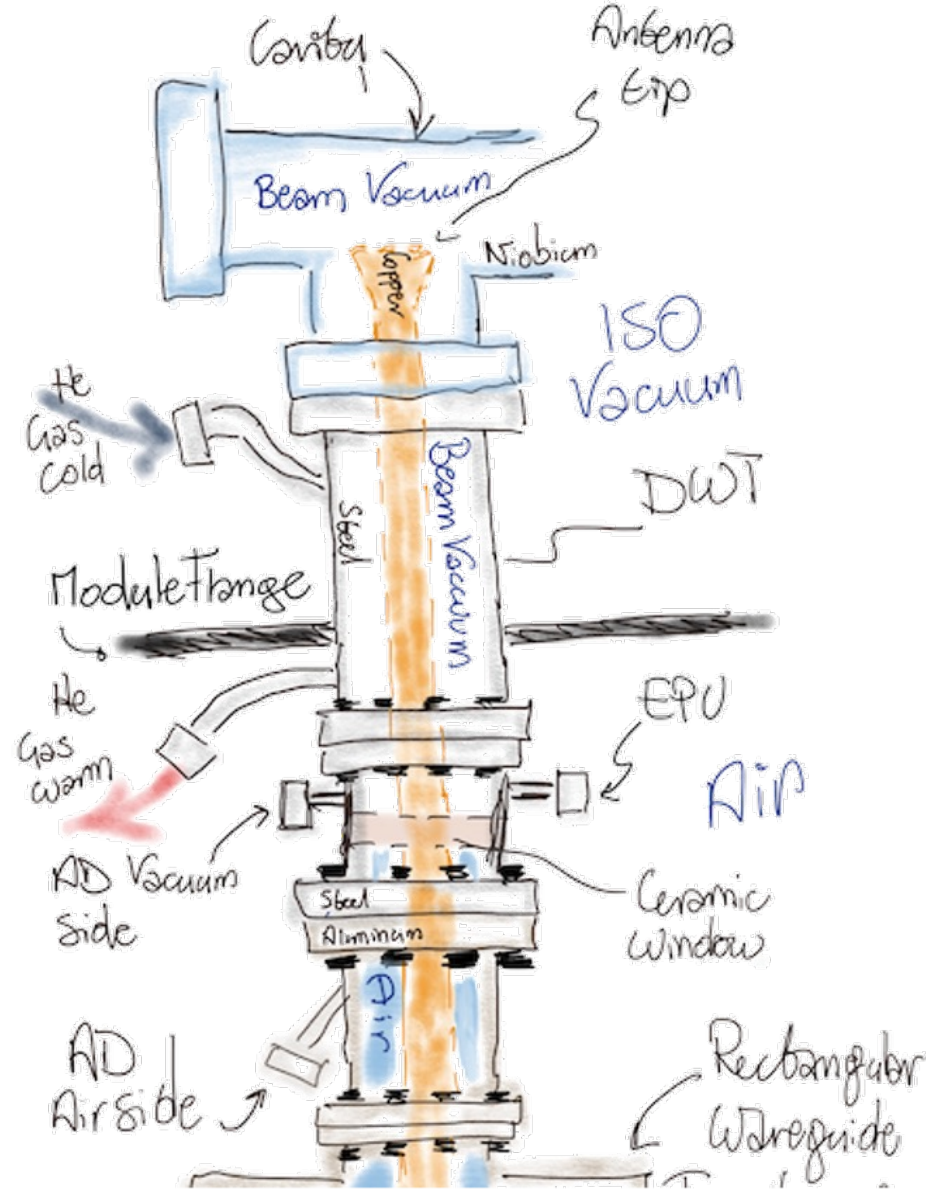
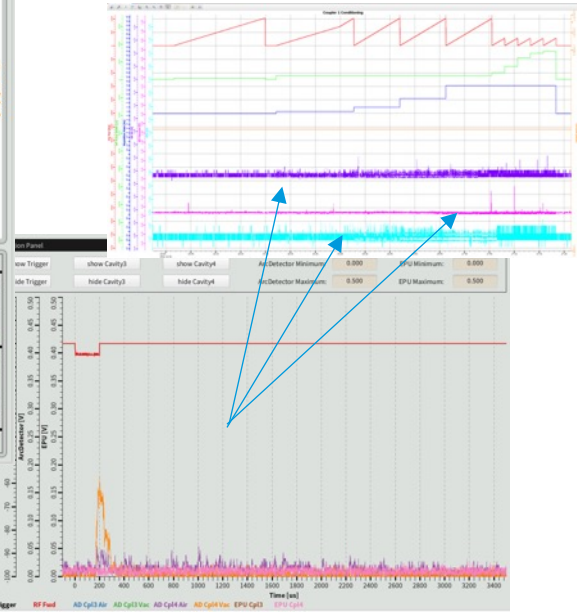
Automated sequencer script runs through the steps, and monitors vacuum, EPU and AD signals.

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

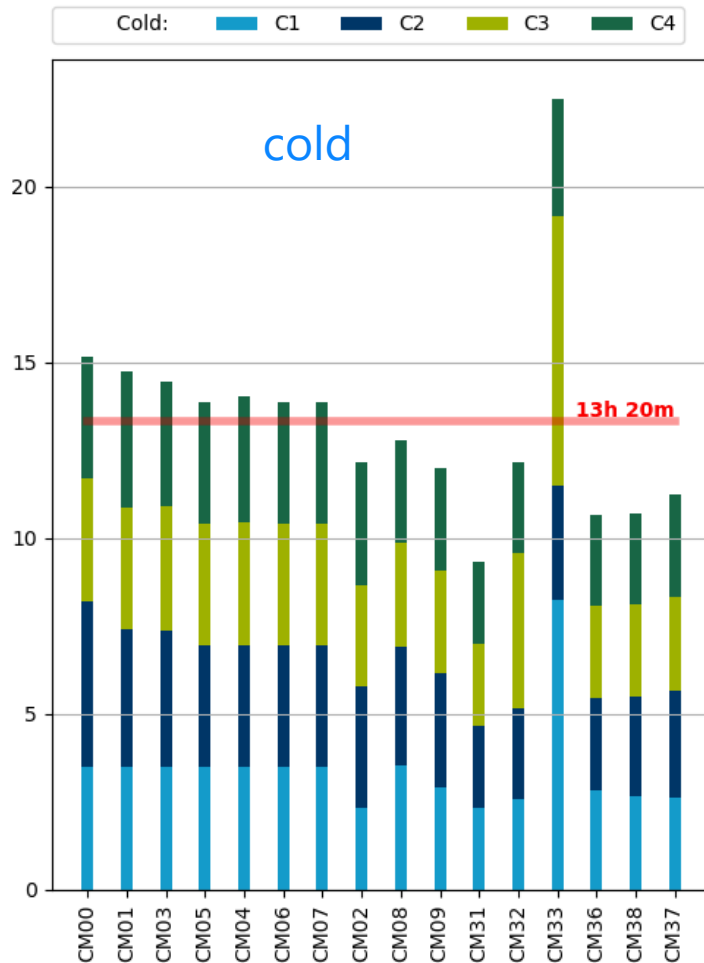
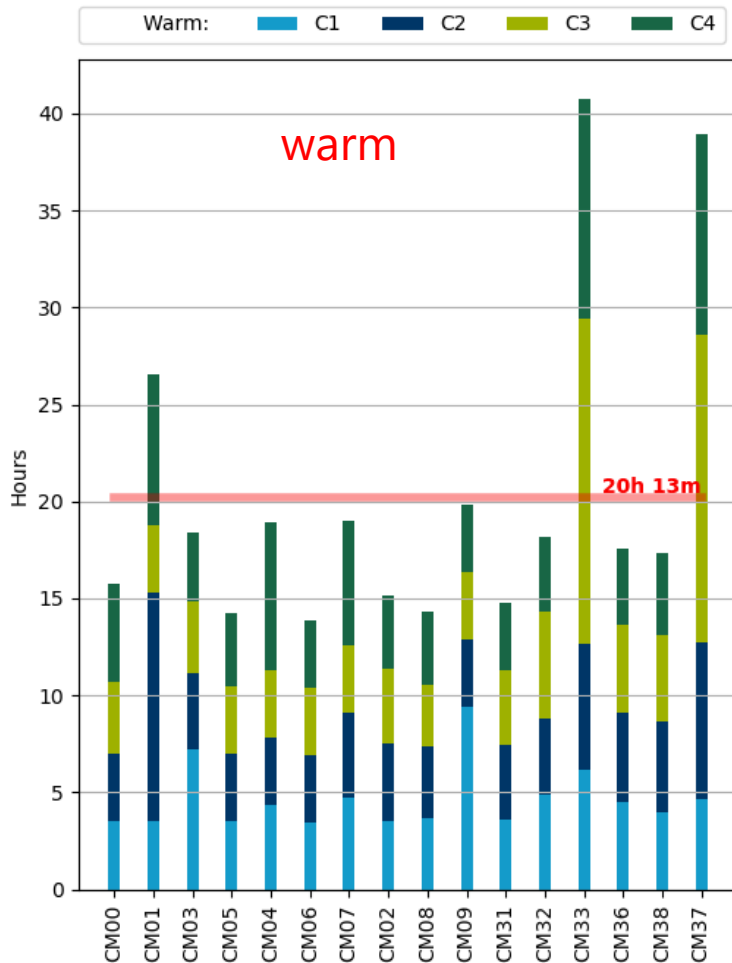


