FLASH LLRF System: Status and Upgrade Plans

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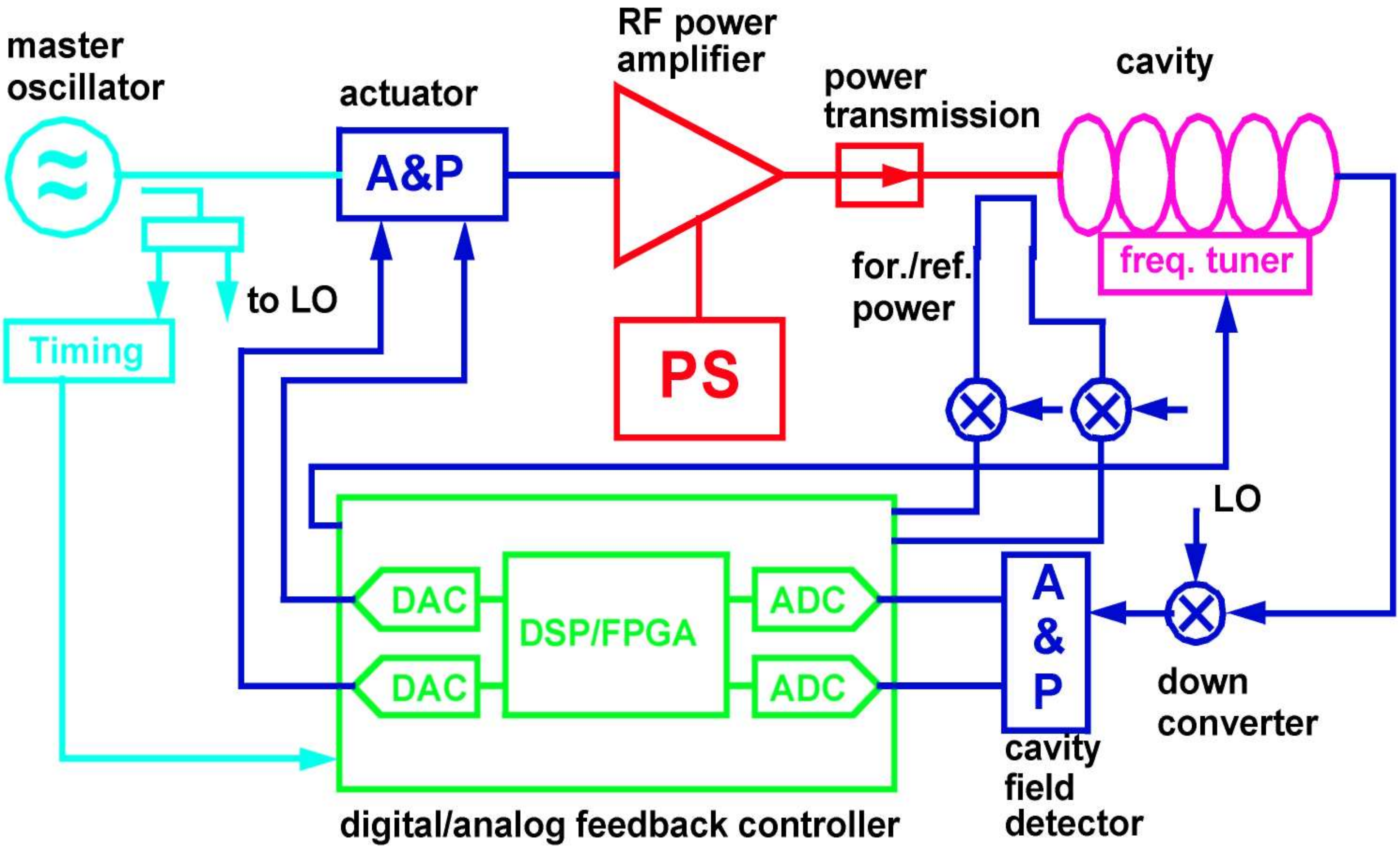
on behalf of LLRF Team

Outline

- LLRF System Status
- Recent Progress
- Operation Experience
- Measured Performance
- Future Plans
- Conclusion

LLRF System Architecture



Requirements: up to 0.03% for amplitude and 0.03 deg. for phase

LLRF Controllers used During User Run

RF System	User operation	Development	Backup
RF Gun	SIMCON 3.1	-	DSP
ACC1	SIMCON DSP 250 kHz IF	SIMCON x3 54 MHz	DSP 250 kHz
ACC23	DSP 250 MHz IF	-	Redundant FF DAC8
ACC456	DSP 250 MHz	SIMCON x3 ATCA 54 MHz	Redundant FF DAC8

and monitoring signals for all modules (forward/reflected/probe)

DSP (2000), SIMCON (2006), ATCA (2009)

Recent Progress at FLASH

- Master oscillator and distribution
- RF Gun control
- Optimization of HPRF drive control
- Improvements of tools/panels
- New learning feed forward algorithm
- Lorentz force compensation (piezo tuner)
- Next generation of down converter development
- Successful 9mA tests at FLASH
- Exception detection
- A proof of principle running system in new crate standard ATCA
- 3.9 GHz System in CMTB

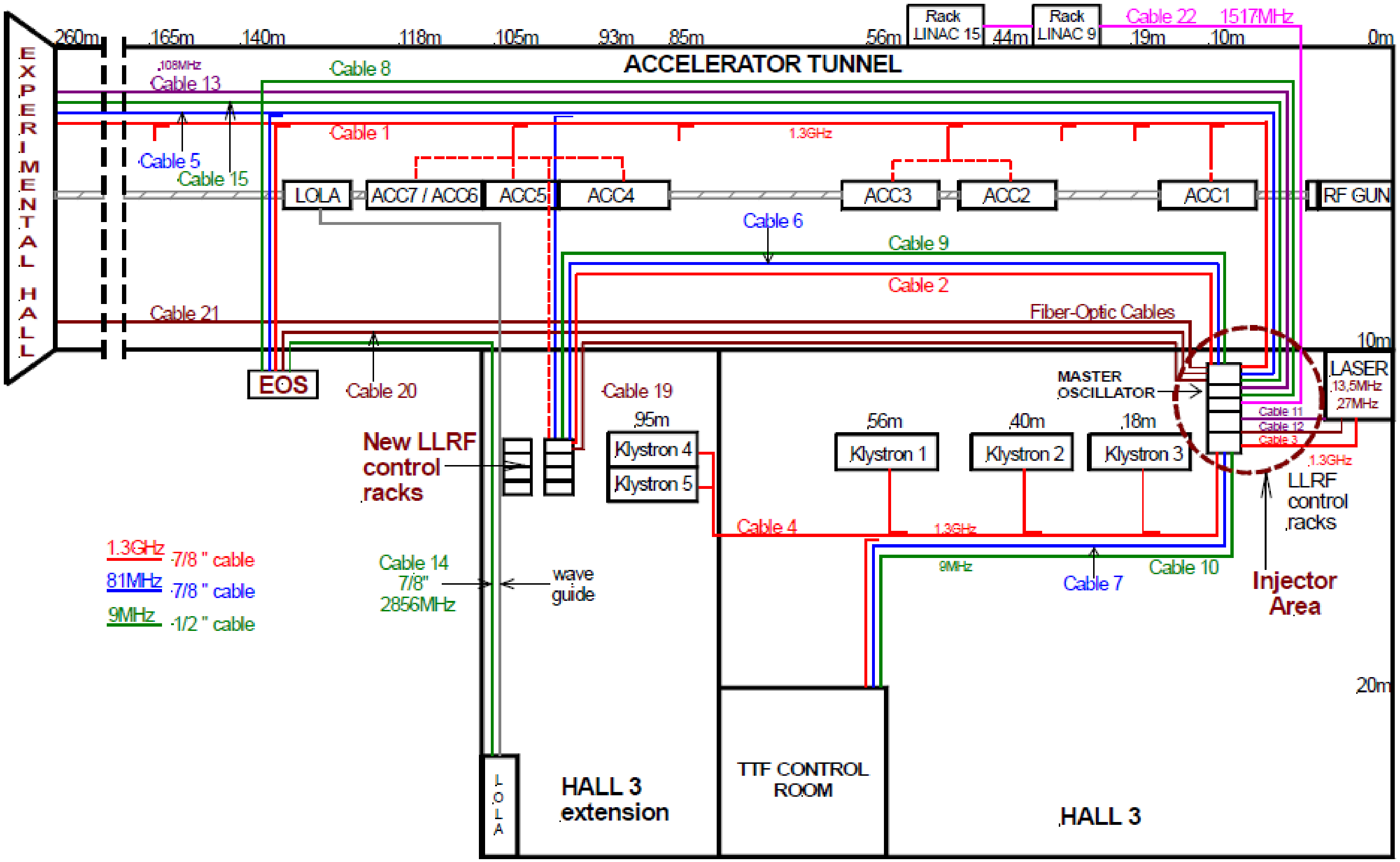
Operation Experience with New MO

Generated and distributed frequencies:

