XFEL Operator Training

Low Level Radio Frequency (LLRF)

Marco Diomede, for the DESY LLRF team

Contents

1. Introduction

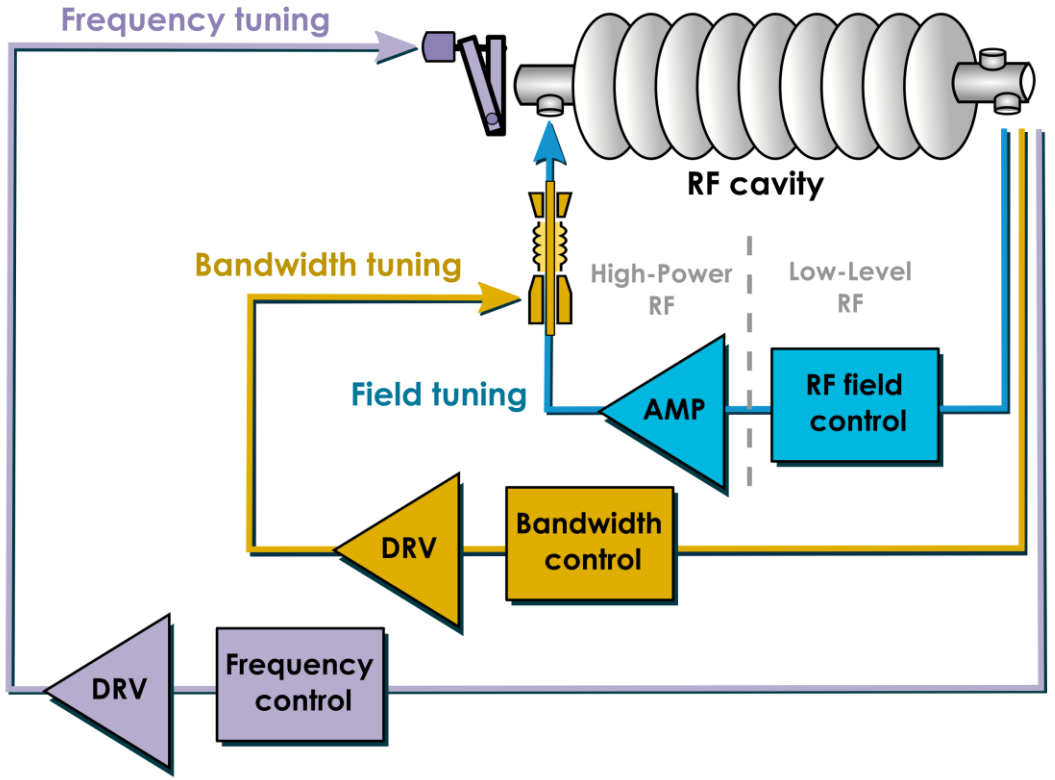
- What is **LLRF**?
- **RF cavities**: equivalent circuit and main parameters
- Cavity **tuning and coupling**
- LLRF and HPRF **system overview**

Introduction

LLRF system

- **L**ow **L**evel **R**adio **F**requency: ***Low Level*** means ***low power*** (i.e. < 1Watt)

- Our task: **digital control of accelerating fields inside the cavities**
  - Normal conducting
    - Gun 1.3 @ GHz
    - TDS Injector @ 3.0 GHz
    - TDS BC2 @ 3.0 GHz
  - Super conducting cavities
    - A1 – A25 @ 1.3 GHz
    - AH1 @ 3.9 GHz



LLRF : measures and **controls**

- the **accelerating field** inside the cavity
- the **bandwidth** of the cavity
- the **resonant frequency** of the cavity

Cavity as an Electrical System

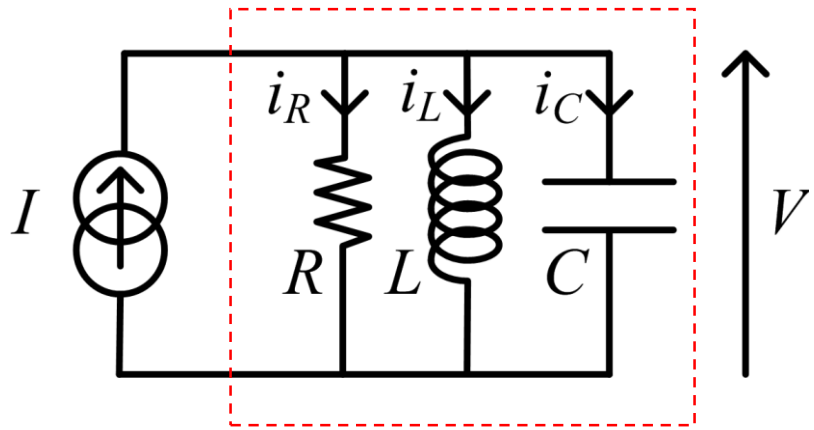
The standard RLC model (simplified)

$$i_R + i_L + i_C = I \quad (1)$$

$$i_R = \frac{V}{R}$$

$$\frac{di_L}{dt} = \frac{1}{L}V \quad (2)$$

$$i_C = C\frac{dV}{dt}$$



$$(1) \rightarrow \frac{di_R}{dt} + \frac{di_L}{dt} + \frac{di_C}{dt} = \frac{dI}{dt}$$

$$(1)\,\&\,(2) \rightarrow \frac{1}{R}\frac{dV}{dt} + \frac{1}{L}V + C\frac{d^2V}{dt^2} = \frac{dI}{dt}$$

$$\rightarrow \quad \frac{d^2V}{dt^2} + \frac{1}{RC}\times\frac{dV}{dt} + \frac{1}{LC}\times V = \frac{1}{C}\times\frac{dI}{dt}$$

$$\ddot{V}(t) + \frac{1}{RC}\dot{V}(t) + \frac{1}{LC}V(t) = \frac{1}{C}\dot{I}(t)$$

2nd order linear differential equation has a solution in the form of

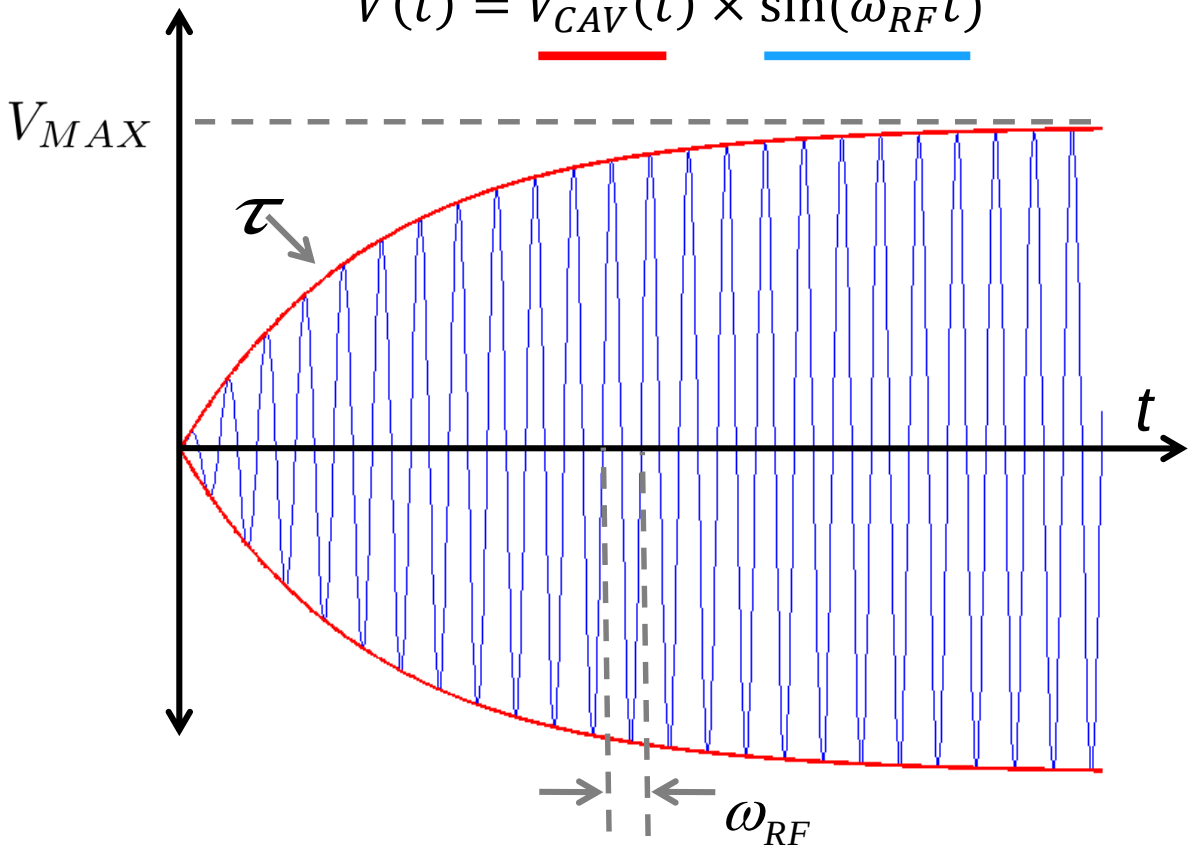
$$V(t) = V_{CAV}(t) \times \sin(\omega_{RF} t)$$

envelope carrier

Cavity as an Electrical System

The envelope equation

$$V(t) = V_{CAV}(t) \times \sin(\omega_{RF} t)$$



V_{CAV} : envelope

$$V_{CAV} = V_{MAX}(1 - e^{-\frac{t}{\tau}})$$

τ is the **cavity time constant**

it depends on the **cavity bandwidth**

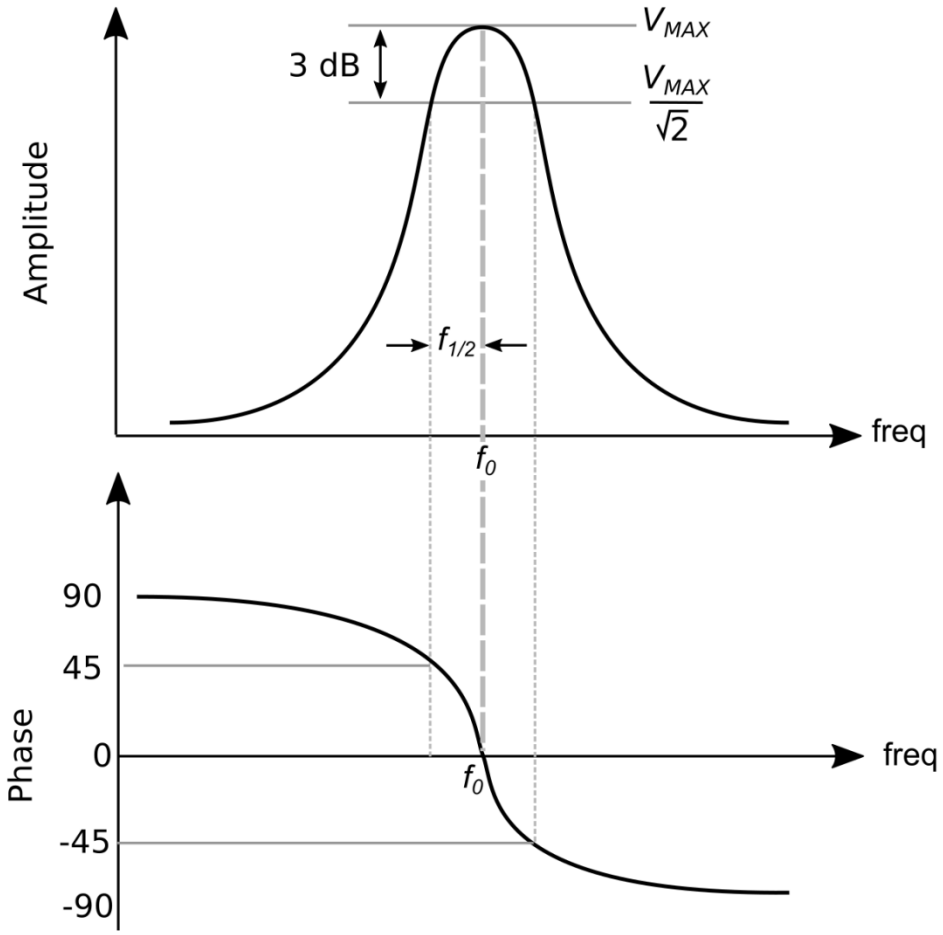
$$\tau = \frac{1}{2\pi f_{1/2}}$$

cavity half bandwidth
(i.e. half of the cavity bandwidth)

Cavity as an Electrical System

In the frequency domain

- Cavity behaves as a **band pass filter**
  - Center frequency f_0
  - Half bandwidth $f_{1/2}$



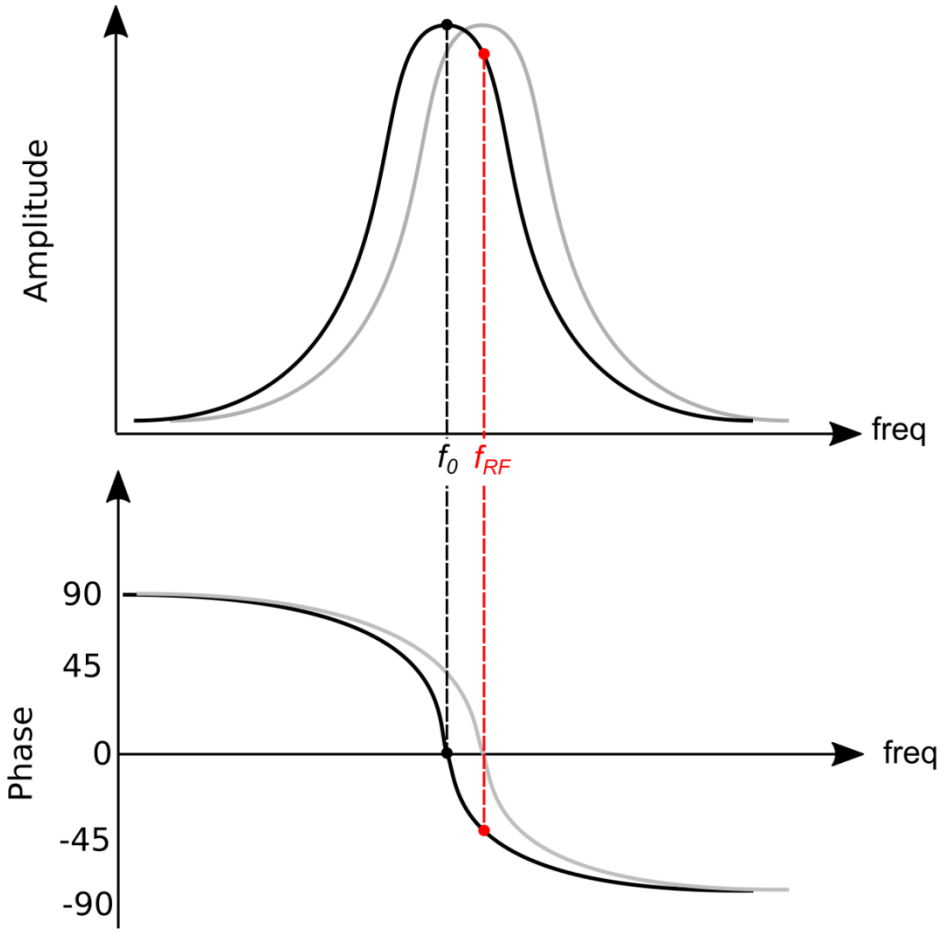
Cavity as an Electrical System

In the frequency domain

- Cavity behaves as a **band pass filter**
  - Center frequency f_0
  - Half bandwidth $f_{1/2}$

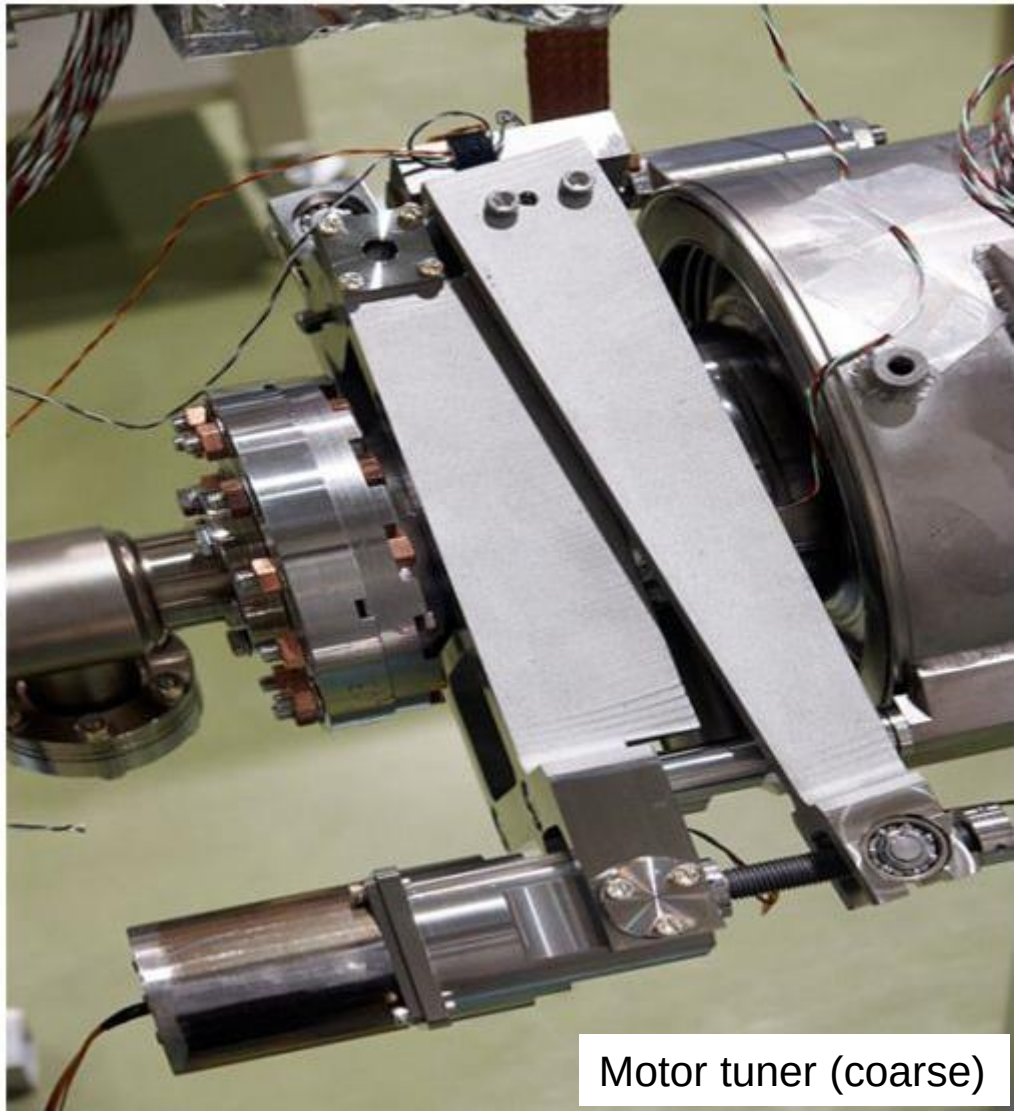
- We can define **detuning** as the difference between the **cavity center frequency** (f_0 = resonance frequency) and the frequency of the **RF drive** (f_{RF})

$$\Delta\omega = \omega_0 - \omega_{RF} = 2\pi(f_0 - f_{RF})$$

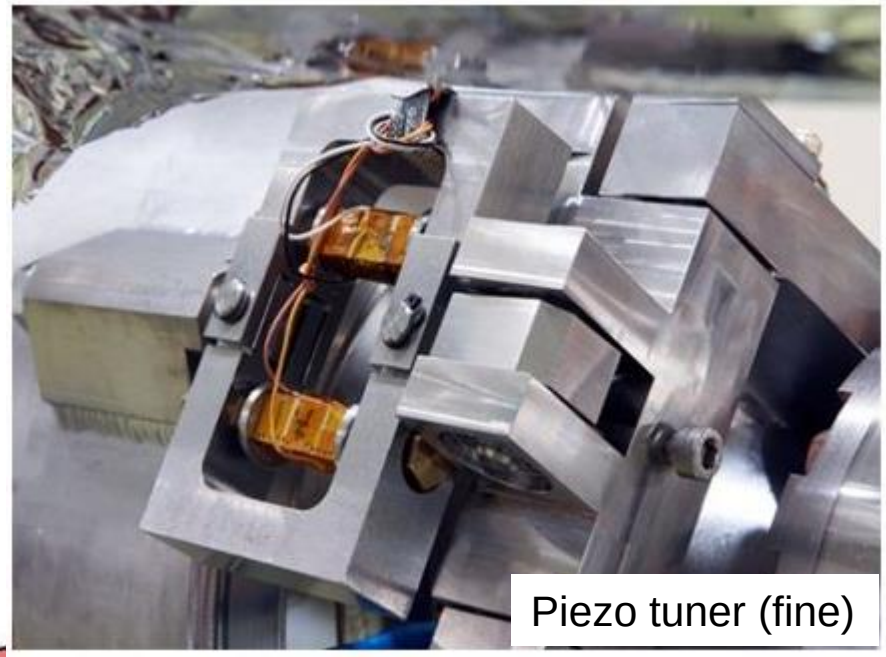


Tuner examples

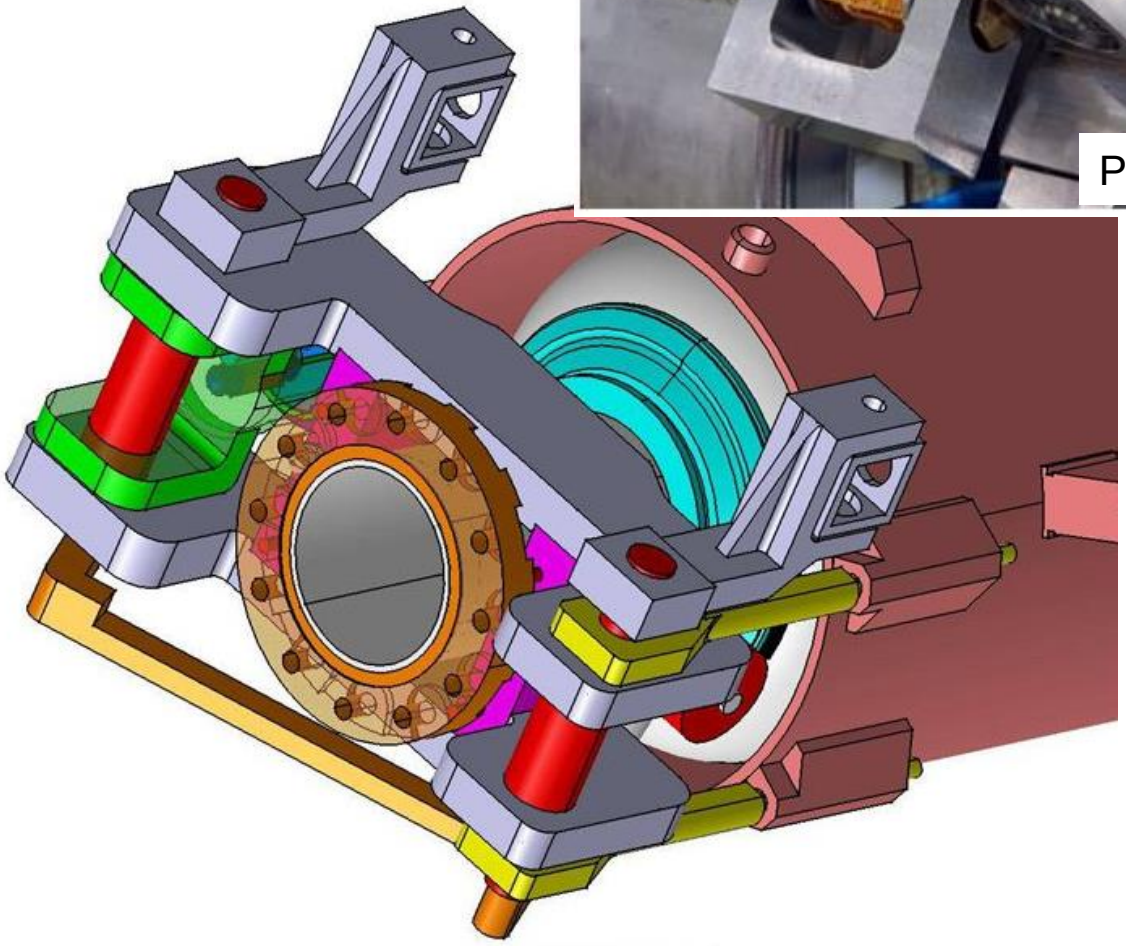
Saclay type (EuXFEL)



Motor tuner (coarse)



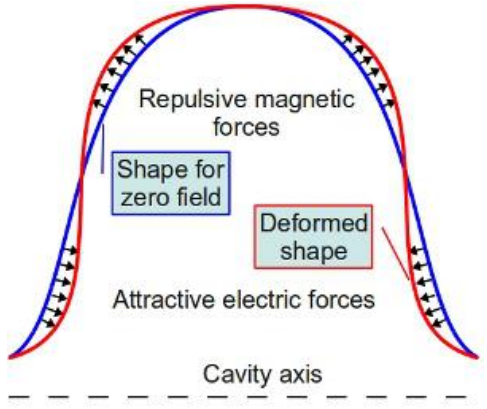
Piezo tuner (fine)

