Low Power RF (LLRF) Part II

S. Simrock
DESY, Hamburg, Germany

Lecture Schedule (March 2008)

- LLRF Part I (Requirements and Design)
  - March 6, 13:30
- <u>LLRF Part 2 (Maschine Studies at FLASH)</u>
  - <u>March 7: 10:00</u>
- LLRF Part 3 (LLRF for the XFEL)
  - March 11 at 13:30
- Timing and Sync. Part I (Concepts)
  - March 14 at 10:00
- Timing and Sync. Part II (Design)
  - March 17 at 10:00
- European XFEL (Project Overview)
  - March 26 at 13:30

Outline LLRF Part II

- Installation at FLASH
- Control of ACC1 with SIMCON
- Controller Studies
- Beam loading compensation
- RF GUN control with SIMCON
- Downconverter performance
- Piezocontrol at ACC6
- Klystron linearization
- Radiation measurements
- Automation
- Operation with alternating gradients
- Availability

Installation at FLASH

Collaboration

DESY

WUT-ISE

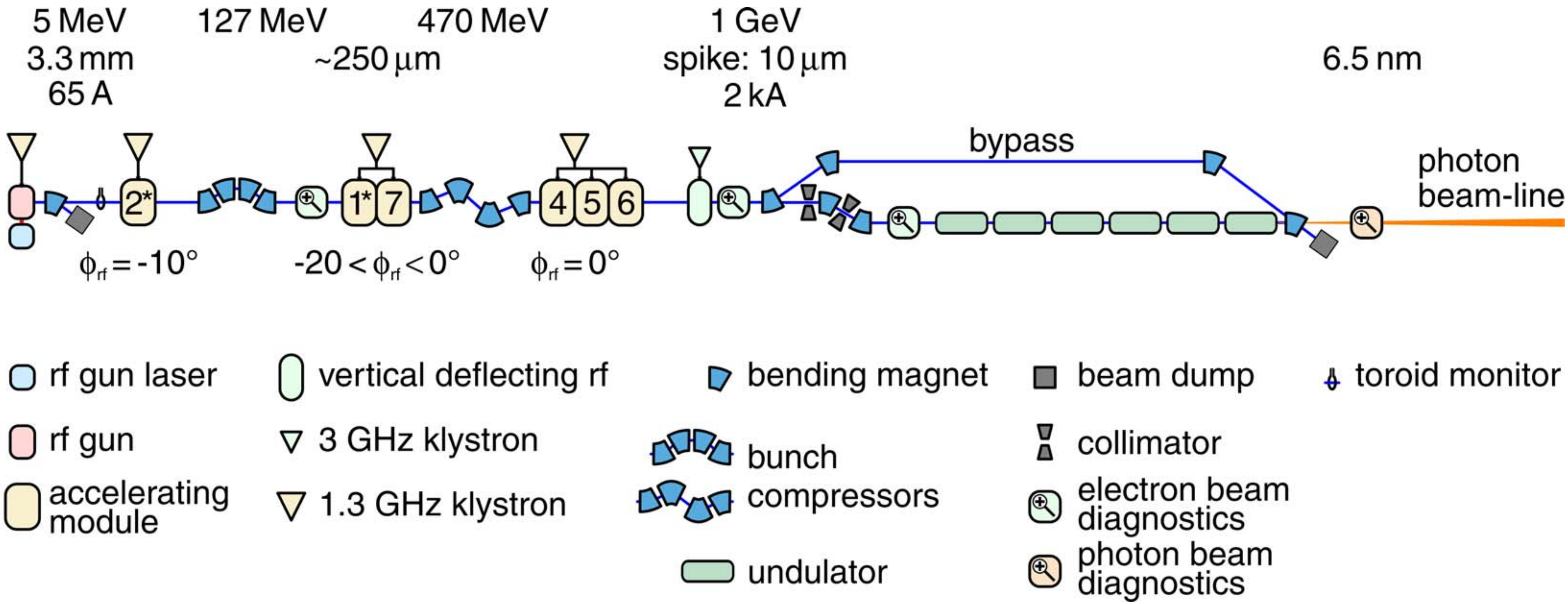
TUL-DMCS

PSI

also worldwide participation by
FNAL, KEK, IHEP, ORNL, JLAB ...

LLRF Collaboration at Work (24.9.07 early morning)

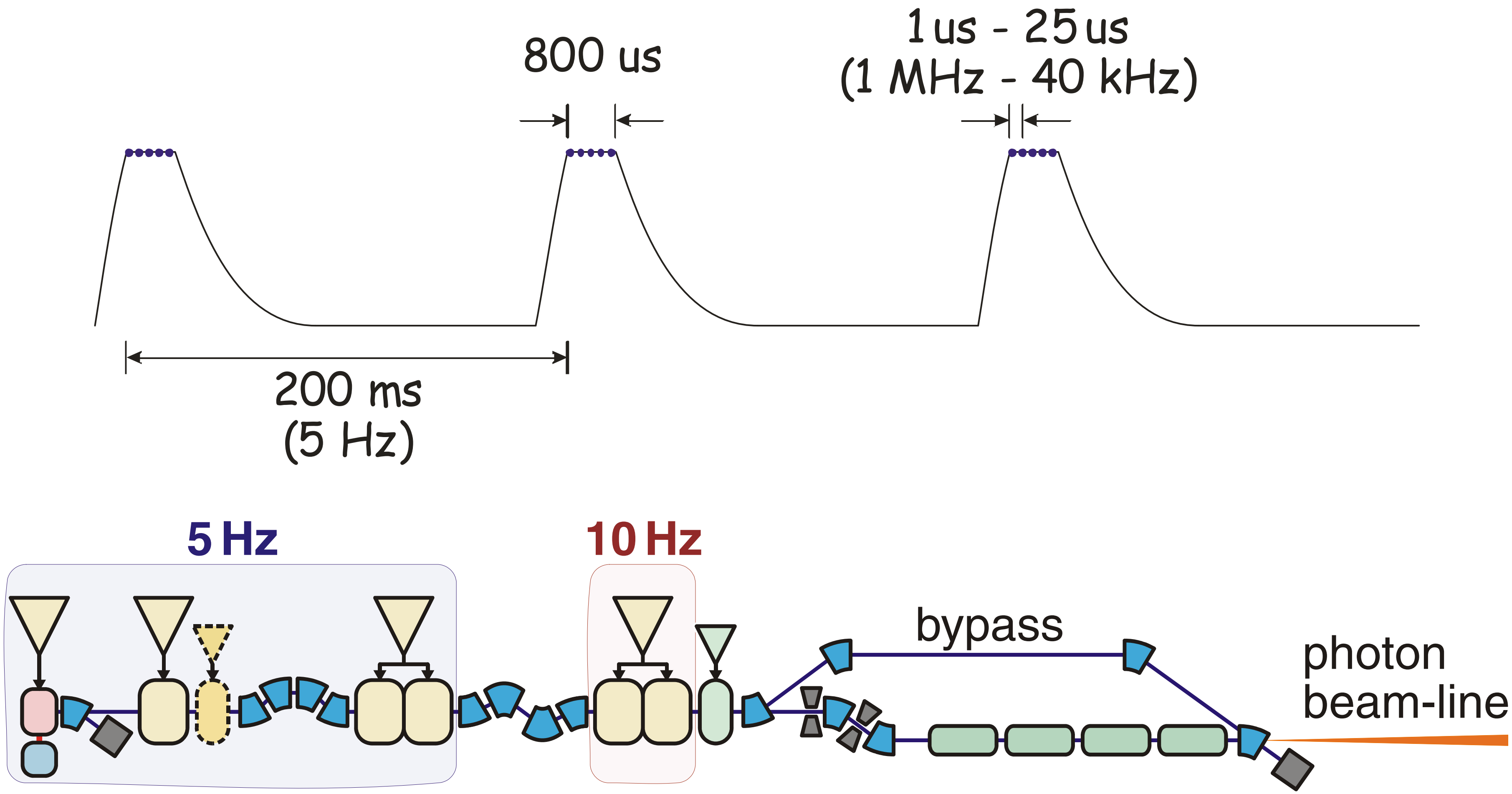
FLASH – the machine (in autumn 2007)



- initial bunch length restricted by collective effects
- two stage bunch compression
- off crest acceleration in ACC1 and ACC2/3
- requires good rf field stability

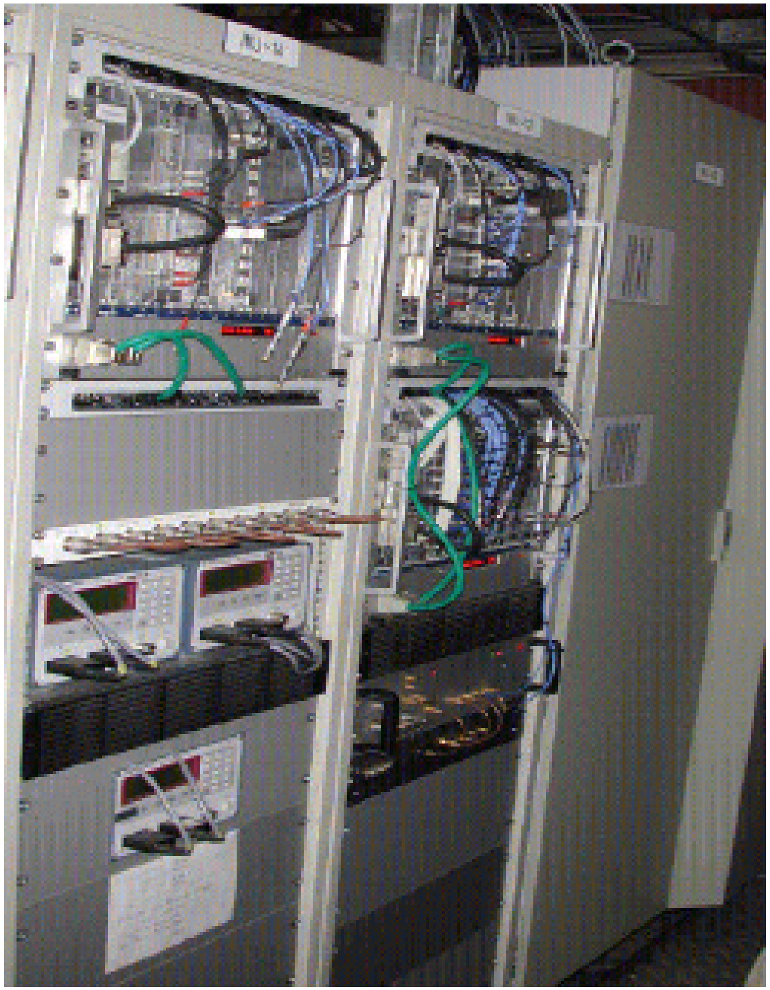
FLASH time structure

High gradients and moderate cooling demand (cryogenic load) by using pulsed rf:

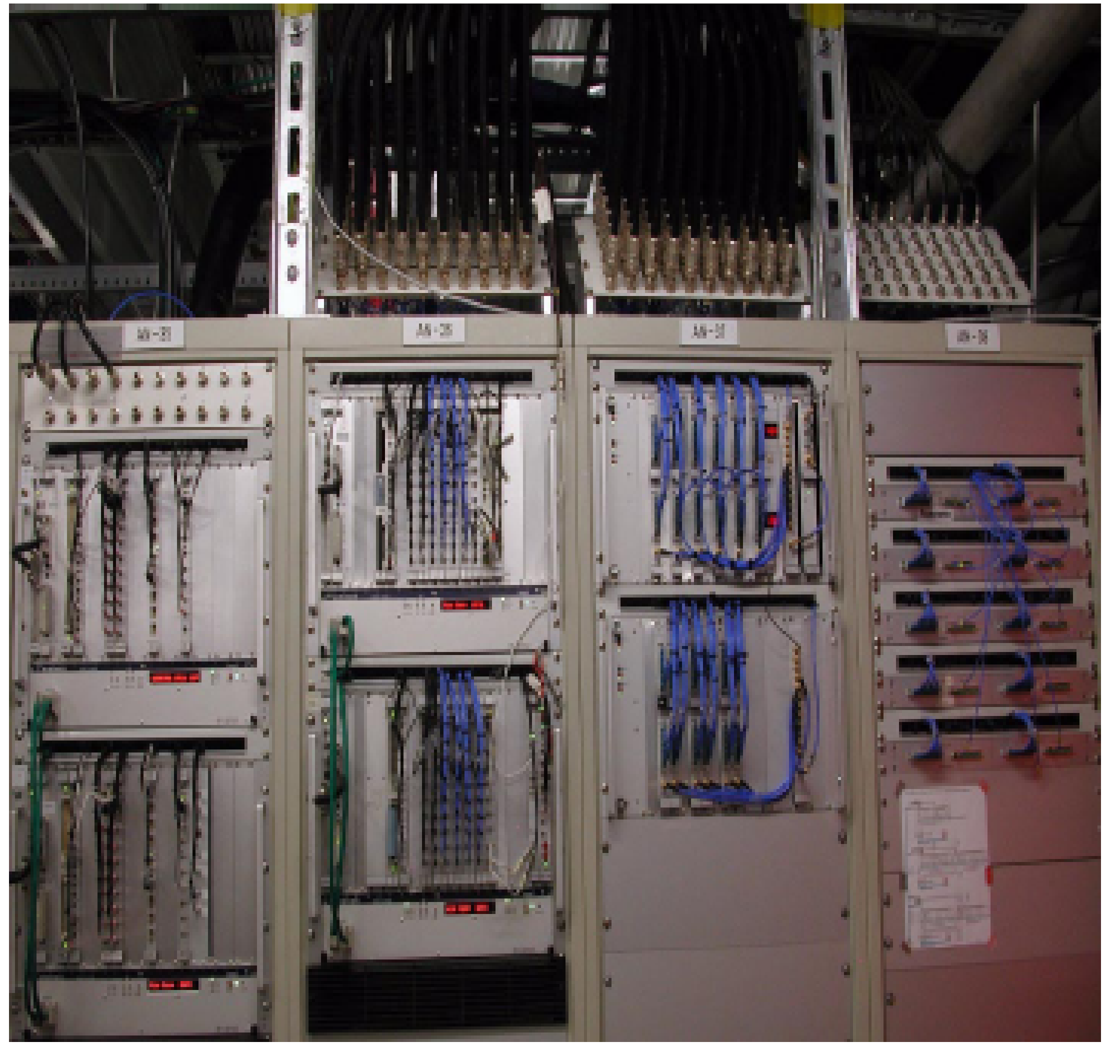


Infrastructure (Cabling, Racks, Crates)

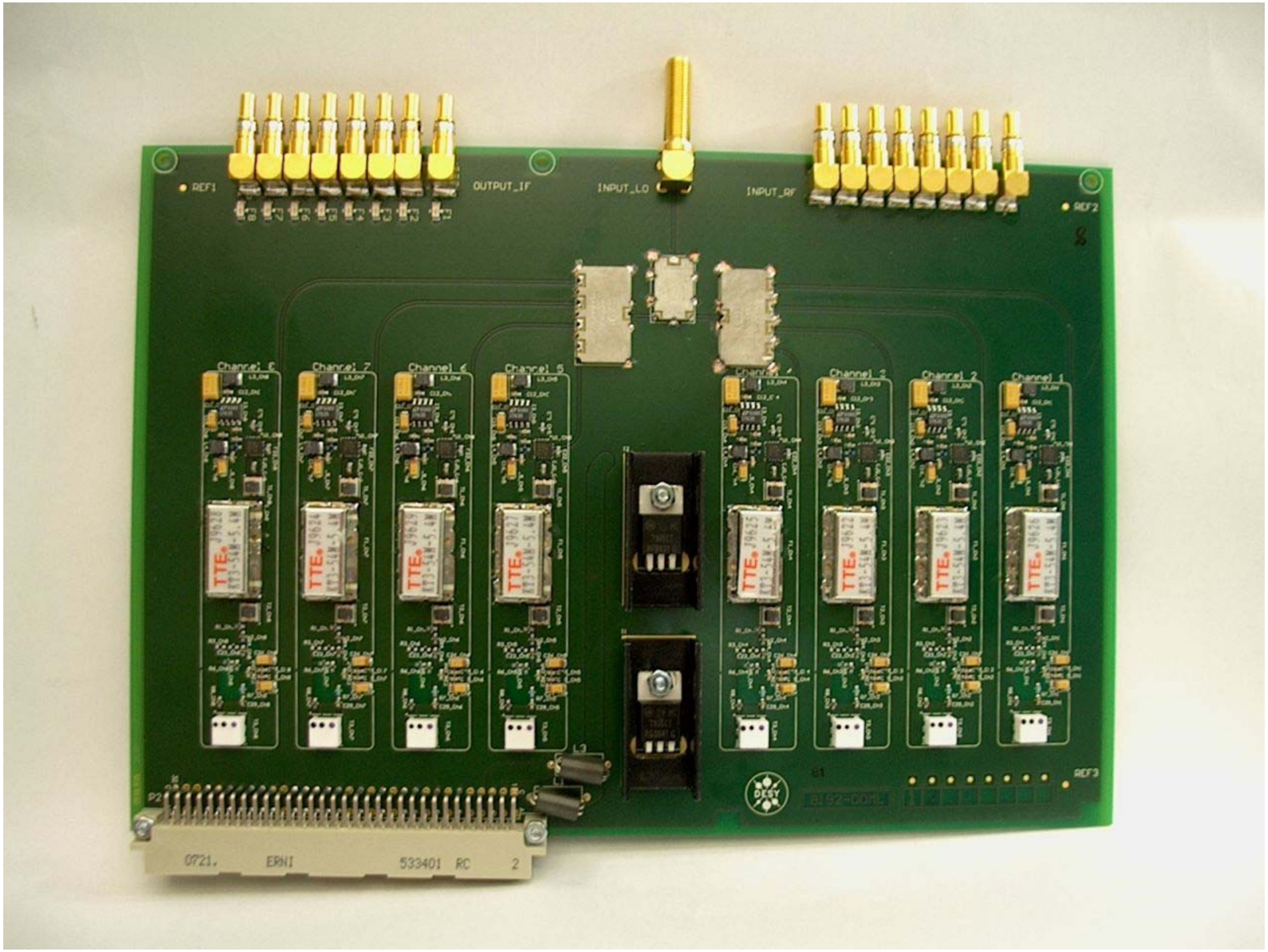
Gun and ACC1



ACC2, ACC3, ACC4 & ACC5



Hardware (Downconverter)



Hardware (SIMCON DSP)

The Mission

- Add DSP to SIMCON 3.1 to support floating point processing
- Increase number of analog I/O channels
- Add SystemACE (for PPC)
- Improved clock distribution (separate for ADC/DAC)
- More memory

Features:

-Xilinx Virtex II Pro, PowerPC

-DSP, Tiger Sharc,

-10xADC, 8xDAC

-2 opto gigalinks

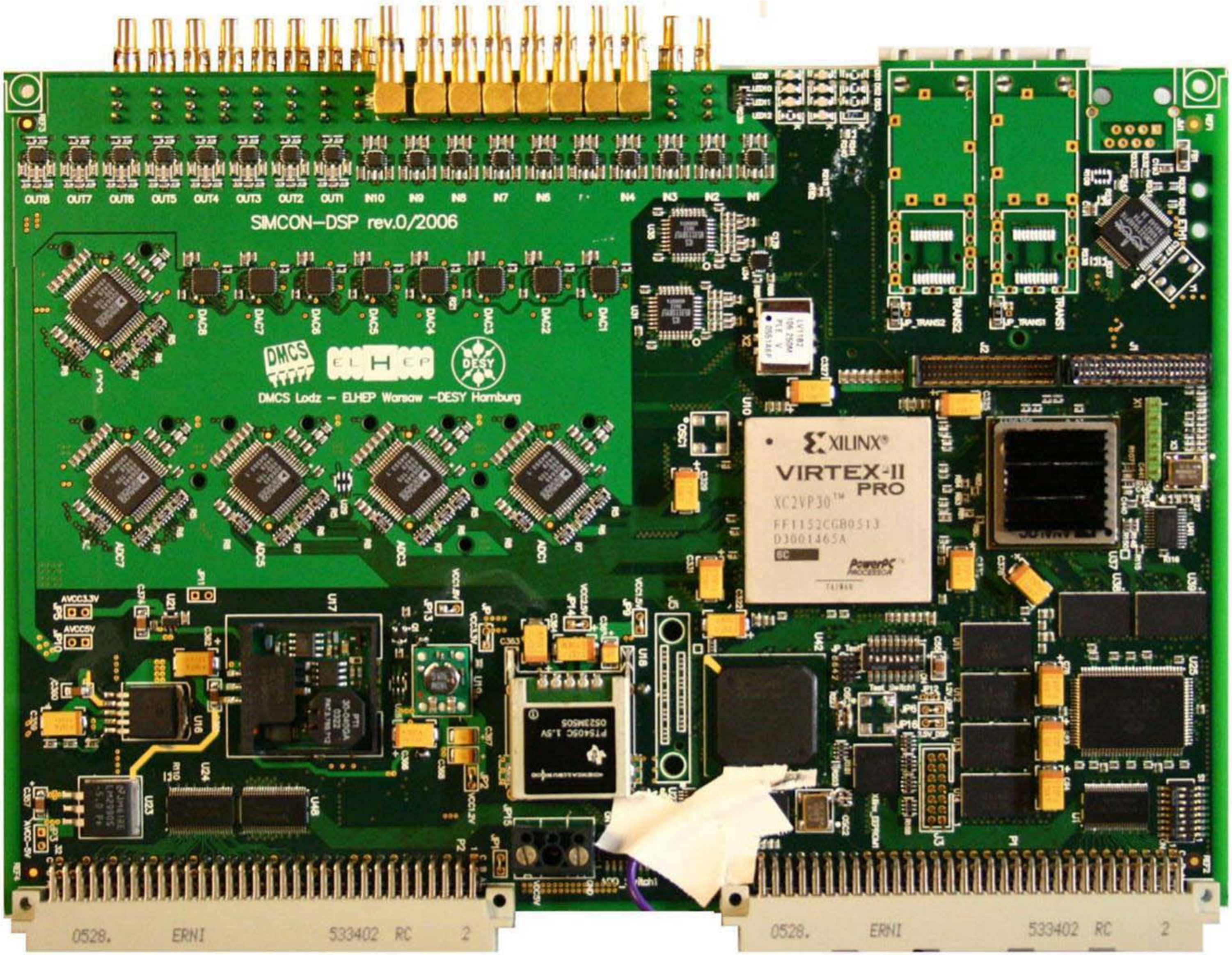
-VME interface

-SystemACE (Flash memory)

History of SIMCON DSP

- Design work start February 25, 2006
- Schematic done March 27
- Critical parts ordered March
- Layout done June 2
- Board production and assembly end July
- General vacation time in August
- Debugging starts September 25

SIMCON DSP



SIMCON-DSP rev.0/2006
DMCS Lodz - ELHEP Warsaw -DESY Hamburg
XILINX
VIRTEX-II PRO

Debugging SIMCON DSP

- Debug power (ok)
- Debug FPGAs (VME, JTAG)
  - JTAG problem, 2 wrong connections
- Debug communication with DSP (4 weeks)
  - No communication
    - Diagnosed hardware problem (!)
  - Obtain JTAG programmer for DSP
    - Again hardware problem, no communication
  - One day after lunch system worked for few minutes
    - And never again …
  - Found that chip revision change resulted in changed assignment of 2 out 500 pins.

- Decision to unsolder DSP, disconnect the 2 pins and solder new DSP
  - ZE needs 4 weeks
- Debugging resumed (December)
  - No communication with FPGA to DSP
  - Unstable communication with JTAG (3,3V!)
    - After solving 3,3V problem stable JTAG comm. and booting DSP through JTAG
  - Again after lunch DSP booted through FPGA
    - Then again problem

Debugging SIMCON DSP

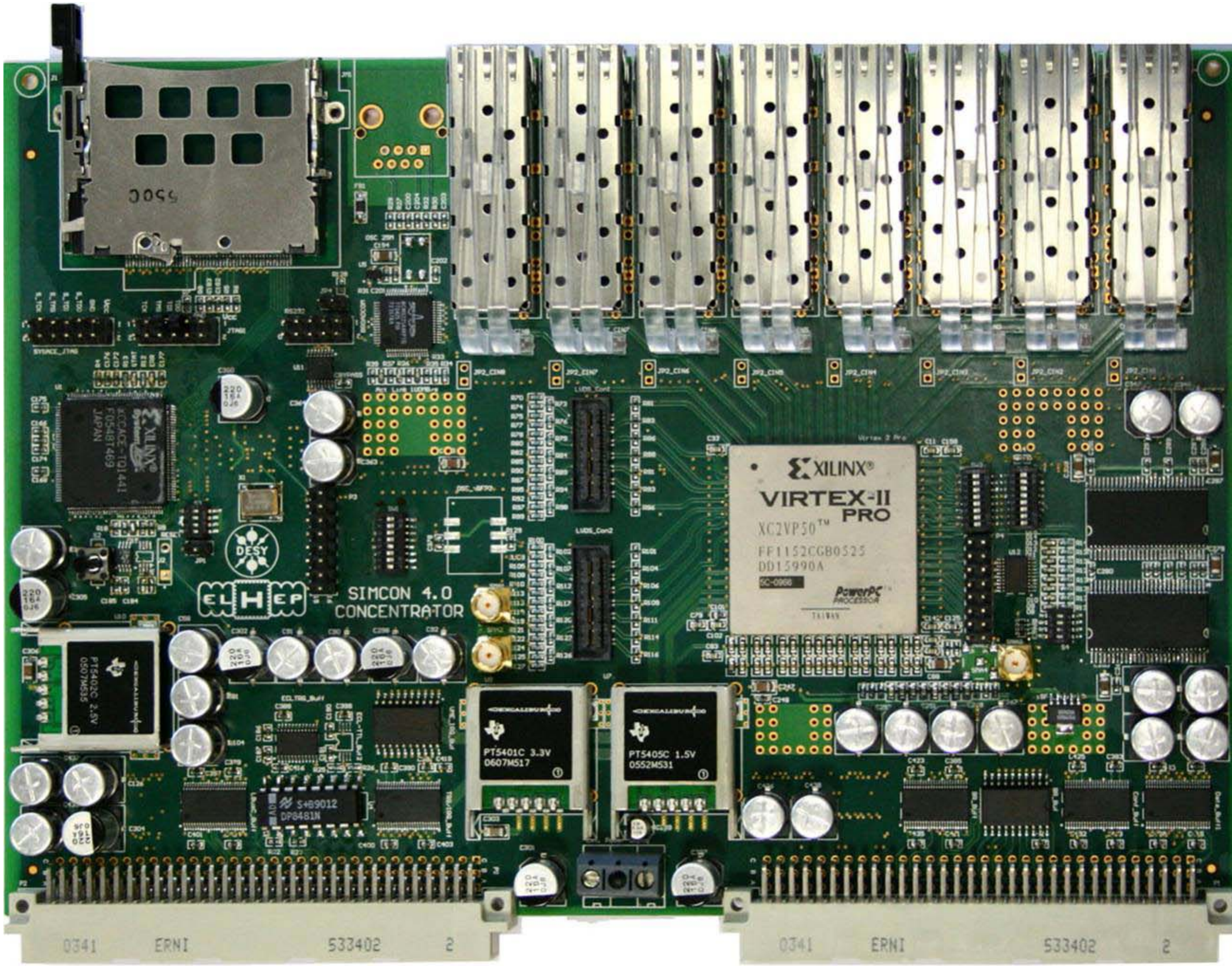
- Found that booting whole crate solved problem.
  - Reason: need to wait at least 1 ms after DSP reset for booting DSP (before we were always to fast except when rebooting the crate).

- Final changes have been made production of SIMCON DSP has started.

Purpose of SIMCON DSP

- Serve as platform for LLRF software development.
- Demonstrate phase stability of 0.01 deg. using high IF (50 MHz) and high frequency sampling (~100 MHz)
- Many applications
  - Rf gun control (FLASH,PITZ)
  - ACC1 control with Probe, P_for, P_ref
  - MTS
  - 3.9 GHz (Modulator and control)
  - Special diagnostics and beam feedbacks
  - Piezo tuner control (INFN)

SIMCON 4.0

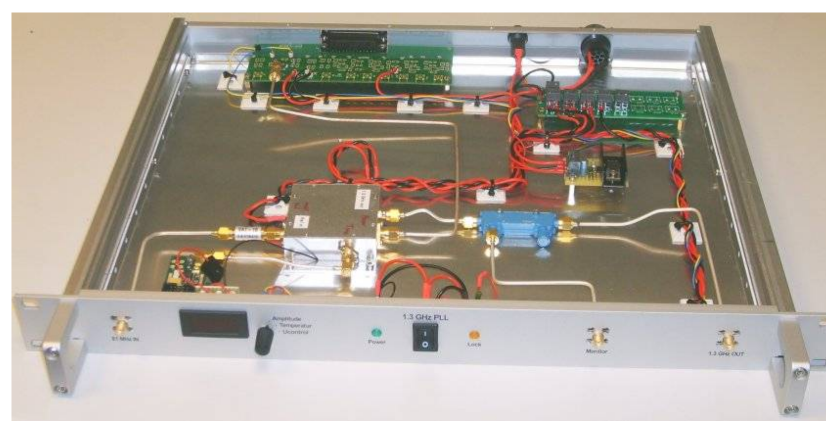

SIMCON 4.0
CONCENTRATOR
XILINX
VIRTEX-II PRO
XC2VP50™
FF1152CGB0525
DD15990A
PowerPC PROCESSOR
PT5401C 3.3V
0607M517
PT5405C 1.5V
0552M531
0341 ERNI 533402 2
0341 ERNI 533402 2

Test setup in laboaratory

Left rack: RF crates for generating, amplifying and splitting the MO signals

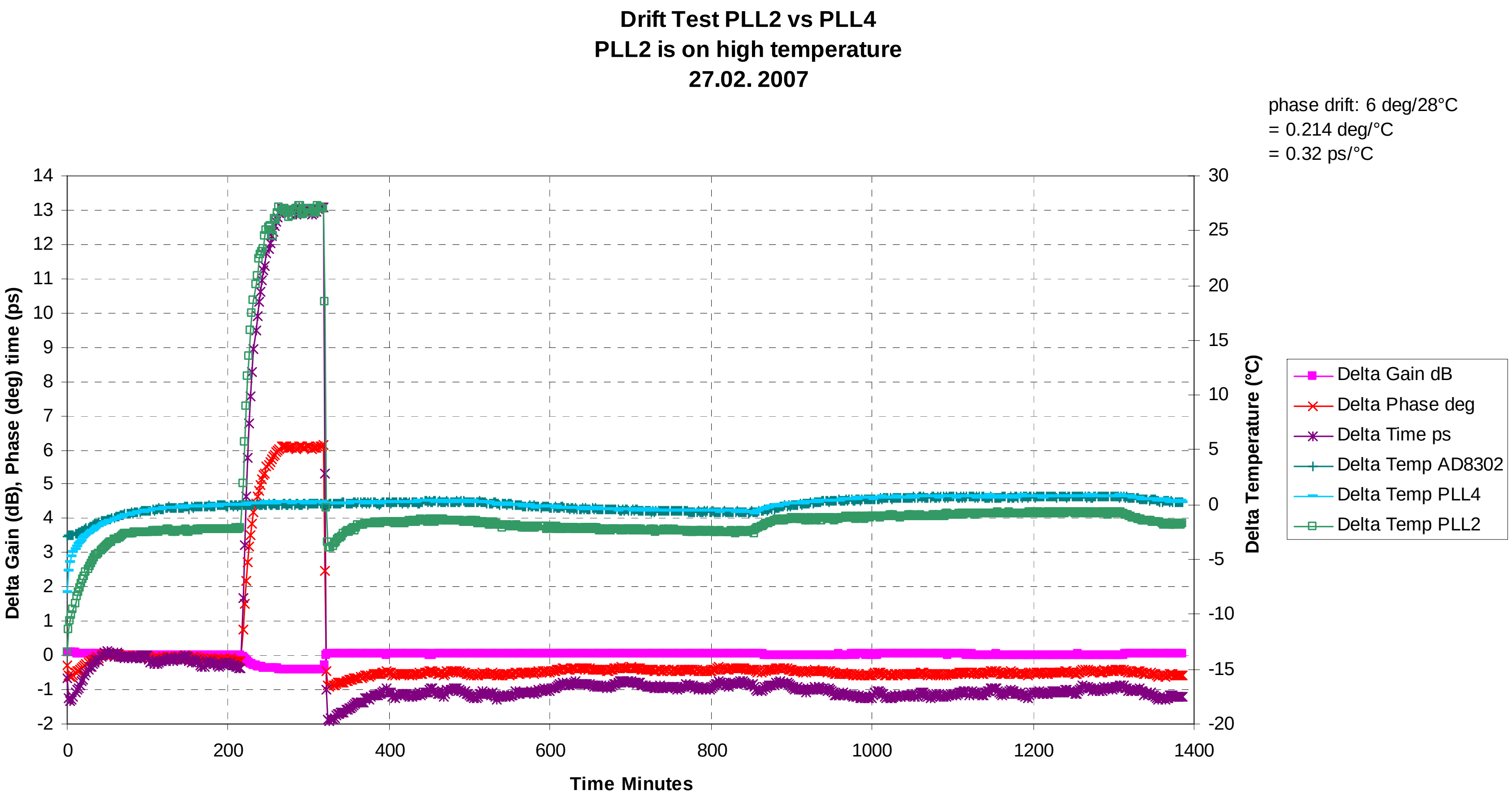
Right: bottom 19´´
linear regulated power supplies,
Above: battery backed up PS for LPP
On top: 3 crates with microcontrolers
Collecting supervision signals from crates,
transmitting them via Ethernet
to the DOOCS control system

NEW MASTER OSCILLATOR SYSTEM

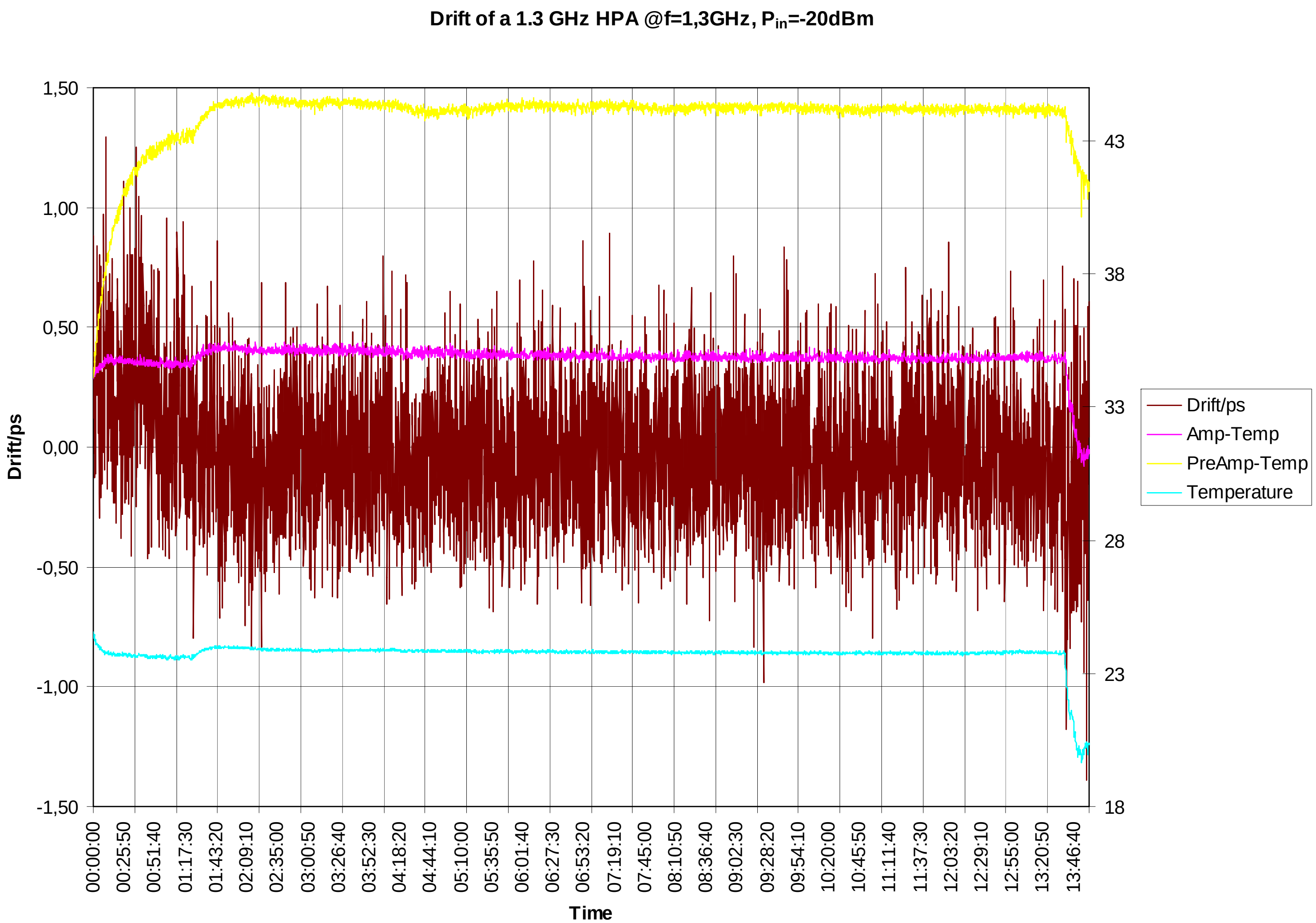


Drift tests

1.3 GHz PLL´s driven from the same source, but on different temperatures

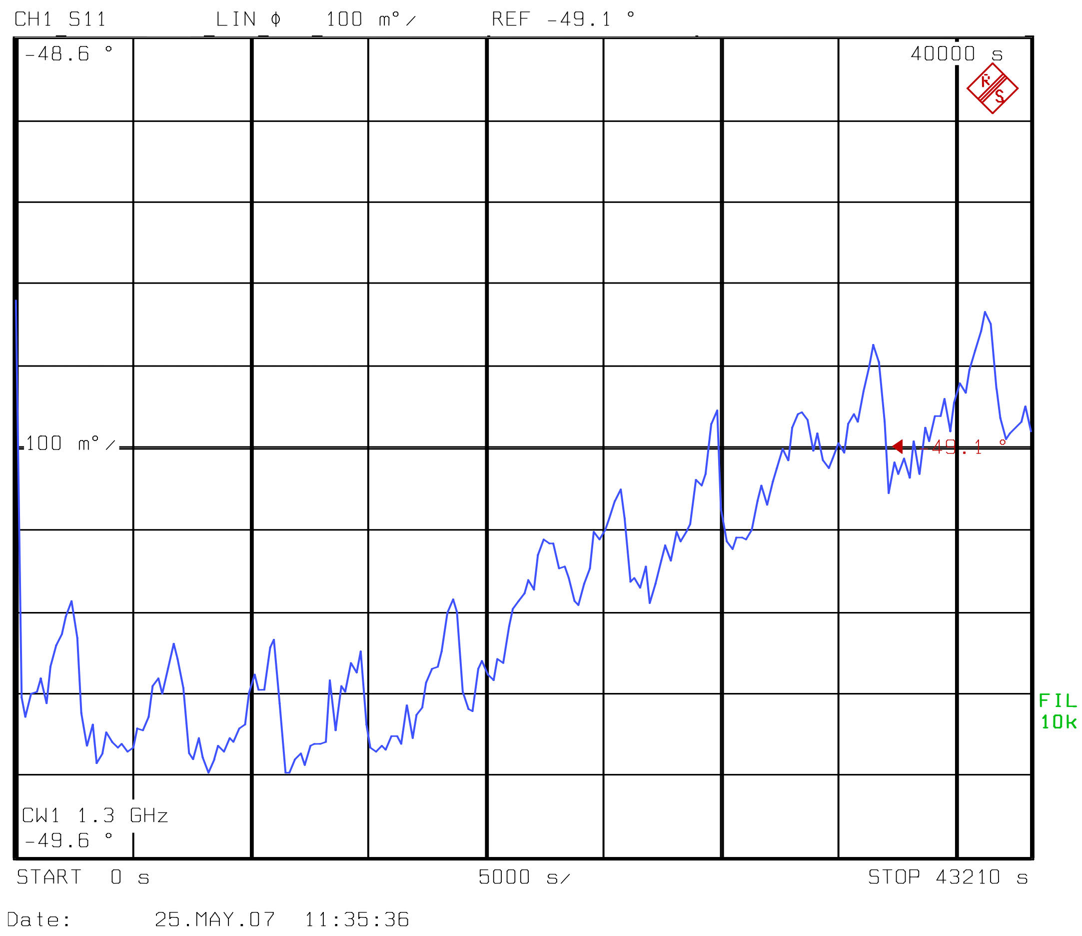


Drift of a 1.3 GHz HPA

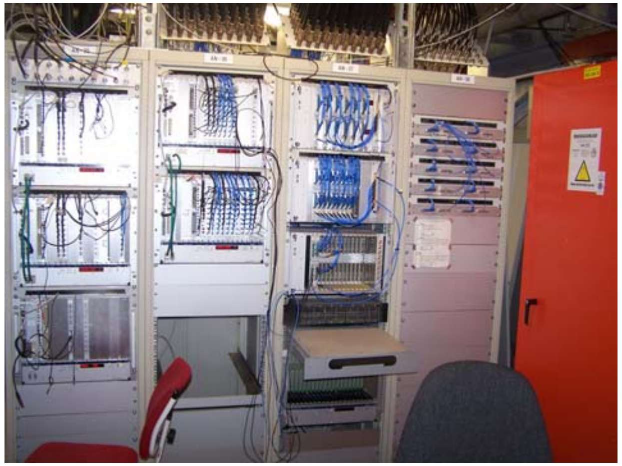
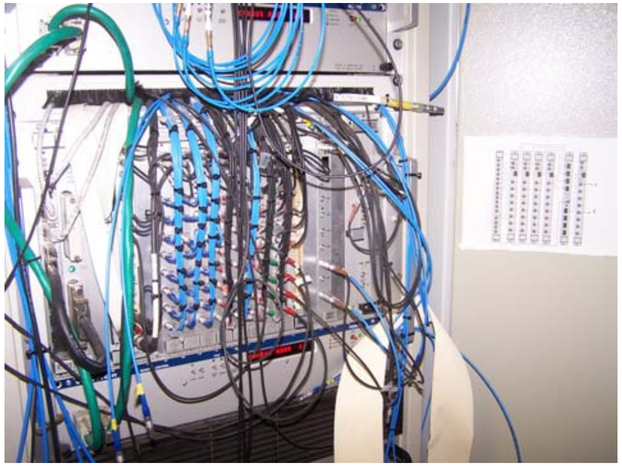
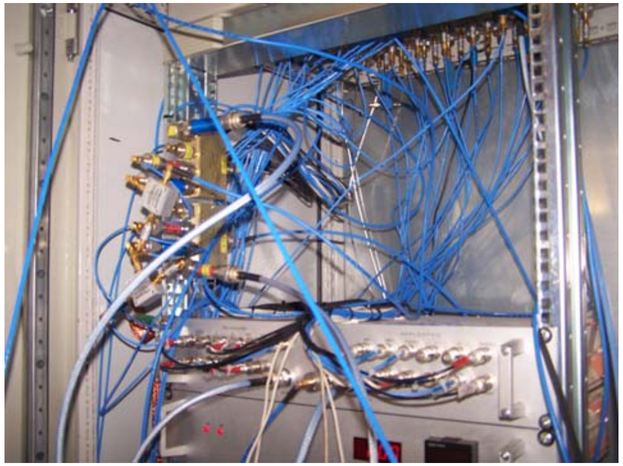
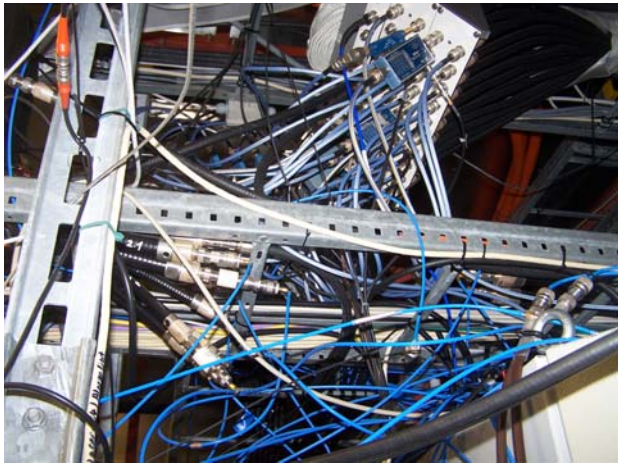


Cable drifts in accelerator

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

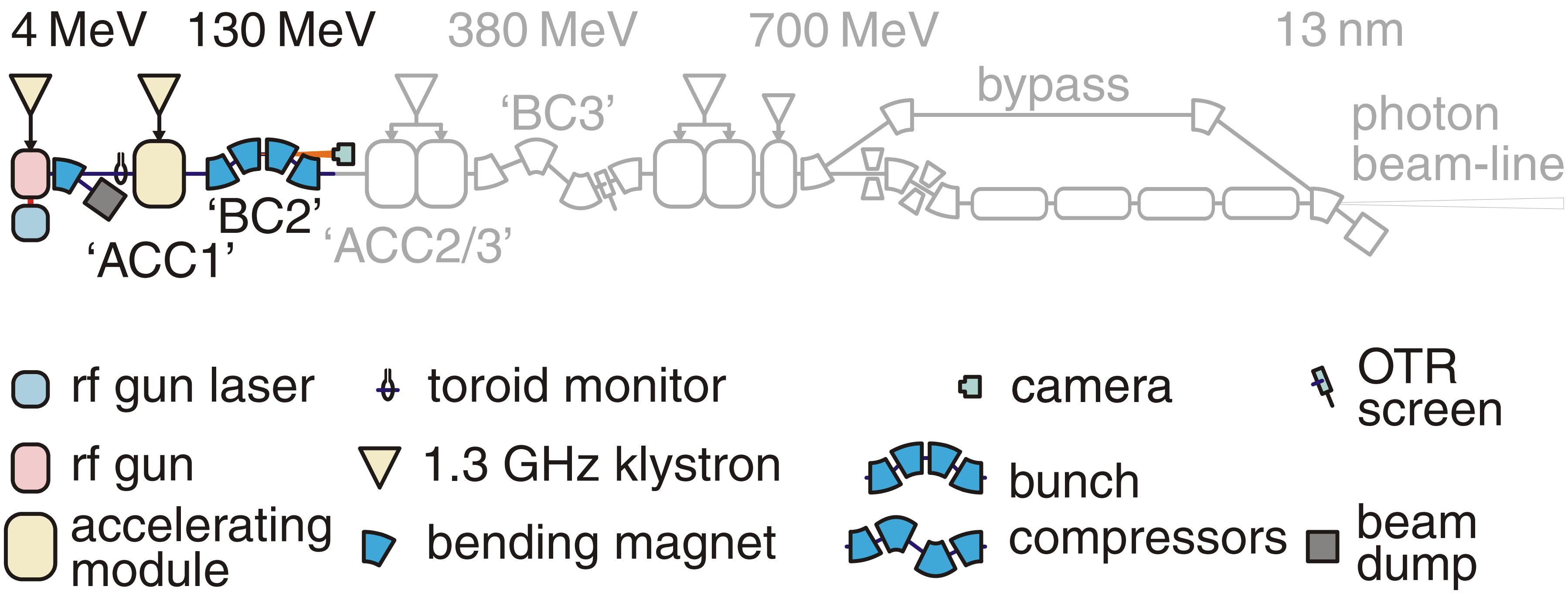


The good, bad and ugly in assembly and cabling

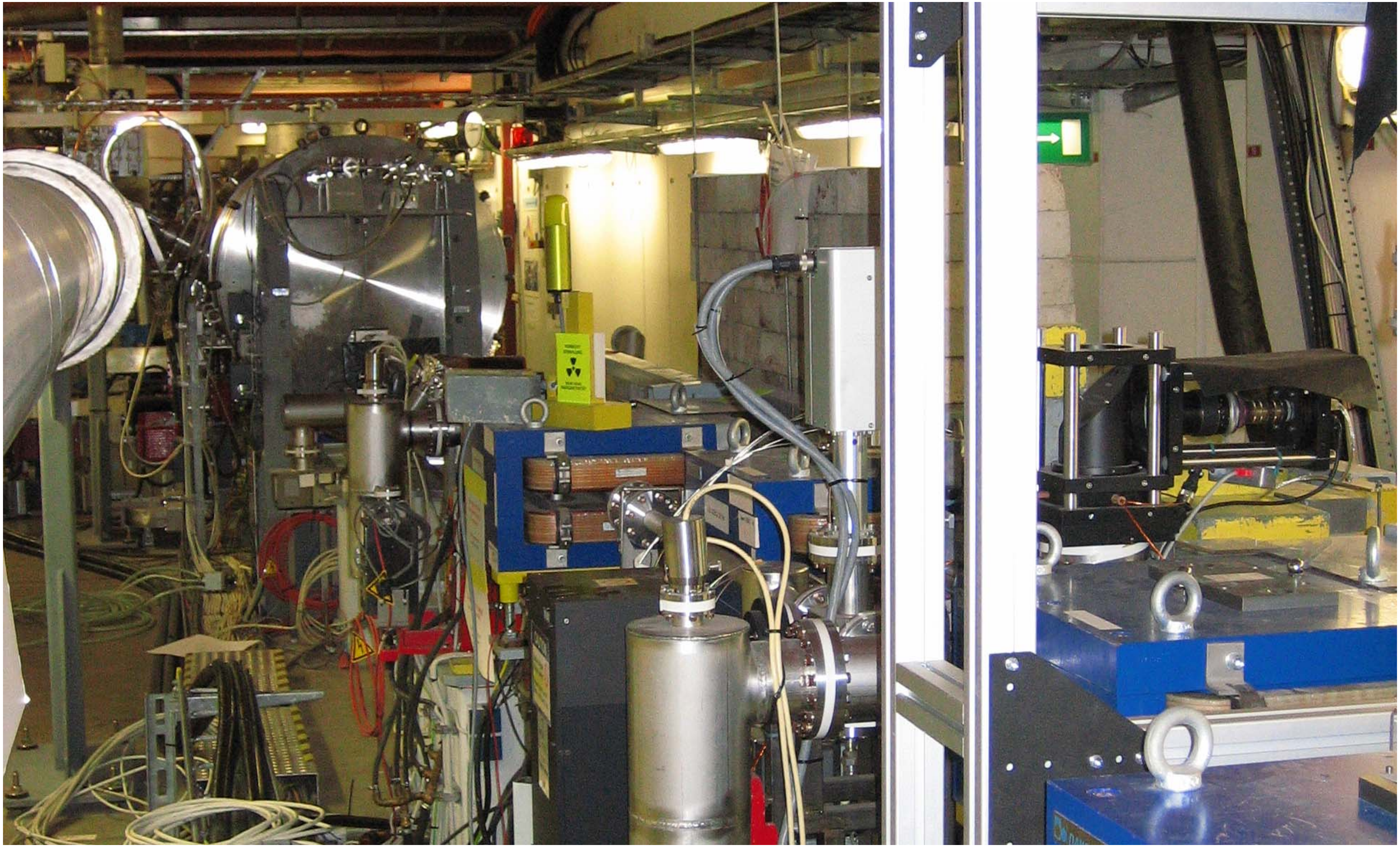
Control of ACC1 with SIMCON

Accelerating the bunches up to 130 MeV



- beam stability measurement via synchrotron light monitor in BC2
- beam energy in BC2 dominated by ACC1 energy gain (only 3% from gun)
- beam energy stability measured in BC2 yields upper limit for ACC1 rf stability

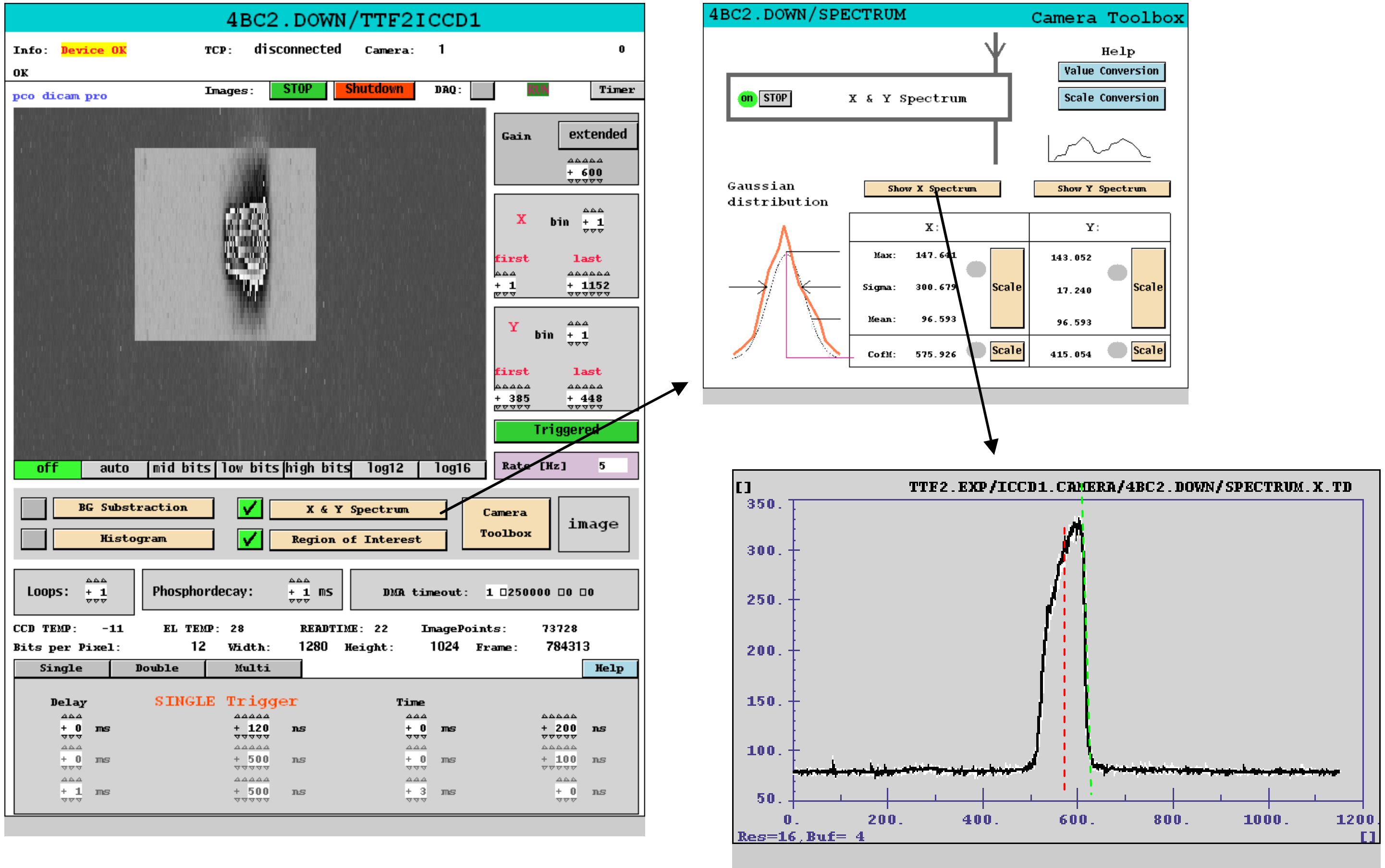
To make the material less monotonous: picture of ACC1 and BC2



Beam energy determined by synchrotron light spot at BC2

Fitting methods:

- Fit 1: slope at head
  → gives information on rf amplitude
- Fit 2: Gaussian fit to profile
  → information on rf amplitude and rf phase



Resolution:

- $\Delta E/E = 10^{-4}$

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

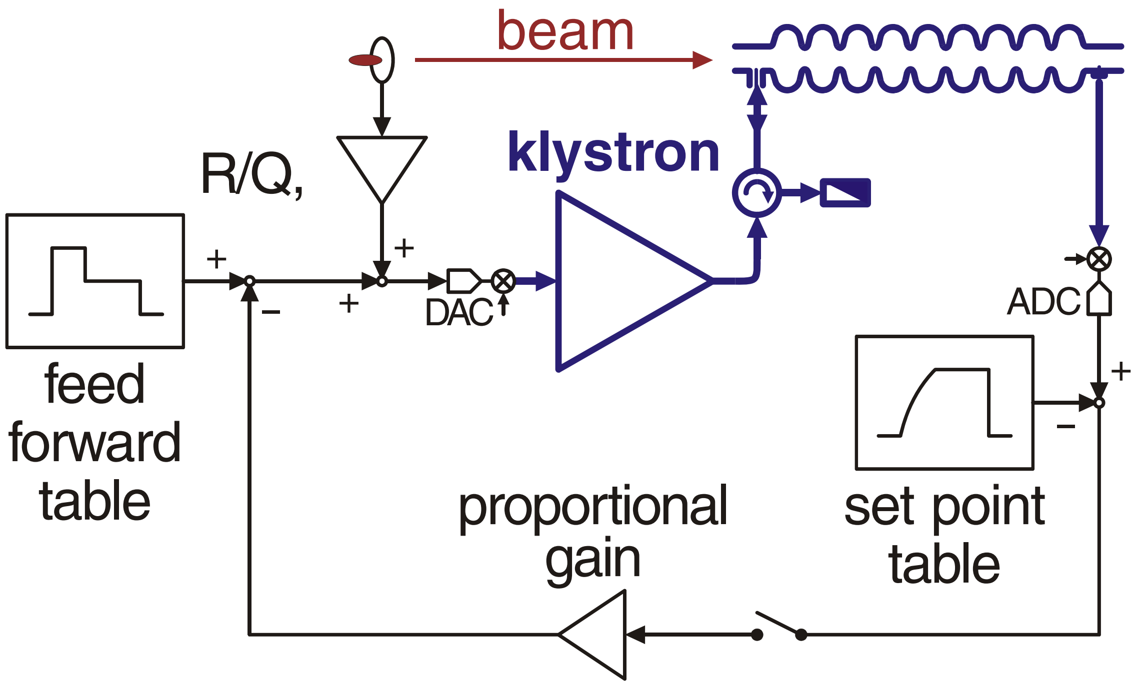
Problem:

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

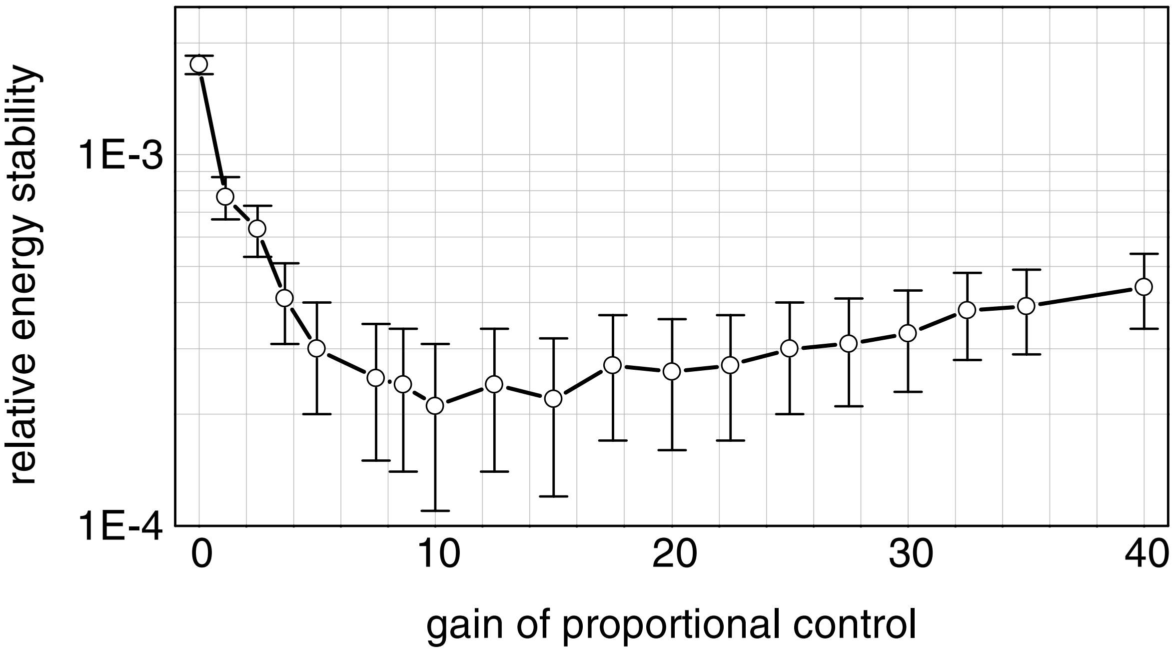
Countermeasures:

- 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:

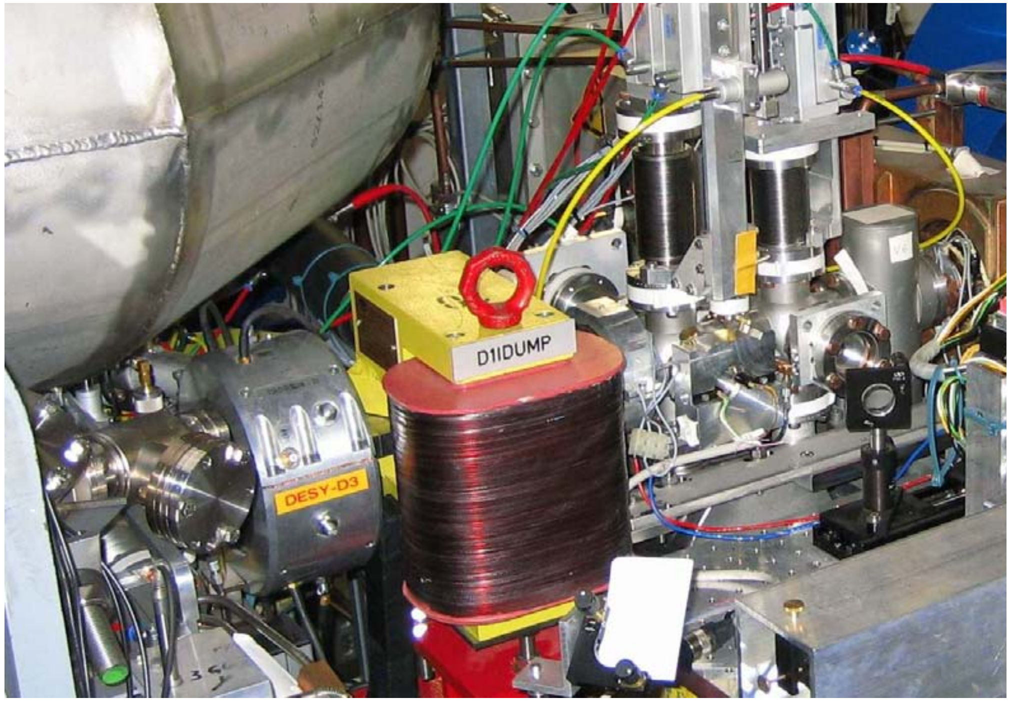
- error suppression for small gain values
- noise amplification for large gain values
- 'ideal' gain between both cases
- best single bunch stability: $\Delta E/E = 2\text{x}10^{-4}$

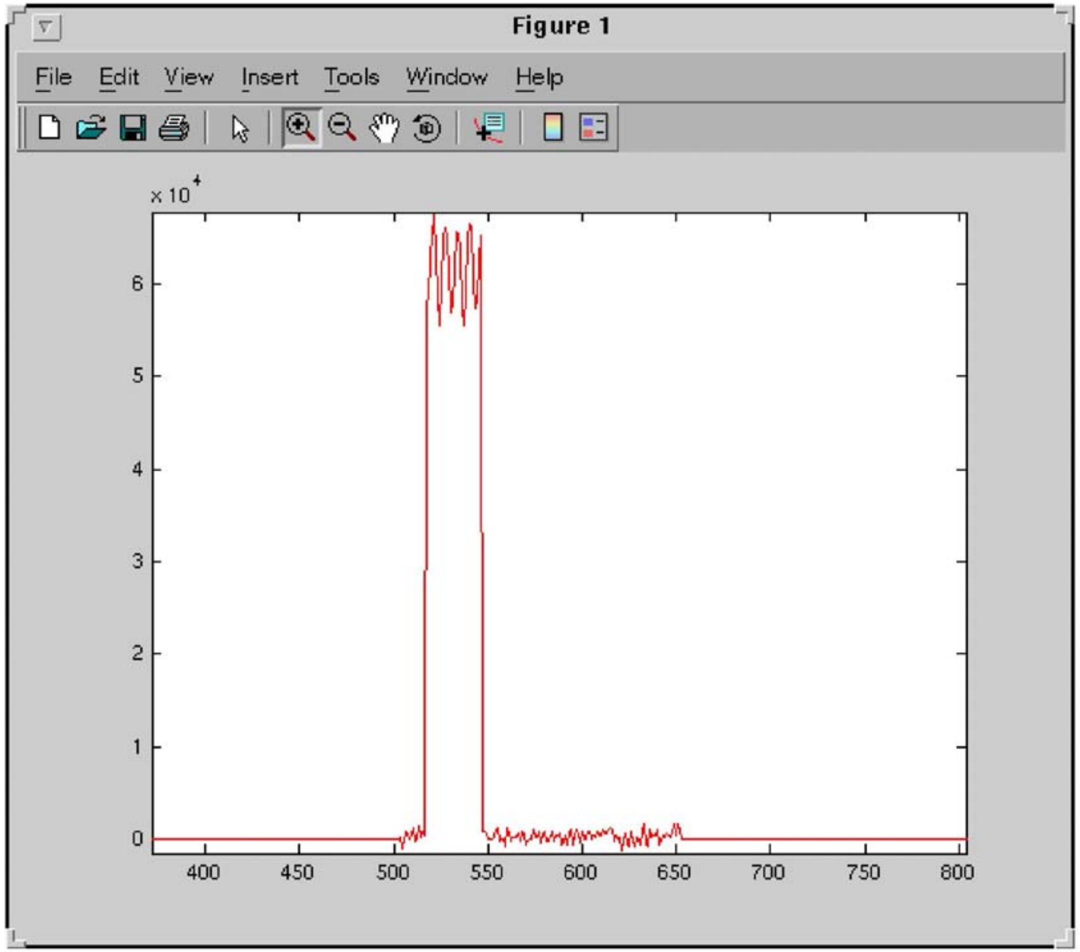
If we accelerate multiple instead of one bunch…

