Automation algorithms for LLRF operation.

2019 LLRF Workshop, Chicago

Sept. 29 - Oct. 03 2019

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Chicago, Sept. 30th 2019







What we want operators to see

Interface to the "ultimate LLRF" system

MainWindow	- • ×
ACCELERATOR	R LLRF
O SYSTEM C	ок 🥥
AMPLITUDE 31.5	MeV
PHASE 0.0	deg



What is automation?



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

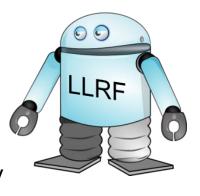
- Only examples from pulsed, SRF electron machines (FLASH/XFEL)
- Influenced by machine culture: scale, vector sum operation, etc...



"Automation is the technology by which a process or procedure is performed with minimal human assistance"

Automation for LLRF operations

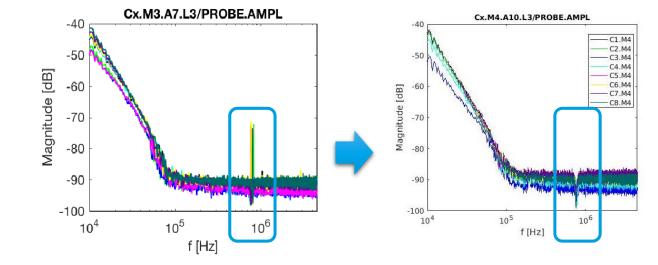
- Automatic control
- Automatic start / stop
- Automatic fault detection / recovery





Source: gifsec.com

- Automatic setup
 - Filters ($8\pi/9$ 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



MAIN_GUI

Version 2.0 ; © S. Pfeiffer (sven.pfeiffer@desy.de Advanced System Setup Tool

Facility

Module

Location

5000

4000

3000

2000

1000

-1000

-2000

-3000

-4000

-5000

-30

[gp] -40 n

700

800

900

1000

Time [µs] Single-Sided Amplitude Spectrum of U(t)

1100

1200

1300

▼ Input

Check output

- Output

IN1 IN2

Welcome sesp0915 at flashlxuser1

Define facility, location and module

DEMO.RF/LLRF.SINCAV DEMO/DEMO/*

Define system inputs and outputs

CTRL/FFC I.DEMO&FFC Q.DEMO

Define and set I/O permanently

Feed-Forward Output Vector Correction

MIMO FB

Feed-Forward Correction

Feedback

Learning FF

186.7 Bit scaling

VS/VS I.DEMO&VS O.DEMO

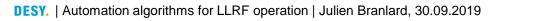
Check input

General Settings

LLRF.SINCAV DE... -

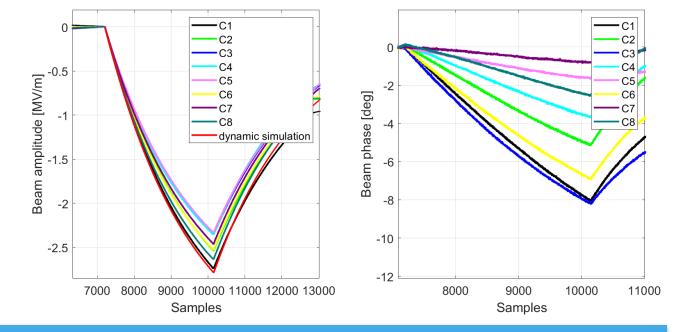
Automatic setup •

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 - Beam-based probe calibration
 - Forward / Reflected signals
 - On-crest phase
- Automatic tuning •
 - Frequency (slow, fast)
 - Bandwidth (Q_1)
 - Phase modulation (feed forward, set point) ۲
 - Output vector correction



Input-20 Sampling freq. [MHz] 9.028 10 Operating frequency [Hz] -60 30.0177 610.988 Delay [us] Filling [us] Flattop [us] -70 -80 u(1) - u(2) -90 10⁴ 10⁵ 10^{6} 107 103 Frequency (Hz) Reference: "Advanced LLRF system setup tool for RF field regulation of SRF cavities" Page 6 SRF 2019 S. Pfeiffer et al.

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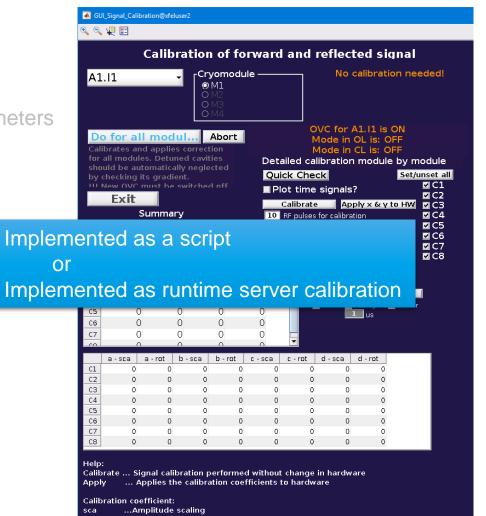


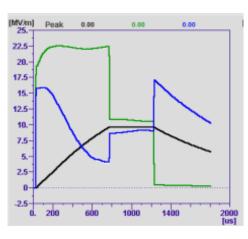
Several techniques developed over the years based on beam transients analysis:

