Technical Commissioning of the ESS Linac Cavities for the Beam on Dump Phases

Marten Koopmans on behalf of the Linac Group

2026/08/20 – Linac 2026, Daejeon, Korea

Agenda

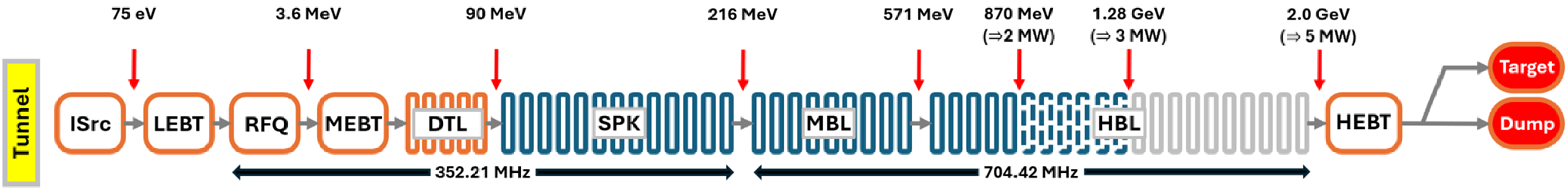
1. The ESS Accelerator Project
2. Normal Conducting Linac (NCL) experience
3. Superconducting Linac (SCL) experience
4. Cryo Operation

The ESS Accelerator Project

Accelerator Project and Status

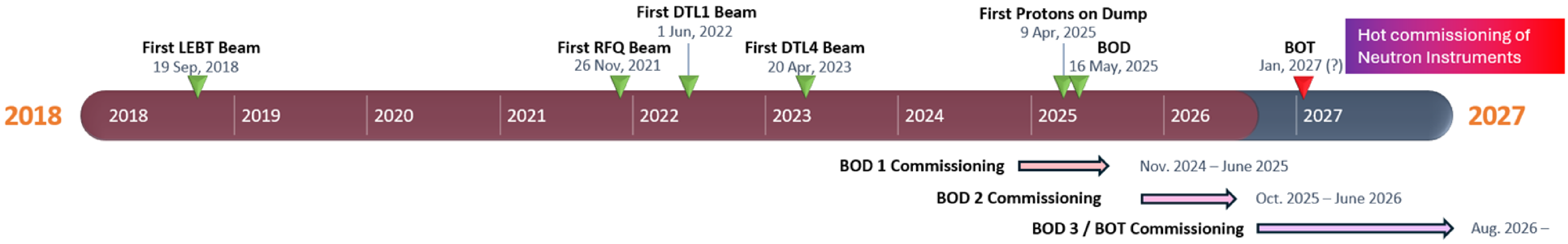
ESS Proton Linac

- Ultimate avg. Beam power 5 MW
- Ultimate beam energy 2 GeV
- Beam current **62.5 mA**
- Beam pulse length 2.86 ms, cavity pulse **3.2 ms**
- Repetition rate **14 Hz** (⇒ Beam duty Cycle 4 %, cavity 4.5 %)
- NCL to 90 MeV: Ion source, LEBT, RFQ, MEBT with 3 Bunchers, 5 DTLs
- SCL to 2 GeV:
  - 13 Spoke Cryo Modules (CM) with two double spoke cavities
  - 9 Medium-ß Linac (MBL) & 21 High-ß Linac (HBL) CM with 4 MB/HB cavities each



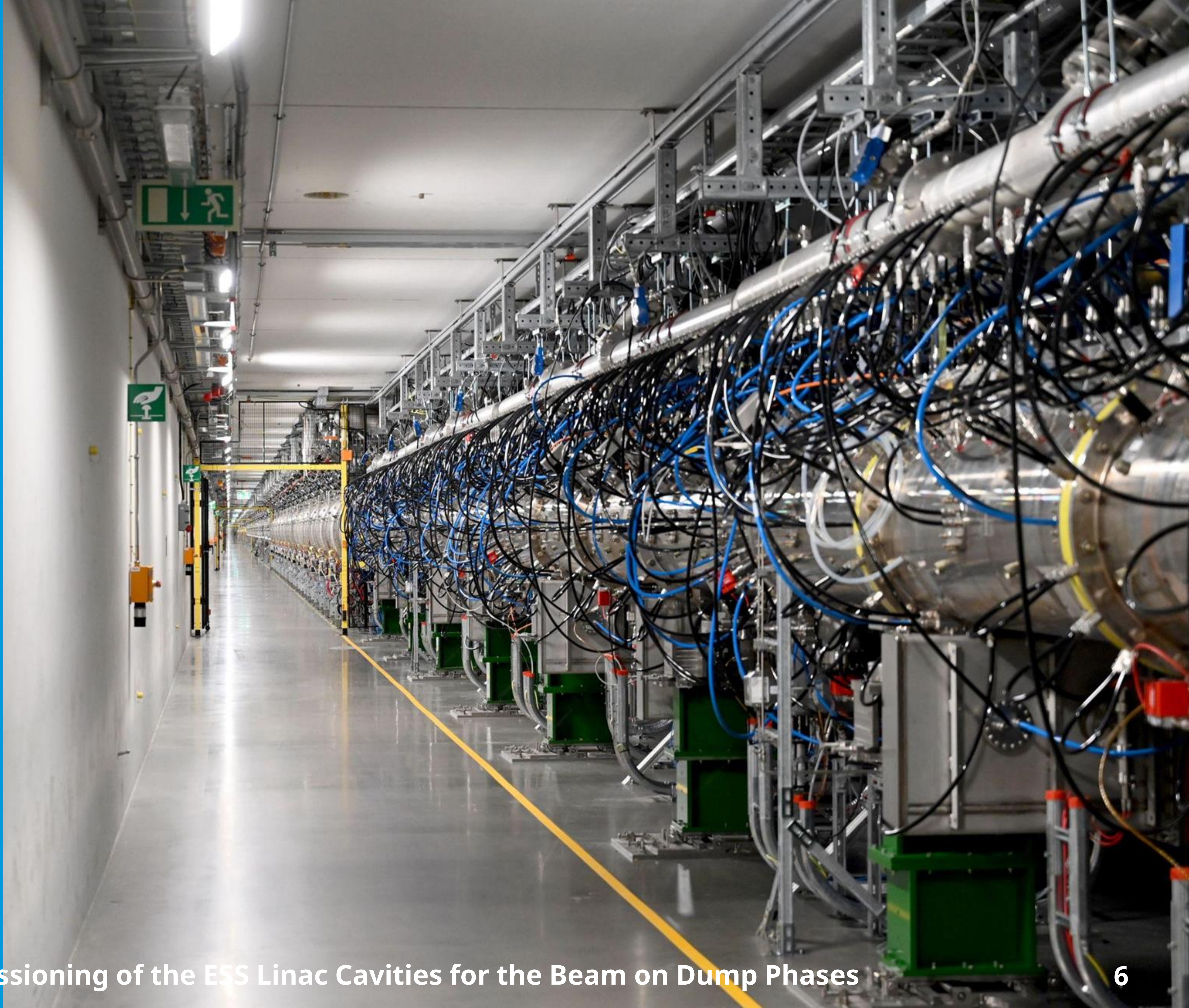
Accelerator Project and Status

Timeline and Status



- First beam on dump (BOD1) commissioning
  - Reached first beam on dump milestone
  - Max. beam parameters in SCL, beam current of 5 mA for 5 us (50 us) at 1 Hz
- Second beam on dump (BOD2) commissioning goals
  - Stable RF operation at 14 Hz, 3.2 ms
  - Separately demonstrate the design parameters (long pulse > 1ms at 5 mA, nominal current of 62.5 mA to the beam dump)
  - 80 % availability of accelerator

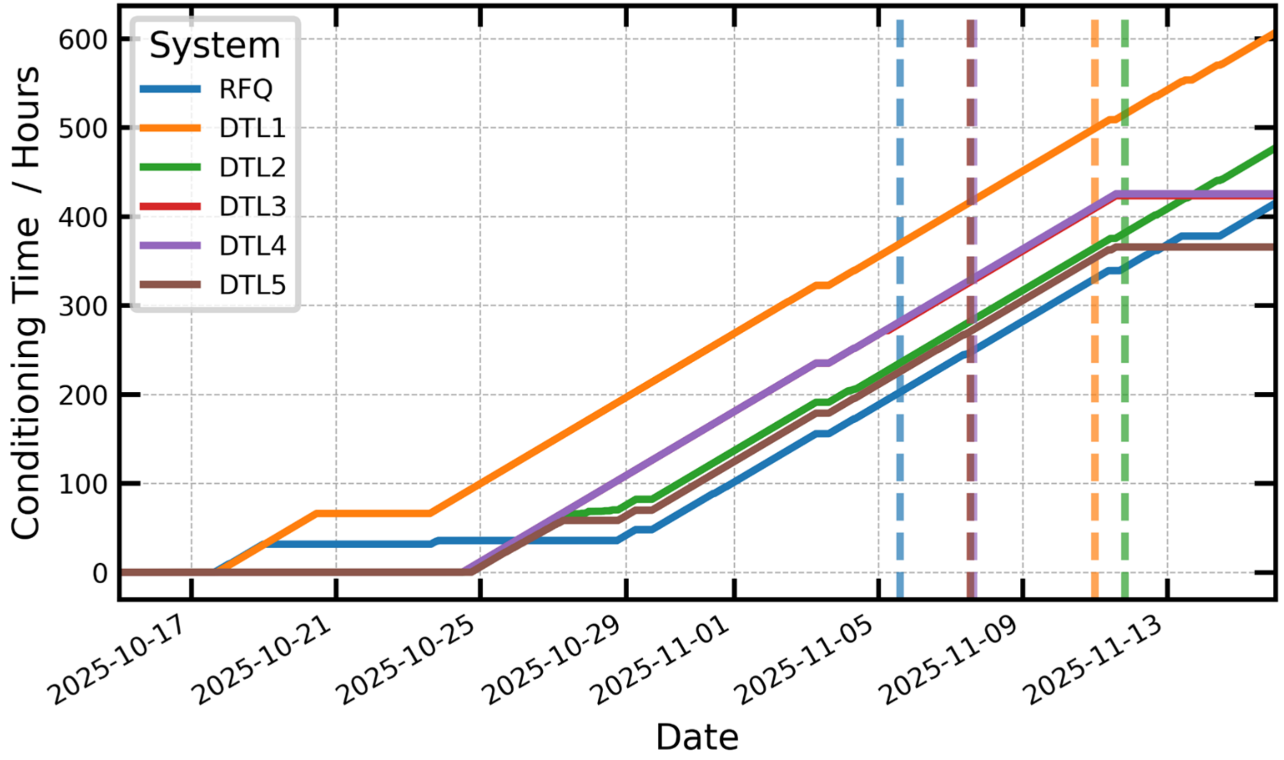
NCL Experience



NCL Preparation

RFQ and DTL RF Conditioning

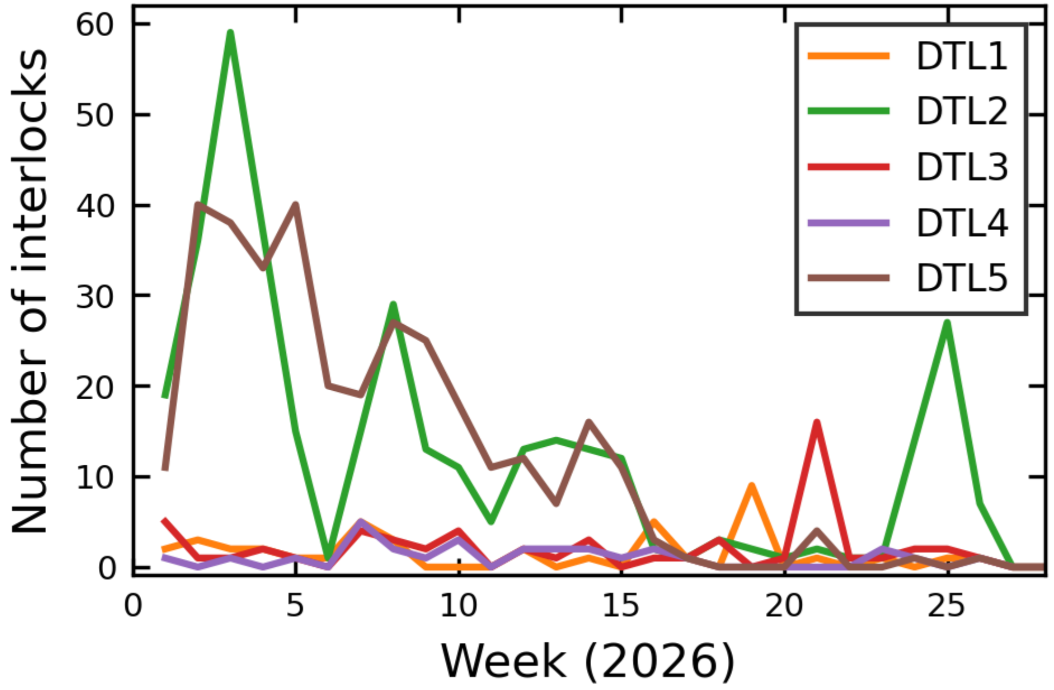
- Quickly reached nominal duty cycle compared to BOD1
- Majority of beam commissioning still had to be ran with 1 Hz RF
- Periodic recondition required for operation at high duty cycle
- With LLRF AFF upgrades now possible to run RF independent of beam frequency
- Foreseen for the next commissioning to run all NCL RF constantly at 14 Hz



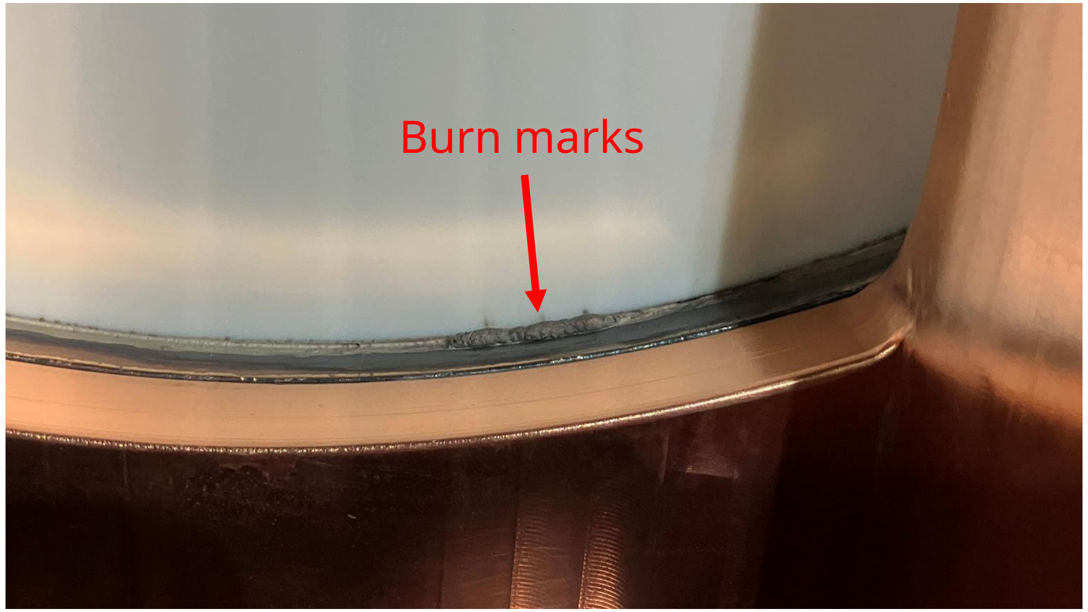
Cavity	BOD1 / Days	BOD2 / Days
RFQ	44	9
DTL1	28	21
DTL2	38	16
DTL3	28	14
DTL4	22	14
DTL5	73	11

DTL Conditioning

- Generally no problem reaching full duty cycle in conditioning
- Trouble is more to keep everything stable for long time (in closed loop)
- Sometimes some DTLs (1 and 4) become sensitive to tuner movements in closed loop
- Window arcing problem with RF windows of DTL 2 and 5, one window on DTL1 already had to be replaced after BOD1
- Trips often start a cascade due to coupling in cooling loops



