Automation algorithms for LLRF operation.

2019 LLRF Workshop, Chicago

Sept. 29 - Oct. 03 2019

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for the DESY LLRF team

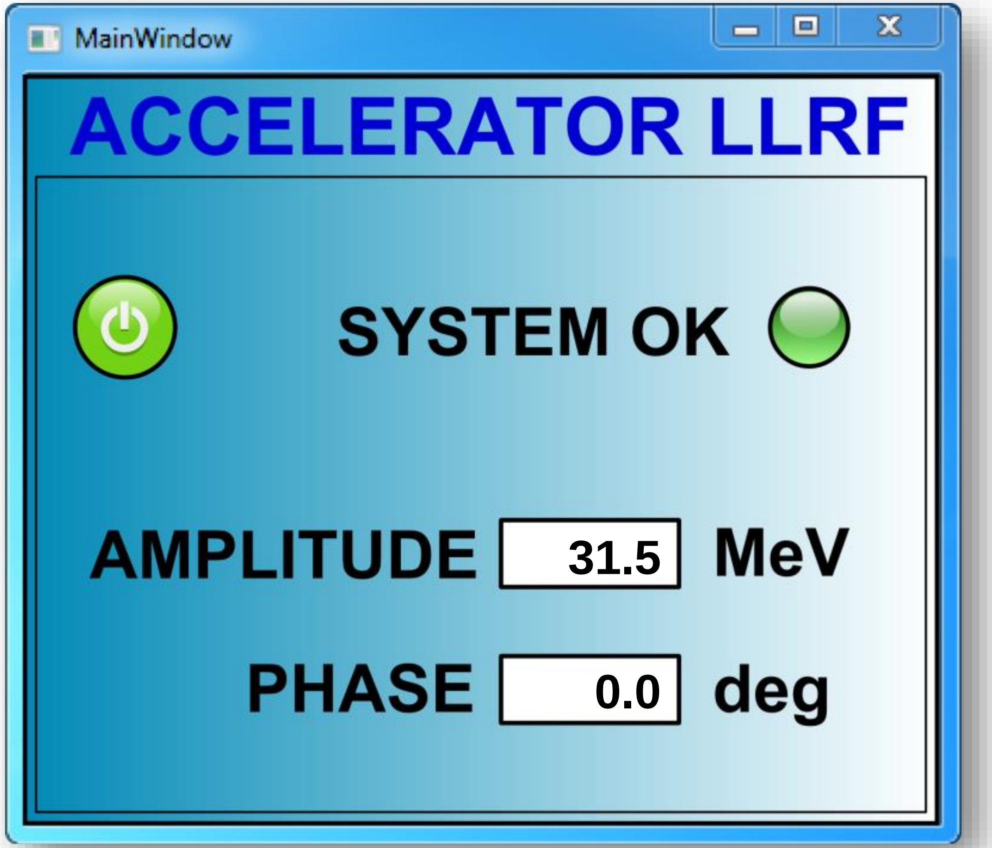
Chicago, Sept. 30th 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

What we want operators to see

Interface to the “ultimate LLRF” system



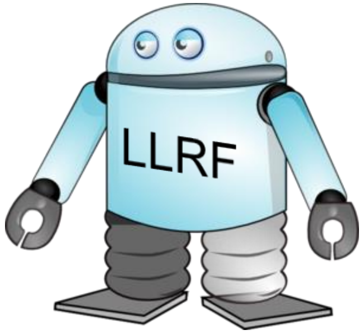
What is automation?

WIKIPEDIA
The Free Encyclopedia

“**Automation** is the technology by which a process or procedure is performed with minimal human assistance”

Automation for LLRF operations

- Automatic control
- Automatic start / stop
- Automatic fault detection / recovery



Several levels of automation: *does-everything-for-you*, or *simple scripts* to perform repetitive tasks or to bring up relevant data

Agenda

Automation for routine operation

- Automatic setup
- Automatic calibration
- Automatic tuning

Automation for FB and RF operation

- SP and FF phase modulation
- Output Vector Correction
- RF – Cryo operations
- Finite State Machine

Automation for fault detection and analysis

- Post mortem statistics
- Run-time detection

Disclaimer

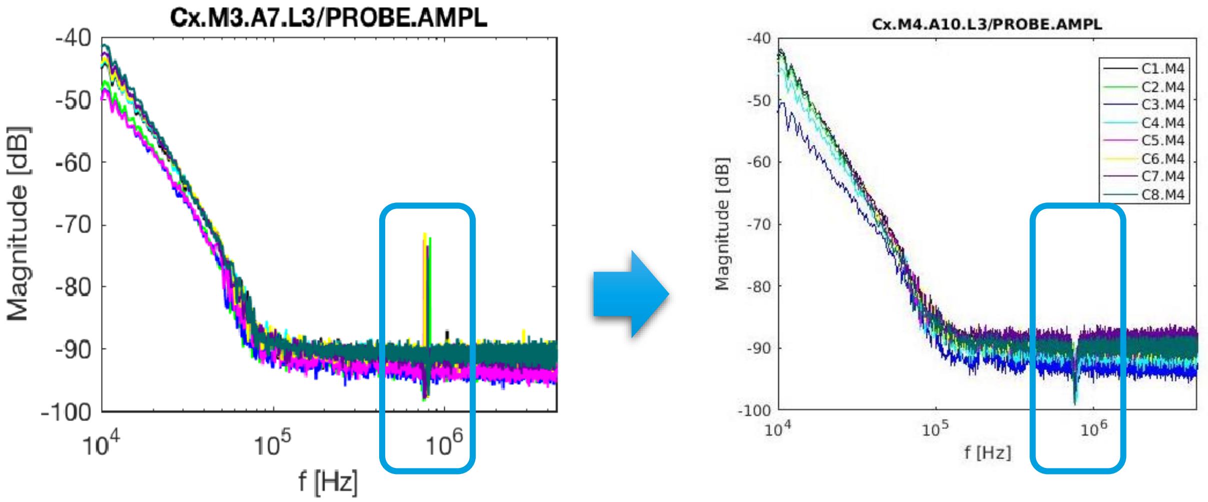
- *Only examples from pulsed, SRF electron machines (FLASH/XFEL)*
- *Influenced by machine culture: scale, vector sum operation, etc…*

Automation for routine operations

Source: gifsec.com

Automation for routine operation

- **Automatic setup**
  - **Filters (8π/9 notch for ex.)**
  - Dynamic range adjustment
  - System identification and FB controller parameters
  - Learning FF parameters
- **Automatic calibration**
  - Beam-based probe calibration
  - Forward / Reflected signals
  - On-crest phase
- **Automatic tuning**
  - Frequency (slow, fast)
  - Bandwidth (Q_L)
  - Phase modulation (feed forward, set point)
  - Output vector correction



Reference: *“LLRF XFEL : Automated Commissioning, Deployment and Systems Integration”*
LLRF 2017 tutorial

Automation for routine operation

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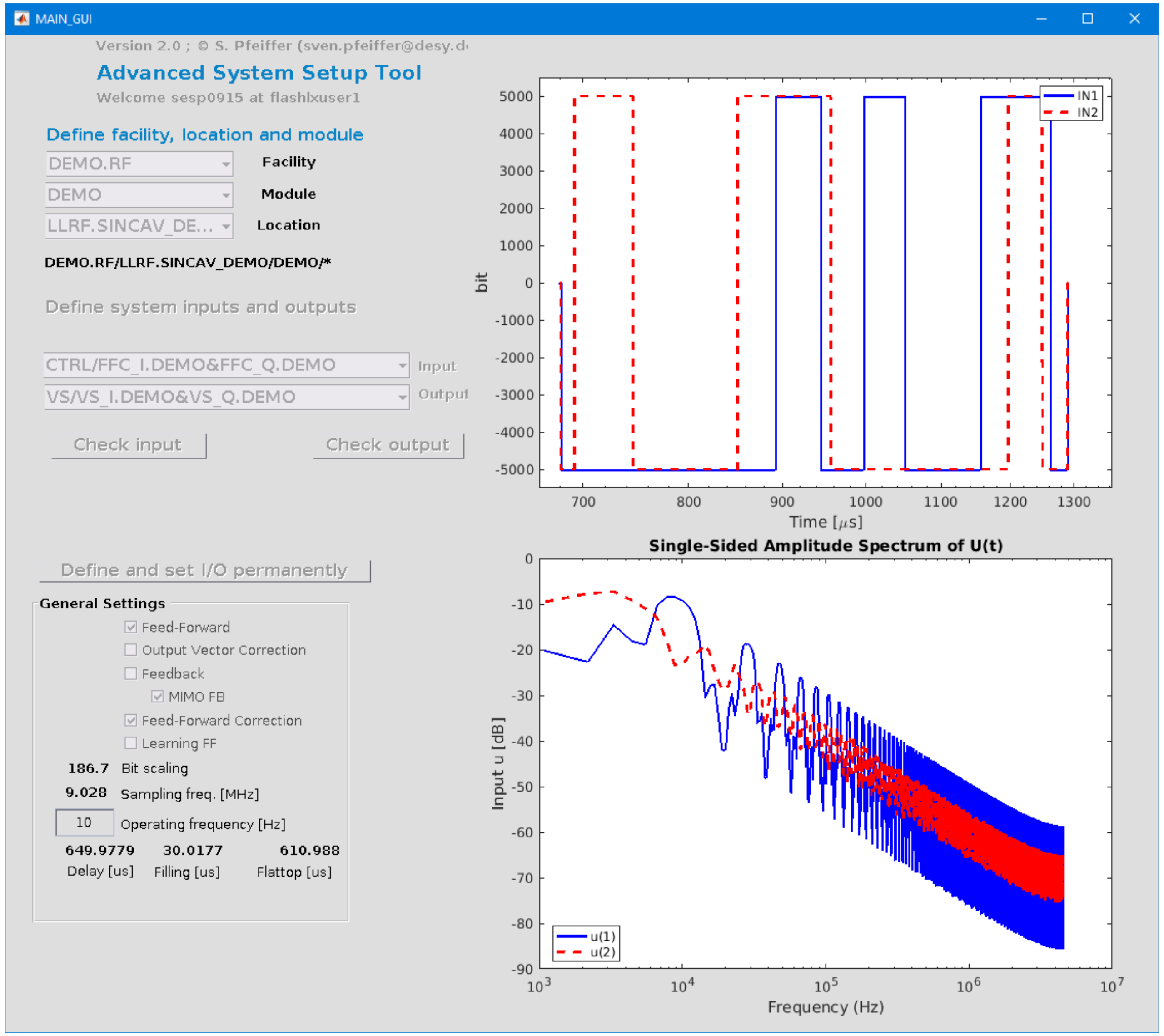

Reference: *"Advanced LLRF system setup tool for RF field regulation of SRF cavities"* SRF 2019 S. Pfeiffer *et al.*

Automation for routine operation

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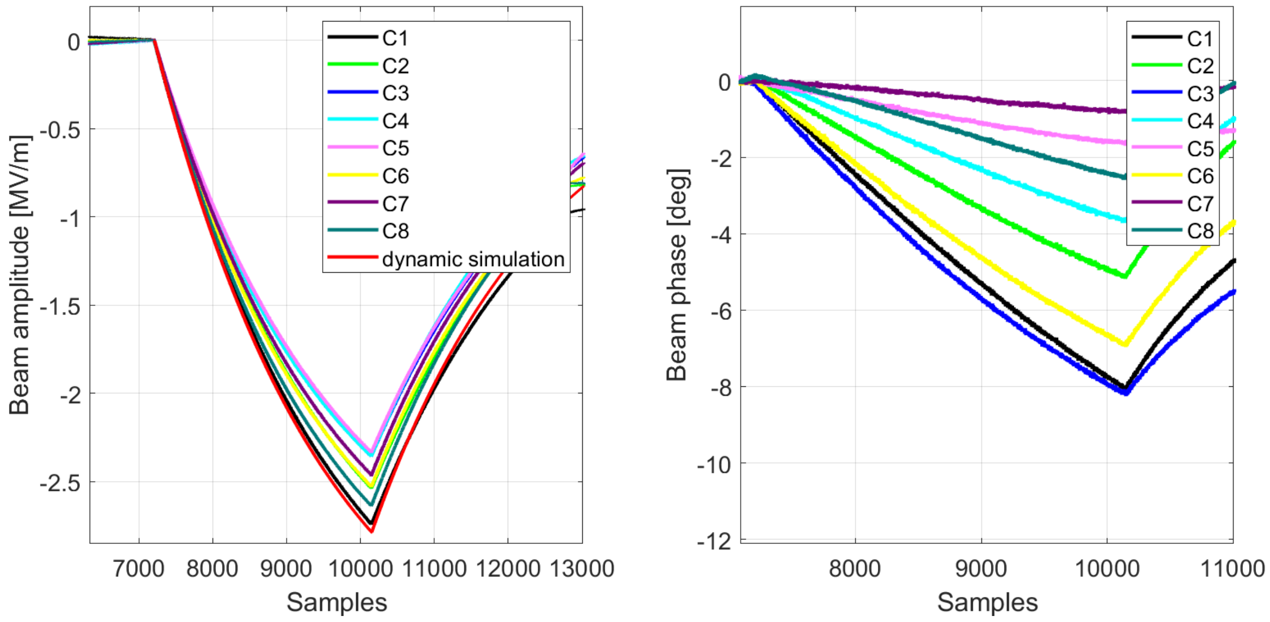

Several techniques developed over the years based on beam transients analysis:
- at nominal gradient (no extra setup required)
- at 0-gradient (removes RF uncertainties from the equation)
- on-line (less intrusive)

