Progress in LLRF System at FLASH

Low Level RF Workshop, Lake Tahoe, California, USA, October 1-4, 2013

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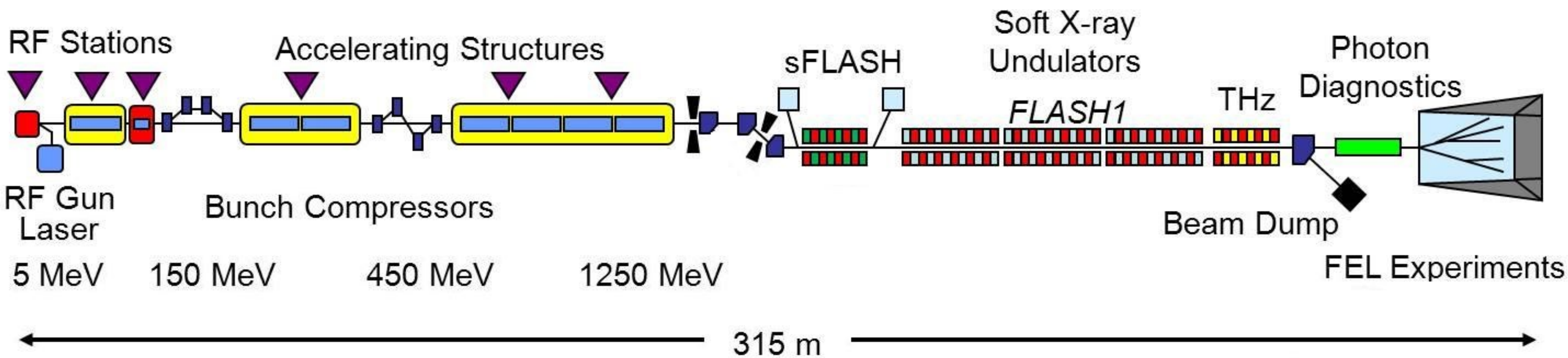
on behalf of LLRF team

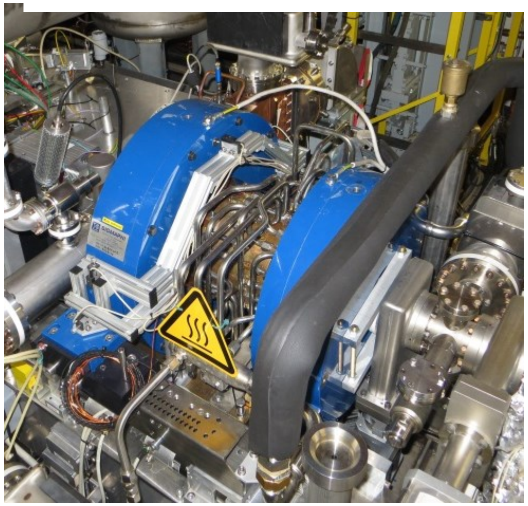
Outline

- Overview
- Hardware Upgrade
  - Digital feedback installations
  - Piezo control status
- Recent Software Developments
  - Automation tools
  - Performance
- FLASH II Project
  - LLRF Requirements
  - Initial tests results
- Conclusion and Outlook

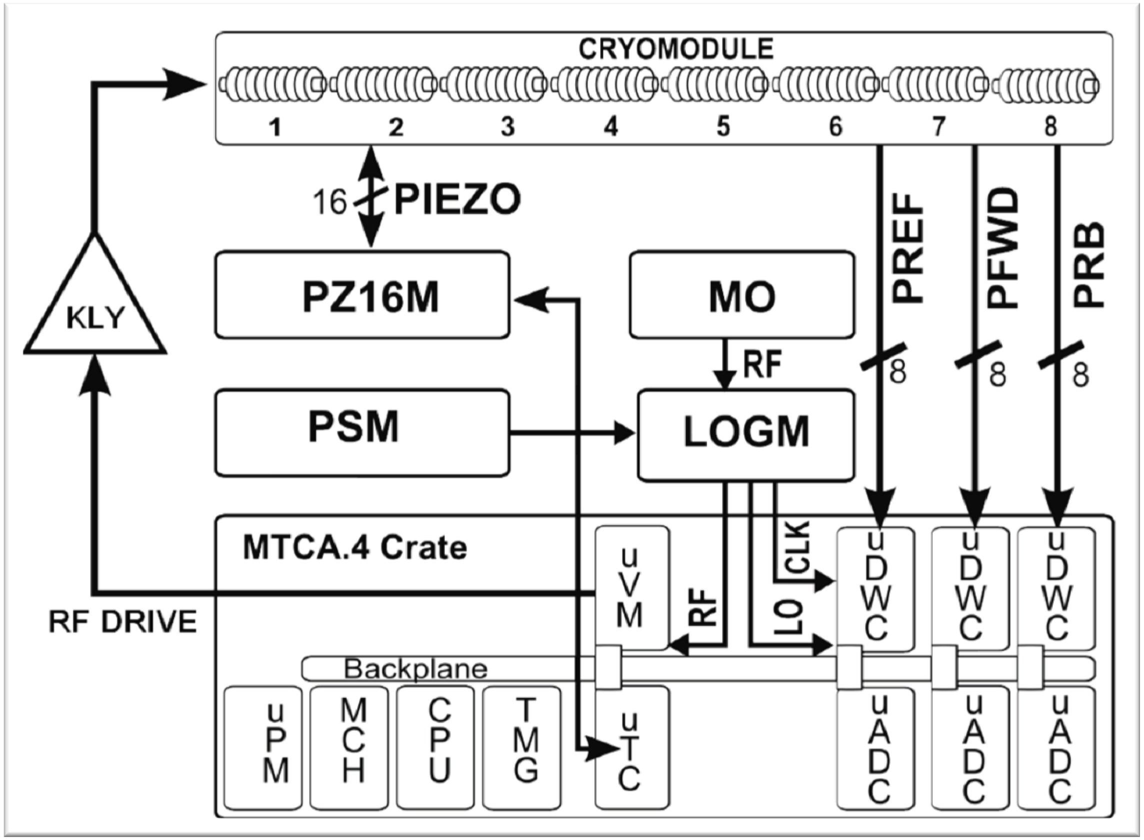
The FLASH Facility

Free-electron **Las**er in **H**amburg - user facility since 2005

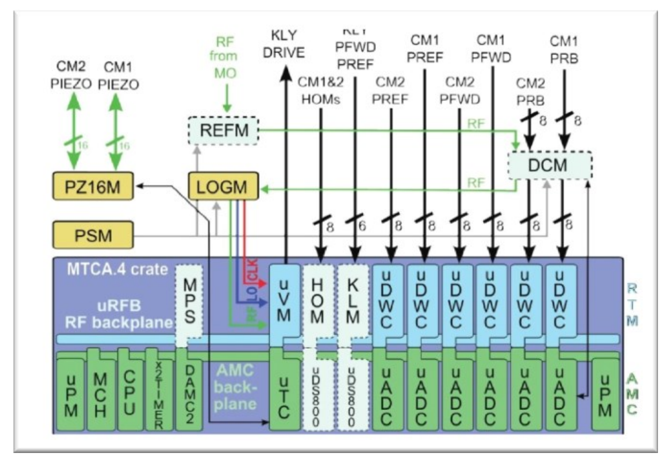




LLRF System Overview



- Six pairs of down-converters and digitizers
- One pair controller and vector modulator
- CPU running the front-end controller server
- Management controller hub
- Power entry modules
- Timing module
- Machine protection system module



- Drift calibration module (DCM)
- Reference module (REFM)
- Local oscillator generation module (LOGM)
- Piezo controller module (PZ16M)
- Power supply module (PSM)

Courtesy: J.Branlard

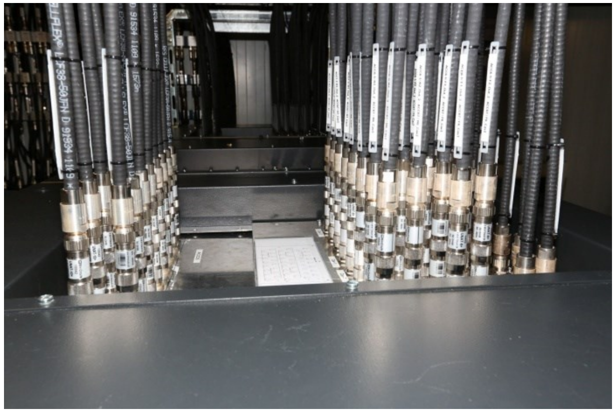
MTCA System Installations

- RF Gun, ACC1, ACC39 and ACC23 inside the tunnel (16U)
- ACC45 and ACC67 outside the tunnel (28U)

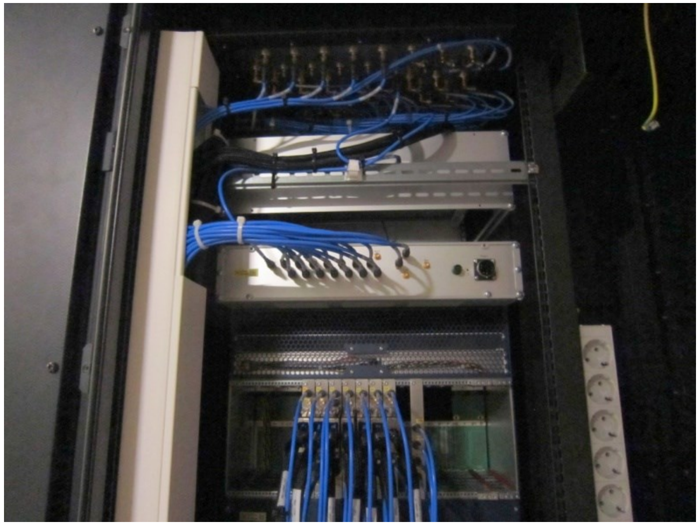
MTCA System Installations (2)