DTL 2 Window Air Side

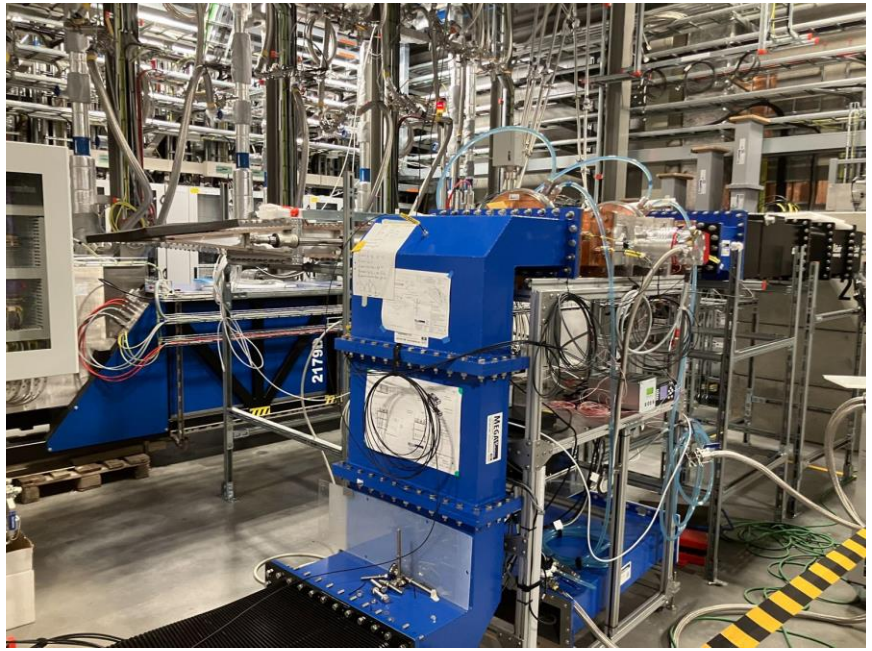


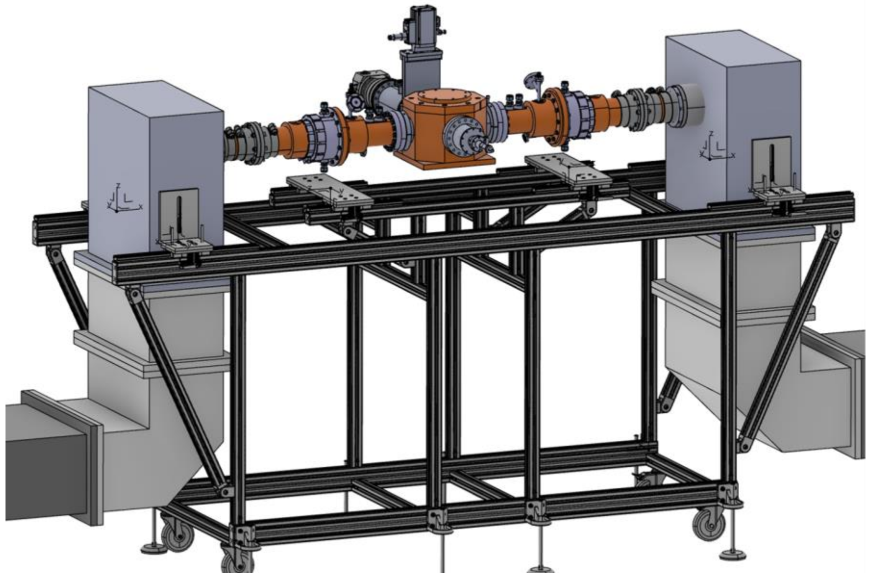
NCL Maintenance Strategies

Strengthening NCL RF Reliability

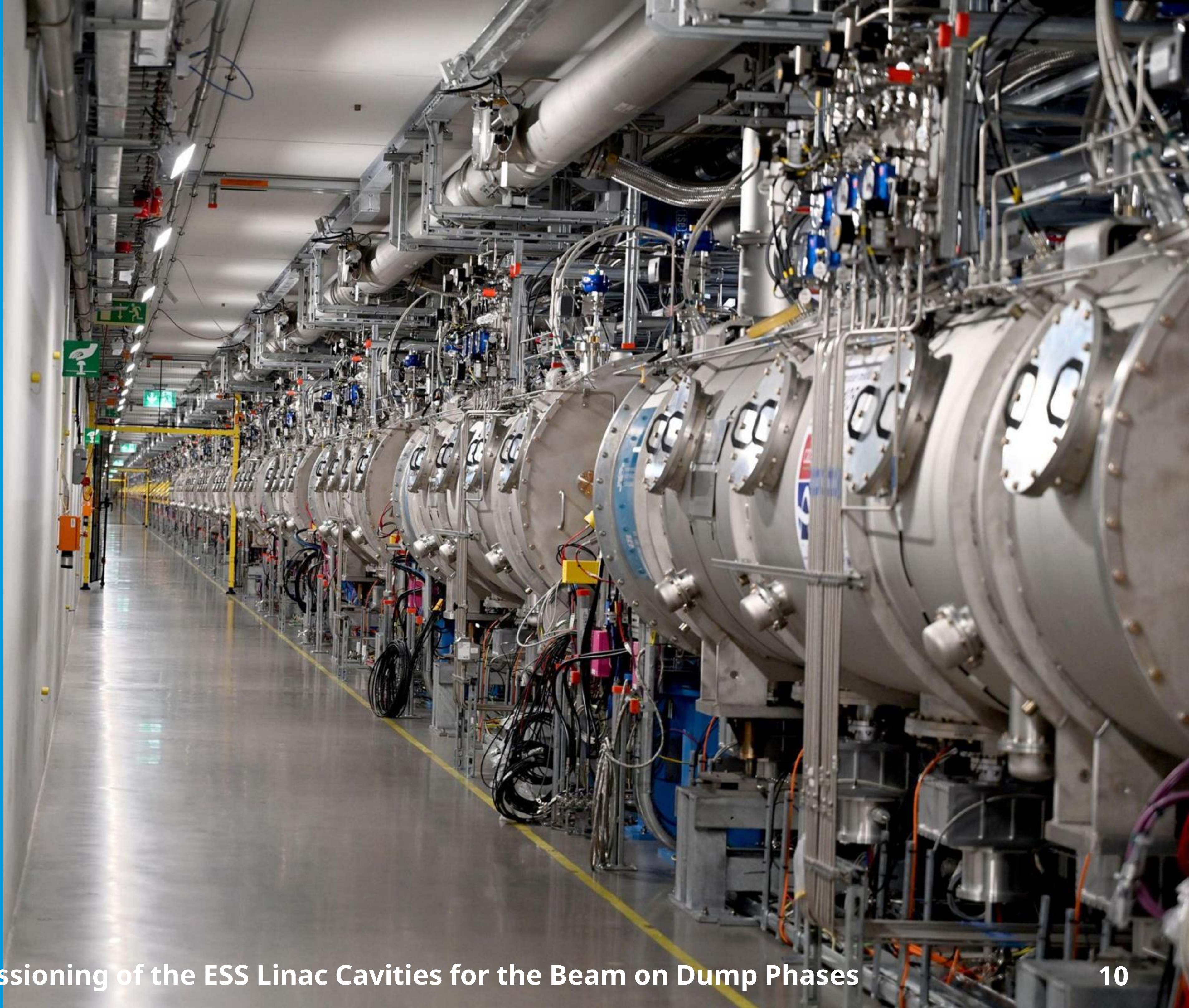
A. Passarelli
TUPO043

- Testing and qualification of critical RF components
- Installation of a 352 MHz teststand in gallery
- Setup of test rig for DTL windows
- One refurbished DTL window has been successfully conditioned
- RFQ power coupler test stand is being commissioned





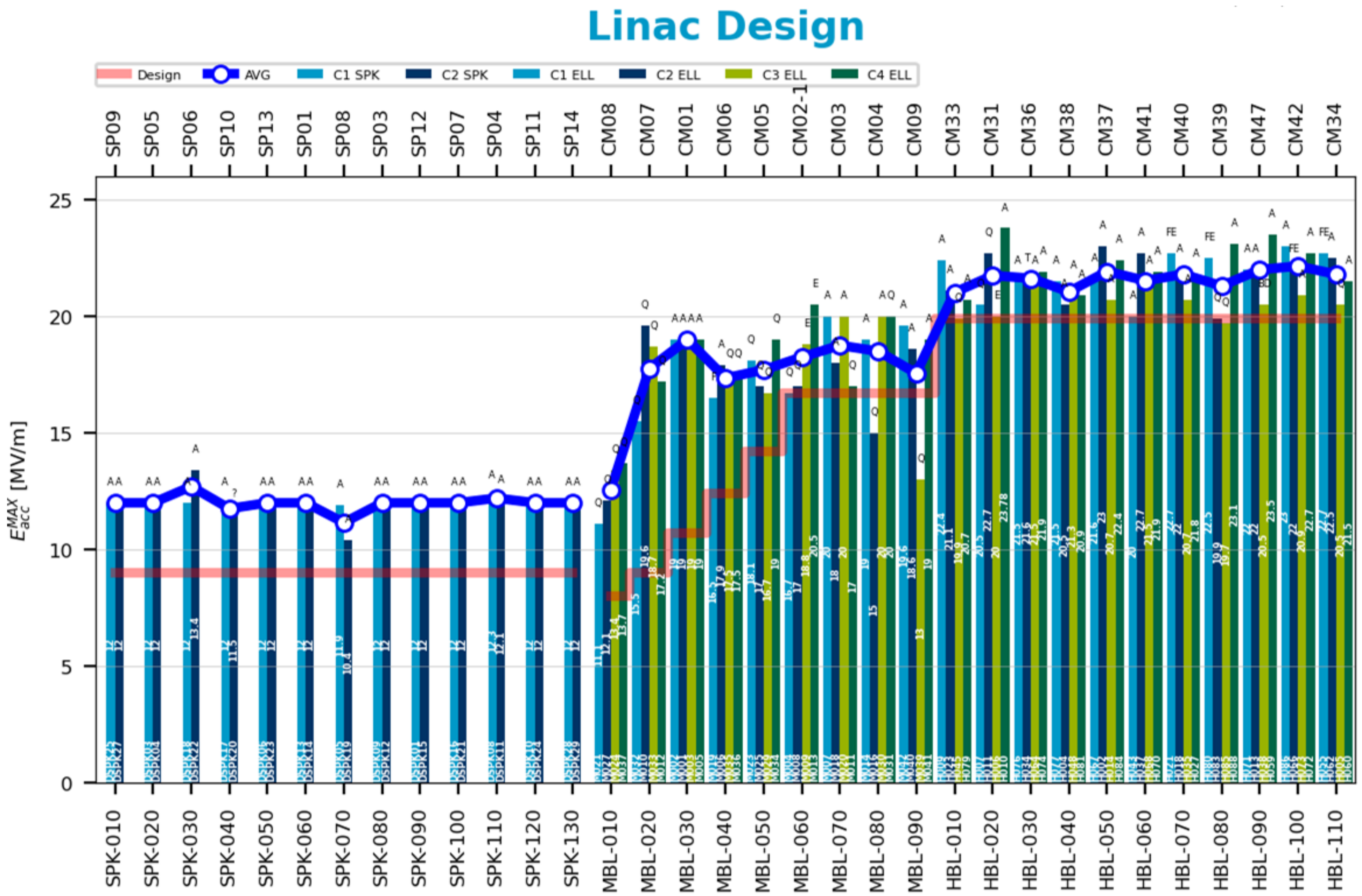
SCL Experience



SCL Cavity Preparation

For full duty cycle

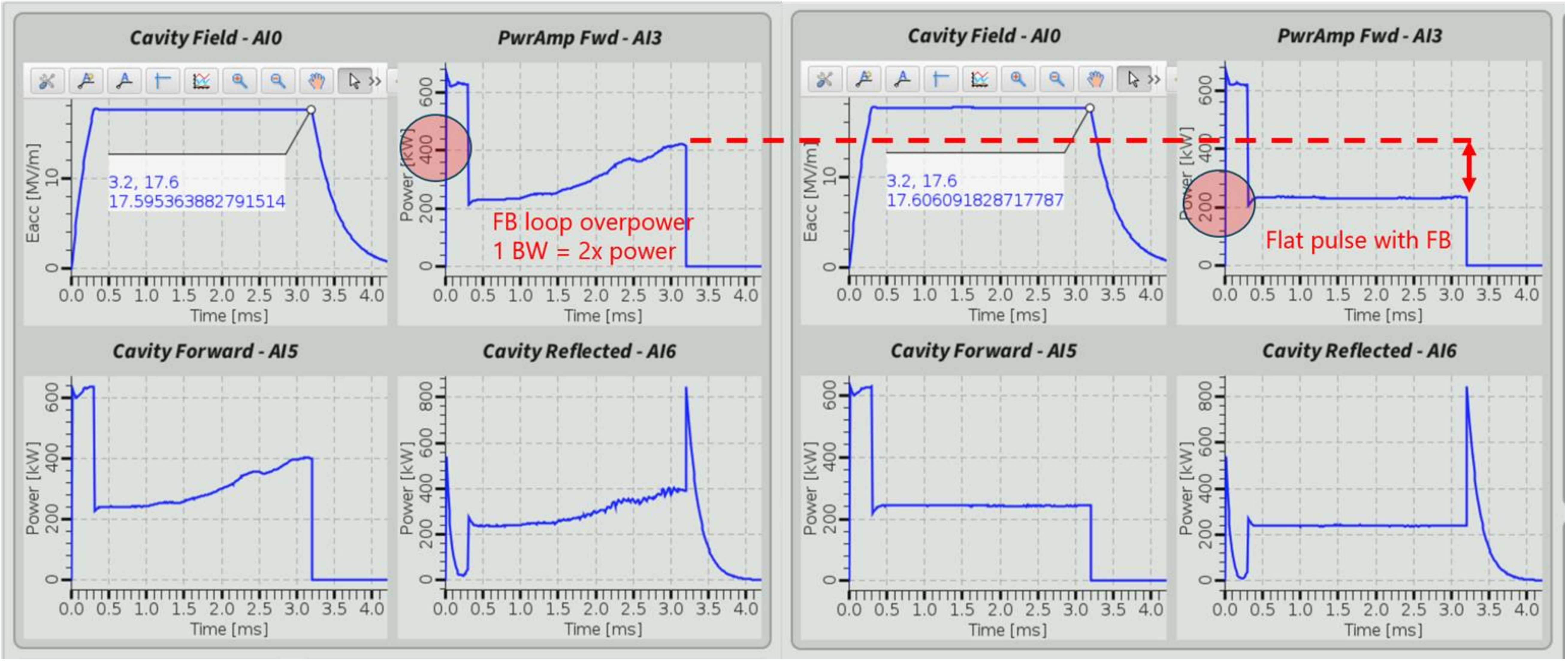
- For BOD1 cavities were only running at low duty cycle (1 Hz, 1 ms)
- For BOD2 we need to prepare everything for full DC
    - Piezo to compensate for Lorentz Force Detuning (LFD) in pulses > 1 ms
    - Dynamic heat load compensation to “save” cryo when the whole SCL trips at high duty cycle
    - Radiation studies
- Experience from elliptical cavity qualification and testing at ESS test stand 2



LFD Compensation for Long Pulse

Piezo Operation (Manual Mode)

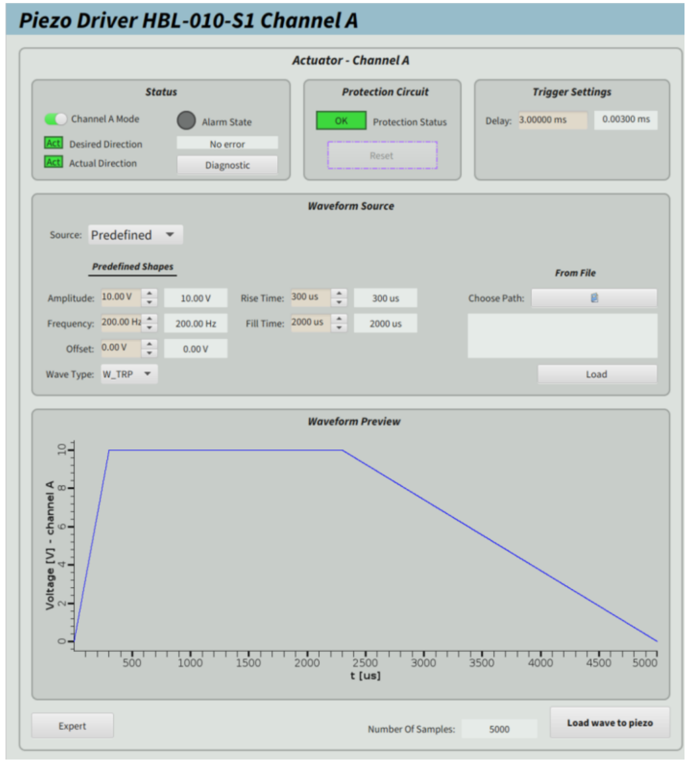
Piezo OFF Cavity detuning at high field (LFD) requires > 50% extra power at pulse end! **Piezo ON**