See Mariusz Grecki's talk on Tuesday

Automation for routine operation

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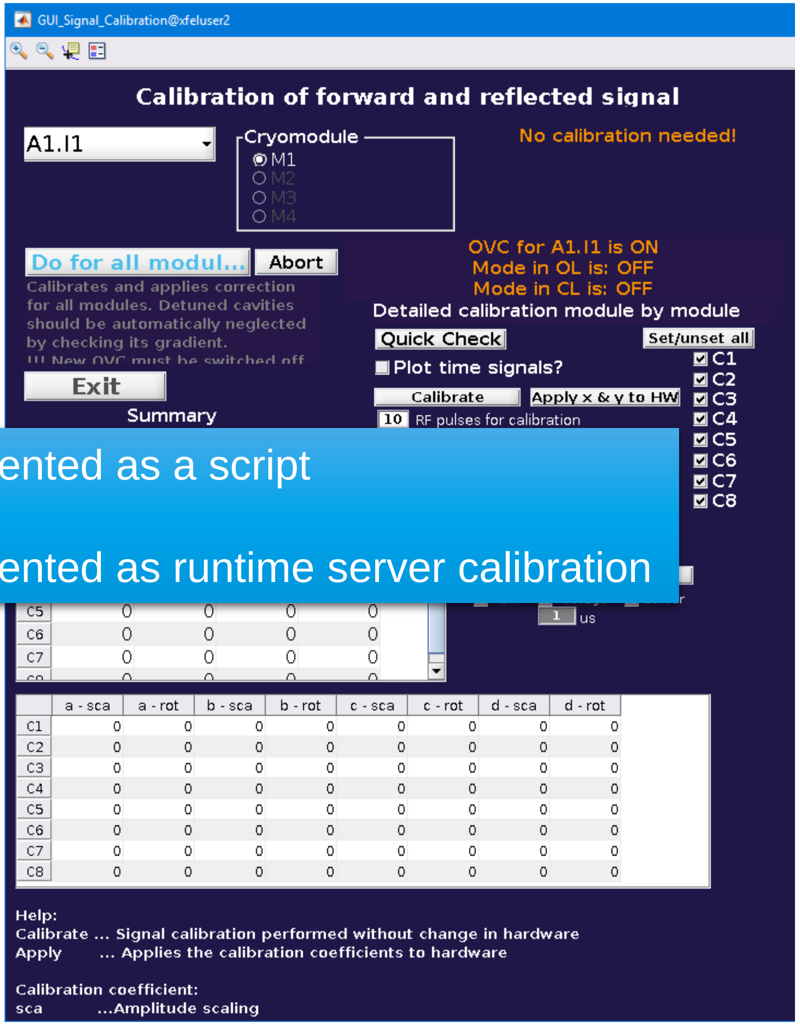
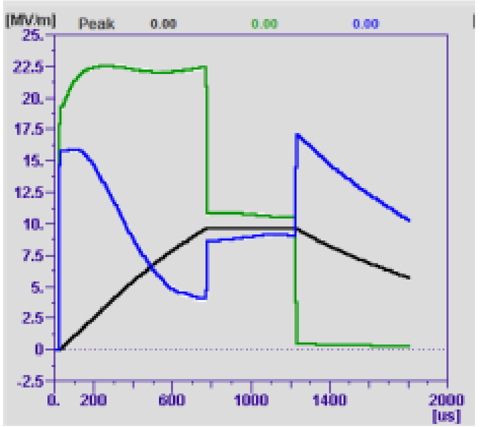
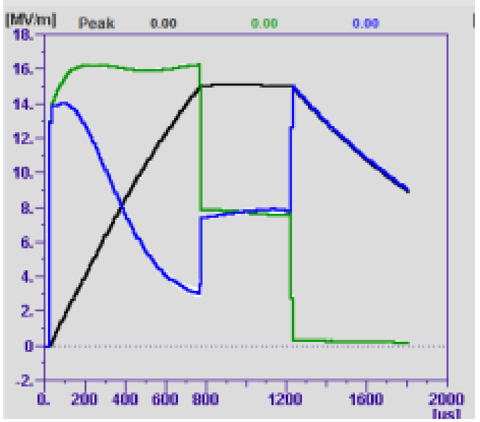


Implemented as a script
or
Implemented as runtime server calibration





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  - **On-crest phase identification**
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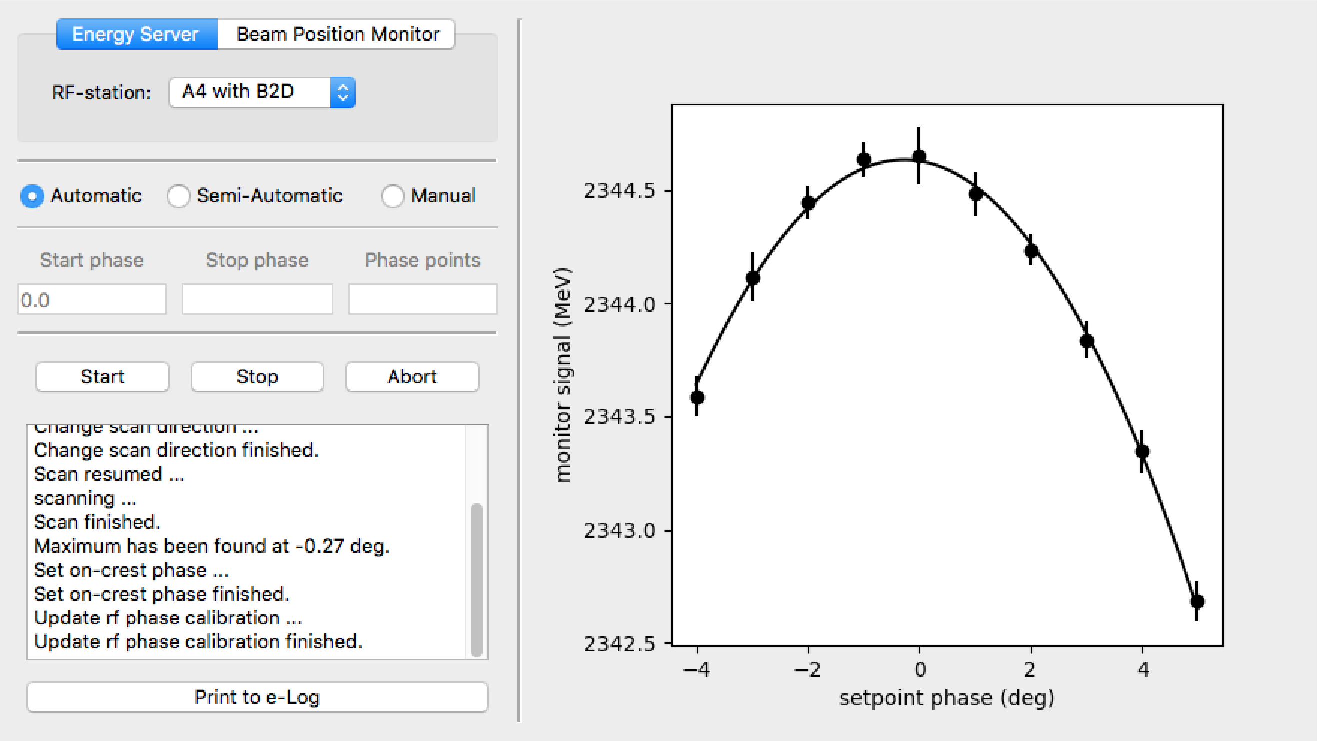

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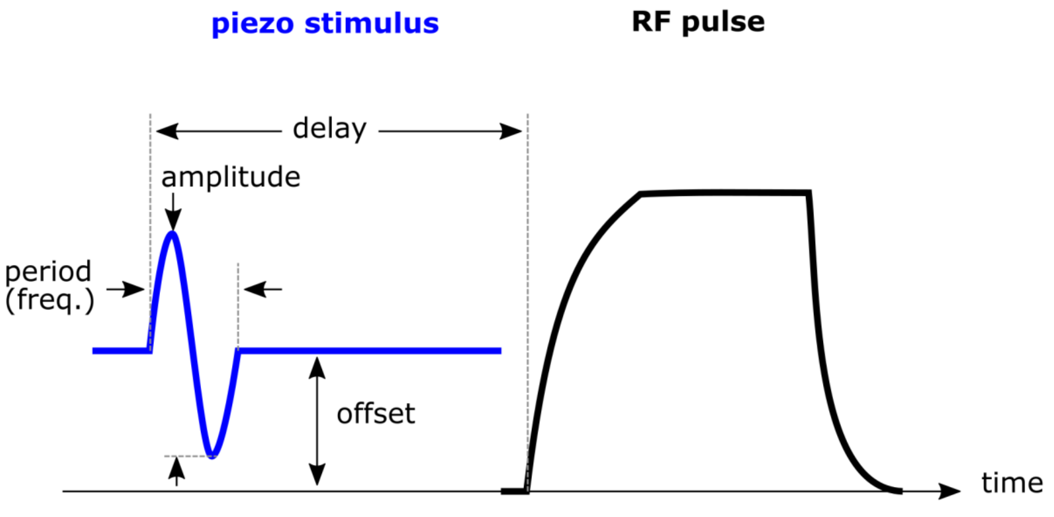
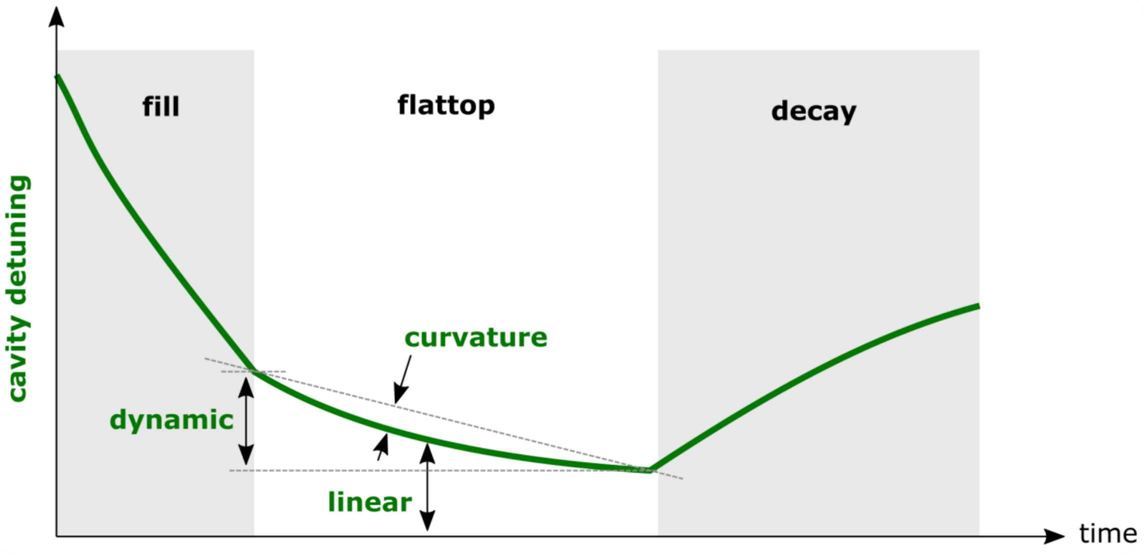
Piezo tuning automation

- Piezo tuning range +/- 1 kHz
- Basic approach followed at FLASH/XFEL
  - Sine kick preceding the RF pulse
  - Few parameters to adjust
- Limitation:
  - Can't compensate for detuning during fill time AND flat top with this approach
- Automation = proportional feedback on detuning parameters
- Exception handling
  - Cavity freq. drifts lead to automation hitting rail
  - How to handle slow tuner adjustments ?





Piezo tuning automation

Example at XFEL (16 piezos)

Slow tuner automation

Example at XFEL (32 cavities)

Option to combine slow tuner AND fast tuning (so-called “piezo relaxation”)

Tuner “knows” which cavities should **NOT** be tuned

Each cavity has its individual tuning set point (could be ≠0)