- all bunches shall show similar relative energy stability $\Delta E/E$
  $\rightarrow$ ok with the proportional control
- all bunches shall show similar absolute energies E
  $\rightarrow$ beam loading compensation required

Charge proportional signal from toroid monitor

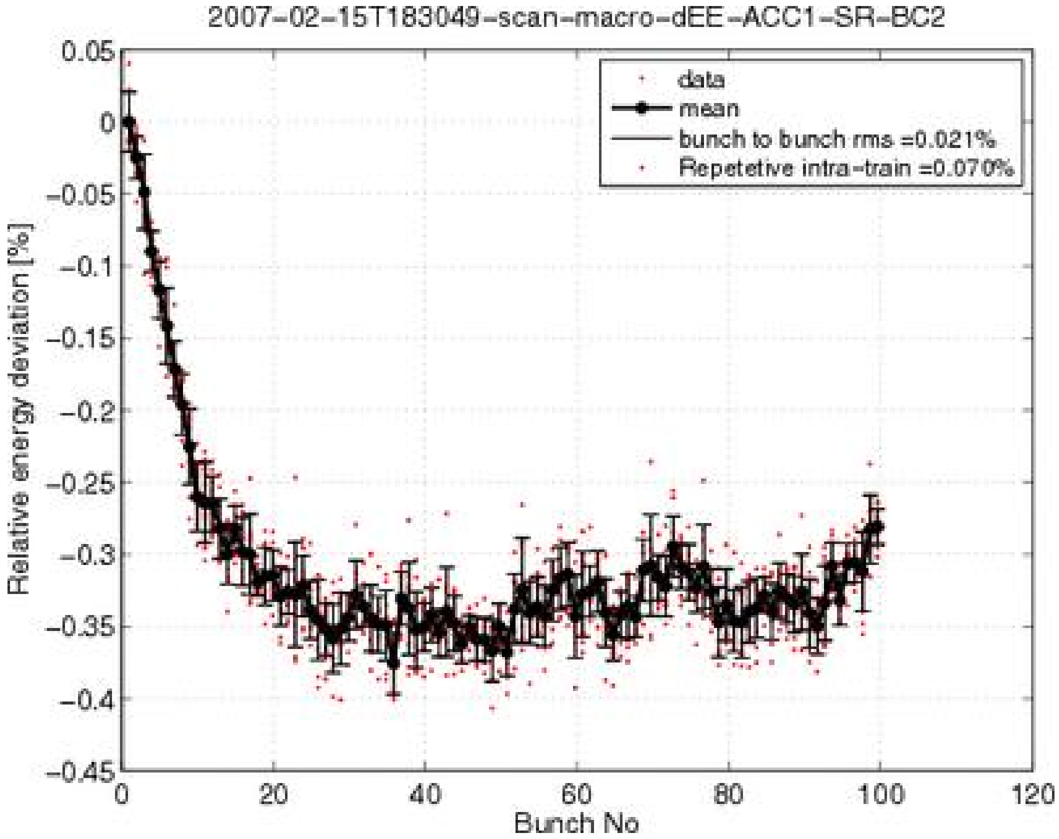
- taking several samples (5) per bunch from analogue monitor signal
- sum of samples
- offset correction using samples at times without beam



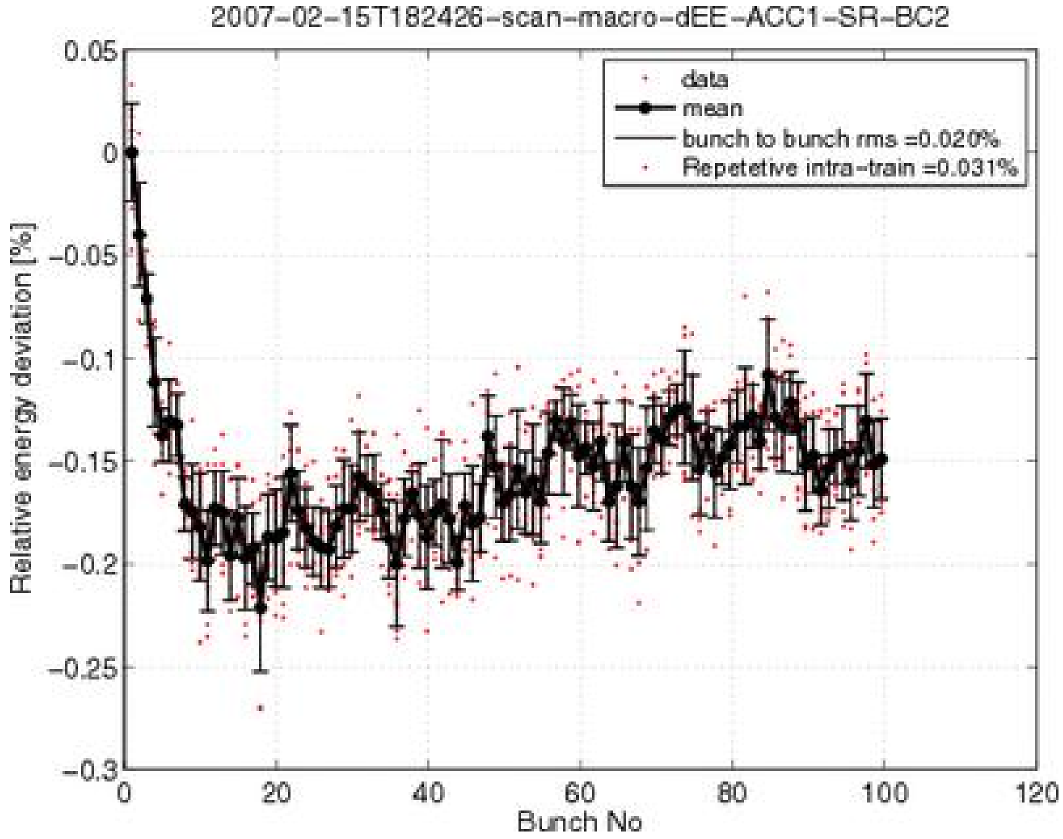


Actual status of the beam loading compensation

Operation with P control only (G = 15)



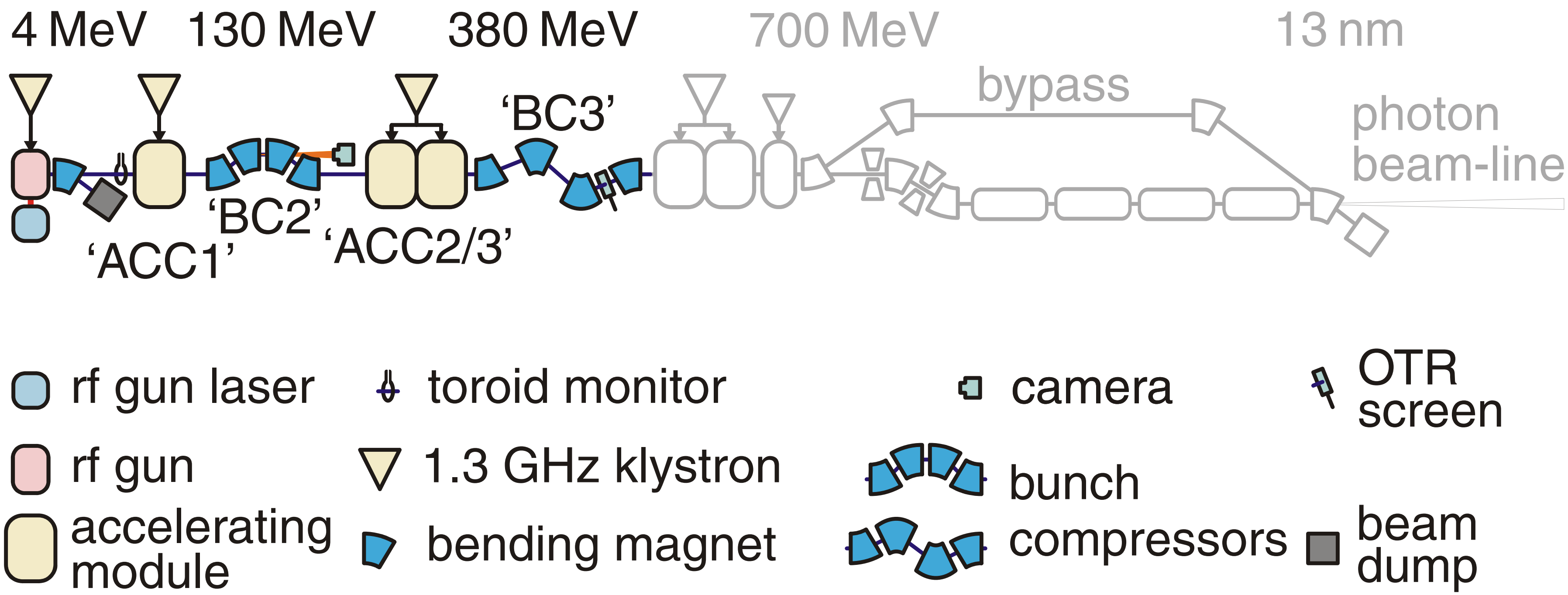
Beam loading compensation switched on



Next steps:

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

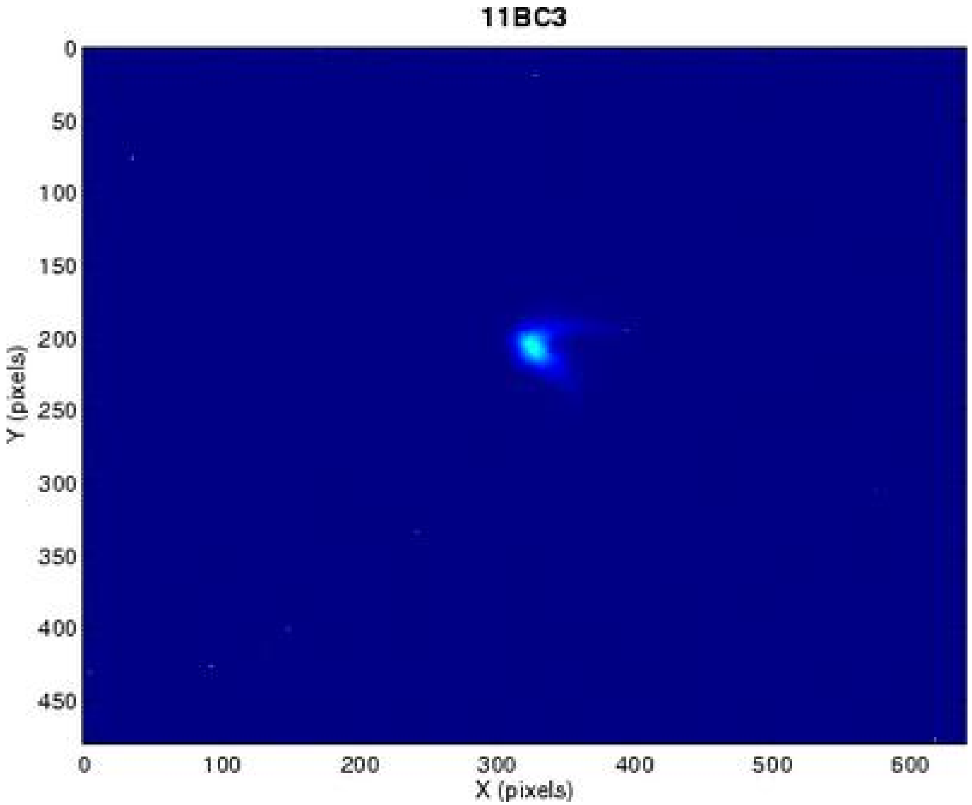
Accelerating the bunches up to 380 MeV



- beam stability measurement via OTR screen in BC3
- beam energy in BC3 is a results from the ACC1 and ACC2/3 rf stability
- nevertheless, the beam energy stability measured in BC3 yields an upper limit for the ACC2/3 rf stability

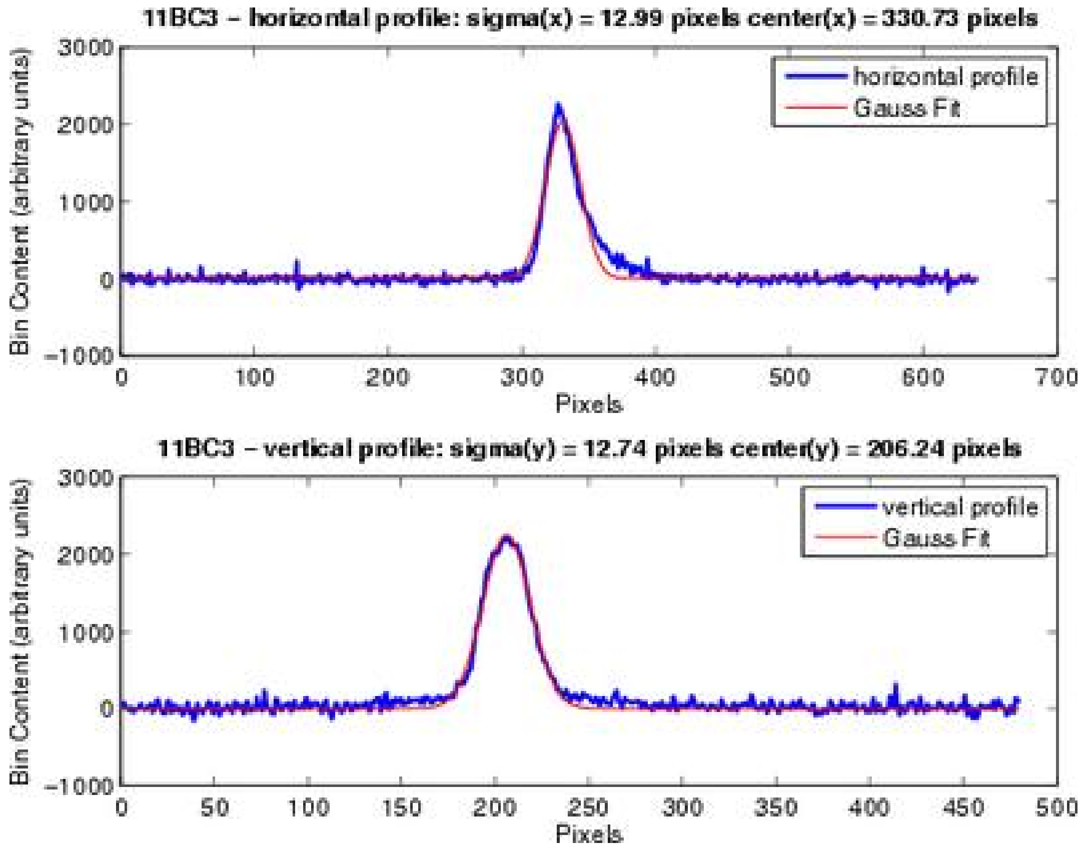
Beam energy determined by OTR screen in BC3

The beam position measured with an OTR screen in a dispersive section



yields beam energy information.

Gaussian fit to profile for beam position:



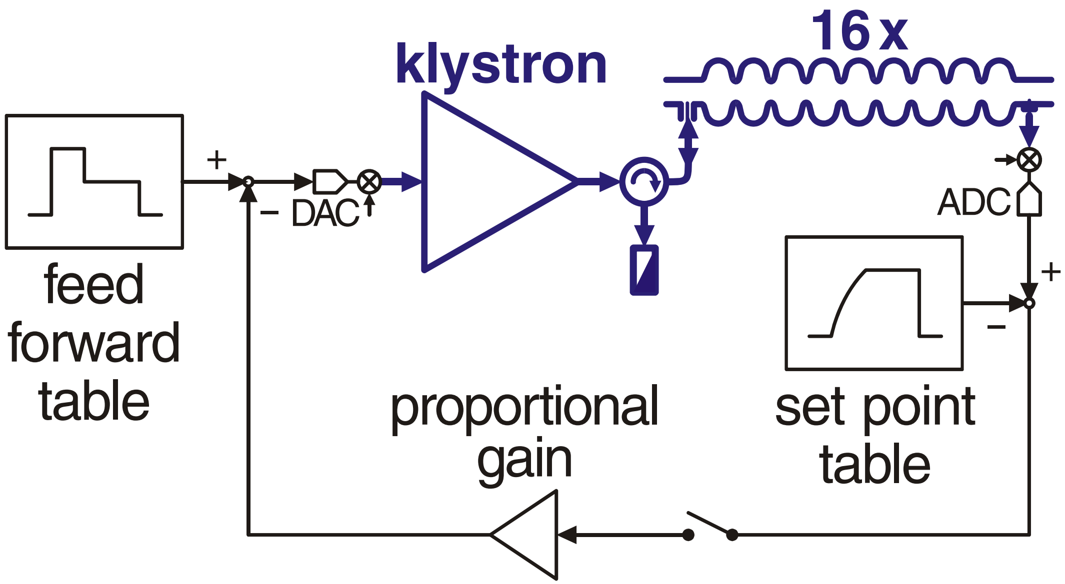
Resolution: $\Delta E/E = 3 \times 10^{-5}$

ACC2/3 rf control: proportional control for 16 cavities

Key features for this control:

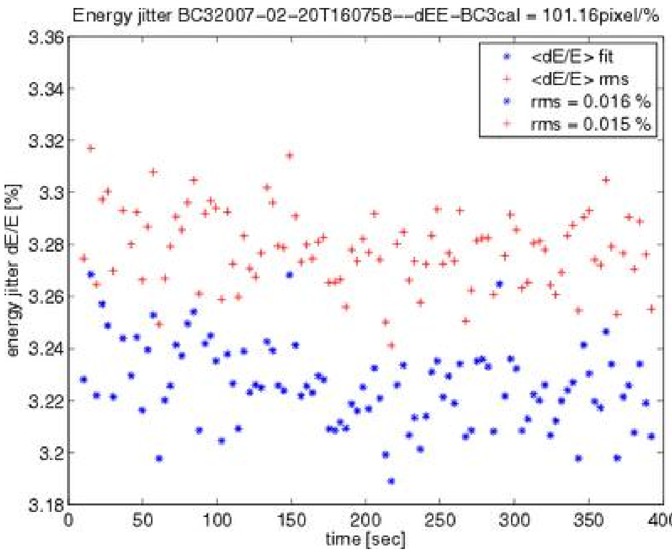
- connection of two SimCon 3.1 boards as master and slave to control the vector sum of 13 cavities (3 cavities have been excluded form the control)
- klystron linearization was switched on
- no beam loading compensation applied as only two bunches has been accelerated within this studies

Control scheme used at ACC2/3:



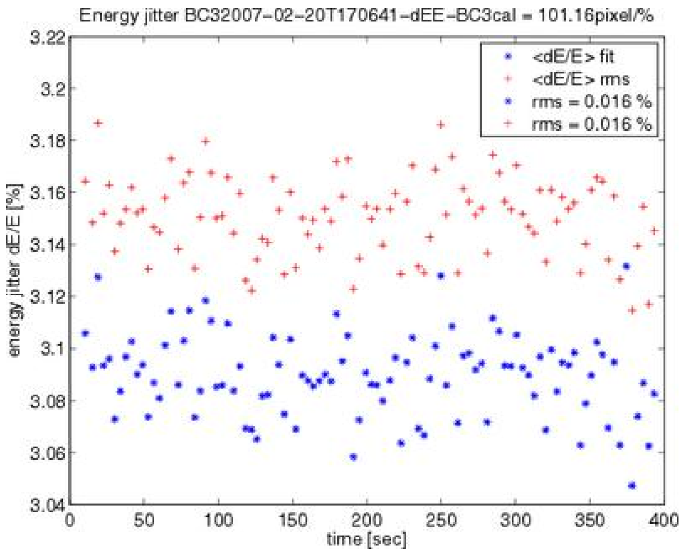
Beam energy stability observed at BC3

P control with gain = 0



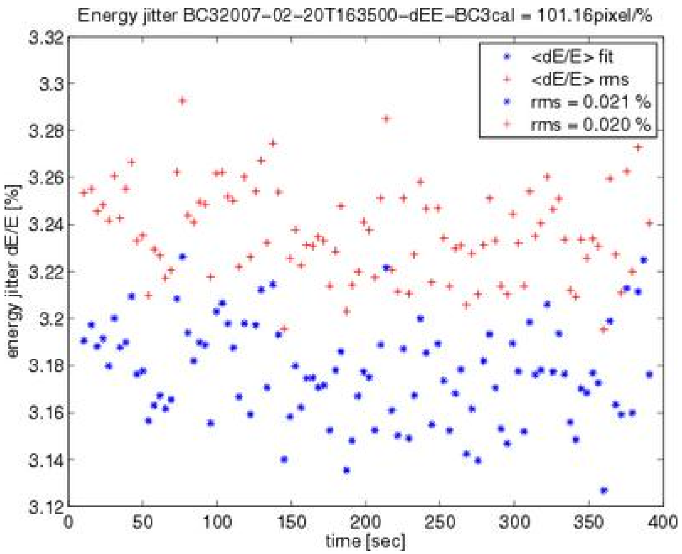
$\Delta E/E = 1.6 \times 10^{-4}$

P control with gain = 10



$\Delta E/E = 1.6 \times 10^{-4}$

P control with gain = 40



$\Delta E/E = 2 \times 10^{-4}$

No beam energy stability improvement due to rf control?

- sensor noise (down converters)
- the **klystron it selves** seems to be **well stabilized** due to the **gain = 0 result!**

Controller Studies

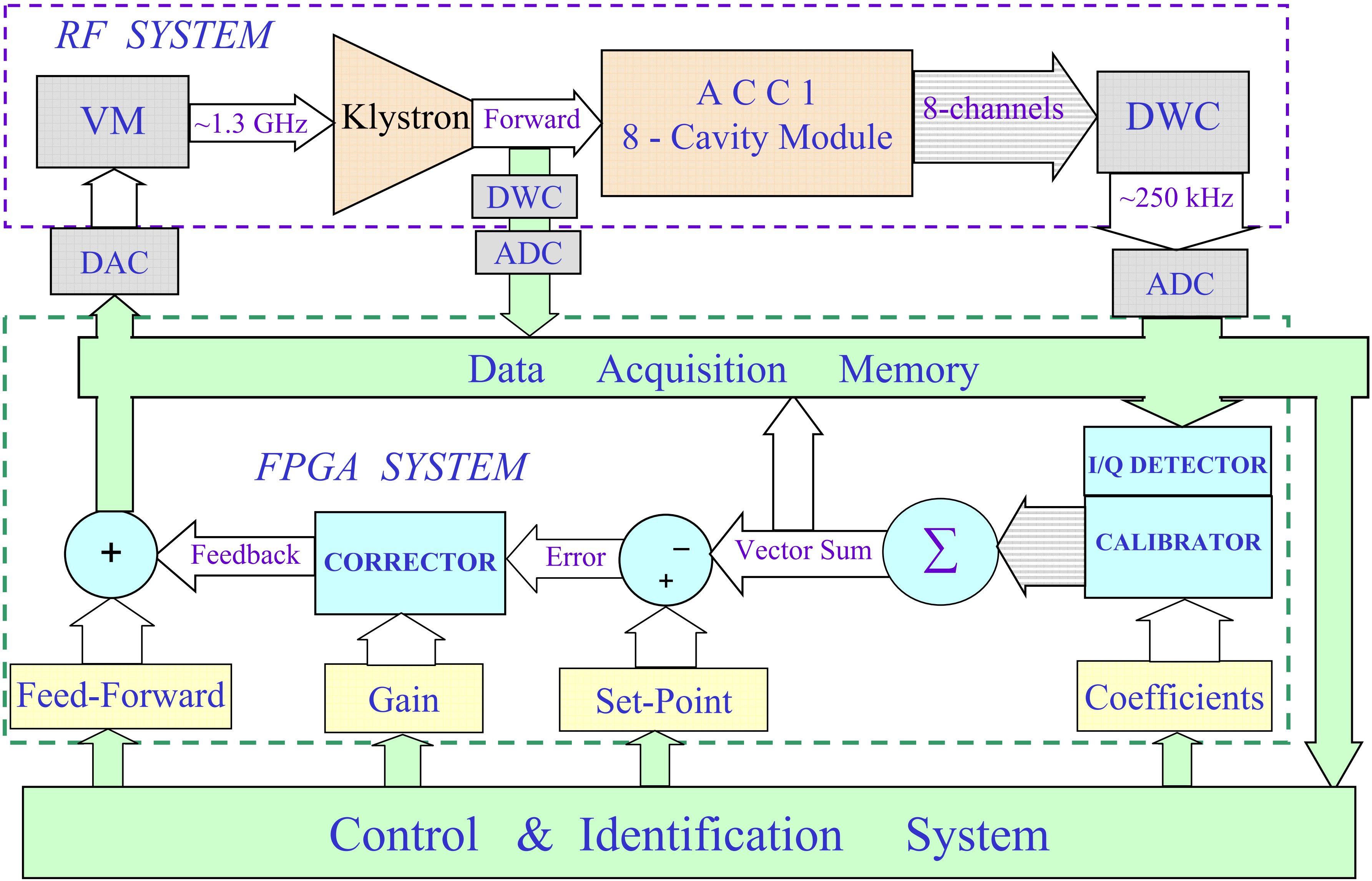
Motivation and goal of the experiments

Development of the Multi-Cavity Complex Controller based on the system parameters identification

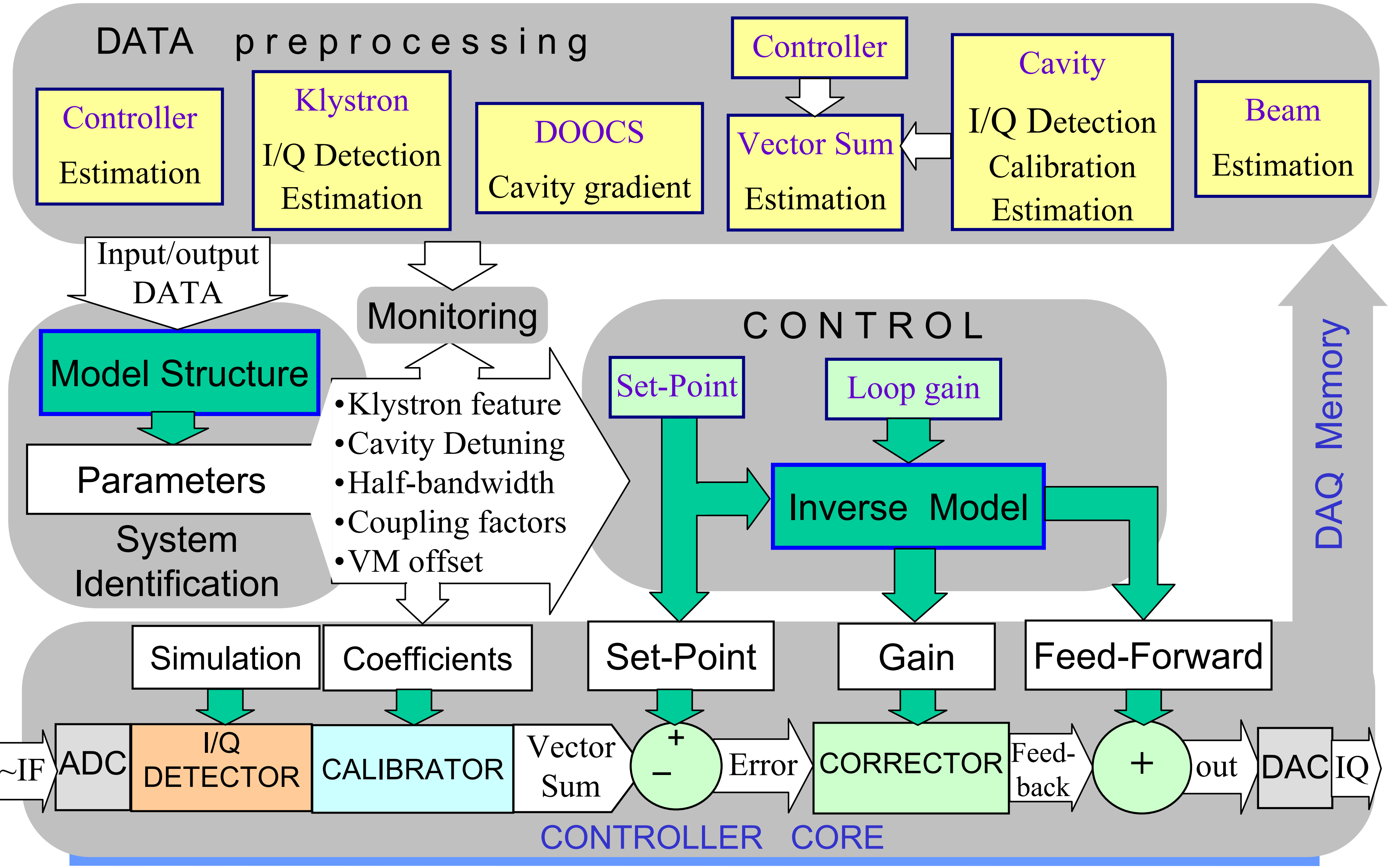
Main topics of the presentation

- System setup
- Control system algorithm
- Experimental results
- Achievements

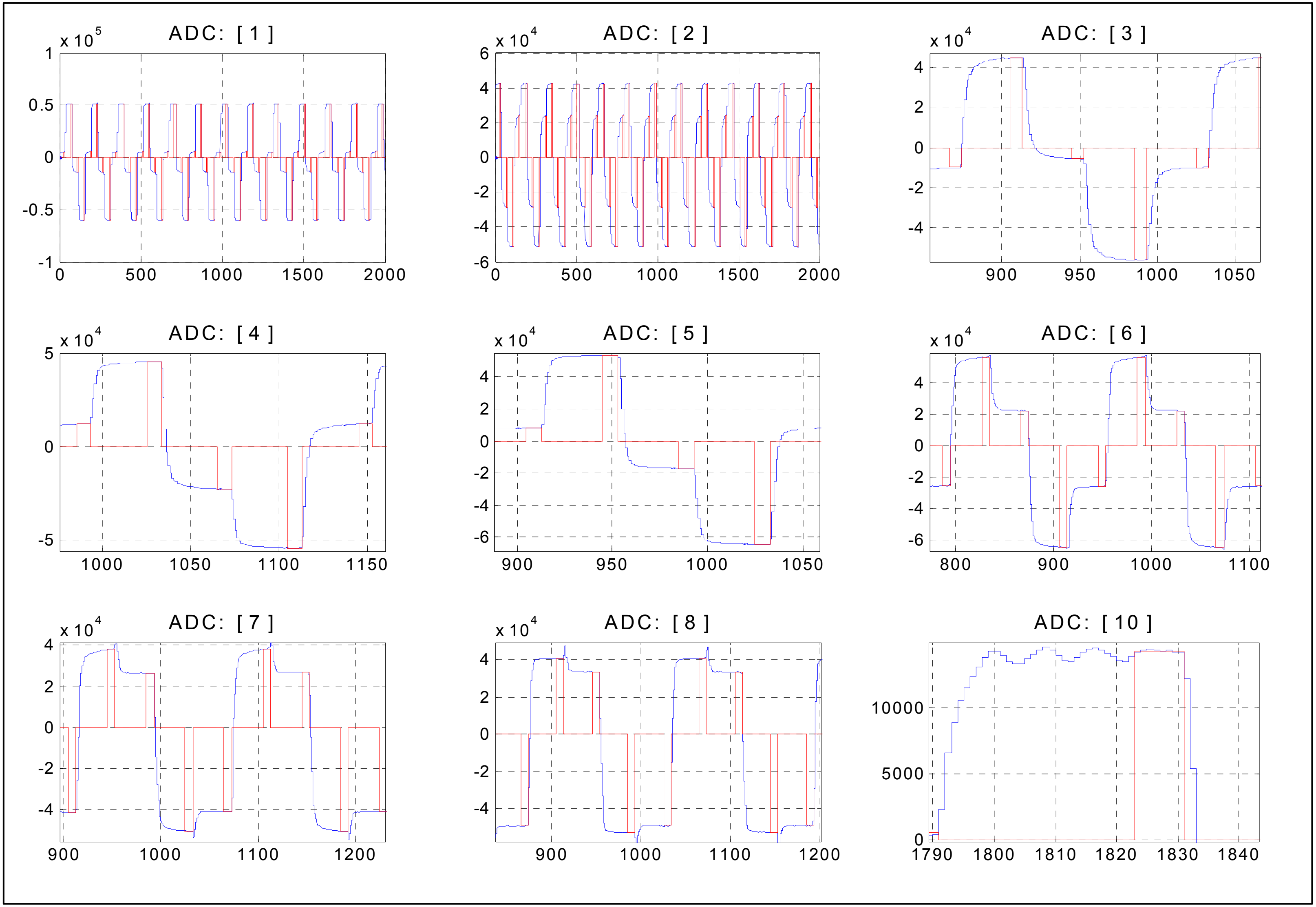
Functional block diagram of Multi-Cavity Control System



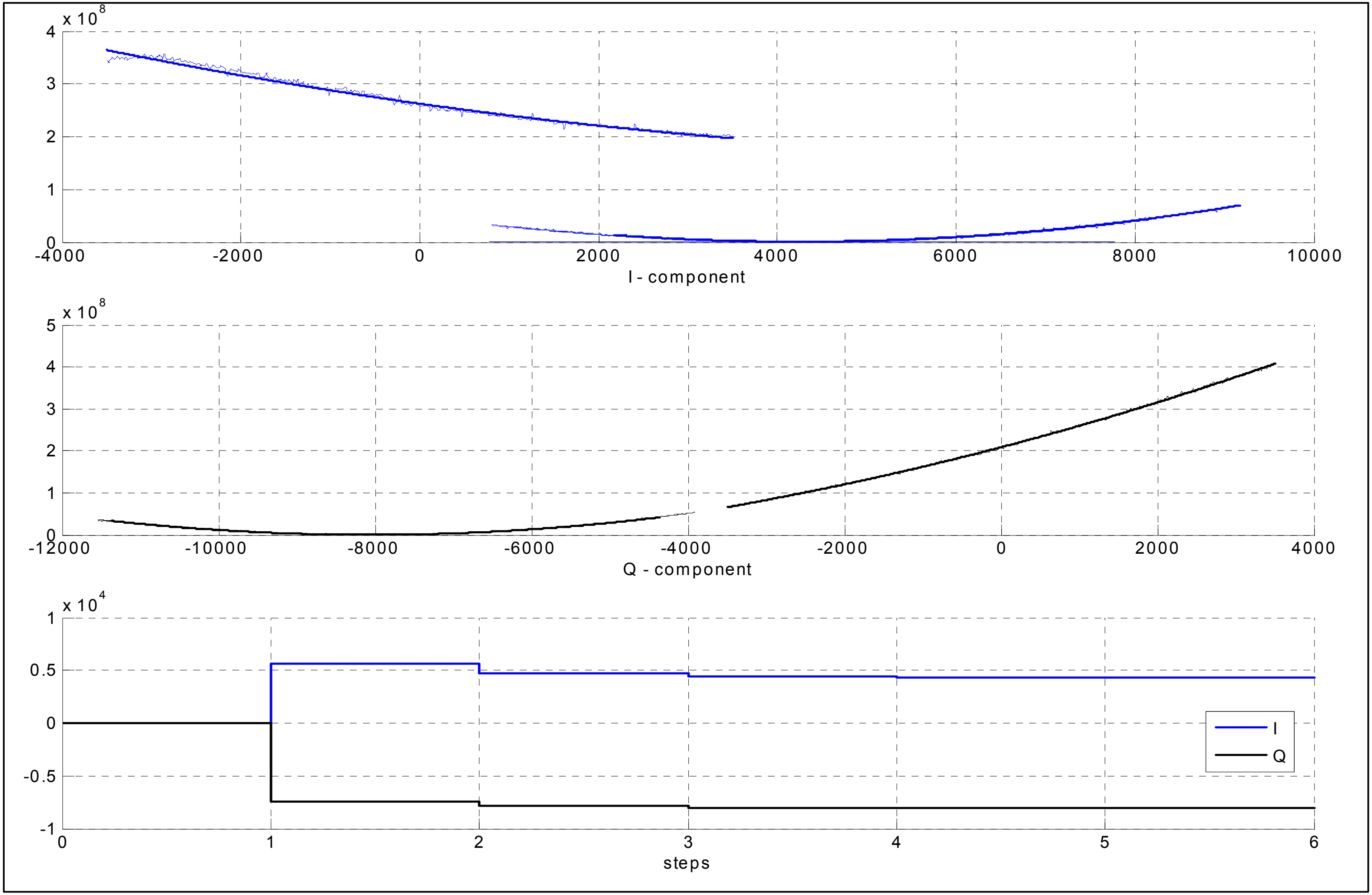
Control & Identification System



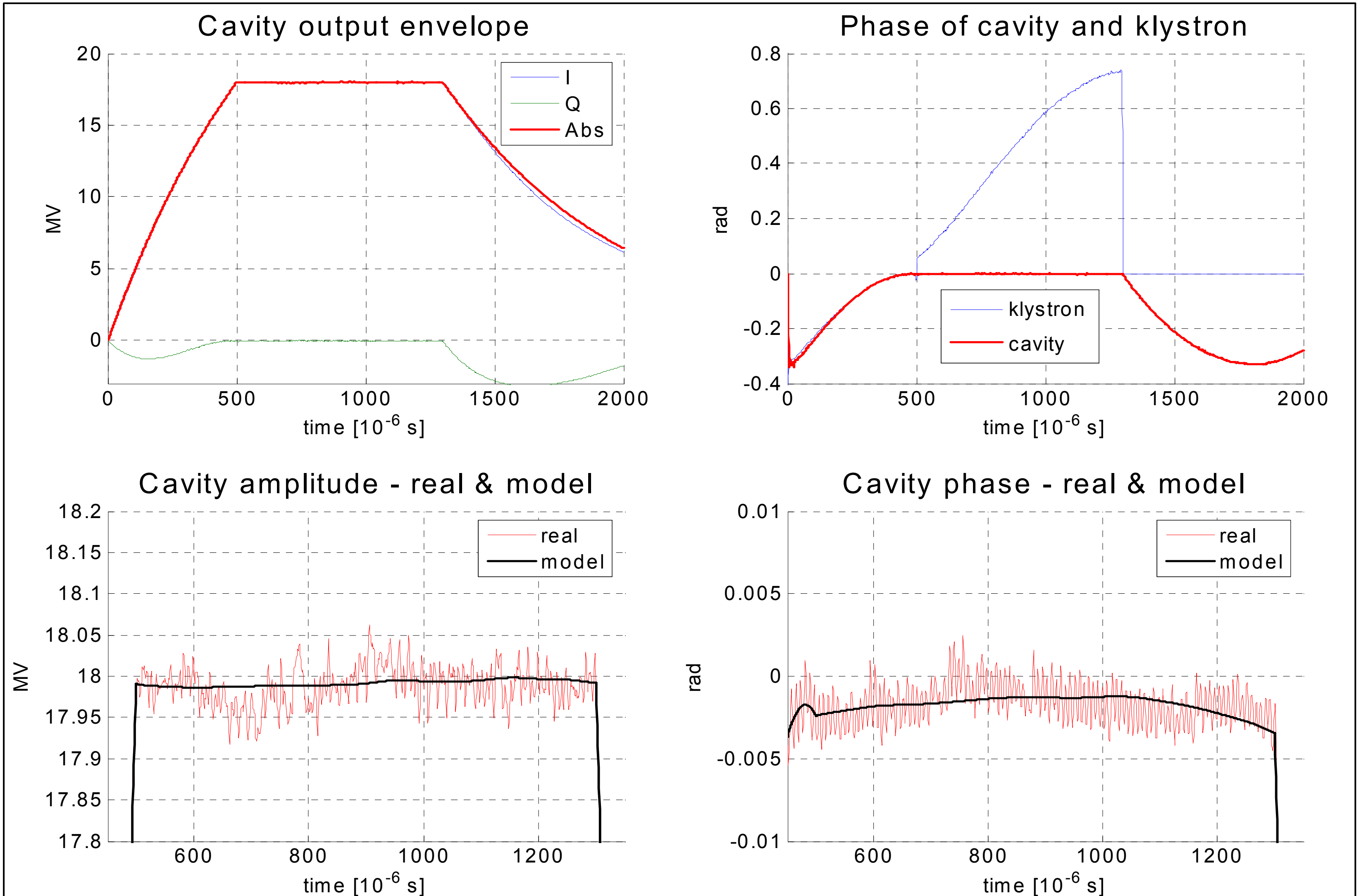
ADC fast readout



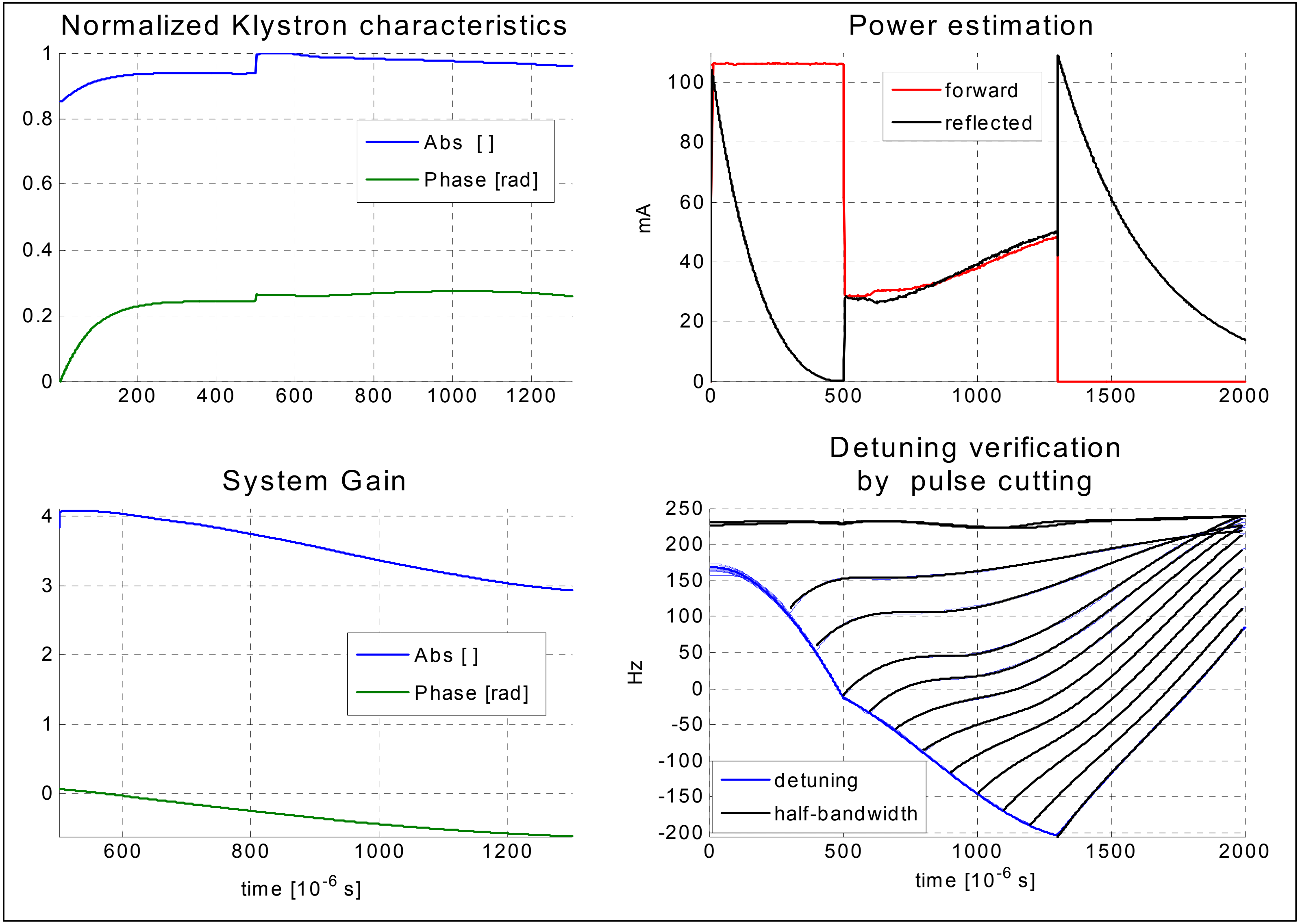
Vector Modulator offset auto-compensation



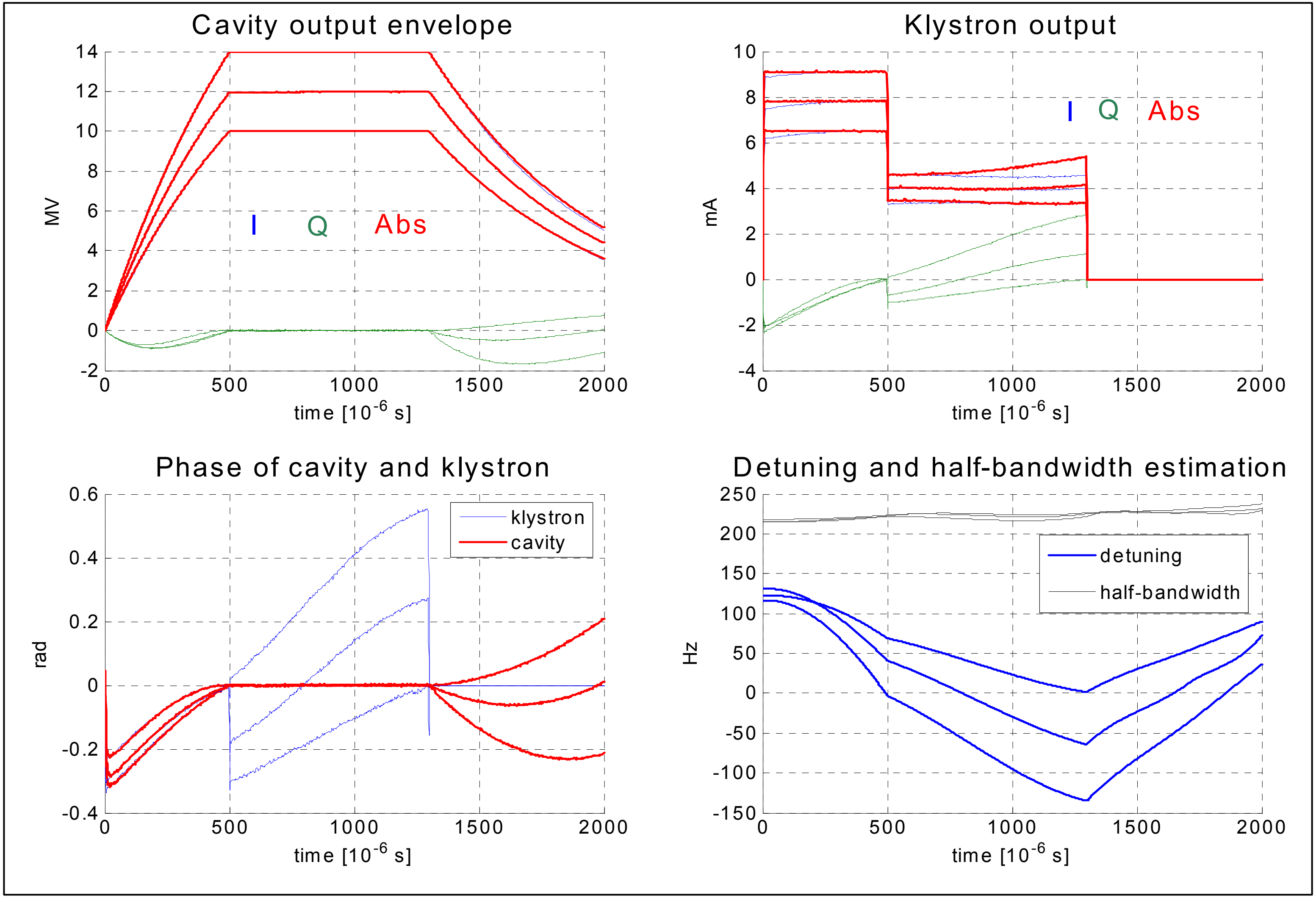
System Identification - Model verification
Cavity 8 – Adaptive Feed-forward (gain=0)



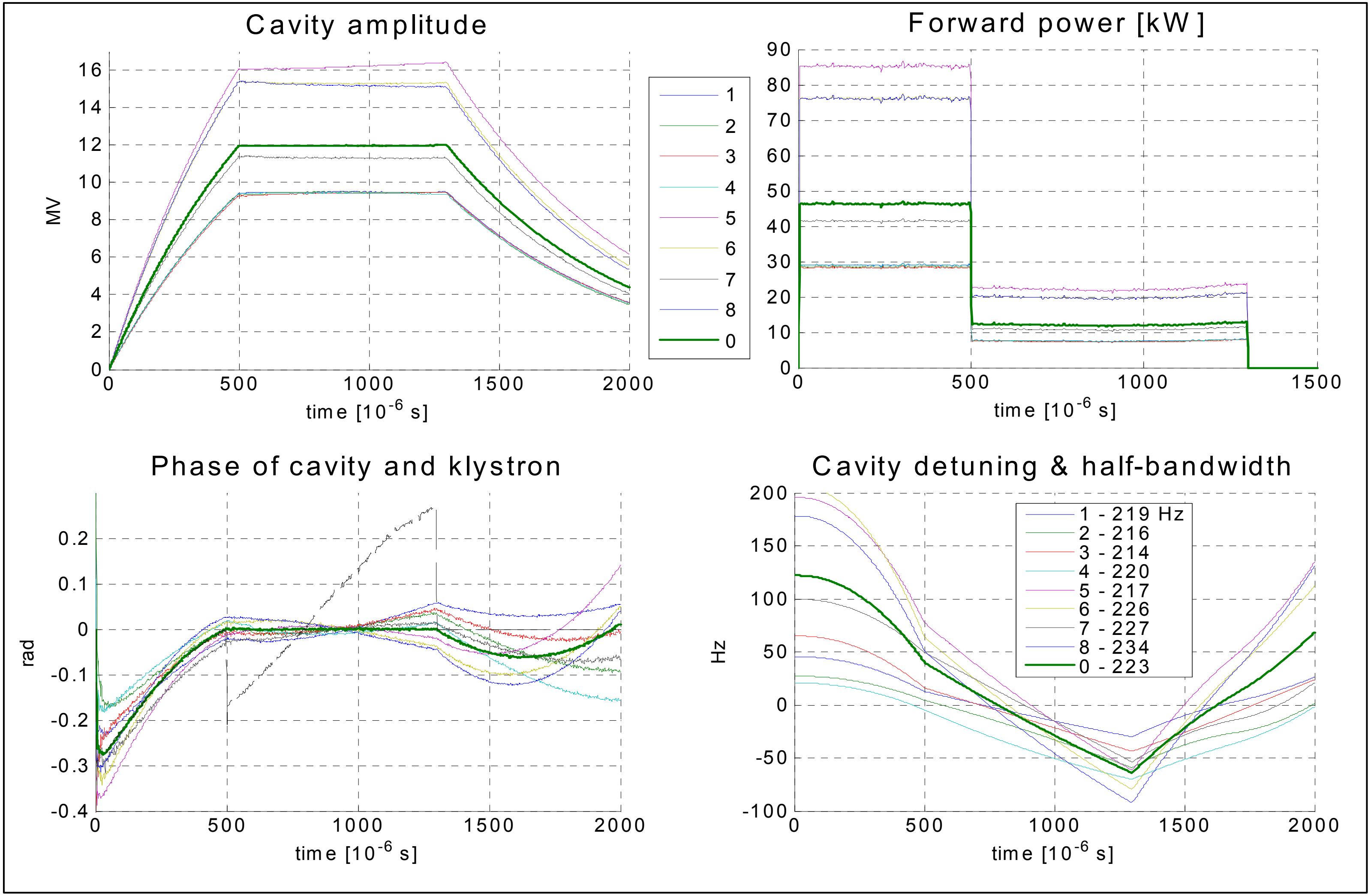
Results from System Identification - Cavity 8



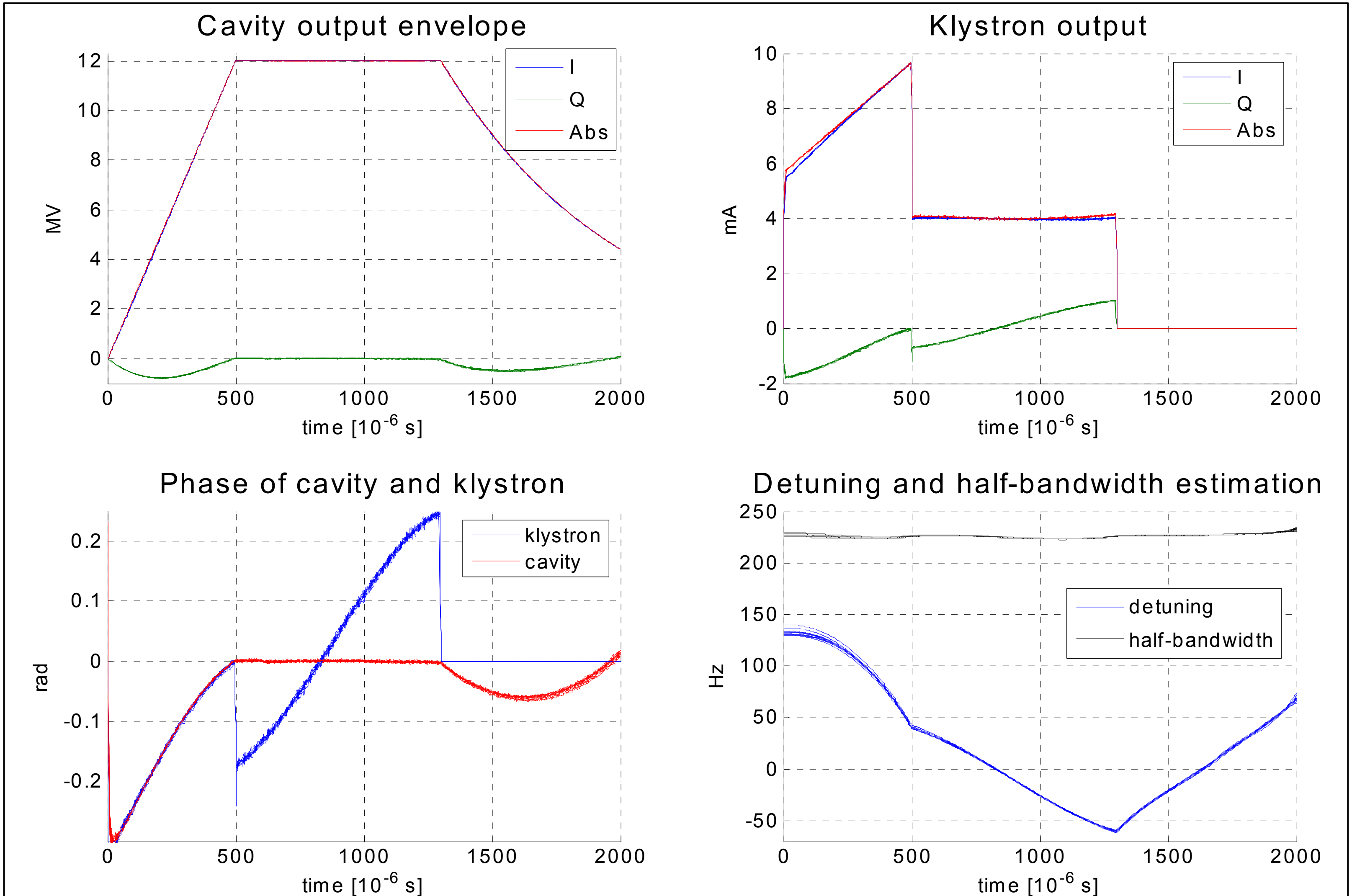
Vector sum control of 8 cavities ACC1
Adaptive Feed Forward (gain=0) for three gradient levels



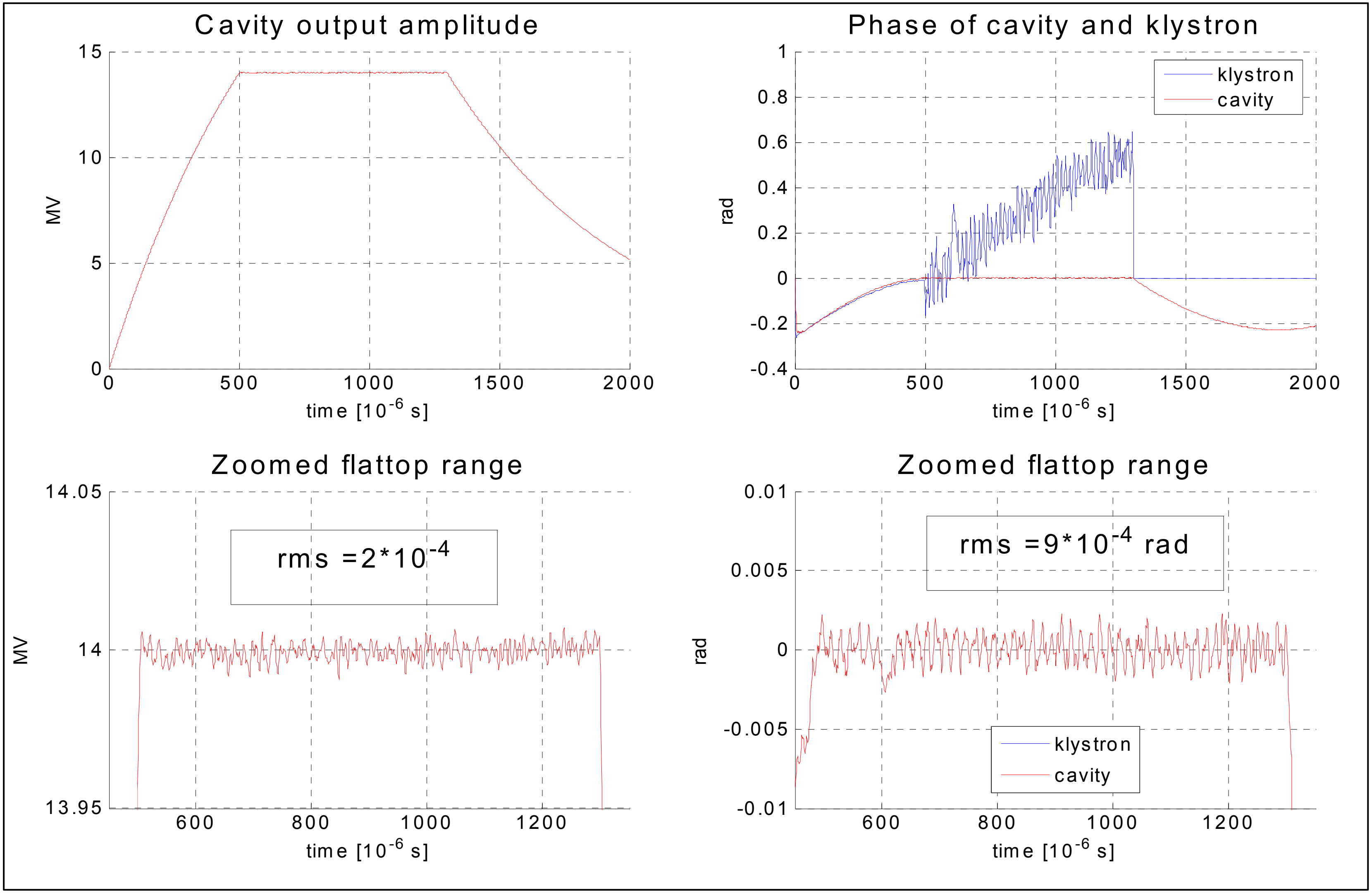
Vector sum control of 8 cavities
Adaptive Feed Forward – all cavities monitoring



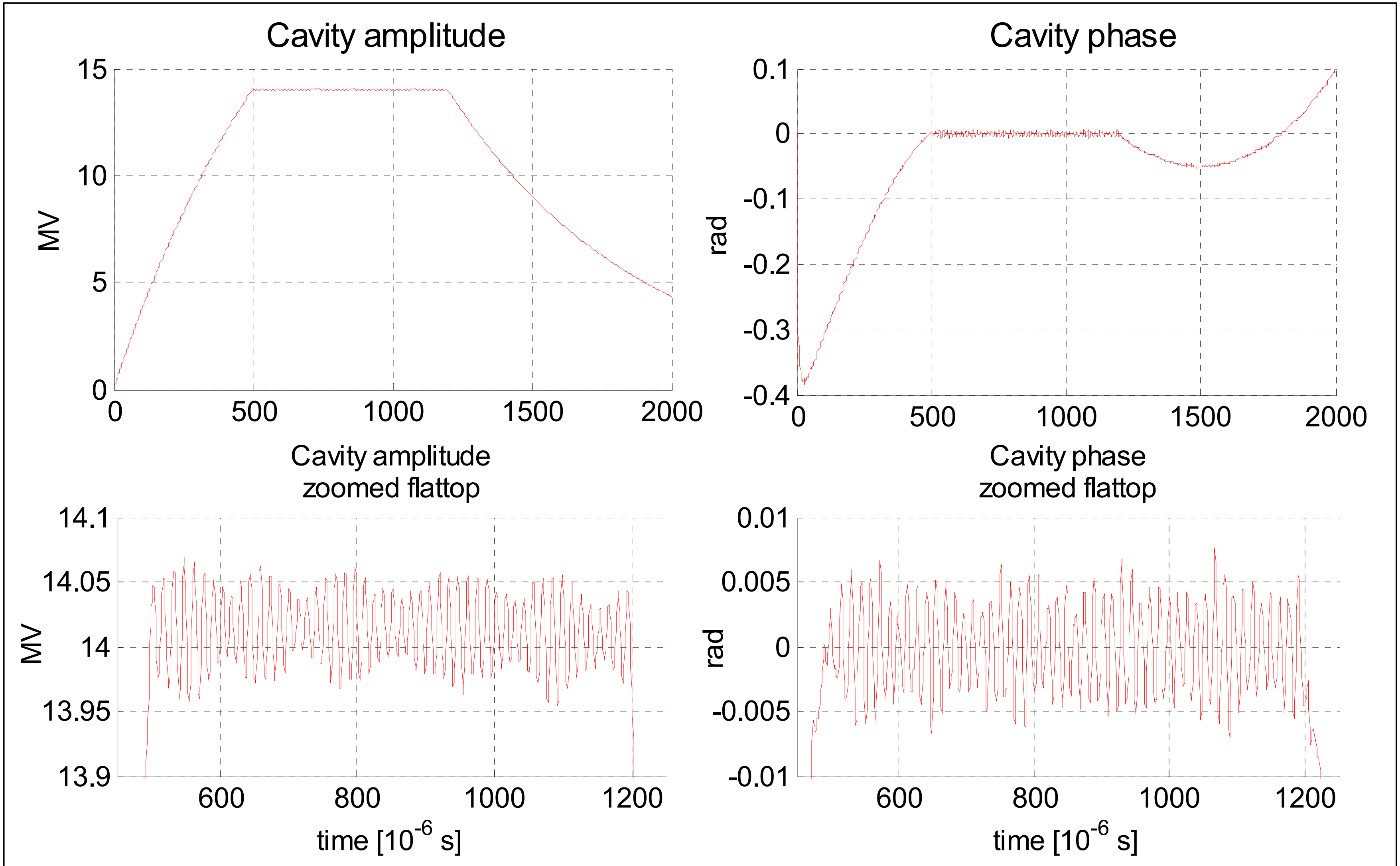
Vector sum control of 8 cavities ACC1
Adaptive Feed Forward (gain=0) - 10 repetition readouts



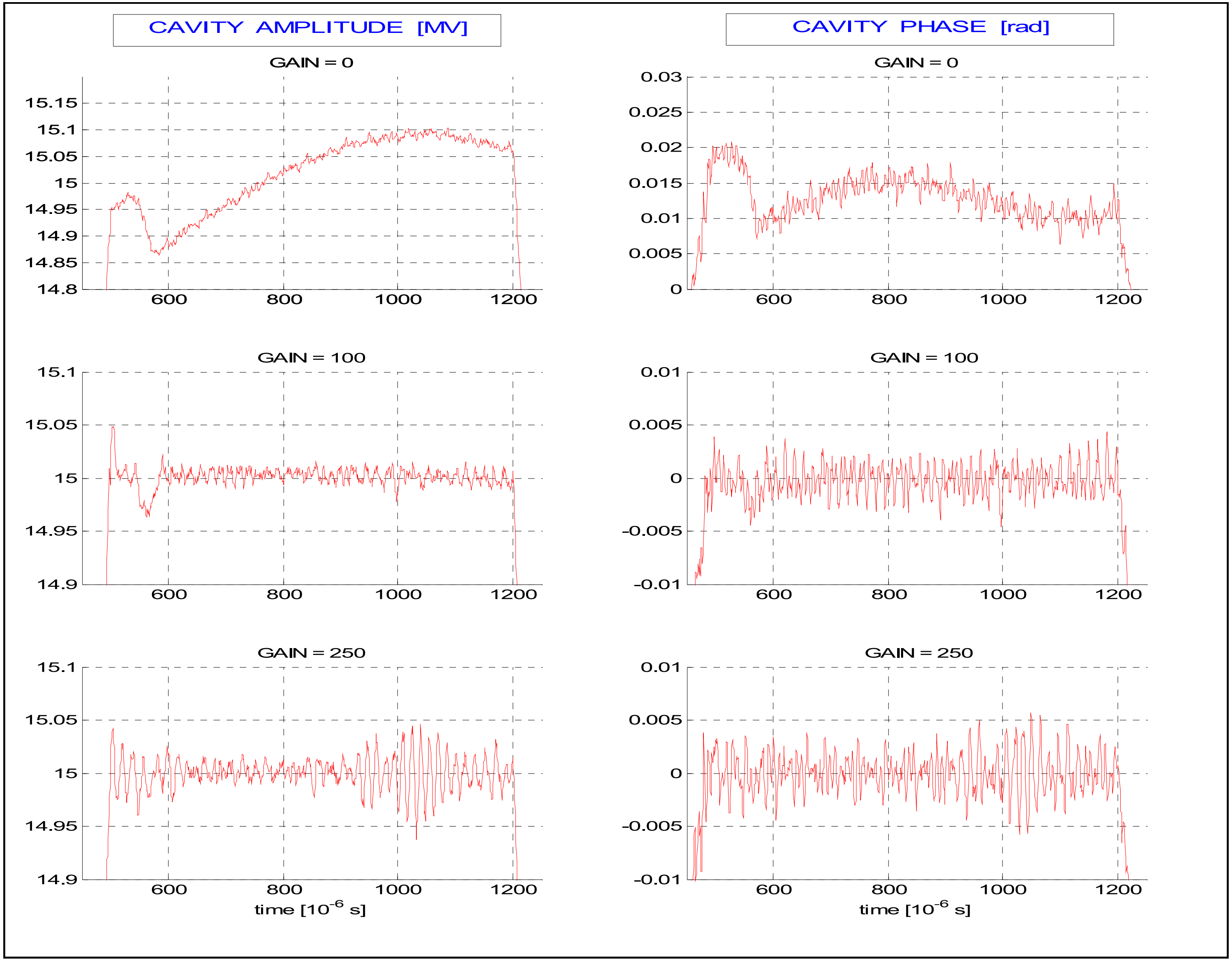
Vector sum control of 8 cavities – ACC1
Feed Forward and feedback (gain=100)



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



Beam loading testing



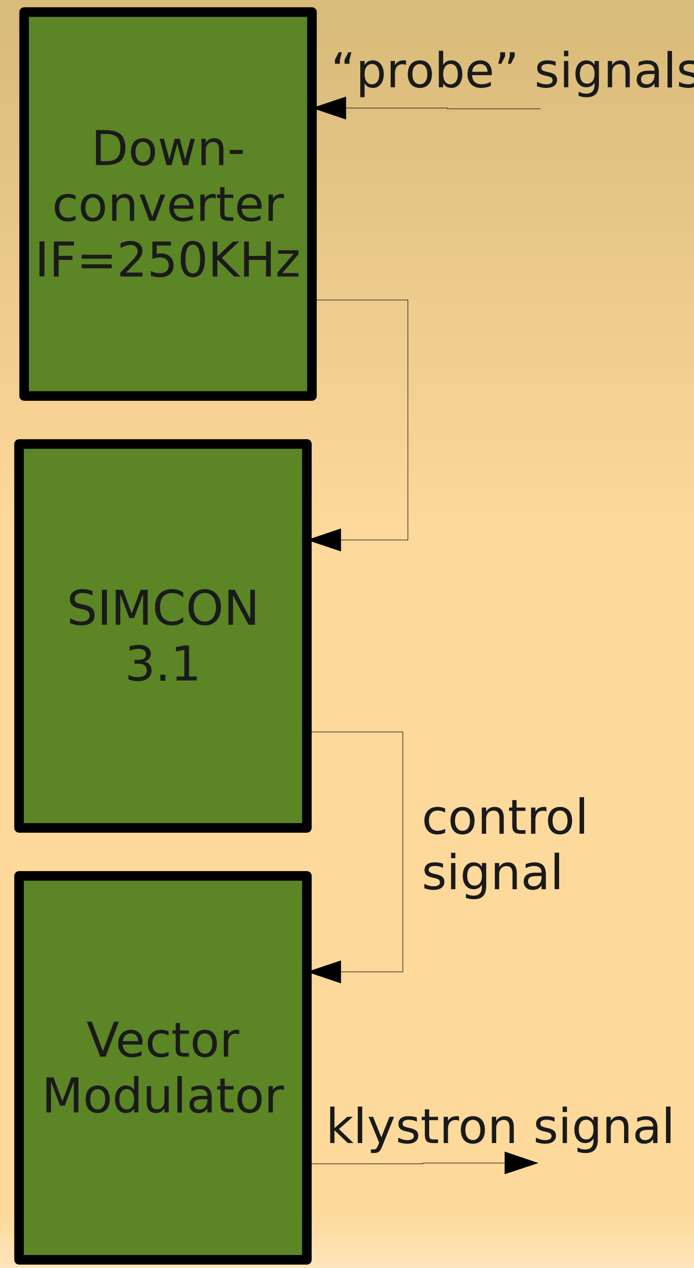
Current status of the project

FPGA based controller permanently installed in ACC1.

