"LLRF system development for the XFEL and performance evaluation at FLASH"

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or

Why does the LLRF development require so little machine study time at FLASH

Outline

- Development for the XFEL
  - Strategy
  - Hardware
  - Software
- Performance Evaluation at FLASH
  - Machine Studies
- Upgrade Plans for FLASH

Tasks for LLRF System for XFEL

Design and build
XFEL LLRF System

Team building

Work Breakdown

Requirement Capture

Conceptual Design

HW Design

SW Design

Production

Install and Commission
LLRF System

Maintain LLRF
at FLASH

LLRF Machine
Studies
at FLASH

Improve LLRF
at FLASH

Strategies (1)

Design and build XFEL LLRF System

- Outsource
- COTS
- In-house
- Collaboration
- Copy

Install and Commission LLRF System

- Outsource
- In-house
- Collaboration
- Evaluate commissioning procedures at FLASH
- Install XFEL LLRF system at FLASH

Strategies (2)

Team Building

Hire qualified people with experience

Hire and train young people

Qualified collaboration

Train new collaboration

Requirement Capture

Industrial Study (long learning process)

Requirement writing by team (problem with experience)

Trial and Error

Learn from experience at FLASH

Strategies (3)

LLRF Improvement at FLASH

- Identify Problems with LLRF System at FLASH
- FLASH/XFEL equal priority
- Synergy FLASH/XFEL LLRF
- Dilemma:
  FLASH needs short term
  XFEL needs long term
  solution

Conceptual Design

- LLRF Review
- Learn from FLASH
- System Engineering Language
- System Engineering Tool
- System Engineering Methodology

Strategies (4)

HW Design

- SIMCON
- SIMCON DSP
- ~~SIMCON Gigalink~~
- ATCA

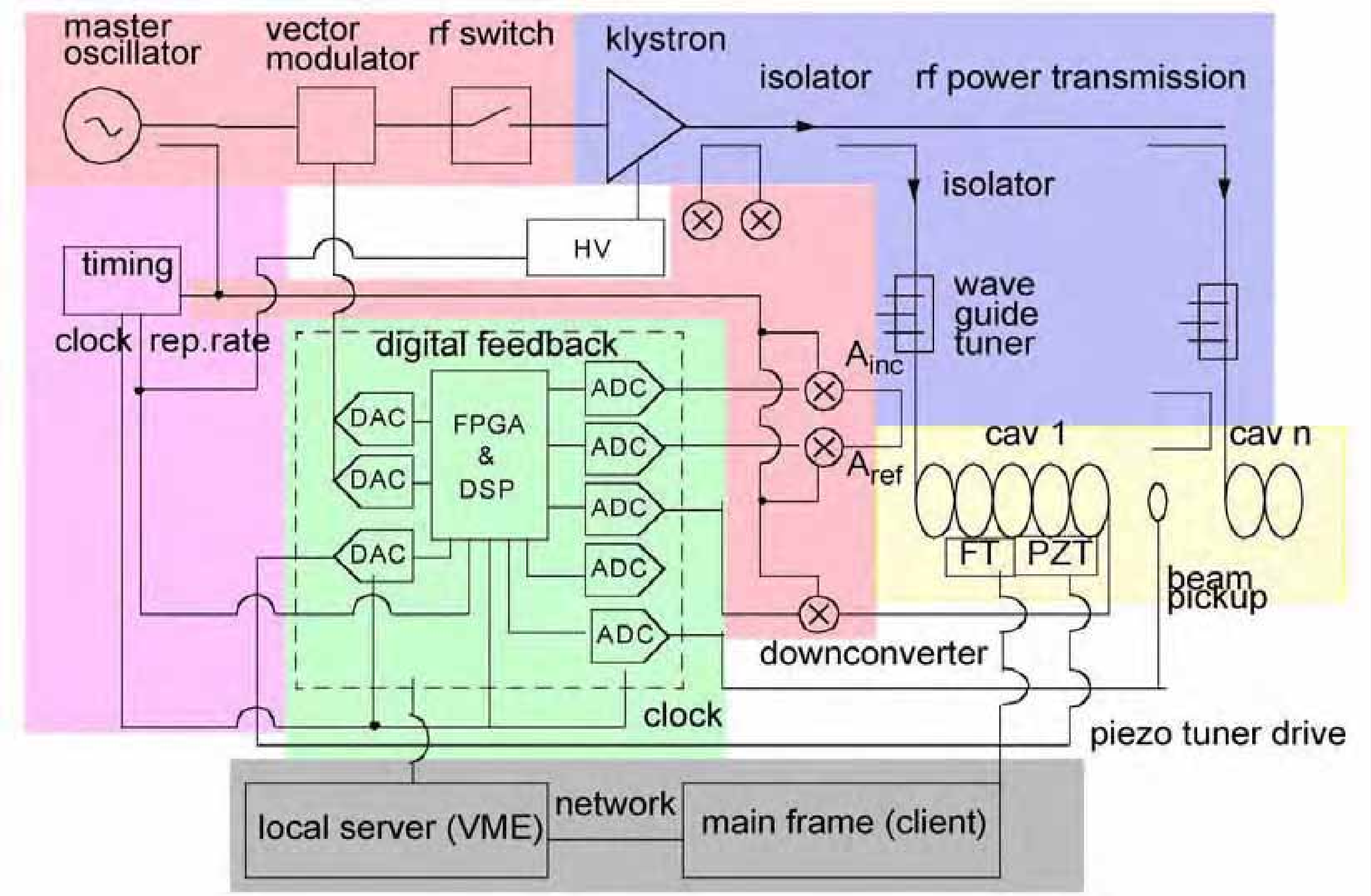
Evaluate Prototype at FLASH

SW Design

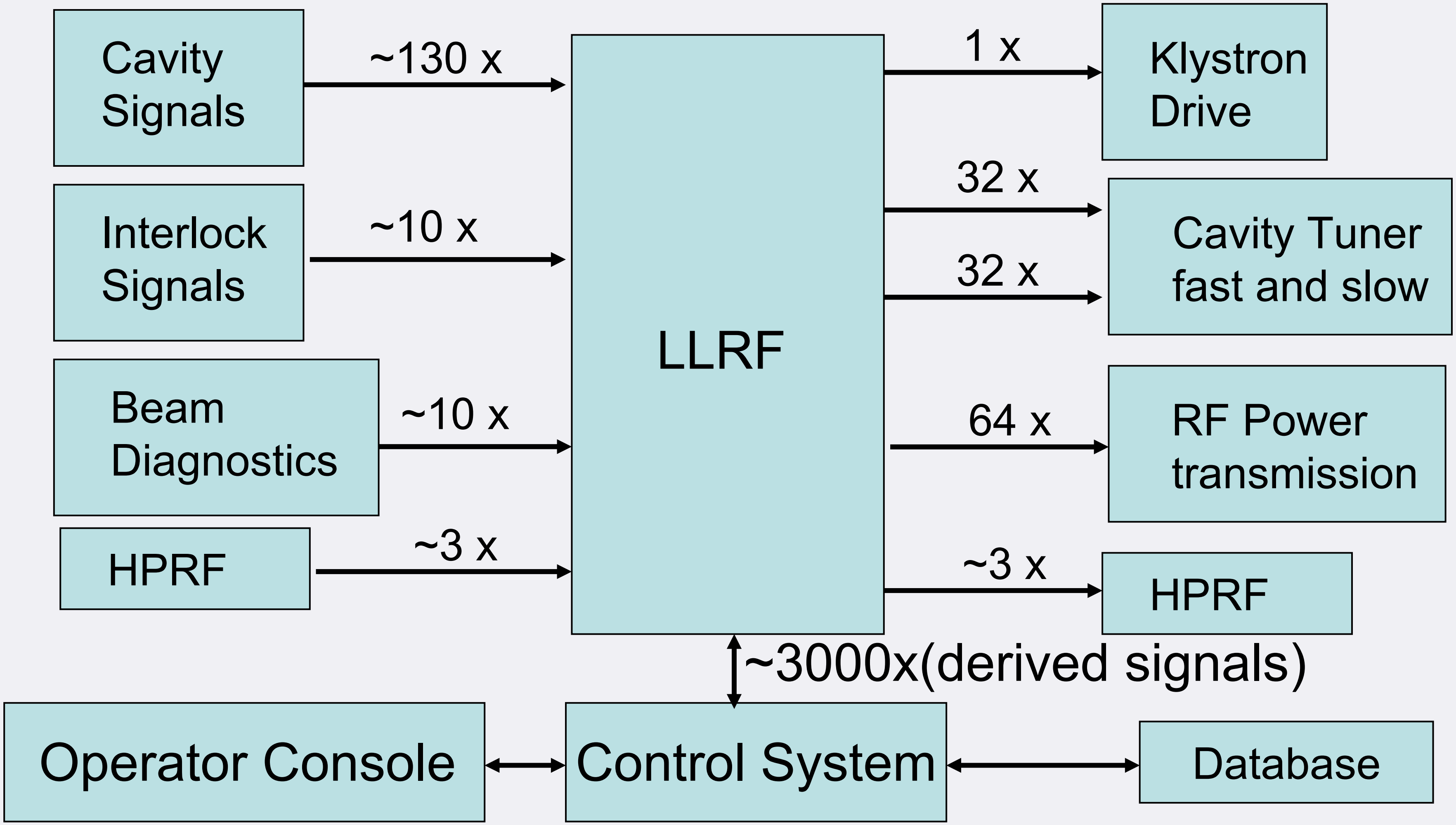
- SIMCON Development System at FLASH
- ATCA Development System at FLASH
- Studies at CMTB

Lab System Cavity Simulator

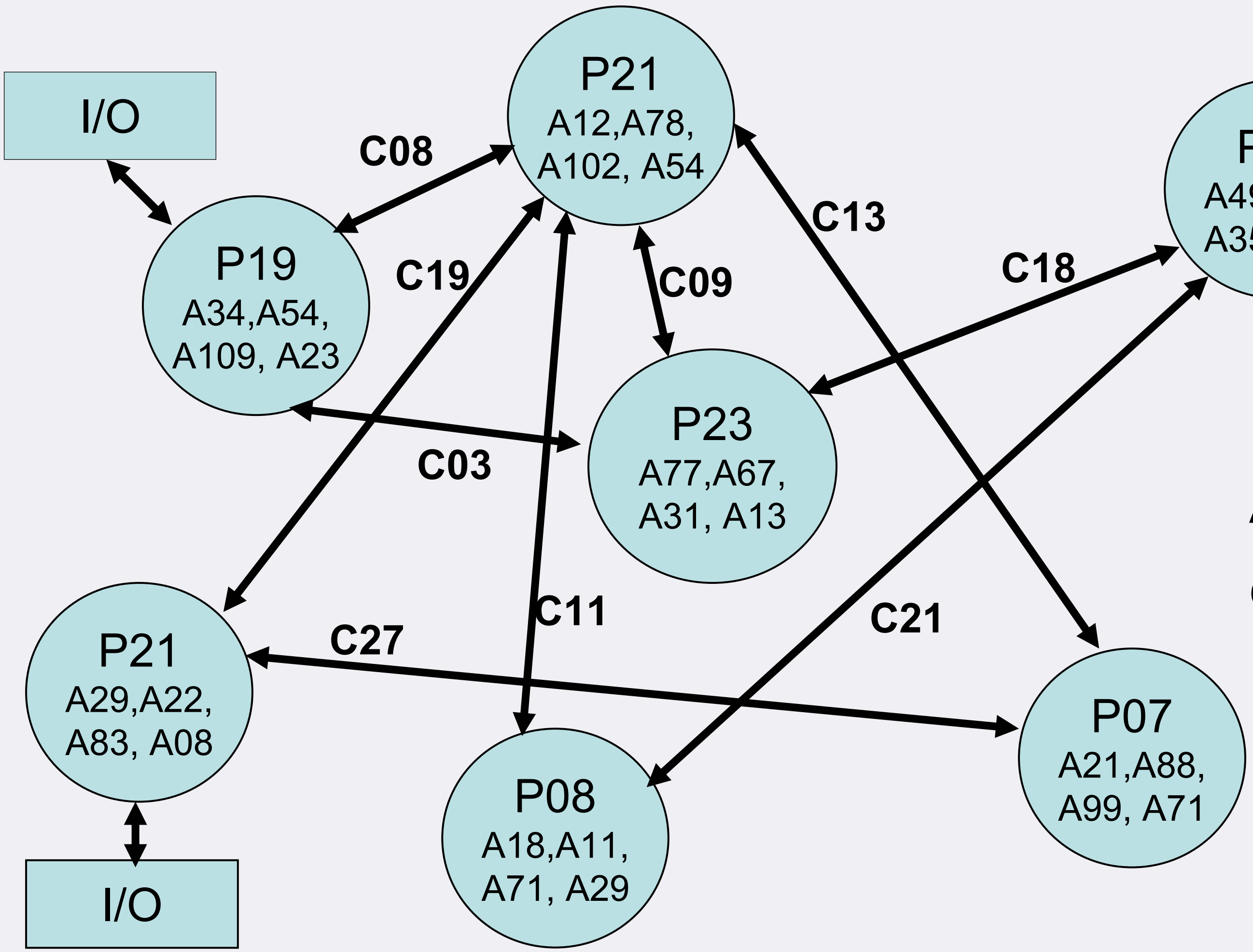
System Architecture Details



Signal diagram for RF Control (1 RF Station)



Challenge for Software Development



Pxz = Processor
(FPGA,DSP, CPU)

Anm = Application

Ckl = Communication Link

Use cases for LLRF System (RF Station)

Standby

Establish moderate RF power

Enable measurements

Field control

Calibration

Database
Application

Determine Performance Statistics

Beam Feedback

Energy
Beam load. Comp.
Bunch compression

Resonance Control

Motor tuner
Piezo tuner

Change Settings

Gradient
Pulse length, rep. rate
Beam current
Prepare new settings

Parameter Optimization

Field error
Robustness

Exception Detection and Handling

Klystron, Modulator
Power Transmission
Cavity, coupler
Frequency Tuners
Timing, Synchronization
LLRF hardware
LLRF software
Networks

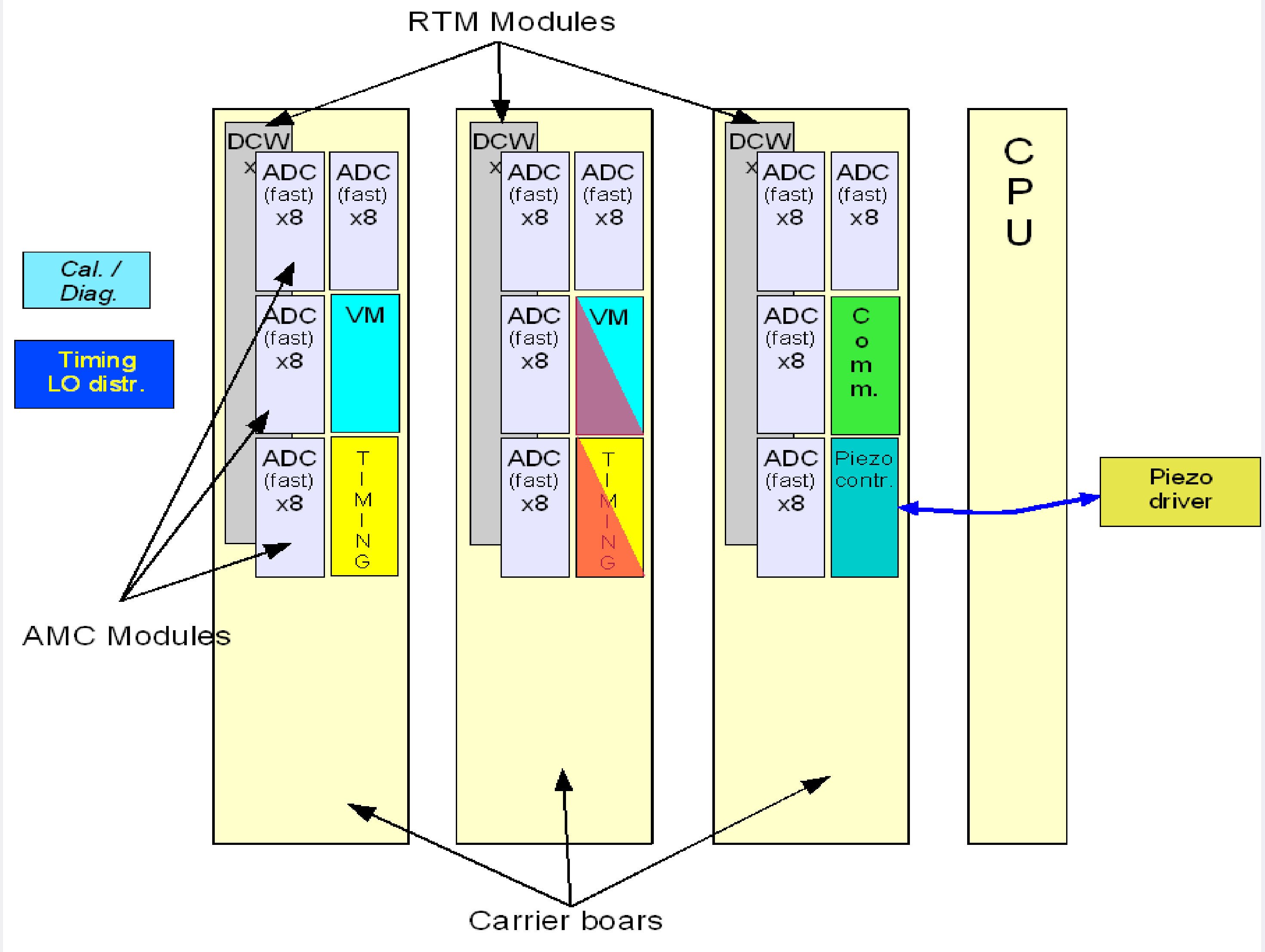
Main LLRF Requirements for the XFEL

1. Provide settability of voltage and phase to the desired values in all 4 quadrants up to a klystron peak power output level of 0.9*P_sat.
2. Maintain stability of voltage and phase of the calibrated and high precision vector-sum of individual rf stations within given tolerances for the range of useable operating parameters.
3. Provide highly stable rf references at specified frequencies at selected locations. Includes calibration reference signals.
4. Provide adequate interfaces to other accelerator subsystems.
5. Diagnose faulty or missing hardware and software and localize areas of functional and technical performance degradation including severeness of degradation. For use by operators and experts.

Main Requirements for the XFEL (Cnt'd)

6. Optimize and/or limit operational and system internal parameters such that the performance function based on rms field stability, accelerator availability, and component lifetime is maximized.
7. Provide a simulation mode, where the klystron-cavity system is replaced by a simulator and which provides performance predictions for planned parameter changes.
8. Provide a high degree of automation of operation to assist the operator and system experts.
9. Provide calibration functions for selected signals.
10. Provide low and high level applications supporting automation.
11. Provide exception detection and handling.
12. Provide operating modes for rf system conditioning (ex. coupler and cavity).
13. Support rf system and accelerator commissioning procedures.

Concept – modular system based on ATCA

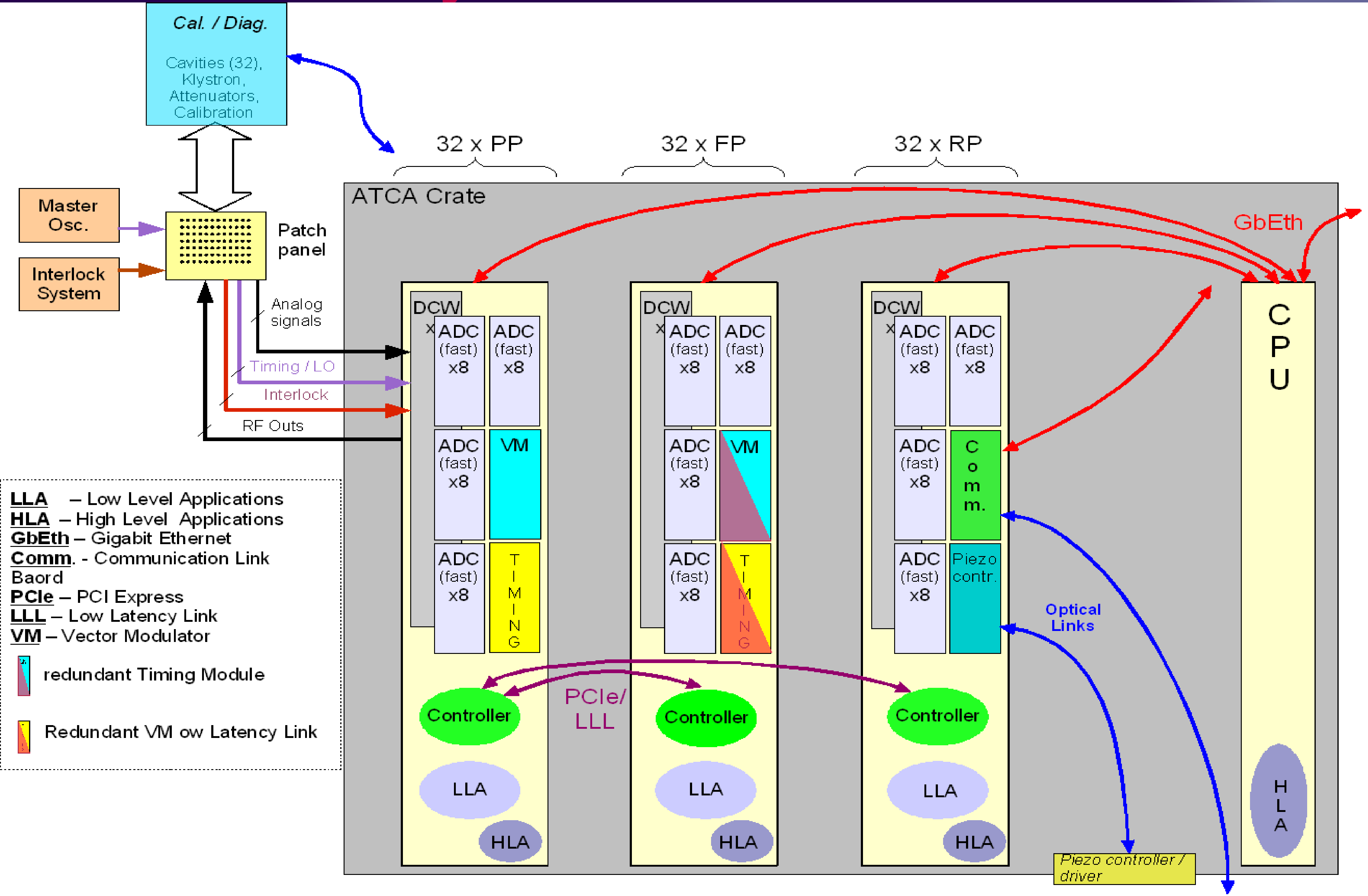


Problems:

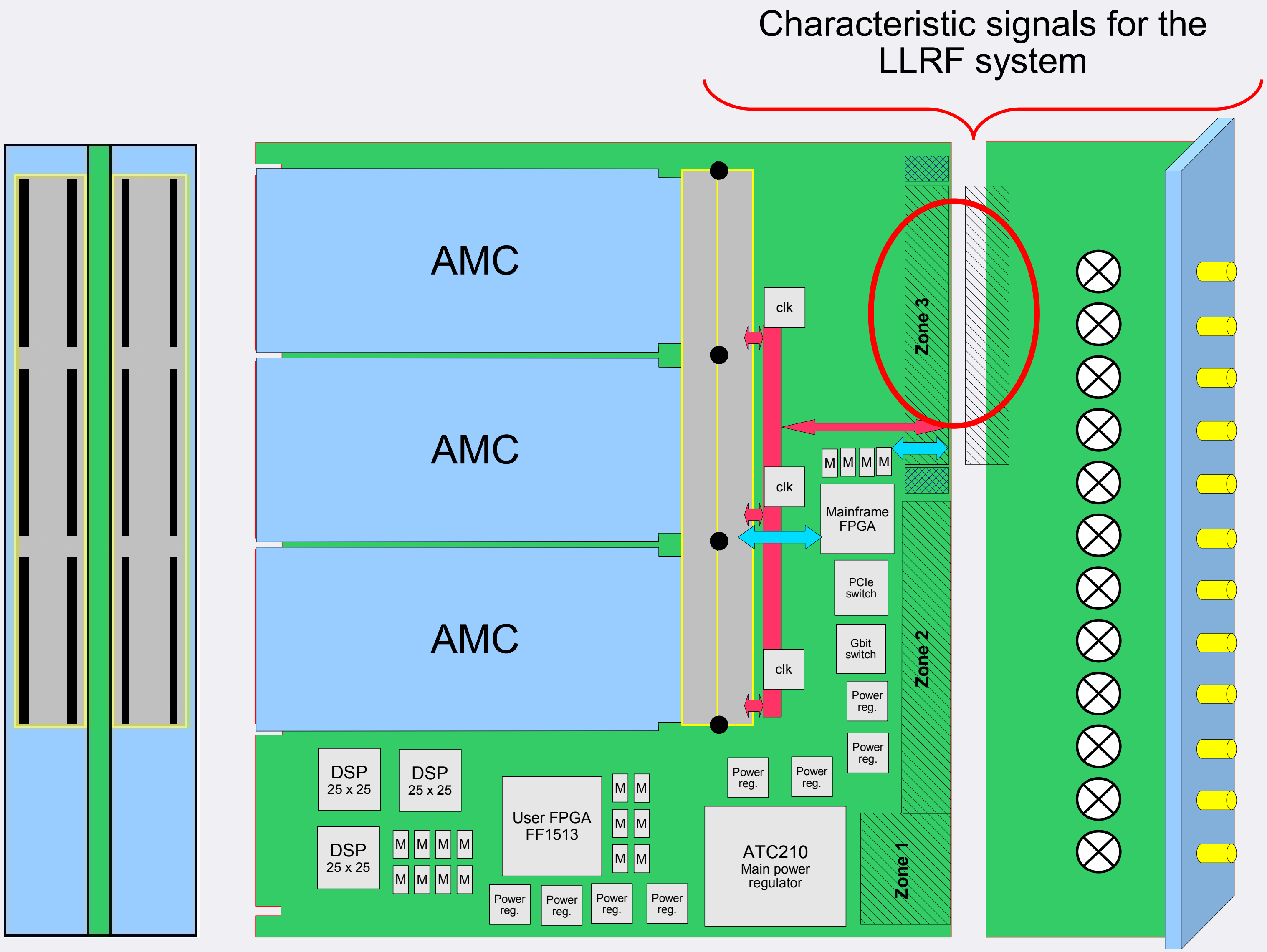
- analog signals in ATCA are not defined
- no analog IOs connected from rear