Exceptions handling and built-in safety mechanisms to avoid over driving tuners

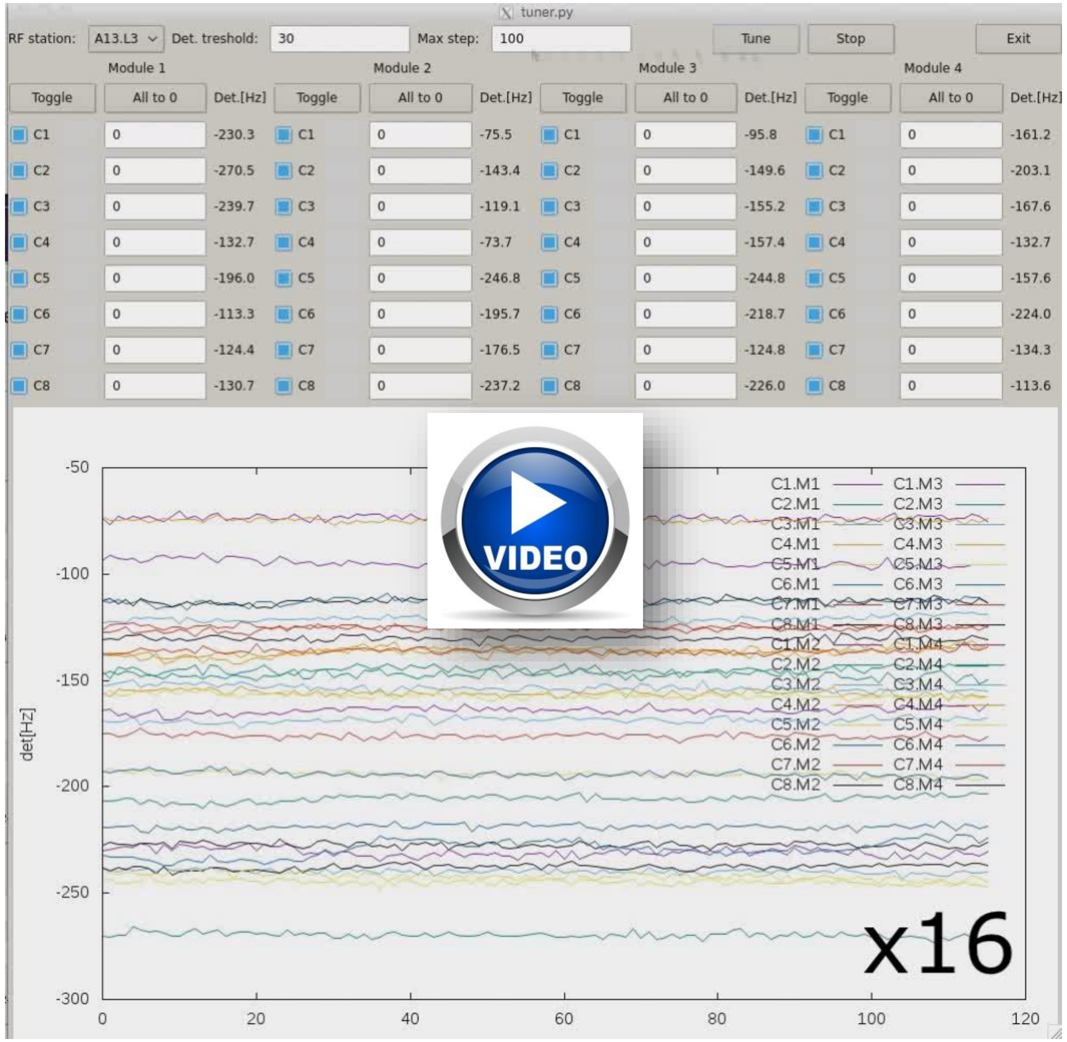
tuned

could be tuned

detuned

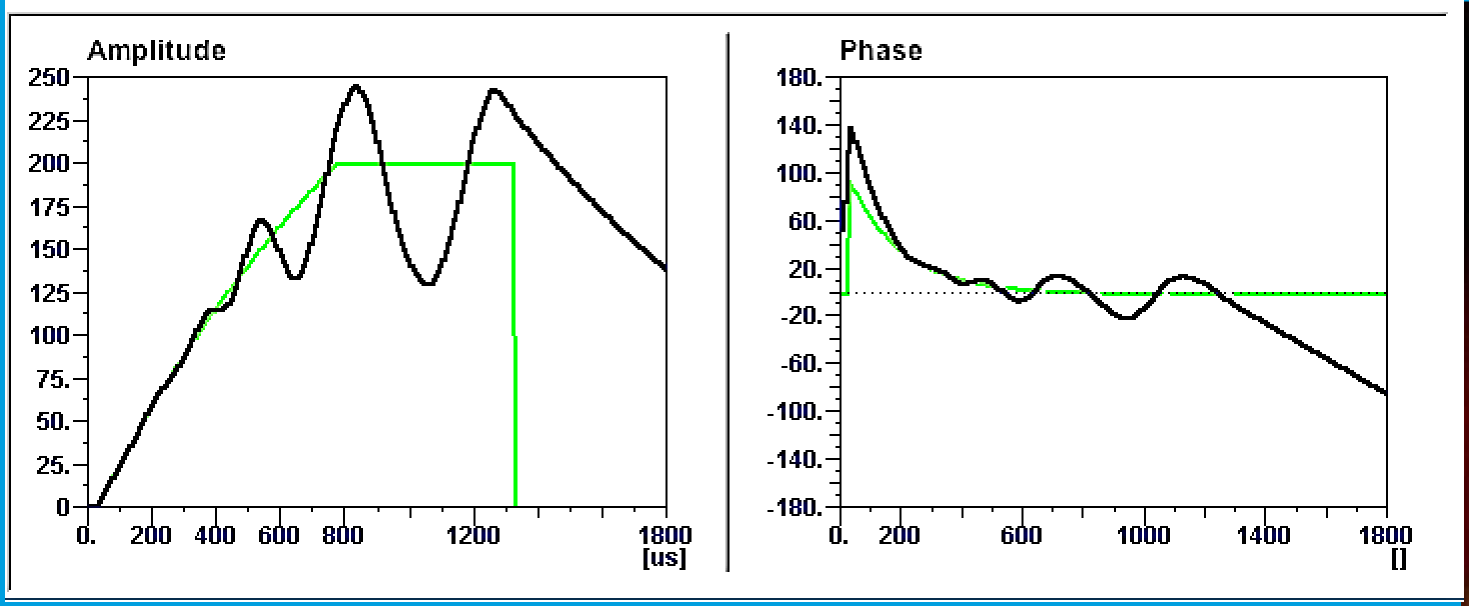
Slow tuner automation

Example at XFEL (32 cavities)



Automation for FB and RF operations

shoot… I shouldn't
have closed the loop…

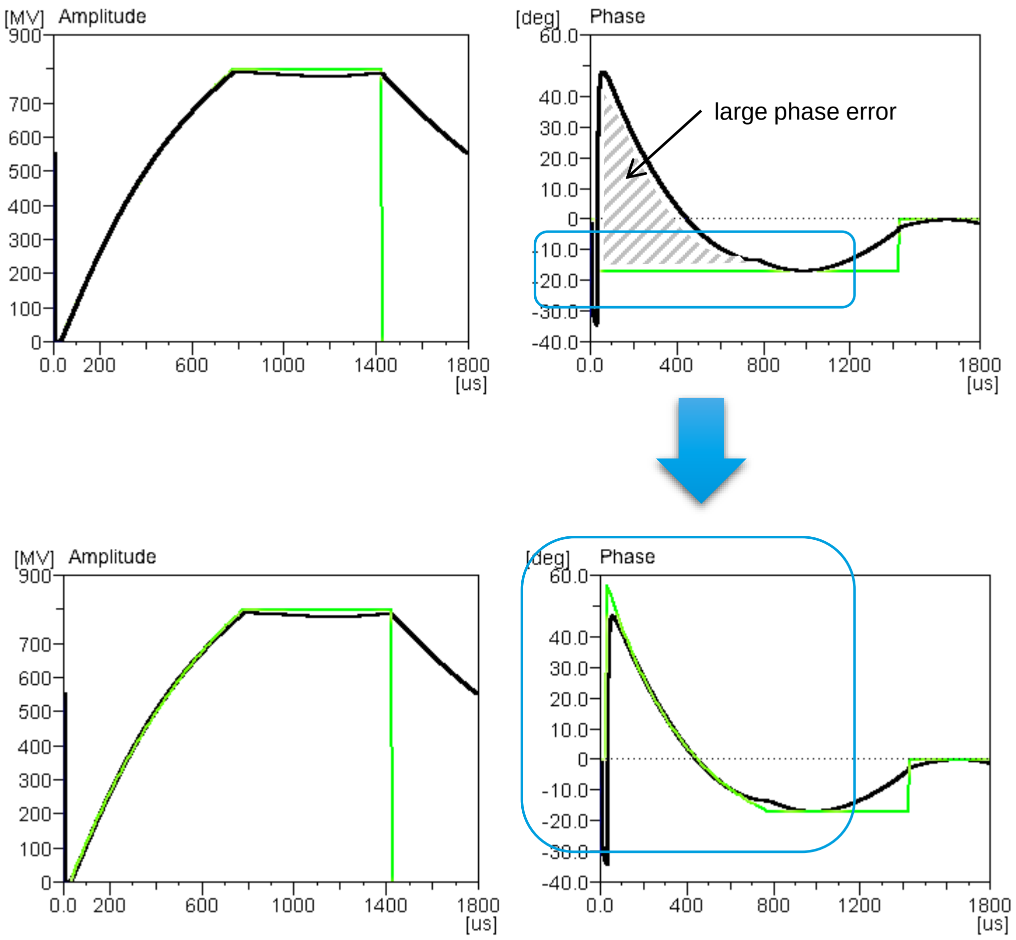


Automation towards FB operation

Set point phase modulation

- Goal is to shape the set point phase to minimize the controller input error
- (controller output is limited for protection)
- One approach consists of **empirically fitting an exponential** through the cavity (vector sum) phase roll
  - Easy to implement, only a few parameters to optimize
  - Exponential fit is OK for first order approximation
- Another approach is to derive the optimal cavity (vector sum) phase roll **based on the cavity model**

See Sven Pfeiffer’s poster for details



Automation towards FB operation

Feed forward phase modulation

- Goal is to shape the FF phase to follow the klystron phase roll during ramp up
- Note: this is not necessary with klystron linearization

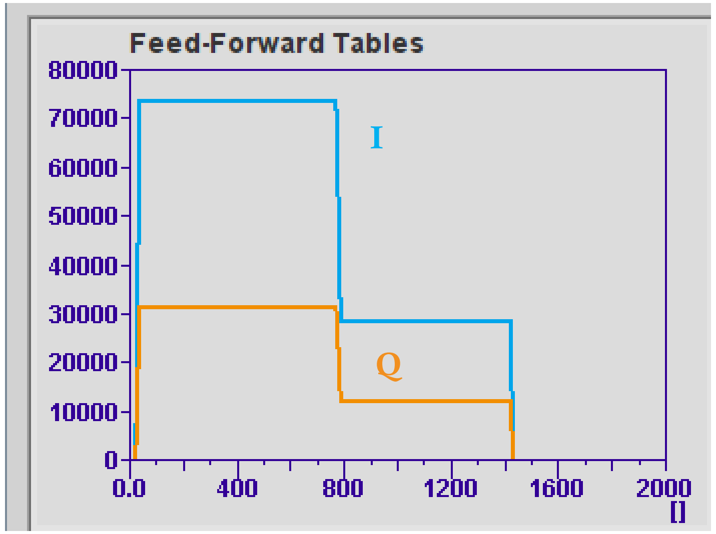
Approach presented a long time ago:

"Optimization of filling procedure for TESLA-type cavities for klystron RF power minimization for European XFEL" IPAC 2010 V. Ayvazyan *et al.*

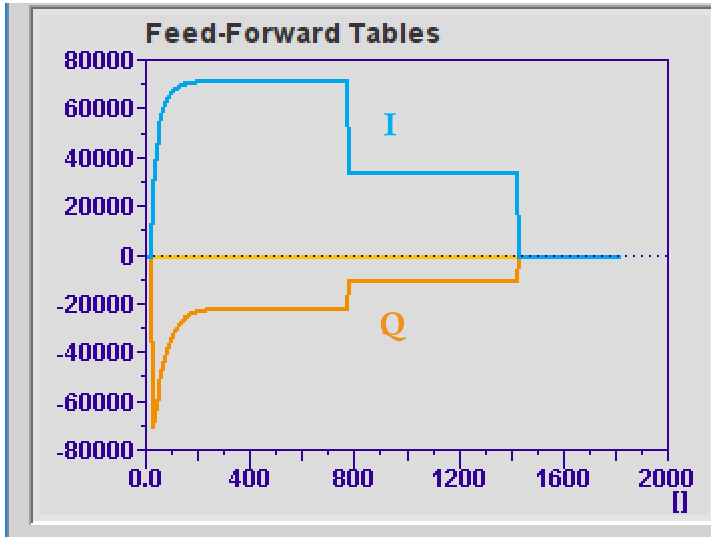
- Here too, one simple approach consist of **fitting an exponential to maximize Vcav**
- Another approach is **model-based** and can **predict** how the FF phase should be modulated to minimize Prefl during fill

