Course of RF for Accelerators

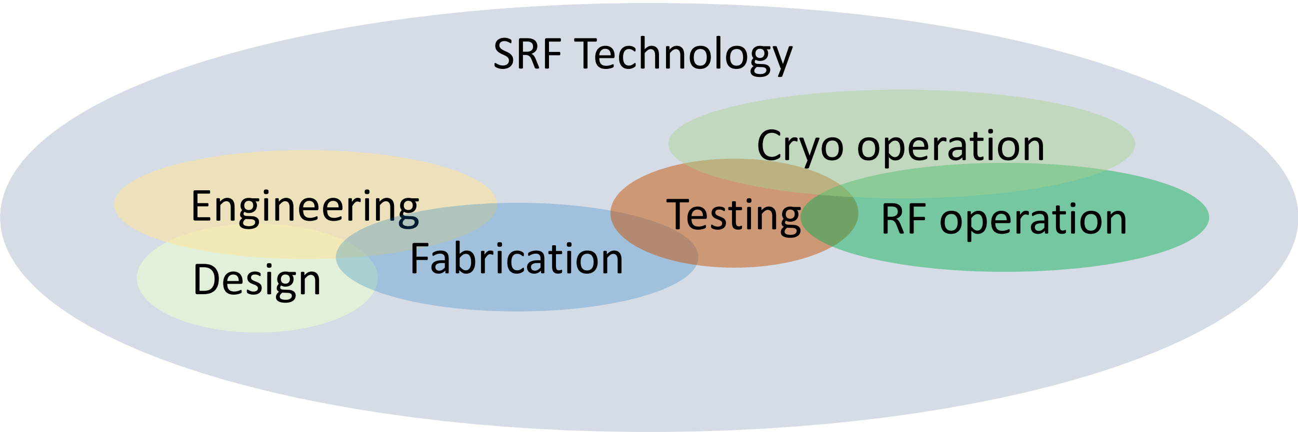
SRF Cavities

[Mostly about Technology]

Paolo Pierini, ESS

This week:

Theory of EM fields I-II
Overview Cavities I-II
RF measurements I-II
EM simulations I-II



Next week:

LLRF I-III
Beam Loading
Power coupling

Multipacting
HOM

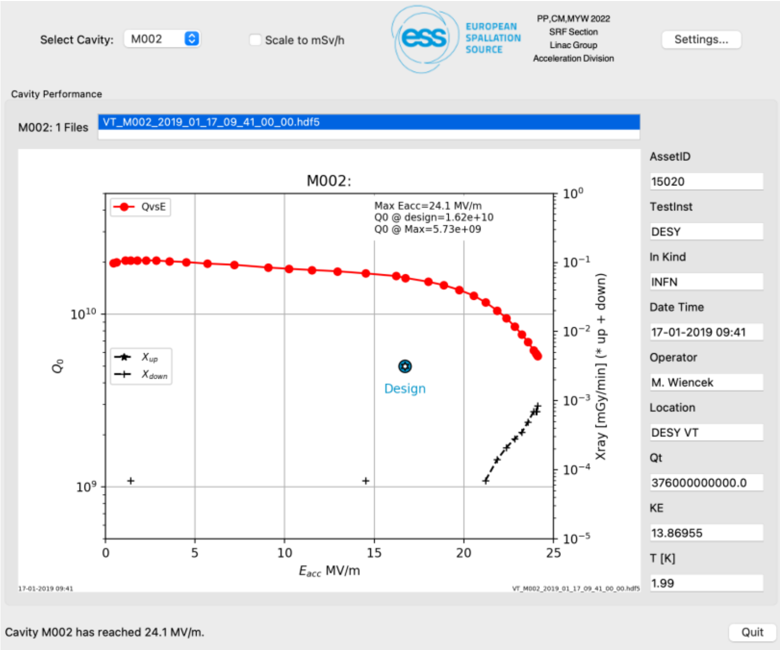
Course of RF for Accelerators

Outline

- Part I
  - Why SRF?
    - Surface resistance
    - Choice of temperature & thermodynamics aspects
  - From Design to Fabrication & Preparation
    - Material
    - Fabrication
    - Surface preparation (chemical processing) and preservation
    - Cavity ancillaries (tuners, couplers, …)
- Part II
  - The Environment: Cryomodule fundamentals
    - Carnot cycle & efficiency, cryoplants and cryomodules
    - Cooling, heat loads, mass flows
- Part III
  - Testing & operation of Cryomodules

Now the fun starts

- We have cavities ✓
  - We tested them, typically in a vertical test setup in a bath cryostat
    - Assessed performances: Q vs E curve at 2 K
    - Recorded calibration factors
      - $E_{acc} = k_{VT}\sqrt{P_{PU}}$
    - Recorded field emission behavior
    - Noted limit during tests
      - Quench? Thermal breakdown?
      - FE load?
      - Hard MP levels?
      - Power limit?



- We have put them into a Cryomodule (hard work, lots of details) ✓
- What's next ?

SRF is (a lot) about preserving cleanliness

Pffff… Again?

- Are we able to preserve it from cavity to cryomodule?
  - Several pumping and venting operation required during the process
    - Opening of beamline flanges, exposing the surface to clean room environment
    - Risk of dragging particulate inside the RF volume
  - Long **transport** may be required (shocks, vibrations!)
    - XFEL: Saclay to DESY ~ 920 km
    - SNS: JLAB to Oak Ridge ~ 800 km
    - ESS: Saclay to Lund ~ 1140 km
    - PIP-II: Overseas from EU to FNAL (Airplane!)
    - Care needs to be taken (damping, loading, logging…)
- No matter what we do …

  …we still have to prepare the surfaces for operation
    - “conditioning”, at several stages

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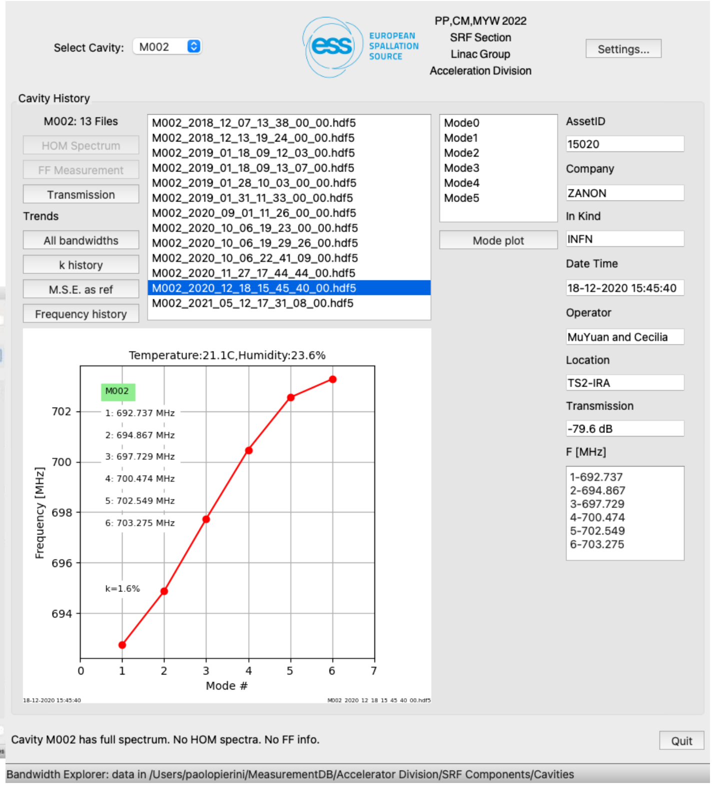
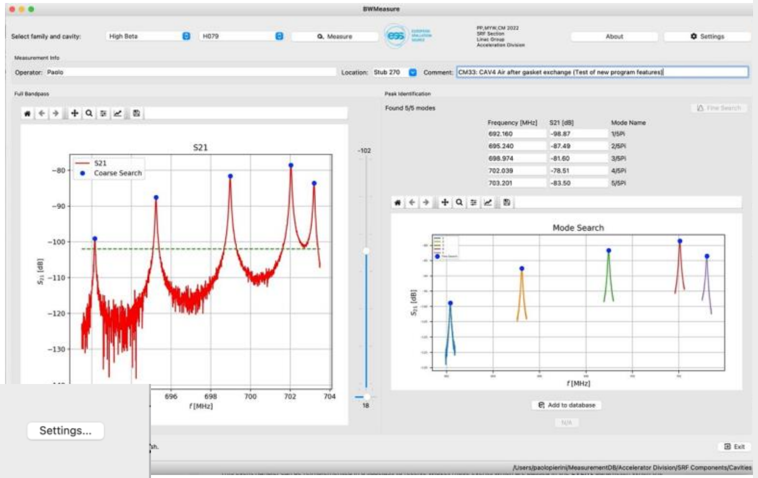
First/Foremost: know you CAVs!