System Architecture

The European
X-Ray Laser Project

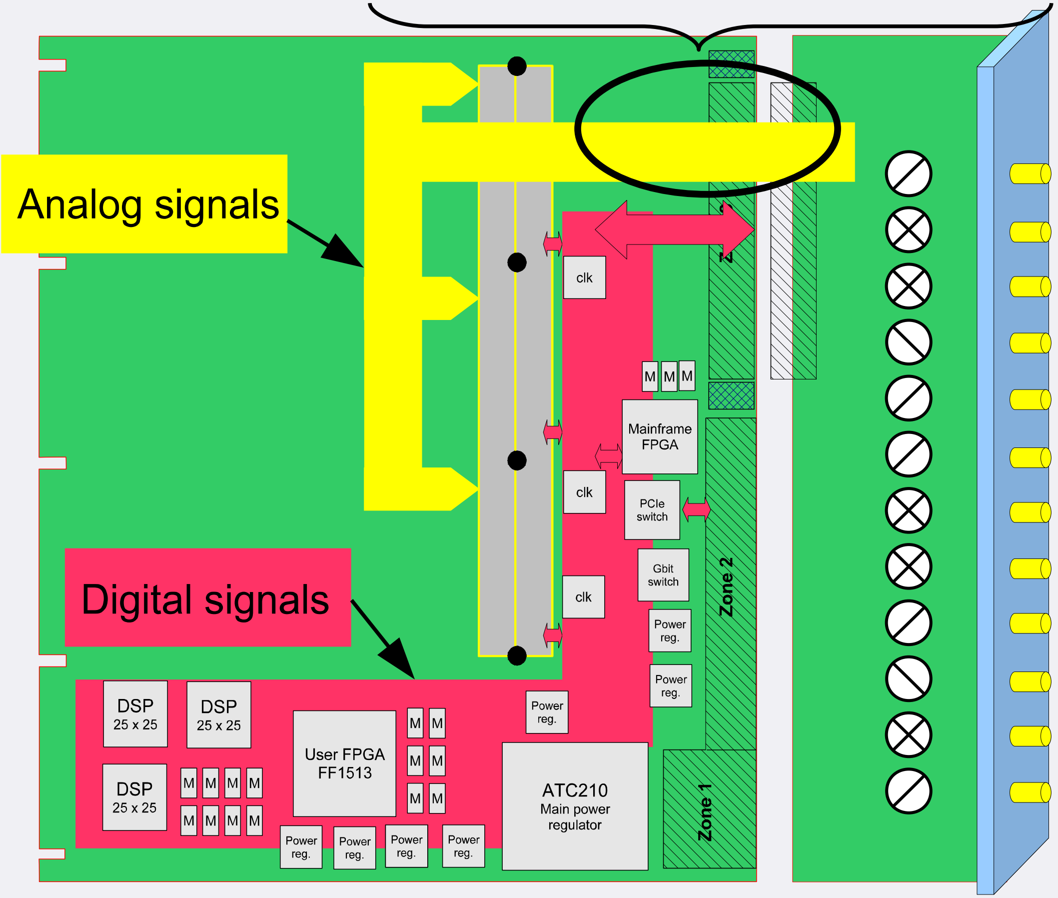


Carrier board - concept

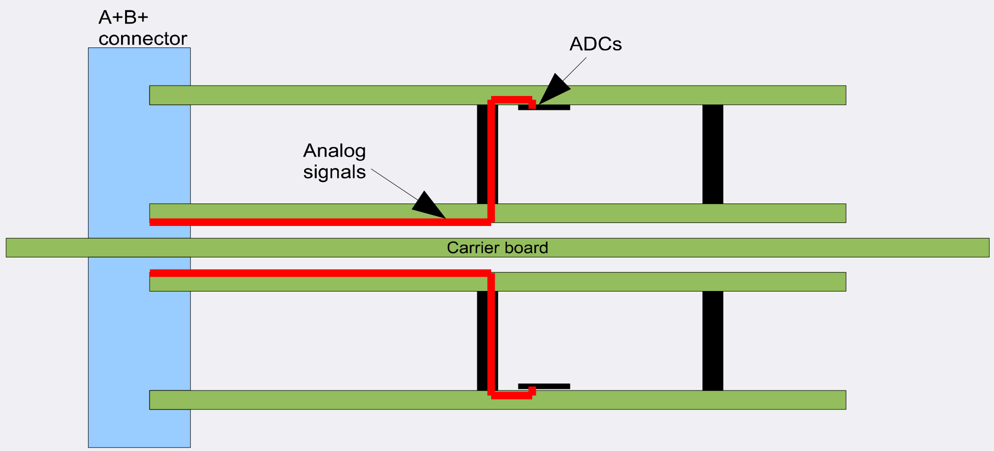


Analog signals

- 6 x 10 differential lines for IF (p-t-p)
- 6 RF output 1.3 GHz for VM
- reference clock – 1.3 GHz (multi drop)
- coded clock – 2.6 GHz (multi drop)



- Analog and digital lines are separated
- For analog signals and fast digital lines strip-lines are designed



The main aim of Piezo Control system

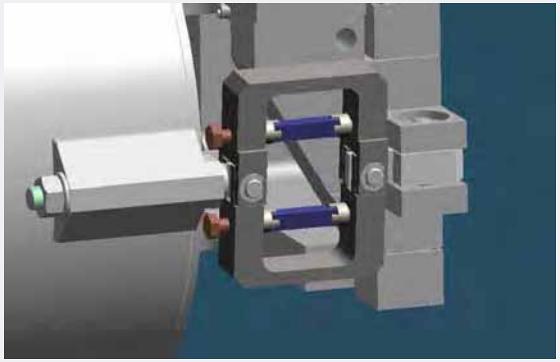
Drive the piezoelements assembled in fast tuners frames to minimize the Lorentz force and microphonics effects

Dimensions: **10x10x30mm**
Manufacturer: **NOLIAC**

On-line frequency detuning calculation

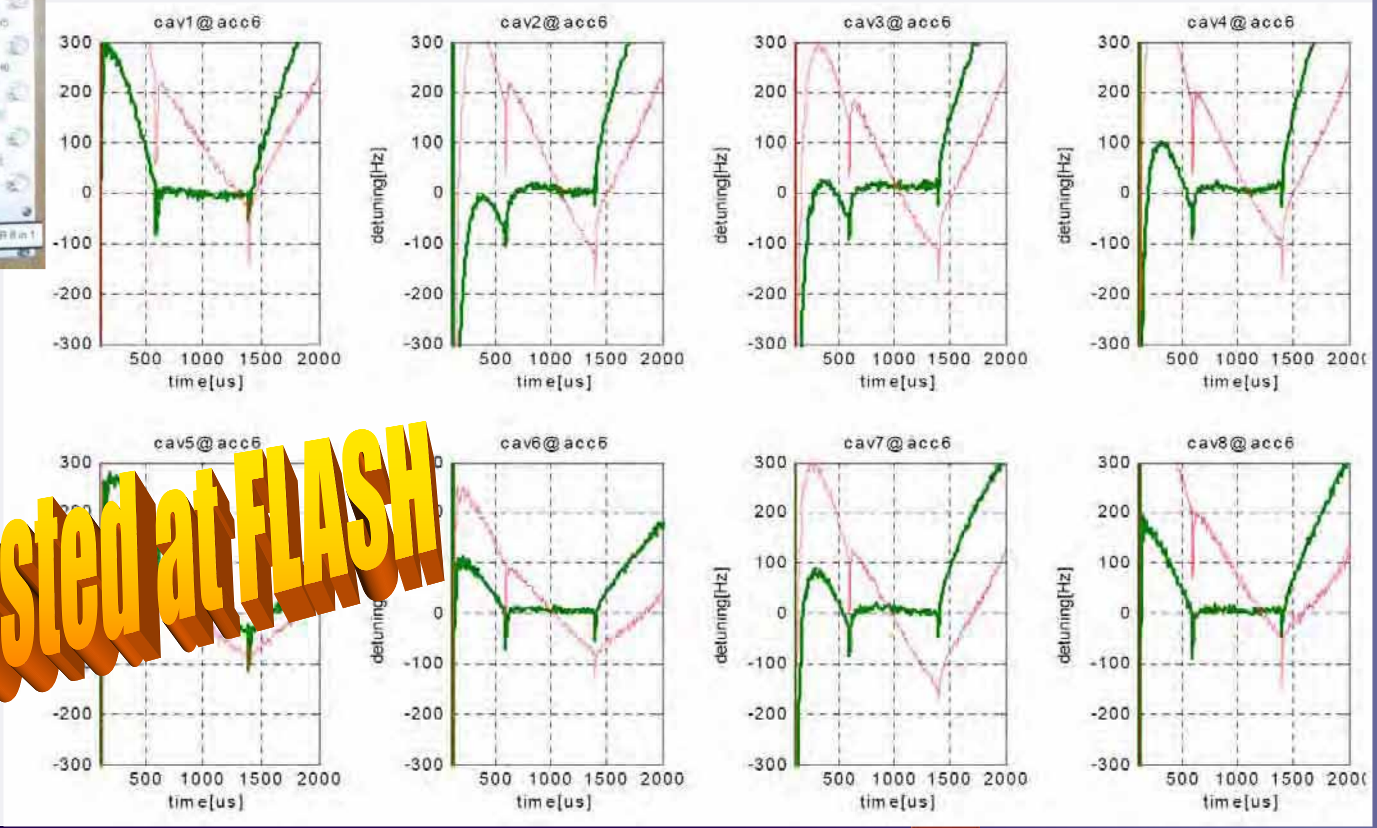
Microphonics measurement (i.e. diagnostics of cryogenic system)

Dimensions: **10x10x36mm**
Manufacturer: **PI**



Results

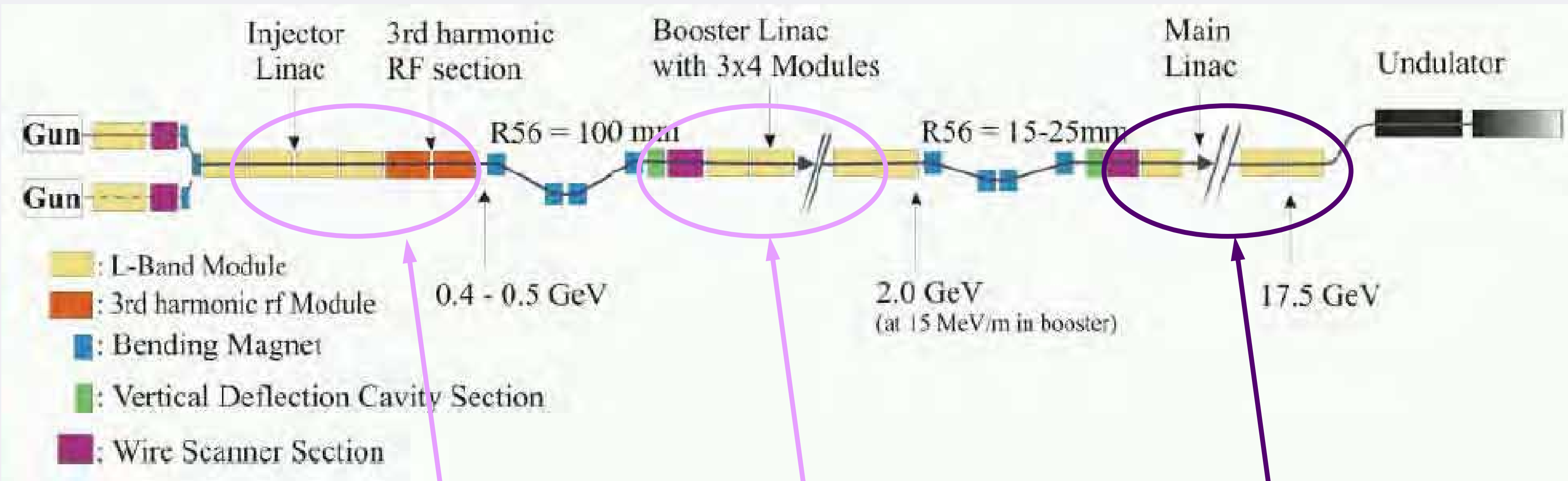
FLASH, ACC6
Acc. Grad = 22MV/m, Rep. Rate=5Hz



Successfully tested at FLASH

Cavity Field Detection Requirements

- Requirements for different LLRF-stations:



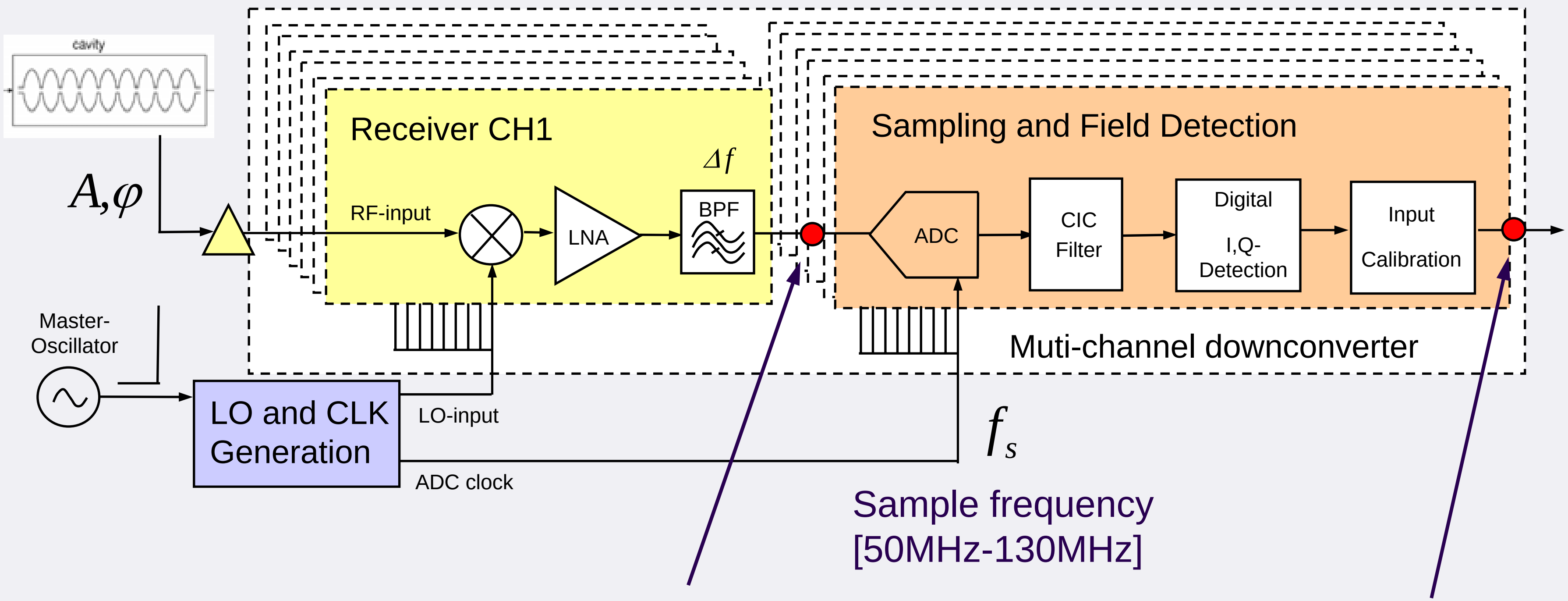
Amplitude and
Phase stability :
$f_{CAV} = 1.3GHz$

$$\Delta A / A_{rms} = 0.01\%, \quad \Delta\varphi_{rms} = 0.01\,deg$$

$$\Delta A / A_{rms} = 0.03\%, \quad \Delta\varphi_{rms} = 0.03\,deg$$

$$\Delta A / A_{rms} = 0.1\%, \quad \Delta\varphi_{rms} = 0.1\,deg$$

Downconverter for LLRF



Sample frequency
[50MHz-130MHz]

Intermediate frequency
[10MHz, 50MHz]: f_{IF}

Single cavity field in
amplitude and phase

Achieved Performance from FLASH studies

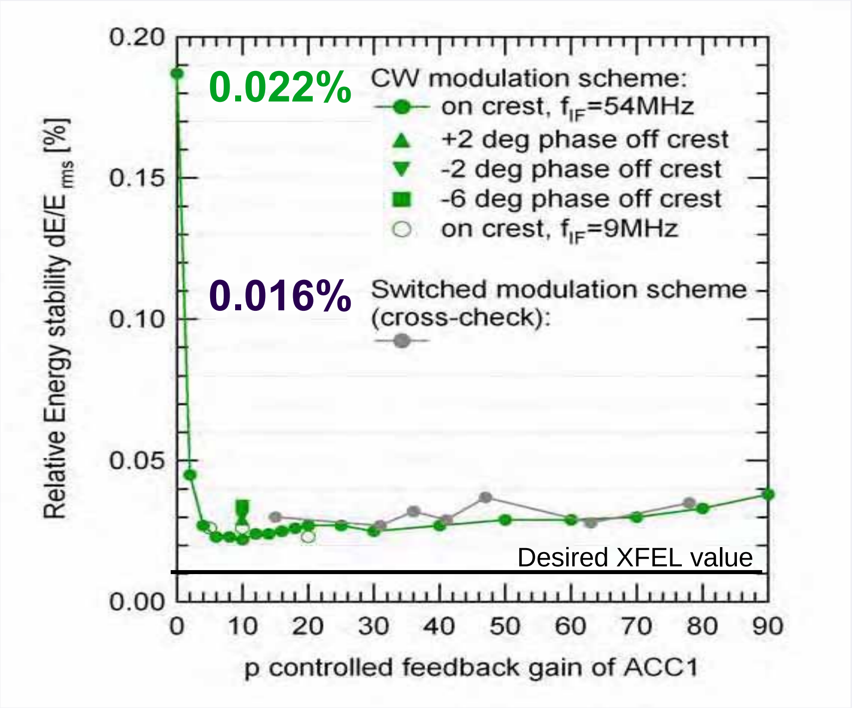
- Multi-channel downconverter :

8 channel Gilber-mixer receiver VME based
+ SIMCON DSP (14-bit ADCs) VME based

Stability results (single channel) :

- Shortterm, bunch-to-bunch (800us) :
  $\Delta A/A_{rms} = 0.015\%, \quad \Delta\varphi_{rms} = 0.0092\ deg$
- Midterm, pulse-to-pulse (10min) :
  $\Delta A/A_{rms} = 0.016\%, \quad \Delta\varphi_{rms} = 0.0147\ deg$
- Longterm, drifts (1hour) :
  $\Delta A/A_{pkpk} = 0.09\%, \quad \Delta\varphi_{pkpk} = 0.05\ deg$
  θ_A = 2e-3/°C, θ_P = 0.2°/°C
  (Need for drift calibration)

- Pulse-to-Pulse Beam Stability :

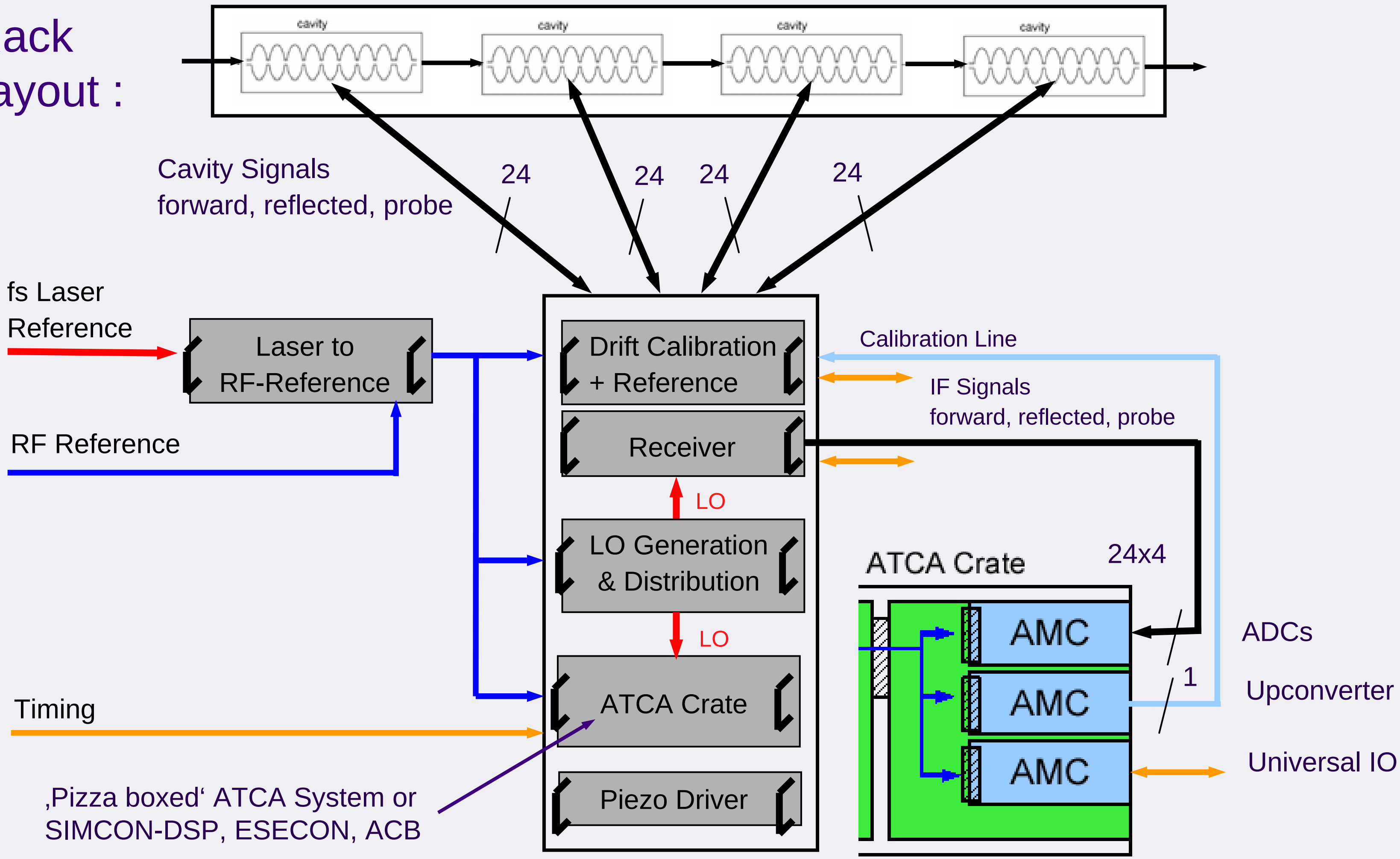


Main and Booster section requirements are fulfilled - Injector and 3rd harmonic requirements only nearly.

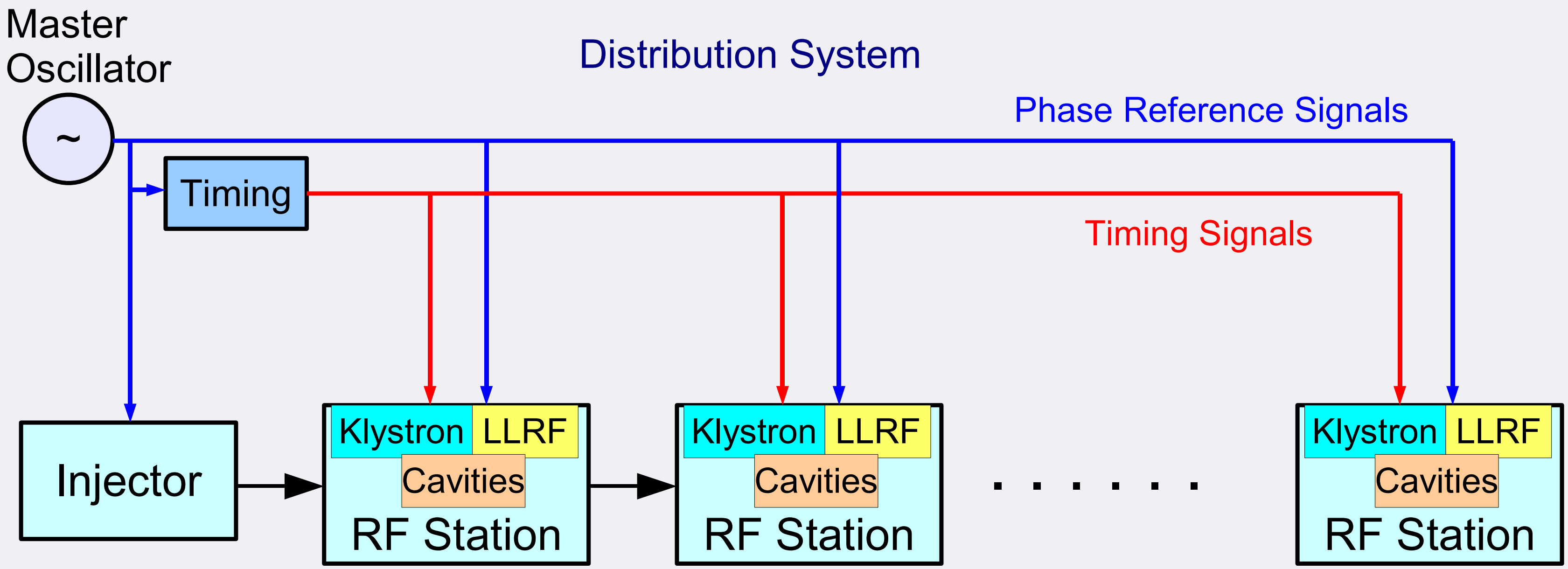
Can the ATCA system fulfill this too?

Injector and 3rd Harmonic Section Downconverter

- Rack Layout :

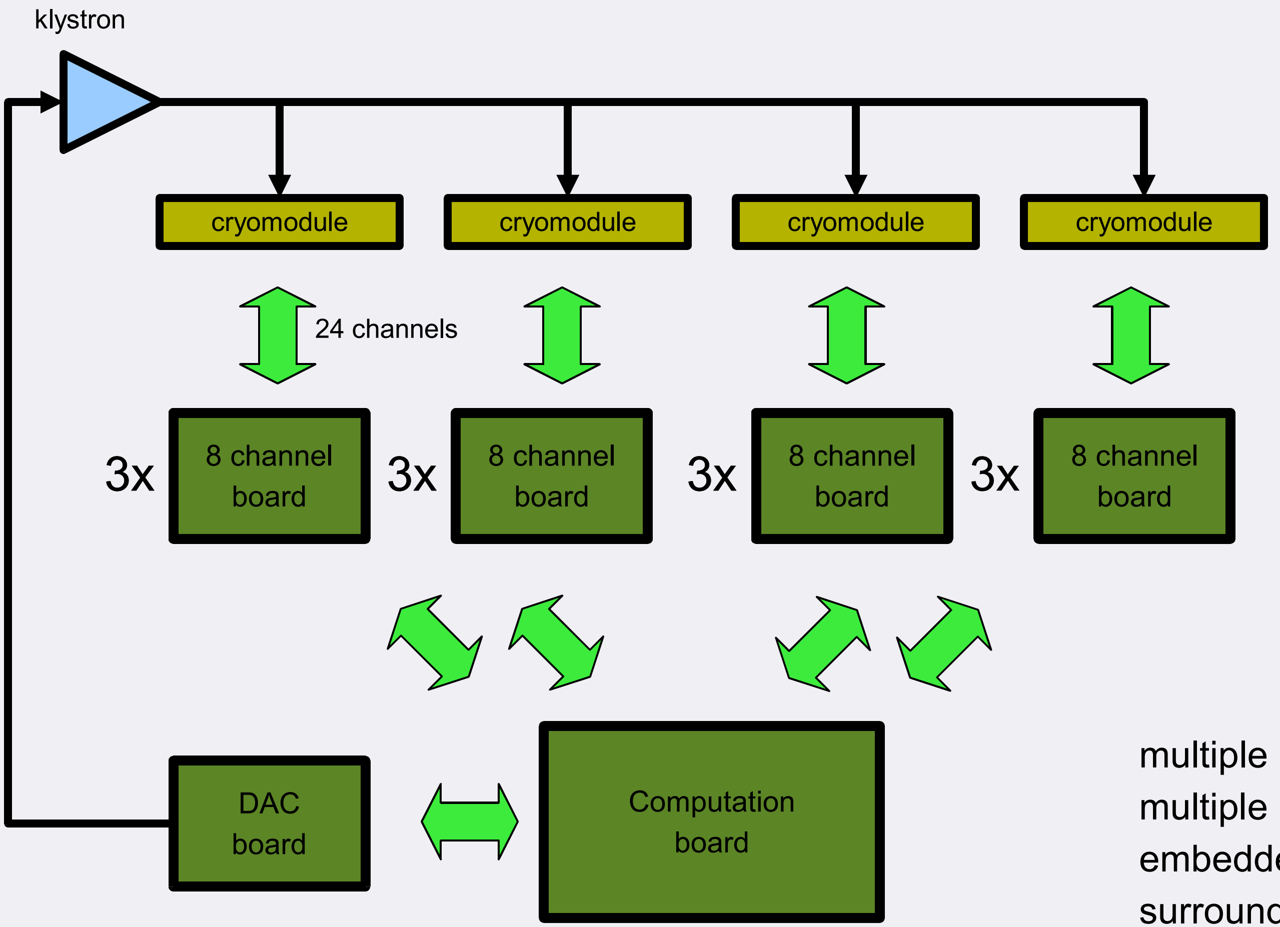


Need for Precise Synchronization



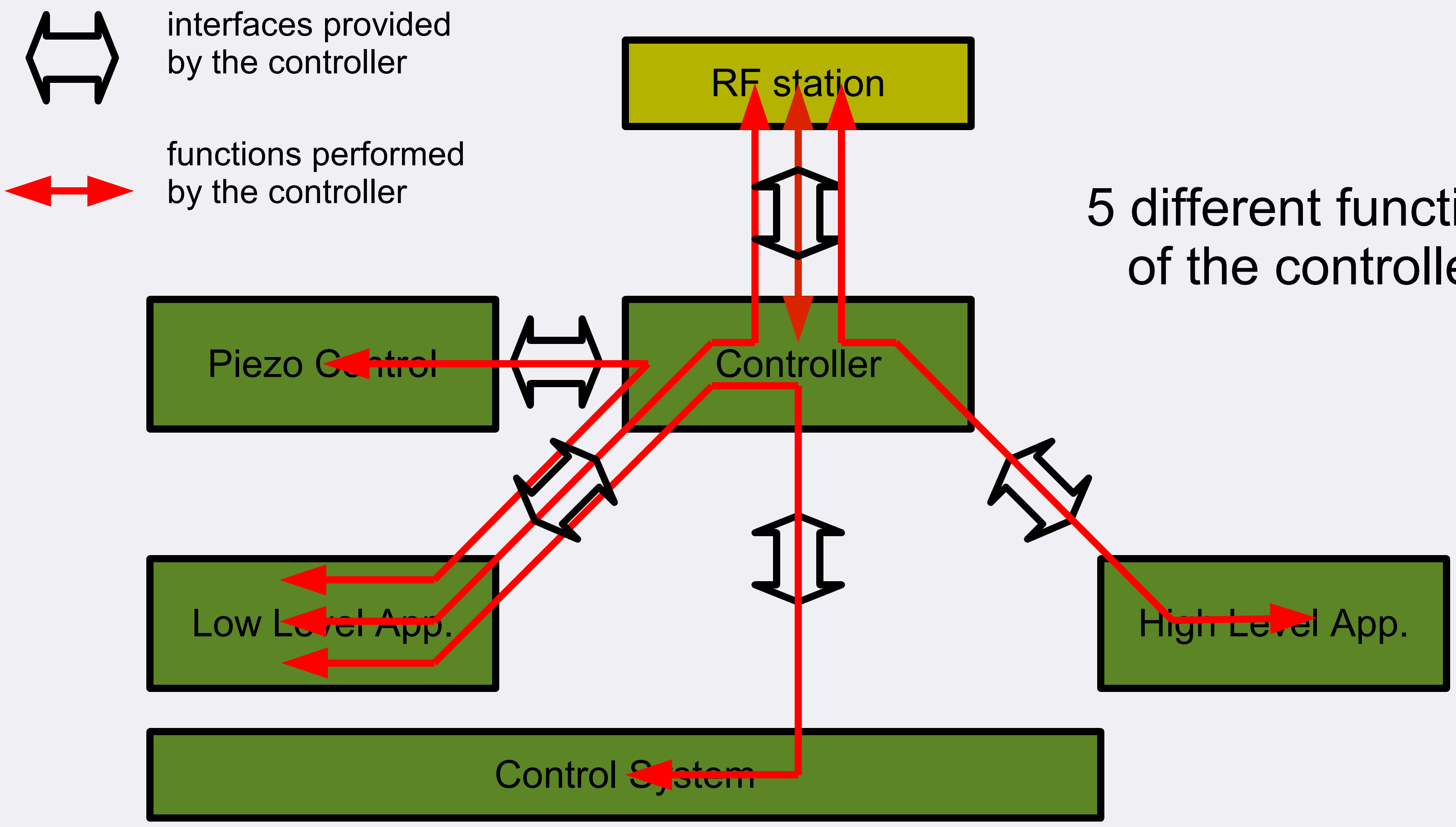
- Electronic devices should be synchronized with high accuracy
- Required jitter for phase reference signals:
  - 0.1 ps short term (10 fs at some locations in XFEL)
  - 1 ps long term