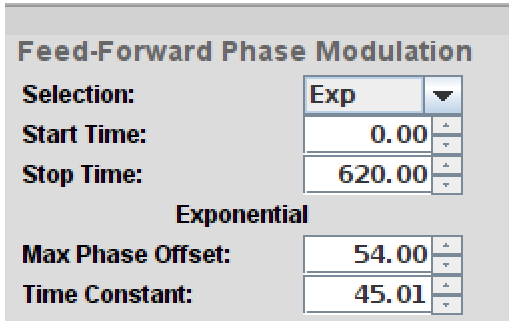
See Sven Pfeiffer's poster for details

Example: A2 : no FF phase modulation



Example: A17 : FF phase modulation

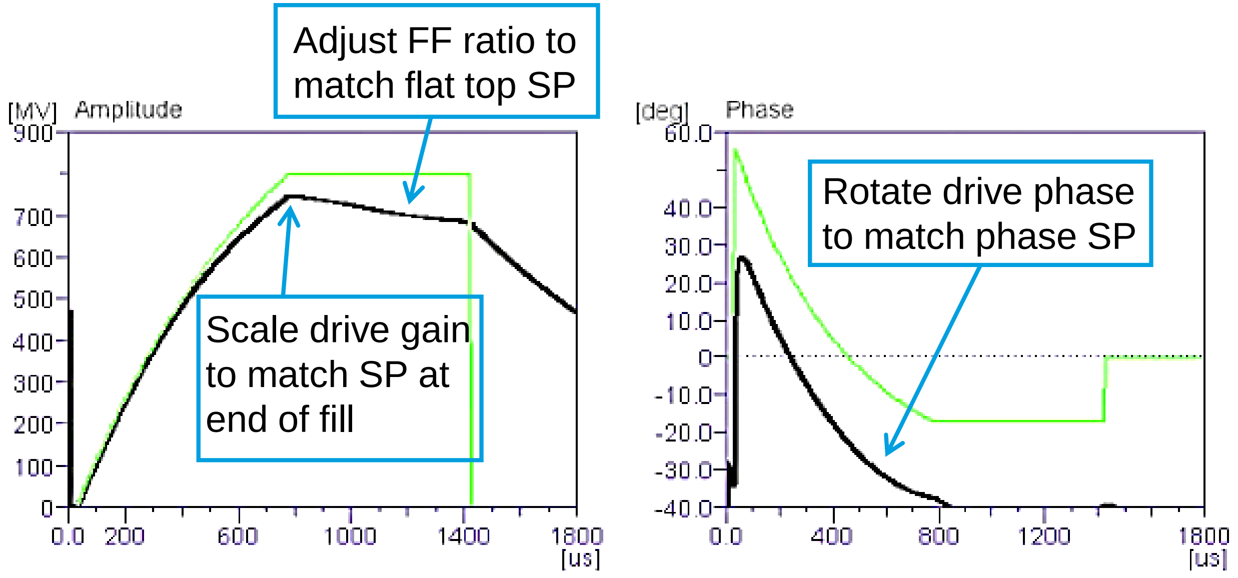




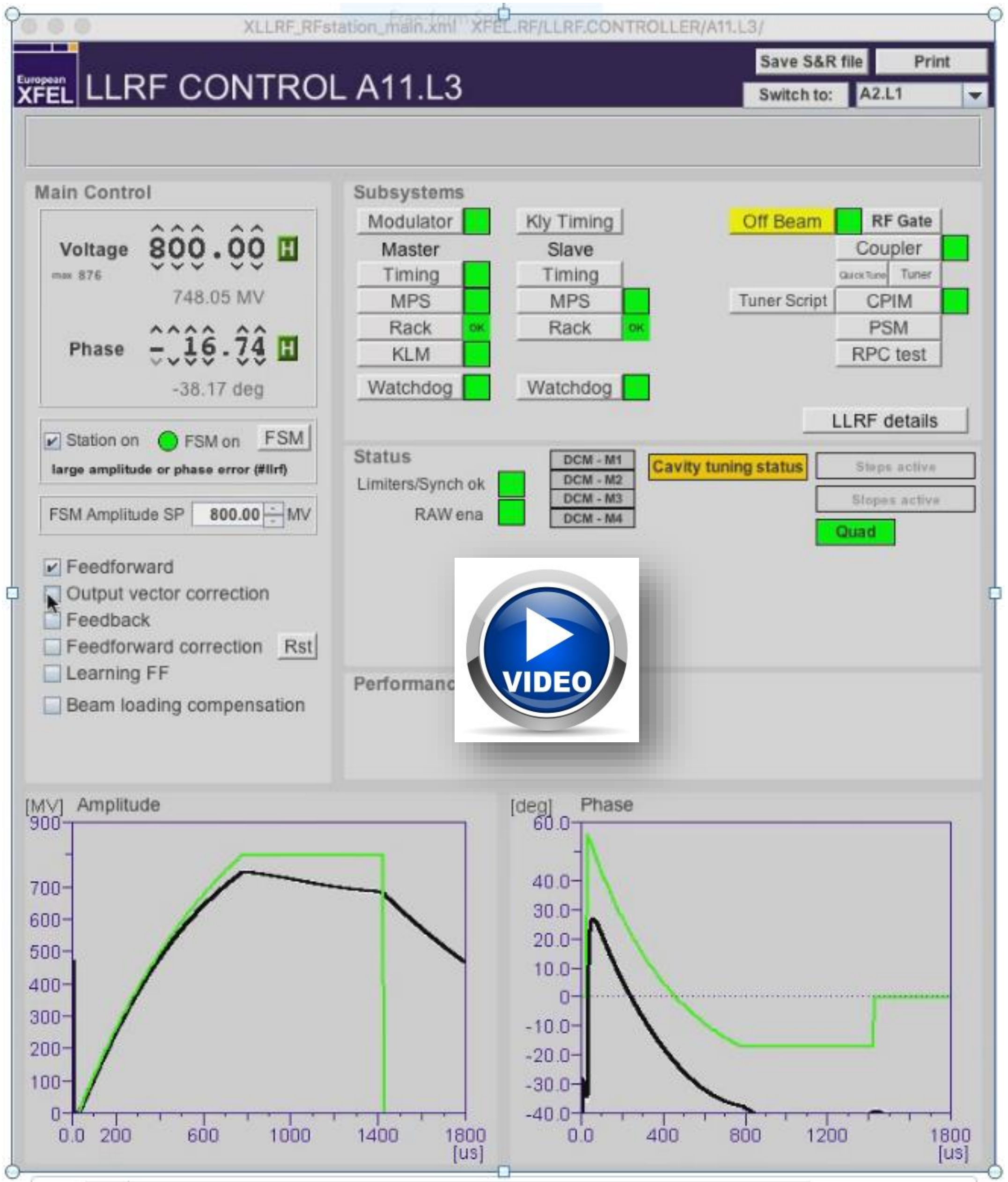
Automation towards FB operation

Output Vector Correction

- Goal is scale in amplitude and rotate in phase the output drive to meet the set point
- Loop phase/gain might have changed during operation
- Automating this process allows for a fast ramp up



Open loop OVC behavior



Automation for RF operations

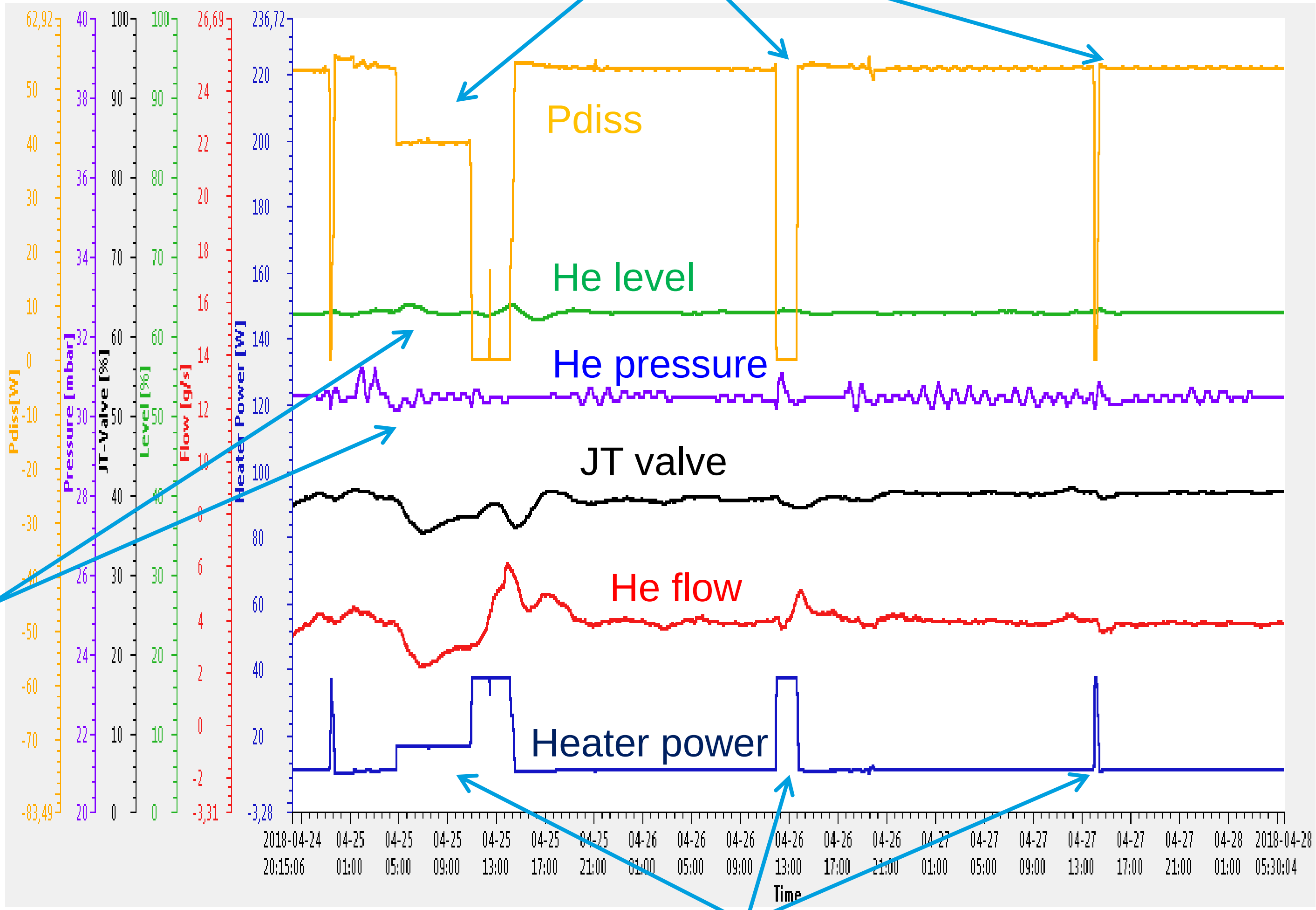
Dynamic heat load compensation

- XFEL runs with cold compressors
- Need a regular He flow
- Avoid disturbance induced by RF changes
  - Quenches
  - Sudden massive gradient changes
- Dynamic heat load fluctuations compensated by heaters

Stable He level and pressure

Pdiss computation based on RF gradient, flat top duration, and quench alarms

XFEL RF shutdowns



Heater compensation

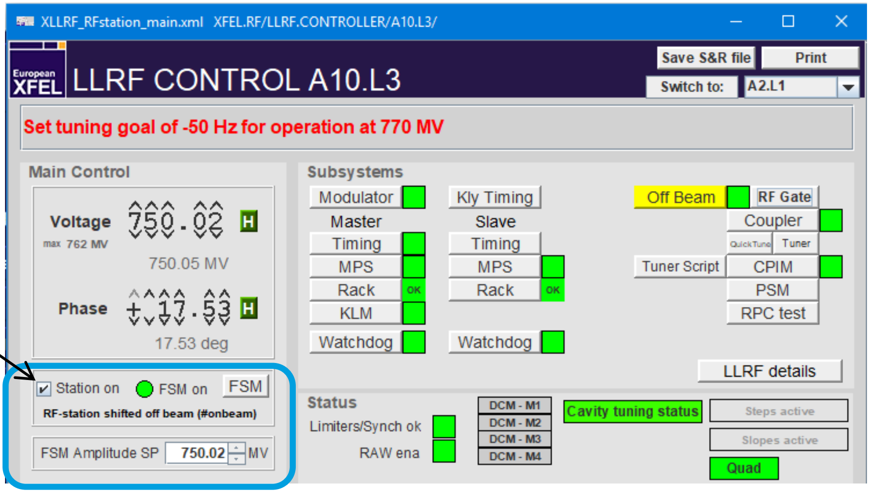
Courtesy Jörg Penning

Automation for RF operations

Finite State Machine (1/2)

- **Works as a sequencer**
  - Ramp up / down
  - Station / machine -wise
- **Works as high level monitoring server**
  - Gathers interlock from diverse sources (klystron, modulator coupler, cryo, quenches, etc…)
  - Provides post mortem information (what tripped, when)
- **Works as soft interlock**
  - Compares RF set point to vector sum read back
  - Stops the RF if anything abnormal pops up

one-click ramp up / down

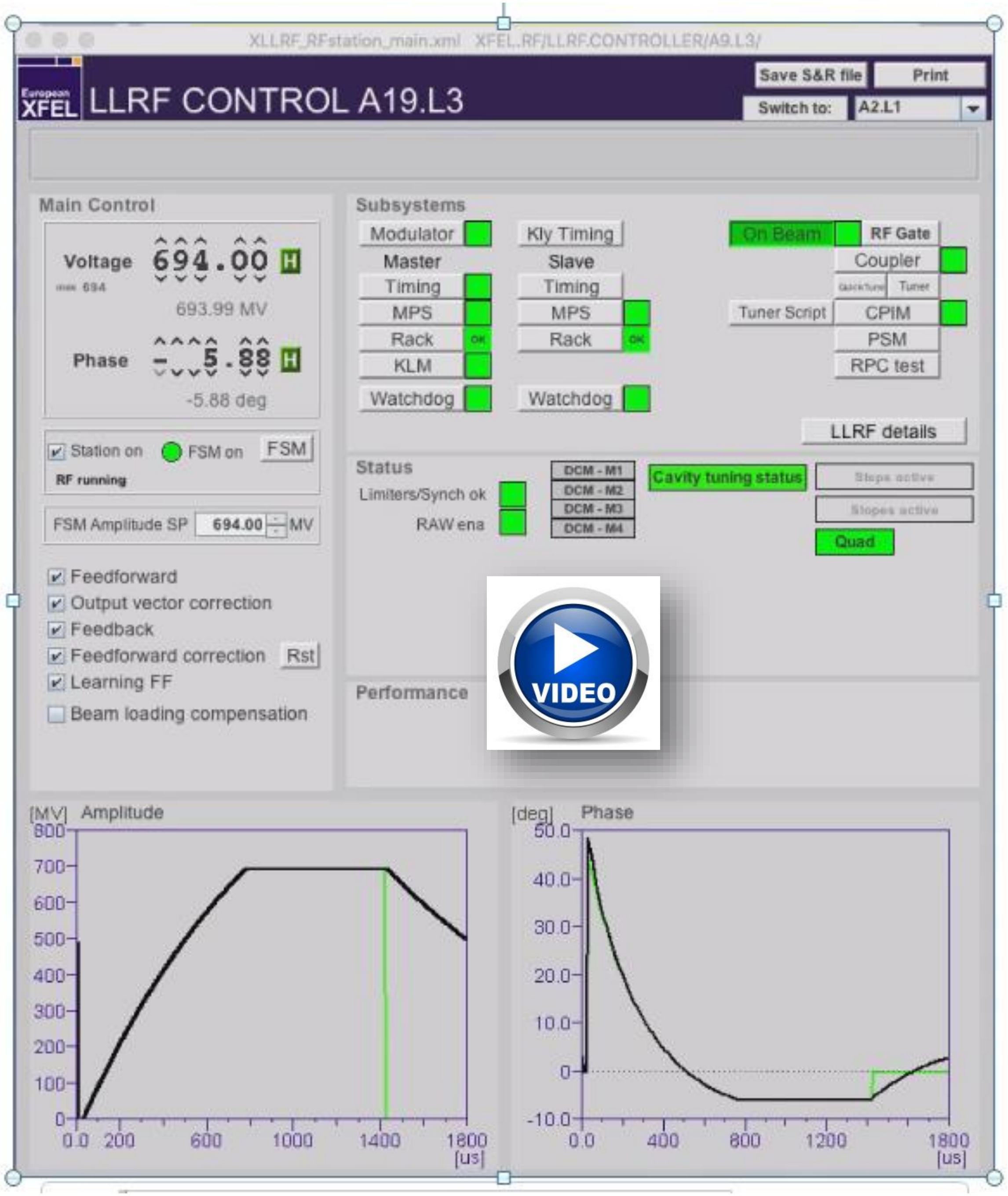


LLRFFSMserver A13.L3 19:50.46 9.09.2019 -> EqFSMmain::tripaction called by AMPLTRIP_ONSTATE with big **error between SP and VectorSUM (#mismatch)**
LLRFFSMserver A13.L3 19:50.46 9.09.2019 -> A13.L3 entering recover mode
LLRFFSMserver A13.L3:tripaction 19:50.46 9.09.2019 -> running for station: A13.L3
LLRFFSMserver EqFctLLRFFSM_MAIN::block_laser 19:50.46 9.09.2019 -> block both laser
LLRFFSMserver A13.L3 19:50.47 9.09.2019 -> EqFSMmain::run: enter recover mode to startup
LLRFFSMserver A13.L3 19:52.13 9.09.2019 -> A13.L3 leaving recover mode