- at nominal gradient (no extra setup required)
- at 0-gradient (removes RF uncertainties from the equation)
- on-line (less intrusive)

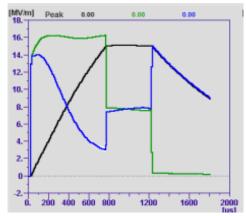


- Automatic setup
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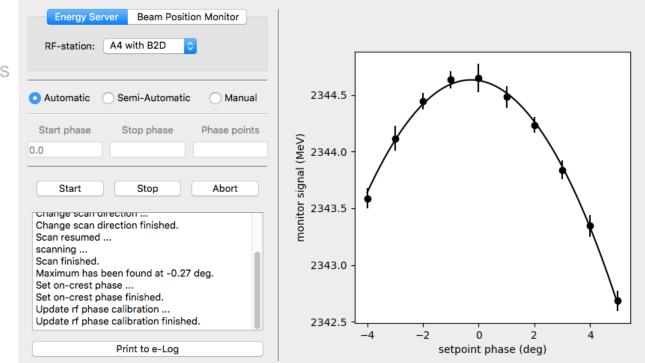








- Automatic setup
 - Filters ($8\pi/9$ notch for ex.)
 - Dynamic range adjustment
 - System identification and FB controller parameters
 - Learning FF parameters
- Automatic calibration
 - Beam-based probe calibration
 - Forward / Reflected signals
 - On-crest phase identification
- Automatic tuning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



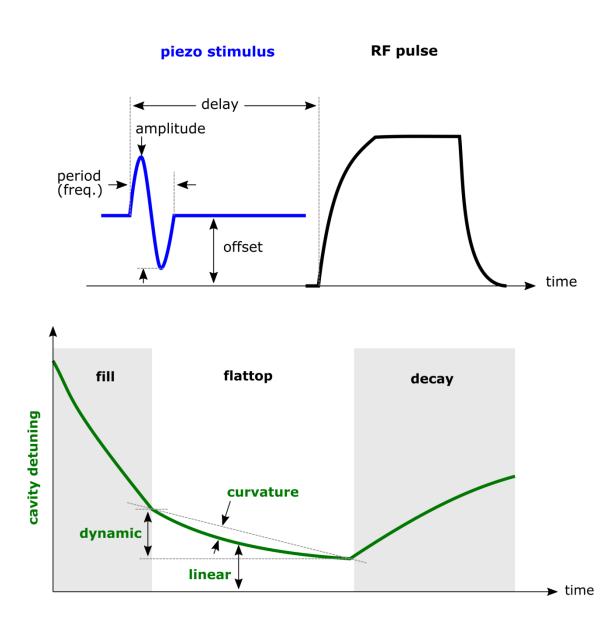
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 - Forward / Reflected signals
 - On-crest phase

Automatic tuning

- Frequency (slow, fast)
- Bandwidth (Q_L)
- Phase modulation (feed forward, set point)
- Output vector correction

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

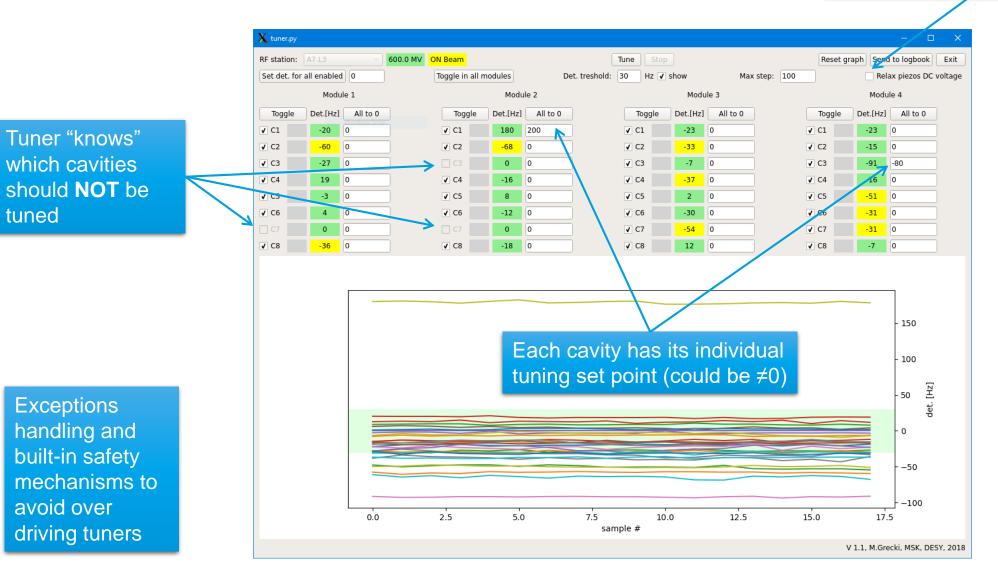
Example at XFEL (16 piezos)