Overview of the distributed system



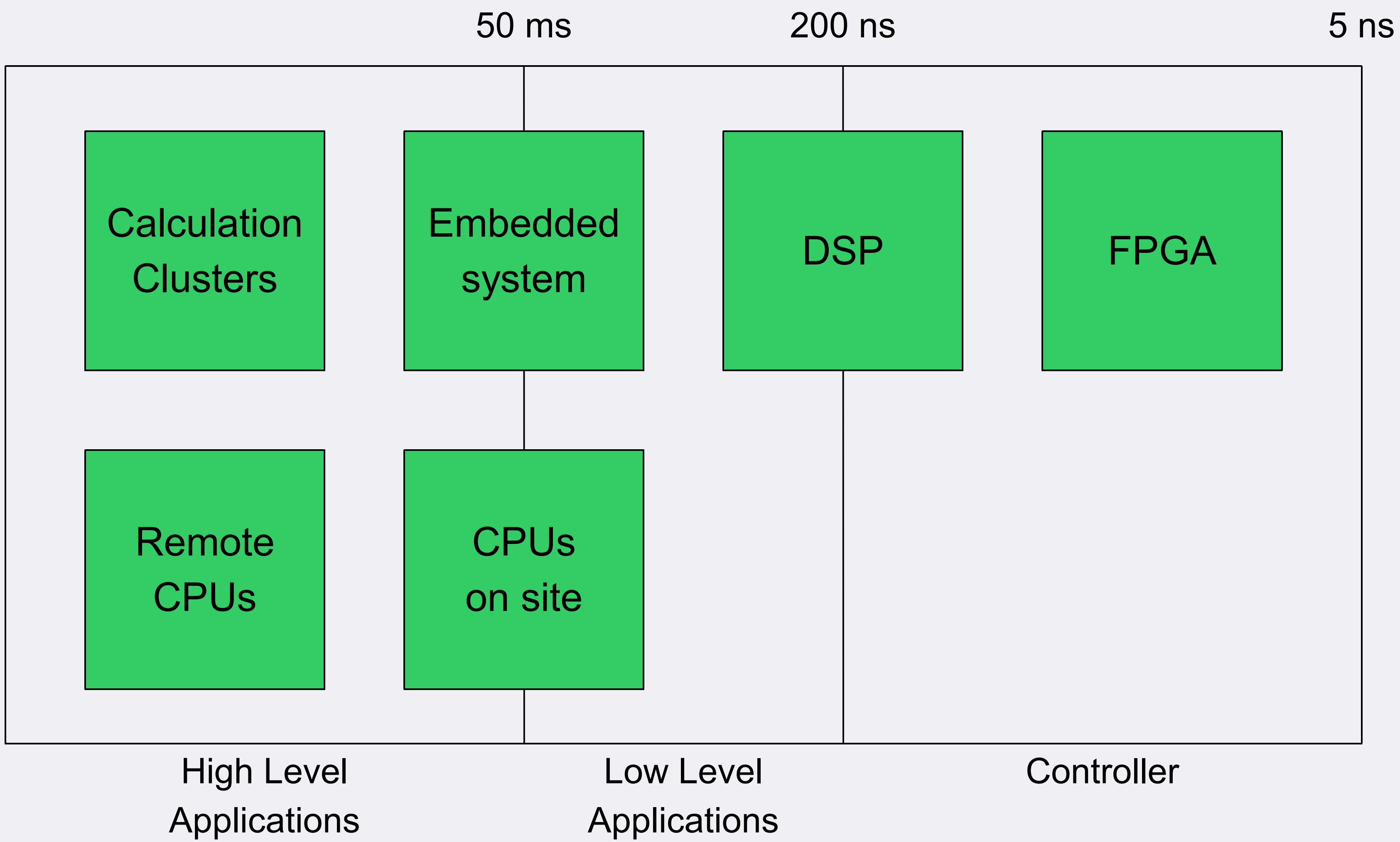
multiple FPGAs
multiple DSPs
embedded systems
surrounding devices

Against the background of the whole system



5 different functions
of the controller

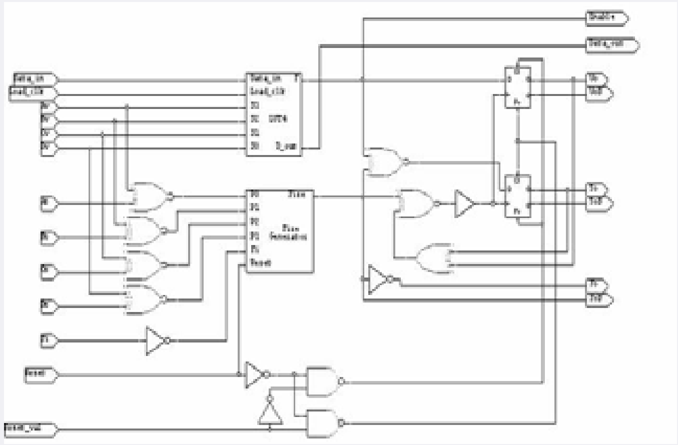
Possible algorithm locations

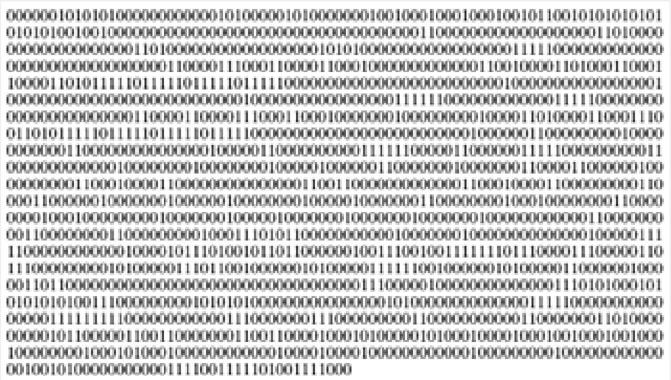


Low Level Applications

This includes:

- Adaptive Feed-Forward
- System Identification
- Loop gain and loop phase calculation
- detuning and loaded Q calculation
- Vector sum calibration
- Beam Diagnostic
- Exception Detection and Handling



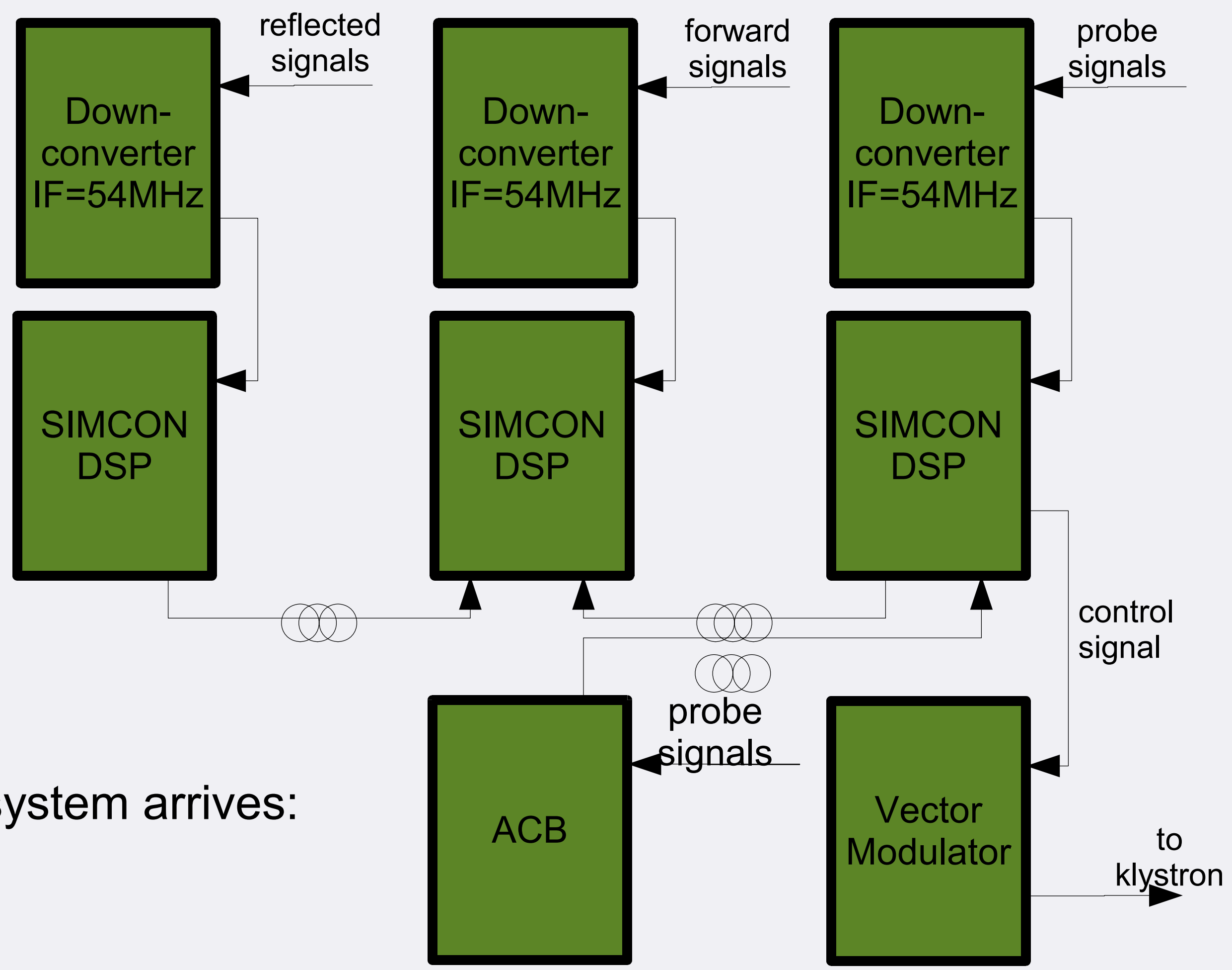


High Level Applications

This includes:

- Adaptive Feed-Forward
- Vector sum calibration
- Beam Diagnostic
- Automated frequency tuning
- Exception Detection and Handling
- RF-Gun control

Development environment



Before ATCA system arrives:

Functional features

Field detection module includes:

- Field measurement
- Support for different IFs
- Input linearization
- Field calibration
- Field I component detection
- Field Q component detection
- Components conversion to field amplitude
- Components conversion to field phase
- Measurement filtering

Feedback module includes:

- Field error calculation
- PID transfer function
- MIMO controller

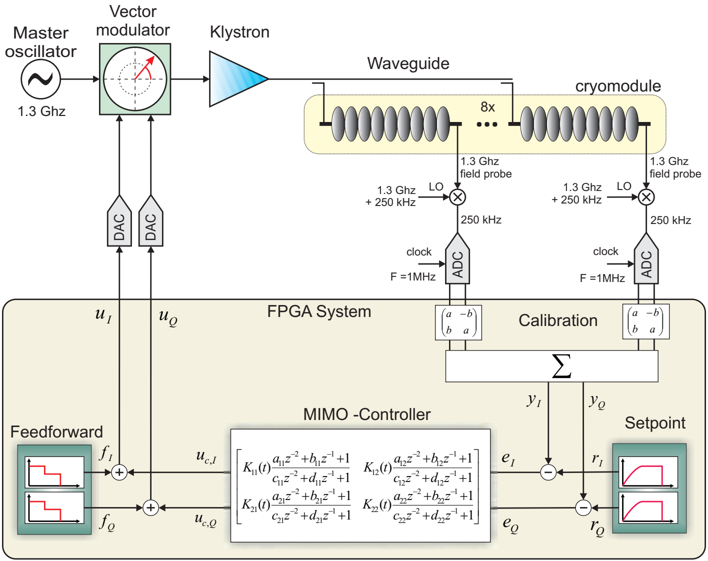
Output module includes:

- Output linearization
- Correction tables
- Offset compensation
- Control signal adjustments
- Control signal limiters
- Loop phase adjustment
- Loop gain adjustment
- Output delay

The features can be used both in control and diagnostic mode.

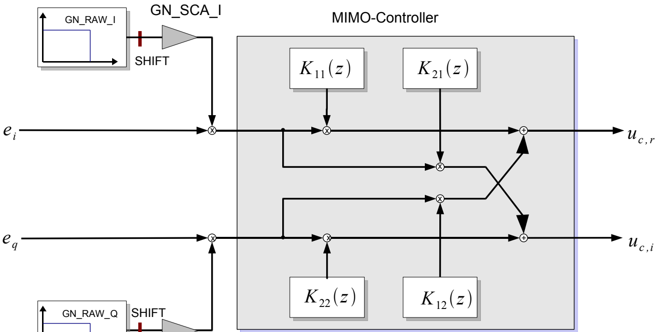
Diagnostic mode provides such functionality as SEL or Frequency Sweep mode etc.

Schematic View of the LLRF Control System



Controller Structure

- so far a decentralized P Controller is used
- new FPGA implemented controller is given by:



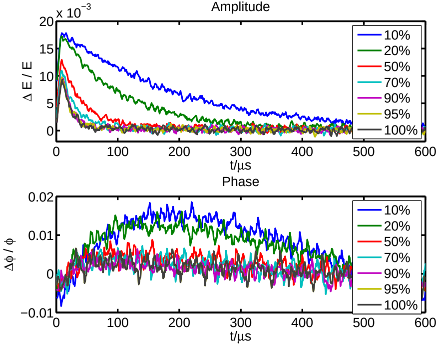
$$K_{ij}(z) = k_{ij} \frac{a_{ij} \cdot z^{-2} + b_{ij} \cdot z^{-1} + 1}{c_{ij} \cdot z^{-2} + d_{ij} \cdot z^{-1} + 1}$$

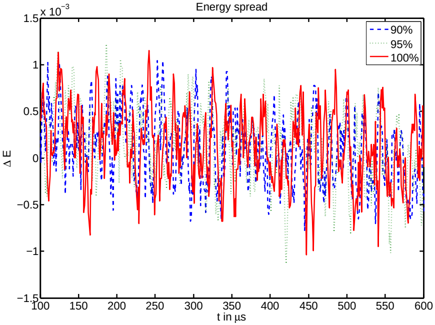
- tuning 20 parameters manually is not possible for users

First implemented controllers

slow approach (C) to estimated controller gain

$$K(z) = C \cdot \begin{pmatrix} K_{11}(z) & K_{21}(z) \\ K_{12}(z) & K_{22}(z) \end{pmatrix}$$





- highest performance reached so far (P)
- instability problems with full order controller parameters
- limited measurement time restricts online tests

Summary of the LLRF ATCA Review

- Focused on evaluation of an ATCA based LLRF system:
  - With demonstrated technical performance with beam at FLASH
  - With demonstrated operability by machine operators
  - Which serves as development platform for XFEL LLRF software
  - Which is close to what is needed for XFEL
  - Project time line: January – December 2008
- Covering all LLRF subsystems to be installed at FLASH
  - Master Oscillator, frequency distribution and timing
  - Downconverters, vector-modulators
  - Digital feedback hardware, piezo controller
  - Controller software, low and high level applications software
  - Automation

Note: This was not a review of the XFEL LLRF system although it covered many aspects.

Individual Comments from reviewers

- The change from R&D to production mode for the XFEL requires a change of mode of operation :
  - Senior personnel (responsible for workpackages) from collaboration partners must join the core team at DESY for a significant portion of their time (~6 months / year) and commit their participation for the duration of the project.
  - Collobration partner must be involved in project management
  - Must commit to agreed schedule and deliverables
  - Work on LLRF cannot be sacrified by committments toward the universities.
  - Intellectual property must be accessible to all collaboration partners

Performance at FLASH

Beam Energy Stability

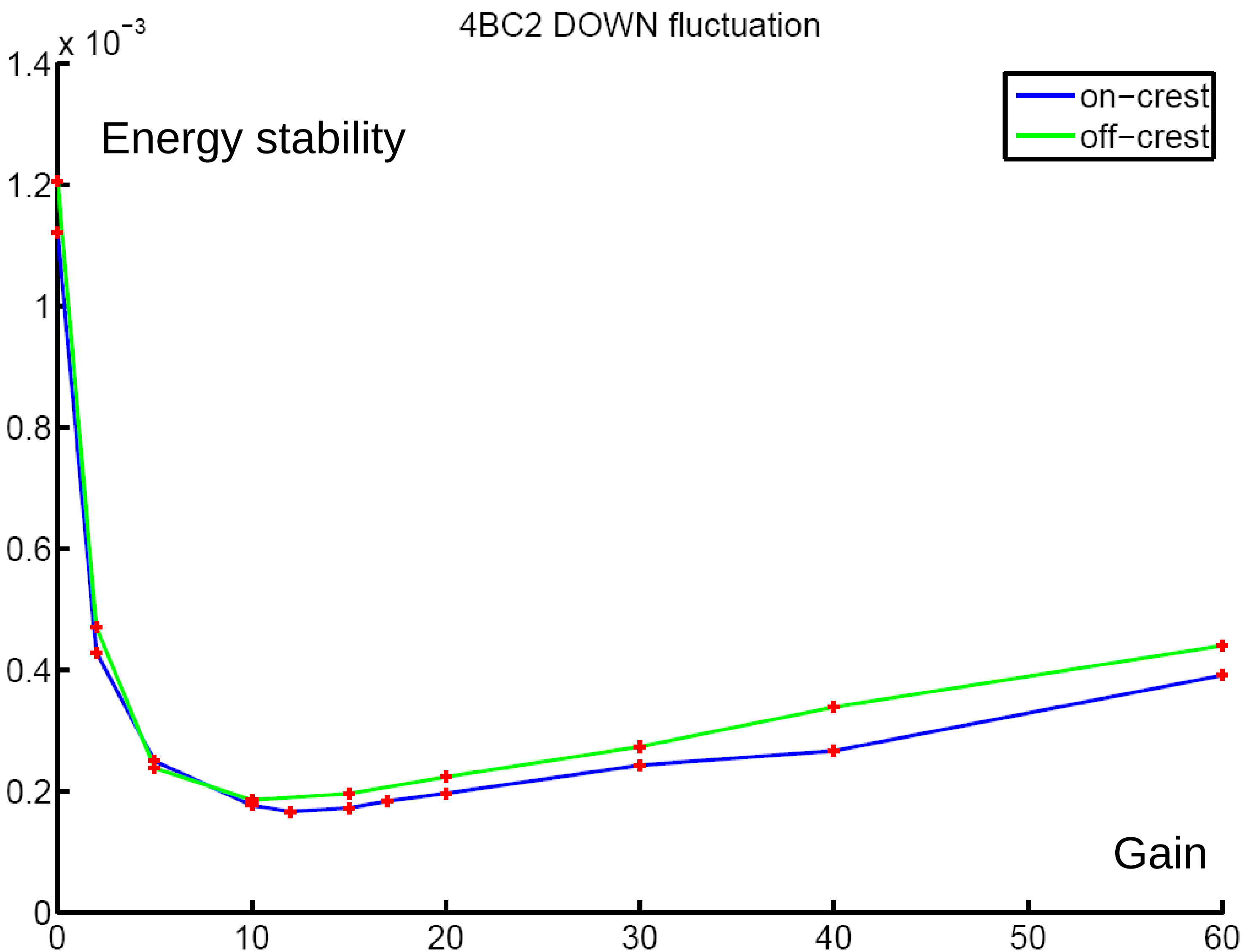
- So far at FLASH a beam stability of 0.008% was achieved during 01/2008 studies by using the 250kHz modulation scheme for cavity field detection and on-crest operation.
  - Unfortunately this result was not reproducible although a 3 times lower noise down-converter was in operation. For off-crest operation, this is still unknown and would have a great impact for the future 3.9GHz system and the XFEL.
  - Especially the influence of the rf-phase and ACC1 gradient is unclear. To clarify this, the following measurements were suggested:

Proposed Measurements

- Semi-automized vector-sum beam based calibration (CS).
- Accurate 3-stub tuner adjustment (CS, VA).
- ACC1 feedback gain dependent beam stability measurements using SR-BC2 (CS, FL).
- Off-crest gain sweep using low-noise, but highly nonlinear down-converter (CS, FL).
- Off-crest beam stability in dependence of rf-phase and ACC1 gradient (CS, FL).
- Off-crest beam stability in dependence of IQ-driver degradation (GM, FL).
- MO Reference feed into installed down-converter (GM, FL).

Note: The blue marked items were successfully performed.

Energy stability as function of feedback gain



Operational Experience

Some Examples from Logbook

- **April 16, 2008:**
  - Another crash of the **LLRF** server (15 min)
- **April 7, 2008:**
  - Down**: 7.3 h =** 4%
  - **RF-gun reflected power: 5.1 h (71%)**
  - LLRF **(phase jumps or wrong tables): 1.7 h (24%)**
  - **ACC2/3 coupler interlock: 0.2 h (3%)**
  - **RF-4: 0.1 h (1%)**
  - **Vacuum valves closed in dump area: 0.1 h (1%)**
- **April 4, 2008:**
  - Difficulties: Phase jump of ACC2/3 caused coupler interlocks ACC2/3 -> 0.2 h **LLRF**

Some Examples from Logbook

- **April 1, 2008:**
  - Problem with **LLRF** in ACC456, adaptive FF error after interlock trip (1 h)
- **March, 2008:**
  - **LLRF (lost ACC1 tables): 0.1 h (3%)**
  - **wrong calibrations ACC1 after LLRF studies (1 h)**
  - **difficulties to boot LLRF server after LLRF studies (1 h)**
  - **There is something wrong with the ACC2&3 LLRF: quench, leave LLRF running without FB.**
  - **The klystron is in saturation -> amplitude is not regulated by LLRF (RF Gun).**
  - **Lost 1 h due to messed up LLRF of ACC1 (by night shift, fixed by Valeri)**
  - **ACC1 calibrations wrong (after LLRF studies in Monday night shift), 1 h**

Some Examples from Logbook

- **LLRF: 0.1 h (3%) :Jump ACC1**
- **LLRF: 0.1 h (10%) , Phase and amplitude jumps of ACC1 and ACC2/3**
- **It looks like we have some problem with KL5 or LLRF.**
- **LLRF: 2.5 h (10%) : Phase jump ACC1**
- **LLRF: 2 h (12%) : 81 MHz LLRF: 1.5 h (7%)**
  - Work on MO: 1 h
  - Wrong LLRF tables ACC1: 0.3 h
  - Sudden phase jump ACC1: 0.2 h
- **LLRF adjustments: 1 h (21%)**

Typical Problems of LLRF

- Phase drifts of the order of the order of ~ 1 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 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. Must be always on call.