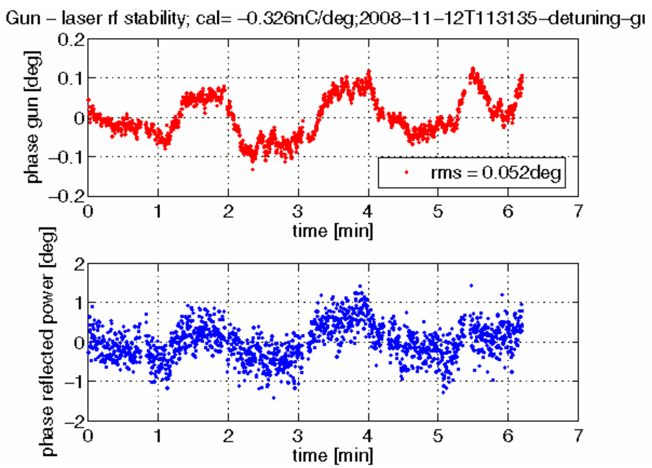
50 Hz, 1 MHz, 9 MHz, 13.5 MHz,
27 MHz, 81 MHz, 108 MHz,
1.3 GHz, 1.517 GHz, 2.856 GHz

- RF power levels adequate for all users
- Less complains about phase stability related to the new MO
- Less sensitive against touching cables
- Extensive diagnostics allows for on-line monitoring of phase drifts and power levels
- No failures (survived power outage)

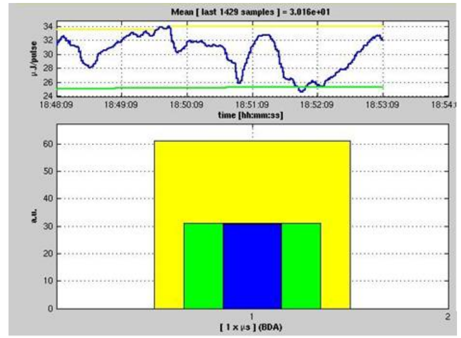
Layout of the Distribution System in FLASH

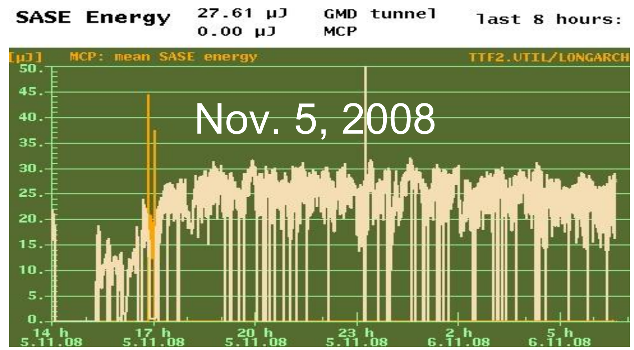


RF Gun Stability



Before calibration

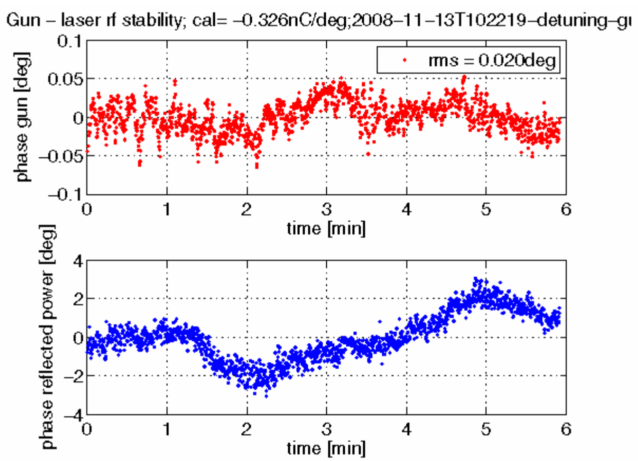




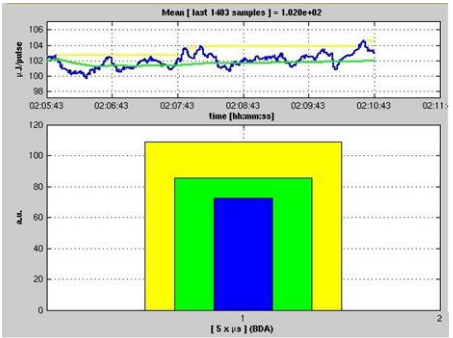
RF Gun field measurement calibration

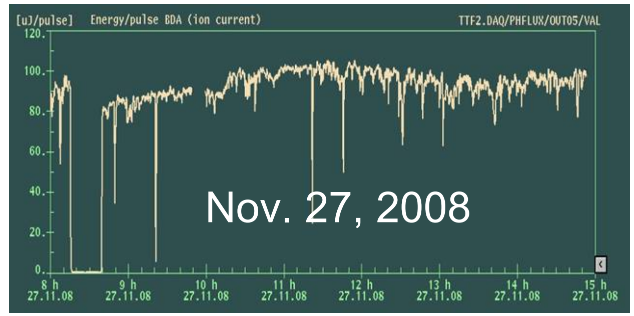
$$U_{trans} = U_{for} + U_{ref}$$

SASE intensity fluctuations down from 25% to a few percent



After calibration



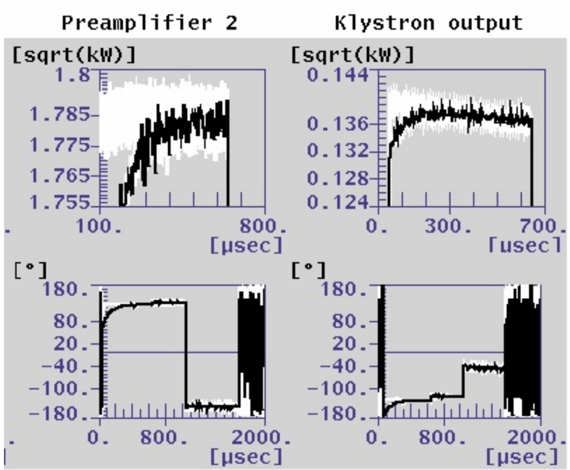


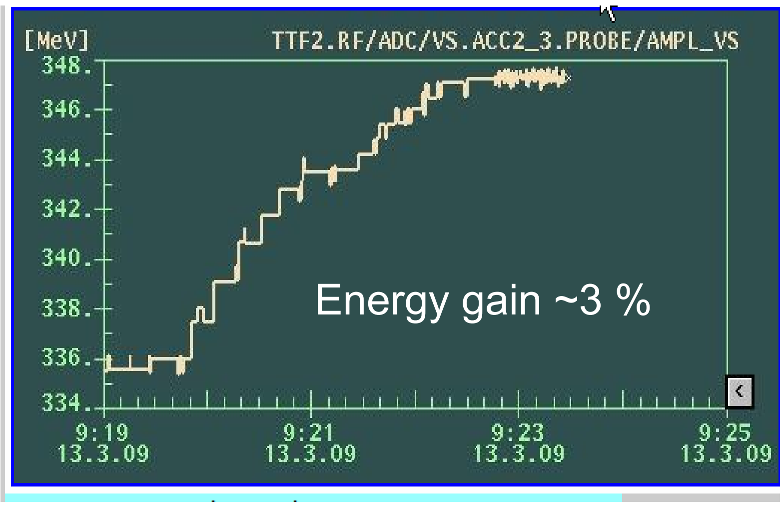
Optimization of HPRF Drive Control

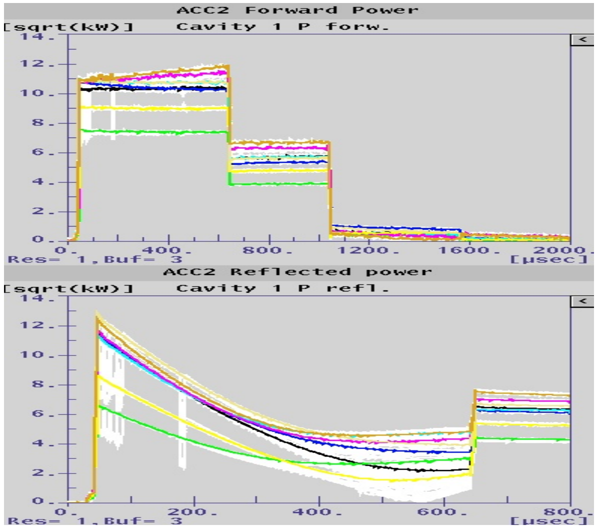
Goal: Efficient use of RF power and reduction of coupler trips