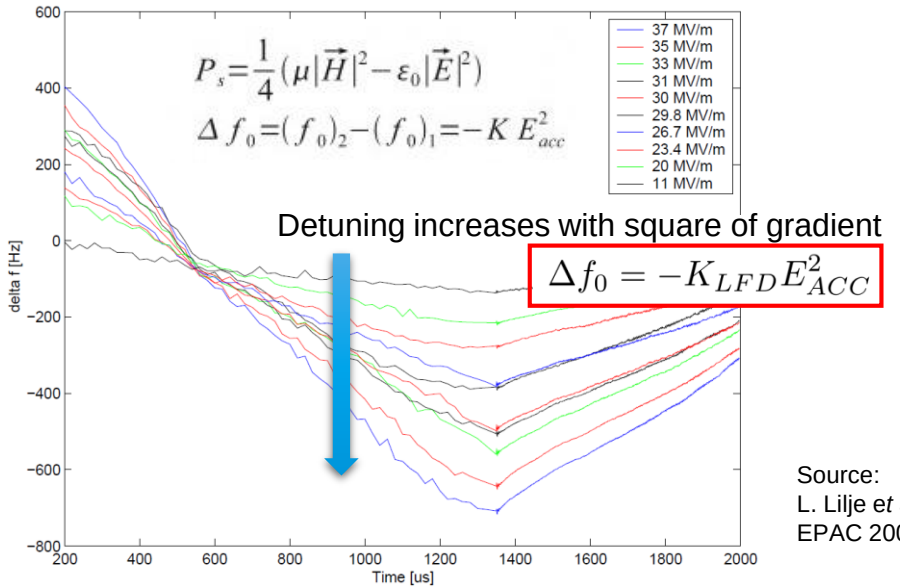


Cavity “fine” tuning

Use of piezo in pulsed mode

- Lorentz Force detuning





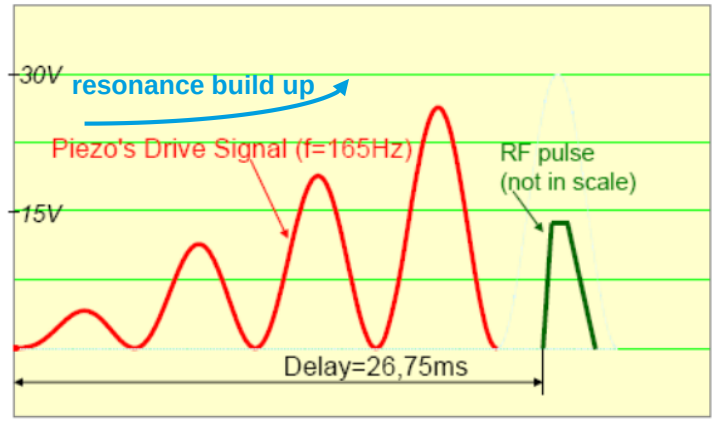
Detuning increases with square of gradient

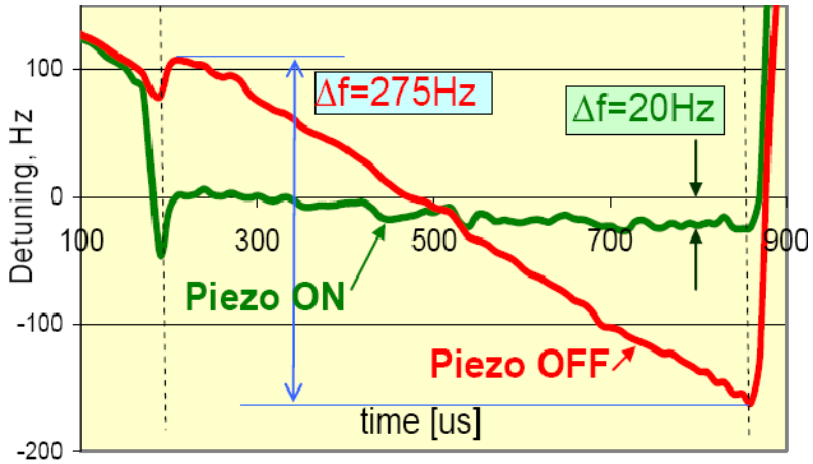
$$\Delta f_0 = -K_{LFD} E_{ACC}^2$$

Source:
L. Lilje *et al.*
EPAC 2006

- Lorentz force detuning compensation using piezo

Piezo stimulus:
- Frequency
- Delay
- AC amplitude
- DC offset





Example from FNAL 2007
R. Carcagno *et al. SRF 2007*

Cavity coupling

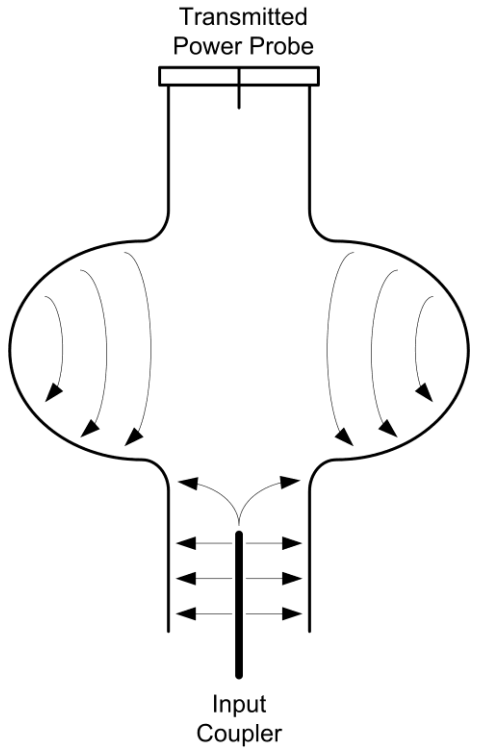
Coupling power in and out of a cavity

Input coupler

- An antenna carries power from an RF source to the cavity
- The strength of the **input coupler** is adjusted by changing the penetration of the center conductor

Output coupler (pick up)

- the **transmitted power probe** (fixed coupler) picks up power transmitted through the cavity



Measurable "resulting" quality factor (**loaded** Q)

$$Q_L = \left(\frac{1}{Q_{ext}} + \frac{1}{Q_0}\right)^{-1}$$

External quality factor modified by the coupler antenna position

Cavity **unloaded** quality factor

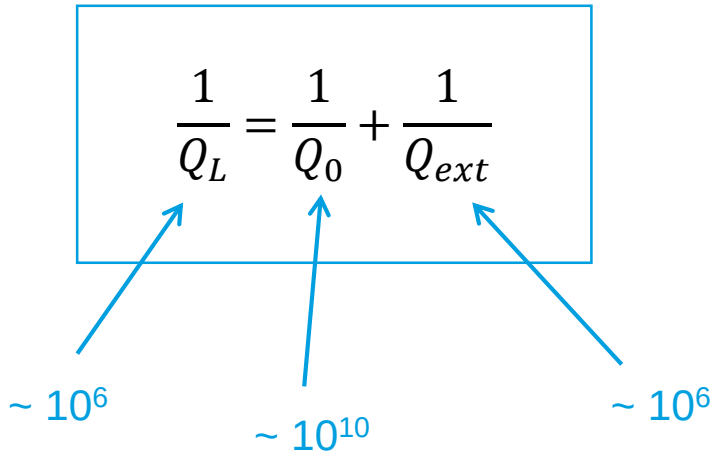
Cavity coupling

Understanding unloaded, loaded and external coupling

- Q_0 = **unloaded** quality factor
  - Measured without the cavity power coupler
  - Is a direct indication of the power dissipated in the cavity walls (high Q0 → low losses)

- Q_{ext} = **external** quality factor
  - Can be changed when moving the coupler antenna
  - Impacts how the incoming RF power couples into the cavity
  - High Q_{ext} means slow response time, but less power required to reach high gradient

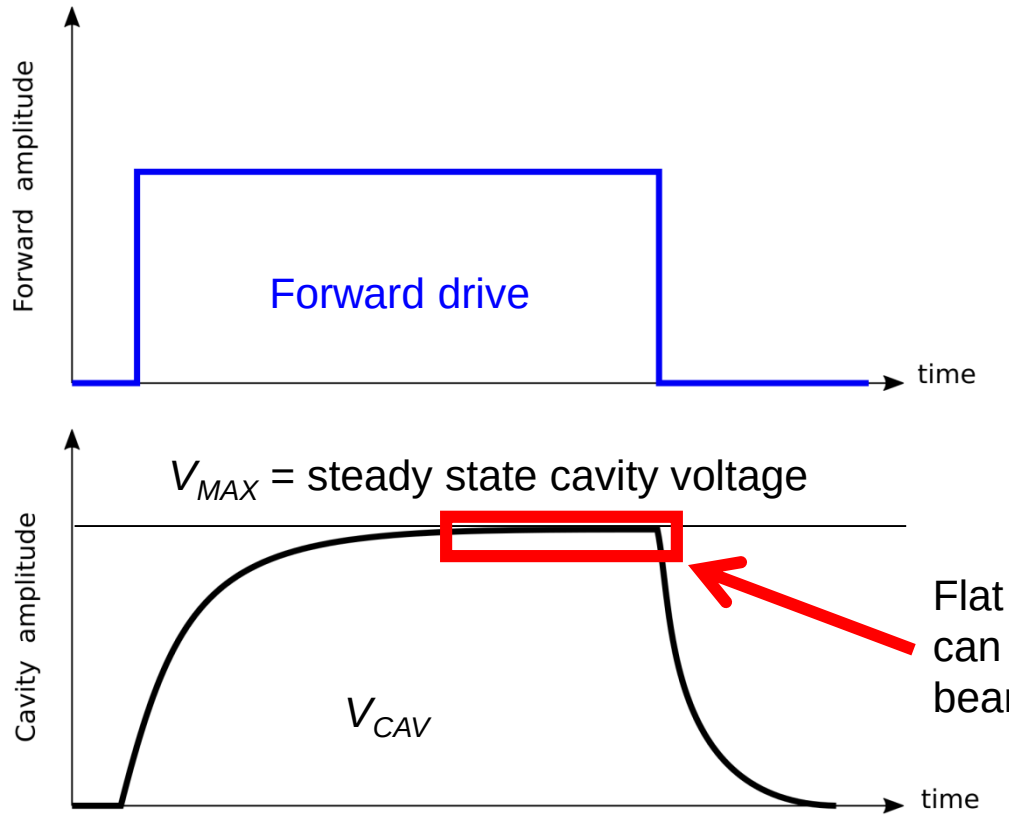
- Q_L = **loaded** quality factor
  - “Resulting” or “Effective” quality factor
  - Is what can be measured during operation
  - Changes in Q_0 are masked by Q_{ext}



LLRF System

Feed Forward

- Cavity response to a square pulse



Flat RF region that can be used for beam acceleration

Q_L affects the cavity rate of filling and cavity bandwidth

Q_L is there → $\tau = \frac{Q_L}{2\omega_0} = \frac{1}{2\pi f_{1/2}}$

$$V_{CAV} = V_{MAX}(1 - e^{-t/\tau})$$

$$V_{MAX} = 2\sqrt{P_{FWD}\frac{R}{Q}Q_L}$$

Q_L is there

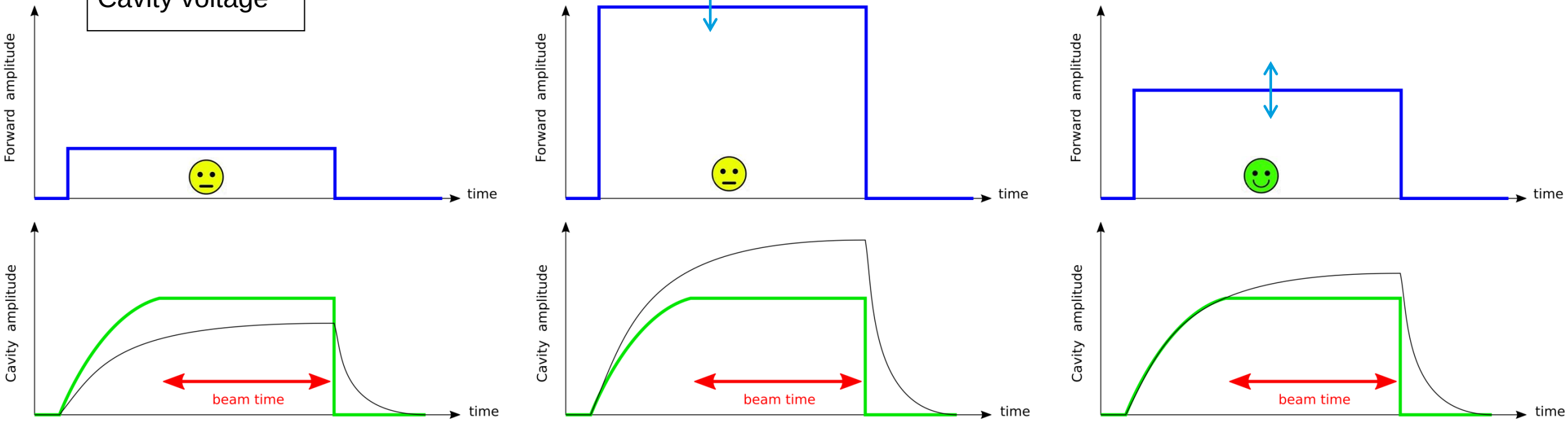
Q_L affects the cavity maximum voltage (for a given forward power)

LLRF System

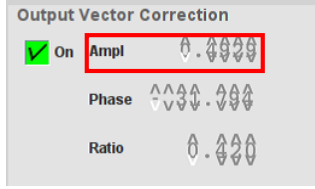
Feed Forward

- Adjust amplitude of the **forward drive** to match the set point gradient **at the beginning of the beam time**

Forward drive
Cavity set point
Cavity voltage



OVC amplitude!

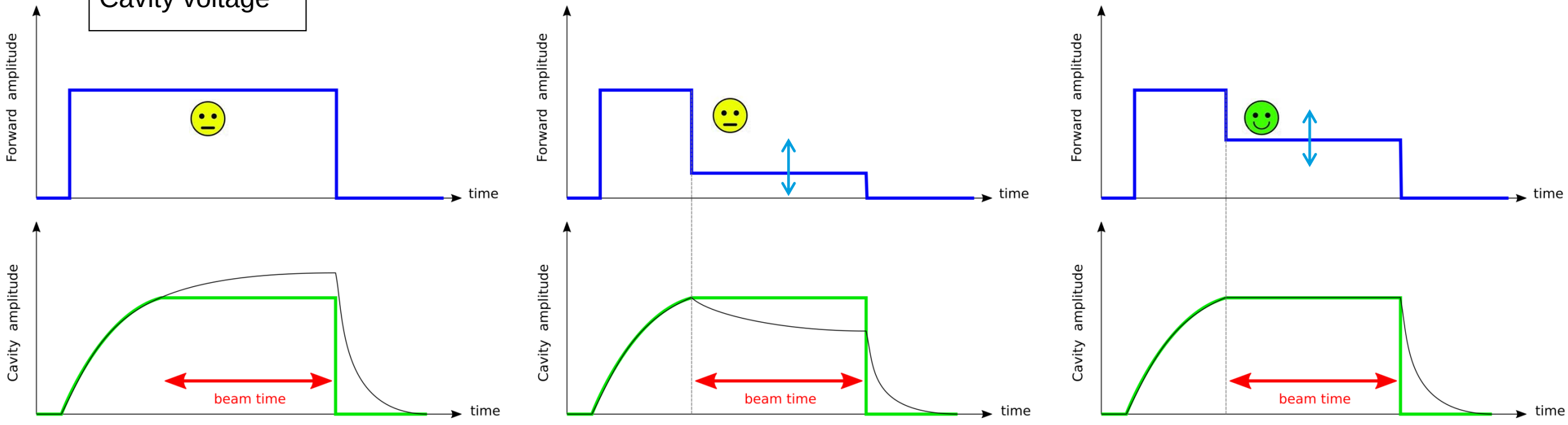


LLRF System

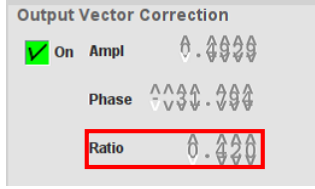
Feed Forward

- Adjust the drive **during the beam time** to **maintain a flat accelerating gradient**

Forward drive
Cavity set point
Cavity voltage



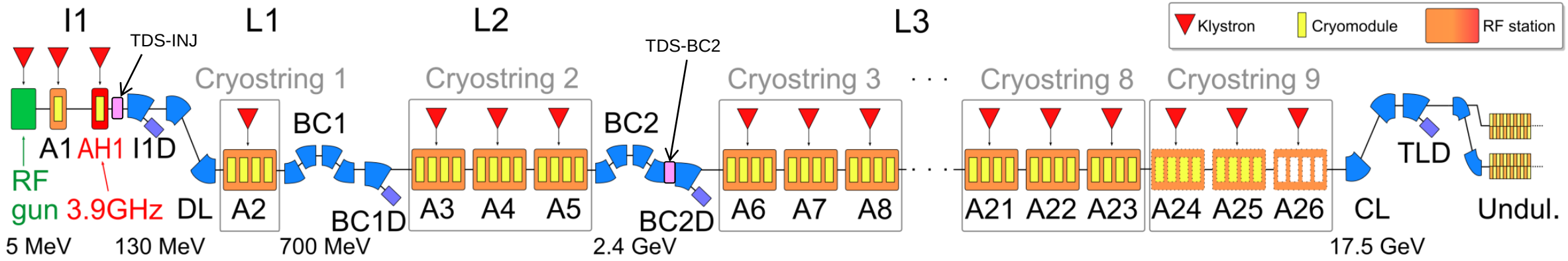
OVC ratio!