RF Gun, ACC1 & ACC39

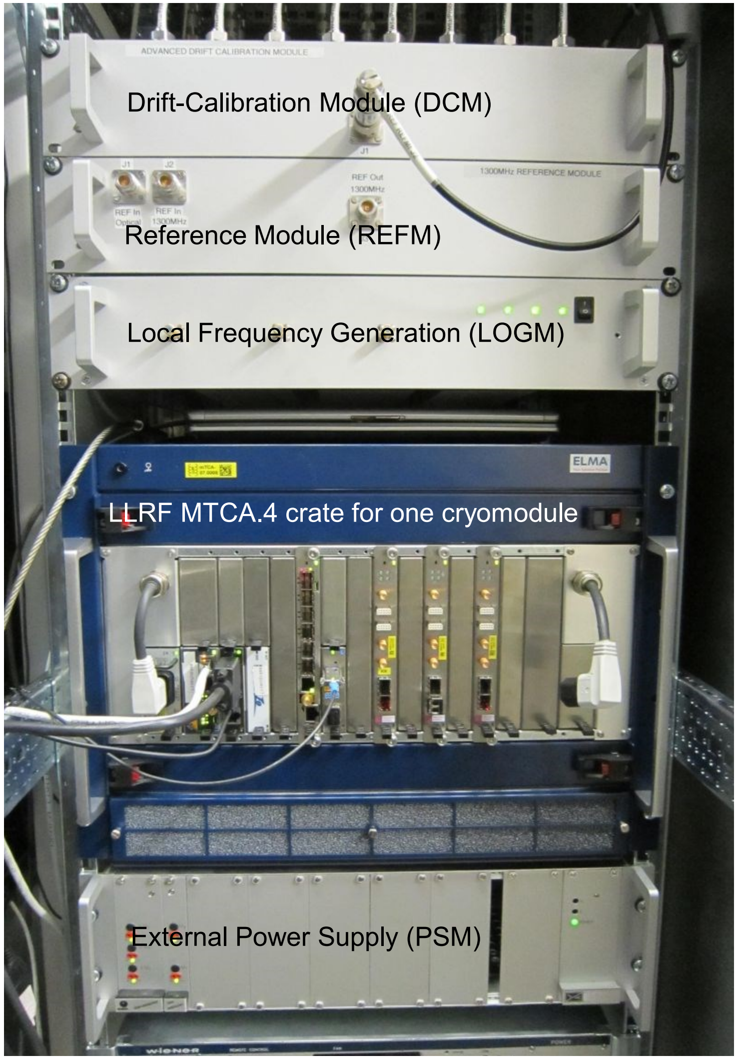
ACC45 & ACC67

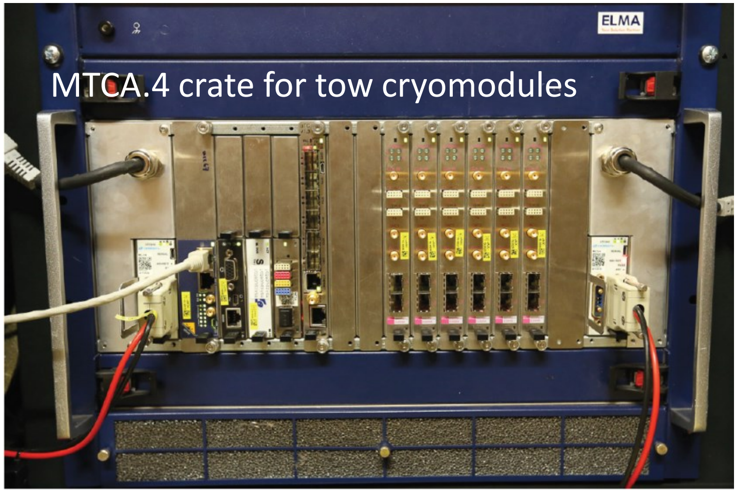


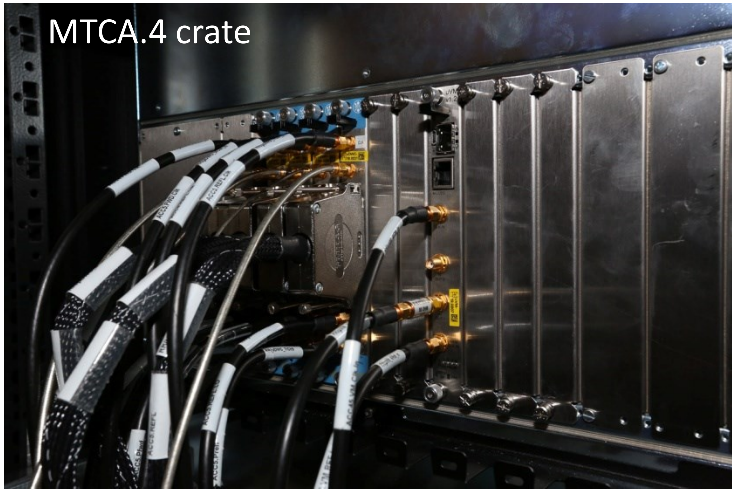
ACC23



LLRF Rack Installation (one RF station)



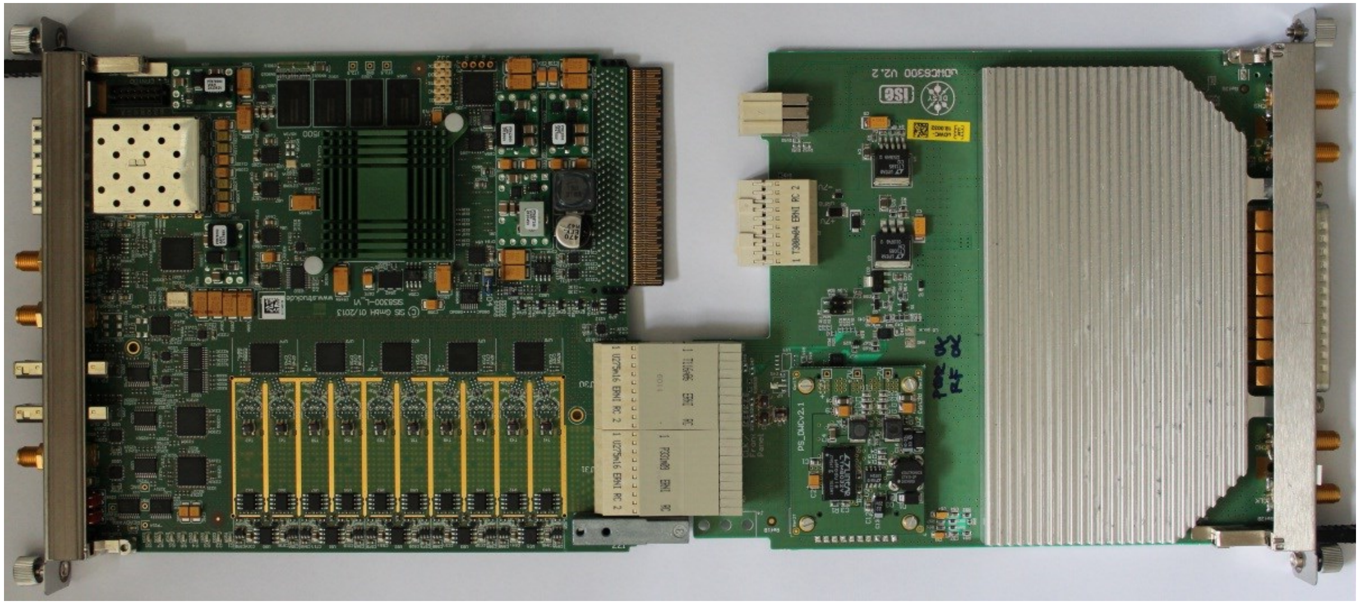




Digitizers and Downconverters

- 10 channel digitizer board
- 125 Msps,16 bit high speed ADCs
- LLL data transmission on backplane
- Control of additional subsystems connected (optical links)
- Data acquisition

- 10 channel down-conversion from 700MHz – 4GHz
- Supports intermediate frequencies between 5MHz and 65MHz
- Programmable attenuators
- LO, CLK from front panel or RF-backplane

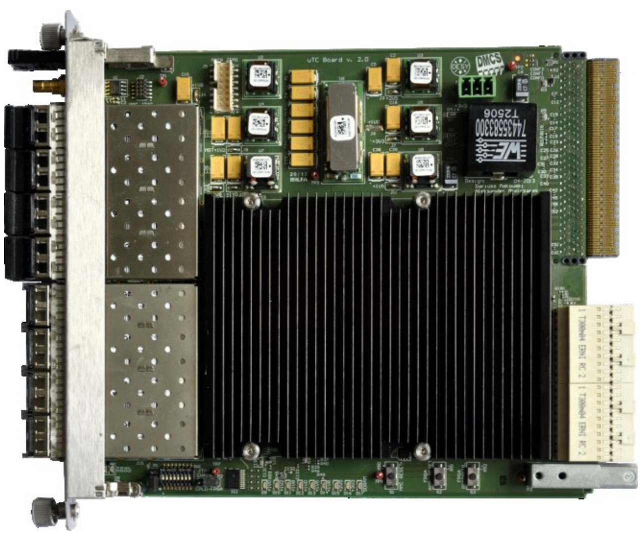


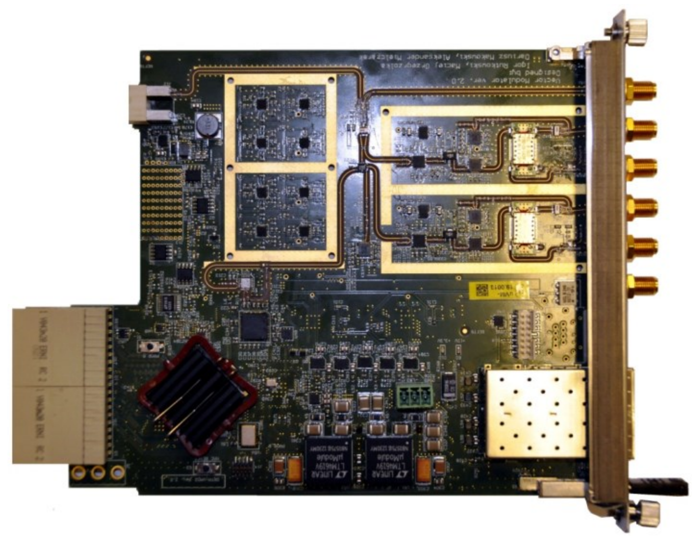
Courtesy: SIS & F.Ludwig

Digital Controller & Vector Modulator

- High-performance, low-latency data processing unit compatible with MTCA.4
- Powerful Kintex 7 FPGA, 16 Gb DDR 3
- Class D1.2 compatible
- 10 Gbps low latency connections on backplane and front panel, PCIe x4 gen. 3
- Partial reconfiguration and firmware upgrade support
- Advanced diagnostic, monitoring and debugging