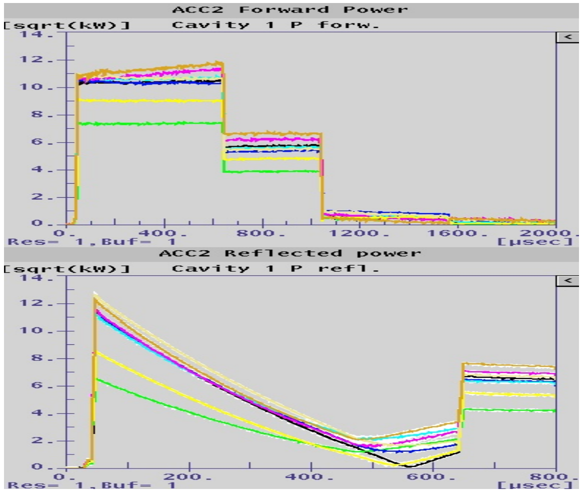
Phase modulation during filling

Minimum reflection at the end of filling time has been reached



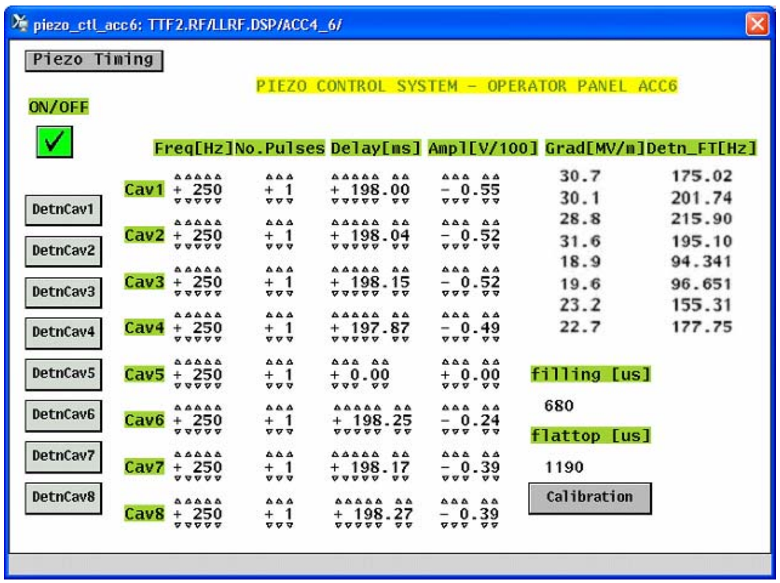


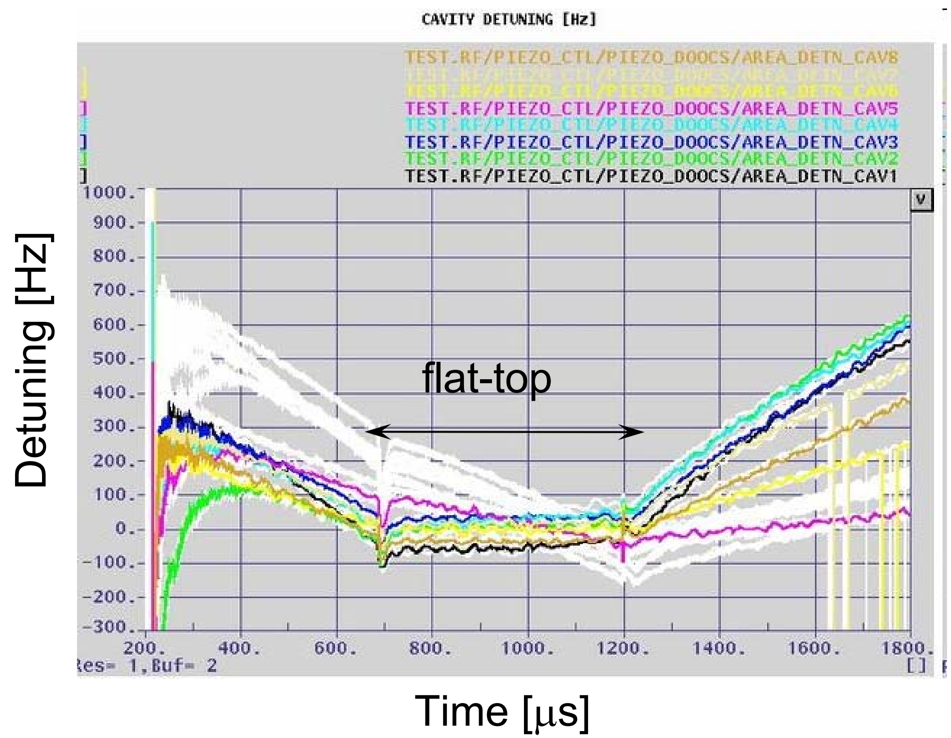




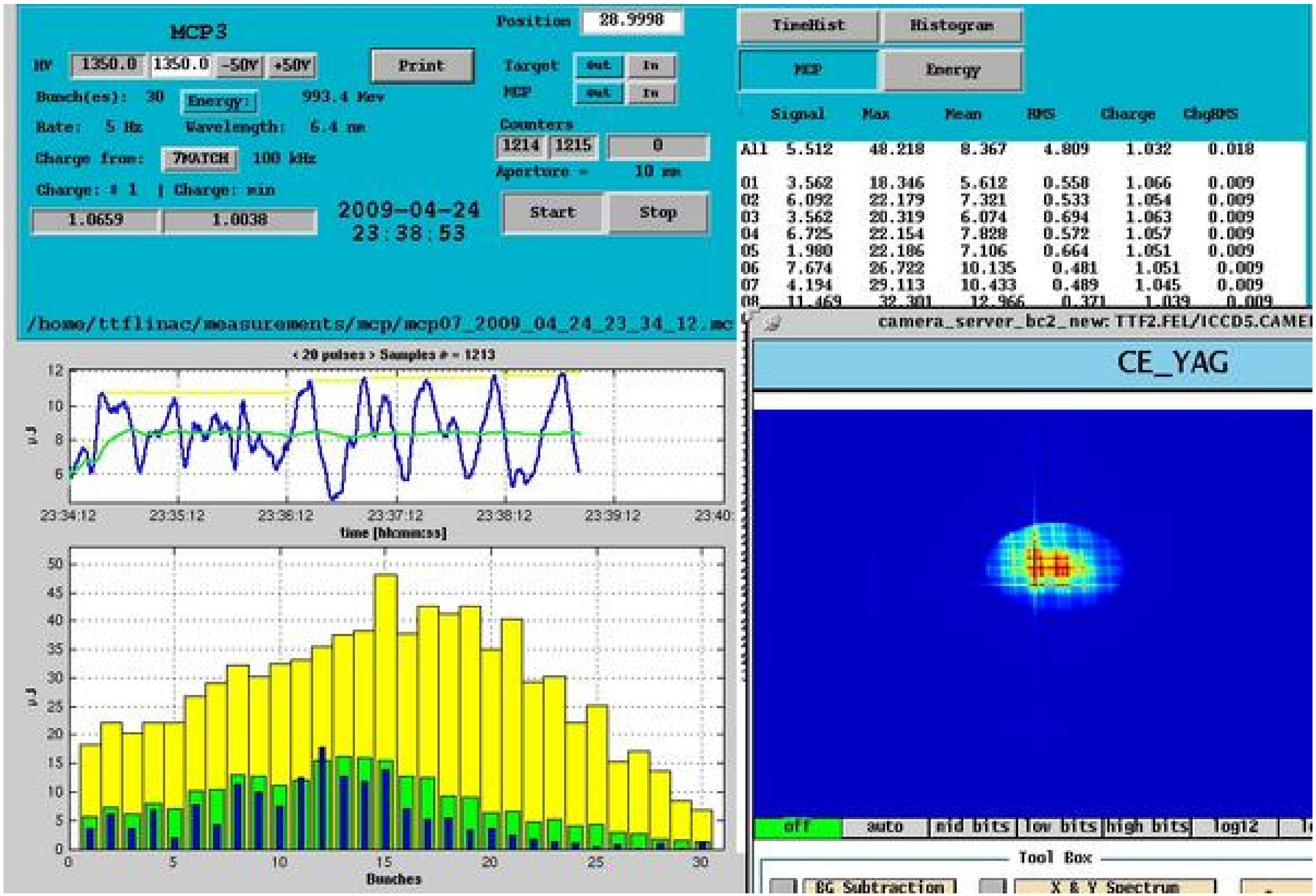
Piezo Control

Permanent piezo control system installation at ACC3, ACC5 and ACC6 with operator interface