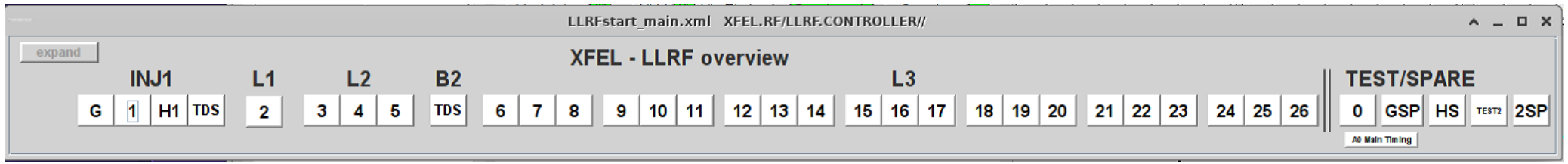


Introduction

LLRF Systems

- Where are we involved?
  - In every RF station
  - 29 LLRF systems



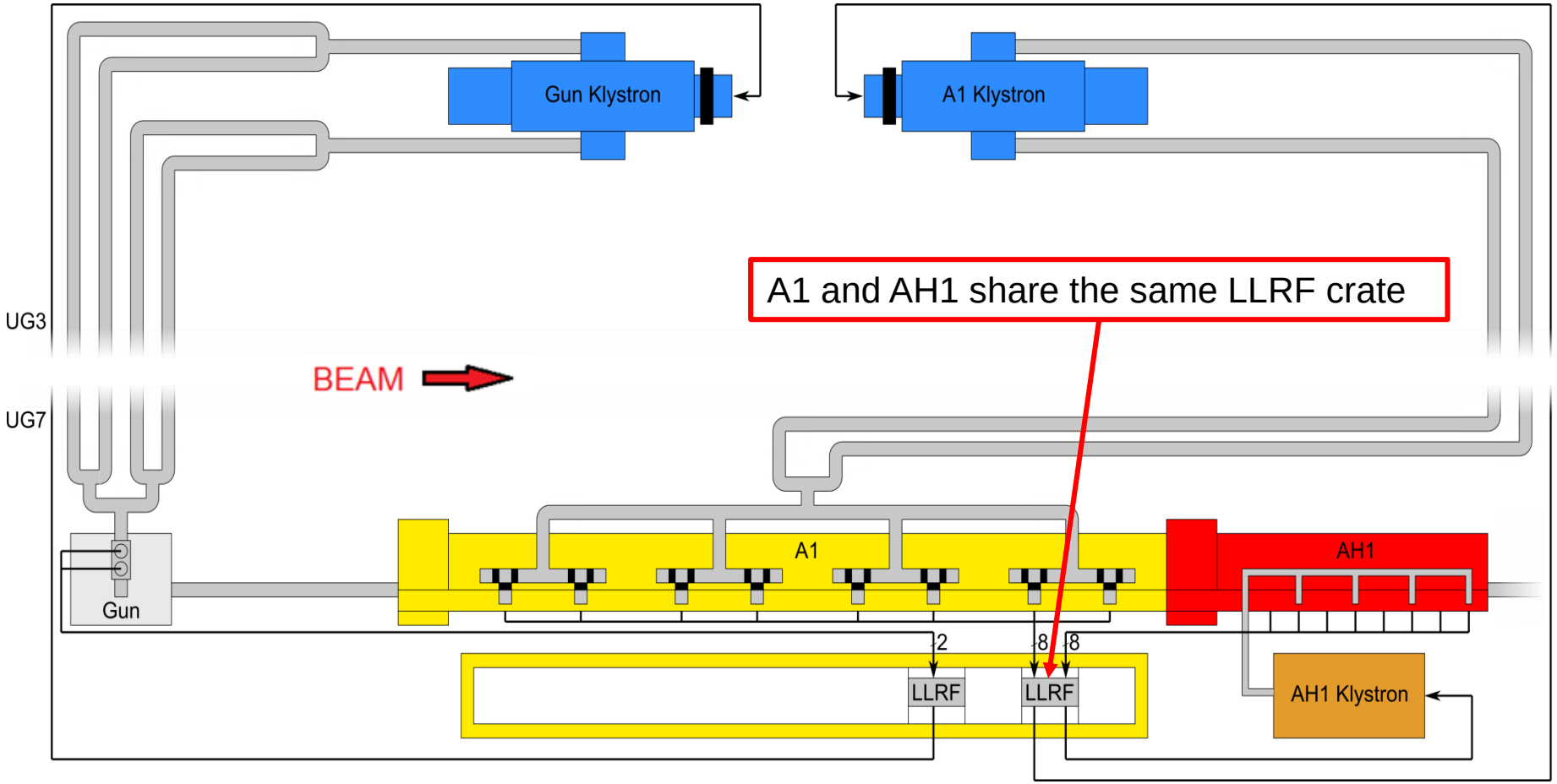


reserved for tests

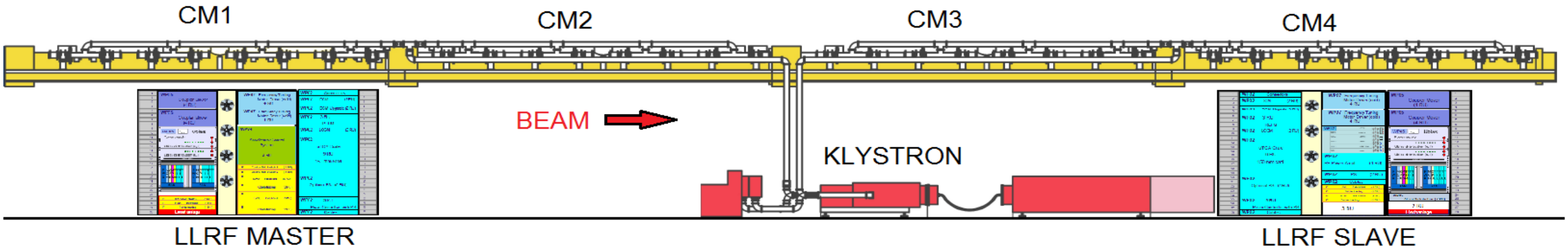
Introduction

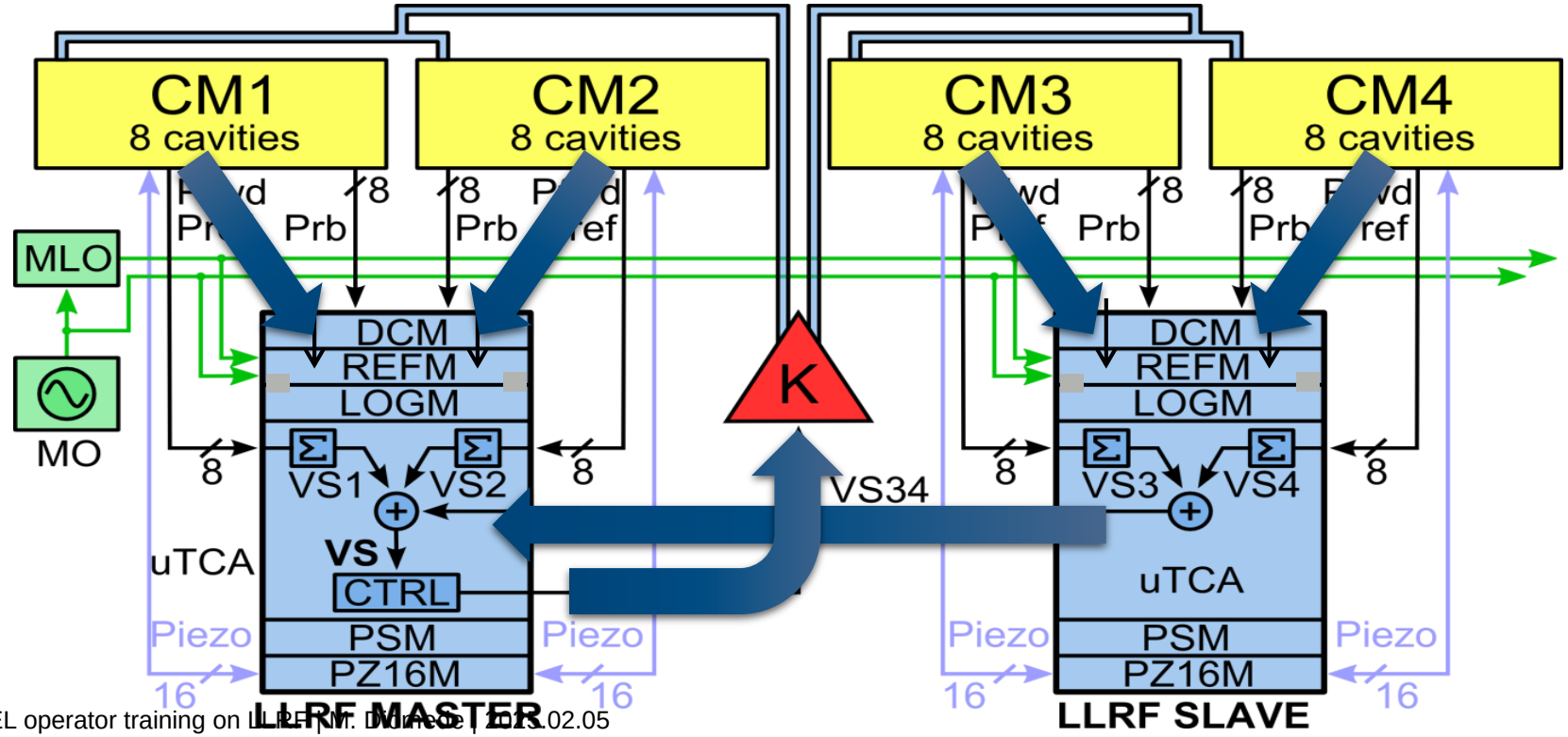
LLRF Systems

- RF Stations in the **injector**



Introduction : LLRF Station Overview





DCM
Drift Compensation Module

REFM
RF Reference Module

LOGM
Local Oscillator Generation Module

PSM
Power Supply Module

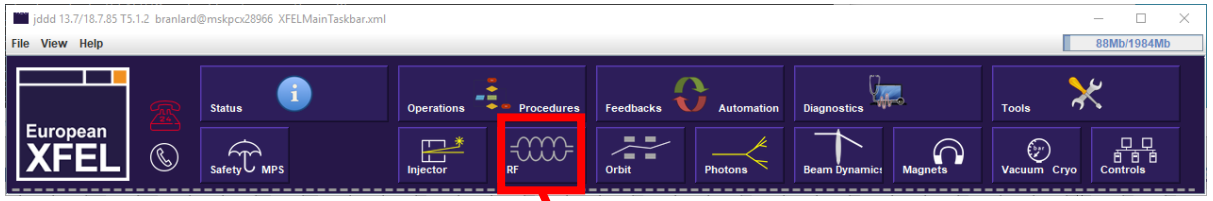
PZ16M
Piezo Driver Module

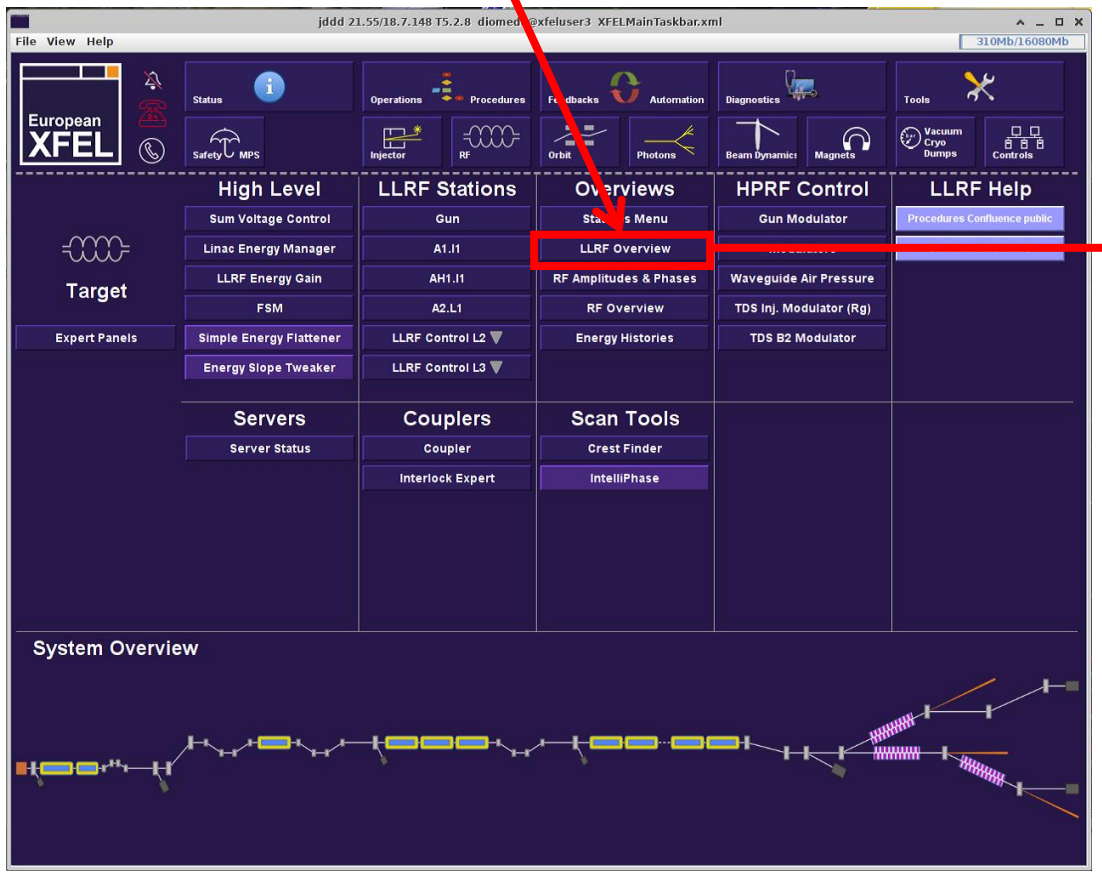
2. What an operator should know

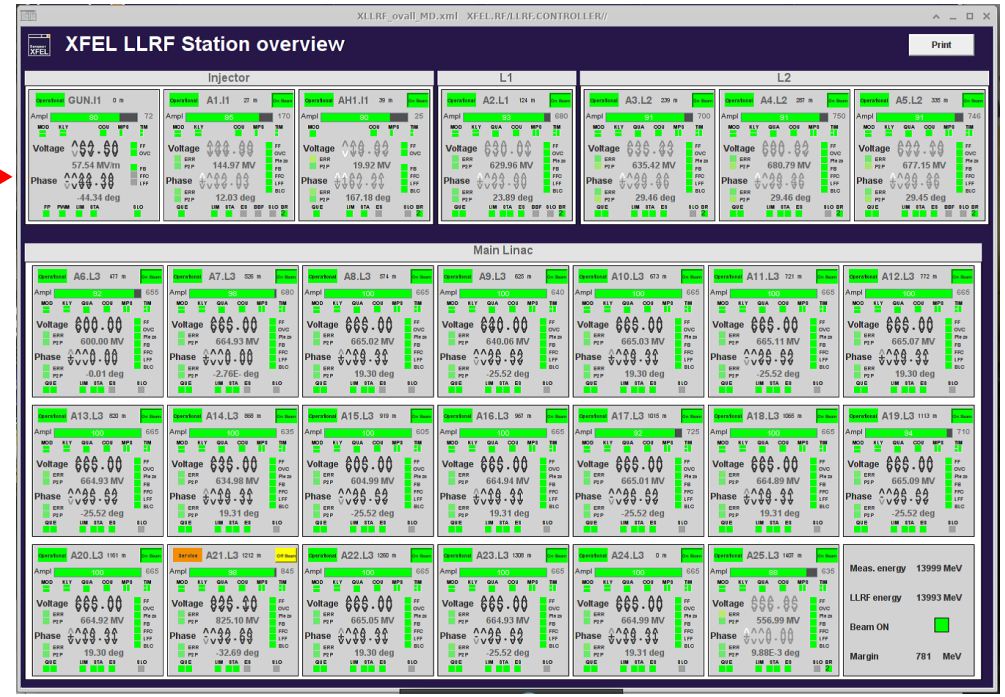
- LLRF tasks of the XFEL operator:
  - Turn an RF station **ON / OFF**
  - Adjust the vector-sum **voltage / phase**
  - **Tune** cavities, if necessary
  - Adjust **output vector correction** and **ratio**, if necessary
  - Set a certain phase as **on-crest phase**

What an operator should know

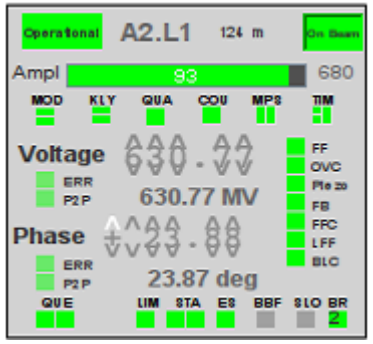
LLRF overview





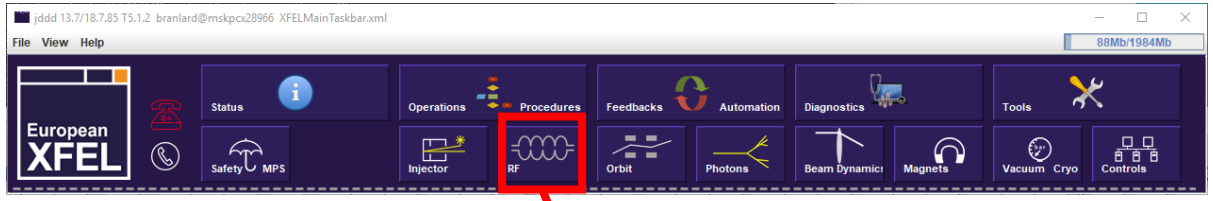


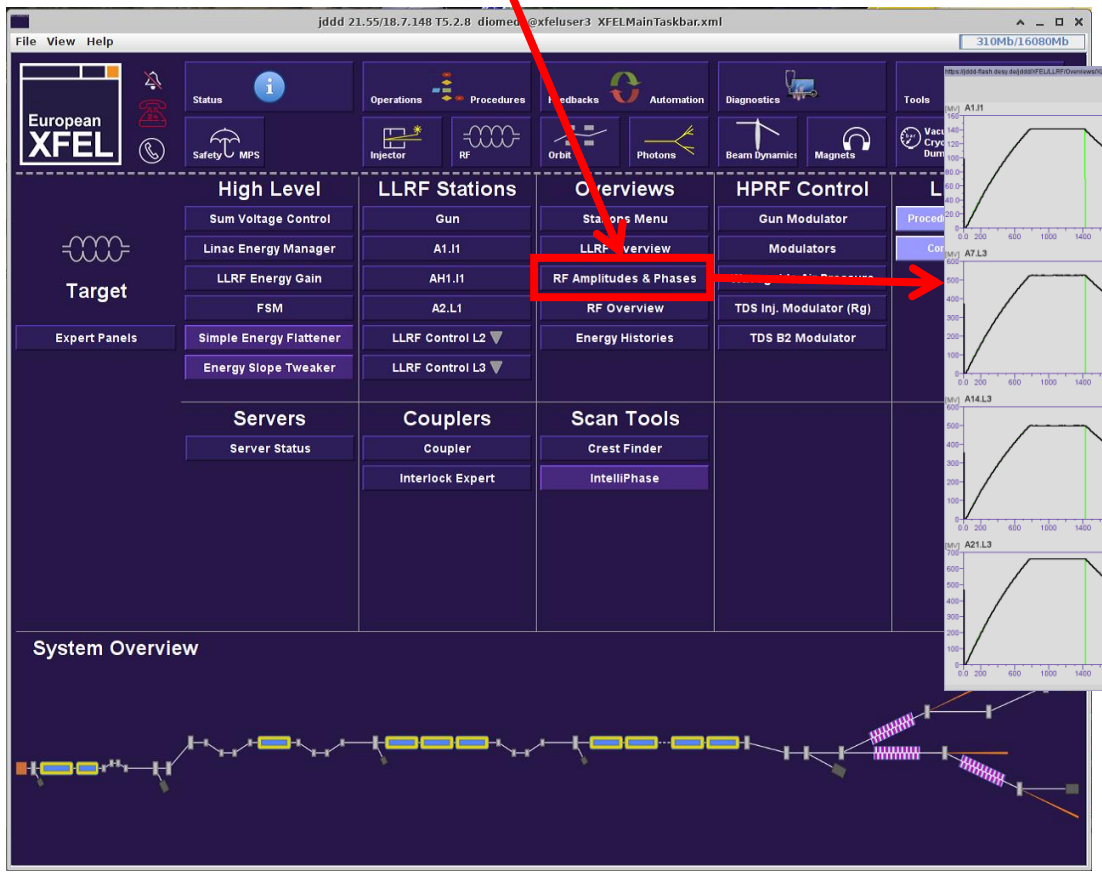
Check amplitude and phase set point, RF control settings and flat tops

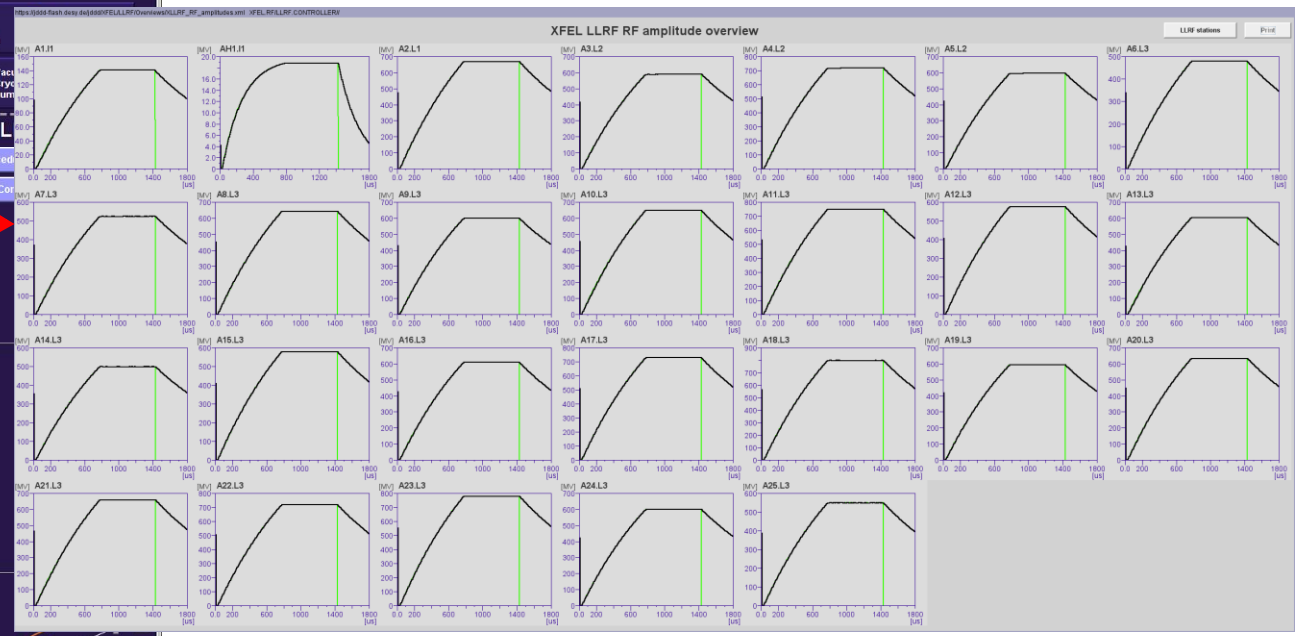


What an operator should know

RF Amplitudes





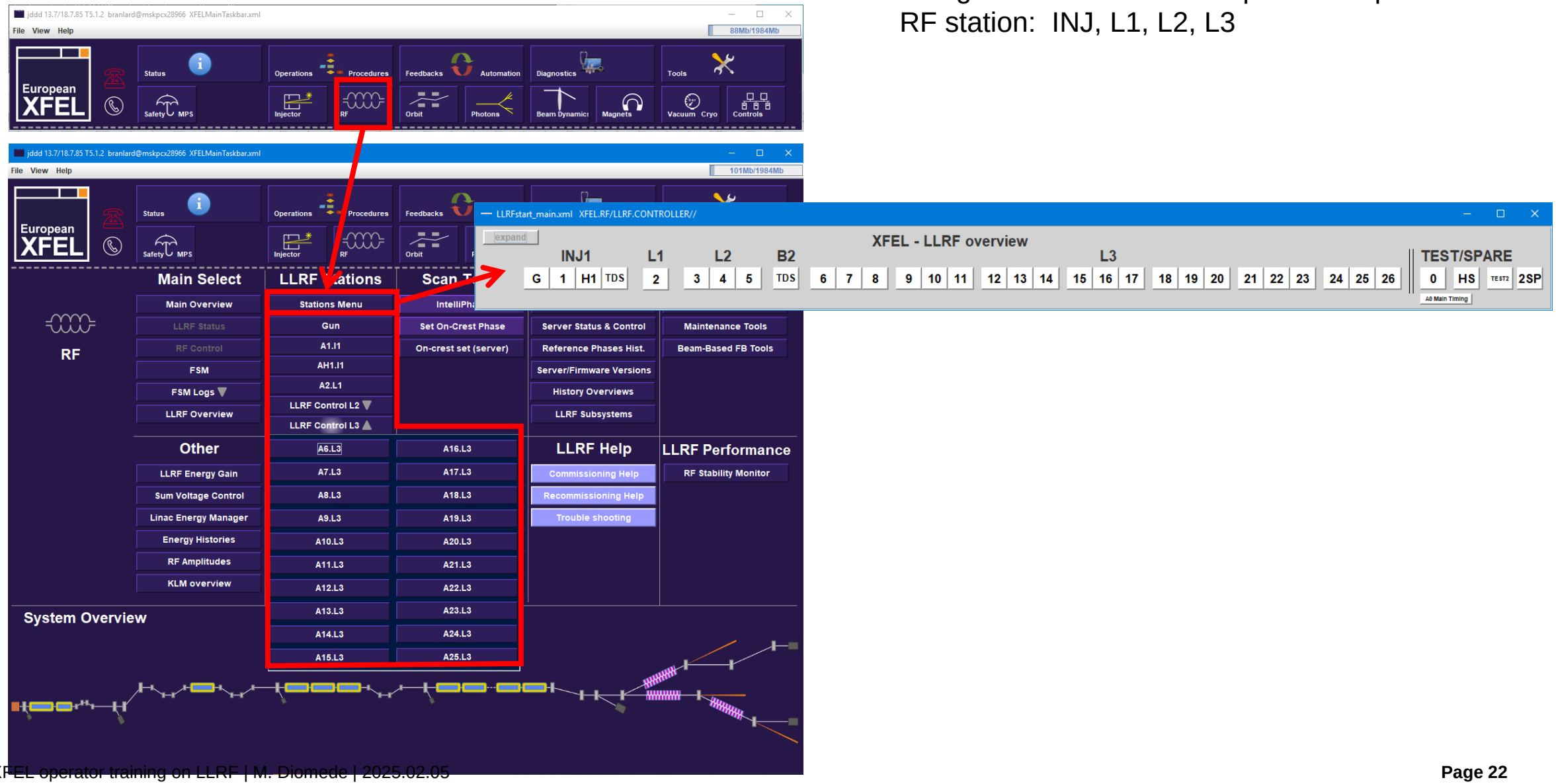


Check waveform profiles
(open loop, glitches, etc…
i.e. deviation from set point)

What an operator should know

LLRF selector

Navigate to the main LLRF panel of a particular RF station: INJ, L1, L2, L3



What an operator should know

Scalar/Table mode

Voltage setpoint

Phase setpoint

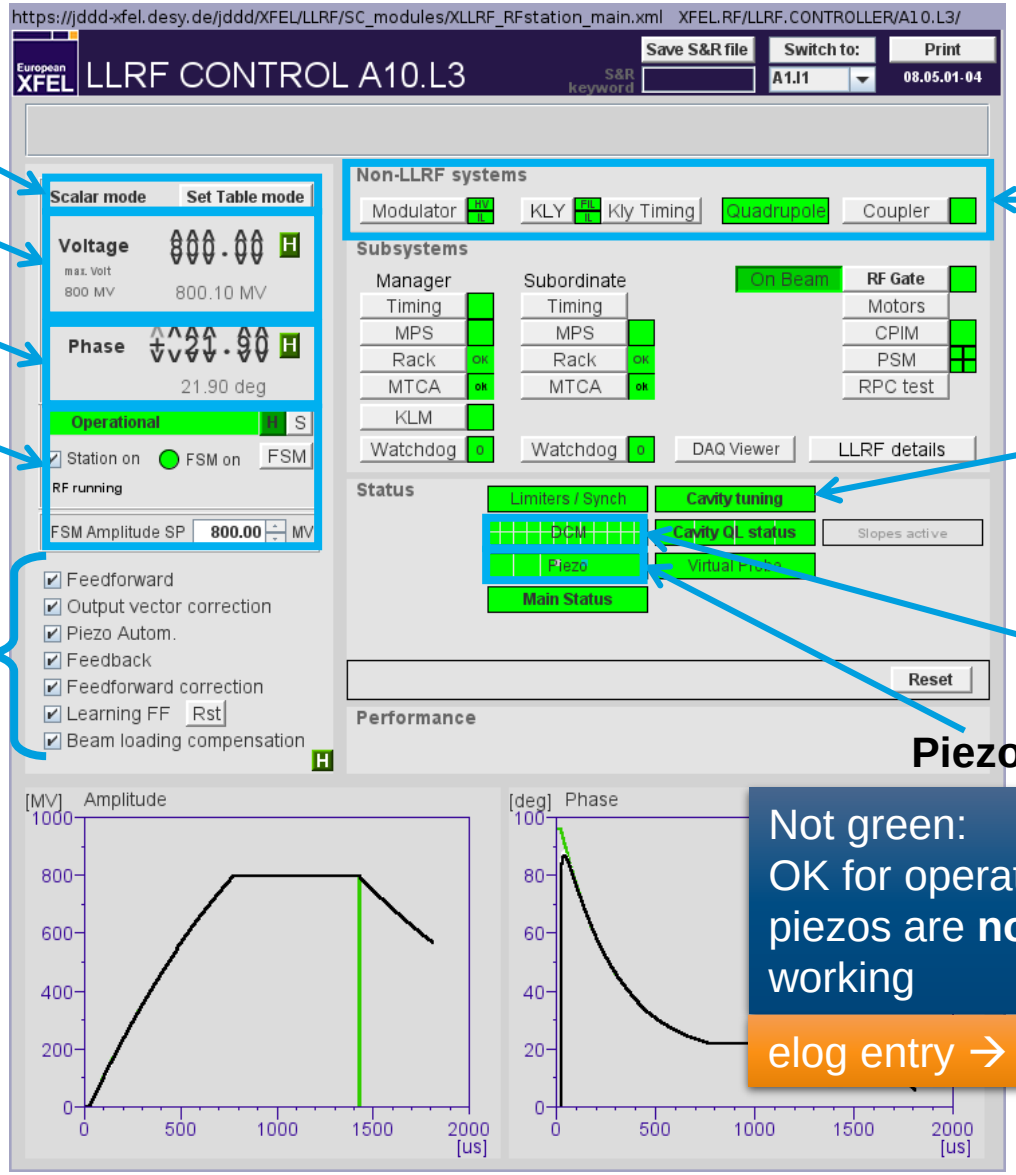
Ramp station with FSM
Check for ON,
FSM should be green
FSM recovery voltage
Quench notifications

Ramp-down
(open loop)

ALL these settings
should be enabled*

Ramp-up

* exception gun



Non-LLRF systems!

Cavity tuning indicator (should be green)

Drift compensation module (DCM)

