RF Control (“LLRF””) Development Activities at Major Accelerator Sites

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ASD-RF, 3-2-2016

OUTLINE

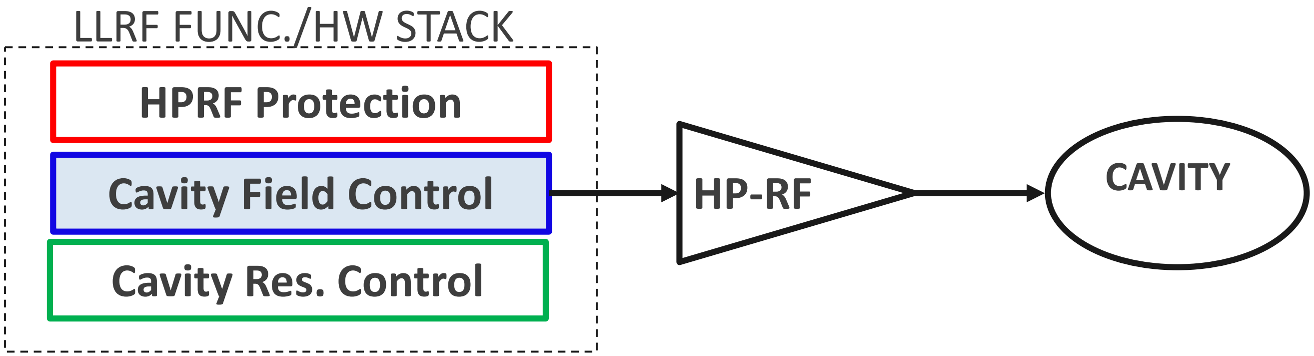
- Brief Review of digital LLRF –
  - Essential functionalities,
  - Expected features from a modern system.
- Examples of successful implementations
  - SNS @ ORNL – first large-scale deployment in the nation,
  - SPX @ ANL – the state of art DSP implementation
- LLRF activities over the world (LLRF'15 Workshop samples)
  - DESY, PSI, CERN, etc.

…… If time allows

- Commercial solutions
- Issues in LLRF Development

What do we expect from a LLRF ? Essential Functions

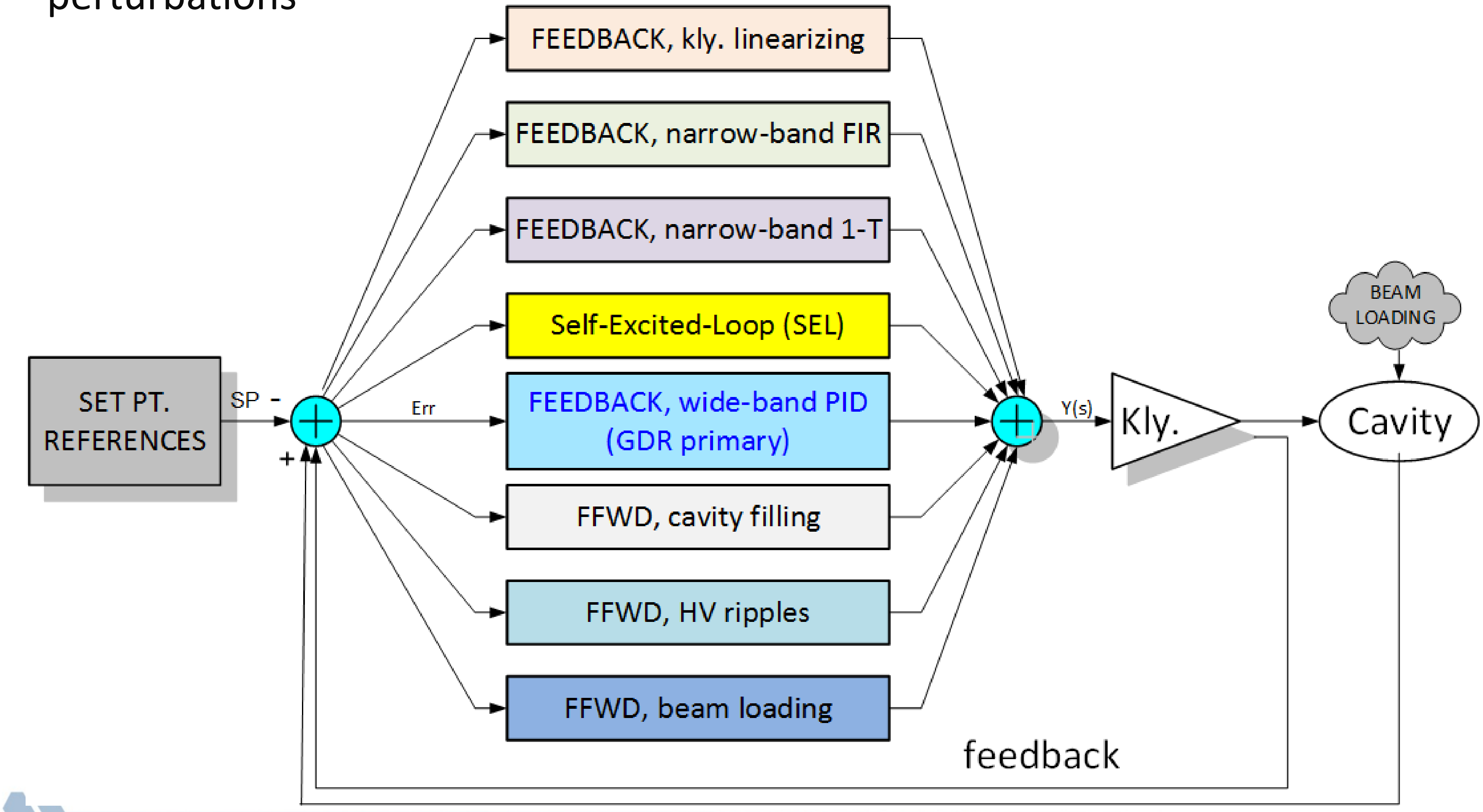
- Traditional list
  1. Cavity Field Control ("rf loops") – fighting against all perturbations
  2. Cavity Resonance Control ("frequency loops") – Tuner cntl./SEL
  3. Interlocks ("exception handling")



- Modern additions
  1. **Data** streaming (LLRF as rf data source, -> fast bus/network)
  2. **Data** timestamping (-> embedded EVR)
  3. Built-in System diagnosis (essential & possible now)
  4. Built-in System calibration (necessary for today's rf specs)

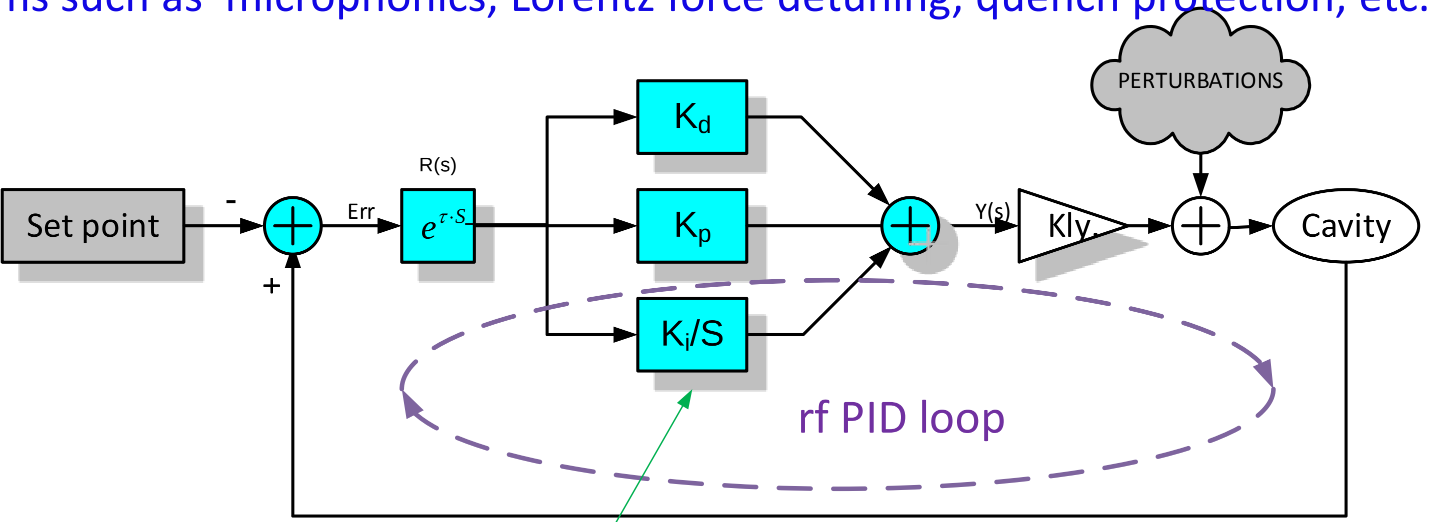
Cavity Field Controller – a collection of Loops & Paths

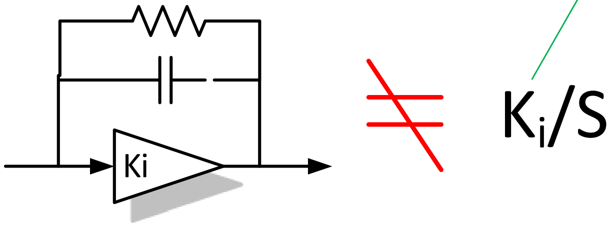
- Two basic control categories: Feedback vs. Feed Forward (FFWD)
  - Feedback control is a REACTIVE ACTION -> requires no prior knowledge; delayed correction
  - Feed forward control is a PREEMPTIVE ACTION -> based on prior knowledge, no delay.
- Every Control block is specially designed to suppress specific types of perturbations



LLRF control toolkit: 1. fast cavity rf feedback loop

- Targets: RANDOM, RAPID, SMALL perturbations in rf, still the center-piece of a LLRF
- Method: wide-band, plain PID loop -> A REACTIVE ACTION (vs. preemptive FFWD)
- Usually needs feed forward to handle large dynamic range control
- Digital implementation is practically required for SRF applications due to special problems such as microphonics, Lorentz force detuning, quench protection, etc.



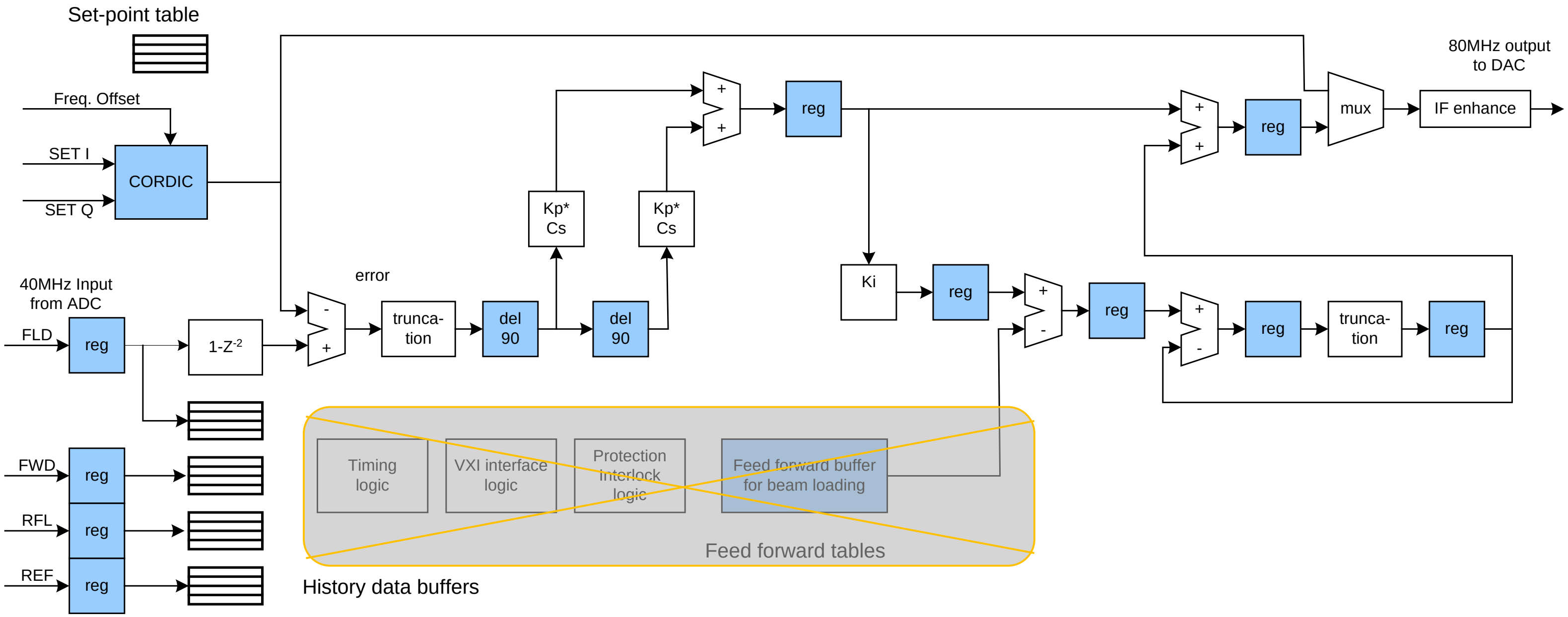


$$\frac{C_{pid}(s)}{E(s)} = K_p + K_i \frac{1}{s} + K_d\, s$$

- Proportional control term Kd alone can only provide a "TYPE-0" control -> always has residual steady-state error
- Integral control term Ki creates a "TYPE-1" system -> reduces control error to ZERO
- Analog circuit cannot realize a TRUE integral term, therefore, control error remains. For NC cavities, that is just a matter of inconvenience, but for SC cavity application, it can be a real weakness.

LLRF control toolkit : 1. fast cavity rf feedback loop (2)

- Actual data processing flow in FPGA (SNS implementation) – serialized data path for “I” and “Q” results in a very efficient resource utilization.



Set-point table

Freq. Offset

SET I

SET Q

CORDIC

40MHz Input from ADC

FLD

reg

$1\text{-}Z^{-2}$

error

-

+

truncation

del 90

del 90

Kp* Cs

Kp* Cs

+

+

reg

Ki

reg

+

-

reg

+

+

reg

mux

80MHz output to DAC

IF enhance

+

-

reg

truncation

reg

FWD

reg

RFL

reg

REF

reg

~~Timing logic~~

~~VXI interface logic~~

~~Protection Interlock logic~~

~~Feed forward buffer for beam loading~~

~~Feed forward tables~~

History data buffers

Examples of LLRF Control Screens in MCR

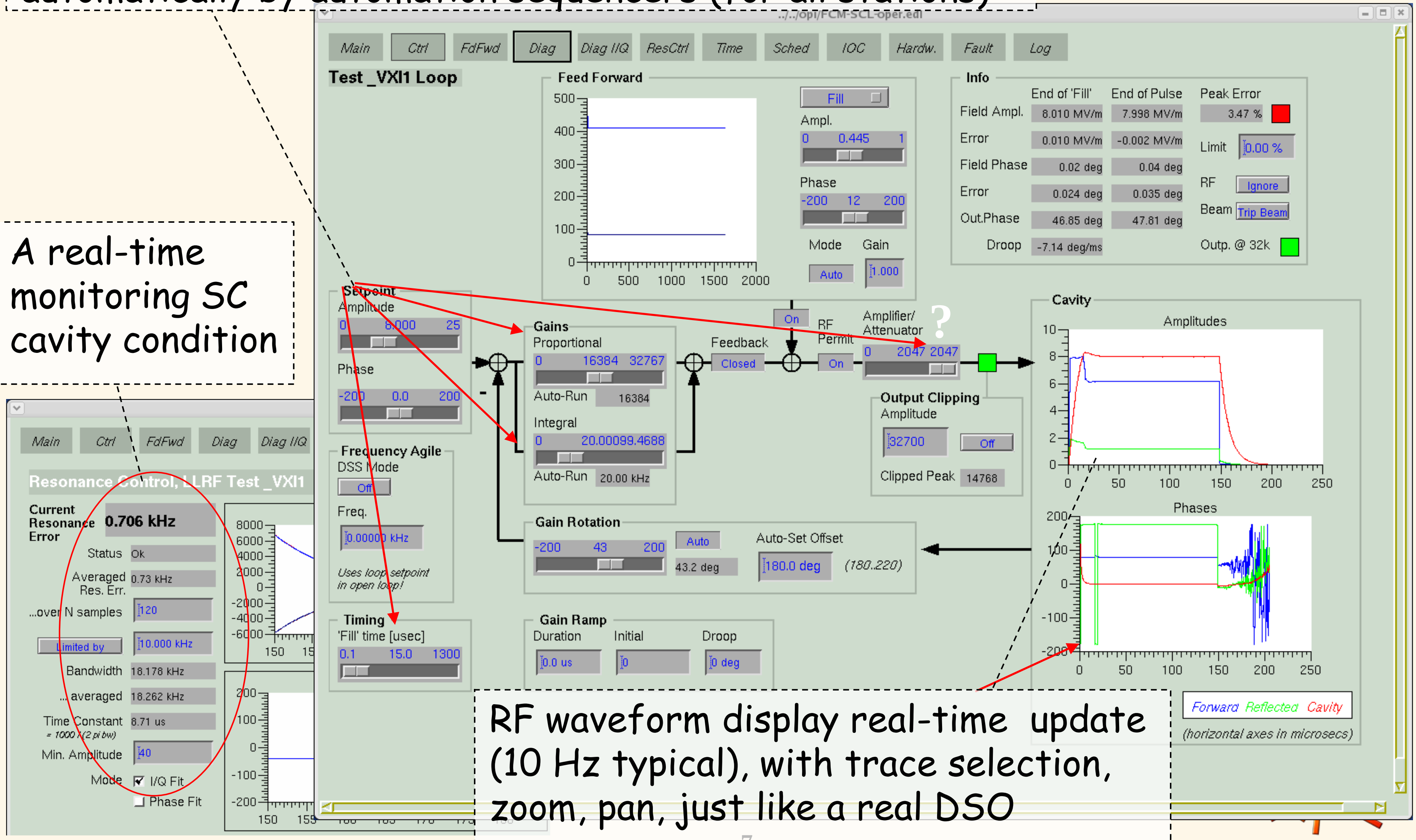
(for each of all 96 LINAC RF stations)

Hengjie Ma, 07/07

All control knobs can be operated either manually or automatically by automation sequencers (for all stations)

A real-time monitoring SC cavity condition

RF waveform display real-time update (10 Hz typical), with trace selection, zoom, pan, just like a real DSO



Test _VXI1 Loop

Feed Forward

Ampl.: 0 0.445 1

Phase: -200 12 200

Mode: Auto

Gain: 1.000

Info

	End of 'Fill'	End of Pulse
Field Ampl.	8.010 MV/m	7.998 MV/m
Error	0.010 MV/m	-0.002 MV/m
Field Phase	0.02 deg	0.04 deg
Error	0.024 deg	0.035 deg
Out.Phase	46.85 deg	47.81 deg
Droop	-7.14 deg/ms	

Peak Error: 3.47 % 🟥

Limit: 0.00 %

RF: Ignore

Beam: Trip Beam

Outp. @ 32k 🟩

Setpoint

Amplitude: 0 6.000 25

Phase: -200 0.0 200

Gains

Proportional: 0 16384 32767

Auto-Run: 16384

Integral: 0 20.000 99.4688

Auto-Run: 20.00 kHz

Feedback: Closed

RF Permit: On

Amplifier/ Attenuator: 0 2047 2047

Output Clipping

Amplitude: 32700 Off

Clipped Peak: 14768

Frequency Agile

DSS Mode: Off

Freq.: 0.00000 kHz

Uses loop setpoint in open loop!

Gain Rotation

-200 43 200 Auto

43.2 deg

Auto-Set Offset: 180.0 deg *(180.220)*

Timing

'Fill' time [usec]: 0.1 15.0 1300

Gain Ramp

Duration: 0.0 us

Initial: 0

Droop: 0 deg

Resonance Control, LLRF Test _VXI1

Current Resonance Error: 0.706 kHz

Status: Ok

Averaged Res. Err.: 0.73 kHz

...over N samples: 120

Limited by: 10.000 kHz

Bandwidth: 18.178 kHz

... averaged: 18.262 kHz

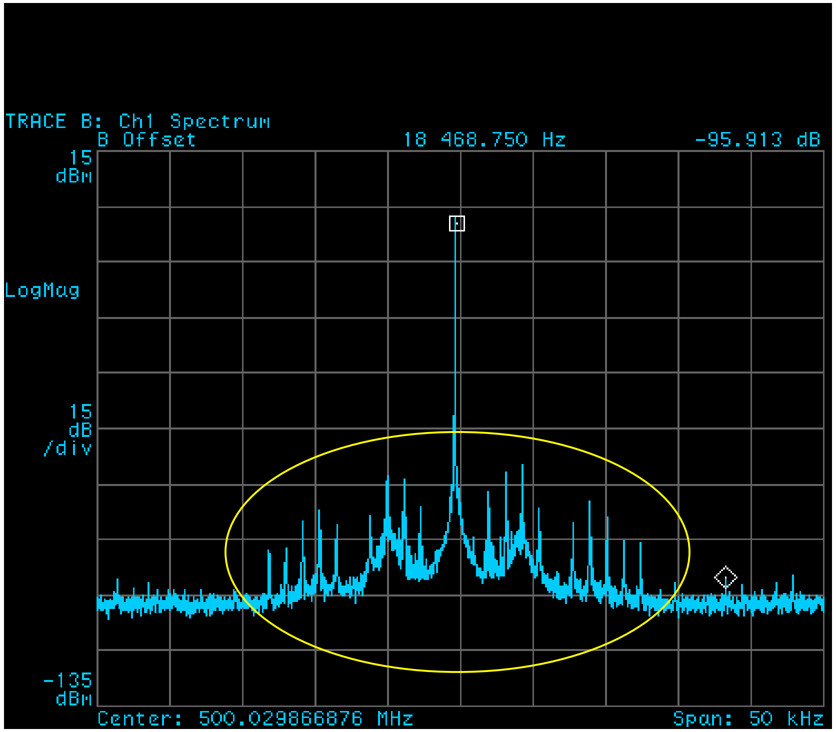
Time Constant *= 1000 / (2 pi bw)*: 8.71 us

Min. Amplitude: 40

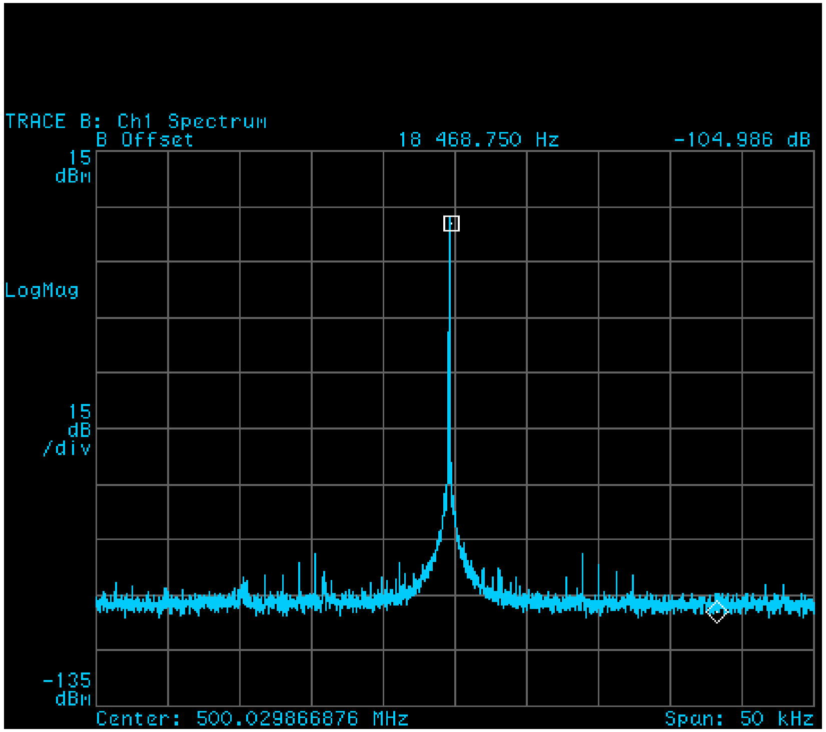
Mode: ☑ I/Q Fit ☐ Phase Fit

Benefits of Digital LLRF
Without Beam

(Analog LLRF) **CLS Drive**



(Digital LLRF) **NSLSII Drive**

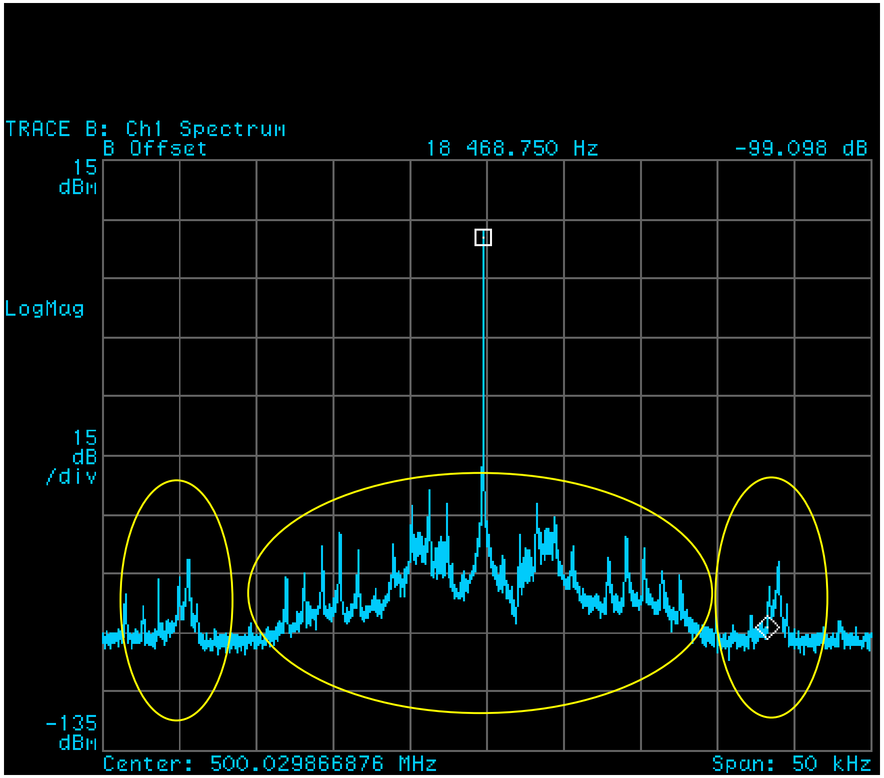


SC cavity field spectrum verified with an independent spectrum analyzer

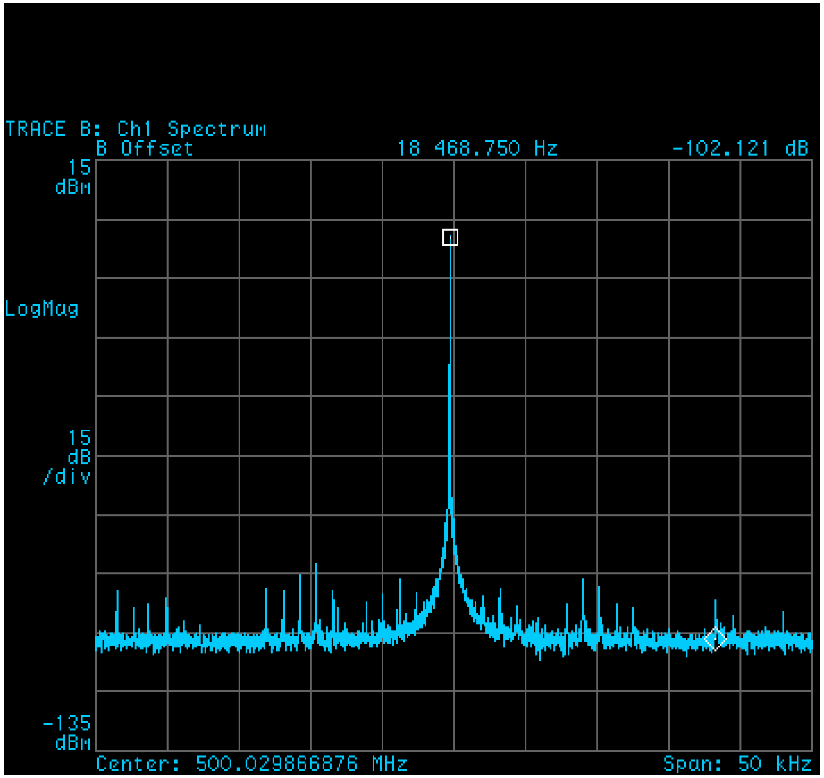
250mA @ 2.9 GeV

Analog LLRF vs. Digital LLRF

CLS Drive



NSLSII Drive

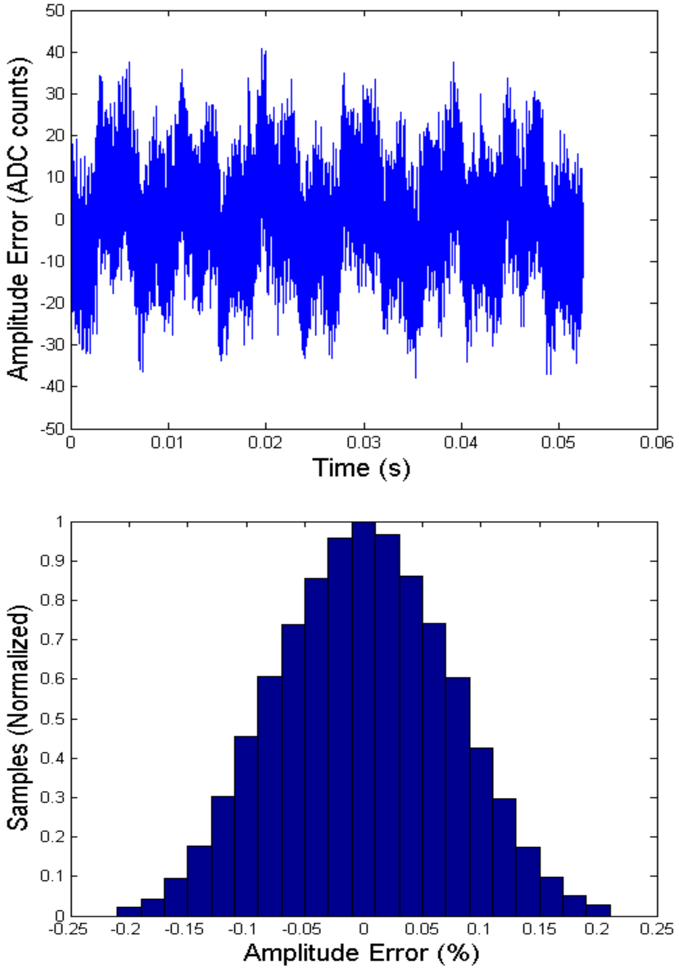


After the LLRF loop phase setting is adjusted to compensate the klystron phase, the synchrotron oscillation stopped, and the LLRF control returned to normal again