- Fast (>30MHz modulation BW), high resolution (16-bit) and high precision Vector Modulator device
- 2 independent channels
- Modulated frequency range: 50 MHz – 6 GHz
- On-board FPGA and DACs for modulator control
- On-board low jitter clock generation circuits
- Programmable attenuator for output signal
- Integrated interlocks and RF-Gate
- Power level and temperature monitoring

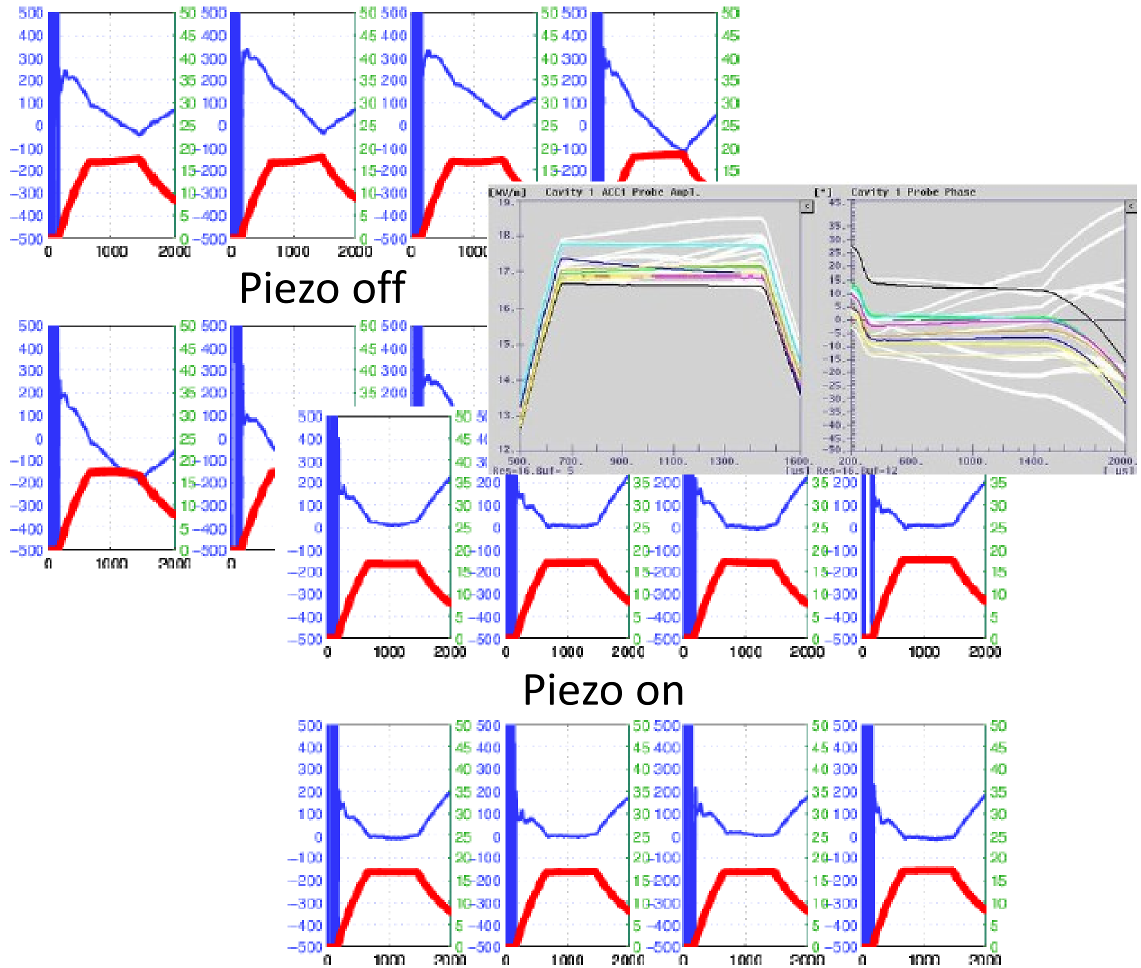




Courtesy: D.Makowski & I.Rutkowski

Piezo Control Instatallations

- ACC1, ACC3 piezo control (PZ16M) is installed
- ACC5, ACC6, ACC7 Installation work is on progress



Courtesy: K.Przygoda

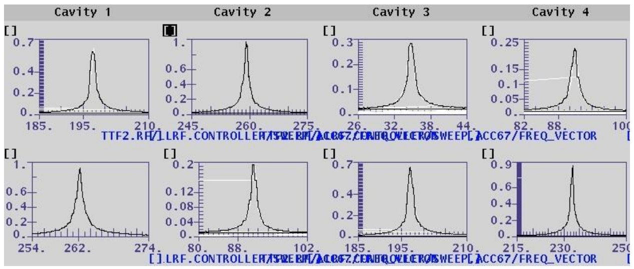
Software Status

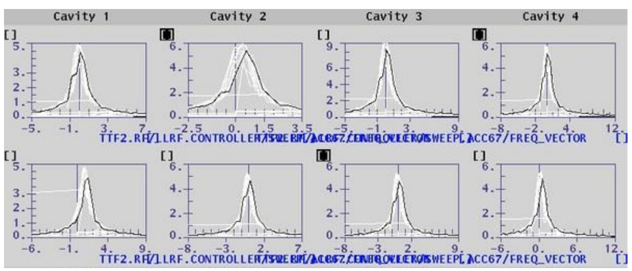
- Controller firmware upgrade
- Controller DOOCS server upgrade
- Learning feed-forward
- Beam based calibration
- Beam based controls algorithms are developed
- Piezo control integration
- Automation and new diagnostic tools are developed

Automation Tools

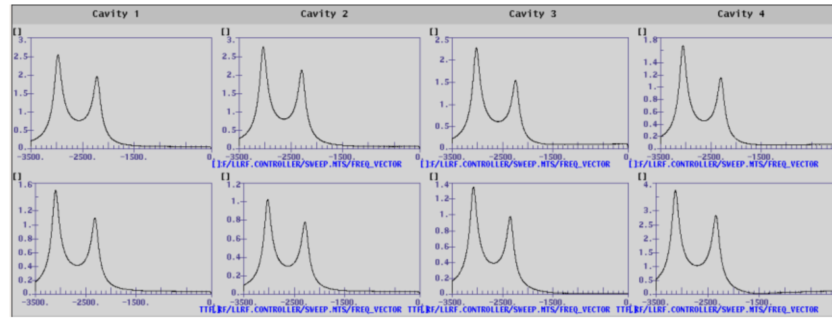
- Automation for Machine Operation
  - Cavity initial tuning
  - Cavity fine tuning with piezo
  - Loaded Q adjustment
  - Finite state machines
- Automation for Machine Protection
  - Cavity gradient limiters and pre-limiters
  - Quench detection and handling

Cavity Resonance Frequency Measurement and Tuning

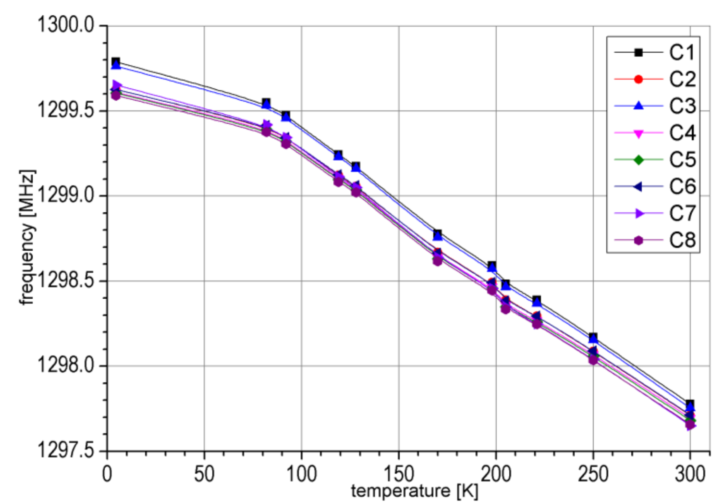




Resonant frequency measurement before and after cavity tuning in ACC6



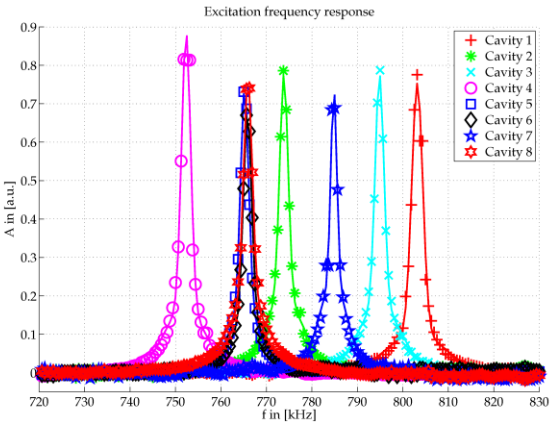
8π/9 and π modes. F=1.300MHz + dF, dF[kHz], T=300K



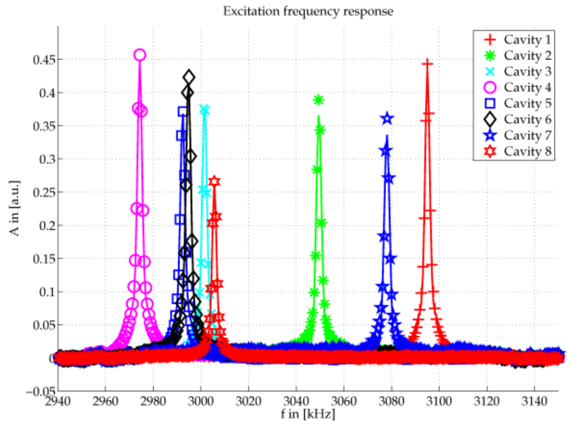
π-mode resonance frequency vs. temperature