Piezo

Not green:
OK for operation but piezos are **not** working

elog entry → LLRF

Not green:
OK for operation but drifts are **not** compensated

elog entry → LLRF

What an operator should know

Limiters

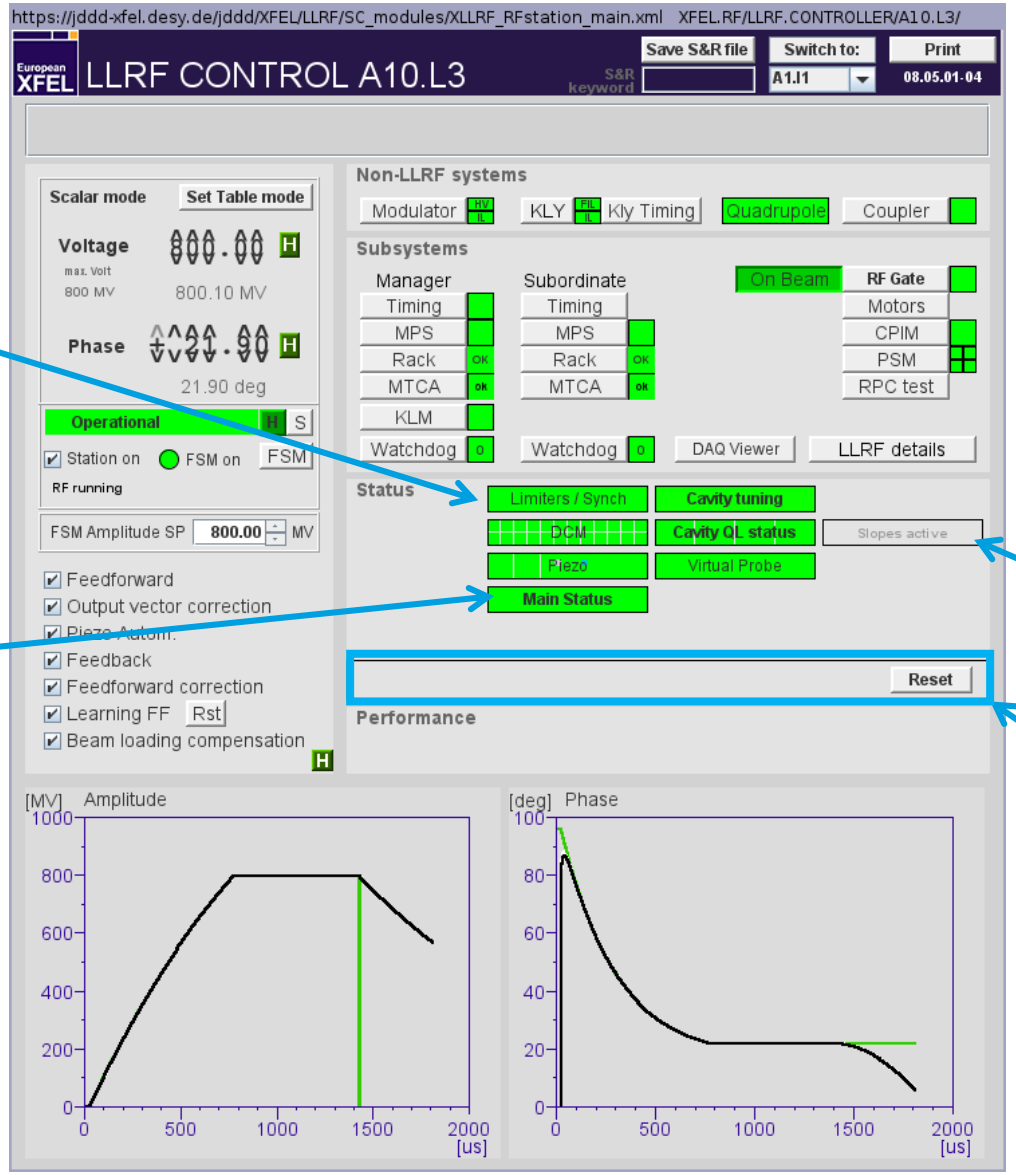
Not green:
Might lead to RF pulse cuts

elog entry → LLRF

Main status

Not green:
Operation might still be possible

elog entry → LLRF

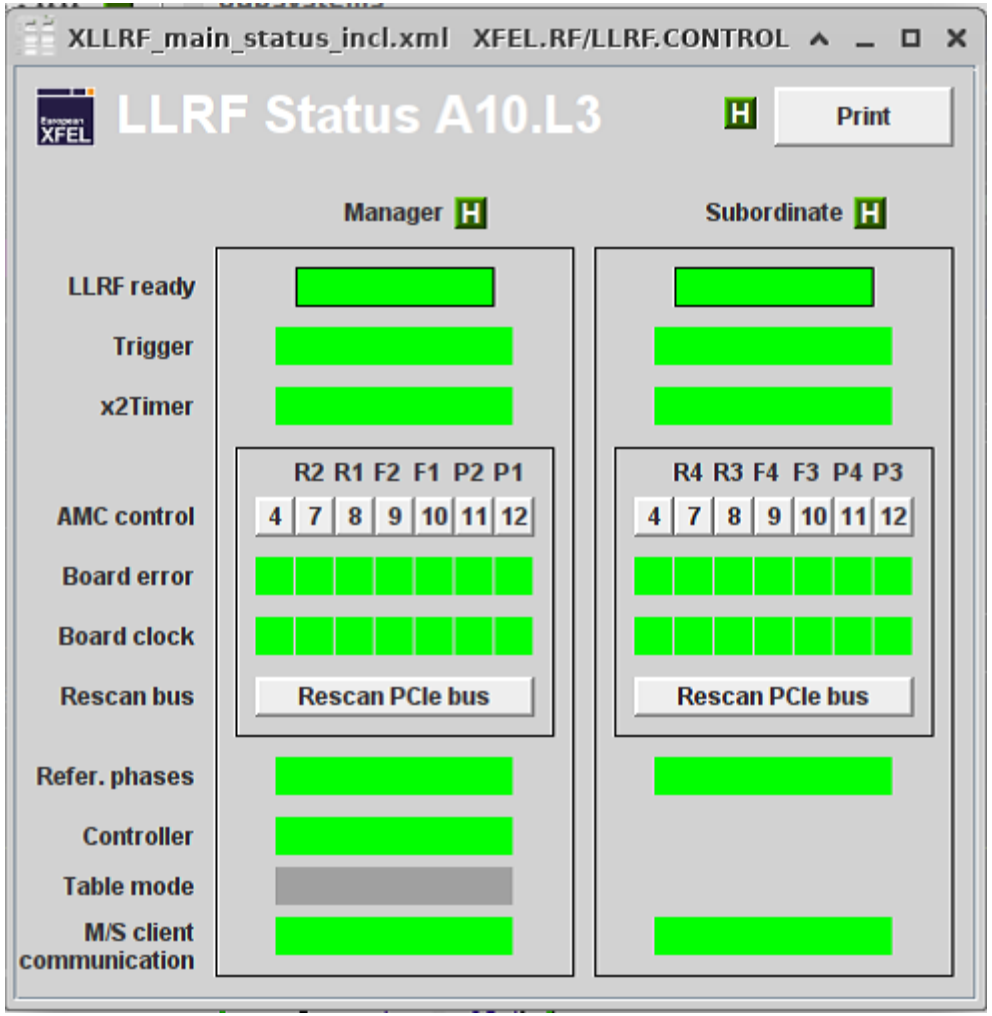


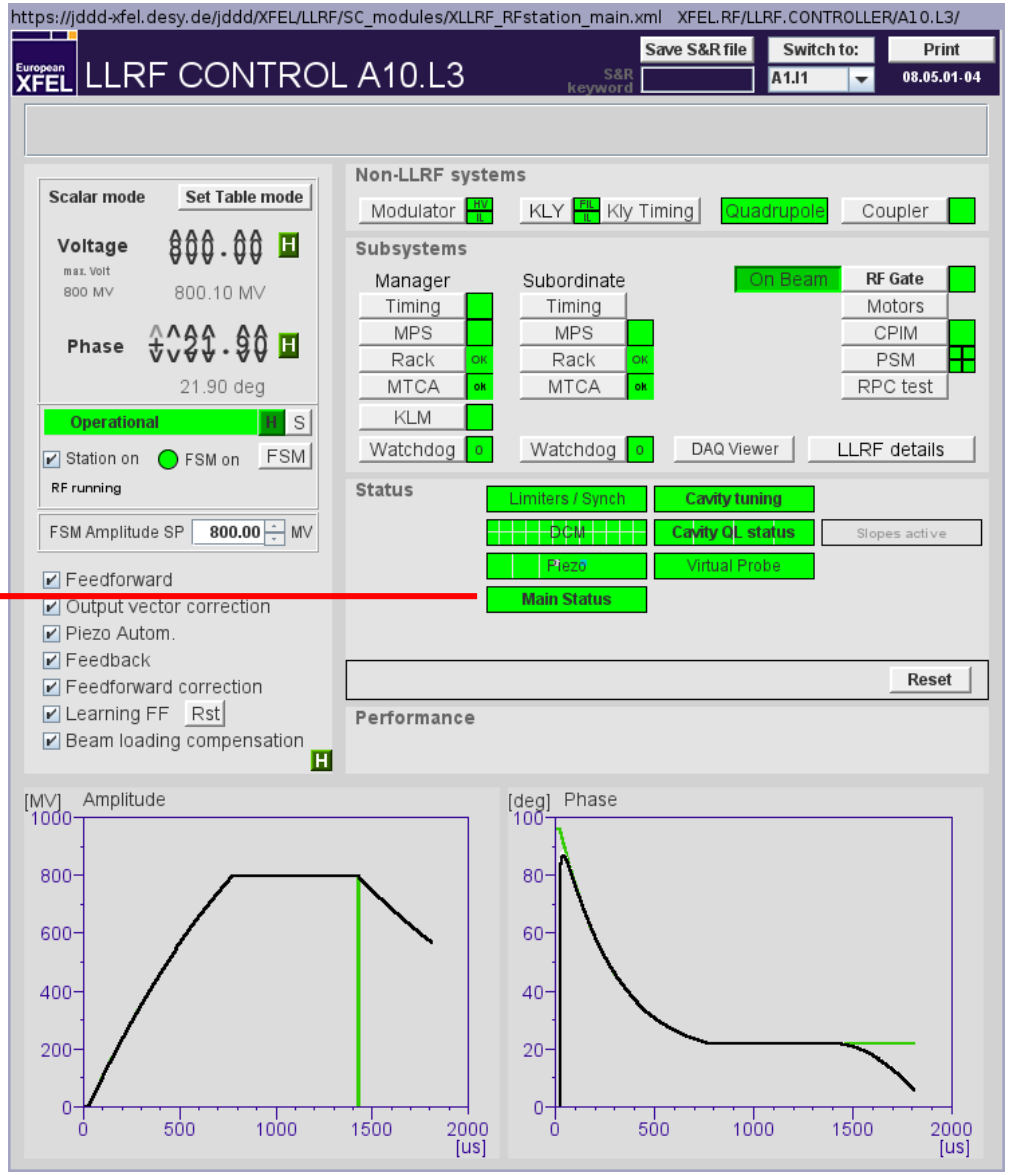
Slopes active (yellow): i.e. RF slope across the flat top

Error message area (it self-clears after 5 minutes after the error is gone)

What an operator should know

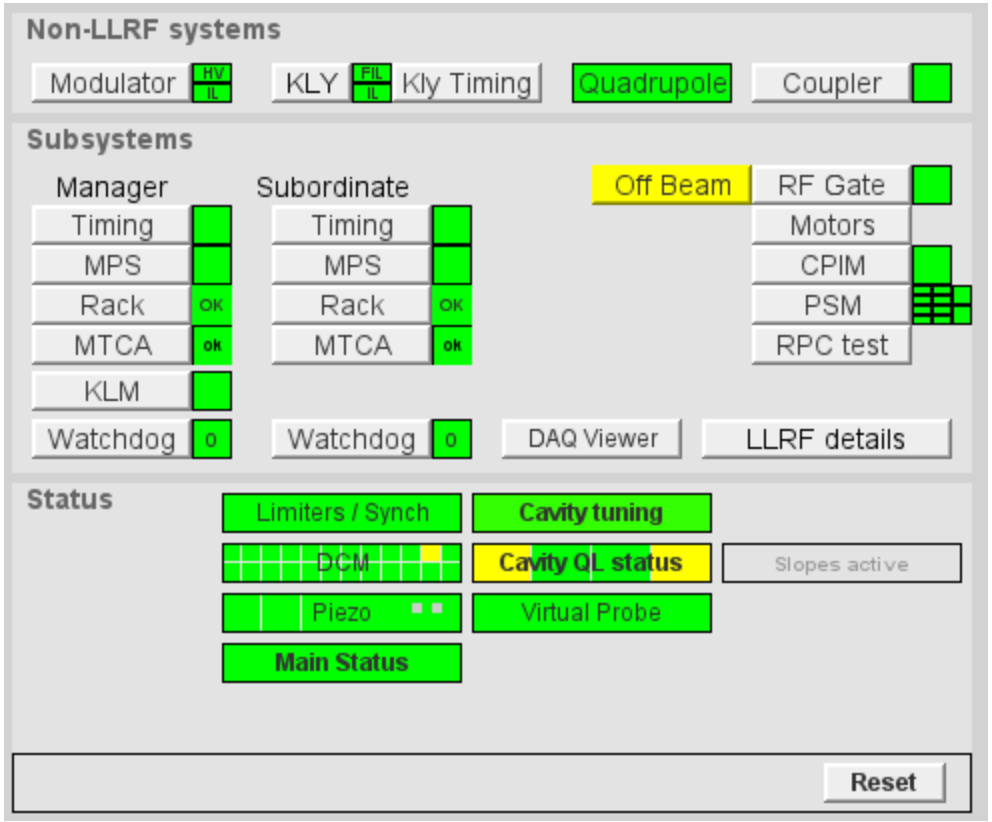
What an operator should know



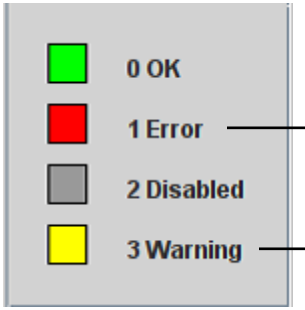


What an operator should know

LLRF color code



Color code



Operation probably not possible

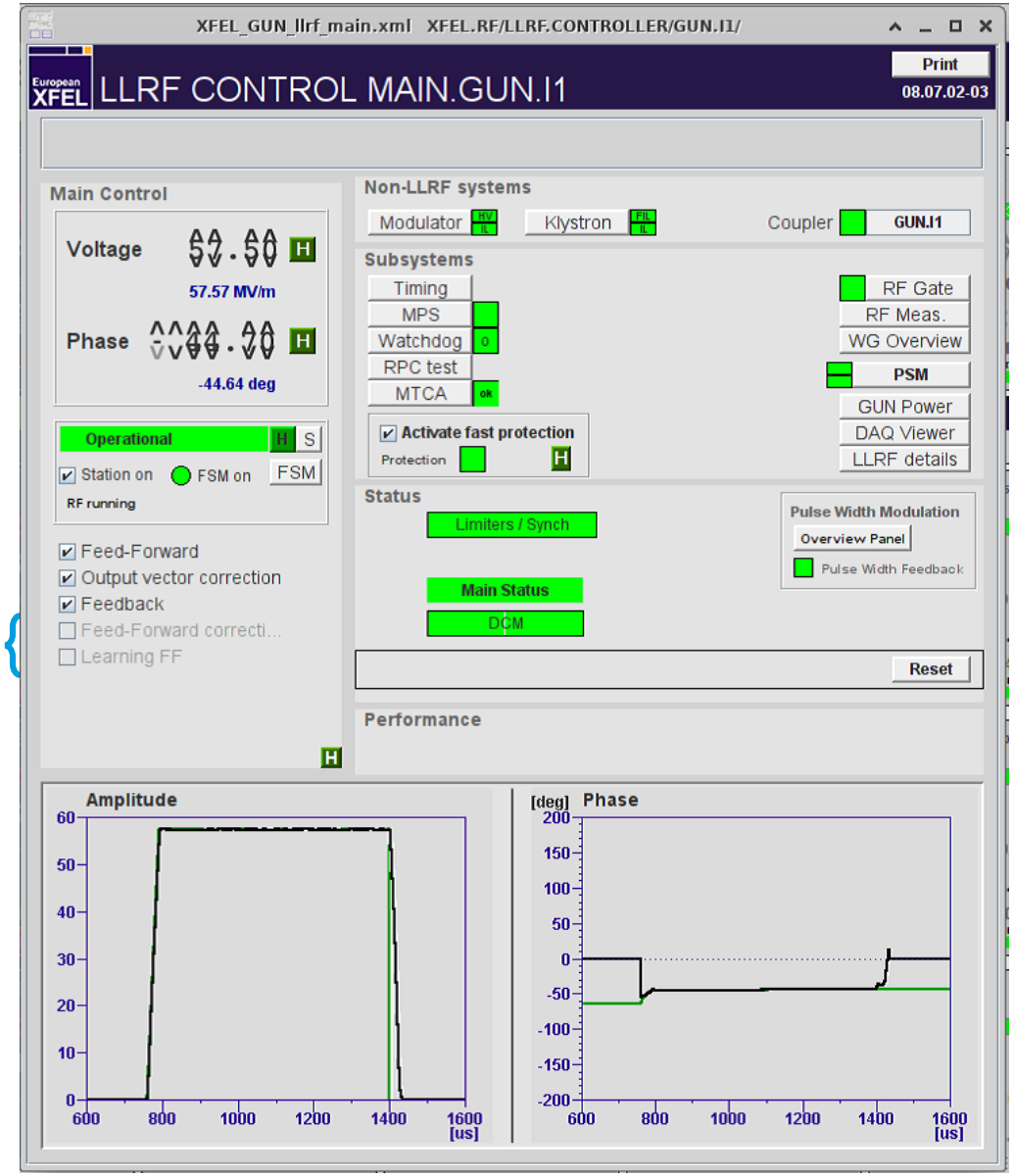
Operation still possible!

What an operator should know

Special case GUN

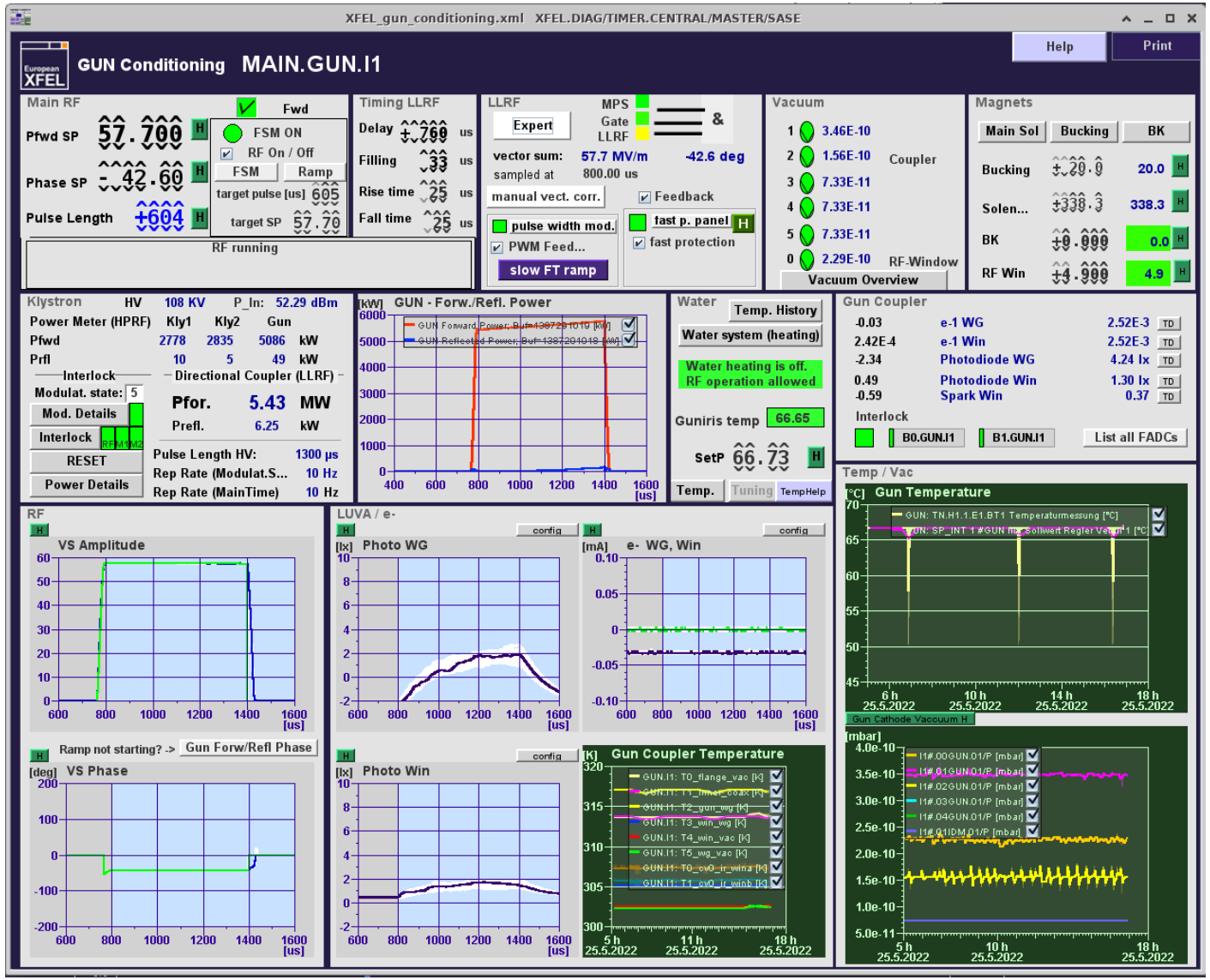
Note that for the gun, the following features are **greyed out** and should stay **disabled:**

- Feed-forward correction
- Learning FF



What an operator should know

Special case GUN



More familiar

What an operator should know

Drive with FF only (i.e. **open loop**) **no feedback** trying to minimize error between signal and set point

Linear scaling of amplitude and phase drive to minimize error (automation)

Enables cavity tuning using piezos (including Lorentz force detuning)

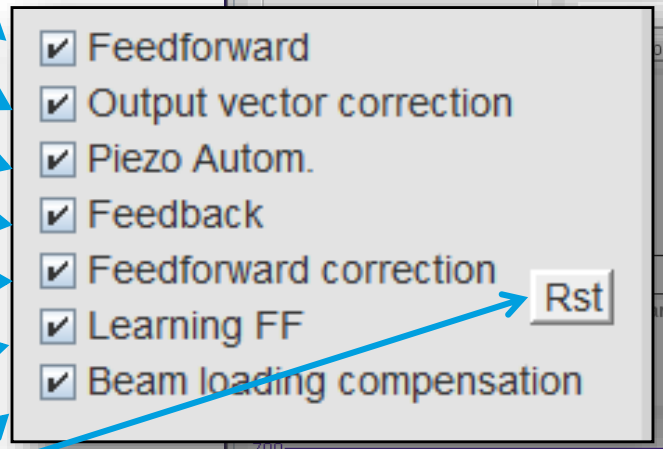
Drive with FB (closed loop)

Applies small corrections to FF to compensate for systematic errors

Learns from pulse to pulse to adapt these small corrections

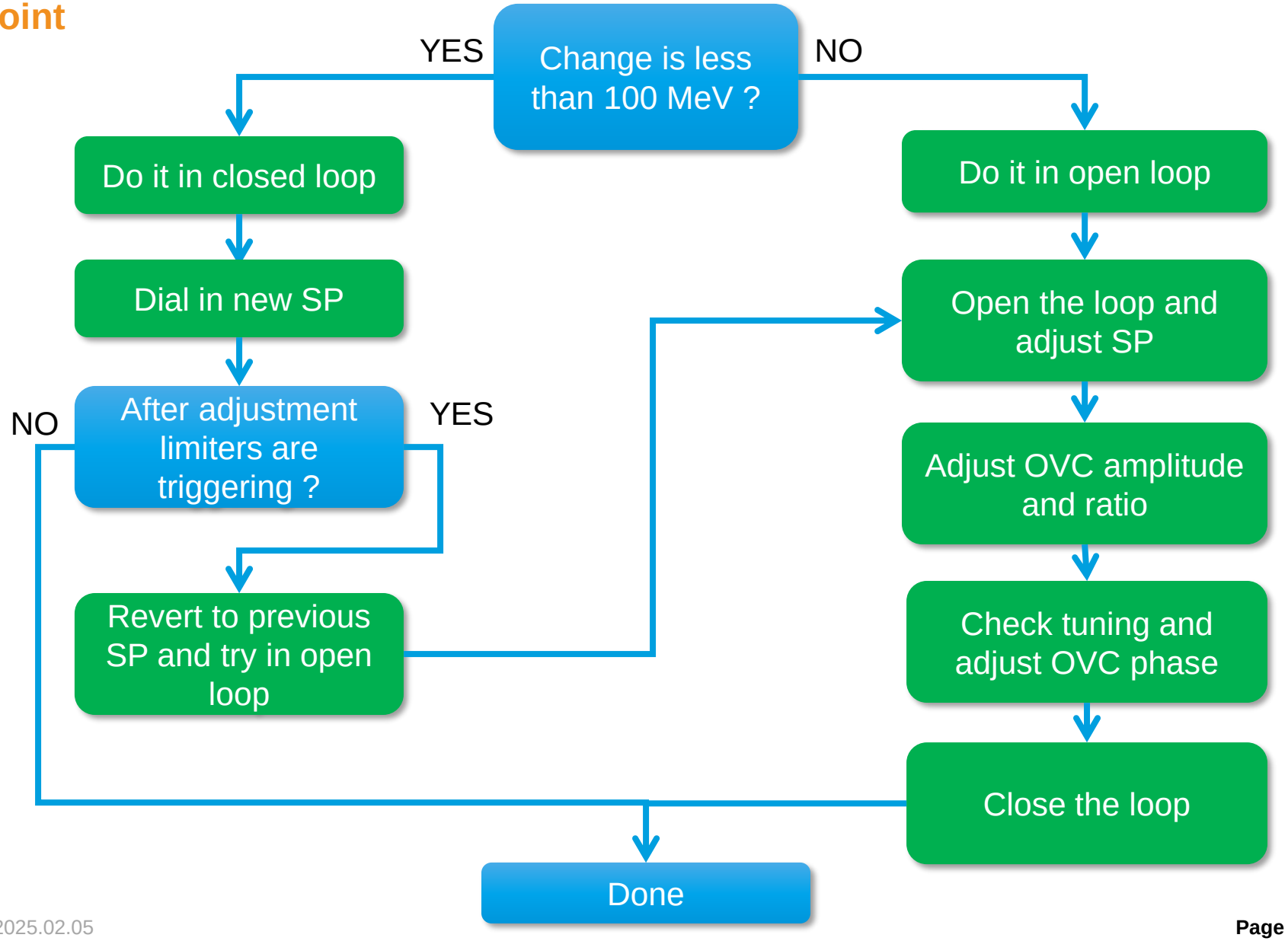
Re-initialize what has been learnt so far (i.e. start from empty correction)

Applies small correction to the drive to compensate for the presence of beam (i.e. scales with beam parameters)



What an operator should know

Changing RF amplitude set point

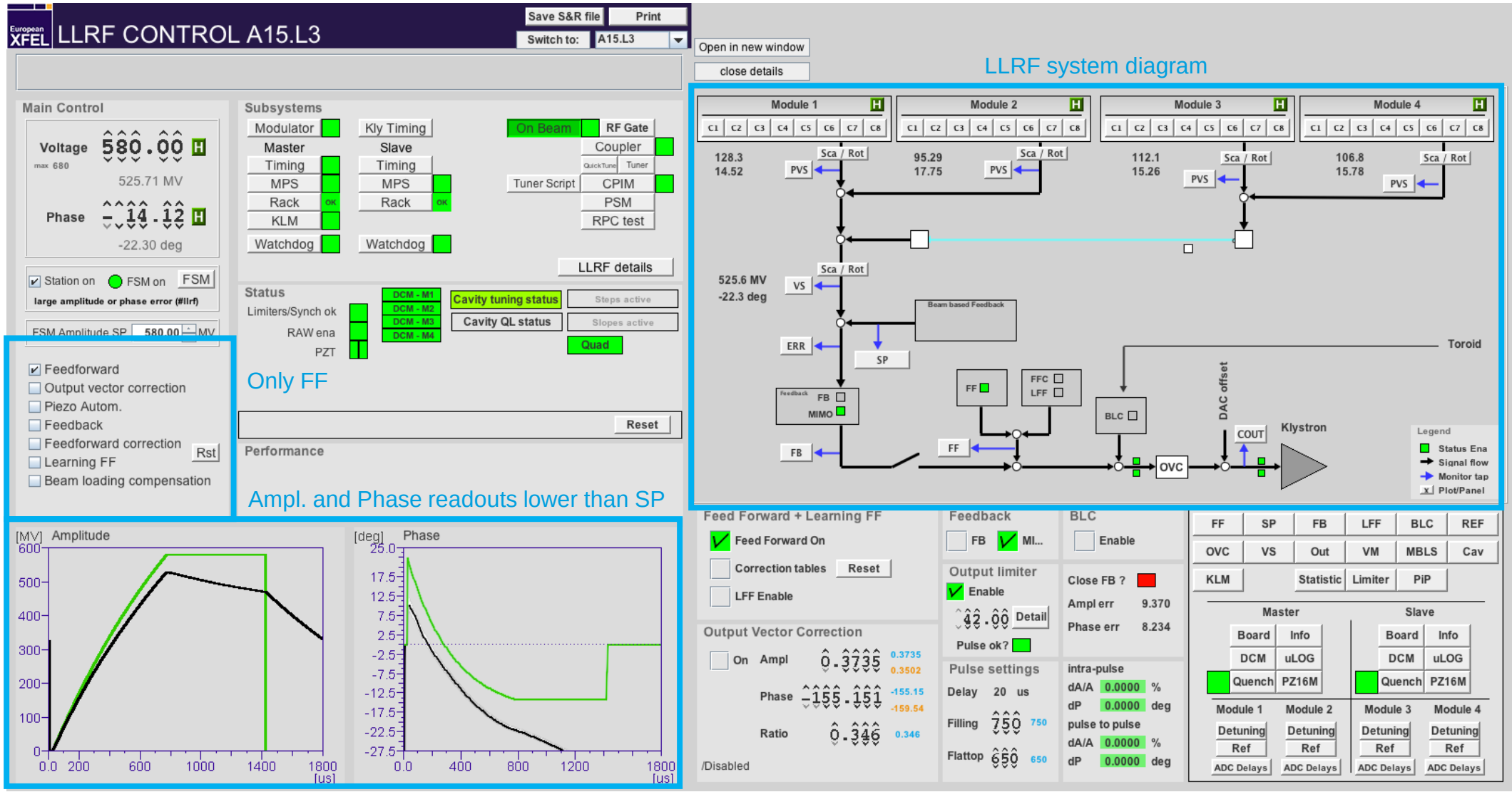


Note:

Changing **SP phase** does not require so much care, but should be also done progressively (i.e. steps of 10 deg.)