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	tunn	ing al	iu pi	e20	conu	0101	vervi	ew							FBMICT	-	Expert	J	Print
Z16M : N	/1.A23.	L3								PZ16M :	M2.A23	.L3							
Cavity iezo Load	1 On	2 Din	3 On	4 On	5 On	6 On	7 On	8	all on off	Cavity Piezo Load	1 Dn	2 0n	3 On	4 On	5 Dh	6 On	7 01	8 01	all
liezo Ena	31	On 👻	On 👻	On 👻	On 🔫	On 👻	On 👻	On .	on off	Piezo Ena	On 🔫	On 👻	On 👻	On 👻	On 👻	Dn 👻	On 👻	On 👻	on
AC Enable	On	On	On	Dn	On	On	<u>On</u>	Ðn	on off	DAC Enable	.00	On	Dat	.On	Dn	On	On	Dn	on
uto Tuning	0#	nc	190	Off	-08	100	Off		on off	Auto Tuning	1		off.		On	- Dn	06	On	on.
tatic Det.	-33.	-49.	-61,	-81.	-109	-25.	.71.	-6.9		Static Det.	12.7	4.5	17.4	-58.	-36.	-18.	-42.	-54.	
DC Volt	0.5	1.0	1.0	1.0	1.0	1.0	0.5	0.0	to zero	DC Volt	0.0	0.0	-0.5	0.5	0.0	0.0	0.5	0.0	to ze
C status	tuning	tuning	tuning	tuning	tuning	tuning	tuning	tun		DC status	tuned	tuned	tuned	tuning	tuned	tuned	tuning	suned	
near Det.	-339	-336	-495	-330	-418	-345	-409	-4			-203	-210	-163	-295	-262	-270	-327	-358	
AC Volt	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1.0	-1			-0.5	0.0	-0.5	-0.5	0.0	0.0	-0.5	-0.5	to ze
C status	tuning	tuning	tuning	tuning	tuning	tuning	tuning	tun	VID		tuning	tuned	tuned	tuning	tuned	tuned	tuning	tuning	
	Details	Details	Details	Details	Details	Details	Details	Det		50	Details	Details	Details	Details	Details	Details	Details	Details	
Detu	uning cur	ves								Detur	ing curve	05							
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700.0	2.M1.A23.L3/		Butesta							500	2 H2 A231 3	DET_PULSE		1					
500.0	LMID SI									400	4.M2 A23 64	DET_PULSE	i auns (-
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200.0								-		-200-						-	-		-
300.0							~	-											
400.0	400.0	600.0	800.	0 10	00 12	and the second	400	1600	1800	-300	400.0	600.0	800.0	1000	12	S. 15 0	400	1600	1800

Slow tuner automation

Example at XFEL (32 cavities)

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





tuned

could be

tuned

detuned

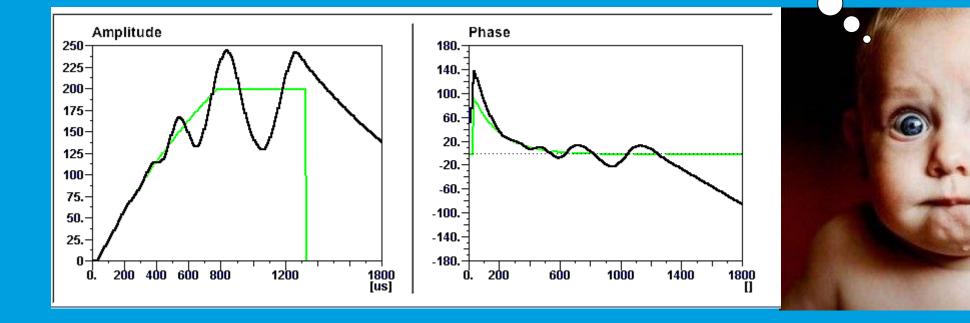
Slow tuner automation

Example at XFEL (32 cavities)

		and a second		L.		X tu					1 0	
RF stat	ion: 4		treshold:	30	Max st	ep: 100		L	Tune	Stop		Exit
		Module 1			Module 2			Module 3			Module 4	
Tog	gle	All to 0	Det.[Hz]	Toggle	All to 0	Det.[Hz]	Toggle	All to 0	Det.[Hz]	Toggle	All to 0	Det.[H
C1		0	-230.3	🔲 C1	0	-75.5	🔲 C1	0	-95.8	🔲 C1	0	-161.2
C2		0	-270.5	C2	0	-143.4	C2	0	-149.6	C2	0	-203.1
С3		0	-239.7	C3	0	-119.1	C3	0	-155.2	C3	0	-167.6
C4		0	-132.7	C4	0	-73.7	C4	0	-157.4	C4	0	-132.7
C5		0	-196.0	📕 C5	0	-246.8	C5	0	-244.8	C5	0	-157.6
C6		0	-113.3	C6	0	-195.7	C6	0	-218.7	C6	0	-224.0
C7		0	-124.4	C7	0	-176.5	C7	0	-124.8	C7	0	-134.3
C8		0	-130.7	C8	0	-237.2	C8	0	-226.0	C8	0	-113.6
	-100	~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~	~~	~~~~		VID)EO		C1.) C2.) C3.) C4.) C5.) C6.)		C1.M3 C2.M3 C3.M3 C4.M3 C5.M3 C6.M3	
det[HZ]	-100 -150 -200					VID			C2.1 C3.1 C4.1 C5.1	M1 M1 M1 M1 M1 M1 M2 M2 M2 M2 M2 M2 M2 M2 M2 M2	C2.M3	
det[Hz]	-150								C21 C31 C41 C51 C61 C71 C21 C31 C41 C21 C31 C41 C31 C41 C51 C61 C51 C61 C71	M1 M1 M1 M1 M1 M1 M2 M2	C2.M3 C3.M3 C4.M3 C6.M3 C6.M3 C7.M3 C1.M3 C1.M4 C3.M4 C3.M4 C3.M4 C5.M4 C5.M4 C5.M4 C5.M4 C5.M4 C5.M4 C5.M4 C5.M4 C5.M4	5