Cavity Sub-harmonic Resonance Frequencies Measurement

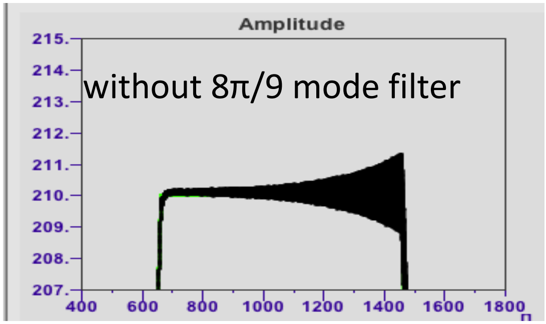
- Measurement of 8 π/9 and 7π/9 sub-fundamental modes
- Notch filter center frequency and bandwidth for all cavities
- Derive the filter coefficients used in the controller

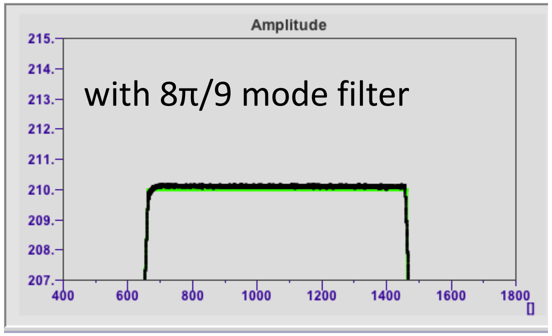


8π/9 modes for eight cavities



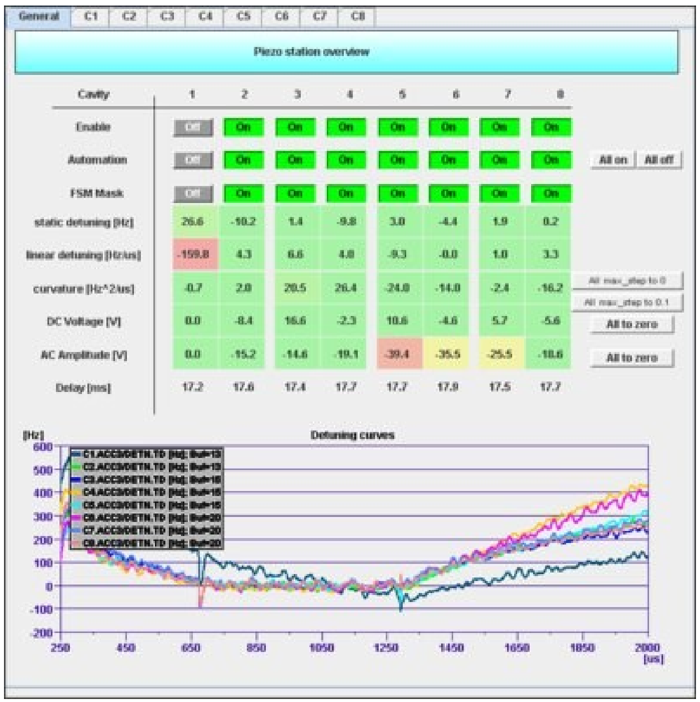
7π/9 modes for eight cavities





Cavity Automatic Tuning with Piezo's

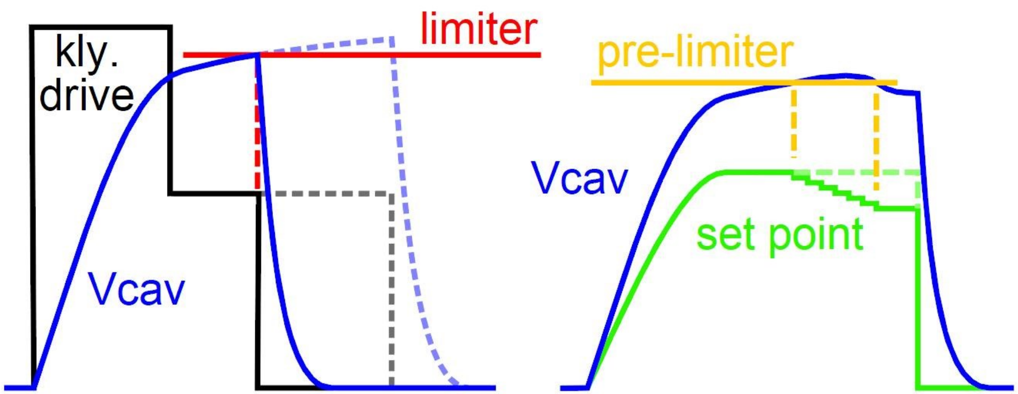
- VME system: was running for ACC1/3/5/6/7 (DOOCS and automation)
- MTCA system: automation work is on progress

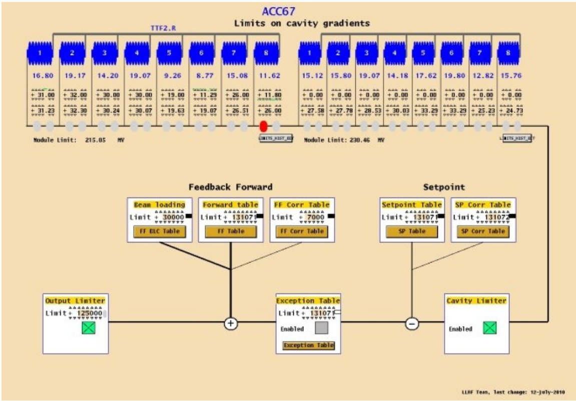


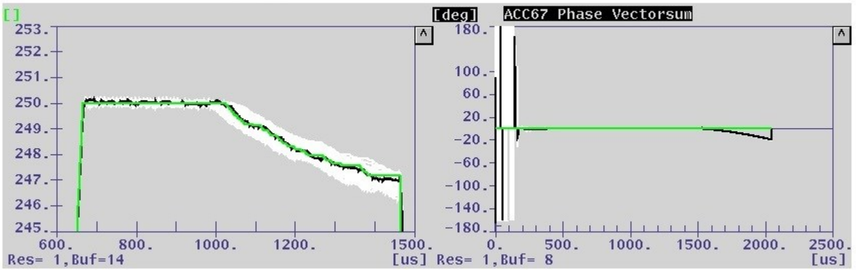
- Pulsed sinusoidal excitation of the piezo is used to compensate for LFD
- Computing the cavity detuning during the pulse and adjusting the piezo stimulus parameters (DC offset, AC amplitude, frequency and pulse delay)
- Frequency and the maximum total amplitude of the excitation are limited