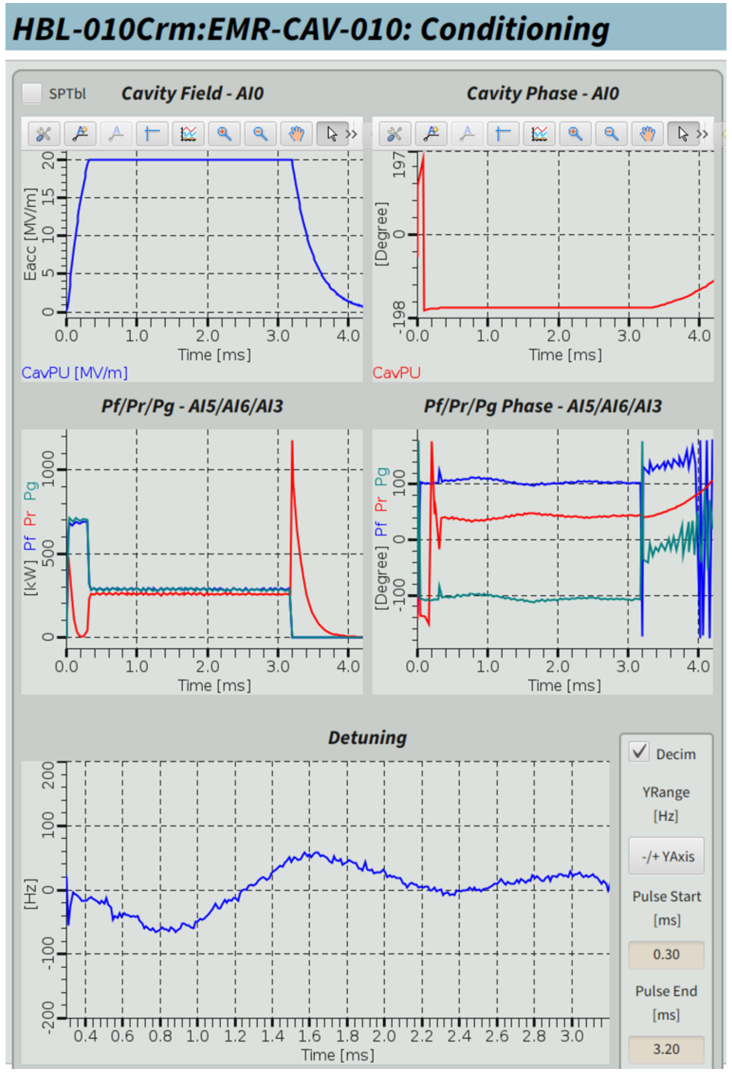


LFD Compensation for Long Pulse

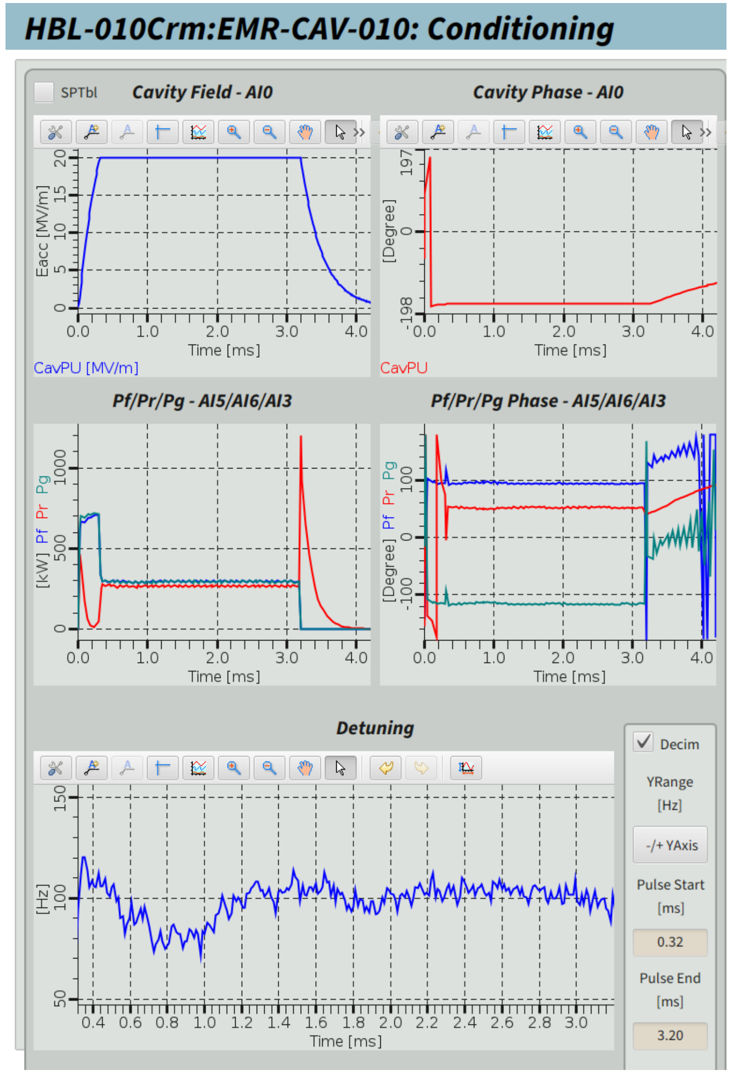
Manual vs. Custom Piezo

Manual Mode



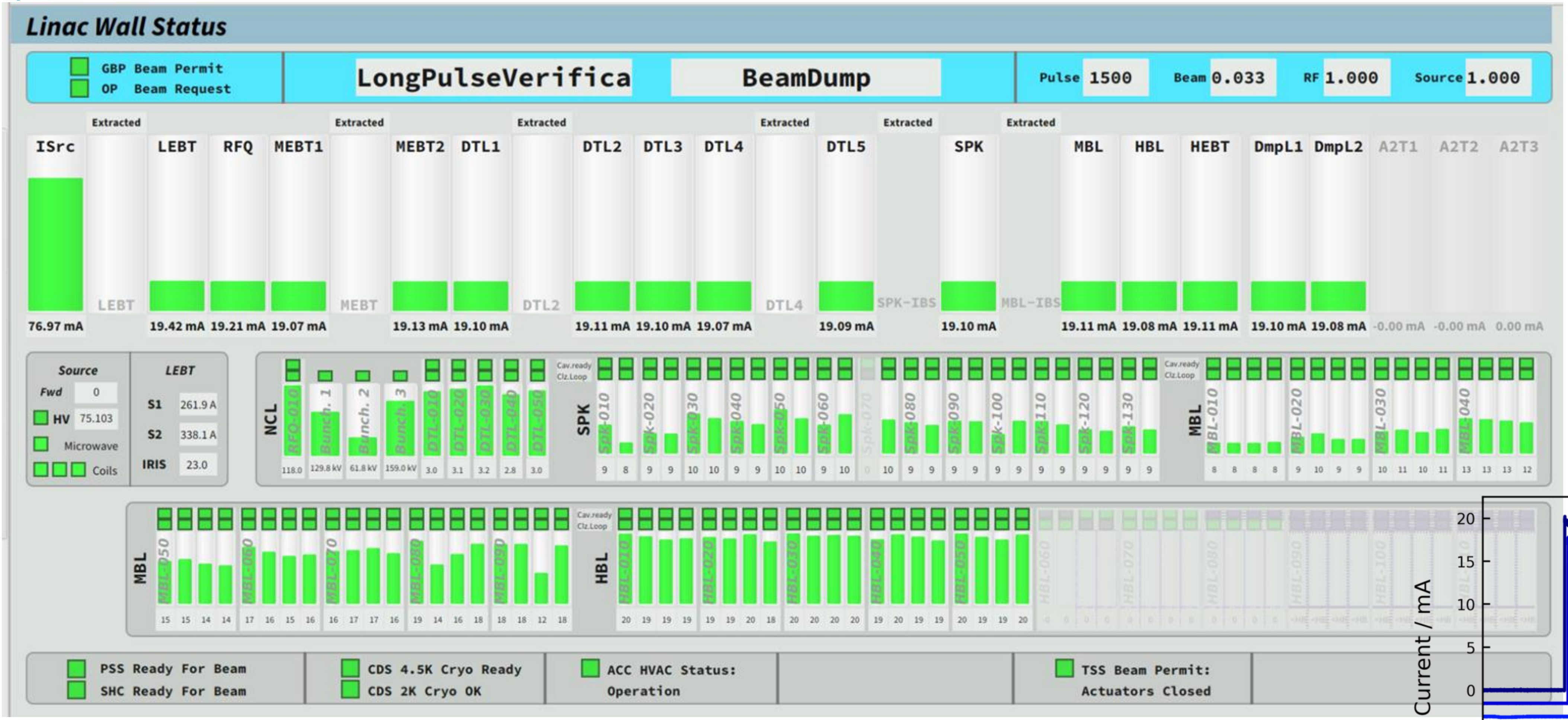


Custom Mode



Long Pulse in the Linac

Verification Run with 20 mA at 1/30 Hz to the Beam Dump



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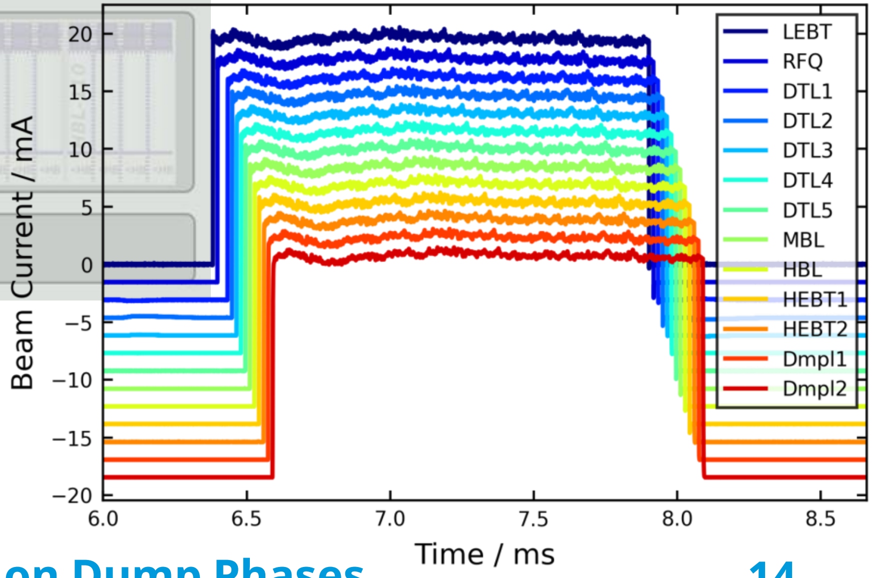
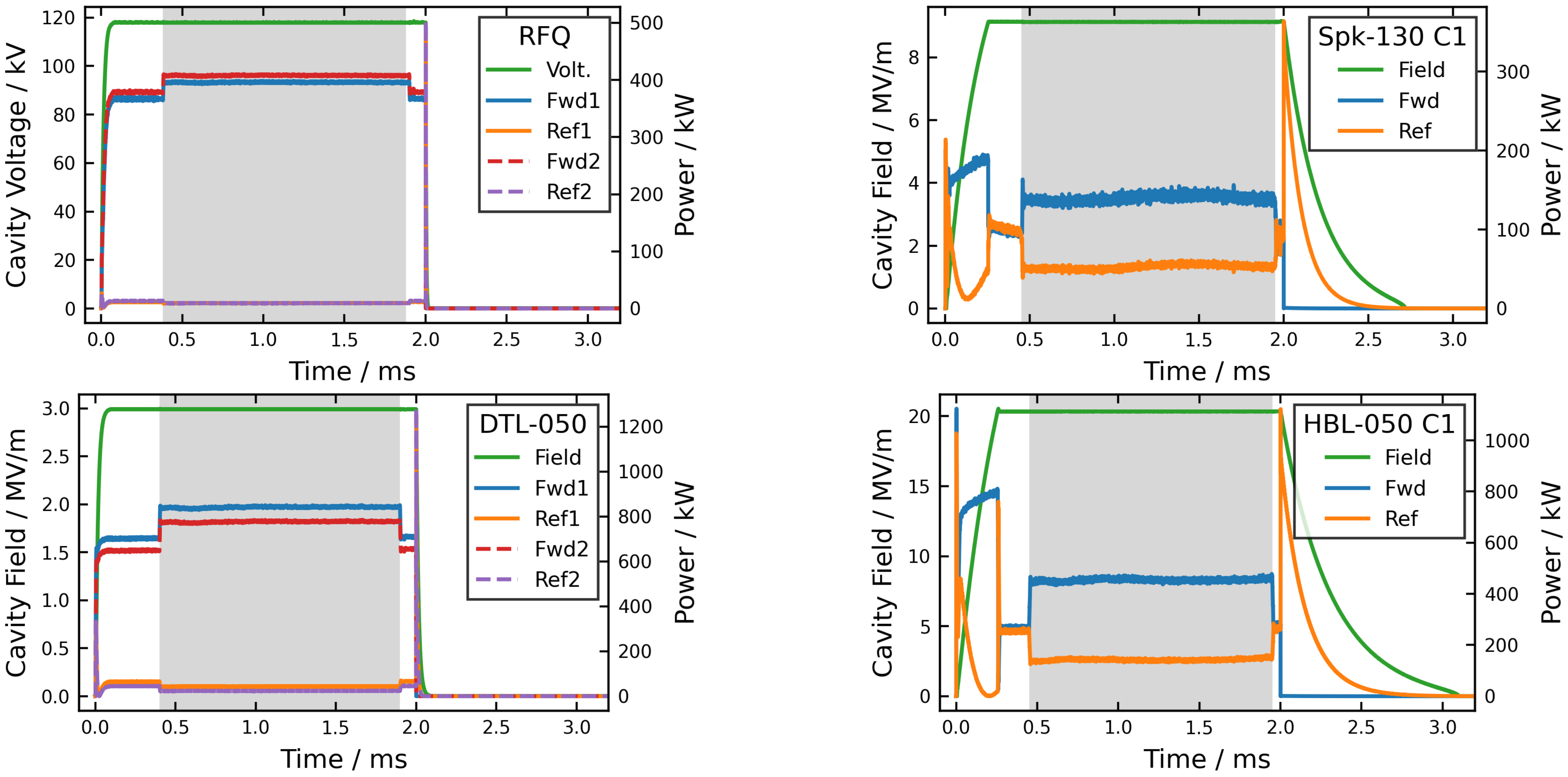


Long Pulse in the Linac

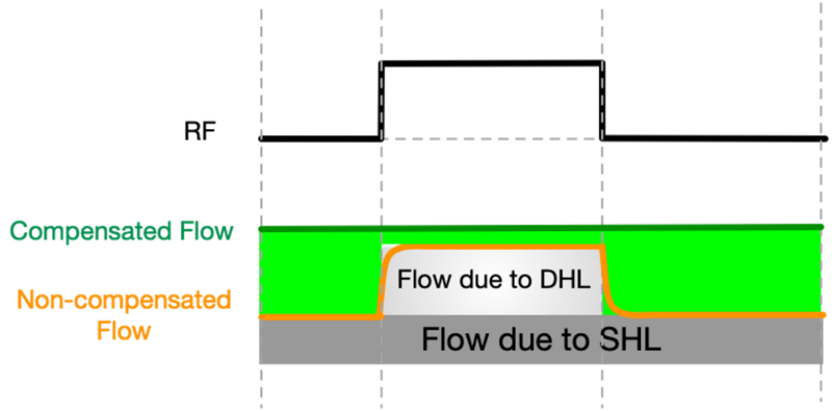
How it looks from the Cavities



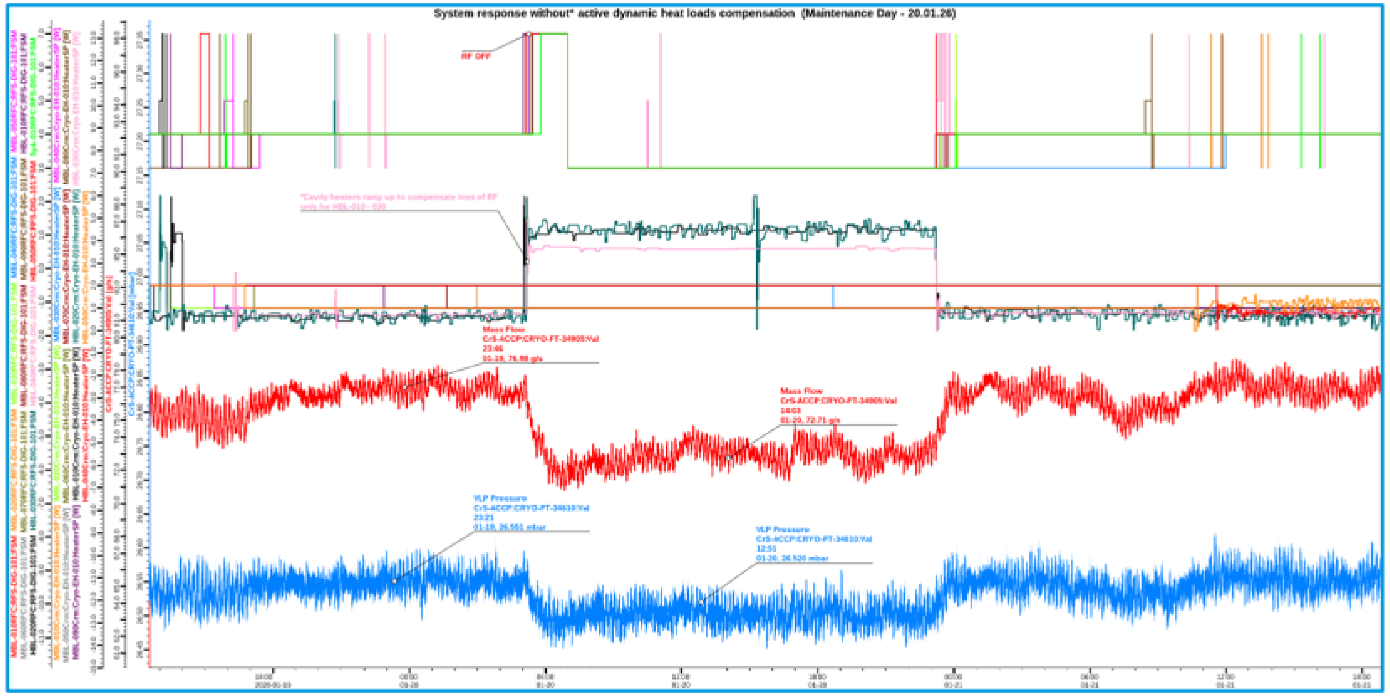
SCL Cavity Prep. for High Duty Cycle

Active Dynamic Heat Load Compensation

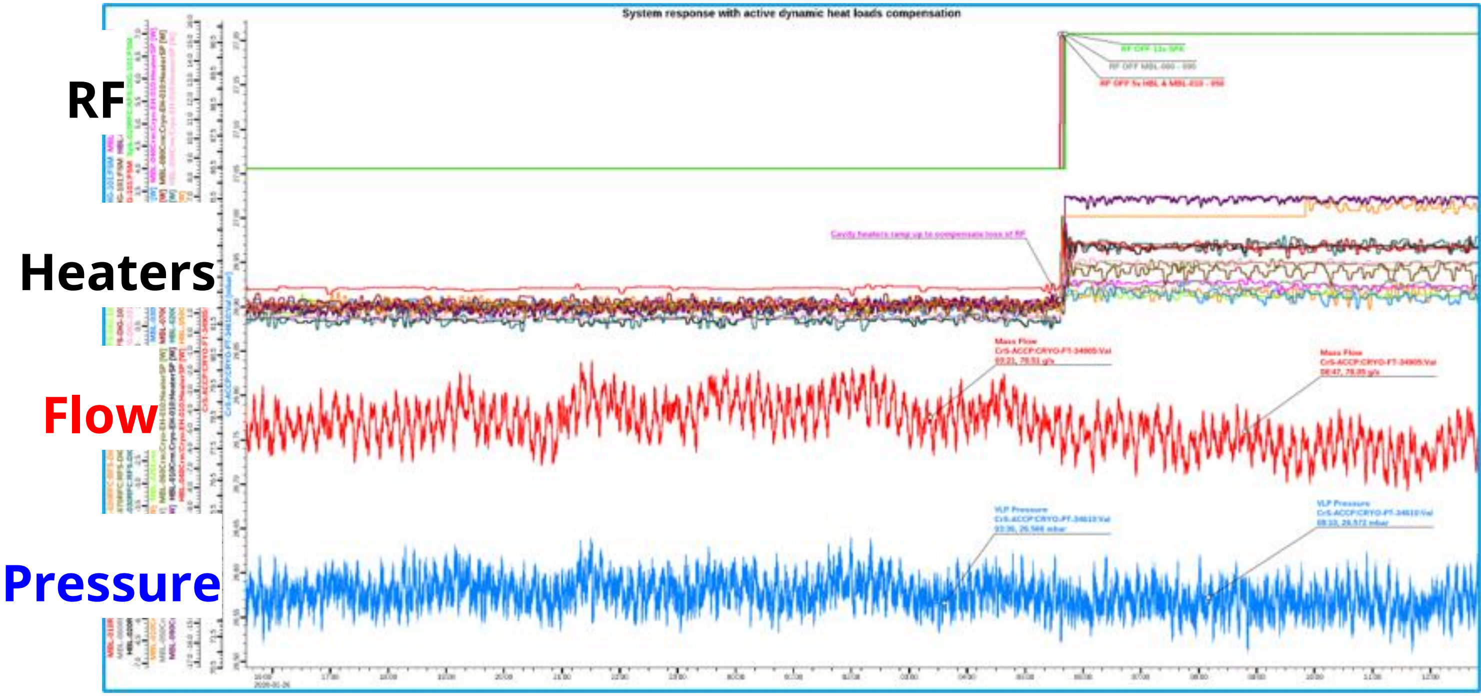
- BOD1 – no compensation, but dynamic heat load was low at 1 Hz, 1 ms
- BOD2 – Needed for full duty cycle to prevent surge/choke at cold compressors (in case of RF trips)



without compensation



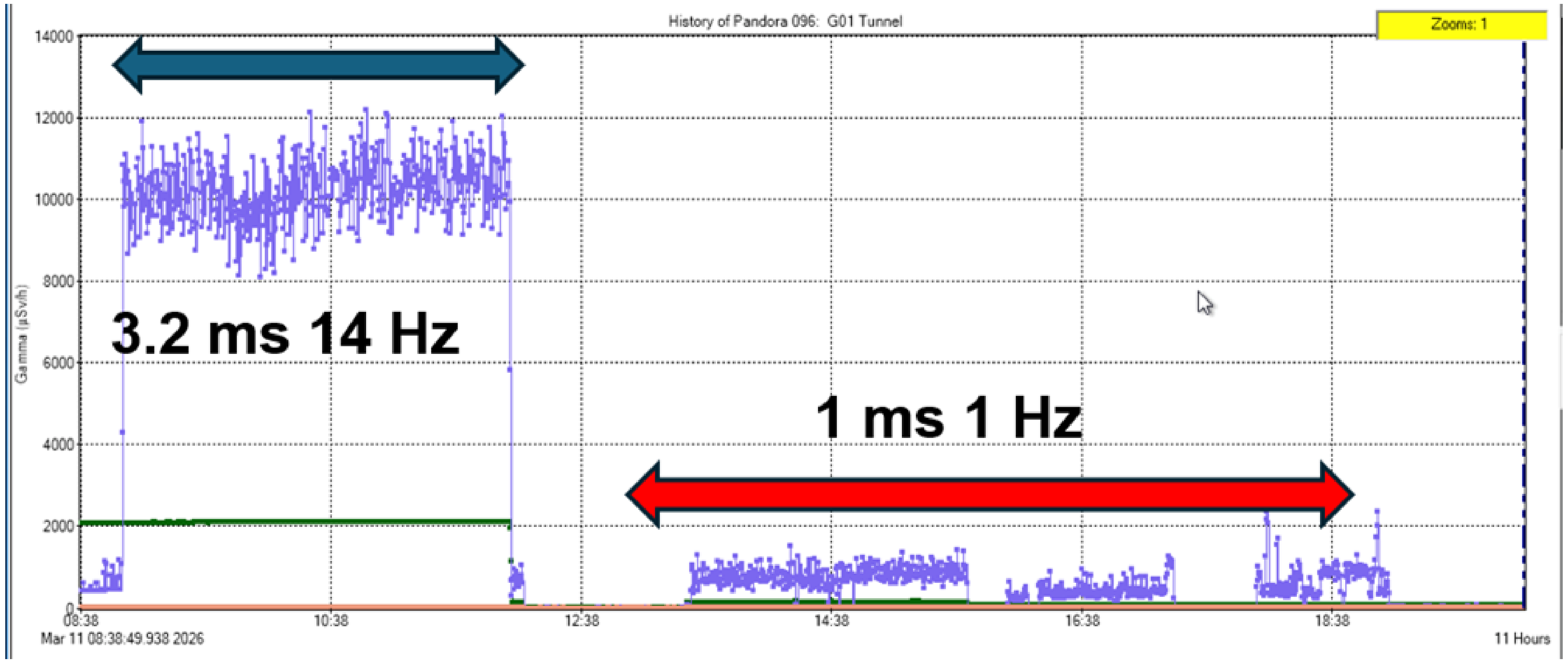
with compensation

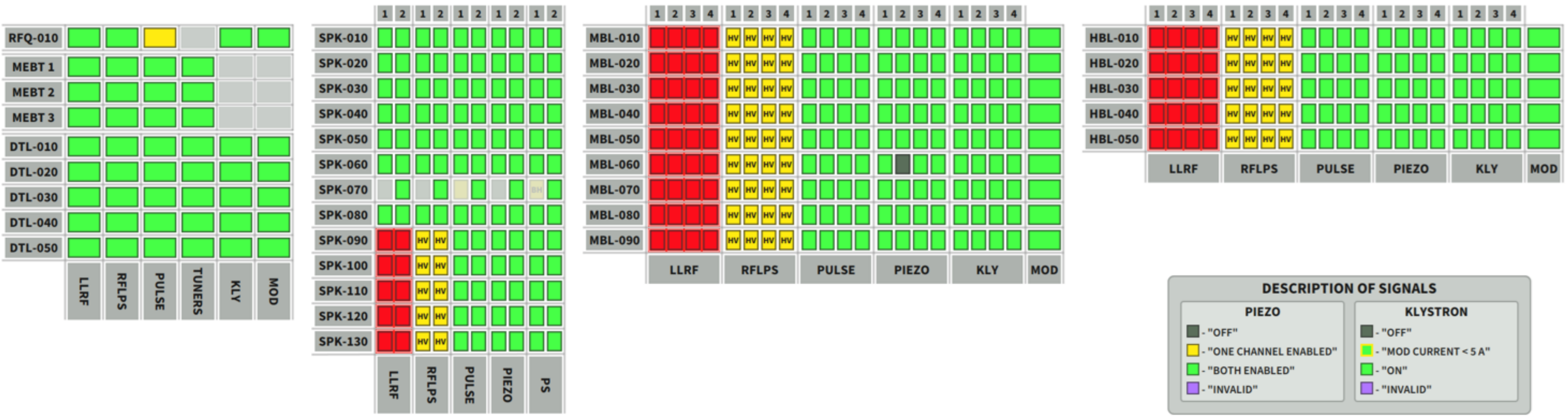


Field Emission Studies

Avoiding Collective Arcs

- Much higher FE rates at full duty cycle
- Cavity degradation (mainly HBL) can cause FE bursts and trip the cavity
- FE seen by the arc detector fibers can trip many cavities as “collective arc”
- Reconditioning with short high power pulses to cure FE degradation
- Exploring filter system with CEA colleagues