Automation for FB and RF operations

shoot... I shouldn't
have closed the loop...

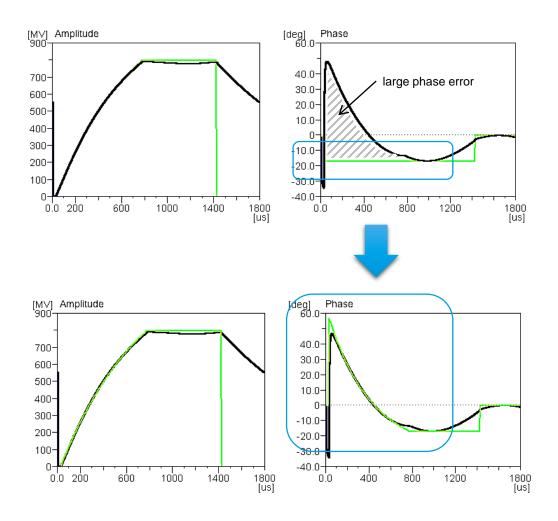


Automation towards FB operation

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:

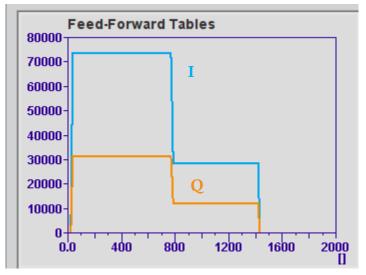
"Optimization of filling procedure for TESLA-type cavities for klystron RF power minimization for European XFEL" IPAC 2010 V. Ayvazyan et al.

- 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

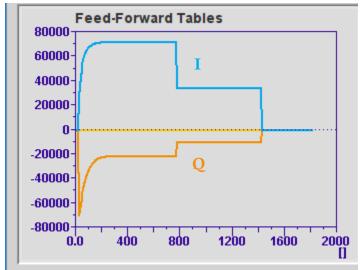


Feed-Forward Phase ModulationSelection:ExpStart Time: $0.00 \div$ Stop Time: $620.00 \div$ ExponentialMax Phase Offset: $54.00 \div$ Time Constant: $45.01 \div$