Piezo Control: Influence on SASE Level



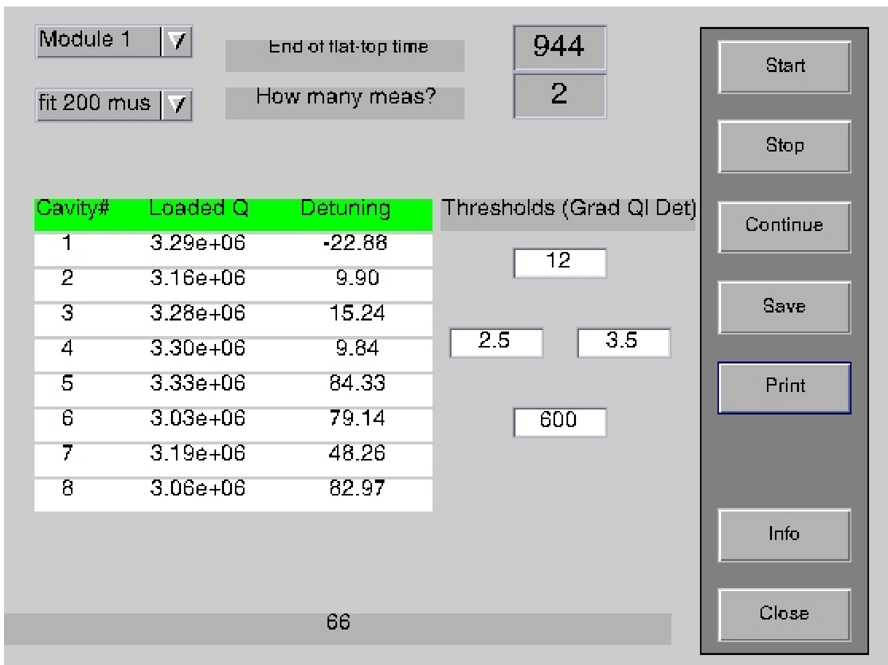
Examples for LLRF Exceptions

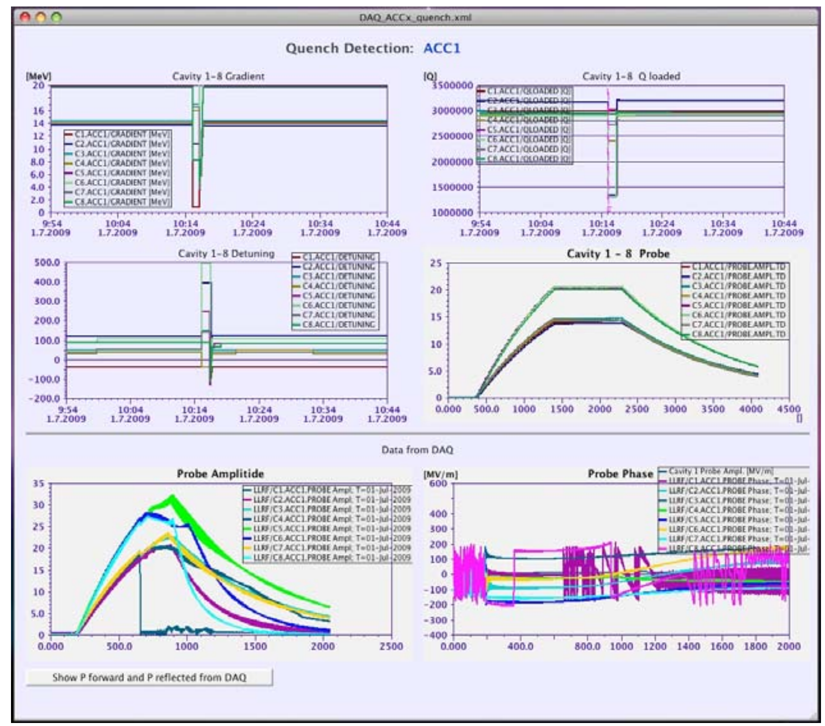
Table 1: Examples for Exceptions, their impact, countermeasures and the resulting improvement

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

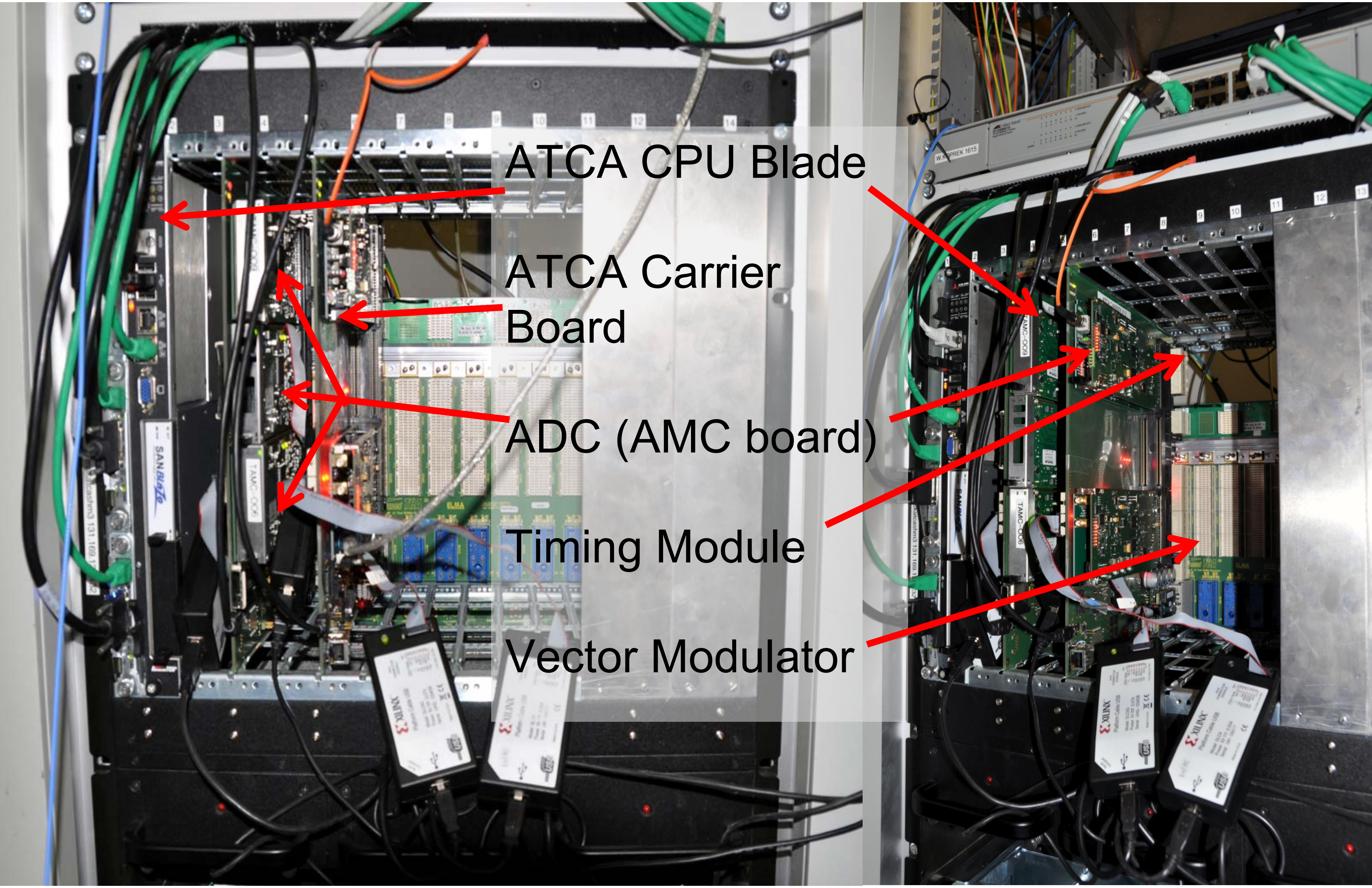
Quench Detection and Handling

- Fast / slow quench detection
- BIC interlock interface
- DOOCS quench detection middle layer server





ATCA-based LLRF System: It Works!



ATCA Set-up in Lab with 4 Carrier Blades

List of Operator and LLRF Expert Functions

Operators:

Setting VS ampl. and phase

Beam loading compensation

Feedback and feedforward

Adaptive feedforward

Feedback gain

Fill and flat top duration

Beam based feedbacks
- Compression (injector)

Slow quench detection

Experts:

Incident wave and loaded Q adjustment

Calibration of VS

Energy profile along bunch train

Cavity slow tuning

Lorentz force compensation

Loop phase adjustment

Loop gain calibration

Measurement of beam phase

Gradient calibration

RF power calibration

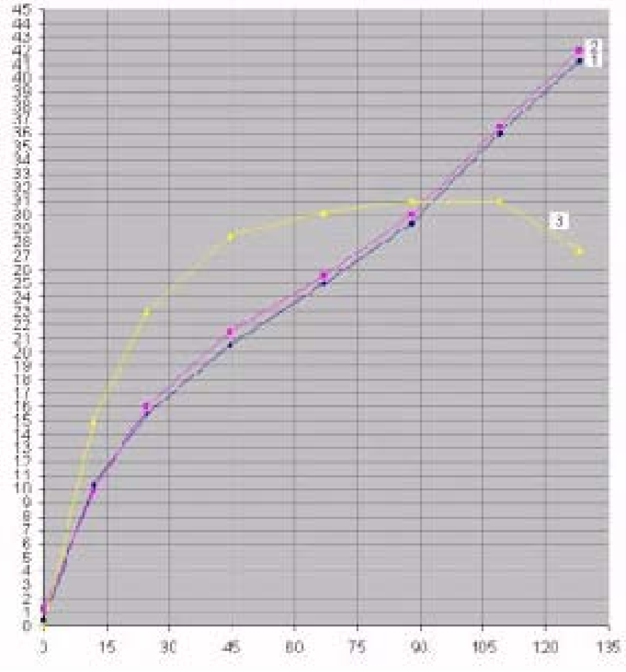
Beam based feedbacks
- Bunch arrival (experimental)
- Beam energy (experimental)