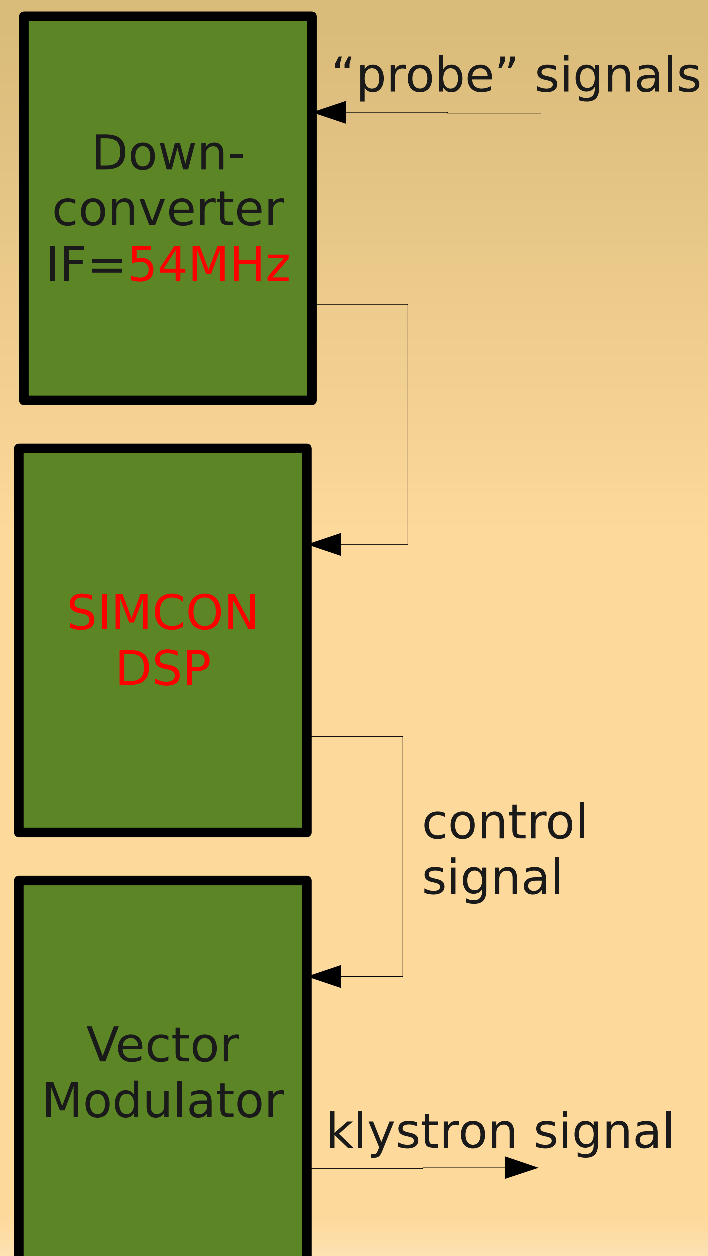
Distributed architecture of the controller was proposed and implemented. It was tested for 24 channels using ACC456.

Test system

Existing system

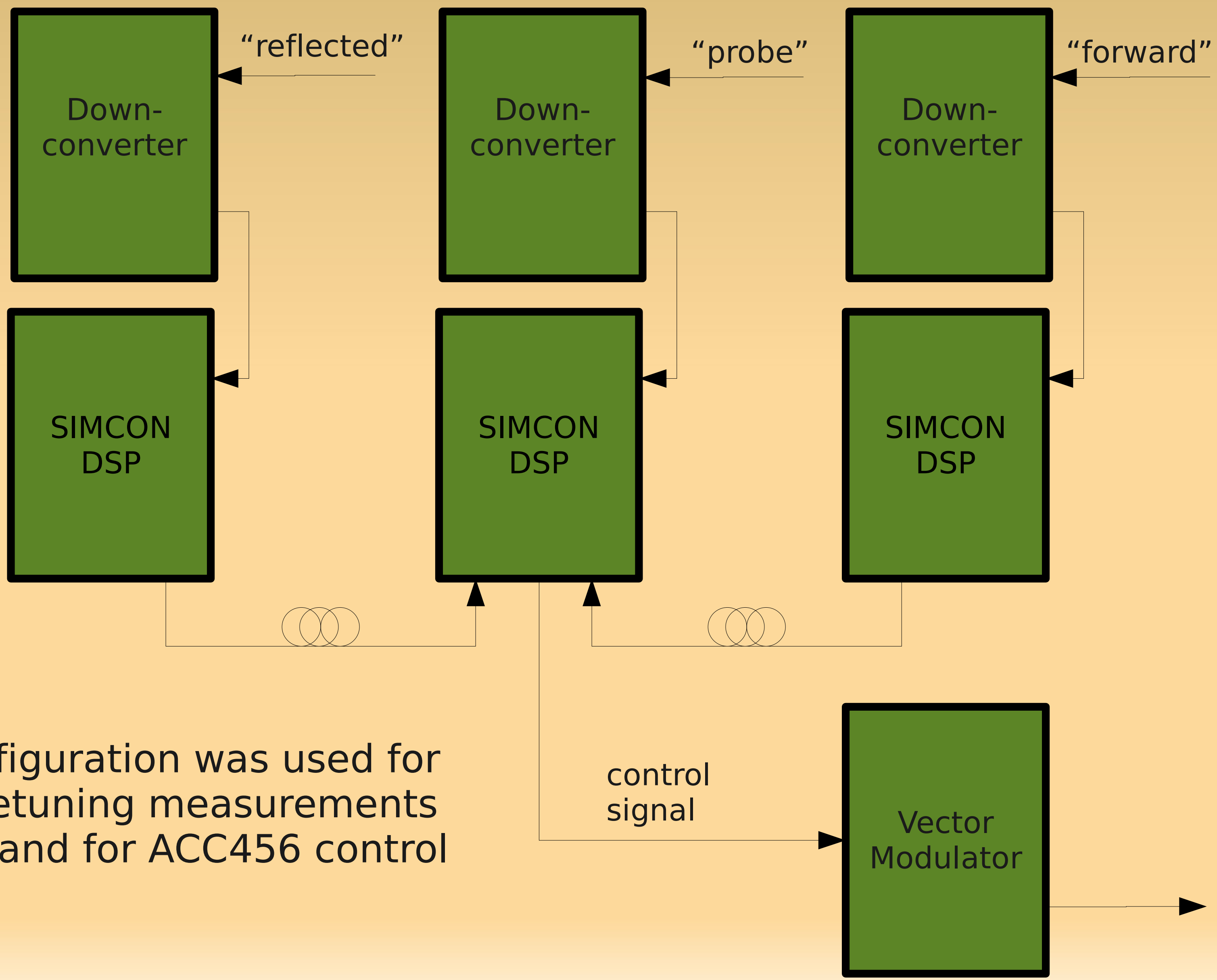


Test system



“probe” signals
Down-
converter
IF=54MHz
SIMCON
DSP
control
signal
Vector
Modulator
klystron signal

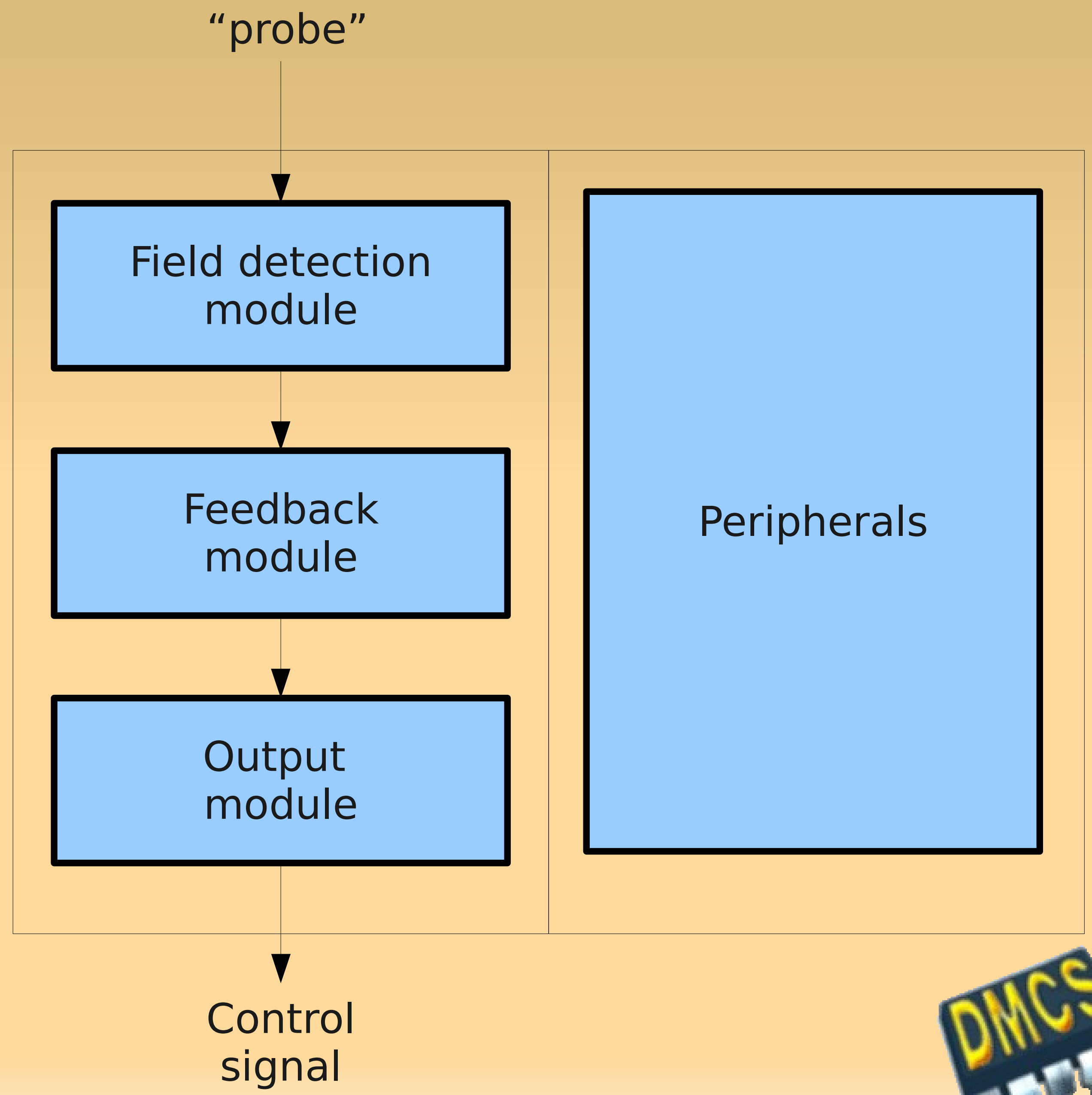
Test system



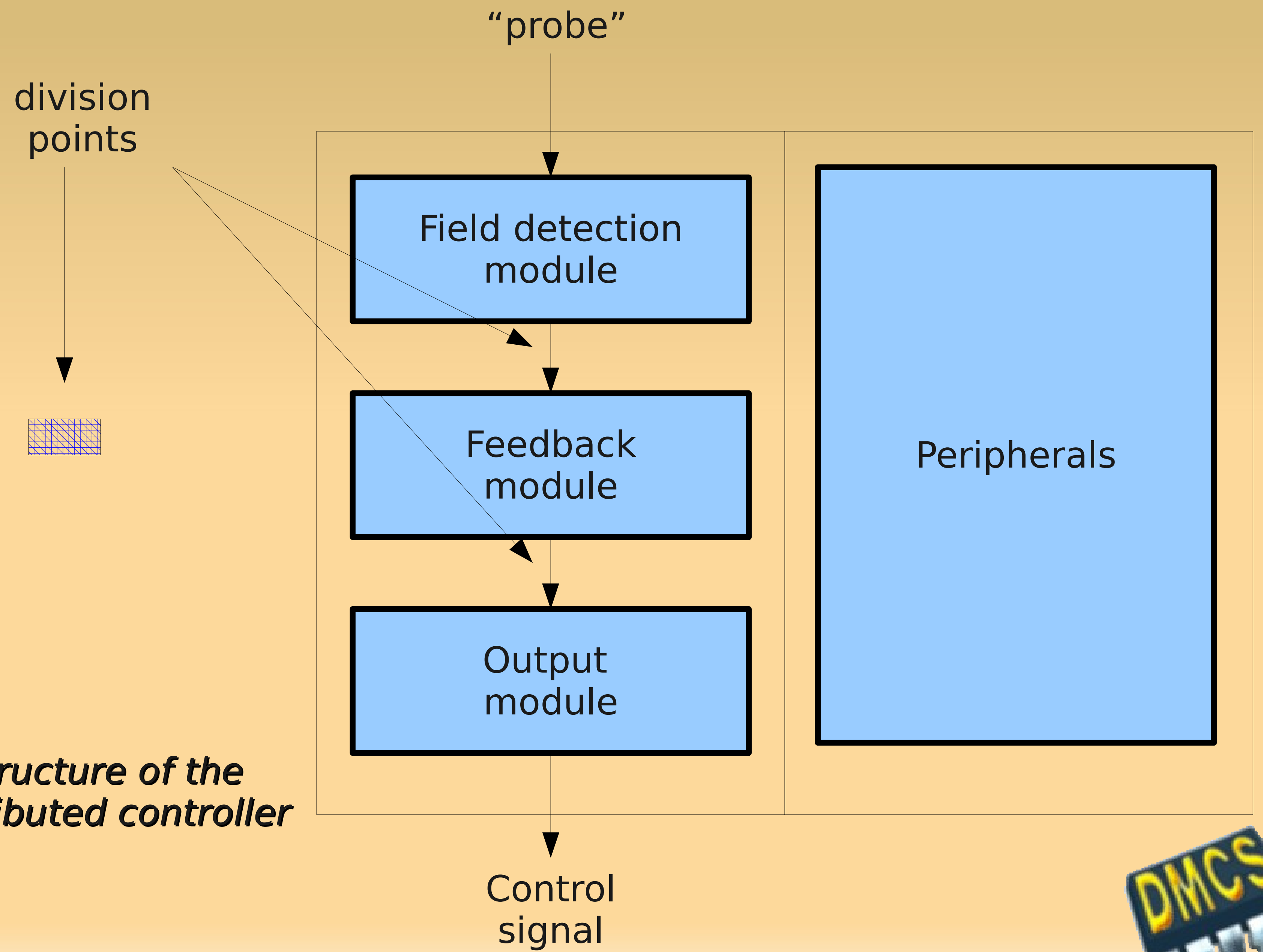
This configuration was used for online detuning measurements in ACC1 and for ACC456 control

Structure of the controller

Centralized structure of the controller

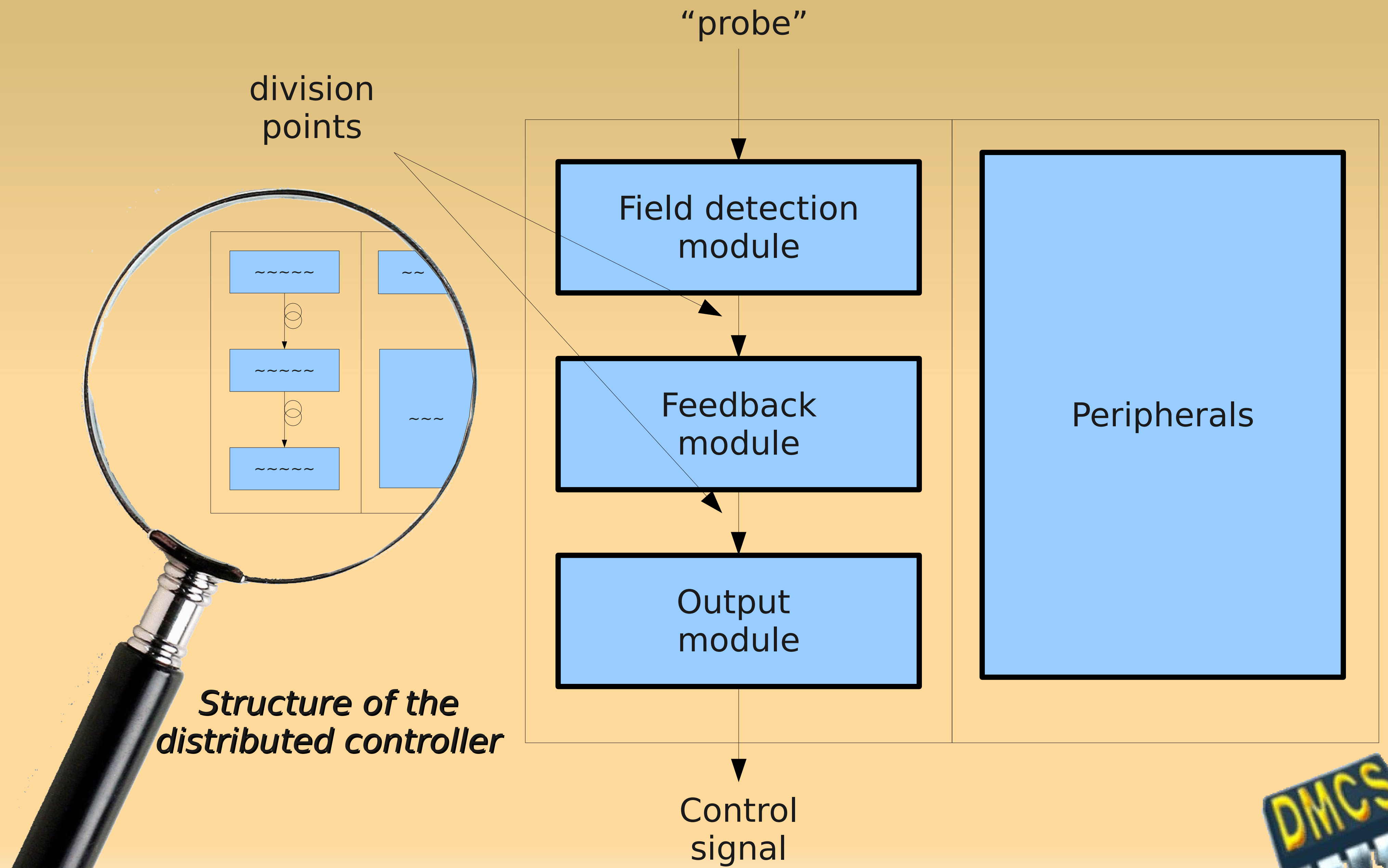


Structure of the controller



Structure of the distributed controller

Structure of the controller



Technical parameters

1. Numerical precision: 18 bits

2. Operating frequency: 100 MHz

3. Resource usage: up to 60% for Virtex 2 Pro 30

4. Tools used: Xilinx ISE package

ACC1 controller

What is currently installed in ACC1 ?

Basic version of the controller with beam load compensation feature together with klystron linearization module.

Tomorrow we will install and test AFF algorithm.

Modes of operation

There are two modes of operation

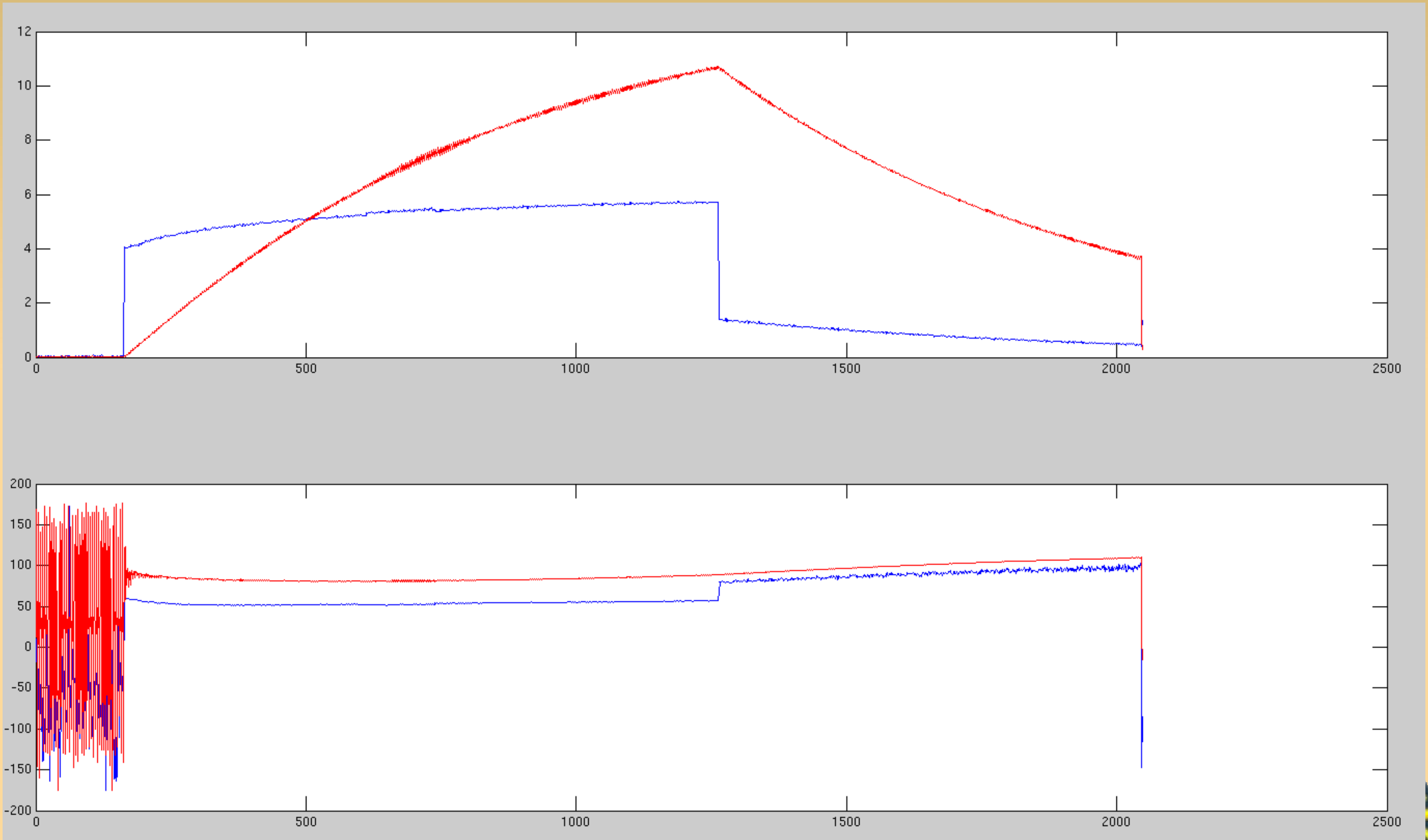
1. Diagnostic mode
2. Operational mode

SEL results

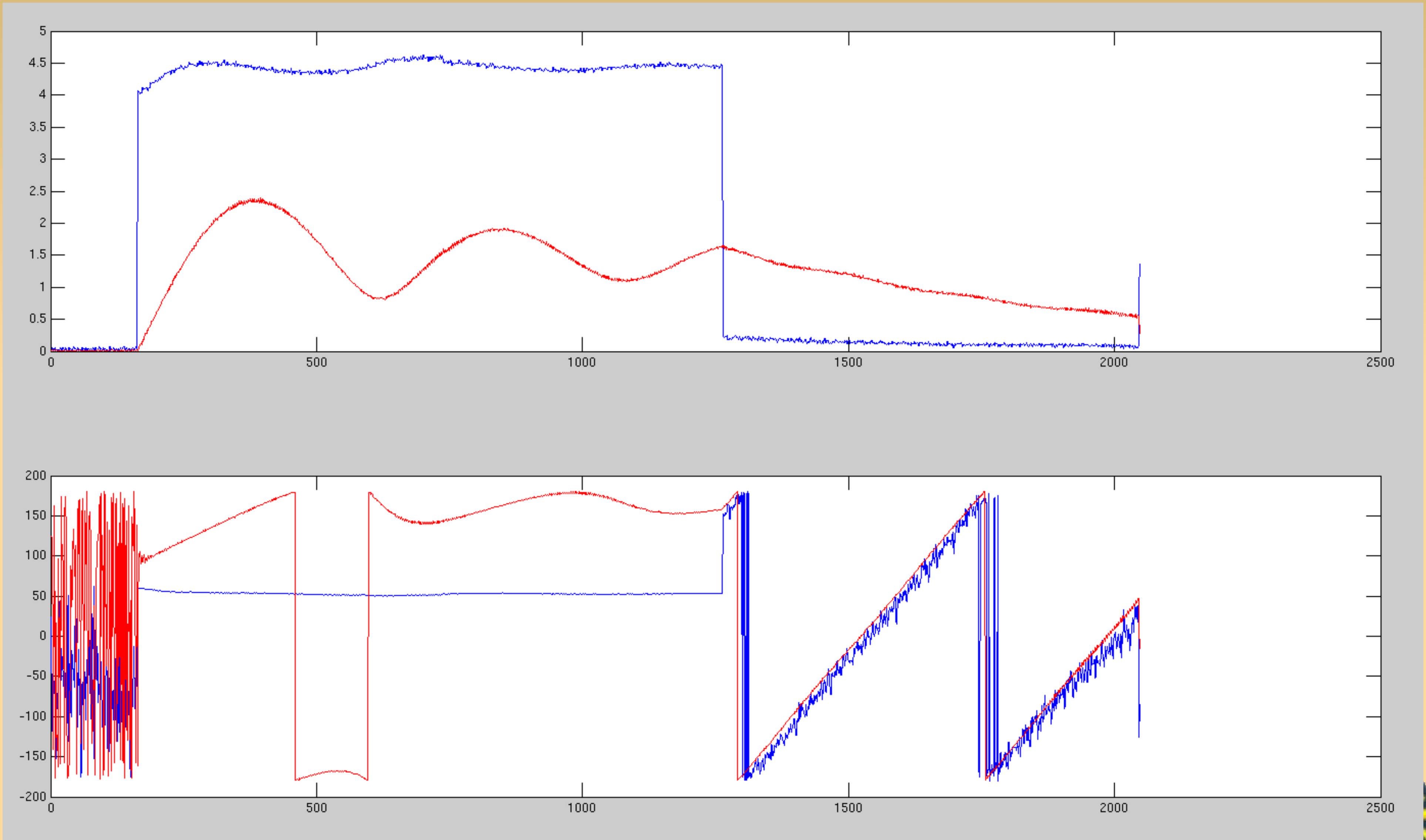
Self excited loop makes it possible to fill the cavity which is detuned from its resonance frequency even by a large offset.

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

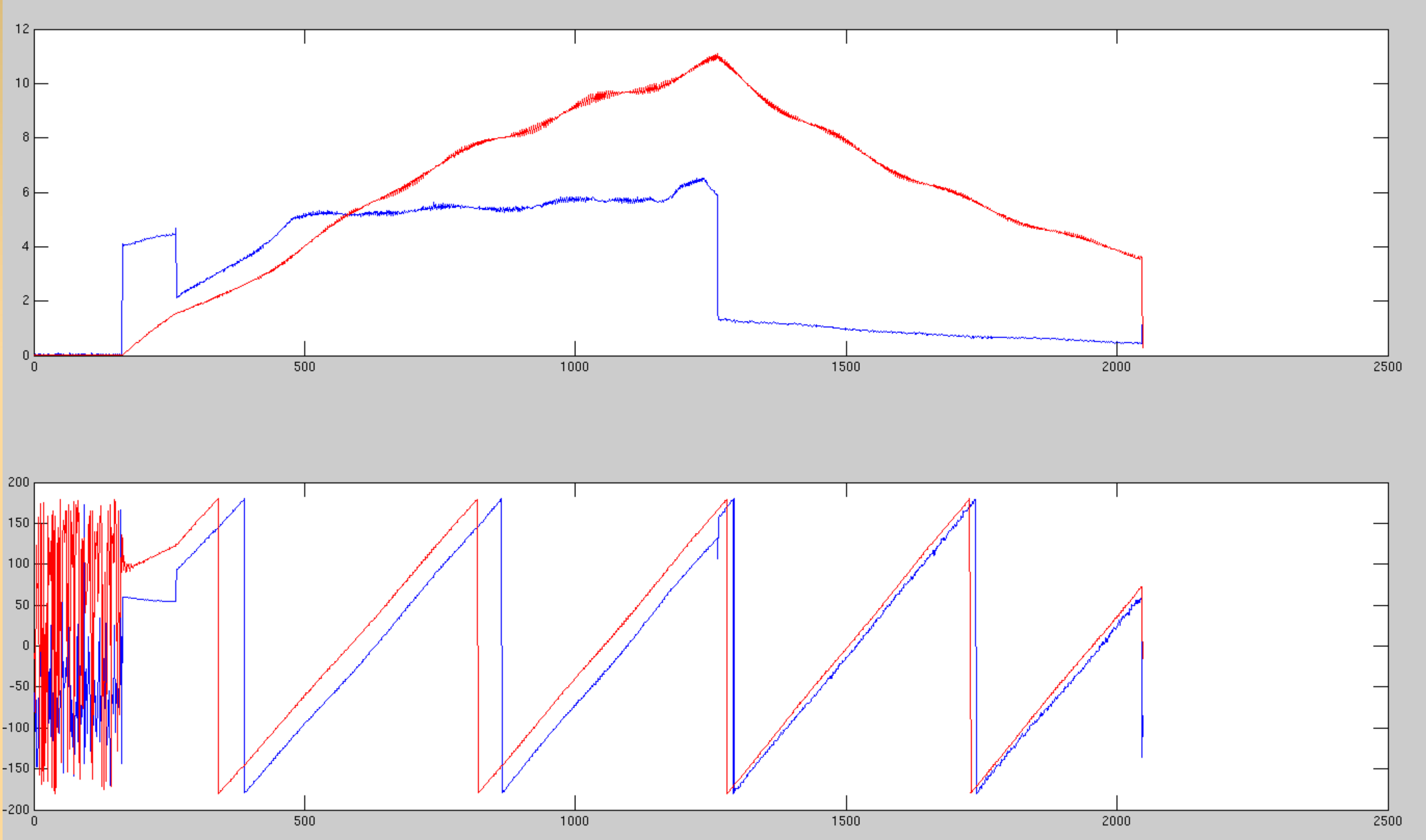
SEL results (1)



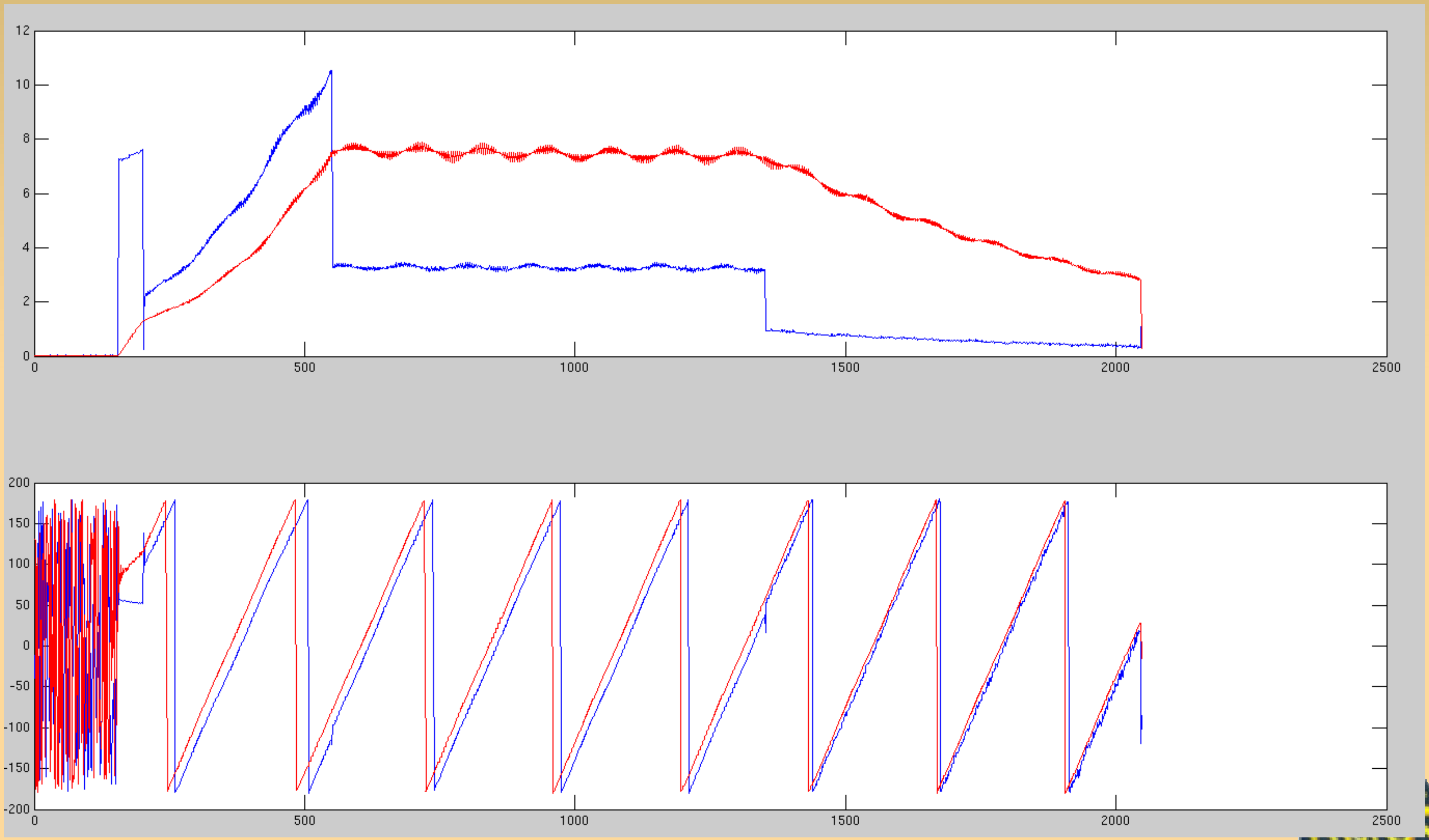
SEL results (2)



SEL results (3)



SEL results (4)

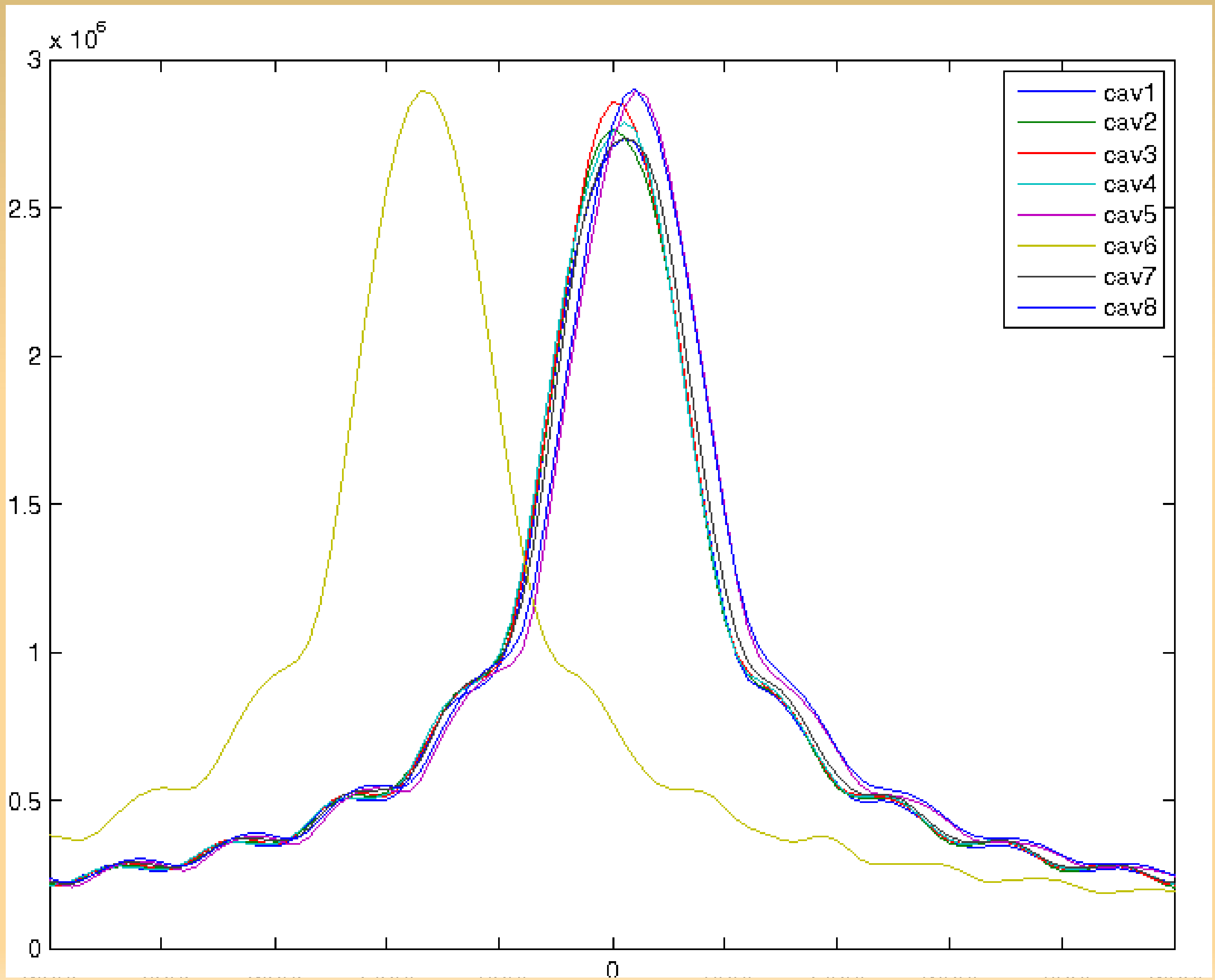


Frequency Sweep Mode

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.

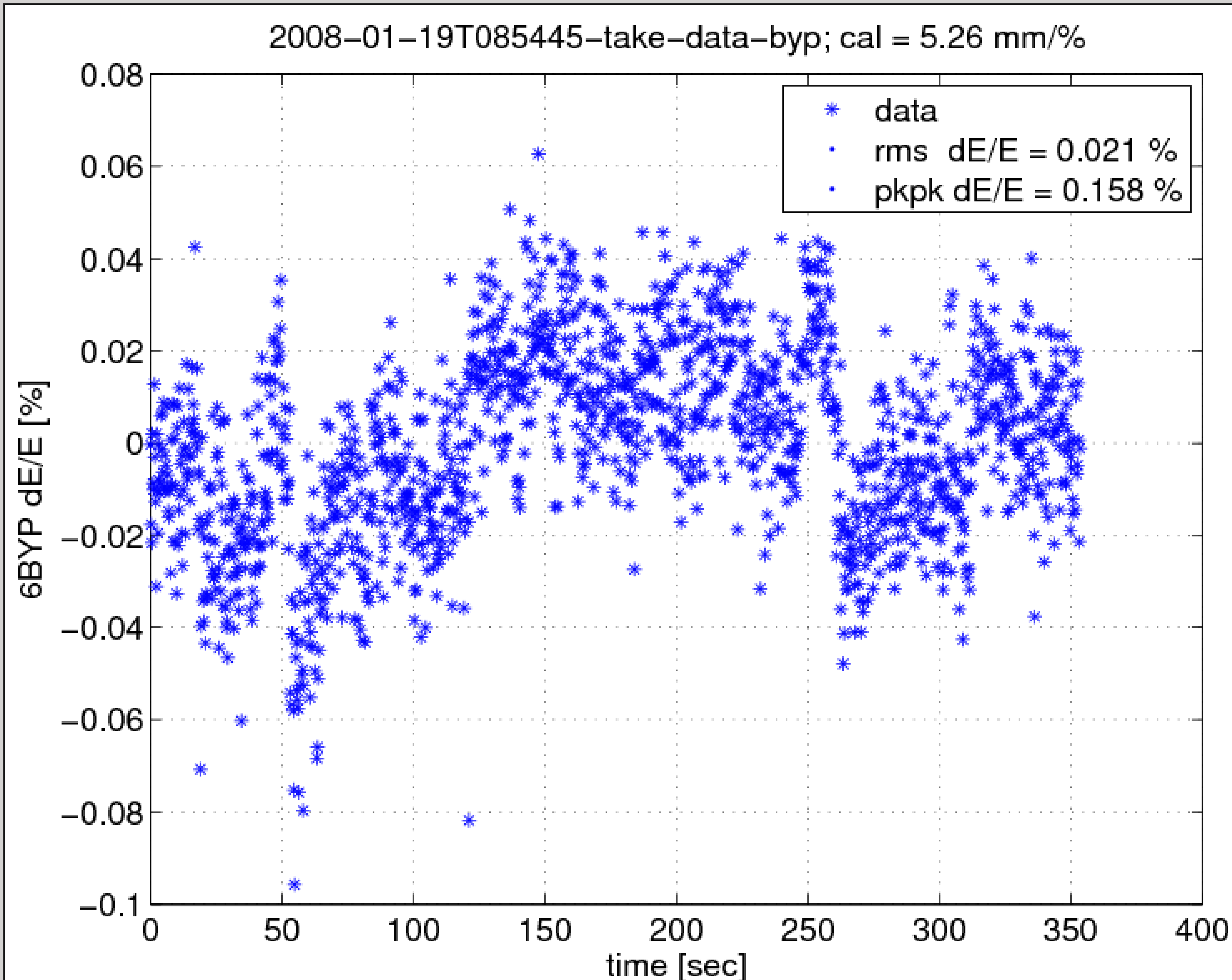
Frequency Sweep Mode



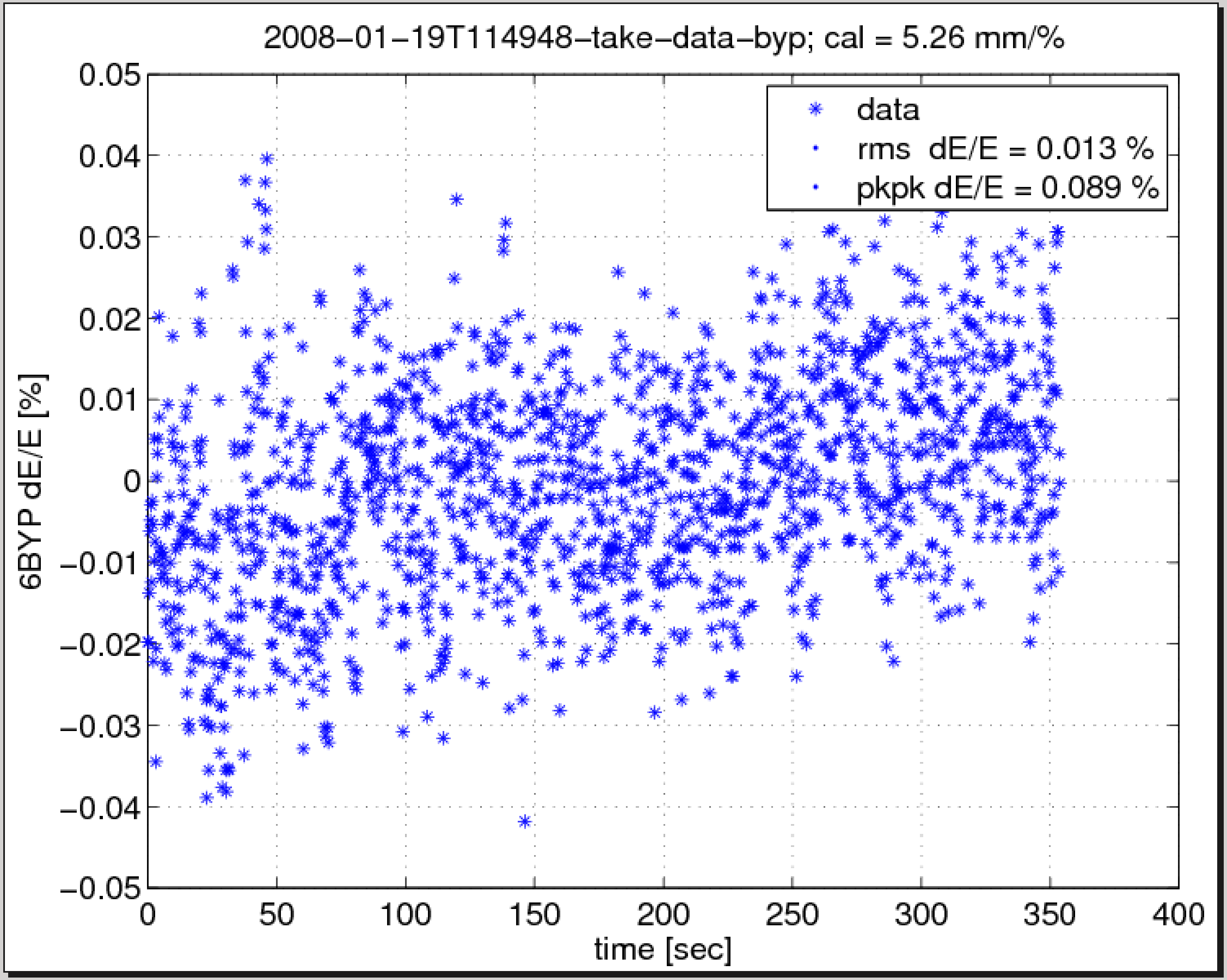
Beam stability – ACC456 (1)

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)



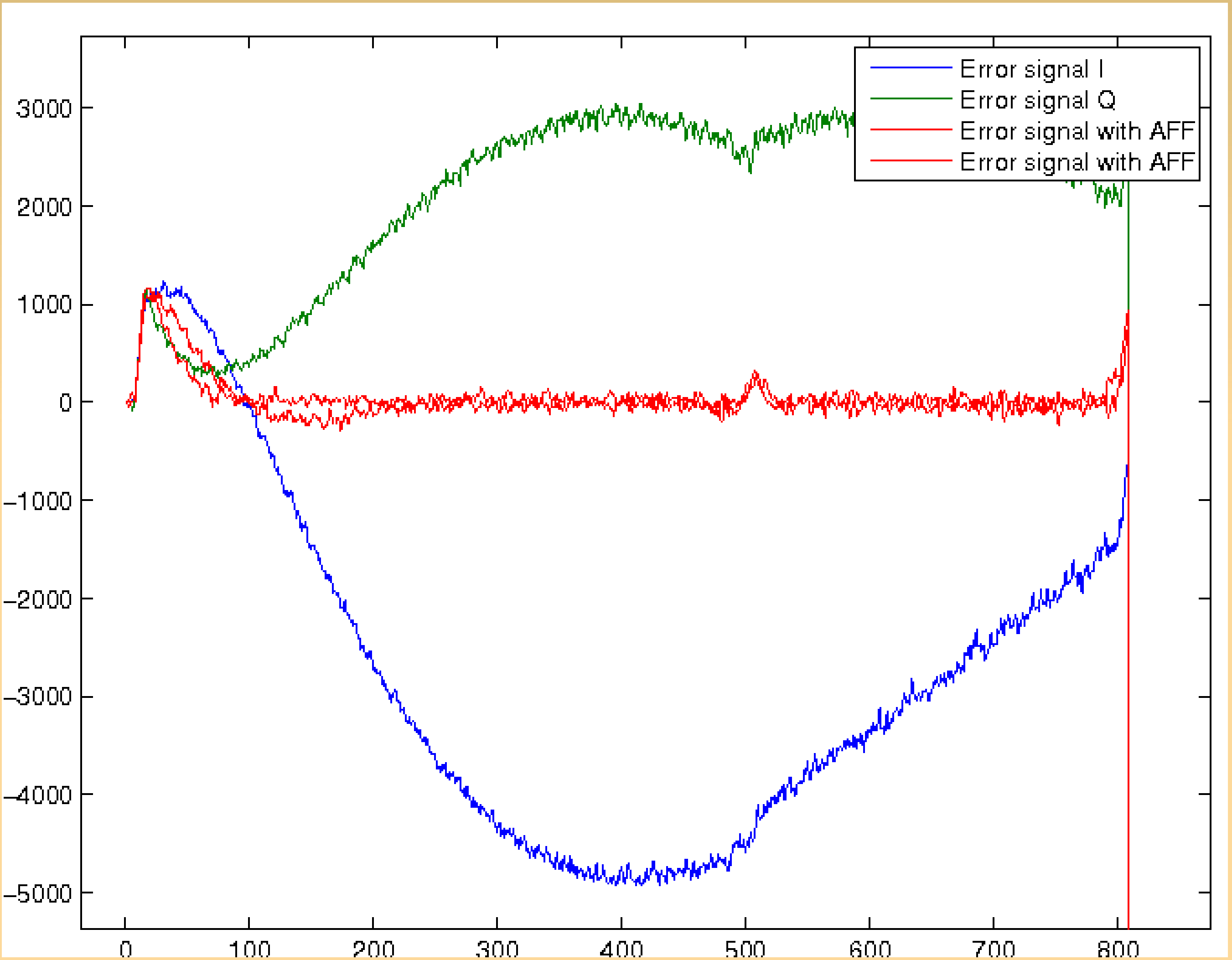
AFF tests

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

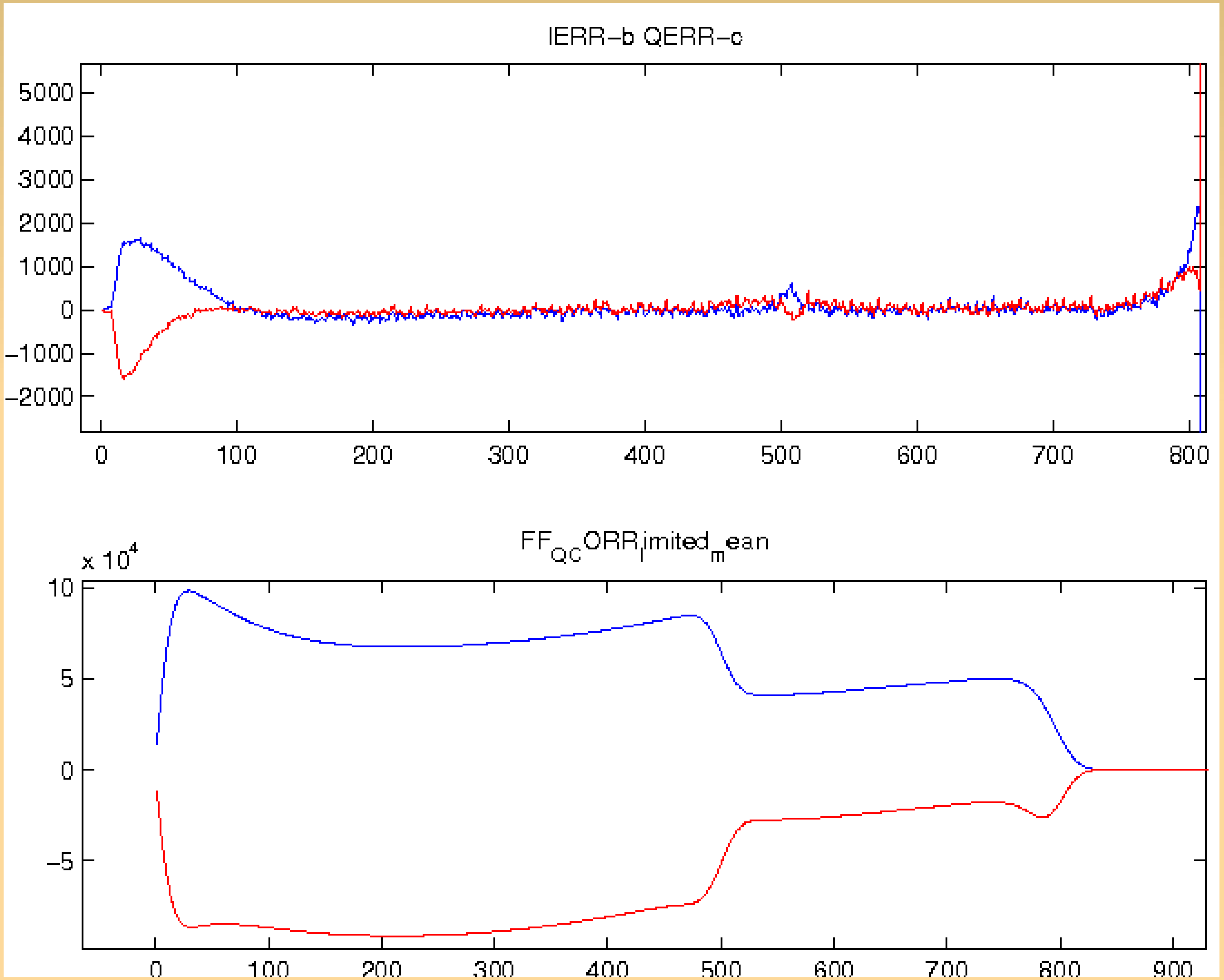
- Matlab implementation
- FPGA implementation
- Embedded system implementation

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

AFF test (2)



IERR−b QERR−c
5000
4000
3000
2000
1000
0
−1000
−2000
0
100
200
300
400
500
600
700
800
FFQCORRlimitedmean
x 10^4
10
5
0
−5
0
100
200
300
400
500
600
700
800
900

Additional results

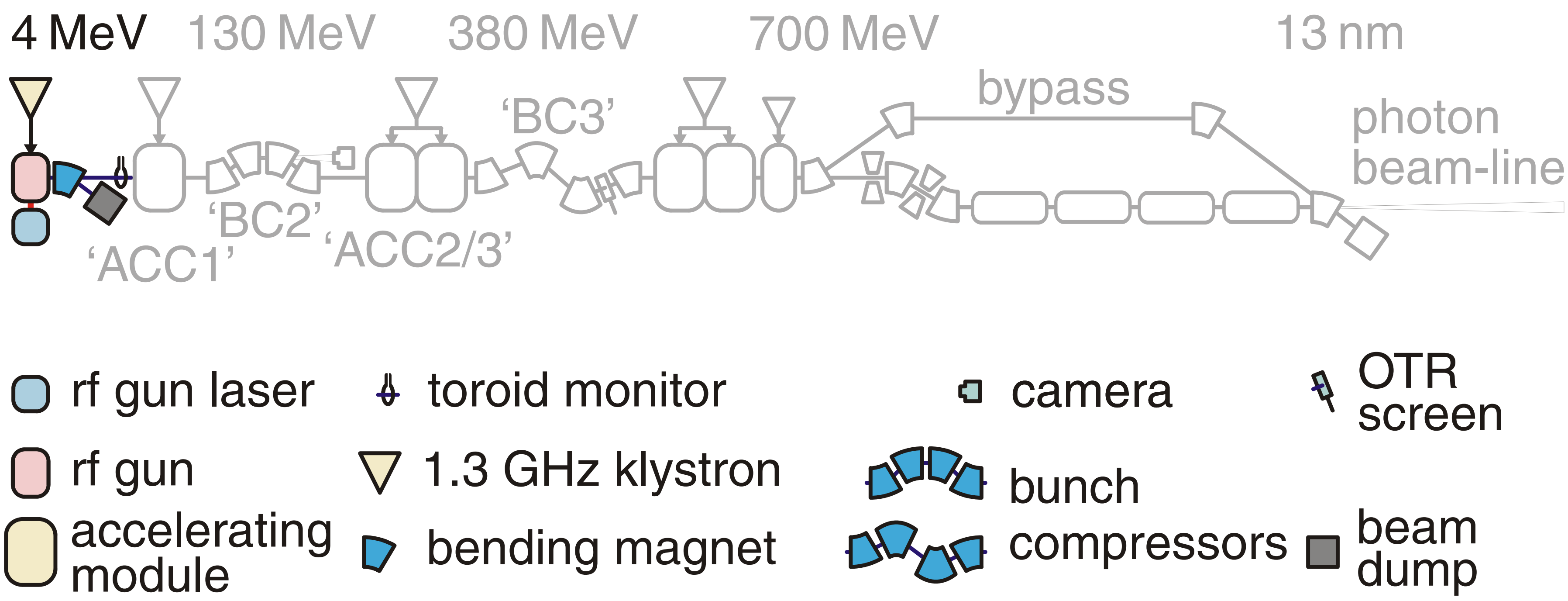
1. Amplitude-Q control
2. Klystron linearization component
3. Control using IF = 54MHz
4. Beam energy stability after ACC1 with tuned parameters
5. Delay scans

Future plans

1. To measure the performance of the controller in ACC23 modules
2. To fully integrate controller with DSP processor on SIMCON DSP board
3. Run the whole machine using FPGA boards and evaluate performance

RF Gun Control

The 'source' of the bunches: rf gun laser and rf gun

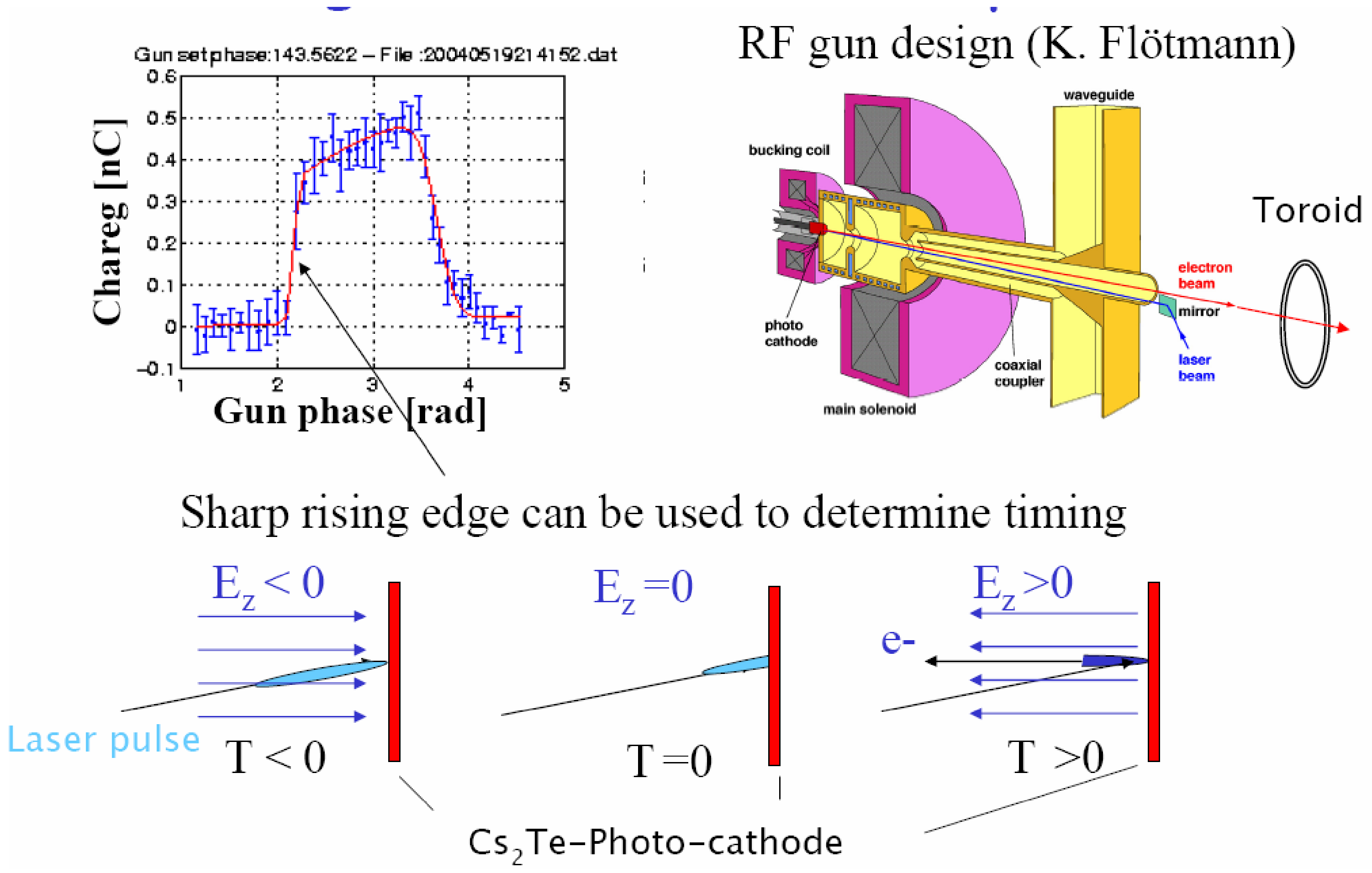


- laser pulses shoot onto the cathode determine the bunch (timing) structure
- a stable gun rf phase is required for minimal arrival time jitter at ACC1
- emission phase measurement with off crest accelerated beam

Emission phase stability measured with beam

Emission phase = phasing between rf gun laser pulses and gun rf

- indirect rf phase measurement
- bunch charge depends on rf phase at 'edge'
- present resolution about ± 0.01° (20 fs)



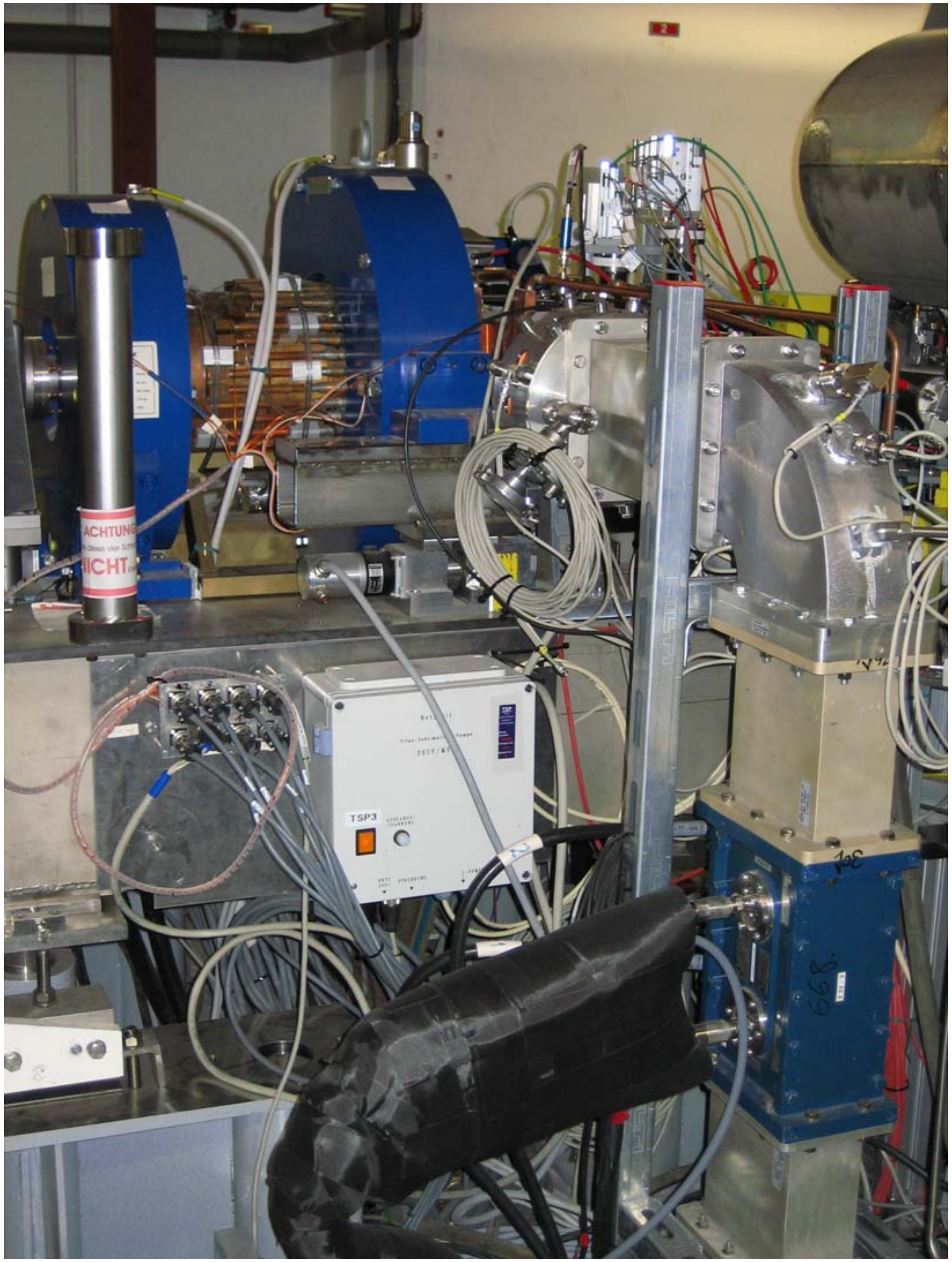
The laser pulse arrival time AND the gun rf phase affect the emission phase!