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

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

Selected Studies Results

LLRF Studies Sep. 2007 (1)

- Test of Multichannel Downconverter for LLRF Matthias Hoffmann
- Beam based beam loading compensation at ACC1 Elmar Vogel
- Beam based ACC1 rf field stability measurement using BC2 beam diagnostics Elmar Vogel
- Multicavity Complex Controller (MCC) Tomasz Czarski
- Vector-Sum Calibration with Beam and Beam Diagnostics Valeri Ayvazyan
- For./ref. rf power cal, w/wout beam, probe calculation Waldemar Koprek
- Multi-bunch transient detection with different electronics Petr Morozov
- Grad./phase calibration with full beam loading Valeri Ayvazyan
- Operation at different gradients (gradient spread) Valeri Ayvazyan
- Operation close to limits (klystron saturation., cavity/coupler limit) Wojciech Cichalewski
- Beam Based RF Amplitude and Phase Calibrations Valeri Ayvazyan

LLRF Studies Sep. 2007 (2)

- Radiation effects on electronics Mariusz Grecki
- Physical System Parameters Identification Christian Schmidt
- Off-crest operation in ACC456 Valeri Ayvazyan
- Performance evaluation of ILC Americas No. 1 LLRF Controller Gustavo Cancelo
- Evaluate ILC America No. 1 Downconverter and Vectormodulator Brian Chase
- Performance evaluation of new FLASH MO and Distr. with beam Henning Weddig
- Evaluation of Operational Procedures for Automation Wojciech Cichalewski
- Test of Components needed for Automation Boguslaw Koseda
- Operation of universal controller Wojciech Jalmuzna
- Test of new features in LLRF controller at ACC1 Waldemar Koprek

LLRF Studies January 2008 (3)

- Beam stability obtained by various rf control settings Elmar Vogel
- Beam based beam loading compensation at ACC1 Elmar Vogel
- Downconverter Drift Calibration and Compensation BRIAN CHASE
- Vector-sum calibration optimization GUSTAVO CANCELO
- Correlation studies beam vs rf measurements Matthias Hoffmann
- System Identification and performance testing of MIMO-LTI feedback Christian Schmidt
- Iterative learning Controller design Christian Schmidt
- Beam phase measurement with single bunch Petr Morozov
- Investigation on the relationship between module gradient and Neutron/Gamma radiation dose Bhaskar Mukherjee
- Measurement of dark current induced Neutron/Gamma Dose Bhaskar Mukherjee
- Lorentz force detuning with piezo tuners Mariusz Grecki

LLRF Studies Jan./Mar. 2008 (4)

- Multi-cavity scope for Lorentz Force Detunig using SimconDSP Wojciech Jalmuzna
- Tests of 24 channel FPGA based controller Wojciech Jalmuzna
- Evaluation of the performance of the universal controller Wojciech Jalmuzna
- Software updates in ACC1 Wojciech Jalmuzna
- RF-Gun recalibration and stability measurement Waldemar Koprek
- Multi-Cavity Complex Controller Tomasz Czarski
- RF Gun to ACC1 DWC signal crosstalk investigation Valeri Ayvazyan
- Multi-Cavity Complex Controller Tomasz Czarski
- Beam Stability Studies of ACC1 Part I Frank Ludwig

LLRF Studies May 2008 (5)

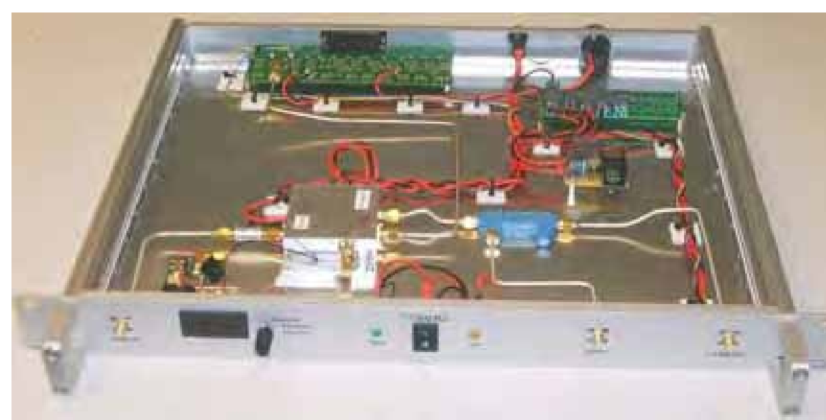
- RF Crosstalk Gun to ACC1 Günter Möller
- Beam properties at BC2 without ACC39 Vogel Elmar
- MIMO-LTI Christian Schmidt FPGA system evaluation for all cryomodules Wojciech Jalmuzna
- FPGA based scope evaluation for Lorentz force detuning with active compensation using Piezo Tuners Konrad Przygoda
- Beam Stability Studies ACC1 Part II Frank Ludwig
- RF-gun automation software components test Boguslaw Koseda
- Multi-Cavity Complex Controller Tomasz Czarski
- Test of LLRF system parameters identification and its applications Zheqiao Geng
- RF-GUN HPC linearization Wojciech Cichalewski
- HPC diagnostics power level adjustement. Wojciech Cichalewski

Infrastructure (Cabling, Racks, Crates)

Gun and ACC1

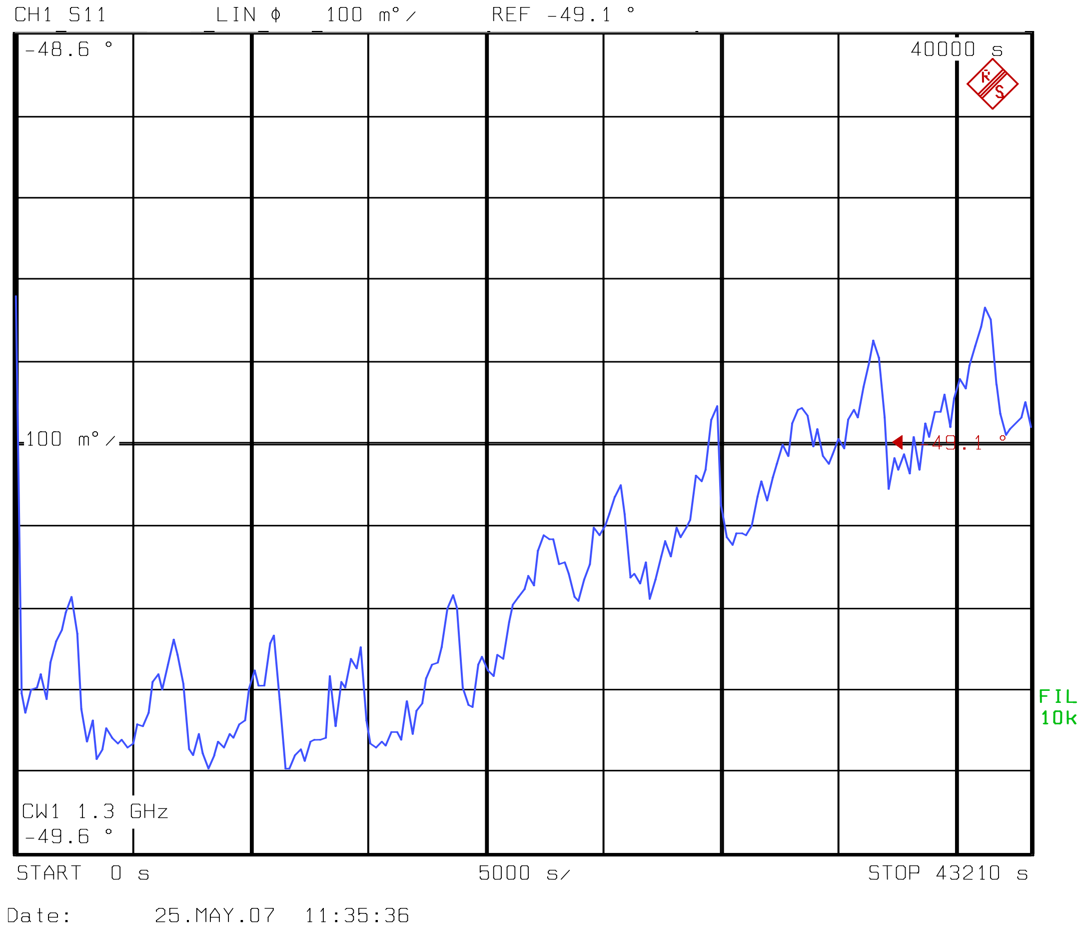
ACC2, ACC3, ACC4 & ACC5

NEW MASTER OSCILLATOR SYSTEM



Cable drifts in accelerator

„cable 6“ to hall 3 extension, open ended, about 100 m long 7/8´´ cellflex cable



Control of ACC1 with SIMCON

ACC1 rf control: P control with beam based beam loading compensation

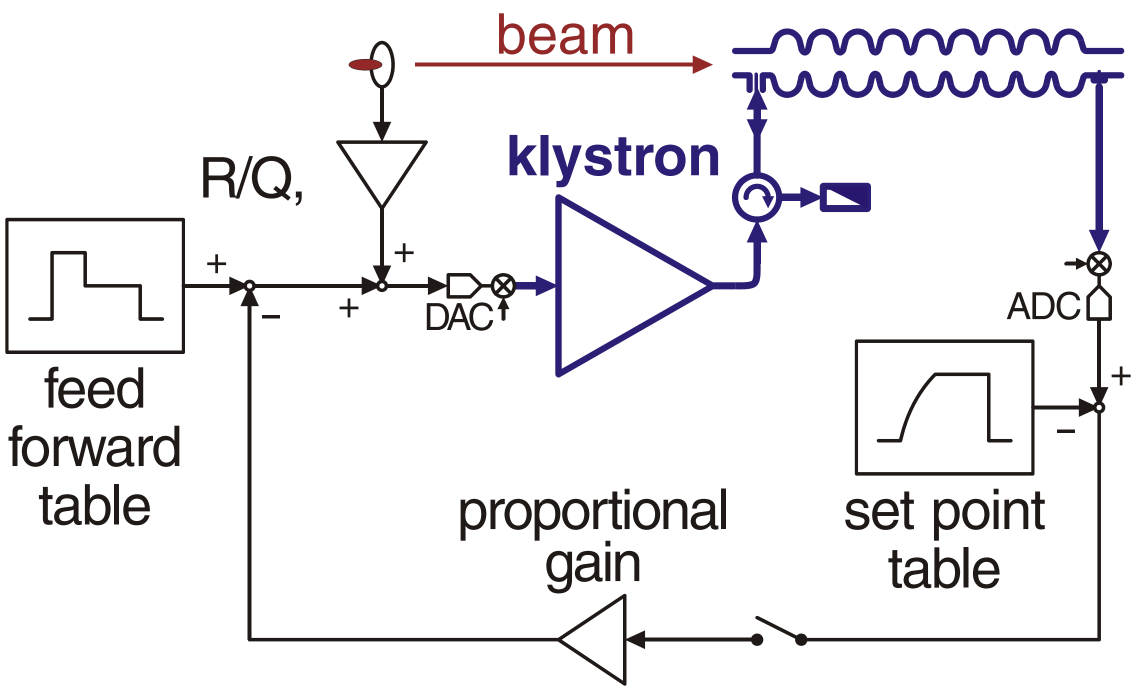
Problem:

- cavity with fast proportional (P) RF control corrects after 20 µs
- first 20 bunches suffer
- correction within 2 bunches required

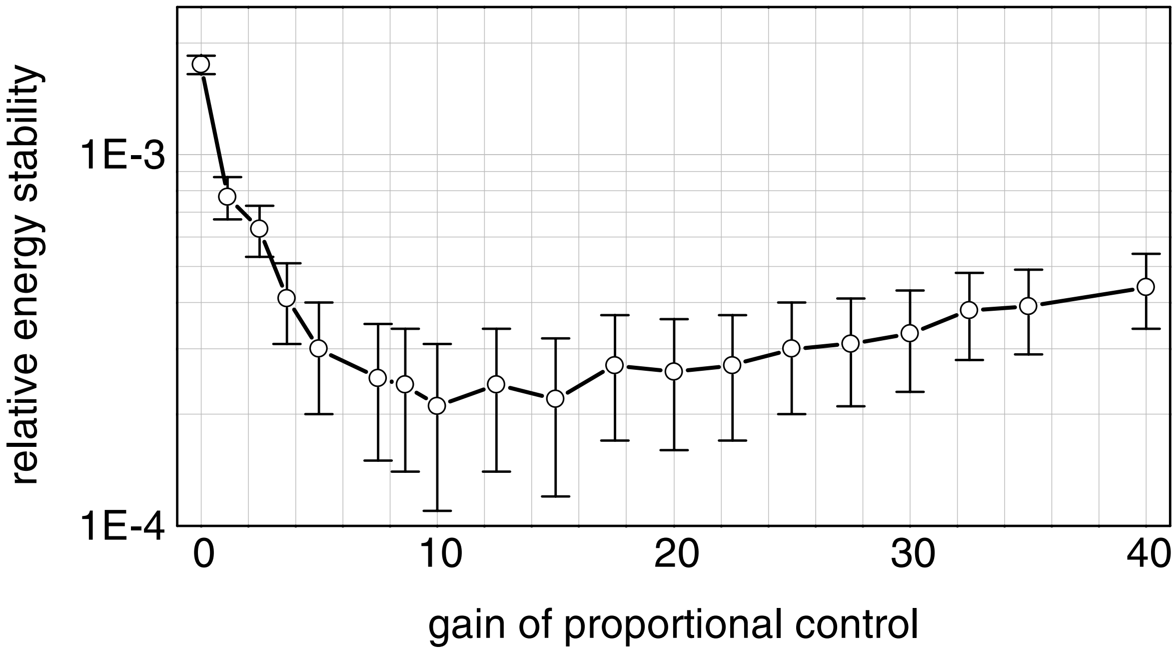
Countermeasures:

- prediction of beam current and derivation of compensation
- measurement of beam current in real time and applying appropriate compensation

Scheme implemented for ACC1 at FLASH:



'Ideal' gain for proportional rf control at ACC1



Gain limitations:

- noise at pick up signal: G = 15
- theory w/o paying attention to the 8/9 π mode: G = 40
- theory with paying attention to the 8/9 π mode: G > 100

Plus points:

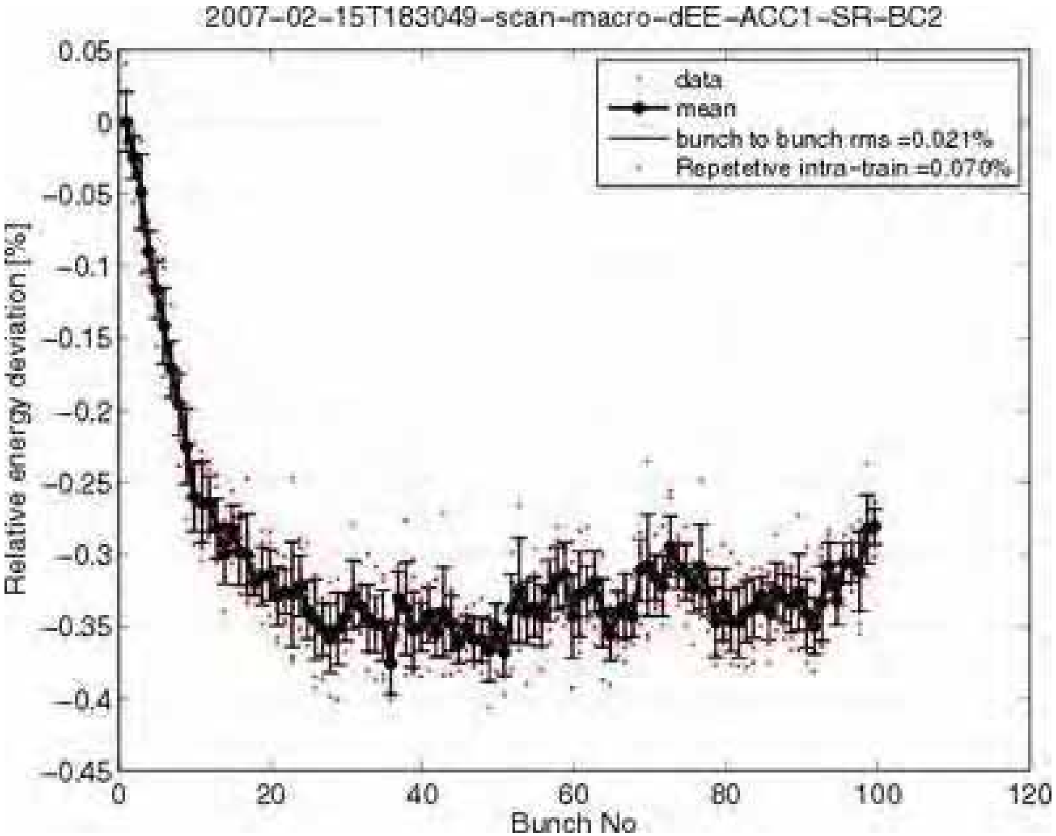
- XFEL requirement: $\Delta E/E = 10^{-4}$
- we controlled only 7 cavities (one pick up makes trouble)
- XFEL injector has four instead of only one module

Gain resulting in most stable beam:

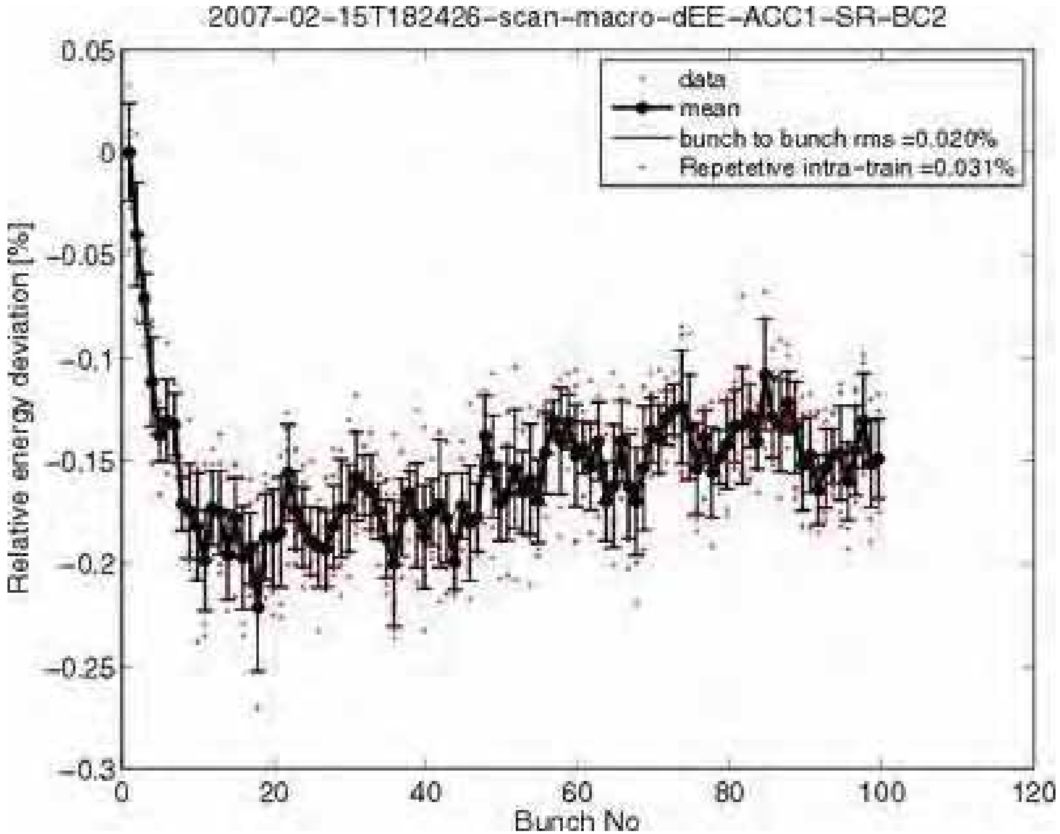
- error suppression for small gain values
- noise amplification for large gain values
- 'ideal' gain between both cases
- best single bunch stability: $\Delta E/E = 2 \times 10^{-4}$

Actual status of the beam loading compensation

Operation with P control only (G = 15)



Beam loading compensation switched on

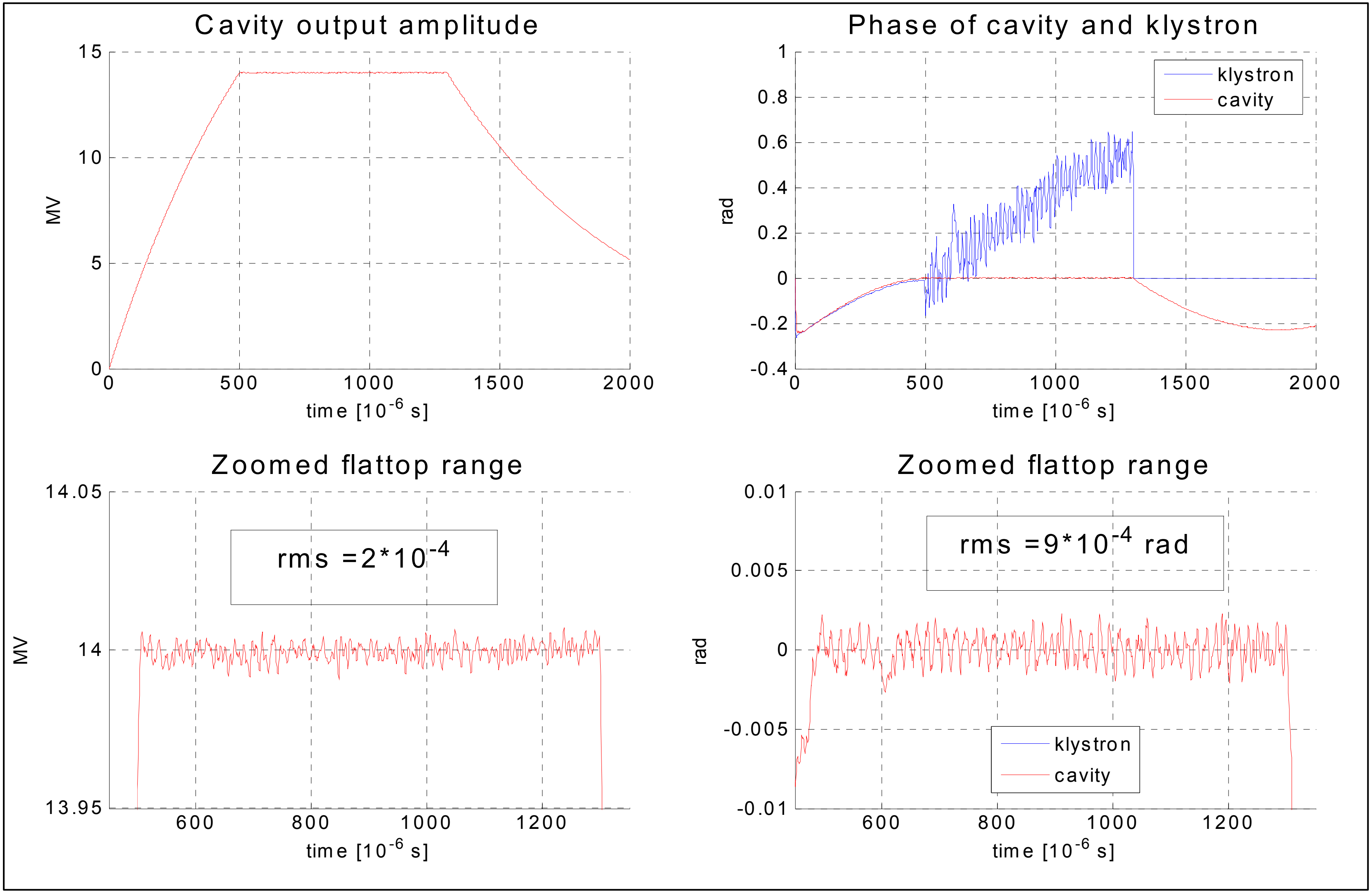


Next steps:

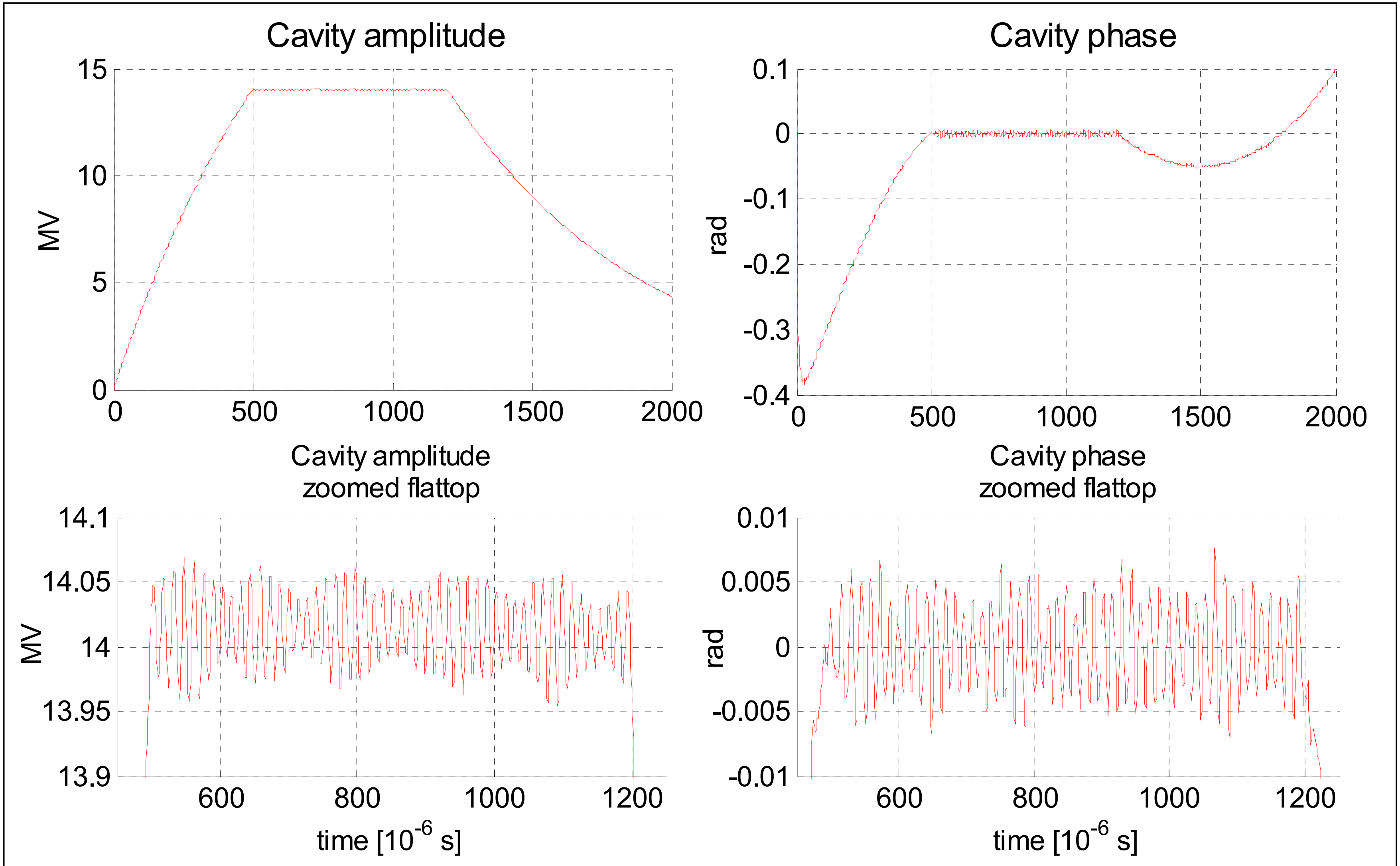
Improvement of the calibration and further qualification of method by measuring energy stability of beam in BC2.