Real time quench detection

Cavity Loaded Q and Phase Adjustment

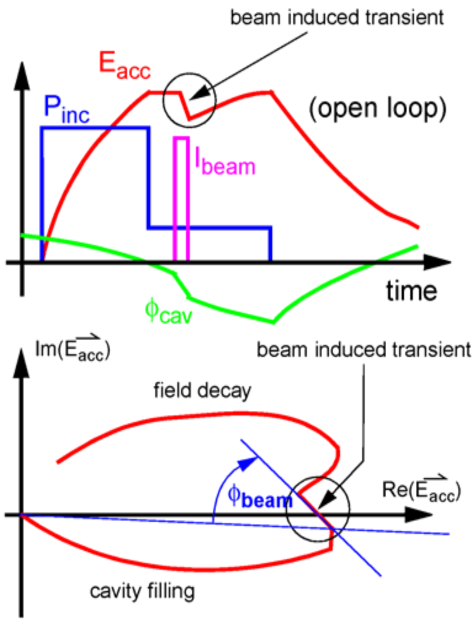
Motorized three stub waveguide tuners are in use

- Different type of tuners at ACC6
- Phase range up to 120 deg.
- Improvement from ±30° to ±3°



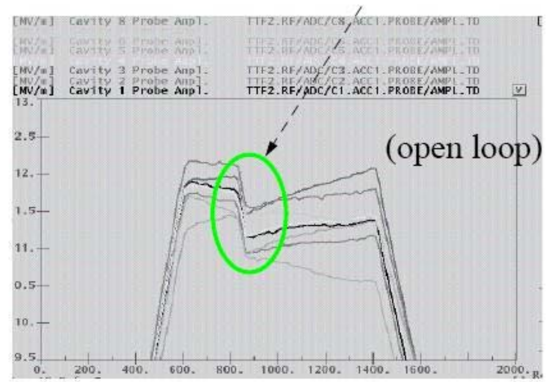
Beam-Based Calibration with Moderate Charge

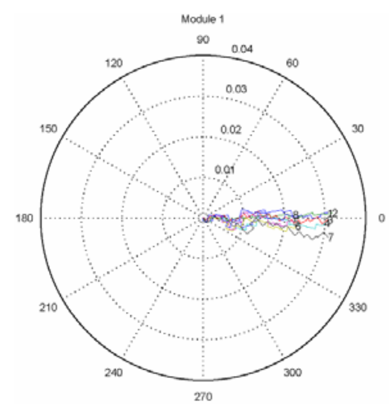
- Preliminary calibration by RF measurement
- Good beam requires: requesting 240nC, usually we got 100 -120nC



for $\Delta t \ll \tau_{cav}$:

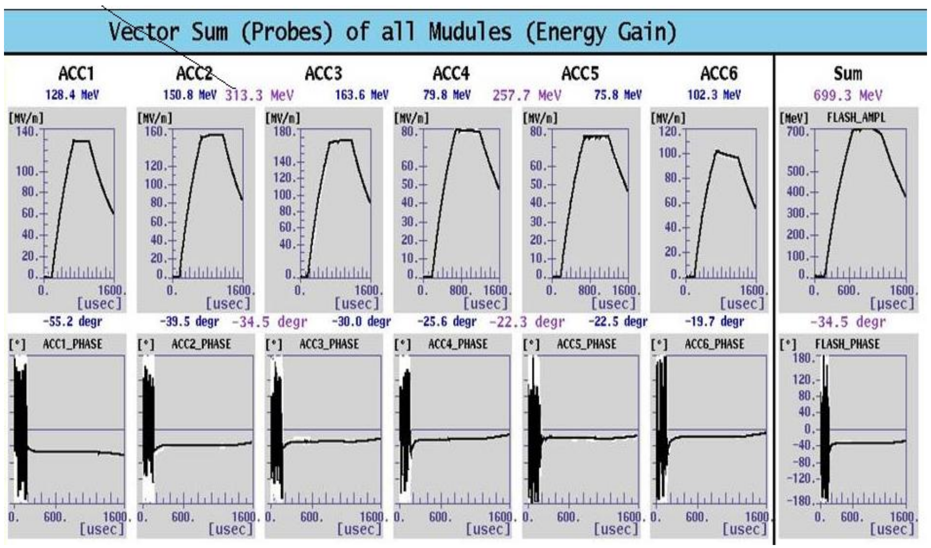
$$\Delta V_{ind} = I \cdot \Delta t \cdot \left(\frac{r}{Q}\right) \cdot \pi \cdot f$$

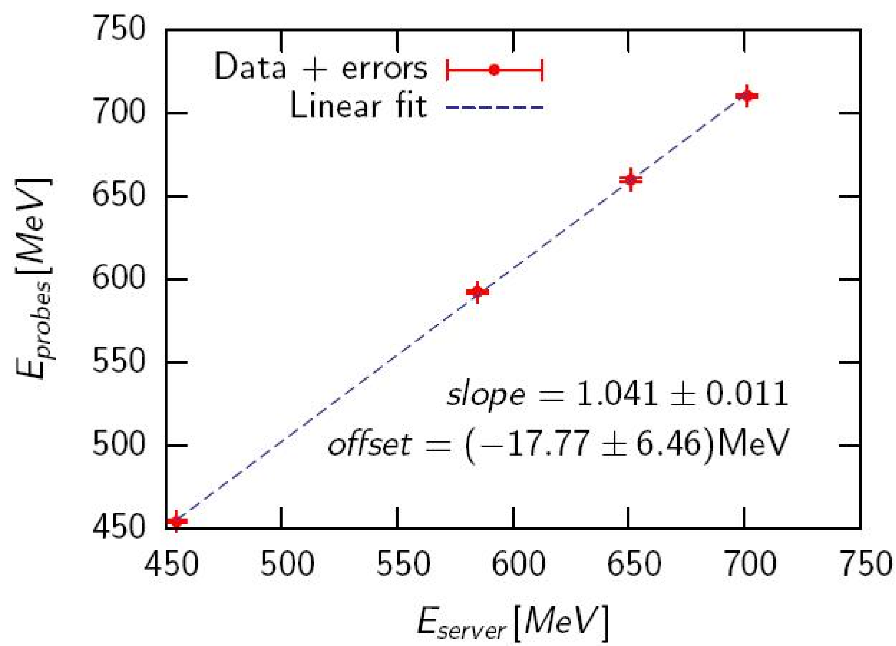




Energy Based Calibration

- Calibration with energy gain measurement by cavity / module detuning (together B.Faatz)
- Different methods are in agreement with ~1%