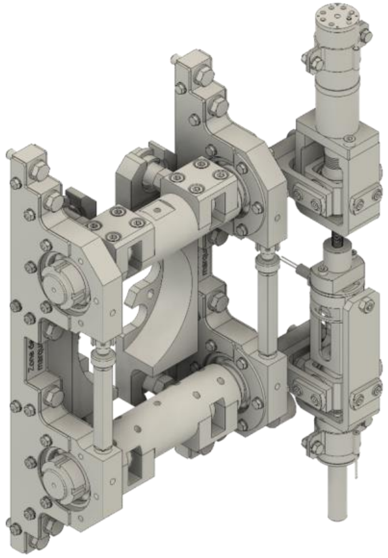


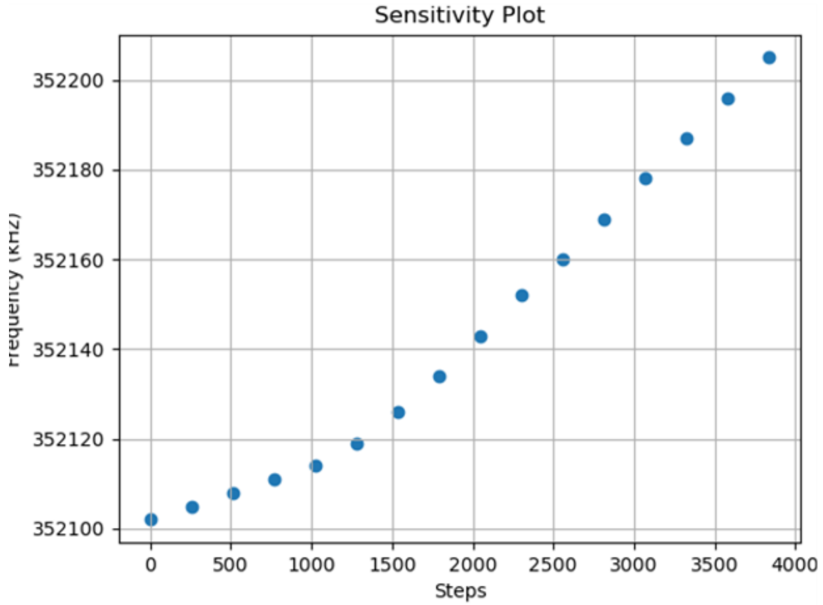


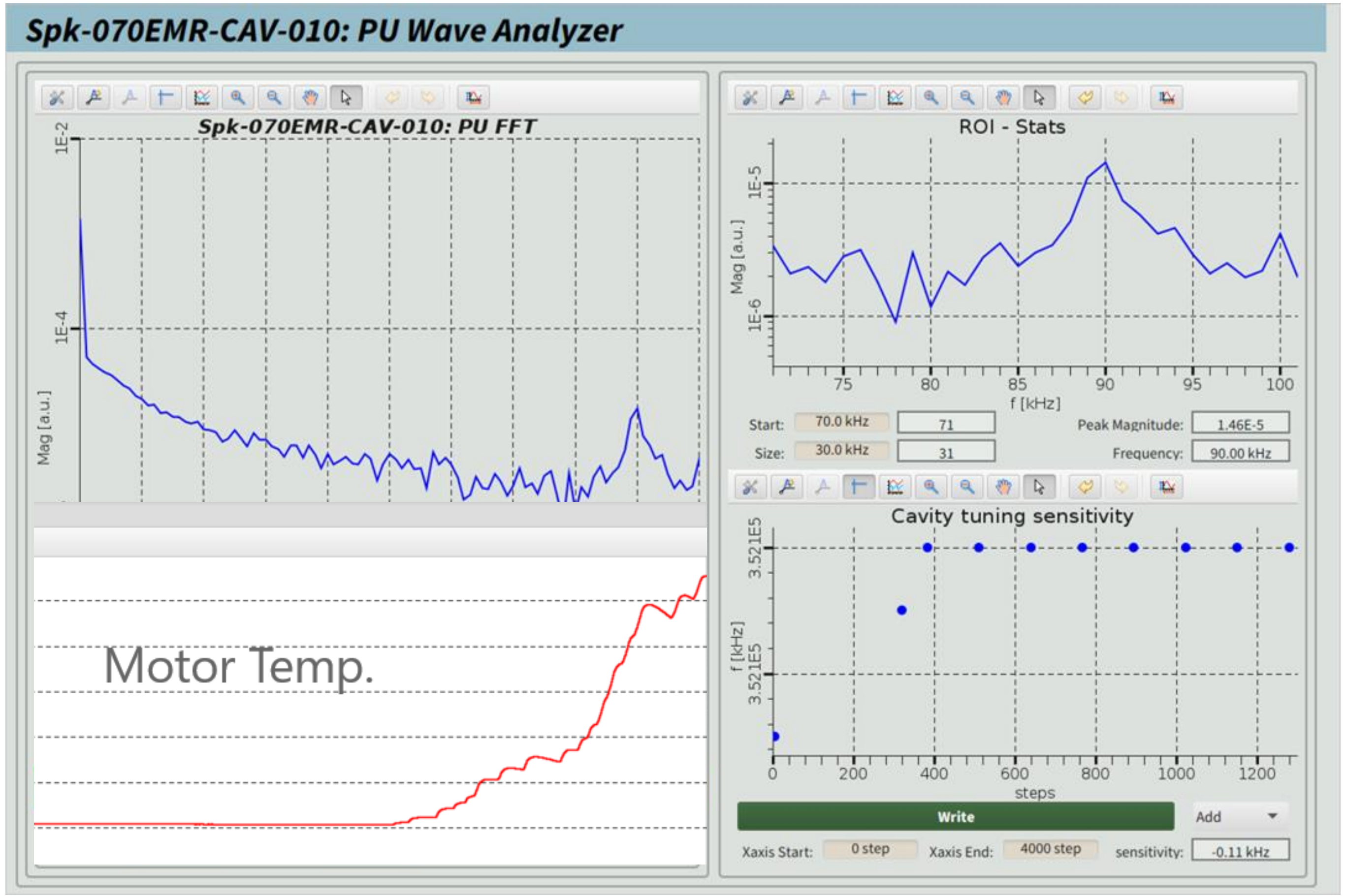
Spoke Motors

Cold tuning motor reliability and failure

- Do not meet reliability (20 cycles)
- We try to run the motors at 600 mA
- When motor is not moving anymore current can be increased
- Two motors not moving at 600 mA anymore but increasing to 900 mA helped
- Spk-070 Motor 1 dead

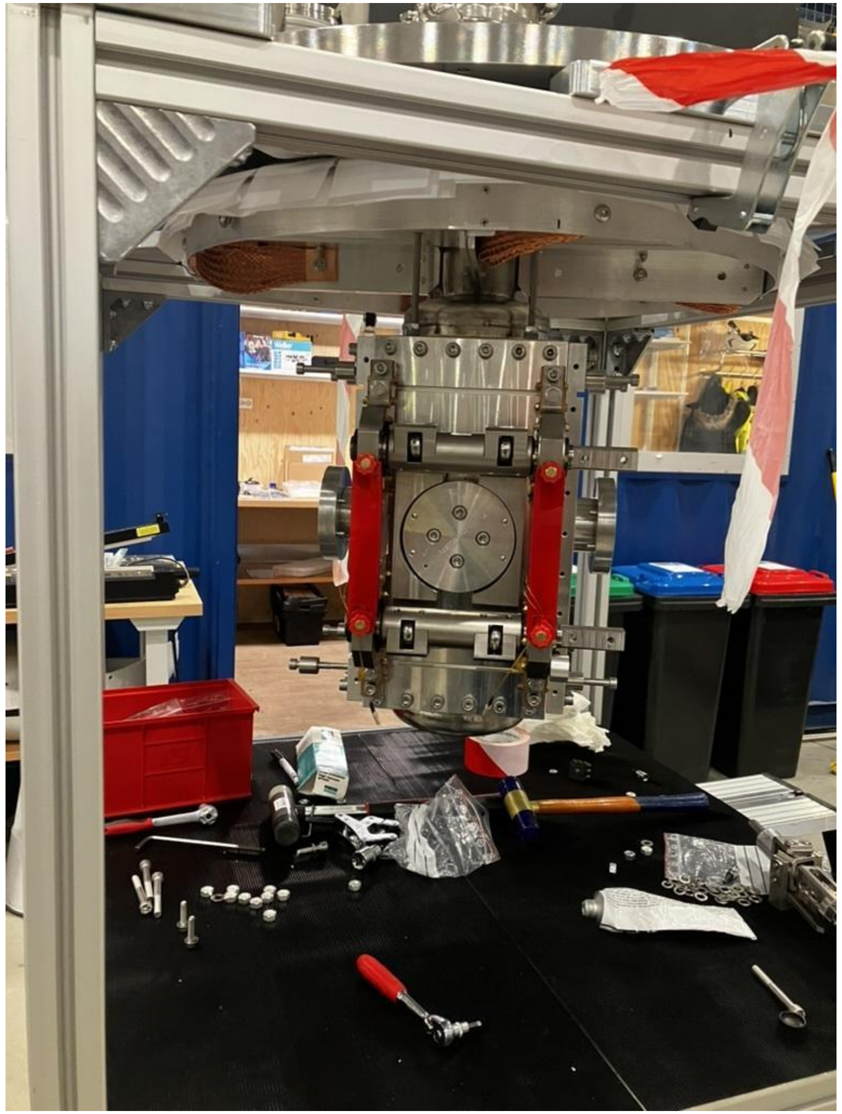






Spoke Cold Tuning System

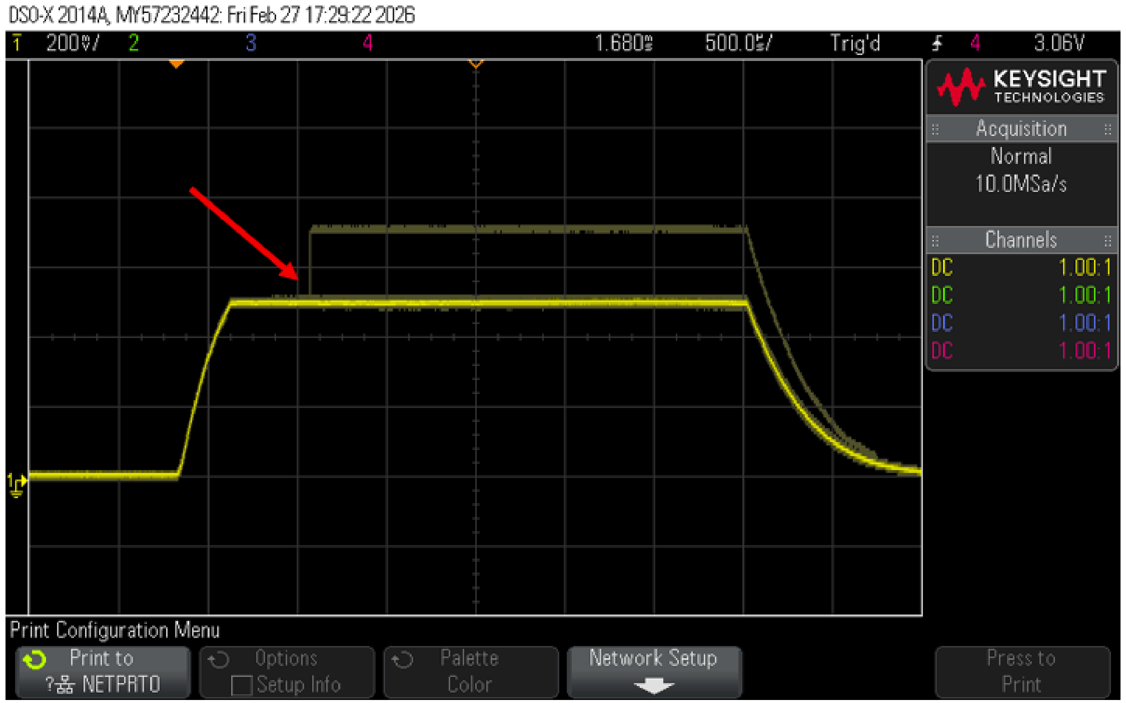
Testing and Qualification of Replacement Motors

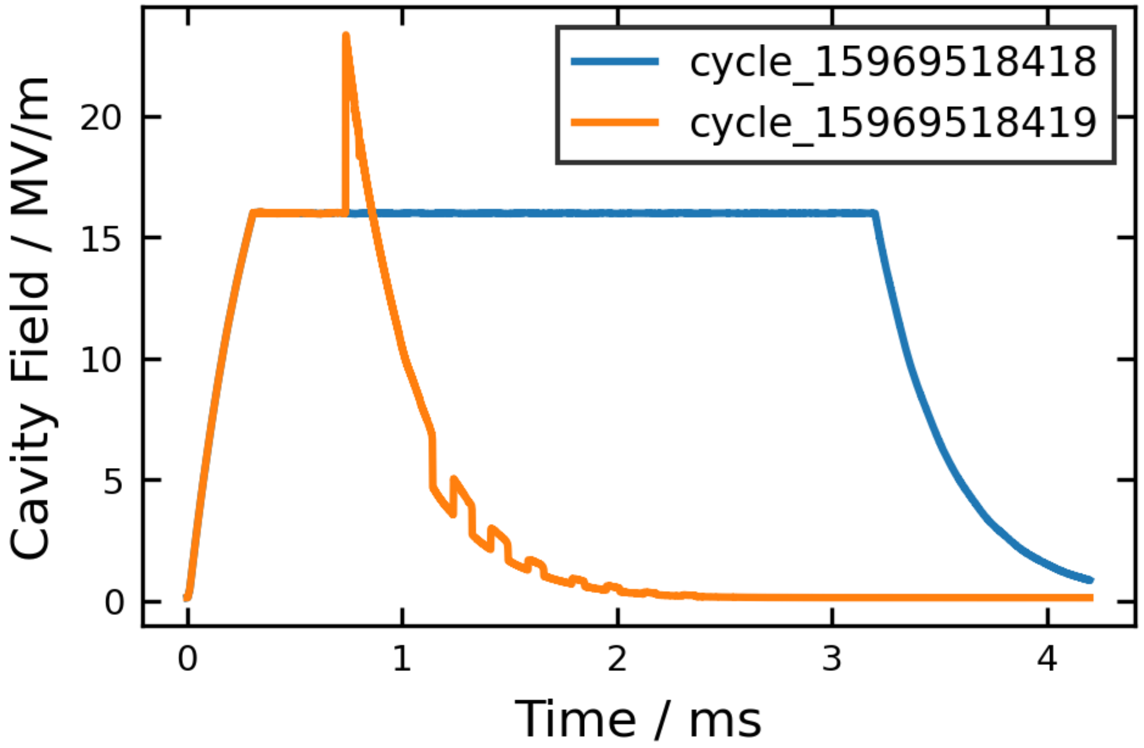


Cavity Field Jumping

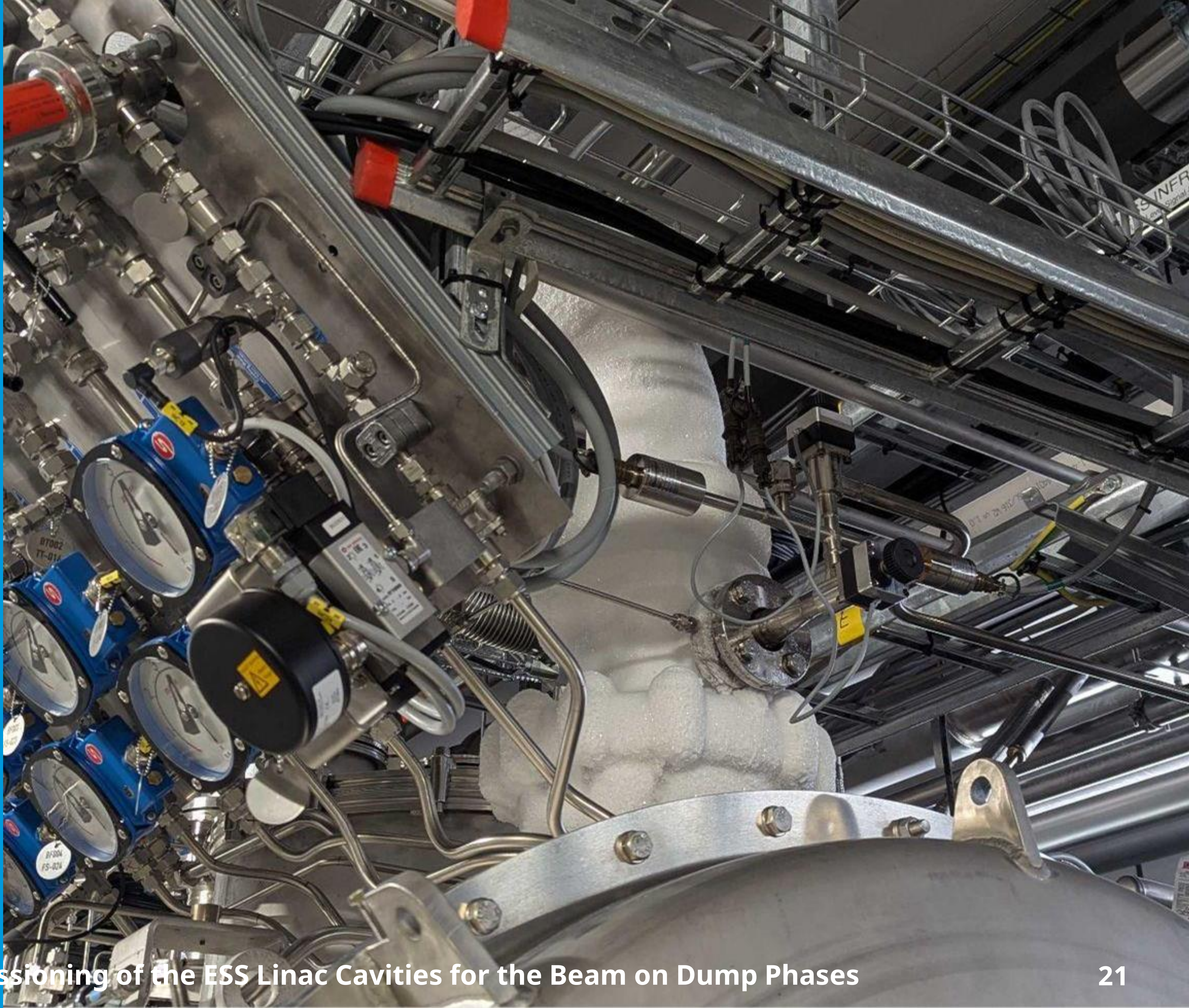
MBL-060 Cavity 2

- Sudden and unphysical jumps ⇒ Trips cavity protection
- Cold connector issue?
- Appears only with piezo in custom mode ⇒ Exciting mechanical mode(s)?
- Investigation ongoing, but running with piezo manual mode was fine for the BOD2 commissioning period