Controller Studies

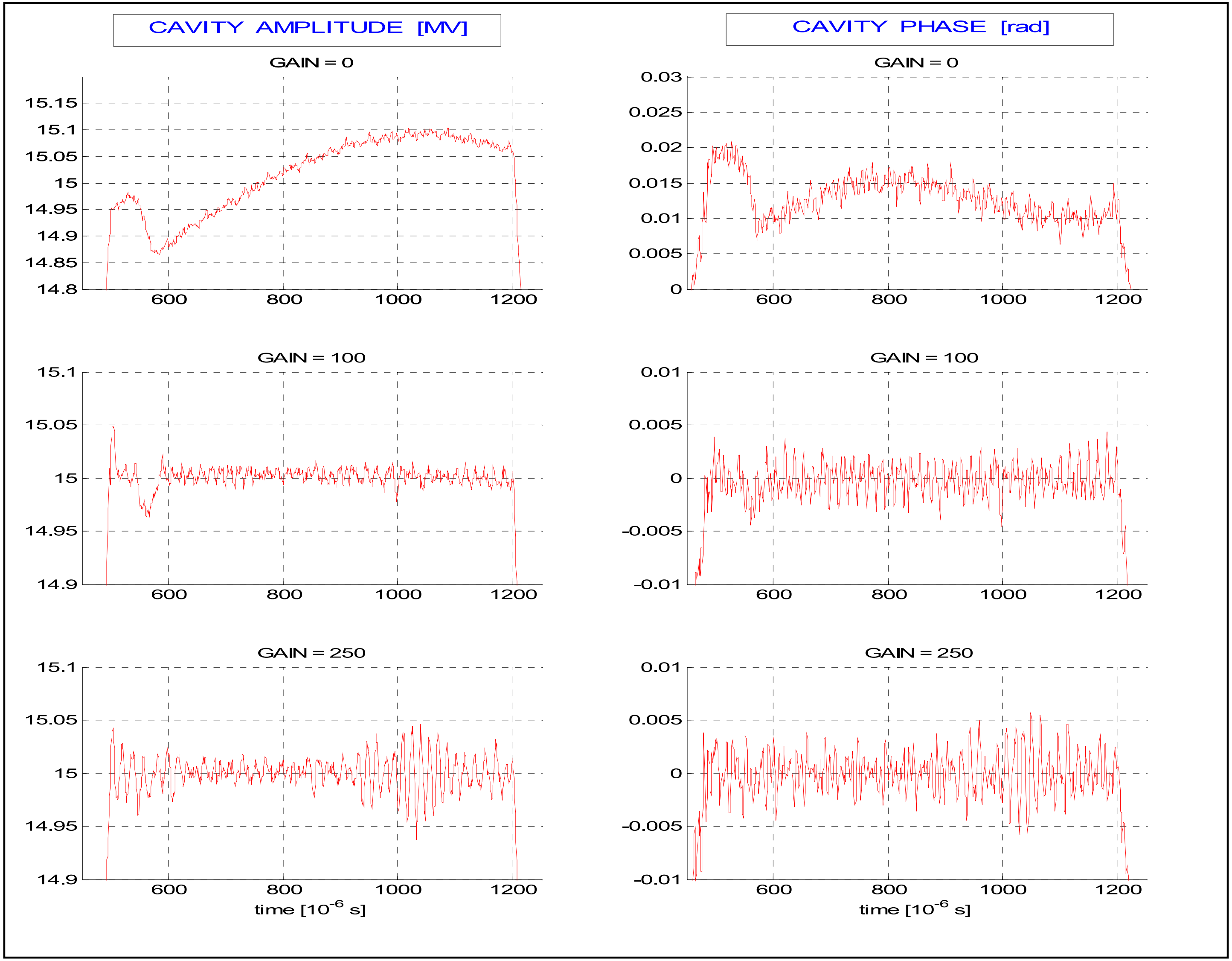
Vector sum control of 8 cavities – ACC1
Feed Forward and feedback (gain=100)



Vector sum control of 8 cavities – ACC1
Feed Forward and feedback (gain = 300)



Beam loading testing

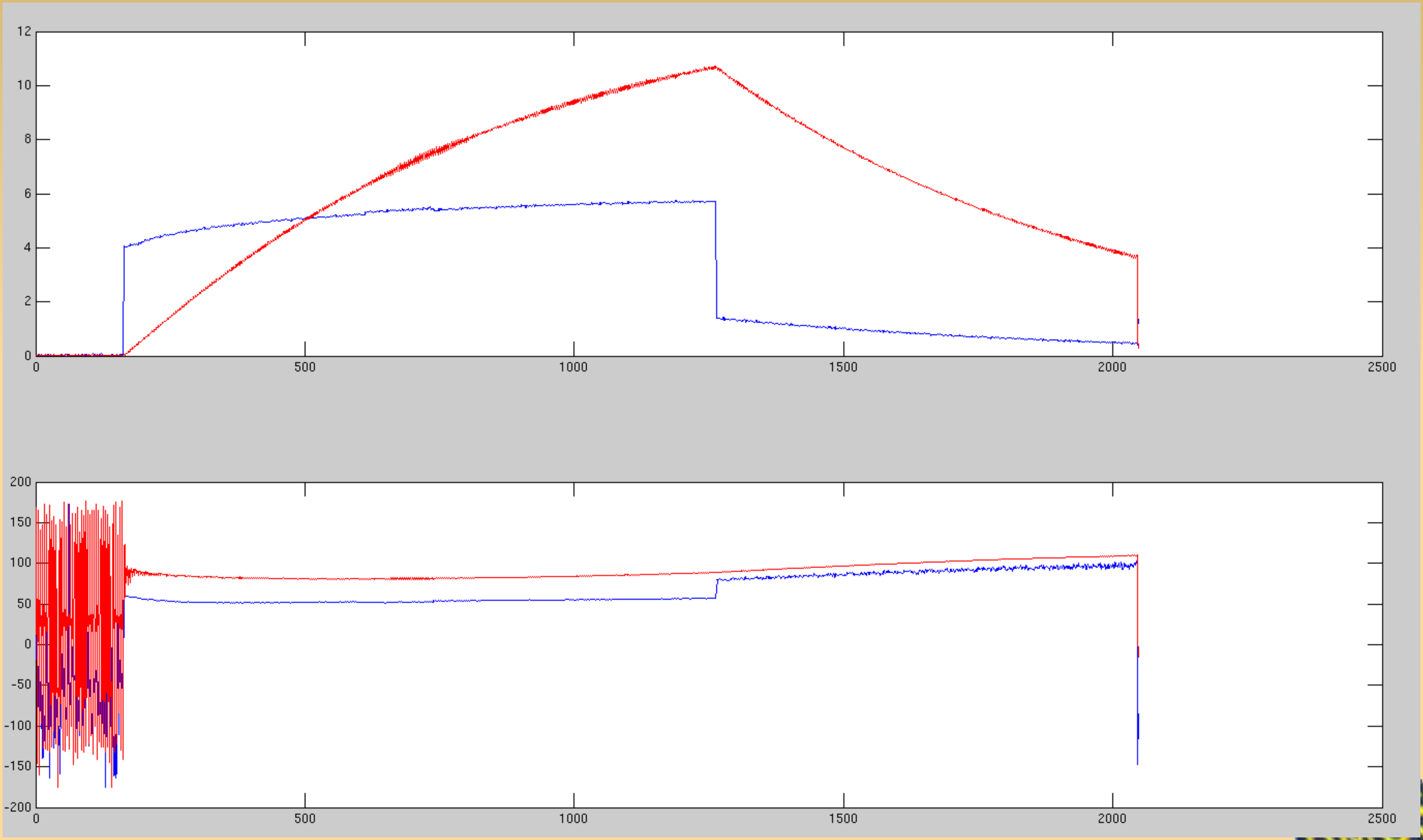


SEL results

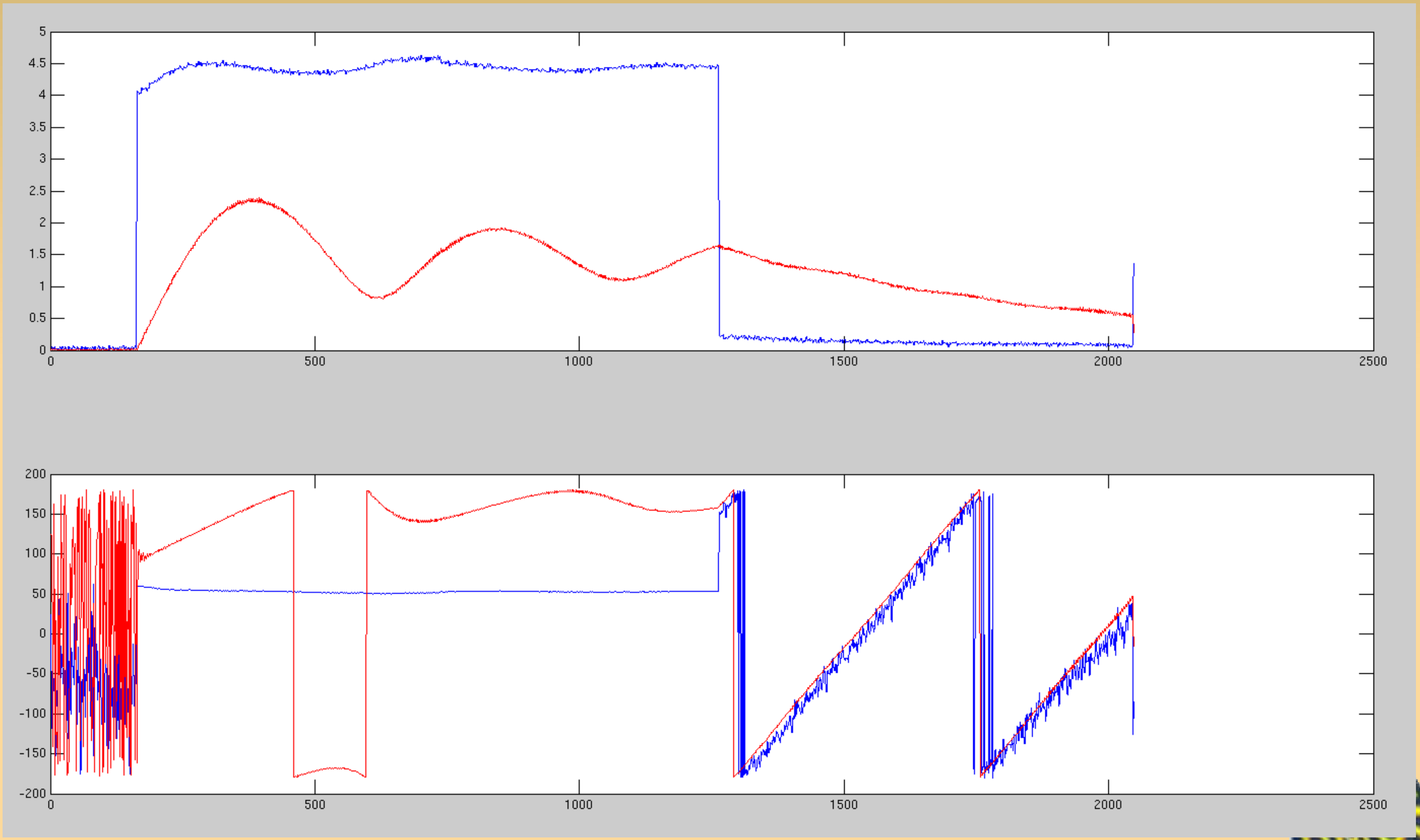
Self excited loop makes it possible to fill the cavity which is detuned from its resonance frequency even by a large offset.

Currently it is possible to work in SEL mode using amplitude limiter on the output of the controller

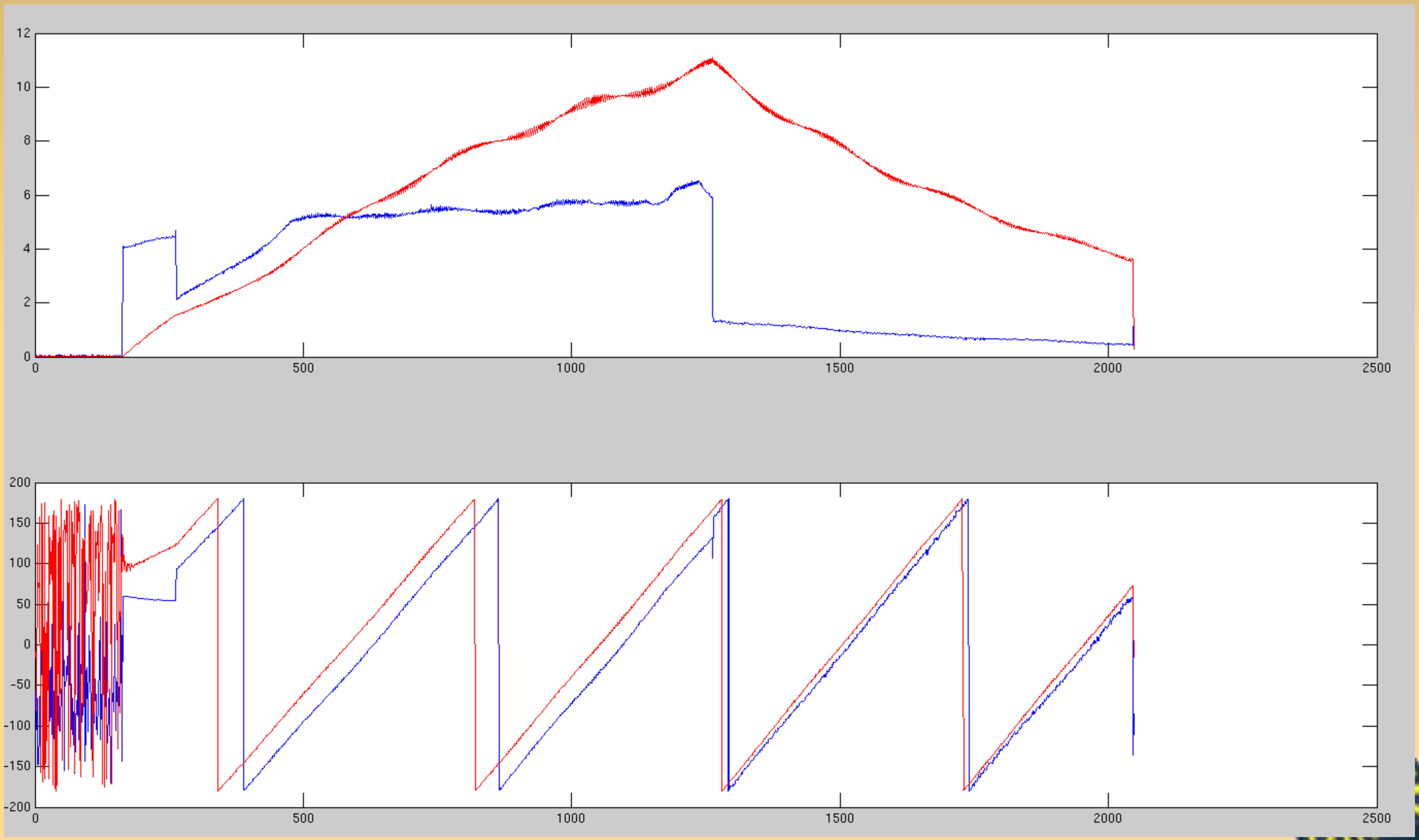
SEL results (1)



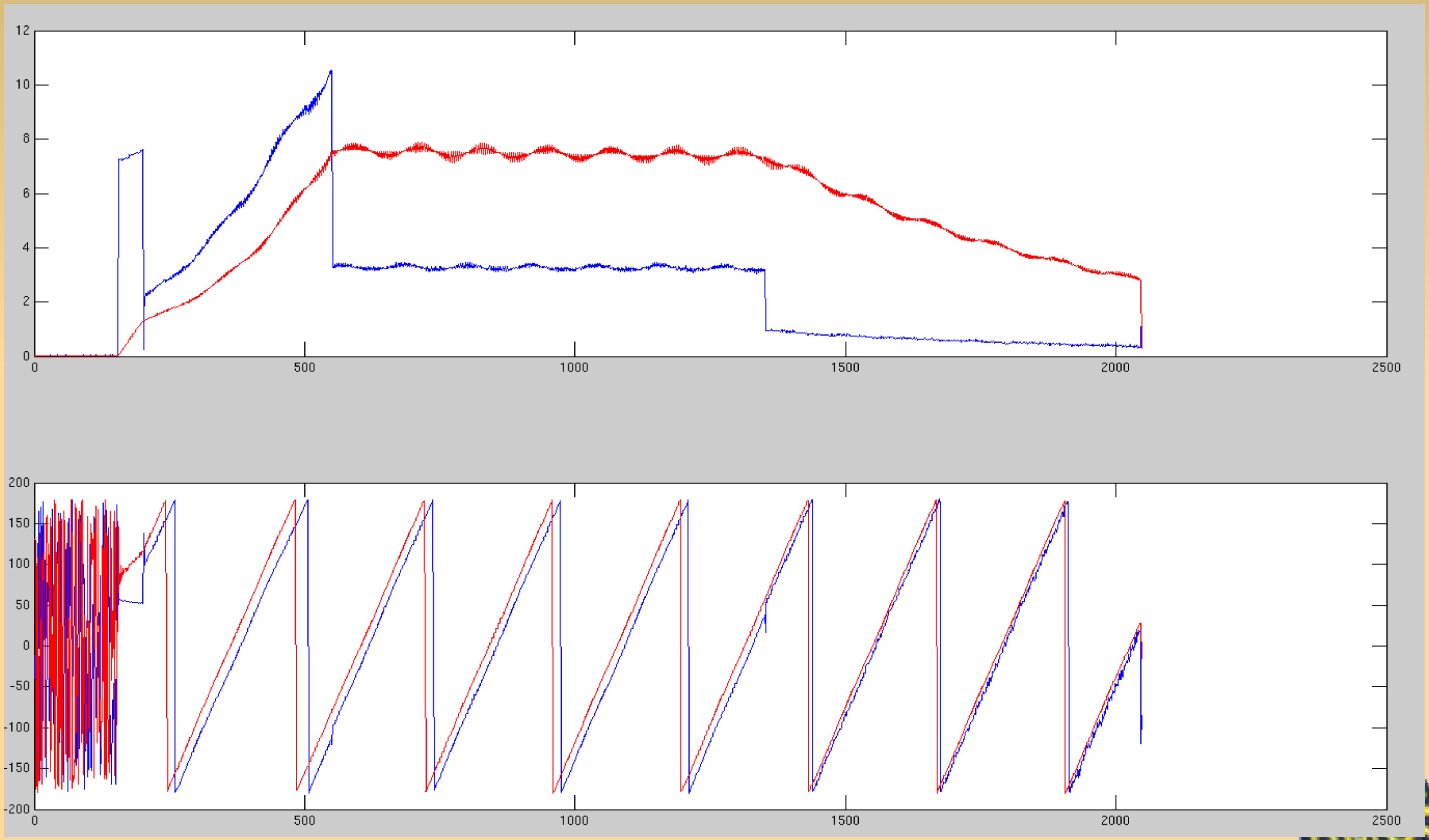
SEL results (2)



SEL results (3)



SEL results (4)

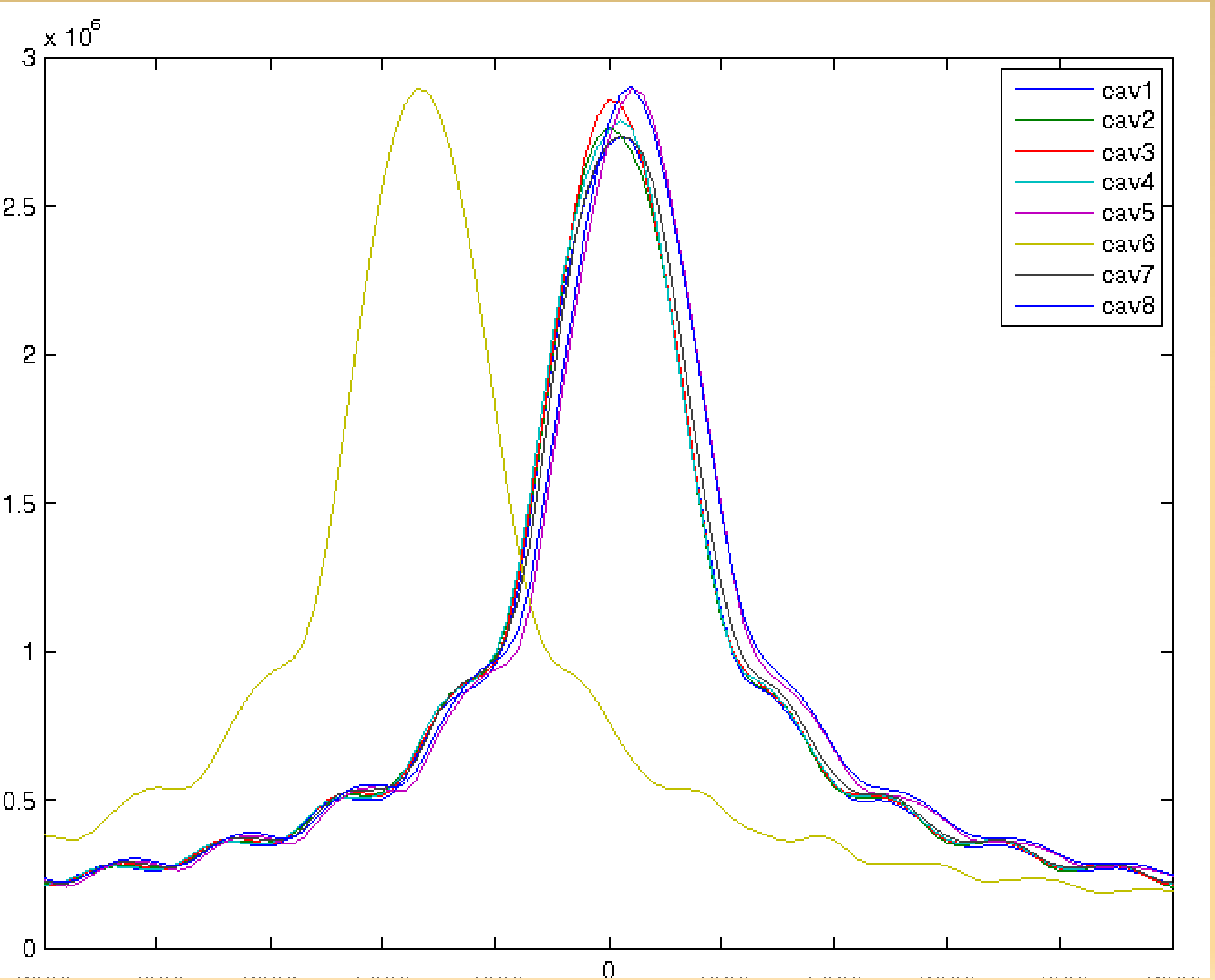


Frequency Sweep Mode

This function measures the frequency response of the individual cavities using constant amplitude and slope on the phase of the control signal .

The final implementation will work with increased frequency of output update rate to get more precise frequency control.

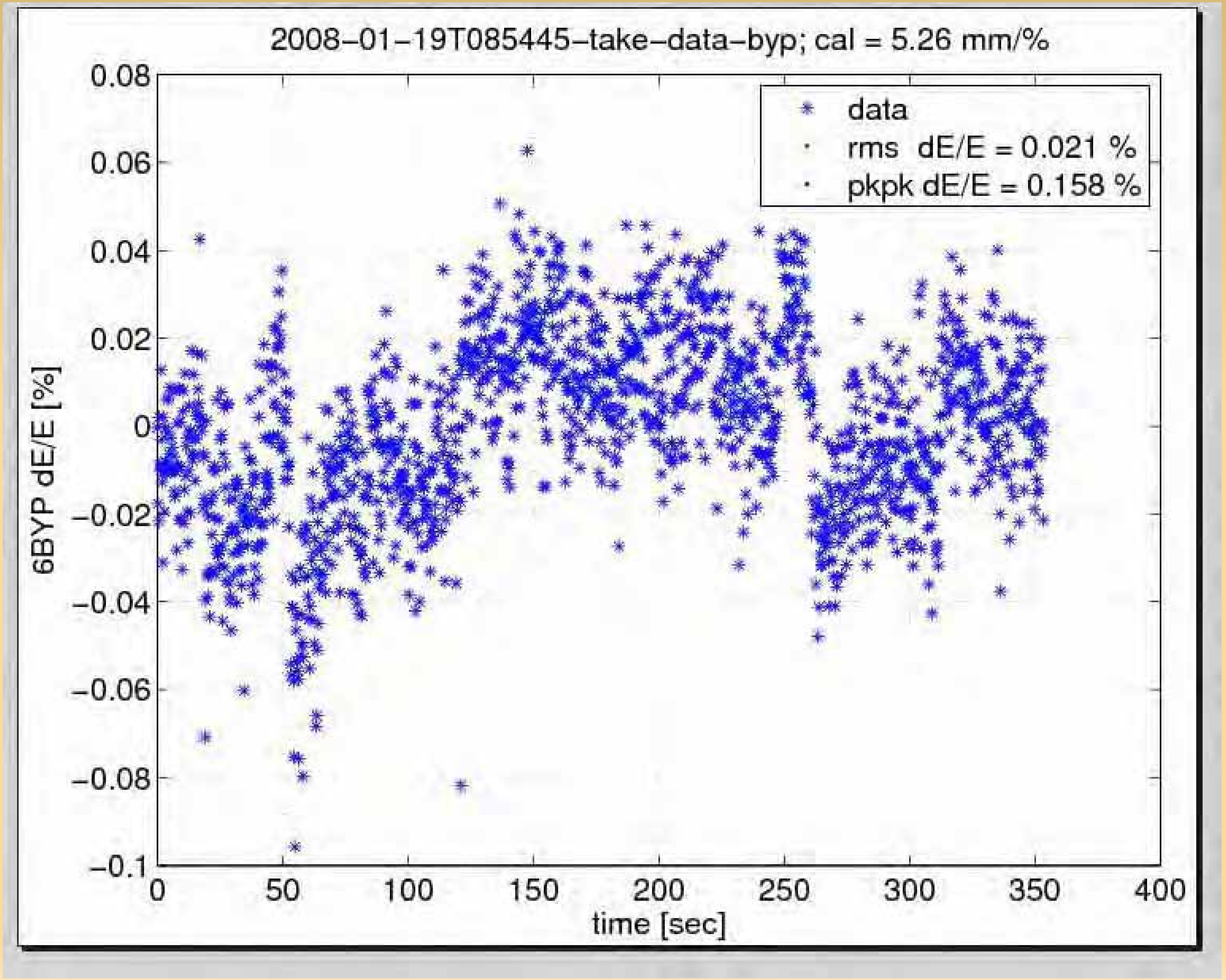
Frequency Sweep Mode



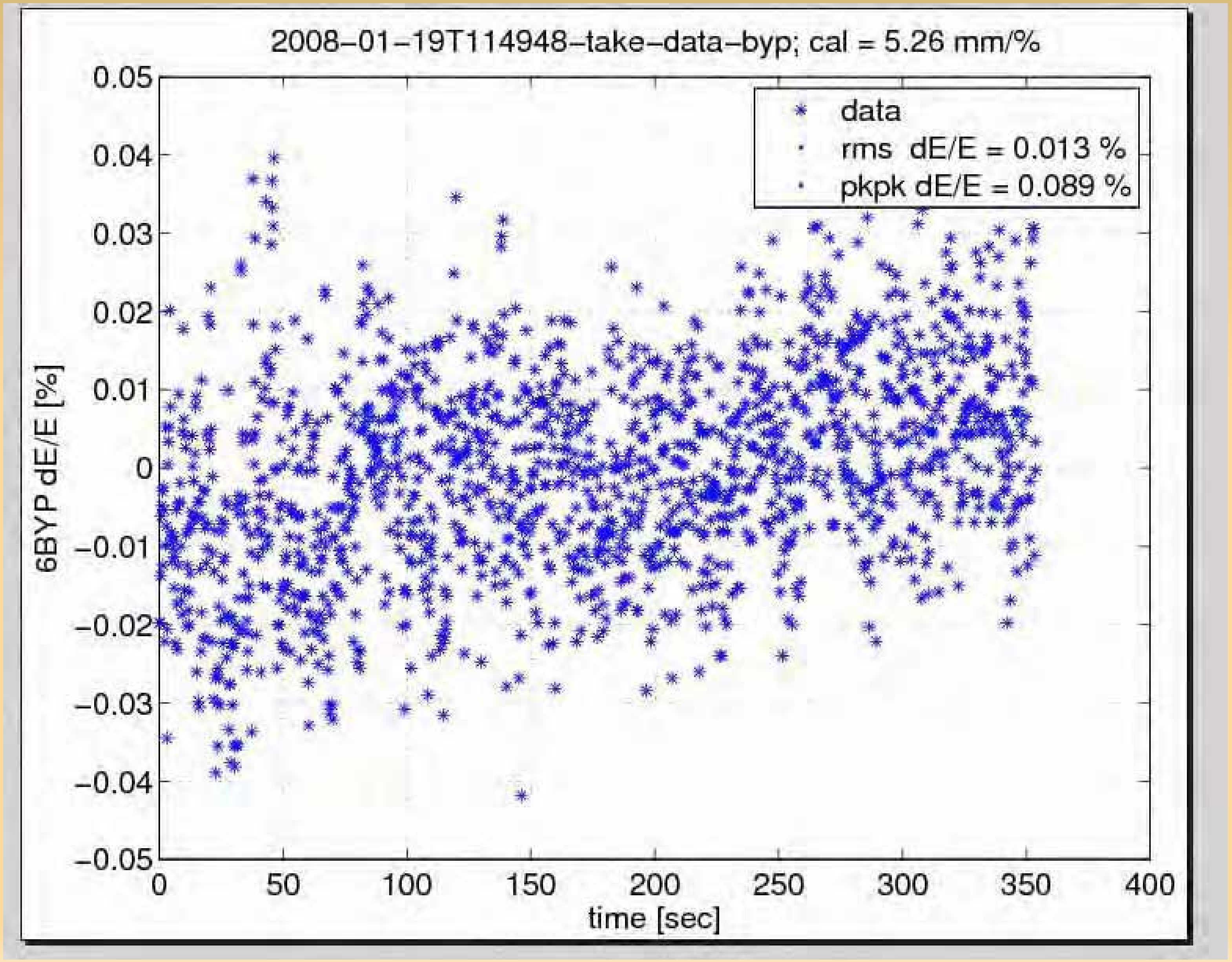
Beam stability – ACC456 (1)

The distributed version of the controller was used to drive ACC456 modules. To compare the quality of the control between DSP and FPGA based systems beam energy stability measurements have been performed.

