



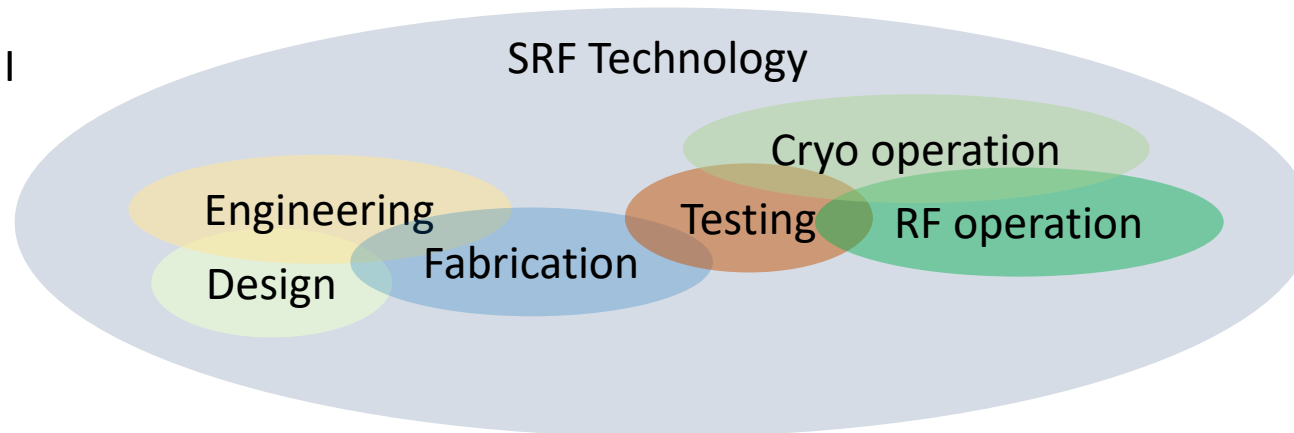
SRF Cavities

[Mostly about Technology]

This week:

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

Paolo Pierini, ESS



Next week:

- LLRF I-III
- Beam Loading
- Power coupling
- Multipacting
- HOM

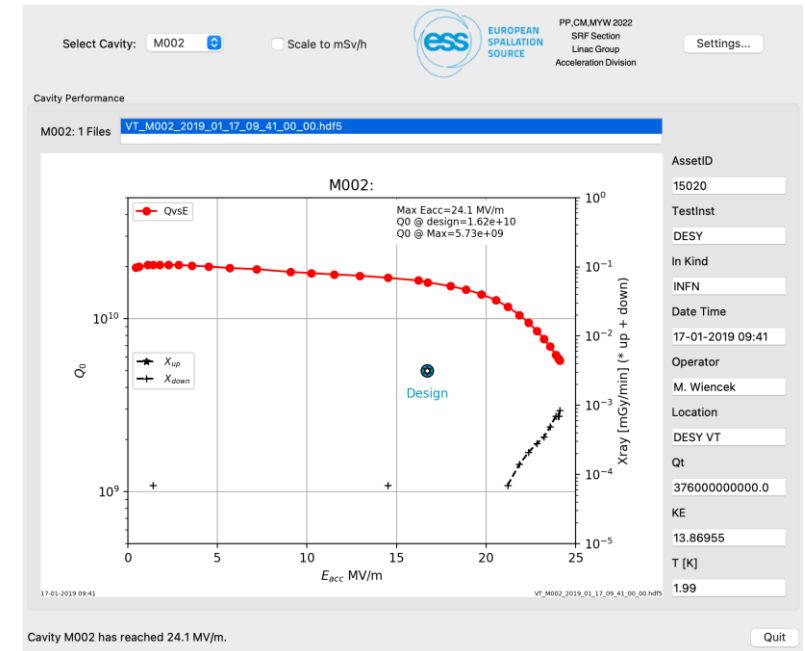
Outline

- 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?

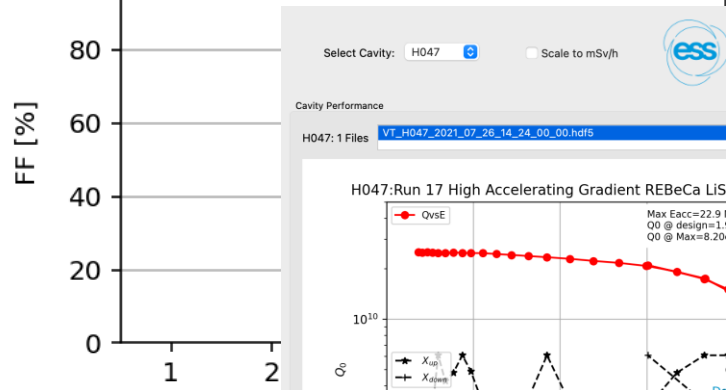
- Are we able to preserve it from cavity to cryomodule?
 - Several **pumping** and **venting** operation required during the process
 - Opening of beamline flanges, exposing the surface to clean room environment
 - Risk of dragging particulate inside the RF volume
 - Long **transport** may be required (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



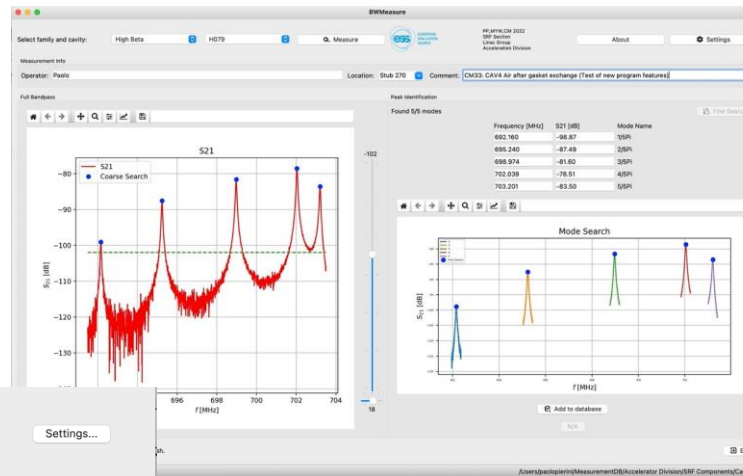
First/Foremost: know you CAVs!

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

M002 Field Flatness 97 %



Incoming measurements



Temperature: 21.1C, Humidity: 23.6%

Frequency [MHz] vs Mode #

Mode #	Frequency [MHz]
1	692.737
2	694.867
3	697.729
4	700.474
5	702.549
6	703.275

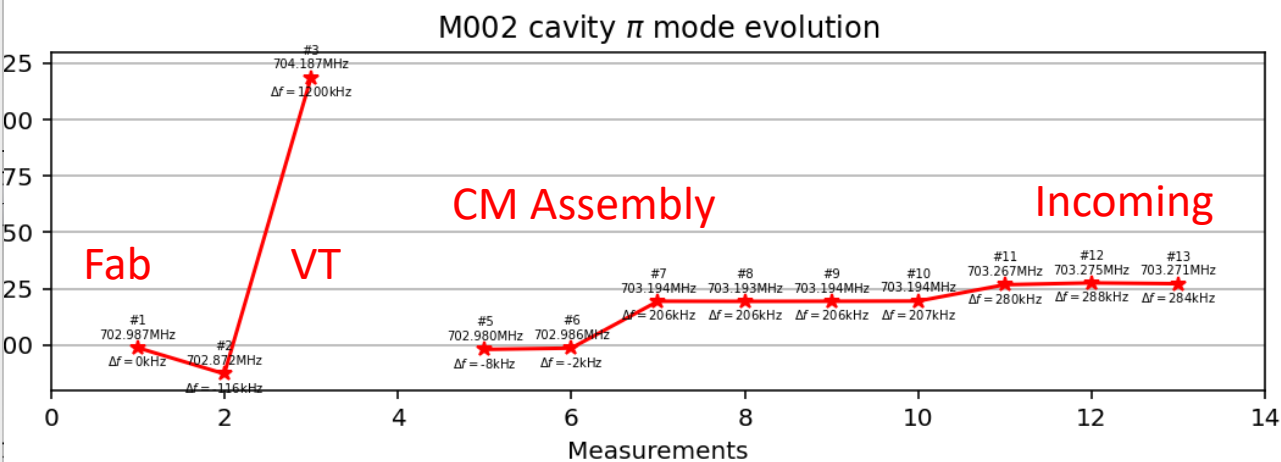
Bandwidth Explorer: data in /Users/paolopierini/MeasurementDB/Accelerator Division/SRF Components/Cavities

H047: Run 17 High Accelerating Gradient REBeCa LiSEL QvsEacc v05.vj

Max Eacc=22.9 MV/m
Q0 @ design=1.92e+10
Q0 @ Max=8.20e+09

Vertical test

Cavity H047 has reached 22.9 MV/m.