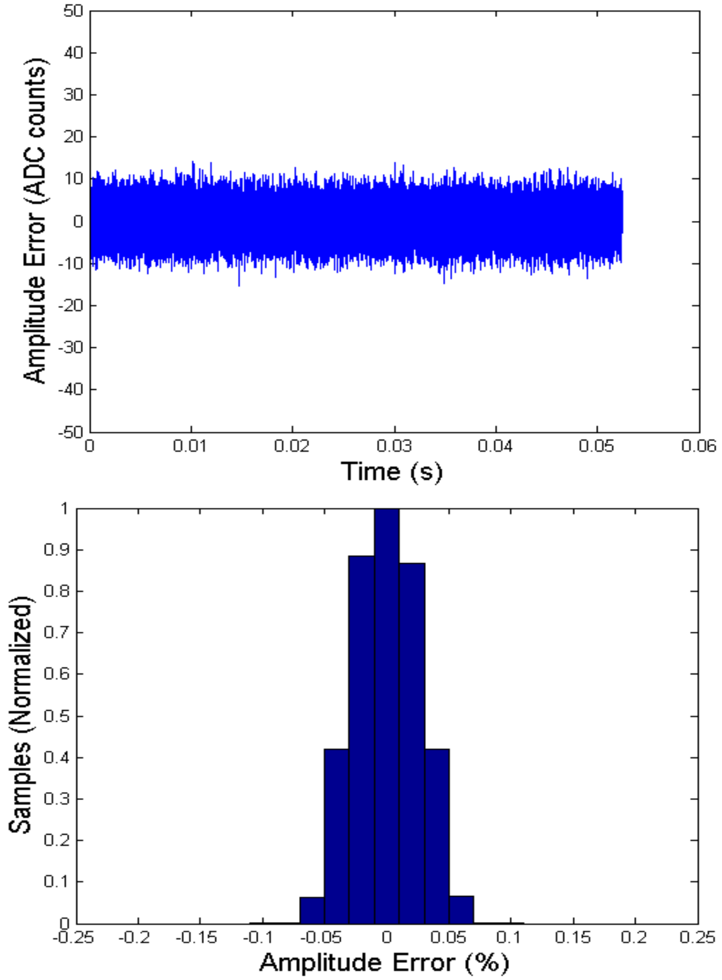
Amplitude Stability with 250mA @ 2.9GeV

(in-loop measurement)

CLS Drive (0.073% RMS)

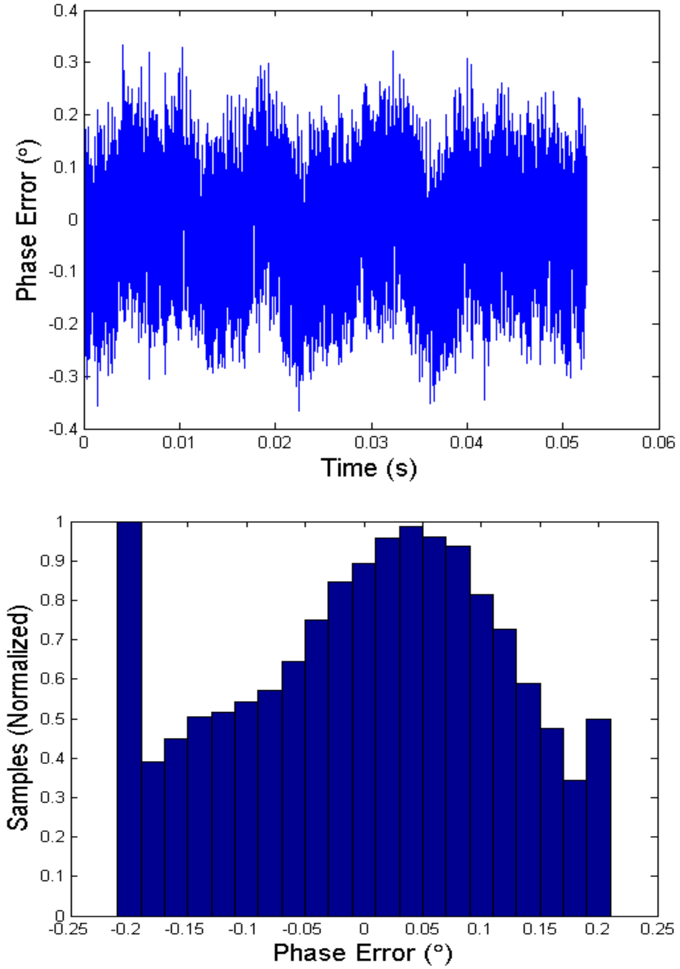


NSLSII Drive (0.026% RMS)

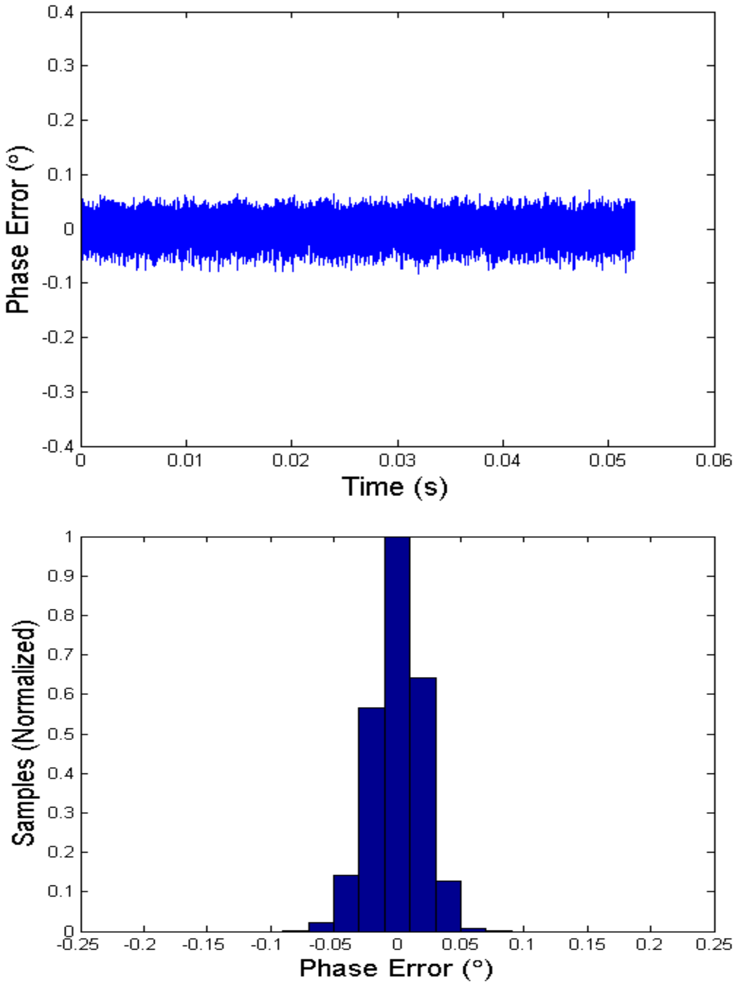


Phase Stability with 250mA @ 2.9GeV

CLS Drive (0.1171° RMS)

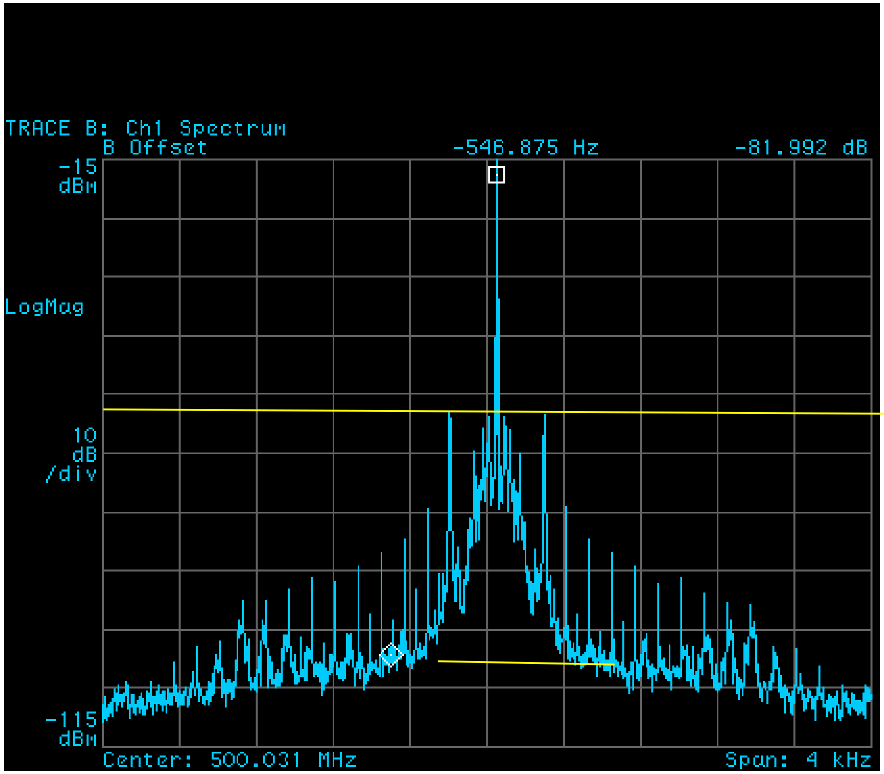


NSLSII Drive (0.019° RMS)

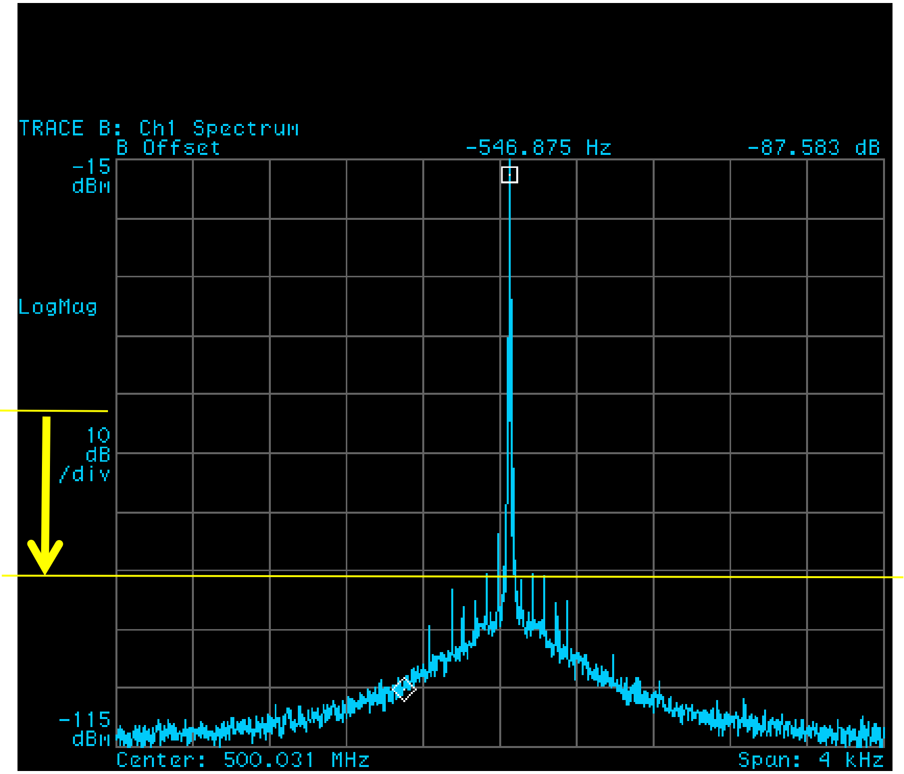


NSLS2 LLRF field at @ Canadian Light Source (300kW SRF)

- The effectiveness of LLRF feedback loop in transmitter HV harmonic level reduction measurement – confirmed with HP VSA (4 kHz span view @ 72kW)



Cavity field: open-loop

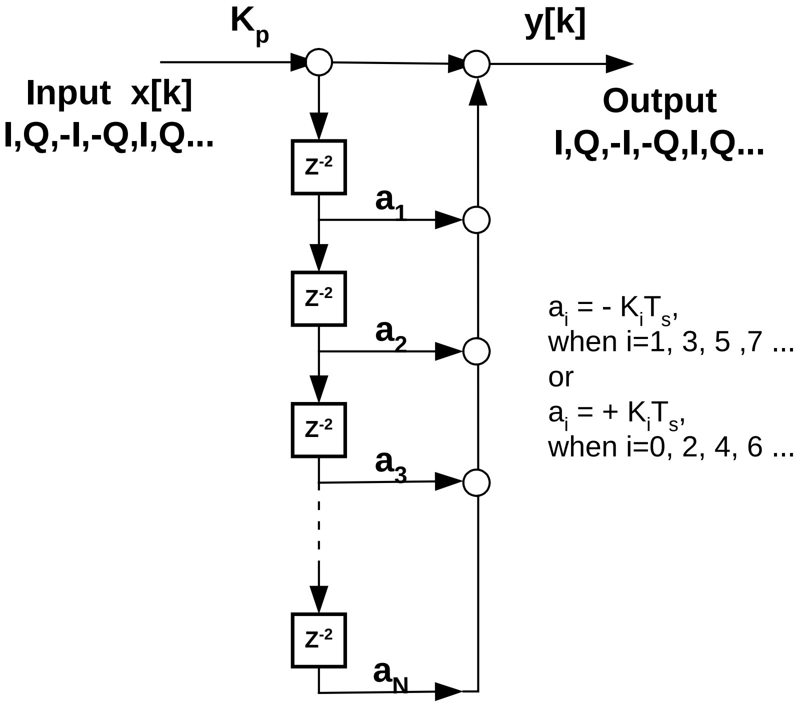


Cavity field: Closed-loop

LLRF control toolkit: 2. Specialty feedback loops w/ FIR

(can be a farm of loops)

- Purposes – to reject/suppress certain frequency components of the targeted perturbations
- Method – tailor-shape the loop passband by inserting specially designed FIR filters in the loop.
- FIR Tap spacing can be as small as 2 sampling period (Ts) as in the case of ADC noise rejection.
- Or it can be as large as one period of ring revolution as in 1-T delay feedback of circular machines.



$a_i = - K_i T_s$,
when i=1, 3, 5 ,7 ...
or
$a_i = + K_i T_s$,
when i=0, 2, 4, 6 ...

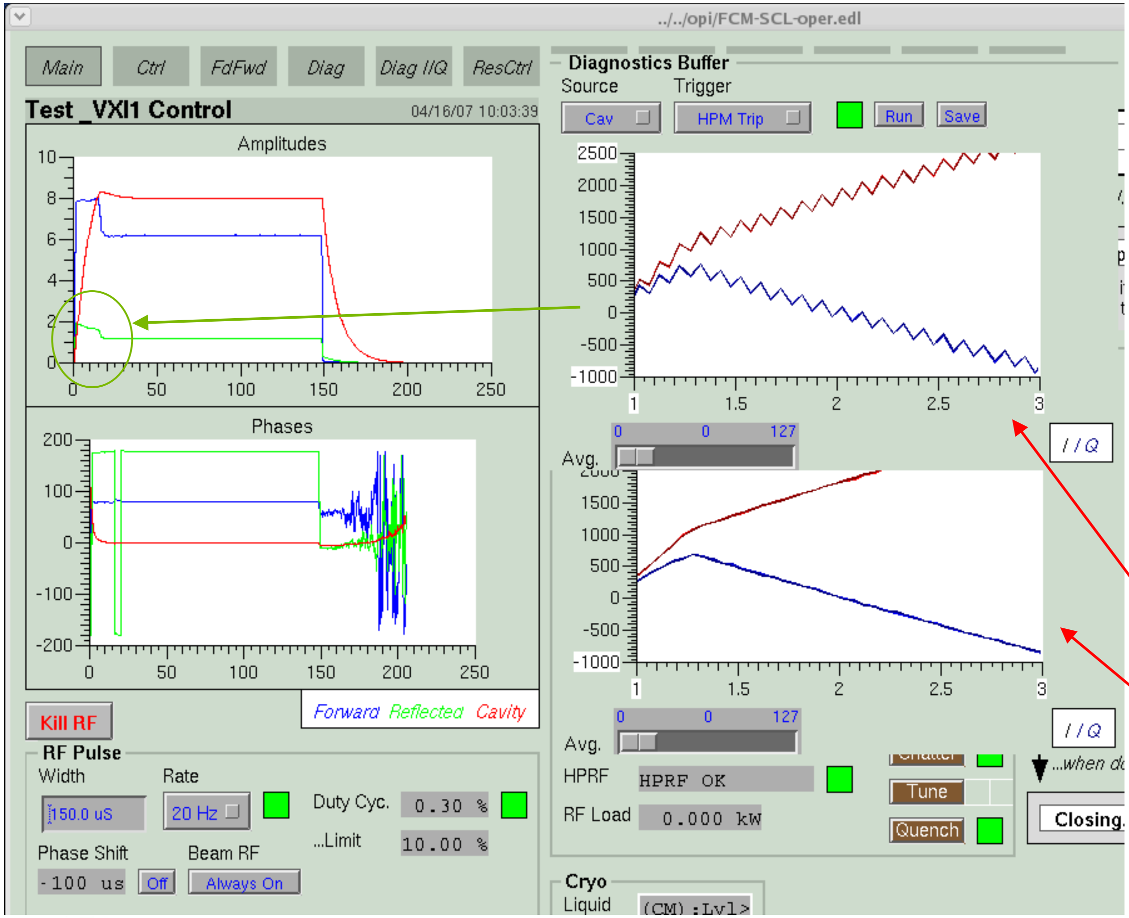
Positional P-I control in a general form

$$\mathbf{G_c}(z) = \mathbf{K_p} \cdot \left(\mathbf{1} + \mathbf{K_i T_s} \sum_{n=0}^{N} a_n \cdot \mathbf{z}^{-2n} \right)$$

LLRF control toolkit: 2. specialty feedback loop w/ FIR (2)

Applation Example : SNS LINAC, Fs = 40MHz

10MHz ADC “bouncing noise” rejection using a 1-tap FIR filter to create a notch at 10MHz in the passband.



Test _VXI1 Control 04/16/07 10:03:39

Diagnostics Buffer

Source: Cav

Trigger: HPM Trip

Run

Save

RF Pulse

Width: 150.0 uS

Rate: 20 Hz

Duty Cyc.: 0.30 %

...Limit: 10.00 %

Phase Shift: -100 us Off

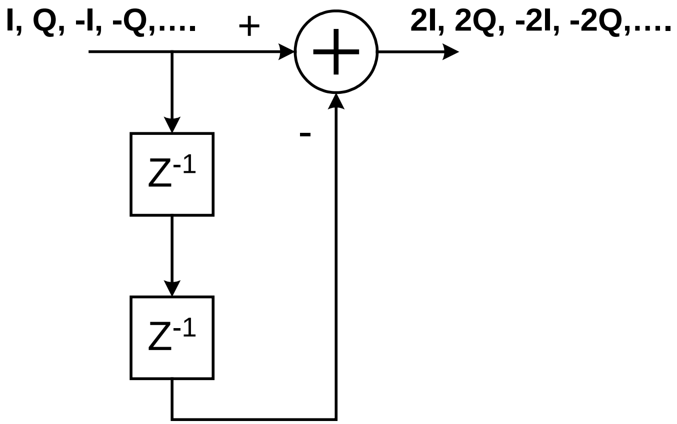
Beam RF: Always On

HPRF: HPRF OK

RF Load: 0.000 kW

Cryo

Liquid: (CM):Lvl>

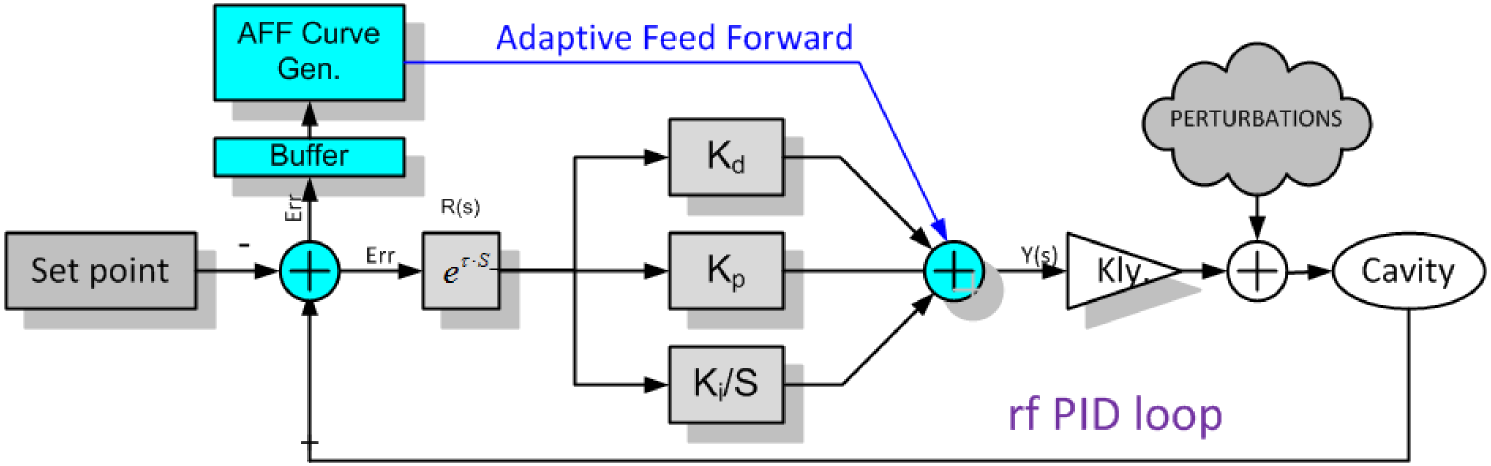


Raw ADC data with noise

After noise cancellation

LLRF control toolkit: 3. Addaptive Feed Forward (AFF)

- Purpose – To suppress repetitive (predictable) perturbing events (we know about it before time).
- Method – Adding canceling component through Feed Forward path to the output, A PREEMPTIVE ACTION (vs. delay feedback action), no transient if timed well.
- Common uses – HV ripple cancellation; beam loading compensation



LLRF control toolkit: 3. Addaptive Feed Forward (AFF) (continue)

Example: Cavity filling and heavy Beam-loading compensation in SNS LINAC where the beam current is 4 times of the rf current.

X /ade/epics/iocTop/R3.14.7/linac/llrf/R6-3/opi/FCM-SCL-oper.edl

SCL 18b LLRF

04/27/06 10:18:17

Amplitude Mismatch w/ Auto-Run goal

Auto−Run 6.000 Sv Rst

Cav. [MV/m] 2.08
Fwd. [kW] 12.8
Refl. [kW] 5.8
HOM B [W] 0.0
1.999 (FCM)

Cavity Field Phase 28.3

Loop Control

Closed
Loop Error 0.06 %
Auto−Run Closed

Broken Loop
Loop Gain 8000
Loop Integr. 0.75 kHz
FF Gain 0.10
Tau(Cavity) 305.0 us
Adaptive Feed Fwd. On
Freq. Offset 0.0

Sequencer
Status

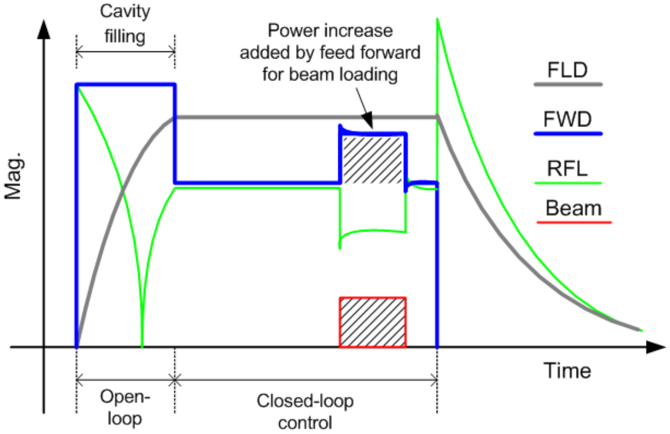
RF Timing
Pulse Width 1300.0 uS
Pulse Rate 2 Hz
Base Rate 1 Hz
HPRF Rate 10 Hz
Phase Shift -100 us

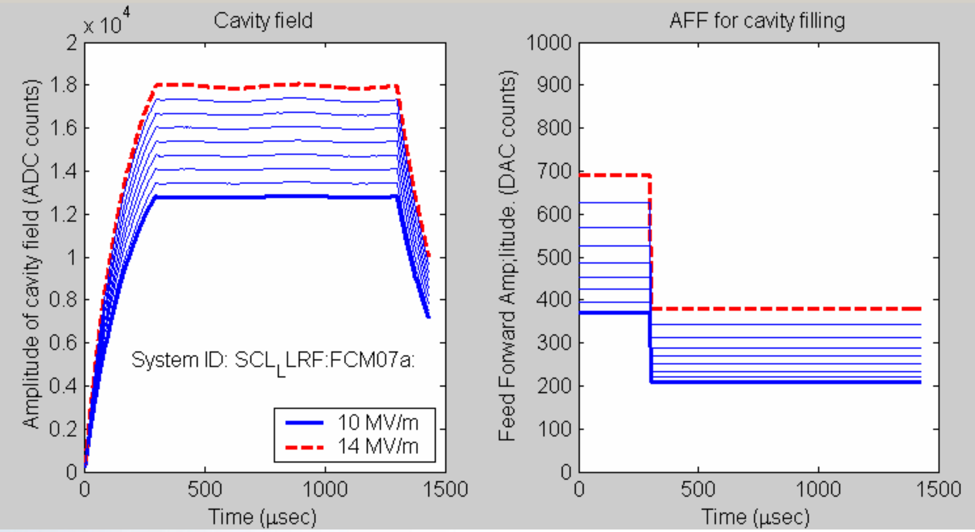
Limits
Res.Err. 0.03 kHz
...Limit 0.80 kHz
Power 12.83 kW
...Limit 500.00 kW
Duty Cyc. 0.26 %
...Limit 0.28 %
RF Load 0.001 kW

Cryo
Liquid Level
Beam Pipe
Coupl.

```
04/26/06 21:53:33  Tripped by HPM Interlock
04/26/06 21:54:49  Clipping phase droop
04/26/06 21:54:49  Closed Loop
```

Feed Forward Drive Pattern



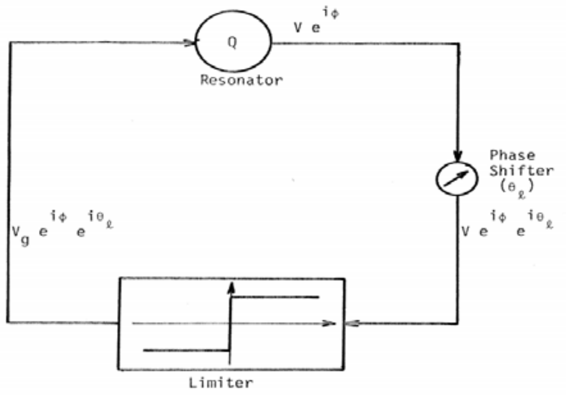


LLRF control toolkit: 4. Cavity Resonance Controls

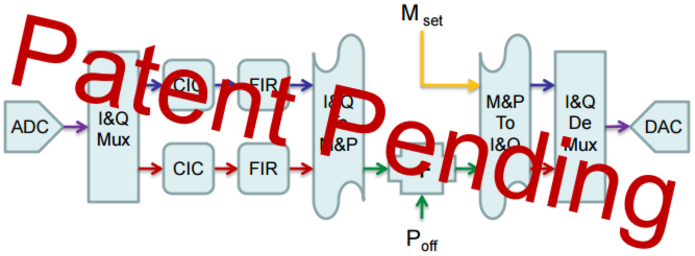
- Conventional Resonance Control: Slow tuner

  with availability of rf data from a digital LLRF, the tune motor control can be performed through a software loop by EPICS.
- A Special Resonance Control: Self-Excited Loop (SEL)

  to make rf generator frequency to follow the instantaneous resonance of the cavity. Essential for SRF operation.
  - SEL Concept first proposed in 1978 (J. Delayen's Ph.D thesis, Caltech).
  - A practical digital implementation based on a "phase-pass" scheme was developed by Jlab in 2008.
  - Implemented and operated with HP SRF in SPX in 2012~13.
  - LHC followed suit in 2015



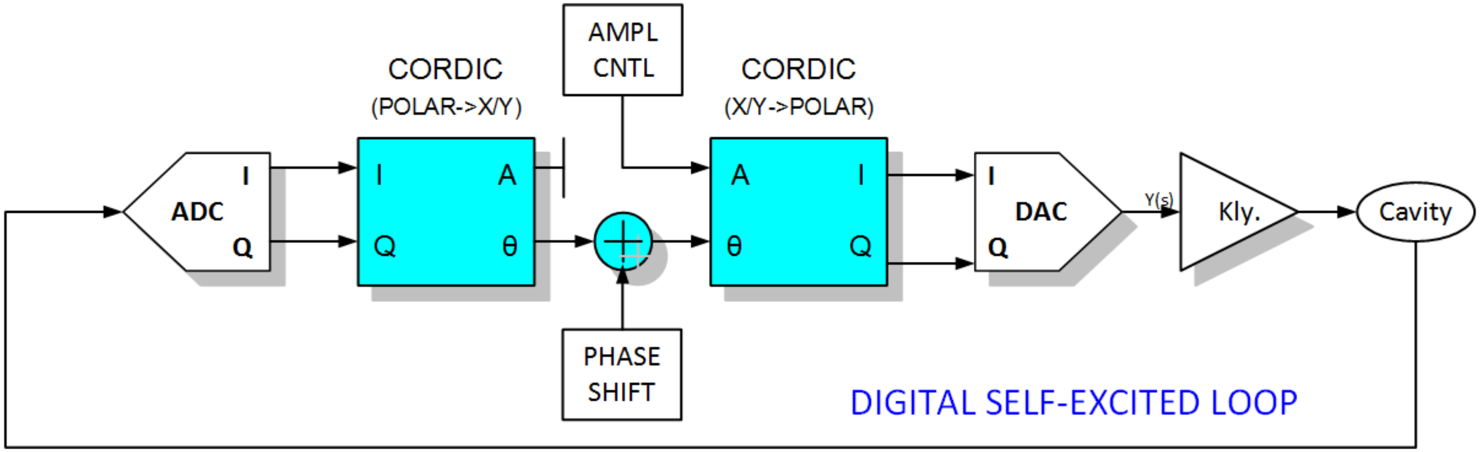
👍 Phase Pass 👍



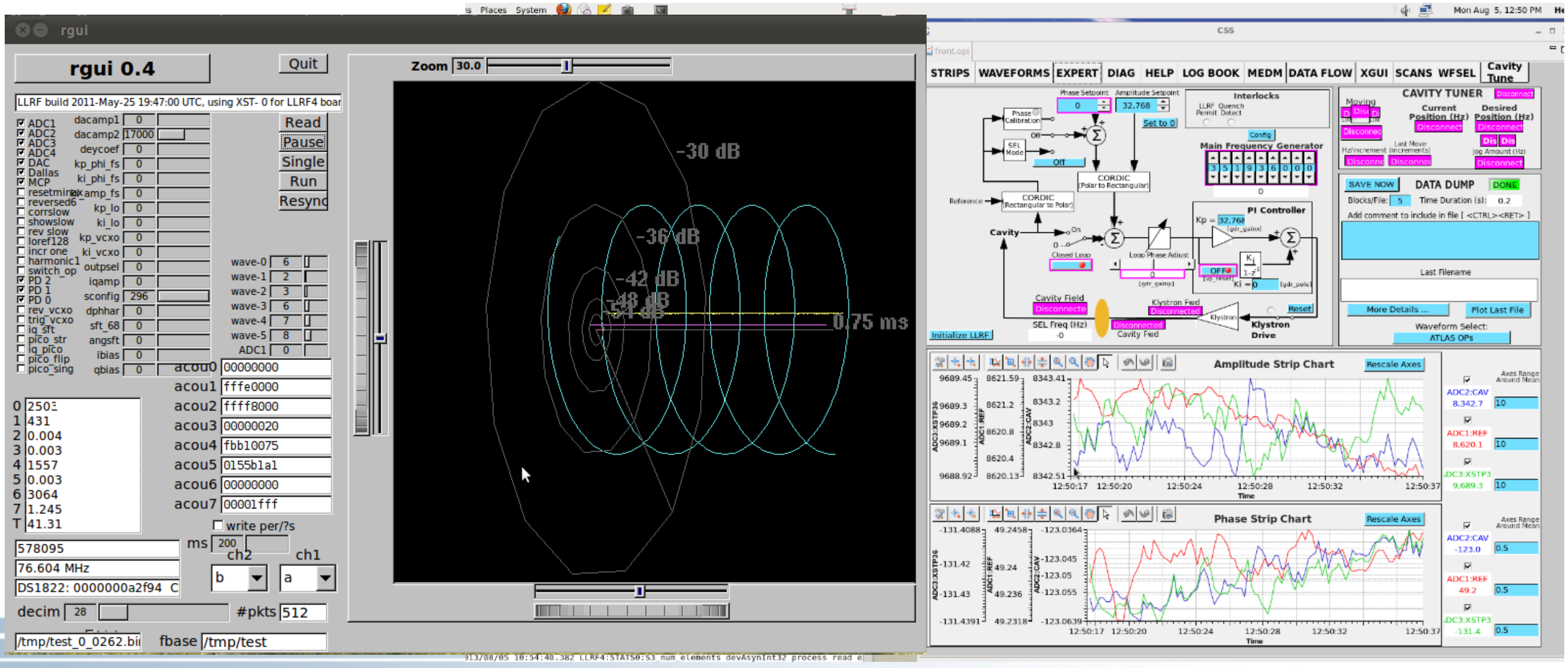
Patent Pending

LLRF control toolkit: 4. Digital Self-Excited Loop (SEL)

Secrete sauce of a practical digital SEL –> phase-pass



Easy, safe operation, totally controlled rf drive power; Naturally fits in SPX LLRF implement.