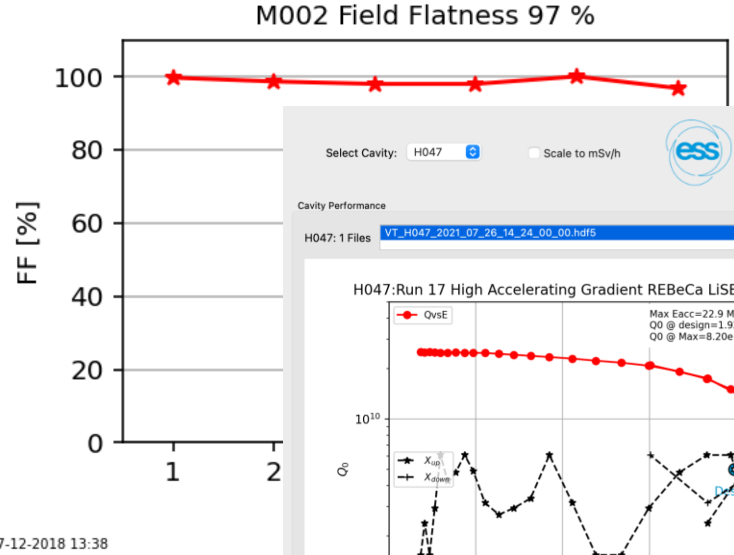
- Cavity DB
- Track cavity lifecycle from vendor to testing, assembly and reception

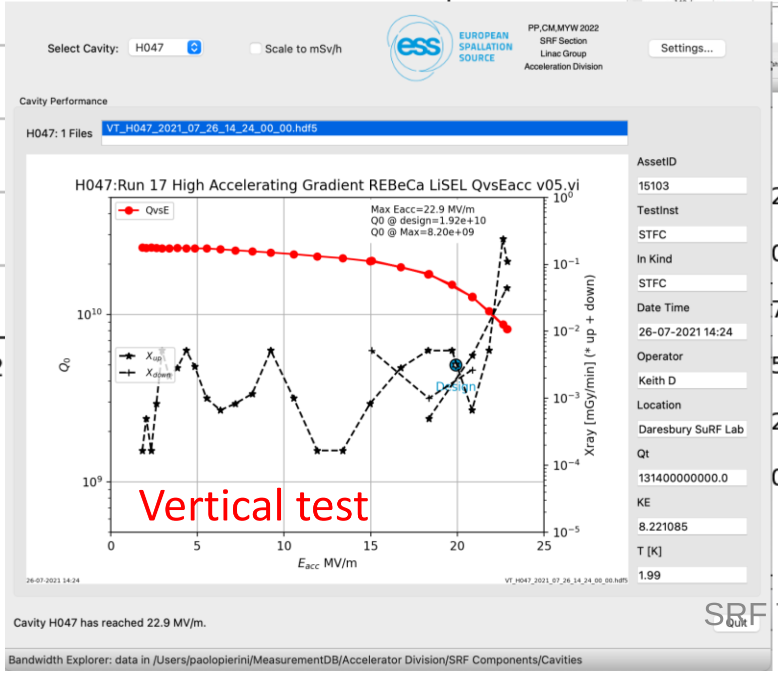
Bandwidth tracking

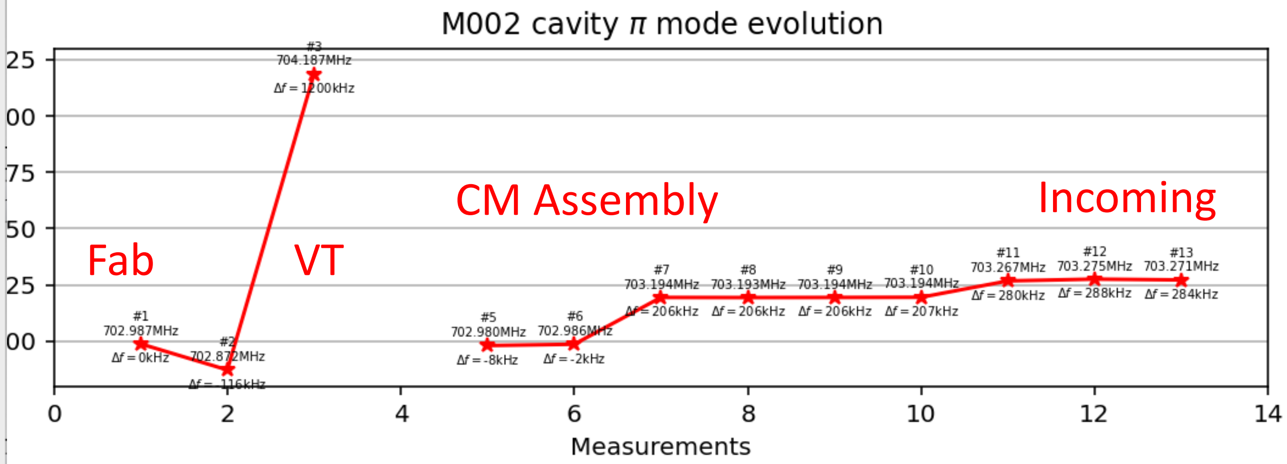


Incoming measurements









Handling CMs from completion to Machine

Hang out with truckers at 7:00 am

Have a comfy nap…

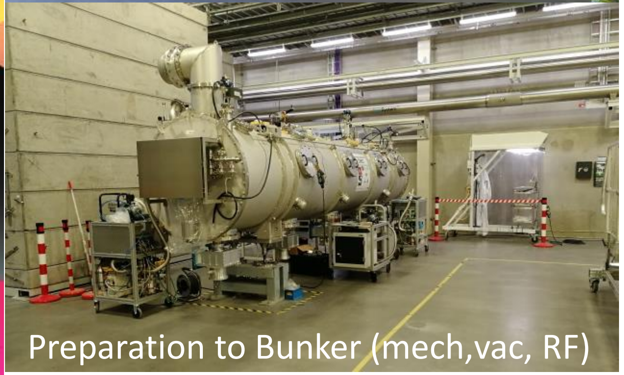
Play with cool tools

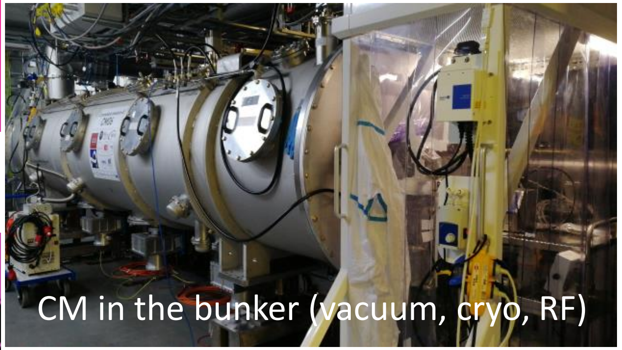
Brainstorming sessions

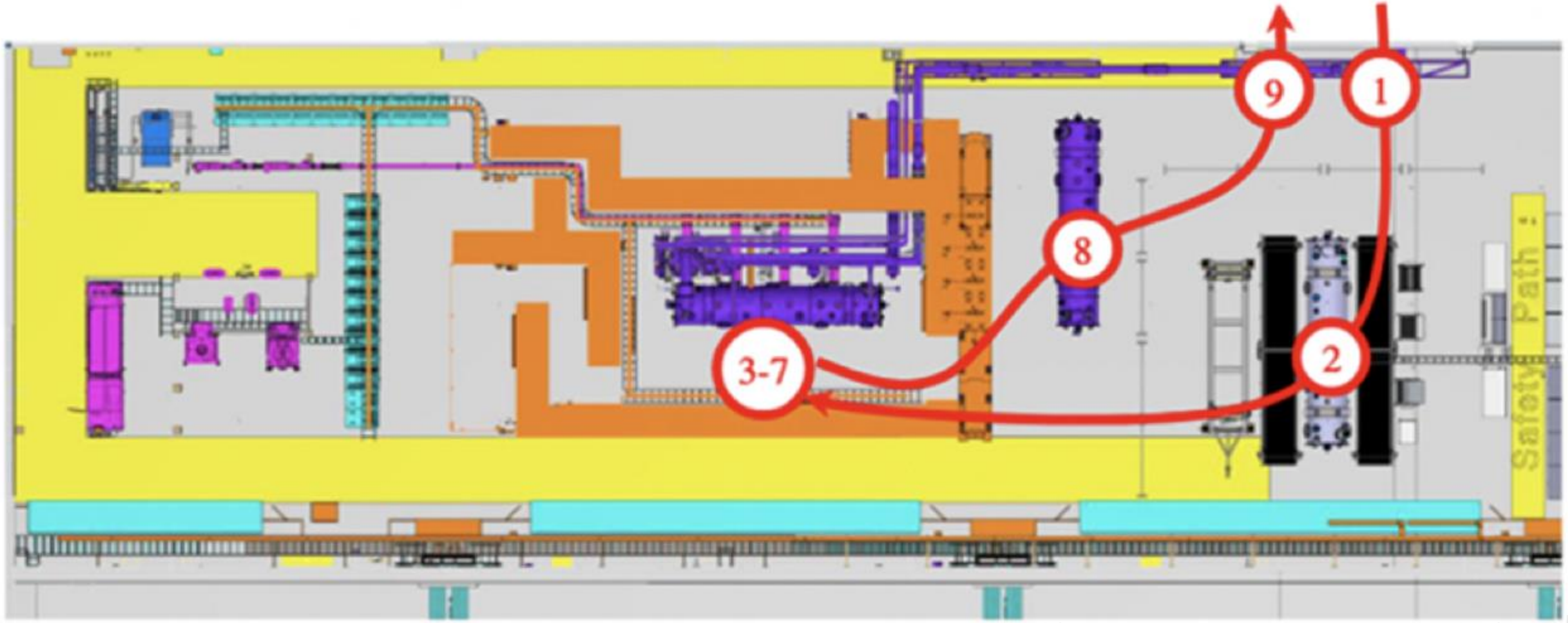
Cross-disciplinar TEAMWORK!