Coupler Conditioning (off resonance)



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

ELL: Conditioning Times



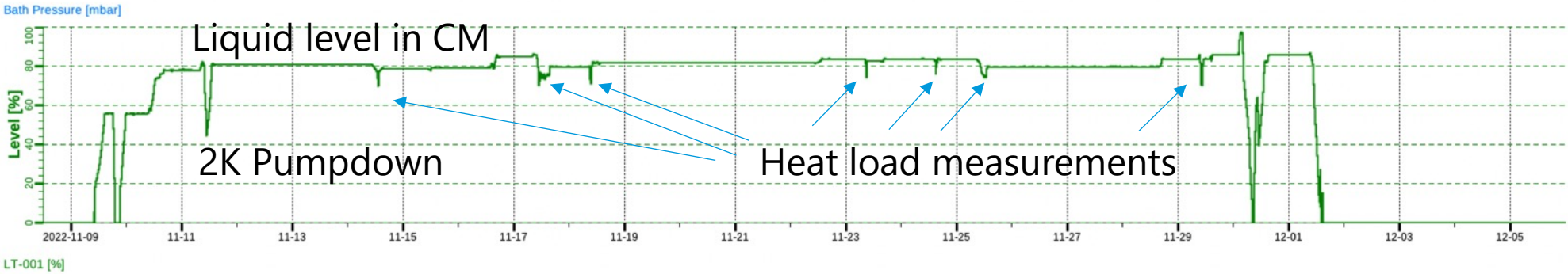
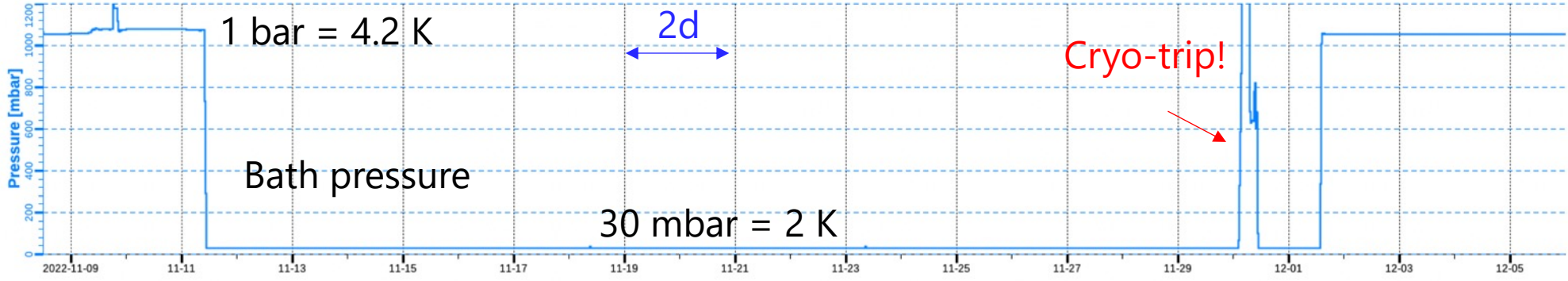
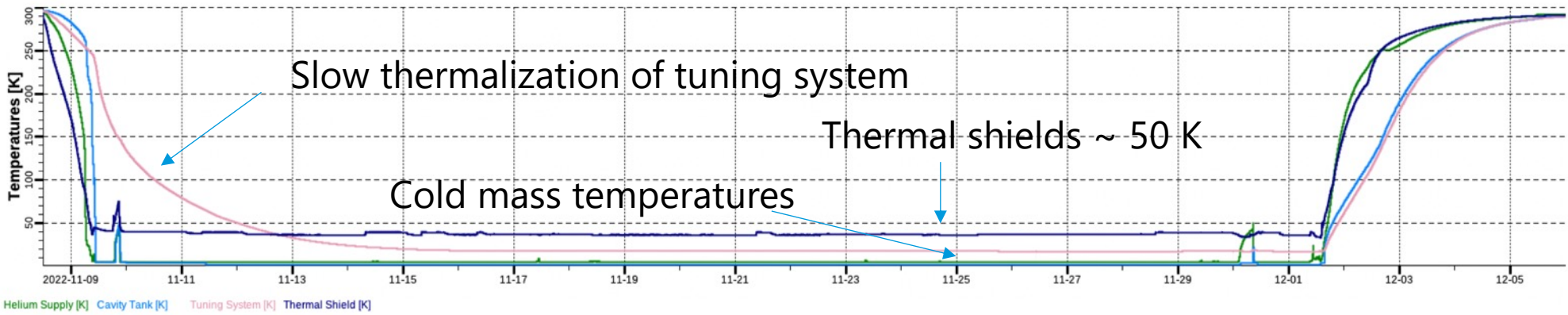
Conditioning times correlate with number of NCR registered during assembly