LLRF build 2011-May-25 19:47:00 UTC, using XST- 0 for LLRF4 boar

☑ ADC1
☑ ADC2
☑ ADC3
☑ ADC4
☑ DAC
☑ Dallas
☑ MCP
☐ resetminmax
☐ reversed6
☐ corrslow
☐ showslow
☐ rev slow
☐ loref128
☐ incr one
☐ harmonic1
☐ switch_op
☑ PD 2
☑ PD 1
☑ PD 0
☐ rev_vcxo
☐ trig_vcxo
☐ iq_sft
☐ pico_str
☐ iq_pico
☐ pico_flip
☐ pico_sing

dacamp1 0
dacamp2 17000
deycoef 0
kp_phi_fs 0
ki_phi_fs 0
kamp_fs 0
kp_lo 0
ki_lo 0
kp_vcxo 0
ki_vcxo 0
outpsel 0
iqamp 0
sconfig 296
dphhar 0
sft_68 0
angsft 0
ibias 0
qbias 0

wave-0 6
wave-1 2
wave-2 3
wave-3 6
wave-4 7
wave-5 8
ADC1 0

acou0 00000000
acou1 fffe0000
acou2 ffff8000
acou3 00000020
acou4 fbb10075
acou5 0155b1a1
acou6 00000000
acou7 00001fff

0 2503
1 431
2 0.004
3 0.003
4 1557
5 0.003
6 3064
7 1.245
T 41.31

☐ write per/?s
ms 200
ch2 b
ch1 a

578095
76.604 MHz
DS1822: 0000000a2f94 C

decim 28
#pkts 512

/tmp/test_0_0262.bi
fbase /tmp/test

Phase Setpoint 0
Amplitude Setpoint 32,768
SEL Freq (Hz) -0
Blocks/File: 5
Time Duration (s): 0.2

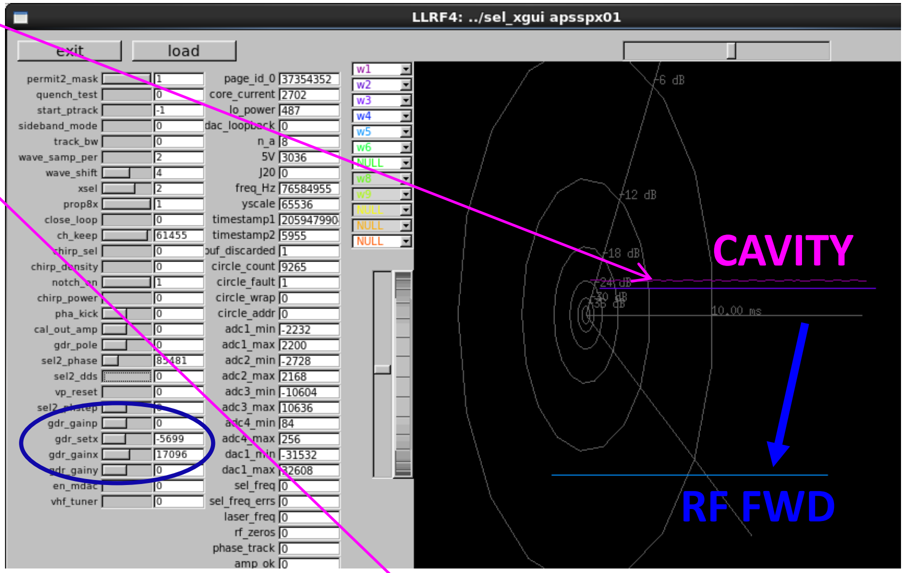
LLRF control toolkit: 5. Drive Output Frequency Agile

- DDS, can be used to perform frequency sweep to test system frequency response.

Cavity started with resonance off by ~5kHz, with lots RF power, but little cavity field

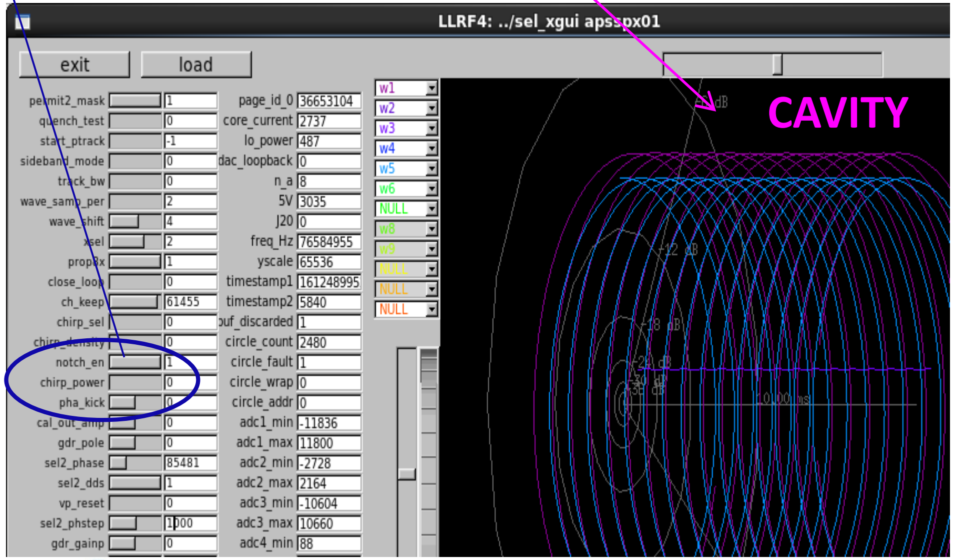
Turn on output DDS, shift the output frequency by spinning the llrf output drive vector, and cavity field starts to grow

As output frequency shift reaches –5kHz, cavity field magnitude reaches a maximum, cavity resonance is found.



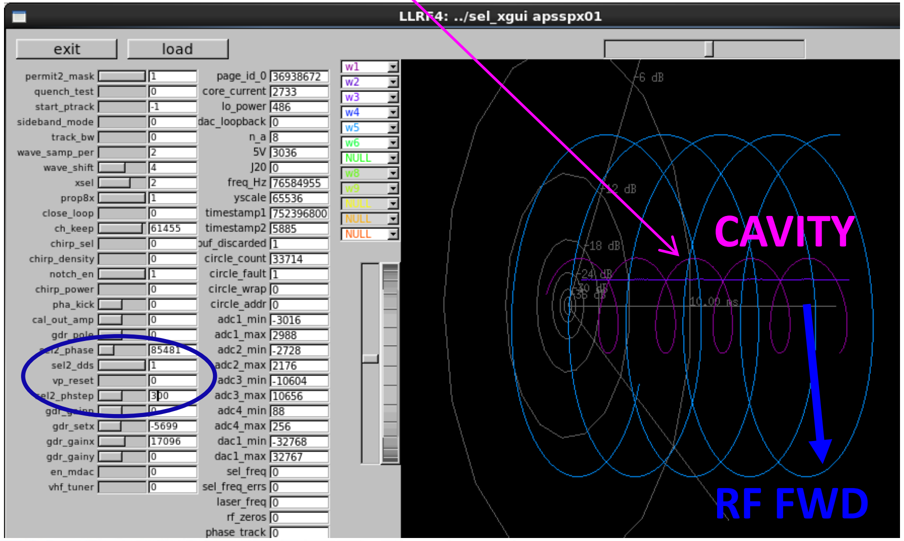
LLRF4: ../sel_xgui apsspx01

permit2_mask	1	page_id_0	37354352
quench_test	0	core_current	2702
start_ptrack	-1	lo_power	487
sideband_mode	0	dac_loopback	0
track_bw	0	n_a	8
wave_samp_per	2	5V	3036
wave_shift	4	J20	0
xsel	2	freq_Hz	76584955
prop8x	1	yscale	65536
close_loop	0	timestamp1	205947990
ch_keep	61455	timestamp2	5955
chirp_sel	0	buf_discarded	1
chirp_density	0	circle_count	9265
notch_en	1	circle_fault	1
chirp_power	0	circle_wrap	0
pha_kick	0	circle_addr	0
cal_out_amp	0	adc1_min	-2232
gdr_pole	0	adc1_max	2200
sel2_phase	85481	adc2_min	-2728
sel2_dds	0	adc2_max	2168
vp_reset	0	adc3_min	-10604
sel2_phstep	0	adc3_max	10636
gdr_gainp	0	adc4_min	84
gdr_setx	-5699	adc4_max	256
gdr_gainx	17096	dac1_min	-31532
gdr_gainy	0	dac1_max	32608
en_mdac	0	sel_freq	0
vhf_tuner	0	sel_freq_errs	0
		laser_freq	0
		rf_zeros	0
		phase_track	0
		amp_ok	0



LLRF4: ../sel_xgui apsspx01

permit2_mask	1	page_id_0	36653104
quench_test	0	core_current	2737
start_ptrack	-1	lo_power	487
sideband_mode	0	dac_loopback	0
track_bw	0	n_a	8
wave_samp_per	2	5V	3035
wave_shift	4	J20	0
xsel	2	freq_Hz	76584955
prop8x	1	yscale	65536
close_loop	0	timestamp1	161248995
ch_keep	61455	timestamp2	5840
chirp_sel	0	buf_discarded	1
chirp_density	0	circle_count	2480
notch_en	1	circle_fault	1
chirp_power	0	circle_wrap	0
pha_kick	0	circle_addr	0
cal_out_amp	0	adc1_min	-11836
gdr_pole	0	adc1_max	11800
sel2_phase	85481	adc2_min	-2728
sel2_dds	1	adc2_max	2164
vp_reset	0	adc3_min	-10604
sel2_phstep	1000	adc3_max	10660
gdr_gainp	0	adc4_min	88



LLRF4: ../sel_xgui apsspx01

permit2_mask	1	page_id_0	36938672
quench_test	0	core_current	2733
start_ptrack	-1	lo_power	486
sideband_mode	0	dac_loopback	0
track_bw	0	n_a	8
wave_samp_per	2	5V	3036
wave_shift	4	J20	0
xsel	2	freq_Hz	76584955
prop8x	1	yscale	65536
close_loop	0	timestamp1	752396800
ch_keep	61455	timestamp2	5885
chirp_sel	0	buf_discarded	1
chirp_density	0	circle_count	33714
notch_en	1	circle_fault	1
chirp_power	0	circle_wrap	0
pha_kick	0	circle_addr	0
cal_out_amp	0	adc1_min	-3016
gdr_pole	0	adc1_max	2988
sel2_phase	85481	adc2_min	-2728
sel2_dds	1	adc2_max	2176
vp_reset	0	adc3_min	-10604
sel2_phstep	300	adc3_max	10656
gdr_gainp	0	adc4_min	88
gdr_setx	-5699	adc4_max	256
gdr_gainx	17096	dac1_min	-32768
gdr_gainy	0	dac1_max	32767
en_mdac	0	sel_freq	0
vhf_tuner	0	sel_freq_errs	0
		laser_freq	0
		rf_zeros	0
		phase track	0

LLRF control toolkit: 6. Exception handling (interlocks)

- LLRF actions in an event of fault, minor or catastrophic -
  - machine/
  - equipment/
  - personal protections etc
- an extremely important topic for large accelerators.
- Requirement is machine specific.
- Simrock's list →

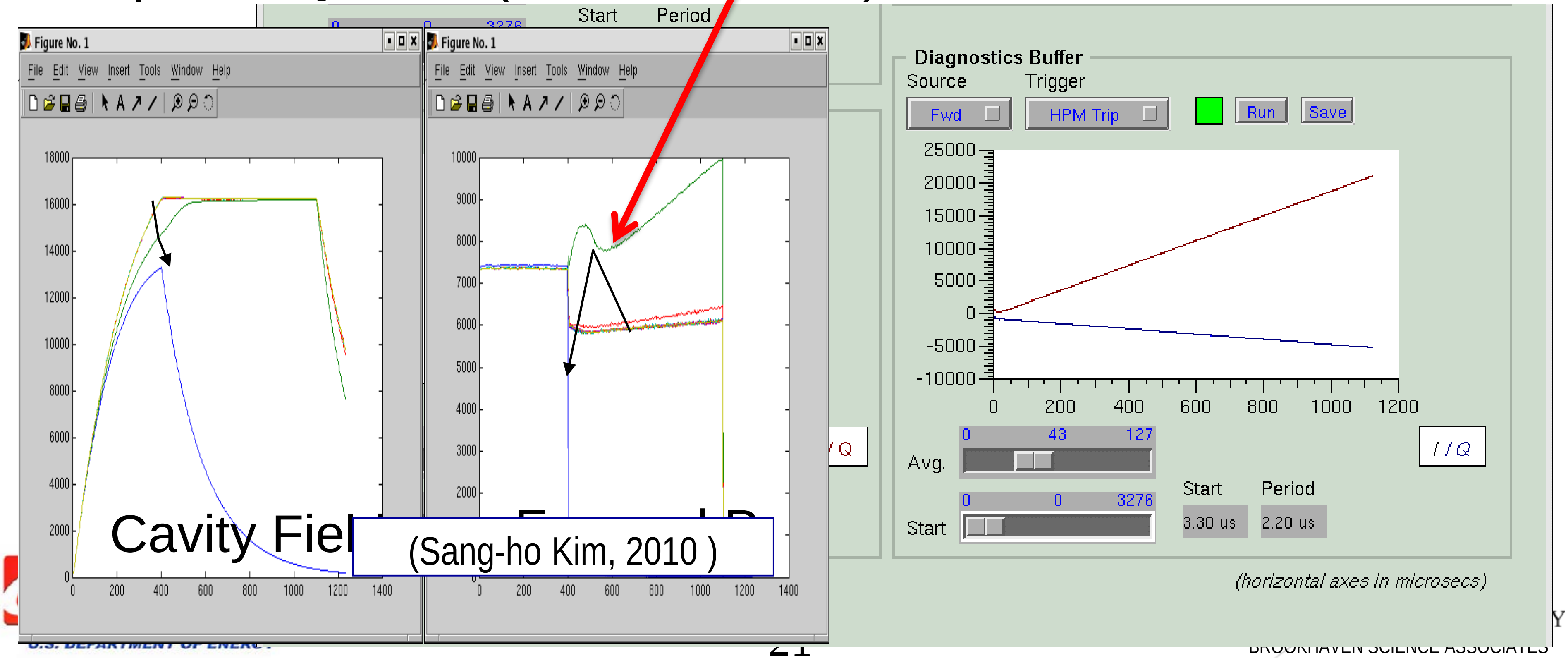
Table 1: Examples for Exceptions, their impact, countermeasures and the resulting improvement

Exception	Impact	Countermeasure	Result
cavity quench hard/soft	Beam energy fluctuation	Lower grad., comp. with other cav.	Recover after few pulses
Cavity field emission	Radiation damage Electronics	Lower grad., comp. with other cav.	Reduce radiation levels
Cavity excessive detuning	Gradient / phase stability	Tune cavity to op. frequency	Recover in few pulses
Cavity incident phase error	Reduced available energy gain	Re-phase with 3-stub tuner	Recover on crest- operation
Cavity loaded Q error	Slope on individual gradient	Adjust loaded Q	Flat top in all cavities
Piezo tuner defect	No Lorentz force compensation	Not available	-
Motor tuner stuck	Cavity lost or strong field slope	Not available	-
Occasional klystron gun spark	Beam energy, Beam loss	Reset, bypass	Recovery after few pulses
Frequent klystron gun spark	Low availability, klystron damage	Lower high voltage	High avail., lower gradient
Occasional coupler spark	Shorten rf and beam pulses	Lower power	Operation at lower gradient
Preamplifier failure	Loss of rf station	Switch to redundant system	Recover after few pulses
Modulator HV unstable	Gradient / phase stability		
Preamplifier saturated	Field regulation reduced	Lower gradient	Recover after few pulses
Timing jitter LLRF/Laser	Loss in peak current, energy error	Not available	-
Timing trigger/clock missing	Loss of linac / rf station	Switch to redundant system	Recover after few pulses
Timing error subsystem	Potential loss of SASE	Adjust timing	Recover after few pulses
M.O. and distribution failure	Loss of main linac	Switch to redundant system	Recover after few pulses
Vector-modulator failure	Loss of field control	Switch to redundant vector-mod.	Recover after few pulses
Calibration reference failure	Slow phase drift, beam energy	Use beam feedback	Stable beam
RF station LO missing	Loss of Gradient	Switch to redundant feedforward	Beam at reduced stability
down converter channel defect	Red. field stability, higher grad.	Estimate cavity field	Recover field stability
Calibration error VS	Field stability	Re-calibrate vector sum	Recover after calibration
Analog input channel defect	Field stability	Estimate lost signal	Partial recovery
Cable connection missing	Field stability	Estimate lost signal	Partial recovery
Processor error fdbck loop	Field stability	Switch to redundant feedforward	Recover with red. Field stab.
Numerical error	Cavity field	Switch to redundant feedforward	Recover with red. Field stab.
Single event setup	System hang-up, calc. error	Redundant FF, Recover system	Recovery with init. Red. Stab.
Total ionizing dose damage	Noisy sign. , sensitivity, offset	Switch to red. feedforward	Recover with red. field stab.
Rack cooling failure	Potential loss of hardware	Turn power off, op. redundant FF	save hw,recover with red. stab.
Crate power failure	Loss of cavity field	Switch to redundant FF	Recover with red. field stab.
Computer network failure	Loss of control of param. settings	Establish connection via red. netw.	Regain parameter control
Communication link failure	Field stability	Switch to redundant feedforward	Recover with red. field stab.
Operator input out of range	Beam energy, beam loss	Limit input range	No impact

LLRF control toolkit: 6. Exception handling (2)

- rf data buffering in an event of fault for study/investigateions (post-mortem analysis)
- (1) A trip freezes the live rf waveform data in FPGA buffer that shows what happened at exact moment of event

At partial Quench (Measured data)



Diagnostics Buffer

Source: Fwd

Trigger: HPM Trip

Avg.: 0 43 127

Start: 0 0 3276

Start: 3.30 us

Period: 2.20 us

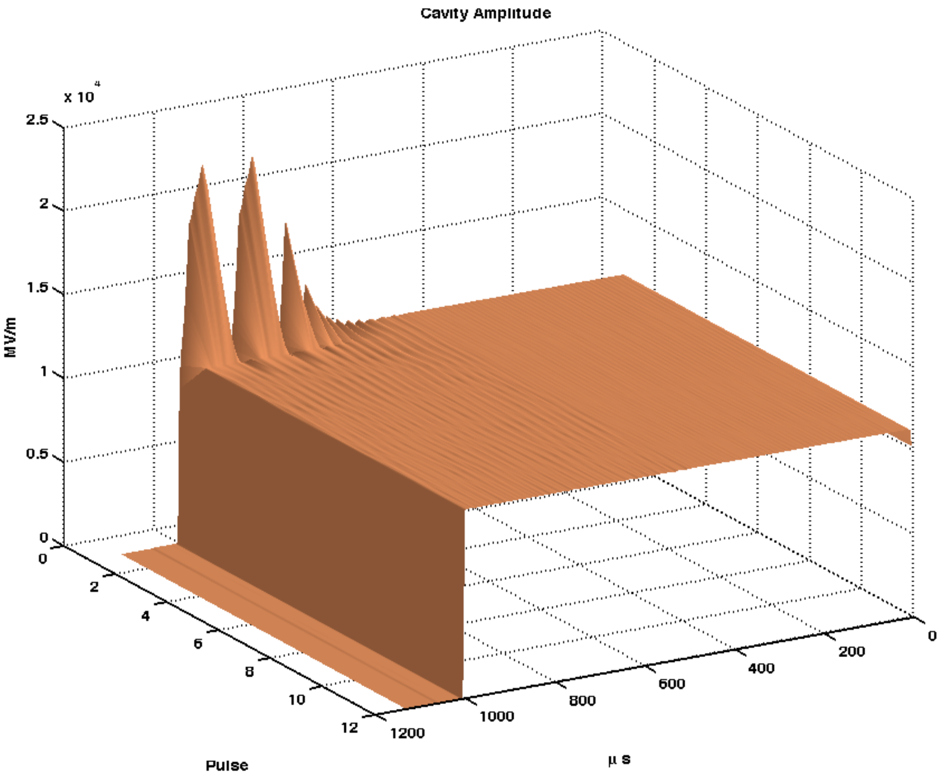
(horizontal axes in microsecs)

(Sang-ho Kim, 2010)

LLRF control toolkit: 6. Exception handling (3)

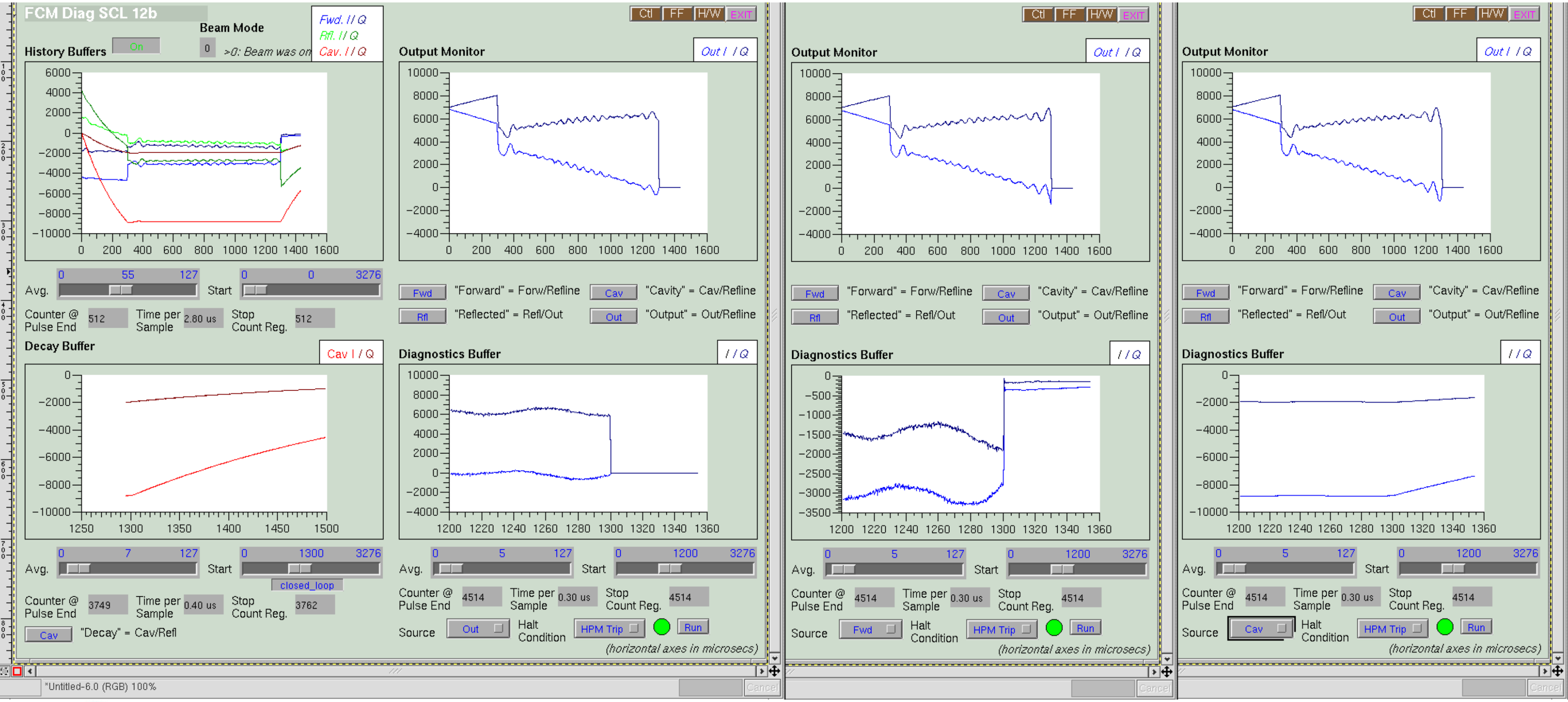
- Last frame of data at moment of a trip is frozen in FPGA data buffer
- Last 60 frames before the trip ˙ recorded in the circular memc buffer in IOC
- The 60 frame of data record i IOC shows (hopefully) how th fault was led to the trip.

Example:
Regulation error trip from selecting wrong gain rotation



LLRF control toolkit: 7. system Monitoring/diagnosis

- Live, high-resolution DSO-type rf waveform display at remote console is essential for supporting a system with a large number of rf stations.



History Buffers: On

Beam Mode: 0 >0: Beam was on

Avg.: 0 55 127 Start: 0 0 3276

Counter @ Pulse End: 512 Time per Sample: 2.80 us Stop Count Reg.: 512

Decay Buffer — Avg.: 0 7 127 Start: 0 1300 3276 closed_loop

Counter @ Pulse End: 3749 Time per Sample: 0.40 us Stop Count Reg.: 3762

Cav "Decay" = Cav/Refl

Diagnostics Buffer — Avg.: 0 5 127 Start: 0 1200 3276

Counter @ Pulse End: 4514 Time per Sample: 0.30 us Stop Count Reg.: 4514

Source: Out Halt Condition: HPM Trip ● Run

Diagnostics Buffer — Avg.: 0 5 127 Start: 0 1200 3276

Counter @ Pulse End: 4514 Time per Sample: 0.30 us Stop Count Reg.: 4514

Source: Fwd Halt Condition: HPM Trip ● Run

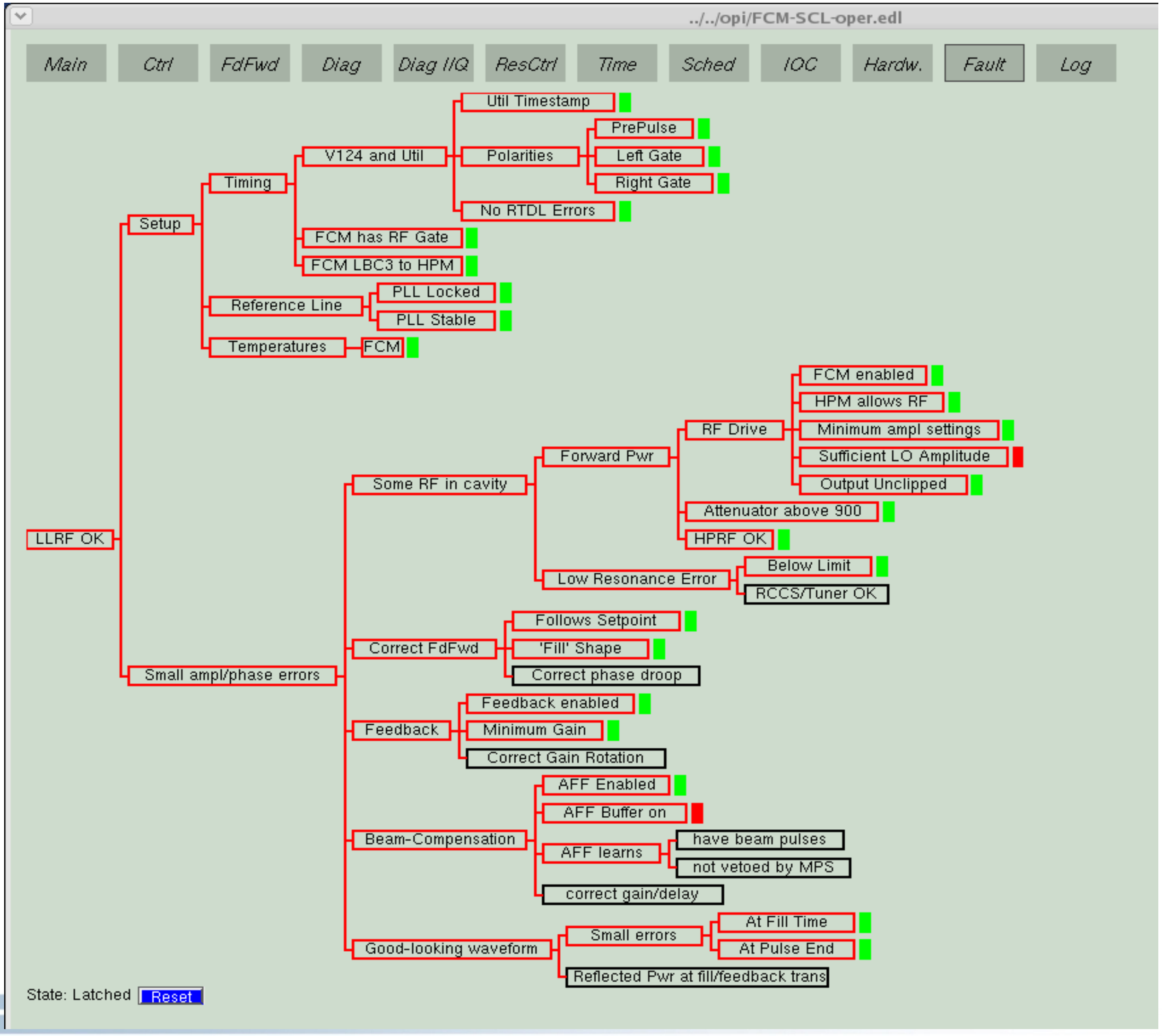
Diagnostics Buffer — Avg.: 0 5 127 Start: 0 1200 3276

Counter @ Pulse End: 4514 Time per Sample: 0.30 us Stop Count Reg.: 4514

Source: Cav Halt Condition: HPM Trip ● Run

LLRF control toolkit: 7. system Monitoring/diagnosis (continue)

- EPICS Fault-tree screen is another example of important tool for op. support.