Example: A2 : no FF phase modulation



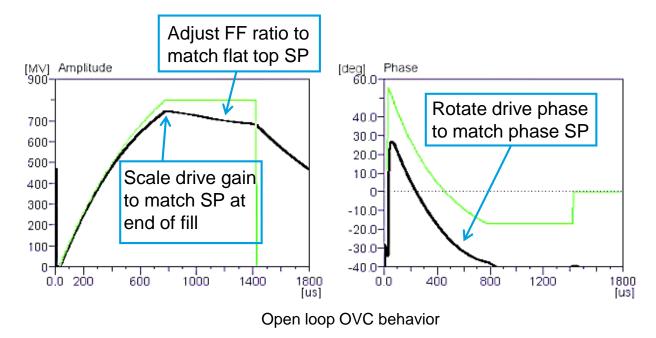
Example: A17 : FF phase modulation

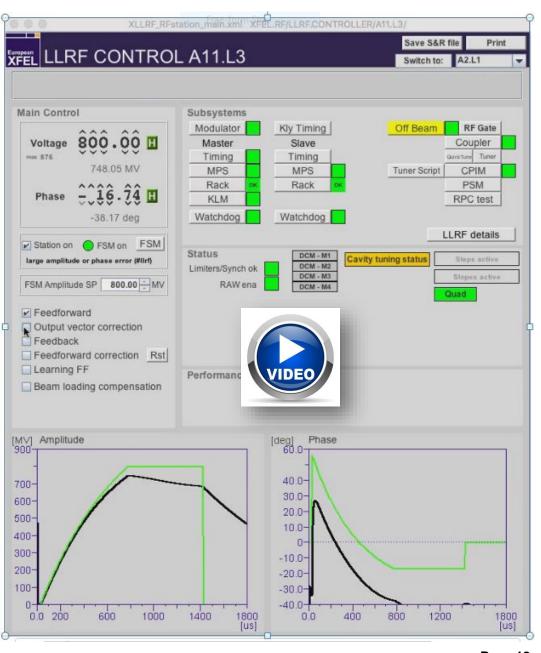


Automation towards FB operation

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



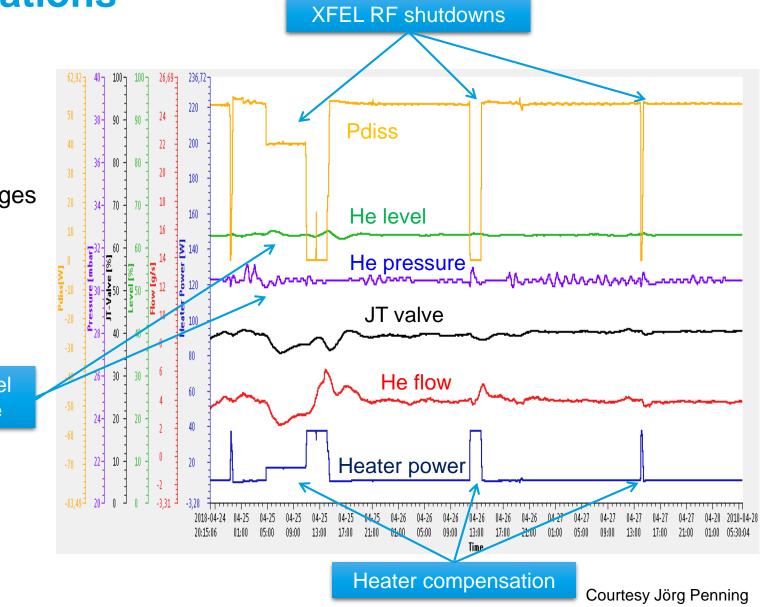


Dynamic heat load compensation

- 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 ٠ compensated by heaters

20 180 34-70 · - 18 160 ₹ 140 Stable He level and pressure 24- 20 -22 10 -0 10 -20

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



Finite State Machine (1/2)

- Works as a sequencer •
 - Ramp up / down •
 - Station / machine -wise
- Works as high level monitoring server ٠
 - 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 •

Save S&R file

Quad

Print

£_17.53 ⊡ Phase 17.53 dec RF-station shifted off beam (#onbeam) FSM Amplitude SP 750.02 - MV

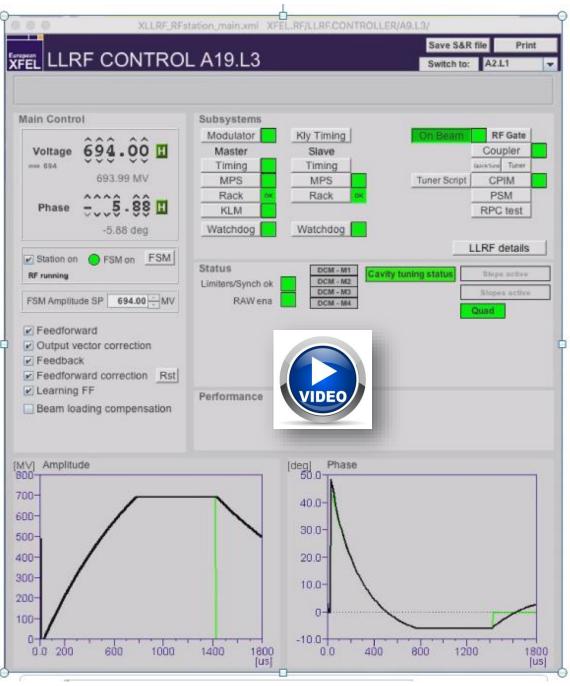
LLRFFSMserver	A13.L3	19:50.46	9.09.2019 -> EqFSMmain::tripaction called by AMPLTRIP_ONSTATE with big
			error between SP and VectorSUM (#mismatch)
LLRFFSMserver	A13.L3	19:50.46	9.09.2019 -> A13.L3 entering recover mode
LLRFFSMserver	A13.L3:trip	action 19:50.	46 9.09.2019 -> running for station: A13.L3
LLRFFSMserver	EqFctLLRF	FSM_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



XLLRF RFstation main.xml XFEL.RF/LLRF.CONTROLLER/A10.L3/

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)



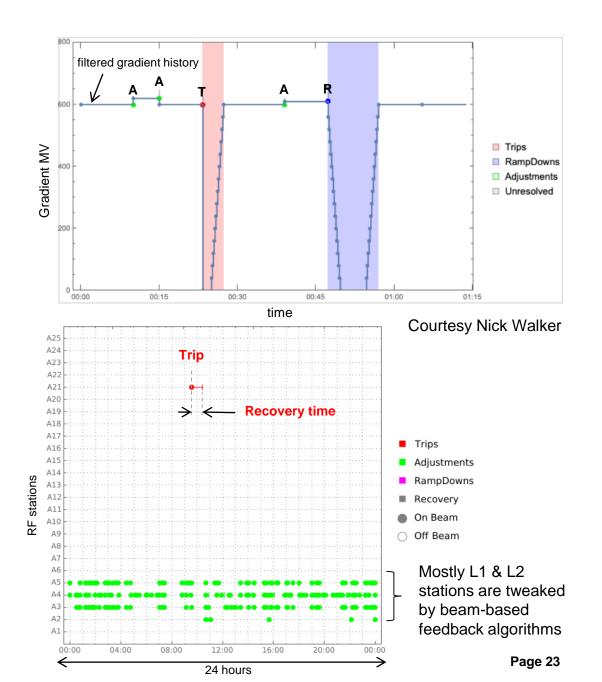
Automation for fault detection and analysis