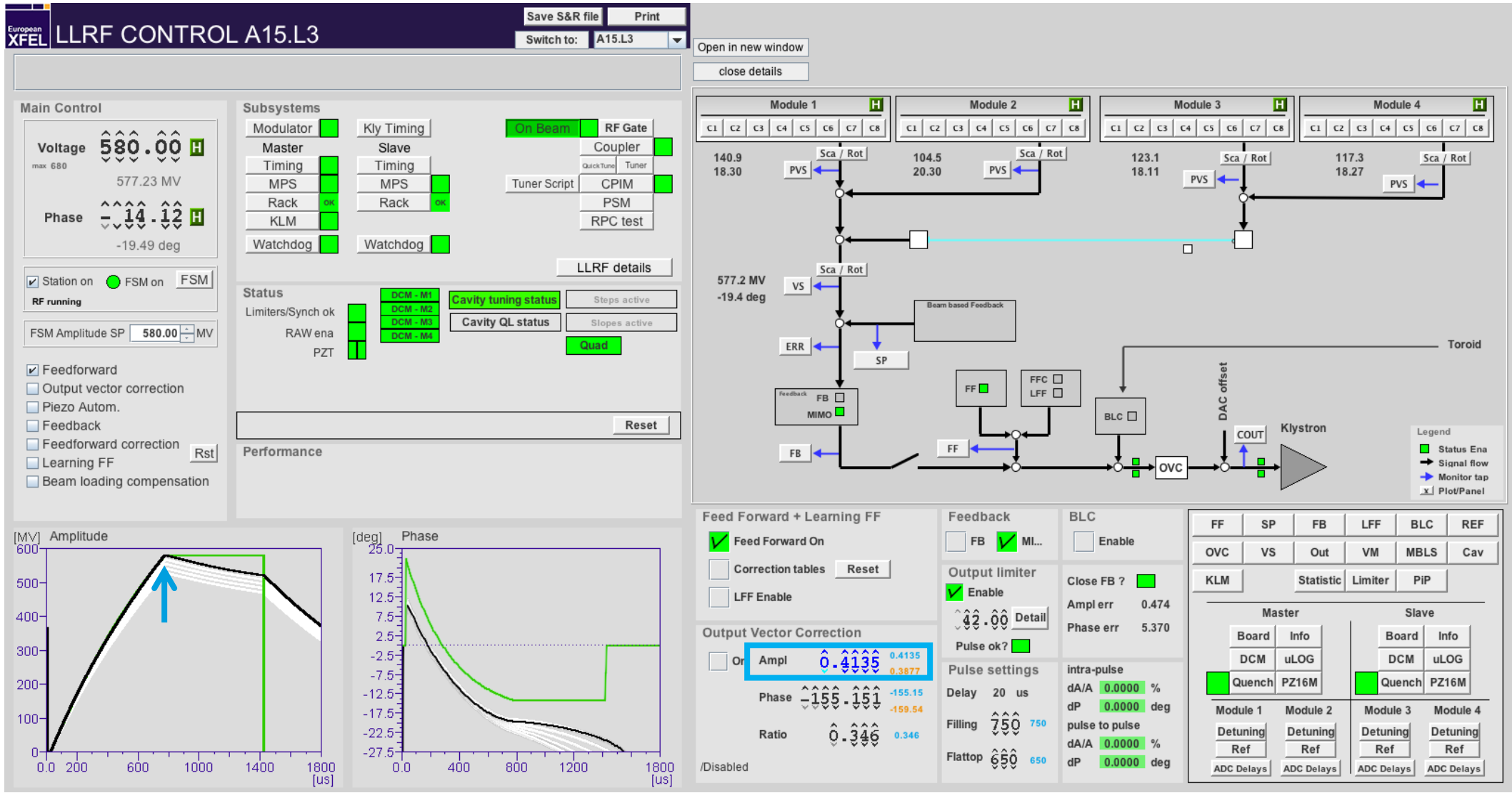
What an operator should know

Changing RF amplitude set point in open loop (1/4)



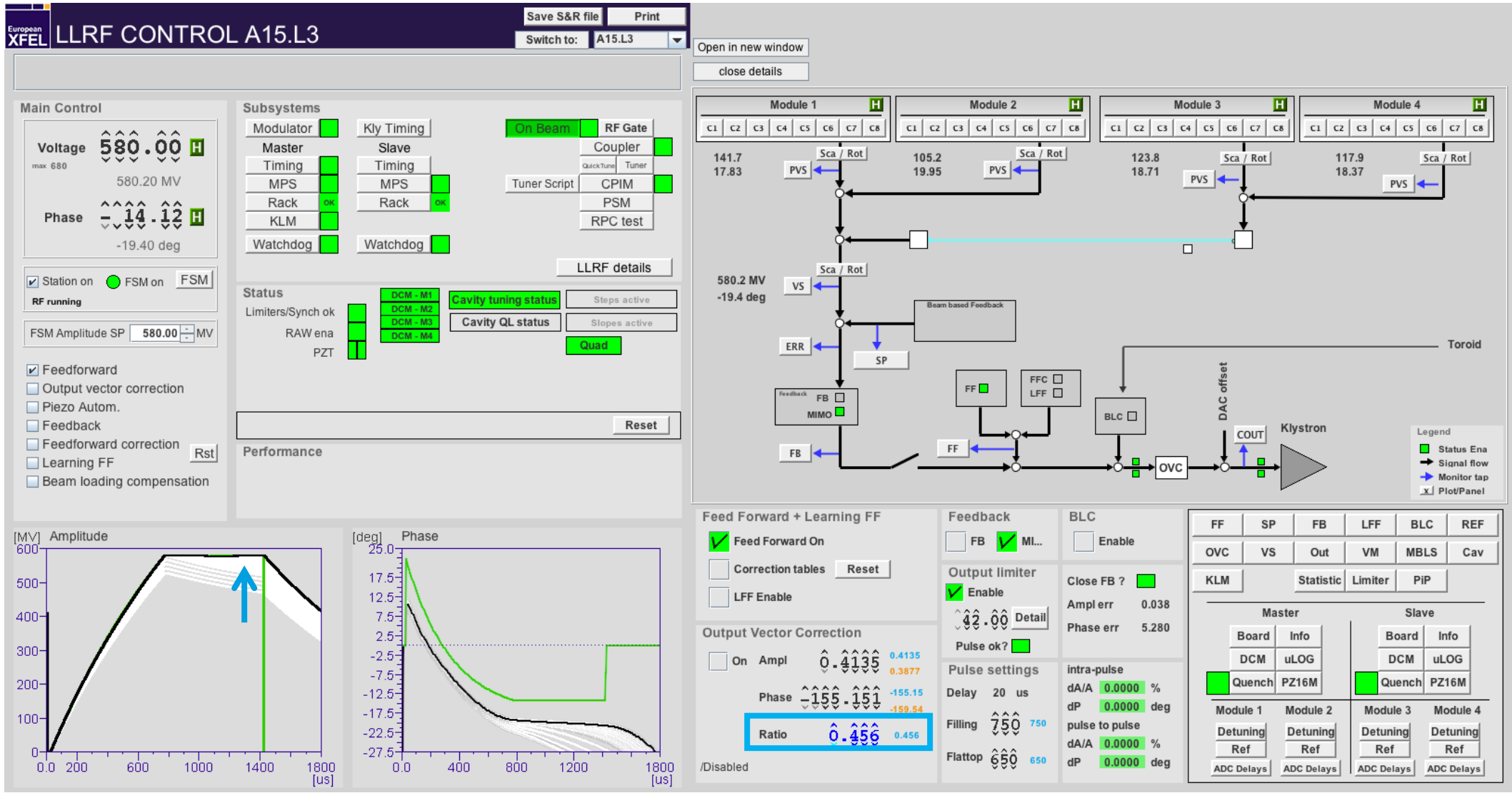
What an operator should know

Changing RF amplitude set point in open loop (2/4)



What an operator should know

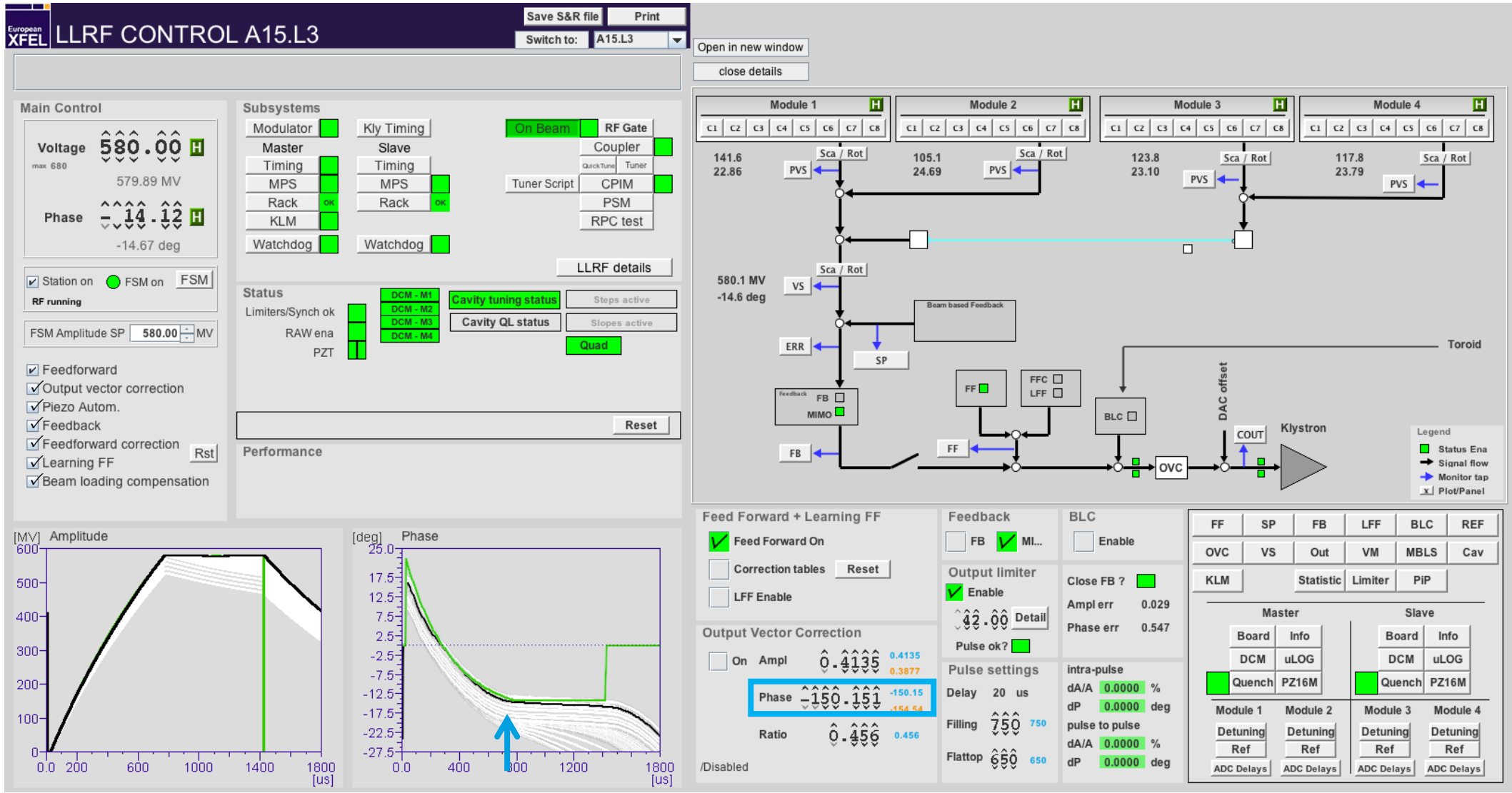
Changing RF amplitude set point in open loop (3/4)



What an operator should know

Changing RF amplitude set point in open loop (4/4)

To close the loop



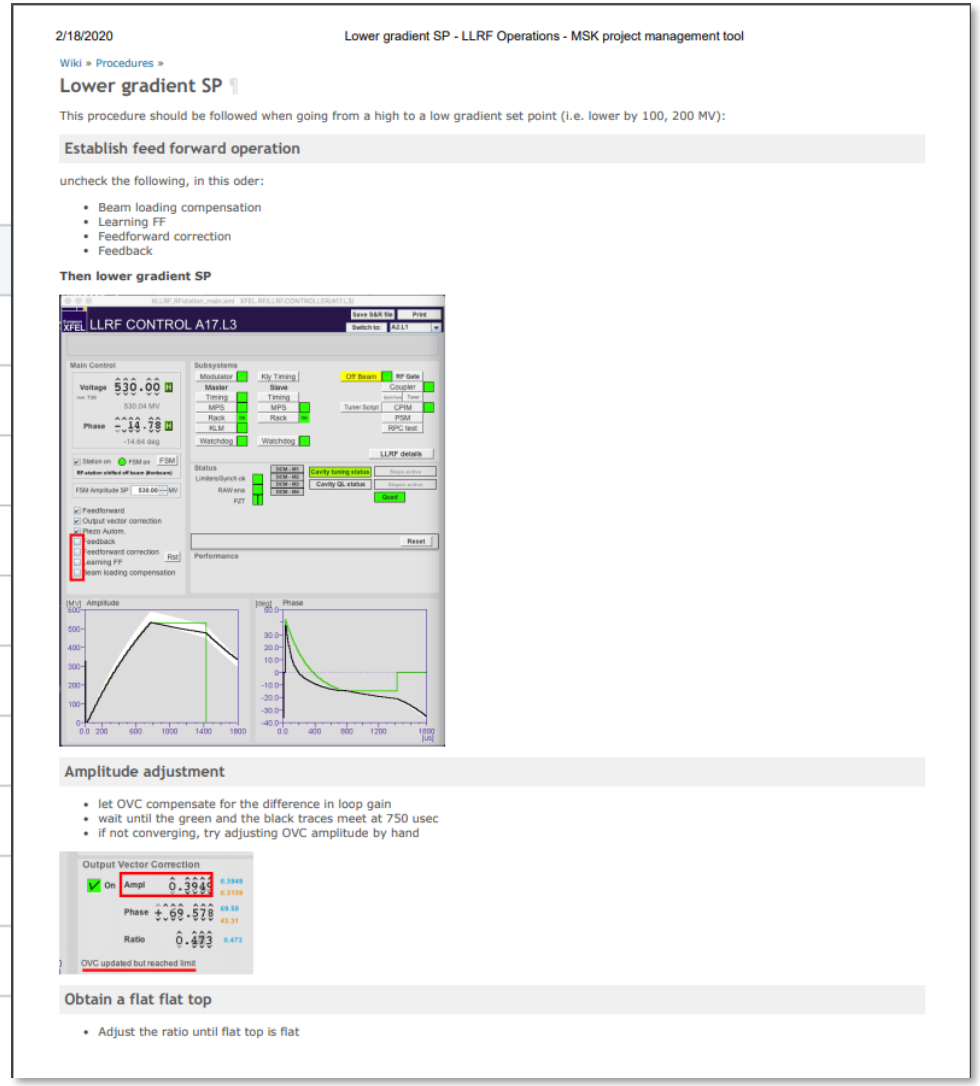
What an operator should know

Procedures

Procedures for machine operation

→ Daily operation

Description (link)	Author
Switch off the EuXFEL accelerator	@ Winfried Decking
Remote access to BKR consoles	@ Matthias Scholz
Join I1 and XTL	
Load a reference trajectory to the orbit feedback	@ Matthias Scholz
How to switch between the injector lasers of EuXFEL	
Bunch Compression Setup Procedure	@ Bolko Beutner
Setup longitudinal intra bunch-train feedback (L-IBFB) at LLRF station A5	@ Bjoern Lautenschlager
Changing photon energy without a prepared file	@ Matthias Scholz
Tuning Strategy for EuXFEL	@ Matthias Scholz
Lower the gradient SP of RF stations	@ Julien Branlard



2/18/2020 Lower gradient SP - LLRF Operations - MSK project management tool

Wiki » Procedures »

Lower gradient SP

This procedure should be followed when going from a high to a low gradient set point (i.e. lower by 100, 200 MV):

Establish feed forward operation

uncheck the following, in this oder:

- Beam loading compensation
- Learning FF
- Feedforward correction
- Feedback

Then lower gradient SP

Amplitude adjustment

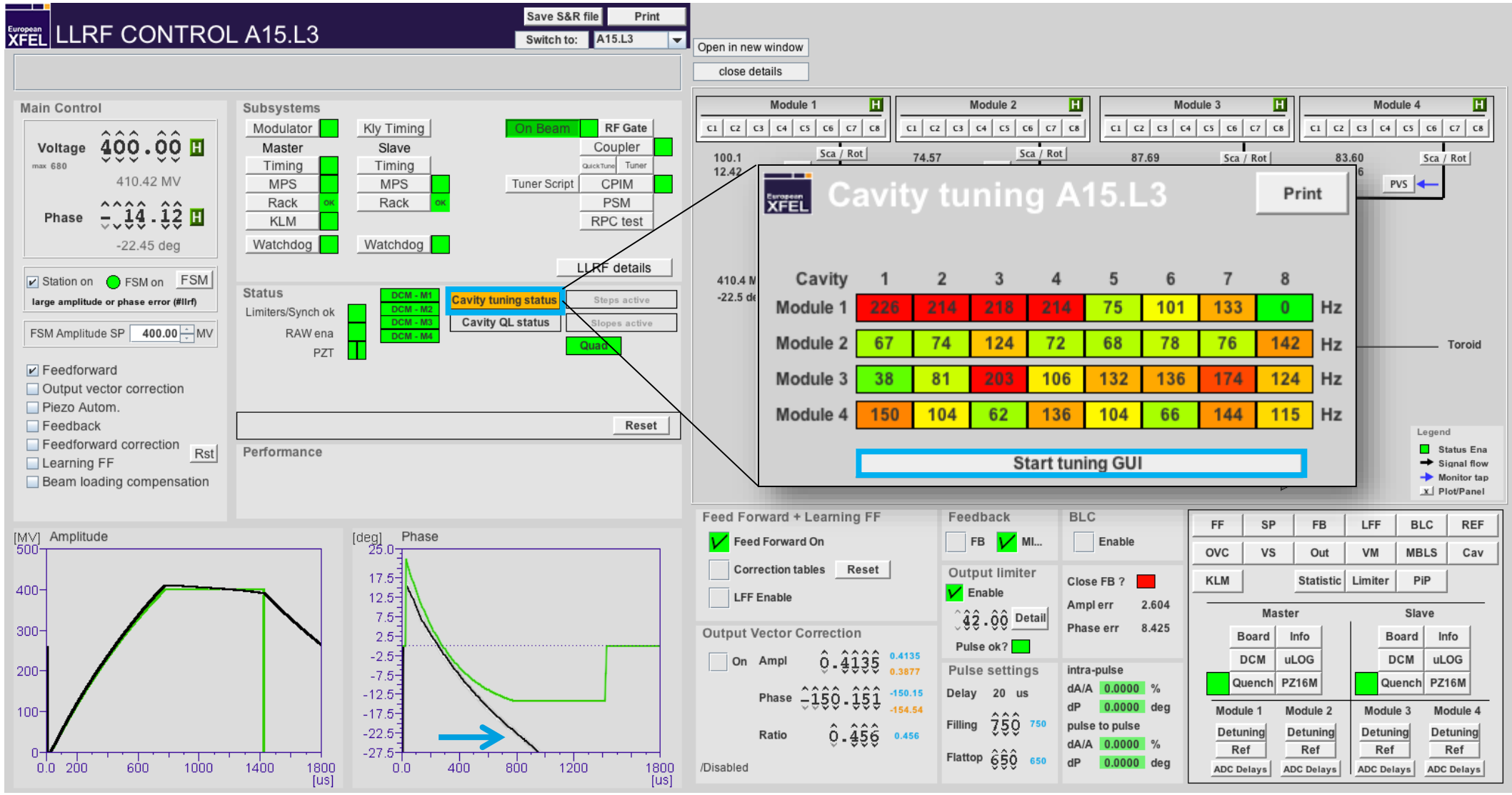
- let OVC compensate for the difference in loop gain
- wait until the green and the black traces meet at 750 usec
- if not converging, try adjusting OVC amplitude by hand

Obtain a flat flat top

- Adjust the ratio until flat top is flat

What an operator should know

Tuning cavities (1/2)



What an operator should know

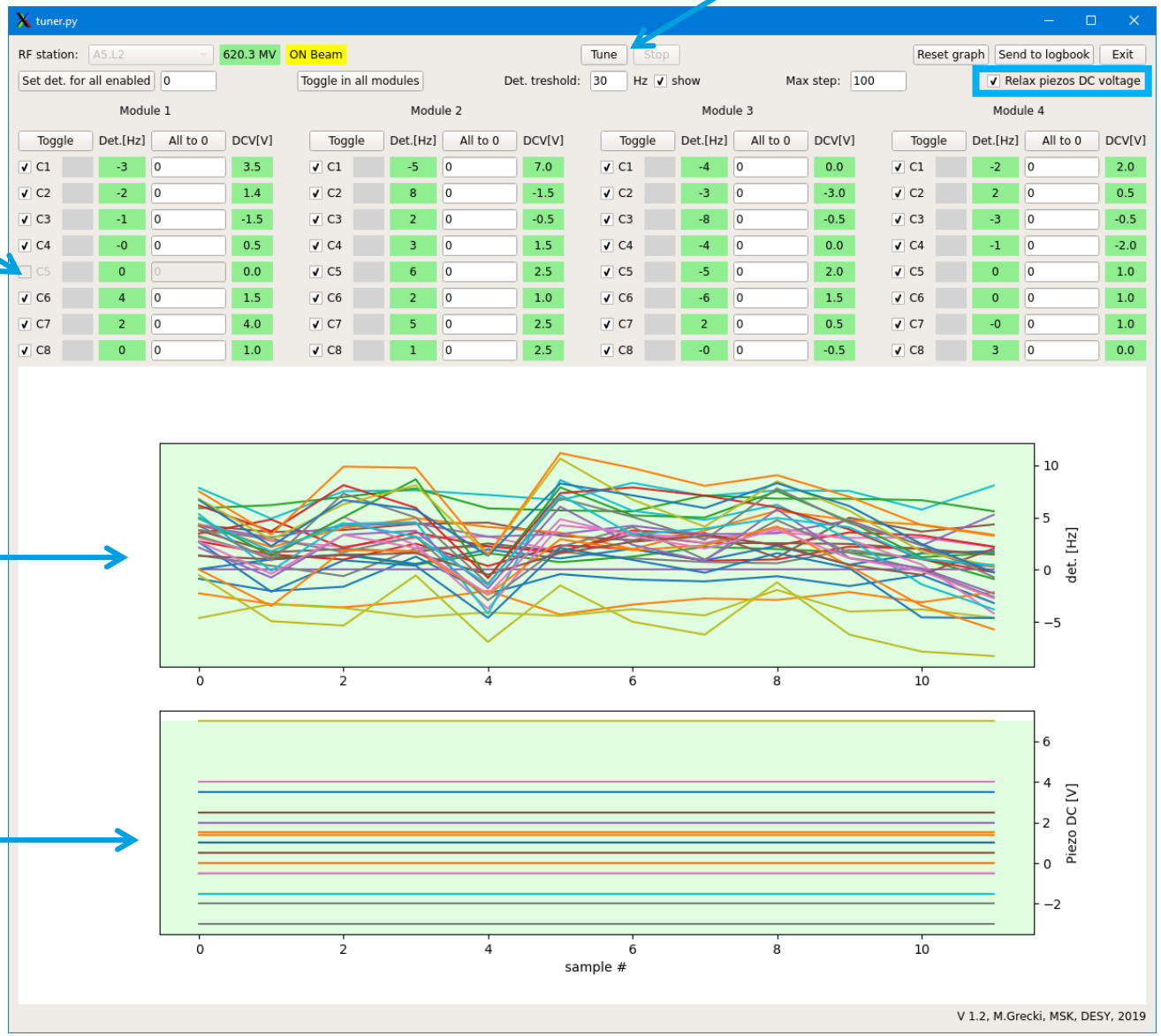
Tuning cavities (2/2)

Click “Tune”

Some cavities should NOT be tuned (greyed out)

Cavity detuning [Hz]

Piezo voltage (DC bias [V])



Relax piezo DC voltage
Shows tuning [Hz] and piezo DC bias [V]

→ both should converge to 0

→ “relax piezo DC voltage” is enabled by default

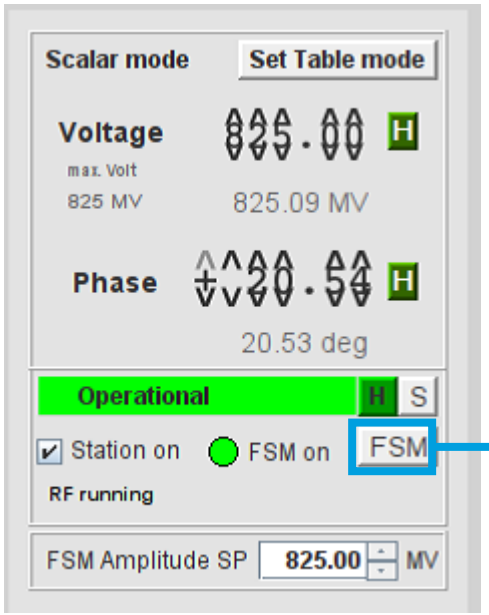
Some error message may pop up

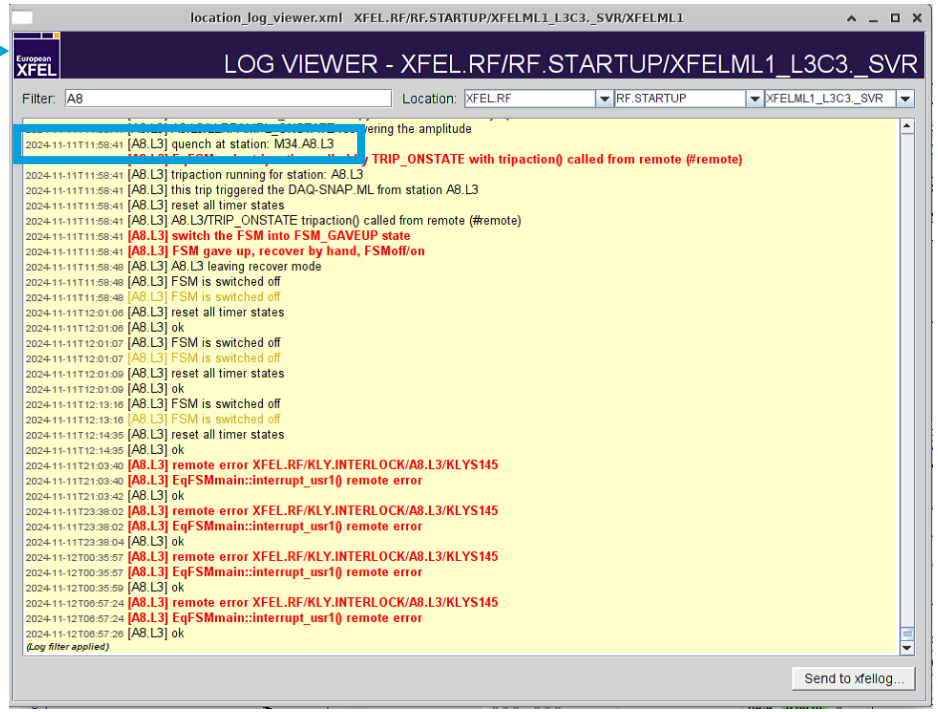
You can choose to ignore once or twice but if problem persists, call expert