07-12-2018 13:38

2023-06-24

SRF Technology



Handling CMs from completion to Machine



Hang out with truckers at 7:00 am



Play with cool tools



Have a comfy nap...



Brainstorming sessions

Cross-disciplinary TEAMWORK!

2023-06-24

SRF Technology

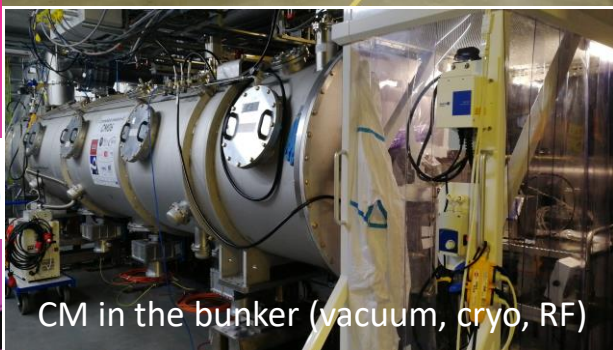
A test stand is (likely) needed



Transport, mechanical & electrical inspections

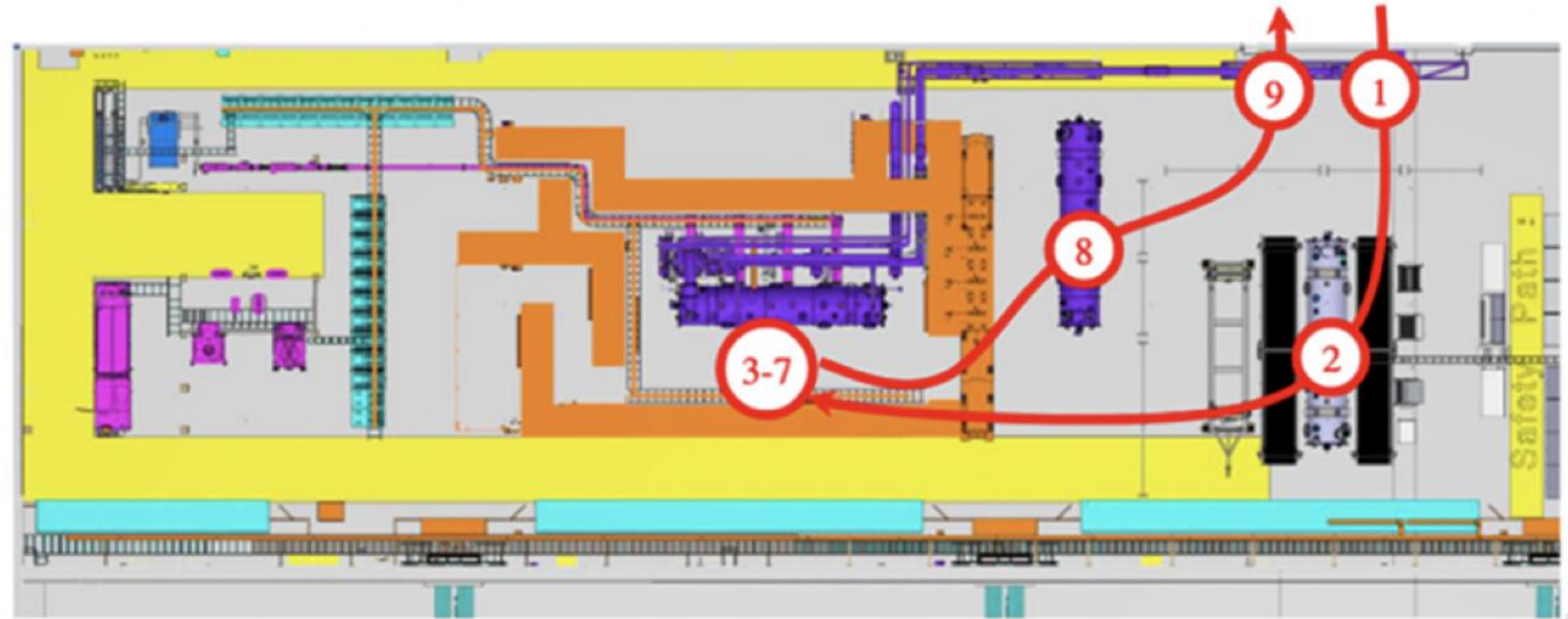


Preparation to Bunker (mech, vac, RF)



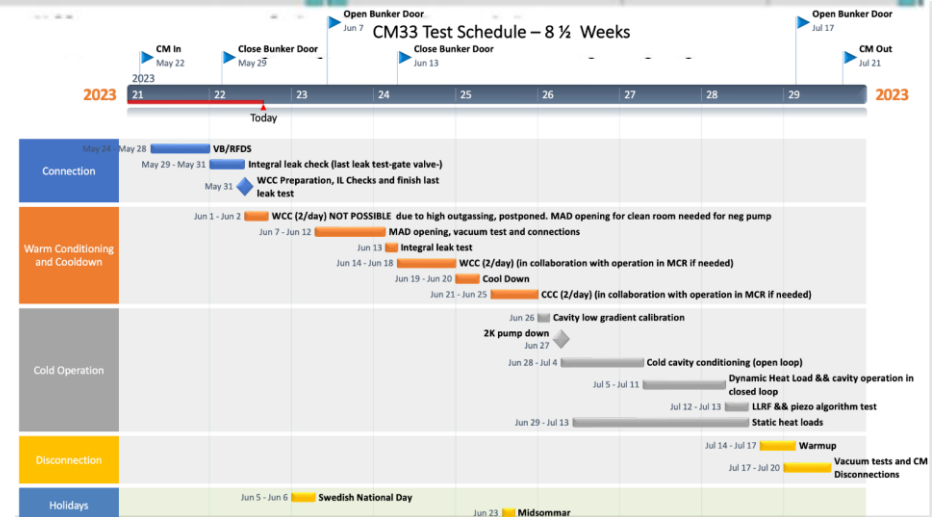
CM in the bunker (vacuum, cryo, RF)

2023-06-24



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:

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

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

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

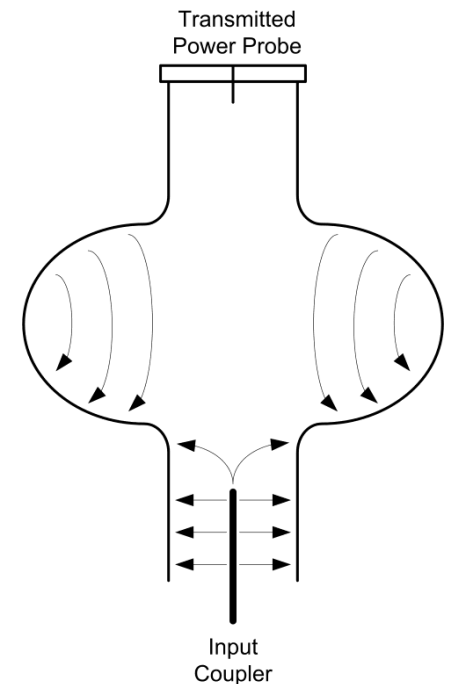
Where the (geometrical) coupling is:

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

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

See F. Gerigk presentation

See J.Branlard, SRF Tutorials, 2019



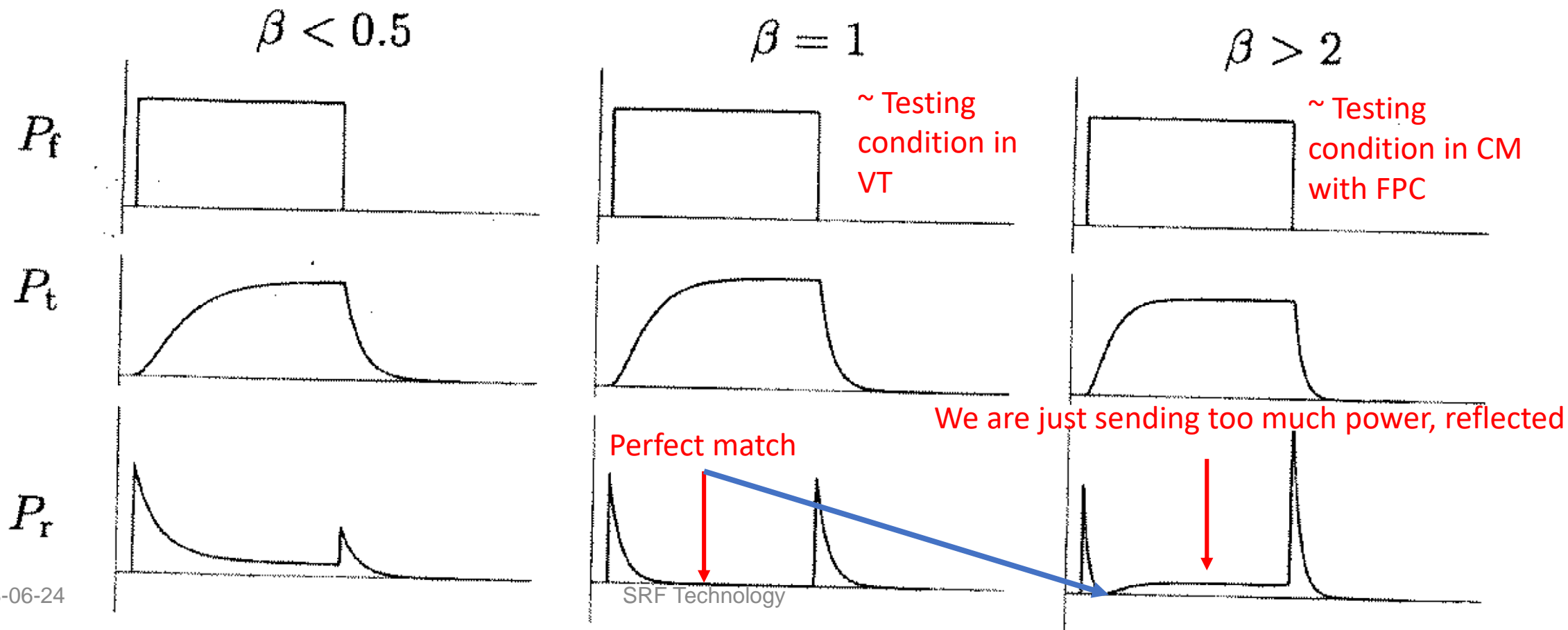
At RF off $U \propto \exp\left(-\frac{2\pi t}{Q_L}\right)$

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
 - $Q_L \sim Q_{ext} \ll Q_0$
 - 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**

The cavity tuner

- The tuner adjusts the cavity frequency to the Master Oscillator of the RF systems
- Usually it shortens or lengthens the cavity to use $(\partial f / \partial z)$
 - Tuning is generally a "slow" process (~Hz/s)
 - A Fast (piezo-based) tuning action can be added to compensate dynamic cavity behavior
 - LFD, microphonics
- Need to work in a well defined mechanical situation
 - Avoid "inversion points"

Yesterday...

Cavity fabrication need to set a goal frequency to account for cavity tunability

Frequency preparation strategy with spreads at all stages

As fabricated, in air $f \sim 1/\sqrt{\epsilon_r}$

$\partial f / \partial z \sim 210 \text{ kHz/mm}$

$\Delta f / f = -\Delta \epsilon_r / \epsilon_r$

ESSELL criteria

June 2023 SRF Cavity Technology 63

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

WCC through a procedure

Coupler 3 - Warm Conditioning Tue, 13 Jun 2023 19:45:04

Status: FF SP Itck

LLRF: **ON** Open-loop

Init Reset

On ERROR

Conditioning Controller

Cavity Type: MB HB

Mode: Sequence

ON

Keep OFF Pause OFF

Conditioning Sequence

Start: SW-S01

Stop: SW-L05

Time: 2 : 5 : 0

Status: ["SW-S02"]

Config: ...

Operation Mode

Start Warm Conditioning

Start Cold Conditioning

Go To Normal

Sequence

Pulse length: 100.00 us Pmin: 10 kw

Duty Cycle: 1.0 Hz Pmax: 1200 kw

Step up: 1.0 kw Step down: 1.0 kw

PBase offset: 10.0 kw PwrBase: 20.0 kw

Step time: 1 s nbPulsestep: 1

Plateau time: 10 s Itck Pwr: 65 kw

Soft Interlock Controller

Coupler 3: 2.10E-7 mBar

vacuum threshold: 1.70E-7 mbar

ARC threshold: 2.0 V 0.09

EPU threshold: 1.0 V 0.28

Soft interlock status: ██████████

LLRF Klystron Output

Data Browser

Power

FF setpoint: 20.00 kW

Klystron output: 22.27

Pwr. difference: 11.3 %

Pwr. threshold: 15 %

Timing

Pulse length: 100.00 us

Duty Cycle: 1.0 Hz

CountPulse: 70035191

		Coupler1	Coupler2	Coupler3	Coupler4
VAC	Vacuum	1.50E-7 mBar	1.80E-7 mBar	2.10E-7 mBar	1.90E-7 mBar
	High SP	5.00E-7 mBar	5.00E-7 mBar	5.00E-7 mBar	5.00E-7 mBar
	Low SP	1.00E-7 mBar	1.00E-7 mBar	1.00E-7 mBar	1.00E-7 mBar
	LPS / Control	█	█	█	█
LPS	EPU	█	█	█	█
	ARC	█	█	█	█
	SIM	HVON		RFON	
	FIM	HVON		RFON	
PLC	CMready	██████████			

- Forward power
 - Pulse length
 - Rep rate
 - Vacuum
 - Arc Detector (Air)
 - Arc Detector (Vac)
 - Electron Pick-Up
- } RF pars
- } Proc var
- } Diag/IL

- Vacuum Interlocks
 - RF Interlocks
 - Cryo Status (warm)
- } PROTECTION

Credits, M.Y. Wang, ESS

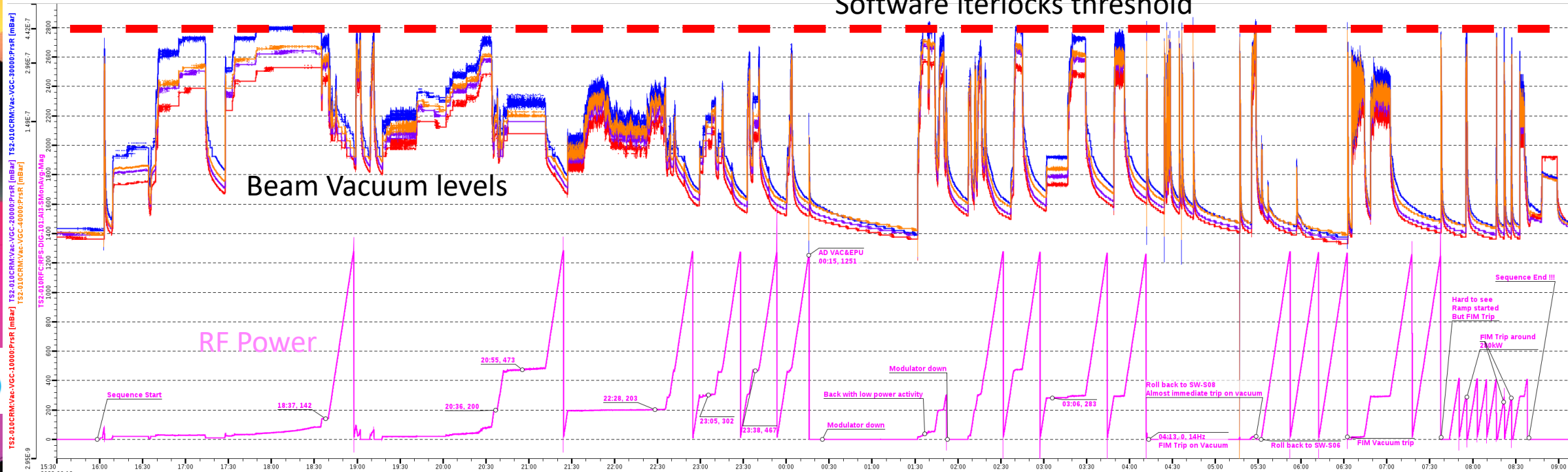


WCC: Warm Coupler Conditioning

- 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...)