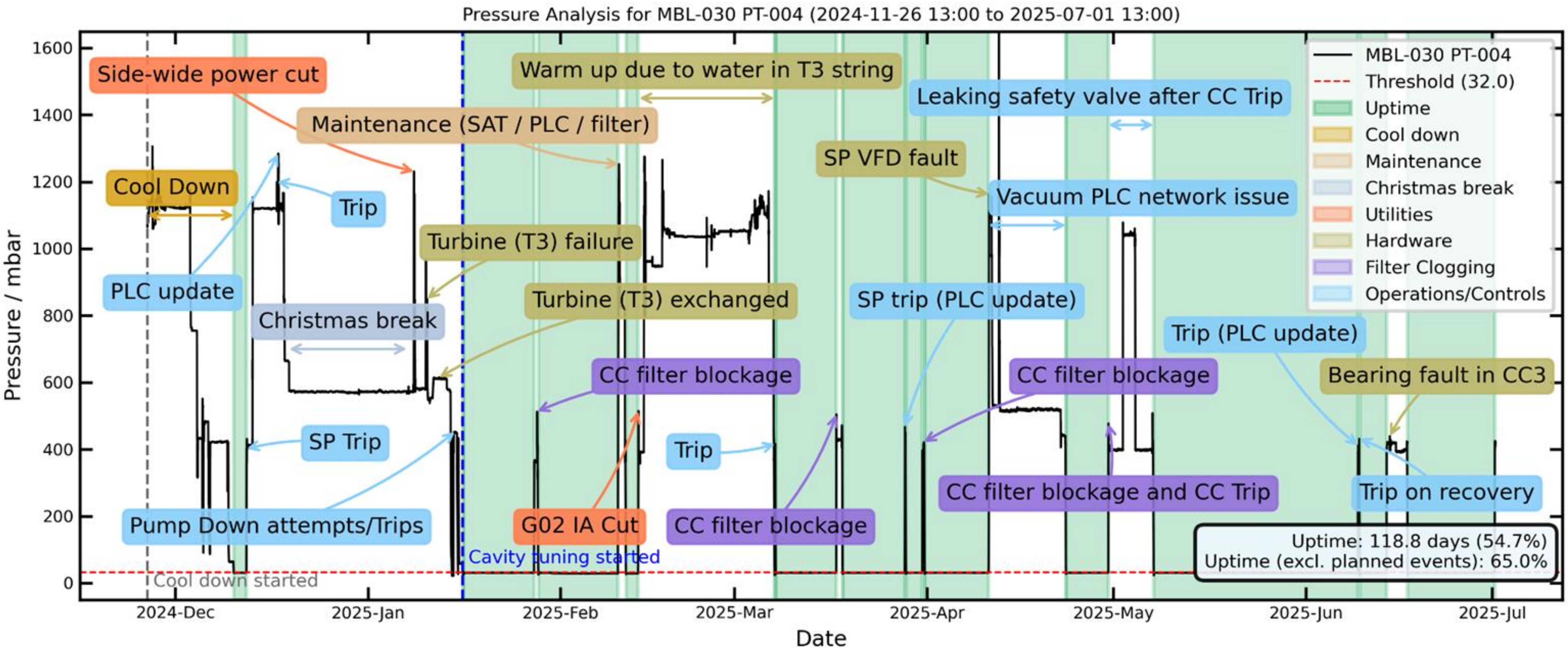


Cryo Operation



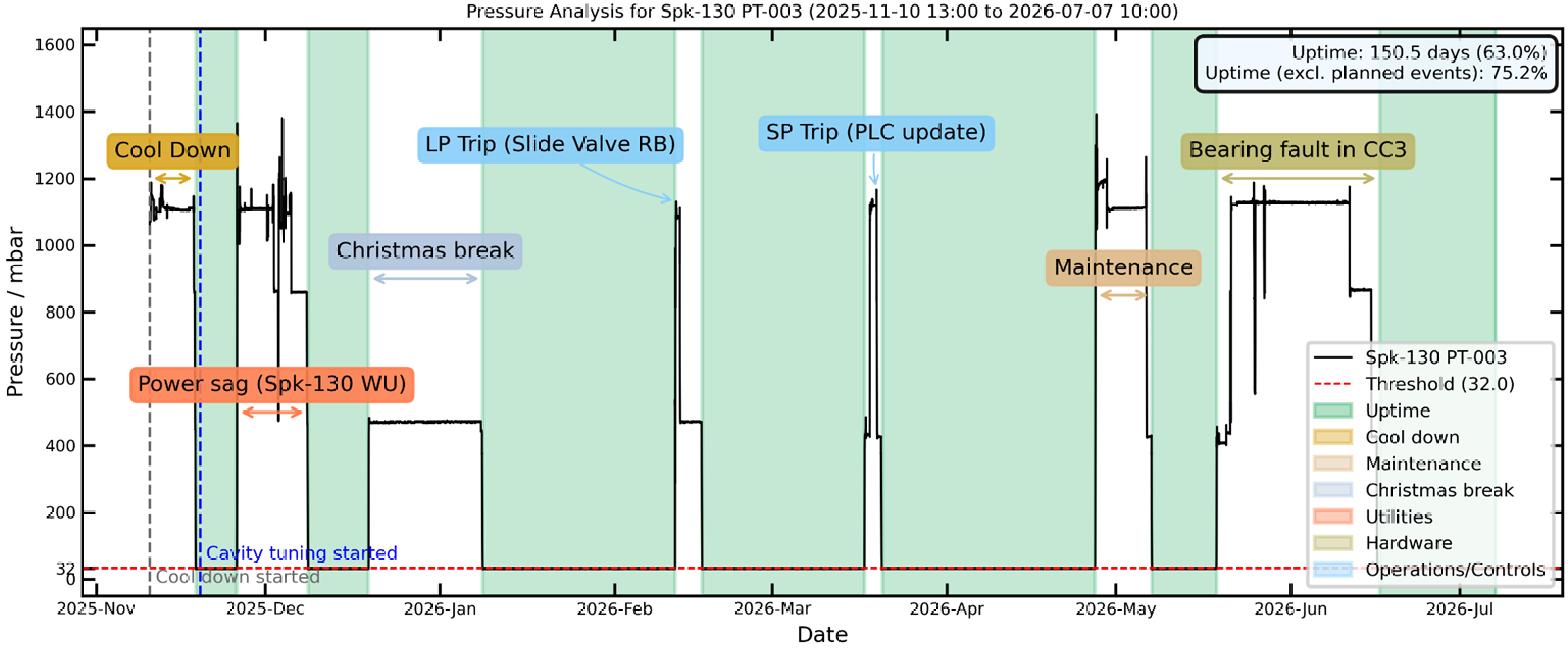
Cryo 2K Uptime

BOD1 Commissioning - 21 Trips



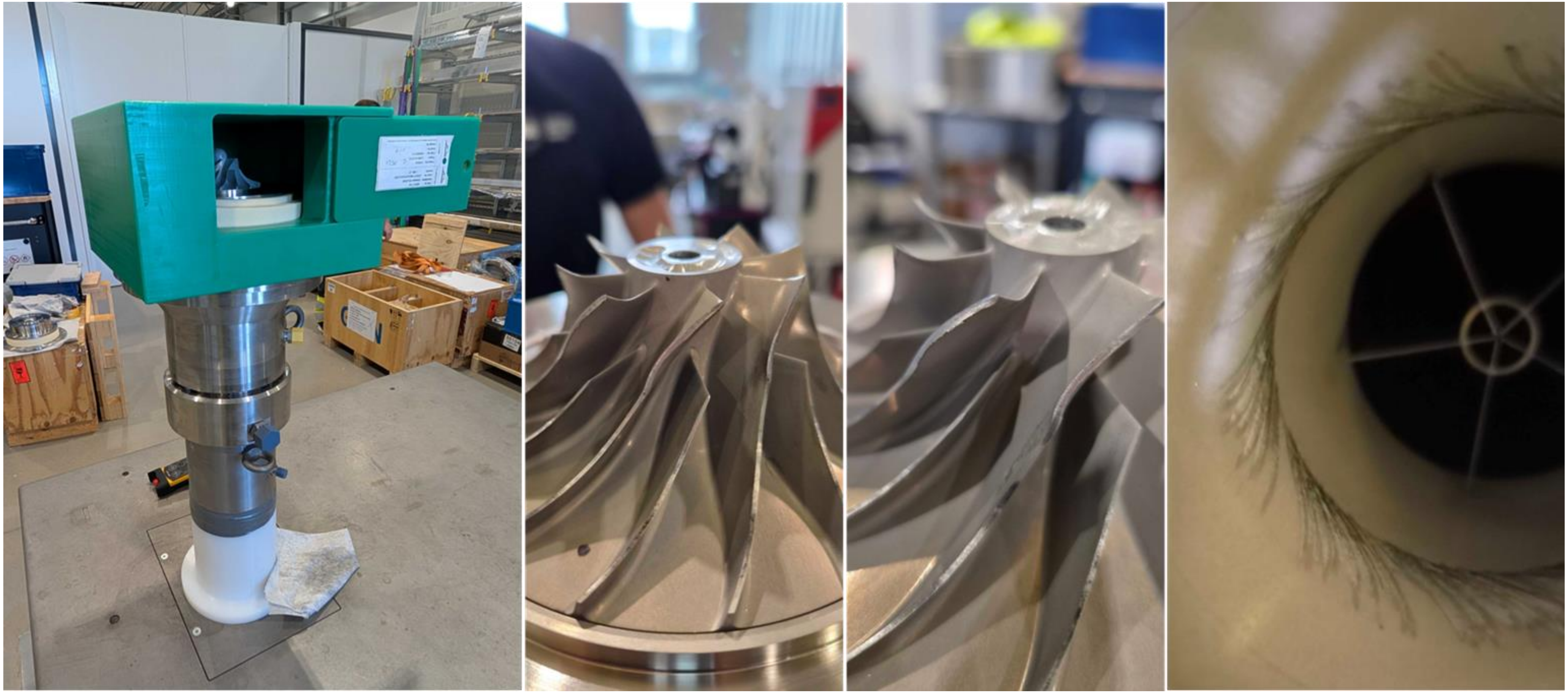
Cryo 2K Uptime

BOD2 Commissioning - 4 Trips



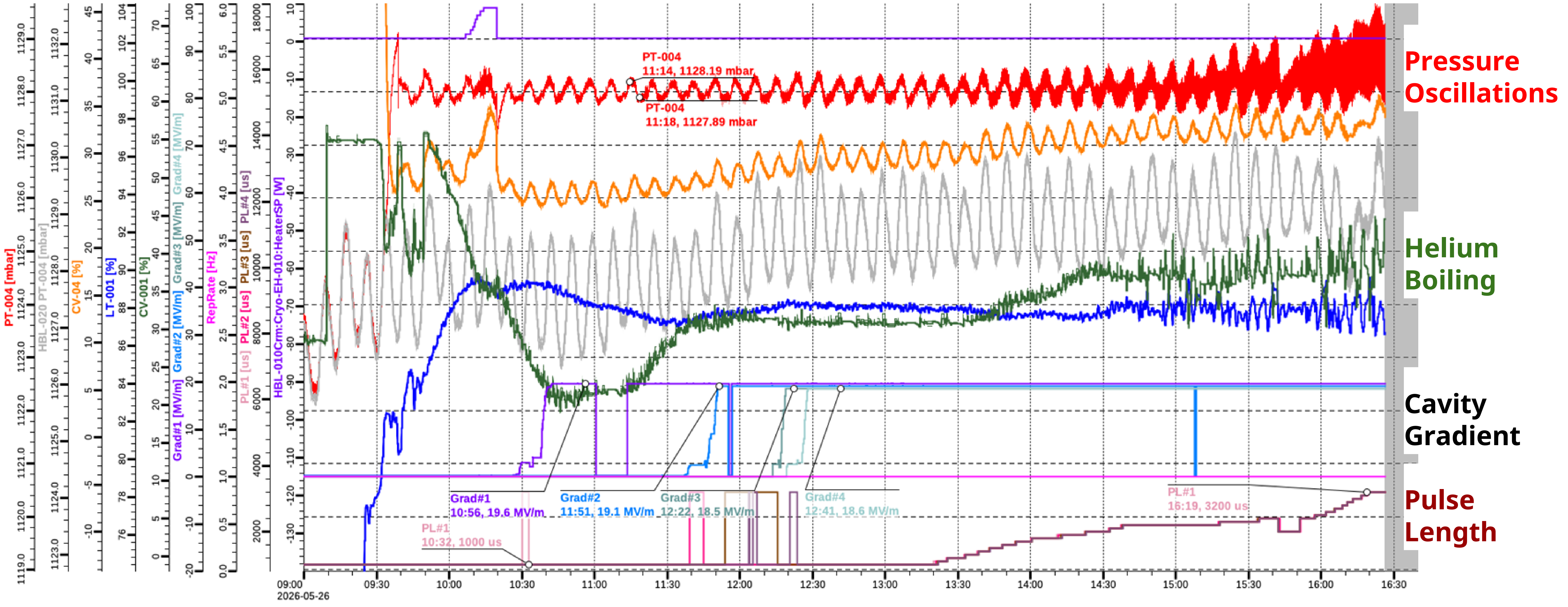
Cold Compressor Bearing Failure

CC3 Damaged after 3000 h (expected 5000 to 10000 h)



CC3 Failure - 4K Operation?

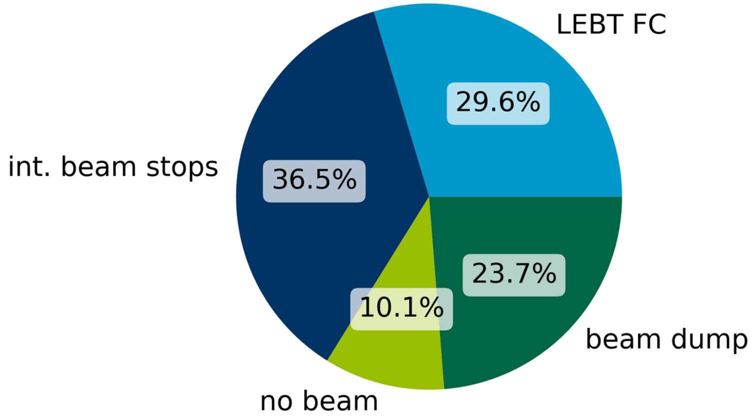
HBL-010, 4 cavities, 1 Hz, Nominal Gradient, 3.2 ms Pulse Length



Summary

ESS Linac achieved BOD2 goals

- NCL all cavities reached full duty cycle at nominal power
- DTL windows arcing - known issue with coating
  ⇒ New windows in production, refurbished window tested at the 352 MHz test stand
- All SCL cavities prepared, conditioned and tested at nominal pulse length (3.2 ms) and at 14 Hz rep. Rate
  - Piezo running in custom mode
  - Dynamic heat load is active
  - Field emission and radiation studies ongoing
- Beam parameters achieved
  - Long pulse of 1.5 ms at 20 mA
  - Nominal current of 62.5 mA for 5 us, 30 mA for 50 us
- BOD3 commissioning run starting September and beam on target is planned to start in January



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Thank you!

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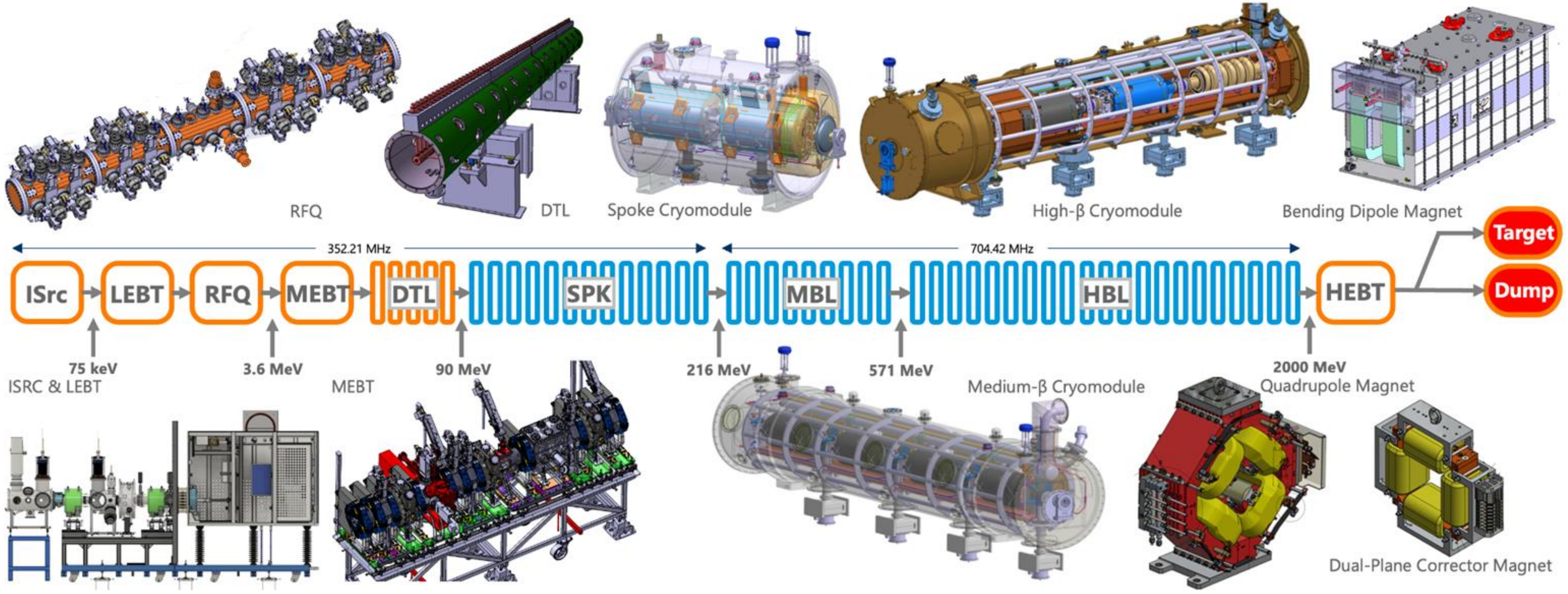
Backup Slides

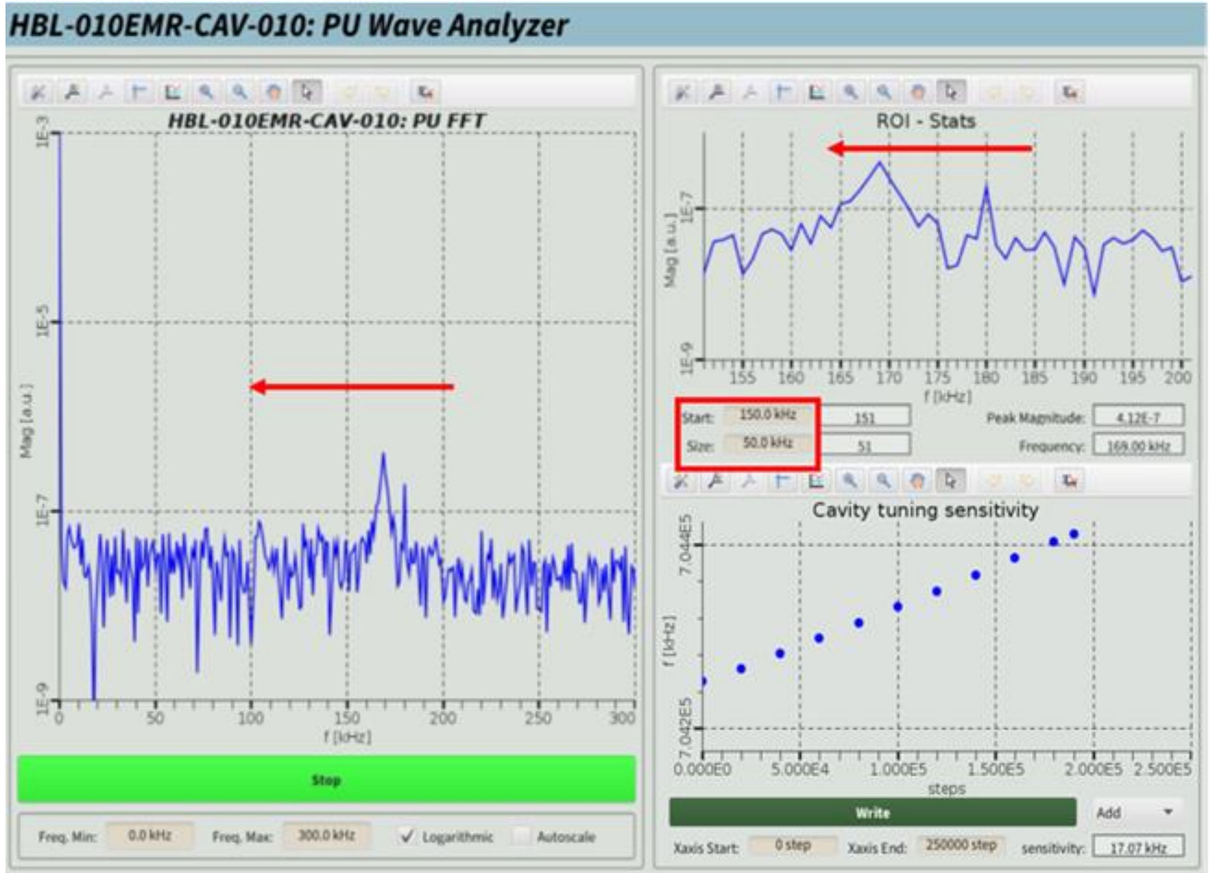
Linac and Cavity Parameters

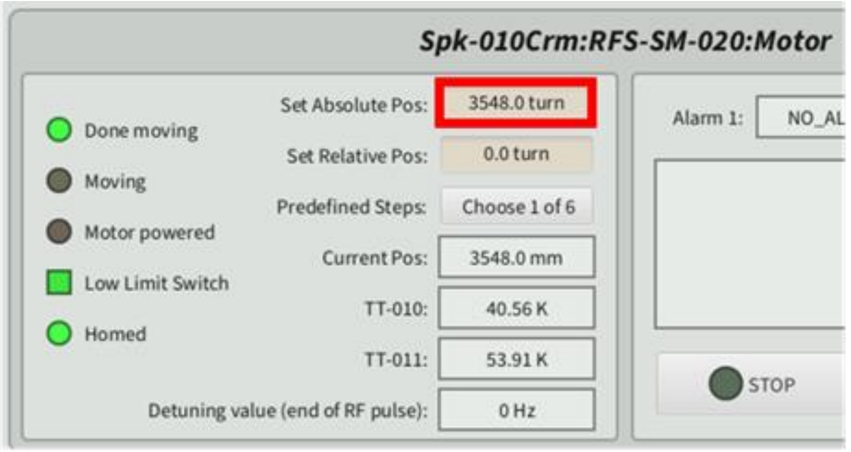


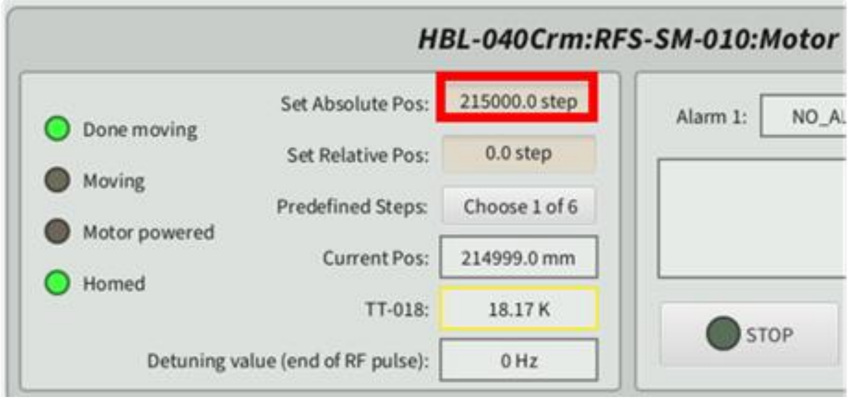
Requirement	Spoke	medium-β	high-β
Frequency / MHz	352.21	704.42	704.42
Optimum β	0.5		
Geometric β		0.67	0.86
E_{acc} / MV m^{-1}	9.0	16.7	19.9
E_{Pk} / MV m^{-1}	39	45	45
B_{Pk}/E_{Acc} / mT/(MV/m)	6.80	4.79	4.3
E_{Pk}/E_{Acc}	4.28	2.36	2.2
Iris diameter / mm	56	94	120
RF peak power / kW	335	1100	1100
G / Ω	130	196.63	241
maximum R/Q / Ω	425	394	477
Q_{ext} / 10^5	1.75-2.85	7.5	7.6
min $Q_0(E_{acc})$ / 10^9	1.5	5	5