What an operator should know

FSM

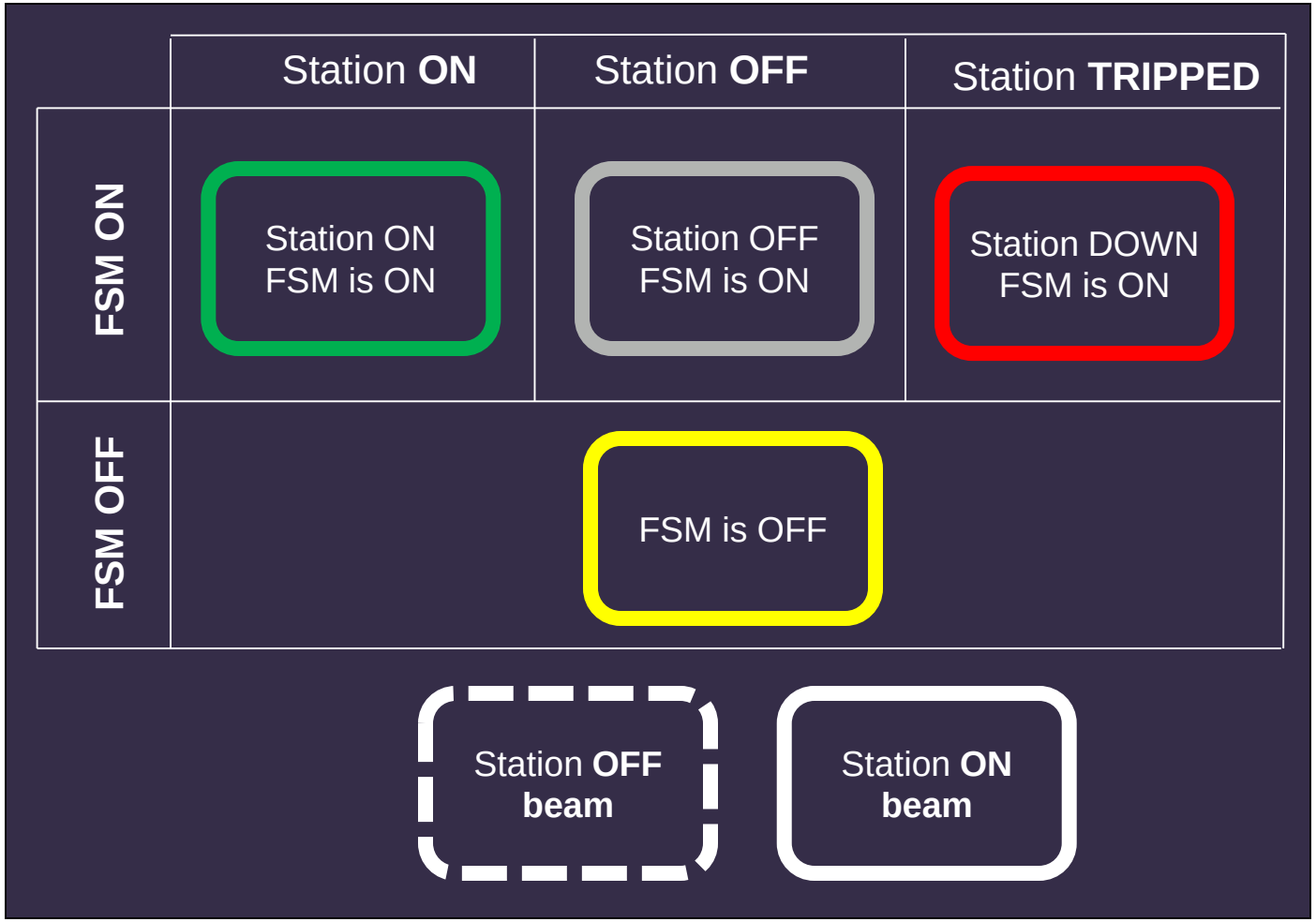
- Not directly LLRF but belongs to RF operation
- Turn the station on/off
- (When possible) RF trips involving LLRF, Modulator, Klystron and Coupler interlock & quench are automatically recovered by FSM (no action needed!)
- The FSM log can tell what is/was the problem





What an operator should know

RF station color code



Note 1:

Sometimes, the station is operational but the color indicator on the main display shows yellow/red instead of green

➔ Simply disable / re-enable FSM to force a status refresh

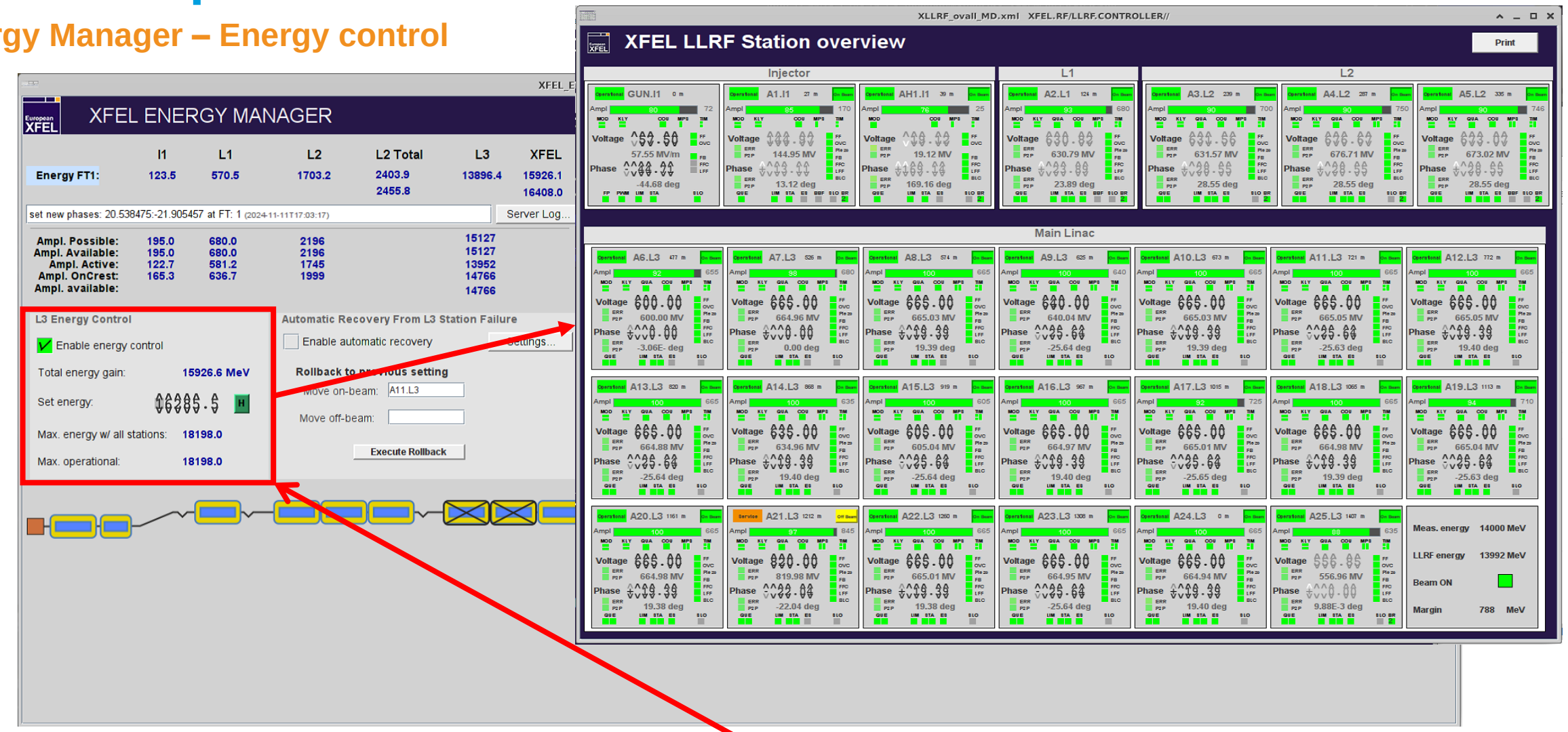
Note 2:

The Status “FSM ON and station in service” is still represented with a green circle but with a label on top (L3 panel)

➔ Unusable stations are now visible from the L3 panel, also the Energy Manager should give this information

What an operator should know

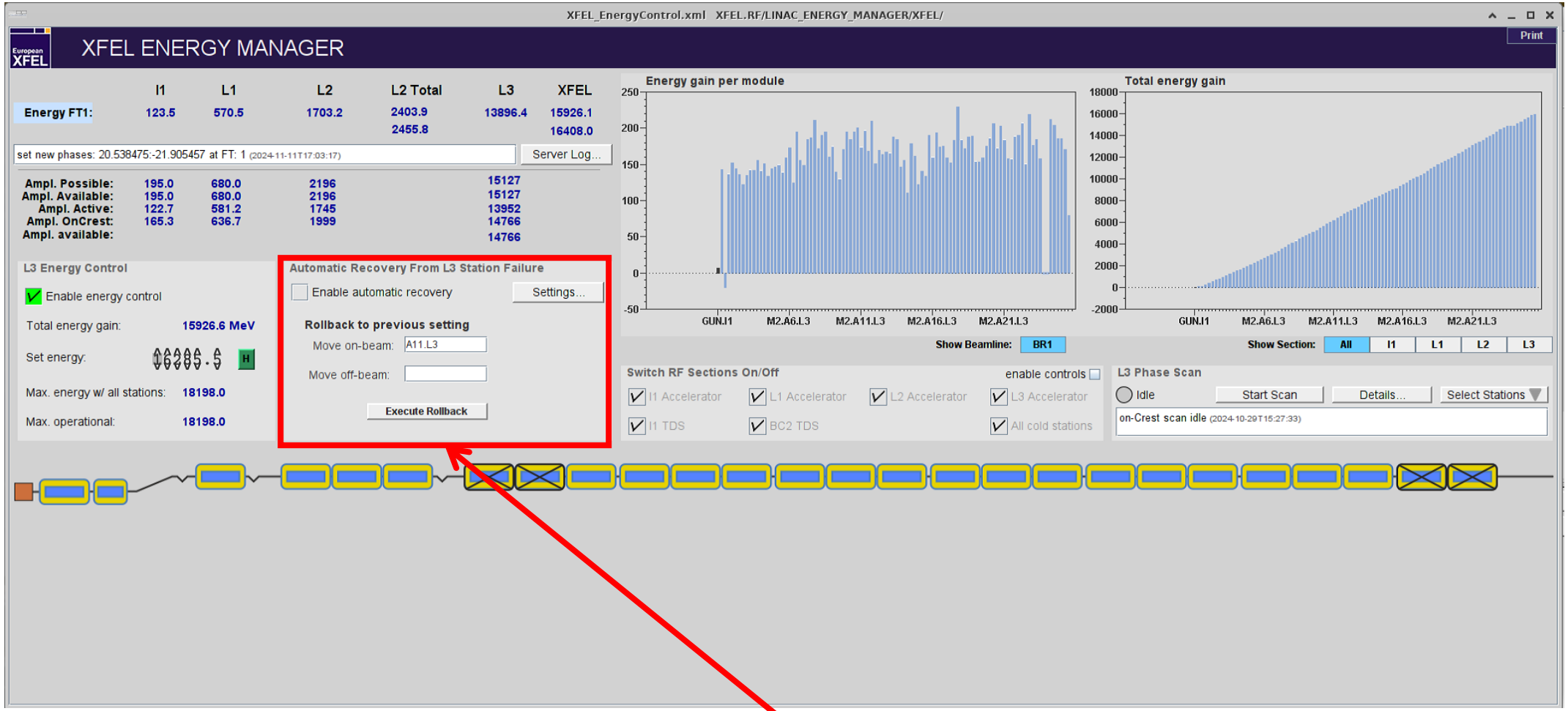
Energy Manager – Energy control



You can set the total RF energy -> It regulates the off-crest phases in L3

What an operator should know

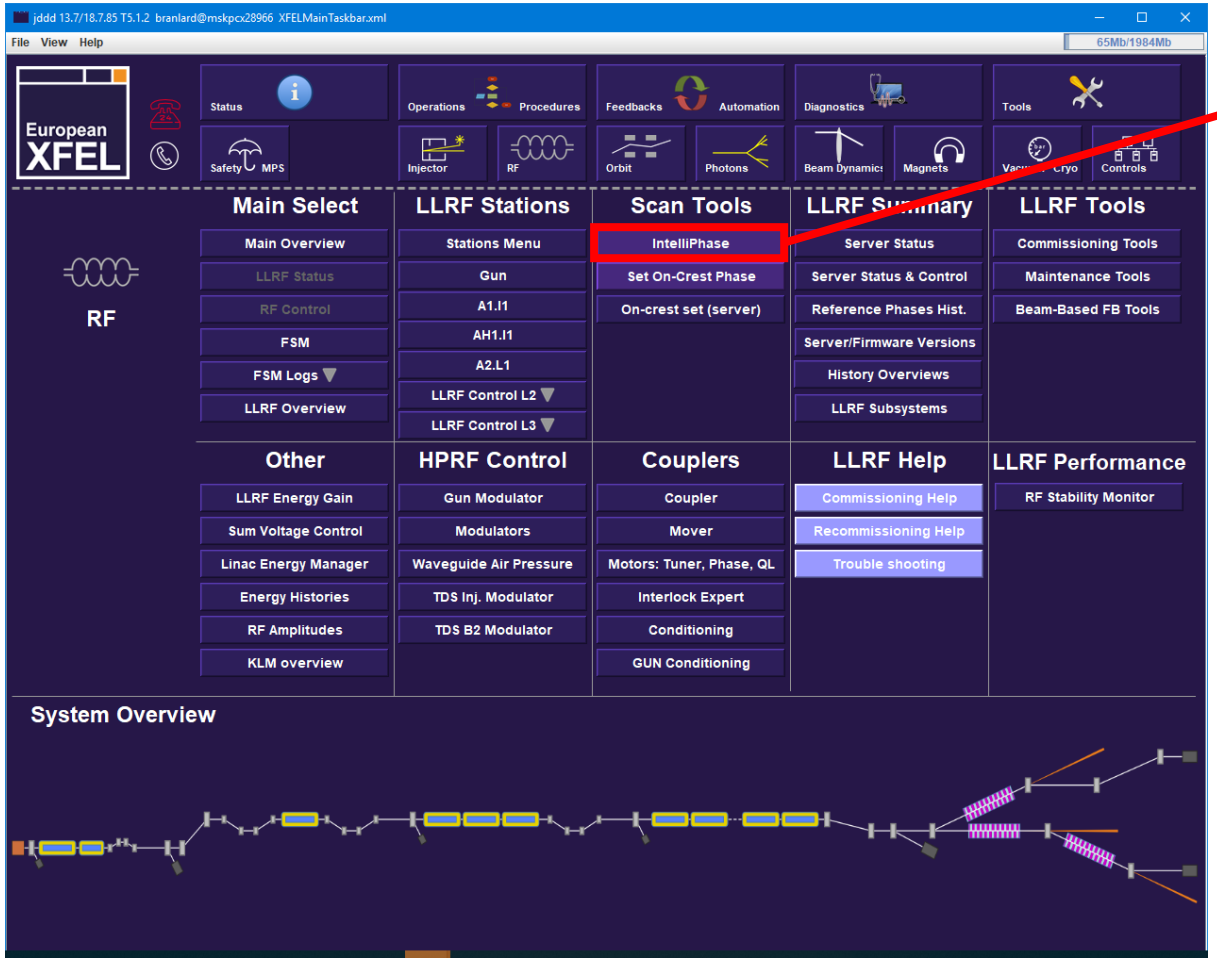
Energy Manager - automatic recovery from failure in L3

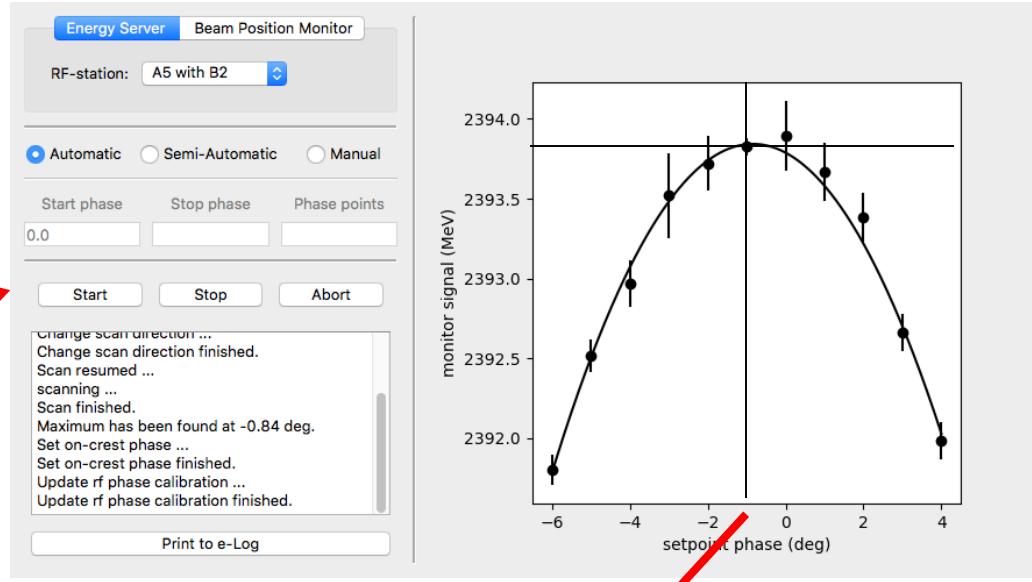


When enabled, if an RF trip is not recoverable within the defined timeout, the RF station is placed off-beam and the magnets scaled (possible to roll back if the station is recovered)

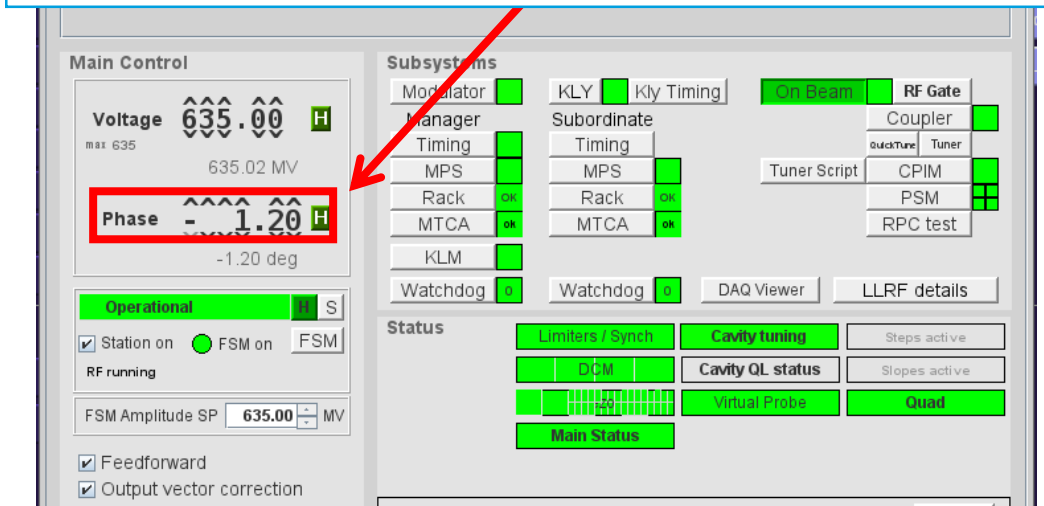
What an operator should know

Setting the on-crest phase



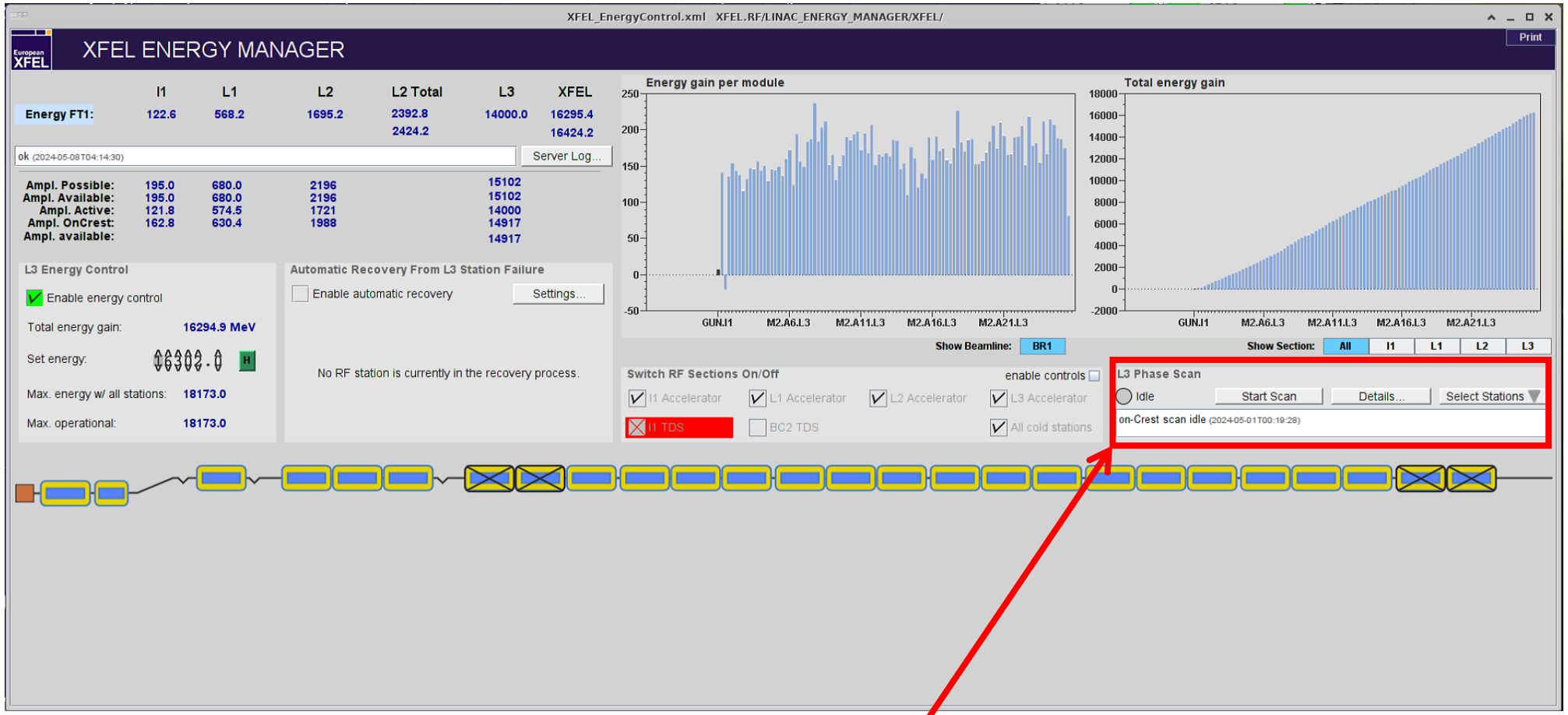


The phase at which the max energy is measured is defined as on crest phase and corresponds to the “new” 0 phase setting in the LLRF controller



What an operator should know

Setting the on-crest phase



For L3 this can also be done “parasitically” with the Energy Manager L3 Phase Scan (slow) -> fine tuning

What an operator should know

Vector Sum Set Point configurations

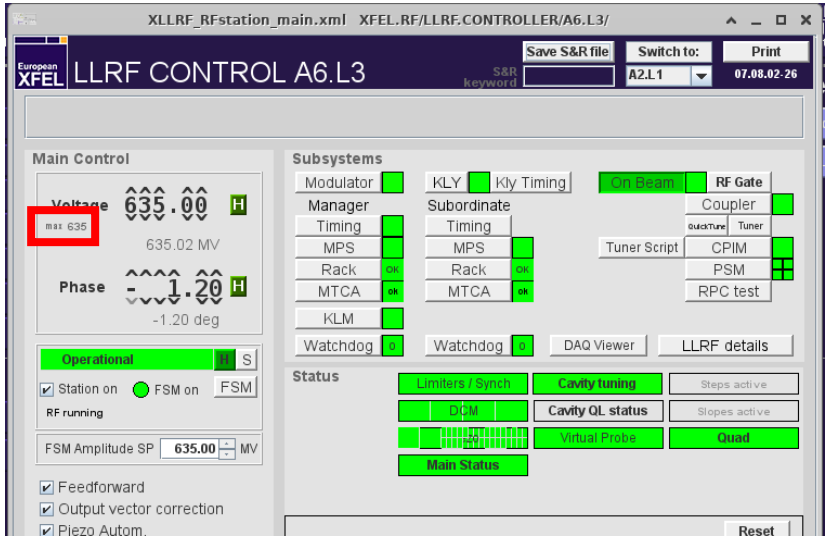
2 RF energy configurations are actually foreseen:

- **Reduced-Energy** (beam energies **up to 14.0 GeV**) -> VS SP 665 MV almost everywhere
- **High-Energy** (beam energy of **16.3 GeV**) -> Max achievable voltage

The purpose of the **Reduced-Energy mode** is to

- **reduce power consumption** (lower modulator HV)
- **lower the radiation level in the tunnel** (e.g. less MTCA issues)

The Maximum SPs are embedded in the LLRF server and they are updated at every change of configuration according to these tables: https://xwiki.desy.de/xwiki/short/b083a



What an operator should know

How to deal with failing RF stations

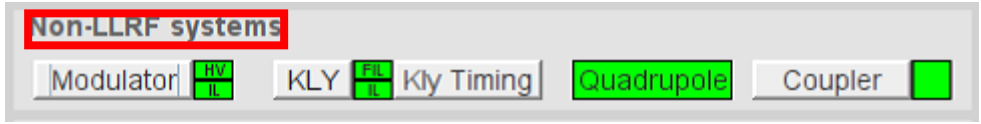
- How to deal with failing RF stations: https://xwiki.desy.de/xwiki/short/a43a1

1 Preparation

1. Wait for the Finite State Machine (FSM) to recover the RF station or try it by hand in case the FSM fails. If both attempts did not work out, continue with this procedure.
2. Inform the respective experts of the failed (sub) system and ask them to start fixing the problem. Please request also an update on the progress of the repair within one hour at the latest.
   - LLRF problems → LLRF expert on call (also LLRF mailing-list)
   - Quadrupole & Modulator problems → MPC shift crew (in BKR)
   - Coupler problems → MSL expert on call
   - Klystron problems → MHFp expert on call (also 1.3 GHz mailing-list)
   - HPRF problems at AH1 → MIN expert on call

Have a generic RF mailing-list?