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



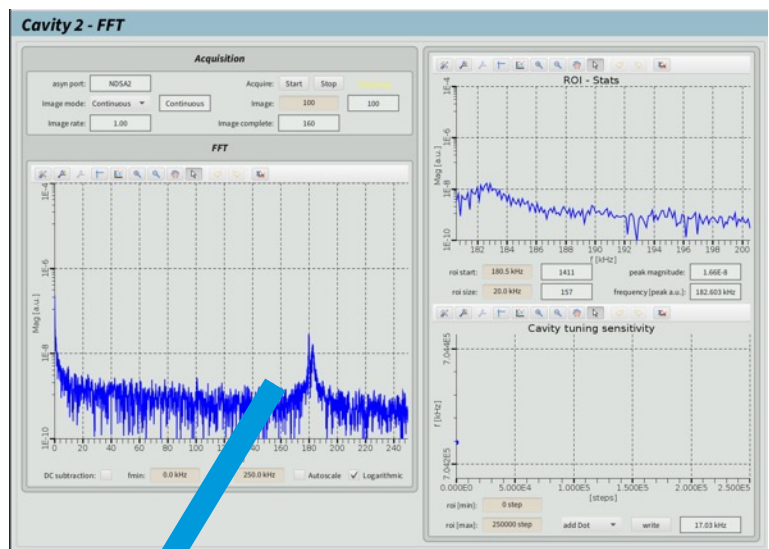
~20 d cold

Credits, N. Elias, ESS

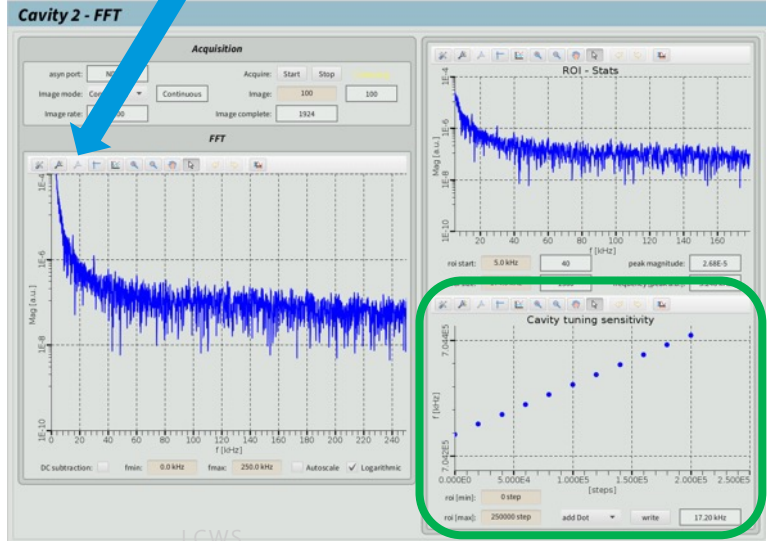


Tuning tool

Far and Fine tuning tools

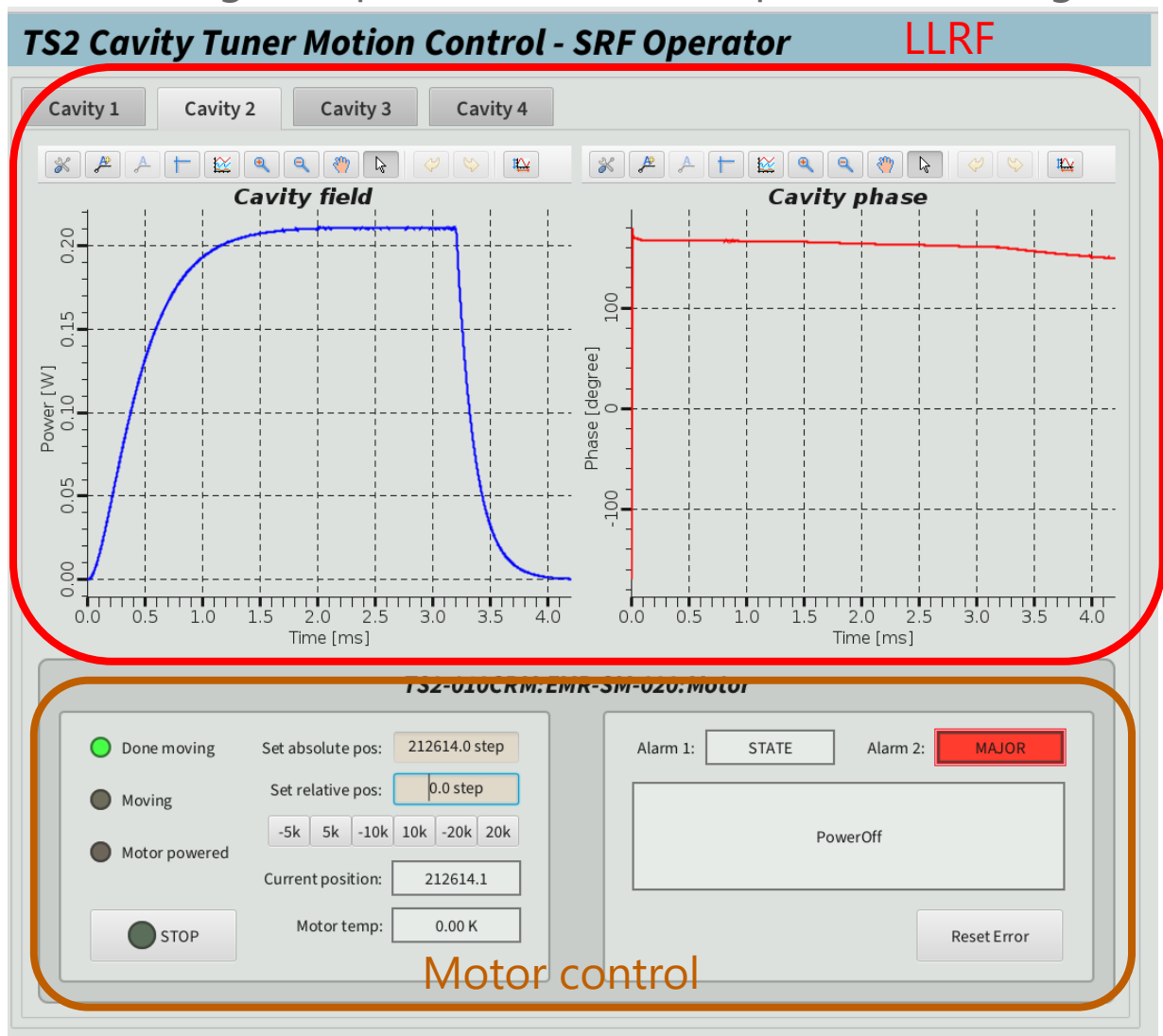


Far tuning with calculations from LLRF Waveforms



Tuning sensitivity (health check)

Fine tuning with power increase and phase flattening



Motor control



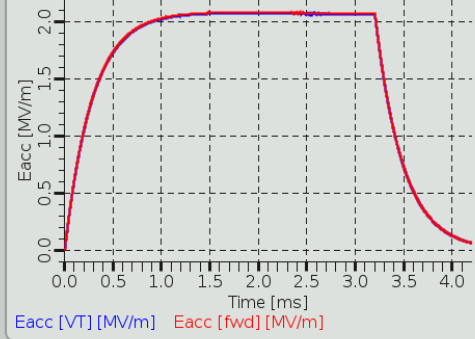
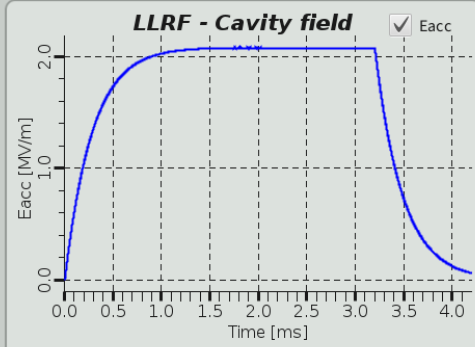
Calibration tool

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

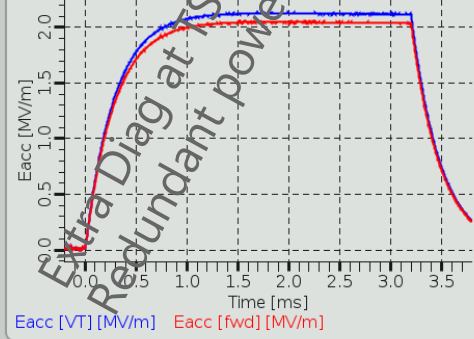
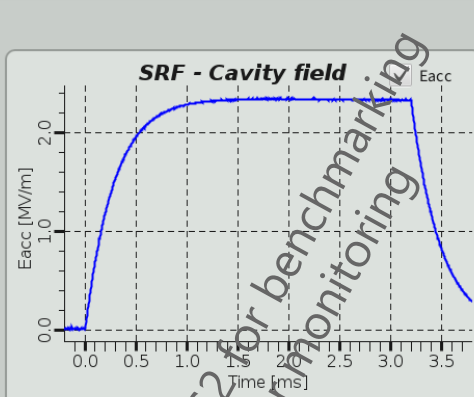
Cavity 4 calibration - HB

Mon, 27 Nov 2023 14:28:02

1. Low Calibration



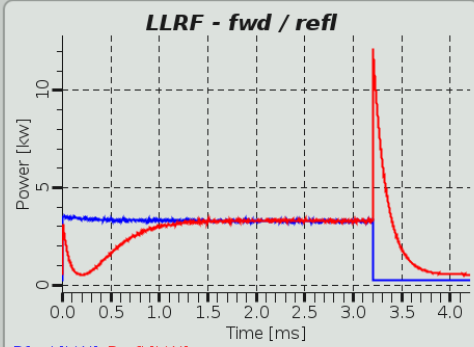
Tau:	142.41 us	QL:	6.30E5
kt [fwd]:	7.85	&kt:	0.37 %
Qt [fwd]:	1.19E11	&Qt:	0.74 %
kt [LLRF]:	7.820	Qt [LLRF]:	1.18E11



Tau:	143.47 us	QL:	6.35E5
kt [fwd]:	7.53	&kt:	3.73 %
Qt [fwd]:	1.09E11	&Qt:	7.32 %
kt [VT]:	7.820	Qt [VT]:	1.18E11

Extra Diag at ISS2 for benchmarking
Redundant power monitoring

2. Tom Powers'



Eacc:	2.21 MV/m	kt:	8.35	Qt:	1.34E11
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Cavity Parameters

is Main (Digitizer):

Cavity type: MB HB

Acc. length: Cavity R/Q:

Low Calibration (valid for Rectangular Pulse)

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

Using cavity parameters and calibration factors

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

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

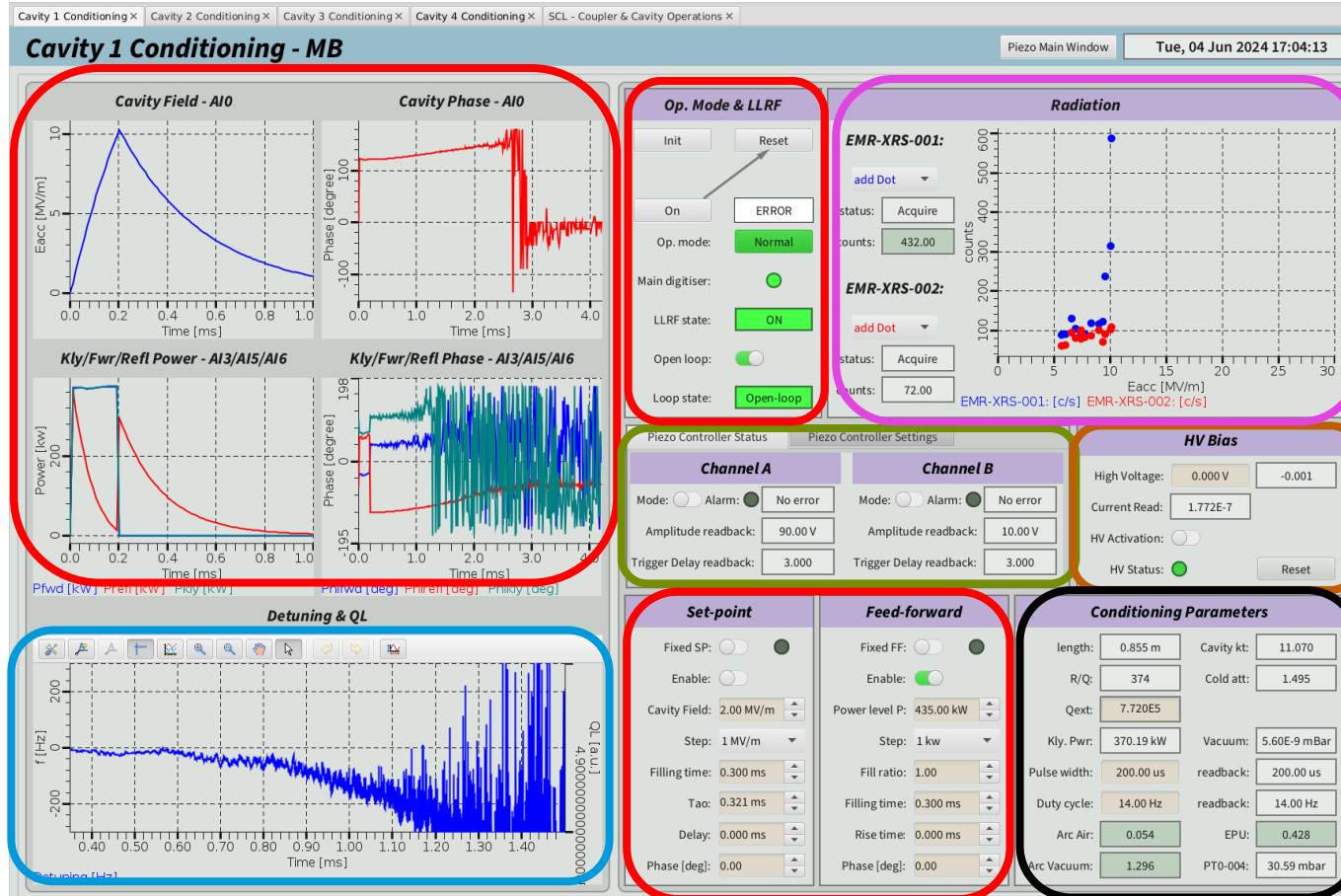
Cavity Conditioning/Operation tool (TS2)