A test stand is (likely) needed


Transport, mechanical & electrical inspections

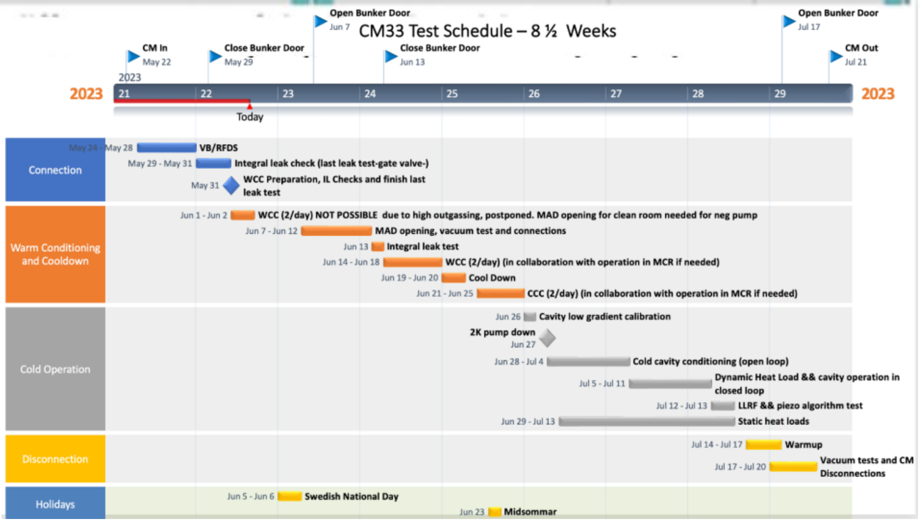

Preparation to Bunker (mech,vac, RF)


CM in the bunker (vacuum, cryo, RF)



Test CM before installation in the machine

- RF Performances
- Heat Loads
- +++++++



ESS CM Test Stand

Cryogenic and RF Test infrastructure

Conditions similar to linac tunnel

Bunker for RF operation (ionizing radiation)

- Install
- Connect to He VB
- Leak test all process pipe connection
- Instrumentation check

RF: Cavity with one coupler port (simplified)

Undriven:

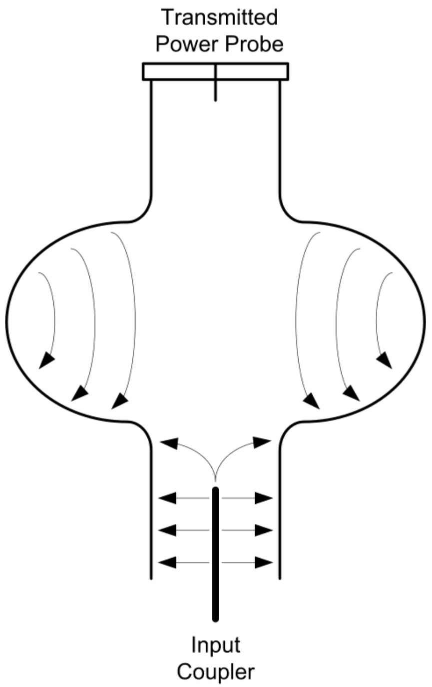
$$P_{tot} = P_{ext} + P_d$$

See F. Gerigk presentation

Defining: $Q_L = \frac{\omega U}{P_{tot}}, Q_{ext} = \frac{\omega U}{P_{ext}}, Q_0 = \frac{\omega U}{P_d}$

See J.Branlard, SRF Tutorials, 2019

$$\frac{1}{Q_L} = \frac{1}{Q_{ext}} + \frac{1}{Q_0} = \frac{1+\beta}{Q_0}$$



Where the (geometrical) coupling is:

$$\beta \equiv \frac{Q_0}{Q_{ext}}$$

Minimal reflection (matched case) obtained at $\beta = 1 + P_b/P_d$

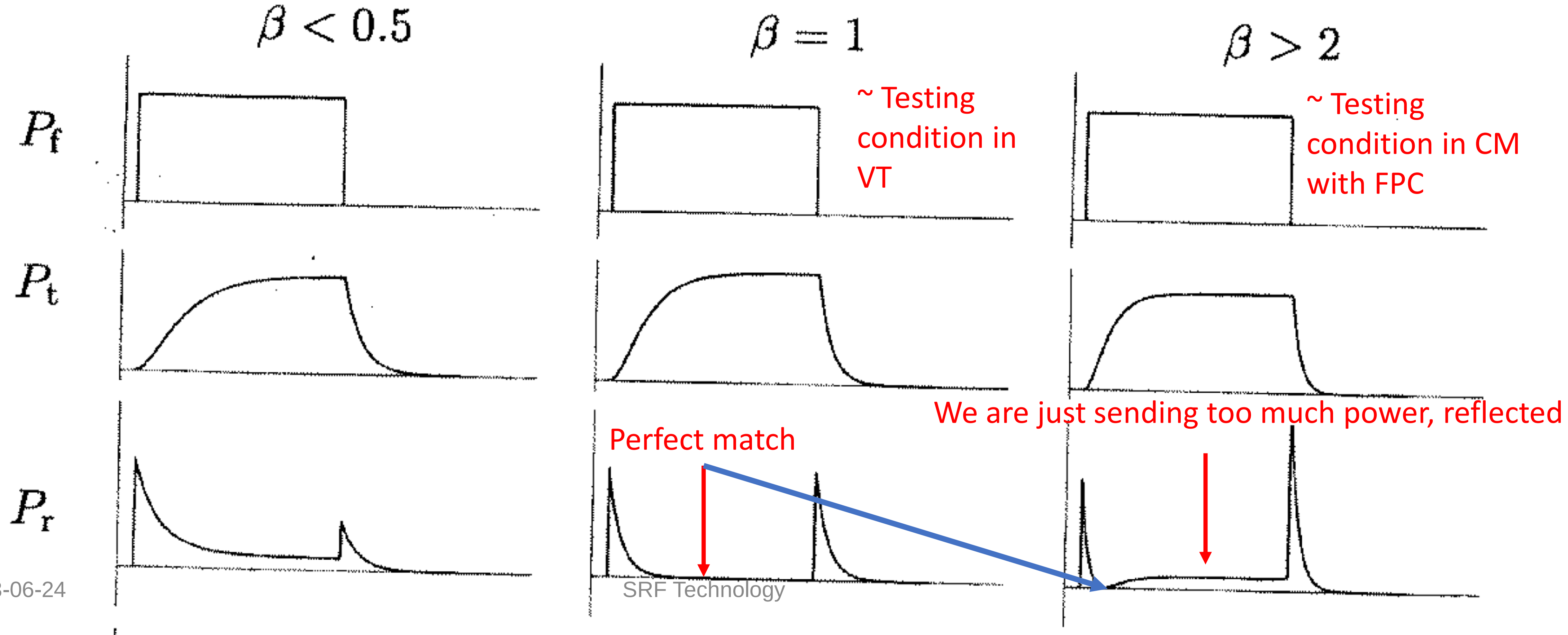
At RF off $U \propto \exp\left(-\frac{2\pi t}{Q_L}\right)$

Cavity coupling… [NO BEAM]

Geom factor, set in design by:

$$\beta = 1 + P_b/P_d$$

- At start of pulse, cavity immediately reflects ALL power
- Then it charges, with time constant $\tau_l = Q_L/(2\pi\ f)$
- See behavior of reflected power for different coupling condition



SRF advantage

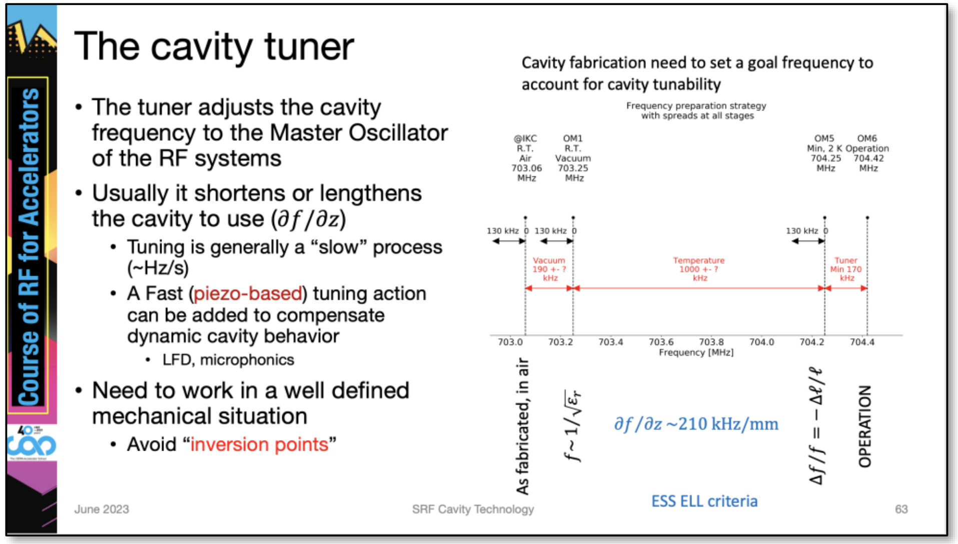
- NC cavities: Typically the dissipated power, P_d, is substantial, and may have similar order of magnitude of the power that needs to be delivered to the beam, P_b
  - Optimal β small, close to critical condition ($\beta = 1$) at all times

- SRF cavities: Usually the dissipated power, P_d, can be neglected with respect to the needed beam power, P_b
  - $Q_L \sim Q_{ext} \ll \mathrm{Q}_0$
    - A bandwidth measurement or a decay time measurement at cold gives Q_{ext}
  - Optimal $\beta \gg 1$ to account for heavy beam loading (coupler design point)
    - When we have no beam we are **severely overcoupled**!