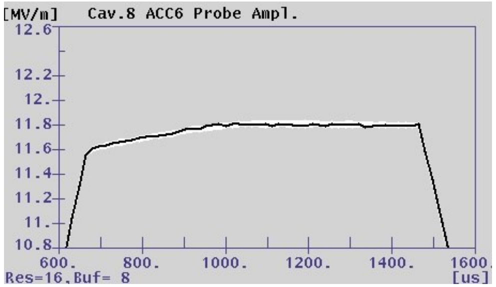
Exception Detection and Handling

- Output Limiter
- Exception table
- Cavity gradient limiter and pre-limiter



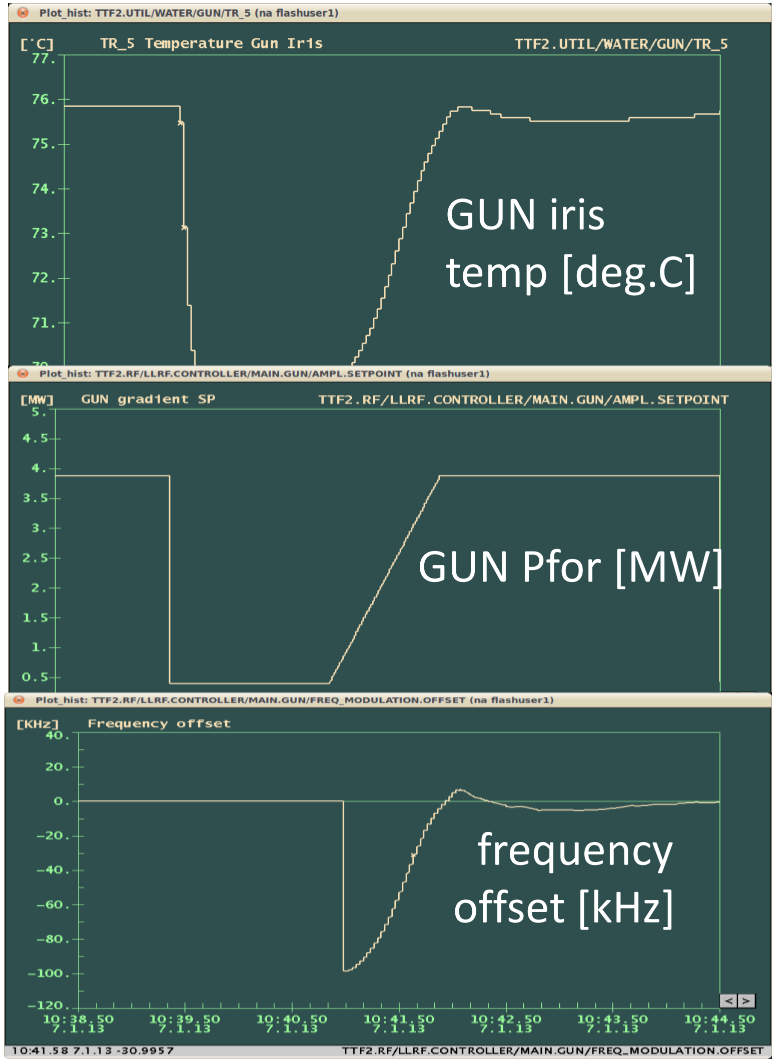






RF GUN Start-up Procedure

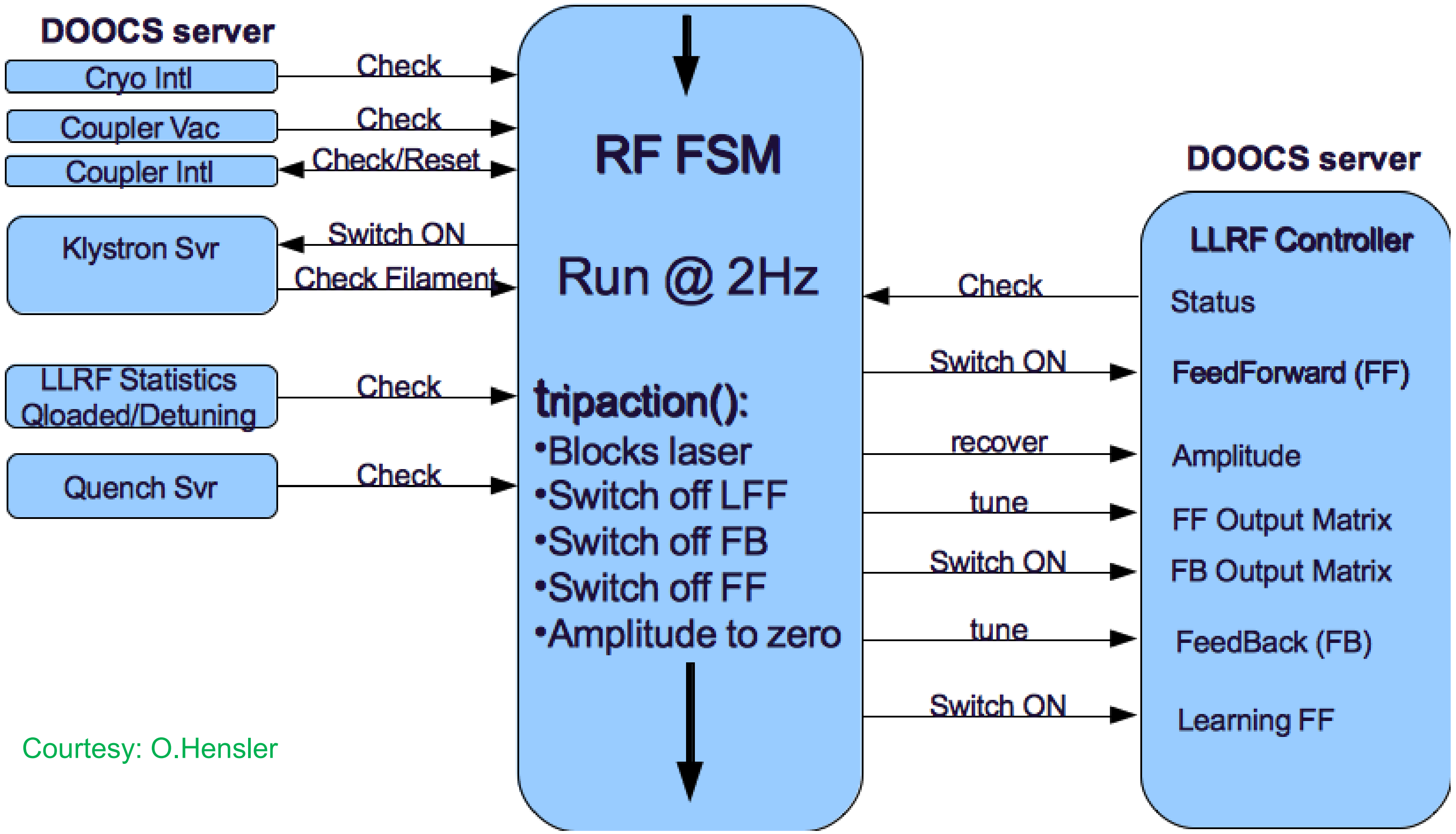
- Tuned to RF through temperature cooling water variations
- Temperature regulation works perfectly in DC conditions (PI type regulator)
- In transient states (when trip happens) the long time is needed to startup the Gun (normally ~20 min with experienced operator)
- Automatic procedure developed for integrating the water cooling regulation and RF frequency regulation – startup time reduced to few minutes



Courtesy: M.Grecki

Finite State Machines

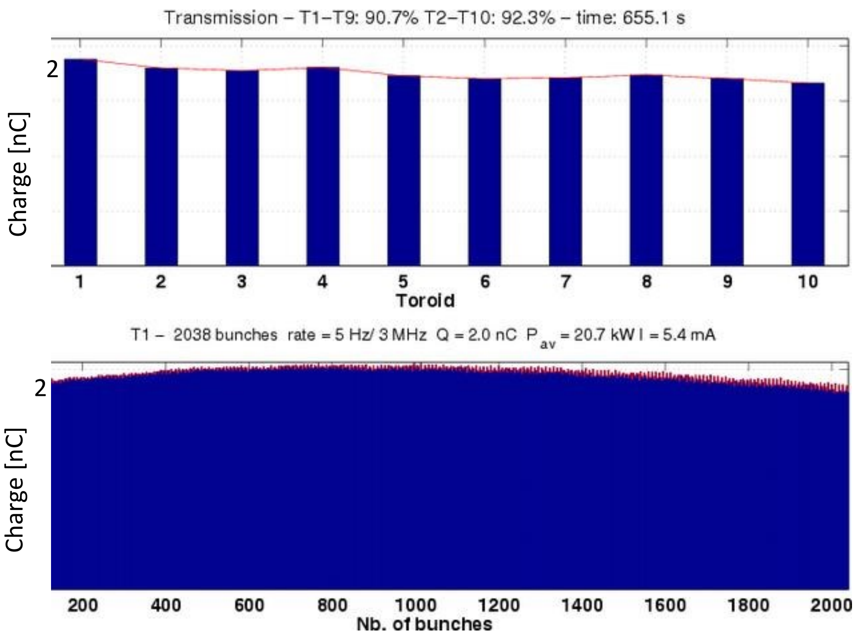
RF start-up, restart and routine operation are automated by FSM

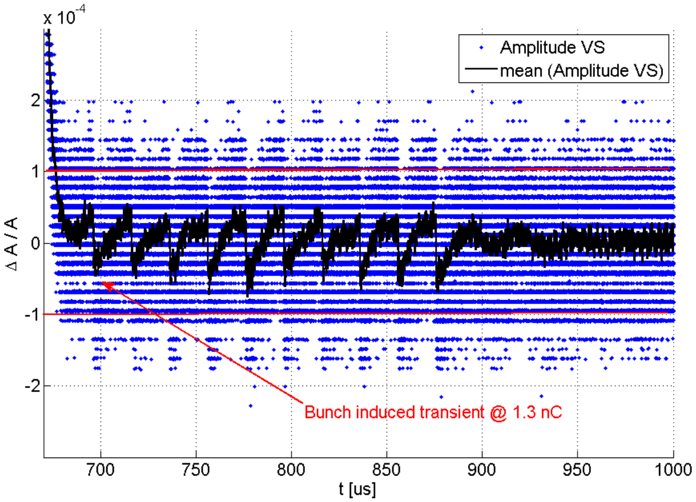


Courtesy: O.Hensler

Beam Loading Compensation

- Toroid based beam loading compensation
- Automatic scaling and extension of actual beam loading tables
- Different bunch rep. rate
- High beam loading
- Important for 9mA ILC tests

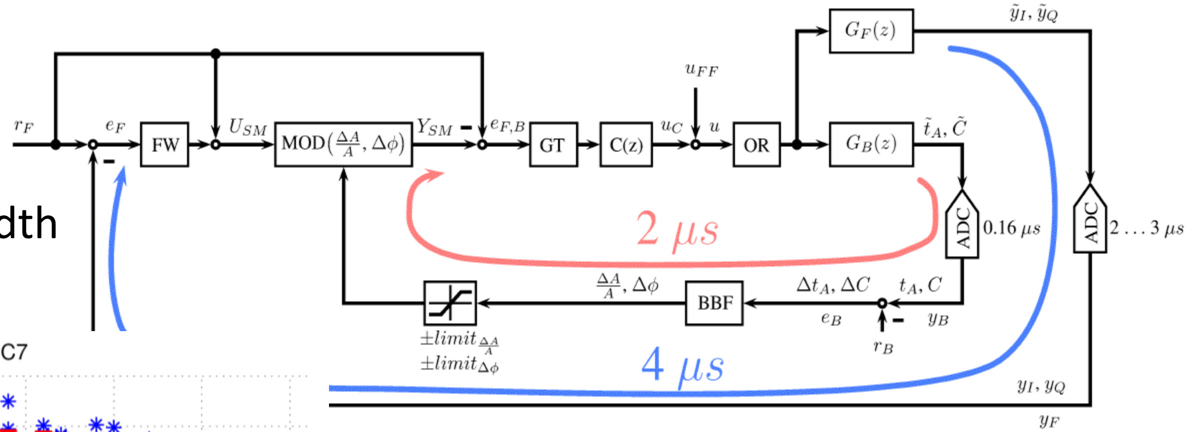


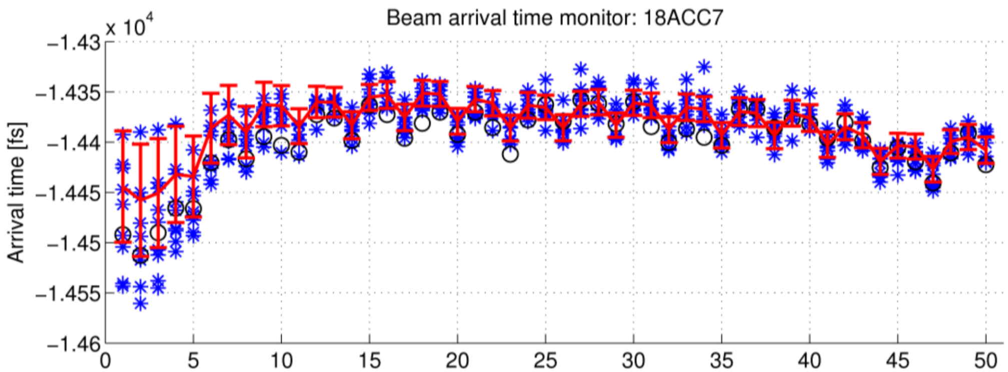


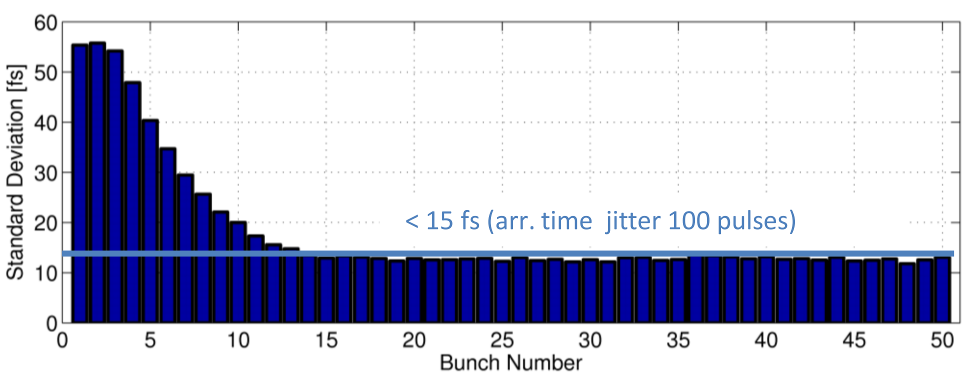
Uncompensated beam loading,10 bunches, 1.3nC, 50 kHz rep