FLASH rf gun

- filling time: typical 55 µs
- flat top time: up to 800 µs
- pulse repetition: up to 5 Hz
- high RF field: 40 MV/m

Perfect rf field symmetry, no sparks and easier cooling by

- no rf probe
- no mechanical tuner
- via the temperature the frequency is controlled (0.1 deg Celsius corresponds to 2.1 deg in RF phase)



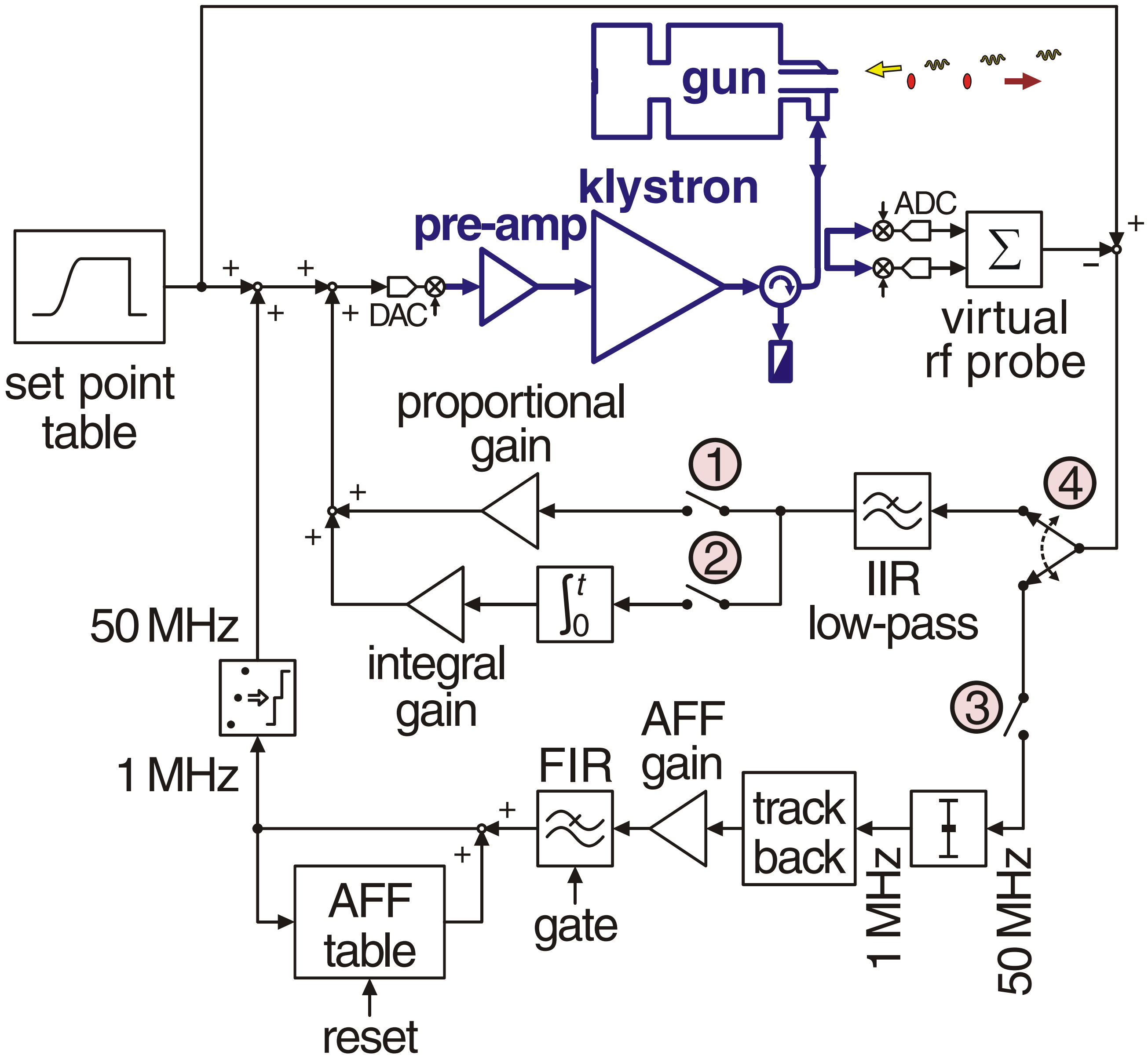
Rf control by SimCon 3.1 and sophisticated algorithms

Implications of missing probe:

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

Algorithms:

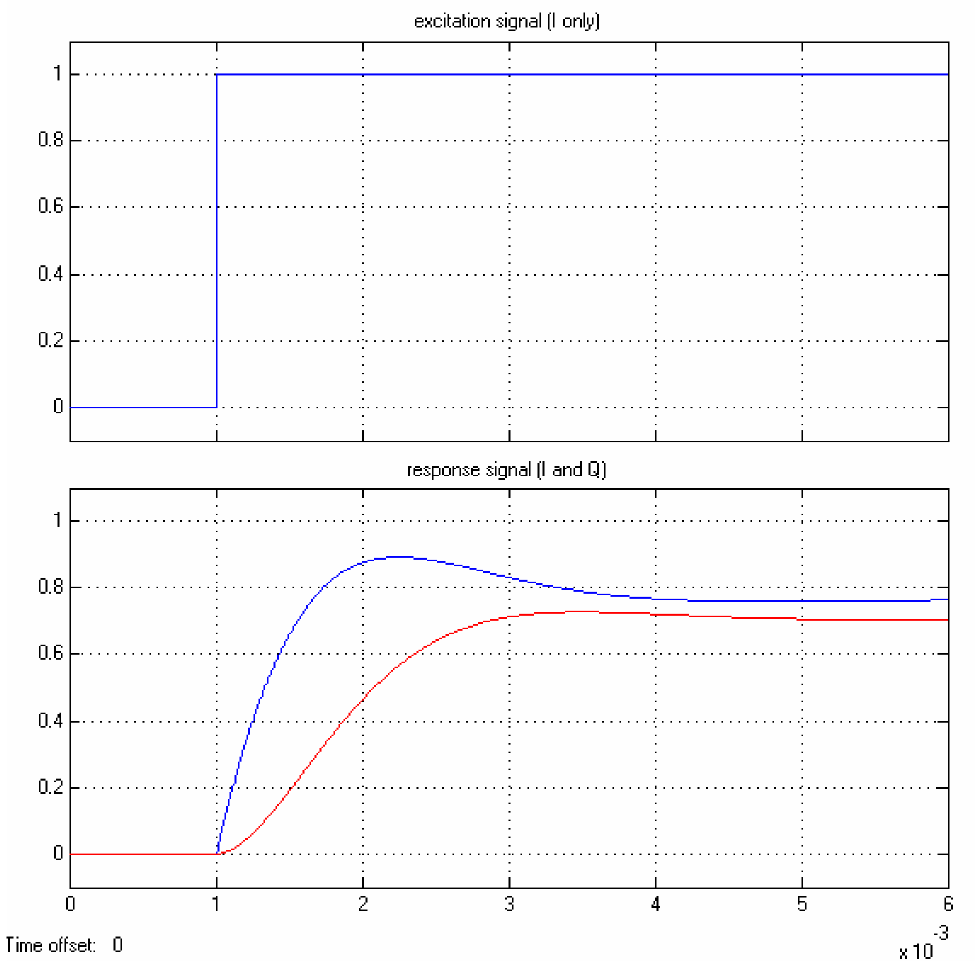
- P(I) control with recursive 20 kHz low-pass (IIR) for stability at 'high' gain (>5)
- Adaptive feed forward (AFF) from rf pulse to rf pulse



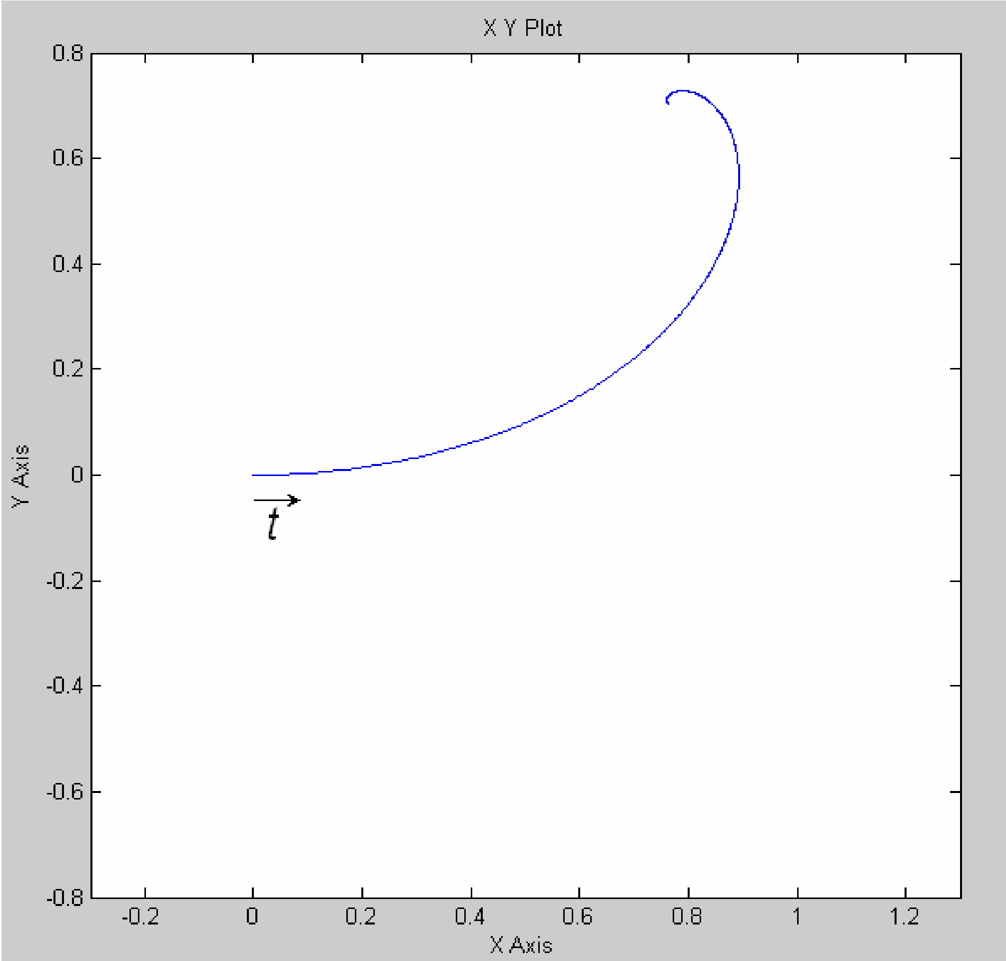
Calibration of virtual probe signal & phase determination

- non zero (loop) phase leads to an unwanted mixture of I and Q
- applying a step function (I only) and recording the response (example for $\Delta f = 200\,\mathrm{Hz}$)

excitation & response in time domain



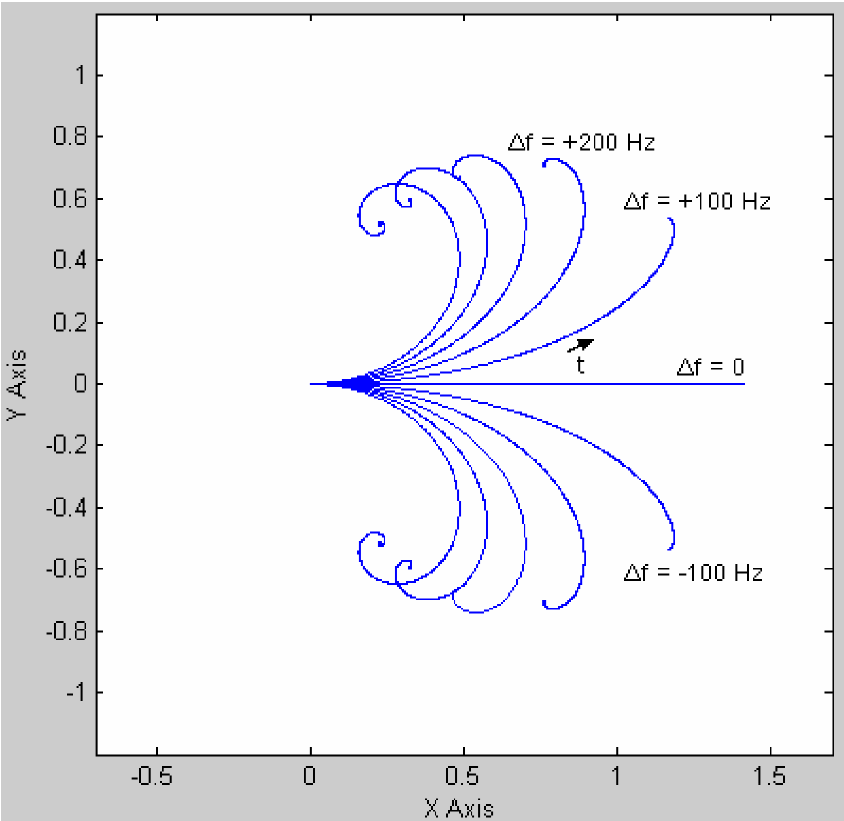
response plotted in IQ plane



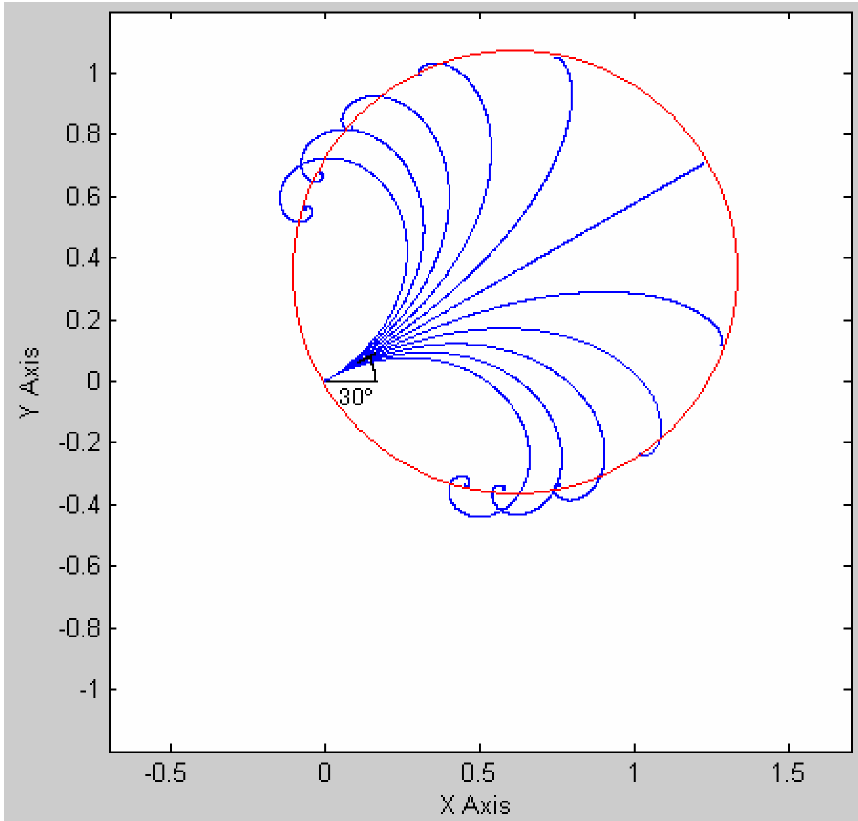
Spiral like cavity response

- the initial angle gives the loop phase
- final IQ values for different tuning describe a circle
- Alexander Brandts loop phase calibration method is based on 'circle fitting'

cavity response for loop phase zero



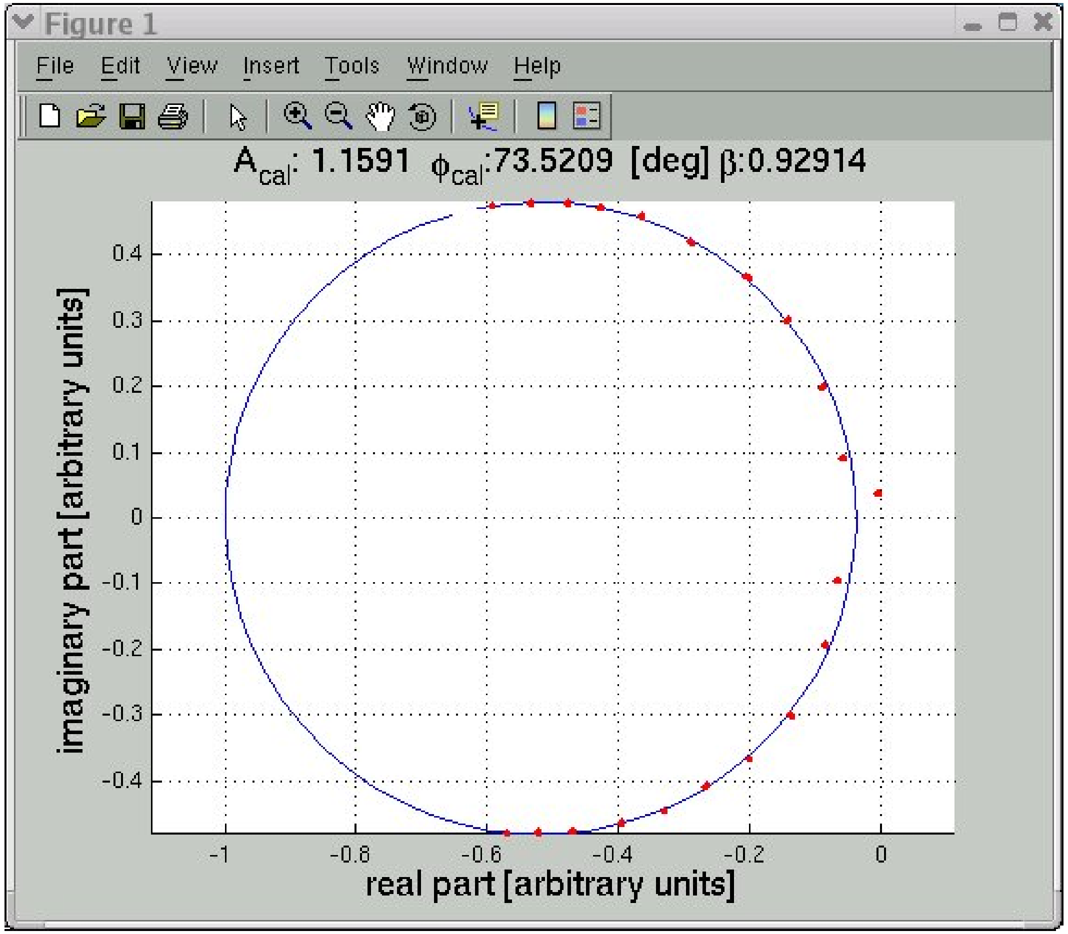
cavity response for (loop) phase 30°



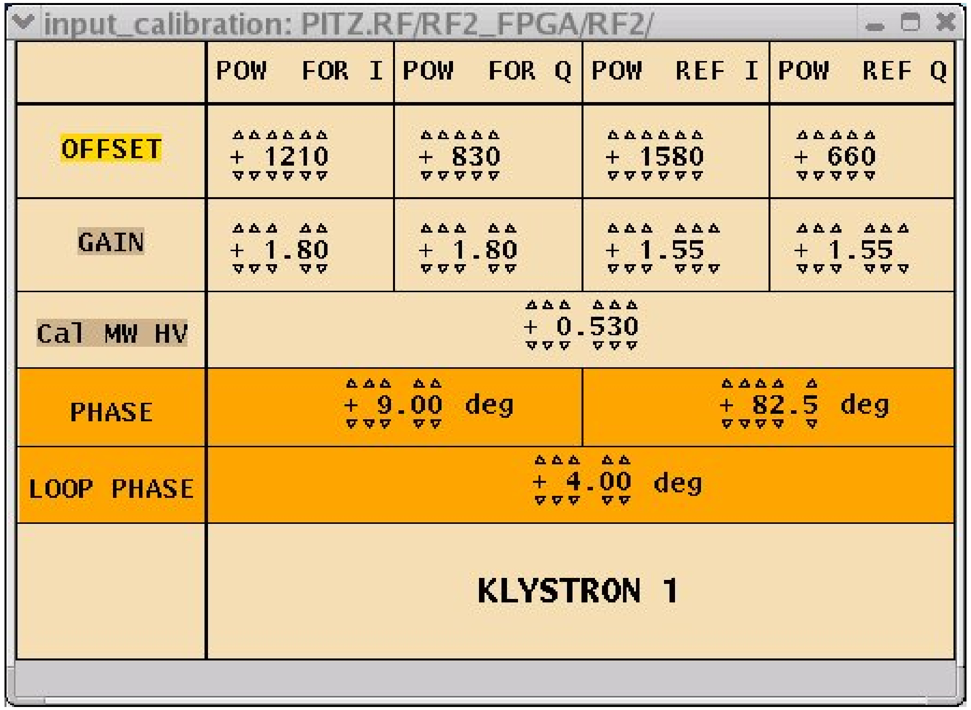
Plots for the sc 1.3 GHz TESLA cavities, the RF gun behaves similar!

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!

Nonlinearity compensation of virtual probe signal

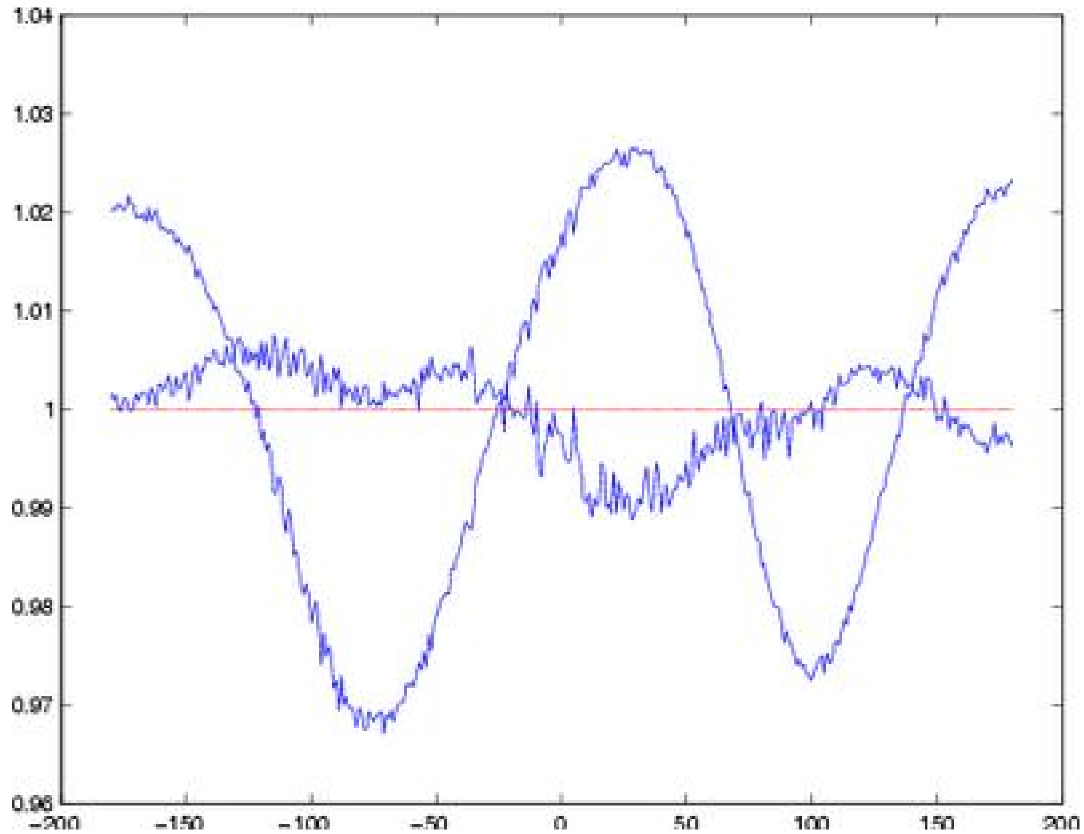
Problem:

- IQ detectors are not perfect
- rf phase changes lead to amplitude changes
- amplitude changes lead to heat load changes within gun and as a consequence within the circulator
- this causes reflected power interlocks at the klystron
- time consuming restart for getting gun temperature equilibrium

Countermeasure:

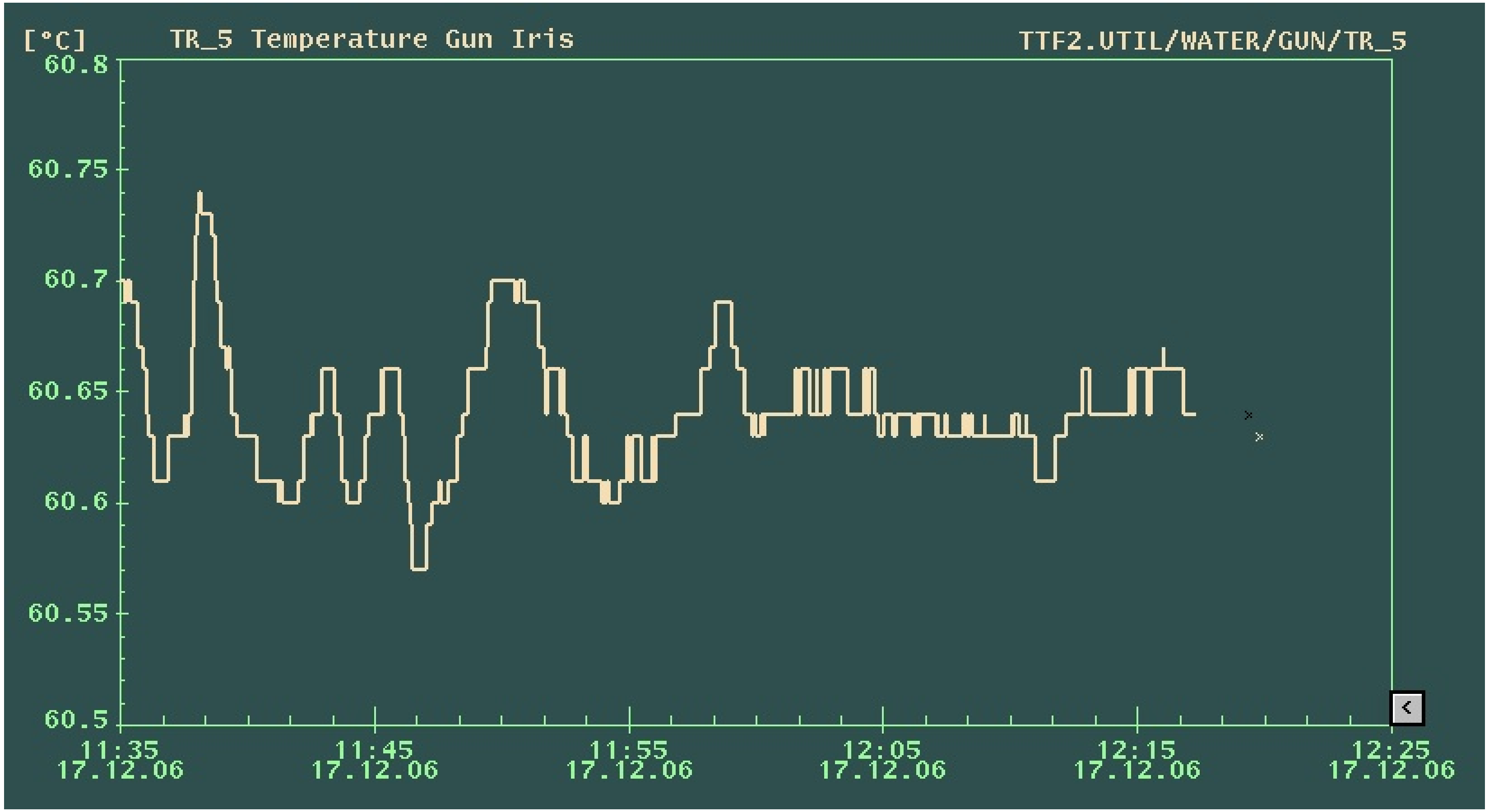
- linearization of virtual probe signal by an algorithm

RF phase scan amplitude response before and after the linearization :



No longer heat load changes caused by rf phase changes

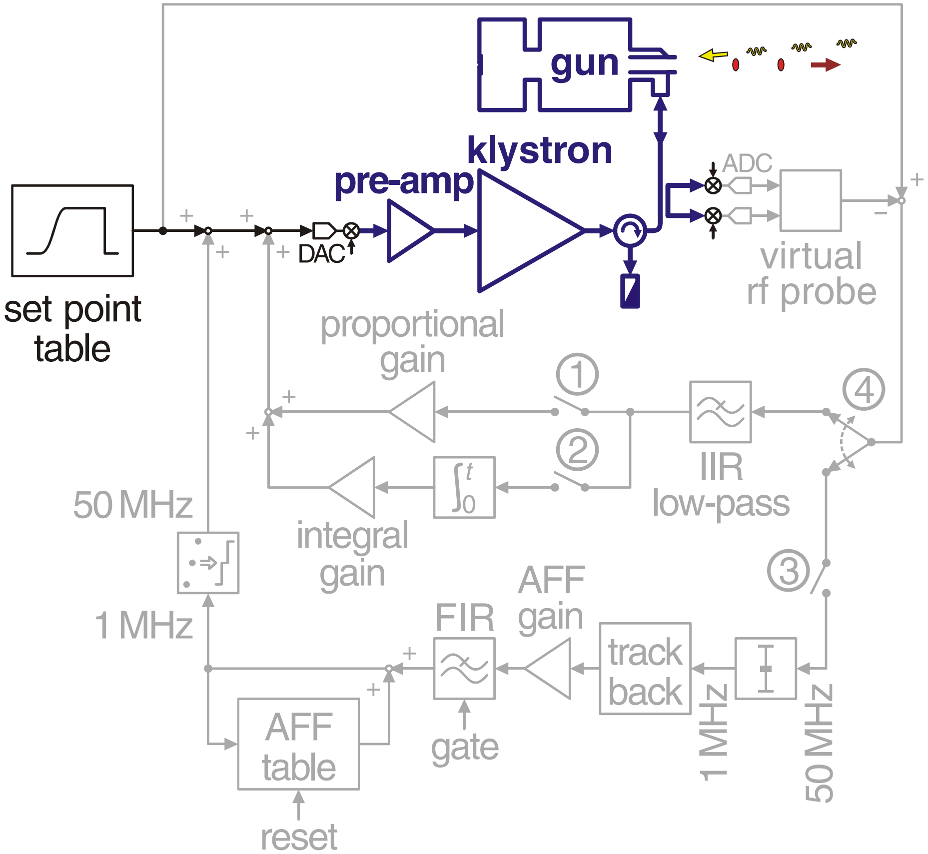
RF gun temperature changes while scanning the rf phase:



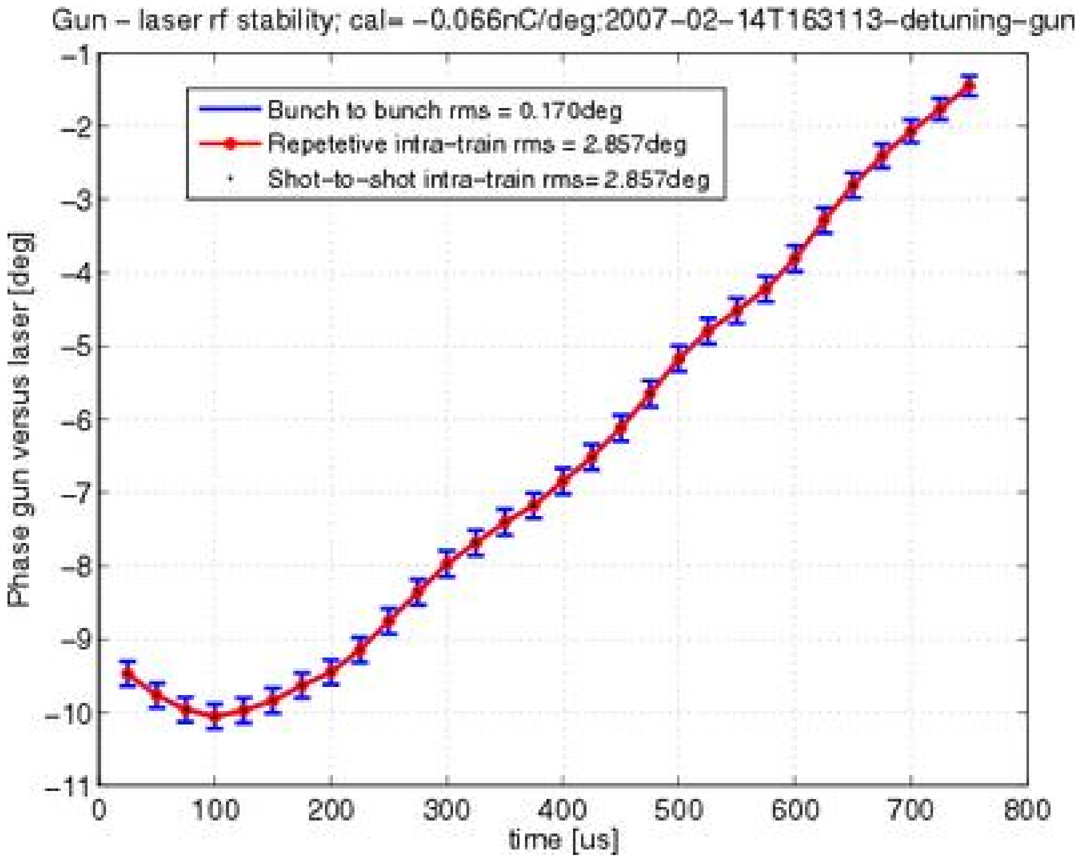
before the compensation

after some iterations to obtain the compensation parameters

Action of control loops - the case without control



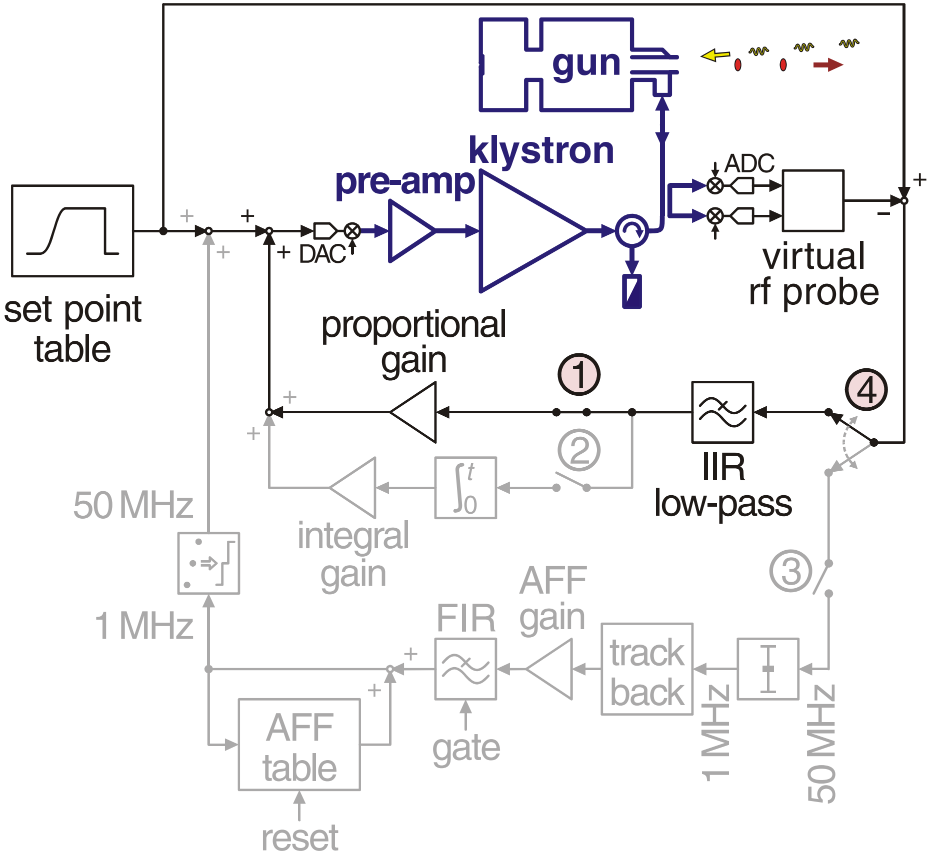
Beam based emission phase measurement:



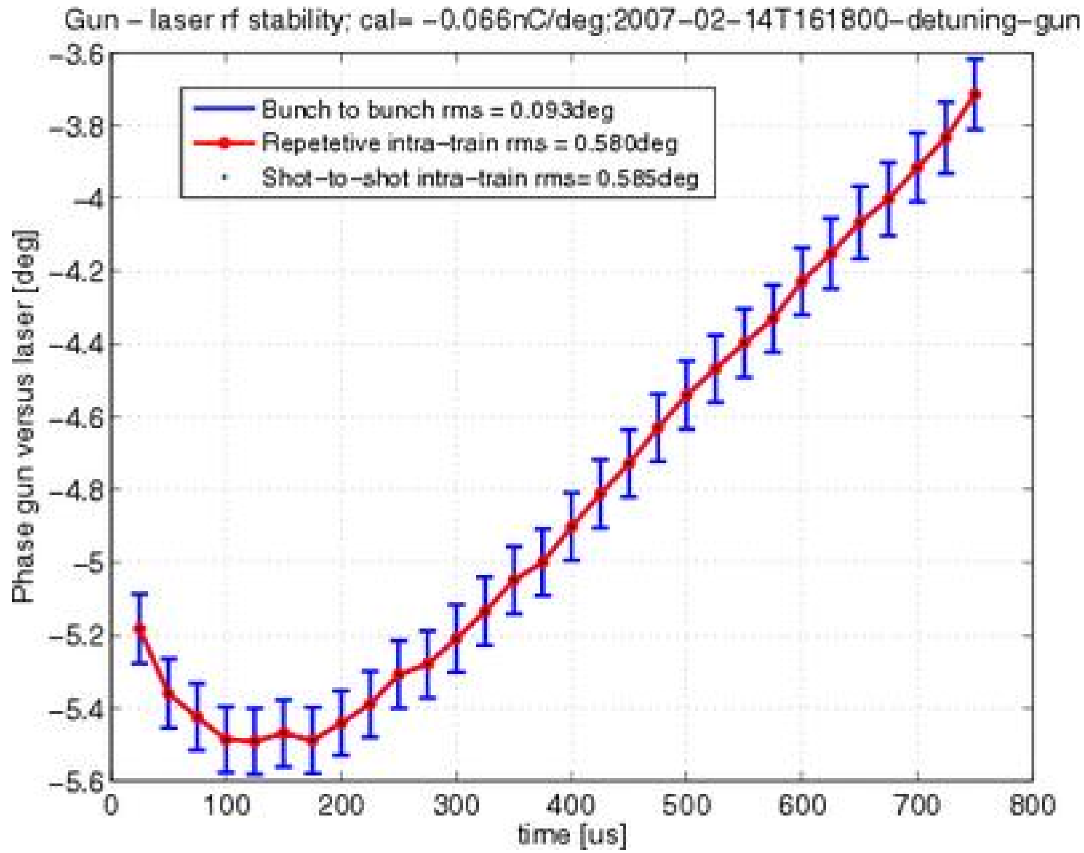
- gun heats up within rf pulse
- gun resonance frequency changes

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

The case with P control only



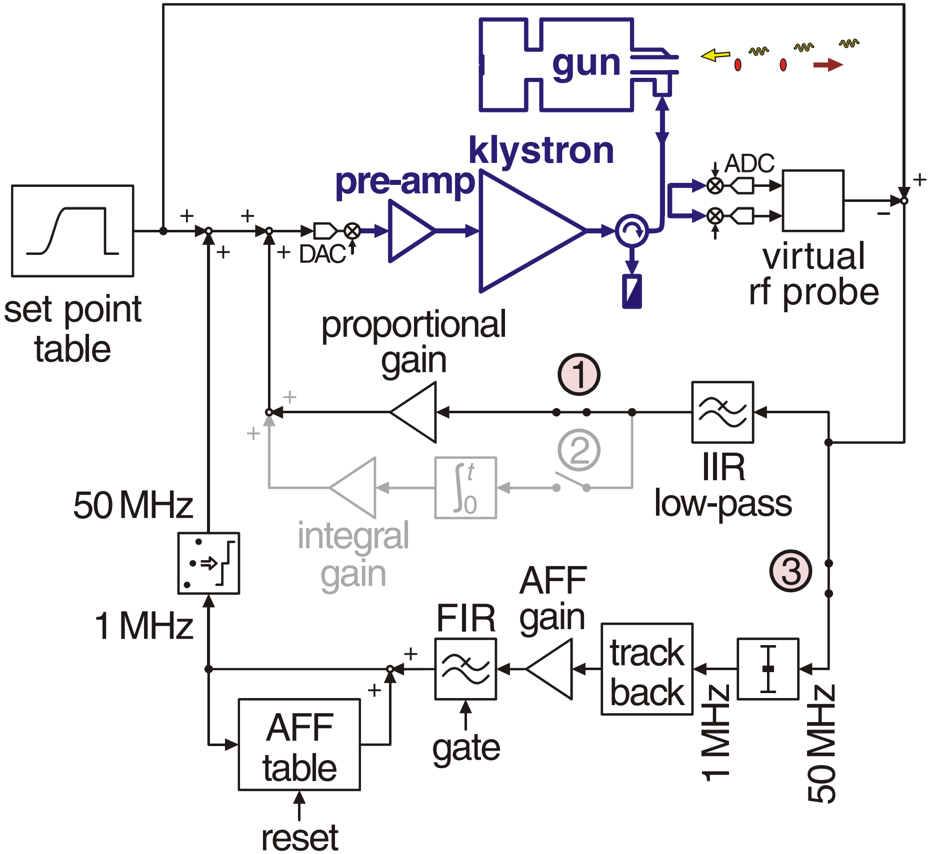
Beam based emission phase measurement:



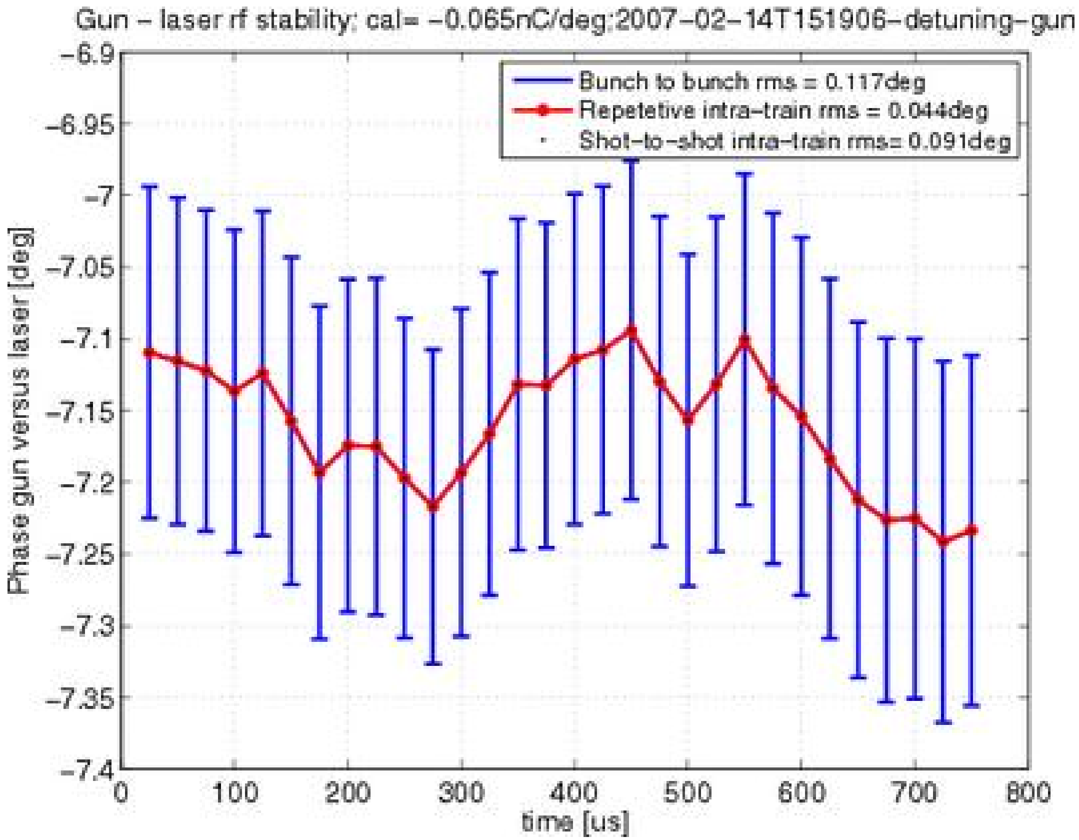
- proportional control with gain 4
- emission phase change suppressed

➢ **the emission phase changes by 1.7°**

Case with P control and adaptive feed forward (AFF)



Beam based emission phase measurement:

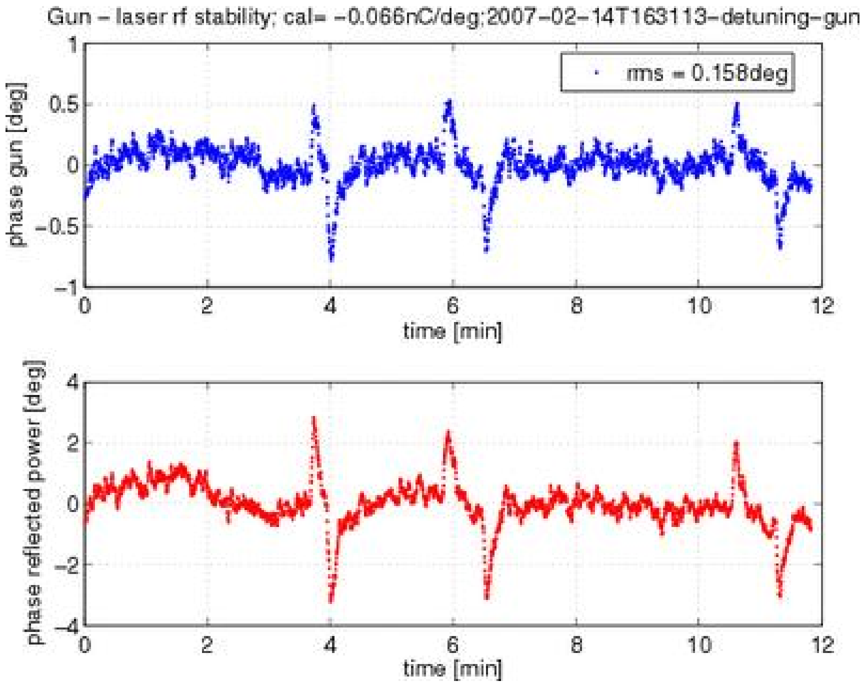


- AFF corrects systematic errors
- AFF gain of 0.4

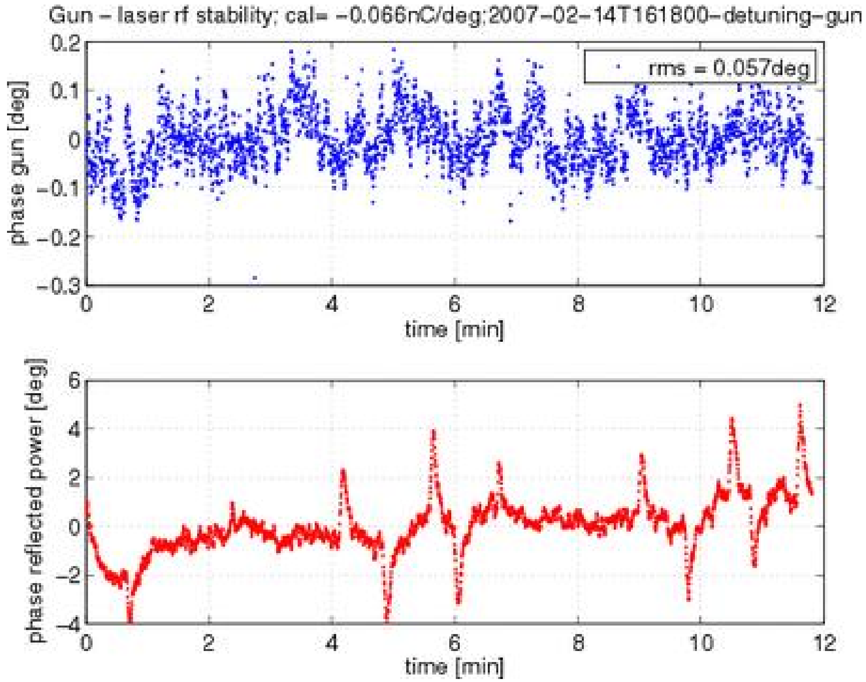
➢ the emission phase changes by 0.14°

Long term stability

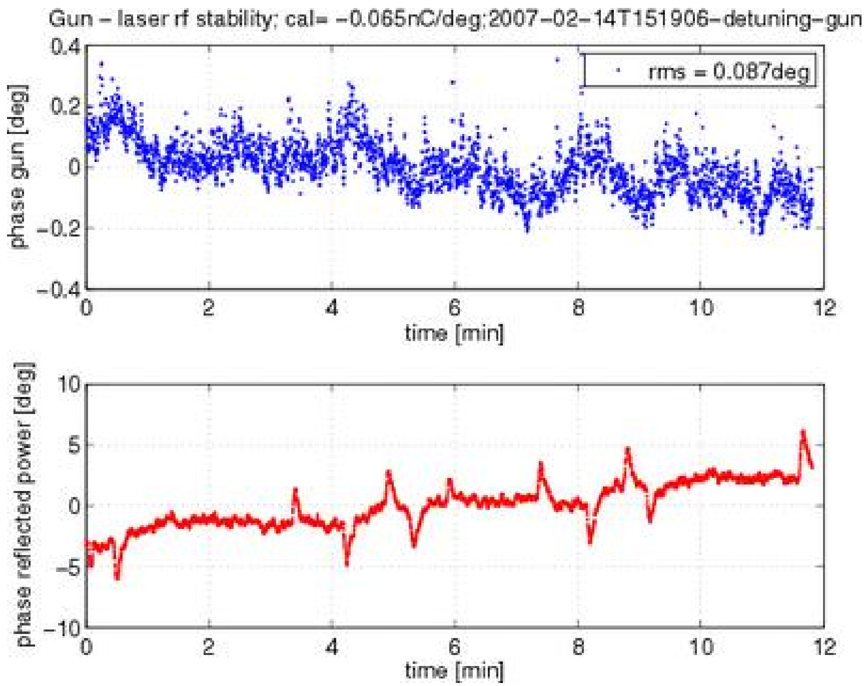
(1)



(2)



(3)



Observed emission phase stability:

(1) RF drive only: peak-to-peak 1.3°

(2) P control only: peak-to-peak 0.4°

(3) P and AFF control: peak-to-peak 0.4°

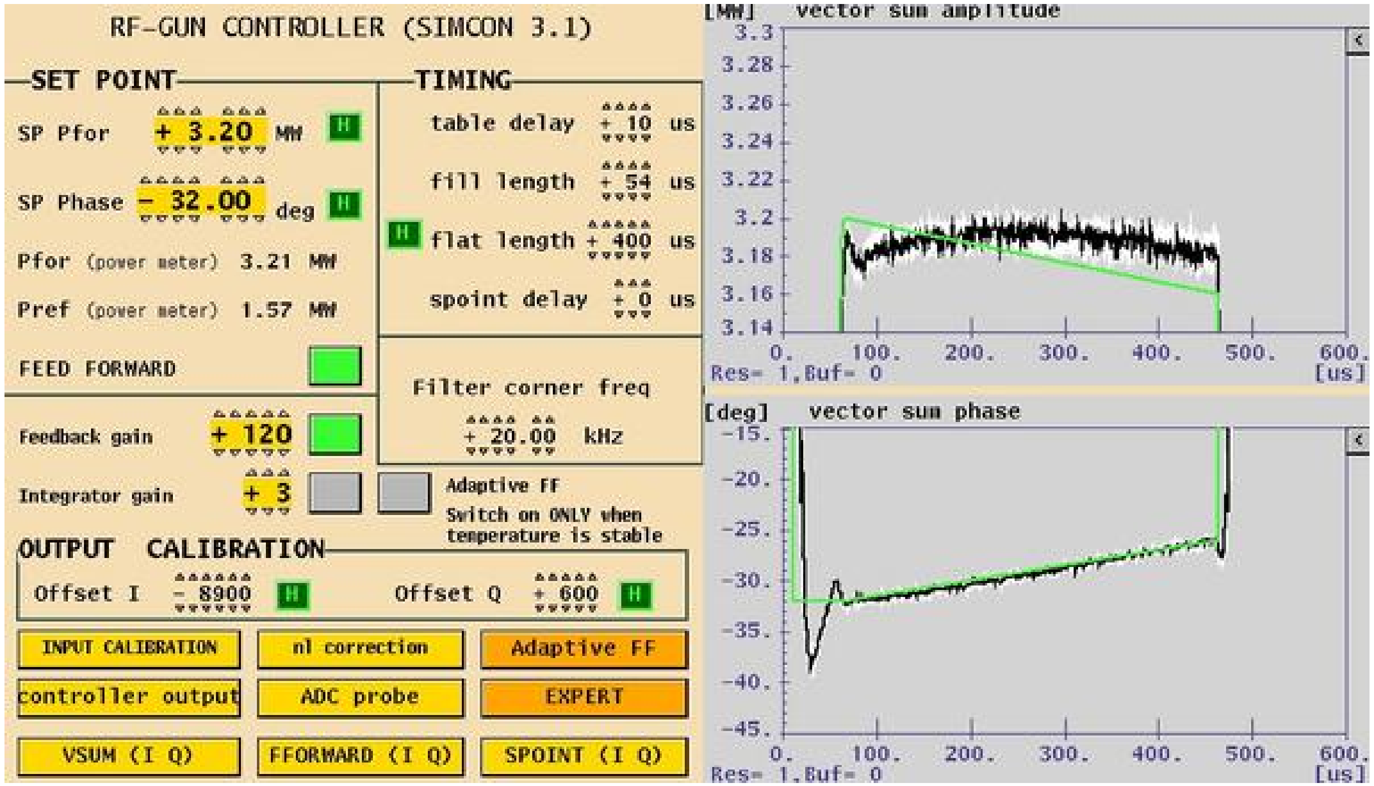
The gun rf phase slope feature

Potential sources of emission phase slopes:

- uncertainties in probe calibration
- gun laser pulse arrival time changes
- drifts due to wave guide heating (distance between directional coupler and gun)
- and so on…

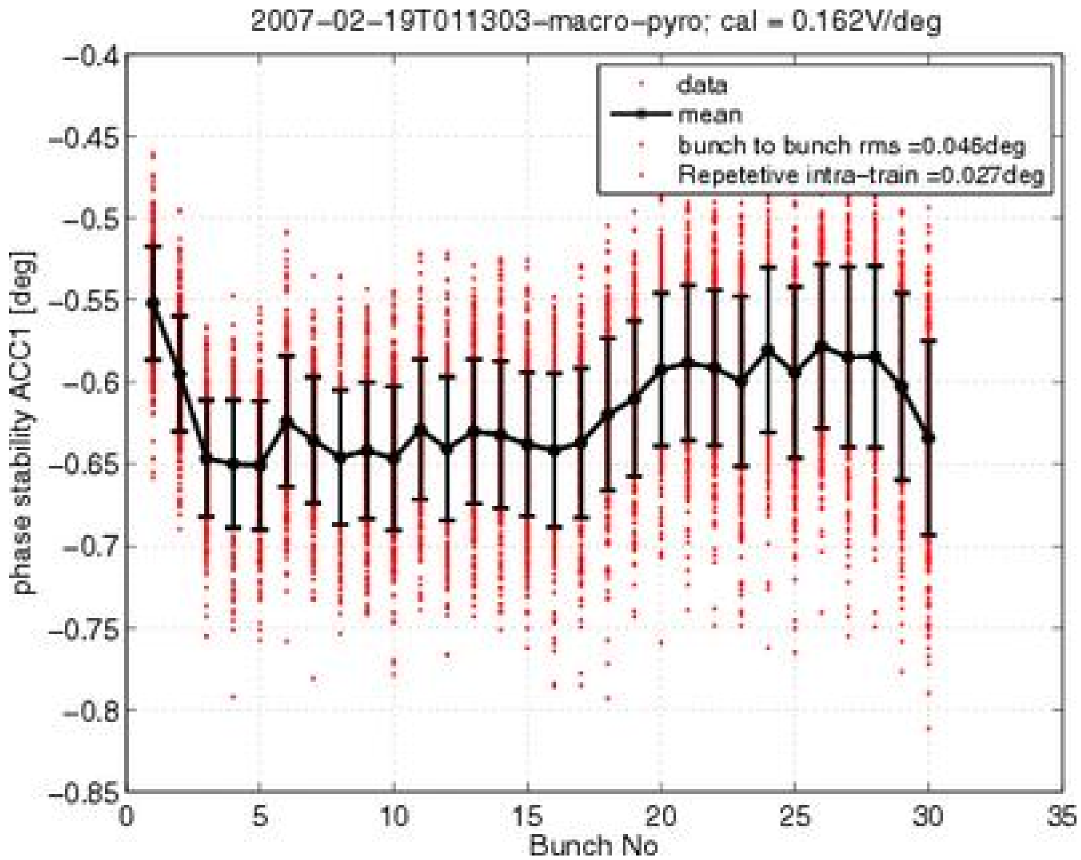
Countermeasures:

- slope at gun laser arrival time changing 1.3 GHz MO EOM phase
- phase slope at gun rf:



Which 'slope' to use at the gun?

According to measurements at BC2, applying a combination of both slopes (gun laser arrival time and gun rf phase) results in the most stable beam!

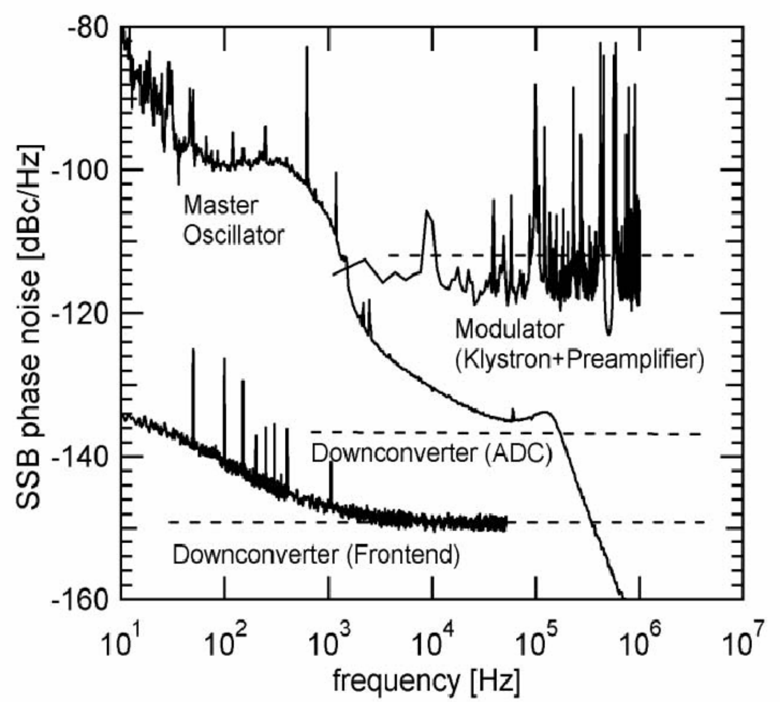


➢ Let's go to ACC1 and beam stability measurements at BC2…

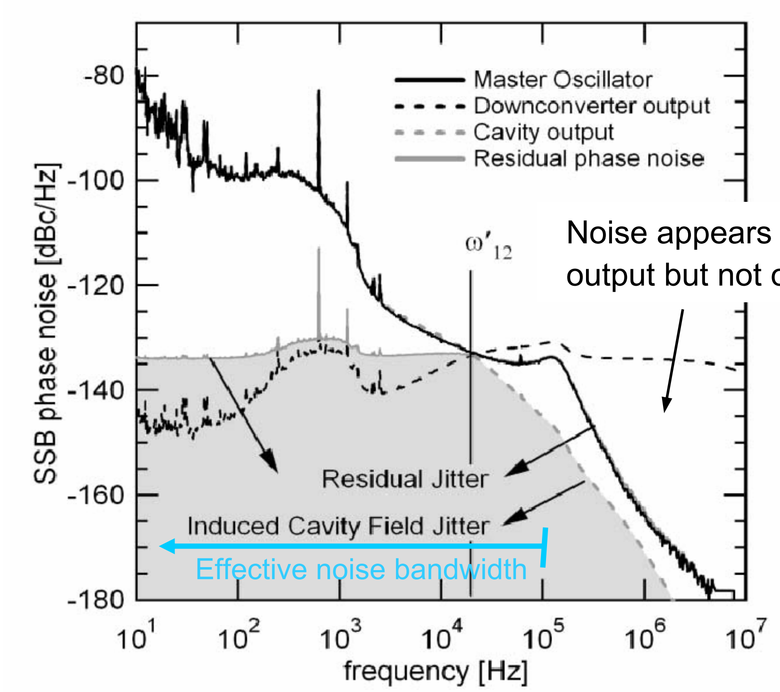
Downconverter Performance

Phase noise budget at FLASH (Switched LO, single cavity)

- **Phase noise measurements :**

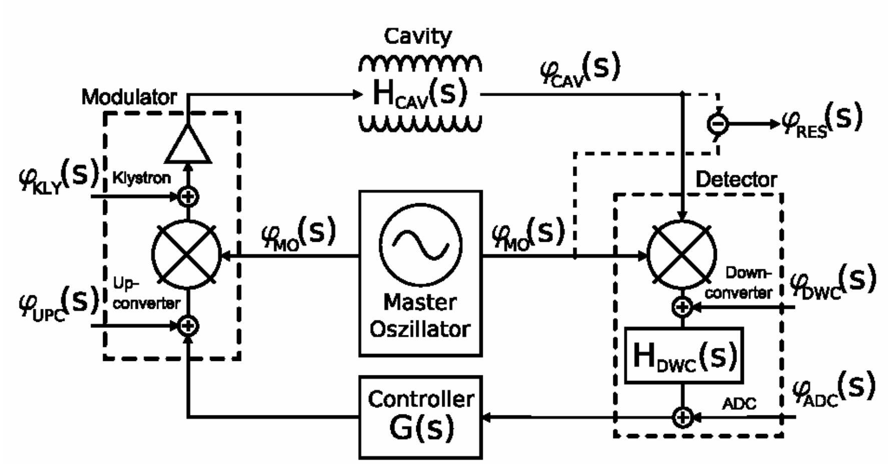


- **Contributions to cavity field jitter :**



Noise appears at the DWC output but not on the cavity field!