- Recognize the root cause



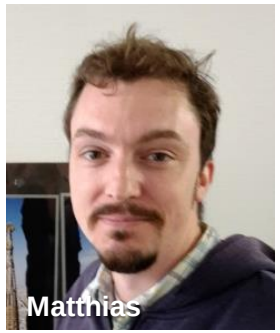
- If you are not sure, please inform all the possible groups (not only LLRF!)

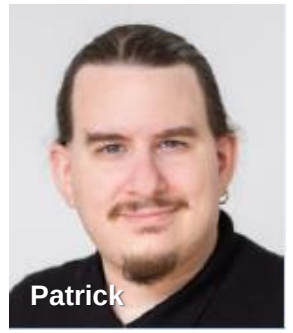
What an operator should know

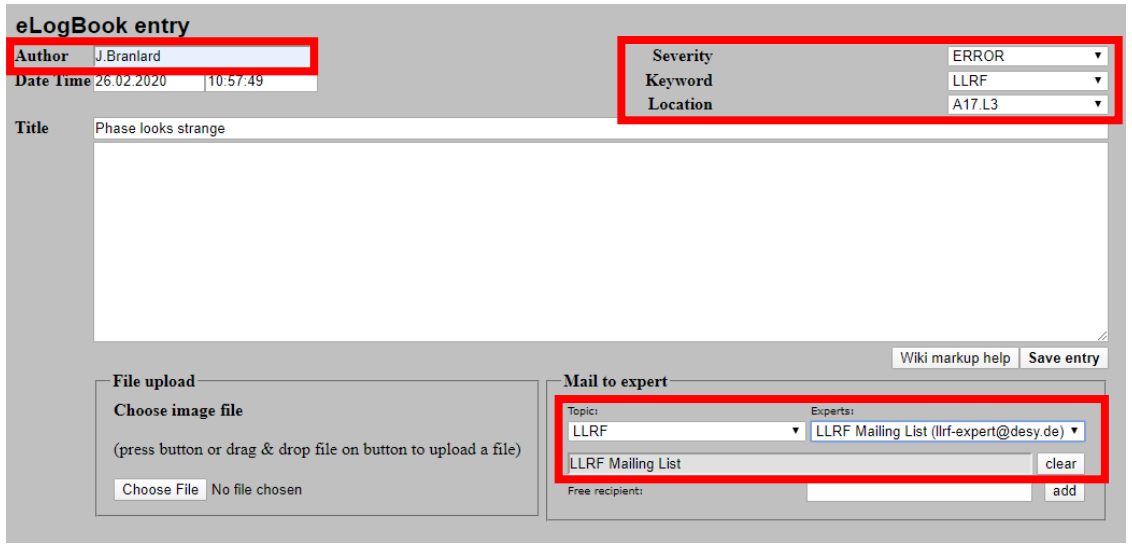
LLRF on-call service

- LLRF on-call **5588**
- 9 experts, 1 available 24/7 every week
- llrf-expert@desy.de

- Send log book entry to LLRF expert list
  - **Write your name / initials**
  - **Edit the title and description**
  - **Use the Tag fields (at least Location)**





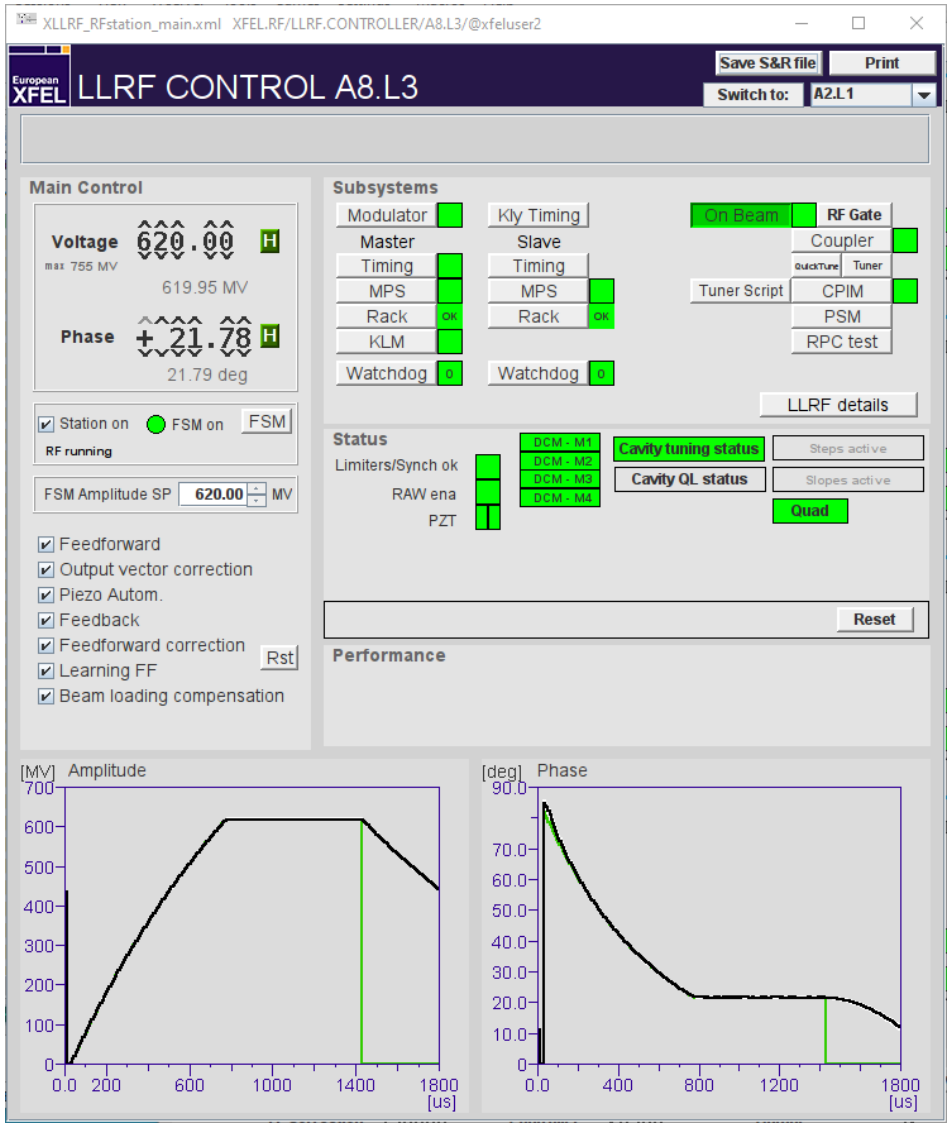


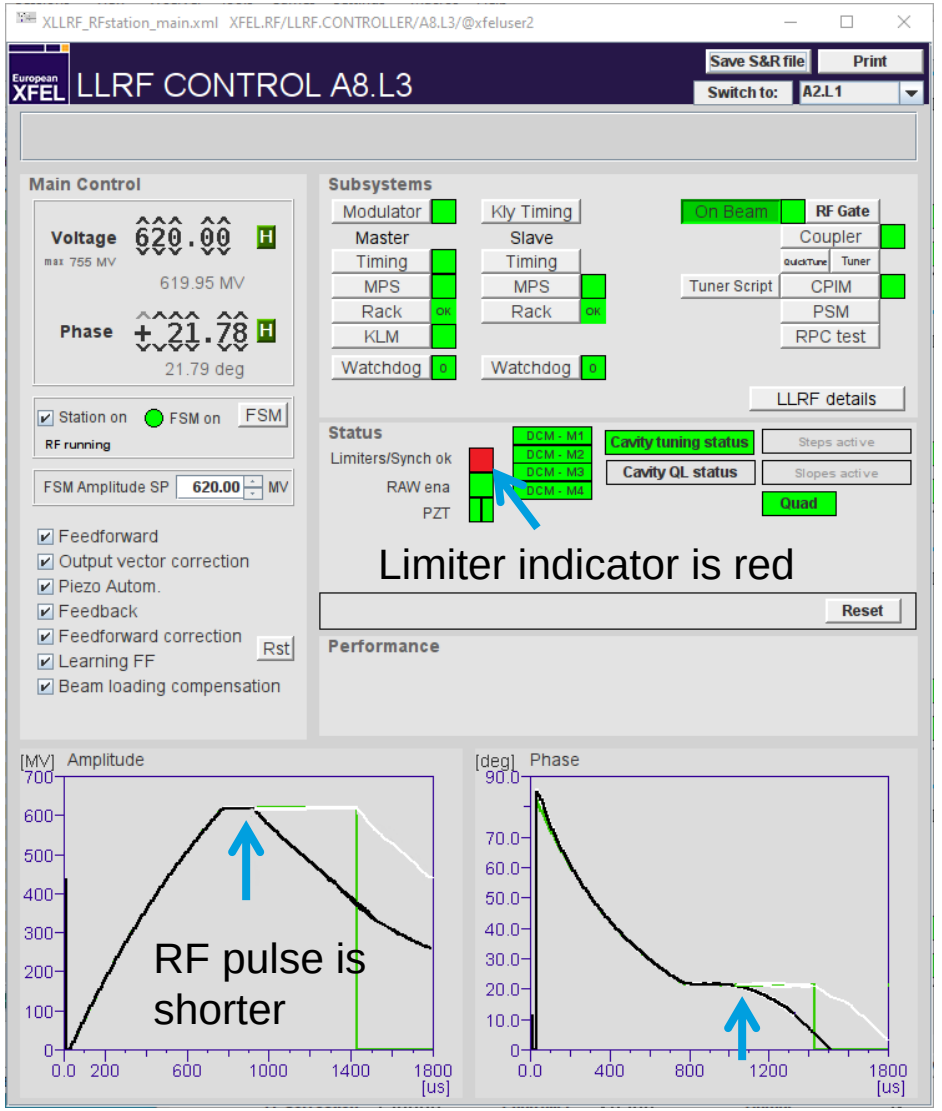
3. Exceptional cases and how to react

- Probe limiter – pulse cut
- KLM limiter – pulse cut
- Output/feedback limiter
- Cavity quenches
- Zombie station
- Lost PCIe connection

Exceptional cases and how to react

Pulse cuts due to gradient limiters





Note:

- **Pulse cuts are displayed on the main panel** (limiter / KLM)
- **The beam is cut if the RF pulse is cut**

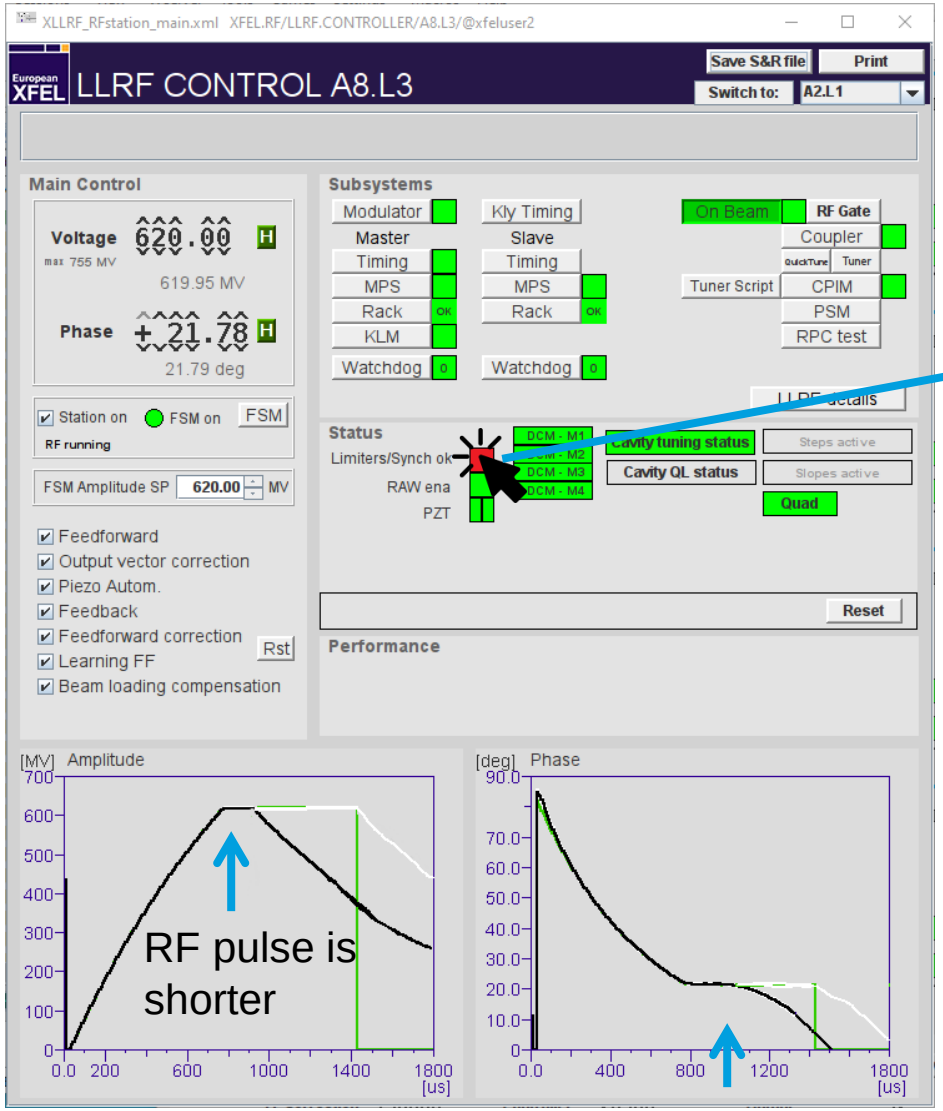
What to do:

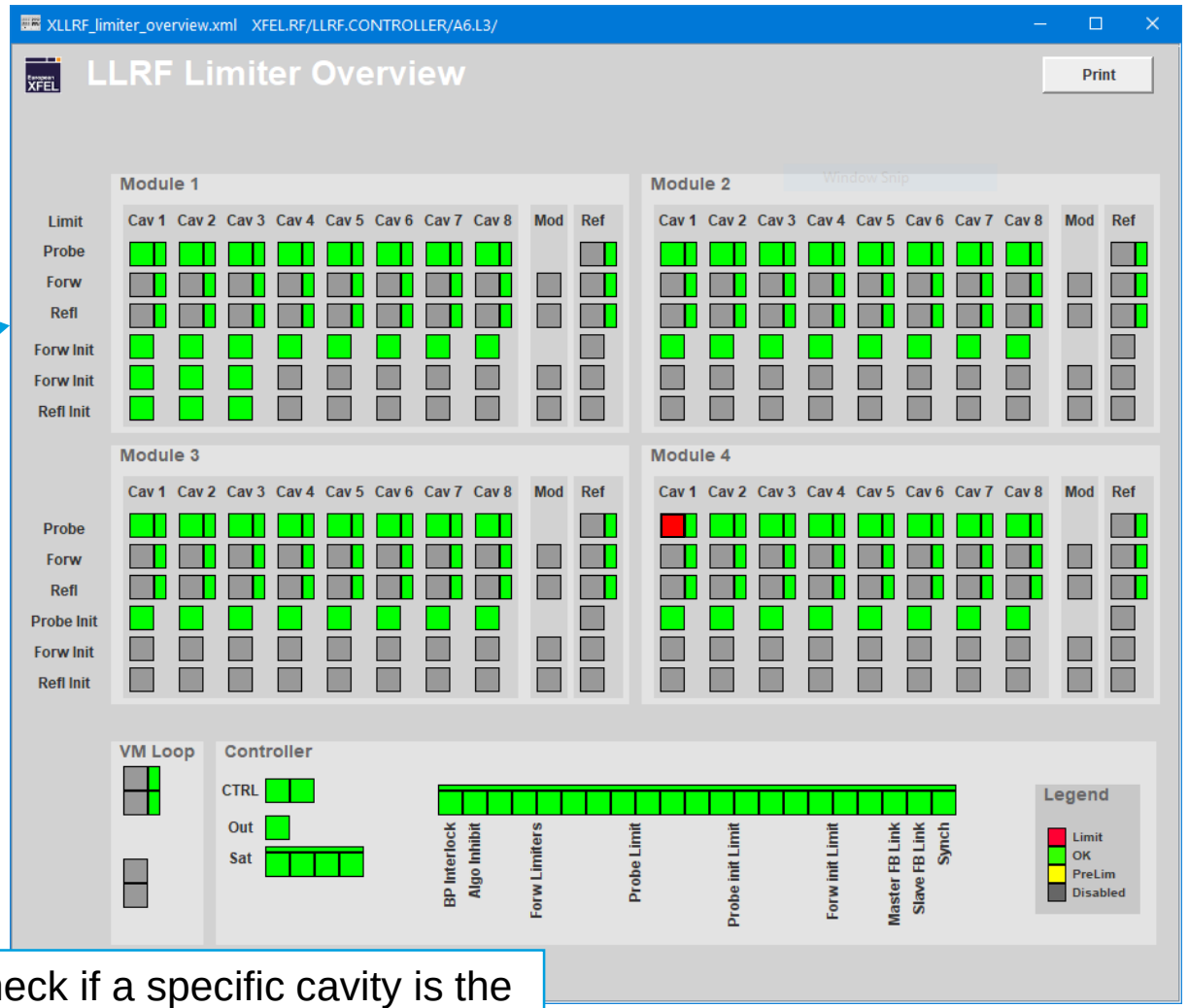
1. Document in log book and send to LLRF
2. Open/close loop
3. Lower the gradient if possible

4. If you want, you can check what is the limiting factor (see next 2 slides)

Exceptional cases and how to react

Pulse cuts due to gradient limiters

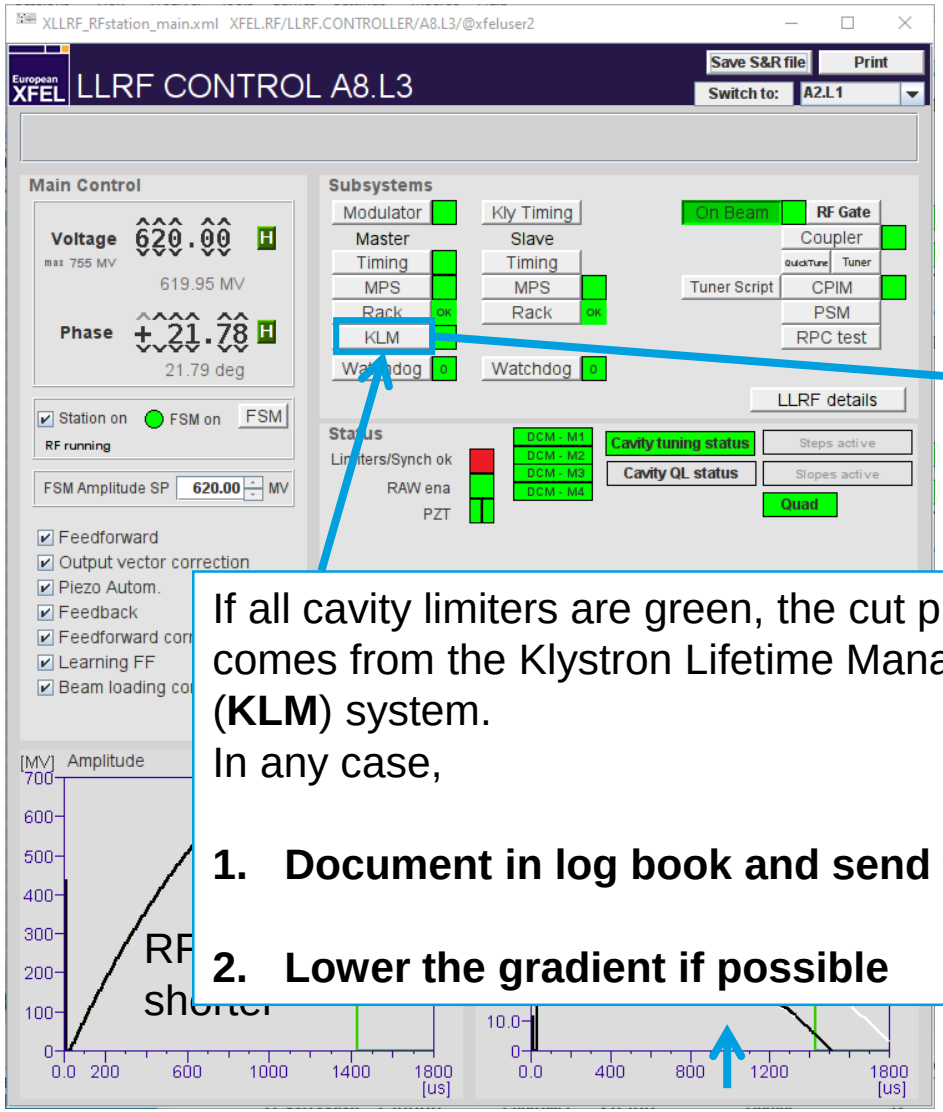


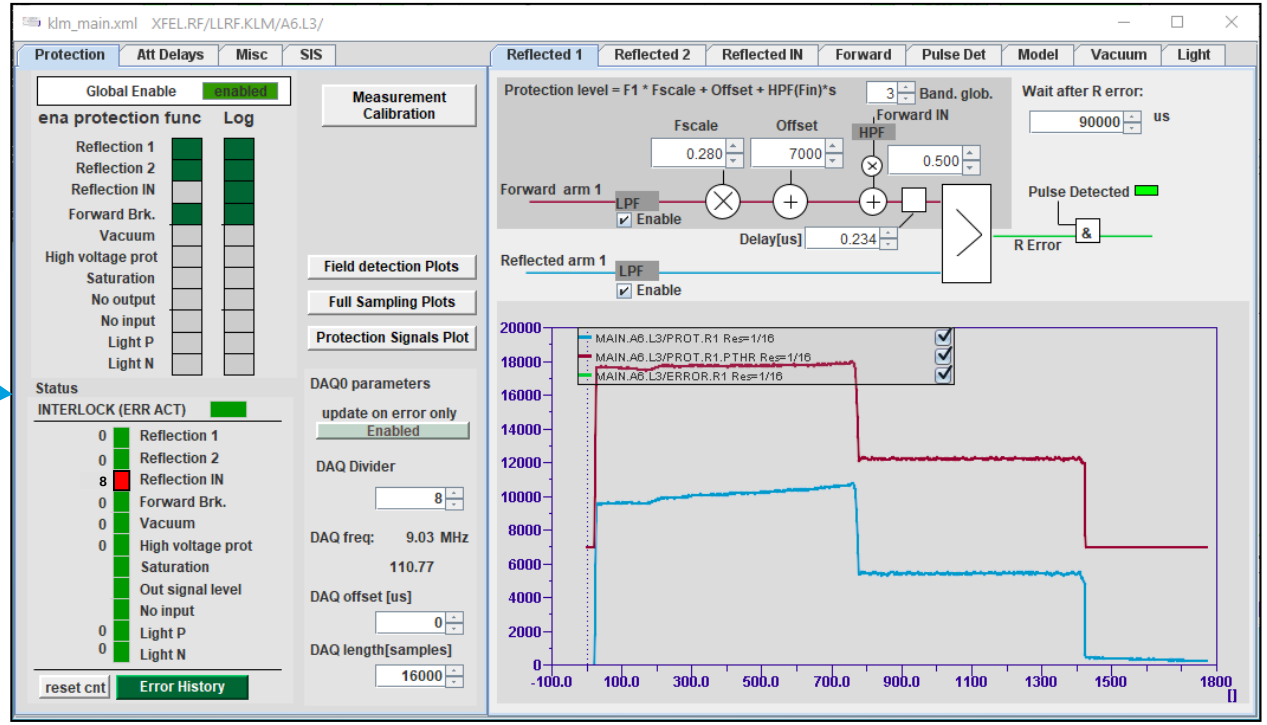


Check if a specific cavity is the reason for the cut

Exceptional cases and how to react

Pulse cuts due to KLM limiters





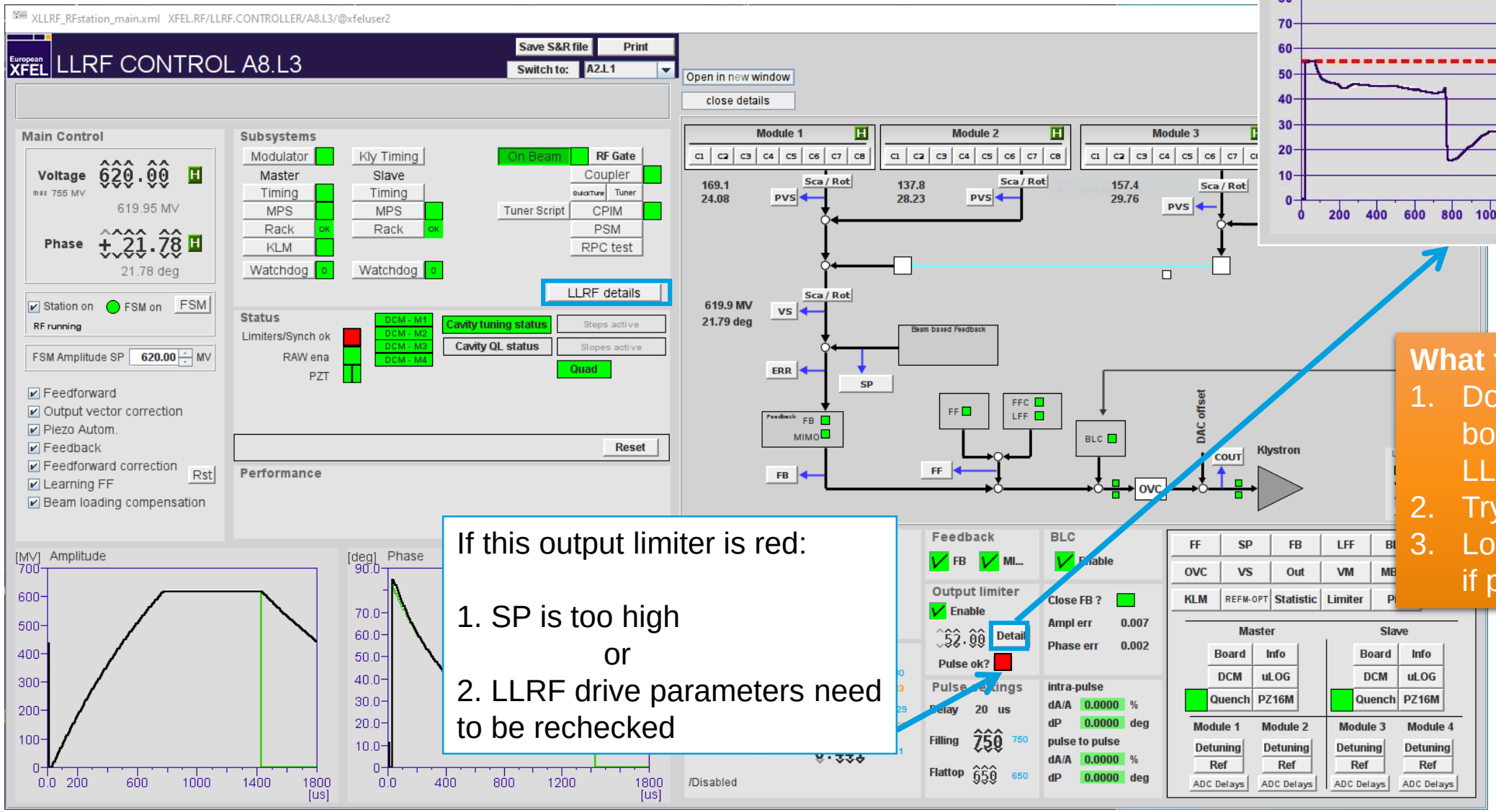
If all cavity limiters are green, the cut probably comes from the Klystron Lifetime Management (**KLM**) system.
In any case,