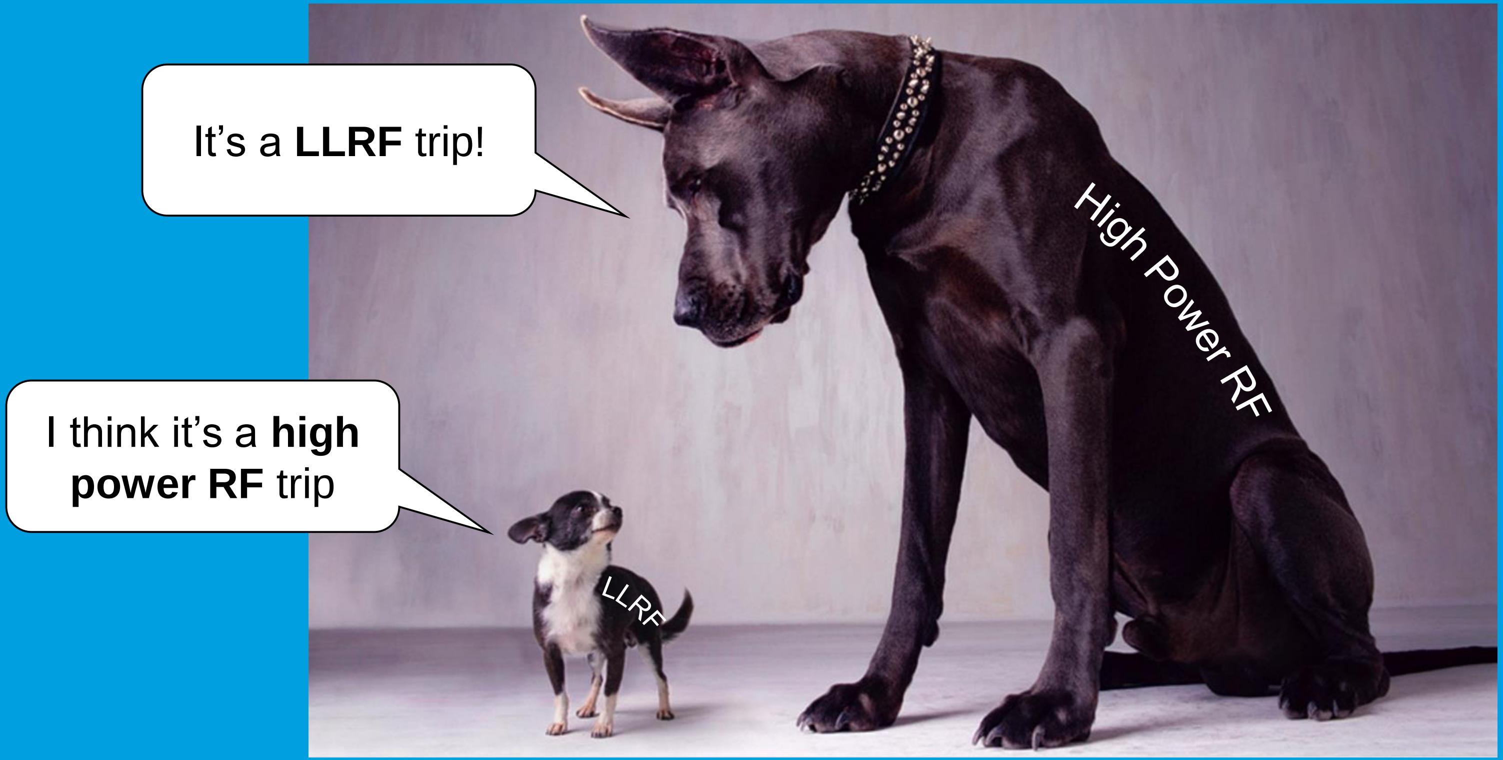
Automation for RF operations

Finite State Machine (2/2)

- Ramp up example:
  - Starts the modulator and wait for HV to be stable
  - Notify cryo that a station will be ramped up
  - Ramps up RF open loop at given pace
  - Recovers previous operating gradient
  - Scales output drive to match set point (fine adjust.)
  - Closes the loop (FB)
  - Clears learning feed forward corrections and starts LFF
  - Start piezo tuning
  - (Enables beam loading compensation)
  - Places station on beam (if was previously on-beam)

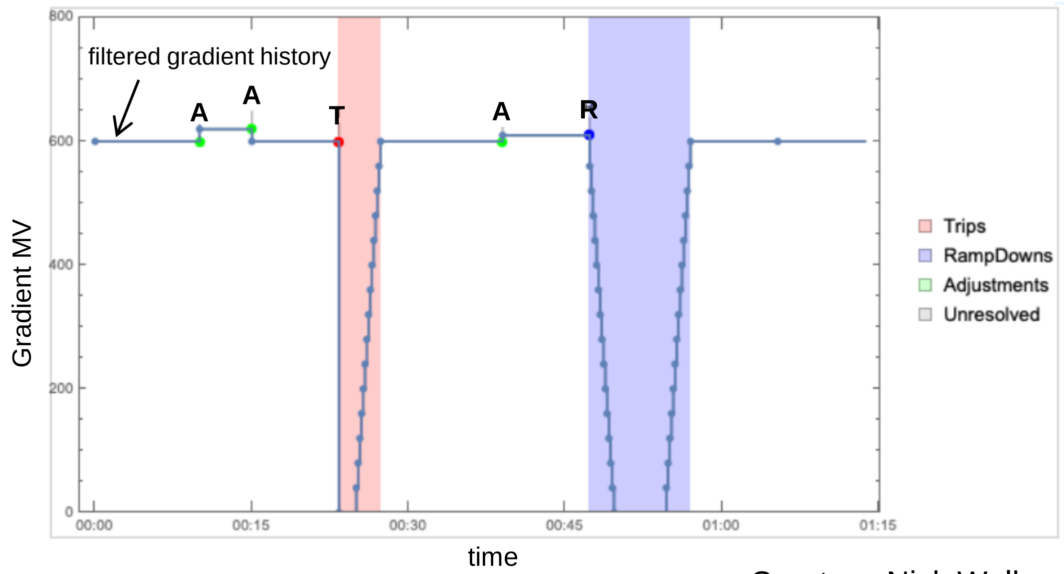


Automation for fault detection and analysis

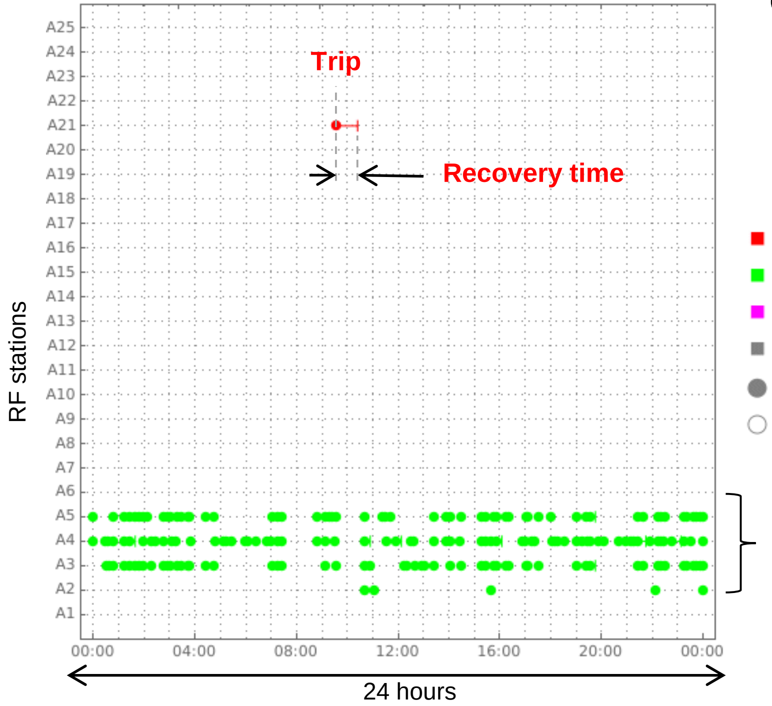


Automation for trip analysis

- **Daily / weekly automatic analysis**
  - Checks histories of gradients, interlock signals
  - Looks at servers log file
  - Distinguishes tuning or ramp down from trips (change rate and amount)
- **When a trip is found**
  - Compute down time and recovery time
  - Fetches the DAQ data (5 secs before, 1 sec after)
  - Saves data (cloud)
- **Generates summary**
  - Overview graphs
  - Summary tables
  - Compiles report, saves it (cloud) and sends email



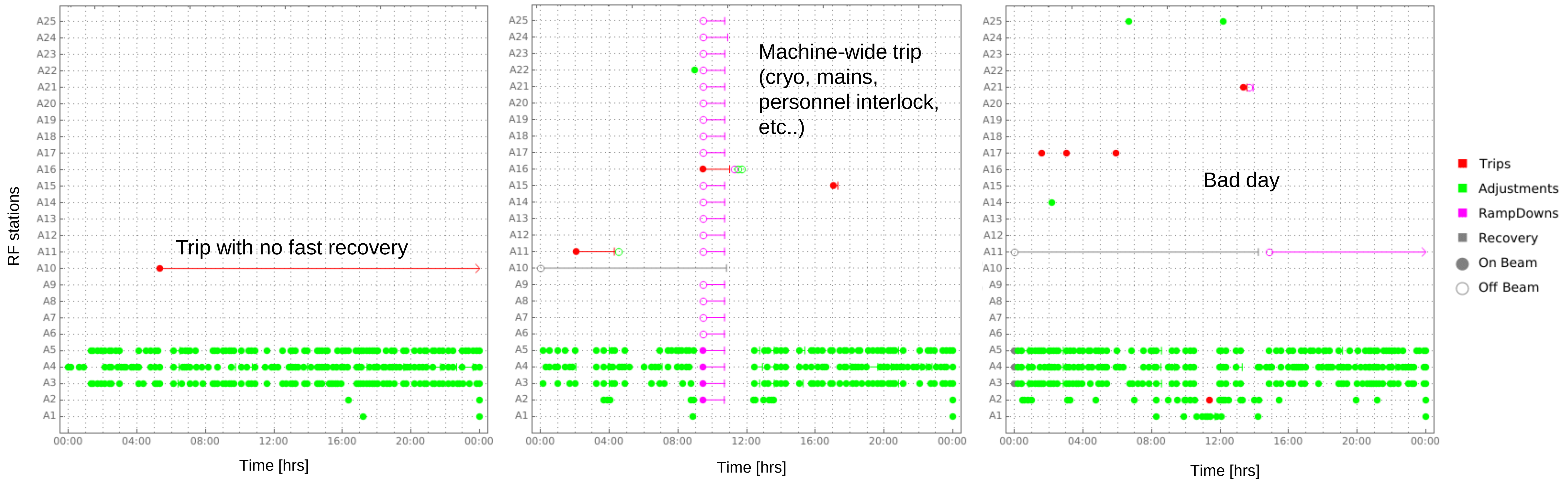
Courtesy Nick Walker



Mostly L1 & L2 stations are tweaked by beam-based feedback algorithms

Automation for trip analysis

Some more examples



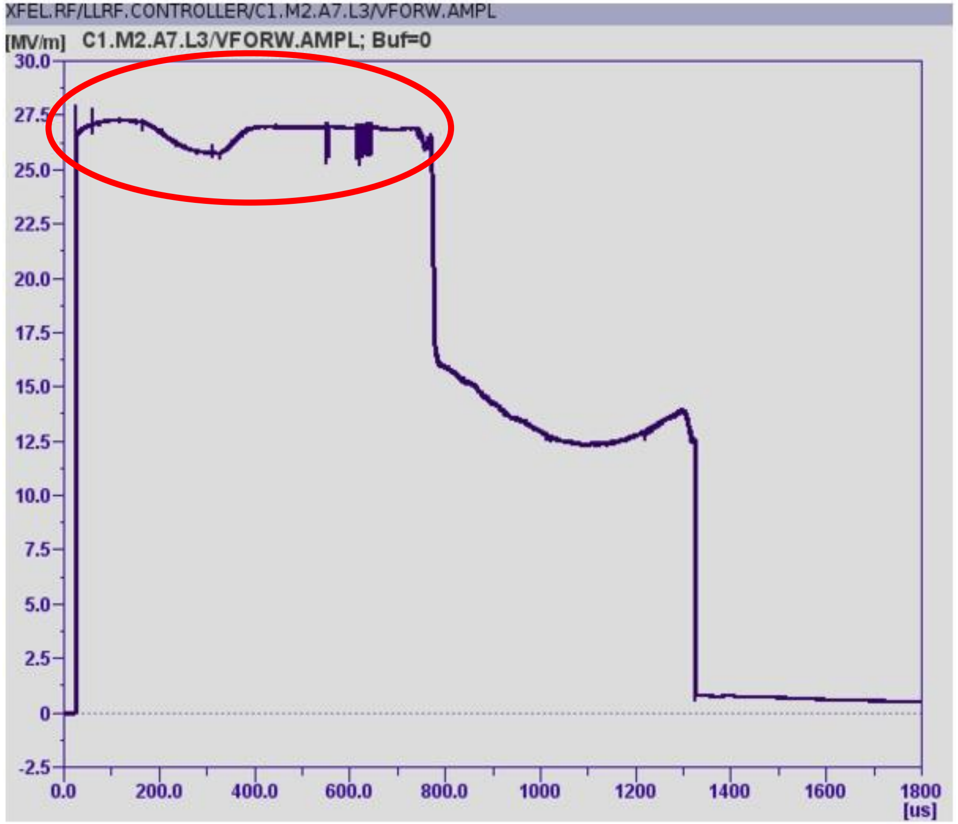
The goal is to gather statistics

- to derive RF availability, up time, MTBF, etc…
- to understand where to focus our effort

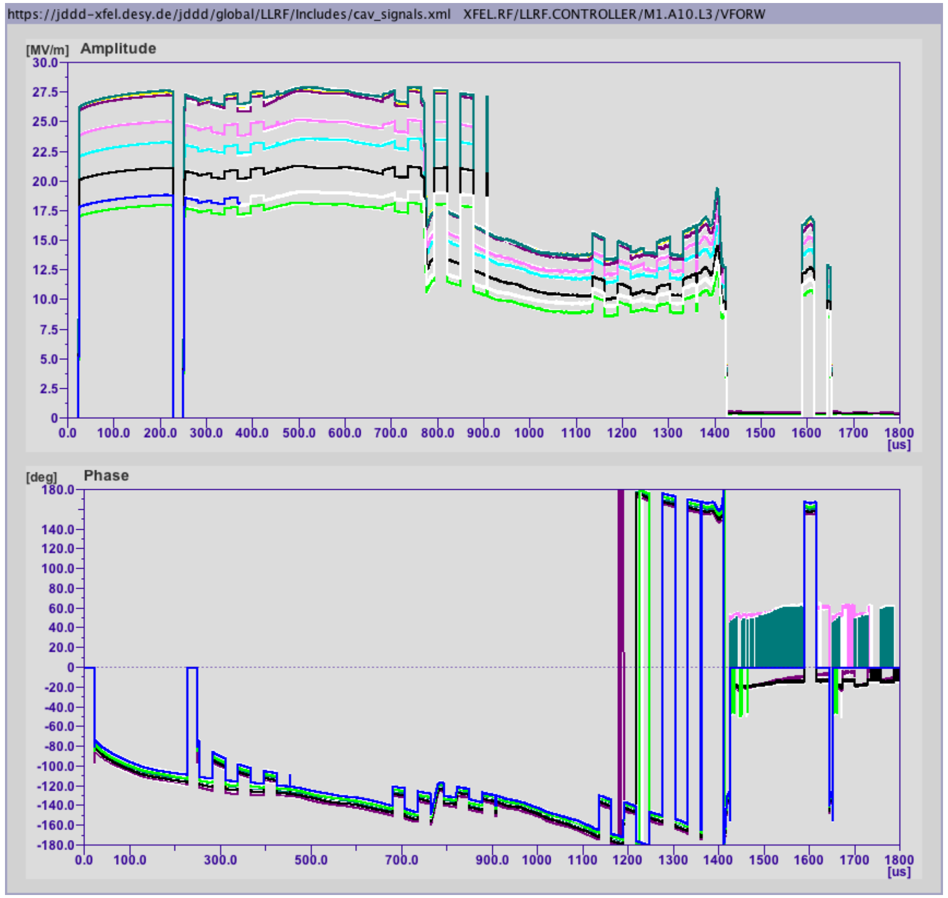
Automation for fault detection

Some “weird stuff” examples (1/3)