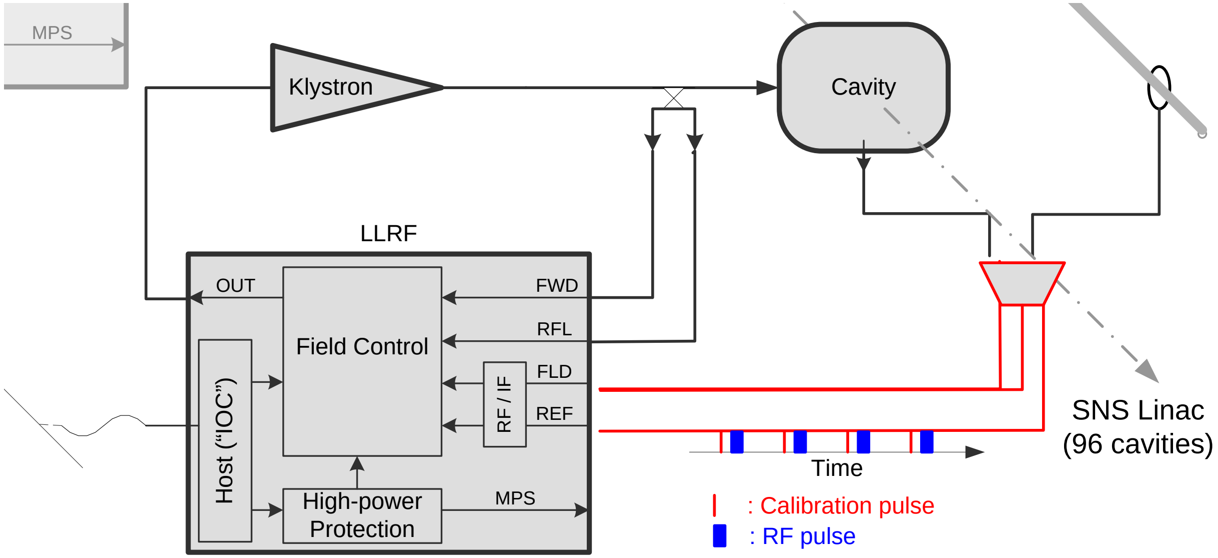
LLRF control toolkit: 8. rf measurement calibration

- Purpose -- Both the rf reference and the LLRF measurement drift, often time due to ambient temperature change.
- Recent accelerators require unprecedented rf stabilities (such as 0.01%/0.01 deg.)
- The LLRF system must have a built-in calibration capability in order to meet the very tide specs.
- Methods
  - RF reference and its distribution must be stabilized, involves themo-control, PLL, reflectometry, interferometry, etc. A subject by itself.
  - Calibration for the phase drifts in the rf path to LLRF
    - Performed during rf-off time (for pulsed-rf)
    - Performed with “pilot-tones” (for CW rf)

LLRF control toolkit: 8. rf measurement calibration (2)

Example: SNS LINAC, pulsed-rf - method

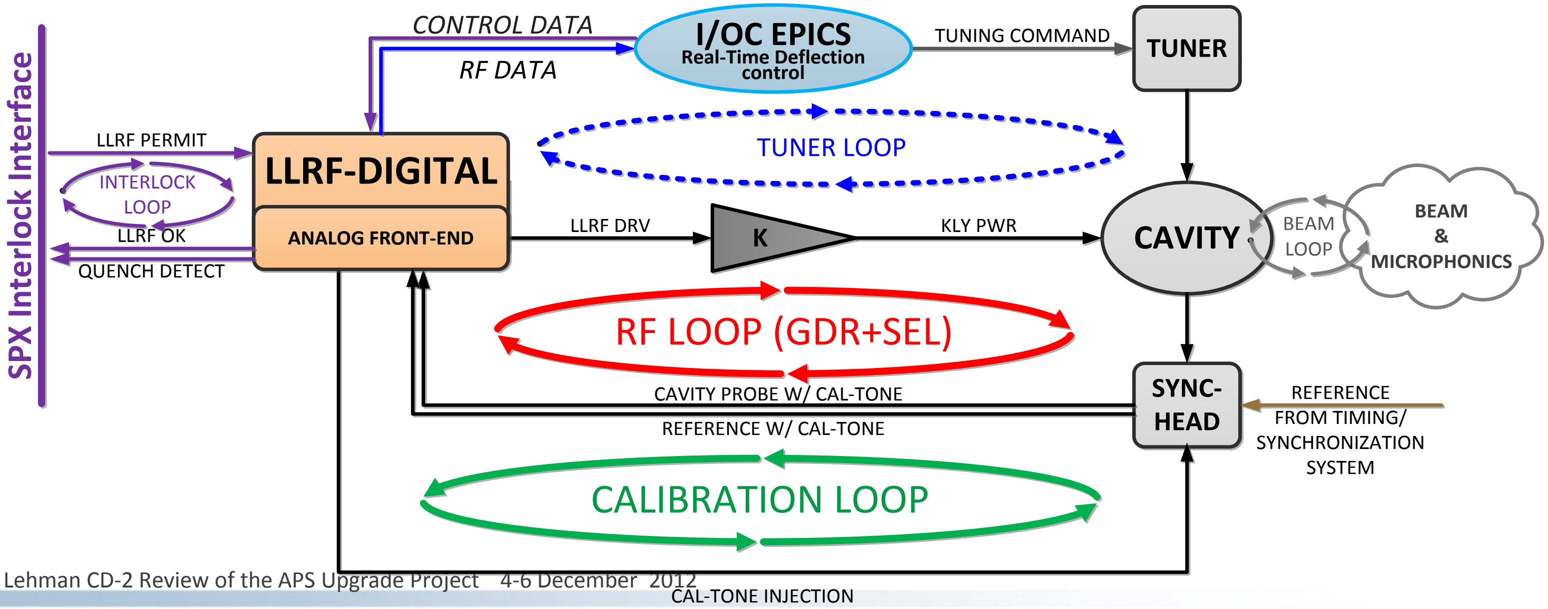
- calibration is performed in off-time between to rf pulses (time-division) by sampling the rf reference.
- Cavity rf and reference signal are sent to LLRF rack in a phase-matched cable pair (temp. controlled), so both are subject to the same ambient temperature.
- LLRF digitally demodulates the received rf and reference to get the phase measurement of the both.
- The reference phase measurement is subtracted from the cavity phase measurement to remove the drift in the rf path (cables and circuits).
- Provision was made for the option of sending a pulsed reference and the cavity rf through the same cable in different time-slot.



LLRF control toolkit: 8. rf measurement calibration (3)

Example : drift calibration scheme of SPX CW RF - method

- LLRF generates a a double-sideband pilot-tone (of +/- 1/48 F0 offset in frequency).
- The DSB pilot tone signal is sent to the cavity location in tunnel and is added to both the cavity pickup signal and rf reference in a device called “sync-head”.
- LLRF digitally demodulates the received rf carrier plus two pilot-tone sideband signals, and obtains the data of the rf vectors at three different frequencies for each channel (cavity and reference).
- The phase drifts in both channel can therefore be computed from the vectors.
- The values of the detected phase drifts are then added to the LLRF phase control settings to compensate the drifts.



LLRF control toolkit: 8. rf measurement calibration (4)

Example : drift calibration scheme of SPX CW RF – more details

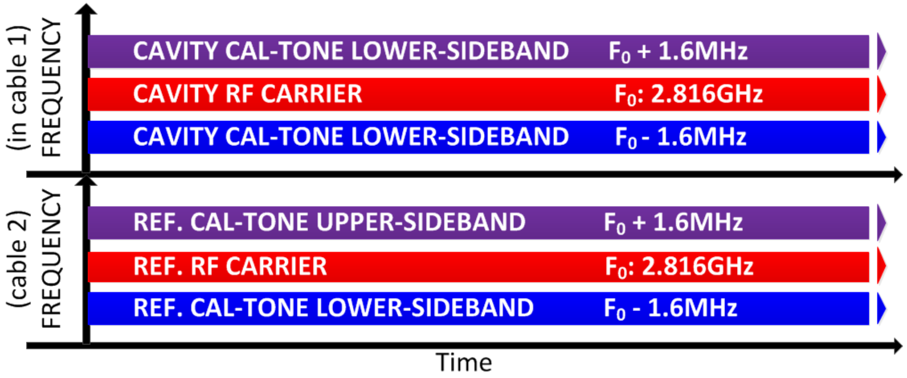
- **Technology developed in LBNL, demonstrated at LCLS/SLAC, and further refined for SPX application.**
- **Phase stabilization performance of 3~15 milli-deg. was demonstrated and reported** (Byrd and Huang et al., BIW'10). (within SPX rf error budget : 0.077/0.28 deg)

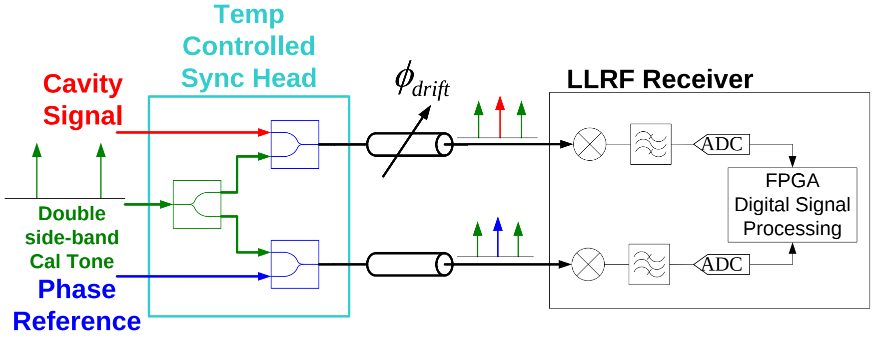
Phase drift detection algorithm

$$\Phi_{REF,CAV} = \left(\Phi_{RE\_REF} - \Phi_{RF\_CAV}\right) - \frac{\left(\Phi_{CAL\_U\_REF} - \Phi_{CAL\_U\_CAV}\right)}{2} - \frac{\left(\Phi_{CAL\_l\_REF} - \Phi_{CAL\_l\_CAV}\right)}{2}$$

where

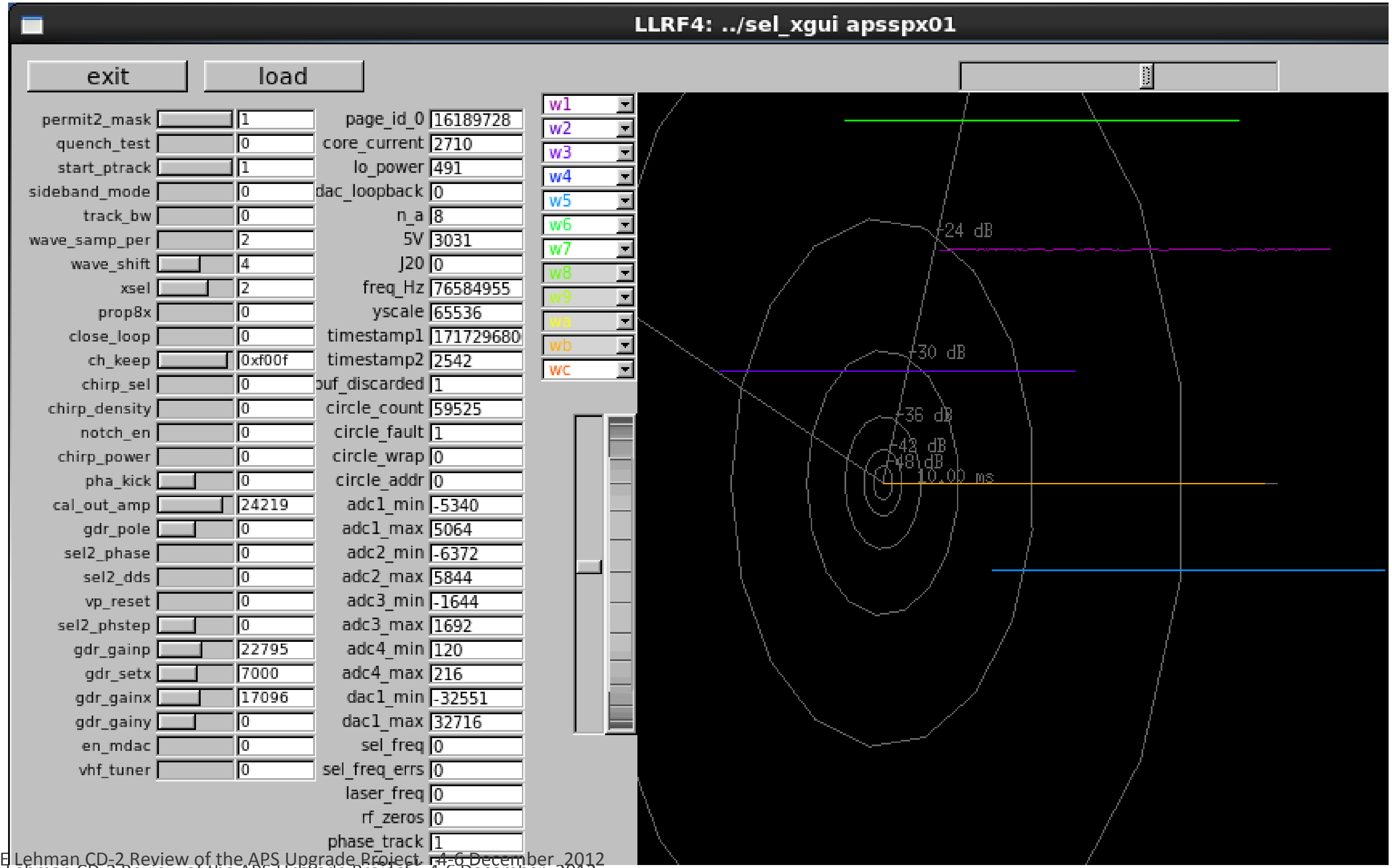
- $\Phi_{REF,CAV}$ *-the calculated phase difference between cavity and ref.*
- Φ_{RF_REF}, Φ_{RF_CAV} *-measured phase of cavity and reference signal*
- $\Phi_{CAL\_U\_REF}$, $\Phi_{CAL\_L\_REF}$ *-measured phase of upper and lower side-band of Cal-Tone signal in Reference cable.*
- $\Phi_{CAL\_U\_CAV}$, $\Phi_{CAL\_L\_CAV}$ *-measured phase of upper and lower side-band of Cal-Tone in Cavity field cable.*





LLRF control toolkit: 8. rf measurement calibration (5)

Example : drift calibration scheme of SPX CW RF – 3-D display of rf carriers and pilot-tone sideband vectors on control screen of the implemented SPX LLRF.



permit2_mask	1	page_id_0	16189728
quench_test	0	core_current	2710
start_ptrack	1	lo_power	491
sideband_mode	0	dac_loopback	0
track_bw	0	n_a	8
wave_samp_per	2	5V	3031
wave_shift	4	J20	0
xsel	2	freq_Hz	76584955
prop8x	0	yscale	65536
close_loop	0	timestamp1	171729680
ch_keep	0xf00f	timestamp2	2542
chirp_sel	0	uf_discarded	1
chirp_density	0	circle_count	59525
notch_en	0	circle_fault	1
chirp_power	0	circle_wrap	0
pha_kick	0	circle_addr	0
cal_out_amp	24219	adc1_min	-5340
gdr_pole	0	adc1_max	5064
sel2_phase	0	adc2_min	-6372
sel2_dds	0	adc2_max	5844
vp_reset	0	adc3_min	-1644
sel2_phstep	0	adc3_max	1692
gdr_gainp	22795	adc4_min	120
gdr_setx	7000	adc4_max	216
gdr_gainx	17096	dac1_min	-32551
gdr_gainy	0	dac1_max	32716
en_mdac	0	sel_freq	0
vhf_tuner	0	sel_freq_errs	0
		laser_freq	0
		rf_zeros	0
		phase_track	1

DOE Lehman CD-2 Review of the APS Upgrade Project 4-6 December 2012

Low Level Radio Frequency Workshop 2015

hosted by Shanghai Institute of Applied Physics, Chinese Academy of Sciences

http://llrf15.csp.escience.cn/dct/page/1

92 participants, 32 institutes, 14 countries/Regions,

173 reports (sample a few)

Australia, Canada, China, EU, Germany, India, Italy, Japan, Korea, Poland,
Sweden, Switzerland, Spain, United Kingdom, United States

LLRF’15 Workshop at a Glance

Reports cover areas of

Facility Overview	10
Hardware	9
Systems	10
Commissioning/Operation exp.	10
SRF	5
Phase Reference	6
Tutorials	4

International Committee

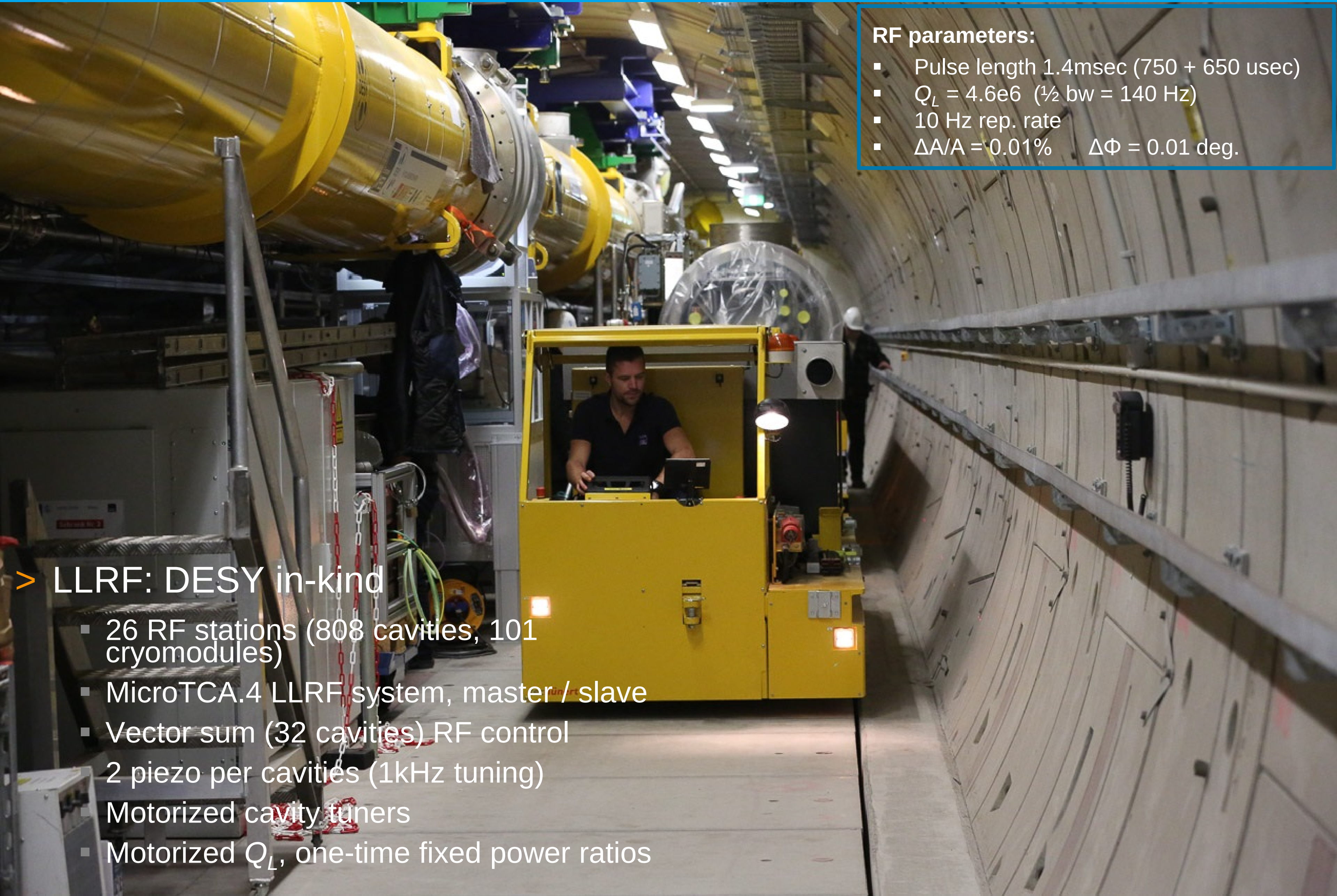
Wolfgang Hofle,	CERN
Tomasz Plawski,	JLAB
Shinichiro Michizono,	KEK
Larry Doolittle,	LBNL
Mark T. Crofford,	ORNL
Aessandro Ratti,	LBNL
Kevin Smith,	BNL
Curt Hovater,	JLAB
Mariusz Grecki,	DESY
Brian E Chase,	FNAL
Matthias U Liepe,	CORNELL
Stefan Simrock,	ITER
Dmitry Teytelman,	DIMTEL
Zheqiao Geng,	PSI

- Digital LLRF is either already used in operations or has been planned for new projects in most facilities.
- Digital LLRF is currently actively being pursued in ALS, Diamond, ESRF (?), ESS, LCLS-II, Spring-8, PSI…

Local Committee

Local Chair: Jianfei Liu
Host: Yubin Zhao
Local Secretary: Qiang Chang, Shenjie Zhao, Xiang Zheng, Kai Xu, Hongtao Hou, Zhigang Zhang, Zheng Li

European XFEL Massive engineering challenge



RF parameters:

- Pulse length 1.4msec (750 + 650 usec)
- Q_L = 4.6e6 (½ bw = 140 Hz)
- 10 Hz rep. rate
- $\Delta A/A = 0.01\%$ $\Delta\Phi = 0.01$ deg.

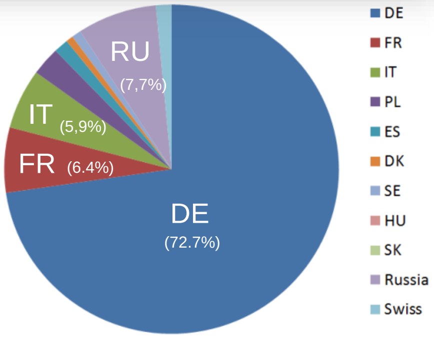
> LLRF: DESY in-kind

- 26 RF stations (808 cavities, 101 cryomodules)
- MicroTCA.4 LLRF system, master / slave
- Vector sum (32 cavities) RF control
- 2 piezo per cavities (1kHz tuning)
- Motorized cavity tuners
- Motorized Q_L, one-time fixed power ratios

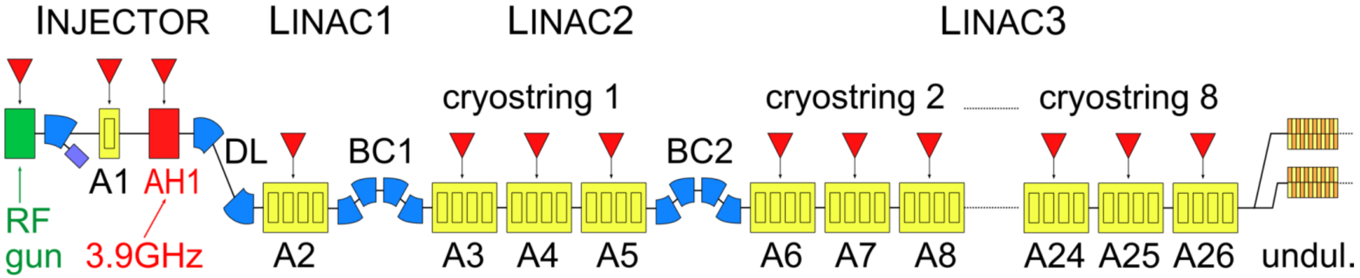
INTRODUCTION: European XFEL

The European X-ray Free Electron Laser

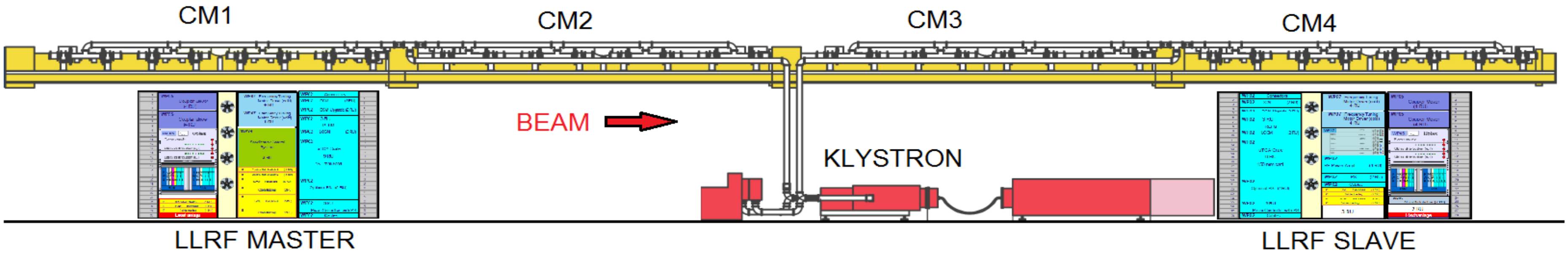
- 17.5 GeV light source, Hamburg, Germany
- TESLA superconducting 1.3GHz RF cavities
- 1.4 msec pulses at 10 Hz
- e- beam 1.35 mA nom. - 4.5 mA max
- 2016: construction / commissioning
- 2017: first user operation



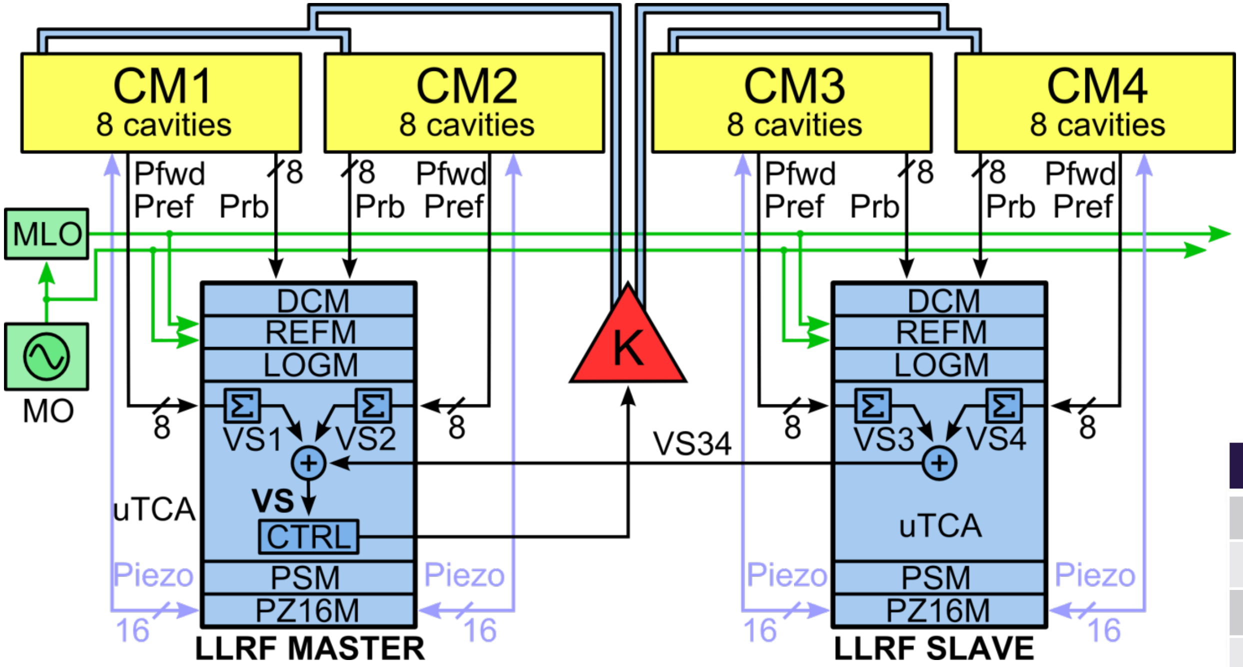
source: http://www.xfel.eu

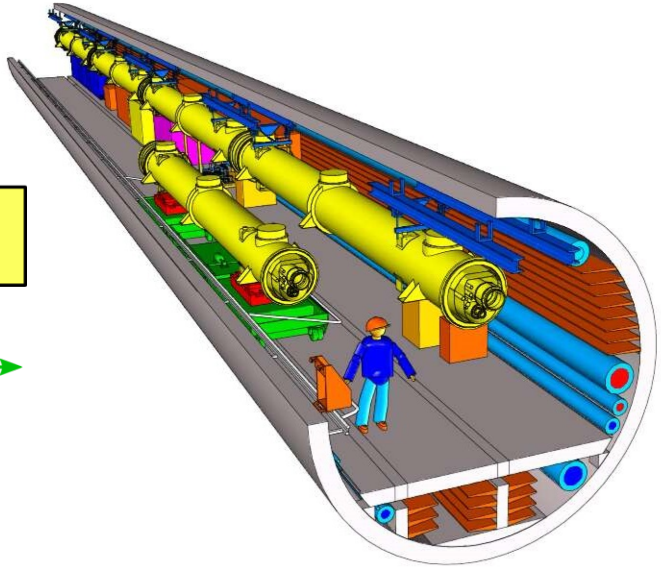


LLRF architecture for an RF station



RF station: semi-distributed LLRF system



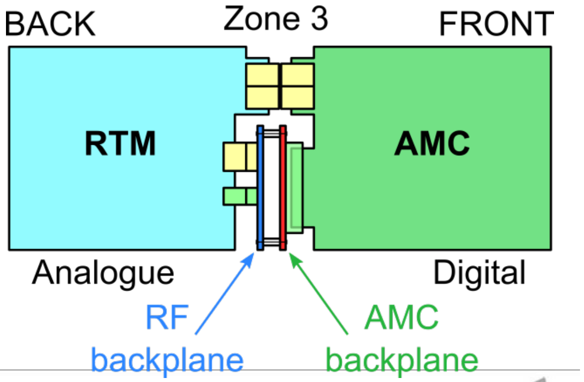


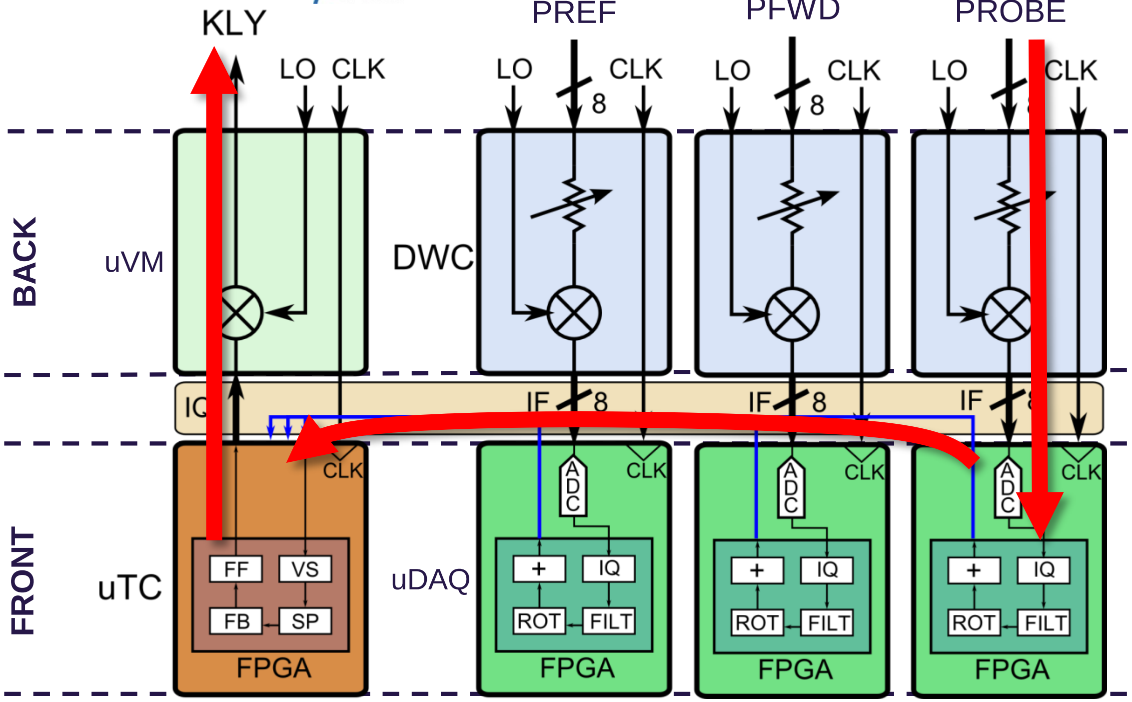
Section	Rack space	Redundancy
Gun, I1, 3H1	16U	Full
Linac 1	28U	Full
Linac 2	28U	No
Linac 3	28U	No