Beam Based Feedbacks

- Updated BBF implementation
- Cascaded feedback loop to:
  - Reduce latency
  - Increase regulation bandwidth





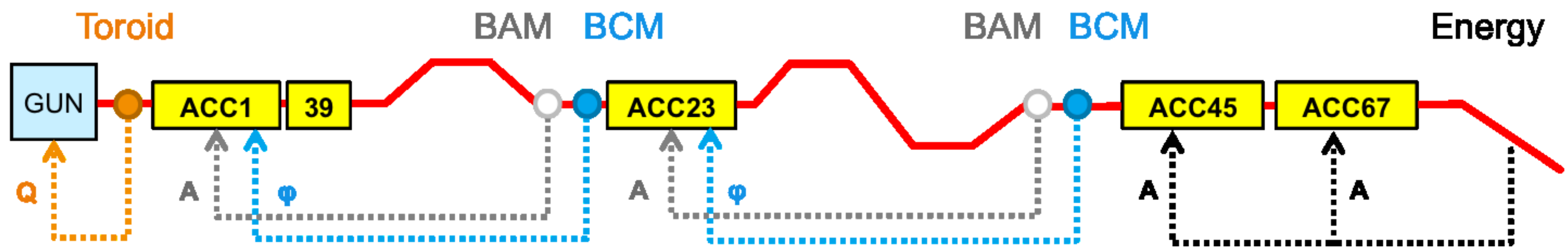


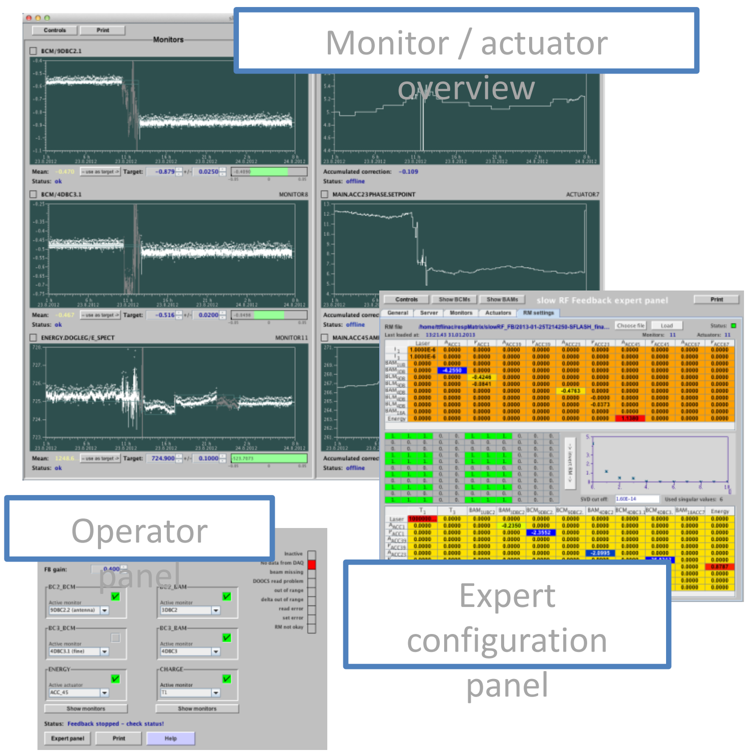
- Out of loop measurement at 18ACC7
  - User arrival time monitor
  - Influence on regulation performance of ACC23
  - Arrival time jitter can be reduced below 15fs (about x4)

Courtesy: S.Pfeiffer & C.Schmidt

Talk: S.Pfeiffer, “Beam Based Feedbacks“

Slow RF Feedbacks





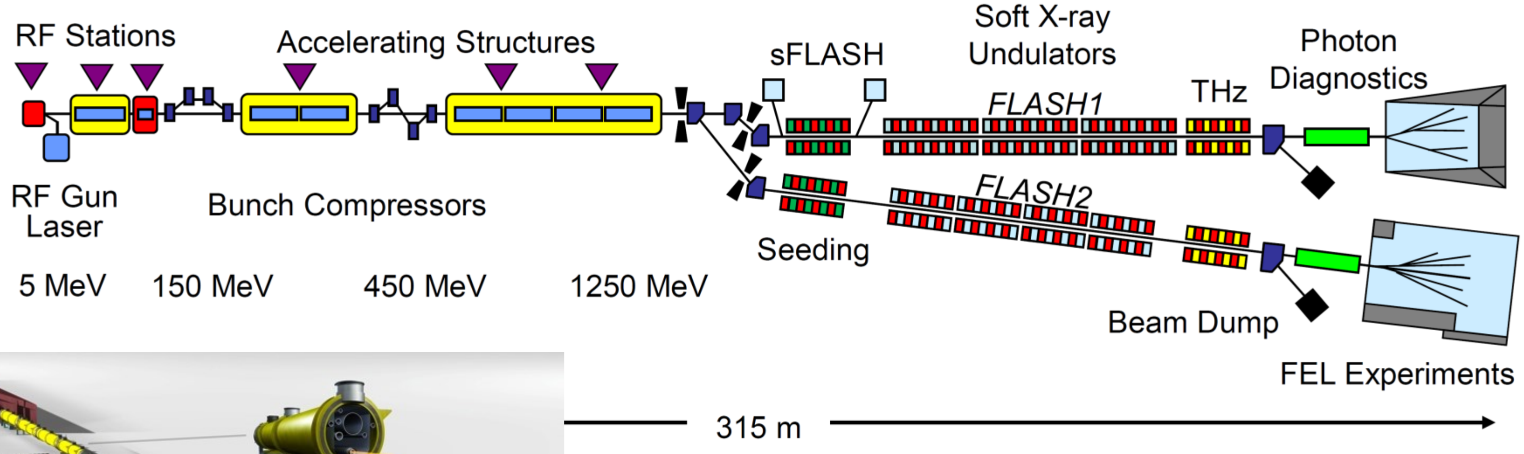
$$\begin{pmatrix} SP.A_{ACC1} \\ SP.P_{ACC1} \\ SP.A_{ACC39} \\ SP.P_{ACC39} \\ SP.A_{ACC23} \\ SP.P_{ACC23} \\ SP.A_{ACC45} \\ SP.P_{ACC45} \\ SP.A_{ACC67} \\ SP.P_{ACC67} \end{pmatrix} = \begin{pmatrix} K_{11} & K_{21} & \cdots & & \cdots & K_{61} \\ & \ddots & & & & \\ & & \ddots & & & \\ & & & \ddots & & \\ & & & & \ddots & \\ & & 0 & & & \vdots \\ & & & & & K_{69} \\ & & & & & K_{610} \end{pmatrix} \begin{pmatrix} BAM_{1UBC2} \\ BAM_{BC2} \\ BCM_{BC2} \\ BAM_{BC3} \\ BCM_{BC3} \\ E_{Dogleg} \end{pmatrix}$$

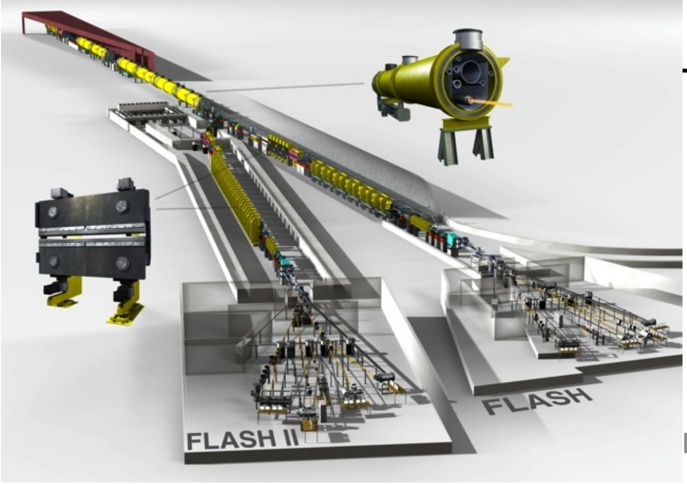
- PI controller, running up to 10 Hz
- Designed to run full coupled RM
- High flexibility in choice of monitors/actuators
- Robust operator interface
- Designed to be well scalable for XFEL needs