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



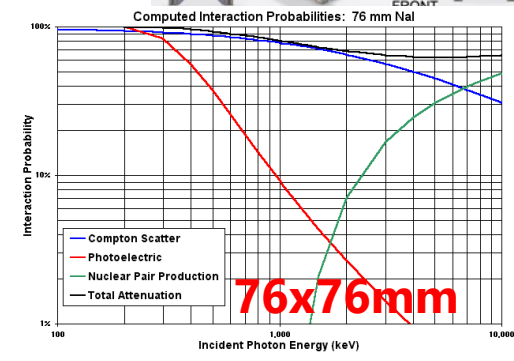
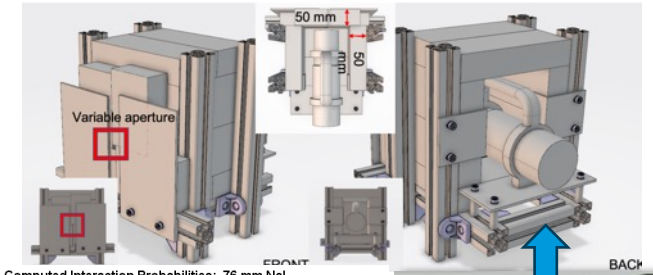
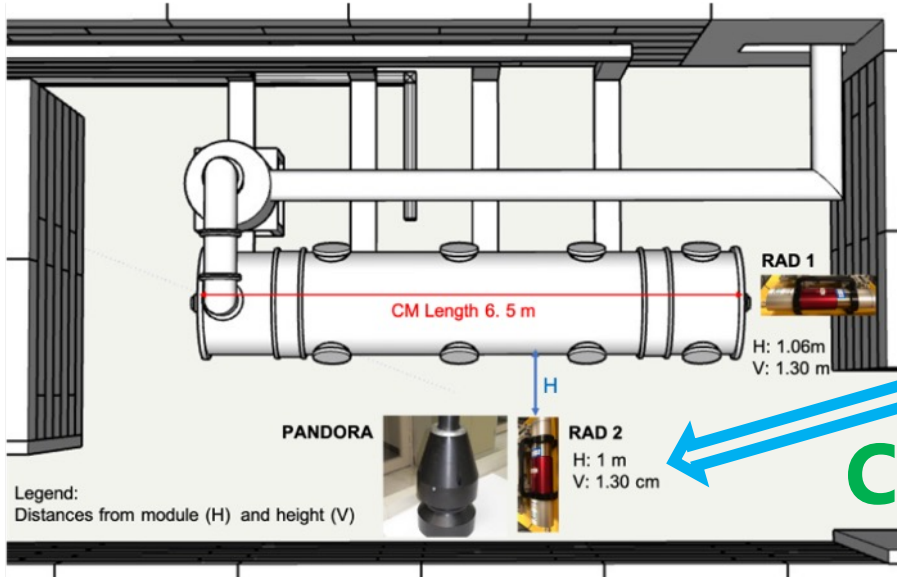
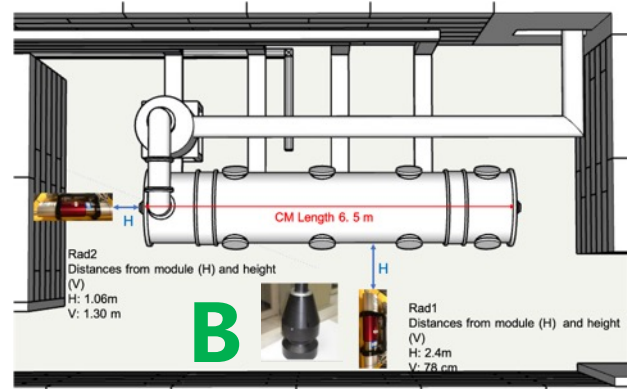
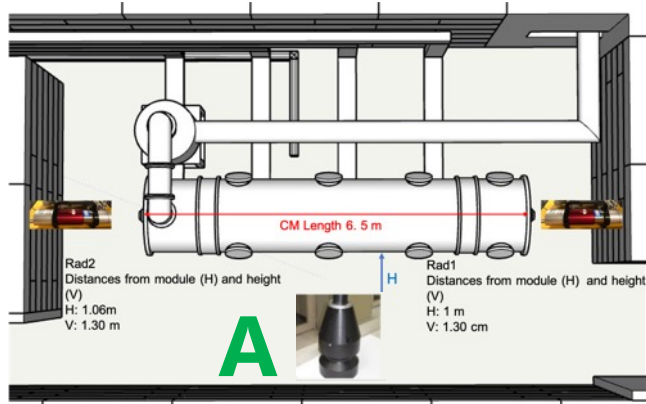
Operational challenges



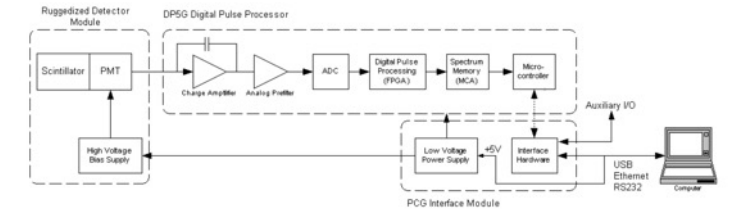
Equipment description for field emission

Nal(tl) detectors with Pb shielding (AMPTeK Gammarad5 76x76mm)

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



RP Pandora
Dose rate:
Neutrons
and gamma



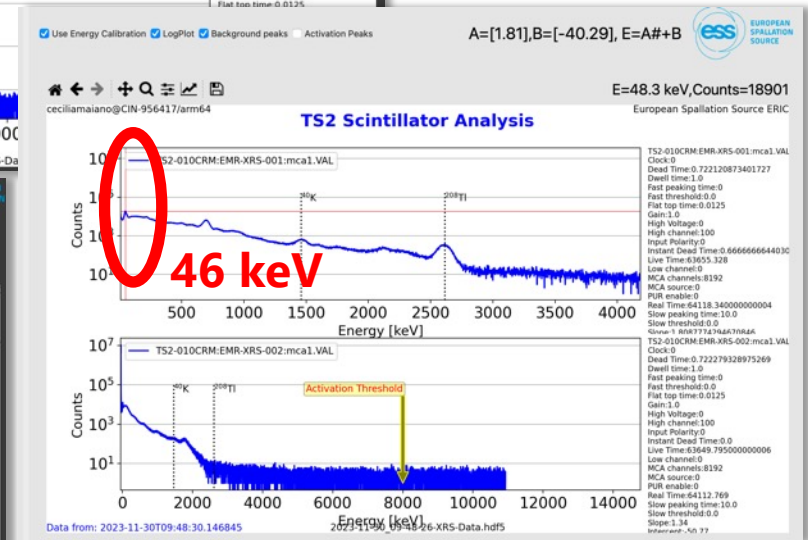
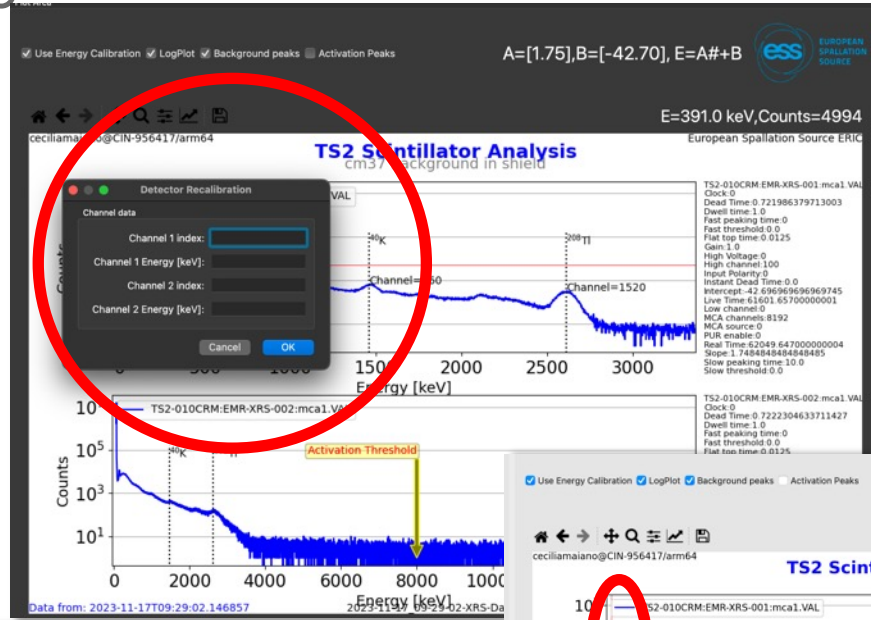
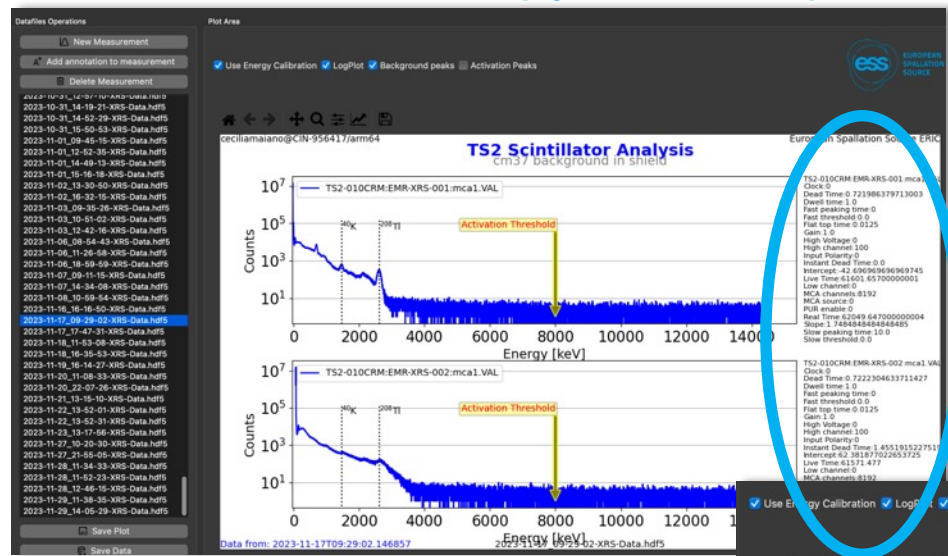