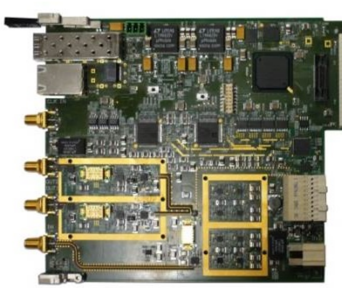
The MTCA.4 LLRF system

RF:1.3 GHz, IF 54 MHz, Fs: 81 MHz -> Vector-sum -> down-sampled to 9 MHz , 16-bit from DWC -> uTC

- AMC: Advanced Mezzanine Card
- RTM: Rear Transition Module
- 12 slots, hot swap
- Redundant power supply

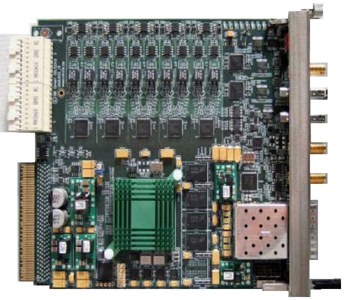





Vector Modulator (uVM)

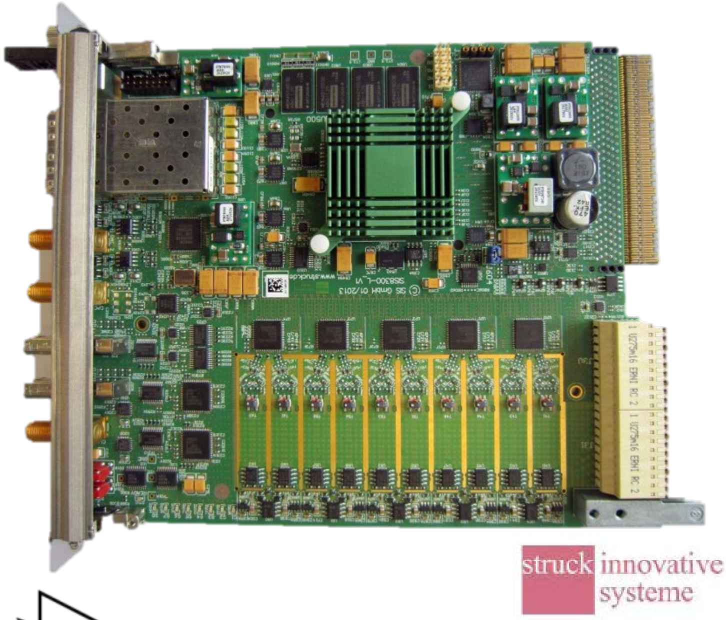

LLRF Controller (uTC)

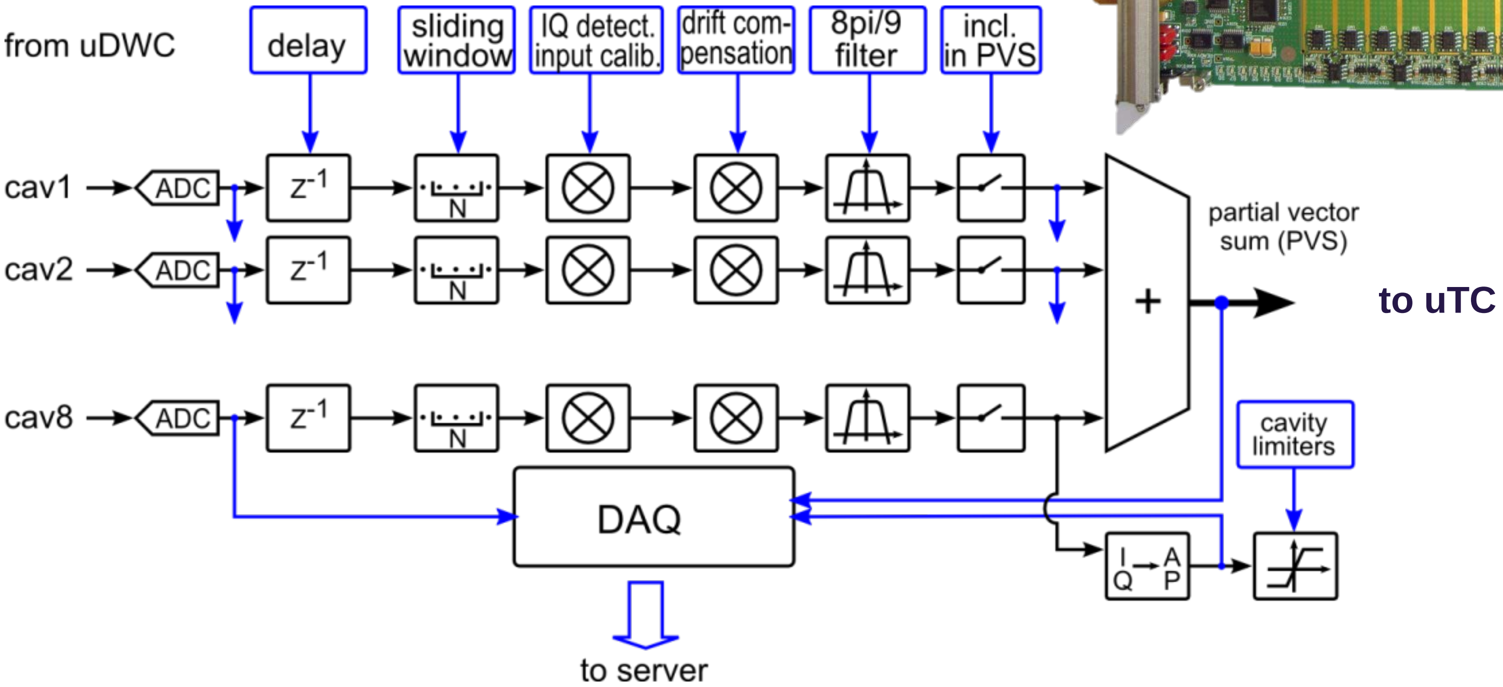

Down Converter (uDWC)


Digitizer (uADC)

MTCA.4 core LLRF modules

- MTCA.4 LLRF digitizer: **SIS8300L**
  - 10 ch. digitizer
  - Virtex VI
  - Application firmware block diagram:

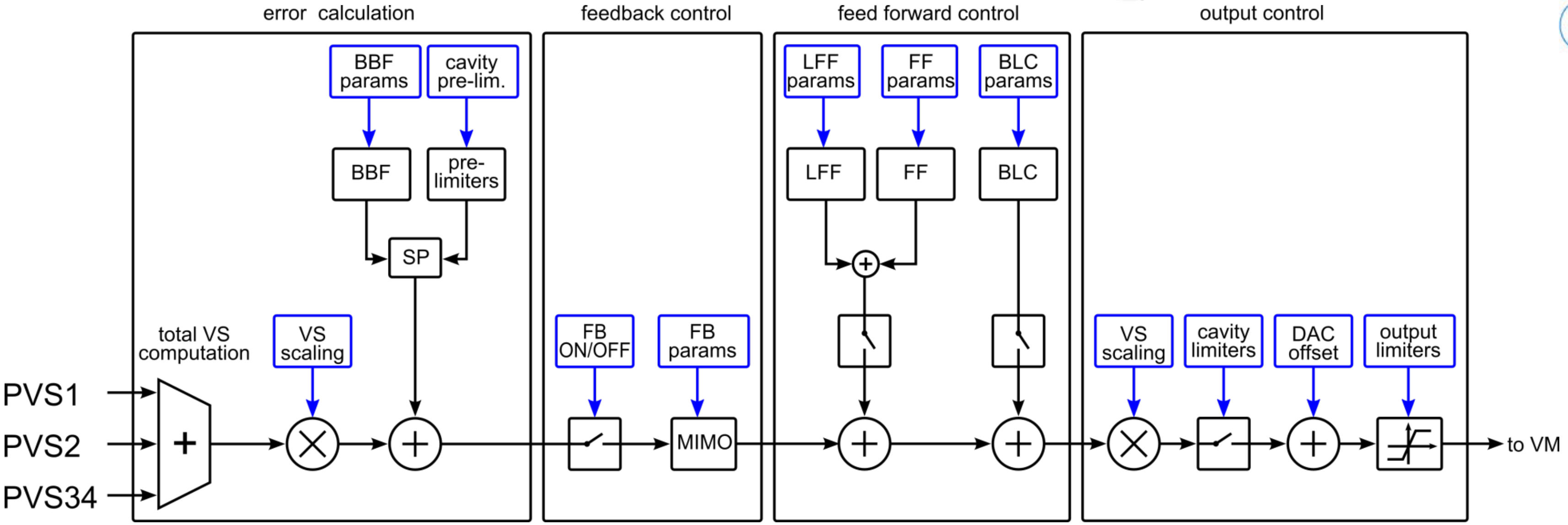




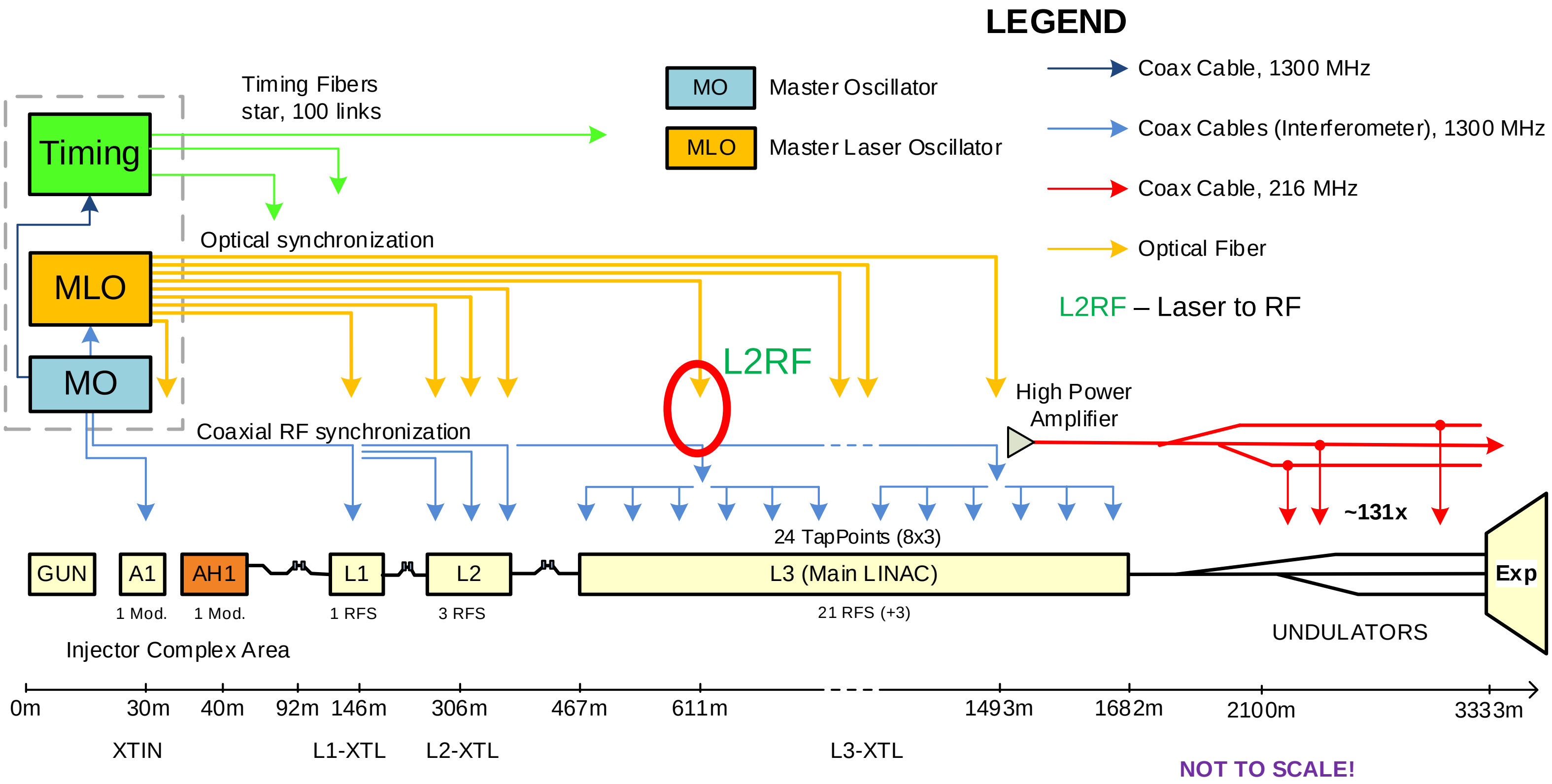
MTCA.4 core LLRF modules

- MTCA.4 LLRF controller: **uTC**
  - Current version 1.3 (Virtex V)
  - Version 2.0 (Kintex VII)
  - 0.5 Tbps processing power
  - 8x SPF+ on front panel
  - Application firmware block diagram:

uTC v.13



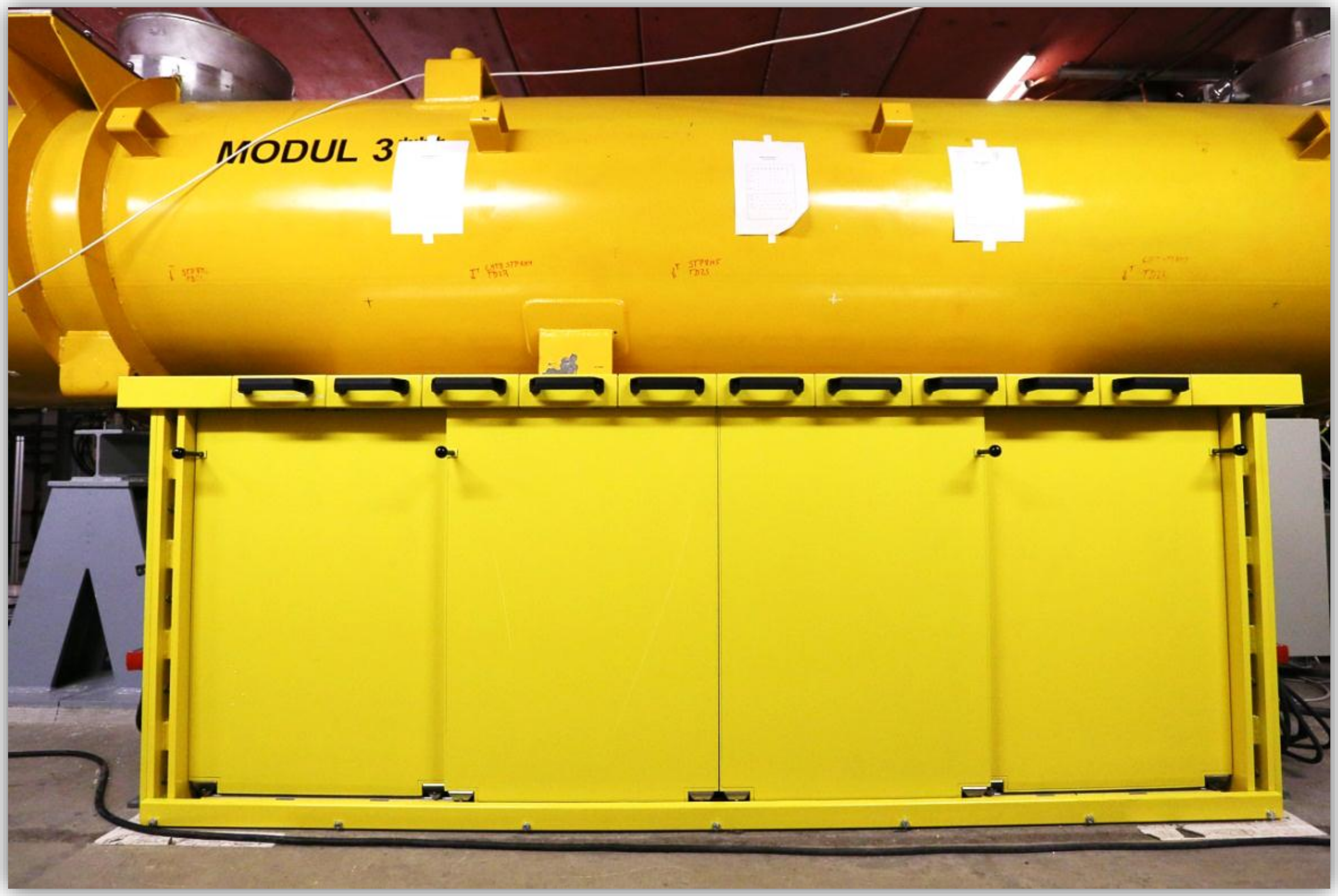
Overall Synchronization System Concept



- Three complementary systems (compromise between performance and cost)
  - Optical synchronization: sub-10fs (jitter, drift) performance, 12 links
  - RF Coaxial distribution: sub-100fs (jitter) and sub-1ps (drift) performance, interferometers, local distribution (44 links, ~260 reference outputs)
  - Timing system
- All systems phase synchronized to the RF Master Oscillator

RF reference stabilization

LLRF Installations (front end)



TUNNEL INSTALLATION 5/5

- Incoming inspection
- Device test
- Crate installation
- Rack installation
- Tunnel installation
  - a. Cabinet transport
  - b. RF cabling (outer rack)
  - c. Connections to mains, water and Ethernet, fibers
  - d. Commissioning checklist

In-tunnel LLRF installation for stable ambient temperature, and the shortest rf cable lengths.

Ready for warm commissioning

INSTALLATION: component inventory, testing, and installation tracking system 3/5

- > Incoming inspection
- > Device test
- > Crate installation
  - a. Selection of components from storage
  - b. Upload configuration in database (KDS)
  - c. Installation of firmware, servers
  - d. Basic functionality checks → checklist

LLRF LOGM-02.0003


History

66 items

http://DCM-03.0017

http://TMCB-21.0016

LLRF-REFM-OPT-500001

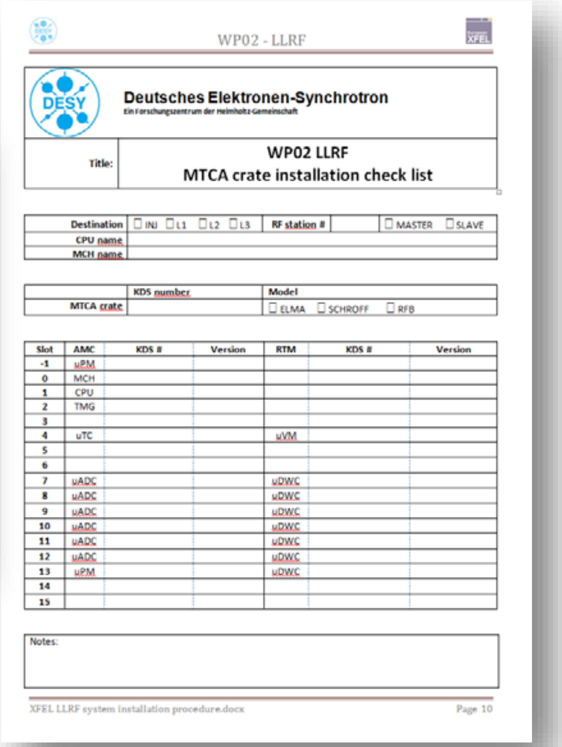
http://LOGM-02.0018

http://LOGM-02.0017

http://TMCB-21.0023

http://LLRF-mTCA-07.0071

http://uTCAPS-09.0147


WP02 - LLRF

Deutsches Elektronen-Synchrotron
Ein Forschungszentrum der Helmholtz-Gemeinschaft

Title: WP02 LLRF
MTCA crate installation check list

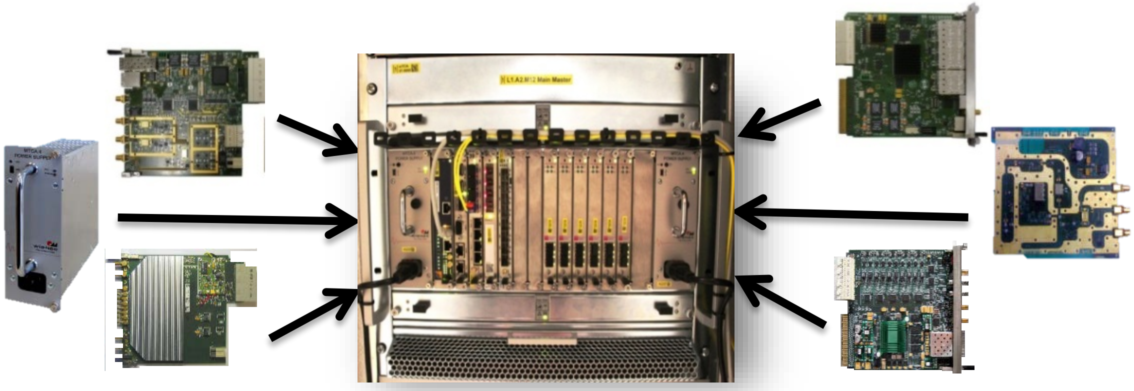
Destination	☐ INJ ☐ L1 ☐ L2 ☐ L3	RF station #		☐ MASTER ☐ SLAVE
CPU name				
MCH name				

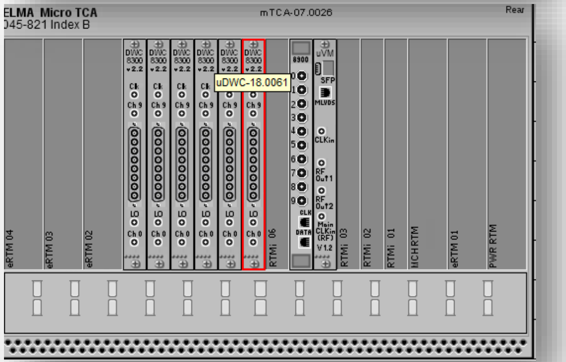
	KDS number	Model
MTCA crate		☐ ELMA ☐ SCHROFF ☐ RFB

Slot	AMC	KDS #	Version	RTM	KDS #	Version
-1	uPM					
0	MCH					
1	CPU					
2	TMG					
3						
4	uTC			uVM		
5						
6						
7	uADC			uDWC		
8	uADC			uDWC		
9	uADC			uDWC		
10	uADC			uDWC		
11	uADC			uDWC		
12	uADC			uDWC		
13	uPM			uDWC		
14						
15						

Notes:

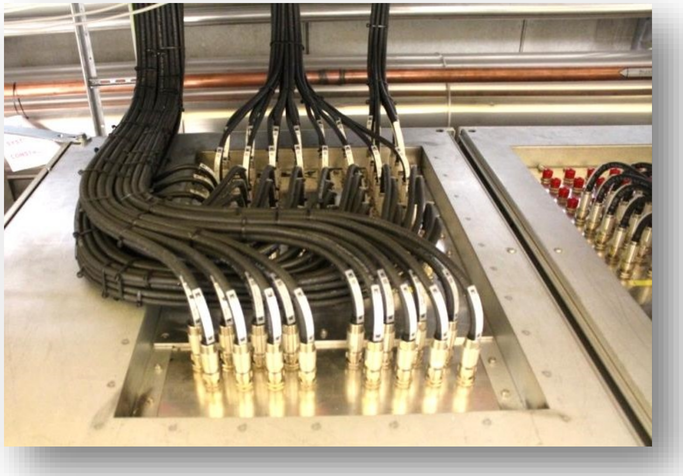
XFEL LLRF system installation procedure.docx Page 10





INSTALLATION: testing, assembly, and storage areas

Professional cabling (in & out)



MicroTCA Assembly Area (**MASSA**)

Rack Assembly and Test Area (**RATA**)

Storage

PEOPLE

THANK YOU

谢谢

Xièxiè

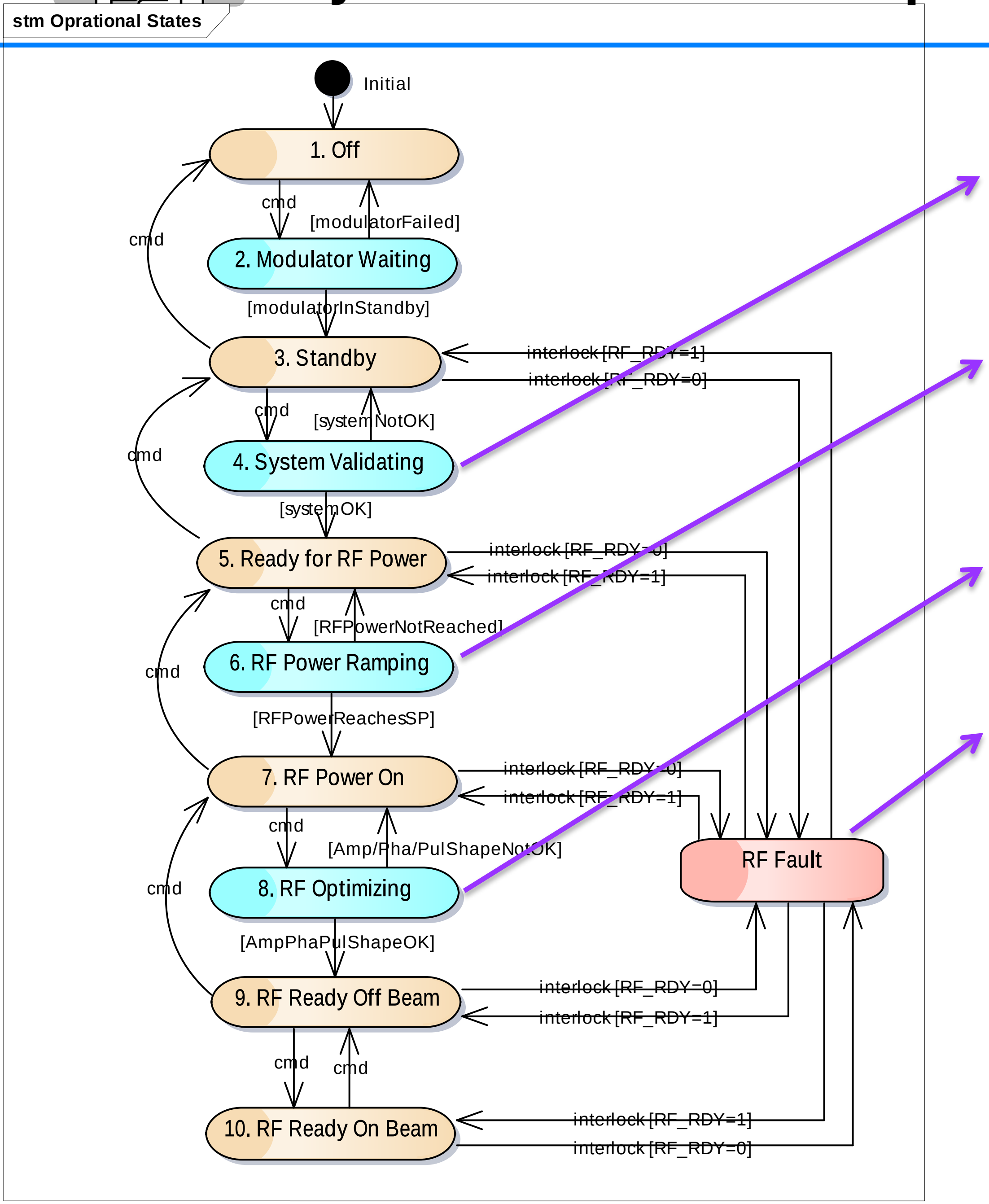

Wir schaffen Wissen – heute für morgen

Automation in LLRF System

Zheqiao Geng
Paul Scherrer Institut (PSI), Switzerland

For LLRF15 Workshop, Shanghai, China
Nov. 3, 2015

System Process Example 1: RF System Startup



Execute Jobs:
- Check system status
- Correct DAC offset

Execute Jobs:
- Determine and set klystron high voltage and drive

Execute Jobs:
- Calibrate loop gain and loop phase
- Adaptive feed forward

Execute Jobs:
- Recover from RF fault trips

Automatic parameter setting:
- Set modulator state
- Set interlock system mode
- Set RF switch on/off
- Set feedback on/off
- Set trigger delays