The “glitch”



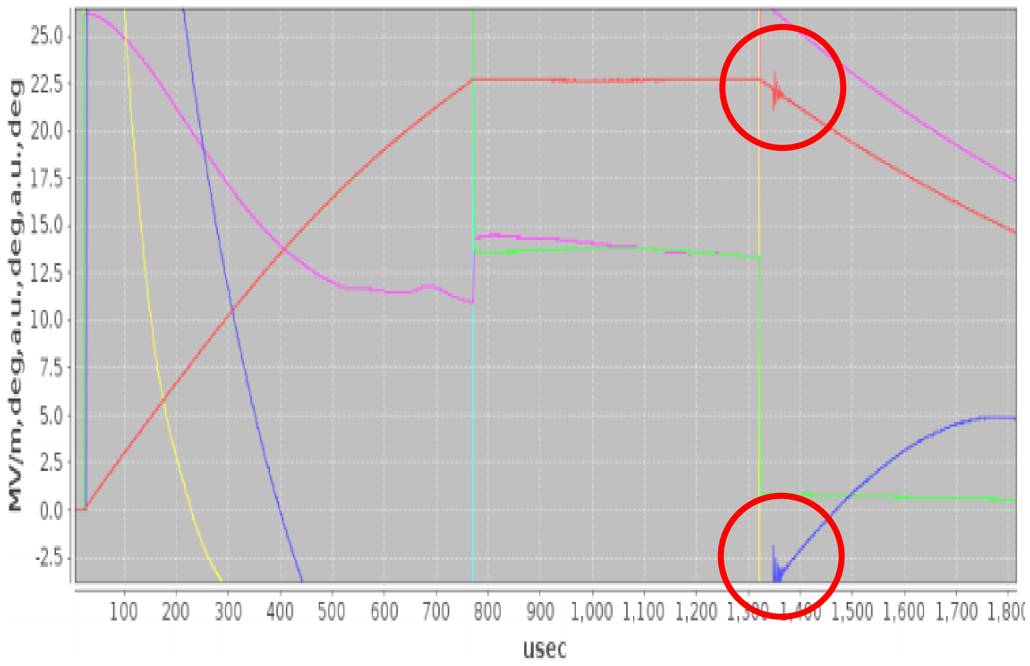
The “castle glitch”



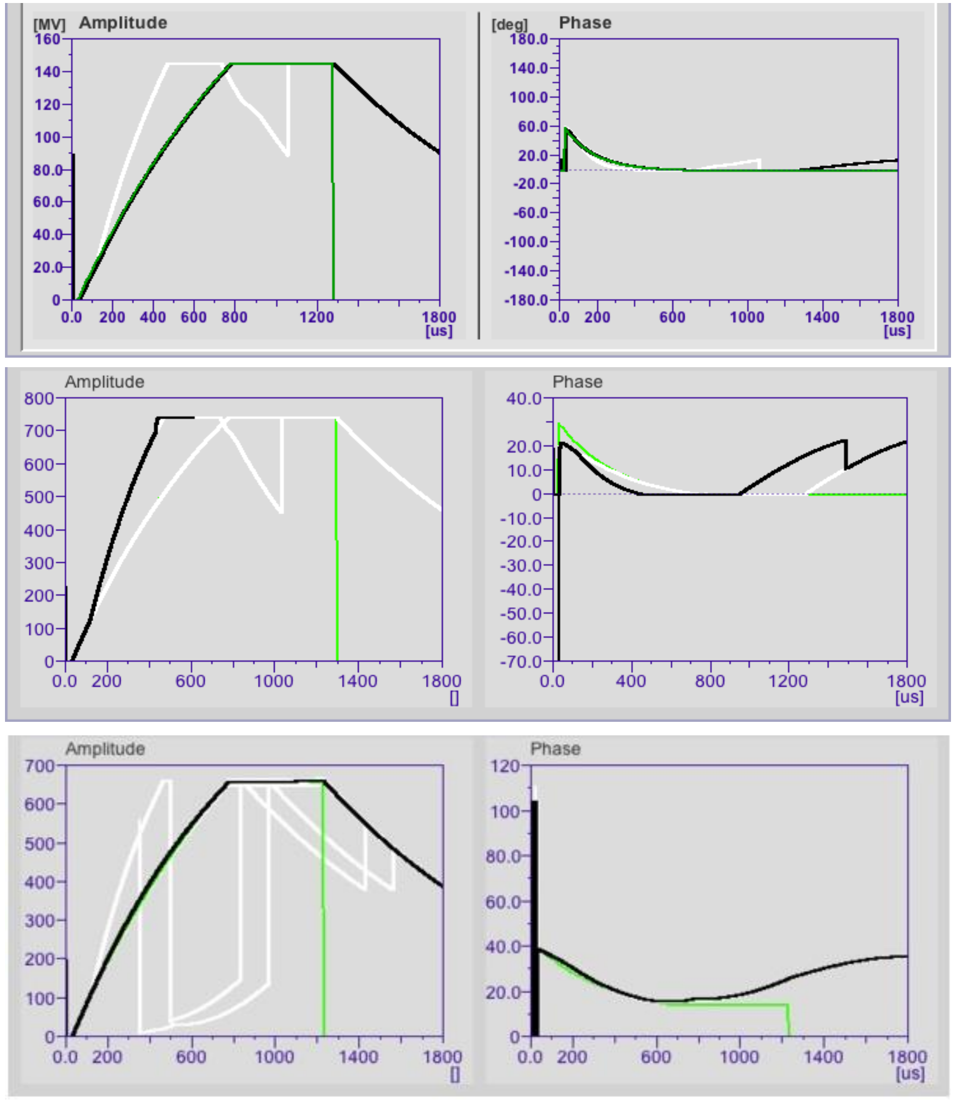
Automation for fault detection

Some “weird stuff” examples (2/3)

The “ringing”



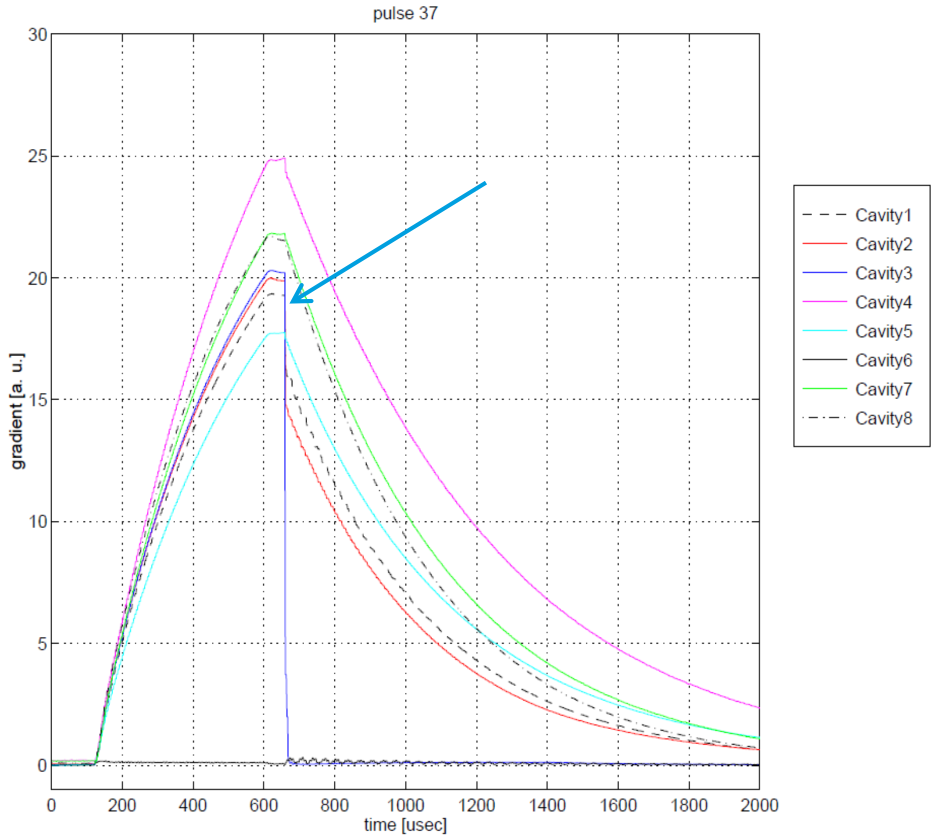
The “time jump”



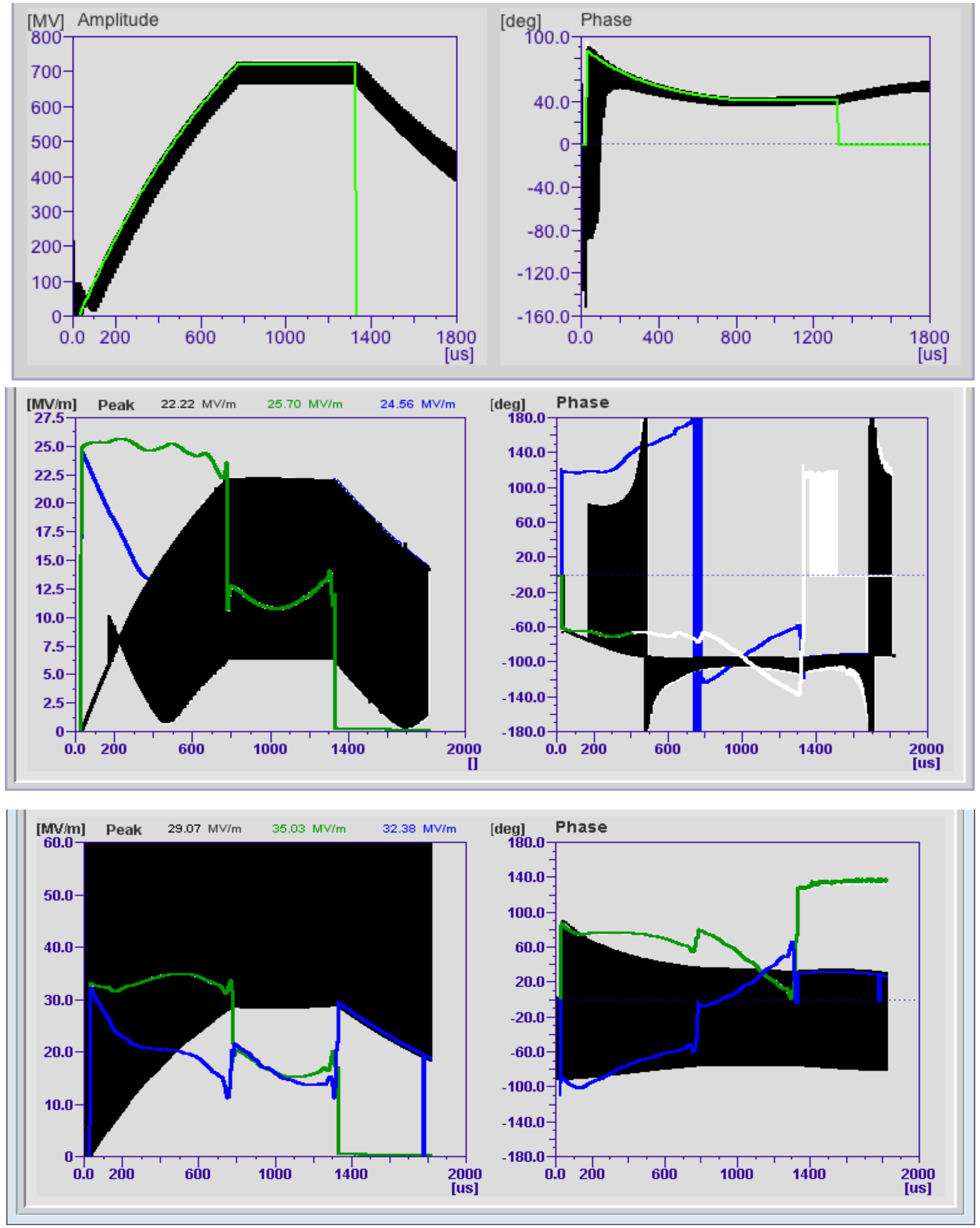
Automation for fault detection

Some “weird stuff” examples (3/3)

The “dark current discharge”