Acquisition and Analysis tool

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

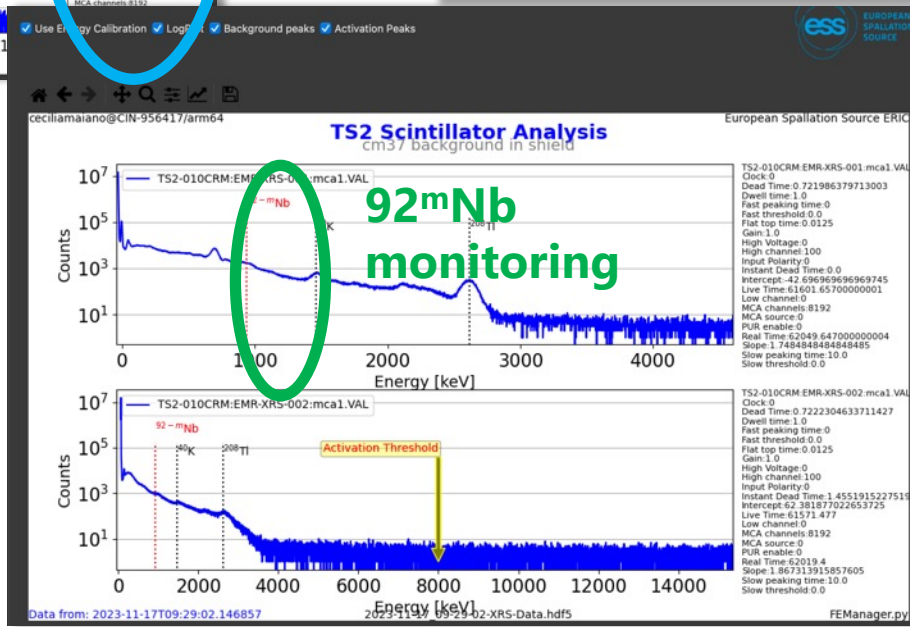
Recalibration,
using

- 208Tl
- 40K
- Pb x-ray 46 keV



Regular measurements

- BKG
- FE meas
- **Configuration parameters**

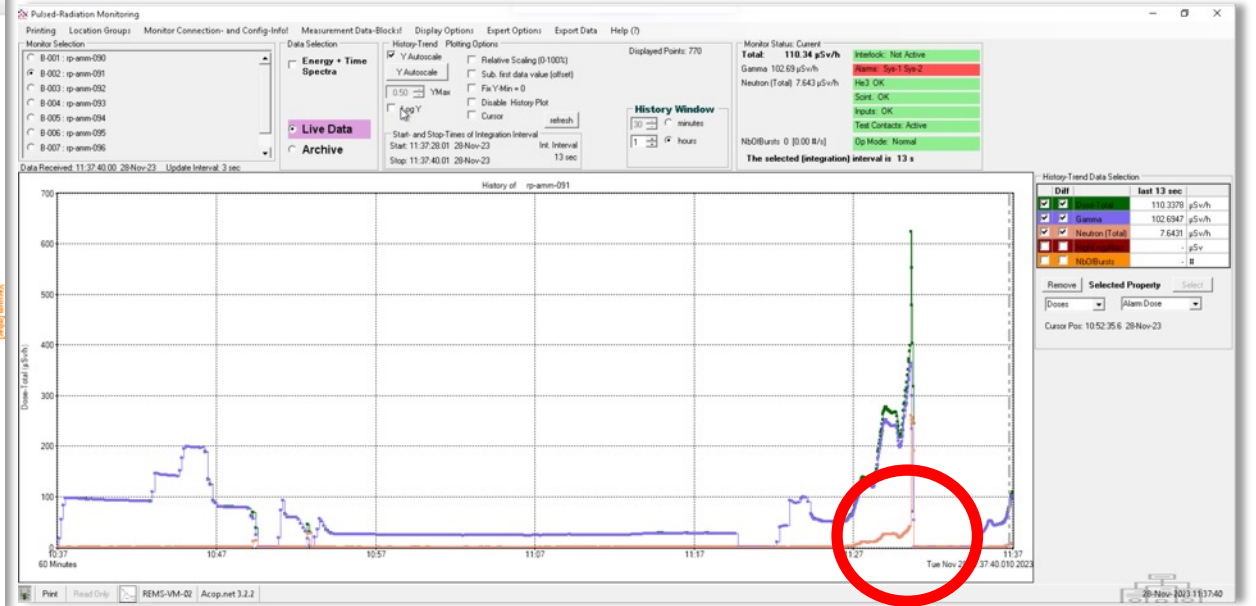
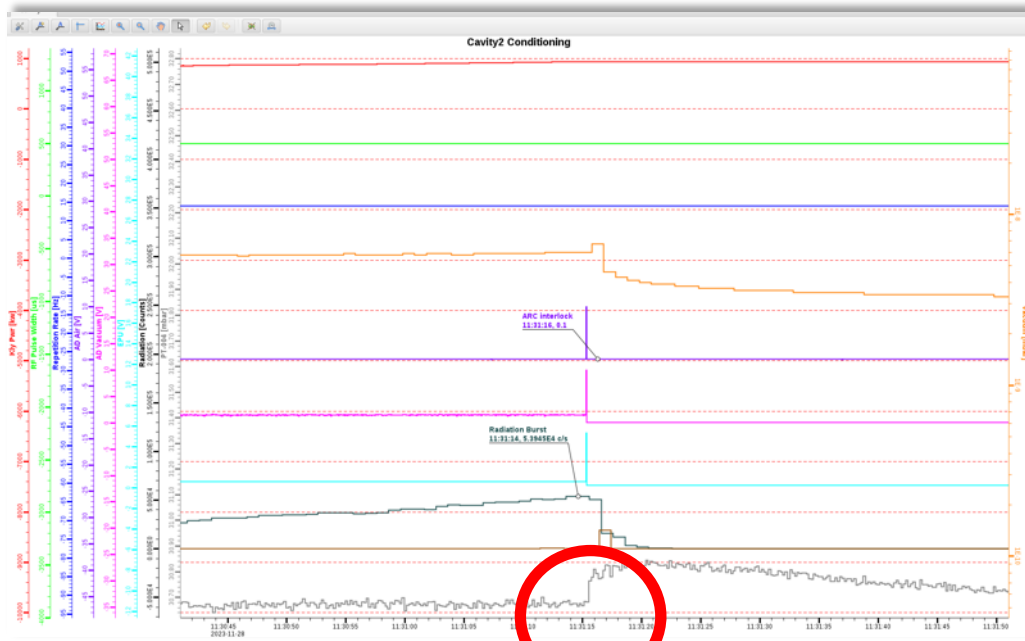


Activation check

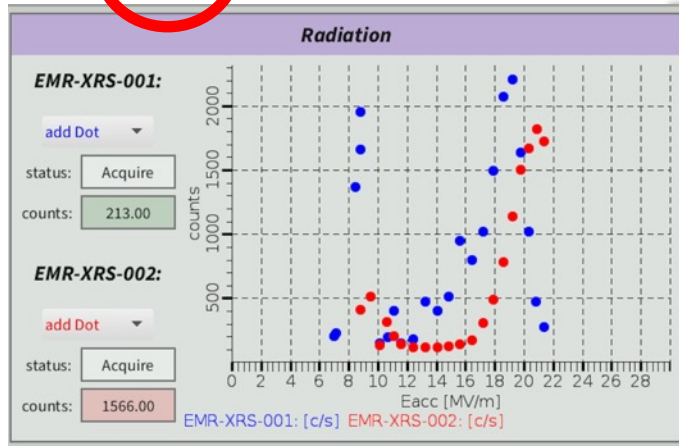
- mainly **92mNb** due to giant resonance (y,n) activation