Beam stability – ACC456 (1)



Beam stability – ACC456 (2)



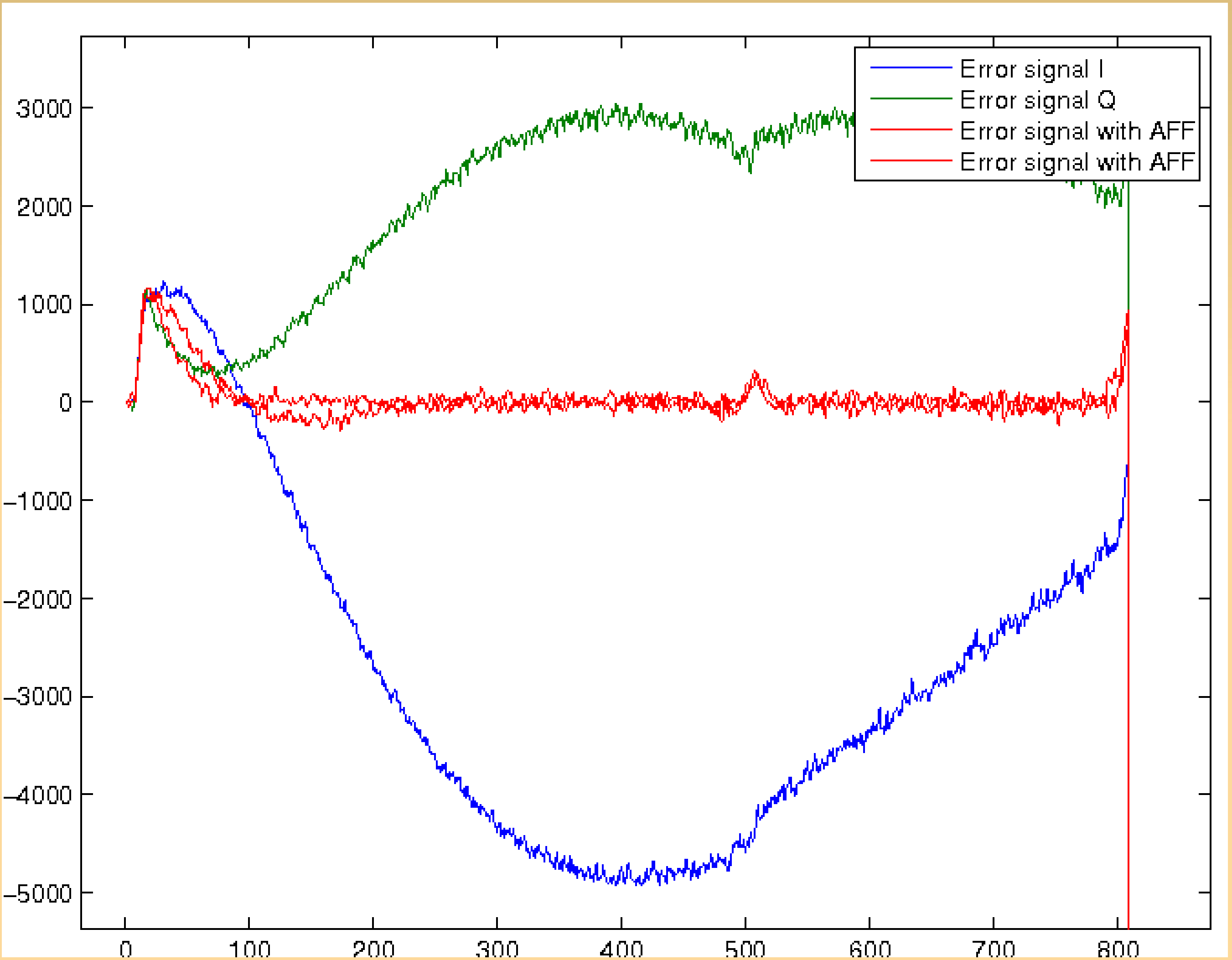
AFF tests

Algorithm proposed by A. Brandt was implemented for FPGA based controller. Currently there are 3 possible ways to run it:

- Matlab implementation
- FPGA implementation
- Embedded system implementation

In near future there will be DSP implementation as well

AFF tests (1)



Error signal I
Error signal Q
Error signal with AFF
Error signal with AFF
3000
2000
1000
0
−1000
−2000
−3000
−4000
−5000
0
100
200
300
400
500
600
700
800

RF Gun Control

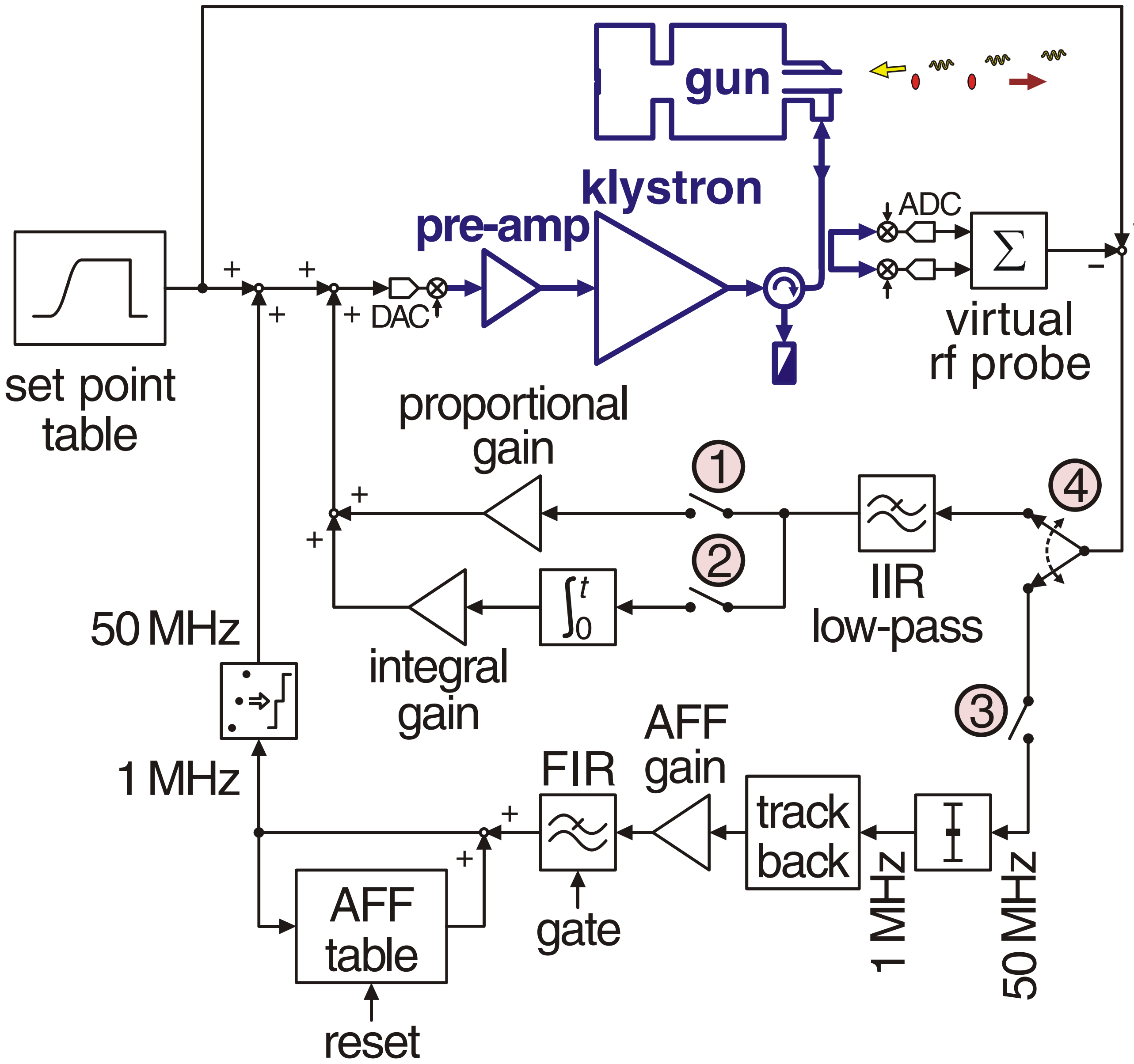
Rf control by SimCon 3.1 and sophisticated algorithms

Implications of missing probe:

- calculation of probe form forward and reflected rf
- calibration and linearization is an issue

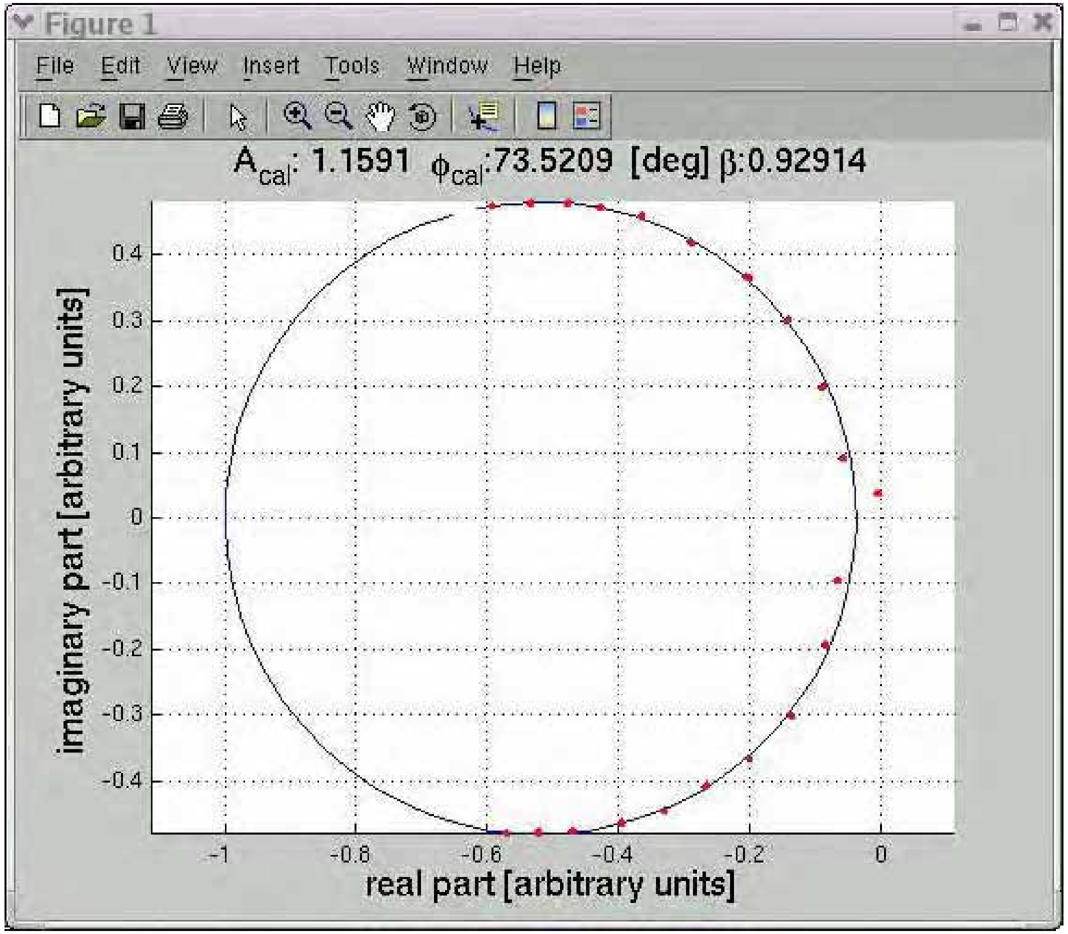
Algorithms:

- P(I) control with recursive 20 kHz low-pass (IIR) for stability at 'high' gain (>5)
- Adaptive feed forward (AFF) from rf pulse to rf pulse

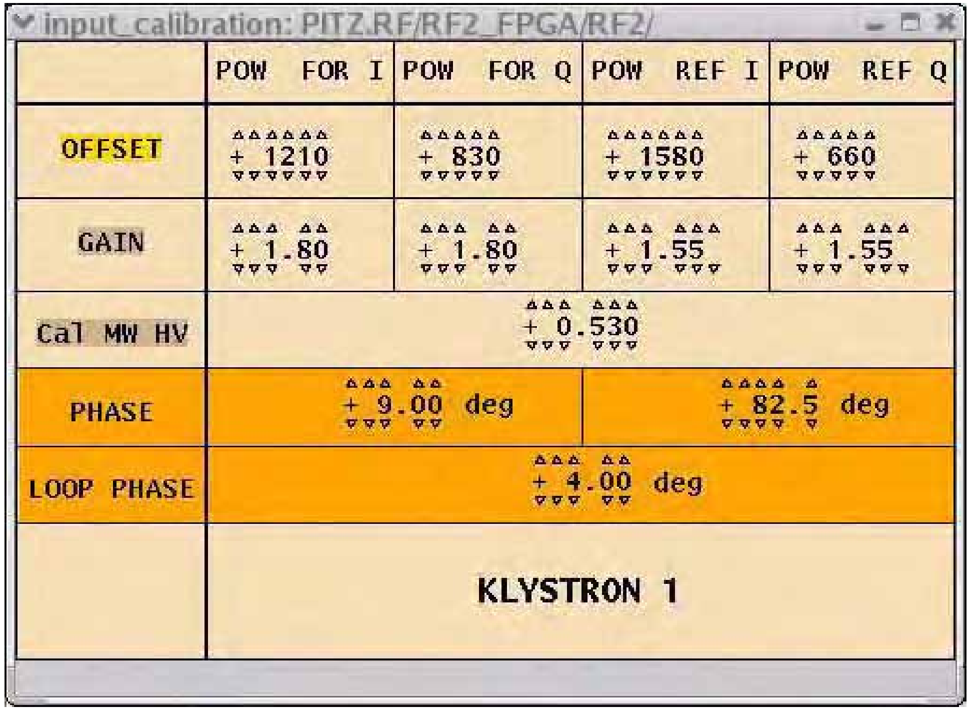


Virtual probe signal calibration (method established at FLASH by A. Brandt)

circle fitting after frequency variation

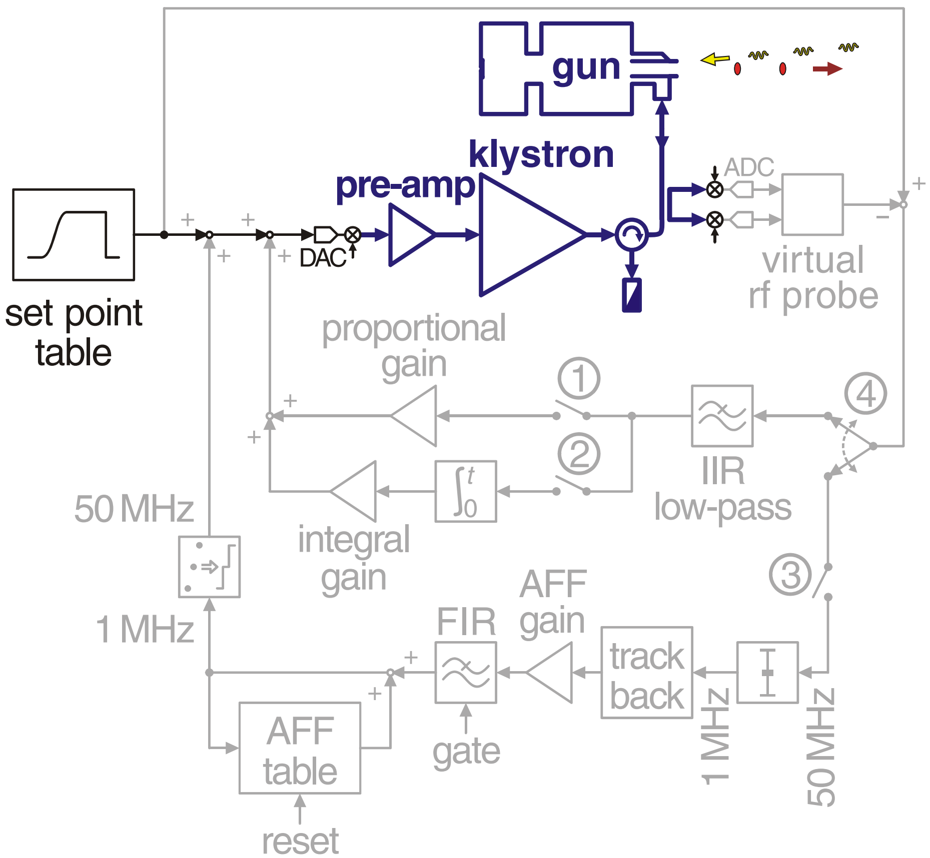


DOOCS panel for calibration parameters

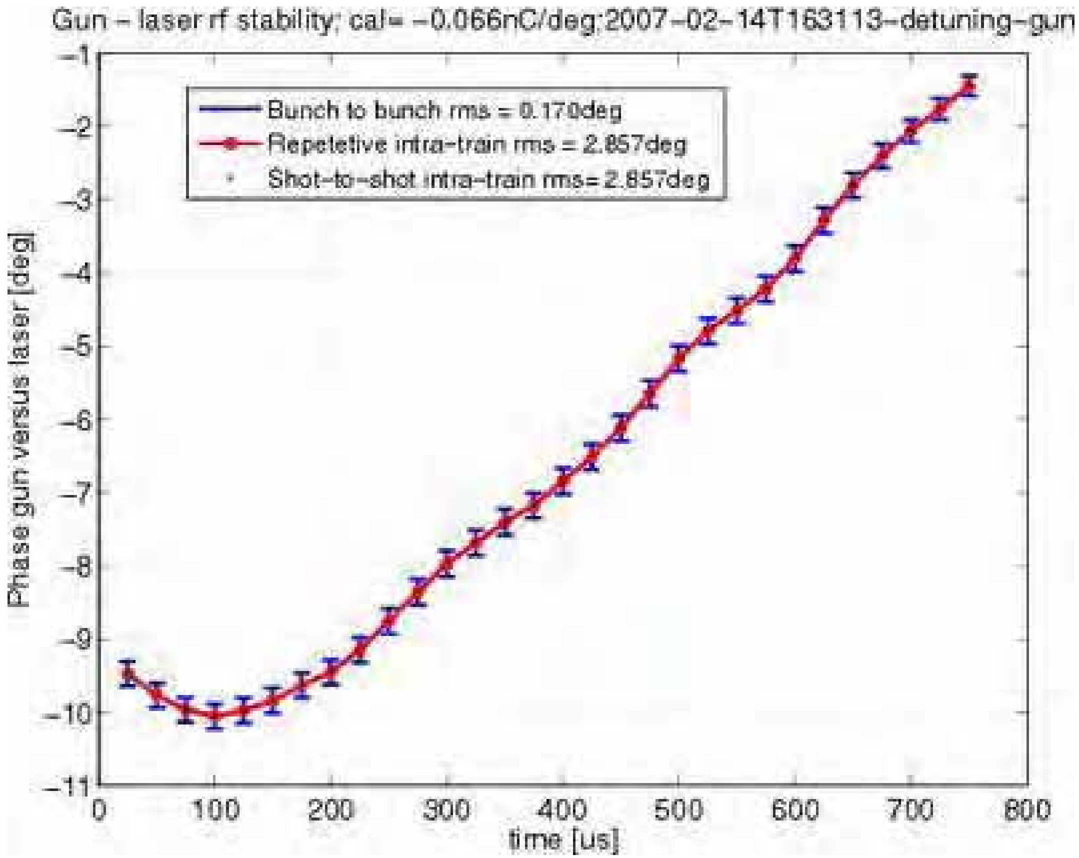


Plots taken at PITZ – the plots and panels look similar at FLASH!

Action of control loops - the case without control



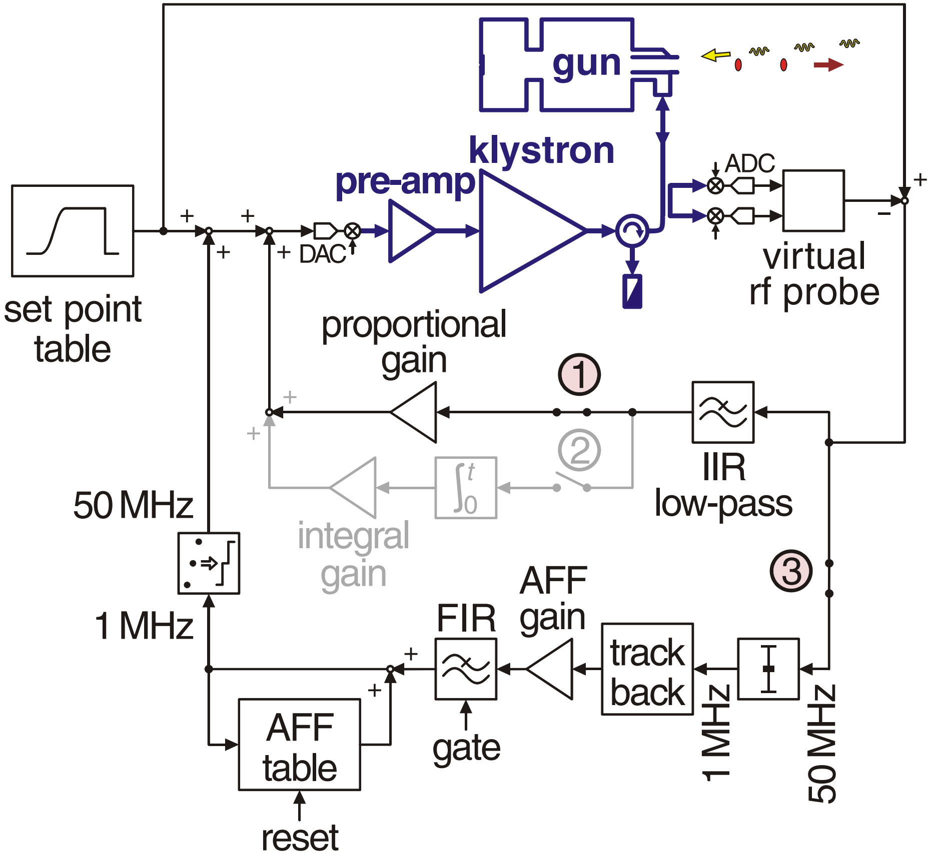
Beam based emission phase measurement:



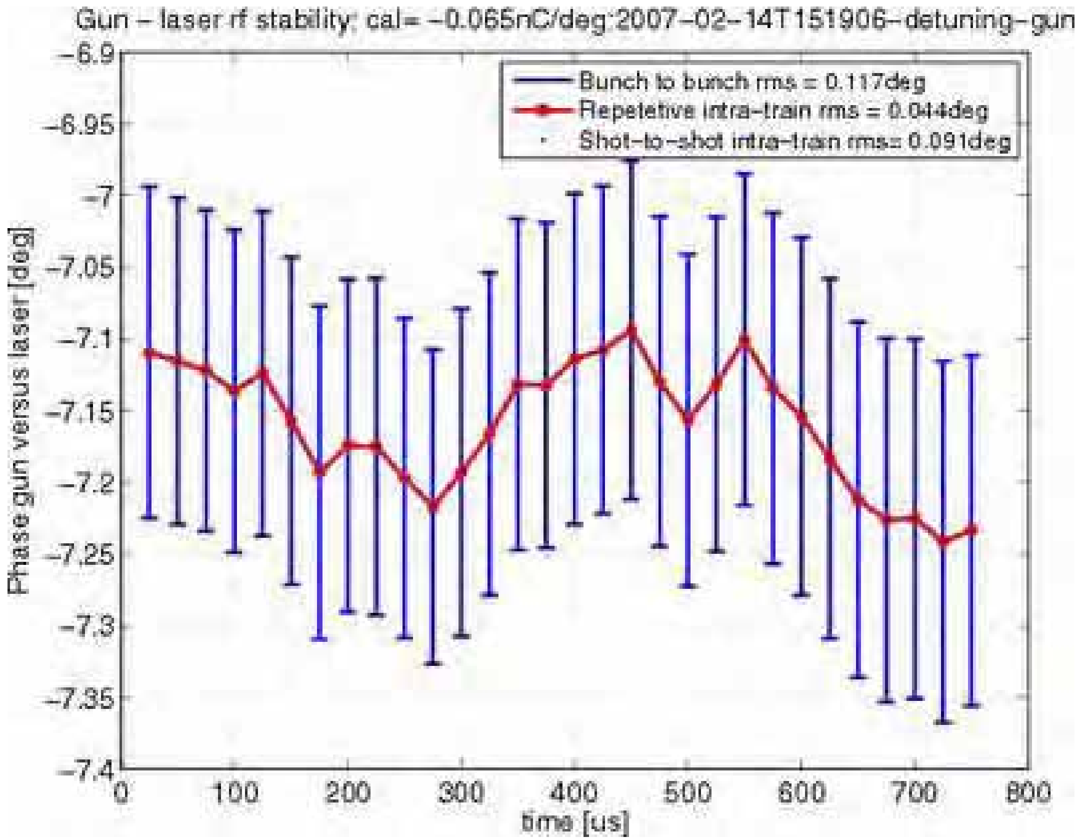
- gun **heats up within rf pulse**
- gun **resonance frequency** changes

➢ **the emission phase changes by 8.5°**

Case with P control and adaptive feed forward (AFF)



Beam based emission phase measurement:



- AFF corrects systematic errors
- AFF gain of 0.4

➢ **the emission phase changes by 0.14°**

Downconverter Performance

- **Single channel stability results:**

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) :

$\Delta A / A_{pkpk} = 0.09\%, \quad \Delta\varphi_{pkpk} = 0.05\ deg$

$\theta_A = 2e\text{-}3/^\circ C$, $\theta_P = 0.2^\circ/^\circ C$

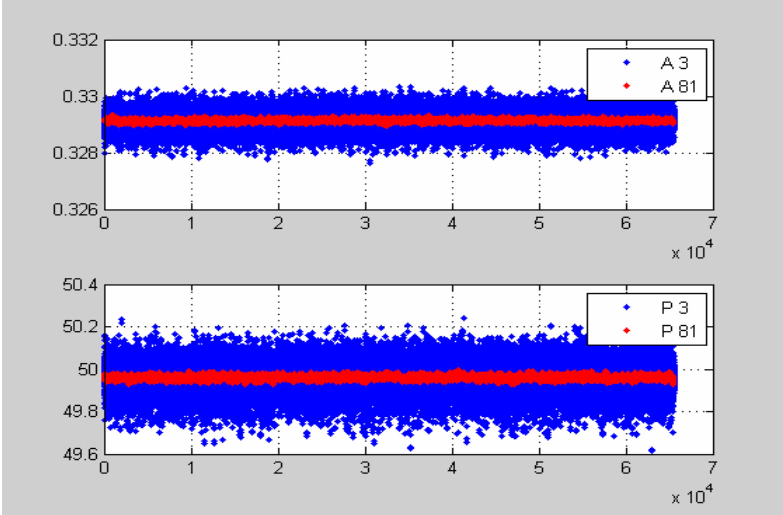
Parameter :

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

81 samples over 1 us
→ 1 IQ value
→ **~5 Hz through 10 minutes**

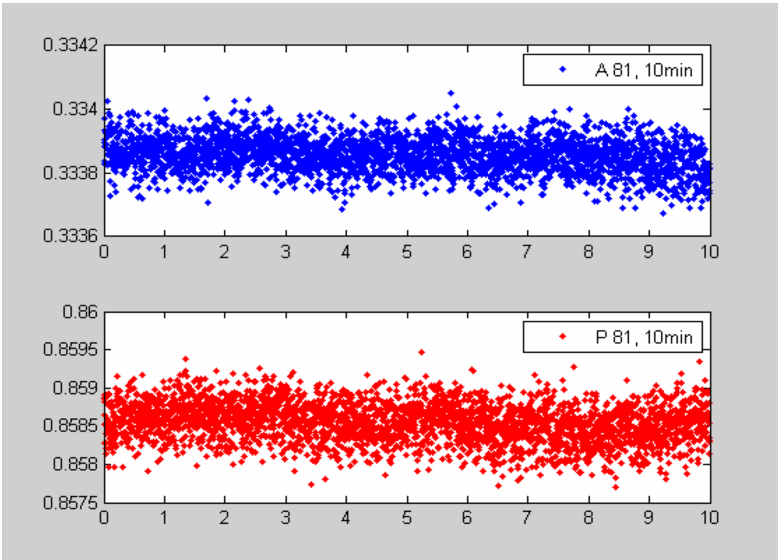
- **Shortterm stability 800us (bunch-to-bunch):**

BW=27MHz
BW=1MHz

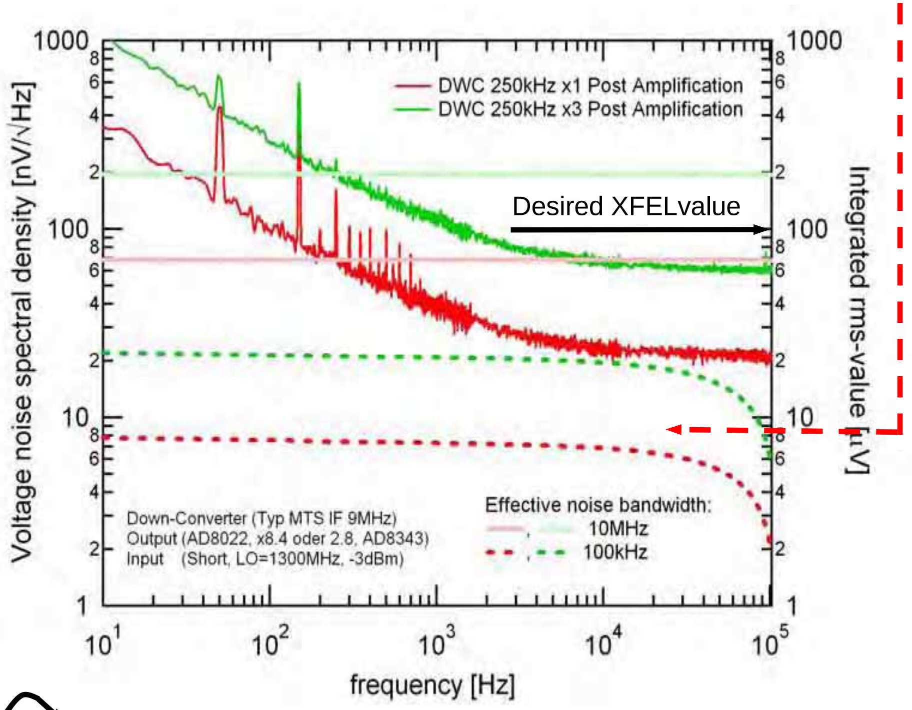


- **Midterm stability 10min (pulse-to-pulse):**

BW=1MHz
BW=1MHz

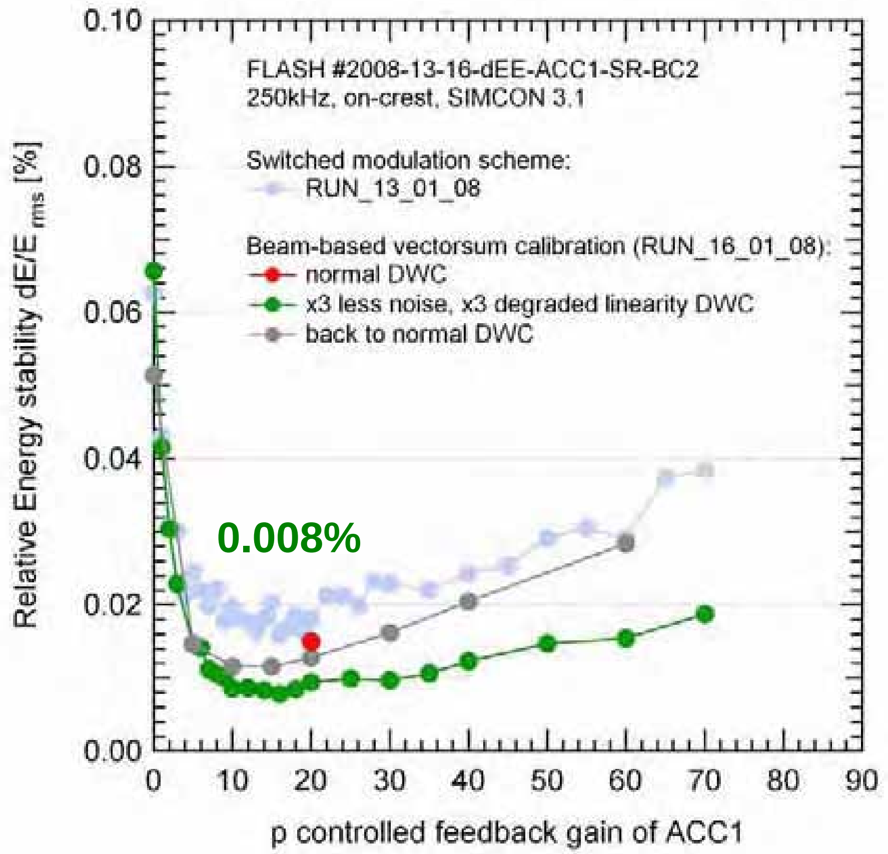


- **Modified DWC performance :**
  - Noise degreases by a factor of 3 to <0.001% of the DWC (without IQ Driver!) within the cavity effective noise bandwidth.
  - Linearity degrades from 0.5%toapprox. 5%



- Automated accurate waveguide adjustment (Indictation from off-crest LO generation limitation).
- Beam stability in dependence of gradient and phase.