Courtesy: R.Kammering

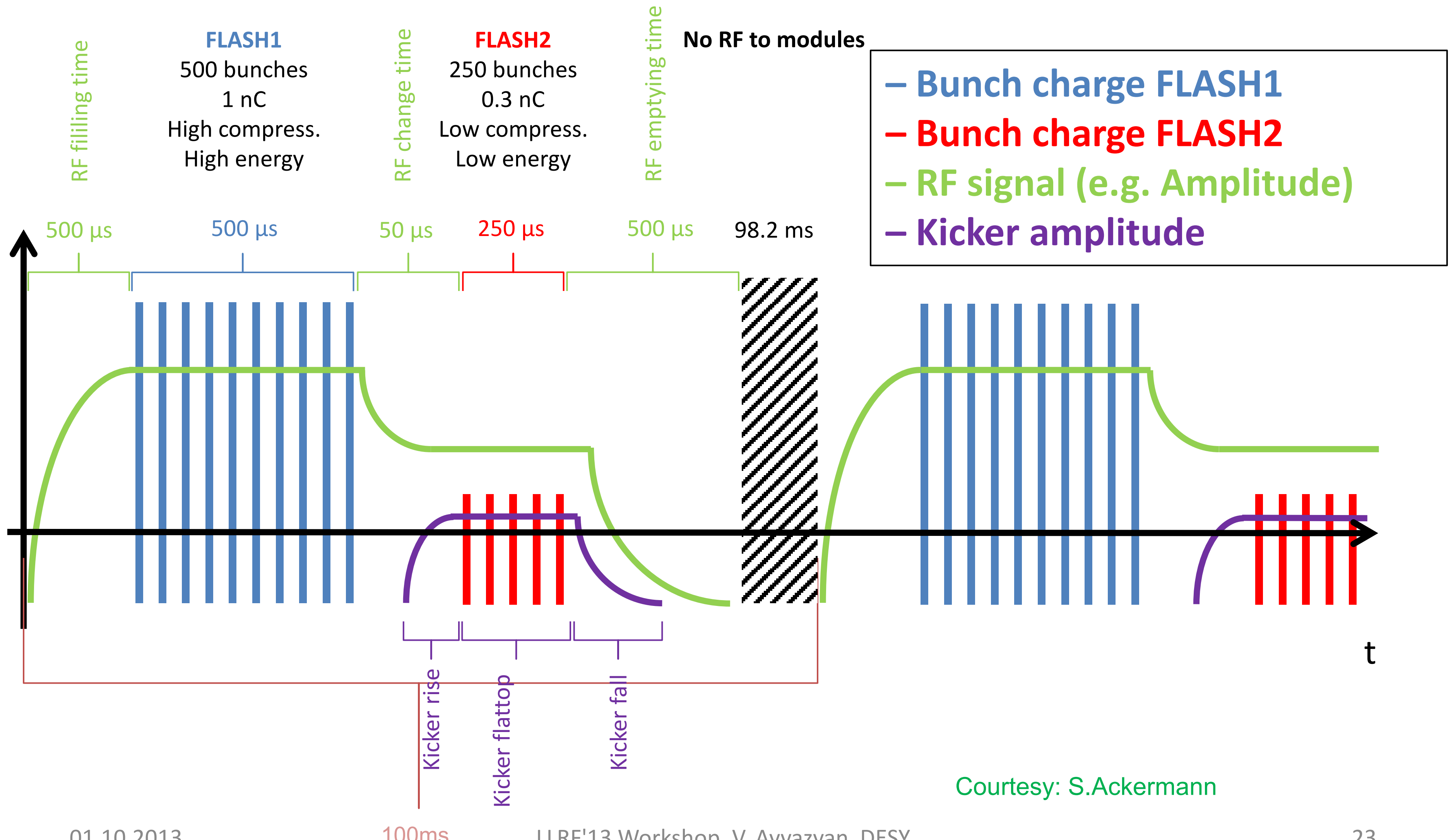
The FLASH II Project

- Separation FLASH and FLASH II behind last accelerator module
- Tunability of FLASH II by undulator gap change
- Extend user capacity with SASE and seeding
- Use of existing infrastructure up to last accelerating module





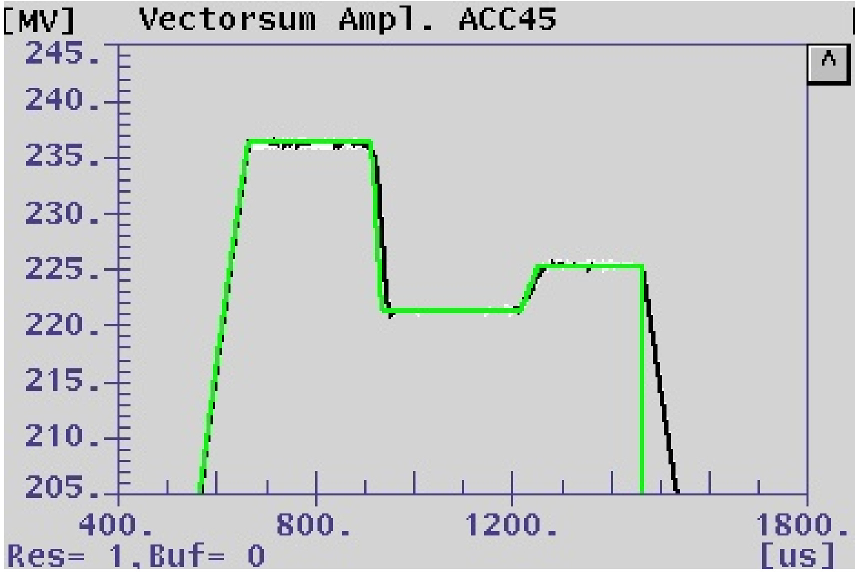
FLASH II – Timing Pattern (Example)

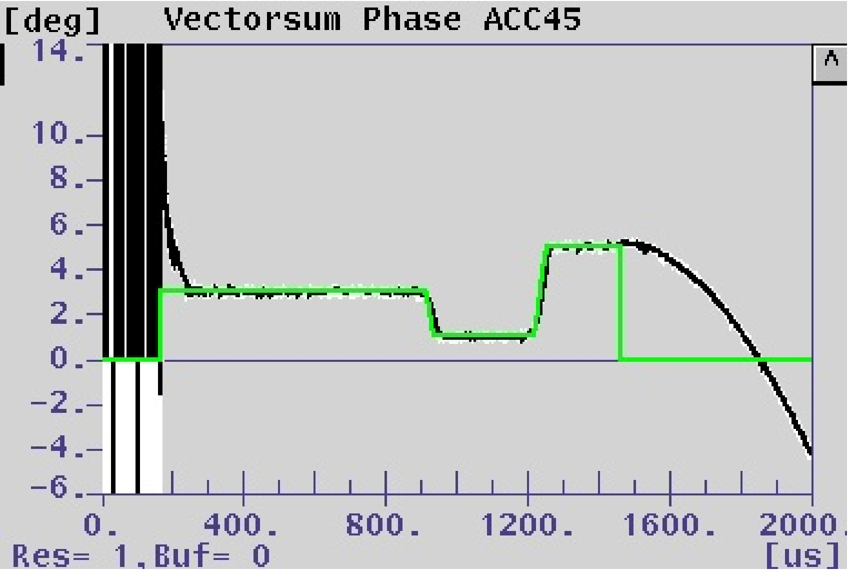


Courtesy: S.Ackermann

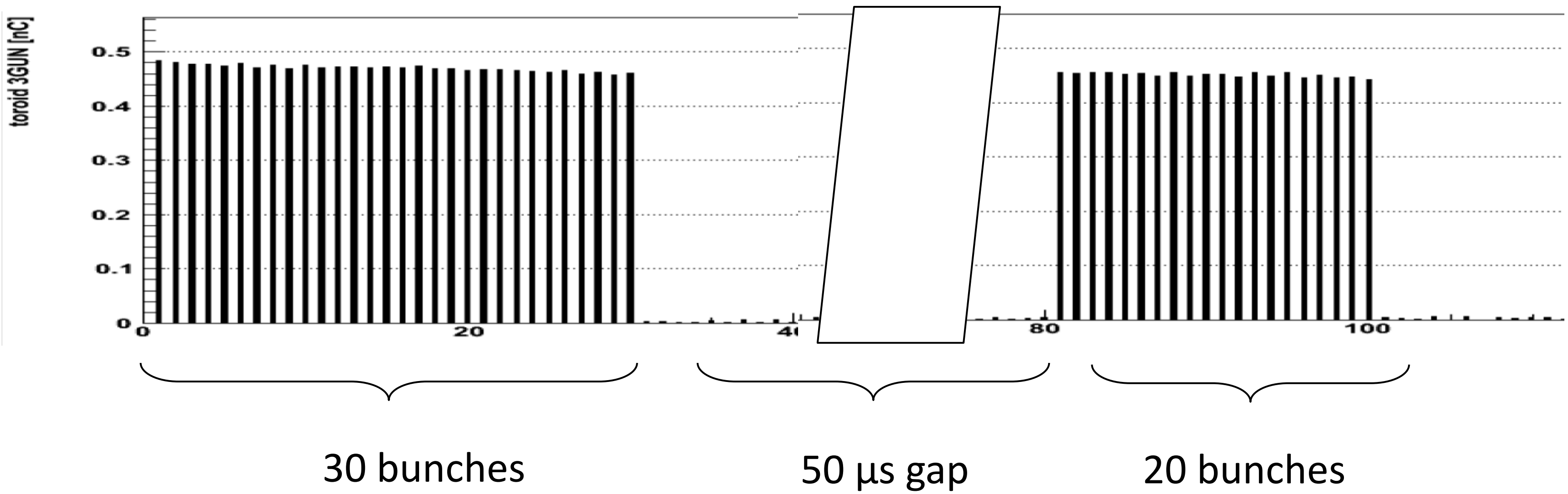
FLASH II LLRF Requirements

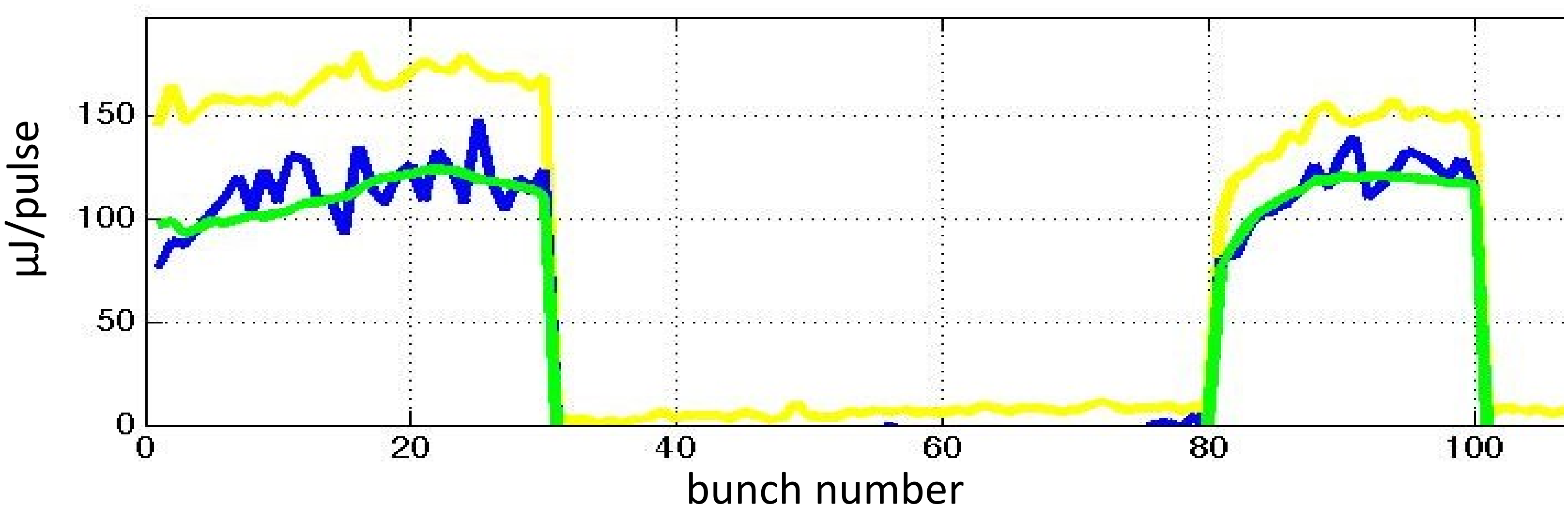
- RF amplitude and phase change within pulse
- RF amplitude and phase change from pulse to pulse
- Different beam loading for FLASH1 and FLASH2
- Ability of gradient tuning of ACC45 and ACC67 (for wavelength scans FLASH1)
- Ability of phase tuning of GUN, ACC1, ACC39 (for variation in compression FLASH1 and FLASH2)
- Ability of independent LLRF parameter adjustment for FLASH1 and FLASH2