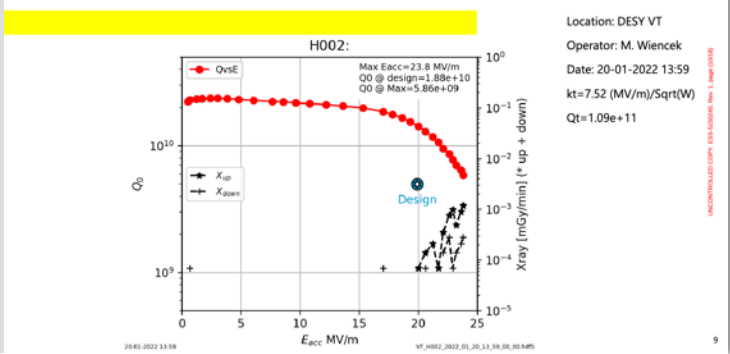
FE as limiting mechanism



Cryomodule test CM



CAV2-H002 Vertical Test Performance

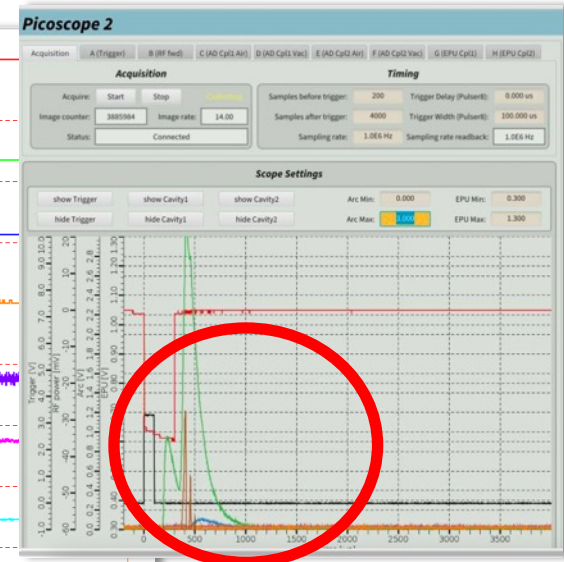
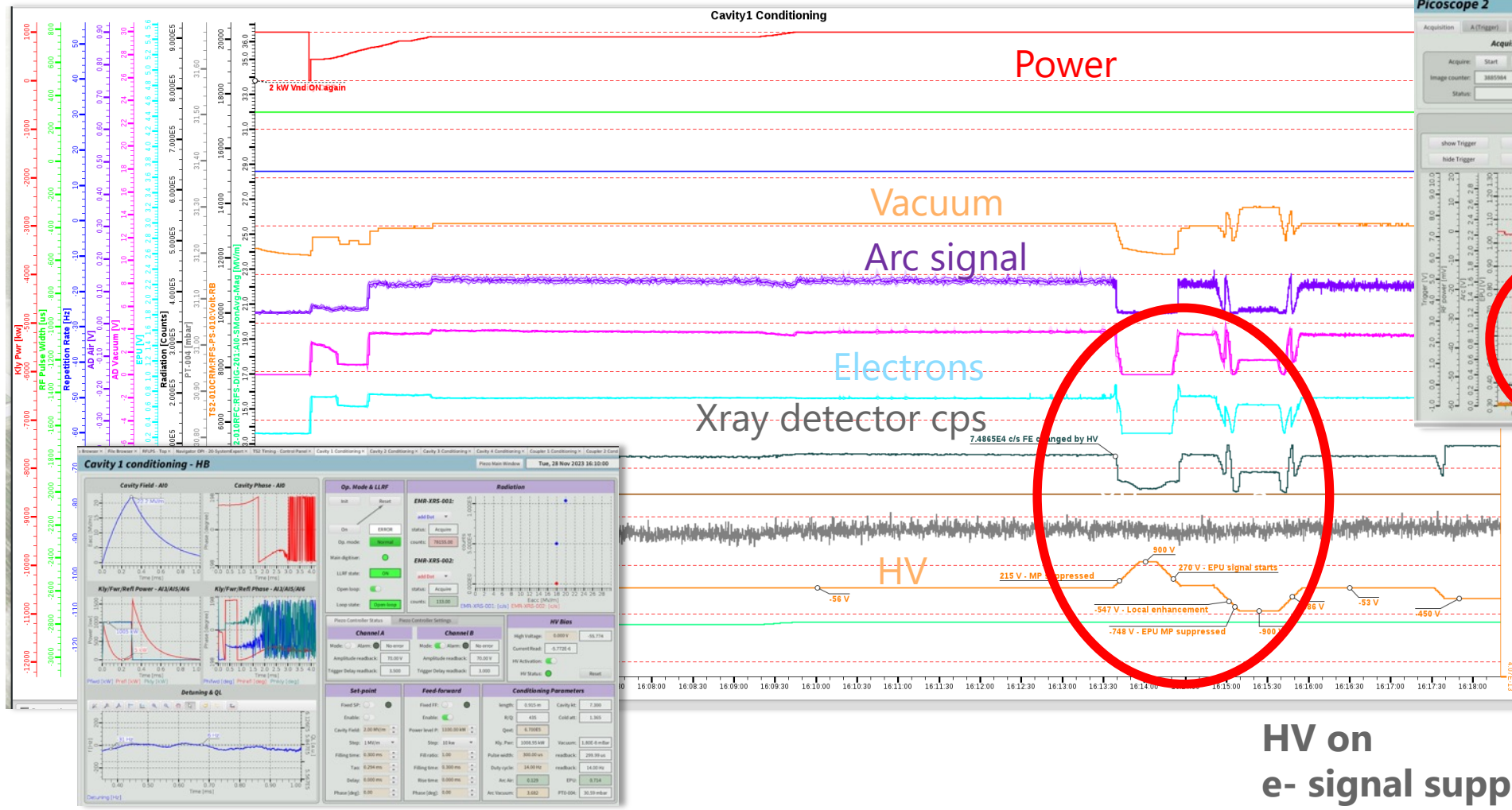


VT Vertical Test

FE as limiting mechanism fed by coupler MP: HV suppression



Cm37 cav1 PL 300 us



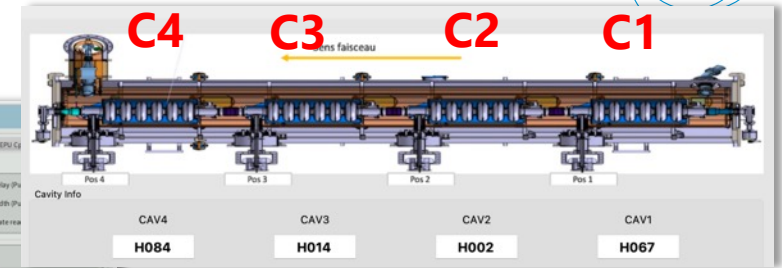
MP in TW (Coupler)
Green – AD
Brown – EPU
Red - PFWD

HV on
e- signal suppressed
Radiation suppressed

FE as limiting mechanism: cherenkov in fibers

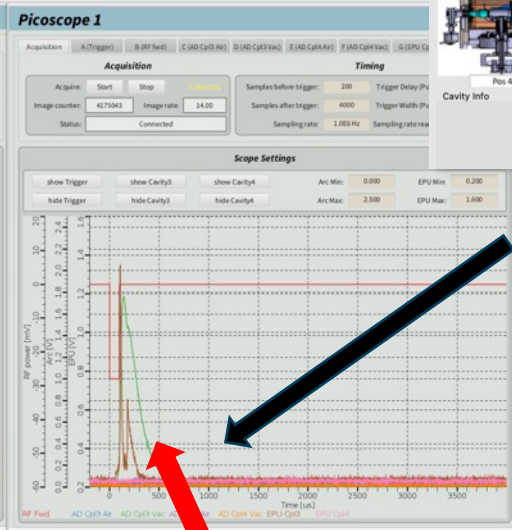
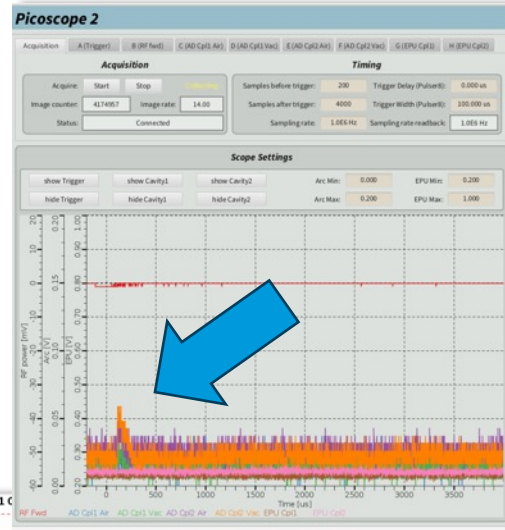