But first, clean the couplers

- Typically the coupler is split in two parts, a cold and a warm part, separated by (at least) one ceramic window
  - Cold part assembled with cavity in clean room
  - Warm part interfacing with cryomodule and installed during CM assembly
- The combined cavity/coupler needs to be conditioned to high fields
- We can use one advantage of SRF
  - At warm and even at cold the cavity has a natural frequency very far from the machine
  - Let's use this fact to separate Coupler conditioning from Cavity Conditioning

Yesterday…



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Coupler conditioning

- Bandwidth of cavity is quite far from the machine (rf source) frequency
  - ESS:
    - Warm ELL Cavity at > 1.3 MHz from Klystron, at warm FWBW ~ 100 kHz
    - Cold ELL Cavity at >150 kHz from Klystron, at cold FWBW ~ 1 kHz
- If we send power to a warm or cold untuned cavity, all power is reflected back!
  - We actually achieve the perfect setup to condition the coupler in a standing wave pattern, without cavity excitation
  - So, we gradually increase RF peak power, RF pulse length and repetition rate to prepare the surfaces to accept high RF power

Conditioning sequence (Project dependent)

- For ESS a sequence of conditioning steps has been defined by CEA, sweeping gradually the average RF power
- Short pulses (< 500 us)
  - Full nominal Klystron power
- Long pulses (>500 us)
  - Limited to nominal power to set cavities at nominal field

Step	Pulse width [ms]	Repetition frequency [Hz]	Duty cycle	Power[kW]
SW-S01	0.05	1	0.005%	15 - 1200
SW-S02	0.1	1	0.01%	15 - 1200
SW-S03	0.2	1	0.02%	15 - 1200
SW-S04	0.3	1	0.03%	15 - 1200
SW-S05	0.4	1	0.04%	15 - 1200
SW-S06	0.5	1	0.05%	15 - 1200
SW-S07	0.5	2	0.1%	15 - 1200
SW-S08	0.5	4	0.2%	15 - 1200
SW-S09	0.5	8	0.4%	15 - 1200
SW-S10	0.5	14	0.7%	15 - 1200
SW-L01	0.8	14	1.12%	15 - 300
SW-L02	1.5	14	2.1%	15 - 300
SW-L03	2.5	14	3.5%	15 - 300
SW-L04	3	14	4.2%	15 - 300
SW-L05	3.6	14	5.04%	15 - 300

Warm Coupler conditioning

Before cooldown

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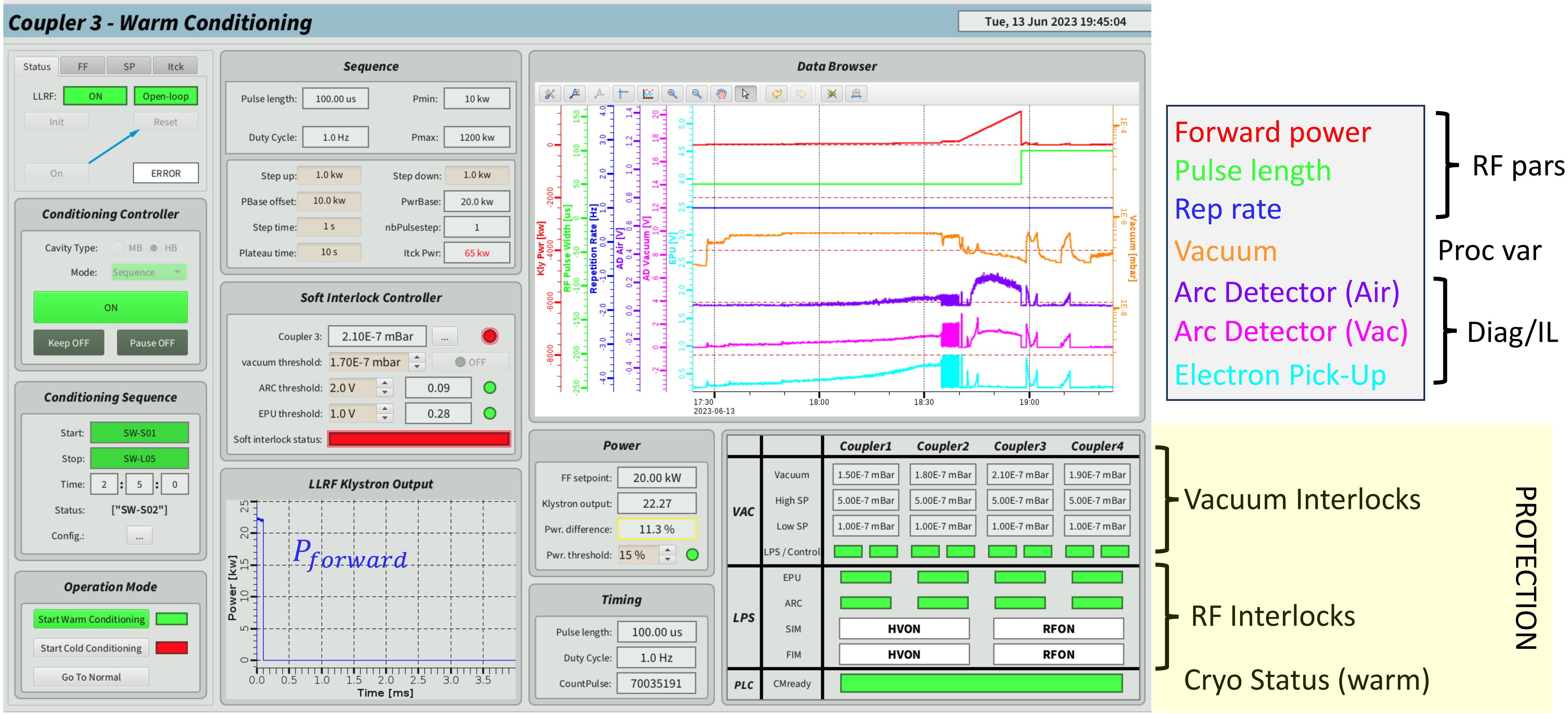
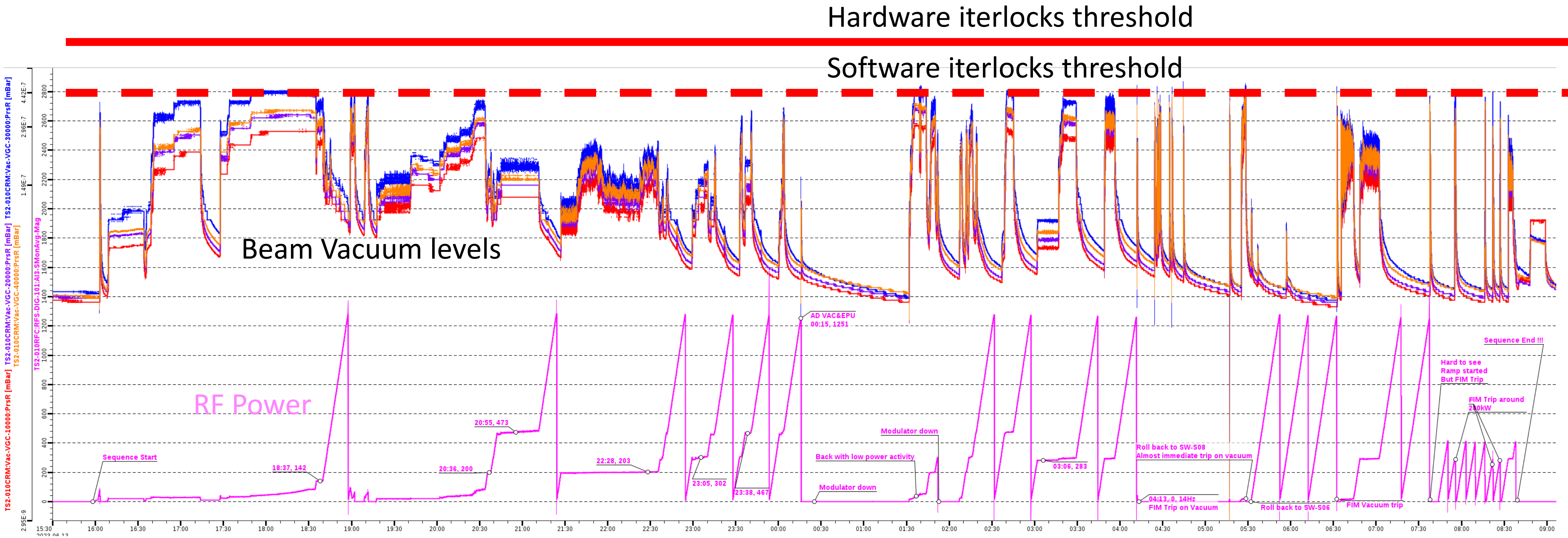
WCC through a procedure