Beam-based monitors

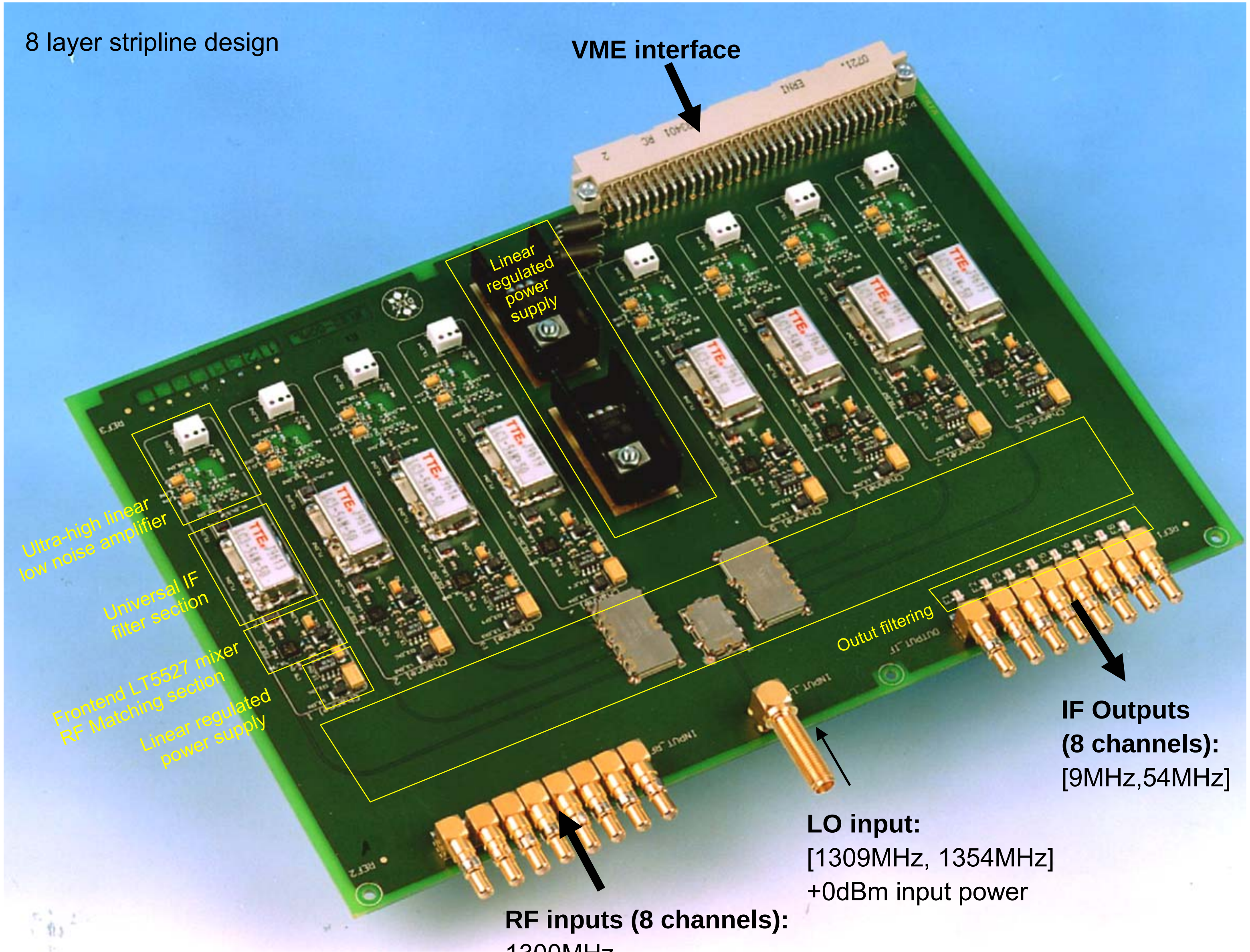


Subsystem	Phase noise [dBc/Hz]	Residual jitter [fs]	Induced jitter [fs]
MO	see Fig.3	14.1	5.5
DWC (Frontend)	−147	1.8	1.8
DWC (ADC)	−135	5.8	5.8
MOD	−110	1.2	1.2

(Complete ADC module)

- High frequency noise is filtered by the cavity, but not drifts or 1/f-noise!
- Beam relevant frequency range [1Hz,100kHz]

Multichannel Packaging and Preprocessing



Single channel receiver performance at FLASH

- **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) :

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

θ_A = 2e-3/°C, θ_P = 0.2°/°C

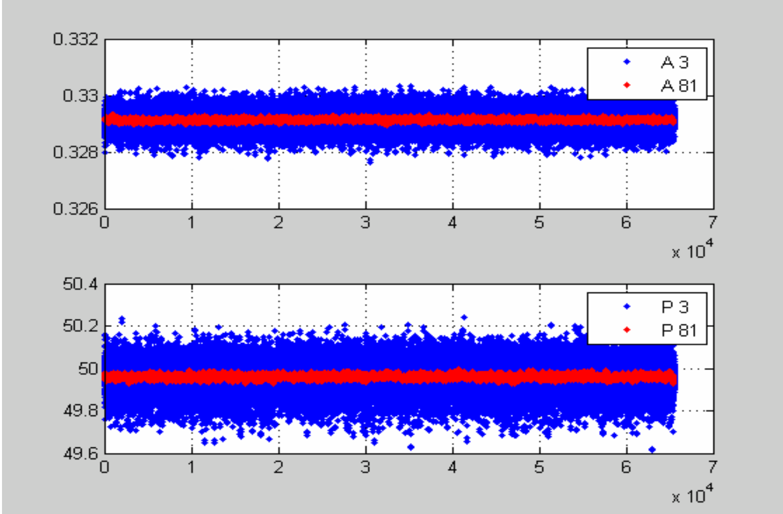
Parameter :

- 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**

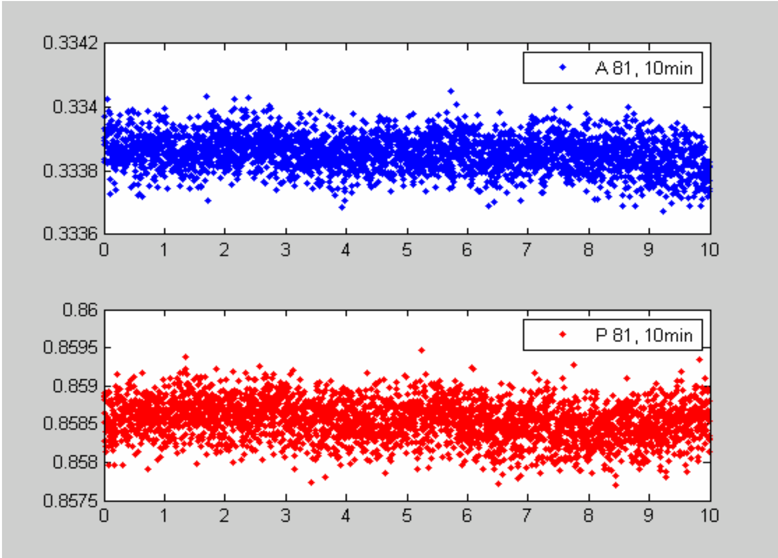
- **Shortterm stability 800us (bunch-to-bunch):**

BW=27MHz
BW=1MHz



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

BW=1MHz
BW=1MHz

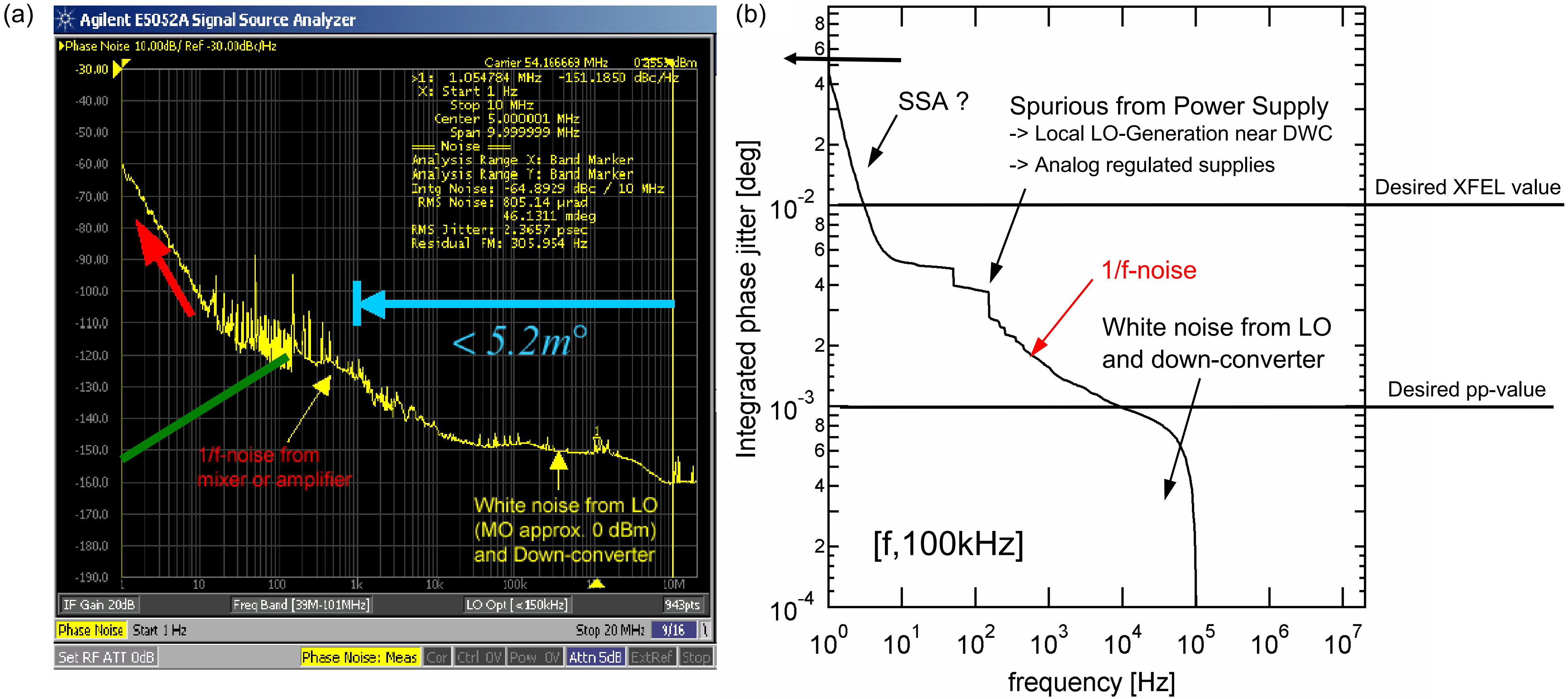


Single channel receiver performance at FLASH

- **Single channel receiver performance at FLASH :**
  - Incl. LO-Generation phase noise

- Analog Receiver has 0.0052 deg [1kHz,10MHz].
- IF[9,54MHz] works also with a lowpass
- Powerful diagnostic using the CW modulation scheme!
- Drift calibration <100Hz is needed!
  (Injector door effect on LO) e.g. injected, reflected or LO or Beam-based feedbacks

Biased by MO reference :



Main Parameters Table

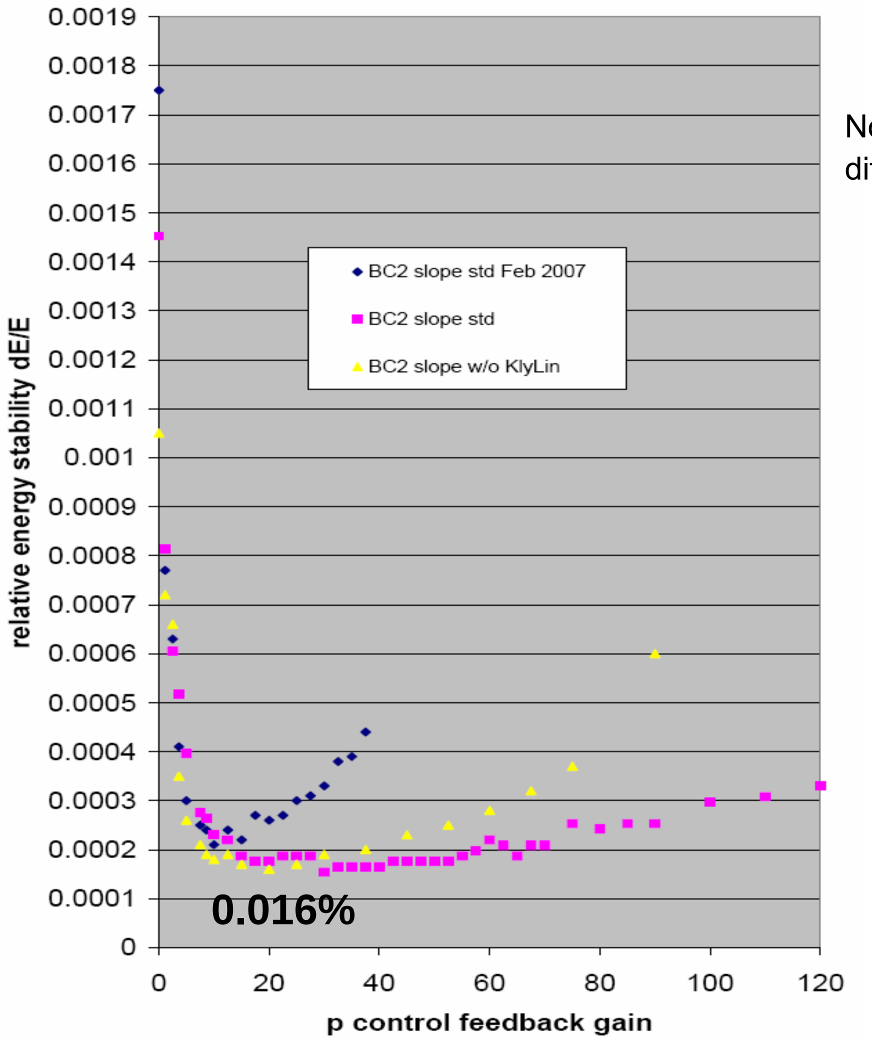
Parameter	*Value*
Amplitude Noise	31dB (Input Noise Figure)
Residual Phase Noise	1e-3° (100kHz & Vec Sum)
Linearity	+35dBm (Input Pip3)
Temperature Sensitivity of Phase	???
Cross-Talk	71-90 dB (7 Ch. Connected)
Power Consumption	8W (1A@+6V/0.4A@-6V)
Number of Channels per board	8
Cost/Channel	150$

LLRF07 Fermilab

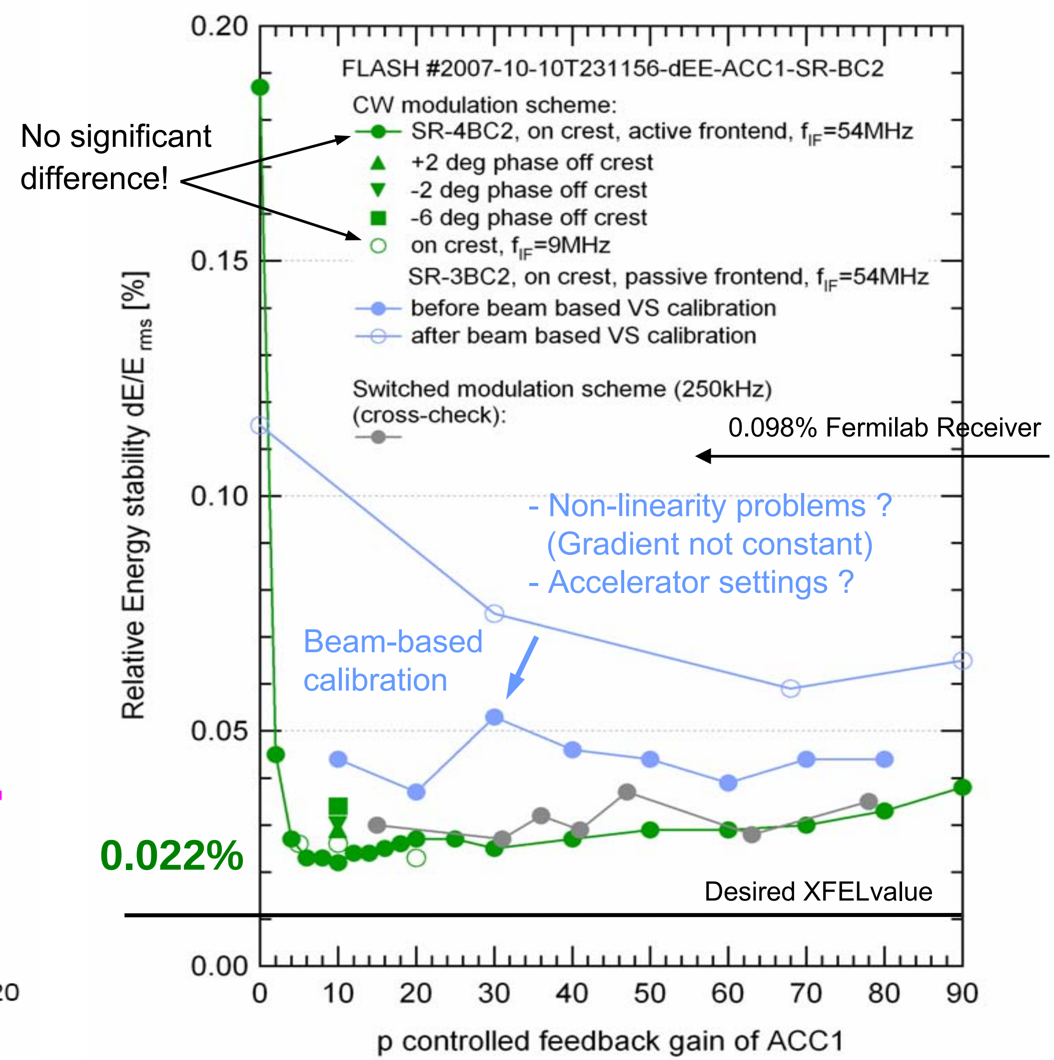
Courtesy of U.Mavric, B.Chase / FNAL

Summary of ACC1 beam stability at FLASH 09/07

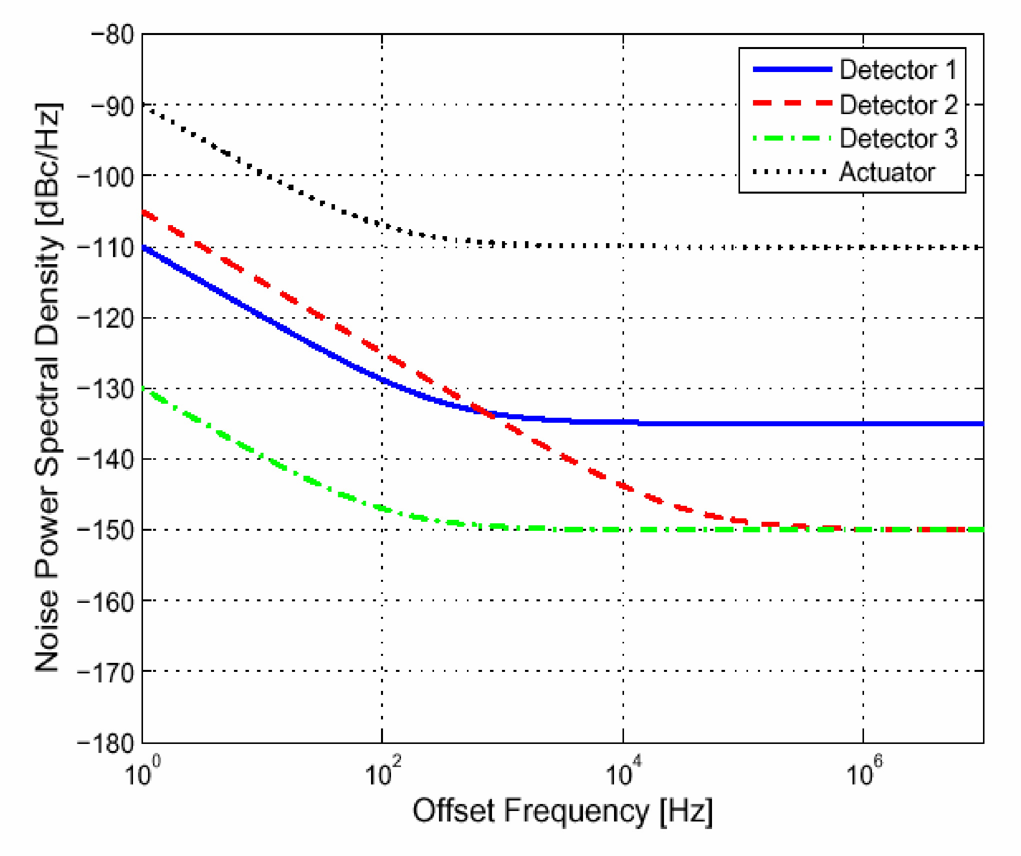
- **IQ sampling down-converter (250kHz):**



- **IF sampling down-converters (9,54MHz):**



- **Effective noise spectral densites for different tested down-converters :**

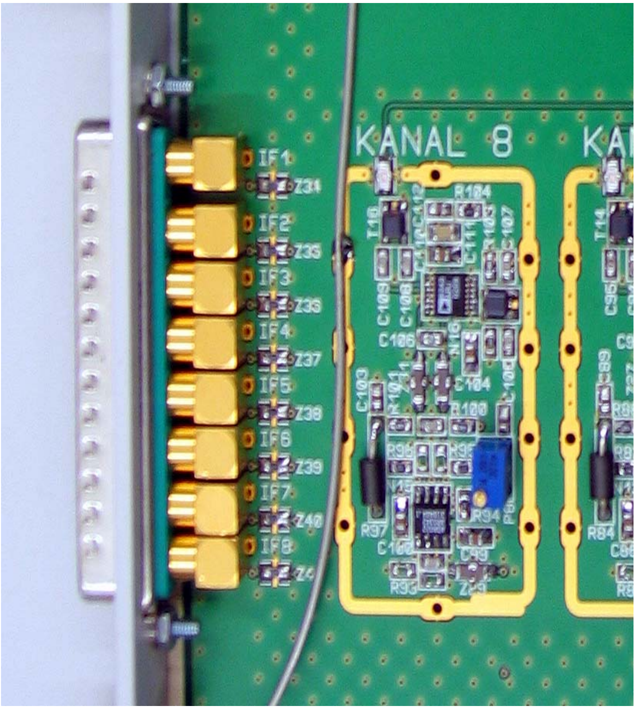


Detector 1 / FLASH:
- IQ Sampling 250kHz method
- Gibert-Mixer active AD8343
- ADC-boards (14-bit, 1MHz) + DSP System

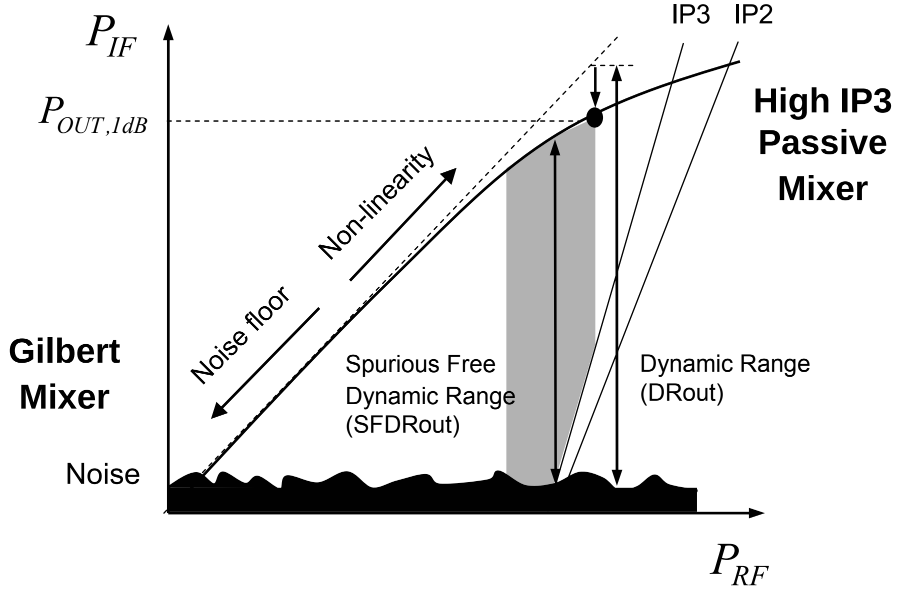
Detector 2 / FLASH:
- IF Sampling 54MHz method
- Passive HMC483
- SIMCON 3.1, LT2207, 16-bit, 81MHz sampling ADC

	b_0 [dBc]	b_{-1} [dBc]
Actuator	-110	-90
Detector 1	-135	-120
Detector 2	-150	-105
Detector 3	-150	-130

$$S_R(f) = b_{r,0} + b_{r,-1} \cdot f^{-1}$$
$$S_A(f) = b_{a,0} + b_{a,-1} \cdot f^{-1}$$

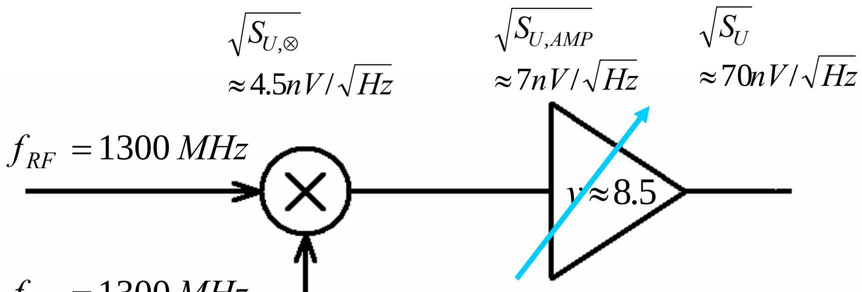


- **Compromise between noise and linearity :**



- Second amplification determines performance
- Expected down-converter performance from baseband measurements:

$$(\Delta A / A) \approx 0.2E-4 \approx 0.2 \delta U_{XFEL},\ \text{(Cavity filtered)}$$
$$\Delta f = 100 kHz,$$

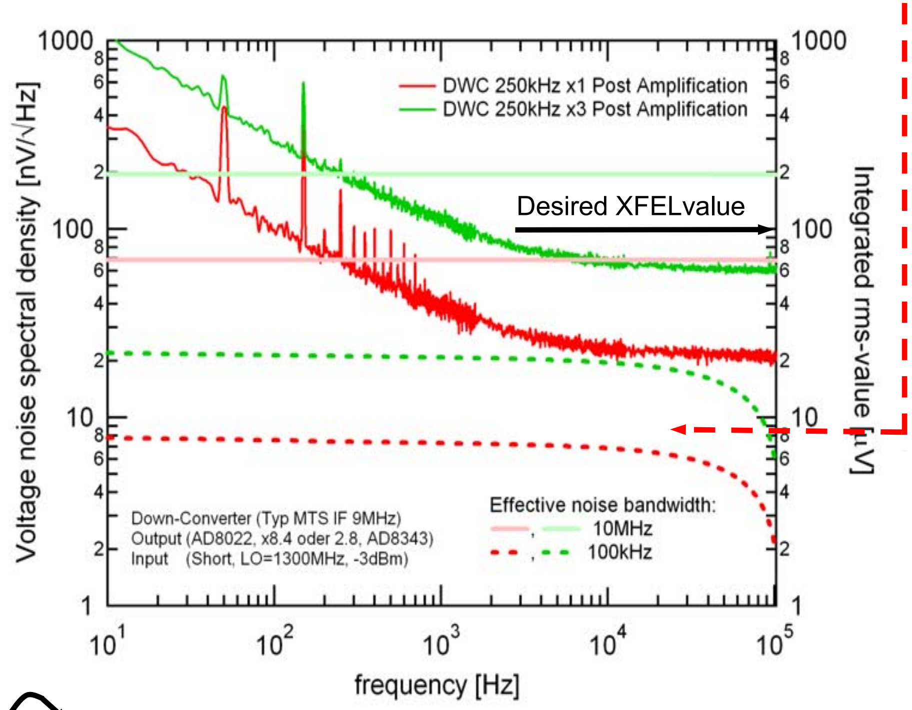


$$S_U = (S_{U,\otimes} + S_{U,AMP})\, v^2$$

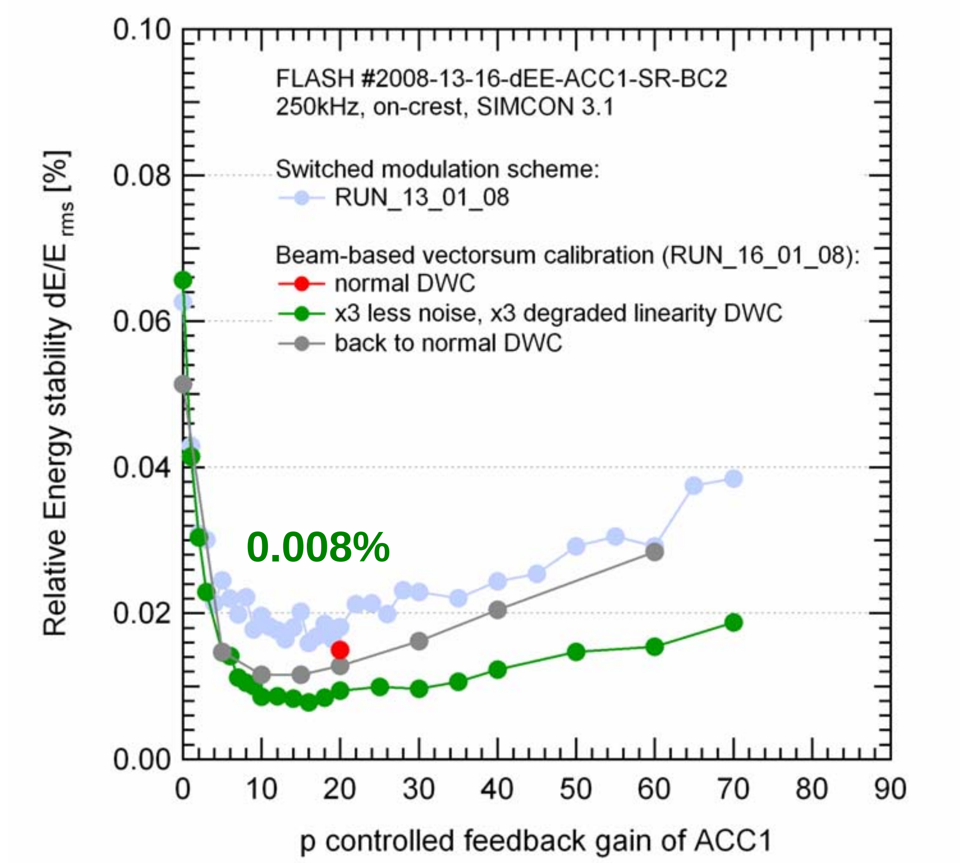
Static influence of the linearity and noise from the down-converter

- **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%



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

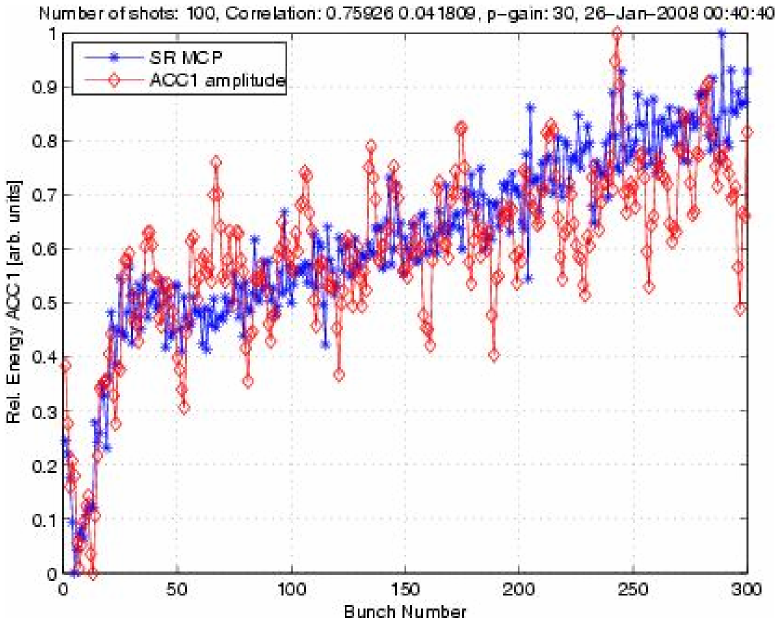


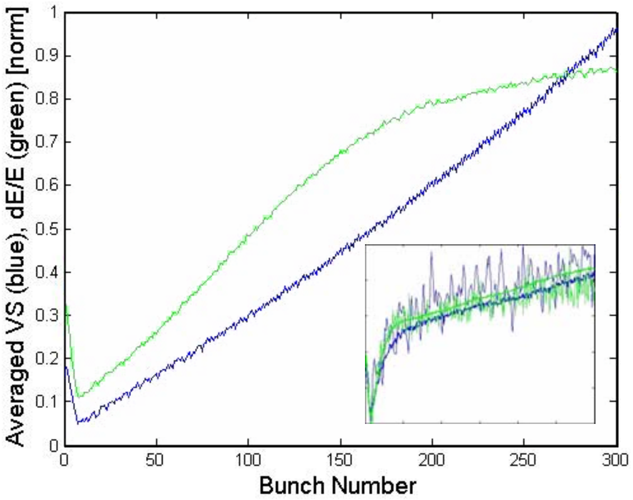
- Automated accurate waveguide adjustment (Indictation from off-crest LO generation limitation).
- Beam stability in dependence of gradient and phase.

- 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.

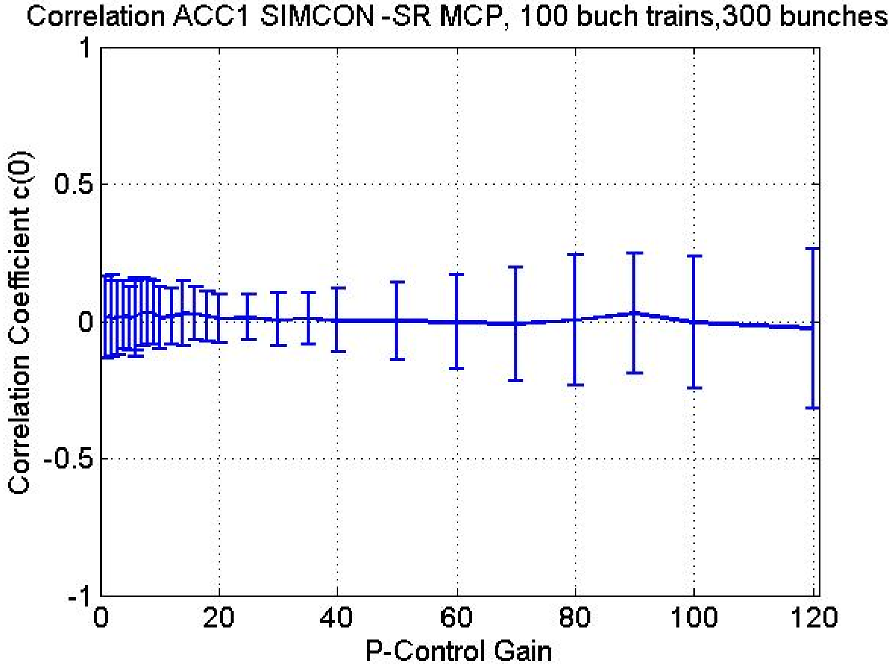
Correlation measurements between vectorsum and beam fluctuations

- **ACC1 vectorsum vs. SR-MCP camera :**





- **Feedback gain dependent correlation :**



- No noise correlation between dE/E vs.VS found ???
  (May caused by MO noise, MCP measures all noise
  VS measures residual).
- Comparison with theoritcal expected correlations.
- Correlation studies for microphonics and MO, LO.

Summary & Outlook

- The amplitude beam stability requirements for FLASH are nearly fulfilled:
  0.008% using the IQ sampling scheme operating at 250kHz and
  0.022% using the IF sampling scheme operating at 9MHz and 54MHz (may be better)

- Possible noise sources of pulse-to-pulse energy jitter are:

  - 1/f-noise and drifts from the Receiver and LO-generation [1kHz, 100kHz] (amplitude and phase noise)

  - ADC noise (to be shown in lab characterization)

  - VS calibration and DWC non-linearity influence is minor (to be investigated off-crest).

  - Accuracy of waveguide phases for all cavities, MO amplitude noise

- The IF sampling scheme offers a powerful error diagnostic tool.

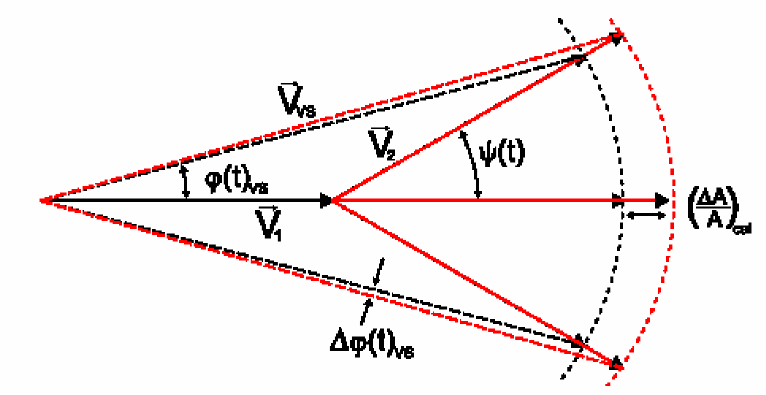
- LO generation is much more complicated and requires a drift calibration scheme.

low noise...->...high linearity... -> ...low drift... -> ... absolute accuracy

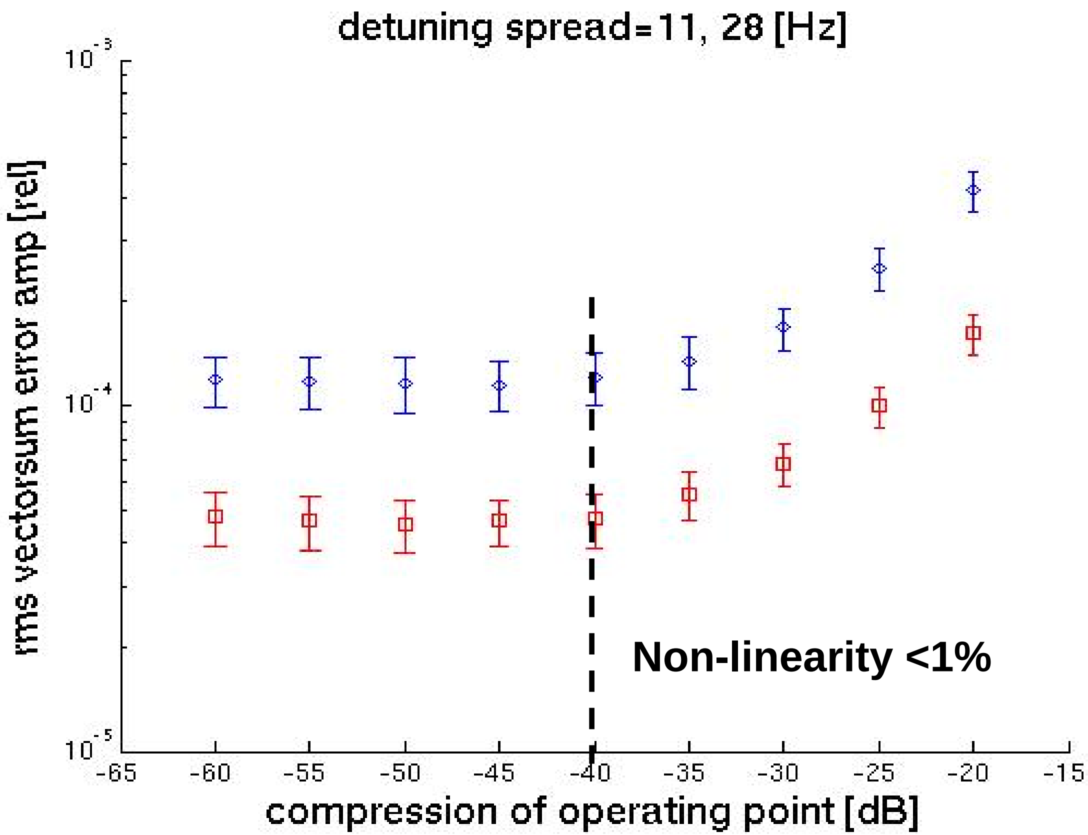
Thanks for your attention!

* Linearity requirement for multi-cell cavity structures

- **Effect on the vectrorsum:**

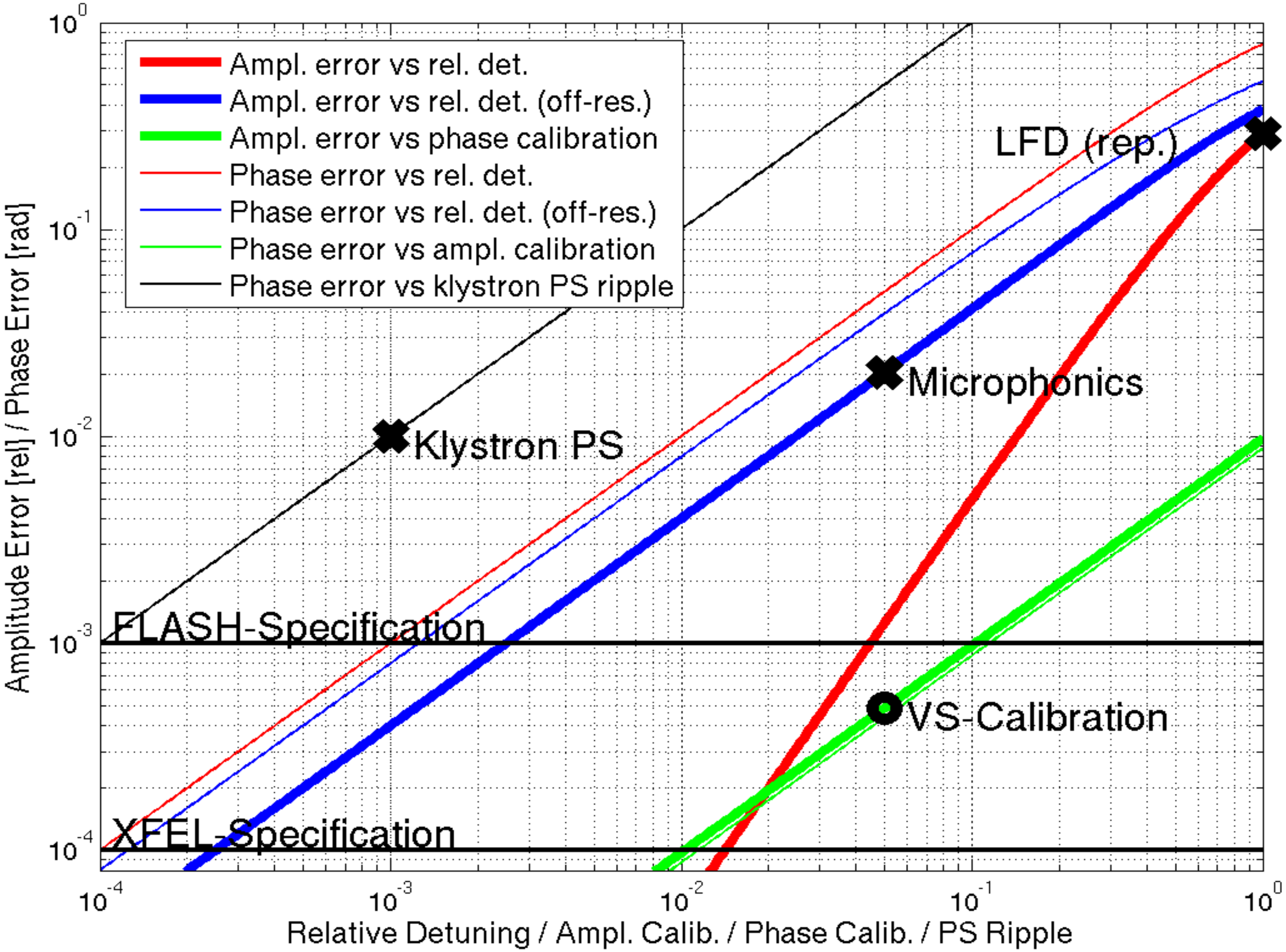


Number of cavities: 32, Predetuning: 50 Hz,
Detuning-Spread: 11 Hz, 28 Hz
Amp. cal. error: 0.005, Phase cal. err.: 0.5°



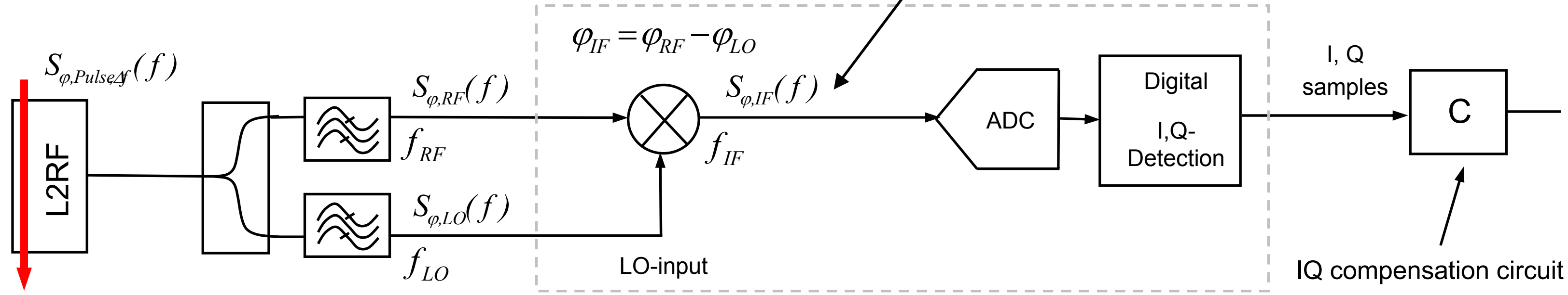
In presence of a vectorsum calibration error microphnics induces additional noise.

Courtesy of A.Brandt / DESY

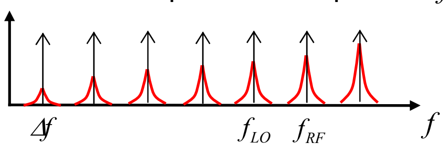

Ampl. error vs rel. det.
Ampl. error vs rel. det. (off-res.)
Ampl. error vs phase calibration
Phase error vs rel. det.
Phase error vs rel. det. (off-res.)
Phase error vs ampl. calibration
Phase error vs klystron PS ripple
LFD (rep.)
Microphonics
Klystron PS
FLASH-Specification
VS-Calibration
XFEL-Specification
Amplitude Error [rel] / Phase Error [rad]
Relative Detuning / Ampl. Calib. / Phase Calib. / PS Ripple
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}

How efficient is the calibrating scheme ? :

This is what we measure at the end with I,Q detection. For a calibration this phase noise caused by the reference must be zero!



n,m th phase noise spectrum from fs-laser laser pulse with rep. rate Δf :



$$f_{RF}=n\Delta f,\ S_{\varphi,RF}(f)=n^2\ S_{\varphi,Pulse\Delta f}(f)$$
$$f_{LO}=m\Delta f,\ S_{\varphi,LO}(f)=m^2 S_{\varphi,Pulse\Delta f}(f)$$

Operation of mixer (down-converter) :

$$\varphi_{IF}(t)=\varphi_{RF}(t)-\varphi_{LO}(t),\ f_{IF}=f_{RF}-f_{LO}$$
$$S_{\varphi,IF}(f)=S_{\varphi,RF}(f)+S_{\varphi,LO}(f)-2\gamma_{RF,LO}(f)\sqrt{S_{\varphi,RF}(f)}\sqrt{S_{\varphi,LO}(f)}$$

$\gamma_{RF,LO}(f)=1$ (RF, LO must come from the same source for a calibration)

$$\frac{\sqrt{S_{\varphi,RF}(f)}}{\sqrt{S_{\varphi,LO}(f)}}=\frac{n}{m}=\frac{f_{RF}}{f_{LO}},\quad S_{\varphi,IF}(f)=\left(\sqrt{S_{\varphi,RF}(f)}-\sqrt{S_{\varphi,LO}(f)}\right)^2$$

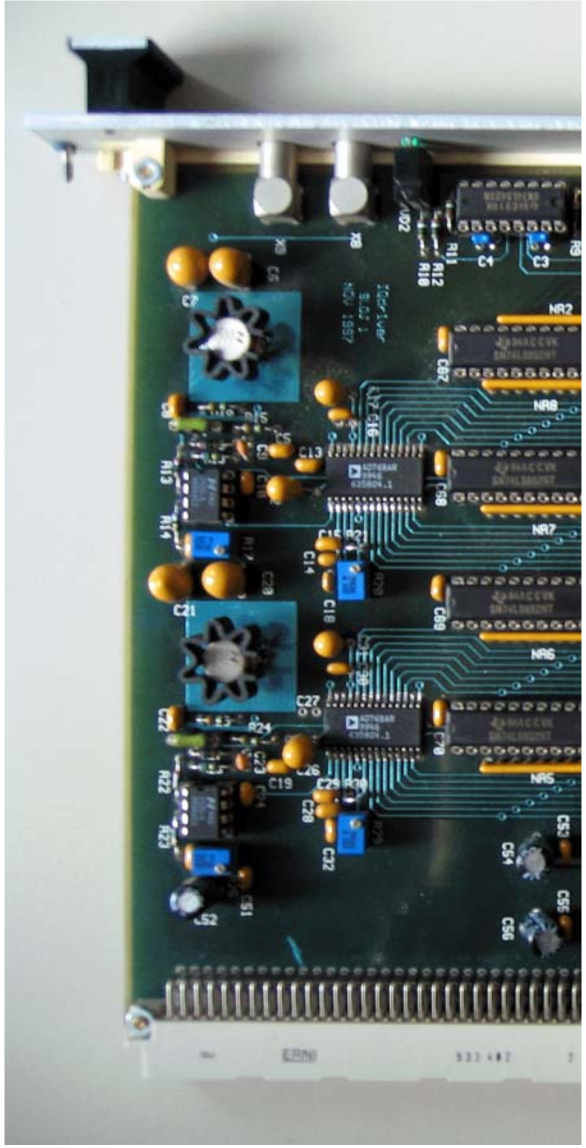
$$S_{\varphi,IF}(f)=S_{\varphi,LO}(f)\left(\frac{f_{RF}}{f_{LO}}-1\right)^2=S_{\varphi,LO}(f)\left(\frac{f_{IF}}{f_{LO}}\right)^2\overset{!}{=}0$$

For a perfect calibration!

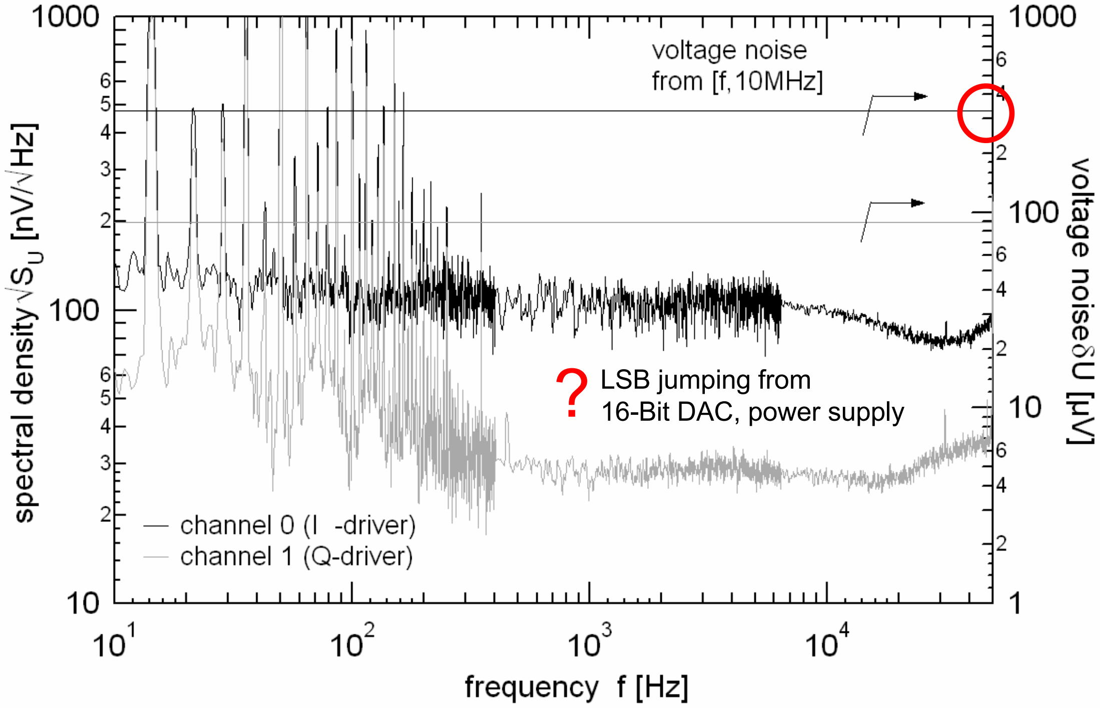
For the actual DWC structure a calibration is only possible in the baseband with $f_{IF}=0$ .The drifts caused by the reference are reduced by a factor of f_{IF}/f_{LO}.

Good calibration requires: (for the mixer structure)

- $S_{\varphi,RF}(f)=S_{\varphi,LO}(f),\ \gamma_{RF,LO}(f)=1,\ f_{RF}\neq f_{LO}$ (I think impossible to fulfill)
- Calibration in baseband, measurement using intermediate frequency.
- Extend the DWC structure (e.g. analyze also sum frequency noise...).
- Accept the calibration error: - Reduce drift from MO (push mixing idea with inwave).
  - Decrease the indermediate frequency.
  - Compare calibration drift errors vs. DWC drift.



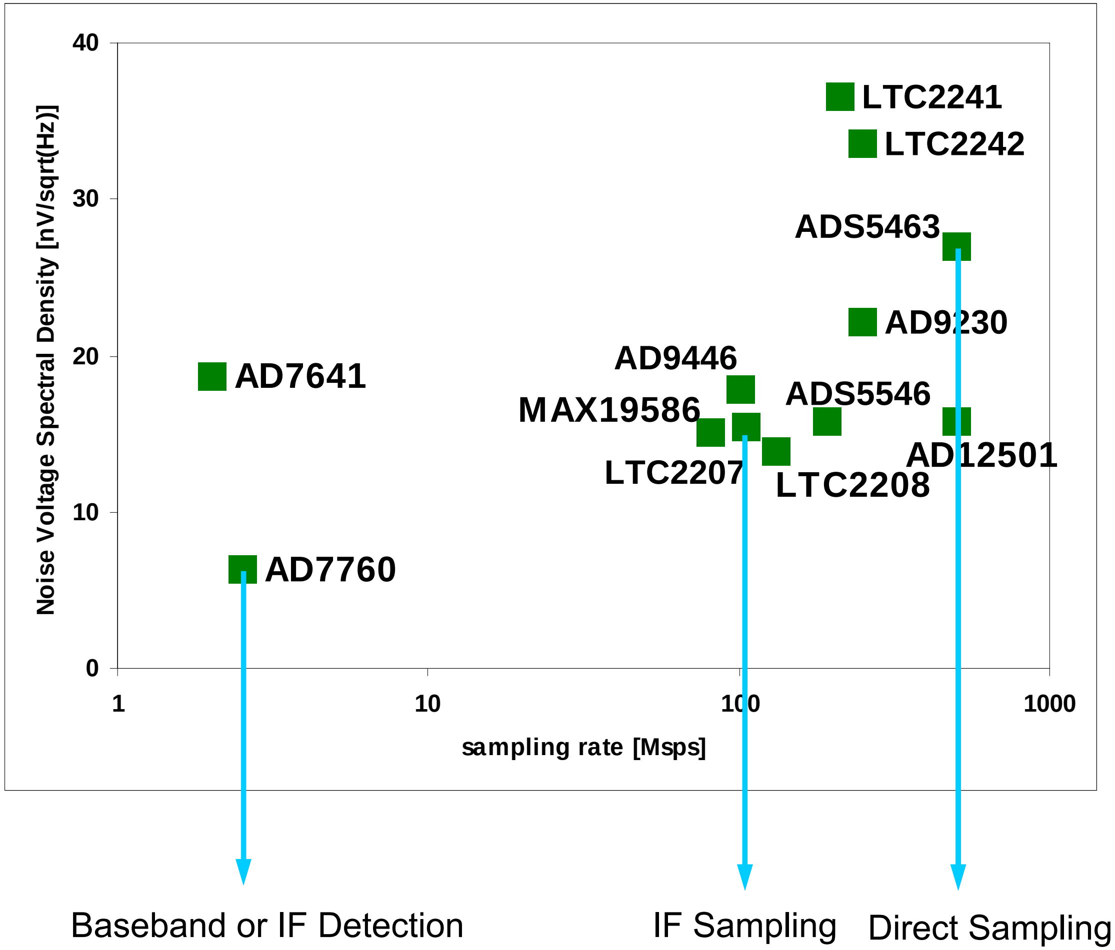
- **Noise from IQ-driver modul :**



$$\delta U_{IQ} \approx 3.5 \times \delta U_{XFEL}$$

- *Merge fiberlink+DAC+VM,*
- *Merge DWC+ADC+fiberlink*
- *Low-noise design down to 10mHz for long term stability!*

- **ADC equilvalent noise spectral density :**



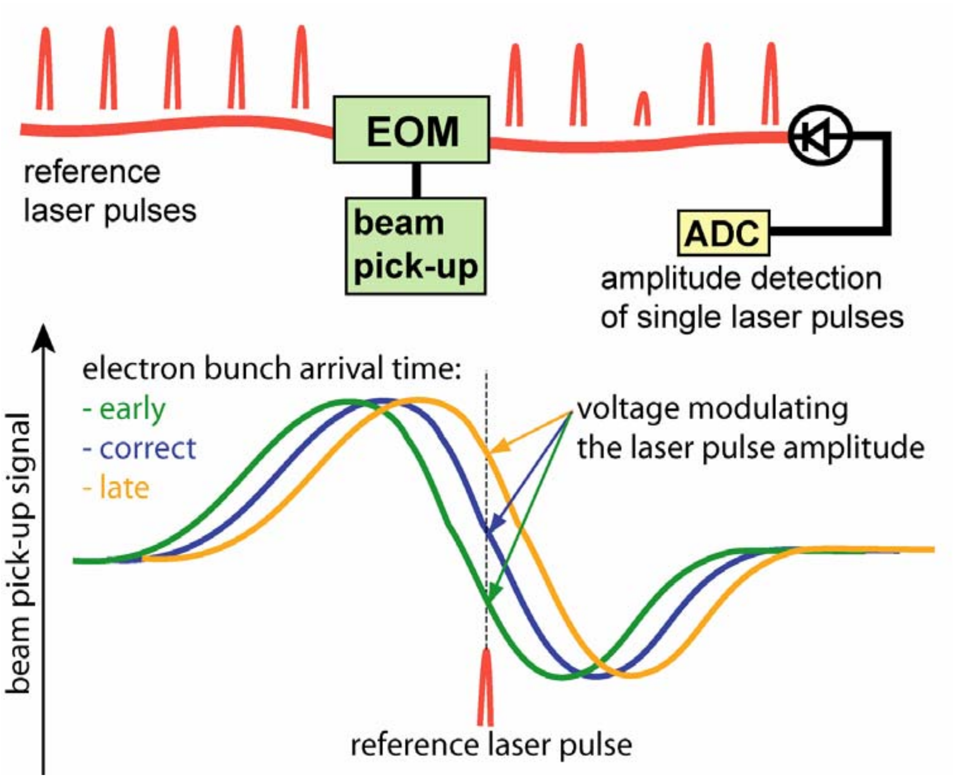
$$e_n = \frac{V_{FS,pp}}{\sqrt{8}} 10^{\frac{SNR(f_s,\varepsilon)}{20}} \sqrt{\frac{2}{f_s}}$$

Typ	Bits	$f_{s,max}$ [MSPS]	SNR [dBFS] 70 MHz	SFDR [dBc] 70 MHz	V_{FS} [V_{pp}]	t_j [fs]
LTC2207	16	105	77.5	90	2.25	80
LTC2208	16	130	77.5	90	2.25	70
AD6645	14	80	73.5	87	2.2	100
AD9461	16	130	77	84	3.4	60
AD9446	16	100	79	89	3.2	60
ADS5546	14	190	73.5	87	2.0	150

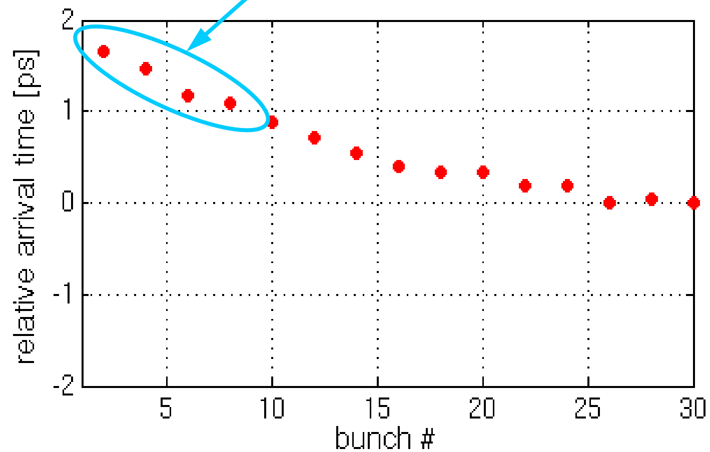
A lot of available ADCs have roughtly the same performance.

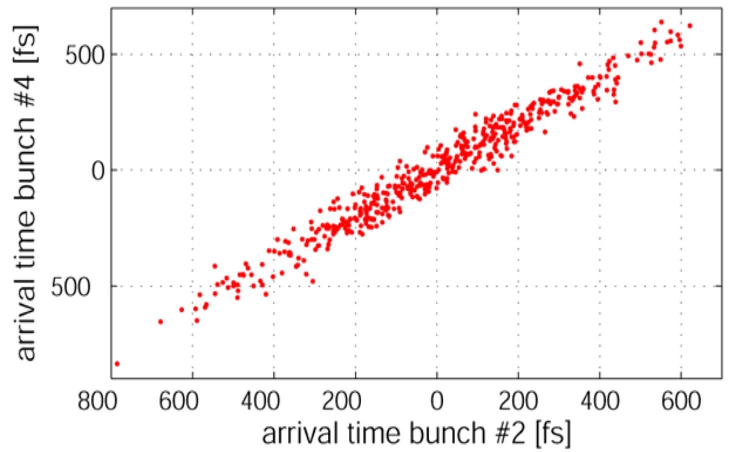
Bunch-to-bunch beam stability

- **Bunch-Arrival Monitor :**



Short-term fluctuation
are filtered by the cavity.