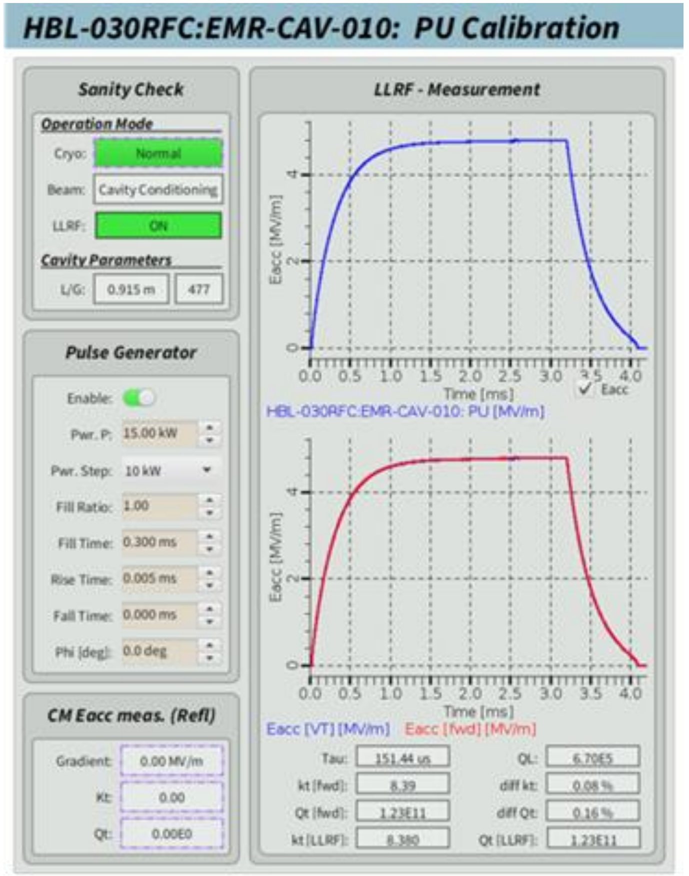
Cavity Tuning and Calibration

- Sensitivity: Spk ~ 8.5 kHz/turn, MB ~ 20 kHz/turn, HB ~ 17 kHz/turn

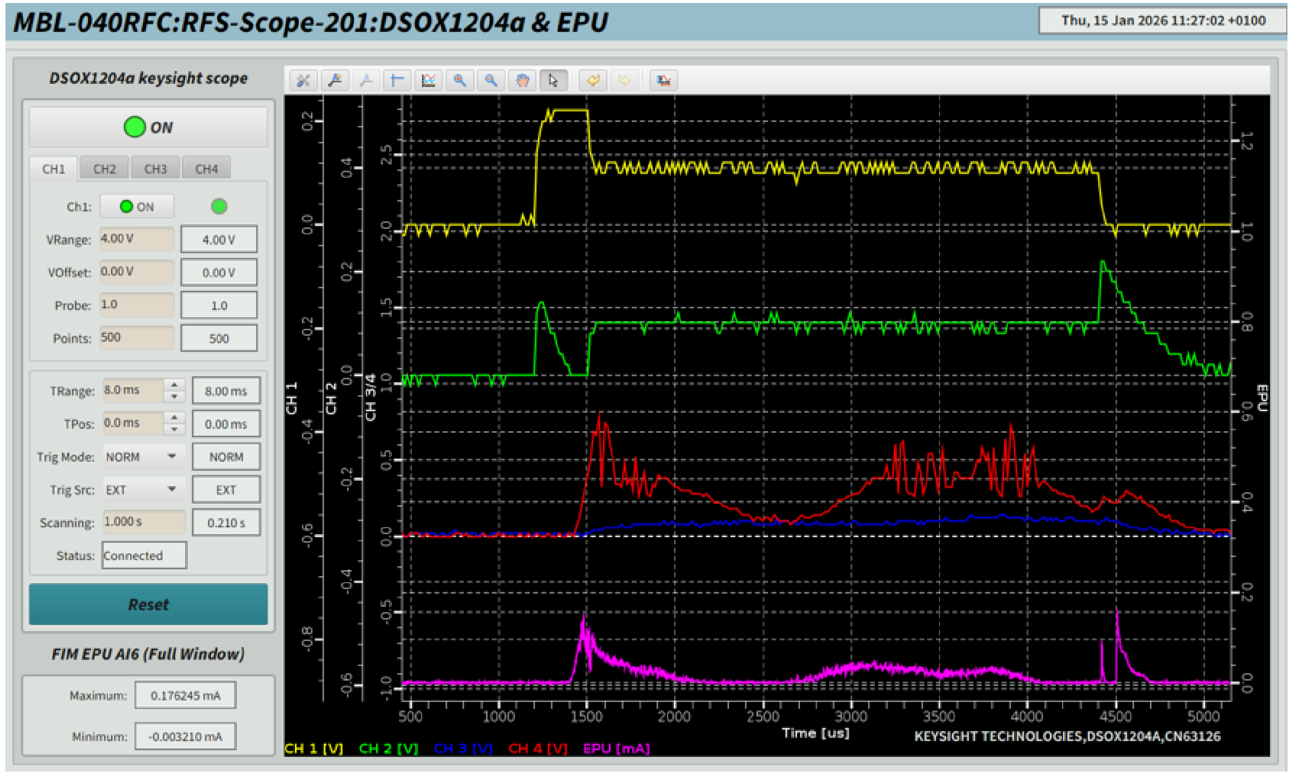


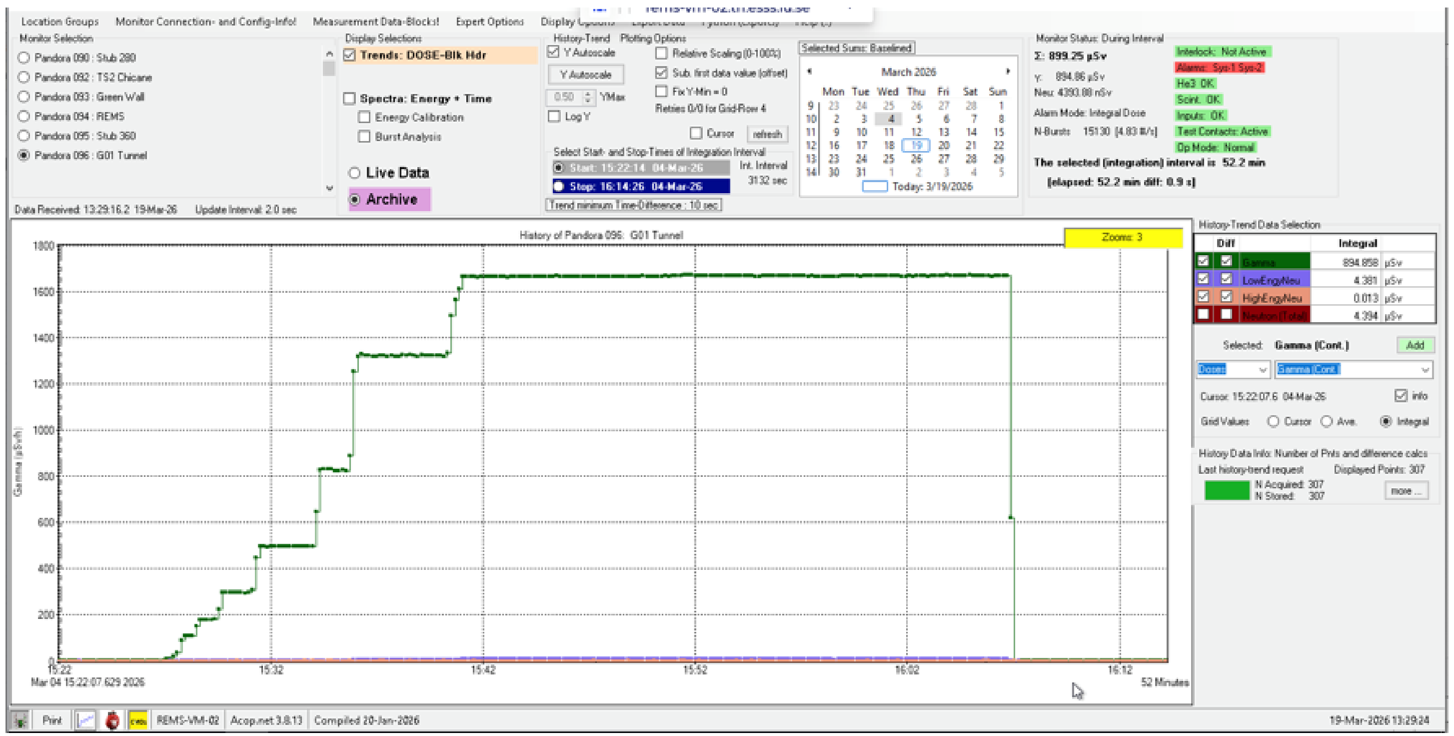






Cavity Conditioning

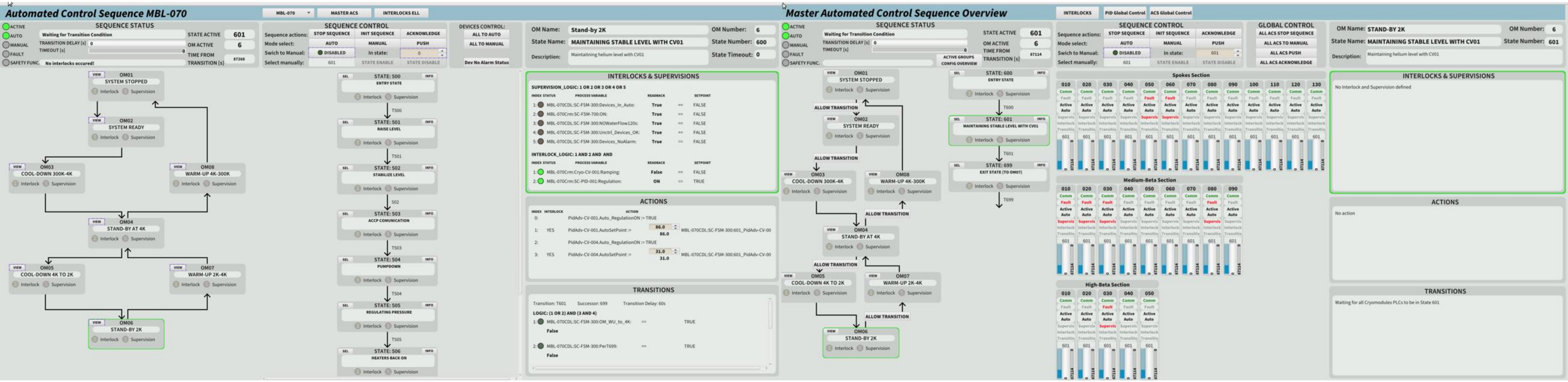




Cryo Control

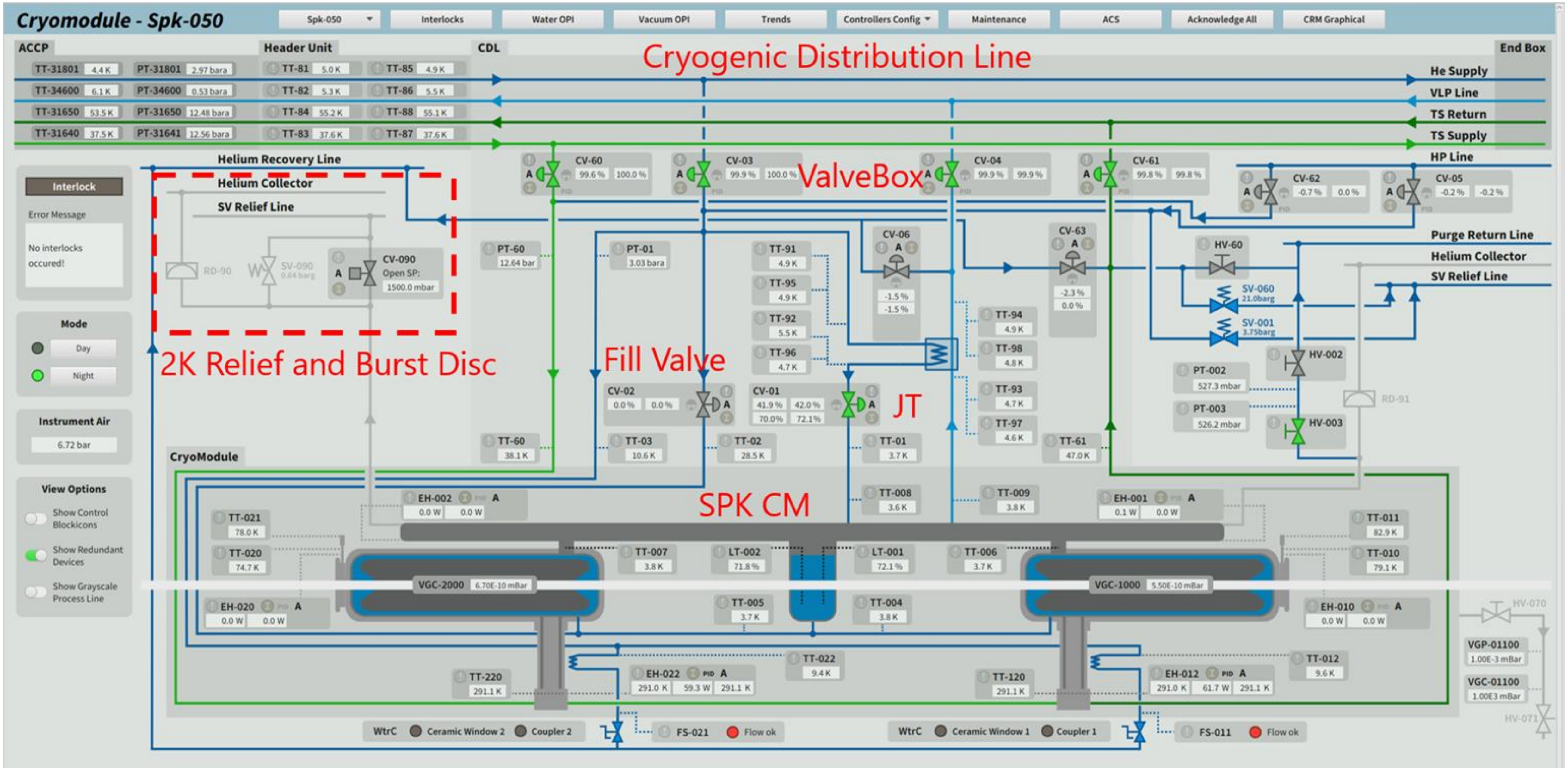
CM/VB handled by state machine

- One State machine for each CM handling transitions/interlocks
- Master control sequence tracking progress for global transitions



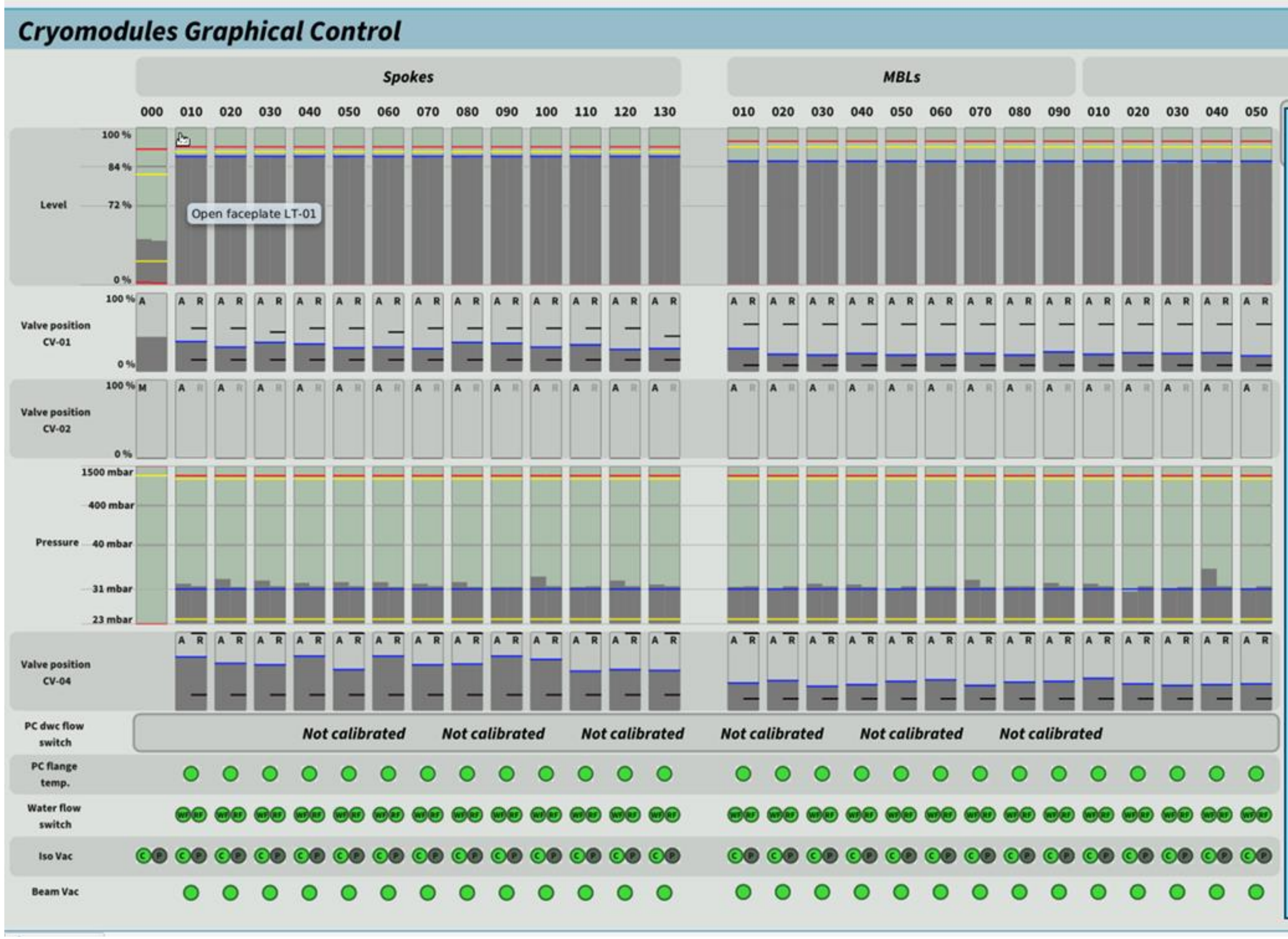
Cryo Control

CM Supervision OPI



Cryo Control

One PLC for loop/Interlocks for each Cryo Module / Valve Box



Level loop using JT-Valve in module to achieve level in 2 redundant gauges

Pressure loop, using outlet valve to regulate pressure at each CM (31 mbar) with no pressure drop from line, all CM in same conditions. CC set usually at 26 mbar suction