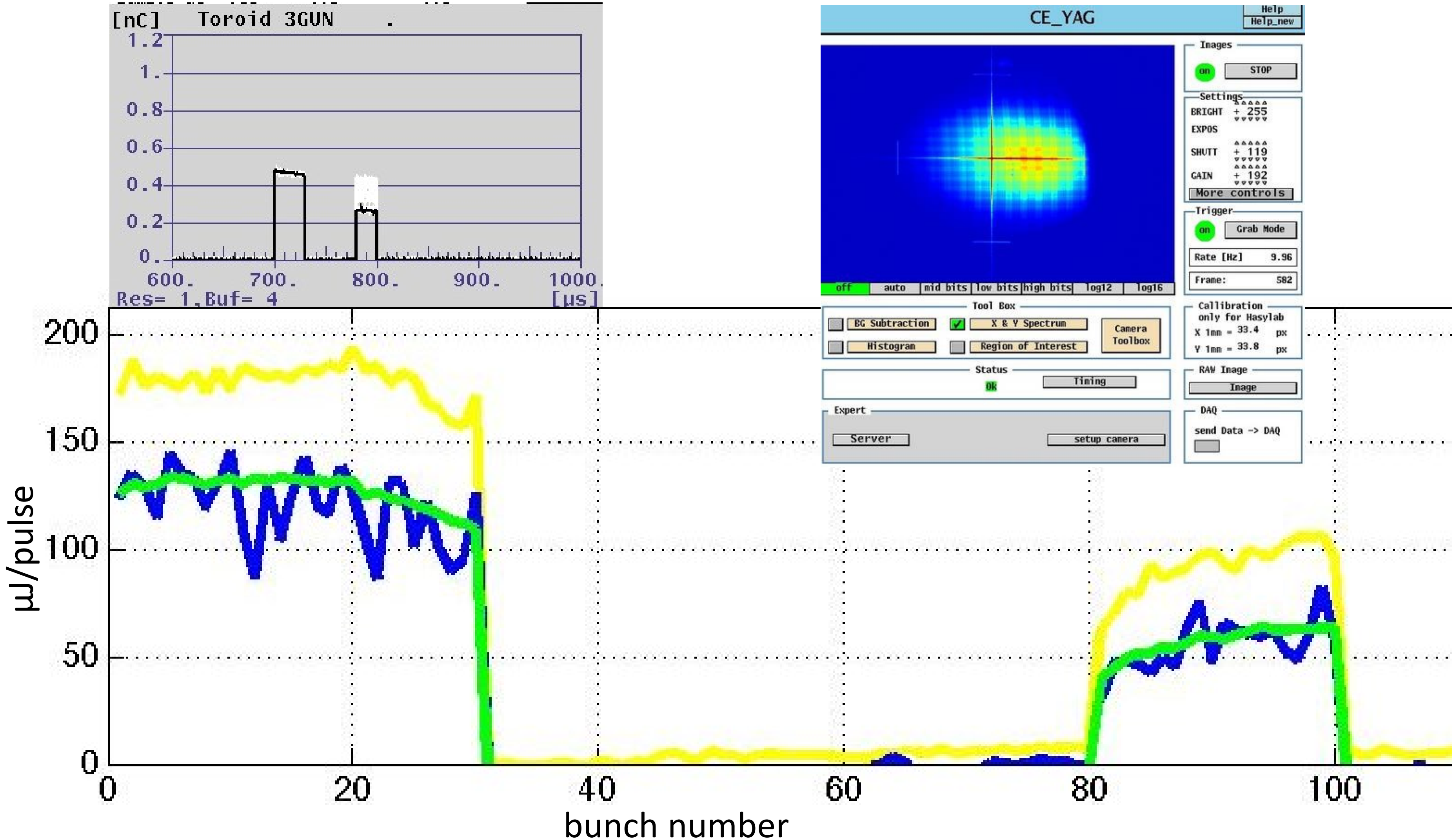


Same Bunch Charge: Same Lasing

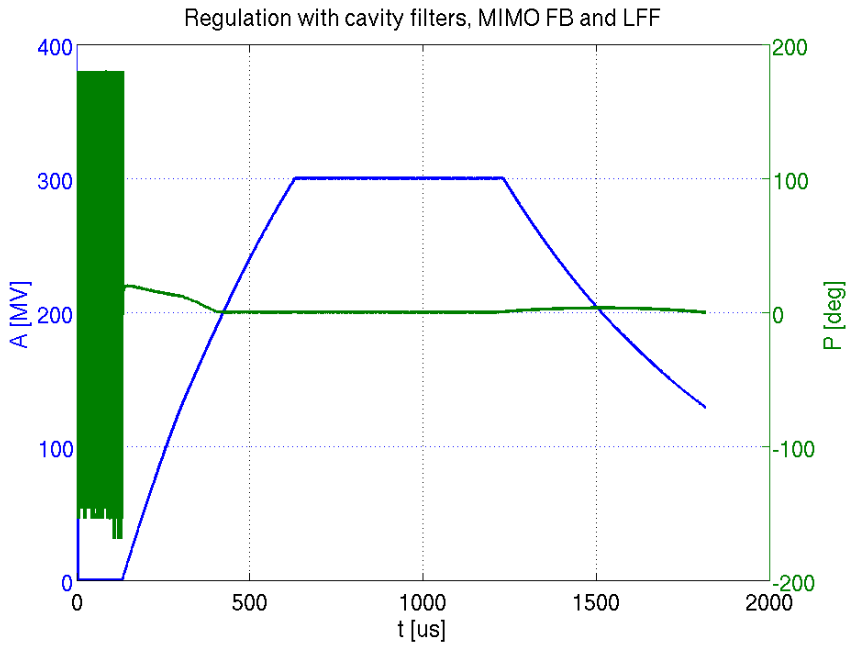


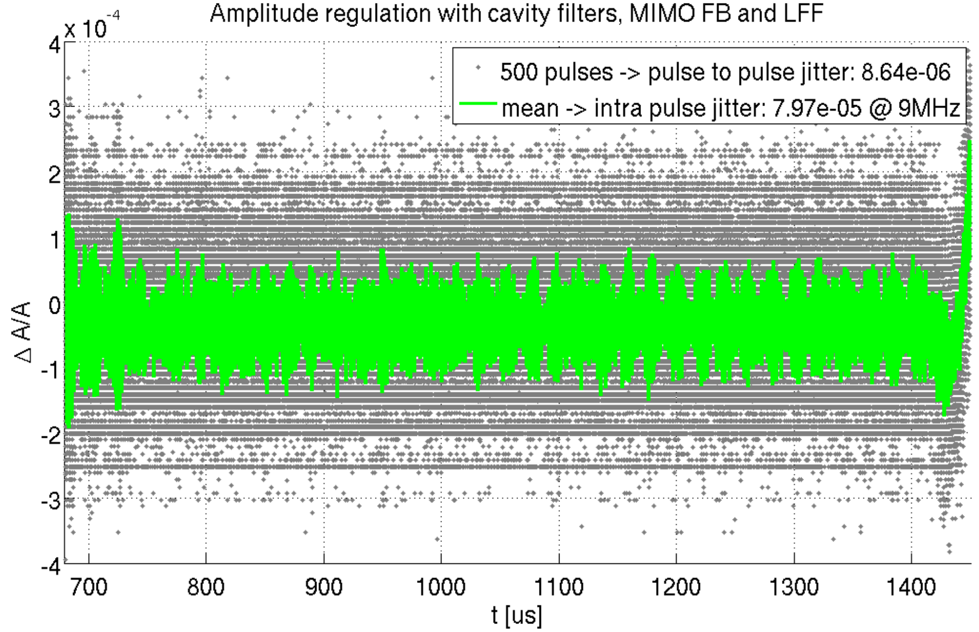


Different Charges: Different Lasing



Performance





Stability (rms) @9MHz	ACC1	ACC39	ACC23	ACC45	ACC67
Ampl. Intra pulse [%]	0,0067	0,0266	0,0055	0,0079	0,0069
Ampl. pulse to puls [%]	0,0017	0,0053	0,0012	0,0009	0,0019
Phase Intra pulse [deg]	0,0100	0,0233	0,0074	0,0099	0,0089
Phase pulse to pulse [deg]	0,0028	0,0108	0,0017	0,0023	0,0031

Courtesy: C.Schmidt

Conclusion and Outlook

- All superconducting modules are controlled by MTCA.4 based LLRF system
- Meet XFEL stability regulation requirements
- Beam-based measurements, LLRF control's algorithms and series of automation tools are developed
- Demonstrates that fast switching with different parameters from FLASH1 and FLASH2 simultaneously is possible

- Upgrade RF GUN control to MTCA.4 based system
- Full integration of beam based algorithms with LLRF system
- New developments for FLASH2: adapting the LLRF system to handle multi-pattern beam