Experience with HB cm37 – cav3 -



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

C1/C2 off

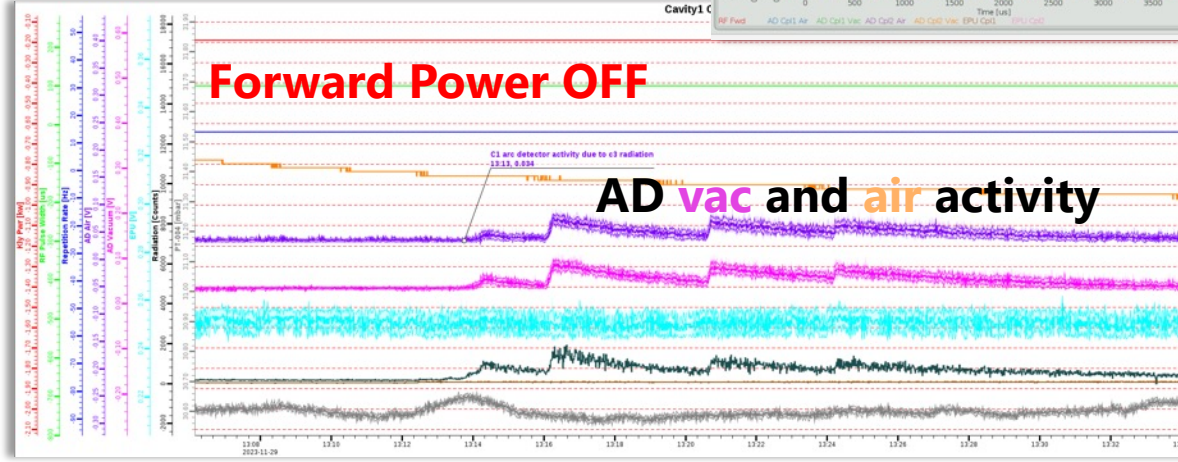


AD and e-pu signal Outside RF pulse (TW – coupler)

C3 on

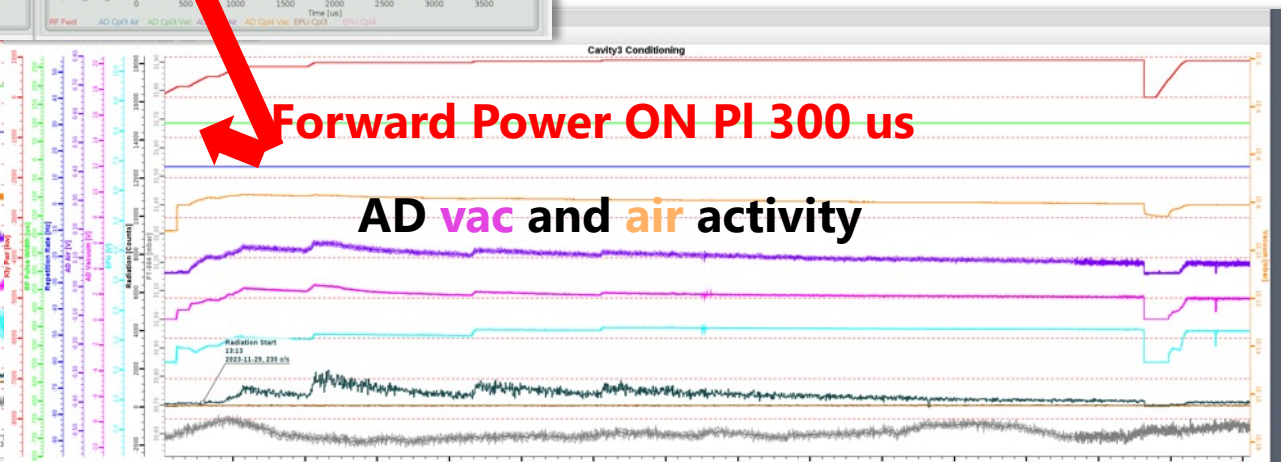
Forward Power OFF

AD vac and air activity



Forward Power ON PI 300 us

AD vac and air activity



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

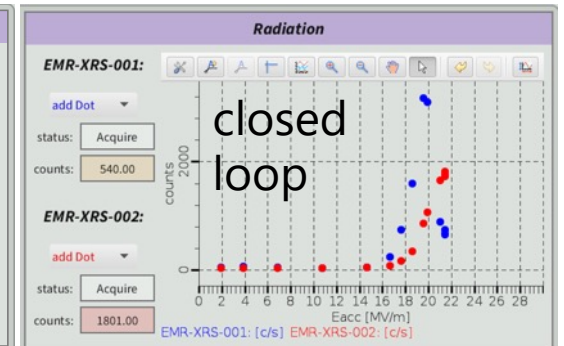
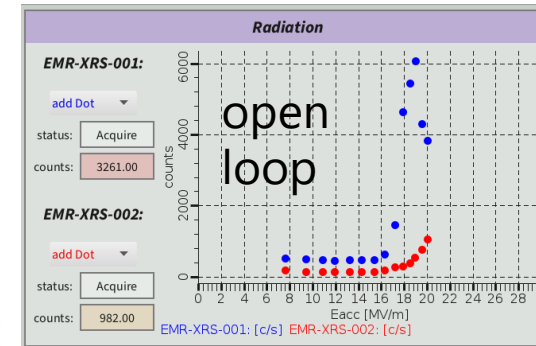
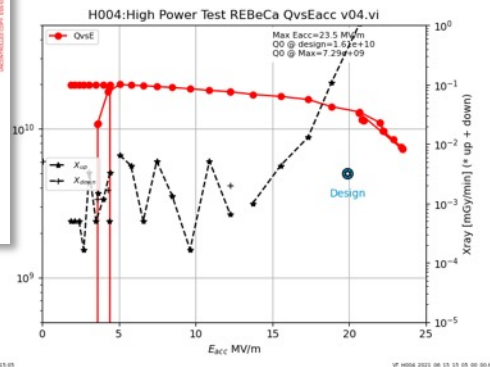


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Date
Revision
State
Confidentiality Level
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1 Module CMM	2 End point Energy Rad 1 (MeV)	3 End point Energy Rad 2 (MeV)	4 Predominant radiation direction (baseline or transverse)	5 Maximum Dose Rate Conditions (uSv/h)	6 Maximum Dose Rate Operation (uSv/h)
CAV1	< 8 MeV	< 8 MeV	Both Baseline and transverse radiation	gamma: 250 neutrons: negligible	gamma: 120 neutrons: negligible
CAV2	< 8 MeV	< 8 MeV	Both Baseline and transverse radiation (multiplicating factor before operation gradient)	gamma: 800 neutrons: negligible	gamma: 1200 neutrons: negligible
CAV3	< 8 MeV	< 8 MeV	Both Baseline and transverse radiation, but negligible activity	gamma: 450 neutrons: negligible	gamma: 12 neutrons: negligible
CAV4	NA	Close to 8 MeV	Mainly transverse direction.	Field emitter has probably been conditioned during open loop operation. gamma: 800 neutrons: negligible	Some comment as for cavity 3, but with no performances degradation. gamma: 120 neutrons: negligible

CM09 FIELD EMISSION REPORT

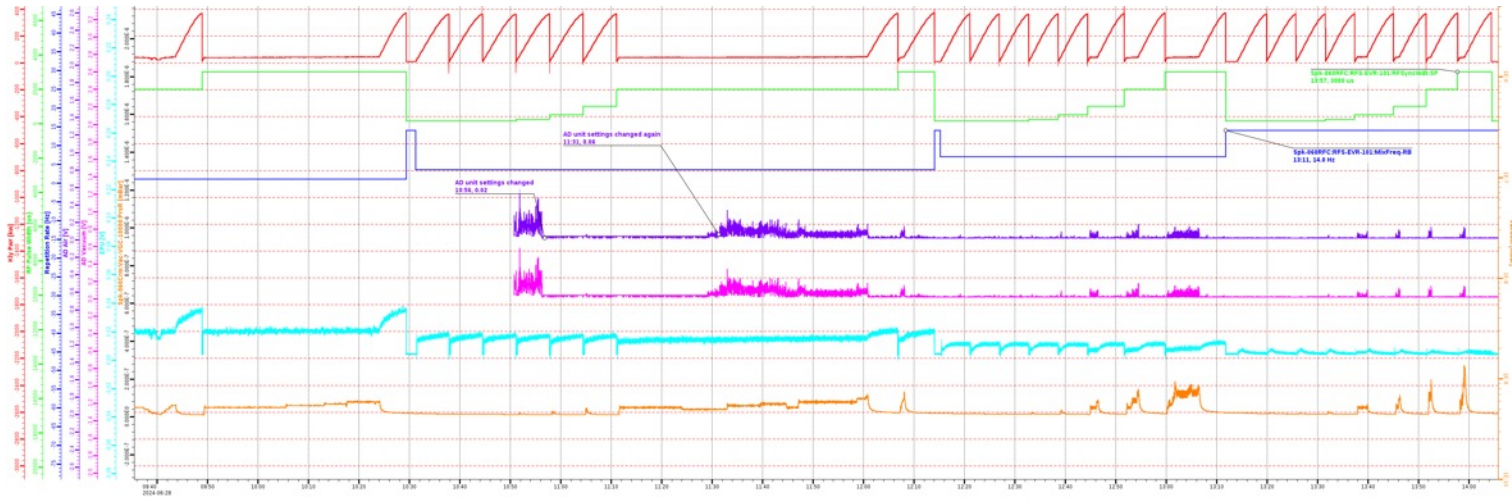
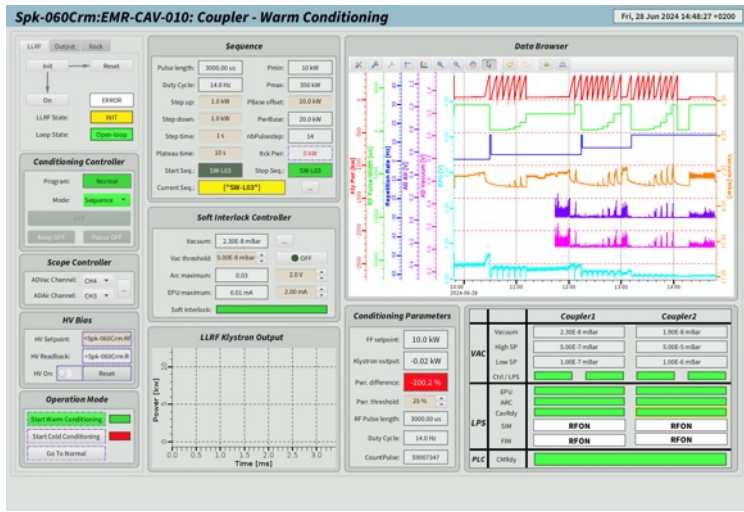
	Name	Role/Title
Owner	Cecilia Maiano	SRF engineer, Linac Group, AD
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Approver	Paolo Pierini	SRF Section Leader, Linac Group, AD, SCL Machine Section Coordinator