Job Example 2: Identify I/Q Imbalances

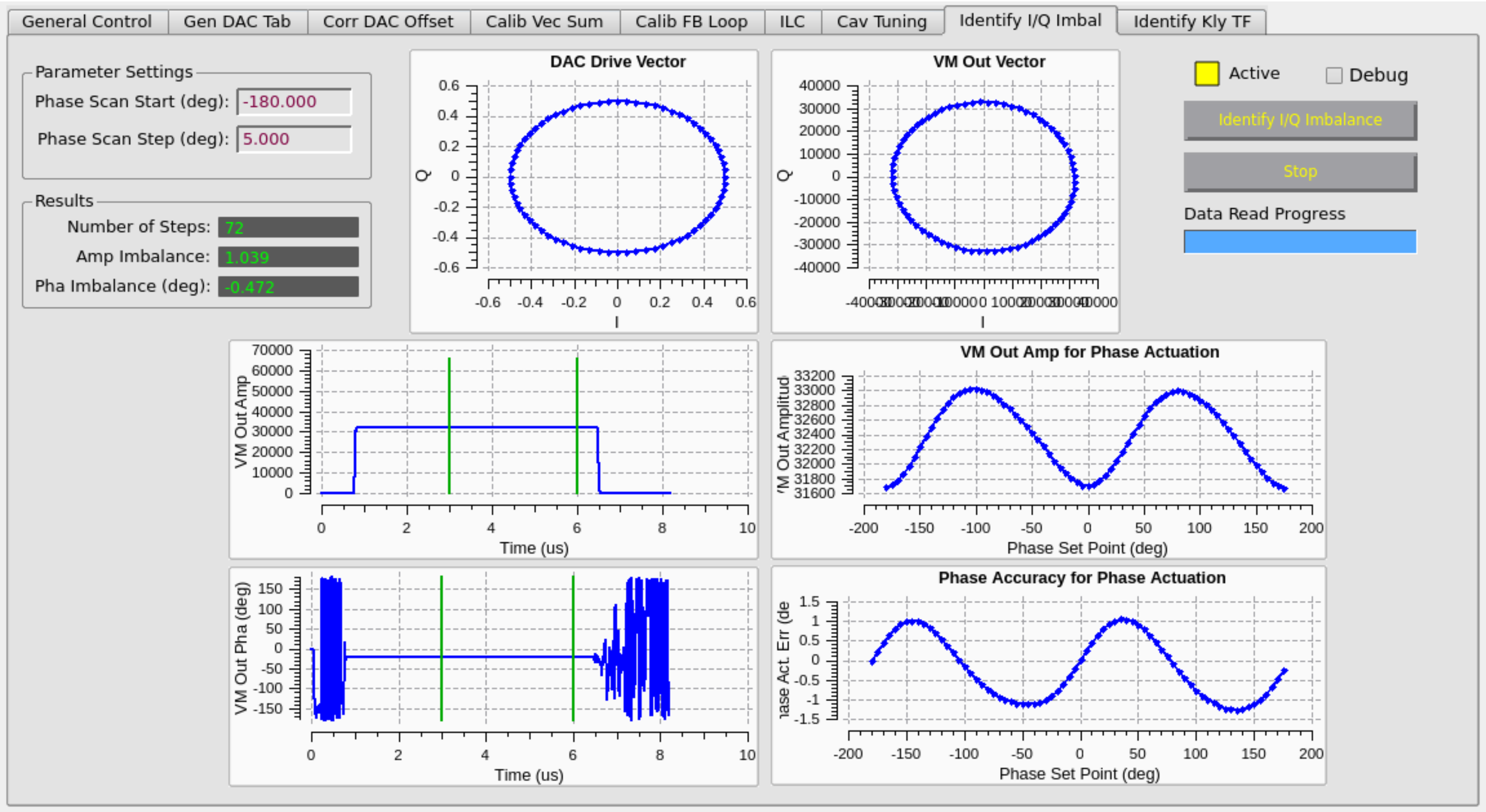
Goal: Qualify the amplitude and phase imbalances of vector modulator

Control: Started by user clicking a button

Inputs: I/Q averages of DAC output and vector modulator output for each scan step

Parameters: Phase scan start and step values

Outputs: I/Q imbalances, amplitude and phase actuation errors



Parameter Settings

Phase Scan Start (deg): -180.000

Phase Scan Step (deg): 5.000

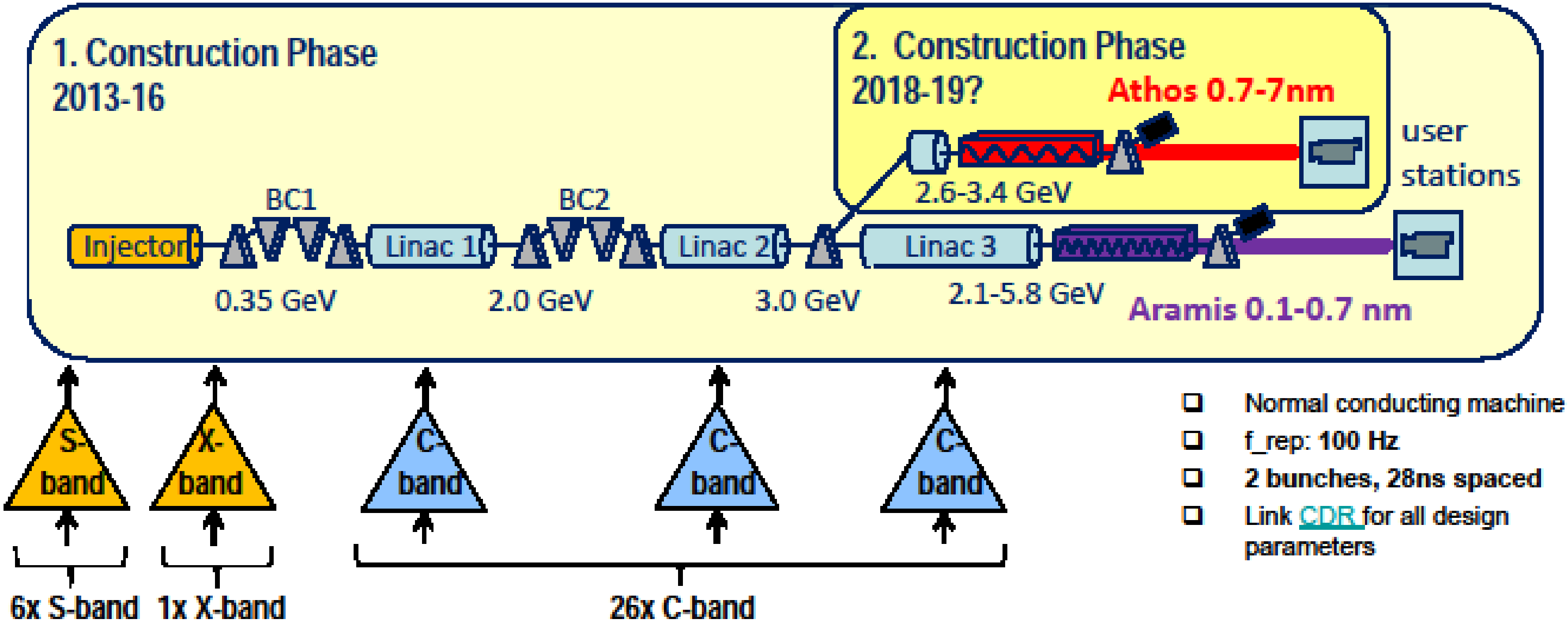
Results

Number of Steps: 72

Amp Imbalance: 1.039

Pha Imbalance (deg): -0.472

Machine Requirements & Performance



- ☐ Normal conducting machine
- ☐ f_rep: 100 Hz
- ☐ **2 bunches, 28ns spaced**
- ☐ Link CDR for all design parameters

SwissFEL performance calculations based on “expected performance” of RF stations:

	Pulse-to-pulse stab.
S-band Phase'	0.018° rms
S-band Voltage'	1.8e-4 rms
X-band Phase	0.072° rms
X-band Voltage	1.8e-4 rms
Linac 1/2/3 Phase	0.036° rms
Linac 1/2/3 Voltage	1.8e-4 rms

SwissFEL beam performance calculations:

electron beam parameters	**stability**
arrival time jitter	<20 fs
intensity jitter	<9%
energy stability	<1.6e-4

RF Tolerances – Subsystem Requirements

phase noise assumptions:

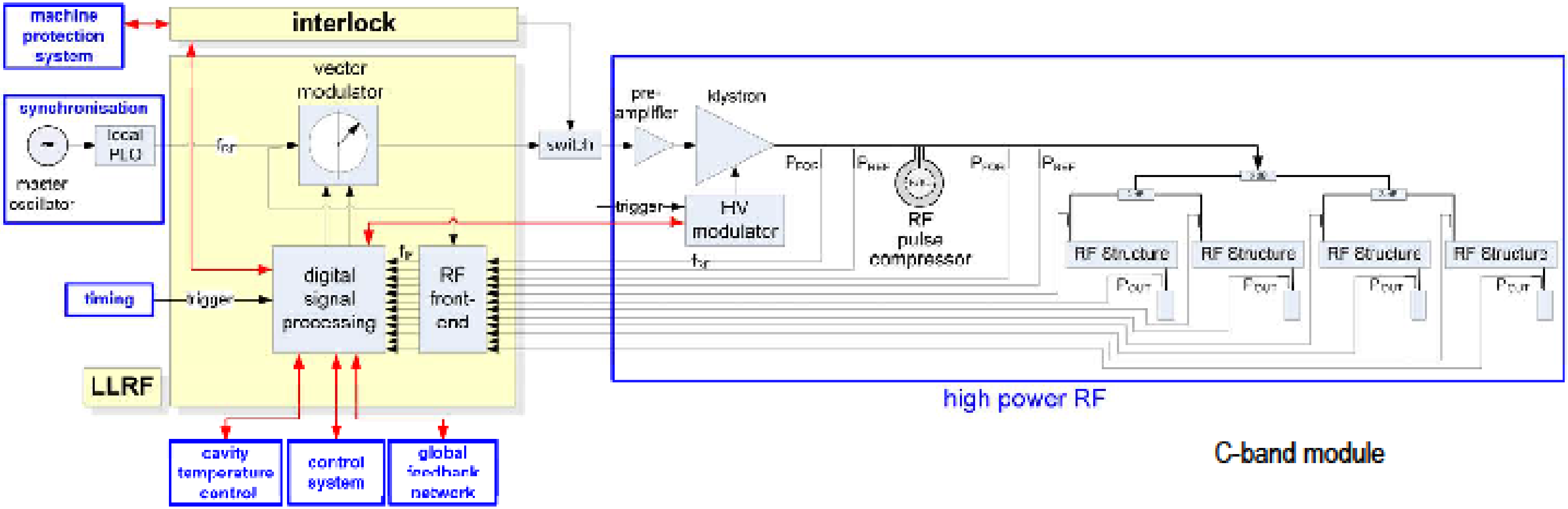
- uncorrelated contributions

$$\sigma_\phi = \sqrt{(\sigma_\phi)^2_{MO} + (\sigma_\phi)^2_{\text{vec. mod.}} + (\sigma_\phi)^2_{\text{pre-amp.}} + (\sigma_\phi)^2_{kly}}$$

- guaranteed max. phase noise contribution from master oscillator / phase locked oscillator (PLO) (10 Hz – 10 MHz)
- equal contributions (!?) of vector modulator, pre-amplifier, klystron (HV mod.) (10 Hz – 10 MHz)

Frequency [MHz]	**RF tolerance / phase noise (rms) [fs] / [°]**	**PLO guaranteed phase noise performance (rms) [fs] / [°]**	**max. added phase noise vec. mod. / pre-amplifier / klystron/HV mod. (rms) [fs] / [°]**
2998.8	17 fs / 0.018°	9.3 fs / 0.01°	8.3 fs / 0.009°
5712.0	17 fs / 0.036°	9.3 fs / 0.02°	8.3 fs / 0.017°
11995.2	17 fs / 0.072°	7 fs / 0.03°	8.8 fs / 0.038°

LLRF Overview / Stability Strategy



RF Stability Strategy:

- pulse-to-pulse stability:
  depends on MO/PLO, vector modulator, pre-amp., klystron/HV modulator, and structure temperature stability
- drift calibration (reference injection) to compensate drifts of LLRF measurement system
- RF pulse-to-pulse feedbacks (vector sum control)
- beam based feedbacks

Consequence:

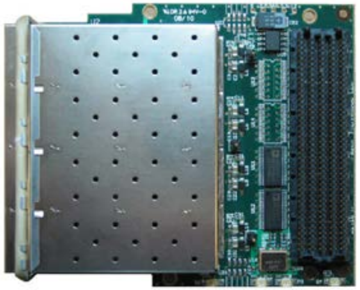
- **100 Hz repetition rate**:
  feedbacks can only suppress disturbances up to ~10 Hz
- **pulse-to-pulse / intra-pulse stability**:
  mainly determined by actuator chain (10 Hz-10 MHz)

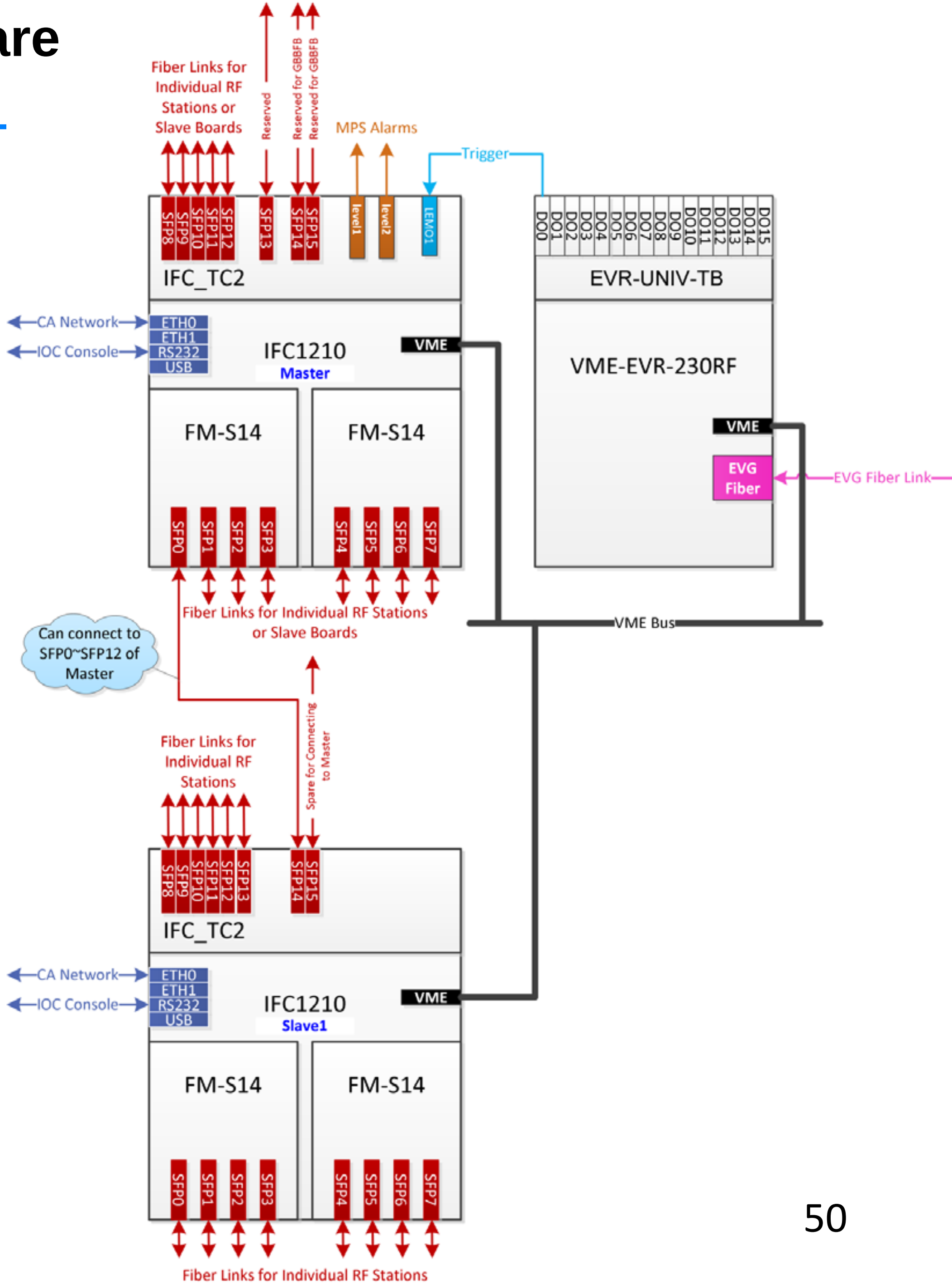
VRF Control Hardware Architecture

IFC1210

IFC_TC2

FM-S14

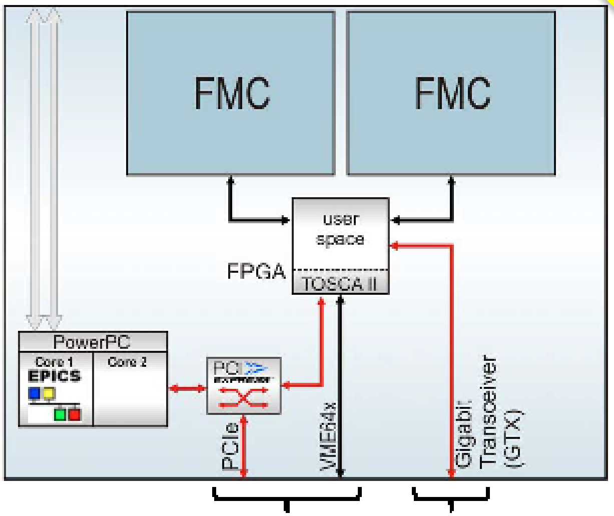




Digital Hardware: FMC carrier as modular unit

ctrl. sys.
interface

LAN
EPICS / EtherCAT



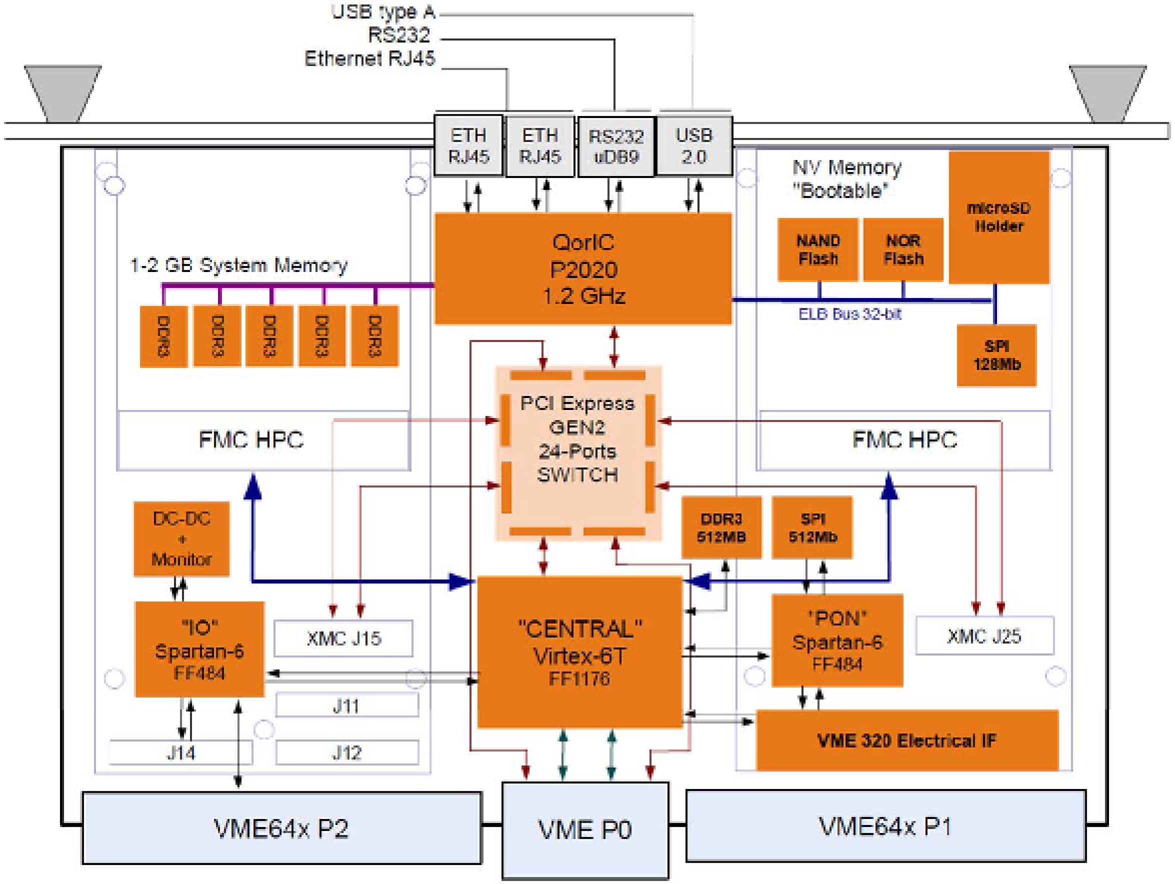
LLRF
board-to-board
communication

interface to
global feedback
network or
LLRF board-to-
board communication

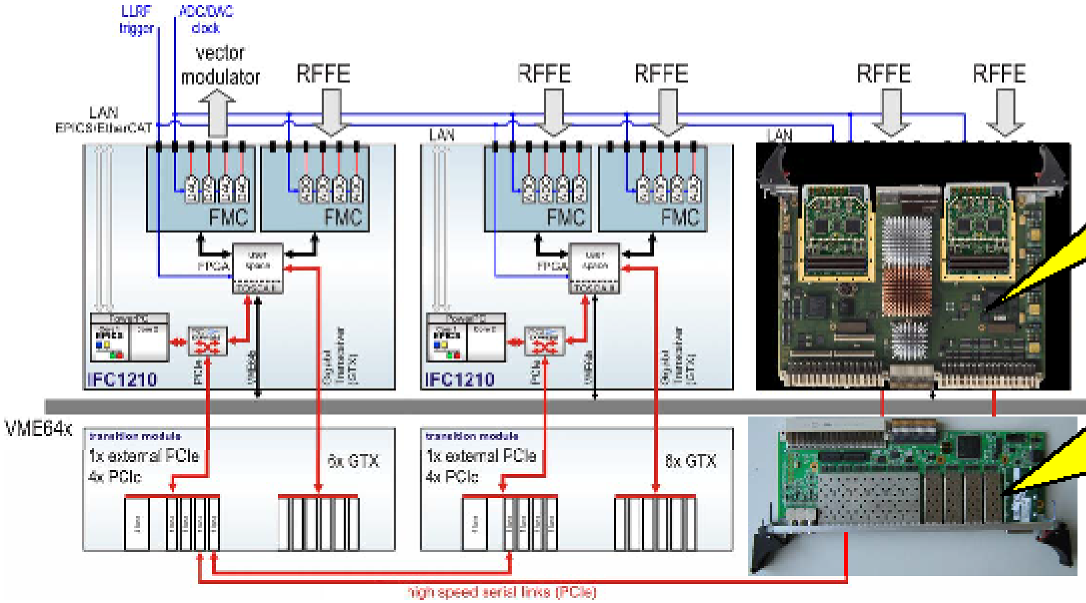
design issues:

- maximize synergy with other PSI facilities
  →VME64x processing board
  → joint venture with controls group
- digital processing board:
  collaboration with company IOxOS
  (board supplier, TOSCA II network on chip IP-core)
- ADC/DAC piggyback: 2x FMC
  (FPGA Mezzanine Card, ANSI/VITA 57.1 HPC (High Pin Count))
- Dual-Core P2020 CPU } RT-Linux
- fast data processing in one FPGA
  Virtex-6 130LXT (smallest)
- scalable system (PCIe, VME64x)

IFC_1210 Block Diagram



Digital Platform: Building Blocks Status



See poster #35:
FMC ADC/DAC experiences for SwissFEL

See poster #56:
PCIe and VME low latency data transfer in scalable LLRF systems

status:

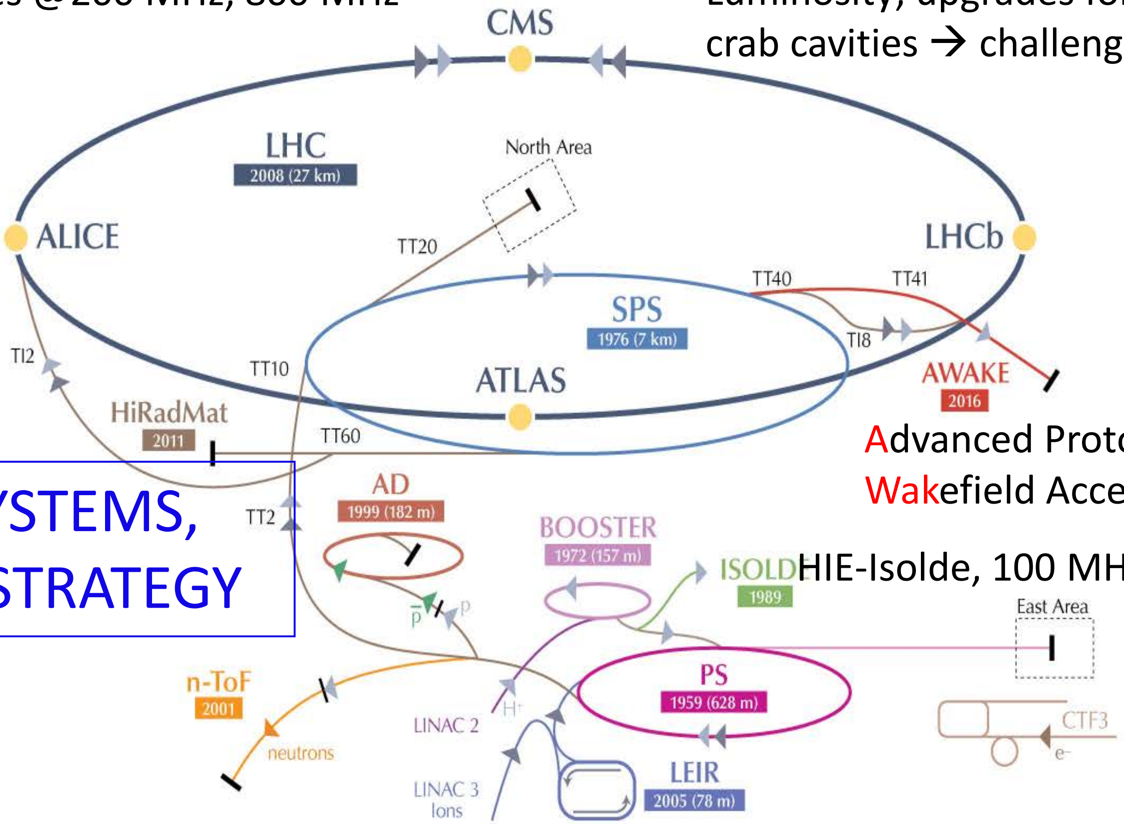
- IFC1210 boards developed in collaboration with company IOxOS SA is commercially available
  - Several FMC ADC and DAC mezzanines tested
  - Inhouse developed transition module prototype available
  - PREEMPT_RT Linux + EPICS environment was set up together with Controls group, based on Denx.de ELDK (Embedded Linux Development Kit)

Recent LLRF Developments at CERN and New Projects

Wolfgang Hofle, on behalf of BE-RF-FB and BE-RF-CS Section

SPS: major LLRF and RF upgrades under way: 4→ 6 cavities @200 MHz, 800 MHz system upgrade

LHC 2015: 6.5 TeV reached, half nominal Luminosity; upgrades for HighLumi: crab cavities → challenging LLRF



Advanced Proton Driven Plasma Wakefield Acceleration Experiment

HIE-Isolde, 100 MHz SRF with DLLRF

TOO MANY SYSTEMS, NEED A LLRF STRATEGY

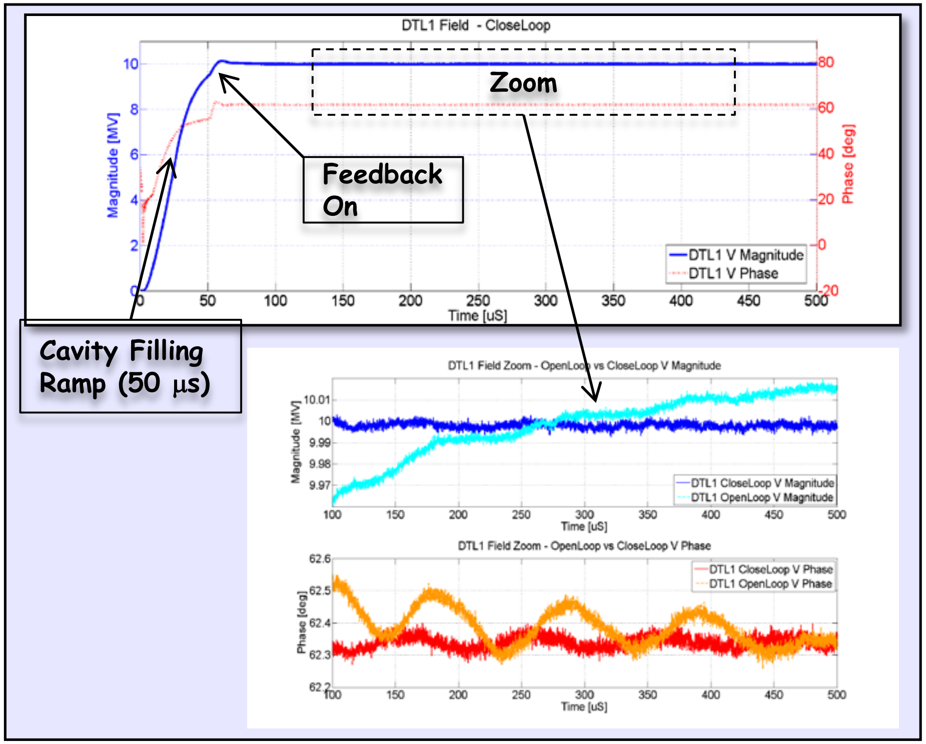
Roll-out of DLLRF: PSB, LEIR, AD, ELENA;
new Finemet system for PSB
PS: Coupled Bunch feedback with Finemet cavities

LINAC4: staged commissioning:
Connection to PSB: 2018/2019

Summary

- **CERN** Focus is on Injector Upgrades during the coming years: many LLRF challenges
- New Projects: AWAKE, HIE-Isolde, ELENA
- Make or buy ? → make
- **Platform ? → VME**
- Solution for data recording (ObsBox)