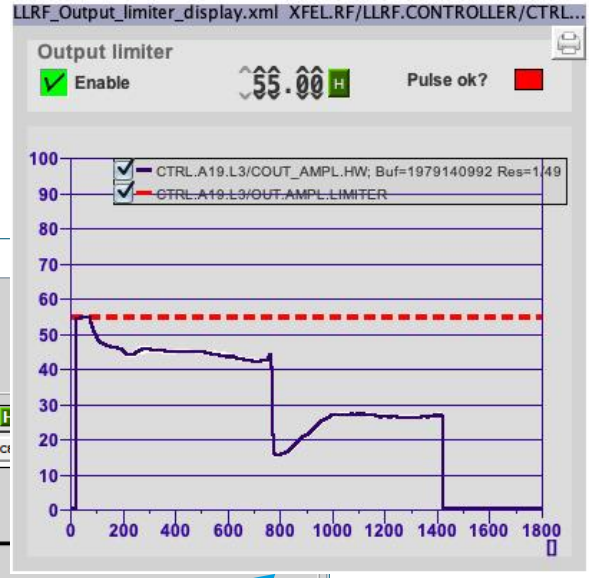
1. **Document in log book and send to LLRF**

2. **Lower the gradient if possible**

Exceptional cases and how to react

Limiter is red (but no cut)



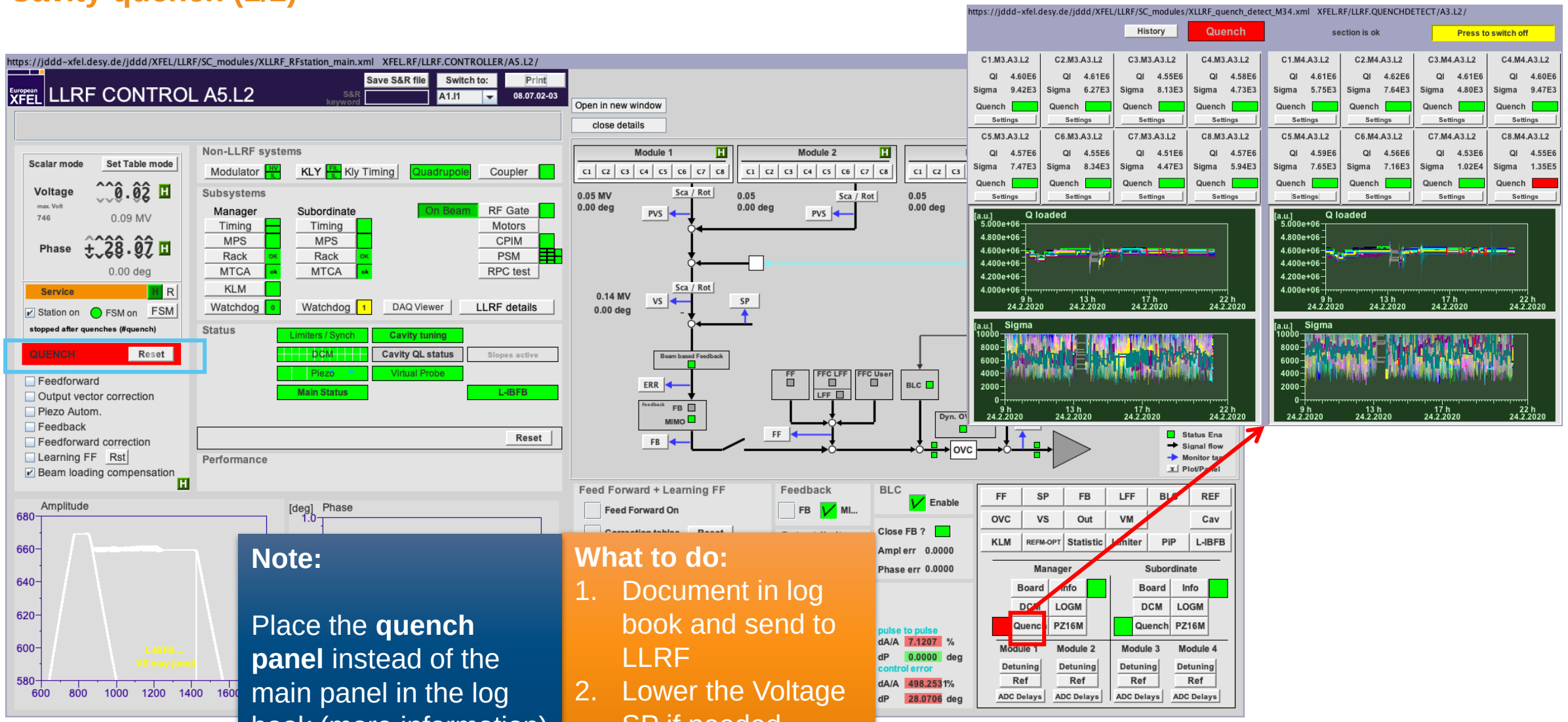


What to do:

1. Document in log book and send to LLRF
2. Try open/close loop
3. Lower the gradient if possible

Exceptional cases and how to react

Cavity quench (1/2)

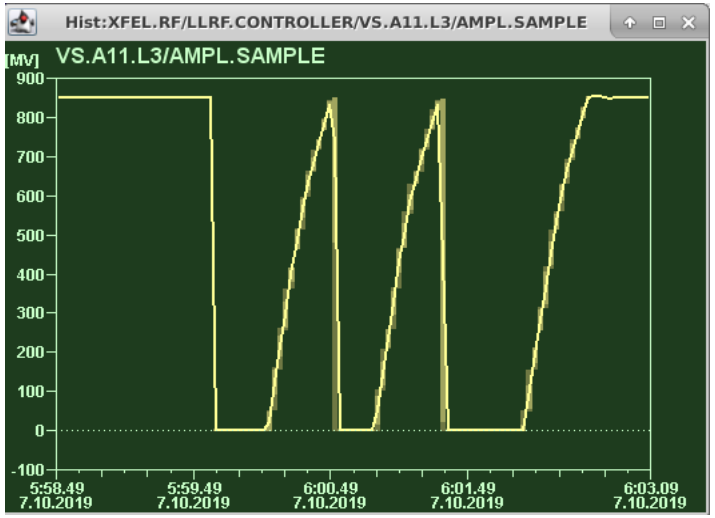


Exceptional cases and how to react

Cavity quench (2/2)

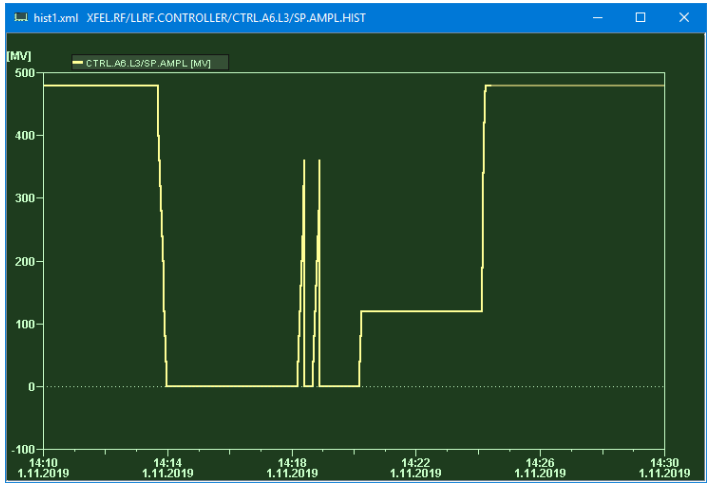
Repetitive quenches

- **Problem description:**
  - The FSM tries to recover a station after a quench, ramps up to the same gradient and quenches again
  - After 3 tries, the FSM gives up
- **What you can try**
  - Lower the recovery gradient in the FSM window (-10 MV ?)



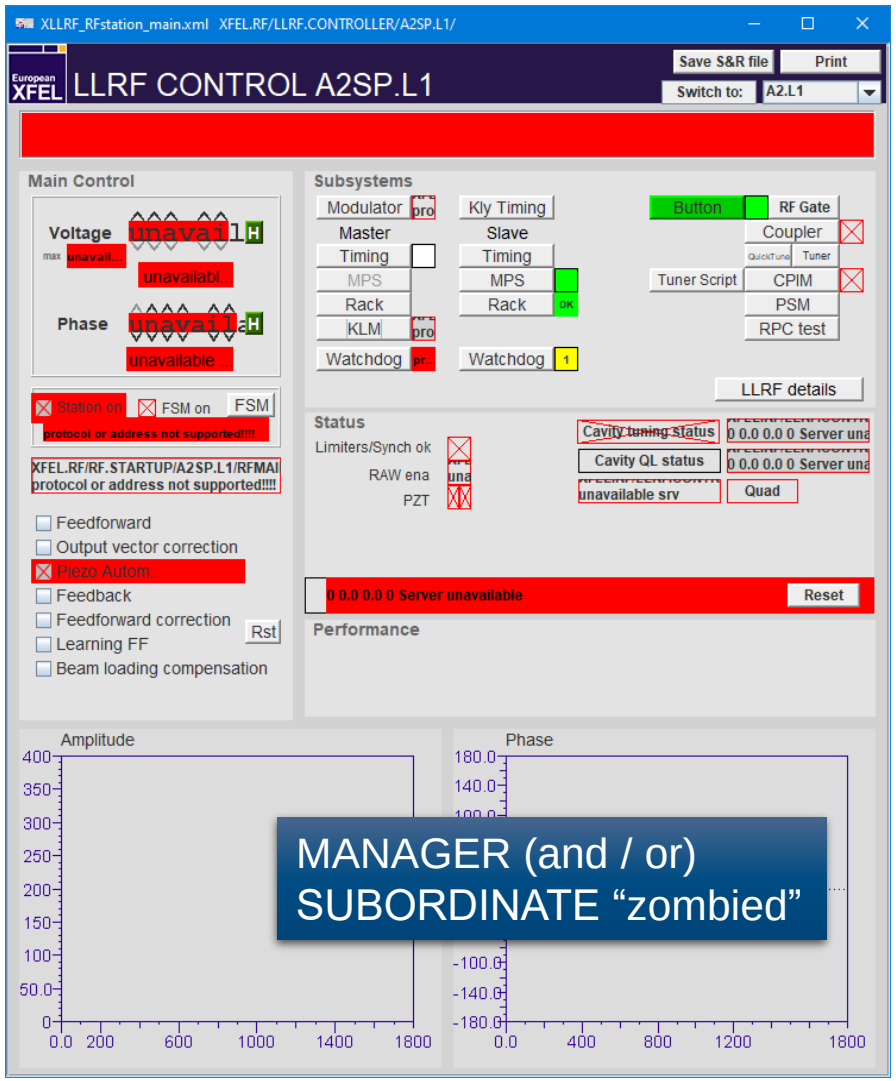
Quench during ramp up

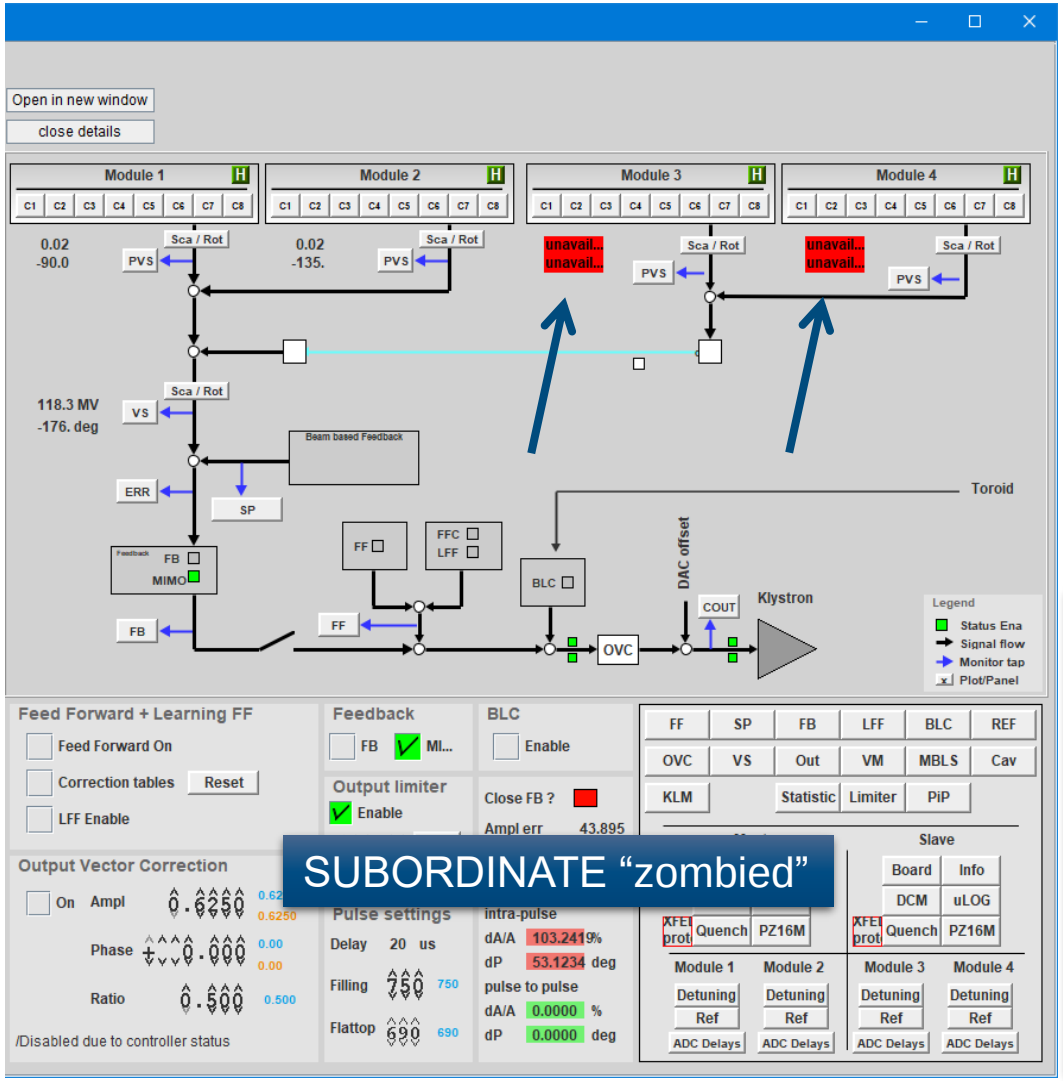
- **Problem description**
  - (After a quench) the RF station trips due to quenches taking place at a much lower gradient
  - Chances are the Q_L computation got corrupted during the quench, hence corrupting the quench detection mechanism
- **What you can try**
  - Disable the FSM, ramp up the station slowly (i.e. 10 MV steps) by hand, and re-enable the FSM



Exceptional case and how to react

“Zombie” station





The llrfCtrl server is not responsive

Chances are the hardware is still working

BUT

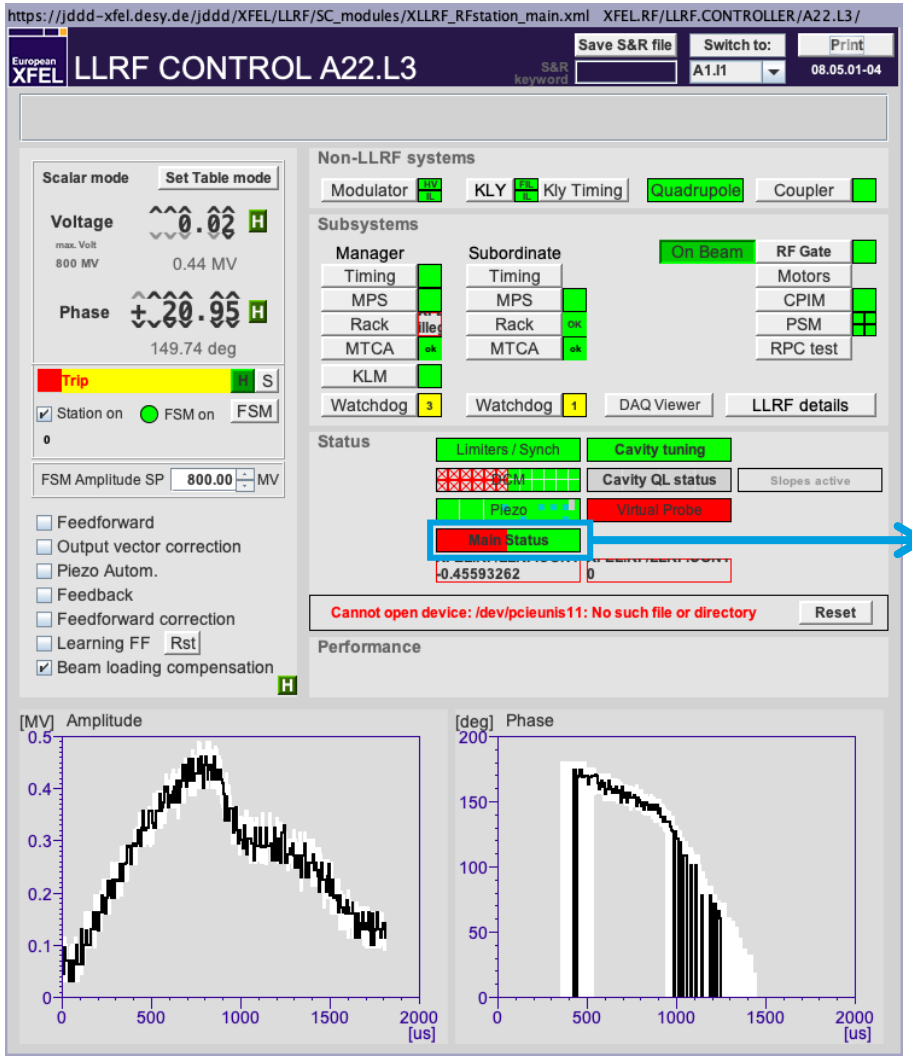
Likely the quench detection is no longer working

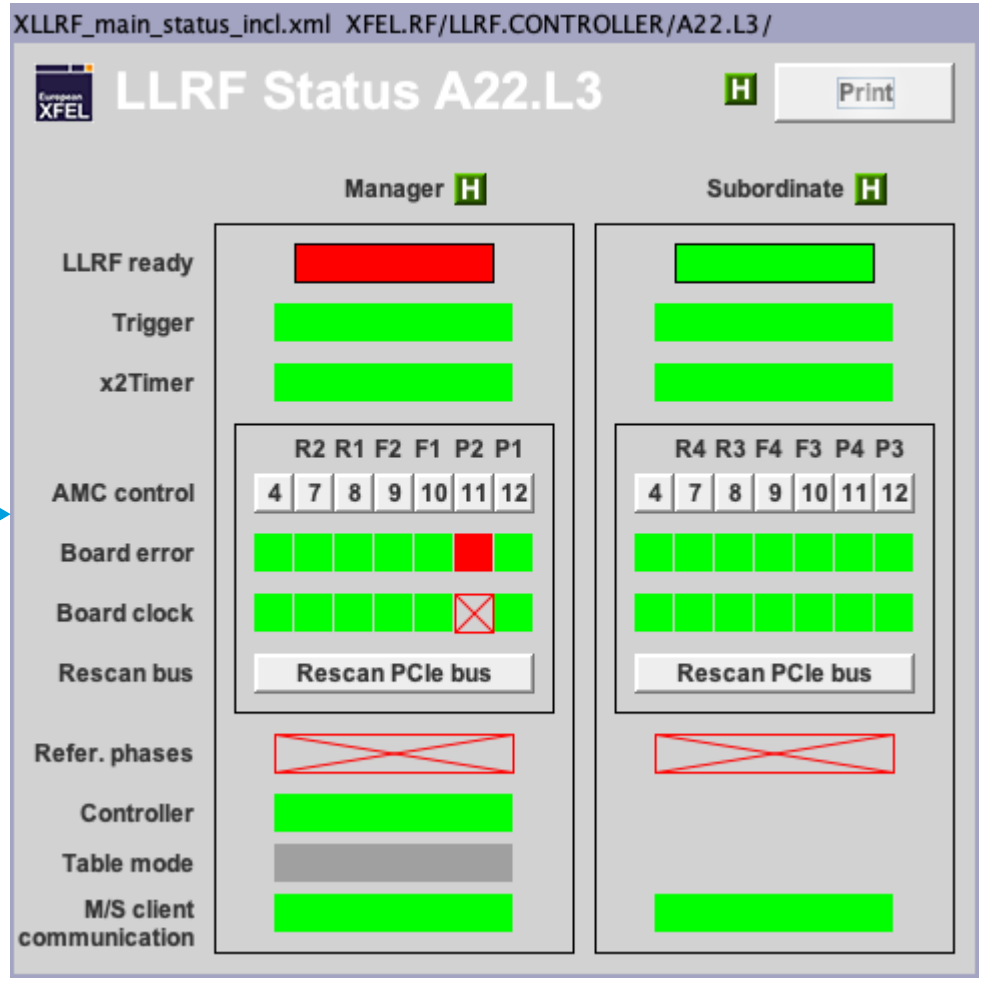
What to do:

1. Document in log book and send to LLRF
2. Agree with LLRF on-call and run coordinator when best to recover the station

Exceptional case and how to react

PCIe connection is lost





Main Status panel

PCIe connection with the board is lost

If it involves boards 4, 11 and 12, the station cannot operate

BUT

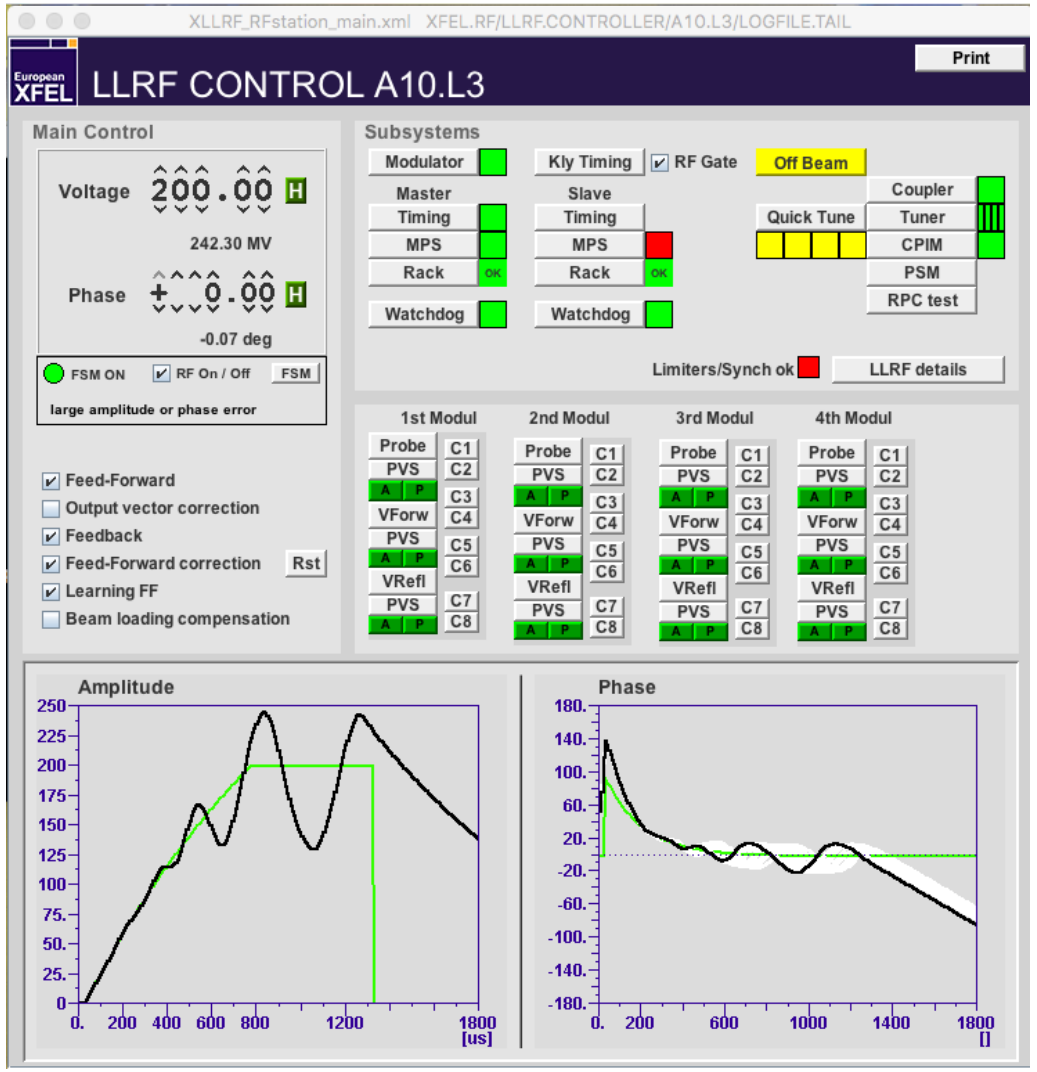
In the other cases, the station might work till fix

What to do:

1. Document in log book and send to LLRF
2. Agree with LLRF on-call and run coordinators when best to recover the station

Summary

- LLRF tasks of the XFEL operator:
  - Turn an RF station **ON / OFF**
  - Adjust the vector-sum **voltage / phase**
  - **Tune** cavities, if necessary
  - Adjust **output vector correction** and **ratio**, if necessary
  - Set a certain phase as **on-crest phase**
- **Special cases**
  - Pulse cut
  - Limiter notification
  - Quench
  - Zombie stations
- **Opportunity for hands-on**:
  - LLRF maintenance ~every Tuesday
  - off-beam stations -> ask LLRF team (& RCs)
- **Document (elog) what you find not normal**
  - **Please include your name, title and description!**



Thanks to Julien for the material

Thank you

Contact

DESY. Deutsches Elektronen-Synchrotron

www.desy.de

Marco Diomede
MSK
marco.diomede@desy.de
1615