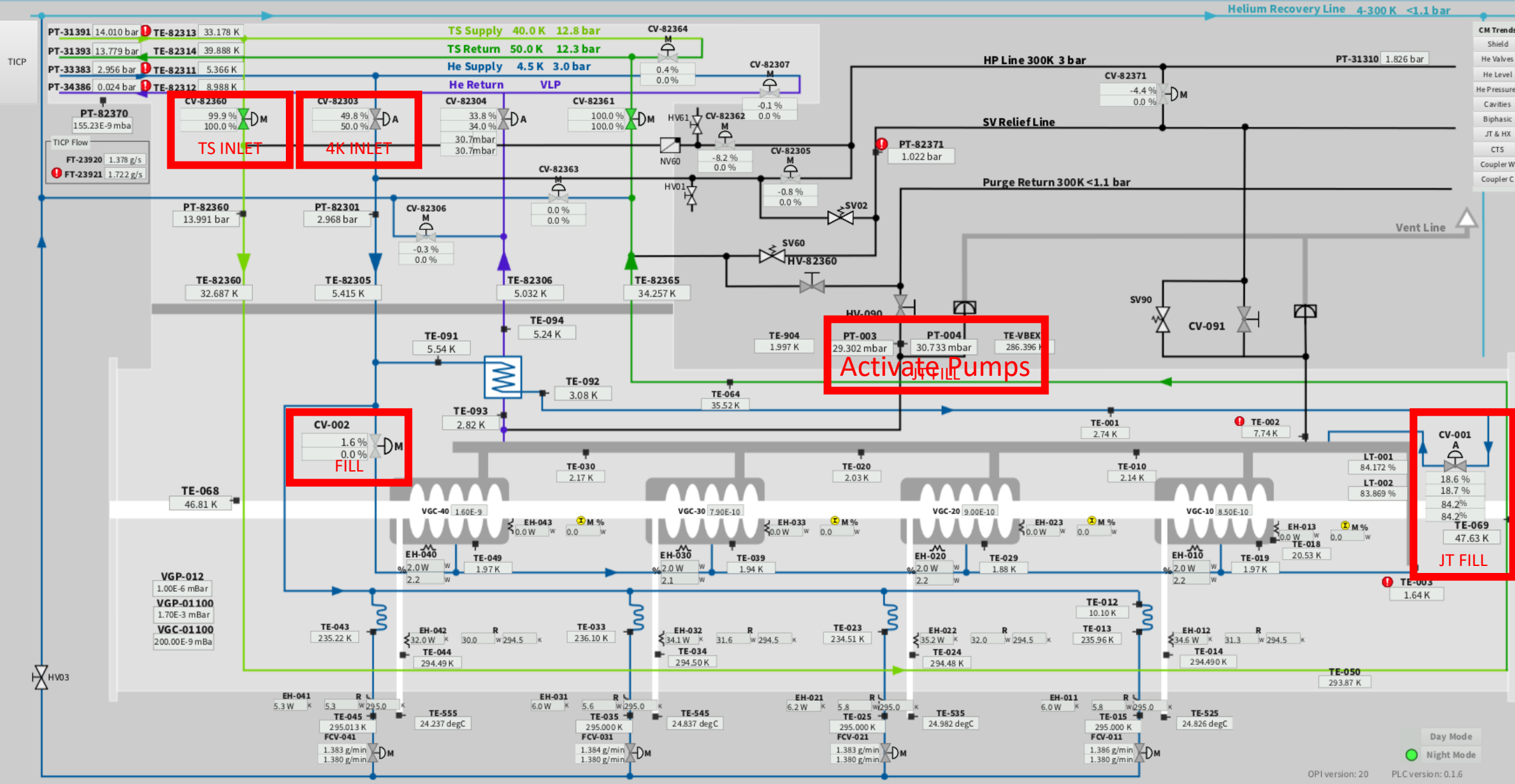
Hardware iterlocks threshold

Software iterlocks threshold



Cooldown

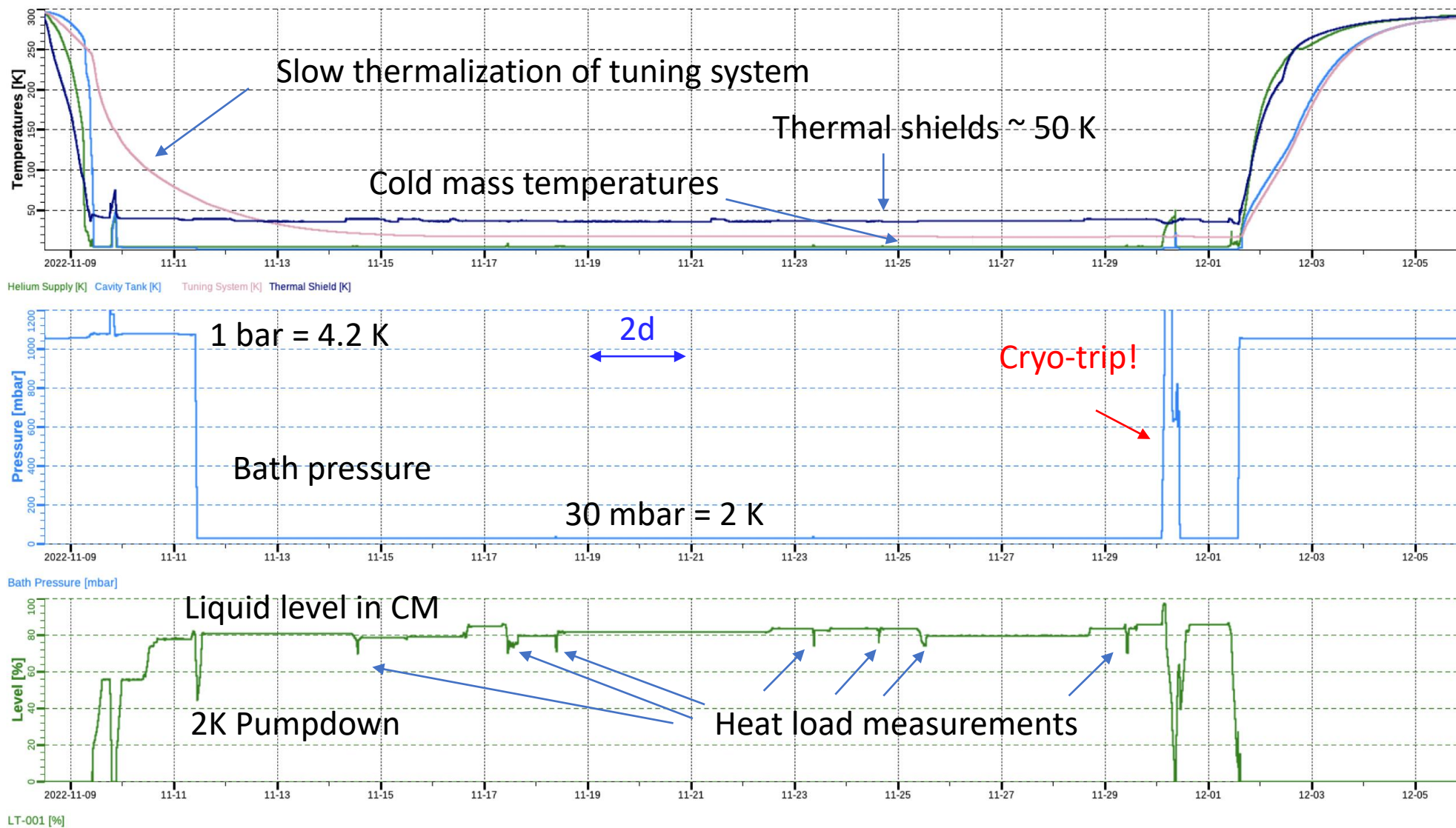
TS2 SERIES Cryomodule



- CM Trends
- Shield
- He Valves
- He Level
- He Pressures
- Cavities
- Biphasic
- JT & HX
- CTS
- Coupler W
- Coupler C