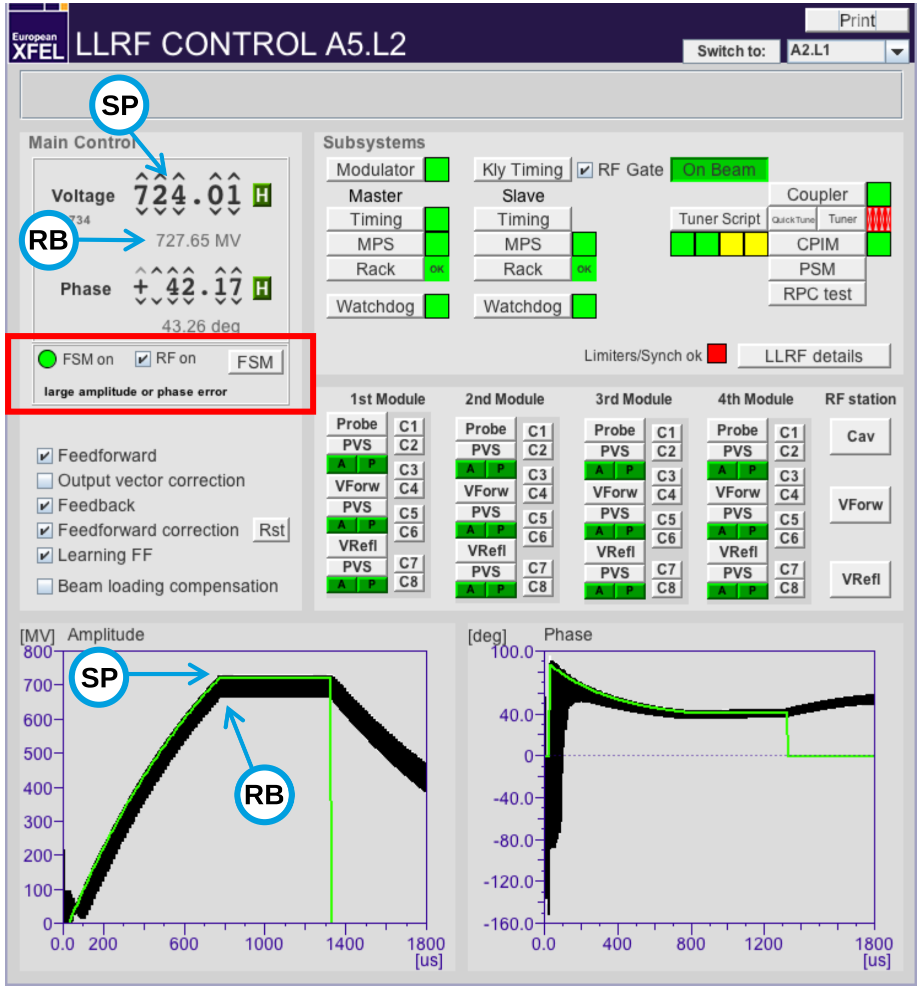
The “SEU”



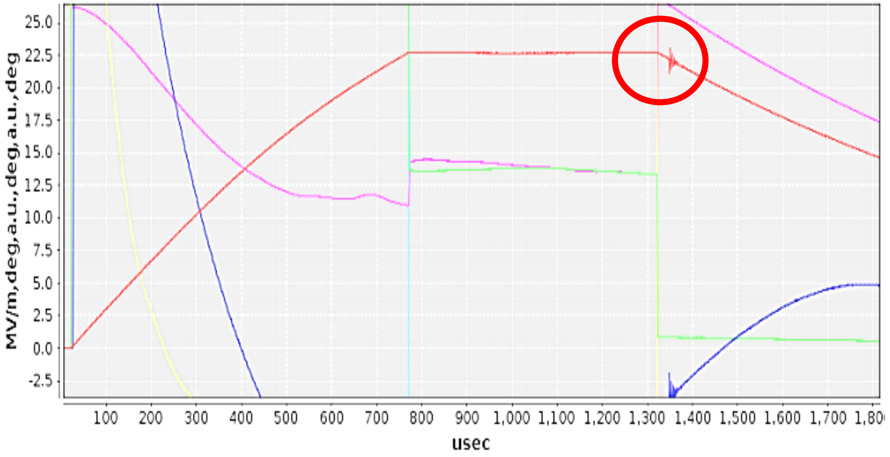
Automation for fault detection

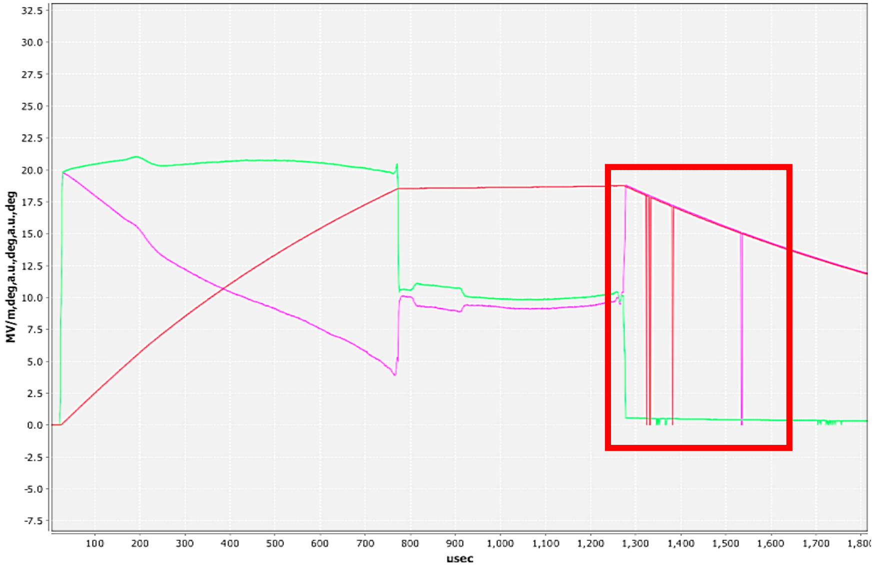
Automation “misuse”

“Accidentally” caught by **Finite State Machine**



“Accidentally” caught by **Quench Detection**



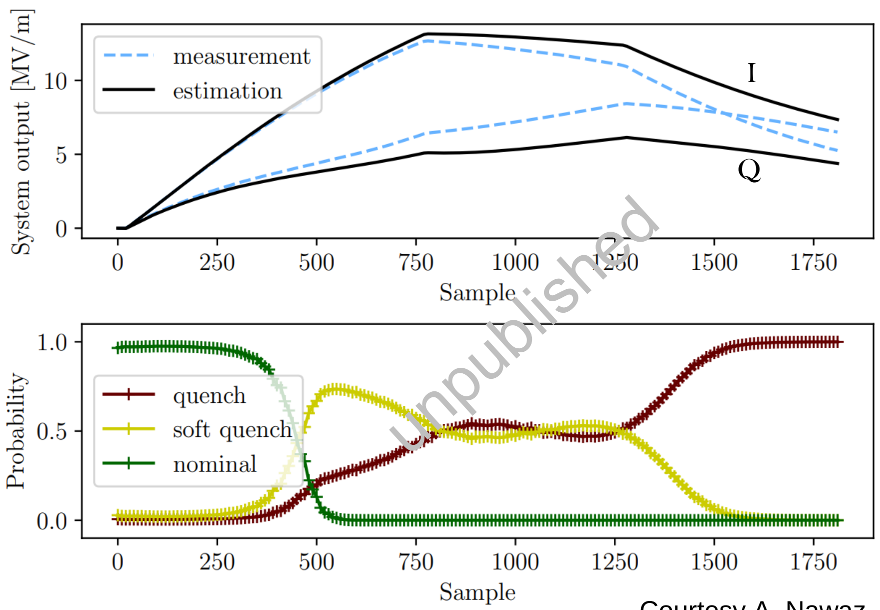


Automation for fault detection

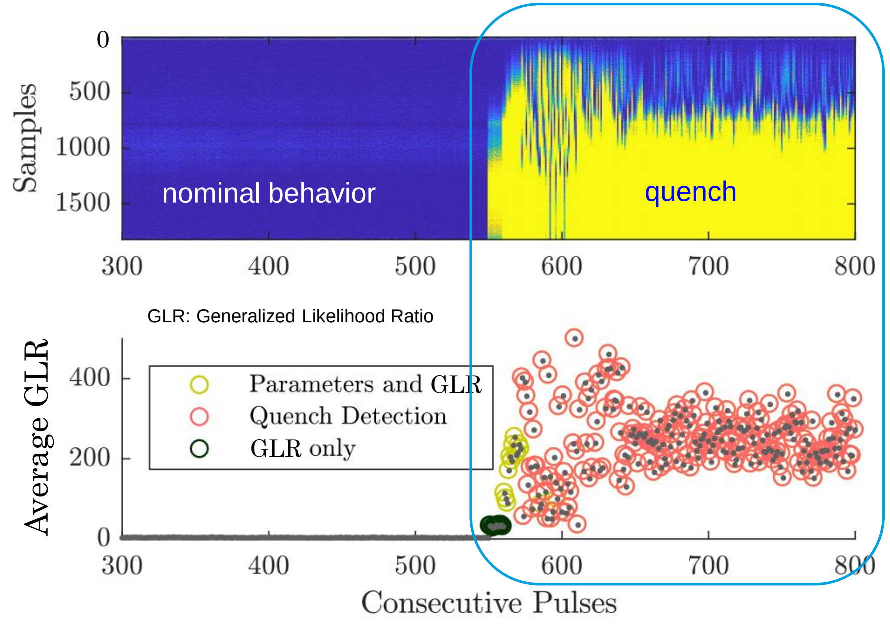
Model-based fault detection

- Model-based techniques can be applied to detect anomalies
- Feed real time waveforms to model and compare measured and expected behaviors
- Can be applied post mortem but the goal would be to apply it at runtime
- This requires fast decision algorithms and high processing capabilities
- PhD devoted to this topic

Reference:
"Fault Detection Method for the SRF Cavities of the European XFEL"
A. Nawaz *et al.*



Courtesy A. Nawaz



Conclusions

Last thoughts…

Automation is essential for

- Repetitive tasks
- Faster and reproducible machine operation
- Synthesizing and analyzing large amounts of data

Automation is a two-edge sword

- It brings a level of abstraction
  → nice
- Makes the system more complex
  → intricate relationship between automation algorithms makes it harder to understand when things go wrong

Writing good automation tools

- Requires a lot of thinking first → specifications
- Requires strong programming skills

“Artificial intelligence” for accelerators

- Is a hot topic…
- Requires people with LLRF expertise

Source: depositphotos.com

Thank you!

Contact

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www.desy.de

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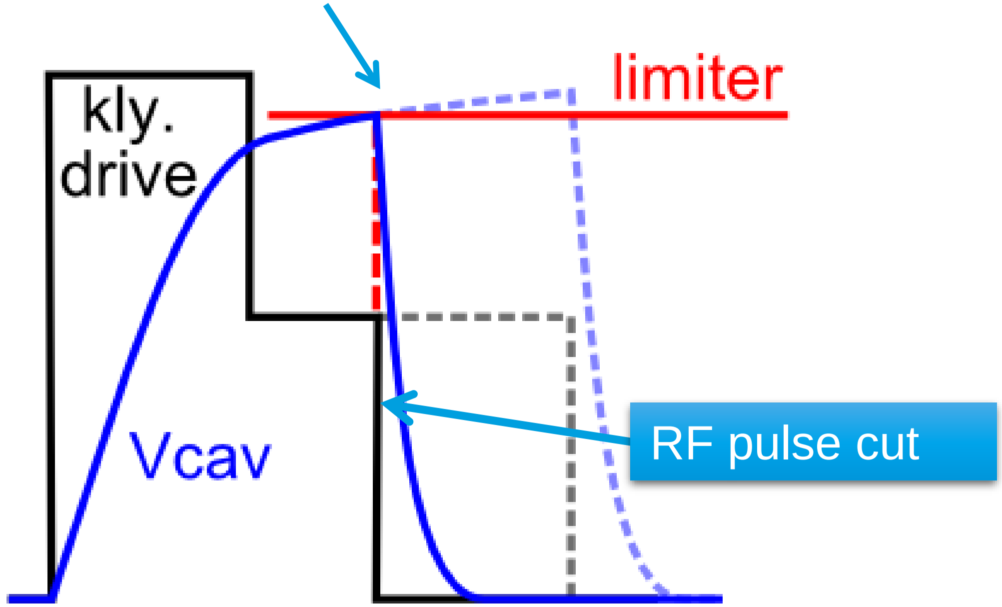
Backup slides

Automation for RF operations

Limiters cutting the RF pulse

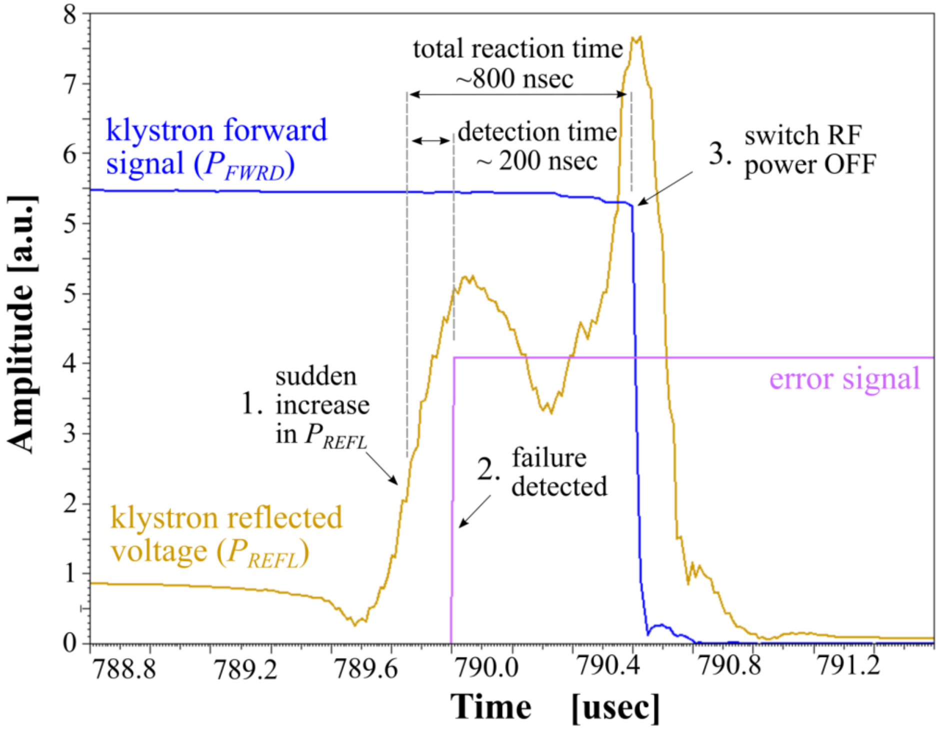
Gradient Limiters

Cavity gradient exceeds **limiter**
→ pulse is cut
→ works in FF and/or in FB mode