Credits, M.Y. Wang, ESS

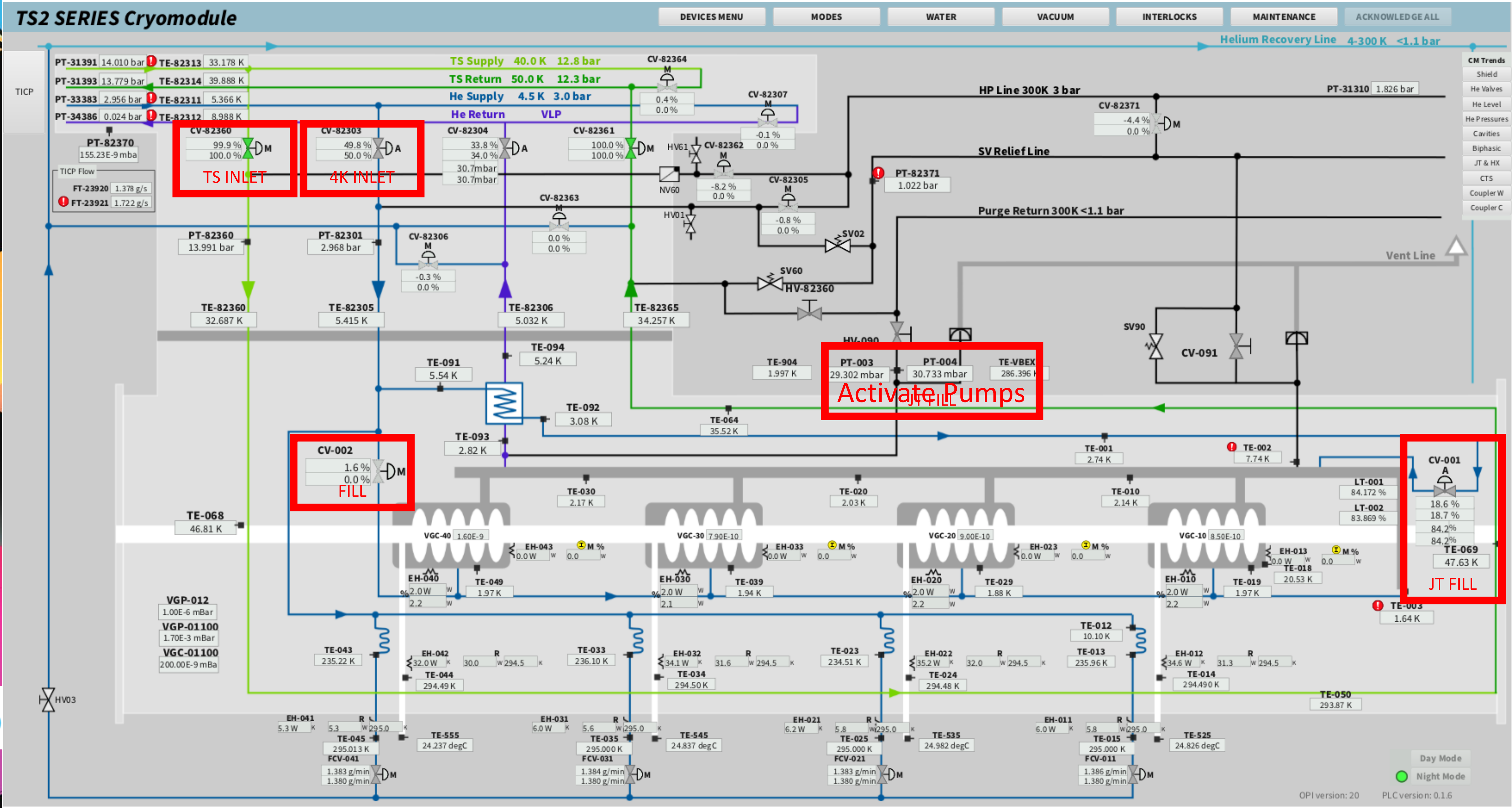
WCC: Warm Coupler Conditioning

- Process to condition MP bareers in the coupler
  - Vacuum is used as the process variable to determine decision on power sent by RF (increase or decrease…)

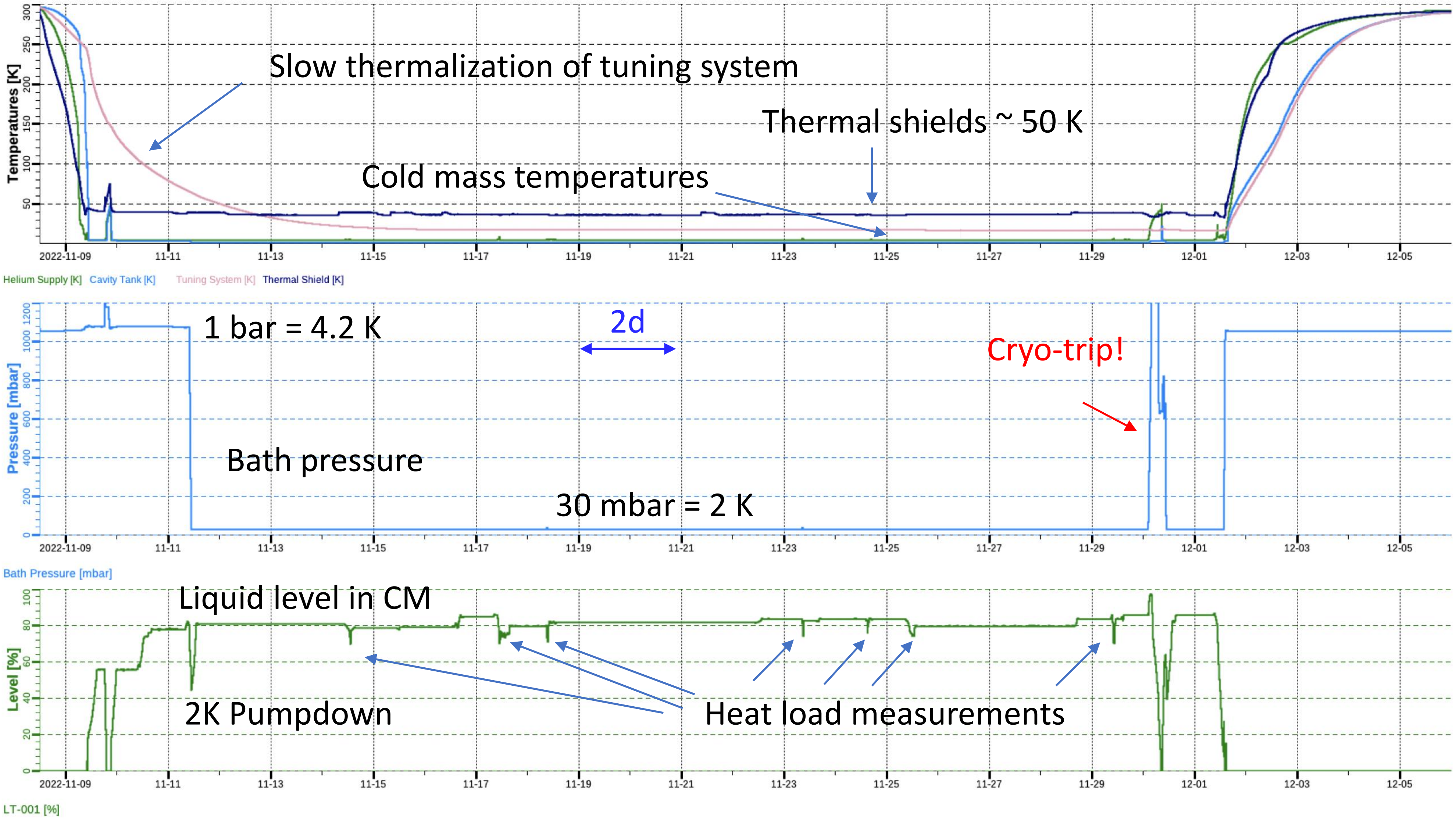


Cooldown

Course of RF for Accelerators



Cooldown timeline



Credits, N. Elias, ESS

Cold coupler conditioning

- At cold temperature another benefit: Cryopumping
  - All gases condense on the cold surfaces (except He)
  - Large pumping from the whole coldmass surface
  - Reduces drastically vacuum evolution
- Opportunity of a further conditioning stage in this condition with improved pumping capabilities
- The same conditioning procedure as WCC is performed at cold to thoroughly process the MP in the coupler
- RF-wise similar situation, cavity is still detuned from resonance so the power is ALL refected back and the coupler operates in SW
  - But remember NOT to engage the tuner…