- Single bunch resolution better 30fs
- Synchronization problems

Courtesy of F.Loehl / DESY

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

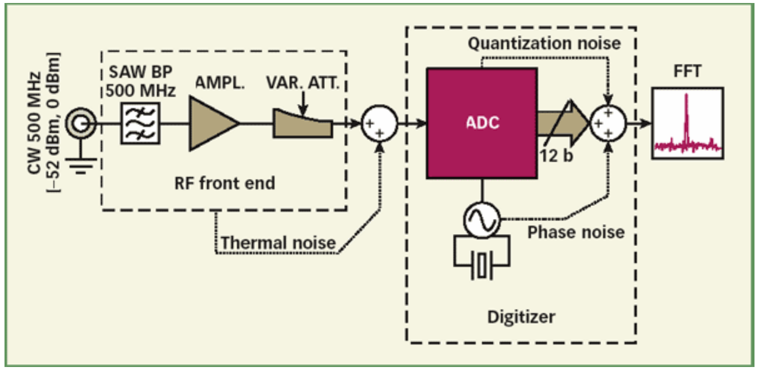
Master
Reference

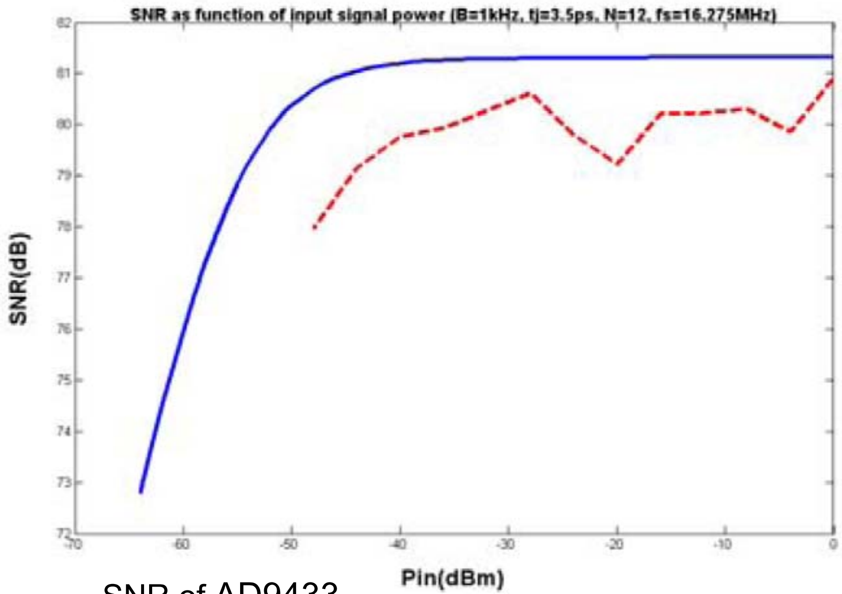
What is most important for a beam stability significantly lower than 0.01% ?

Direct Sampling of RF signals

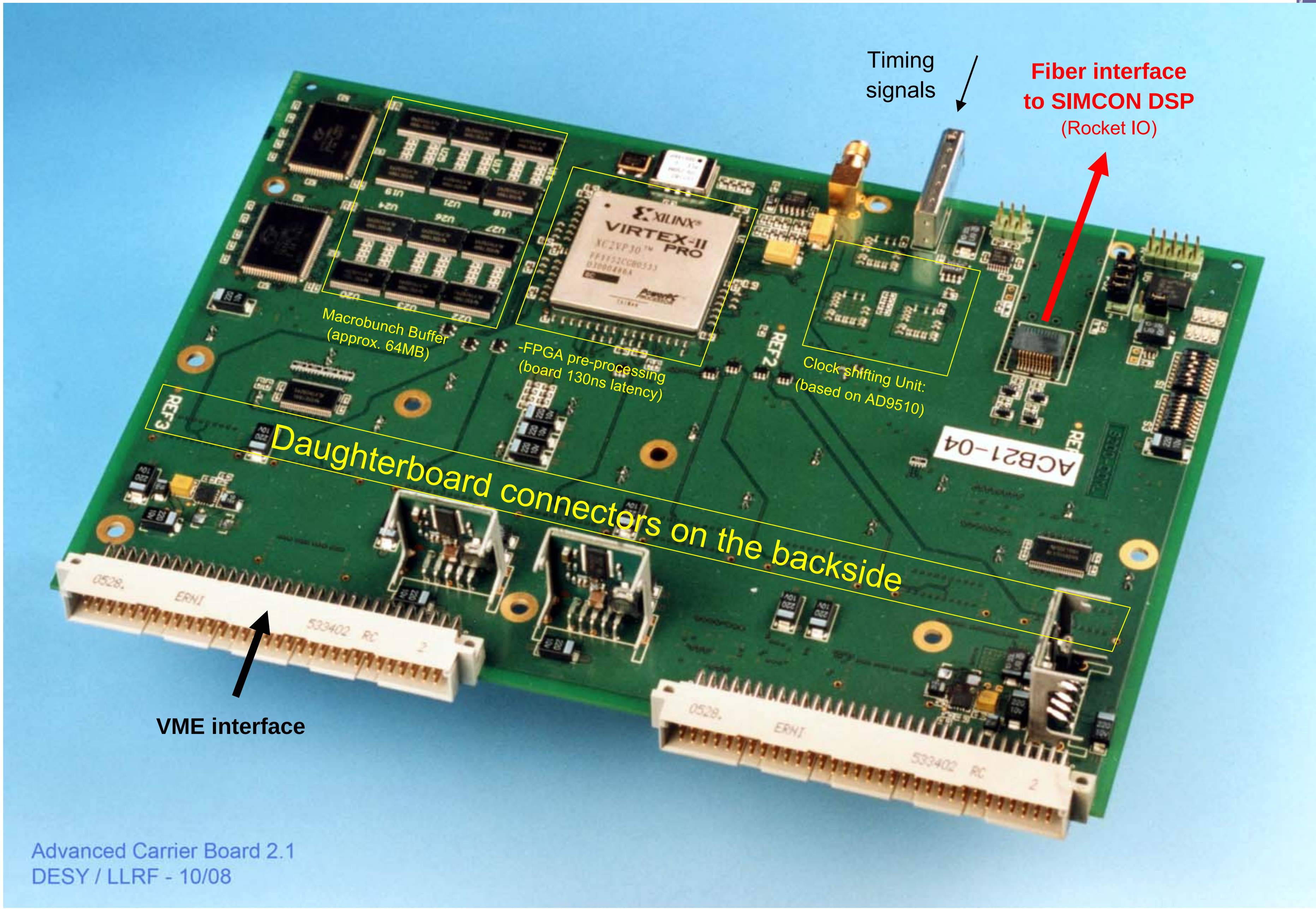
- **Key features :**
  - simplifies RF frontend (no downconversion)
  - amplifier & attenuator to match to the input range of the ADC
  - undersampling inevitable
    → BW < fs/2
- **SNR :**
  - amplifier noise
  - ADC quantization noise
  - clock jitter
- **Linearity :**
  - amplifier linearity (compression)
  - ADC linearity

Courtesy of U.Mavric / FNAL





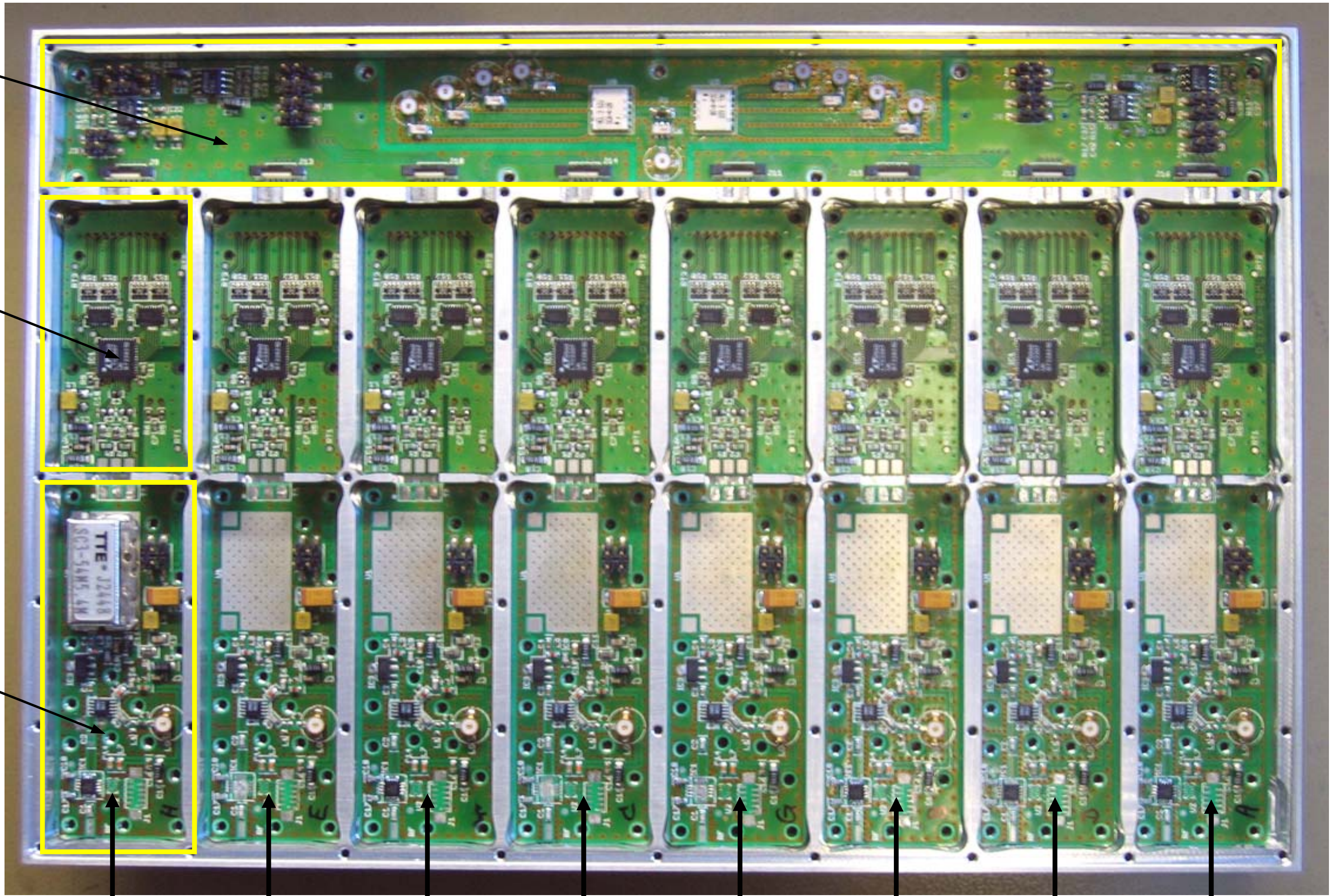
SNR of AD9433
calculated (solid) & measured (dashed)
fin = 200MHz, fs = 16.3MHz


Timing
signals
Fiber interface
to SIMCON DSP
(Rocket IO)
Macrobunch Buffer
(approx. 64MB)
-FPGA pre-processing
(board 130ns latency)
Clock shifting Unit:
(based on AD9510)
Daughterboard connectors on the backside
VME interface
Advanced Carrier Board 2.1
DESY / LLRF - 10/08

LO signal distribution

ADC (8 channels):
(LT2207,16Bit, 105Msps)

Analog frontend
(8 channels):
(based on High IP3
Mixer HMC483)



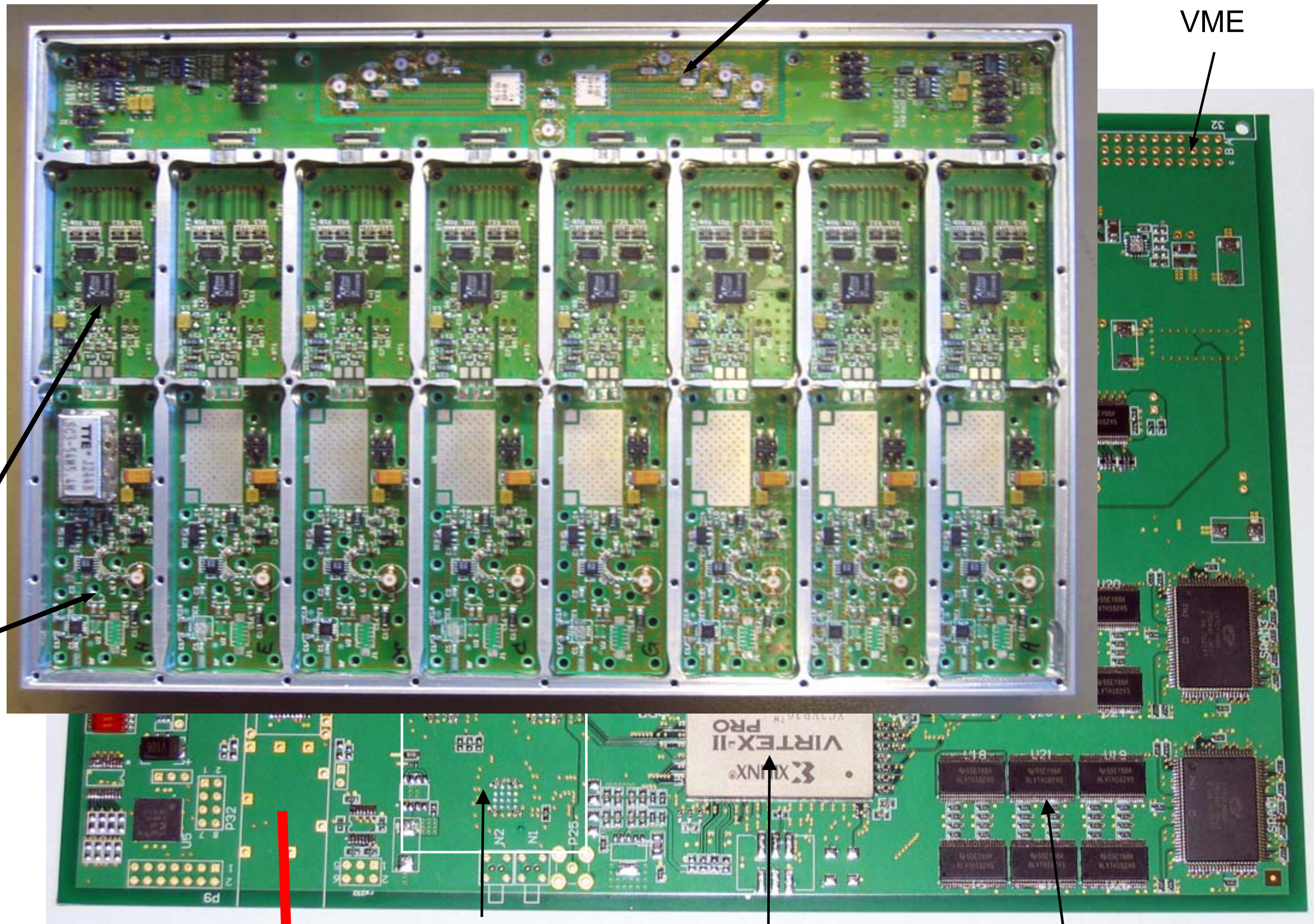
RF inputs (8 channels):
+14dBm input power / channel

Multichannel Receiver frontend + fast ADC board for prototype testing :
(DWC2.0, BAM1.0)

- Shielded subsections
- Strong AGND to RF GND connections
- Frontend mixer and ADC easily changeable
  (Applications:
  Bunch-arrival-monitors,
  Beam-position-monitors,
  Beam-based feedback,
  LLRF passive-active)

LO distribution

VME



ADC:
(LT2207,16Bit, 105Msps)

Analog frontend:
(based on High IP3 Mixer HMC483)

IQ detection + fiber interface board :
(ACB 2.0)

- 1GBit/s Optolink,
- 1GBit/s Ethernet
  (Rocket IO Interface approx. 350ns latency)

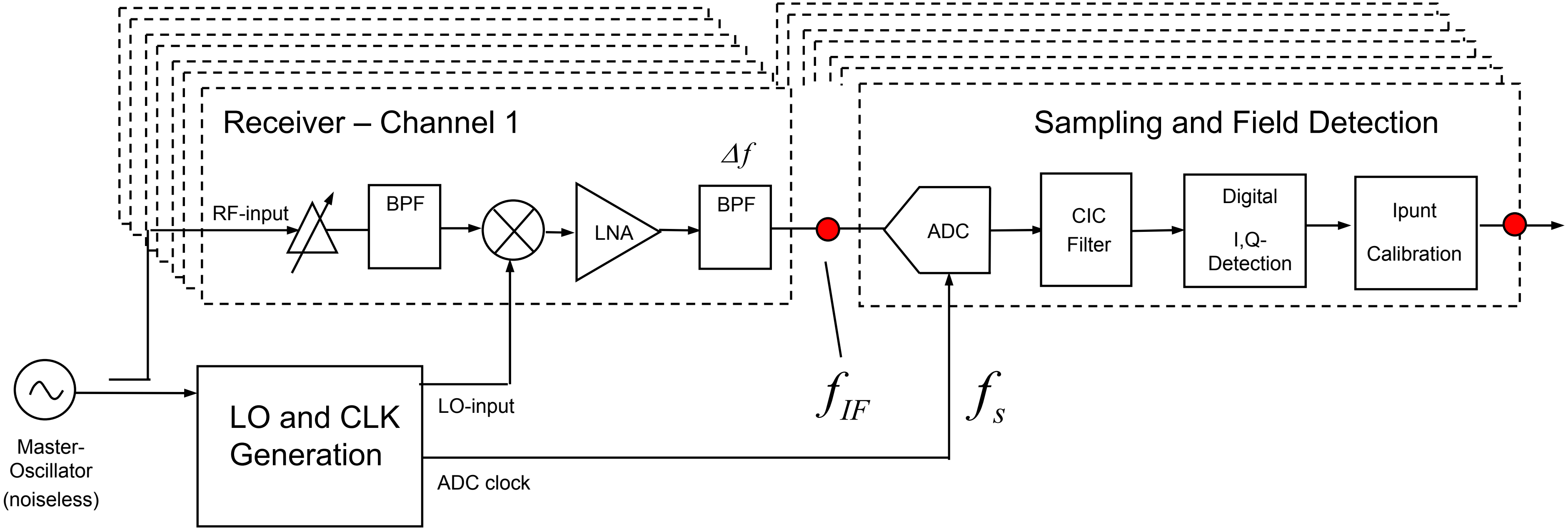
Fiber interface to SIMCON DSP (approx 400ns delay)

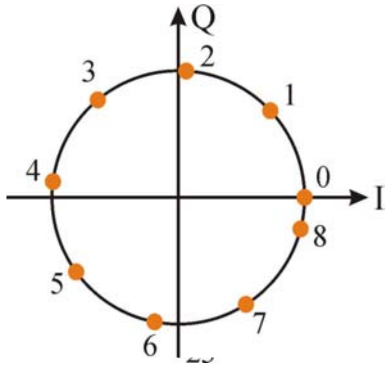
Clock shifting Unit:
(based on AD9510)

-FPGA pre-processing (board 130ns latency)

- Macrobunch Buffer (approx. 64MB)

- **Simplified block diagram of a down-converter :**





Sample frequency:

$$f_s = \frac{N}{M} \cdot f_{IF}$$

N, M: integers

N samples in M IF periods

Phase advance:

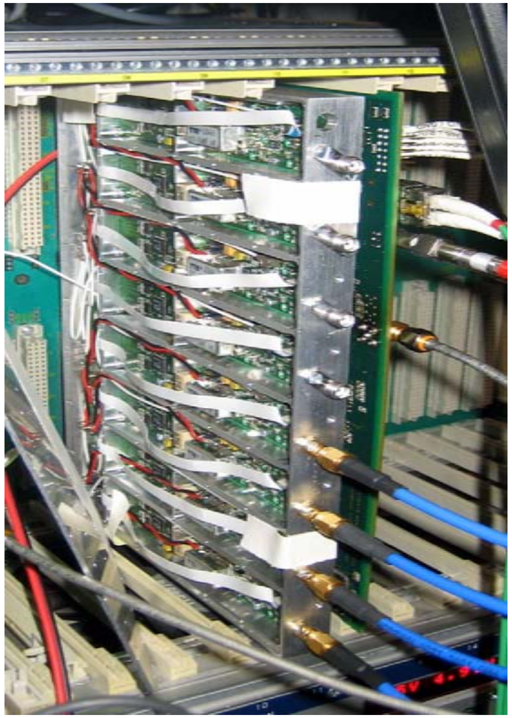
$$\Delta\varphi = \omega_{IF} T_s = 2\pi \frac{T_s}{T_{IF}} = 2\pi \frac{M}{N}$$

$$I = \frac{2}{N} \cdot \sum_{i=0}^{N-1} y_i \cdot \sin(i \cdot \Delta\varphi)$$

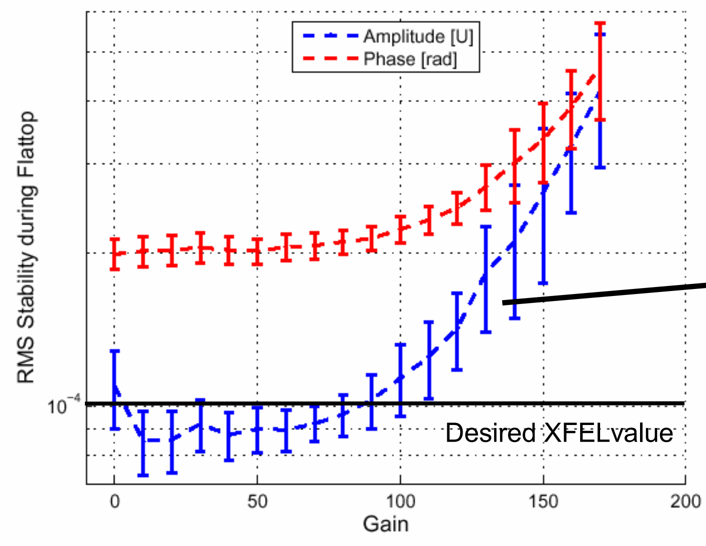
$$Q = \frac{2}{N} \cdot \sum_{i=0}^{N-1} y_i \cdot \cos(i \cdot \Delta\varphi)$$

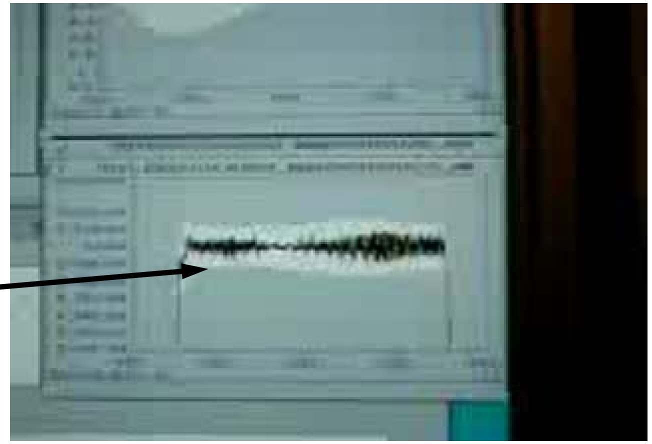
Receiver performance at FLASH

- **FLASH injector :**



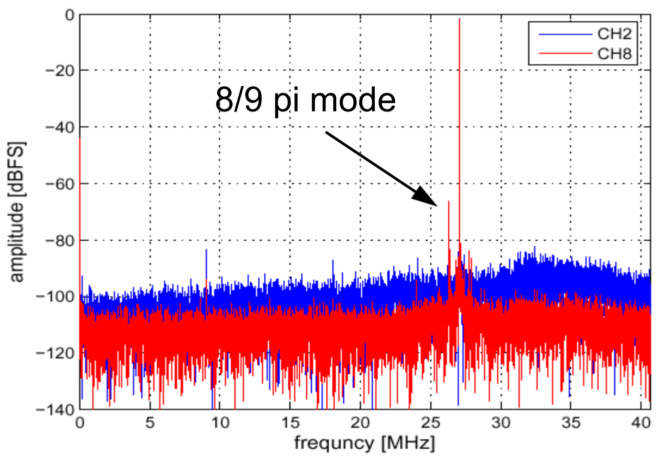
- **Vectorsum stability with closed control loop at ACC1:**





Instability caused by 8/9pi mode

Down-converter biased by Cavity pickup :

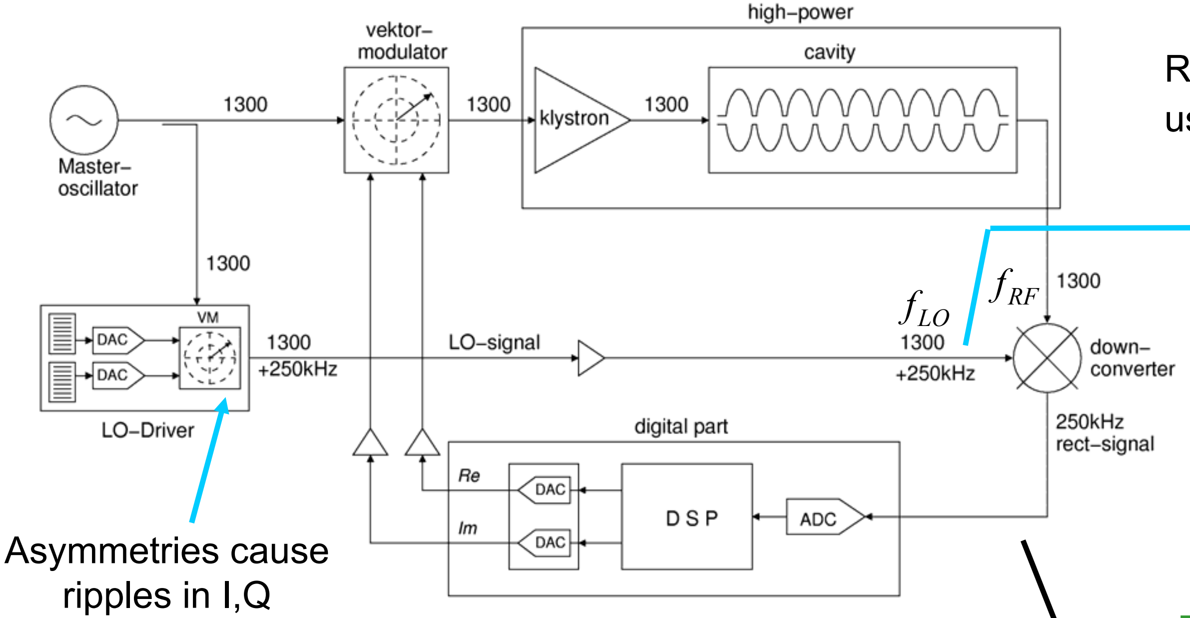


	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
$\Delta A/A$ [10^{-4}]	3.8	5.8	5.1	4.1	2.8	4.1	2.1	3.6
$\Delta\varphi$ [deg]	0.028	0.038	0.035	0.033	0.025	0.032	0.022	0.032
$\Delta A/A$ [10^{-4}]	2.1	2.5	1.9	1.6	1.0	1.5	0.9	1.5
$\Delta\varphi$ [deg]	0.016	0.019	0.018	0.021	0.016	0.020	0.015	0.019

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

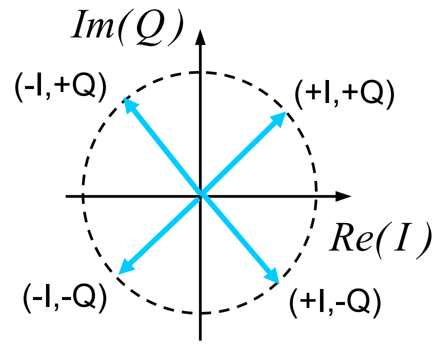
IQ sampling scheme in practice

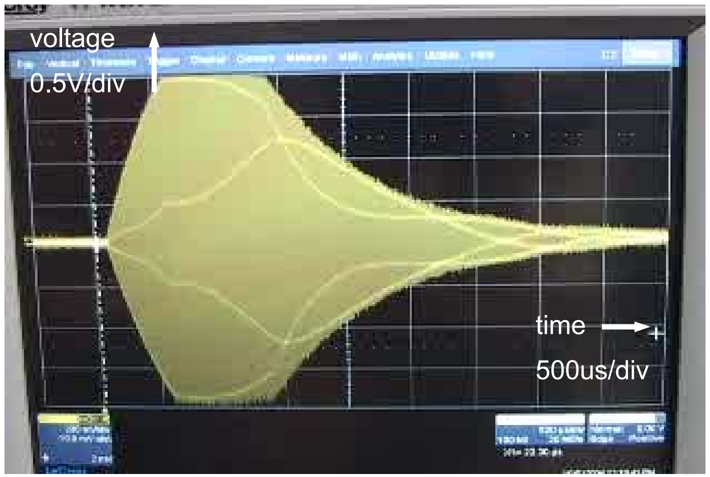
- **Actual LLRF control system using a switched LO-signal :**



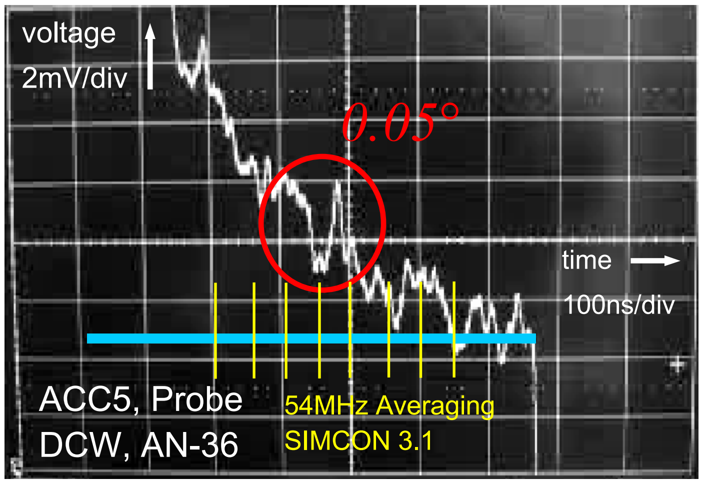
- **Phase and amplitude detection of the cavity field vector :**

Rotation of the LO-signal in four 90° steps, using a 250kHz squared LO-Signal.





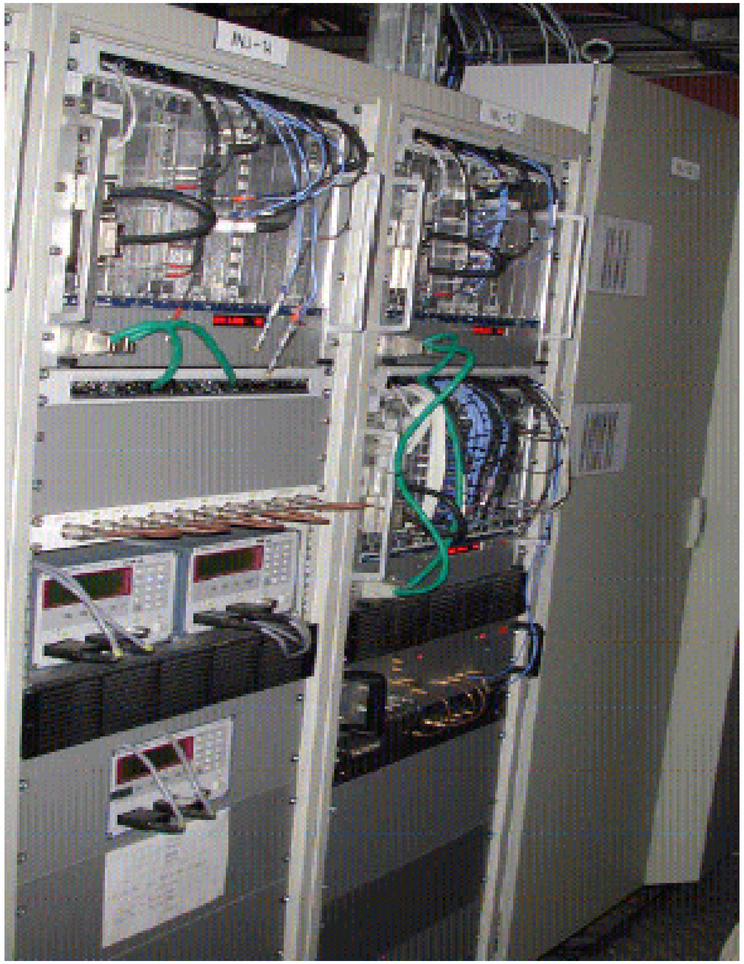
- **Down-converter output IF-signal :**



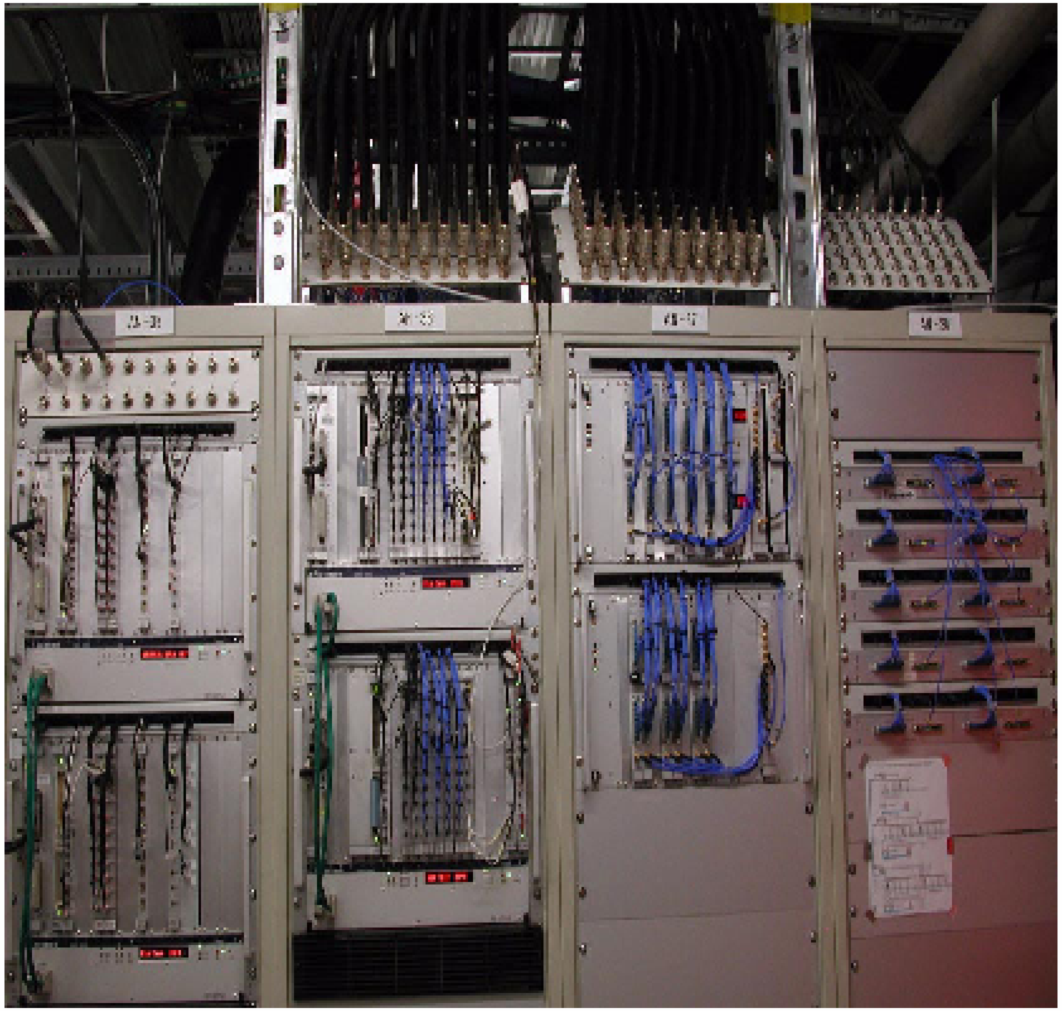
Bandwidth for transforming 250kHz squared pulses :
$\Delta f \approx 10 MHz$

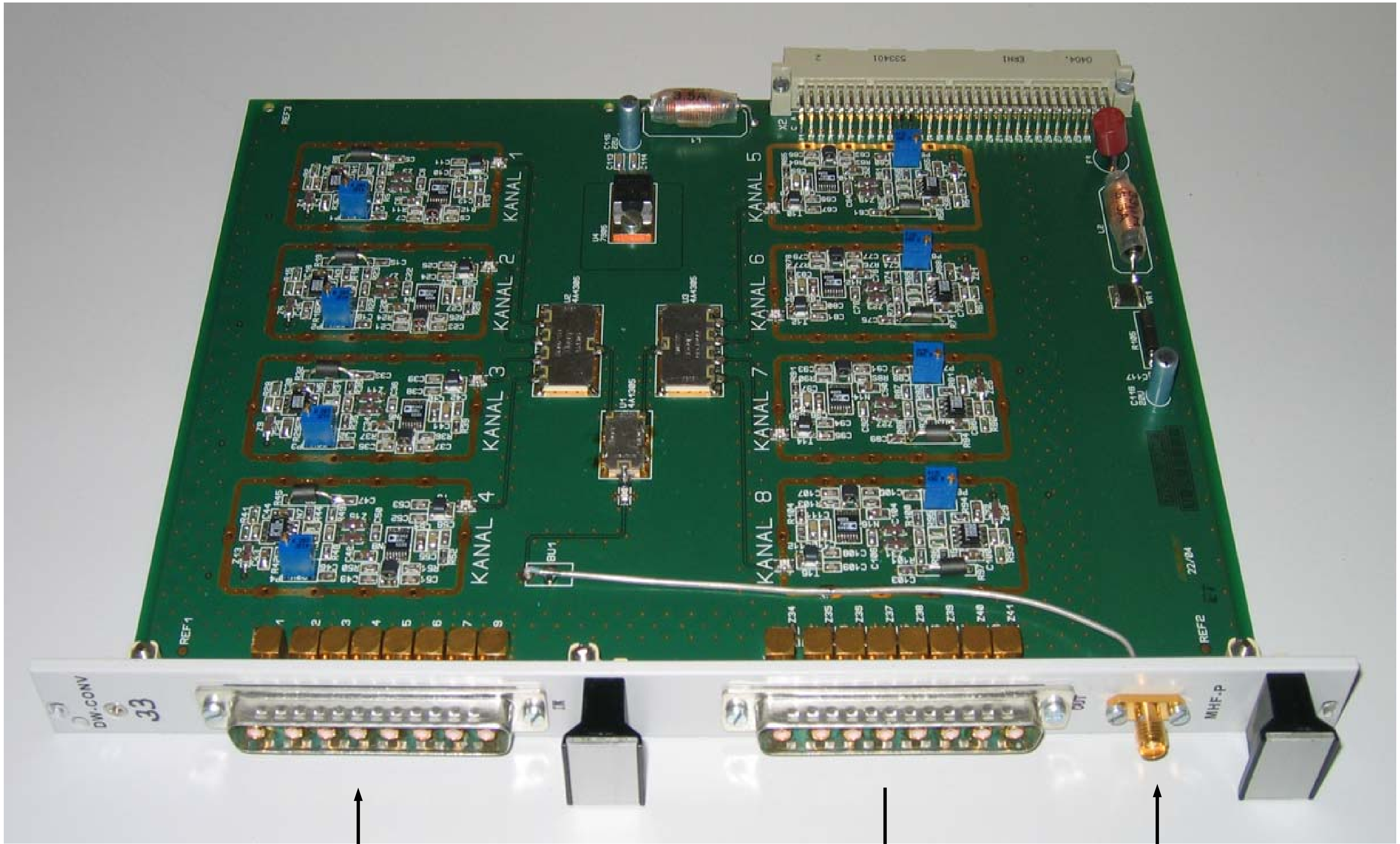
but required regulation bandwidth is only :
$\Delta f \approx 1 MHz$

Gun and ACC1



ACC2, ACC3, ACC4 & ACC5





8-channels from cavity probe :

$P_{RF} \approx [-40\,dBm, -10\,dBm]$

8-channels to ADC-Board :

$\sqrt{S_U} \approx 70\,nV / \sqrt{Hz}$

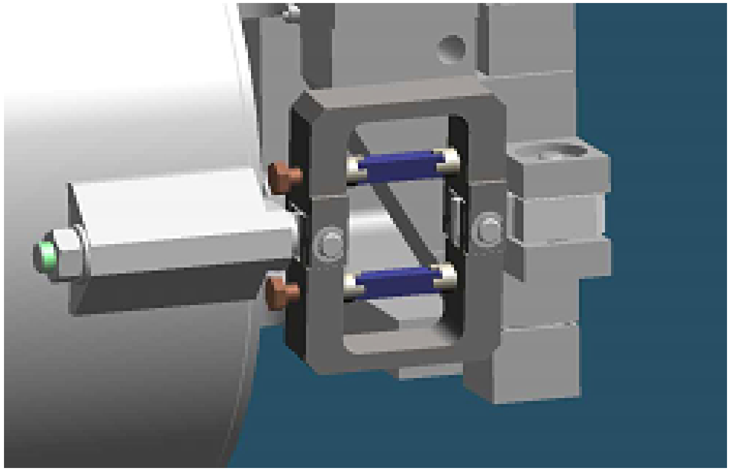
LO-Input :

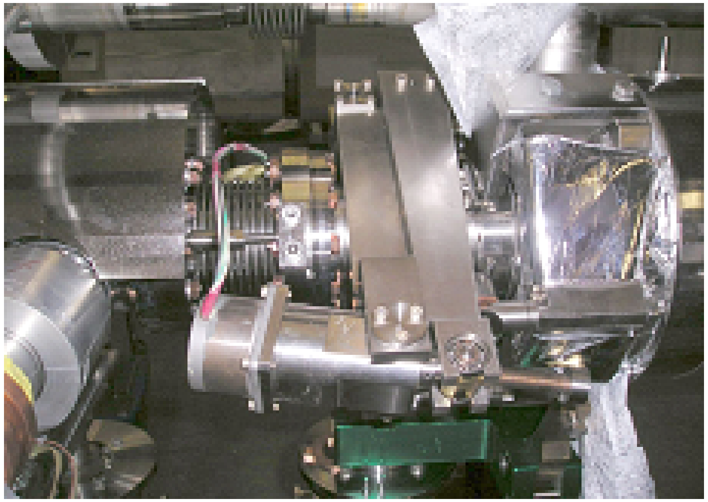
$P_{LO} \approx -5\,dBm$

Piezotuner Control

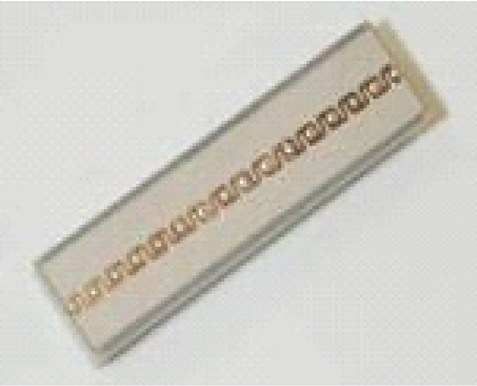
Goal of Piezo Control system

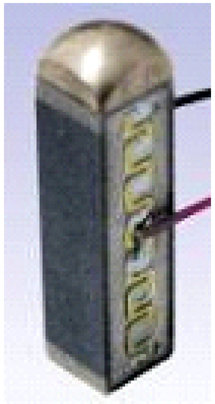
- Drive the piezoelements assembled in fast tuners frames to minimize the Lorentz force and microphonics effects
- On-line frequency detuning calculation
- Microphonics measurement (i.e. diagnostics of cryogenic system)





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





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

General requirements of Piezo Control system

- Lorentz force detuning (LFD) during flat-top $\Delta\omega$< 10 Hz for field up to 30 MV/m (compensation up to 600 Hz – possible resonance compensation up to 1kHz)
- Commercial available piezoelements (PI and NOLIAC) C_{2K}= 3÷5 μF, V_{max}= 100 V, oper. freq. for LFD/microphonics up to 1 kHz (full voltage scale), → I_{load} ~ 300mA
- Maximal repetition rate of RF (LFD compensation) pulse 10 Hz
- Piezo must be protected and monitored (piezo is fragile to over current and over voltage (>150÷200), piezo lifetime must by over 1010 pulses, resonance in the cables, piezo might fall out when stepper motor is wrongly tuned)
- Possible microphonics compensation between the RF pulses (sensor/actuator mode)(microphonics has smaller impact than LFD, constant offset of $\Delta\omega$ during flat top, feedback loop

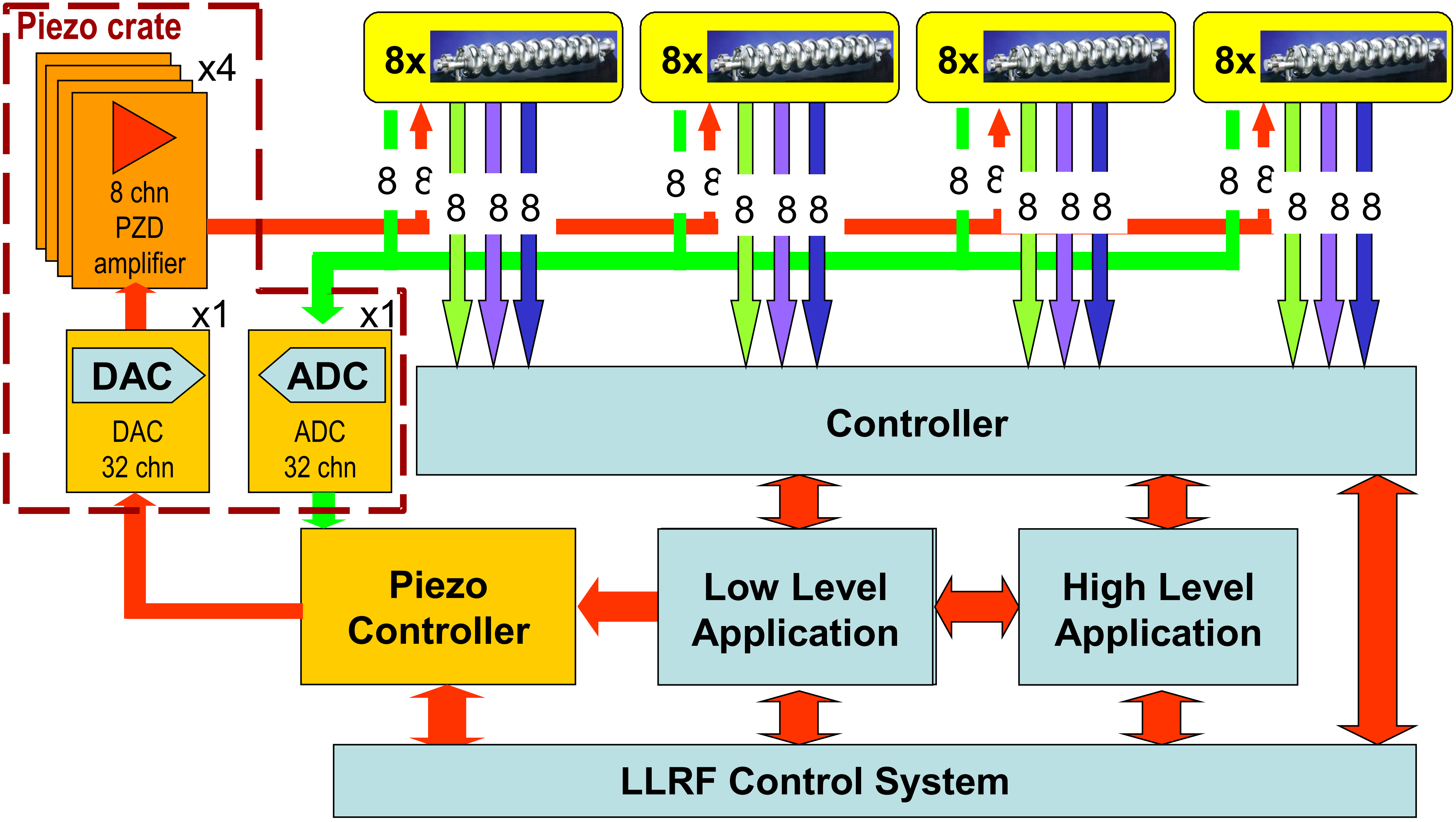
Piezos installed in ACC3,5,6

Producent ratings	Noliac	PI ceramic
Model:	SCMAS/S1/A/10/10/30/200/42/6000	P-888.90
Cells:	8	8
Voltage:	< 200 V	< 120 V
Blocking force:	6 kN	3 kN
Size:	10 mm x10 mm x 30 mm	10 mm x10 mm x 35 mm
Capacitance:	6 μF	12 μF

Piezos Capacitance

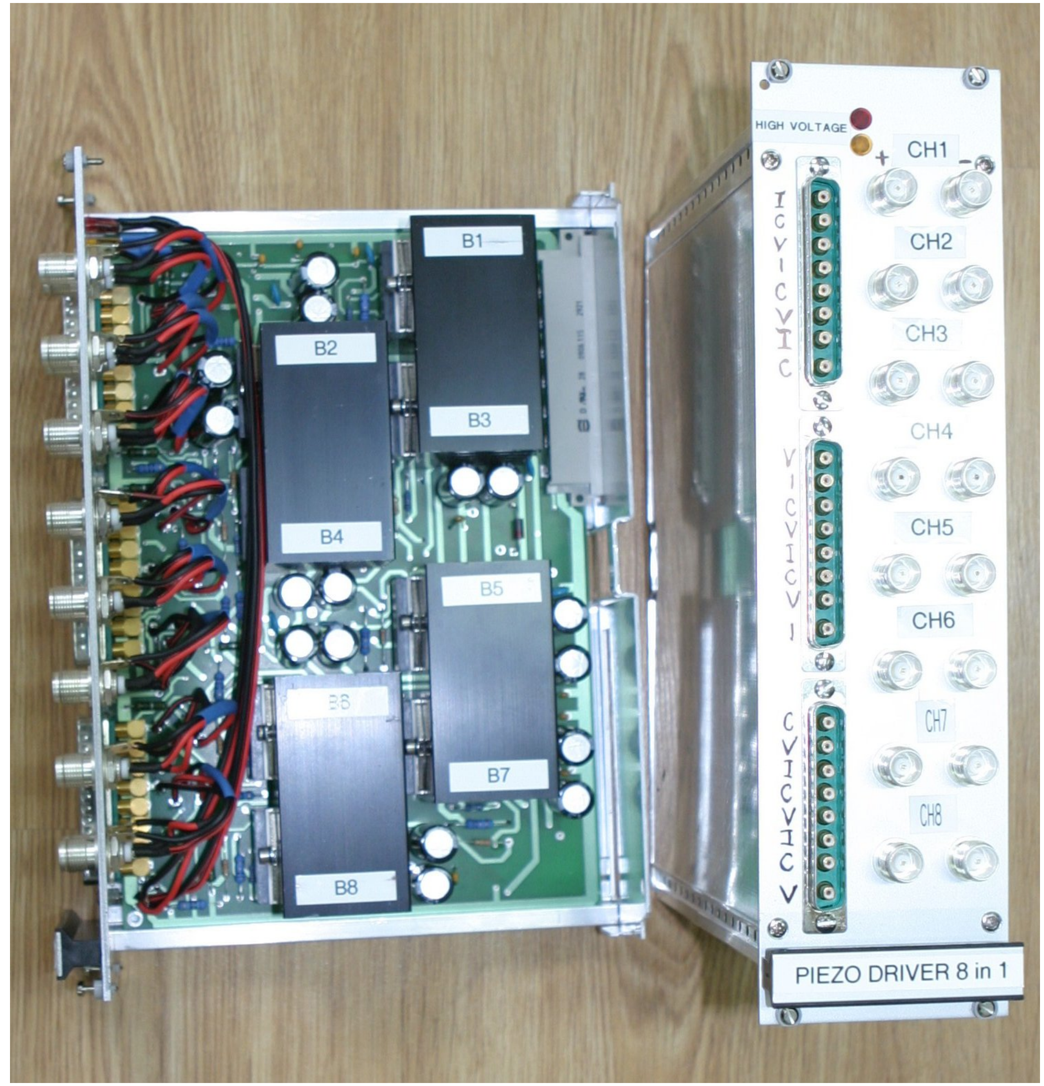
cavity	piezo	model	ACC3/M7	model	ACC5/M5	model	ACC6/M6
1	1	PI	4,93uF	Noliac	2,1uF	PI	4,13uF
	2	-	Unavailable	-	Unavailable	PI	4,45uF
2	1	PI	4,61uF	Noliac	2,22uF	PI	4,4uF
	2	-	Unavailable	-	Unavailable	PI	4,2uF
3	1	PI	4,91uF	Noliac	2,28uF	PI	4,21uF
	2	-	Unavailable	-	Unavailable	PI	4,1uF
4	1	PI	4,6uF	Noliac	3,12uF	PI	3,86uF
	2	-	Unavailable	-	Unavailable	PI	4,2uF
5	1	Noliac	2,6uF	Noliac	2,2uF	PI	4,22uF
	2	-	Unavailable	-	Unavailable	PI	4,28uF
6	1	Noliac	2,13uF	Noliac	2,13uF	PI	3,73uF
	2	-	Unavailable	-	Unavailable	PI	4,41uF
7	1	Noliac	2,22uF	Noliac	2,19uF	PI	4,69uF
	2	-	Unavailable	-	Unavailable	PI	4,41uF
8	1	Noliac	2,21uF	Noliac	2,17uF	PI	4,31uF
	2	-	Unavailable	-	Unavailable	PI	4,2uF

Piezo control for XFEL

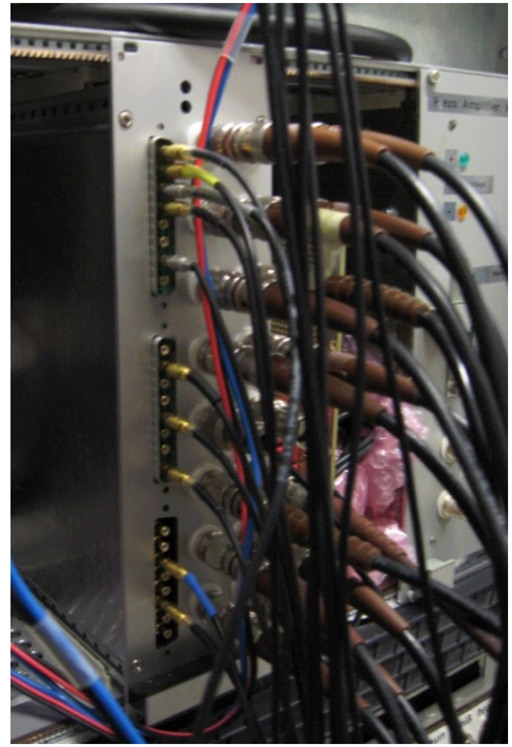


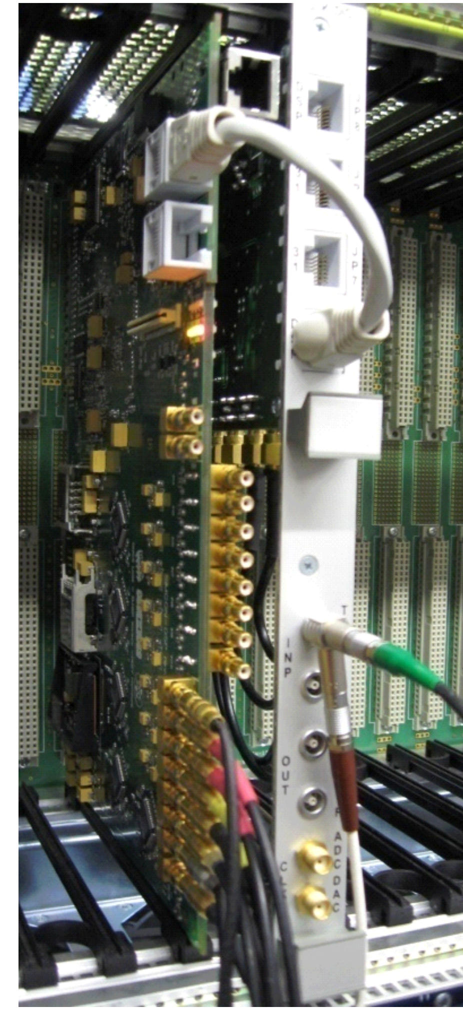
Main parameters of Piezodriver

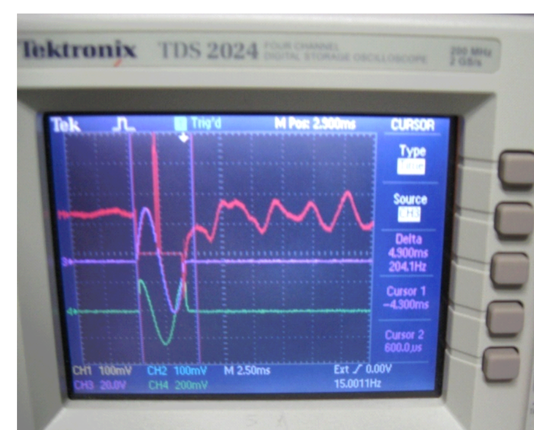
- Suitable for both types of piezostacks up to 5µF:
  - Physik Instrumente (P-888.90 PIC255); C_{2K} 4,4 µF
  - NOLIAC (SCMAS/S1/A/10/10/20 /200/42/6000); C_{2K} 2,4 µF
- Maximal supply voltage up to ± 150 V (nominal operating voltage ±80V)
- Input voltage ± 1 V
- Amplifier gain Gu= 100V/V,
- Operational temperature Tc < 75°C (Tj <125 °C)
- Pass-band frequency up to 5 kHz (for load 5µF)
- Monitoring of output voltage and current
- Single channel PZD with Apex PB51
- 8 channels on single board
- Up to 4 periods of sinus wave 80V, 200 Hz in 5µF load, 10 Hz repetition rate (thermal limit)



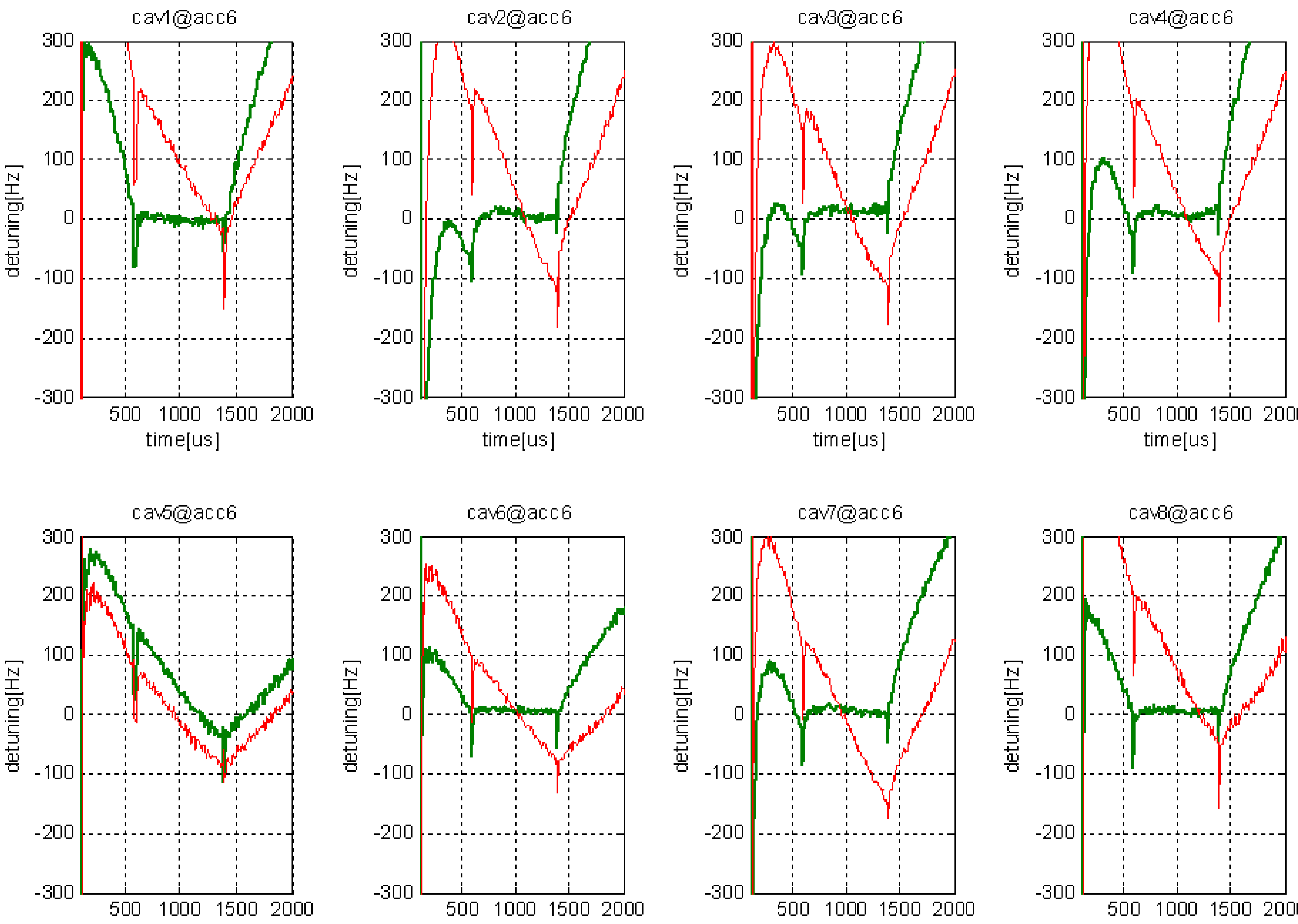
FLASH tests







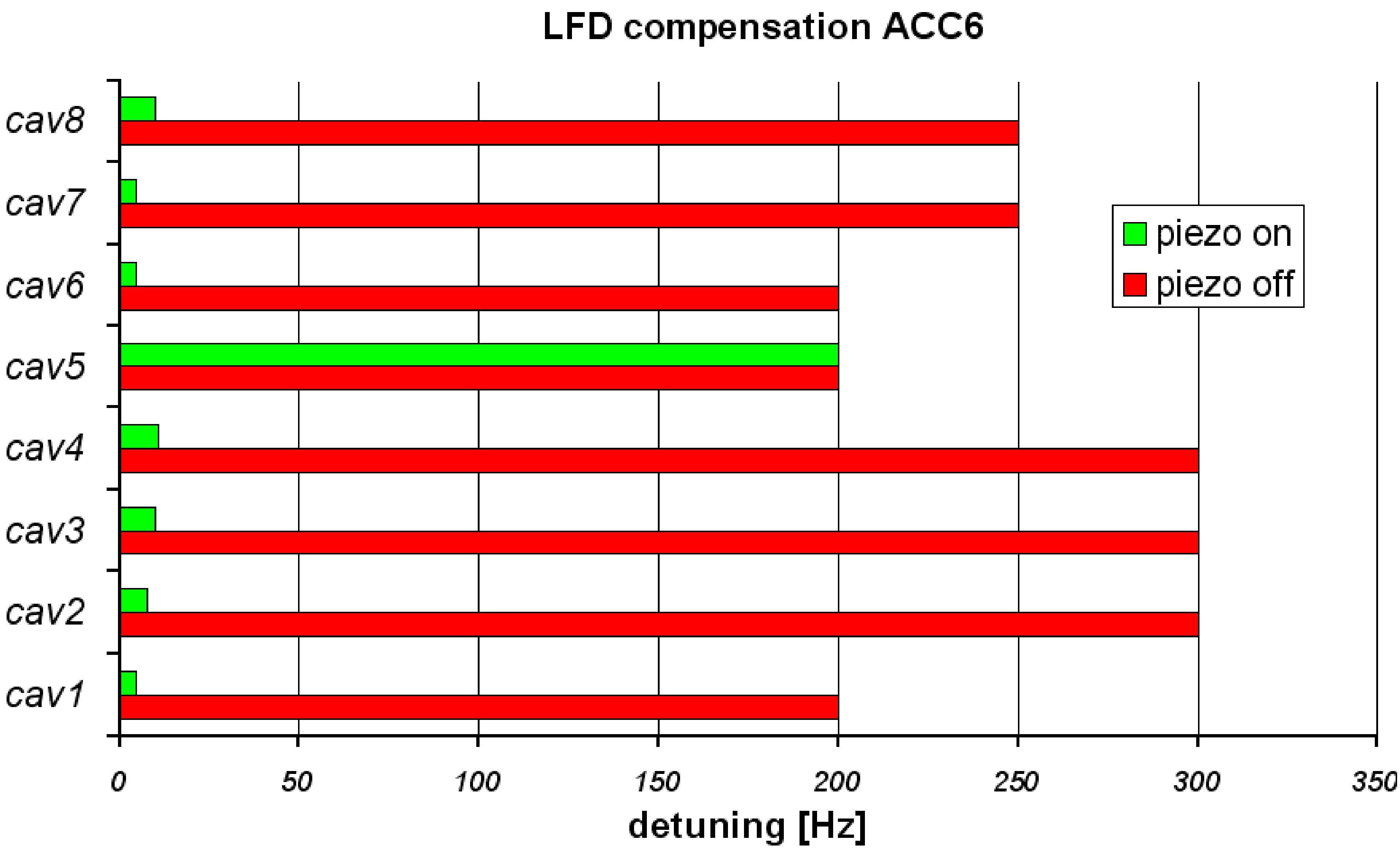
ACC6 (SP = 15 MV/m, Pforw = 220kW, rep = 5 Hz)