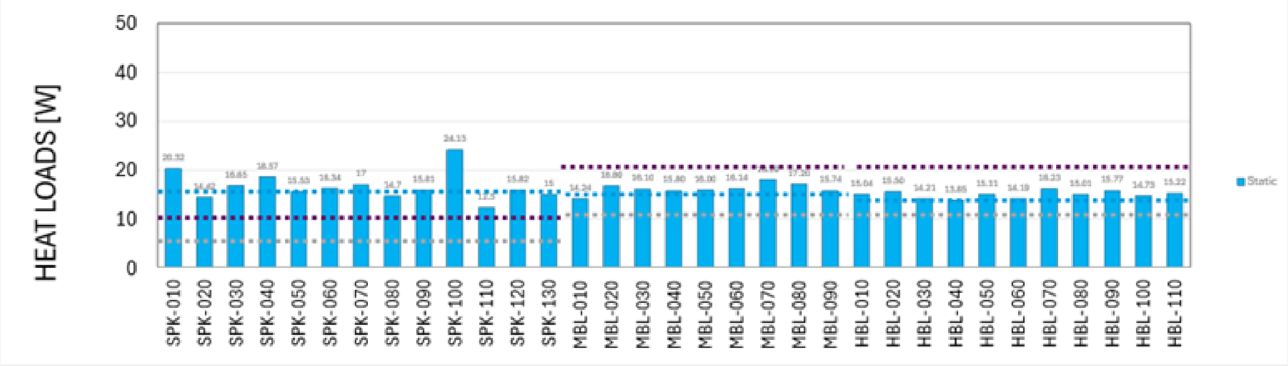
Slow interlocks on Temperature, water flow, Isovac, Beam vac

Heat Loads

Measured Static and Dynamic Heat Loads

Avg/CM | Totals

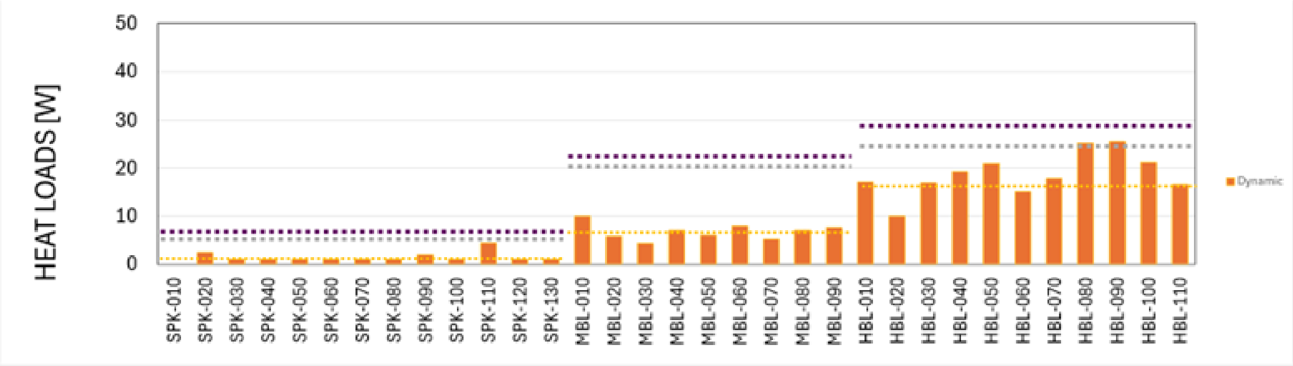
Static



Spk: 16.7 W
Mbl: 16.2 W
Hbl: 15.0 W

tot: 528 W

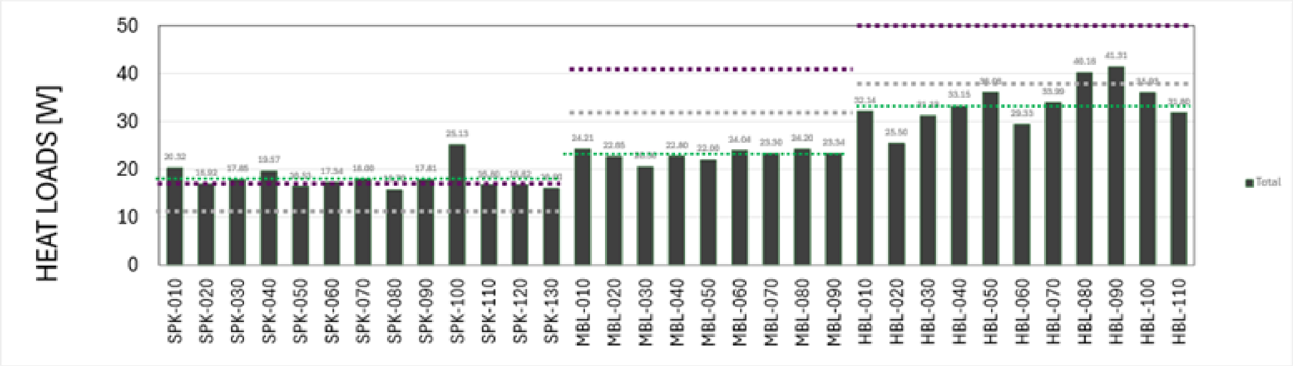
Dynamic



Spk: 1.4 W
Mbl: 6.8 W
Hbl: 18.7 W

tot: 285 W

Total



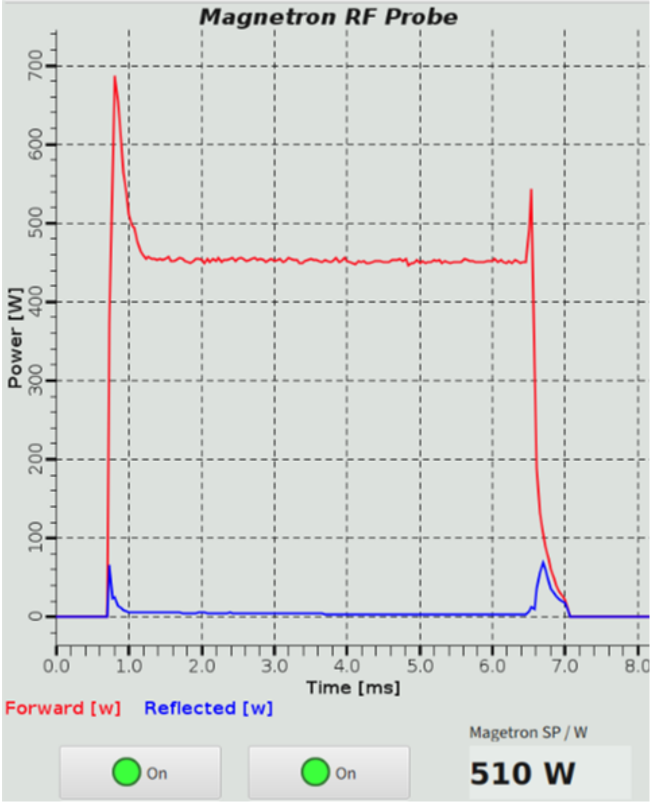
Spk: 18.1 W
Mbl: 23.0 W
Hbl: 33.7 W

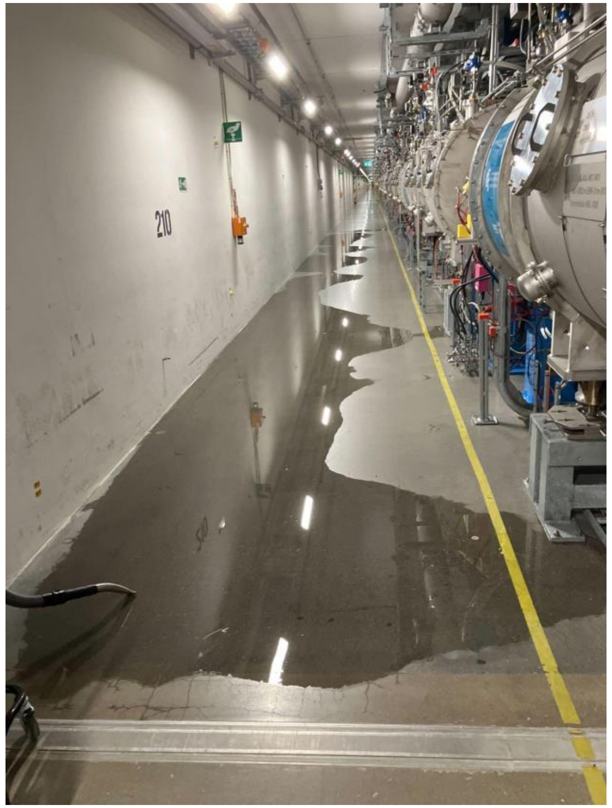
tot: 812 W

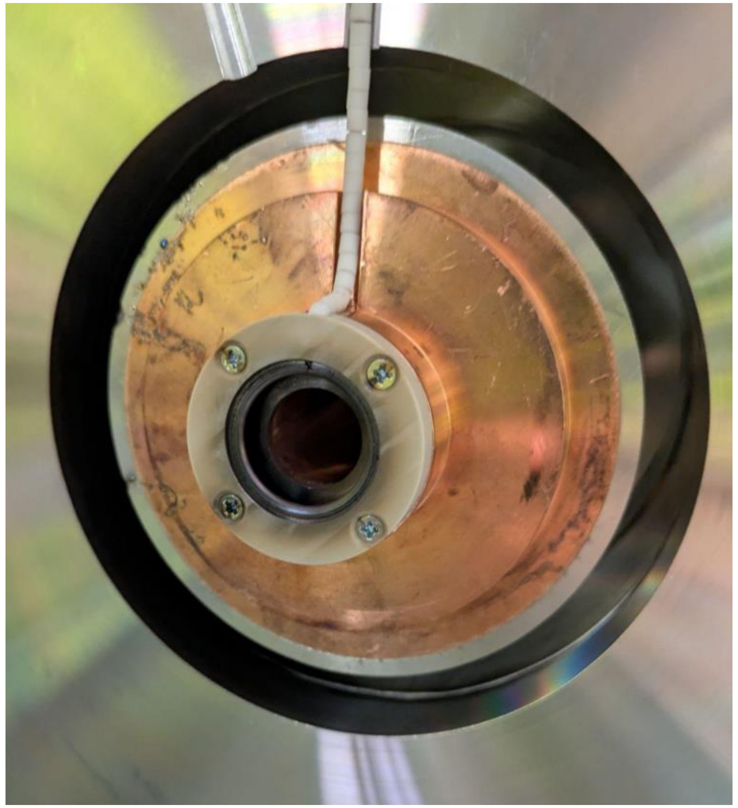
Front-End & Magnets

Ion Source, LEBT, MEBT, Magnets

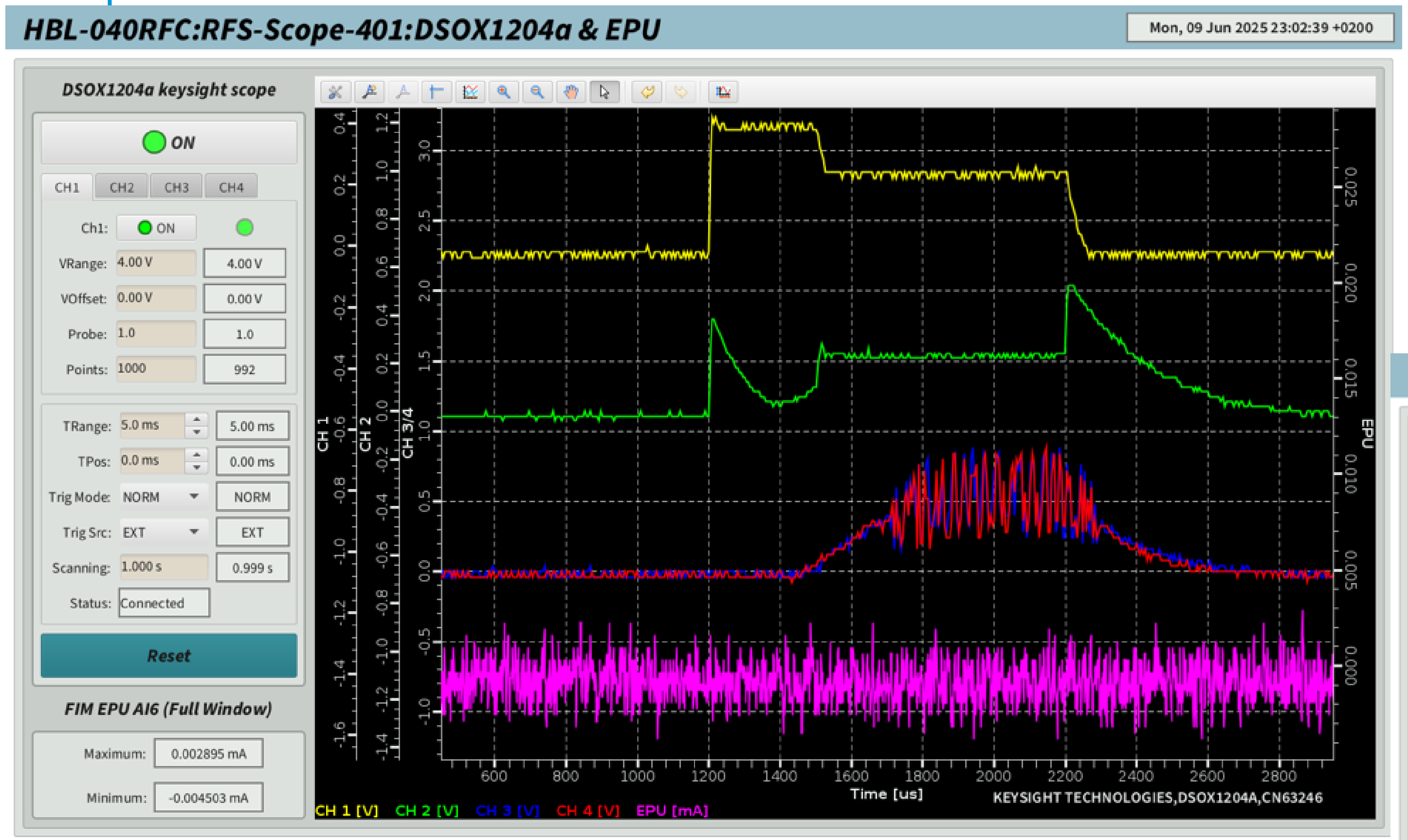
- Magnetron degradation and replacement
- LEBT repeller fried and replaced
- MEBT Bunchers sometimes need “cleaning” but very reliable
- Magnet water leak, some magnet polarisation and “miswiring” corrected





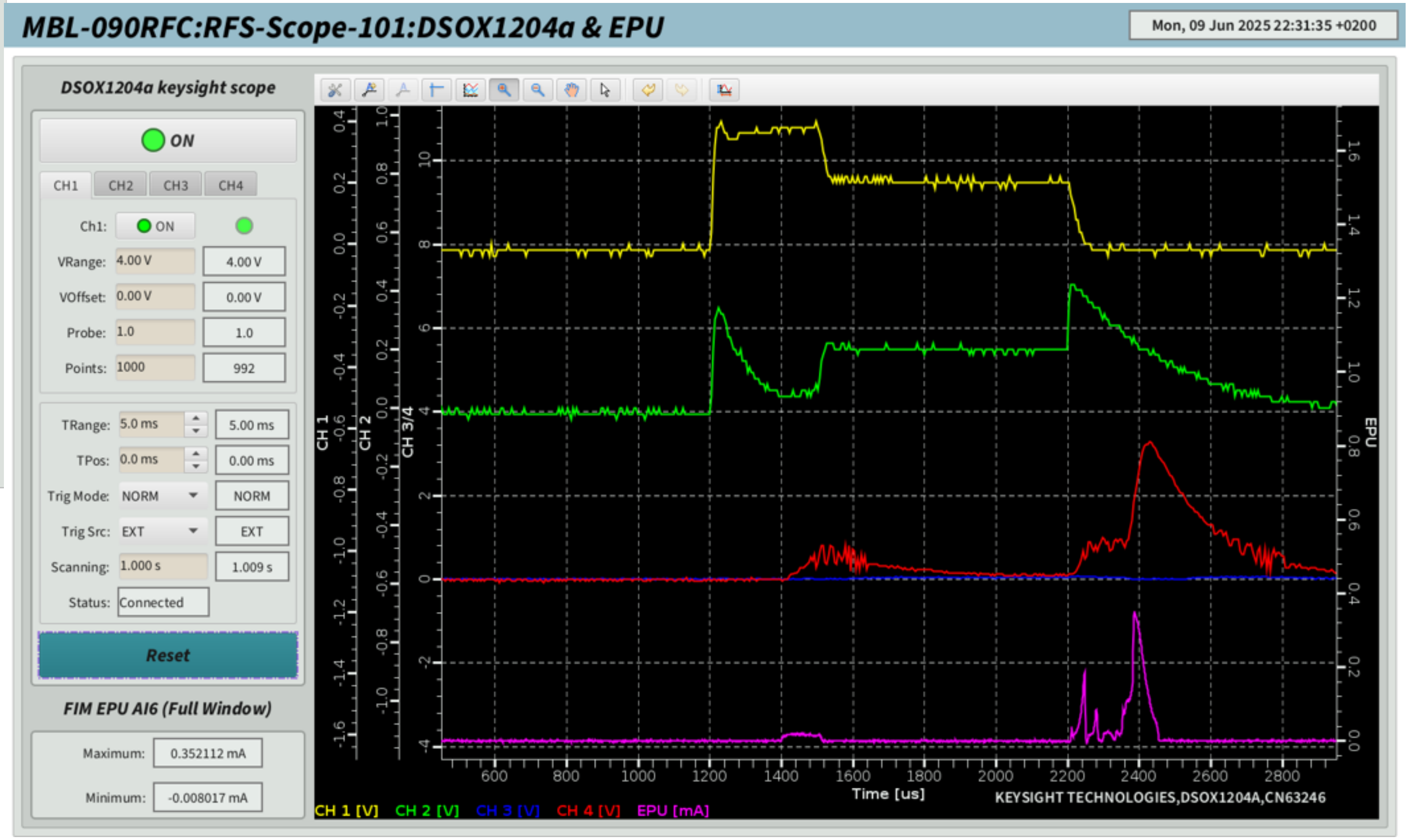


FE Buildup and Couplers showing MP



MP in coupler region during TW mode during cavity fill and decay

⇒ Can be eliminated with 300 to 1000 V bias to run the cavity without needing to fully condition