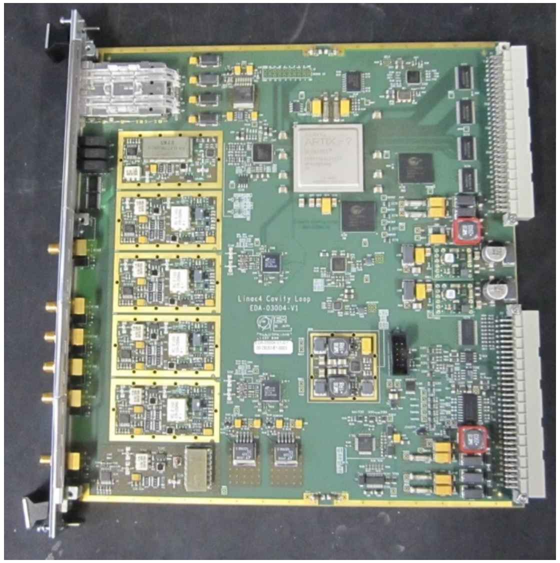
Linac4 LLRF



Zoom

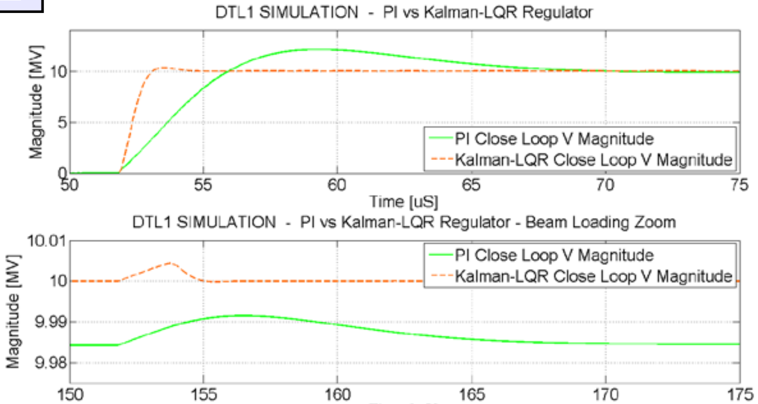
Feedback On

Cavity Filling Ramp (50 µs)



LHC LLRF type VME platform

- Installed on RFQ, Bunching cavities 2-3, DTL1
- Observed ripple: 0.06% voltage, 0.05 deg, without beam
- Transient beam loading: 1% voltage with 8 mA beam
- Pulse to pulse reproducibility: +- 0.05 deg

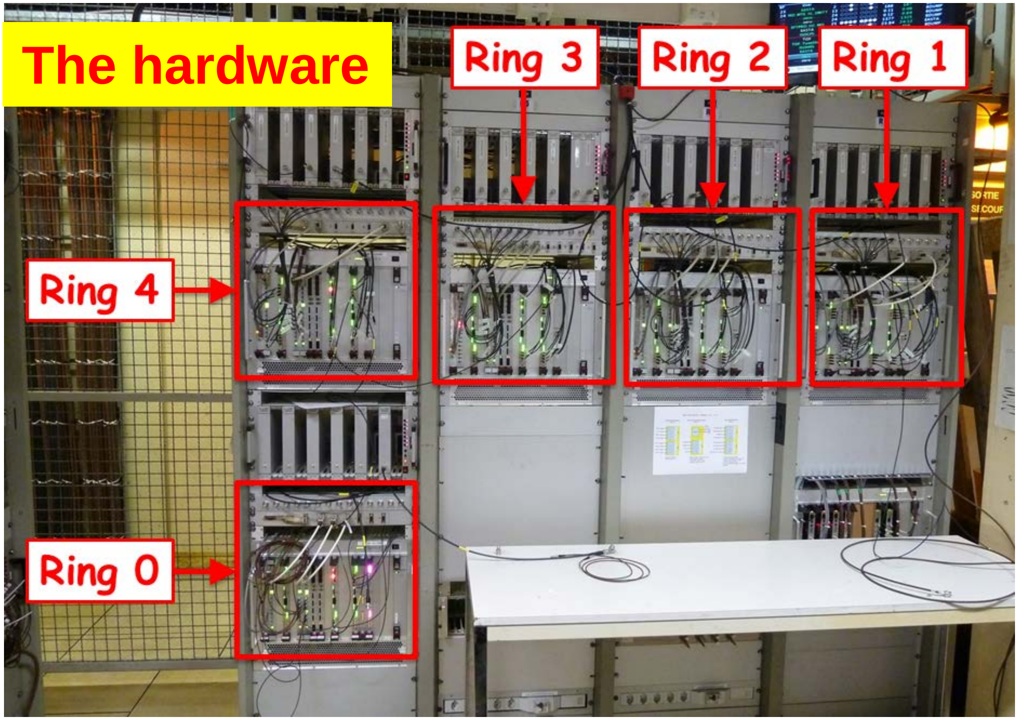


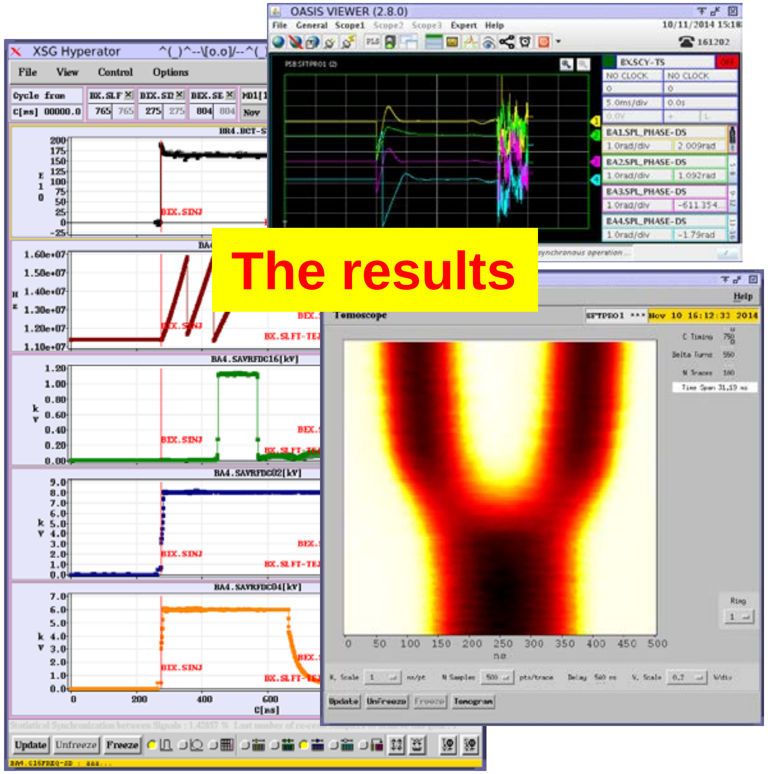
J. Noirjean, J. Galindo, D. Stellfeld, G. Hagmann, P. Baudrenghien , M. Ojeda

See Talk by J. Galindo

New PSB Digital LLRF system

- Four operational Digital LLRF systems (Ring 1 to 4) + development ring (ring 0) which operates Ring 4 beams in PPM with Ring 4 DLLRF.
- Big RF group investment (manpower) for Meyrin machines.
- PSB operational LLRF after LS1
- Mandatory for PSB Finemet R&D campaign (2014-2015).
- Will be deployed in LEIR in 2015 and in ELENA (Anti-proton deceleration) in 2016.

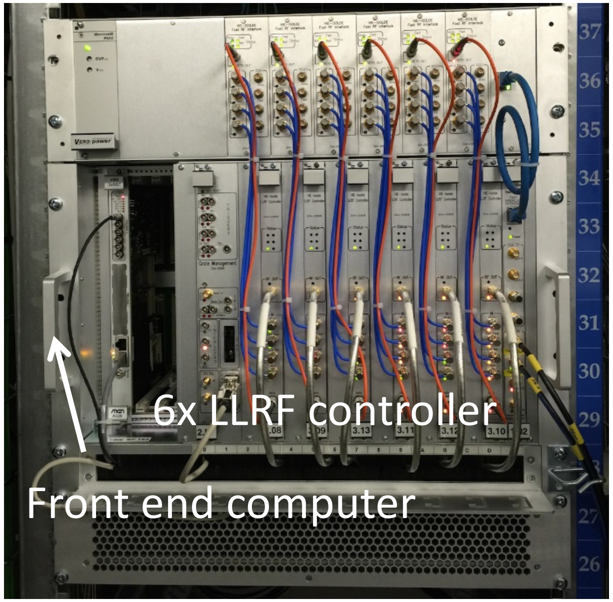




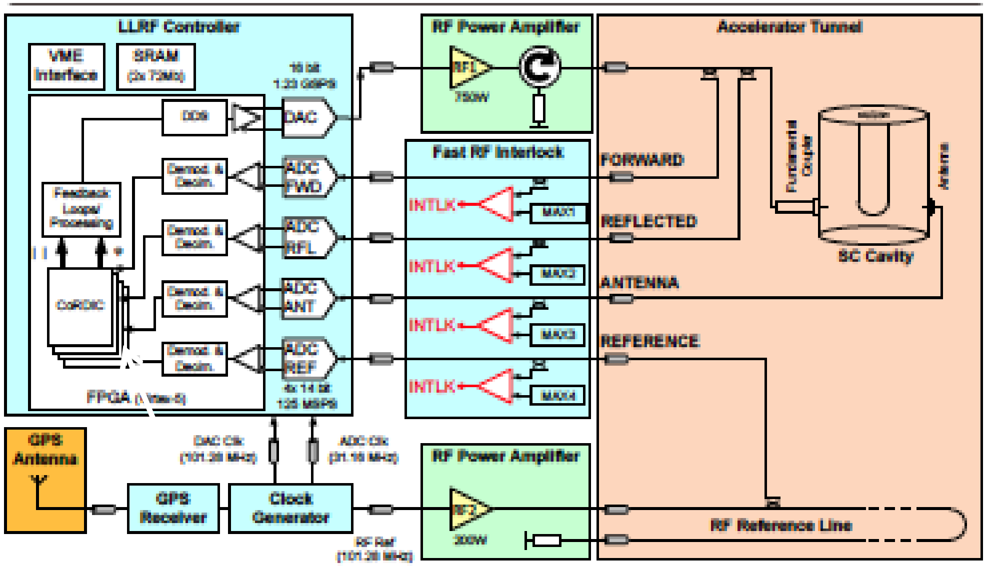
Talks by M.E. Angoletta and J. Molendijk

HIE-Isolde DLLRF (Valuch et.al)

- radioative ions post acceleration (low intensity)
- only 16 meters long, final stage: 32 superconducting cavities (100 MHz)
- challenge to control the cavity, only few Hz bandwidth
- LLRF entirely digital, direct RF sampling, direct RF generation
- 32 solid state RF amplifiers, 700 W each
- commissioning started in summer 2015 (1 RF module with 5 cavities)
- first Beam successfully accelerated last month



LHC type VME Platform

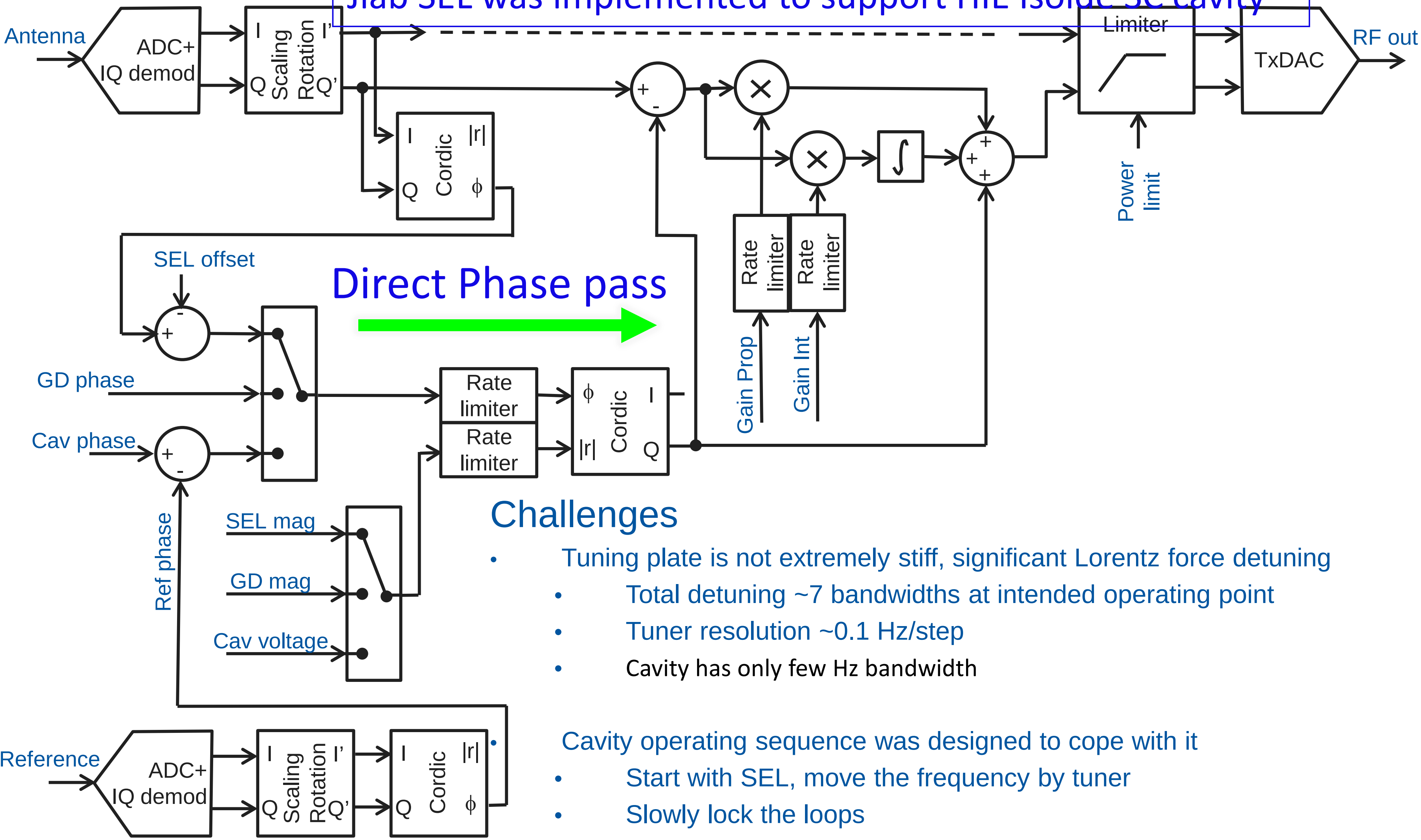


D. Valuch , M. Elias, M. Mician

Poster (M. Mician) and Talk (D. Valuch)

HIE Isolde LLRF controller   Simplified function block diagram

Jlab SEL was implemented to support HIE Isolde SC cavity



Direct Phase pass

Challenges

- Tuning plate is not extremely stiff, significant Lorentz force detuning
  - Total detuning ~7 bandwidths at intended operating point
  - Tuner resolution ~0.1 Hz/step
  - Cavity has only few Hz bandwidth

Cavity operating sequence was designed to cope with it

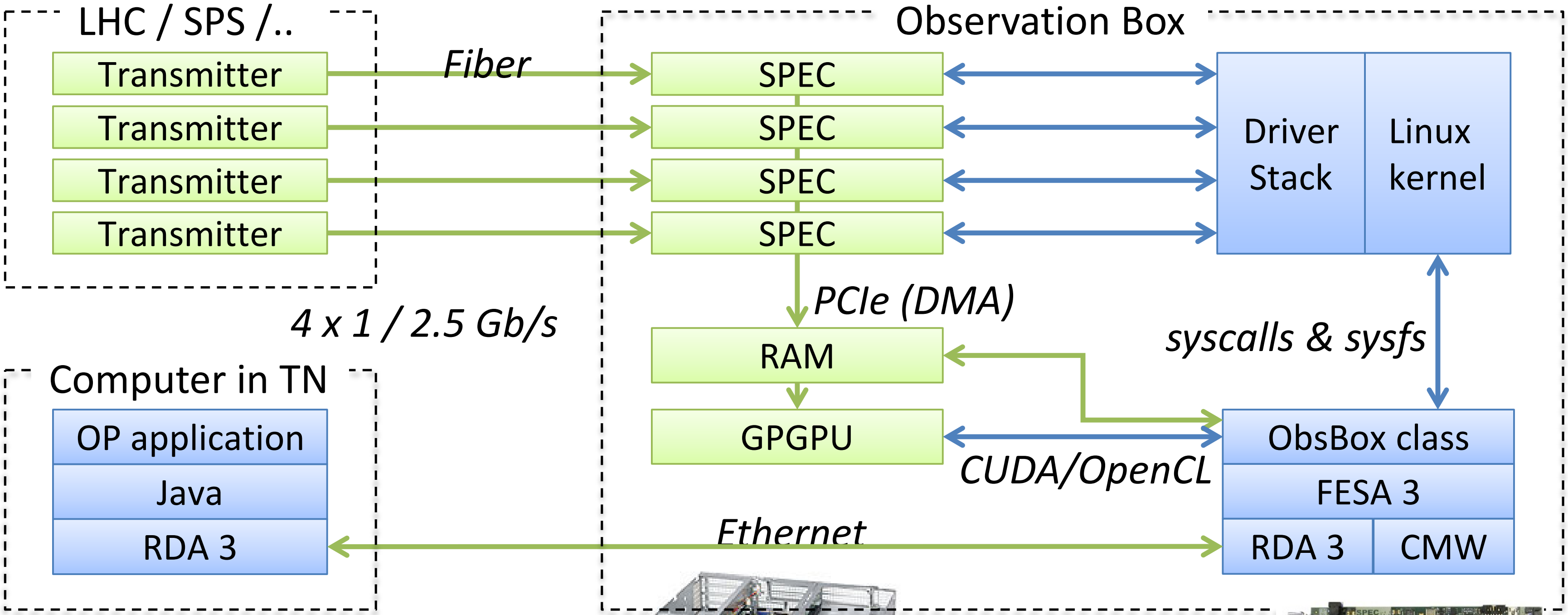
- Start with SEL, move the frequency by tuner
- Slowly lock the loops

Data recording: Observation Box

Objective: Overcome limitation of VME for data transfer to fully explore diagnostic potential of the digital LLRF systems

A. Butterworth, M. Ojeda et al.
ICALEPCS'15, WEPGF062

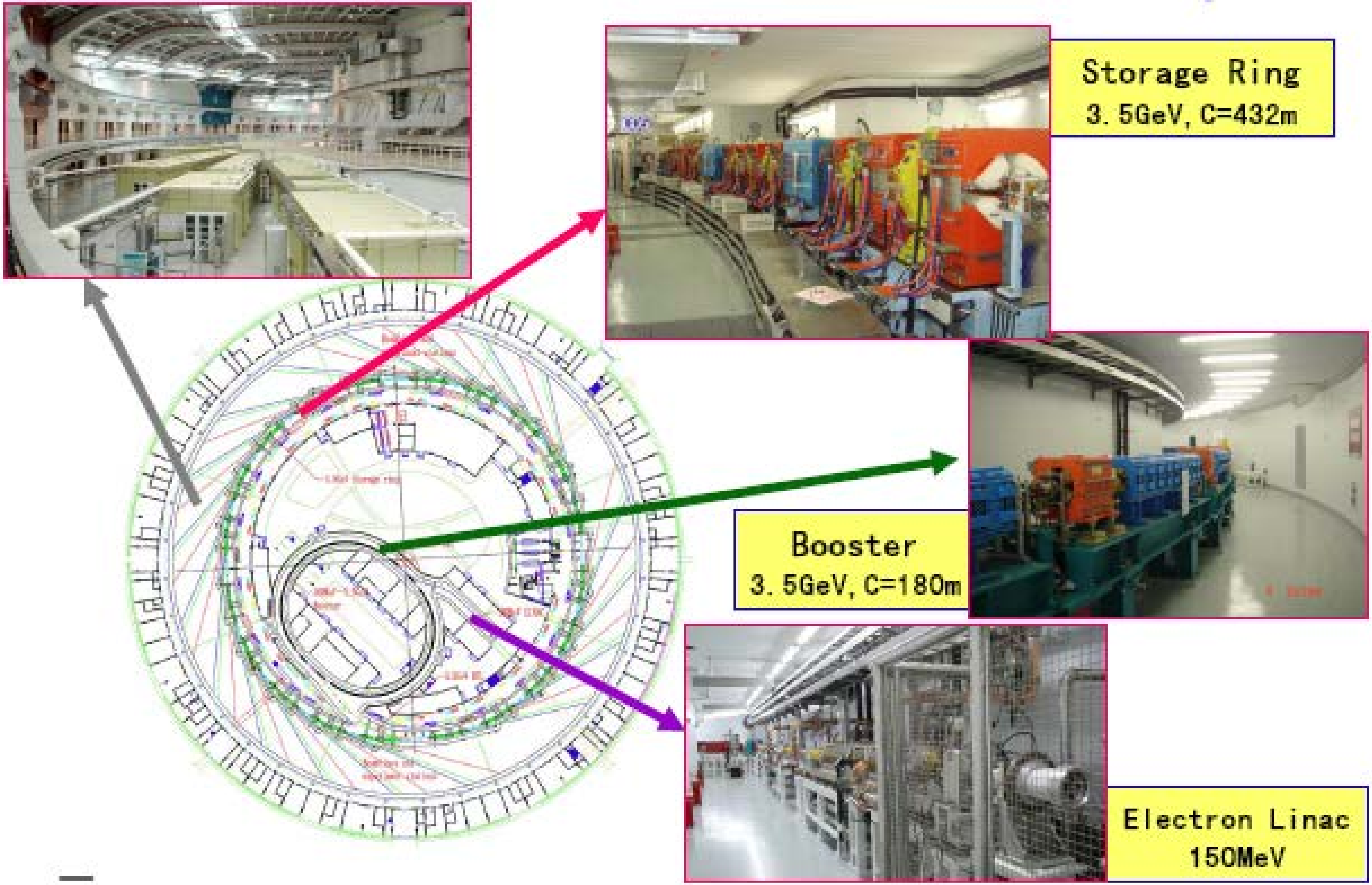
VME modules with integrated Transmitters



SuperMicro's SuperServer
6028U-TR4+

Simple PCIe FMC carrier (SPEC)
RF specific firm ware: T. Levens

SSRF ("Shanghai Light Source")

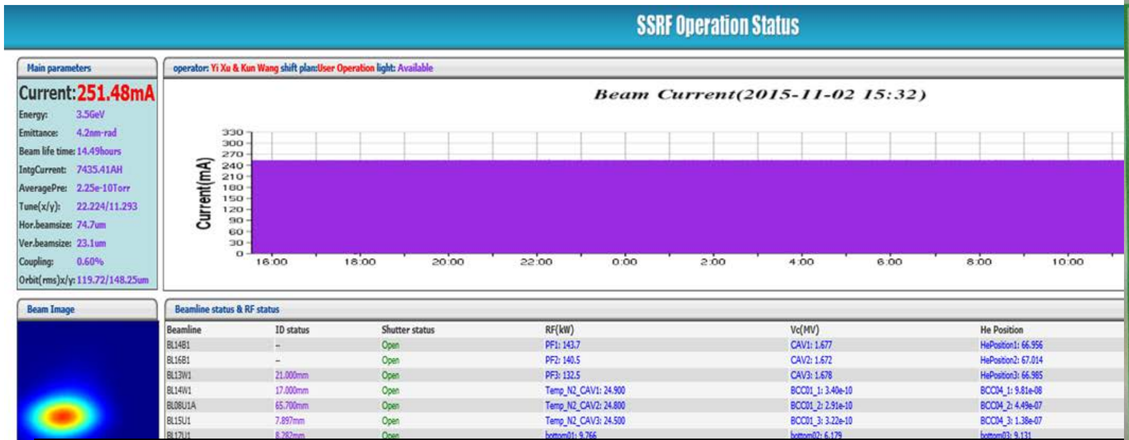


Storage Ring
3.5GeV, C=432m

Booster
3.5GeV, C=180m

Electron Linac
150MeV

SSRF RF system of Storage


SSRF Operation Status

Main parameters

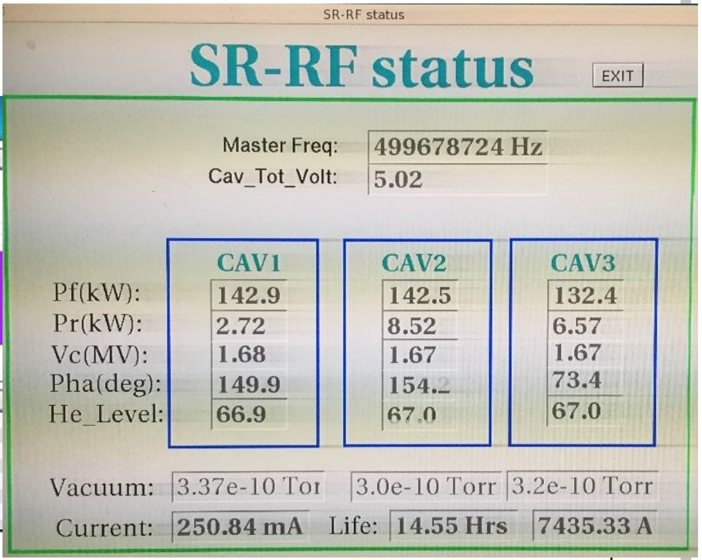
Current: 251.48mA
Energy: 3.5GeV
Emittance: 4.2nm-rad
Beam life time: 14.49hours
IntgCurrent: 7435.41AH
AveragePre: 2.25e-10Torr
Tune(x/y): 22.224/11.293
Hor.beamsize: 74.7um
Ver.beamsize: 23.1um
Coupling: 0.60%
Orbit(rms)x/y: 119.72/148.25um

operator: Yi Xu & Kun Wang shift plan:User Operation light: Available

Beam Current(2015-11-02 15:32)

Beamline status & RF status

Beamline	ID status	Shutter status	RF(kW)	Vc(MV)	He Position
BL14B1	–	Open	PF1: 143.7	CAV1: 1.677	HePosition1: 66.956
BL16B1	–	Open	PF2: 140.5	CAV2: 1.672	HePosition2: 67.014
BL13W1	21.000mm	Open	PF3: 132.5	CAV3: 1.678	HePosition3: 66.985
BL14W1	17.000mm	Open	Temp_N2_CAV1: 24.900	BCC01_1: 3.40e-10	BCC04_1: 9.81e-08
BL08U1A	65.700mm	Open	Temp_N2_CAV2: 24.800	BCC01_2: 2.91e-10	BCC04_2: 4.49e-07
BL15U1	7.897mm	Open	Temp_N2_CAV3: 24.500	BCC01_3: 3.22e-10	BCC04_3: 1.38e-07
BL17U1	8.282mm	Open	bottom01: 9.766	bottom02: 6.179	bottom03: 9.131

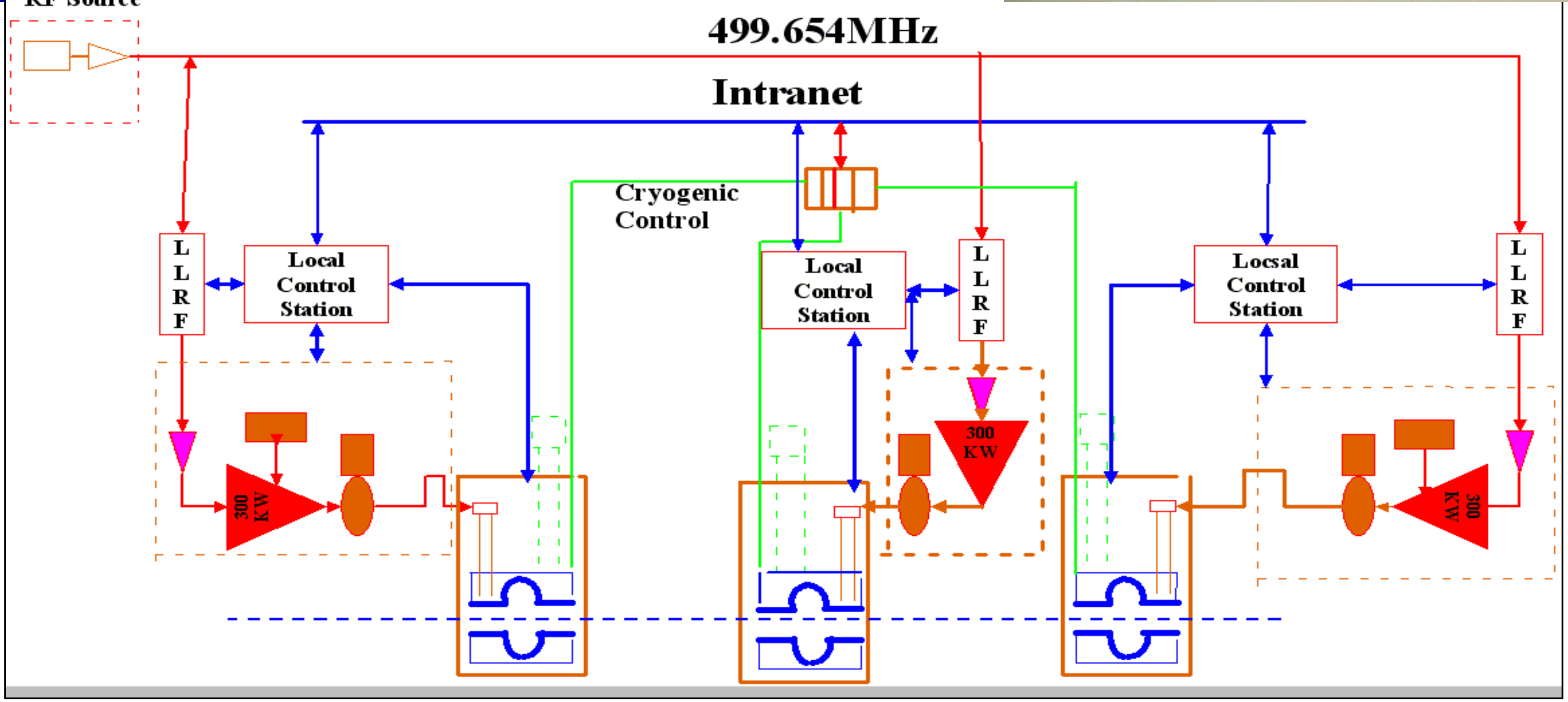

SR-RF status

SR-RF status

Master Freq: 499678724 Hz
Cav_Tot_Volt: 5.02

	CAV1	CAV2	CAV3
Pf(kW):	142.9	142.5	132.4
Pr(kW):	2.72	8.52	6.57
Vc(MV):	1.68	1.67	1.67
Pha(deg):	149.9	154.2	73.4
He_Level:	66.9	67.0	67.0

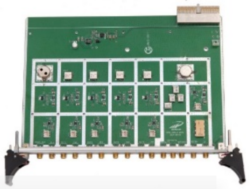
Vacuum: 3.37e-10 Tor 3.0e-10 Torr 3.2e-10 Torr
Current: 250.84 mA Life: 14.55 Hrs 7435.33 A



The third generation LLRF used in the storage ring

cPCI Controller Box

DSP board



Front-end board

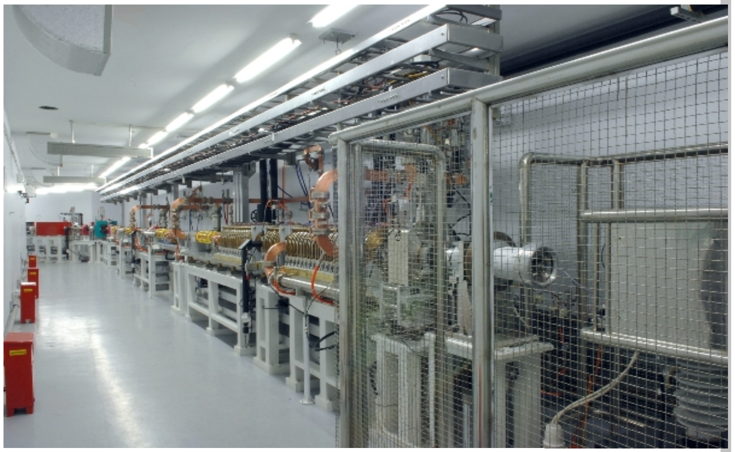
- Board with CPCI package，
- 4 Channel ADC.125MSPS
- 2 Channel DAC，275MSPS
- 4 down-converter and one up-converter channel
- Linear is better than 60dB, isolate is better than 70dB
- CPCI communication.
- EPICS interface