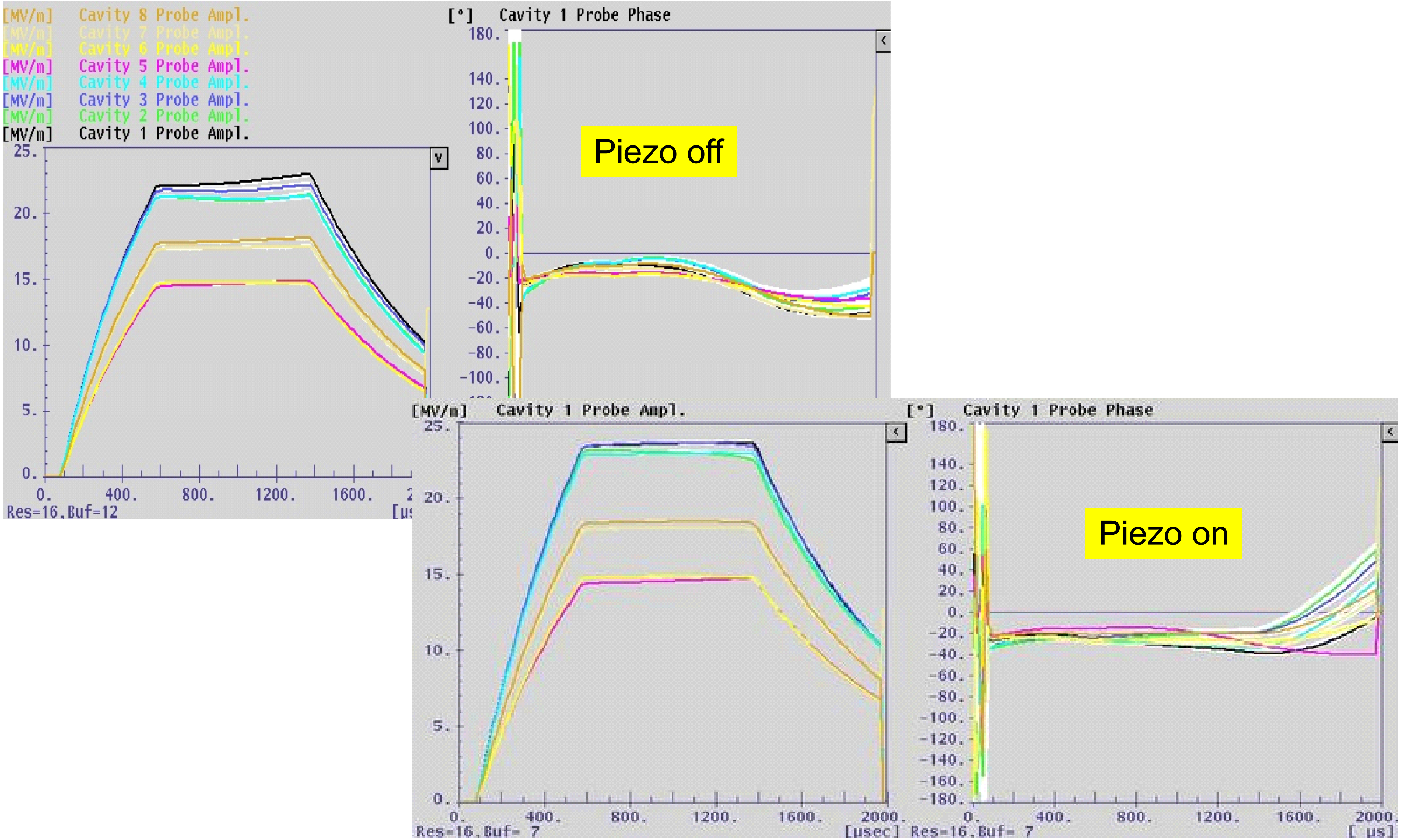
Cav. (1-3)
Amp: 34V
Dly: - 4.1 ms

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

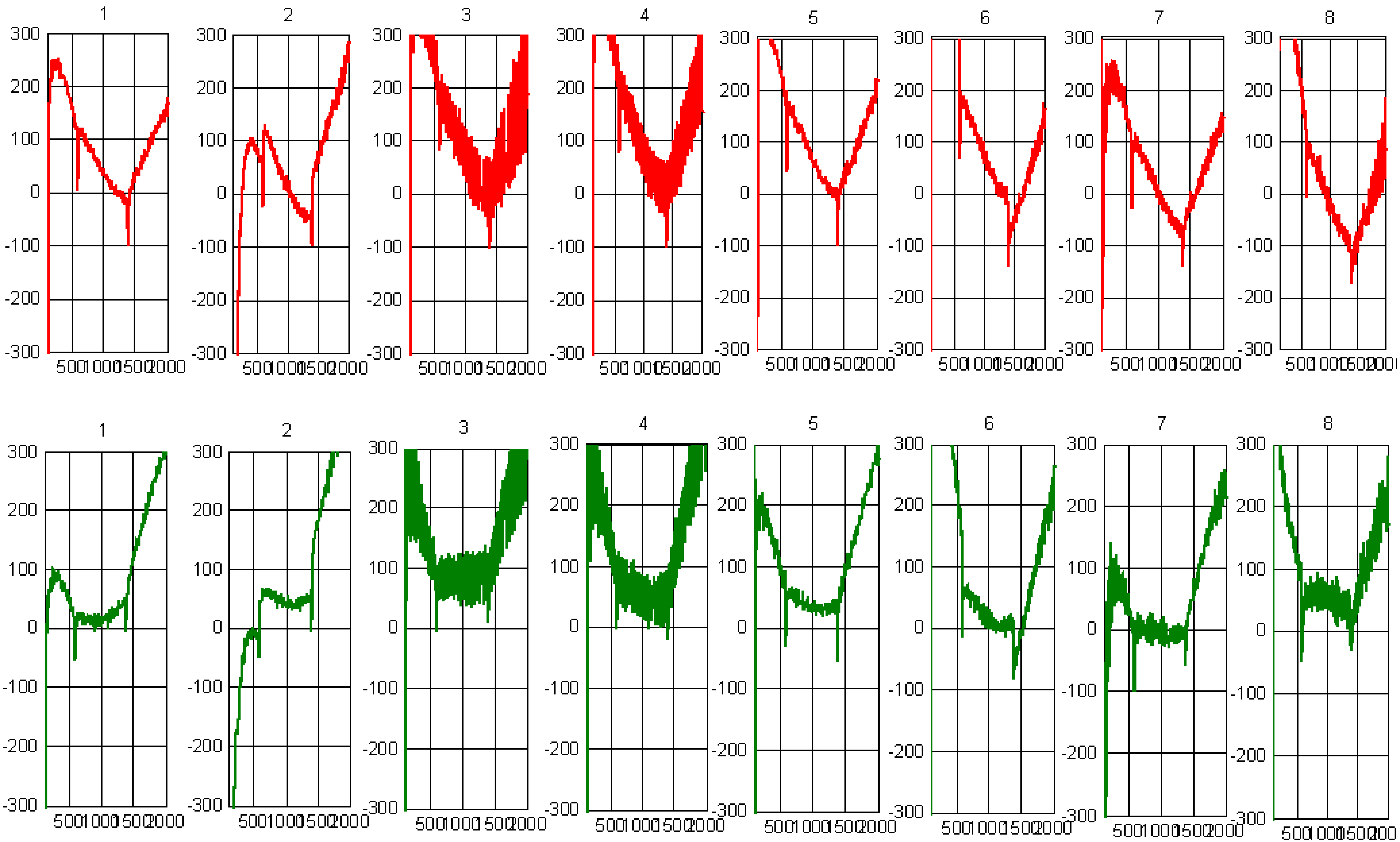
ACC6 – LFD compensation results



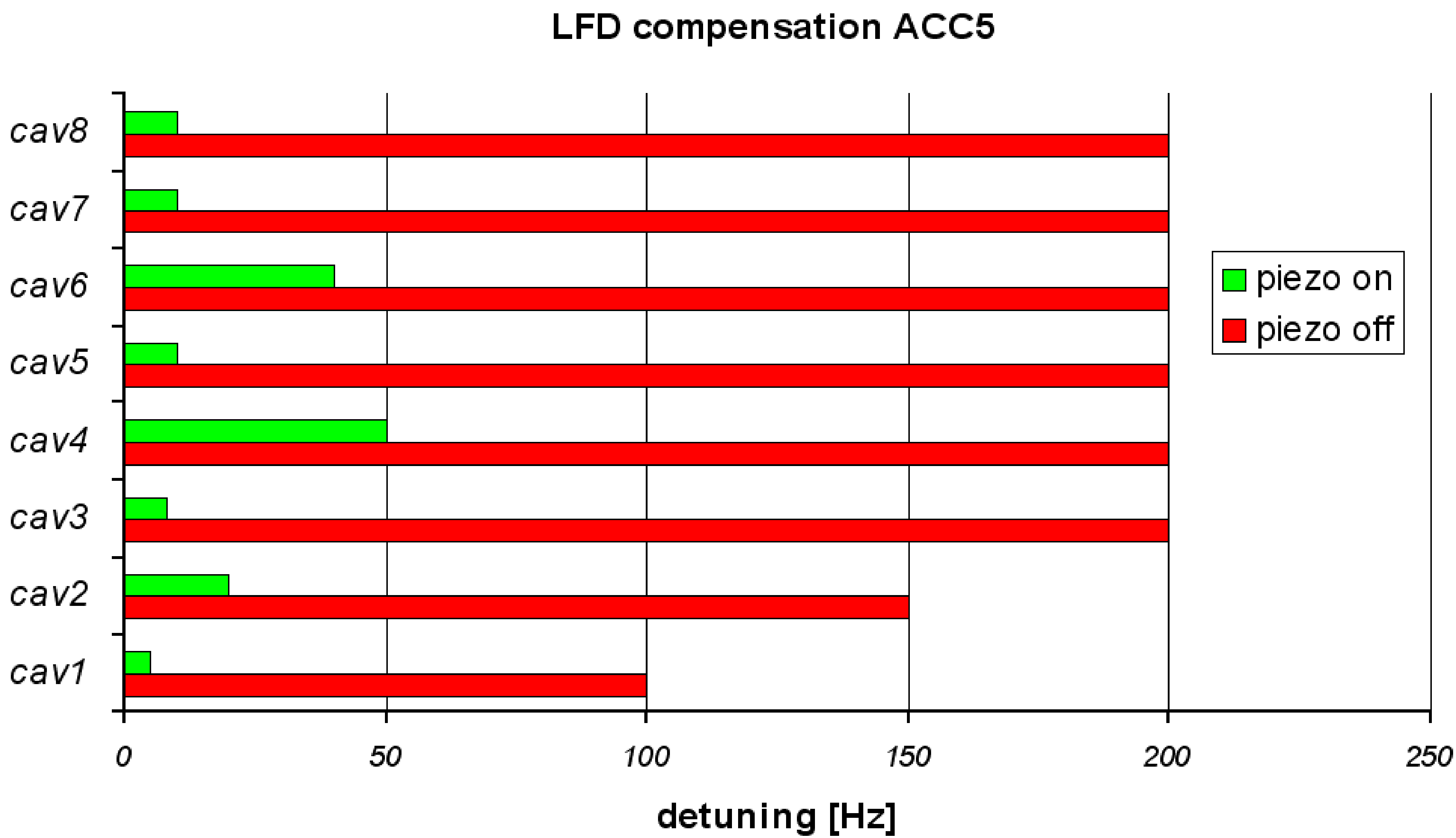
ACC6 – LFD compensation results



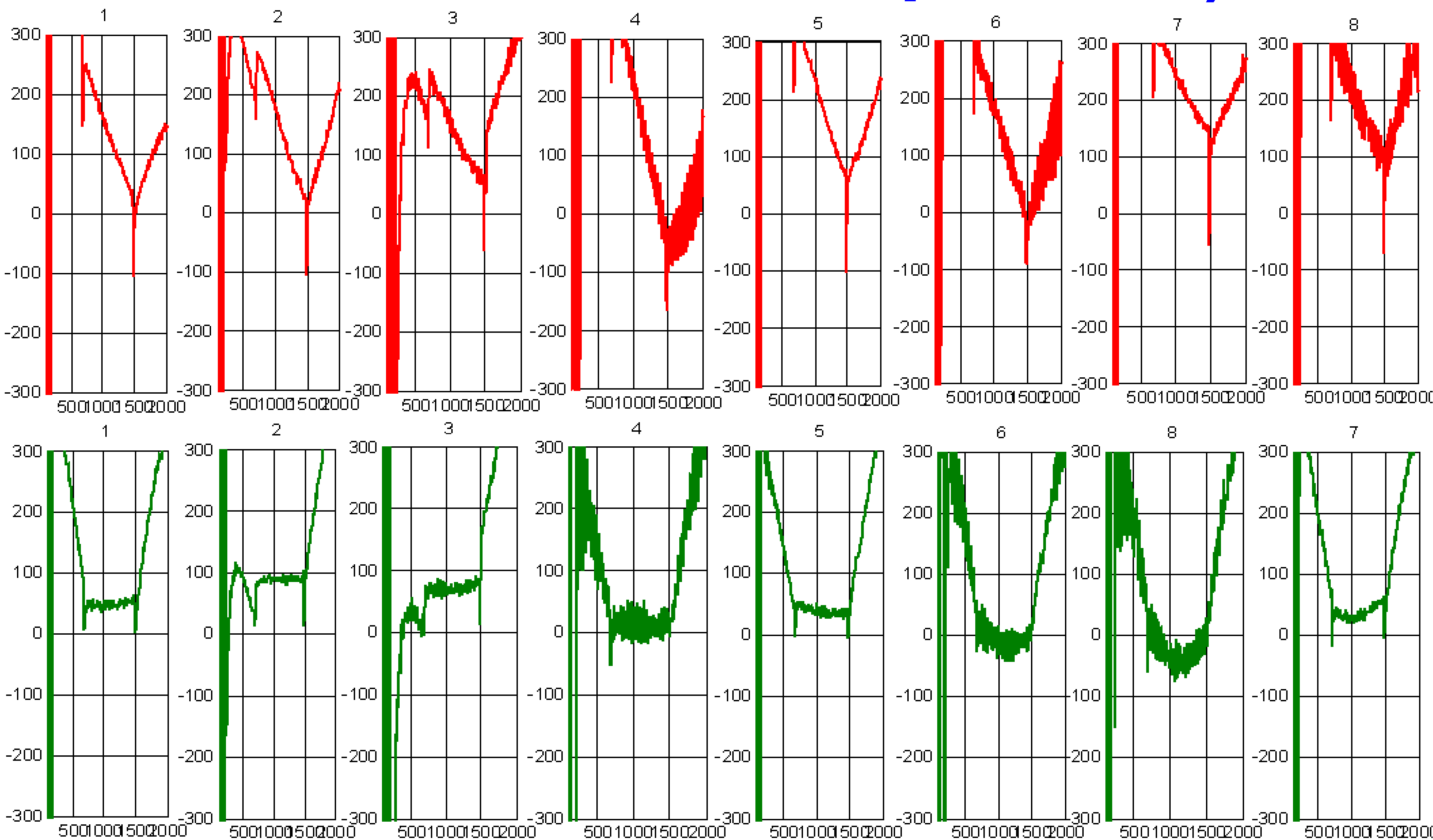
ACC5 (SP = 15 MV/m, Pforw = 90 kW, rep = 5 Hz)



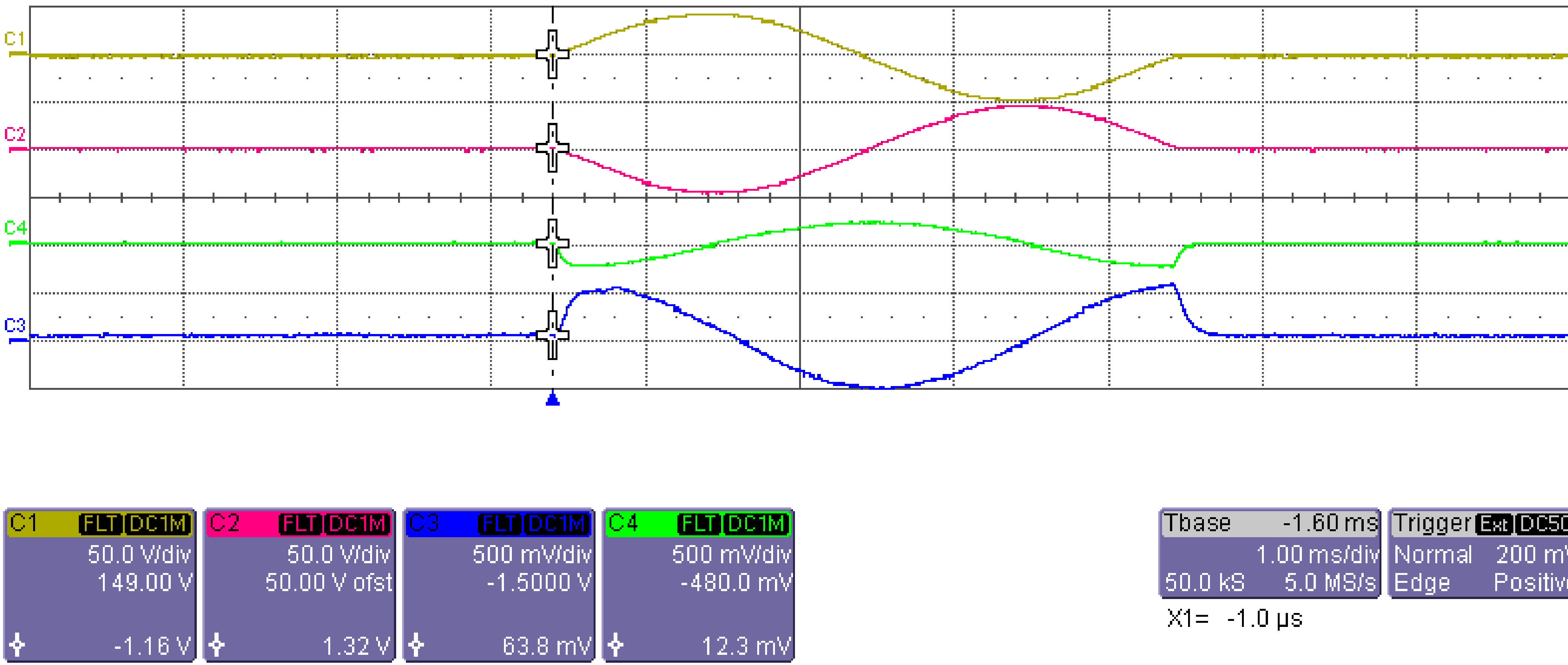
ACC5 – LFD compensation results



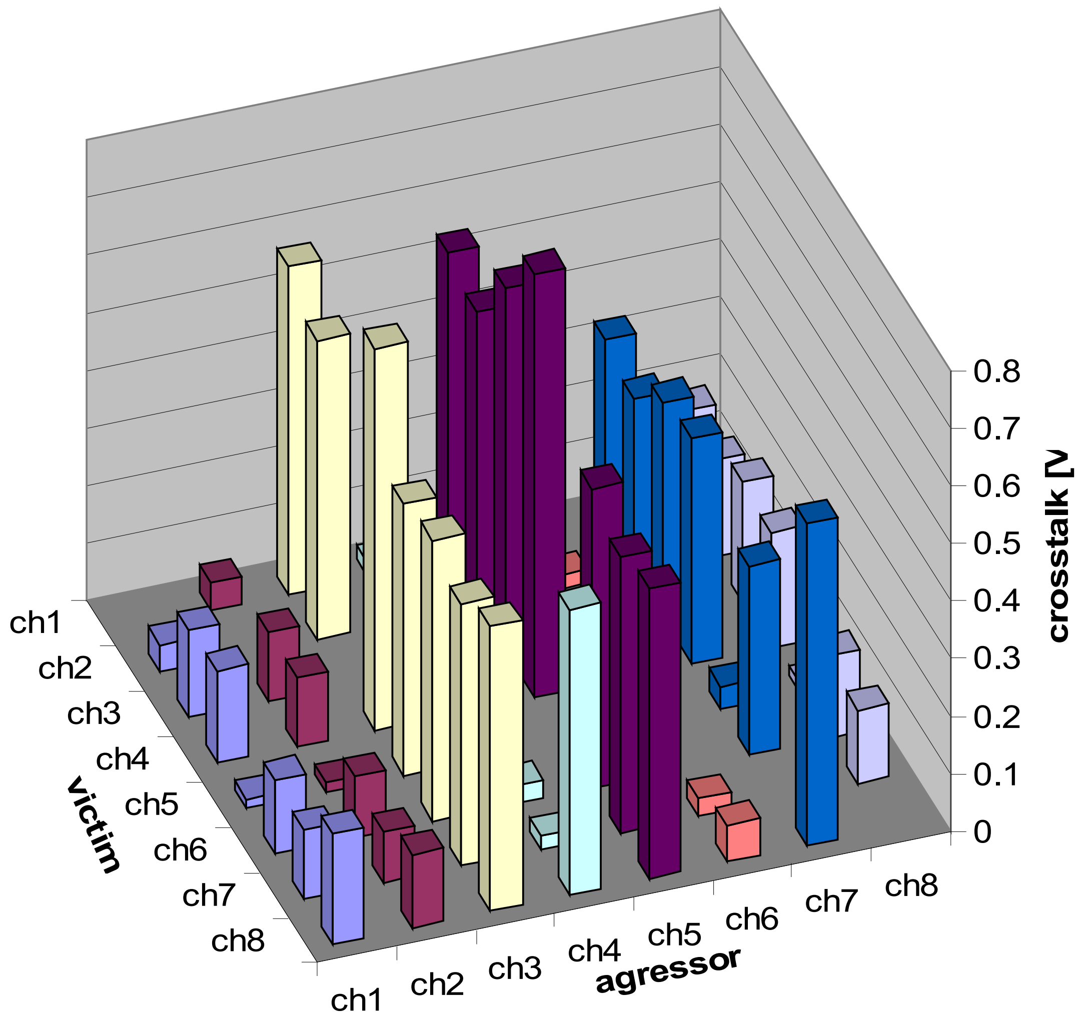
ACC3 (SP = 17 MV/m, Pforw = 220 kW, rep = 5 Hz)



Crosstalk in PiezoDriver

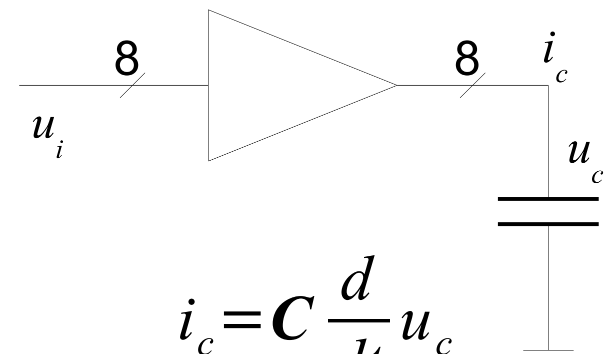


Crosstalk compensation



cross talk matrix

[V]	ch1	ch2	ch3	ch4	ch5	ch6	ch7	ch8
ch1		0.048	0.152	0.16	0.016	0.128	0.12	0.192
ch2	0.048		0.12	0.12	0.016	0.106	0.088	0.128
ch3	0.57	0.52		0.664	0.472	0.488	0.456	0.496
ch4	0.024	0.048	0.016		0.016	0.032	0.024	0.496
ch5	0.536	0.512	0.632	0.736		0.52	0.48	0.504
ch6	0.024	0.024	0.024	0.024	0.016		0.032	0.064
ch7	0.328	0.304	0.376	0.392	0.04	0.328		0.56
ch8	0.176	0.168	0.208	0.2	0.016	0.144	0.128	



$$i_c = C\frac{d}{dt}u_c$$

$$u_c = A u_i + B i_c$$

$$u_i = A^{-1} u_c - A^{-1} BC \frac{d}{dt} u_c$$

$$u_i = \frac{1}{A}\left(u_c - BC\frac{du_c}{dt} \right)$$

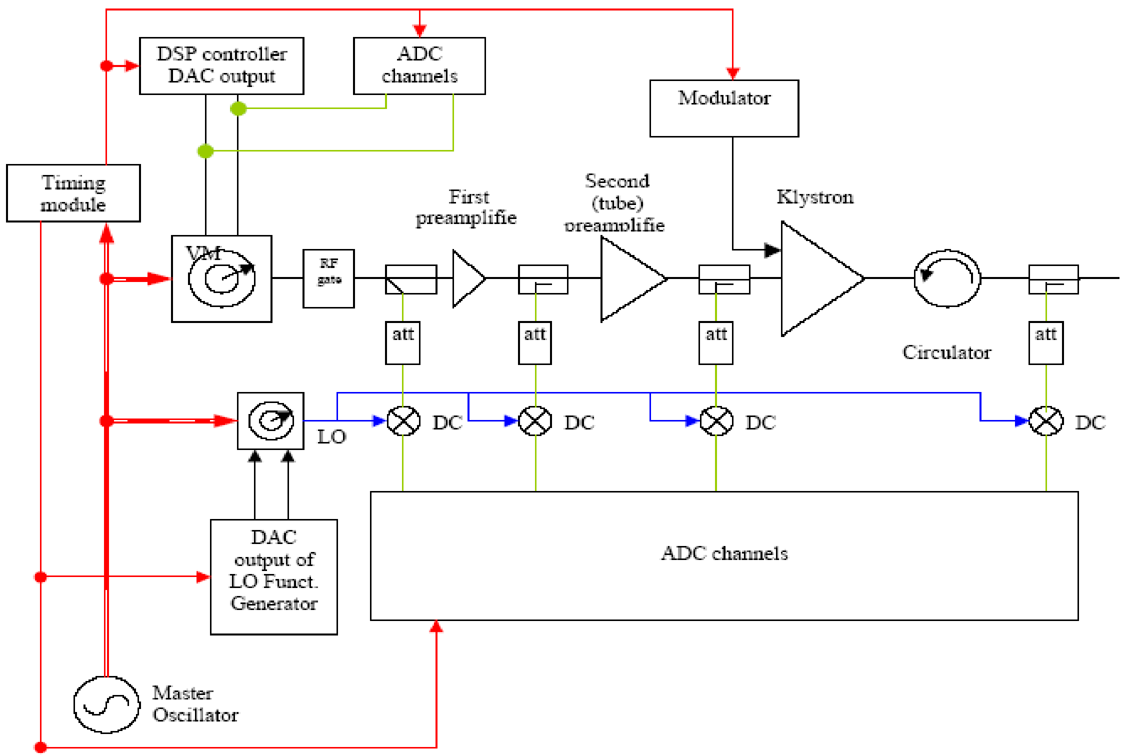
Conclusion

- The tests were succesfull proving the piezos can compensate LFD in new high-gradient accelerating modules
- Future plans
  - redesigning of PZD 8/1 PCB board with more attention to crosstalk between channels
  - integration of temperature sensors
  - design of 32 channel ADC and DAC boards
  - design of HV Power Supply unit

Klystron Linearization

Non-linearities measurement purpose

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



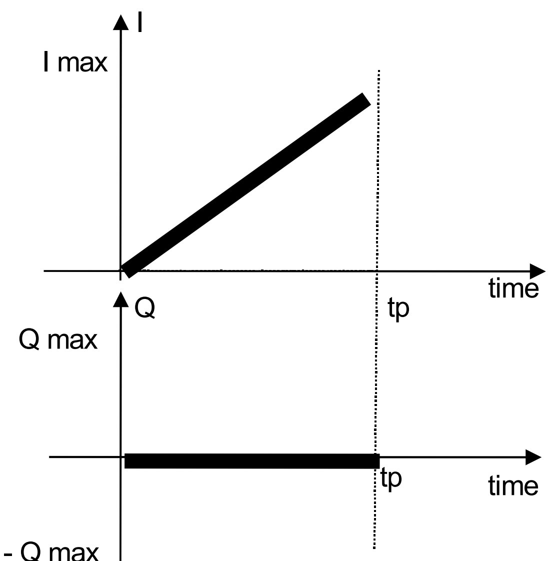
This characterization will be used in the linearization method designing for a klystron and high power amplifiers.

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

High power chain non-linearities

Non-linearities and saturation phenomena:
-increasing the driving power -> non-linear amplifier behaviour
-constant increasing of driving power -> saturation
-different saturation level for a different working parameters values

Test signal (as far as nonlinearities are only amplitude dependent):
Signal parameters:
Pulse length – 1200 us,
Number of steps – 50 stp,
Signal range – 0 up to max. available level



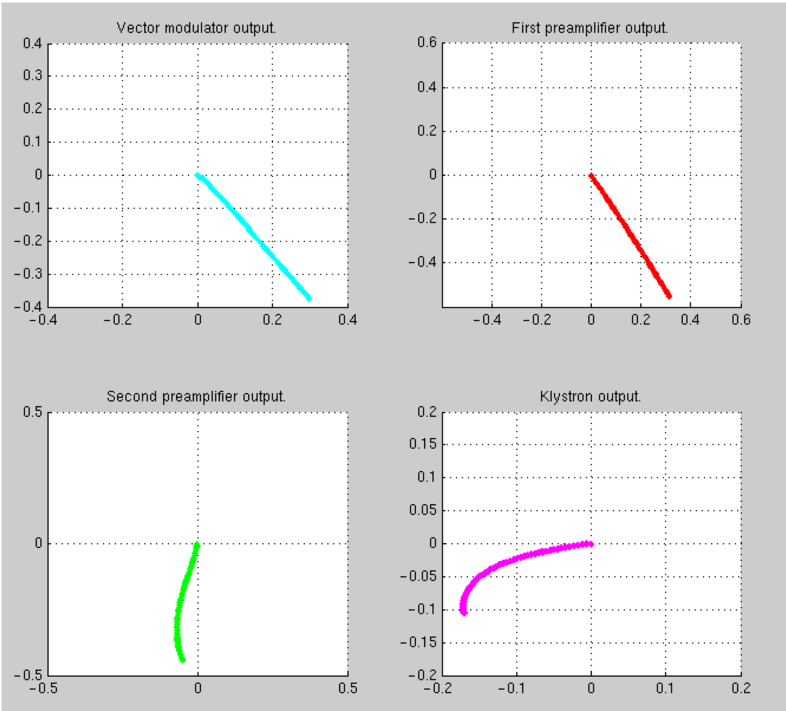
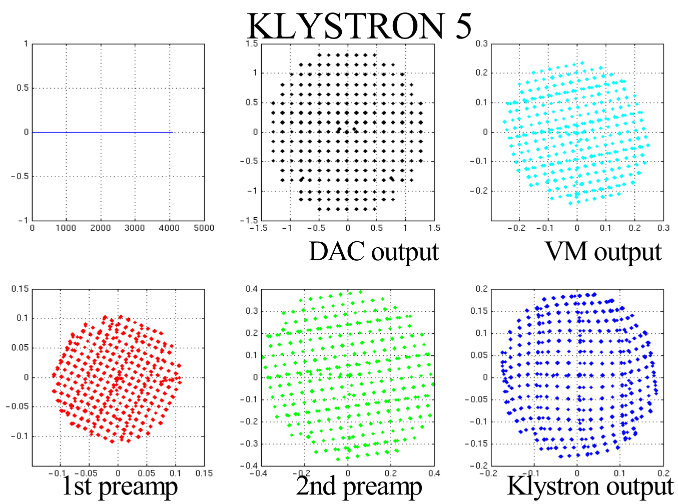
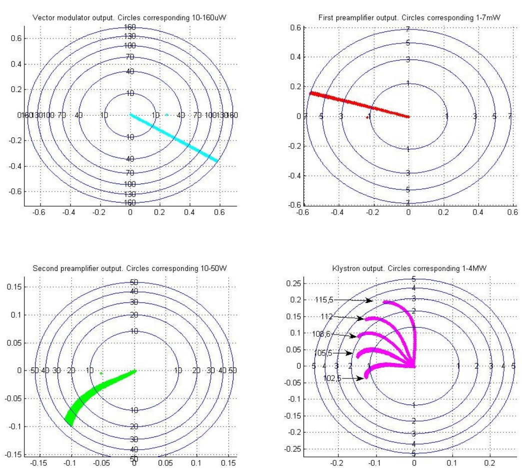


Fig. Complex representation of the HP chain devices
Example for kly. 5 (each axis unit is an ADC voltage)

Results example – klystron 5

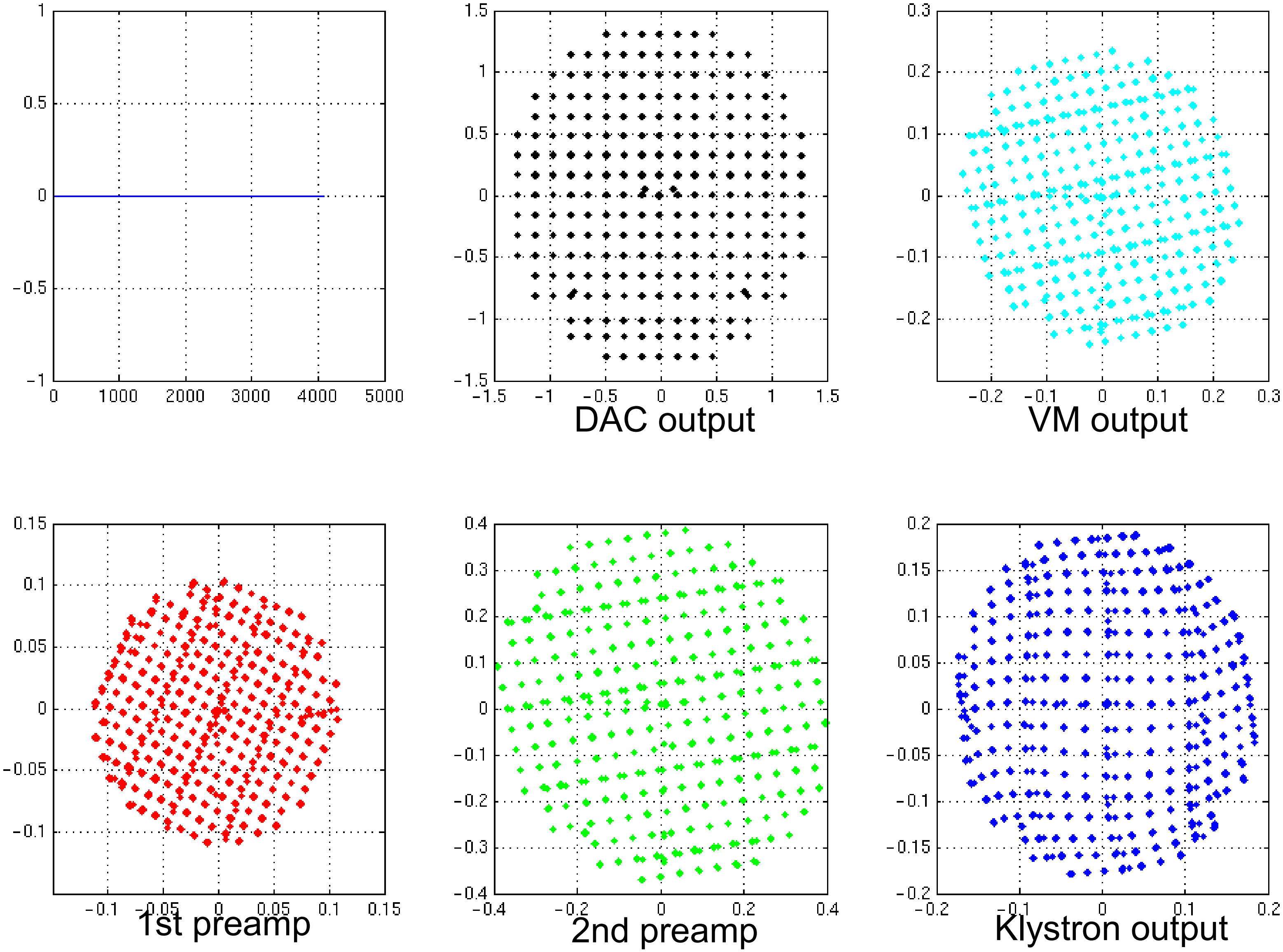


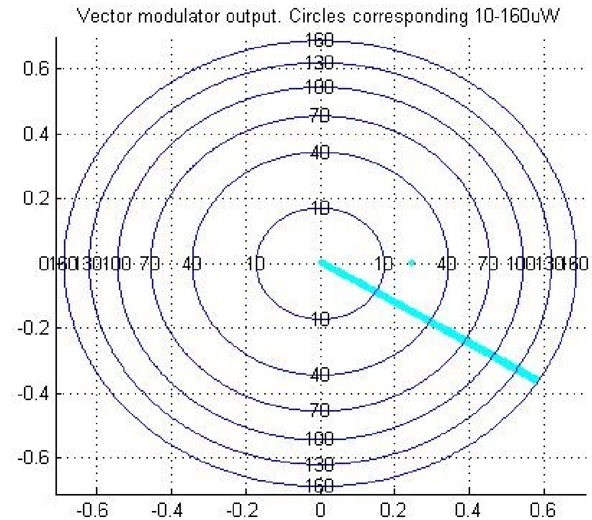
Constellation diagram:
Grid measurement with 20 steps resolution

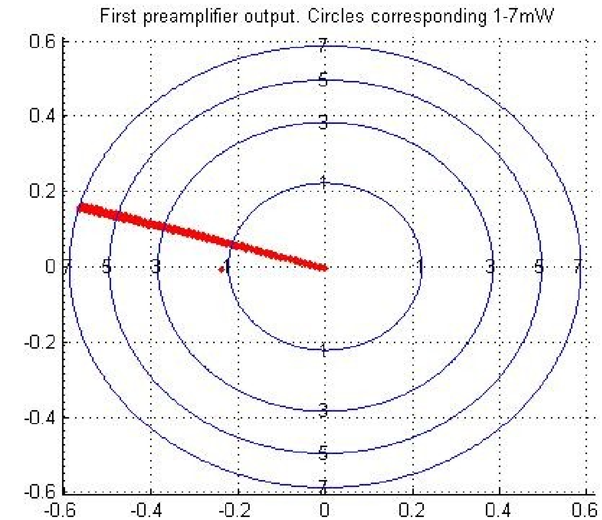


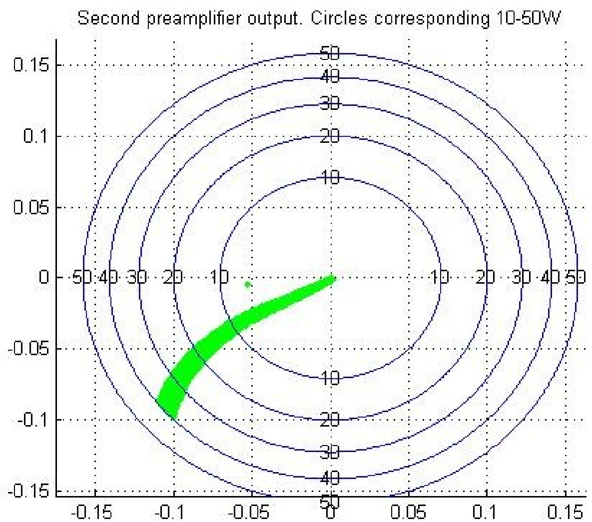
Constellation diagram:
Measurement for one phase - constant Q value (Q=0).
Klystron output characteristics for different HV levels.

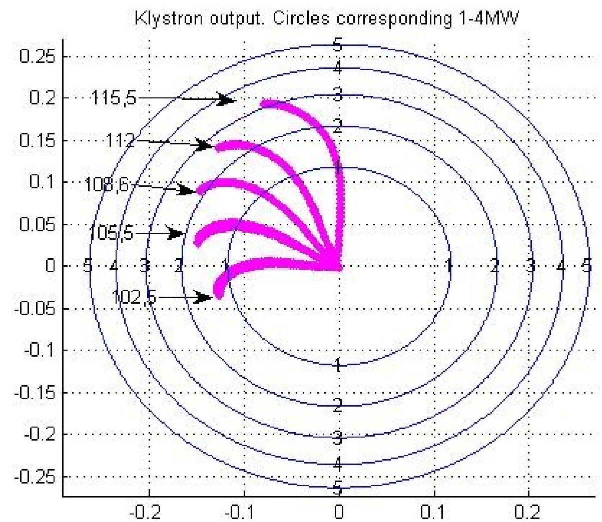
KLYSTRON 5



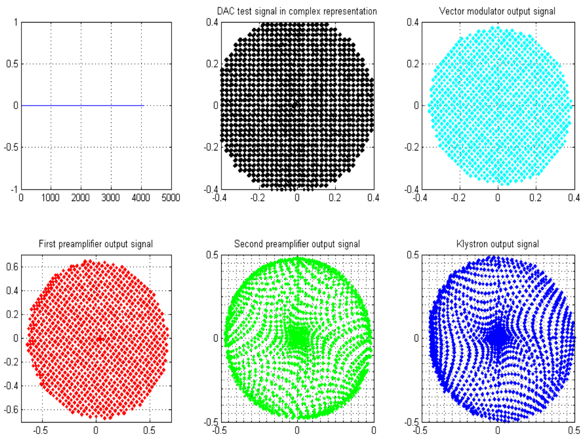

Vector modulator output. Circles corresponding 10-160uW
160
130
100
70
40
10


First preamplifier output. Circles corresponding 1-7mW
7
5
3
1

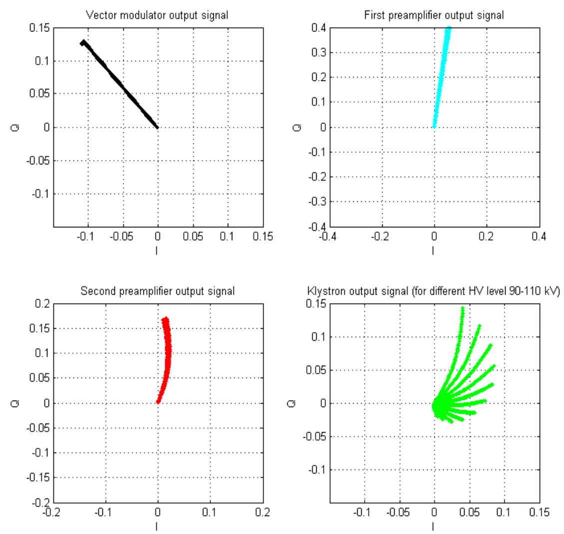

Second preamplifier output. Circles corresponding 10-50W
50
40
30
20
10


Klystron output. Circles corresponding 1-4MW
115,5
112
108,6
105,5
102,5

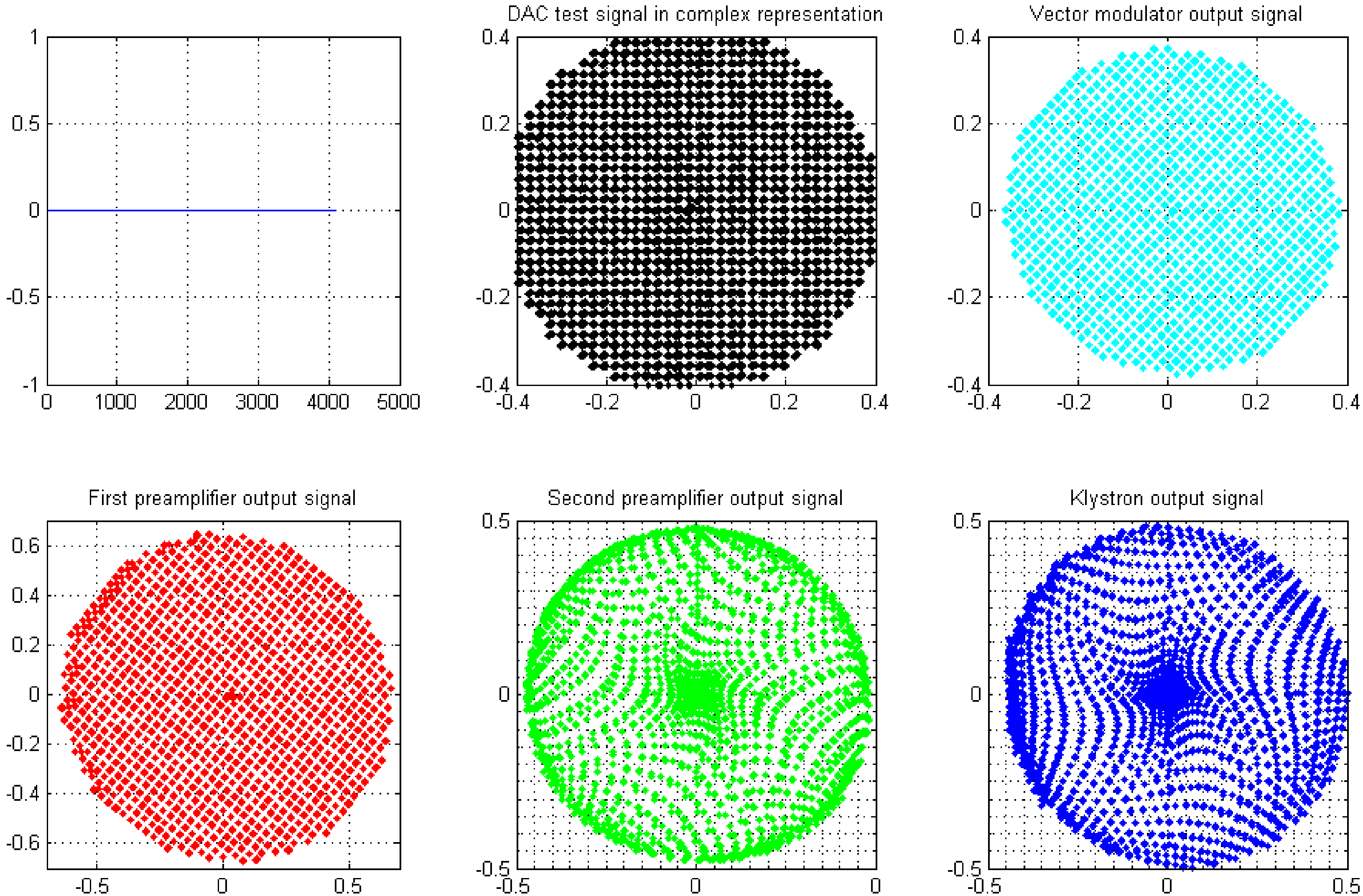
Results example – klystron 2



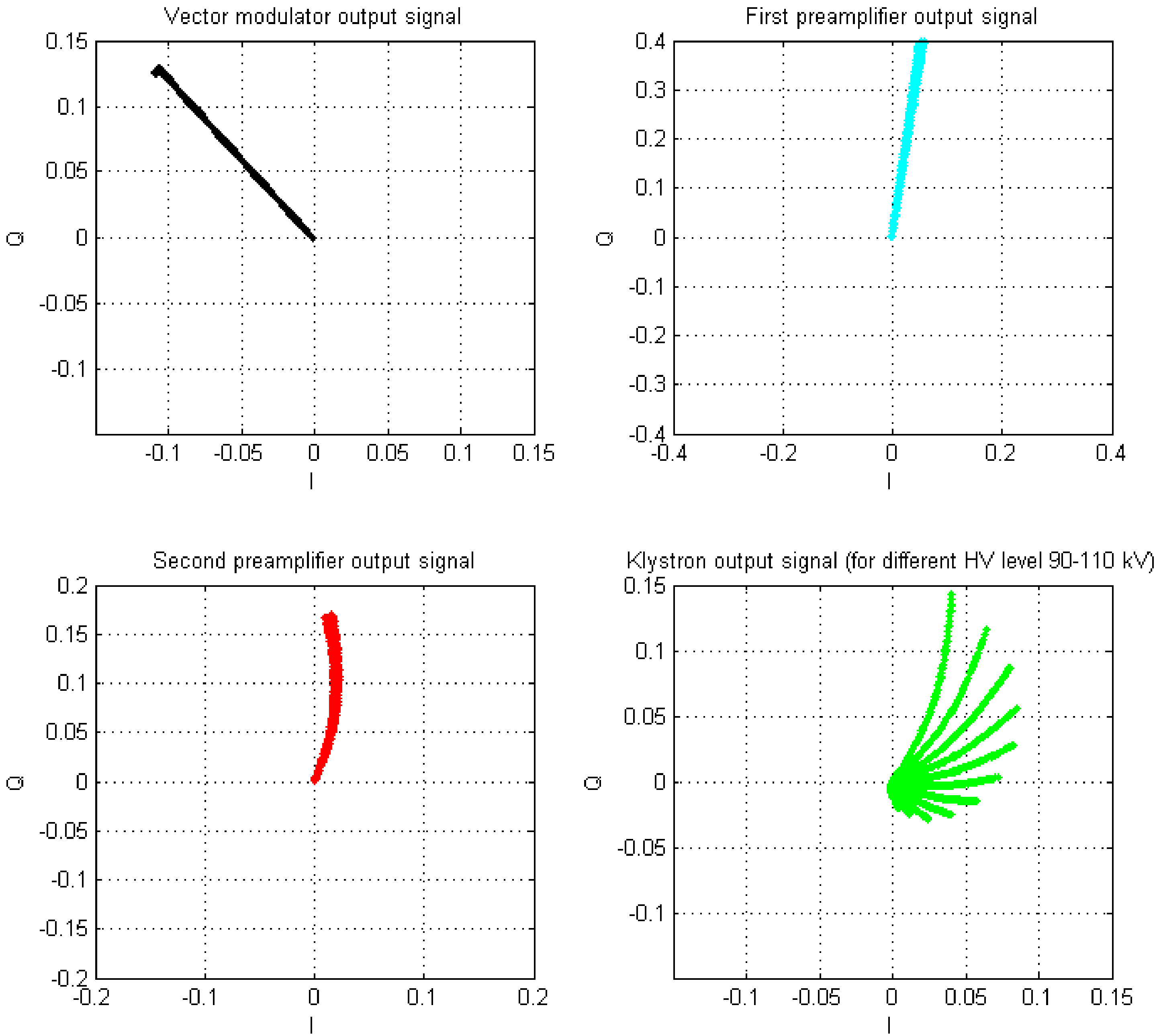
Constellation diagram measurement:
Grid measurement with 50 steps resolution



Constellation diagram measurement:
Measurement for one phase - constant Q value (Q=0).
Klystron output characteristics for different HV levels.
Due to FPGA DAC's output level limitation – input signal range is about half of the regular one.



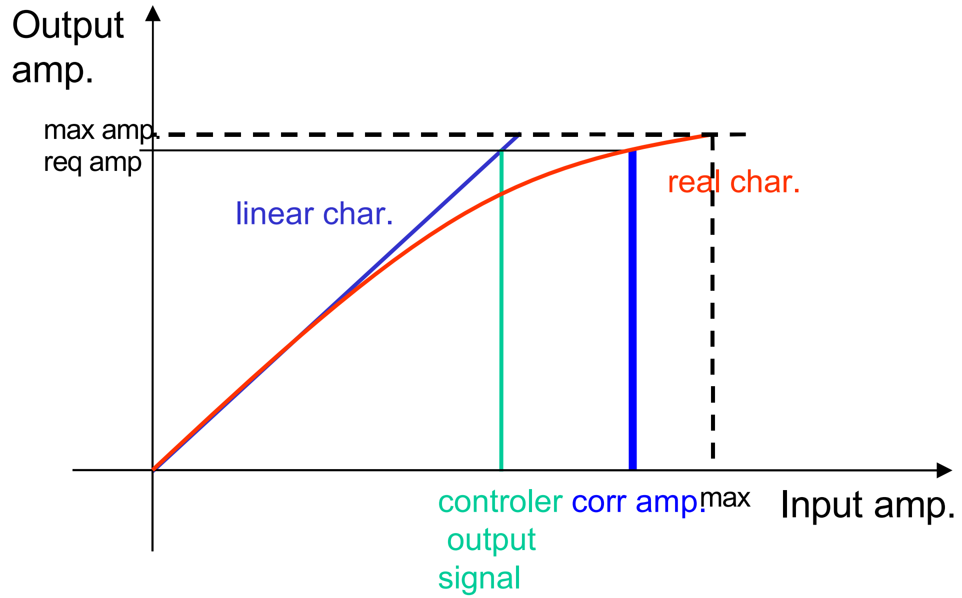
DAC test signal in complex representation
Vector modulator output signal
First preamplifier output signal
Second preamplifier output signal
Klystron output signal


Vector modulator output signal
First preamplifier output signal
Second preamplifier output signal
Klystron output signal (for different HV level 90-110 kV)
Q
I
0.15
0.1
0.05
0
-0.05
-0.1
0.4
0.3
0.2
-0.2
-0.3
-0.4

Linearisation algorithm

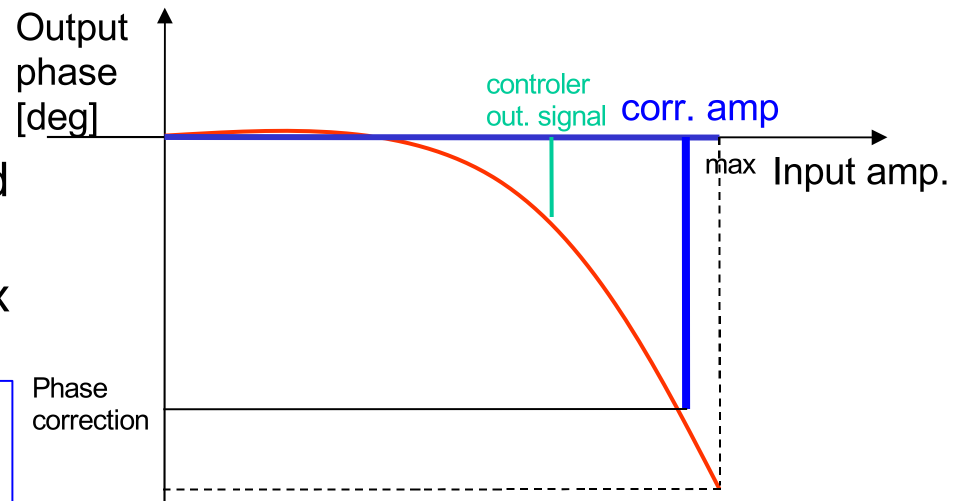
From the non-linearity measurement the AM/AM (amplitude to amplitude) and PM/AM (phase to amplitude) of the high power chain can be achieved.

NOTE!! The nonlinearity is only function of input amplitude.



Driving signal representation:

Z = Id + Qd = |Z| * [cos(phi) + i * sin(phi)]



Correction signal:

C = Ic +Qc = |C| * [cos(th) + i * sin(th)]

From the linearisation both amplitude and phase correction are achieved.

Can be realised using the complex multiplication.

C*Z = Idc + i*Qdc

C*Z = ||Z|*|C||*[cos(phi+th)+i*sin(phi+th)]

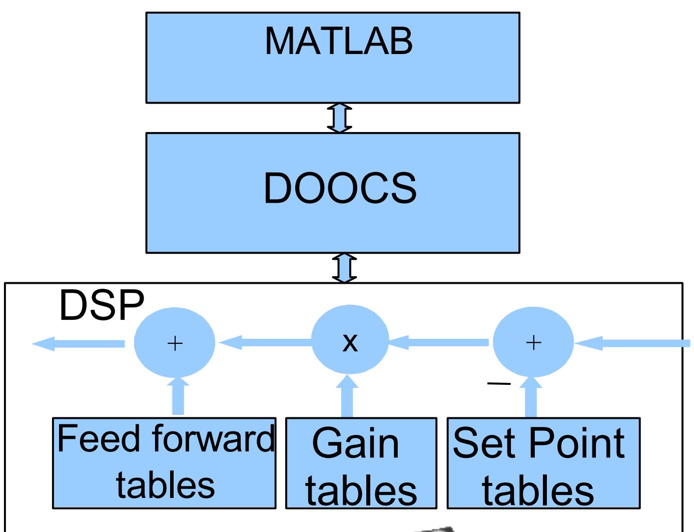
Linearisation algorithm FPGA Simcon and DSP realisation.

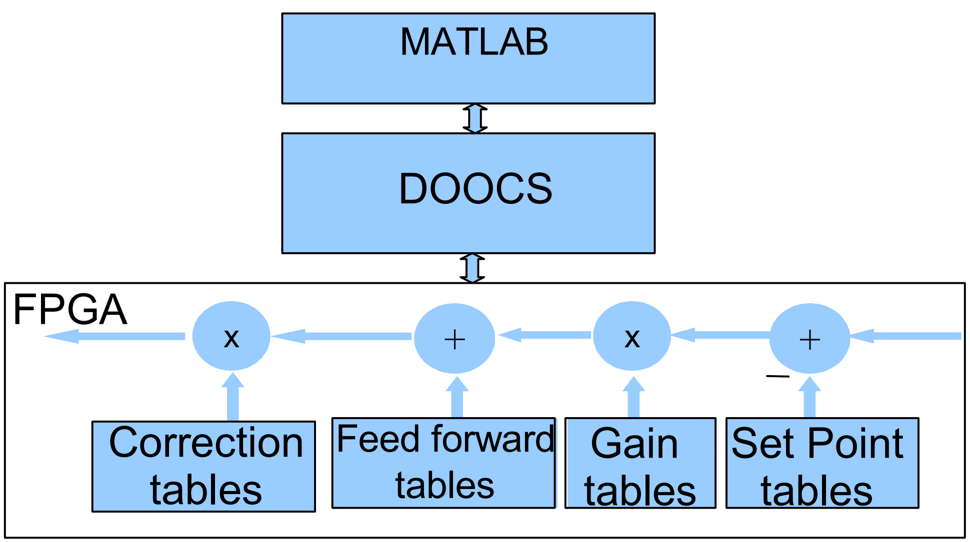
DSP realization:

- correction tables calculated in Matlab,
- controller signal correction performed in Matlab (Feed Forward tables correction),
- correction possible from pulse to pulse (FF tables can be read and write in gap between pulses)
- DOOCS server provided for Feed Forward tables modification and monitoring signals read-out's.

FPGA Simcon realization:

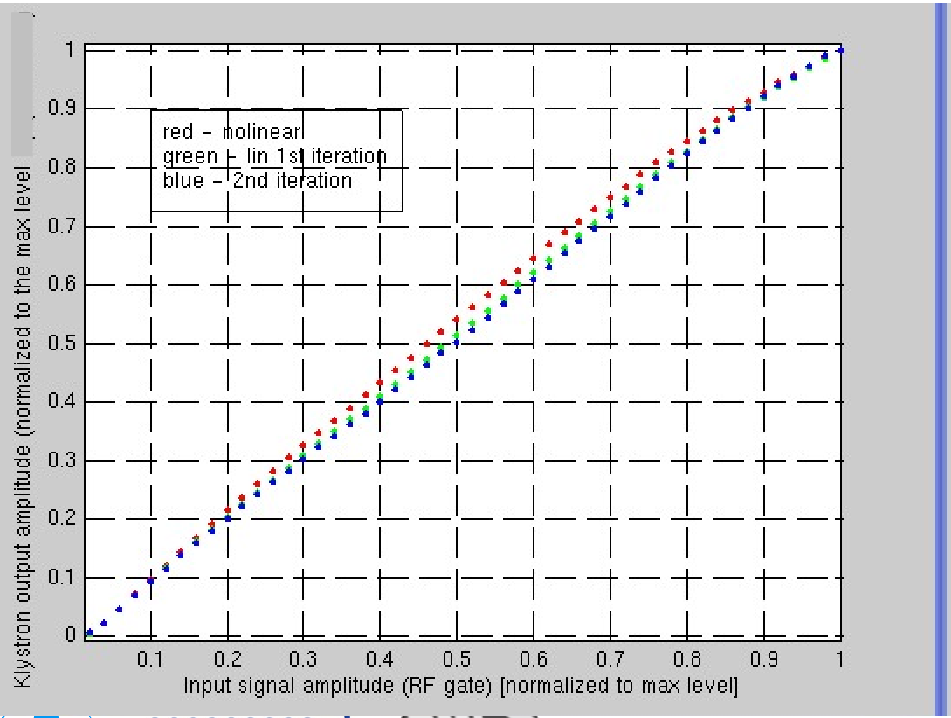
- correction tables calculated in Matlab,
- controller signal correction performed in the FPGA (using: cordic algorithm for amplitude calculation for Ic and Qc tables addressing, and complex multiplication function (WJ)),
- dedicated tables (2048 positions) for I and Q correction vector definition provided (possible slow feedback application)
- correction possible in-pulse to pulse (during the pulse amplitude of each sample generated in open/close loop operation, is corrected)
- DOOCS server provided for tables actualisation (PF)

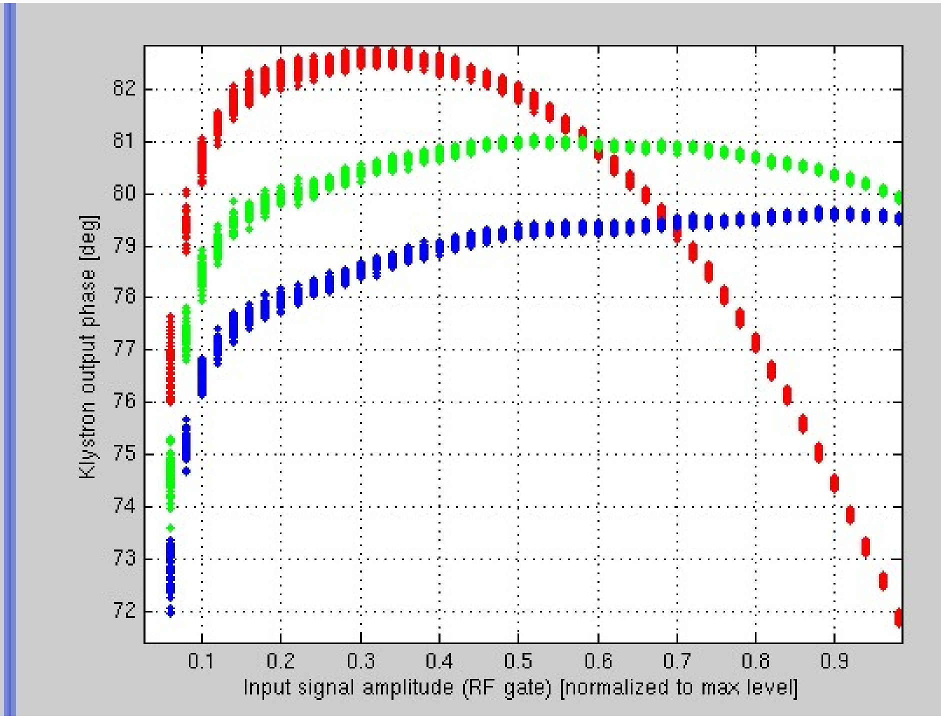




Klystron 5 HPC linearisation results

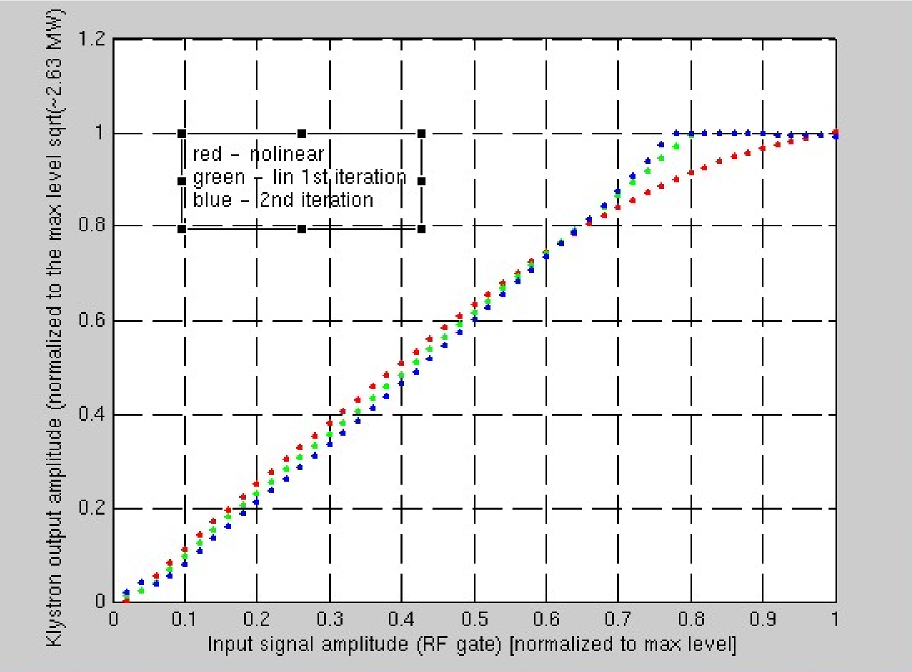
- Linearisation test had been performed using Simcon(FPGA) controler,
- Correction tables were „on”
- HV level – 10800 (value on PLC) about 110kV
- Two iteration of the linearisation were performed.