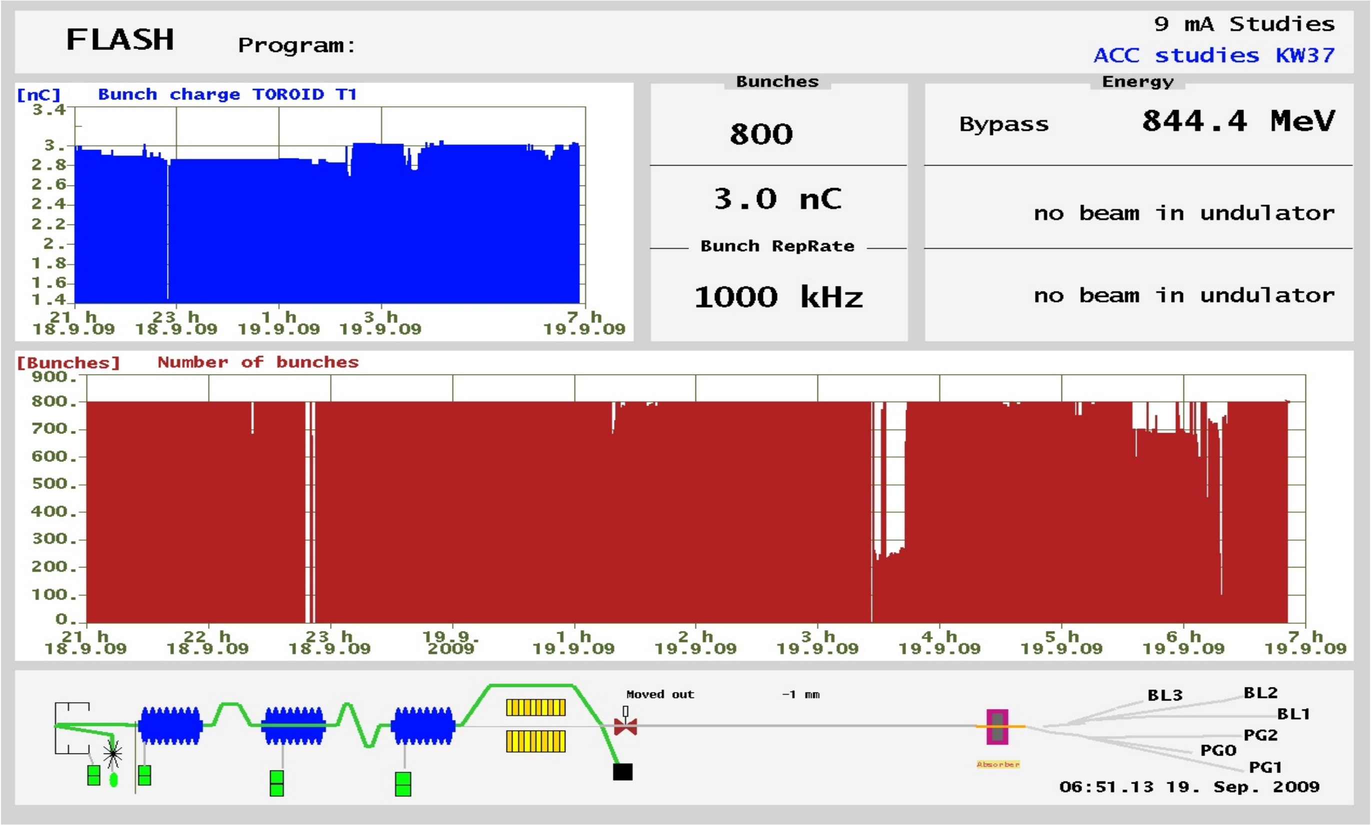




Courtesy: R.Kammering

ILC 9mA Test

- Stable operation at 1MHz beam repetition rate was achieved, resulting in stable 3mA running with a full 800us pulse for over ten contiguous hours.
- Quick start-up after machine access (40 min)
- Several hours of operation at ~9mA but with short trains (300-500us)
- Achieved full pulse length (800us, 2400 bunches) at 6mA for short period



Typical Problem in the LLRF System

Phase drifts of the order of few degree per day.

- Cables, connectors, MO, downconverter

Reproducibility of cavity fields especially cavity phases with respect to the beam after maintenance period.

Large changes of settings (wave length) require presence of rf expert

- Loop phase (if klystron HV is changed)
- Feedforward table
- Beam loading compensation
- Feedback gain
- Vector-sum calibration (sometimes)
- Cavity tuning
- Timing (pulse length)

LLRF expert needs to be available several hours per week to help with different types of problems

Note 1: Often LLRF is blamed for problems in other systems

Note 2: Sometimes LLRF induced downtime is caused by operator error

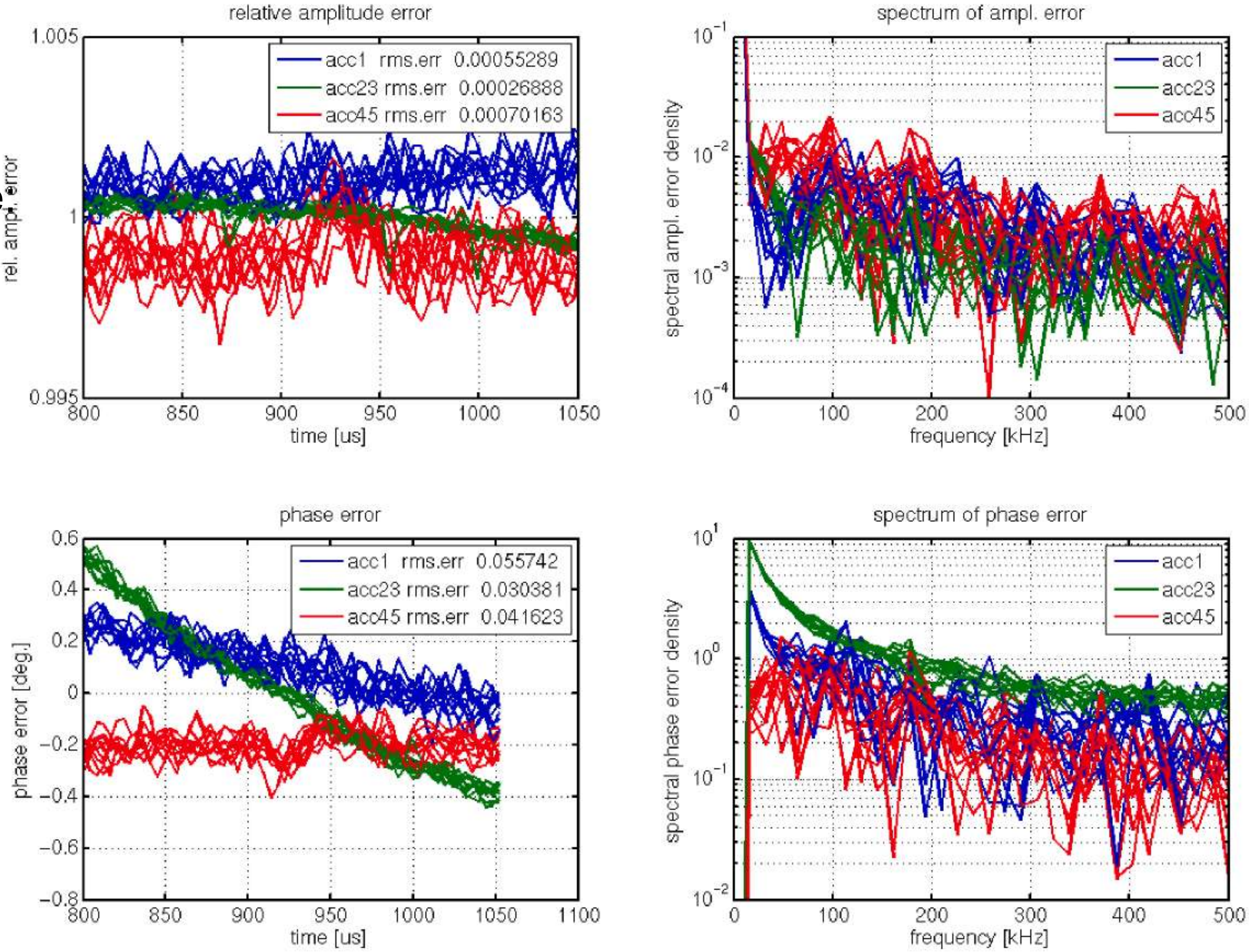
Field Stability in ACC1, ACC23, ACC456

Amplitude:

0.03 %

Phase:

0.03 deg.



Beam Stability – **Performance** Tests at FLASH

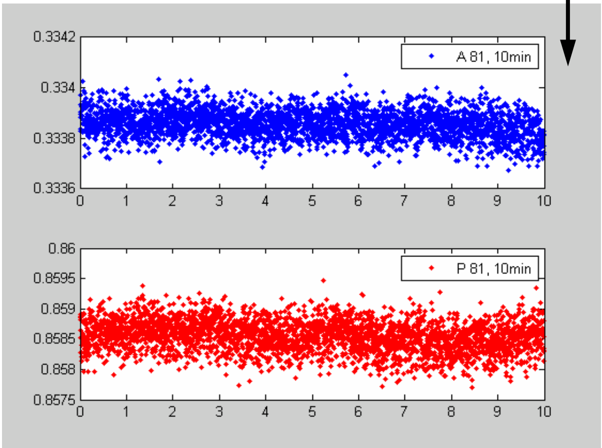
- Stability lab results (single channel) :

Short-term, bunch-to-bunch (800us) :
$\Delta A/A_{rms} = 0.015\%, \quad \Delta\varphi_{rms} = 0.0092\ deg$

Mid-term, pulse-to-pulse (10min) :
$\Delta A/A_{rms} = 0.016\%, \quad \Delta\varphi_{rms} = 0.0147\ deg$

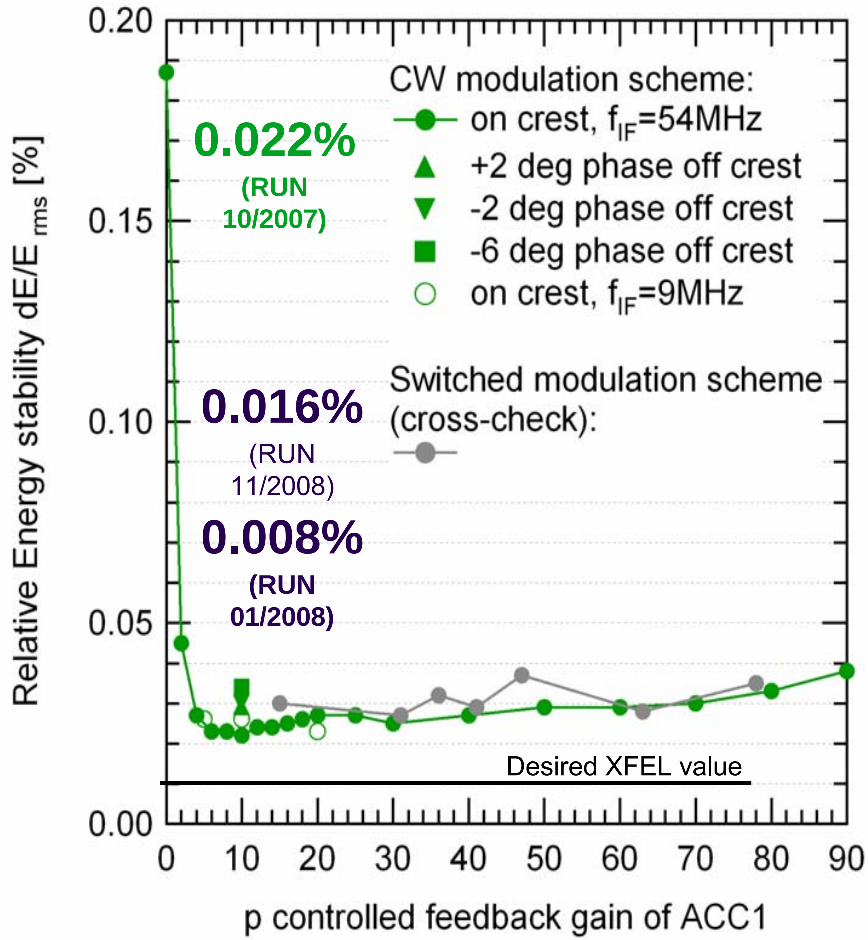
Long-term, drifts (1hour) :
$\Delta A/A_{pkpk} = 0.09\%, \quad \Delta\varphi_{pkpk} = 0.05\ deg$
$\theta_A = 2e\text{-}3/°C, \ \theta_P = 0.2°/°C$