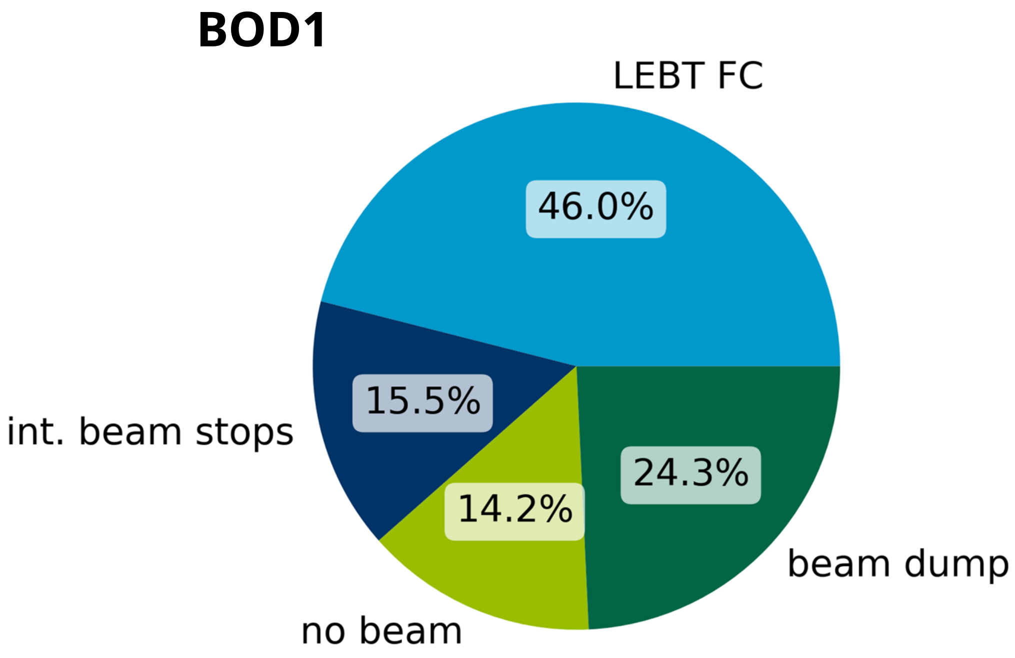


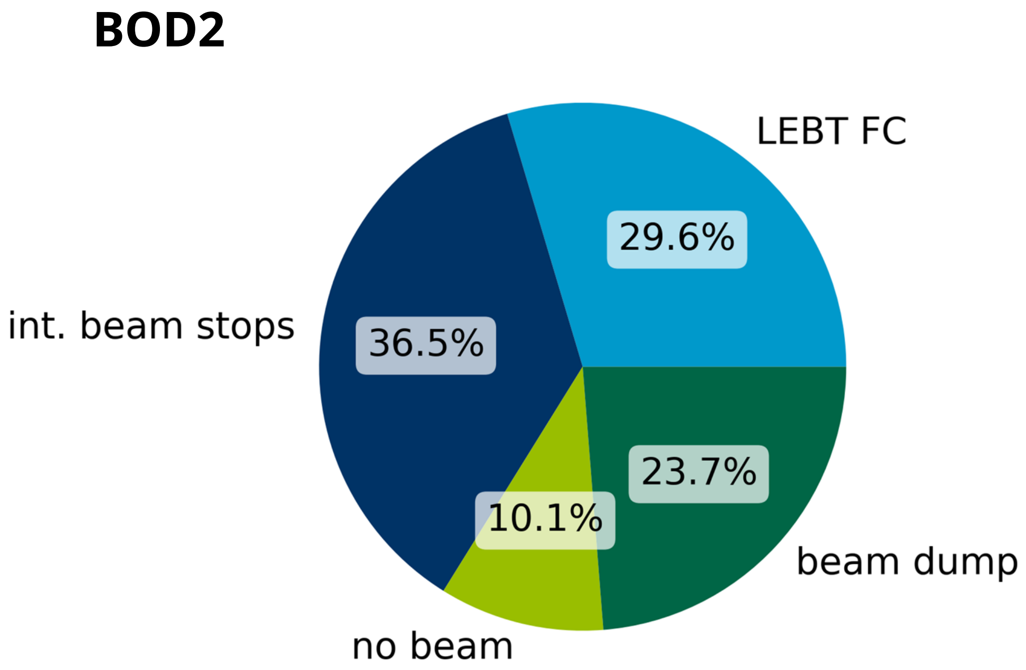
Cavity FE along RF pulse but no EPU

⇒ Cherenkov light occurring in the fibers

BOD Time Usage

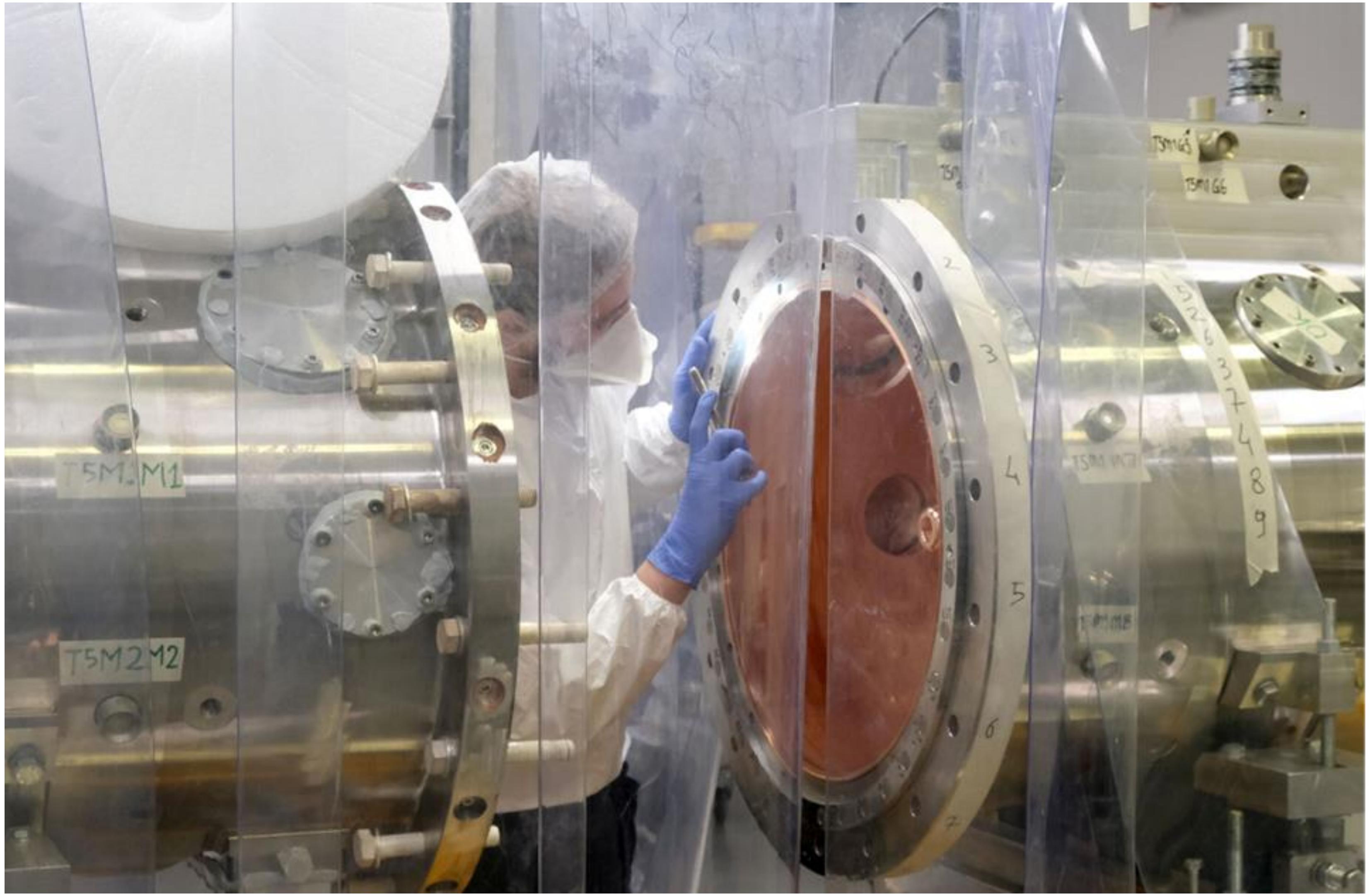
Commissioning time to beam destination





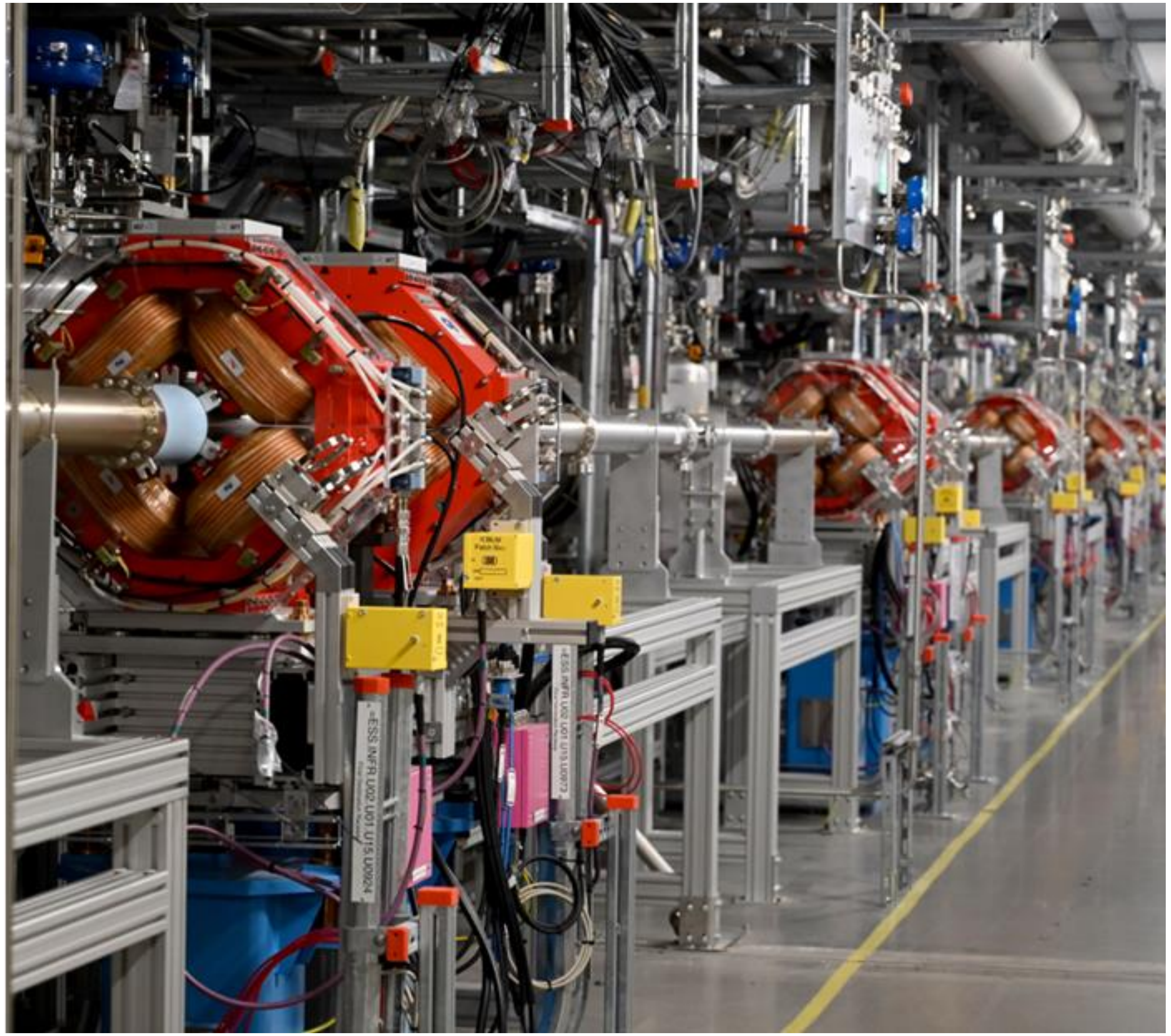
Installations

2 Pilot CM Apr.-June 2023, DTL5 Sep. 2023, 25 CM from Aug. 2023 to July 2024



Installations

Magnets Installed and Tested July - Nov. 24



Spoke CM Installation

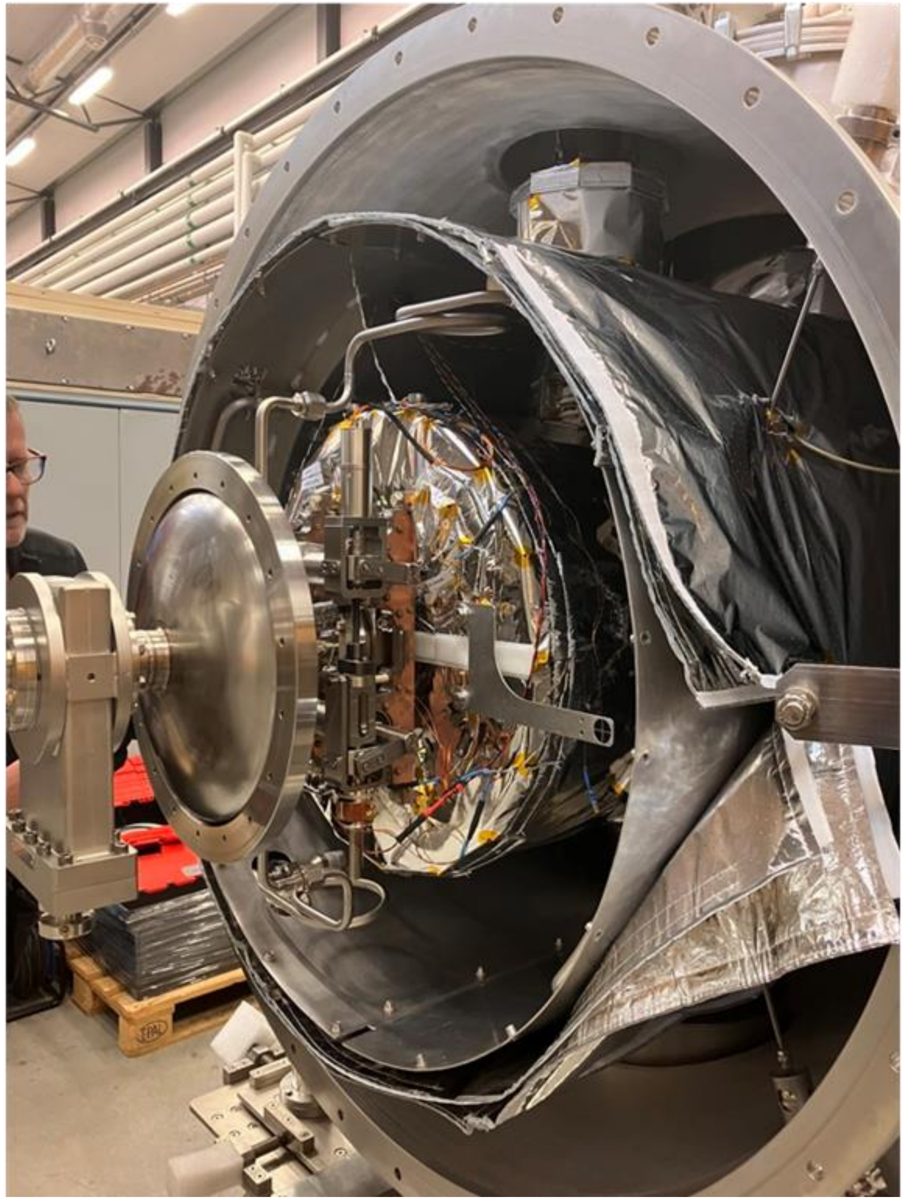
13 Spoke CM

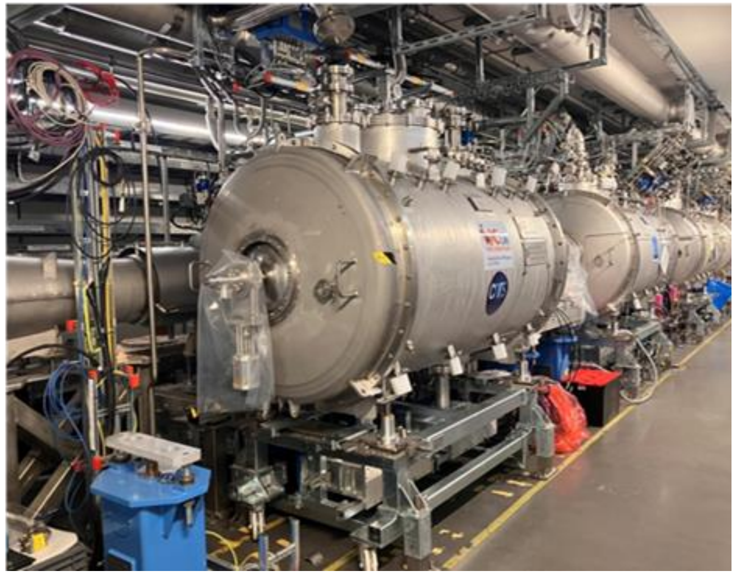
- Test at FREIA identified issues with cold tuner system
- Nearly all CM were opened at ESS removing a clamp and replacing most motors
- CTS test reveal lifetime of ~20 cycles and large statistical variation
- Tight installation space

Spoke CM Vented

Combination of HW malfunction and human error

- 1 CM had to be swapped after venting from LWU in Feb. 24
- Spare Installed
- Module retested, showing severe field emission

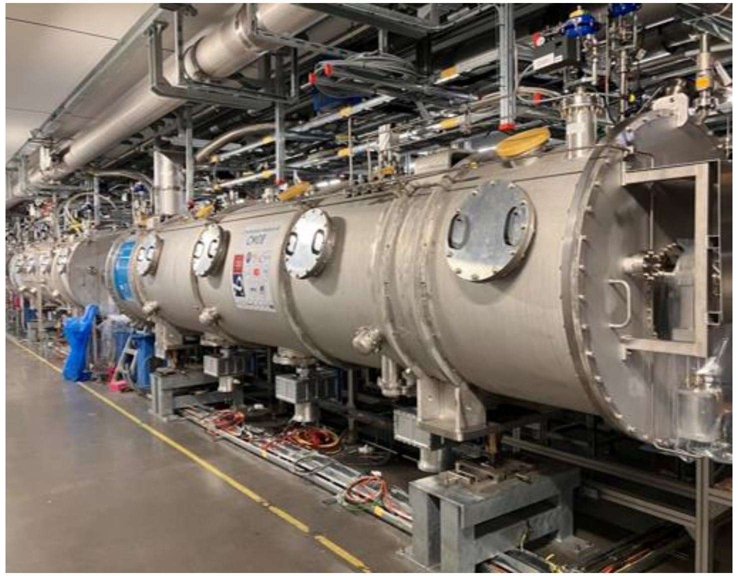




Elliptical CM Installation

9 MB + 5 HB

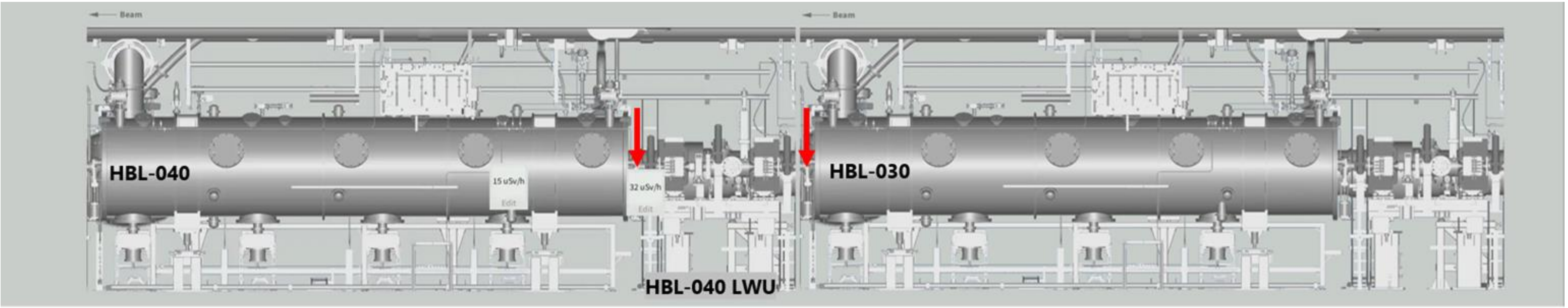
- Installation much easier than Spokes in terms of accessibility
- 14 WtrC manifolds commissioned after CM Testing phase completed



FE & Collective Arcs

Cavity Degradation Example

- After closing gate valves HBL-040 LWU three cavities needed reconditioning
- Reconditioning with short high power pusles to cure FE degradation necessary



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