Cooldown timeline

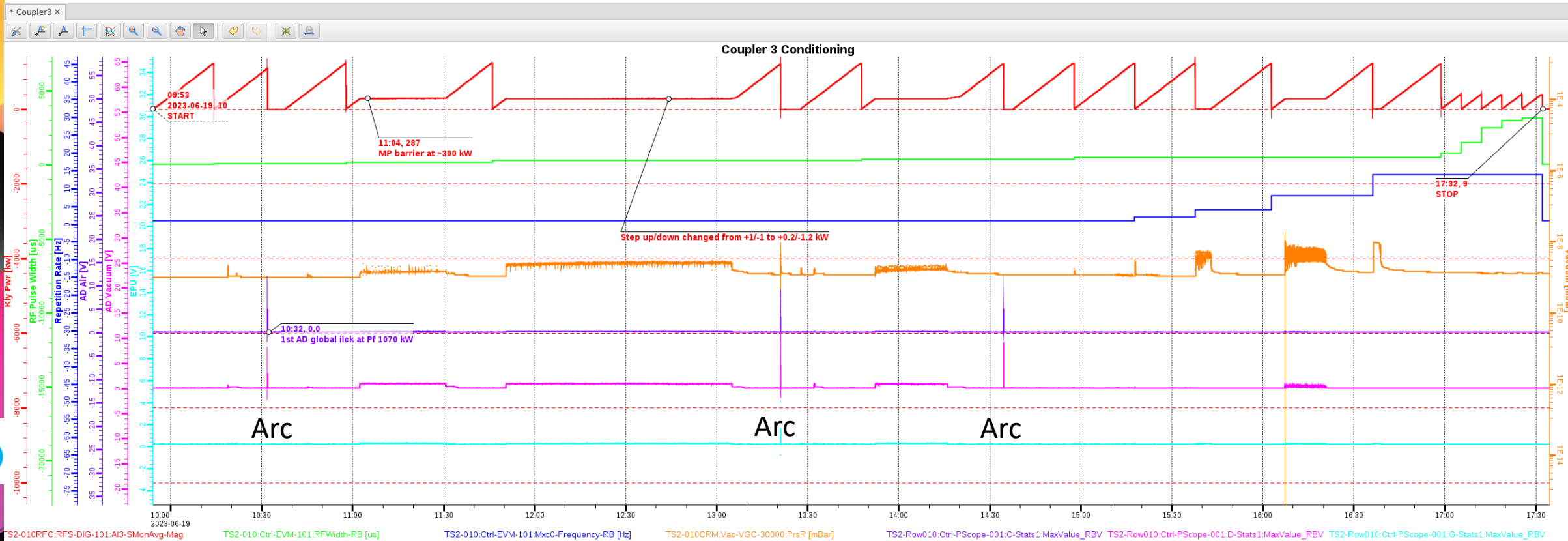


Cold coupler conditioning

- 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 reflected back** and the coupler operates in SW
 - But remember NOT to engage the tuner...

CCC: Cold Coupler conditioning

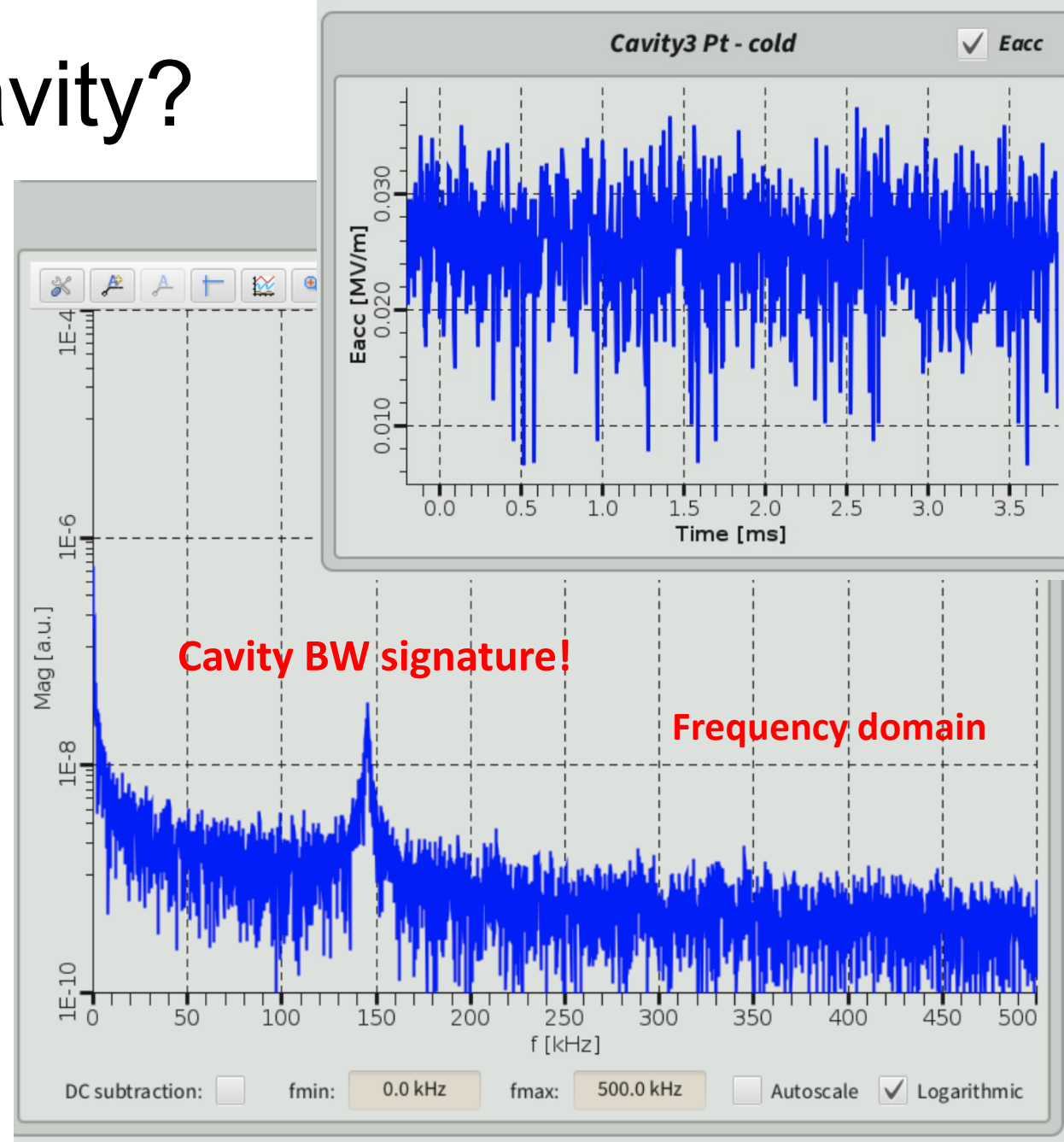
- Same coupler shown before
- WCC effective + higher pumping, only a soft MP at 300 kW



Tuning and Calibration

How do we 'see' the cavity?

- No easy VNA access
- Cavity frequency is below klystron by $\sim 150\text{-}200$ 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!**