Klystron lifetime management

- Monitors klystron signals
- Stops the RF if some exception occurs



See Lukasz Butkowski's poster for details

Automation for RF operations

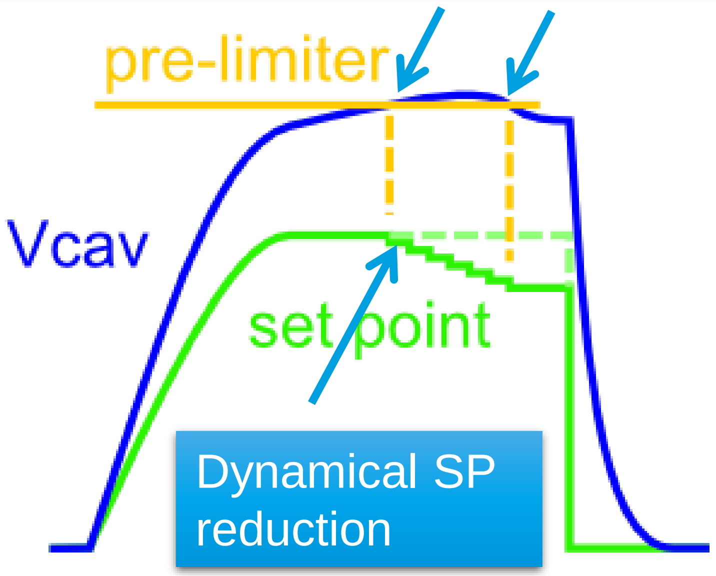
Gradient limiters acting on the Set Point

Gradient pre-limiters acting on the SP

- Introduced for the “9 mA studies at FLASH” (2007-2011)
- Limiters set 0.5 MV/m below quench limit
- Pre-limiters set 1 MV/m below quench limit

Cavity gradient exceeds **pre-limiter**

→ SP is dynamically reduced until gradient drops below threshold
→ works in FB mode only



Reference:
“Automation for the 9mA tests at FLASH” Linac 2012 J. Branlard *et al.*

Automation for RF operations

9mA run at FLASH (2011)

(a)

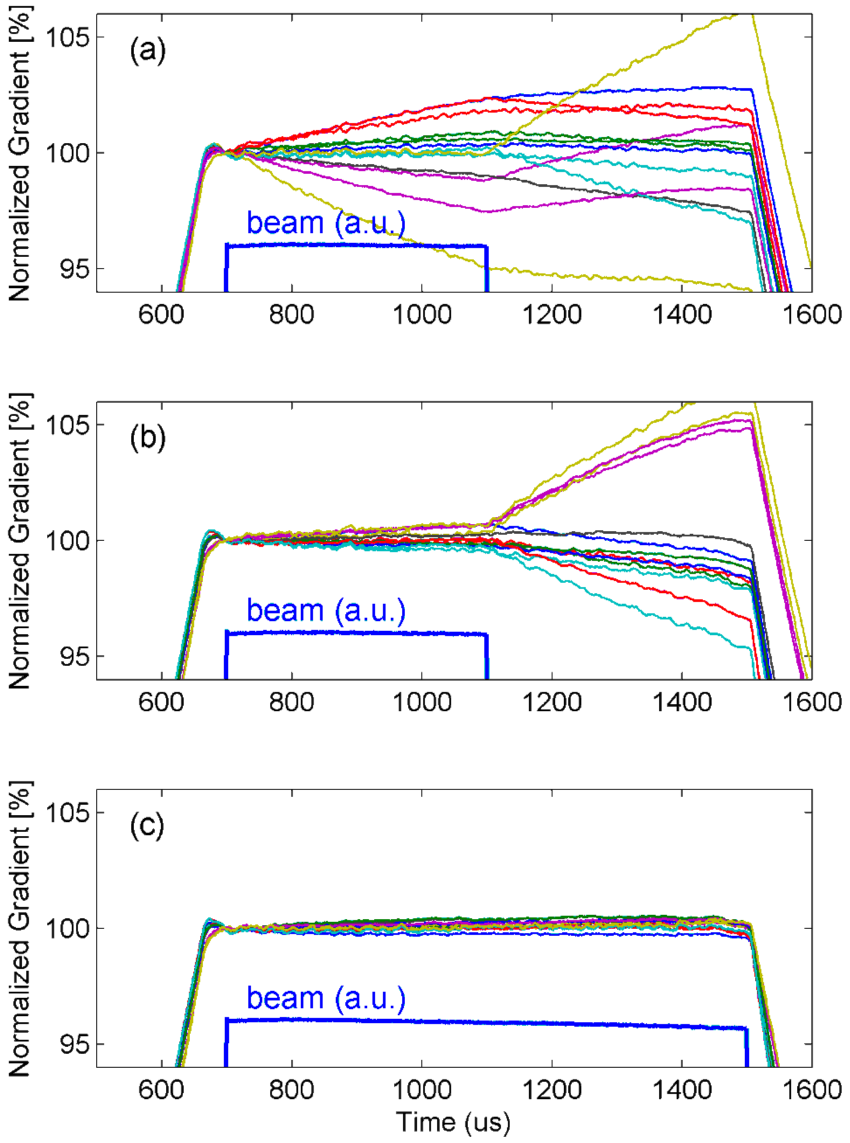
- Short bunch train (400 usec)
- Q_Ls were adjusted for flat w/o beam → tilt with beam
- Pre-limiters reducing SP to avoid quenches

(b)

- Proportional Q_L adjustment to flatten gradients WITH beam
- Pre-limiters reducing SP to avoid quenches

(c)

- Extend to full bunch train (800 usec)

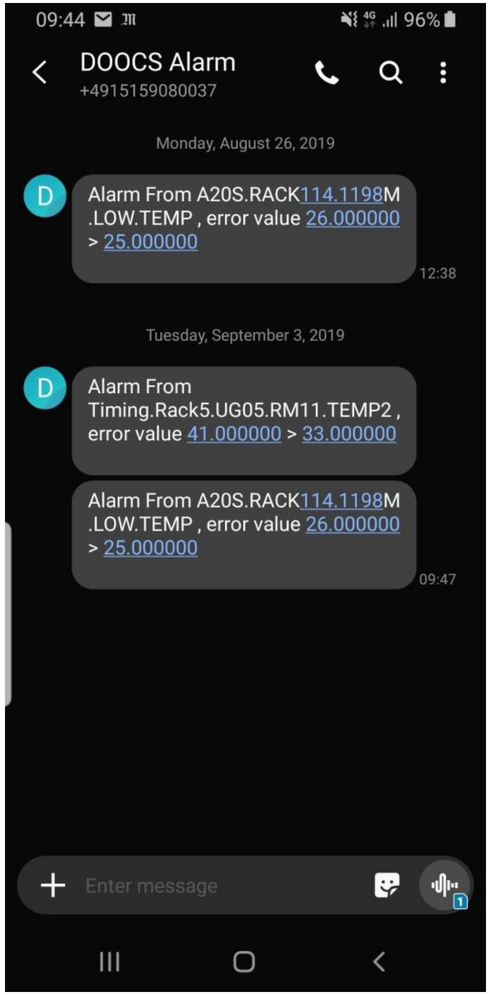


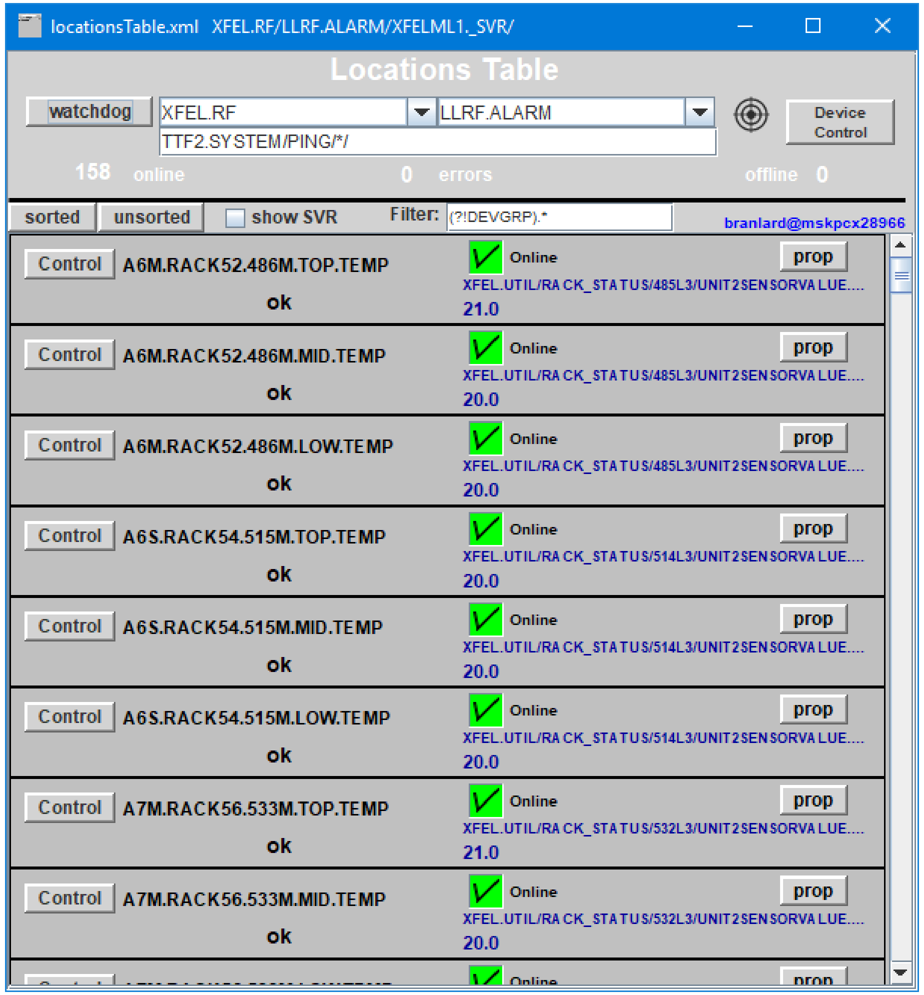
Automation for RF operation

Alarm server

Critical channels monitoring

- Typically temperature (racks, crates, boards etc..)
- Could be extended to fan rotation speed, CPU load, power supply voltages, current etc…
- 3 zones (green orange red)
- Sends warning email / text message
- Alarm notification mechanism
  - 1 time per hour / day
  - Combine alarms in 1 message



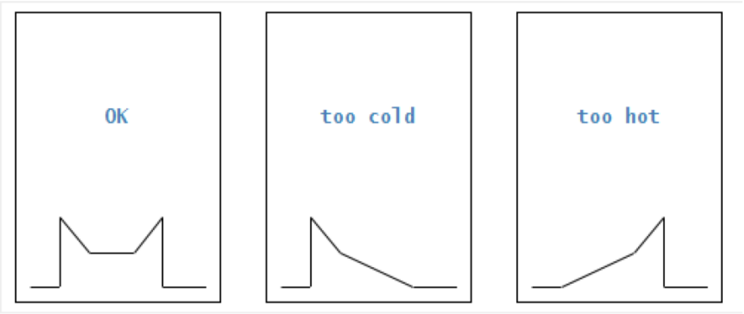


Automation for RF operations

Fast RF gun ramp up

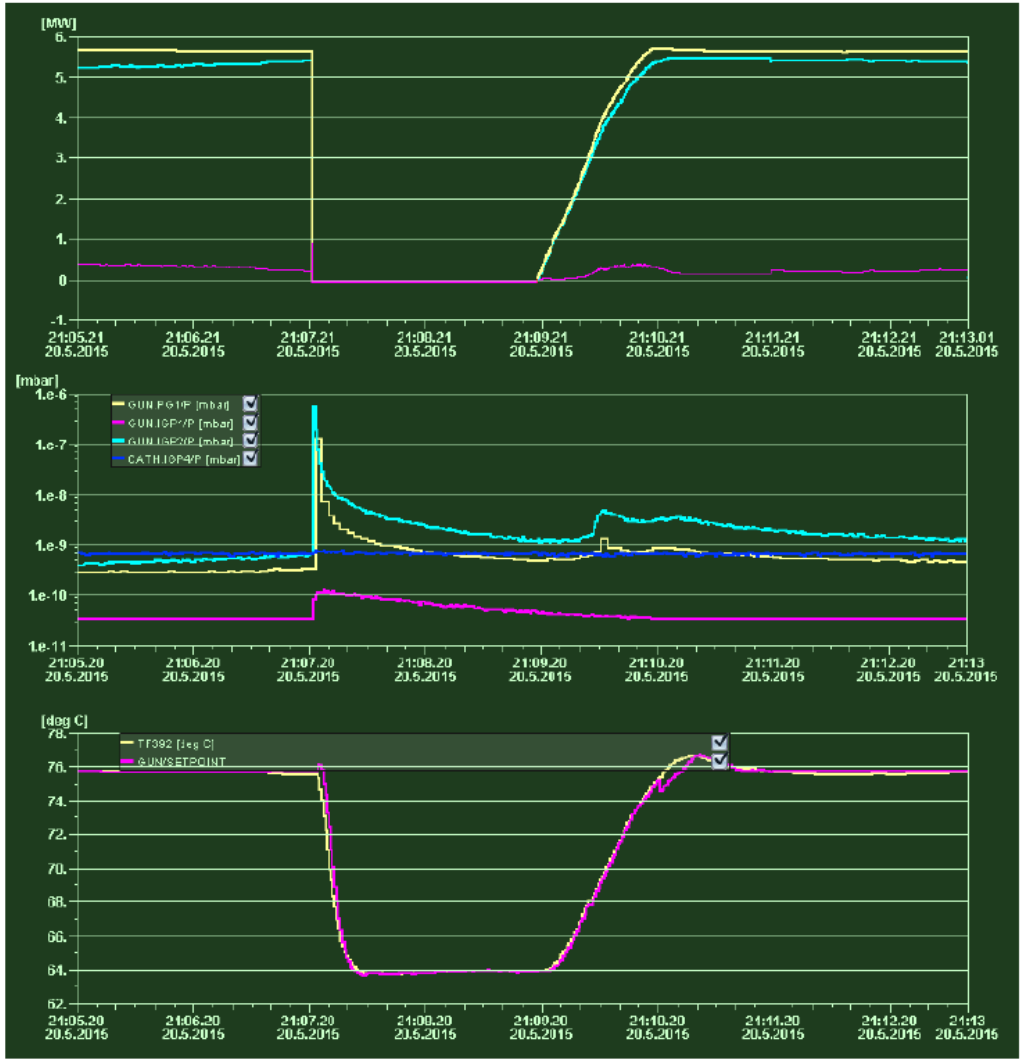
- Ramp up the RF gun tracking its resonance frequency
  - Avoid disturbances to the cooling water system leading to lengthy ramp up procedures
  - Frequency shift achieved by phase modulation
- The gun resonance frequency is derived by looking at the reflected power

Shape of the reflected waveform



$\Delta f=0$ $\Delta f<0$ $\Delta f>0$

Ramp up after gun trip recovery (1 min)



Reference:

"Rapid recovery after RF break down of high average power RF Gun"
LLRF 2015 M. Grecki *et al.*