Automation for trip analysis

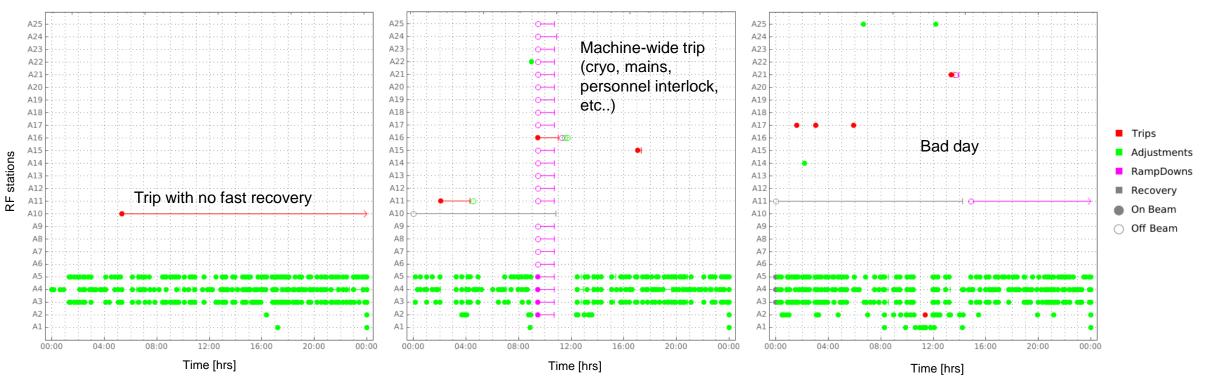
• Daily / weekly automatic analysis

- 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



Automation for trip analysis

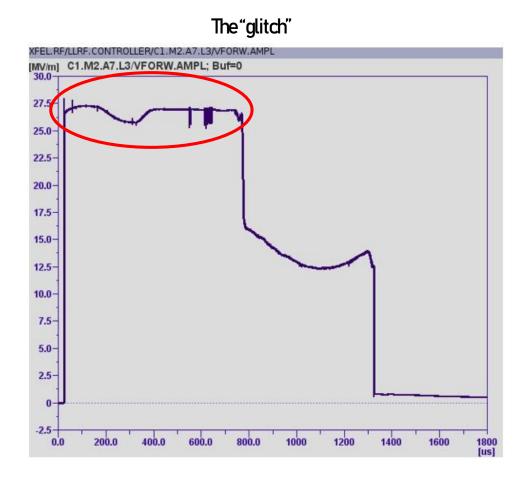
Some more examples



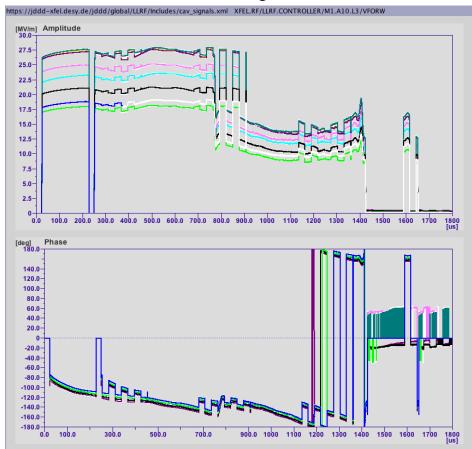
The goal is to gather statistics

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

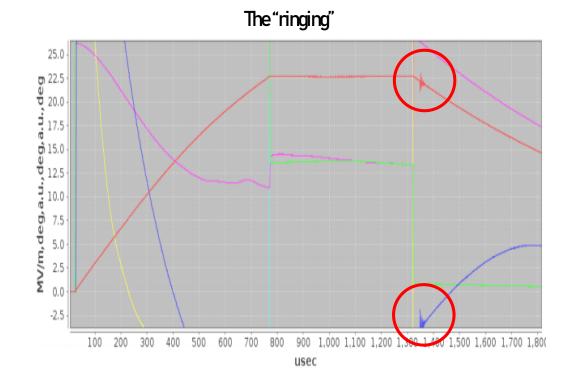
Some "weird stuff" examples (1/3)

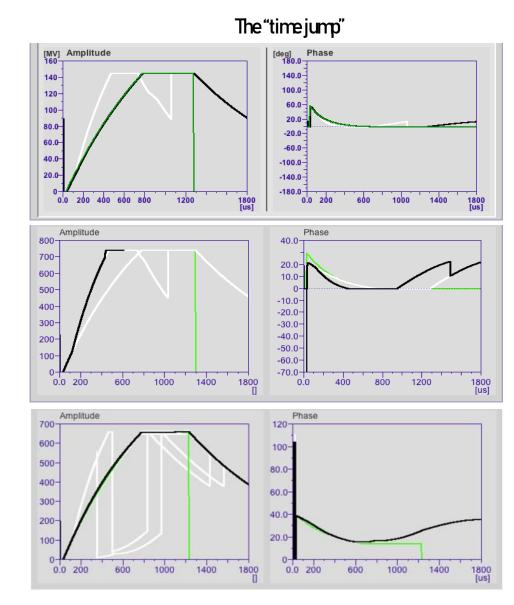


The "castle glitch"