BW=1MHz
BW=1MHz



Parameter :
- VME active multi-channel receiver, Readout bandwidth 1MHz
- LO / IF leakage –72dB, Crosstalk –67...-70dB
- SIMCON DSP (14-Bit ADC)

- Pulse-to-Pulse Beam Stability

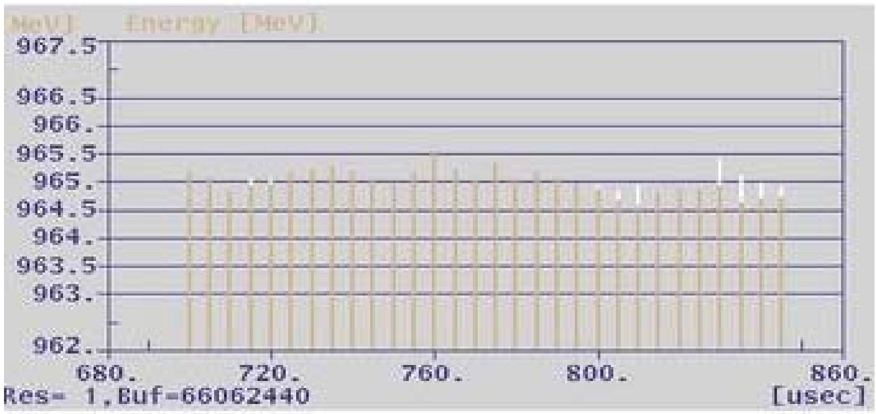


EUROFEL DS3.9, Delivery Report 01/2008, F.Ludwig et.al.

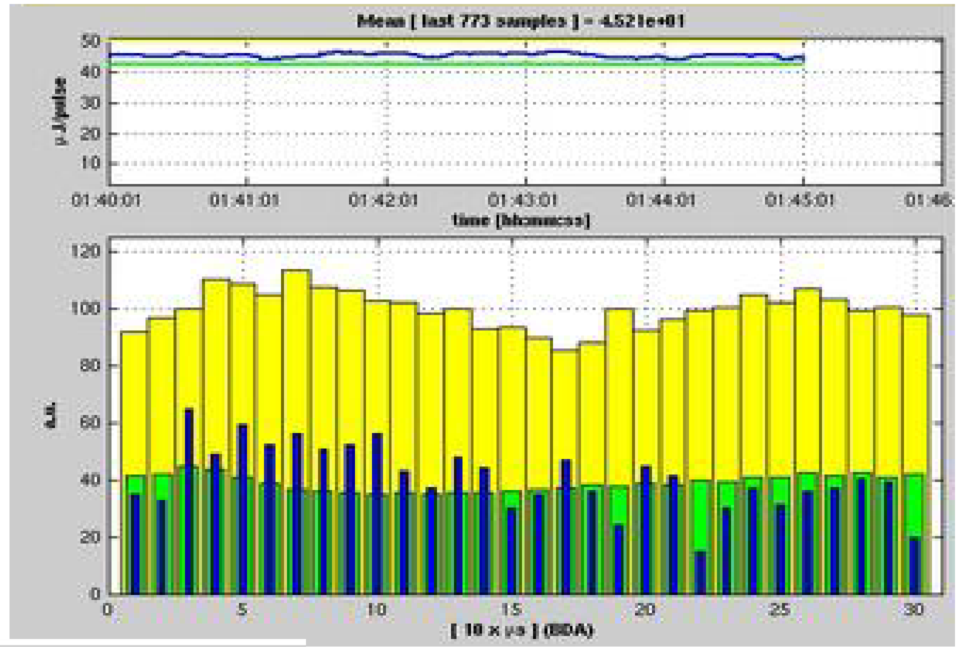
Energy/SASE Performance

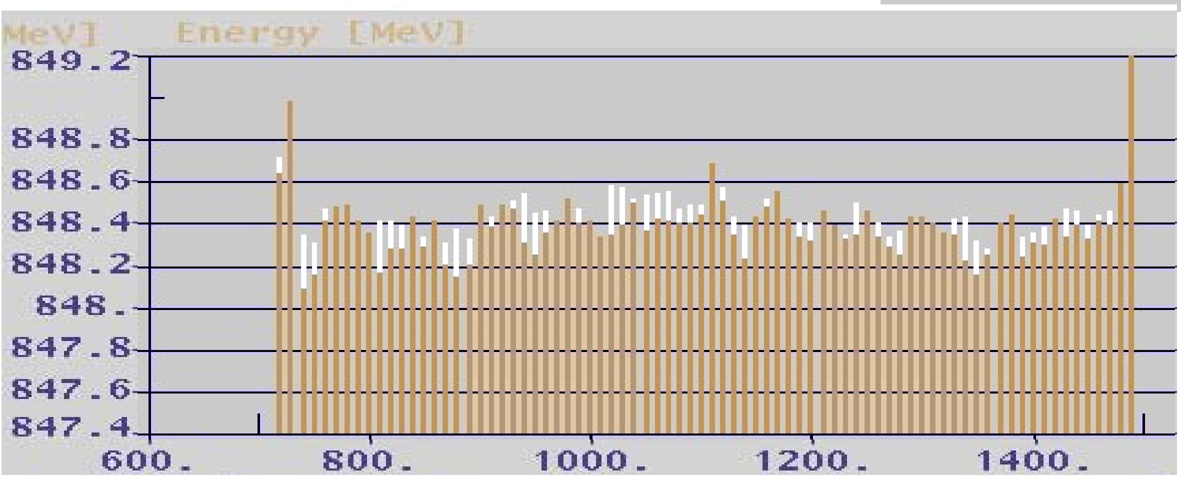
0.02% rms flatness over pulse train

45 μJ for10x10 mm apertures, 100 kHz at 7.02 nm



30 bunches, 100kHz, ~1nC





80 bunches, 100kHz, ~3nC

Upgrade Plans

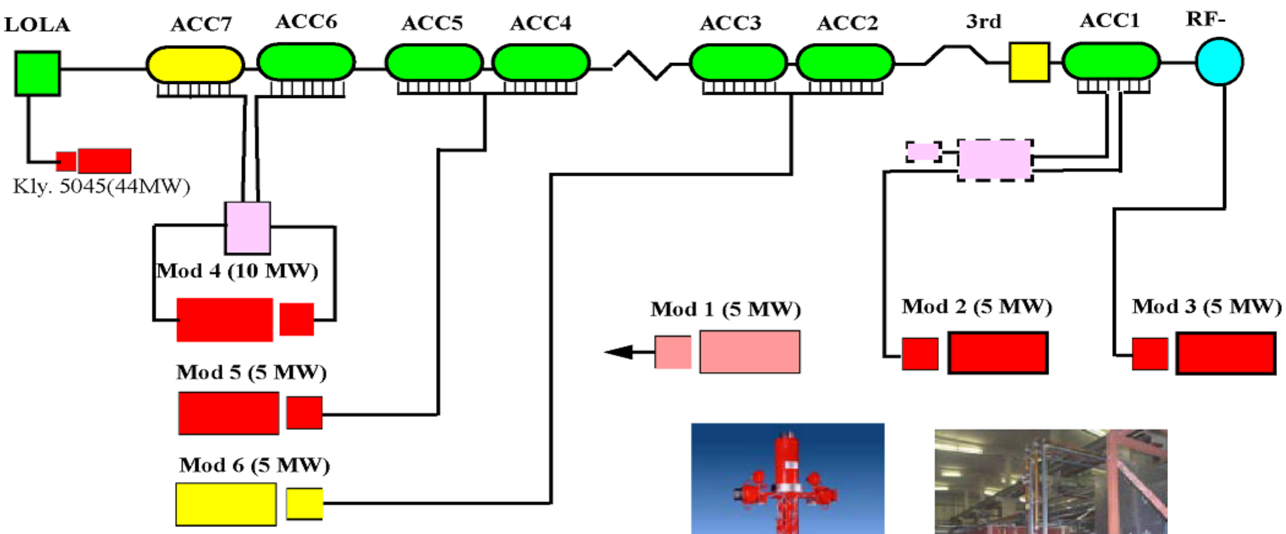
RF upgrade in 2009/2010: major modifications