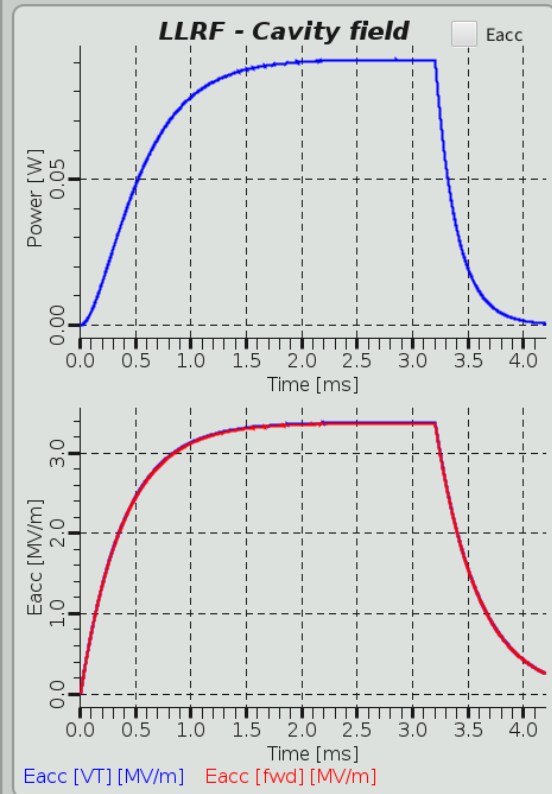
Calibration

Credit, M.Y. Wang, ESS

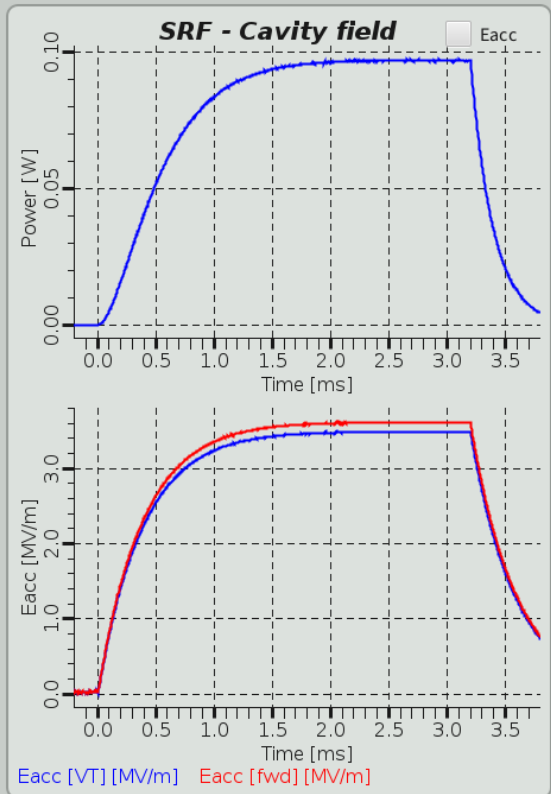
Cavity 2 calibration - MB

Thu, 20 Apr 2023 14:46:57

1. Low Calibration

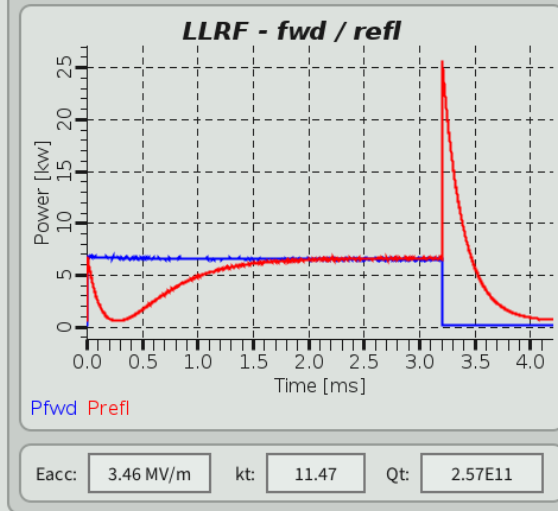


Tau:	192.41 us	QL:	8.52E5
kt [fwd]:	11.17	&kt:	0.37 %
Qt [fwd]:	2.44E11	&Qt:	0.73 %
kt [LLRF]:	11.210	Qt [LLRF]:	2.46E11



Tau:	193.32 us	QL:	8.56E5
kt [fwd]:	11.62	&kt:	3.61 %
Qt [fwd]:	2.64E11	&Qt:	7.36 %
kt [VT]:	11.210	Qt [VT]:	2.46E11

2. Tom Powers'



Cavity Parameters

is Main (Digitizer):

Cavity type: MB HB

Acc. length: 0.855 m Cavity R/Q: 374

Low Calibration (valid for Rectangular Pulse)

$$A = \sqrt{R/Q * QL * (FwdCh[t_RFOff]/CavCh[t_RFOff] * C)}$$

$$B = (1 - e^{-\pi * t_RFOff / QL})$$

C = 10^(Att/10); (only LLRF Method needed)

$$Kt = (2 / Leff) * A * B$$

$$Eacc = Kt * \sqrt{CavCh * C} * 1e-6, [MV/m]$$

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!

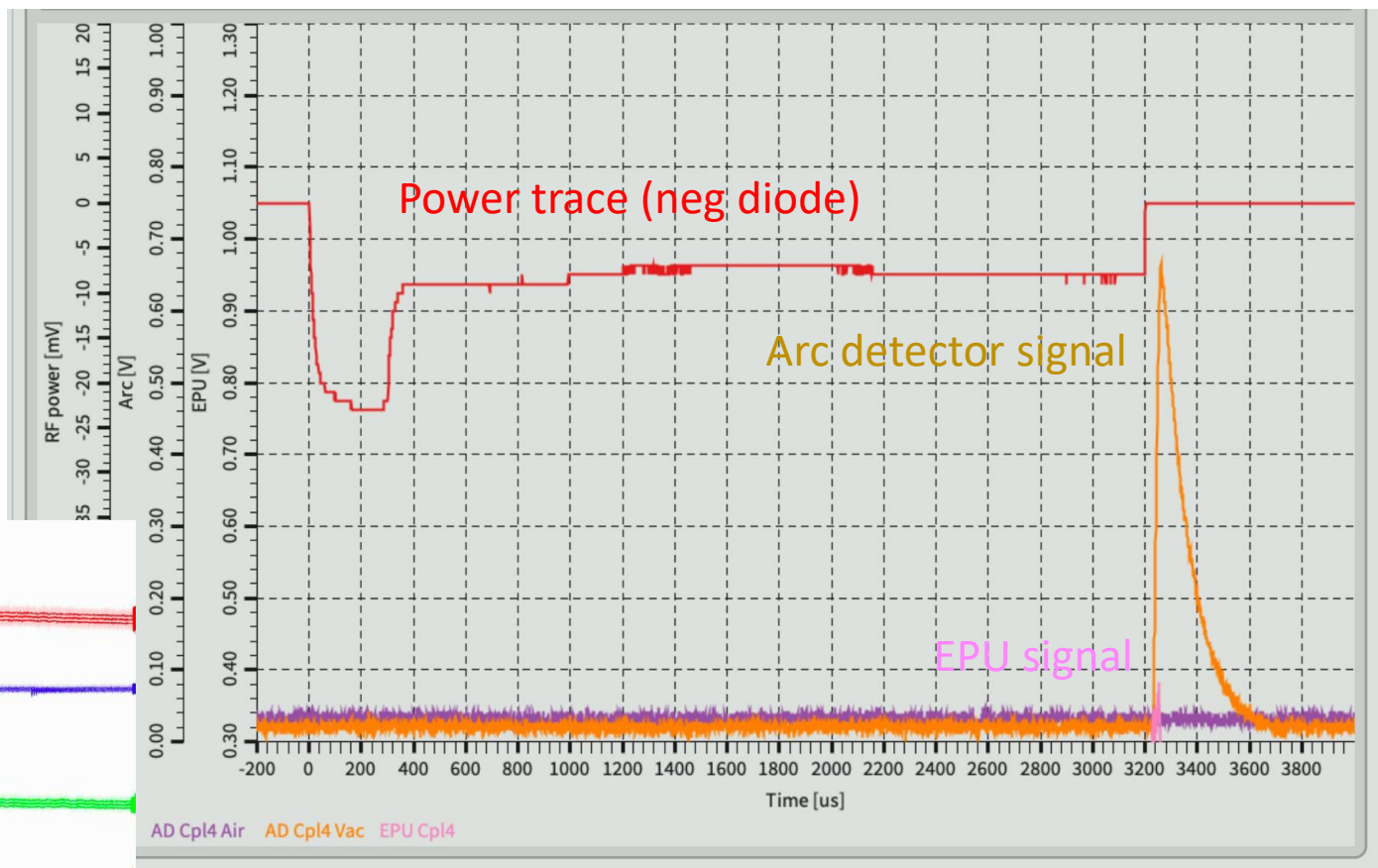
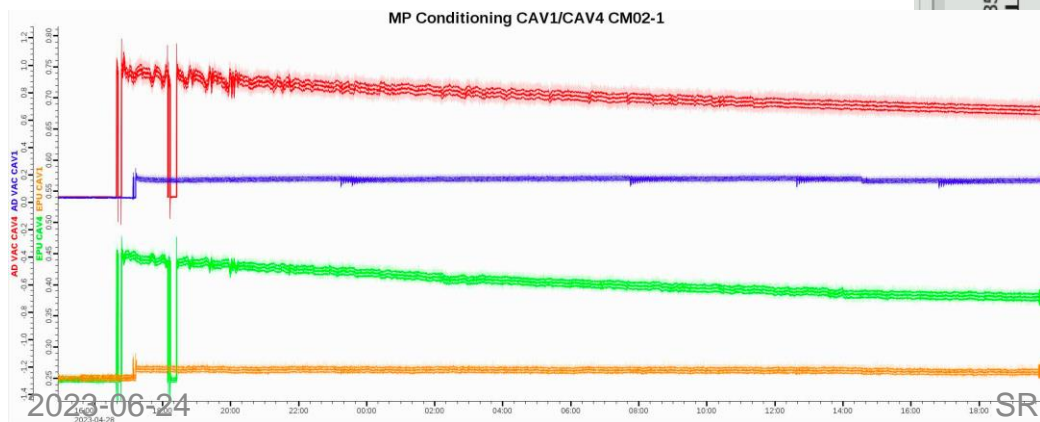