- **Pulse-to-Pulse Beam Stability :**



- 0.008% on-crest beam stability is achieved.
- The DWCs non-linearity has no influence on beam stability for fixed machine parameters.
- DWC is not the limiting factor.

Motivation

Synch. System Signal Generation

Cabeling

Analog Hardware Packaging

Gilbert-Mixer

Linearity

Drifts compensation

Crosstalk

Beam-based feedbacks

High-Level Mixer

Digital Hardware Packaging

Arrival time monitors

Modulation scheme

Energy spread monitors

1/f-noise [1Hz-10kHz]

Scaleable Receivers

Automation

Vectorsum Calibration

Actuator noise

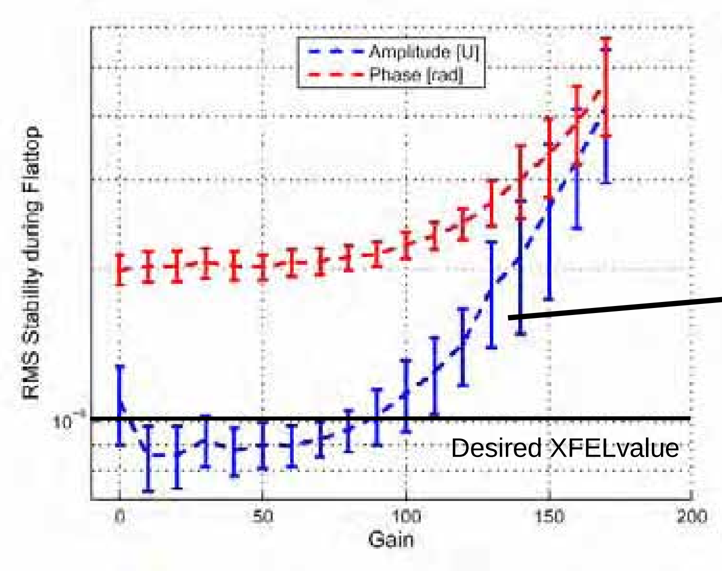
ADC noise

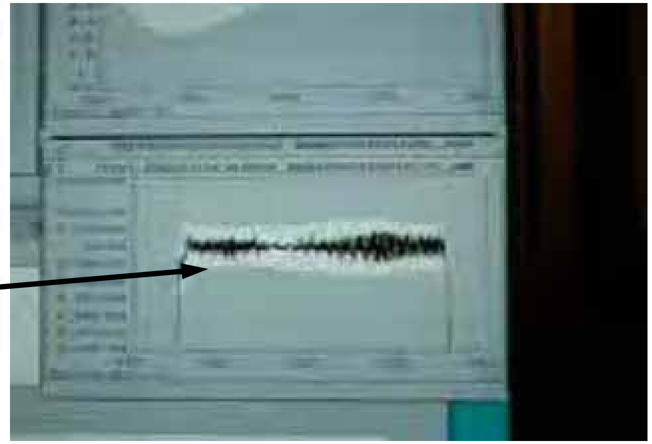
Master Reference

What is most important for a beam stability significantly lower than 0.01% ?

- **FLASH injector :**

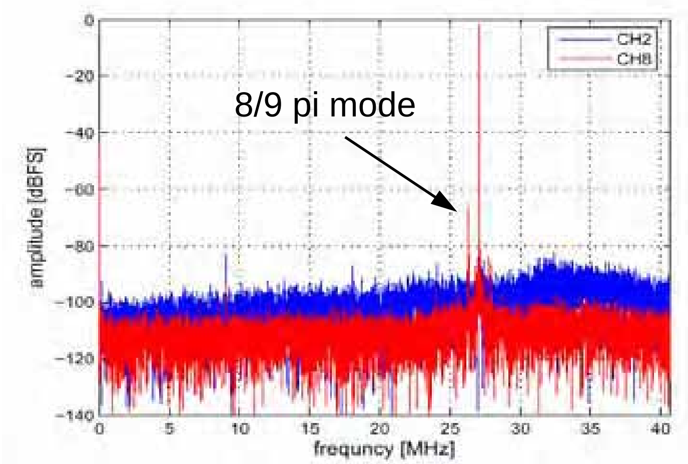
- **Vectorsum stability with closed control loop at ACC1:**





Instability caused by 8/9pi mode

Down-converter biased by Cavity pickup :

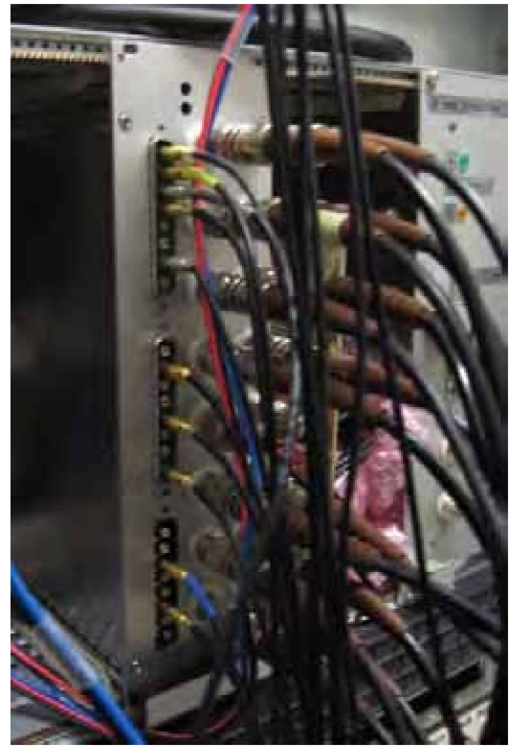


	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
$\Delta A/A\ [10^{-4}]$	3.8	5.8	5.1	4.1	2.8	4.1	2.1	3.6
$\Delta\varphi$ [deg]	0.028	0.038	0.035	0.033	0.025	0.032	0.022	0.032
$\Delta A/A\ [10^{-4}]$	2.1	2.5	1.9	1.6	1.0	1.5	0.9	1.5
$\Delta\varphi$ [deg]	0.016	0.019	0.018	0.021	0.016	0.020	0.015	0.019

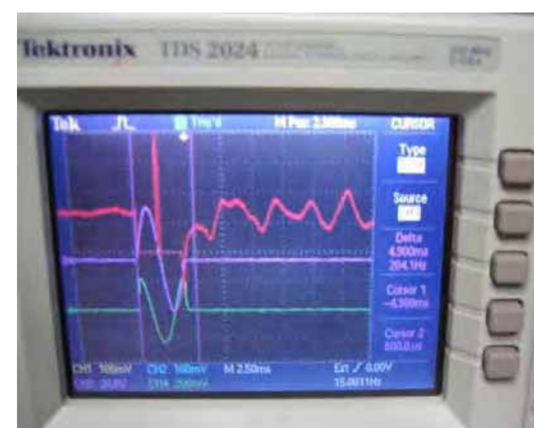
- Down-converter fulfill XFEL specs
- Spurius signals are below 80dBc
- Cavity 8/9pi mode clearly measurable

Piezotuner Control

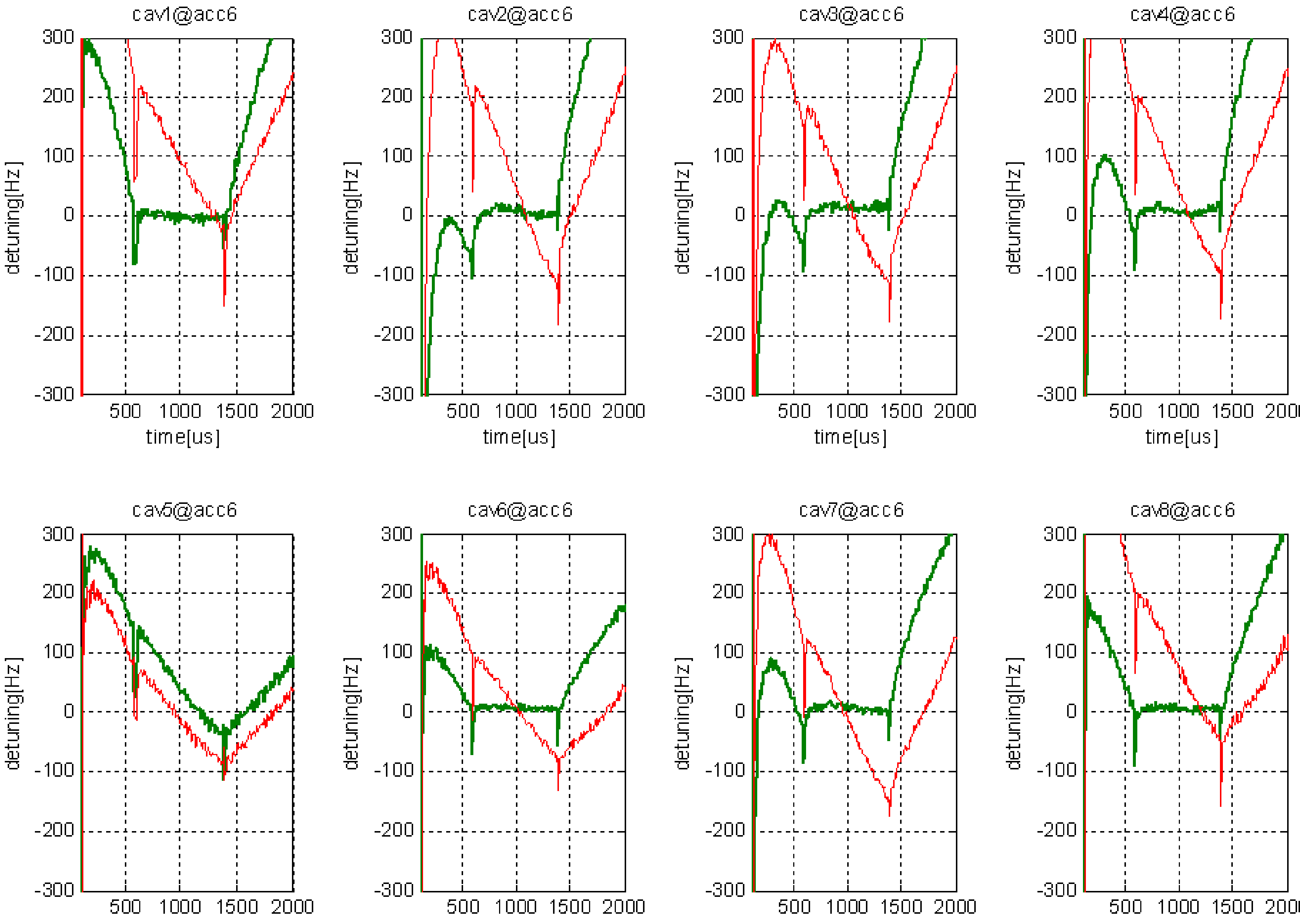
FLASH tests




ACC-6 Piezotuner
grün
gelb
gelb
grün
gelb


Tektronix
TDS 2024

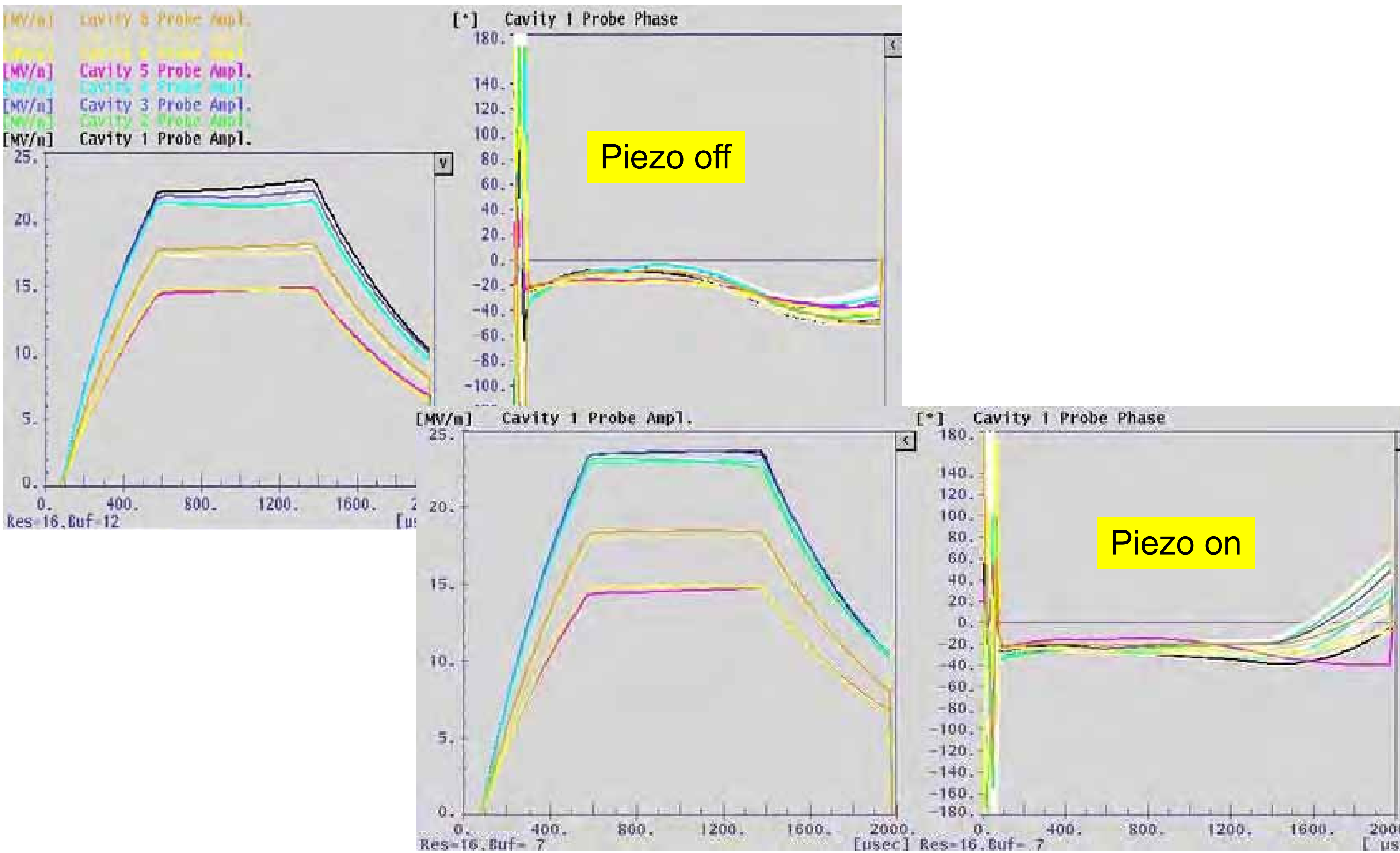
ACC6 (SP = 15 MV/m, Pforw = 220kW, rep = 5 Hz)



Cav. (1-3)
Amp: 34V
Dly: - 4.1 ms

Cav. (4-8)
Amp: 23V
Dly: - 4 ms

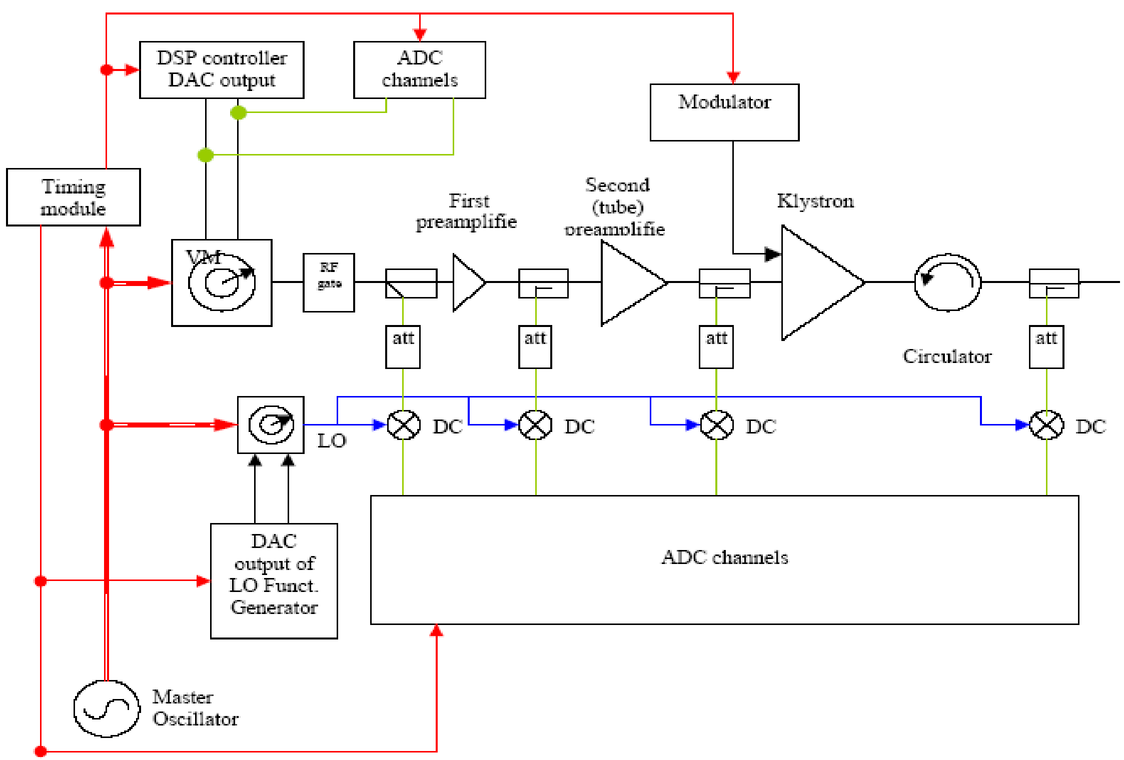
ACC6 – LFD compensation results



Klystron Linearization

Non-linearities measurement purpose

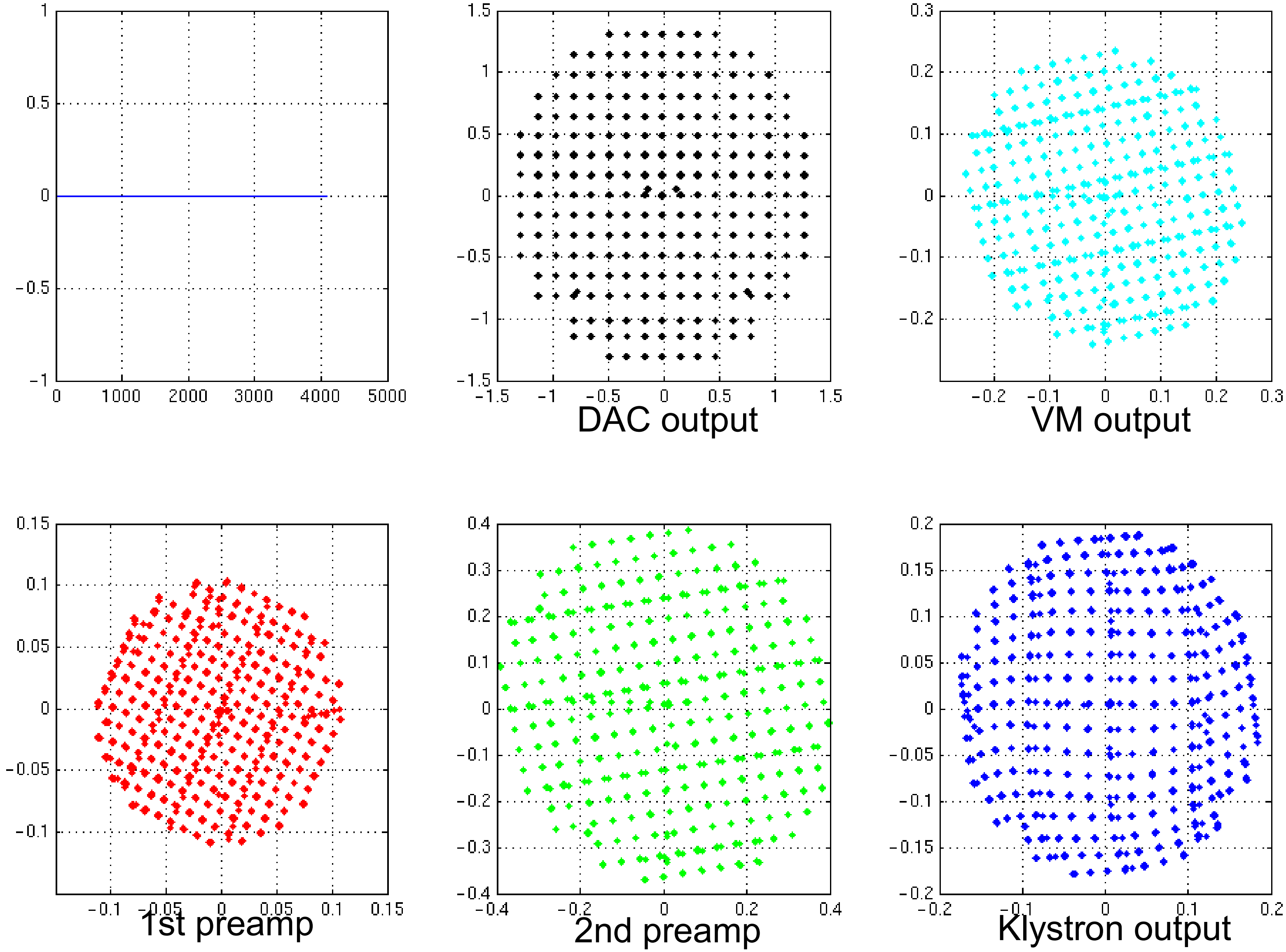
Goal:
To provide high power chain components characterization for the different working parameters.



This characterization will be used in the linearization method designing for a klystron and high power amplifiers.

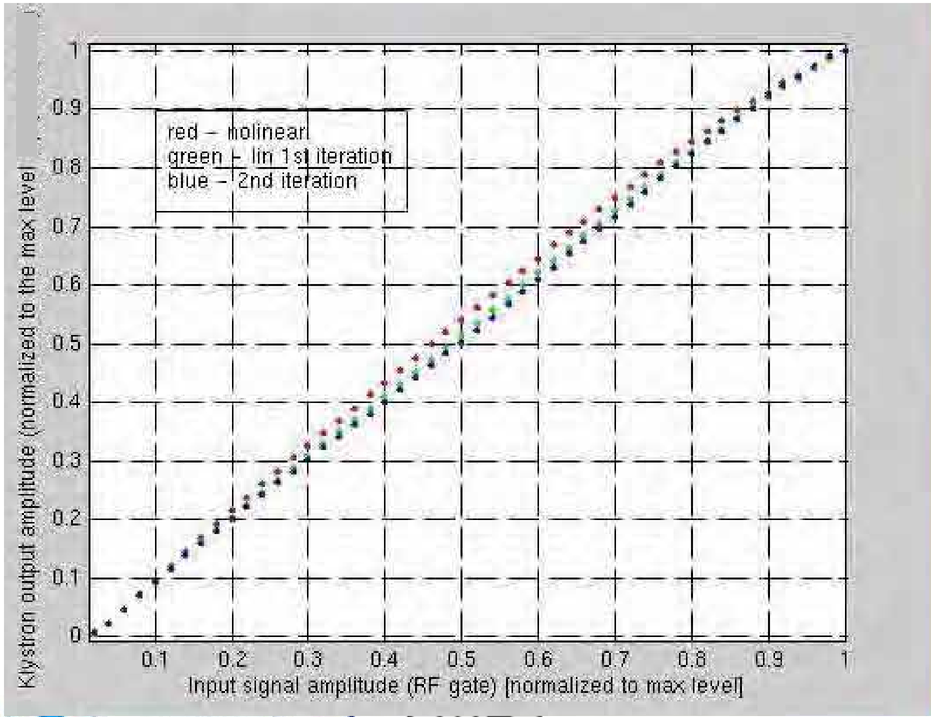
Thanks to provided diagnostic, one can also detect following anomalies:
- different HPC component malfunction,
- components saturations,
- phase or frequency offsets, etc.