– installation the 3rd harmonic (3.9 GHz) accelerating module

– installation of the 7th accelerating module → energy up to ~ 1.2 GeV ↔ <5 nm

– exchange of the RF gun

– upgrades of RF stations and waveguide distribution

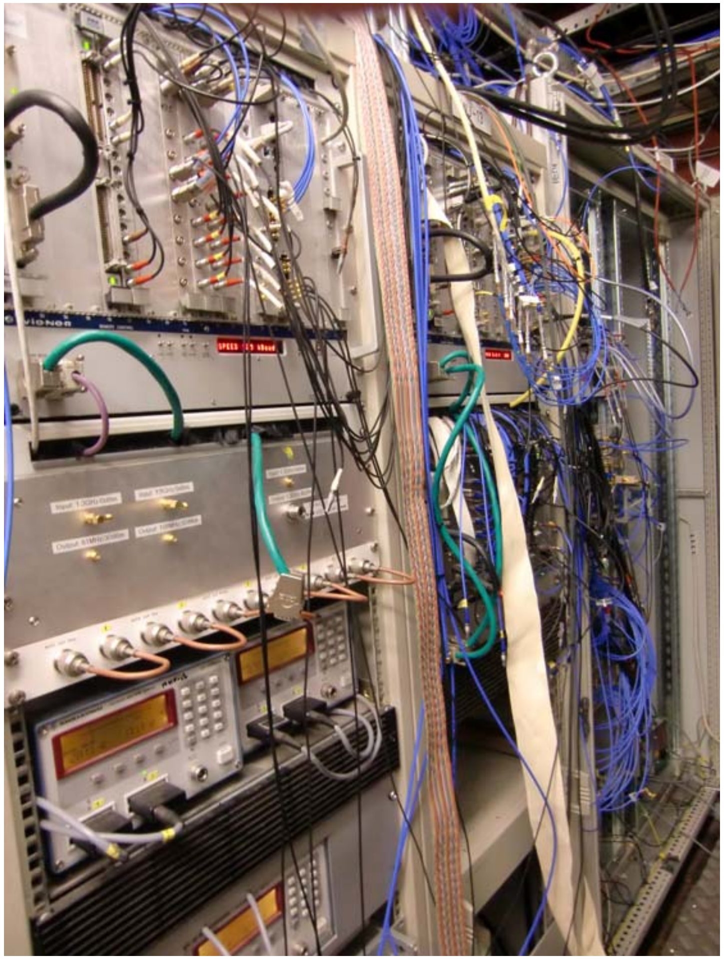


LLRF Installation after FLASH Upgrade

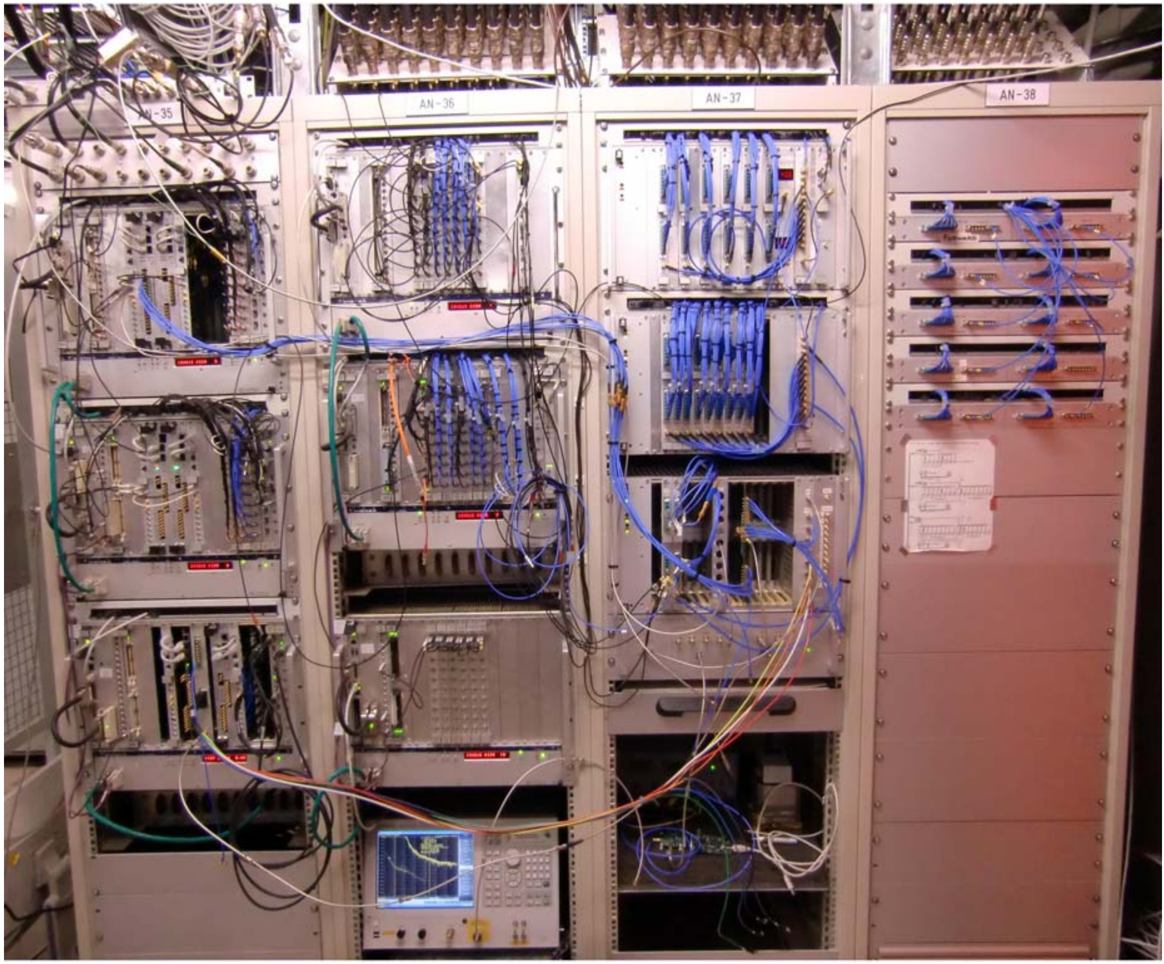
RF System	User operation	Development	Backup
RF Gun	SIMCON	-	DSP
ACC1	SIMCON x1 250 kHz IF	ATCA 54 MHz	DSP 250 kHz
ACC39	SIMCON 54 MHz	-	LIBERA
ACC23	SIMCON x2 250 kHz	-	DSP 250 kHz
ACC45	SIMCON x2 250 kHz	ATCA 54 MHz	DSP 250 kHz
ACC67	SIMCON x2 250 kHz	-	ATCA 54 MHz

DSP (2000), SIMCON (2006), ATCA (2009)

Status of LLRF Installations



GUN, ACC1



ACC23, ACC45, ACC67

MO: Upgrade Plan During Shutdown

- Installation of the second Master Oscillator (90% done)
- Installation of new 1.3 GHz power amps (higher output power to compensate for cabinet cable losses)
- Cleaning up cables in the injector area

  - new cabling for ACC1, ACC39 (ACC1, ACC39 dev.) systems(?)
- New subdistribution rack in Hall 3 extension to provide more „tap points" for MO signals with diagnostics
- Improve DOOCS data aquisition/logging

LLRF Improvement Plans

- Improve long term phase stability (which is of the order of few degrees)
- Fix problems with adaptive feedforward / controller server
  - including handling of exceptions, variable beam loading
- RF Gun control (automatic start-up, calibration)
- Automated calibration of vector-sum
- Reproducibility
  - Restoring beam parameters after shutdown or interlock trip
- Slow feedback for pulse train stability (RF and beam based)
- Implement LLRF control system for XFEL at FLASH
  - improve field regulation, operability, availability, reliability
- Automation of LLRF operation
- High gradient and high beam loading require advanced applications
- Documentation

Conclusion

- RF control performance goals for FLASH achieved

  - 0.03% for amplitude and 0.03 deg. for phase (short term)

  - long term phase stability is +/- 1 deg. (concept for reducing long term drifts demonstrated)
- User FEL experiments in different fields have been performed successfully with RF feedback only
- The specific needs for improvement of the LLRF at the FLASH user facility have been understood
- In the coming years the LLRF at FLASH will be upgraded to the same systems as planned for the European XFEL
- More diagnostics & automation are required
- FLASH as a world-wide unique test facility for SCRF technology can be used parallel to user operation with high efficiency

More Info:

[**http://**mskpc14.desy.de/wiki/index.php/Main_Page](http://mskpc14.desy.de/wiki/index.php/Main_Page)