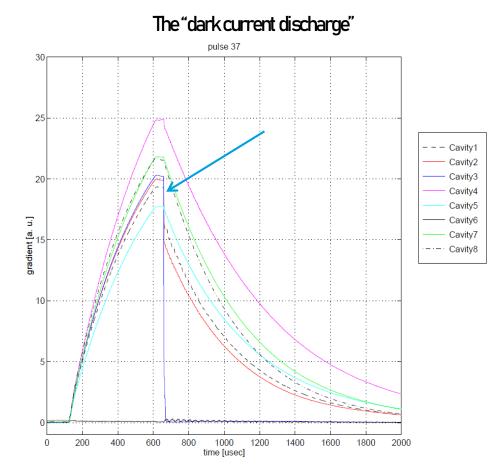


Some "weird stuff" examples (2/3)

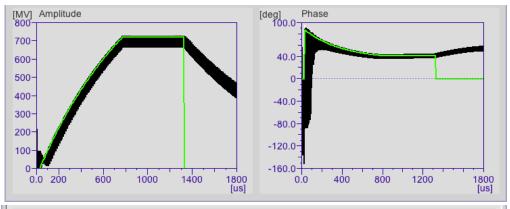


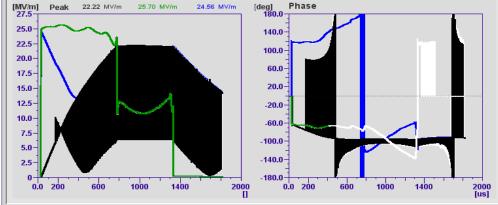


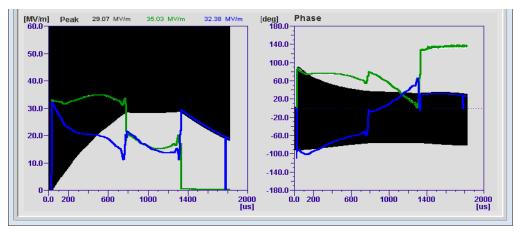
Some "weird stuff" examples (3/3)



The "SEU"

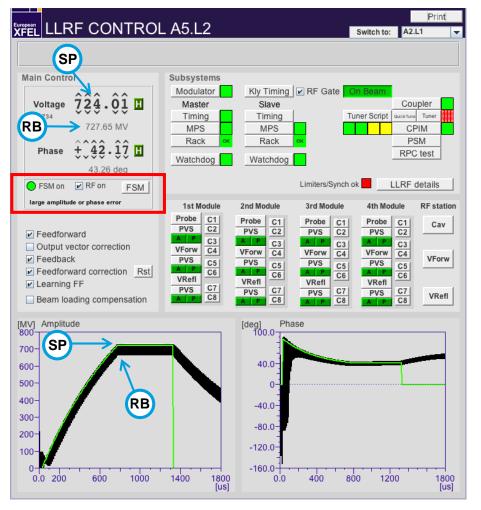




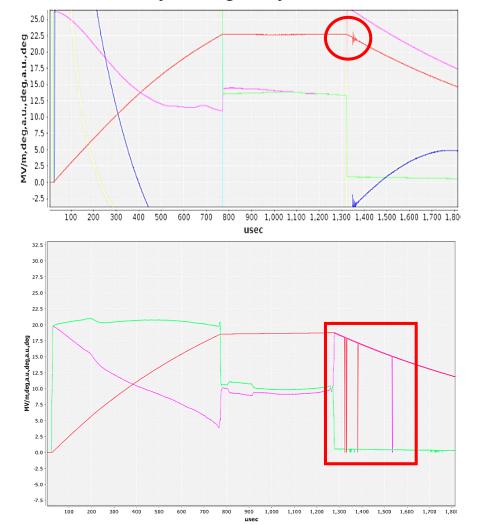


Automation "misuse"

"Accidentally" caught by Finite State Machine



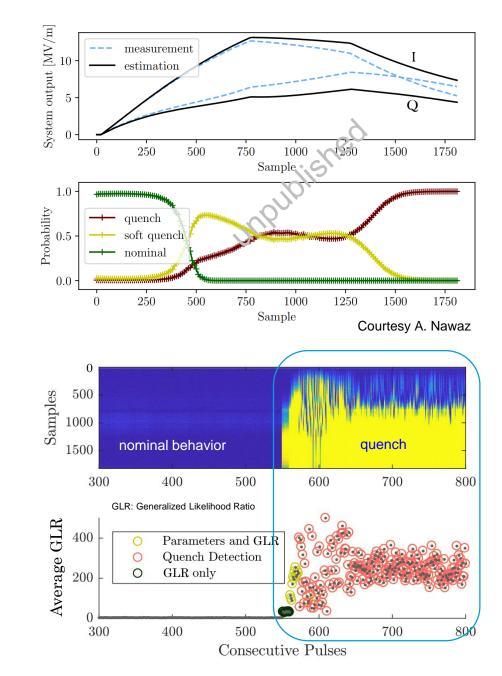
"Accidentally" caught by **Quench Detection**



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.*



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

 \rightarrow nice

Makes the system more complex

 \rightarrow intricate relationship between automation algorithms makes it harder to understand when things go wrong

Writing good automation tools

- Requires a lot of thinking first \rightarrow specifications
- Requires strong programming skills

"Artificial intelligence" for accelerators

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



Source: depositphotos.com

Thank you!