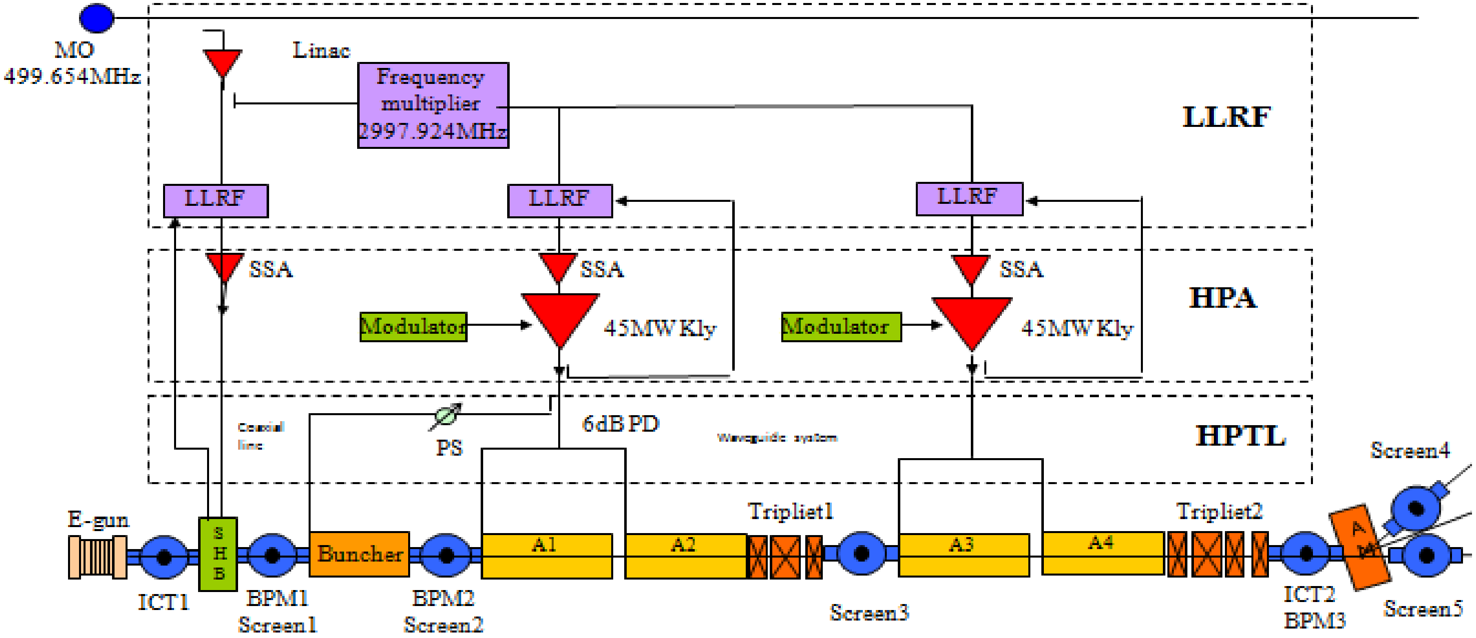
The third generation replaced the first one used in RF station II and III of Storage ring in 2015.2

Linac layout of SSRF

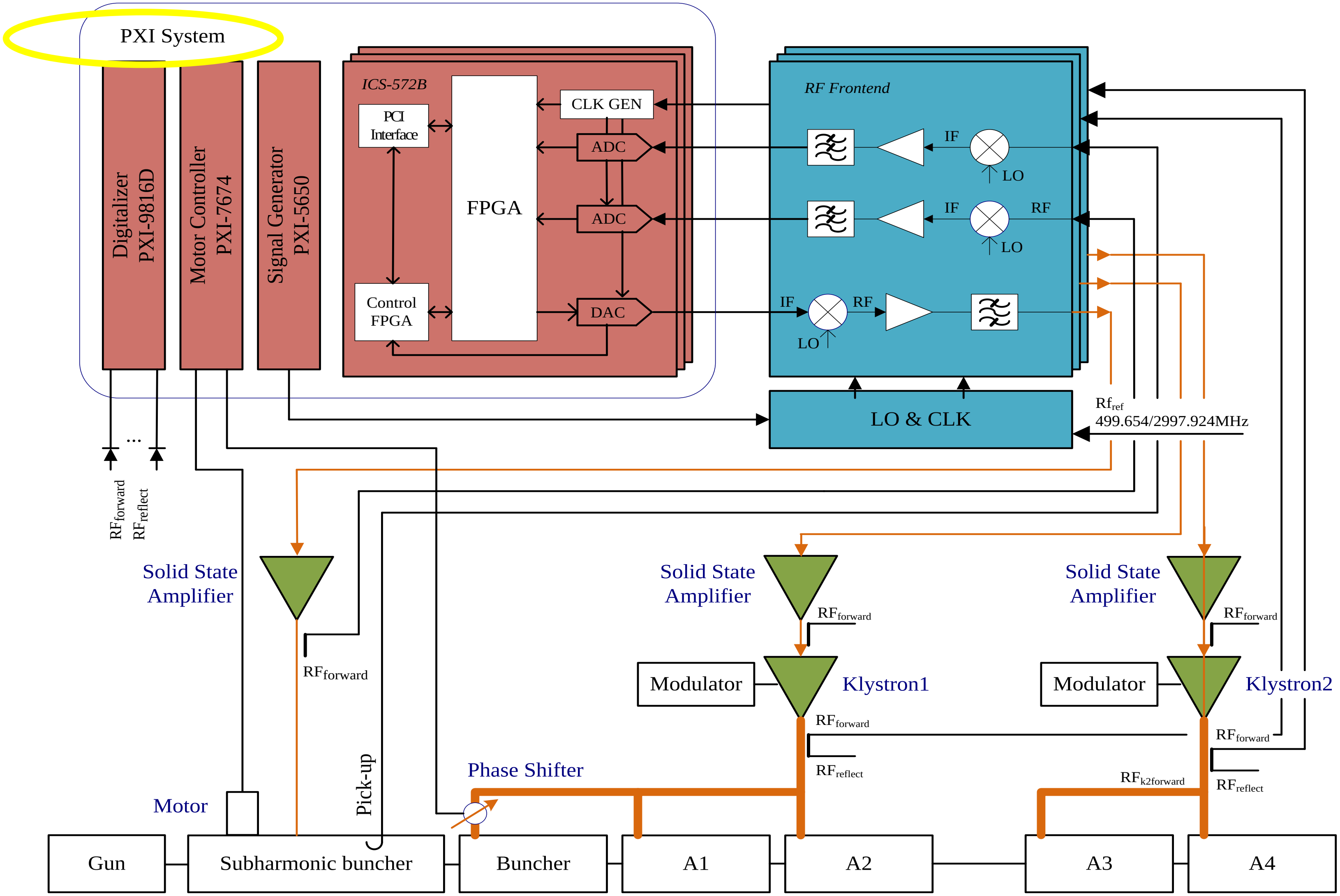
Yubin Zhao, RF Group and Linac Group

LLRF in PXI crate (NI?)





Linac LLRF of SSRF



500MHz sub-buncher

6x rf=2.99GHz AS rf

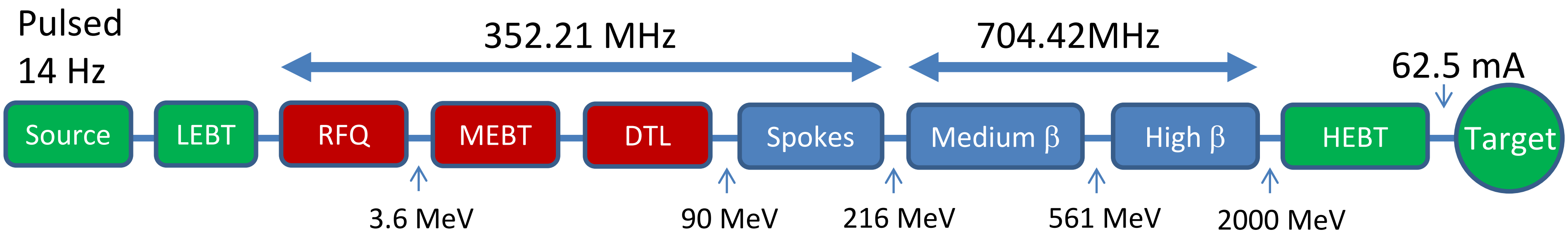
LUND
UNIVERSITY

Overview and System Design for ESS LLRF Systems

ANDERS J JOHANSSON, LUND UNIVERSITY, SWEDEN

5 MW Neutron source
2 GeV proton linac
Pulsed at 14 Hz, 2.86 ms long pulses.
Rotating tungsten target

ESS Accelerator



Pulsed
14 Hz

352.21 MHz

704.42MHz

62.5 mA

Source

LEBT

RFQ

MEBT

DTL

Spokes

Medium β

High β

HEBT

Target

3.6 MeV

90 MeV

216 MeV

561 MeV

2000 MeV

- 1 RFQ
- 3 Pillbox buncher cavities in MEBT.
- 5 Drift Tube Linac sections.
- 26 Superconducting spoke cavities.
- 36 Superconducting medium-β cavities.
- 84 Superconducting high-β cavities.

ESS RF power amplifiers

- One power amplifier per accelerating cavity
  - 2.8 MW Klystron for RFQ
  - 30 kW Solid State for Buncher
  - 2.8 MW Klystron for DTL
  - 2x200kW Tetrode combined for Spoke
  - 1.5 MW Klystron for Medium- Beta Elliptical
  - 1.2 MW IOT for High Beta Elliptical

Field Stability

Current requirements for regulation accuracy of the cavity field.

- RFQ

  +/- 0.2 % RMS amplitude

  +/- 0.2 º RMS*

- Normal Conducting

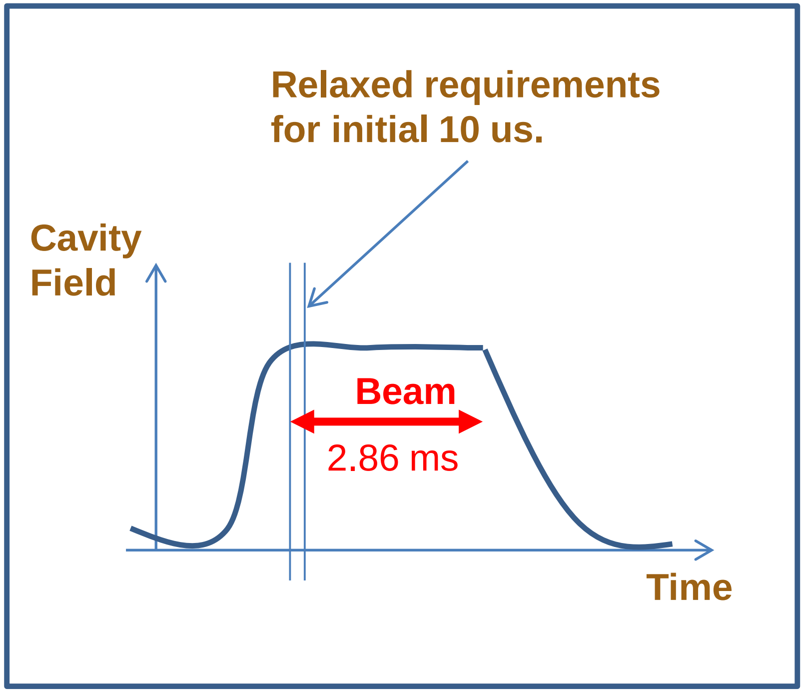
  +/- 0.2 % RMS amplitude

  +/- 0.2 º RMS

- Super Conducting

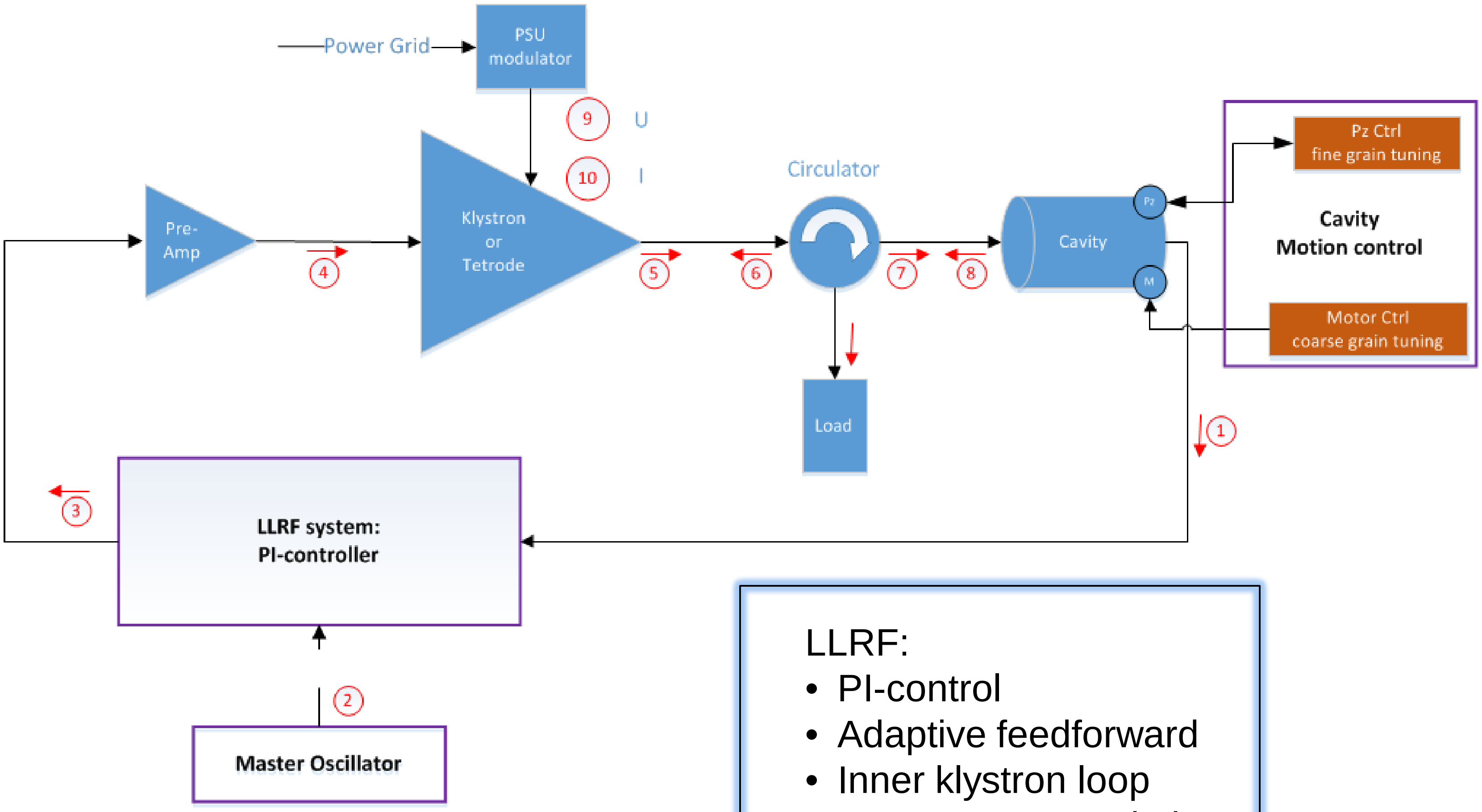
  +/- 0.1 % RMS amplitude

  +/- 0.1 º RMS



*Relative the phase reference line. All other phase requirements relative the beam.

RF Cell



LLRF:

- PI-control
- Adaptive feedforward
- Inner klystron loop
- Beam current variation compensation

Platform: MTCA.4

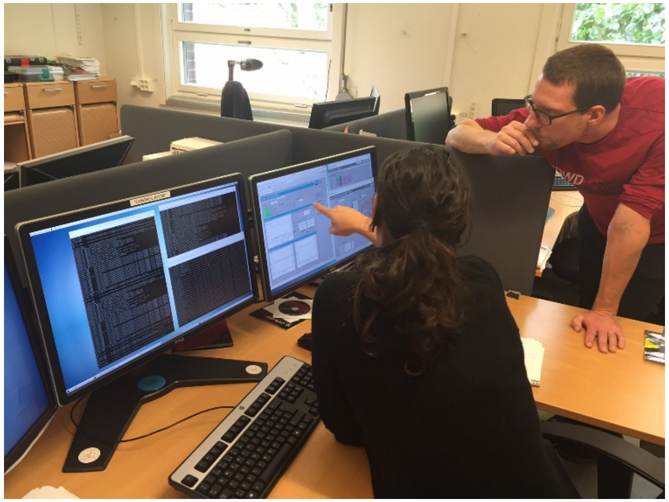
- Modular design
  - Adaptable to different cavities.
  - Facilitates incremental upgrades
  - Simplifies end of life management
- Temperature controlled rack

LLRF is in-kind contribution
(DESY and others)

Status

After 4~5 years…

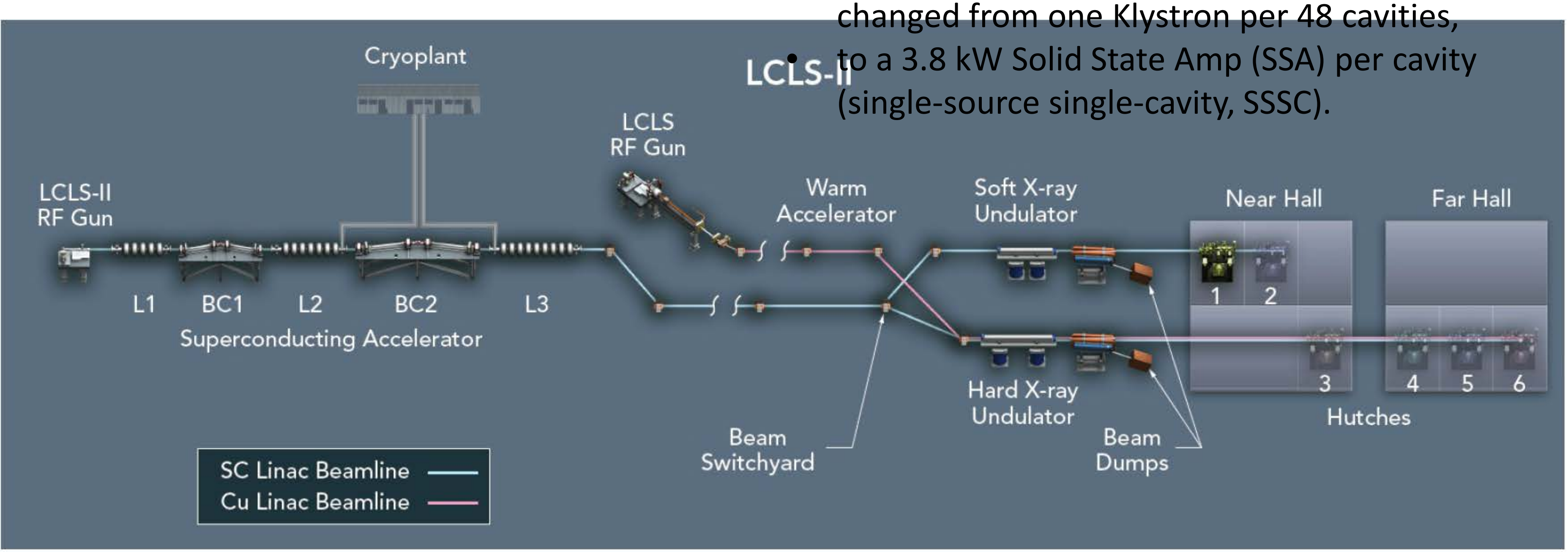
- Two test benches up and running at Lund University
  - 352.21 MHz
  - 704.42 MHz
- Test benches controlled from a central ”control room” computer and screens.
- One prototype running at Freia test hall at Uppsala University.



Linear Coherent Light Source – II (LCLS–II)

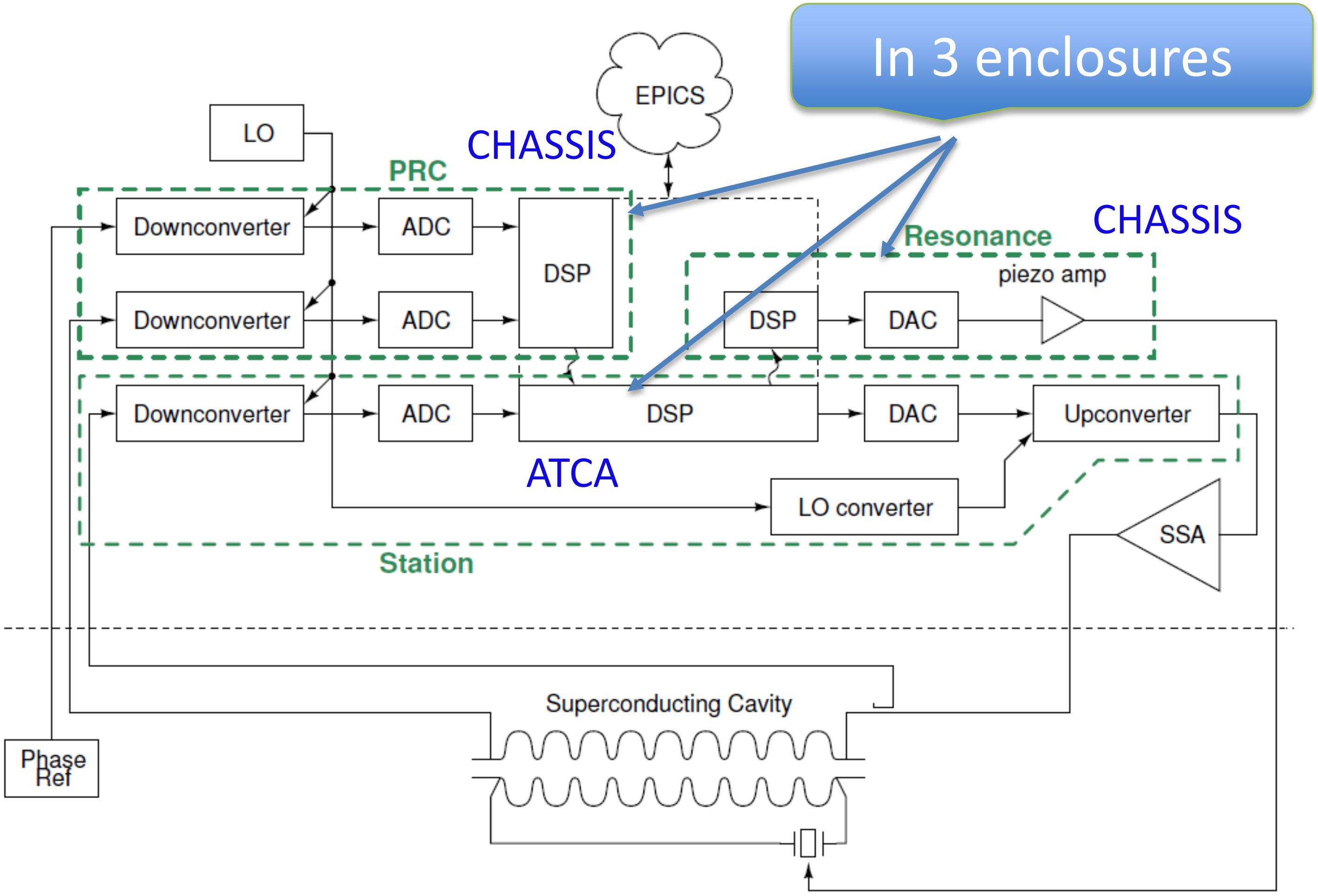
- Collaboration with SLAC, FNAL, JLAB
- System architecture design
  - Modular NAD (network attached device) design
  - Separation of high precision receiver and RF drive station
  - Common FPGA boards in modules
- End-to-end simulation

- LCLS-II is just like XFEL, except ...
- CW instead of pulsed
- 20 Hz bandwidth SRF cavity, instead of 800 Hz bandwidth
- Goal is still 0.01, 0.01%
- Fast beam-based feedback is not part of LCLS-II baseline, for cost reasons
- As of September 2014, the baseline design changed from one Klystron per 48 cavities, to a 3.8 kW Solid State Amp (SSA) per cavity (single-source single-cavity, SSSC).



Subdivided Architecture

LCLS–II LLRF



In 3 enclosures

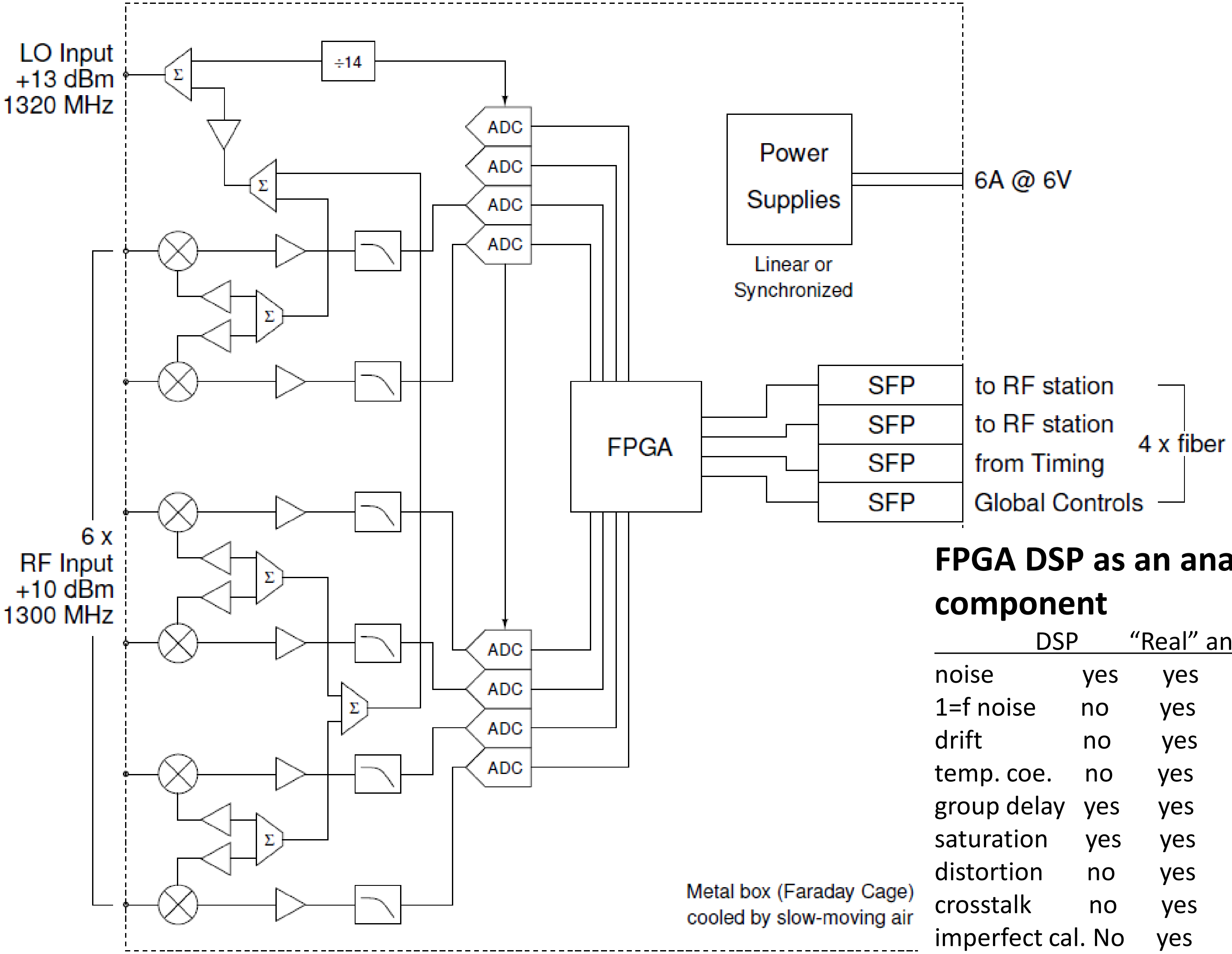
CHASSIS

CHASSIS

ATCA

EMI-proof* Precision Receiver Chassis

LCLS–II LLRF



FPGA DSP as an analog component

	DSP	“Real” analog
noise	yes	yes
1=f noise	no	yes
drift	no	yes
temp. coe.	no	yes
group delay	yes	yes
saturation	yes	yes
distortion	no	yes
crosstalk	no	yes
imperfect cal.	No	yes
power dissipation	yes	yes
simulatable	yes	yes
remote updates	yes	no

* Maybe

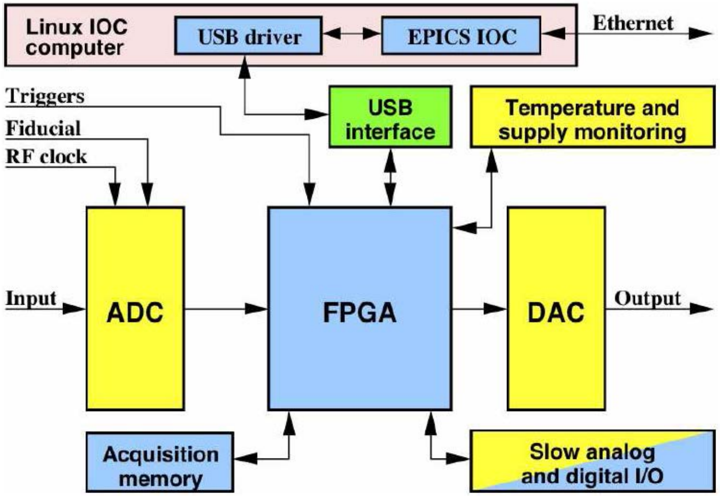
Summary

- Over a decade and half (since 2001), a lot of progress has been made, and basic techniques have been learnt.
- LLRF community has become more mature in both
  - Using proven techniques/designs, and
  - Choosing Pragmatic Implementations
- R&D in reference/calibration continues to be the focus
- Development of the more realistic SRF cavity models in FPGA is being pursued, which would be very useful for SRF systems.

Thanks for your attention

A example of Commercial LLRF Solutions

- LLRF-9 from Dimtel
- Users : ELSA, ANKA, SESAME. The unit has also been demonstrated in Diamond booster and LNLS booster and storage ring.



Linux IOC computer

USB driver

EPICS IOC

Ethernet

Triggers

Fiducial

RF clock

USB interface

Temperature and supply monitoring

Input

ADC

FPGA

DAC

Output

Acquisition memory

Slow analog and digital I/O