Cavity Conditioning/Operation

Manual process

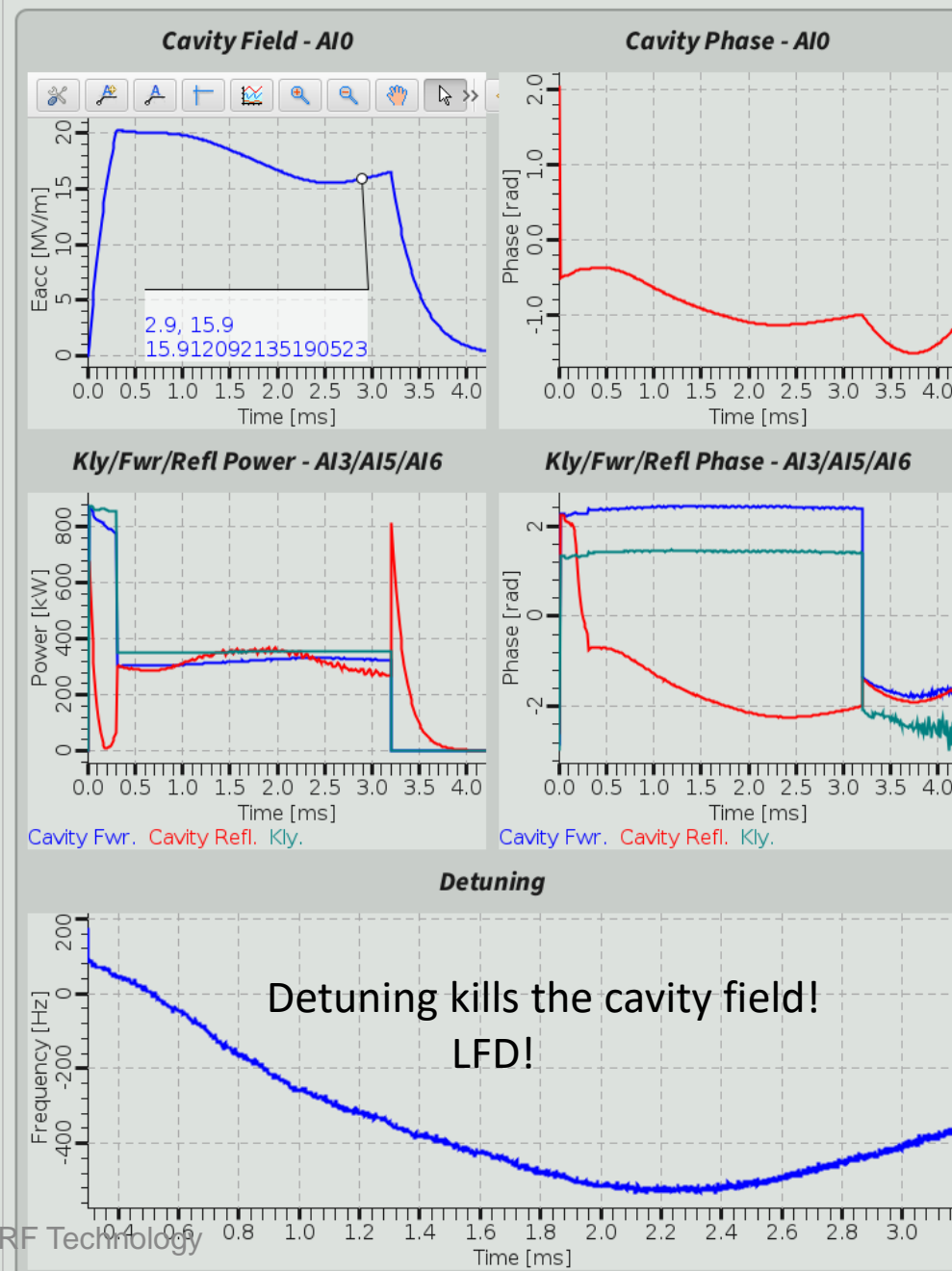
- Usually cavity conditioning is a manual process where we slowly raise RF pulse length and power to clear MP cavity activity controlling
 - Arc activity
 - Electron pickup
 - Vacuum evolution



Pushing to high field

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

Cavity 2 conditioning - High beta



Conditioning Operation

Start Warm Conditioning

Start Cold Conditioning

Go To Normal

LLRF Status

Init Reset

On ERROR

LLRF state:

Open loop:

Loop state:

Output

Fixed SP: Tbl mod

Fixed FF: Tbl mod

Set-point

Enable:

Cavity Field: 4.00 kV

Step: 1 MV/m

Filling time: 0.300 ms

Tao: 0.329 ms

Delay: 0.000 ms

Phase [rad]: 0.00



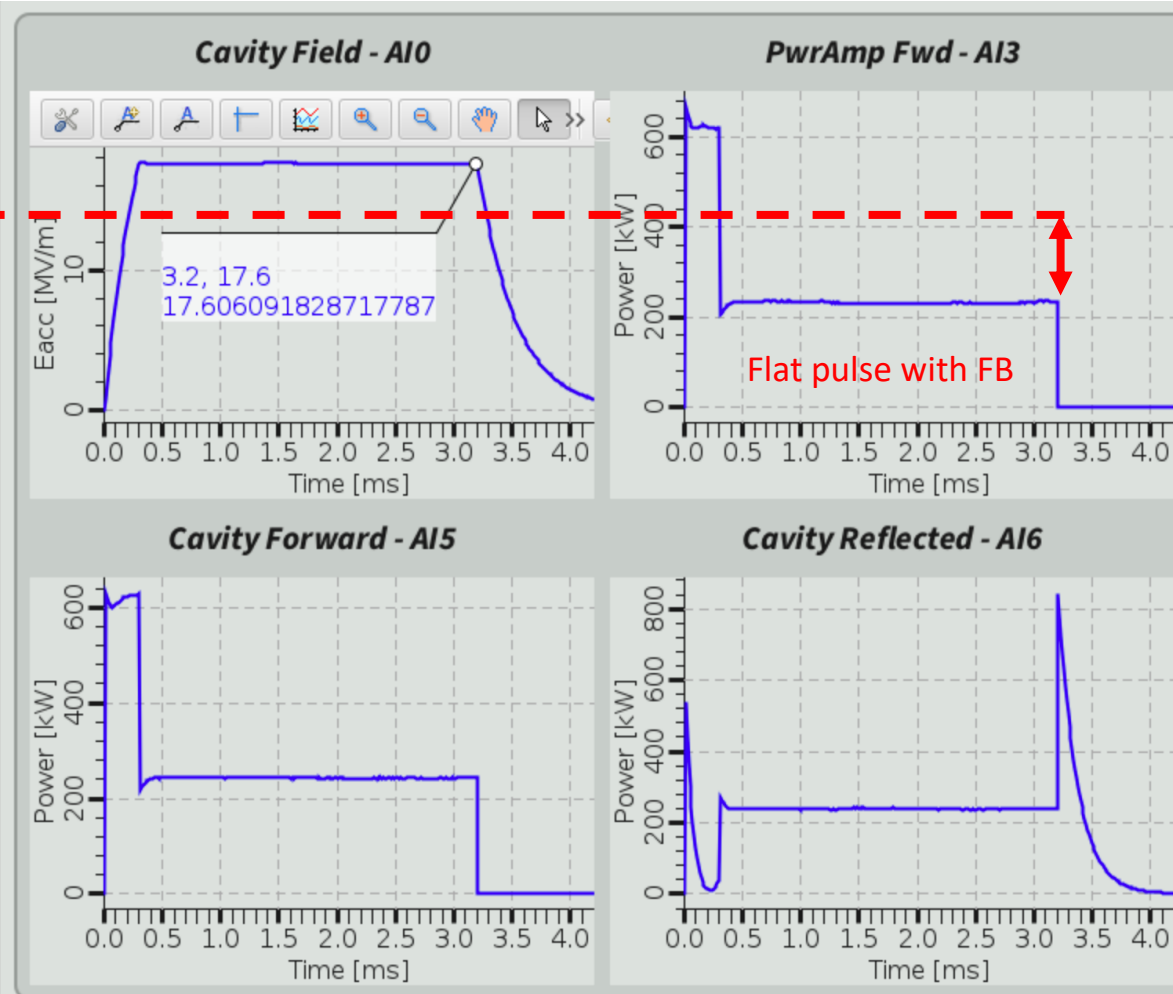
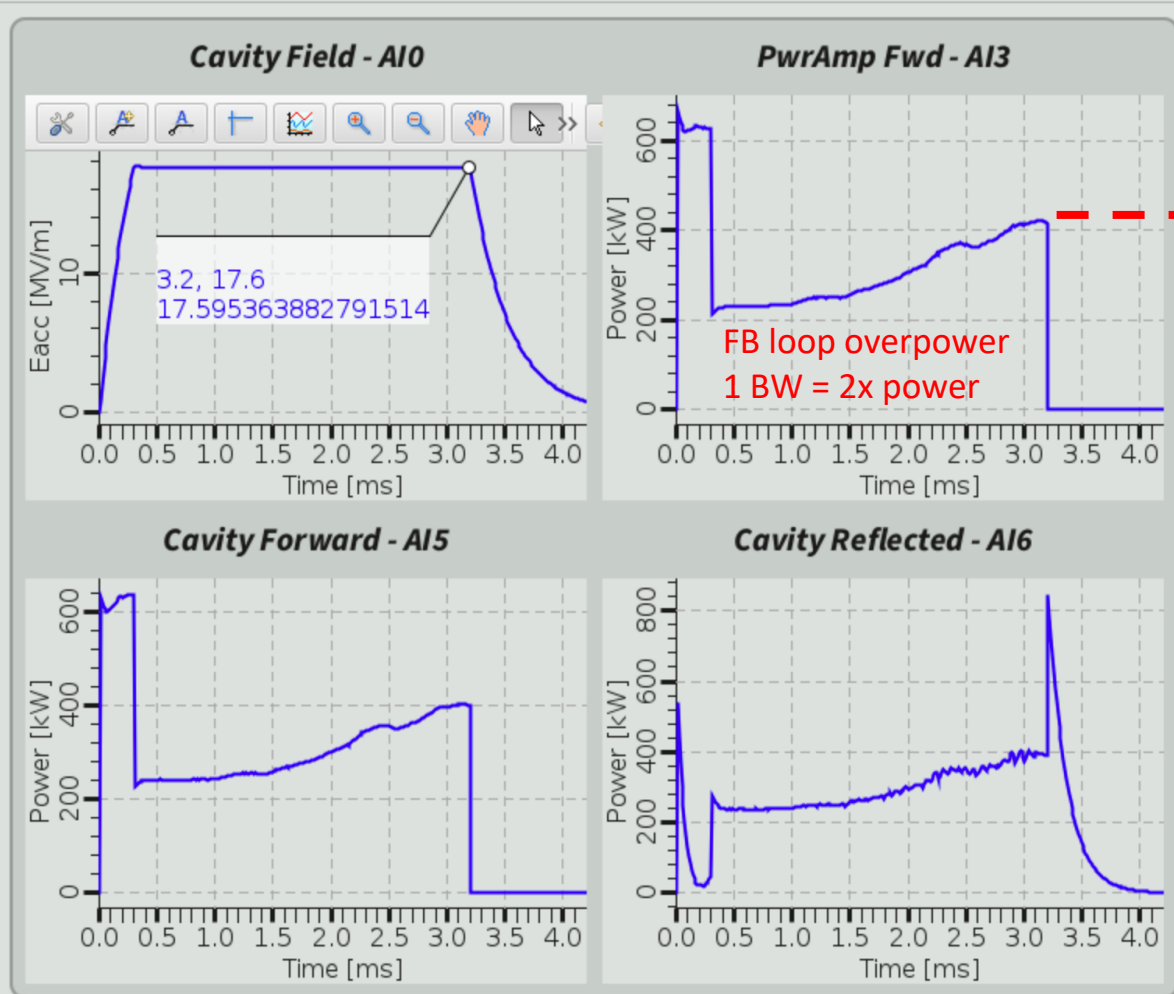


FB Assistance: PIEZO!

Piezo OFF

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

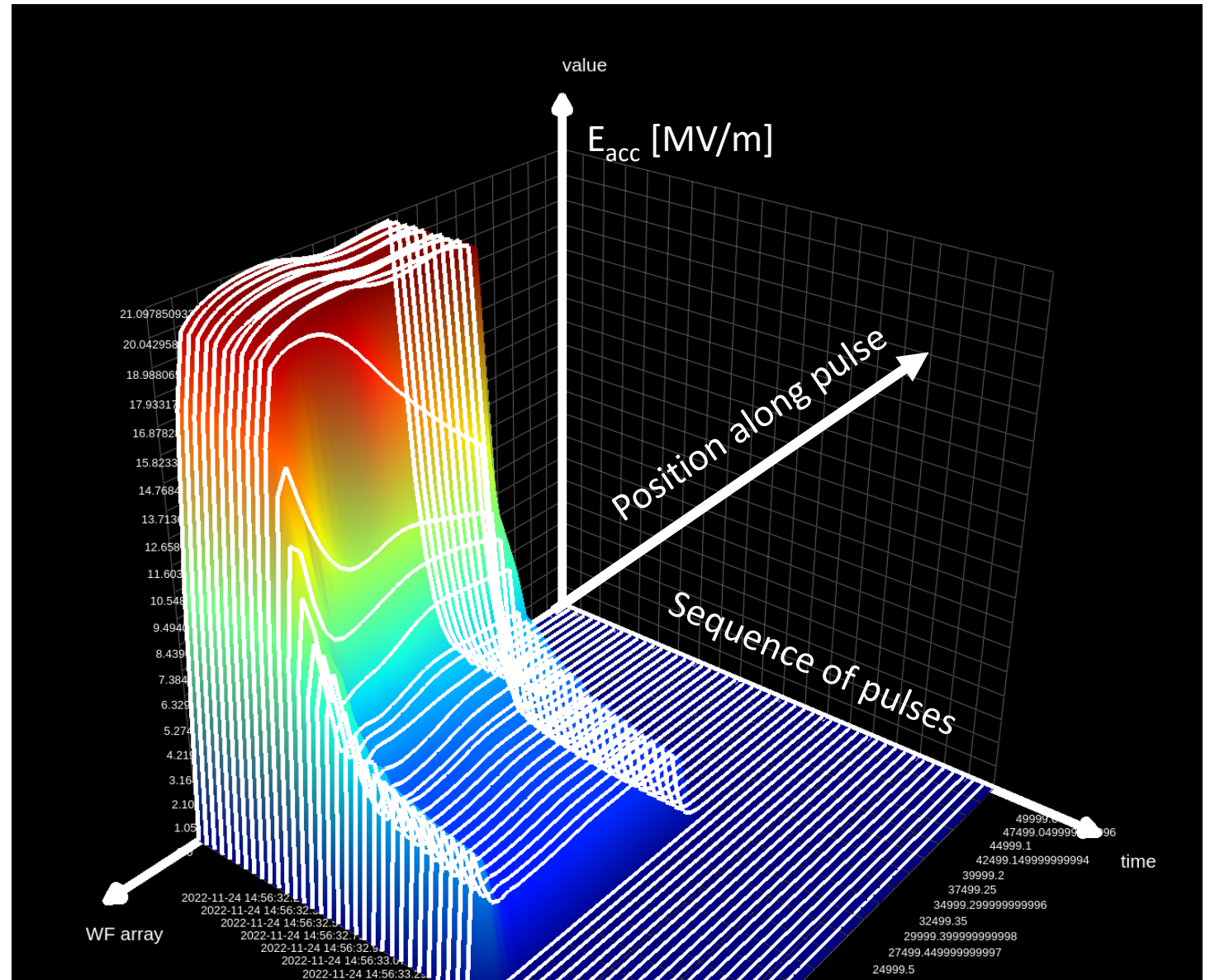
Piezo ON



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