Contact

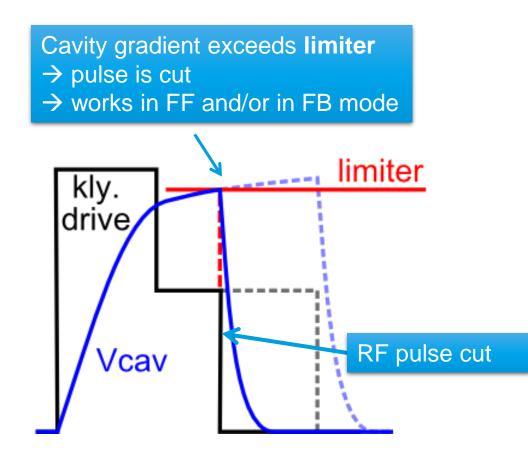
DESY. Deutsches Elektronen-Synchrotron Julien Branlard MSK julien.branlard@desy.de

www.desy.de

Backup slides

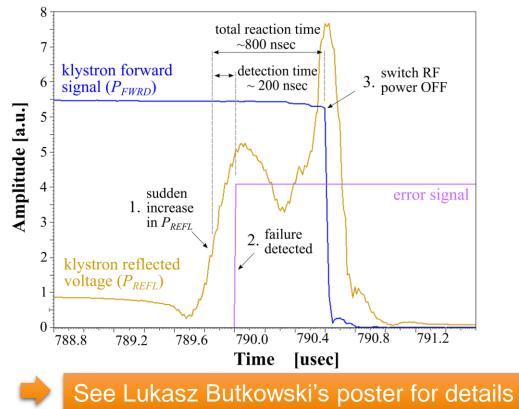
Limiters cutting the RF pulse

Gradient Limiters



Klystron lifetime management

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



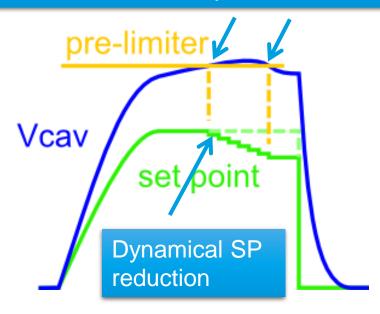
Gradient limiters acting on the Set Point

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.

9mA run at FLASH (2011)

(a)

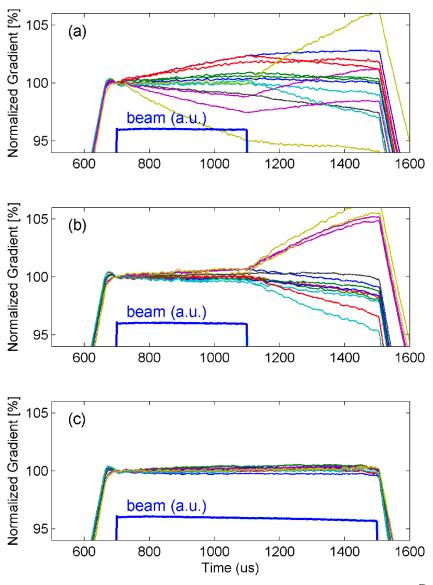
- Short bunch train (400 usec)
- Q_L s were adjusted for flat w/o beam \rightarrow tilt with beam
- Pre-limiters reducing SP to avoid quenches

(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)



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

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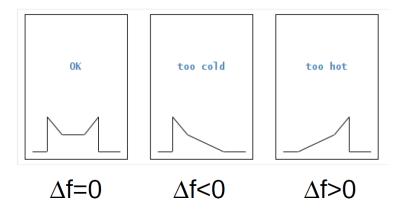
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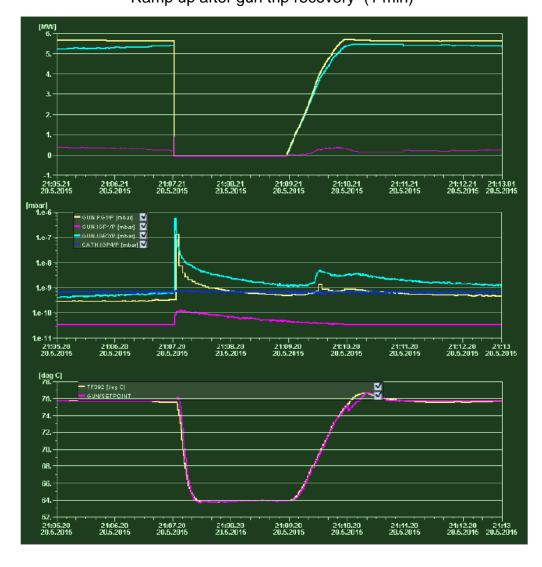
Control

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





Reference:

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

Ramp up after gun trip recovery (1 min)

DESY. | Automation algorithms for LLRF operation | Julien Branlard, 30.09.2019