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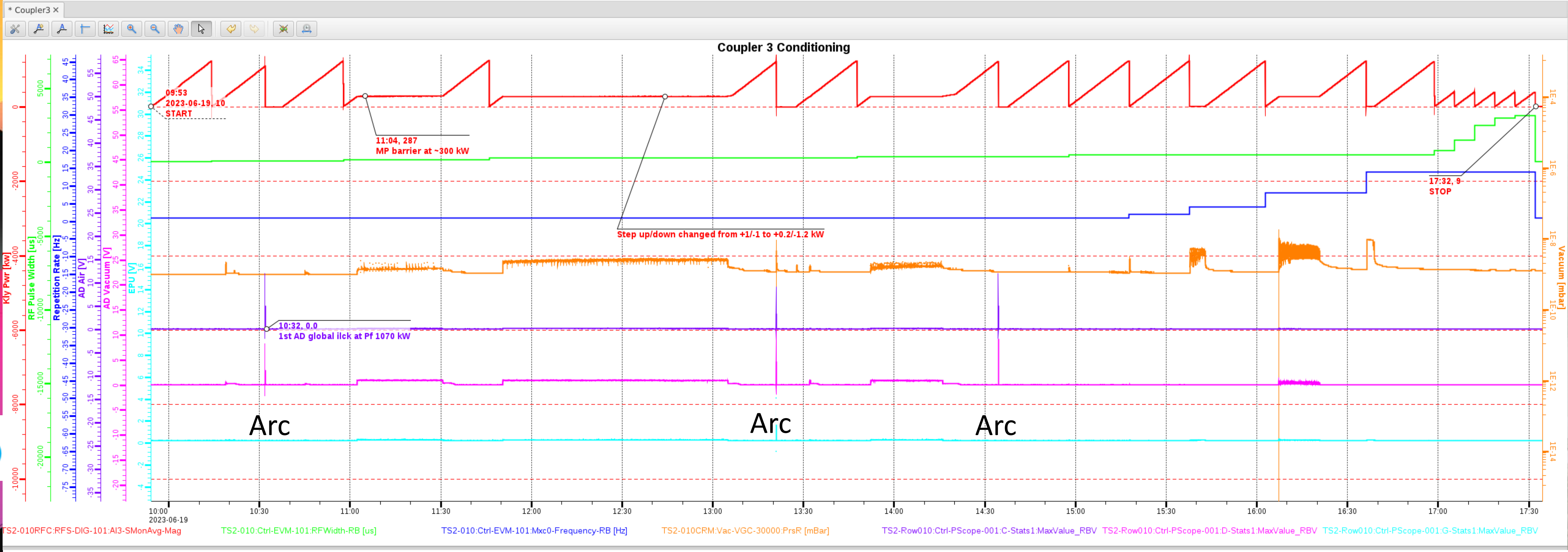
CCC: Cold Coupler conditioning

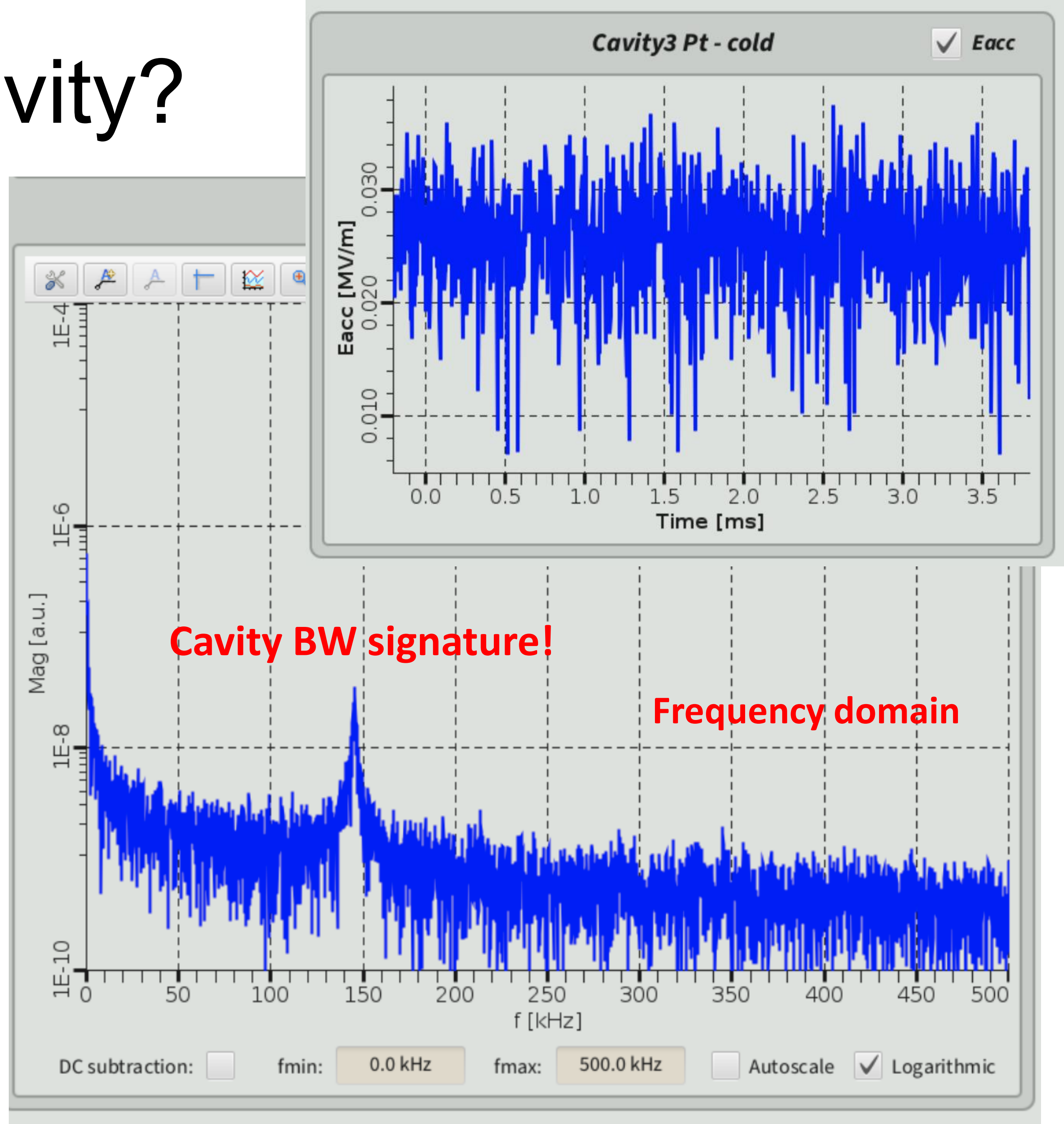
- Same coupler shown before
- WCC effective + higher pumping, only a soft MP at 300 kW



Tuning and Calibration

How do we 'see' the cavity?

- No easy VNA access
- Cavity frequency is below klystron by ~150-200 kHz
  - Full bandwidth is approx 1 kHz
  - NO TRANSMISSION WHATSOEVER in this condition
- Even if we see in the time domain only noise from the PU, the input pulse has wide fourier component reaching the cavity…
  - Idea: use FFT!