Recent achievements

Start and completion of SPK060 Warm Coupler 1 and 2 Conditioning



Sequence Table Spoke x

100 %

Sequence Table Configuration

Steps	RF Width [ms]	Rate [Hz]	Pmin [kw]	Pmax [kw]
SW-S01	0.1500000596	14.0	10.0	350.0
SW-S02	0.1500000596	14.0	10.0	350.0
SW-S03	0.1500000596	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 WCC - AD-OPEN-FORUM



SPK-060 coupler wcc 1



File Browser x [Edit] Display x SCL - Coupler & Cavity Operations x Save And Restore x RF Systems x Spk-060 PS1 - LLRF System x Power Station Operator OPls x Spk-060 PS1 - Digitiser 1 - Expert Screen x Timing System - Back View - Spk-060 PS1 x Spk-060Crm:EMR-CAV-010: Coupler Conditioning x

100 %

Spk-060Crm:EMR-CAV-010: Coupler - Warm Conditioning

Thu, 27 Jun 2024 11:36:03 +0200

Sequence Table Spoke x

100 %

LLRF Output llock

Init Reset

On ERROR

LLRF State: ON

Loop State: Open-loop

Conditioning Controller

Program: Normal

Mode: Sequence

ON

Keep OFF Pause OFF

Scope Controller

ADVac Channel: CH4

ADAir Channel: CH3

HV Bias

HV Setpoint: Spk-060Crm:R

HV Readback: Spk-060Crm:R

HV On: Reset

Operation Mode

Start Warm Conditioning

Start Cold Conditioning

Go To Normal

Sequence

Pulse length: 150.00 us Pmin: 10 kW

Duty Cycle: 1.0 Hz Pmax: 350 kW

Step up: 1.0 kW PBase offset: 10.0 kW

Step down: 1.0 kW PwrBase: 20.0 kW

Step time: 1 s nbPulsestep: 1

Plateau time: 10 s Itck Pwr: 0 kW

Start Seq.: SW-S01 Stop Seq.: SW-L03

Current Seq.: ["SW-S01"]

Soft Interlock Controller

Vacuum: 8.30E-9 mBar

Vac threshold: 5.00E-8 mBar OFF

Arc maximum: 0.16 1.0 V

EPU maximum: 0.01 mA 2.00 mA

Soft interlock: ON

LLRF Klystron Output

Data Browser

Conditioning Parameters

FF setpoint: 258.0 kW

Klystron output: 301.22 kW

Pwr. difference: 16.8 %

Pwr. threshold: 25 %

RF Pulse length: 150.00 us

Duty Cycle: 1.0 Hz

CountPulse: 57950761

		Coupler1	Coupler2
VAC	Vacuum	8.30E-9 mBar	7.40E-9 mBar
	High SP	5.00E-7 mBar	5.00E-5 mBar
	Low SP	1.00E-7 mBar	1.00E-6 mBar
	Ctrl / LPS	ON	ON
LPS	EPU	ON	ON
	ARC	ON	ON
	CavRdy	ON	ON
	SIM	RFON	RFON
FIM	FIM	RFON	RFON
	PLC	CMRdy	ON

Sequence Table Configuration

Sequence Table Configuration

Status	RF Pulse	Duty Cycle	Pmin	Pmax
SW-S01	0.150	1.000	10.000	350.000
SW-S02	0.150	1.000	10.000	350.000
SW-S03	0.150	1.000	10.000	350.000
SW-S04	0.250	1.000	10.000	350.000
SW-S05	0.500	1.000	10.000	350.000
SW-L01	1.000	1.000	10.000	350.000
SW-L02	2.000	1.000	10.000	350.000
SW-L03	3.000	1.000	10.000	350.000

Manual rep rate selection

Duty Cycle: 1Hz

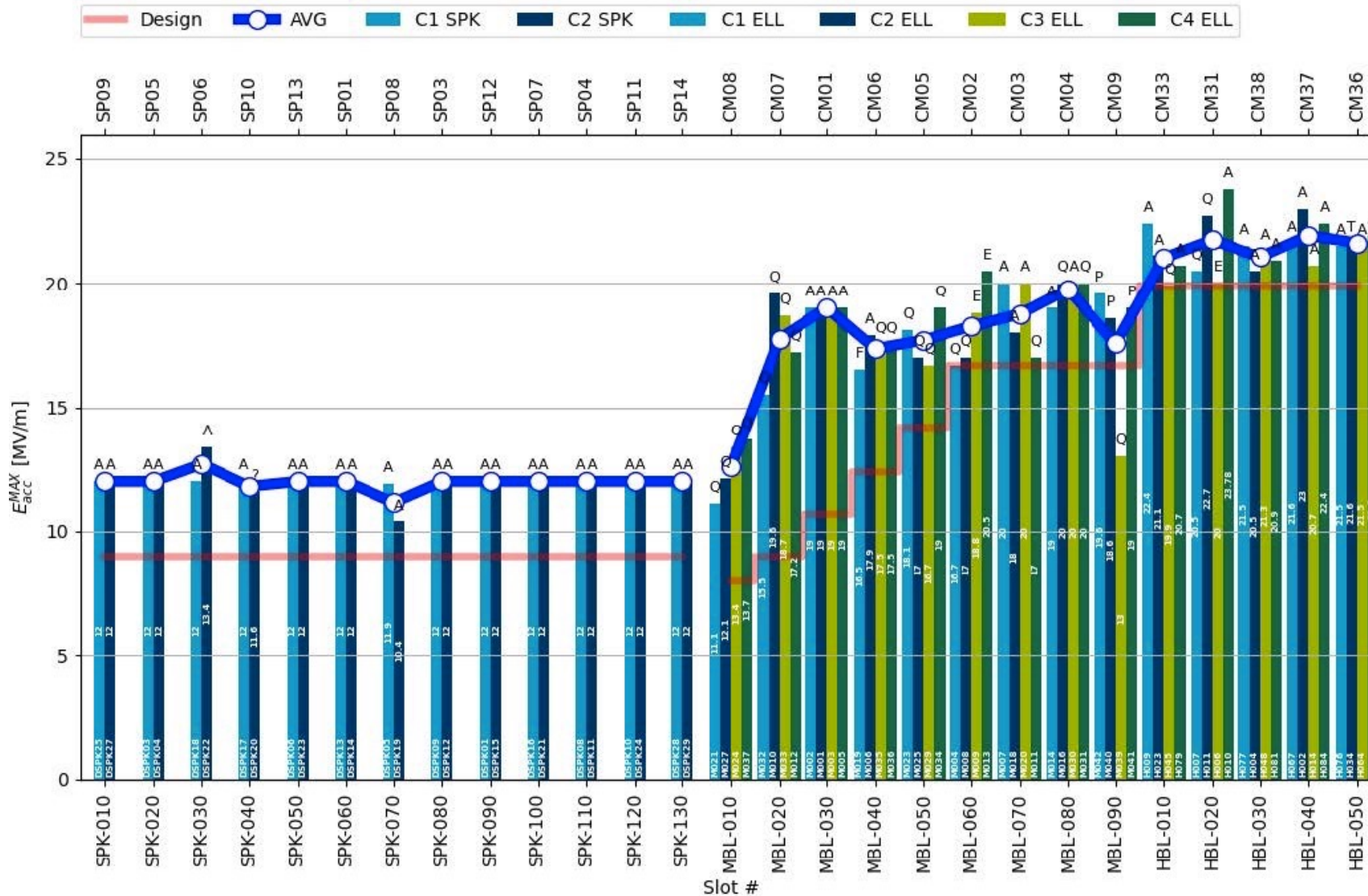
Sta: SW-S01 Stop: SW-L03

Our First spoke operation at ESS SCL tunnel

Linac Configuration



Linac Design



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

Thanks

Acknowledgments

* ESS: TS2 SRF, IFJ, RP, CRYO,
VAC, OPS teams

* CEA/INFN/STFC in-kinds