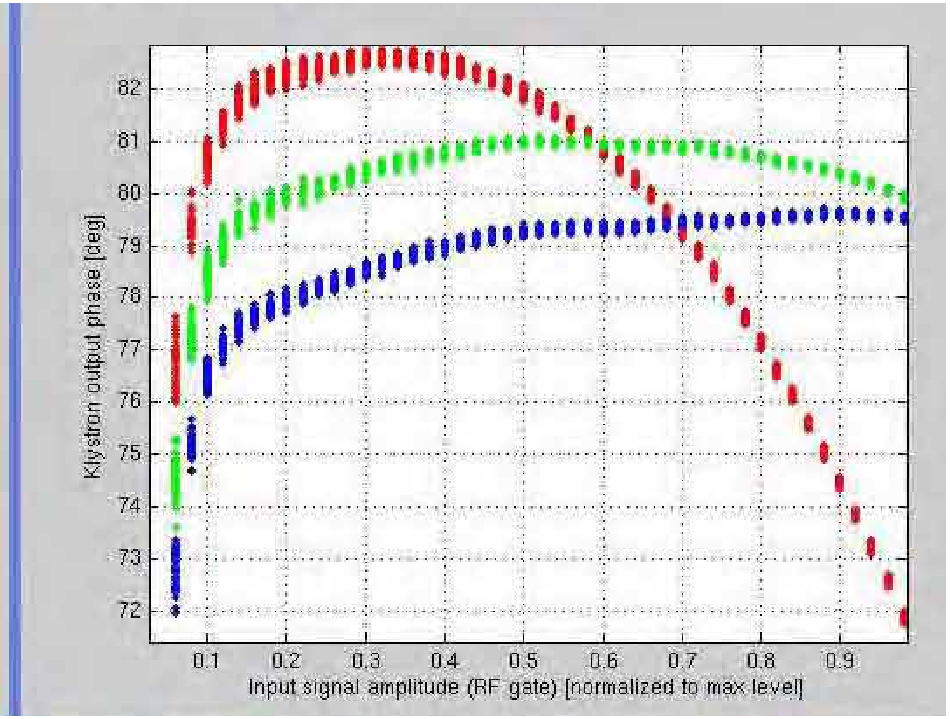
KLYSTRON 5



Klystron 5 HPC linearisation results

- Linearisation test had been performed using Simcon(FPGA) controler,
- Correction tables were „on”
- HV level – 10800 (value on PLC) about 110kV
- Two iteration of the linearisation were performed.





Radiation Measurements

Exp # 1: Results

Gamma does rates along FLASH during Routine Operation at a gradient of ~ 21 MV/m

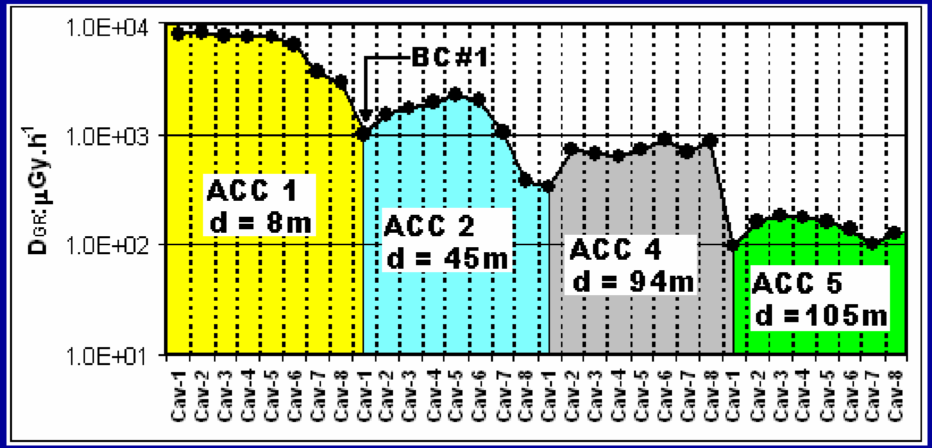


Fig. 3

(R1.1) Accelerated dark current from RF gun is the prime source of gamma dose.

(R1.2) Gamma dose rate drops strongly with the distance from the RF gun.

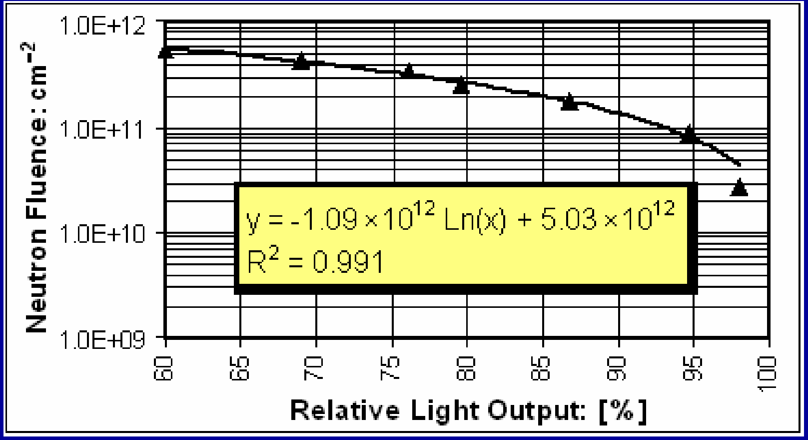
(R1.3) Gamma dose rate at the cryomodule (ACC 1) near bunch compressor (BC #1) is two orders of magnitude higher than the distant module ACC 5.

(R1.4) The radiation dose at modules, far away for the RF gun mainly contributed by the accelerated field emission electrons inside cavities.

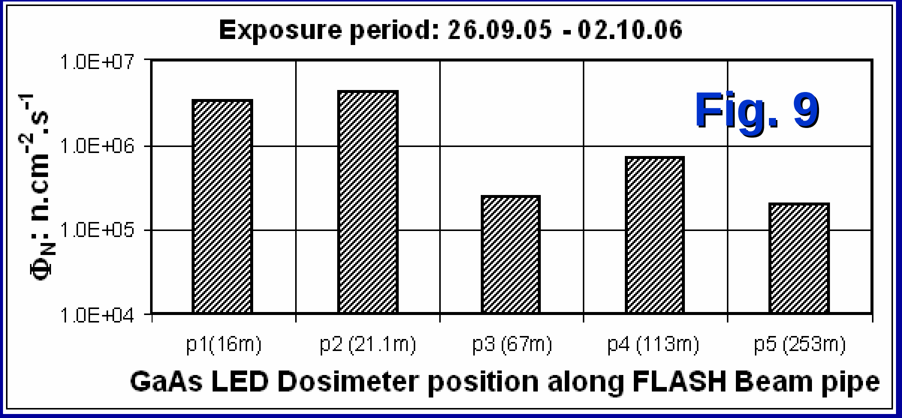
(R1.5) The radiation doses (both gamma and neutron) depends on "locally produced" accelerated (~ MeV) field emissions, "NOT ON" the main Electron Beam (~ GeV).

Exp #5: Results

Fast Neutron Dose Rates along the FLASH Beam pipe Estimated in-situ using GaAs LED (COTS)



Calibration curve of the GaAs dosimeters evaluated using a ^{241}Am/Be Neutron Source.



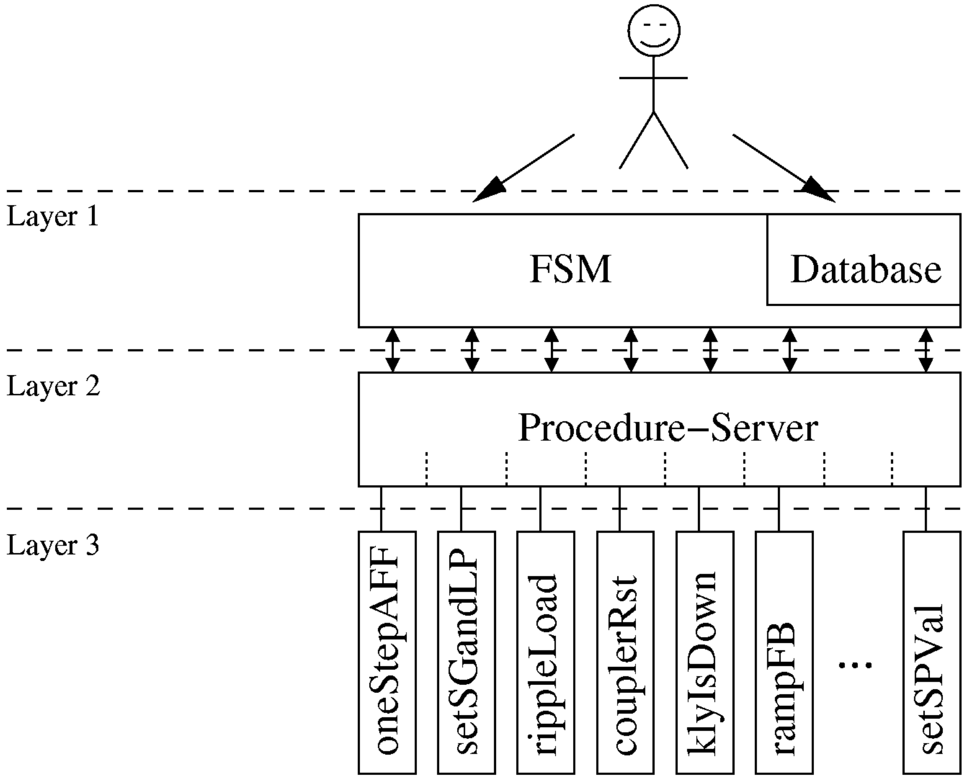
Fast neutron fluence along the FLASH beam pipe estimated with tiny GaAs Dosimeters.

(R5.1) Significant levels of neutron fluence are produced at critical areas (bunch compressors, collimator, injector) due the interaction of "transversally diverted" electrons with the beam tube wall locations p1, p2, p3, p4 and p5 in Fig. 2)

(R5.2) These neutrons are generated in small areas, intensity drops significantly with distance from the production spots (i.e. beam interaction regions), "NIL"effects on LLRF electronics.

Automation

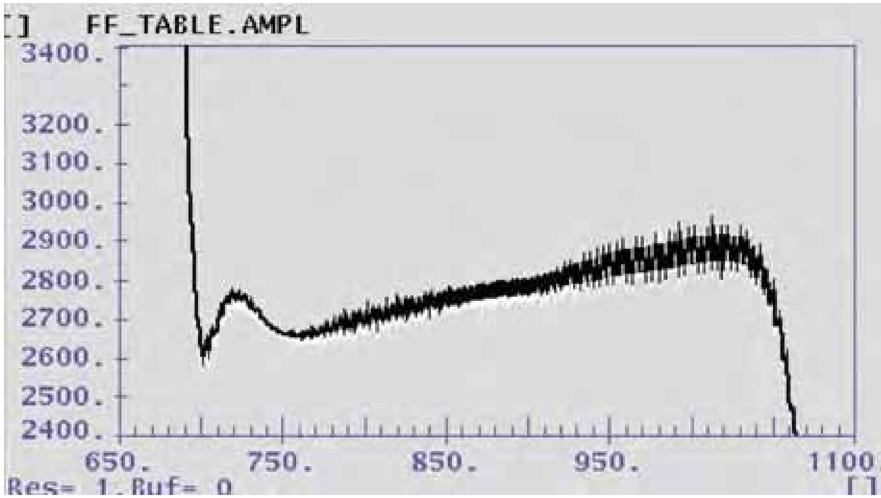
FSM-Architecture



Procedures

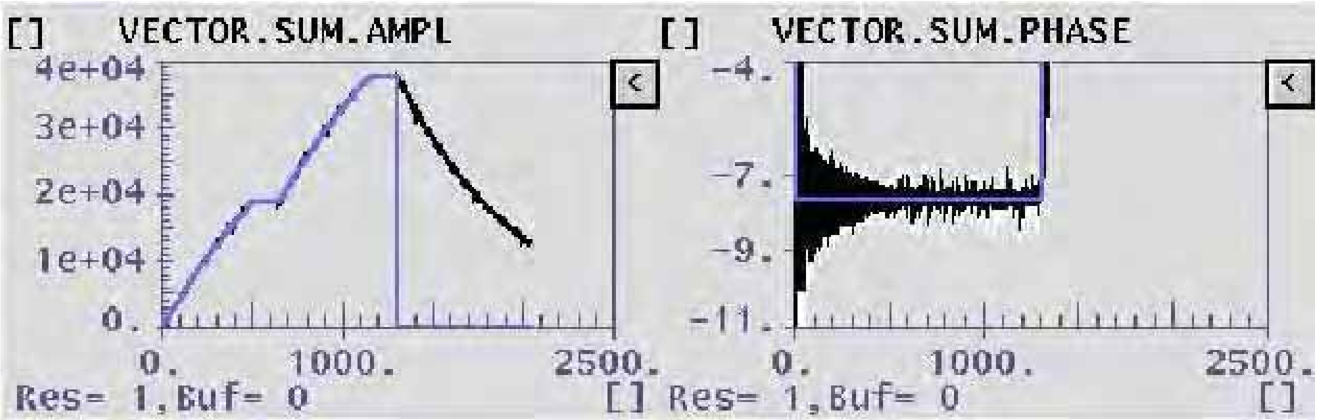
- Compiled scripts of any programming language (and any Matlab-version)
- “Fire and forget”:
  - –Invoke - Run - Return
  - –“Stateless Procedures”
- E.g.:
  - –**Adaptive Feedforward**
  - –Loop-Phase
- Web-Documentation
- Algorithms are identical for all RF-stations and read a config file

Adaptive Feedforward

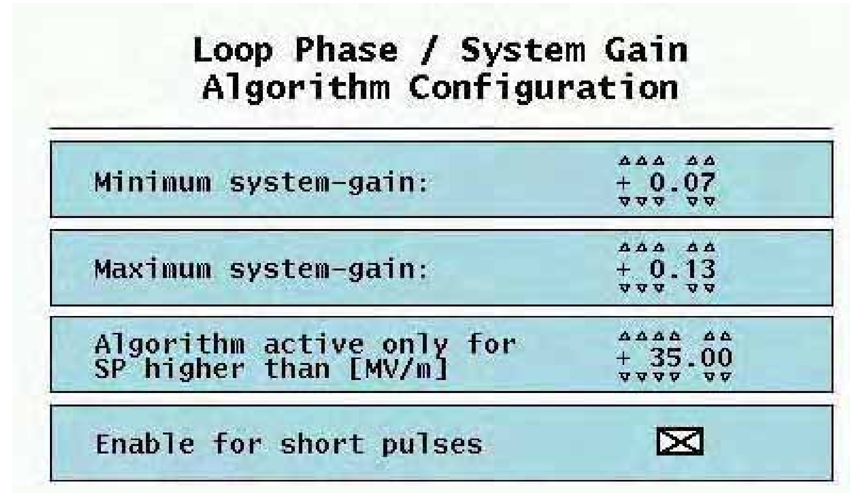


Adaptive FF w/ beam load (ACC2/3, 30us, ~1nC)
Remember, this is just the FF contribution!
E-Log 10/3/2006, 14:15

Fancy pulses w/ adaptive FF
E-Log 25/3/2006, 8:58

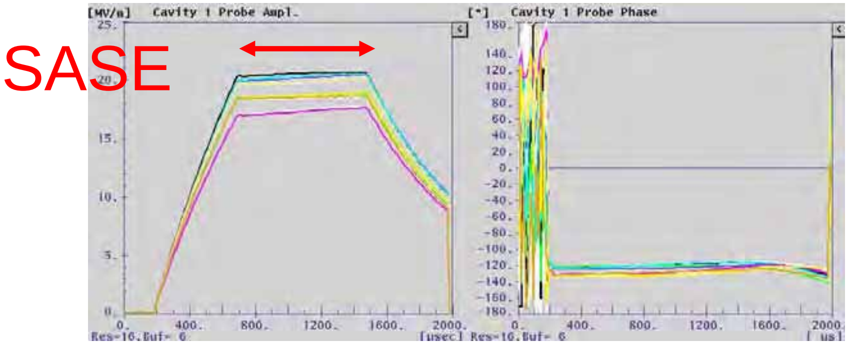


Loop Phase Correction

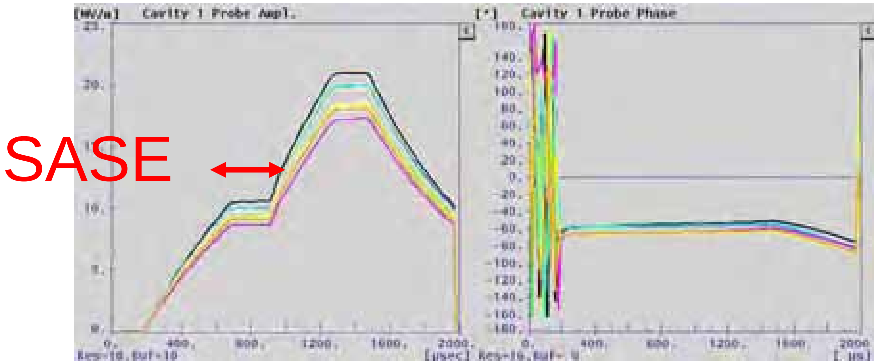


Operation at Alternating Gradients

Two Ramp Modes (2)



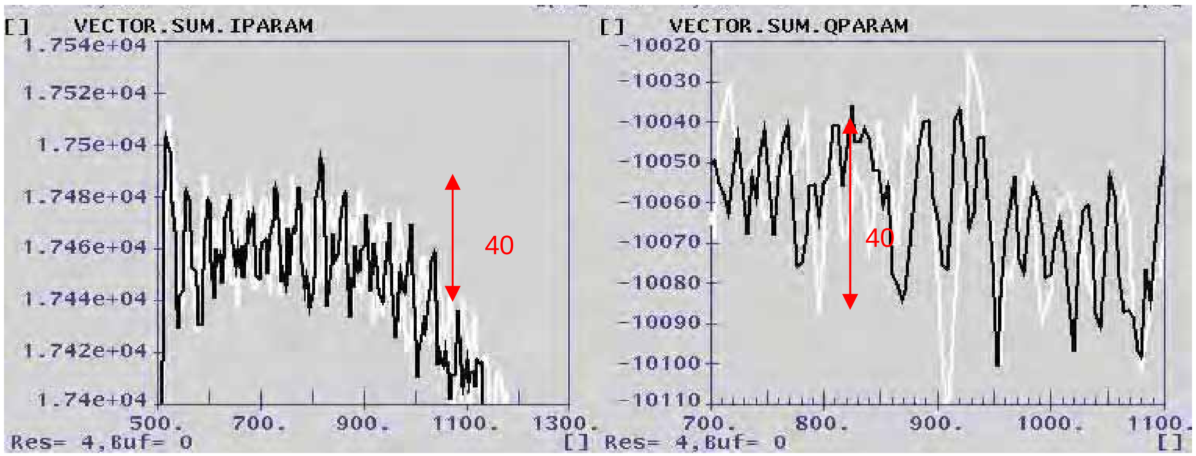
Alternate SASE, standard mode of operation



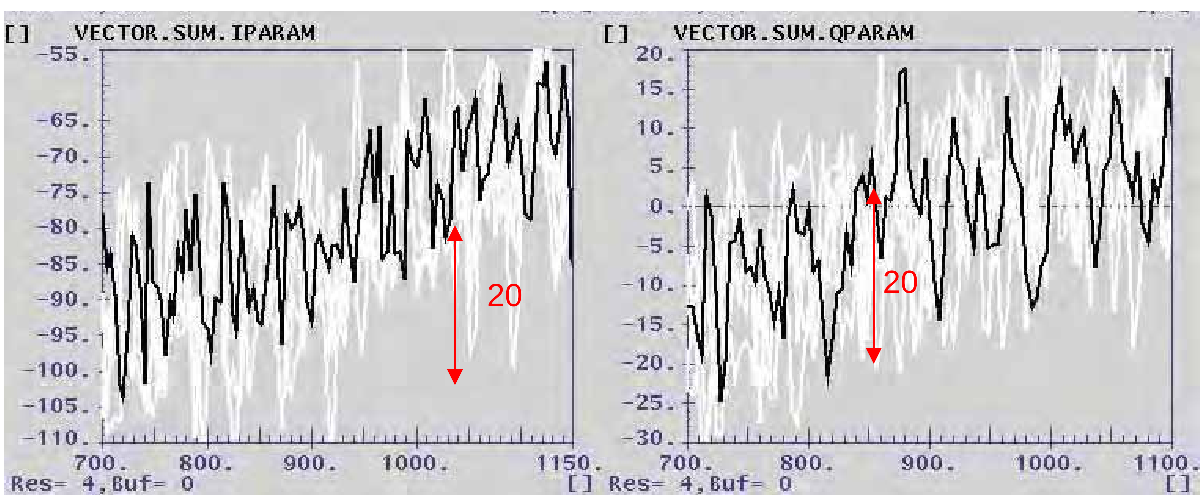
Ramp with two levels, 1st for SASE
Variable RF pulse length

Noise investigation

Measured the ripple on the power supplies for the down-converters for ACC4/5
Cry modules. Discovered short noise spikes with an amplitude of several hundred mV from +-15V.
The repetition rate of the noise spikes was of the order of 50 kHz.
Recommend an experiment where switched power supplies are replaced with linear power supplies.

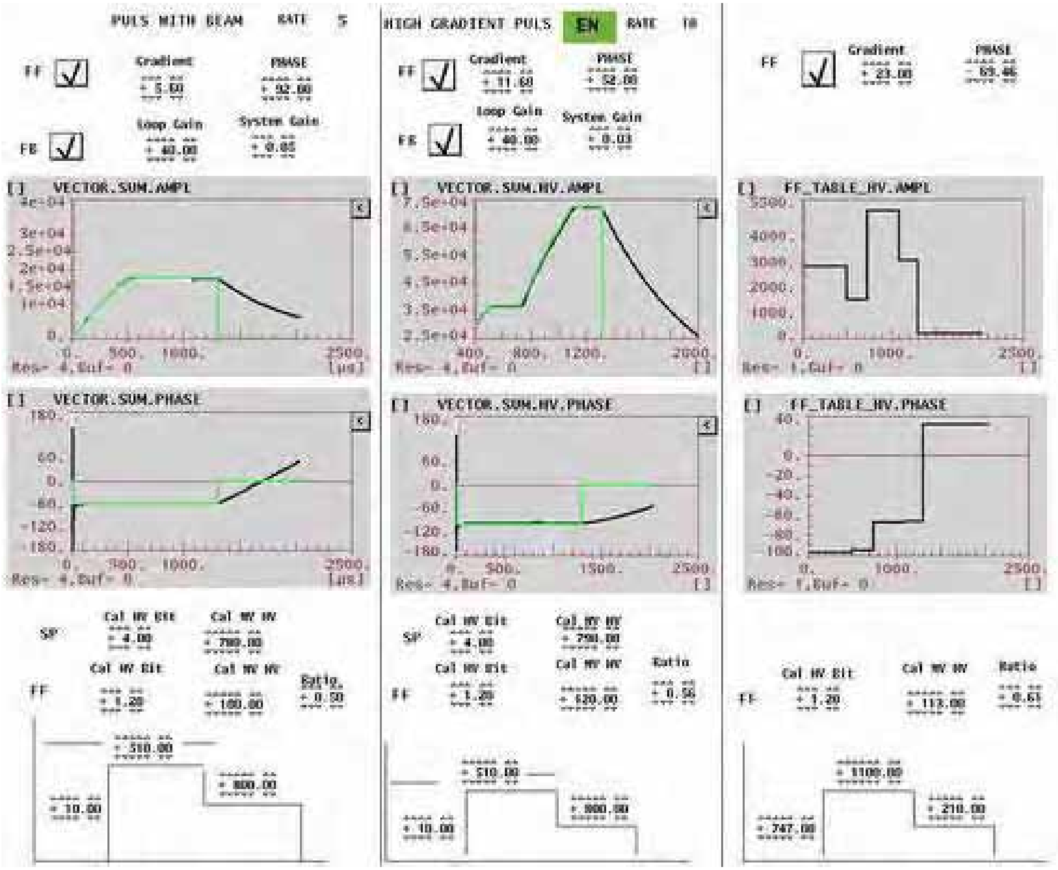


ACC4/5 with close to 20MV/m gradient.



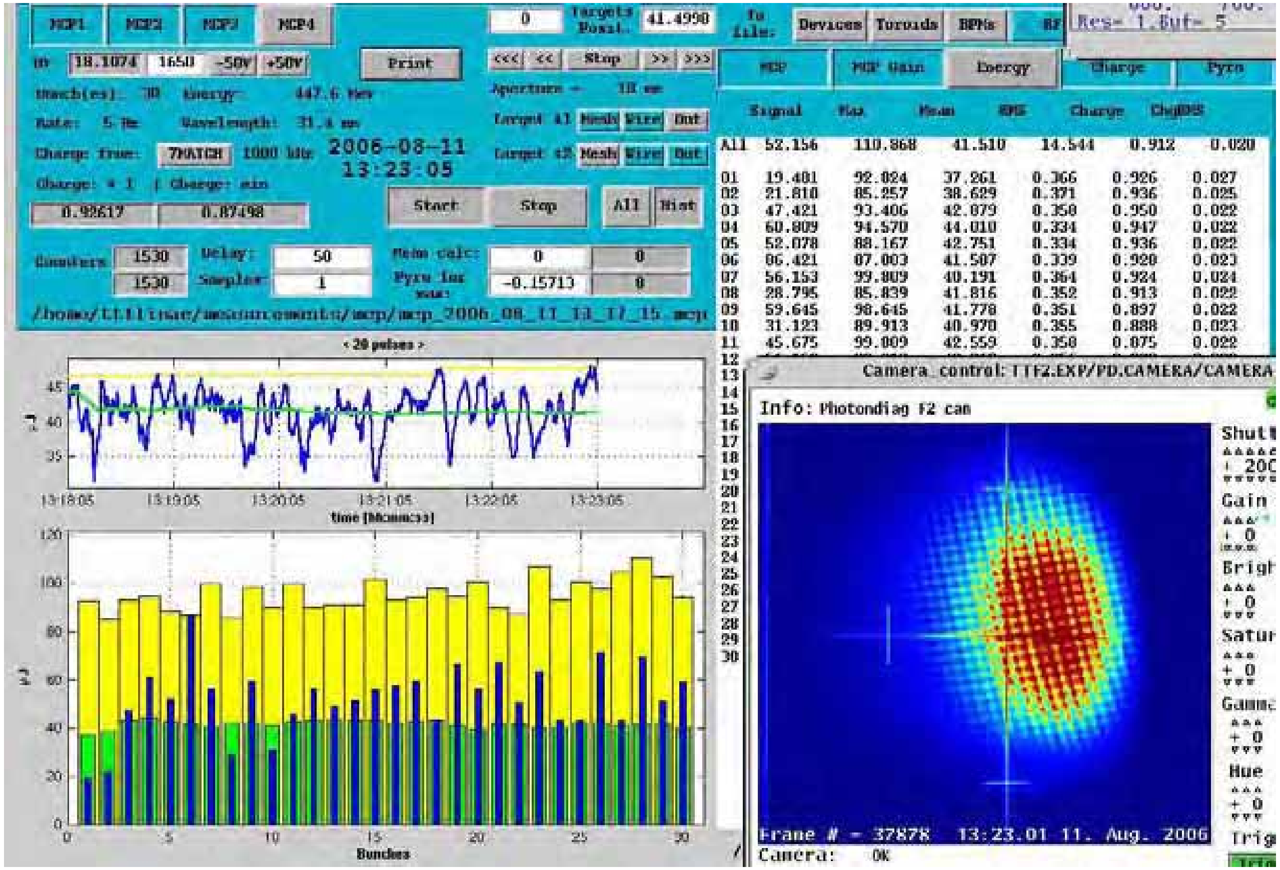
ACC4/5 with 0 gradient (no rf).

11.08.2006 12:58 Ayvazyan,Petrosyan,Yurkov ACC45 is running at 10Hz rep. rate with alternating gradients and SASE conditions.



11.08.2006 12:59

SASE level with alternating pulses. First pulse with beam, second pulse without beam and with 2 level of gradients. The SASE level is the same as with one pulse mode operation (see picture at 12:51).



LLRF Goals for FLASH in 2008

- Install and commission new Master Oscillator
- Install redundant LLRF development system in ACC1
- Investigate Phase drifts/jumps
- Correct problems with ACC1 control
- Study RF Gun control limitations
- Implement improved user interface for the adaptive Feedforward
- Improve beam loading compensation for all modules
- Propose optimum Q_L for FLASH operation
- Design 3.9 GHz LLRF including rf reference for harmonic cavity
- Install redundant ATCA system for ACC456
- Install permanent piezo tuning control for ACC 3 5 6
- Improve user interface for LLRF operation

Some topics for future studies

- Long term beam stability issues
- Beam loading effects
- RF stability vs. SASE performance
- Complete machine stability issue which is coupled with several RF stations
- Control performance of 24 cavities
- Improve/automate beam based calibrations procedures
- Exception detection and handling
- RF Gun control without probe

Shifts required at FLASH

- On average about 1 shift *) / month for the next 5 years (about 0.2% of LLRF project effort)
- Topics which require machine studies
  - **ATCA hardware**
  - **Transient detection**
  - **Beam based feedbacks**
  - **Controller**
  - **Application development**
  - **Cavity resonance control**
  - **Automation**
  - **Radiation tests**

*) Note: Assumes availability of CMTB and developments systems (ACC1 and ACC456) in FLASH and parallel studies.