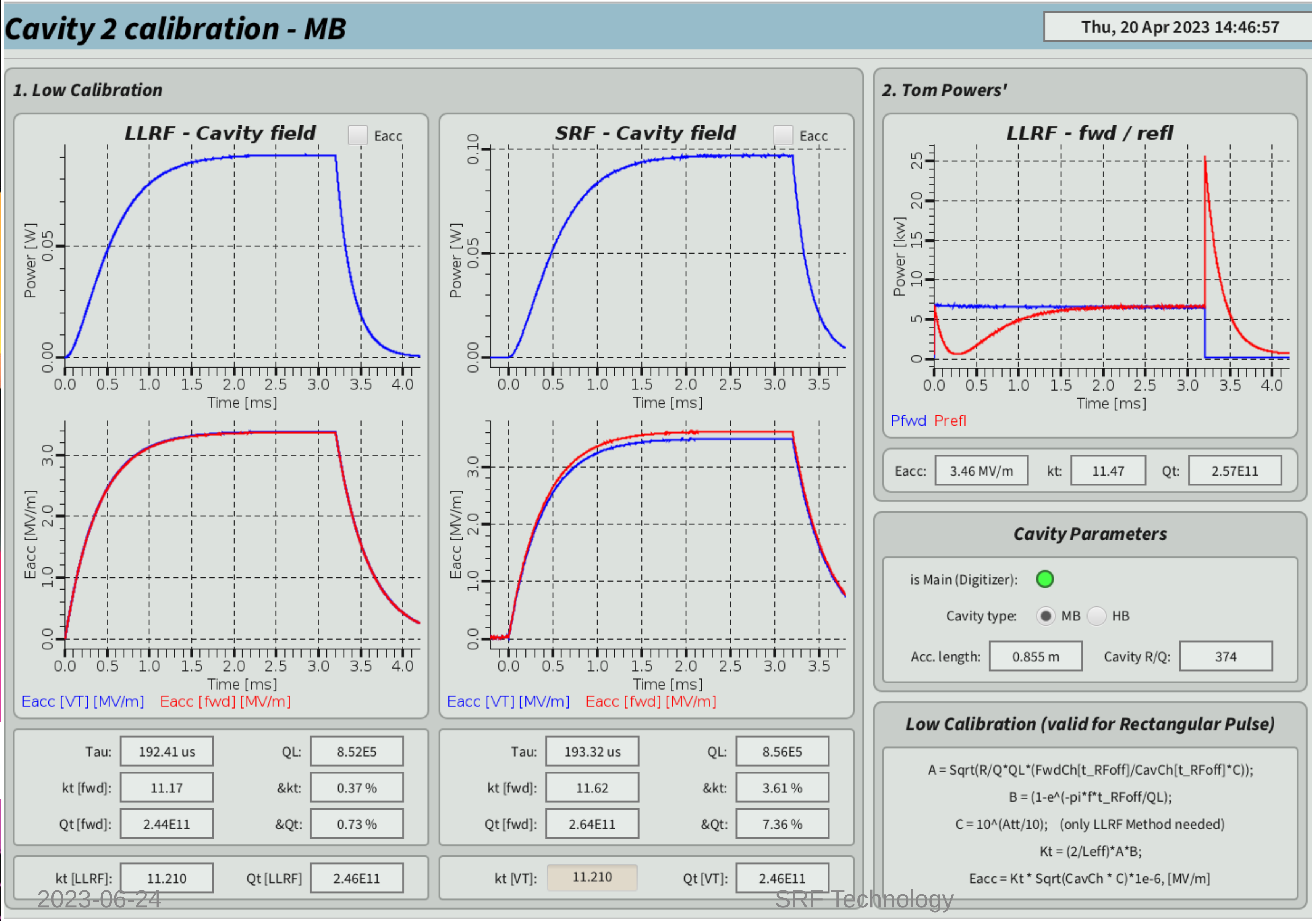


Credit, M.Y. Wang, ESS

Credit, C. Lombard, ESS

Calibration

Credit, M.Y. Wang, ESS



Use several methods

1. Use LLRF signals and rely on LLRF hardware calibration

2. Use COTS power metering to check and independently calibrate

3. Use cavity models to benchmark (e.g. integral of reflected power to determine stored energy)

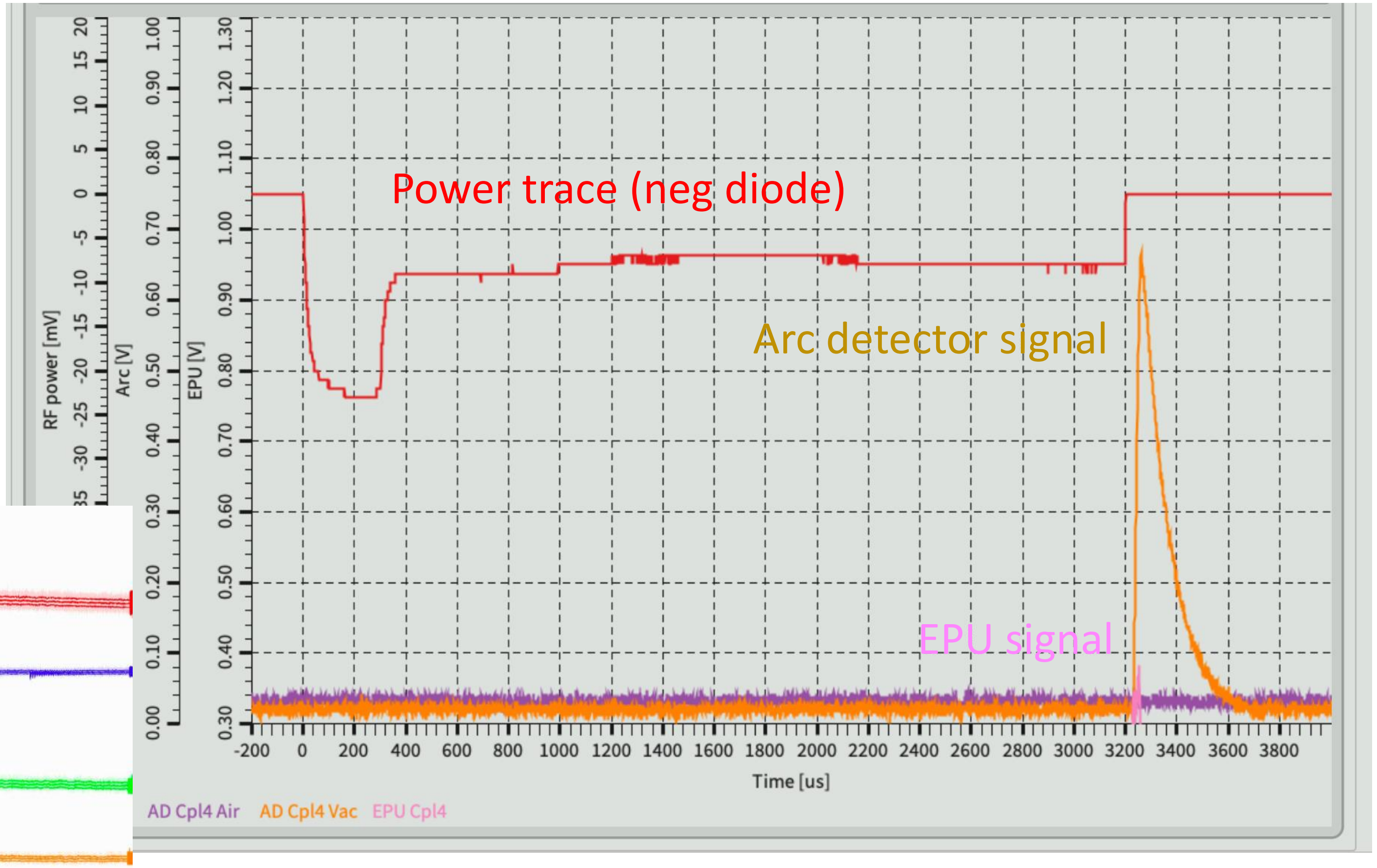
WAIT! Cavity takes too long time to fill with the natural Q, and we can send beam only when field is flat!

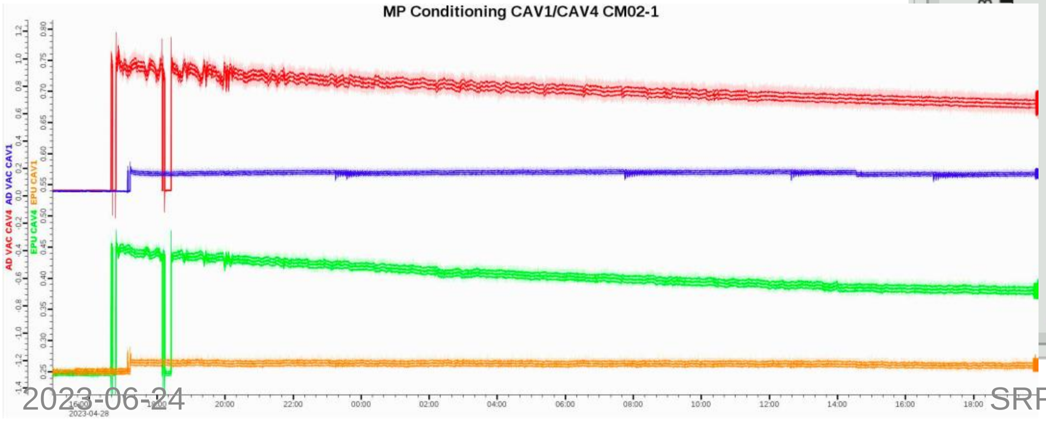
Credit, C. Lombard, ESS

Cavity Conditioning/Operation

Manual process

- Usually cavity conditioning is a manual process where we slowly raise RF pulse length and power to clear MP cavity activity controlling
  - Arc activity
  - Electron pickup
  - Vacuum evolution





Credit, M.Y. Wang, ESS

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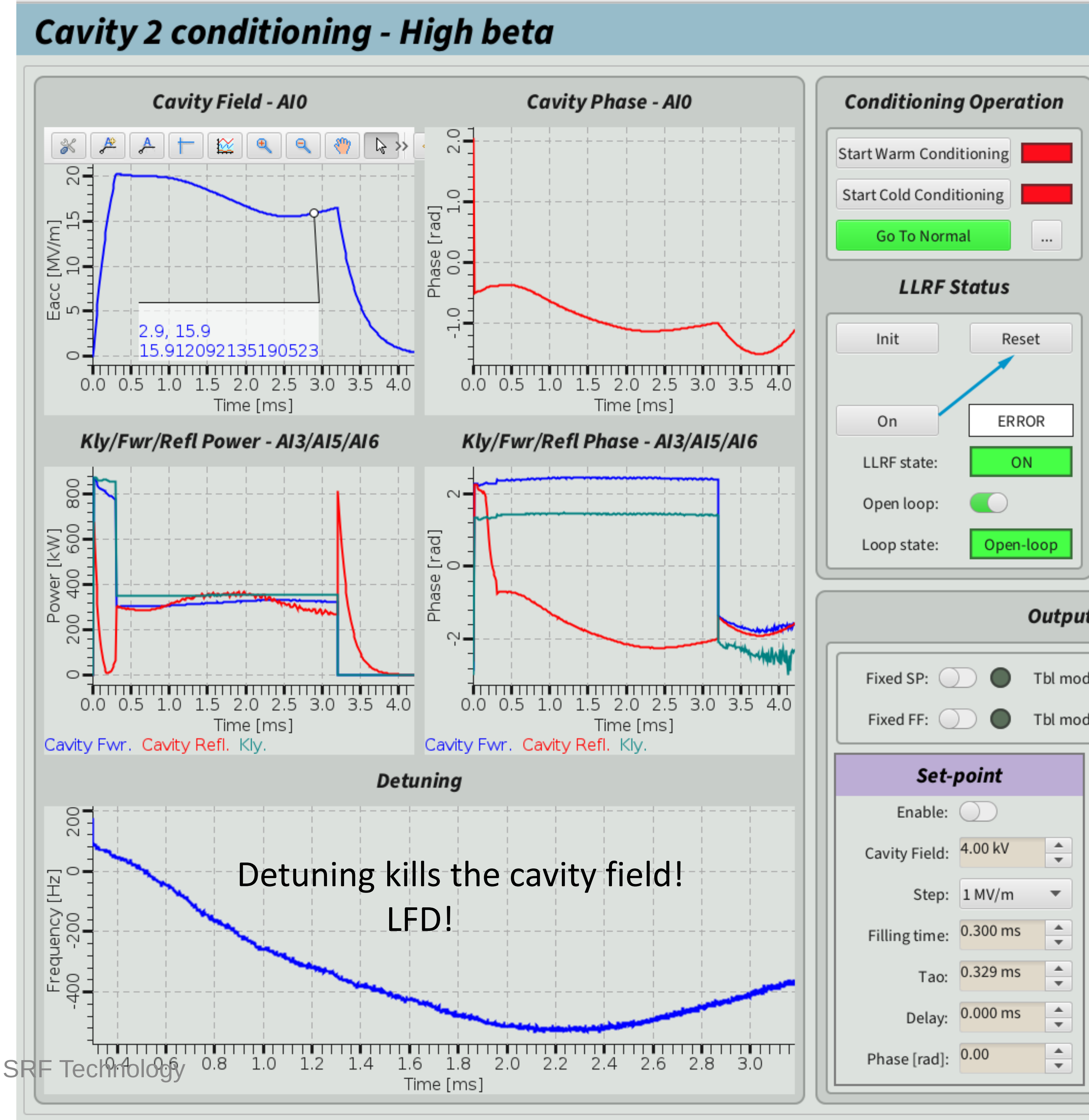
Pushing to high field

- In pure open loop the LFD can kill the cavity field
- Cavity detunes substantially and the field drops

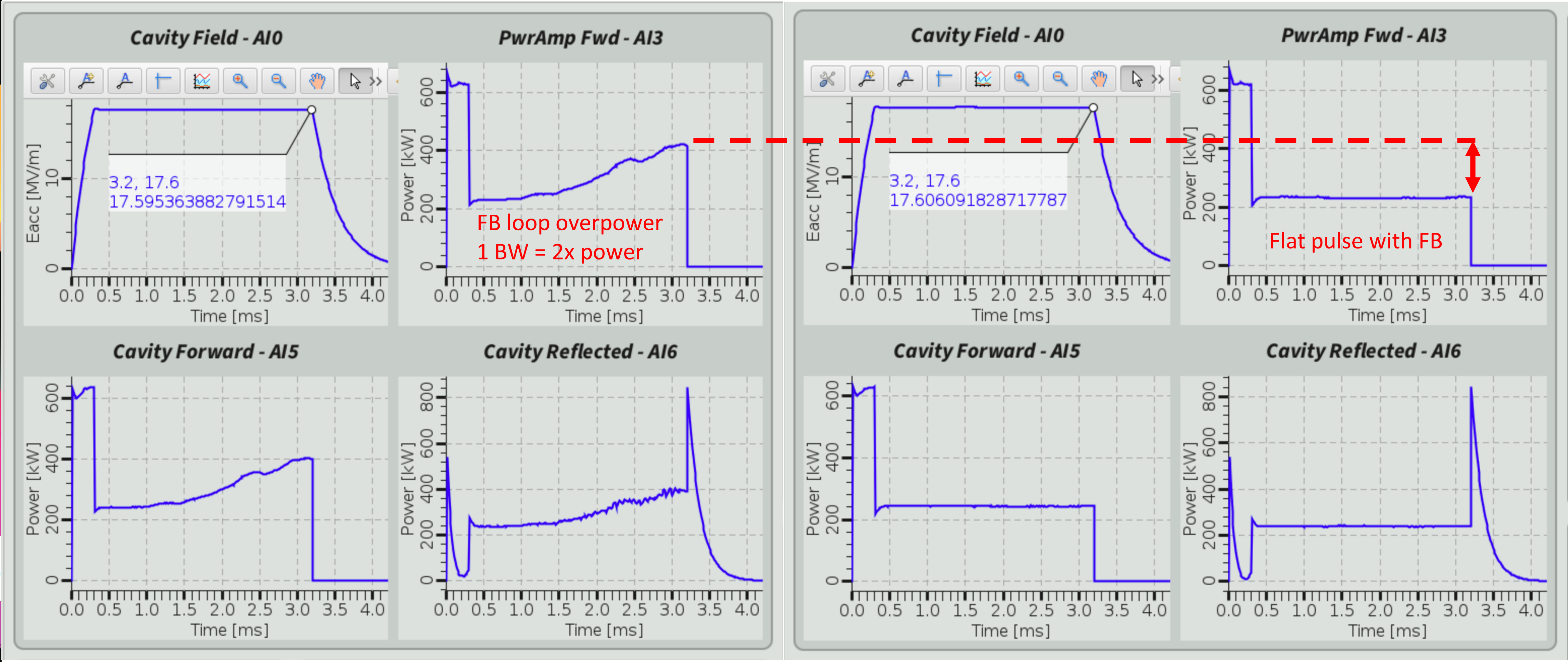


Credit, C. Lombard, ESS

Credit, C. Lombard, ESS

FB Assistance: PIEZO!

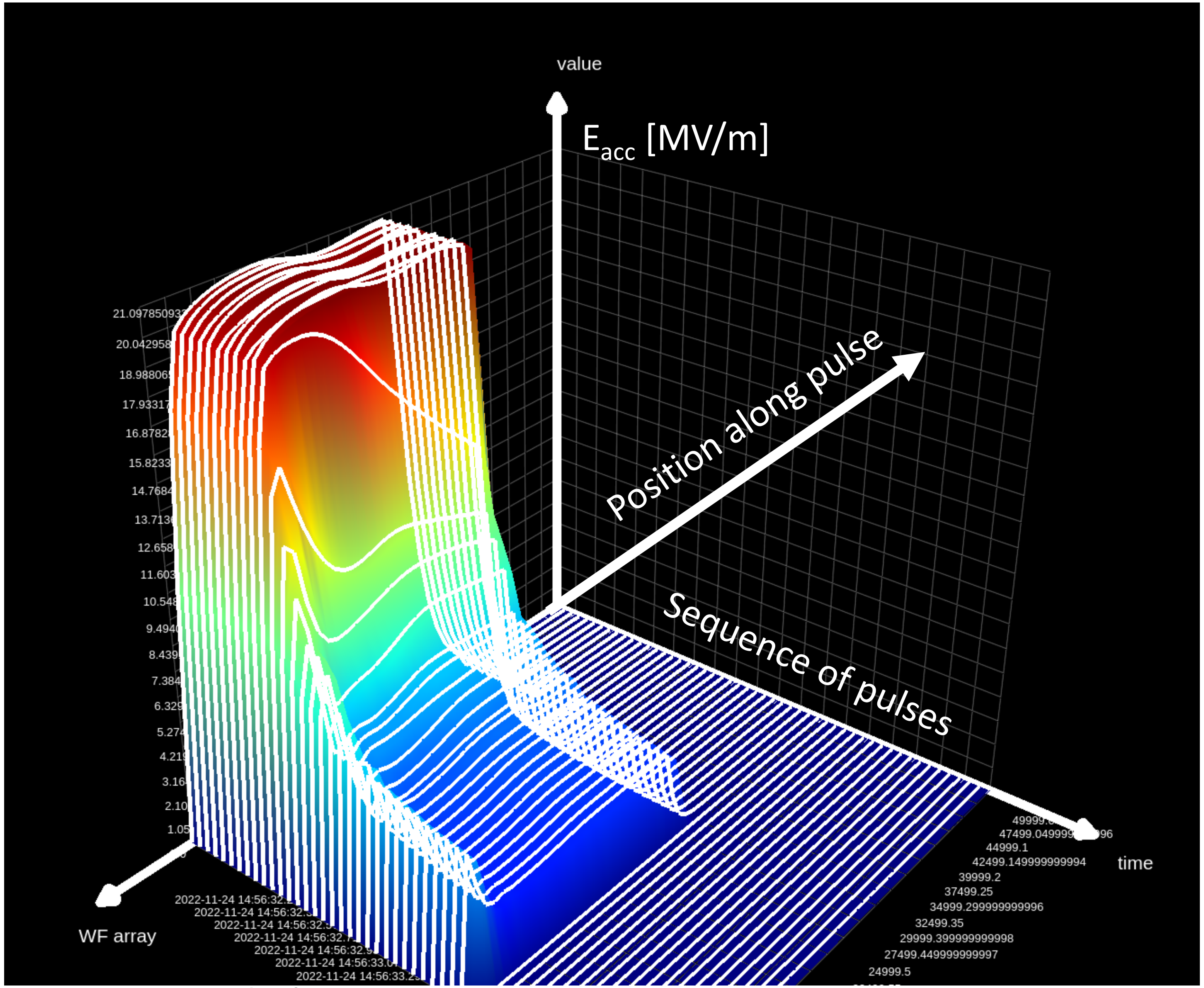
Piezo OFF Cavity detuning at high field (LFD) requires > 50% extra power at pulse end! **Piezo ON**



And then… QUENCH!

Credits: B.Bolling, ESS

- A quench in an SRF cavity is hardly dramatic
- May cause pressure bath increases
- Usually recover fully or partially at the next pulse



Credits

- Credits for these presentations go to too many people
  - The whole SRF community at large, spread in all continents…
  - Many colleagues at INFN, DESY, CEA, IFJLAB, STFC for material related to XFEL and ESS components
  - The great ESS/IFJ-PAN team in Lund for all TS2 activities

Celebrating the latest progress on

ESS *Road to Science*