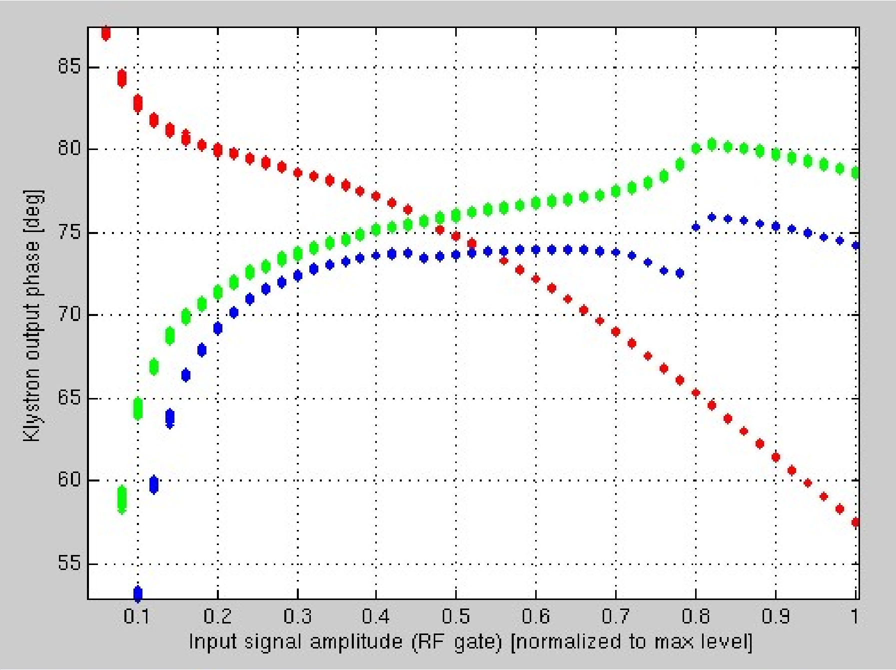




Klystron 5 HPC linearisation results

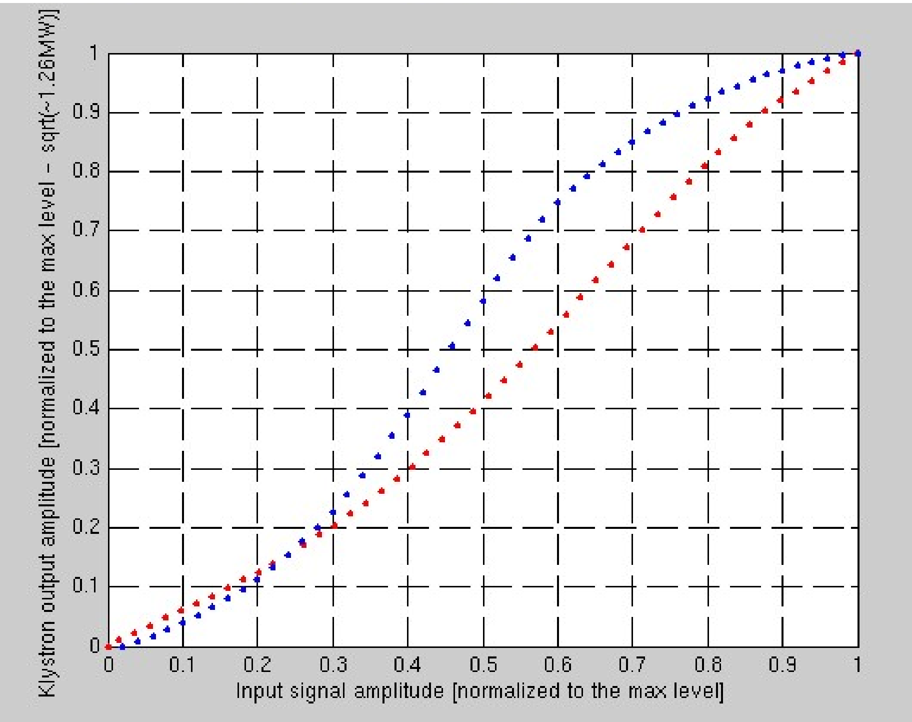
- Linearisation test had been performed using DSP based controler,
- Correction had been applied to the FeedForward Tables
- HV level – 10800 (value on PLC) about 110kV
- Two iteration of the linearisation were performed.

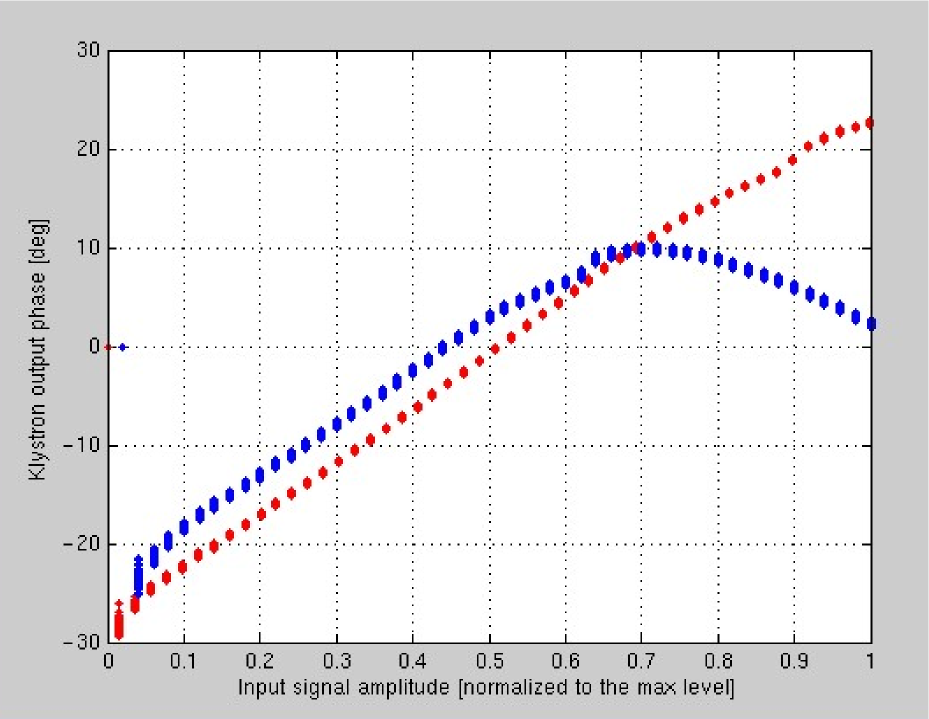




Klystron 2 HPC linearisation results (1/2)

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

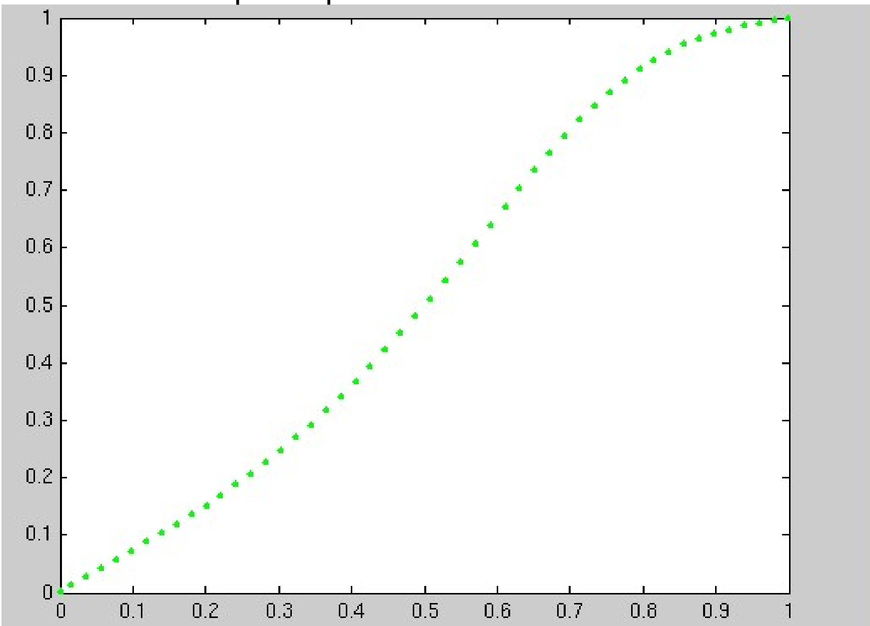




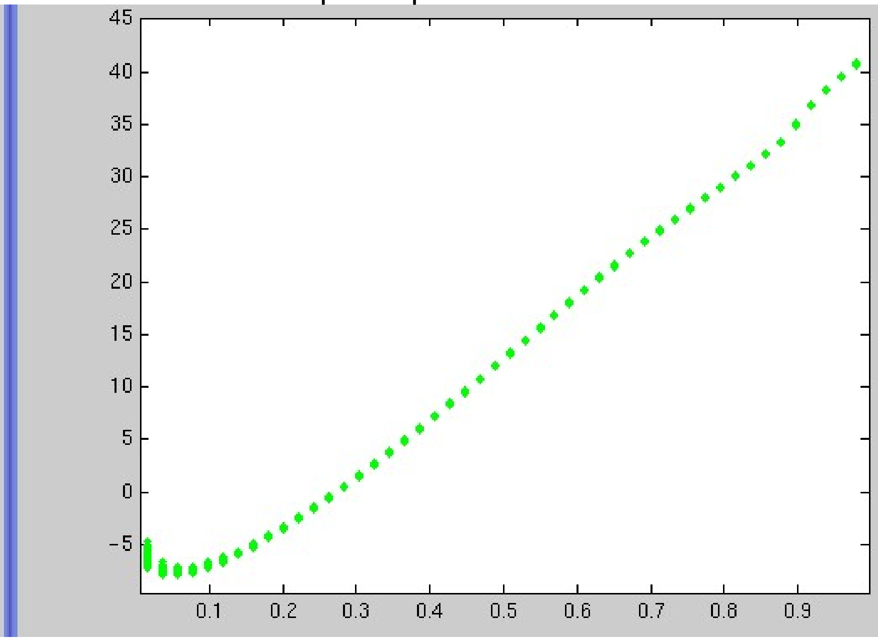
Klystron 2 HPC linearisation results (2/2)

- Strong nonlinearity can be already observed after the second preamplifier.
- Preamplifier exchange from present tube one to this specyfied and ordered by MHF-p should improve situation by factor of 10 or better.

Second preamplifier AM/AM characteristic

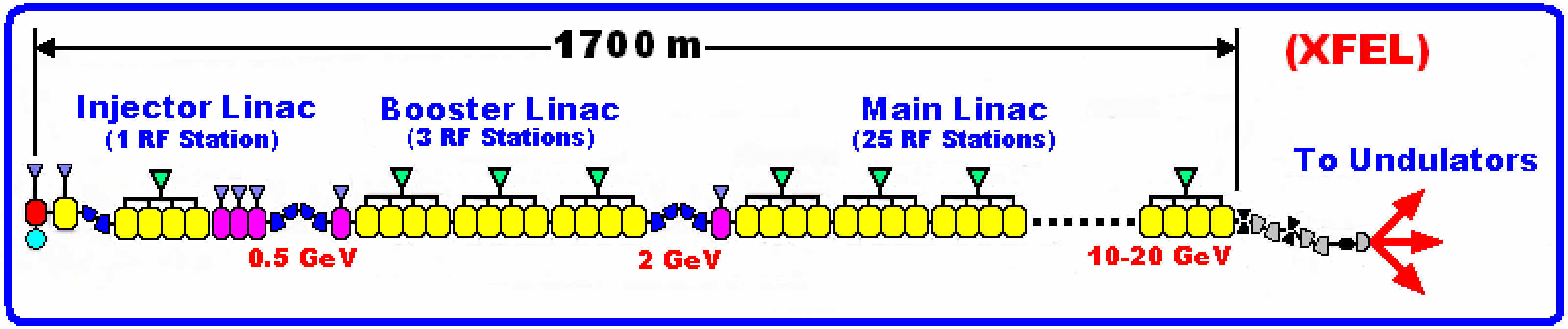


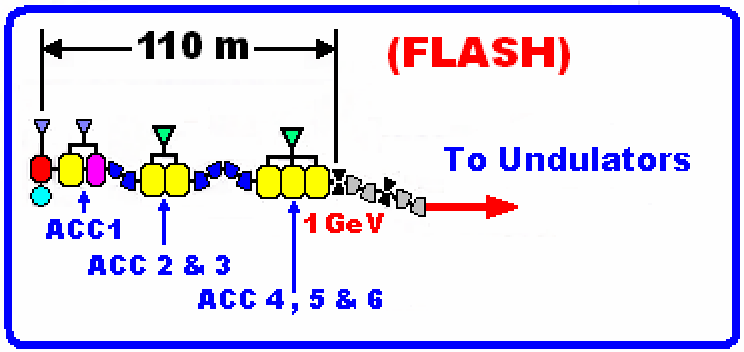
Second preamplifier PM/AM characteristic

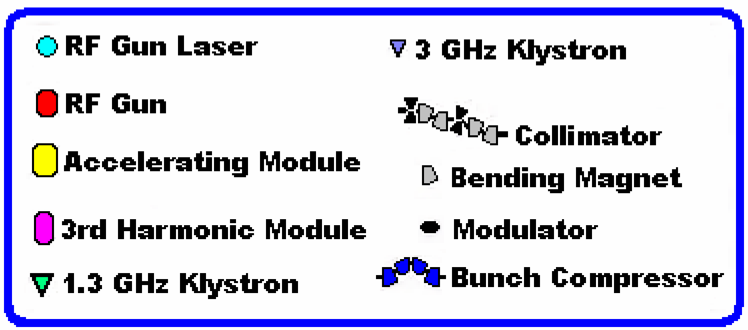


Radiation Measurements

Linac sections of XFEL and FLASH : Intercomparison







PARAMETERS	FLASH	XFEL
Length(m)	110	1700
End Energy(GeV)	1	20
Number of Modules	6	116
Number of Cavities	48	928
Cavity Type	TESLA	TESLA
Number of RF Stations	4	29
Location of RF Stations	Outside	In Tunnel
Gradient (MV/m)	16-21	23.6-30
QF (unloaded)	5.0E09	10E10
Repetition Rate (Hz)	5 - 10	10
RF Pulse Length	1.33	1.40
Beam Pulse Length (ms)	0.80	0.65
Wavelength (nm)	1	0.1
Peak Power (kW)	208	600

BMukh050507

Fig.1

Radiation Measurements conducted at FLASH

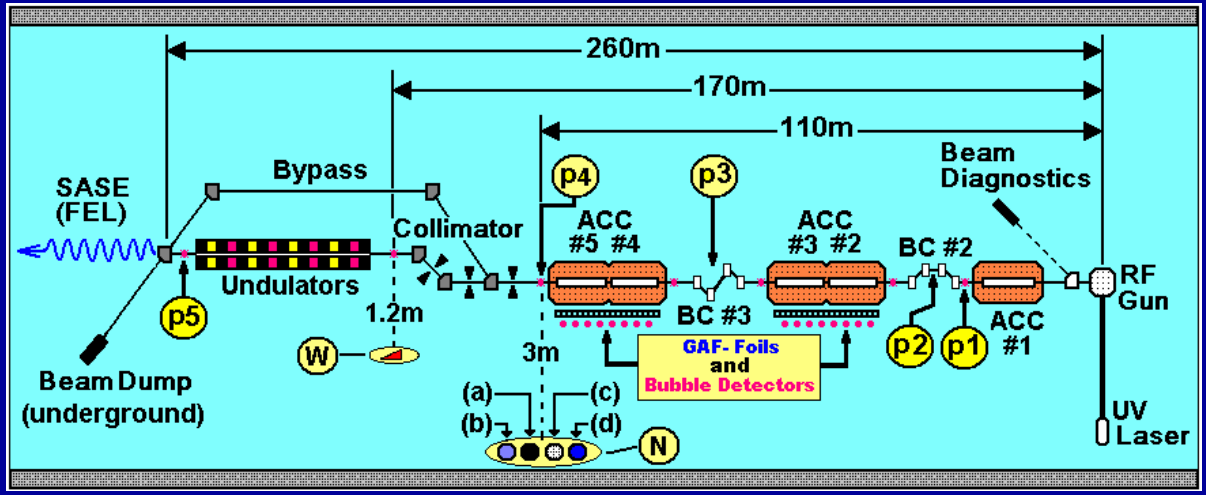


Fig. 2

Exp #1: In-situ gamma dose measurement along accelerator modules ACC1 – ACC5 using radiochromic (GAF) Films and Bubble Detectors

Exp #2: In-situ neutron and gamma dose measurement at accelerator module ACC 5 operating in “Field Emission Mode” using PorTL TLD bulbs and Bubble Detectors

Exp #3: In-situ Photo-Neutron spectrum evaluation near accelerator module ACC 5 (position N) using Bubble Detectors

Exp #4: In-situ unfolding of bremsstrahlung (photon) spectrum near the collimator (position W) using TLD chips embedded in a lead wedge

Exp #5: In-situ measurement neutron dose/fluence at critical locations along the beam pipe (positions p1, p2, p3, p4 and p5)

Exp # 1: Results

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

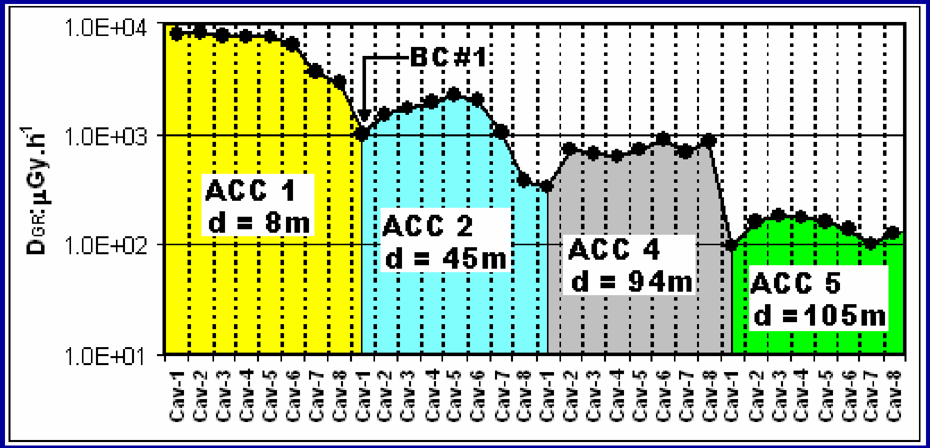


Fig. 3

(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.

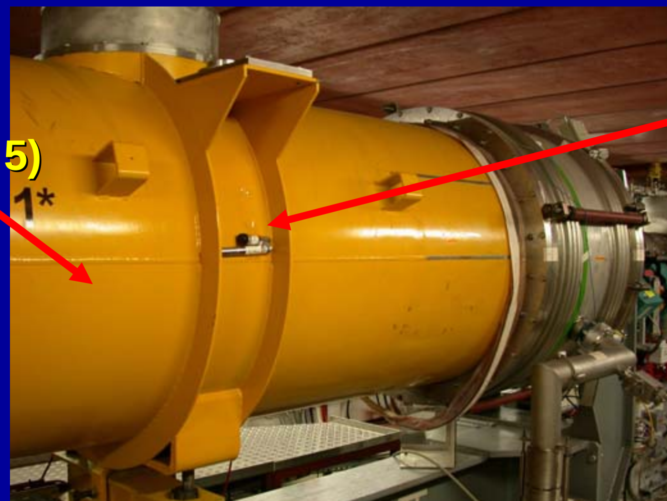
(R1.4) The radiation dose at modules, far away for the RF gun mainly contributed by the accelerated field emission electrons inside cavities.

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

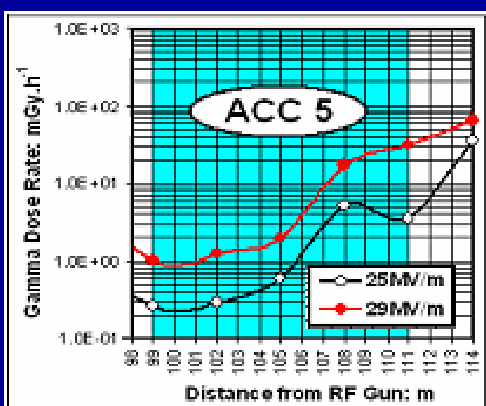
Exp #2: Results

In-situ Gamma/Neutron Dosimetry at FLASH Module

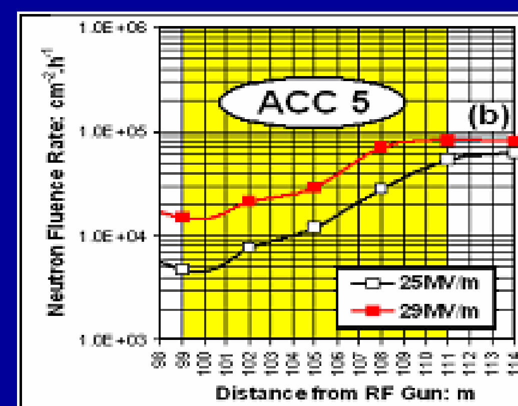
Accelerator Module (ACC 5)



Neutron/Gamma Dosimeter pairs



Field Emission Mode (RF Gun OFF)



Gamma Dose Rate along the module tank, estimated using TLD and GAF-Dosimeters.

Neutron Fluence Rate along the module evaluated with Bubble dosimeters.

Exp #2: Results (continued)

Neutron kerma and Gamma Dose Rates along the Module

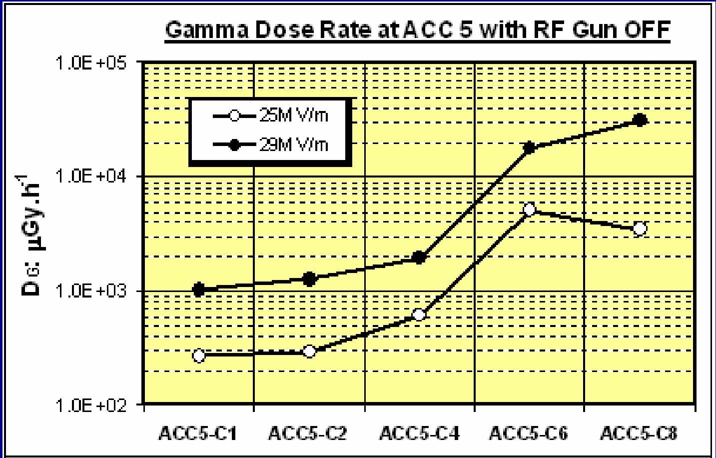


Fig. 4a

Gamma dose rate along ACC 5 running in Field-Emission mode

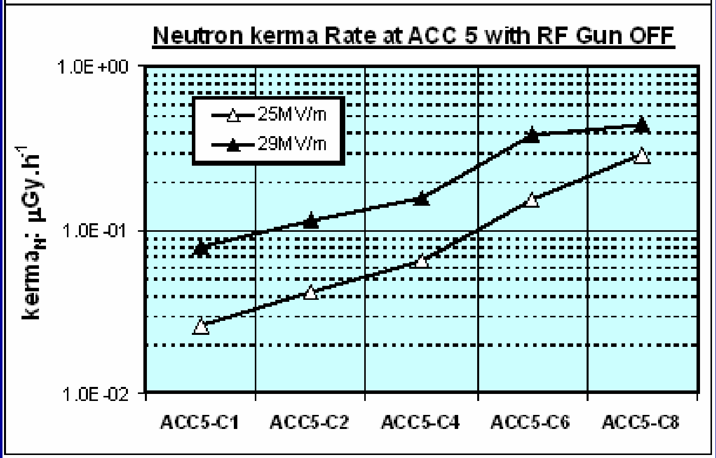


Fig. 4b

Neutron kerma rate along ACC 5 running in Field-Emission mode

- **(R2.1) Gamma Dose rate is 4 orders of magnitude higher than neutron kerma (Si) rate.**

Exp #2: Results (continued)

Gamma Dose Rates evaluated at different Gradient

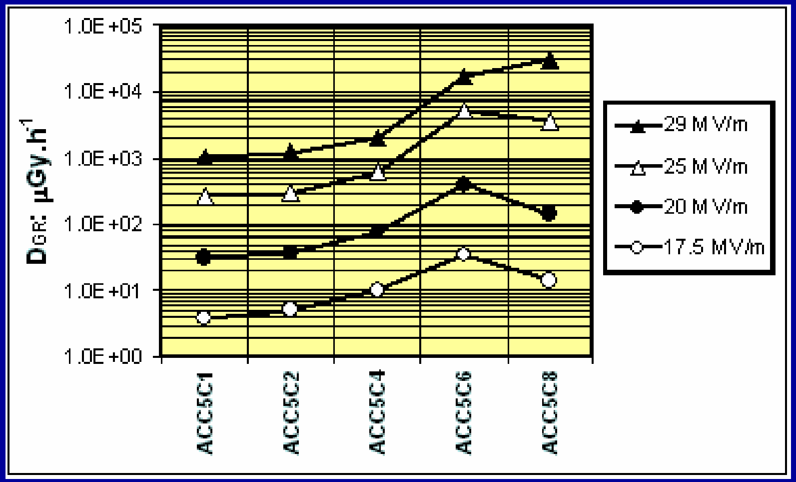


Fig. 5a

Gamma dose rates along ACC 5 estimated using radiochromic films while running in field emission mode (RF gun off).

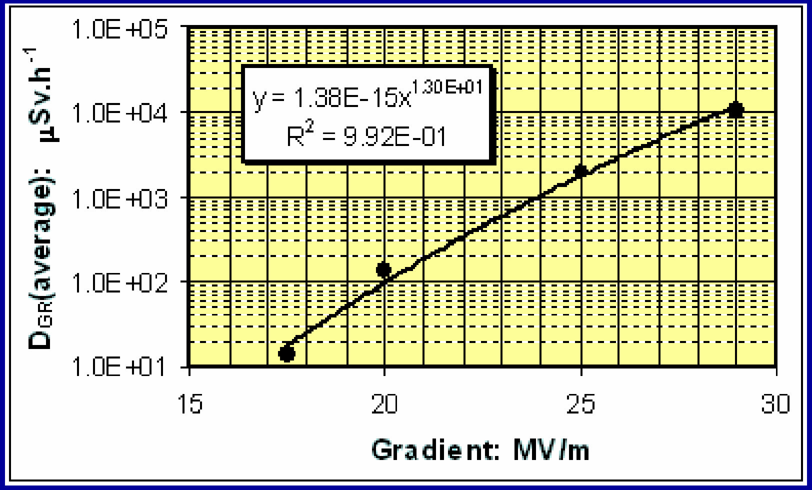


Fig. 5b

Average Gamma dose rate plotted as a function of the Gradient across the module.

- **(R2.2) Gamma Dose Rate skyrockets with the Gradient**

Exp #2: Results (continued)

Radiation induced Cryogenic Loss

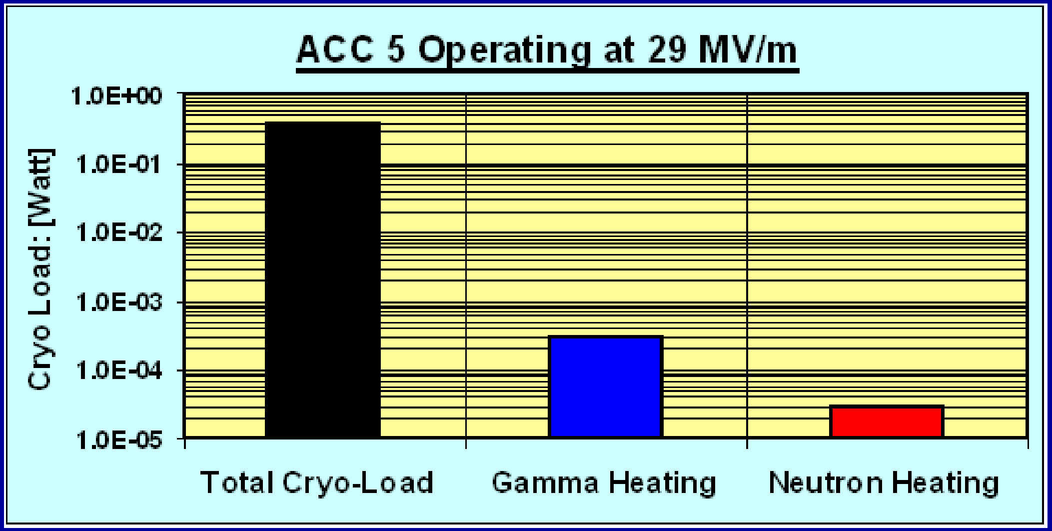


Fig. 6

(R2.3) TLD bulbs (gammas) and Bubble detectors (Neutrons) were used to assess radiation doses (kerma) and then used to derive the Cryogenic Losses (nuclear heating).

(R2.4) Neutron and gamma radiations are produced when high- energy electrons strike the superconducting Niobium cavities.

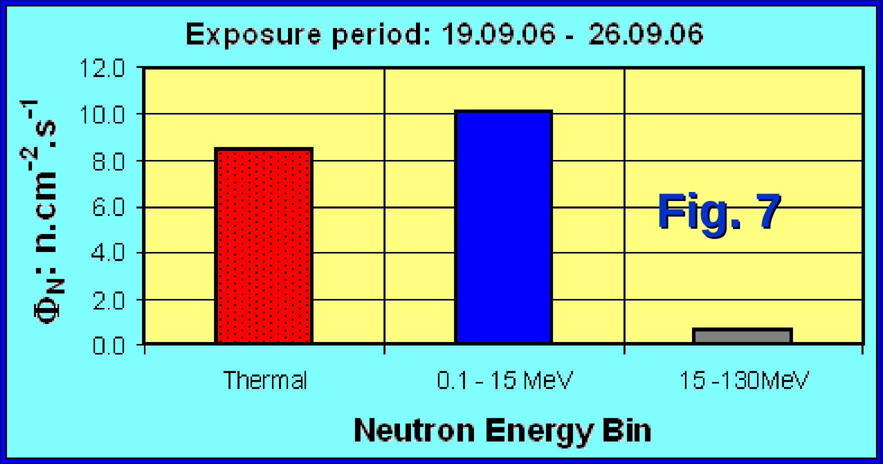
(R2.5) At 2 K, Niobium is superconducting, hence, Ohmic- heat loss is nil. Neutrons and gamma rays interact with liquid He causing Cryogenic Loss.

(R2.6) Radiation induced Heat Generation is more than THREE ORDERS OF MAGNITUDE lower than the loss produced by other sources (???).

Exp #3: Results

Estimation of Photoneutron Energy Distribution (Spectrum) using Bubble Detectors

Bubble detectors are Ideally suited for Pulsed Neutron Dosimetry with a strong gamma background, such as in FLASH/XFEL tunnel.



The 3 bin Neutron Fluence spectrum estimated near ACC 5 (Gradient = 25 MV/m).

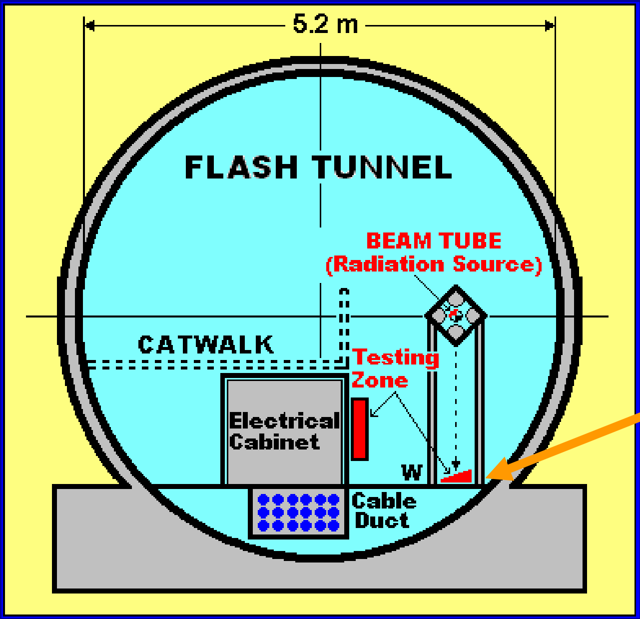
(R3.1) Giant Dipole Resonance neutrons of energy 0.1- 15 MeV are most predominant

(R3.2) Thermal neutrons are produced by room scattering of photoneutrons (s. above) and may trigger SEU in some microelectronic memories.

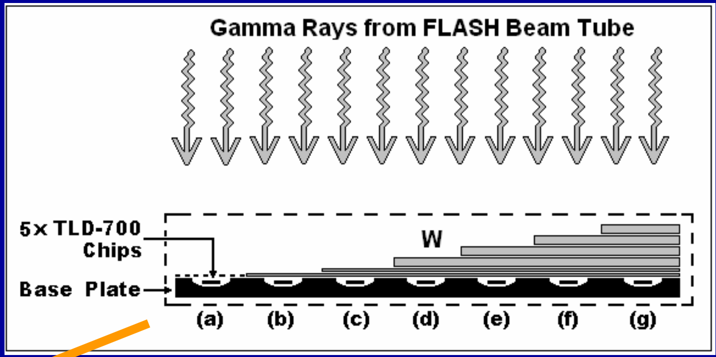
(R3.3) Number of high-energy (> 15 MeV) neutrons are significantly low.

Exp #4: Results

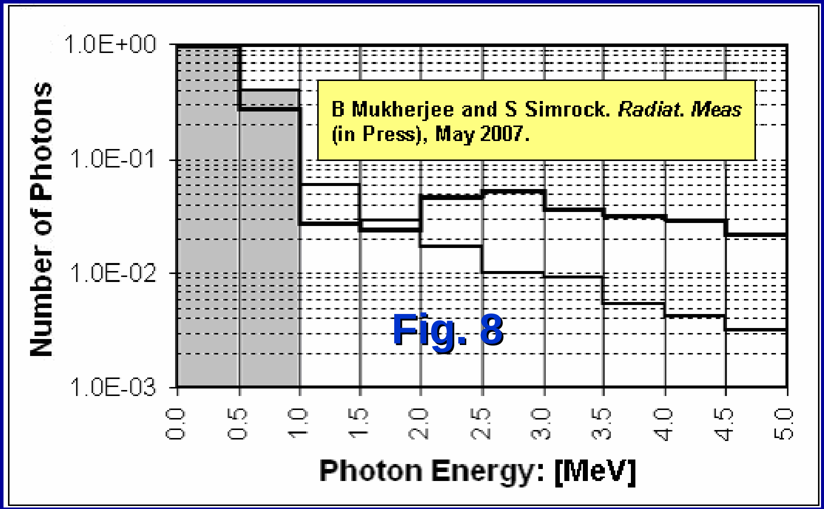
Unfolding of the Bremsstrahlung Spectrum



Location of the Lead Wedge in the FLASH Tunnel



The Lead wedge embedded with TLD Chips



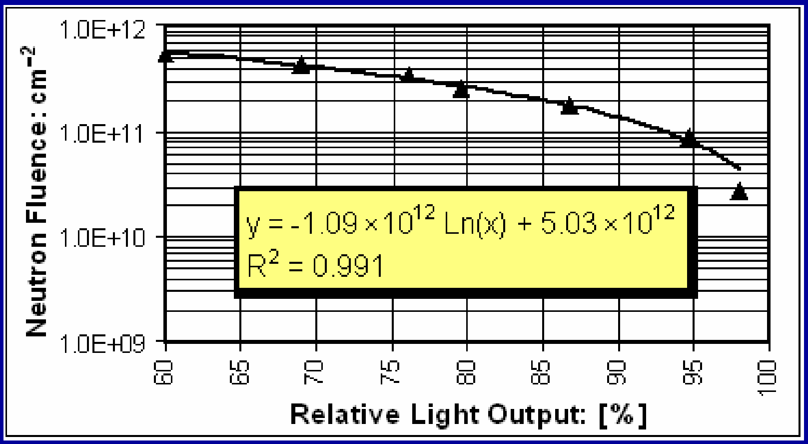
The unfolded bremsstrahlung spectrum

(R4.1) The peak and average bremsstrahlung (BS) photon energy were calculated to be 0.5 and 0.9 MeV respectively

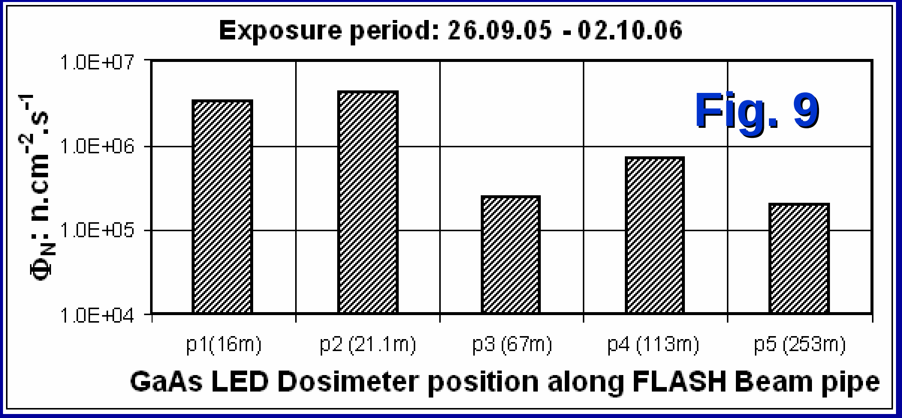
(R4.2) Major (92%) part of the BS is contained within 1 MeV band (shaded area)

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.

Applicability of FLASH Radiation Data for the prediction of Radiation Levels in XFEL

Based on the following grounds

(1) Radiation fields are locally produced by the accelerated field emissions in the cavities itself, not by the primary high-energy electron beam (*Fig. 3*).

(2) The Gamma dose (kerma) outperforms the neutron kerma by excess of 4 orders of magnitude (*Fig. 4a* and *4b*), also be valid for XFEL

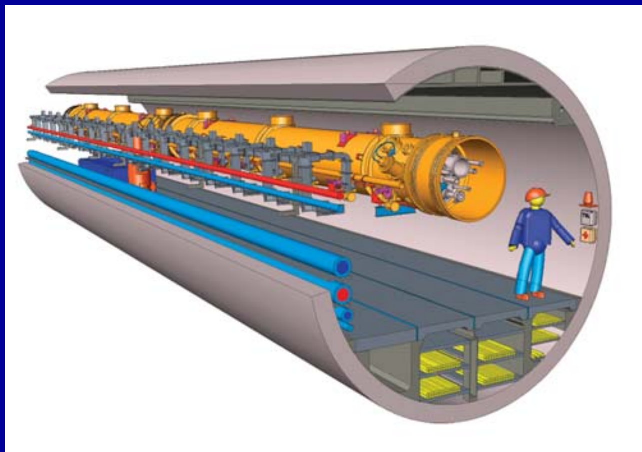
(3) For both FLASH and XFEL the major radiation component are photons, the relevant photon dose depends solely on the gradient across the cavity (*Fig. 5a* and *5b*) and the surface quality (polishing) of the cavities.

(4) Same type of superconducting TESLA cavity presently used at FLASH will be deployed in XFEL project (*Fig. 1* and *2*). Hence, we can predict the radiation induced cryogenic loss will also be very low for XFEL (*Fig. 6*).

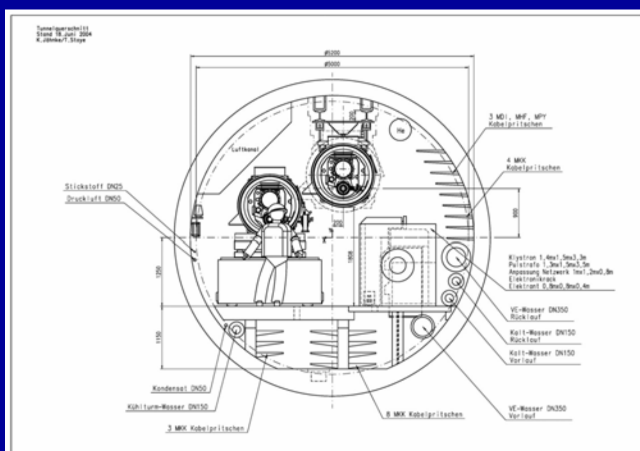
(5) The energy spectra (*accelerated field emission electron generated*) of the photoneutrons (*Fig. 7*) and bremsstrahlung (*Fig.8*) for both FLASH and XFEL will be quite similar.

(6) The electron energy at bunch compressors of FLASH and XFEL (*Fig.1*) will be within the 0.5 – 2 GeV band, hence, the characteristics of the stray neutrons produced in the beam pipe will be the same (*Fig. 9*).

Application: Shielding for LLRF Electronics in XFEL Tunnel



Panoramic view of the XFEL Tunnel showing the Cryomodule, Utility ducts and Electrical cable trays.



Tunnel Cross Section.

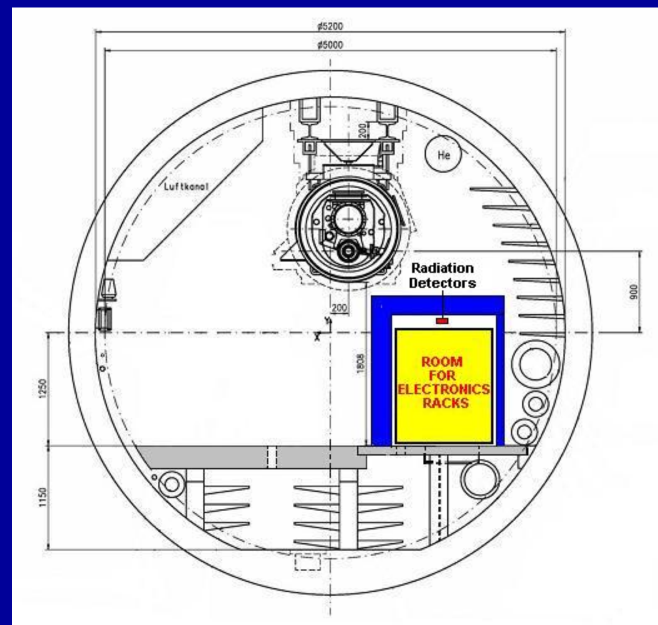


Fig. 10

Shielded Space allocated for the LLRF-Electronics and associated Radiation detectors.

(1) Data from FLASH studies was used as source terms for MCNP simulation

(2) Heavy concrete (ρ = 3.8 g.cm^{-3}) with 10 % B_4C additive was found to be most suitable

Application of FLASH data to predict the Radiation Effects in Electronic Components to be placed in XFEL Tunnel

Radiation Data	G = 30 MV/m		G = 23.6 MV/m	
D_G (no shield): [$\mu Gy.h^{-1}$]	2.2×10^4		9.72×10^2	
D_G (no shield)/10y: [Gy]	1.76×10^3	(a0)	7.78×10^1	(b0)
D_G (shield)/10y: [Gy]	33.4	(as)	1.48	(bs)
Φ_N (no shield): [$cm^{-2}h^{-1}$]	6.91×10^5		5.54×10^5	
Φ_N (no shield)/10y: [cm^{-2}]	5.53×10^{10}	(a0)	4.32×10^{10}	(b0)
Φ_N (shield)/10y: [cm^{-2}]	4.42×10^{10}	(as)	3.46×10^{10}	(bs)

Table 1

Shielding: 20 cm Heavy Concrete
Dose reduction factor: 0.019

Neutrons

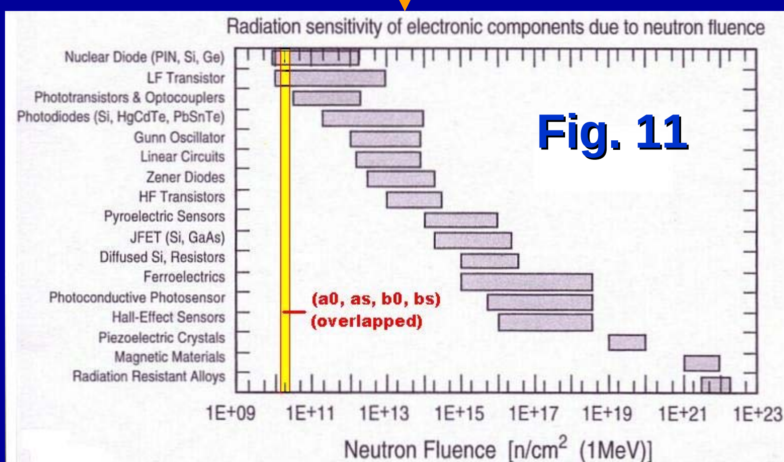


Fig. 11

Gammas

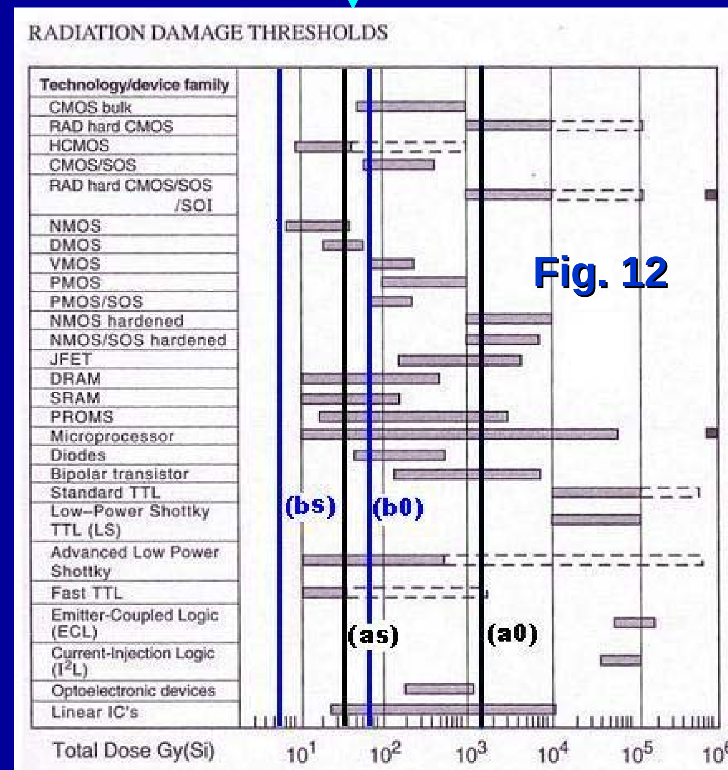
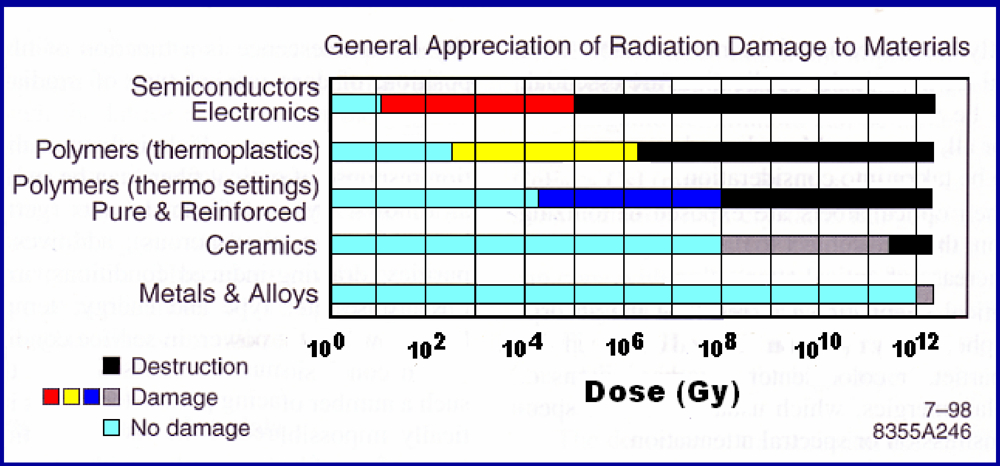


Fig. 12

Reference: A W Cho and M Tigner (Eds): *Handbook of Accelerator Physics and Engineering*, World Scientific, Singapore, London, 3rd Edition, 2006.

Radiation Effects on Various Materials: Summary

Radiation Data	G = 30 MV/m	G = 23.6 MV/m
D_G (no shield): [μGy.h^{-1}]	2.2×10^4	9.72×10^2
D_G (no shield)/10y: [Gy]	1.76×10^3 **(a0)**	7.78×10^1 **(b0)**
D_G (shield)/10y: [Gy]	33.4 **(as)**	1.48 **(bs)**
Φ_N (no shield): [cm^{-2}h^{-1}]	6.91×10^5	5.54×10^5
Φ_N (no shield)/10y: [cm^{-2}]	5.53×10^{10} **(a0)**	4.32×10^{10} **(b0)**
Φ_N (shield)/10y: [cm^{-2}]	4.42×10^{10} **(as)**	3.46×10^{10} **(bs)**



Semiconductors are most vulnerable

Followed by Polymers, i.e. optocouplers, Optical fibre etc.

Example:

Gamma Dose Rate near ACC 1 (Figure 3): 0.01 Gy/h

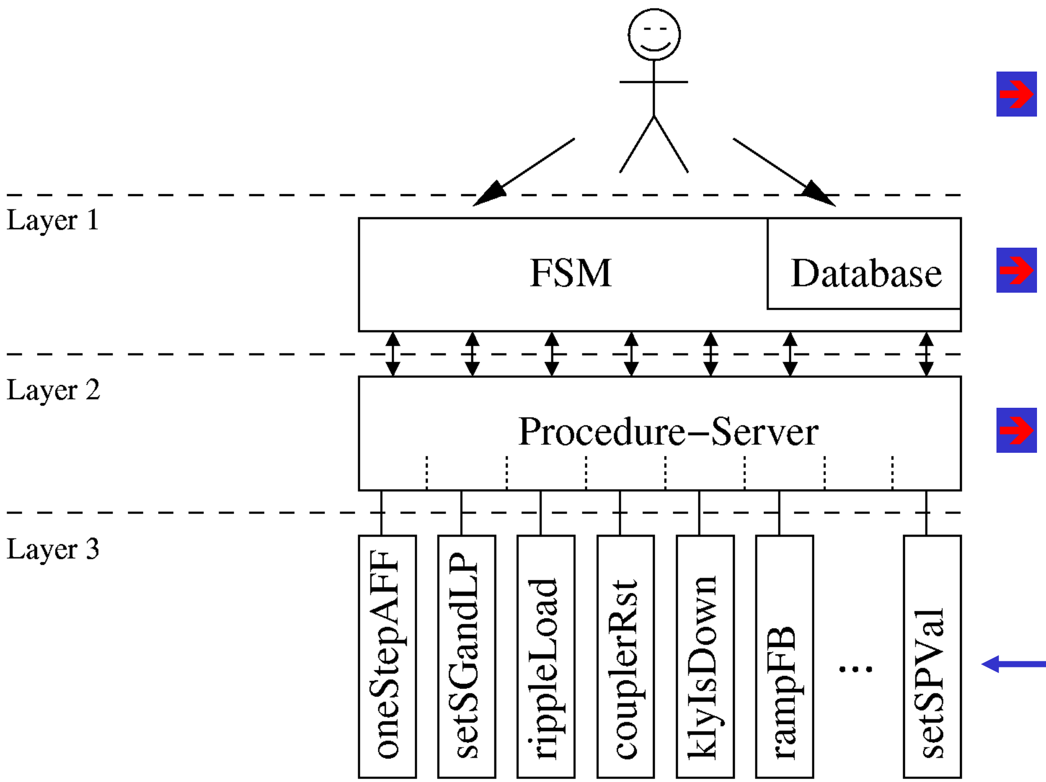
Hence,
Damage threshold for semiconductors will reach after: 1000 hours

Damage threshold for optical devices will reach after: 50000 hours

Reference: A W Cho and M Tigner (Eds): *Handbook of Accelerator Physics and Engineering*, World Scientific, Singapore, London, 3rd Edition, 2006.

Automation

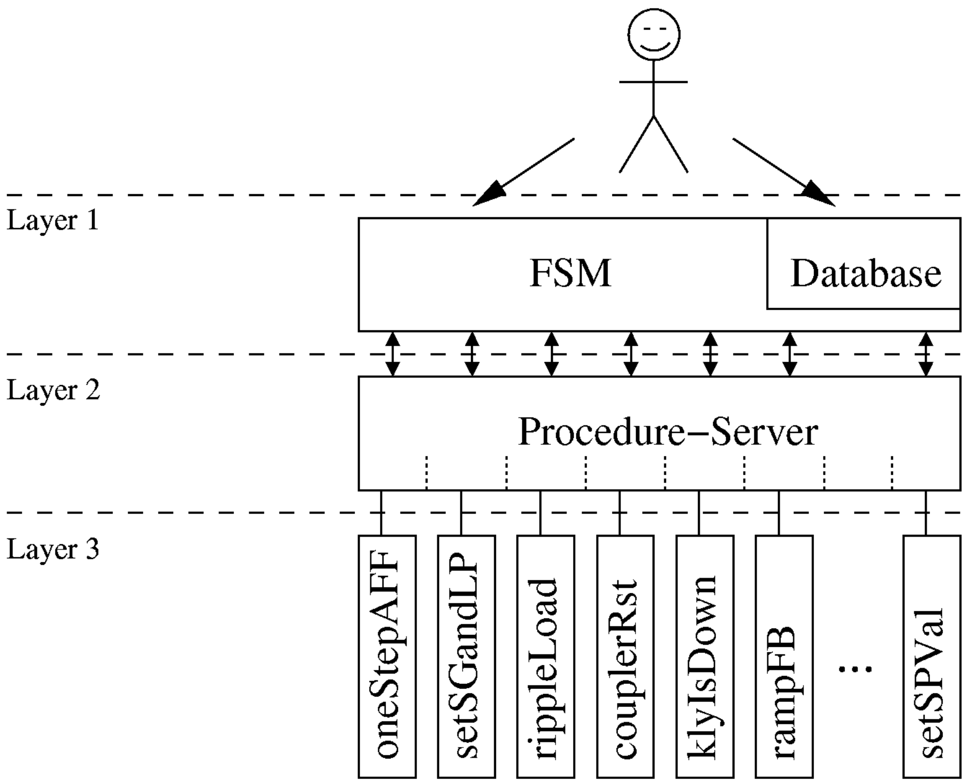
FSM-Architecture



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

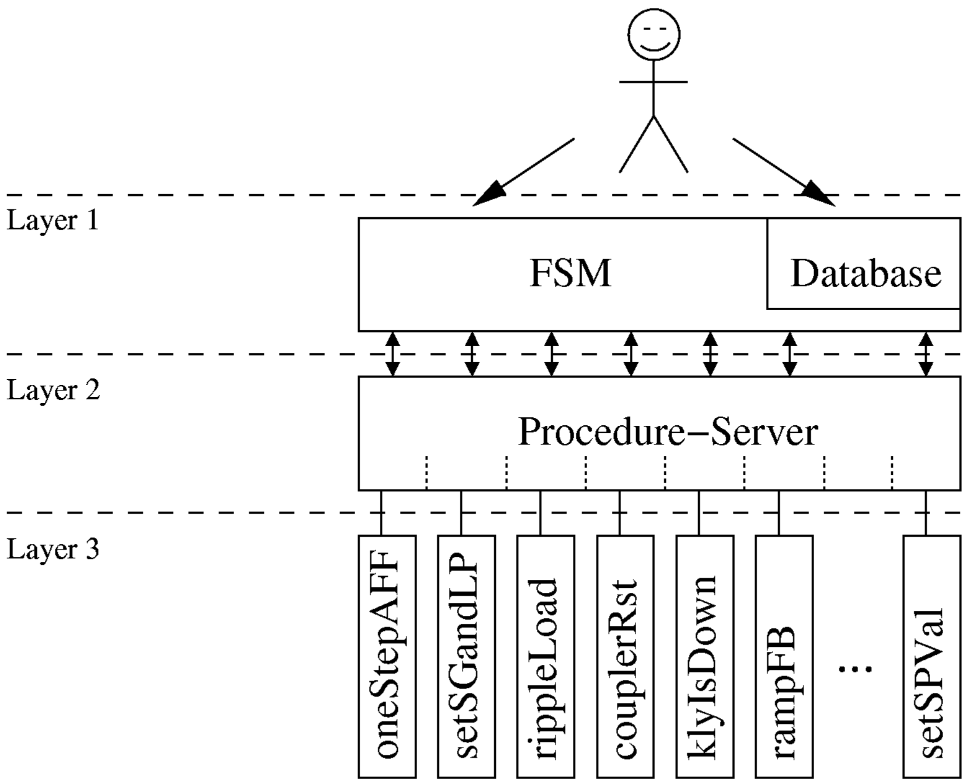
FSM-Architecture



Procedure-Server

- Doocs-interface for configuration and access
- History-Display
- Email-Notification
- Timeout-feature (free configurable)
- Multithreaded

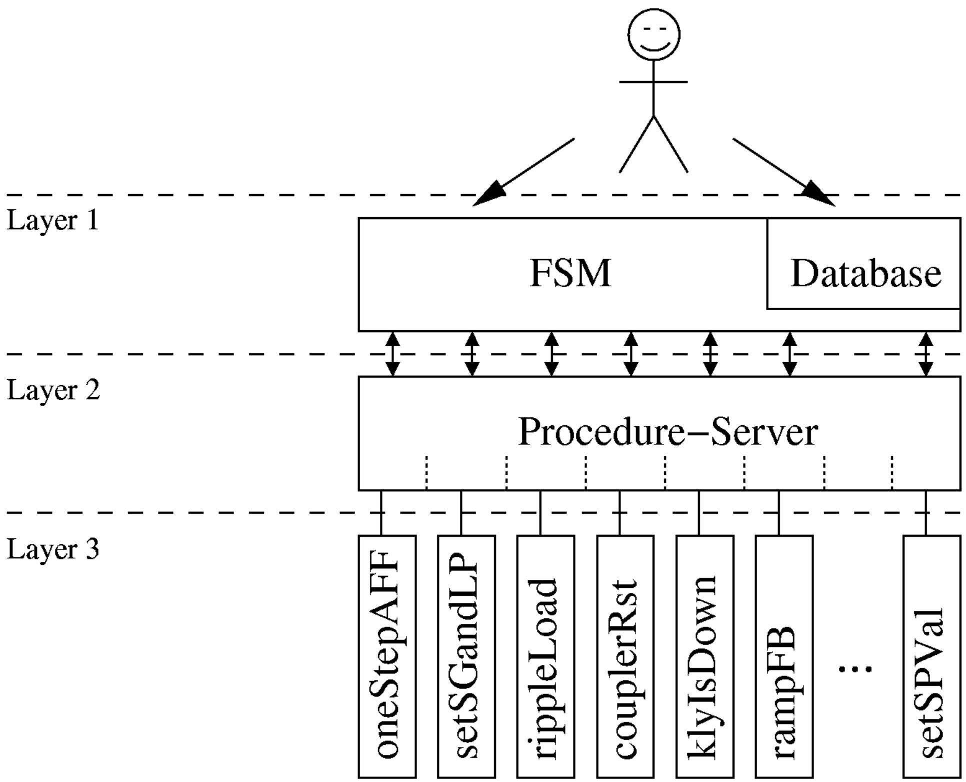
FSM-Architecture



State-Machine

- Moore-FSM:
  - "Do something on enter"
  - Here: trigger a procedure
- Flexible design
  - On-line reconfigurable
  - Off-line "restructurable"
- Current design: model the expert-operator
- "Database" stores all settings, calibration-tables, parameters for the procedures, …

FSM-Architecture

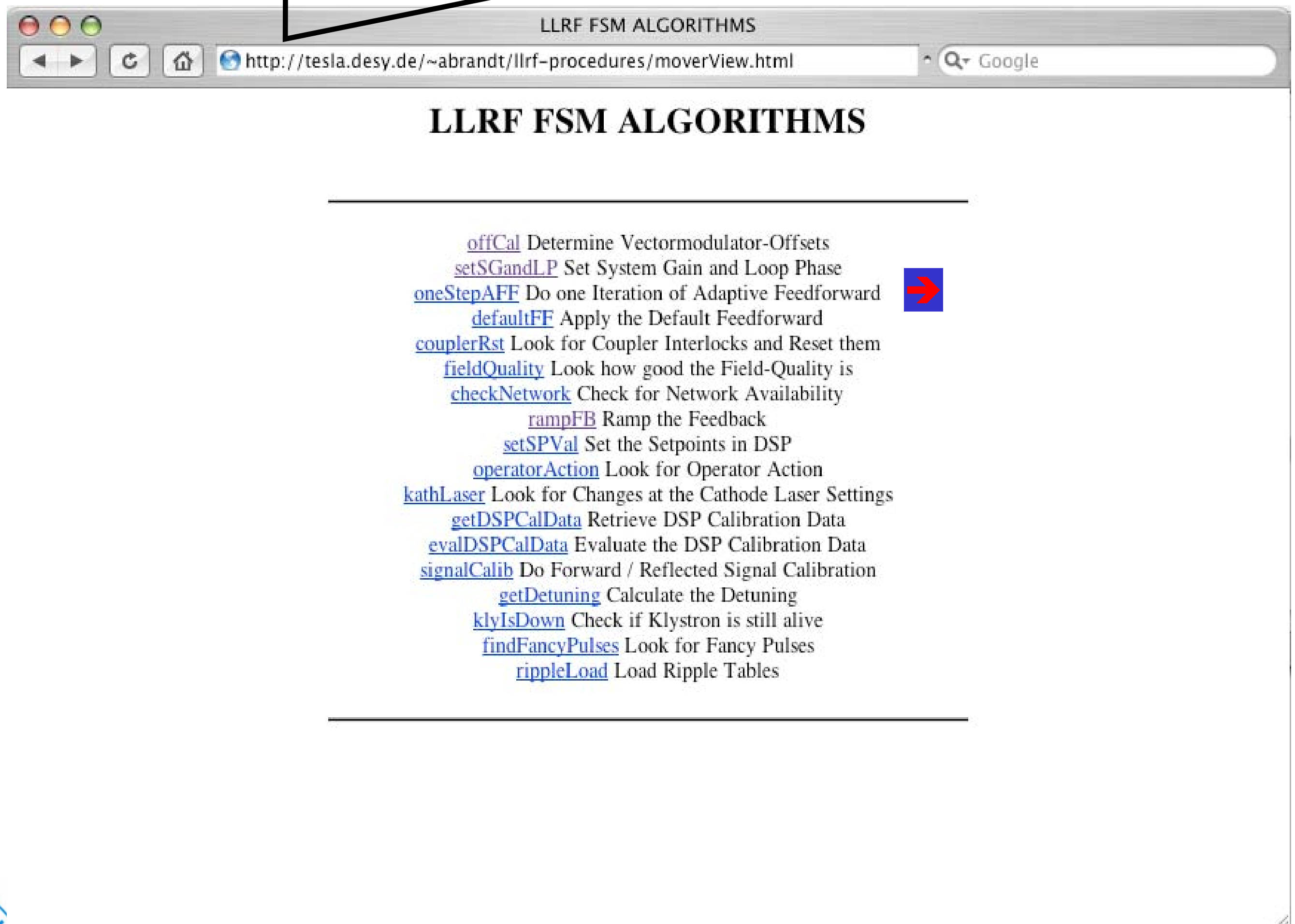


User-Interface

- Simple view for the operator
- Extended view for the expert

Procedure-Documentation

http://tesla.desy.de/~abrandt/llrf-procedures/moverView.html


LLRF FSM ALGORITHMS

http://tesla.desy.de/~abrandt/llrf-procedures/moverView.html

LLRF FSM ALGORITHMS

offCal Determine Vectormodulator-Offsets
setSGandLP Set System Gain and Loop Phase
oneStepAFF Do one Iteration of Adaptive Feedforward
defaultFF Apply the Default Feedforward
couplerRst Look for Coupler Interlocks and Reset them
fieldQuality Look how good the Field-Quality is
checkNetwork Check for Network Availability
rampFB Ramp the Feedback
setSPVal Set the Setpoints in DSP
operatorAction Look for Operator Action
kathLaser Look for Changes at the Cathode Laser Settings
getDSPCalData Retrieve DSP Calibration Data
evalDSPCalData Evaluate the DSP Calibration Data
signalCalib Do Forward / Reflected Signal Calibration
getDetuning Calculate the Detuning
klyIsDown Check if Klystron is still alive
findFancyPulses Look for Fancy Pulses
rippleLoad Load Ripple Tables

"oneStepAFF" Web-Documentation

ONE ADAPTIVE FEEDFORWARD ITERATION

http://tesla.desy.de/~abrandt/llrf-procedures/moneStepAFF.htm

ONE ADAPTIVE FEEDFORWARD ITERATION

NAME

oneStepAFF – One iteration of adaptive feedforward

DESCRIPTION

Performs one step of the iteration for adaptive feedforward.

The algorithm only does something, if the checkbox in the FSM-control-panel is ticked...

The algorithm is iterative, so you can perform as many steps as you like, until the field quality is as you whish it to be. Usually, good convergence is alredy achieved after three iterations.

The algorithm requires the feedback to be on.

The algorithm does a lot of consistency/exception-handling checks. If something suspicous occures, the algorithm simply does nothing during the current iteration.

In the expert panel, one can adjust from which setpoint value on the algorithm will be active. Nothing is done if the current setpoint is below that value.

Since the current DSP-code is not compatible with the adaptive feedforward concept in case beam compensation is turned on, the algorithm will turn off the beam compensation in case it was on.

RETURN-VALUES

0=Adaption successfull! OR: Feedforward was off. No adaption is done. OR: Feedback was off. No adaption done. OR: Successfully set default feedforward in case the checkbox is un-ticked.

1=Not allowed to touch tables (checkbox...) 2=Gradient lowe than threshold. Nothing done.

3=Switched off old beam compensation.

4=Veto from BIS. Nothing done.

-10=doocs r/w error

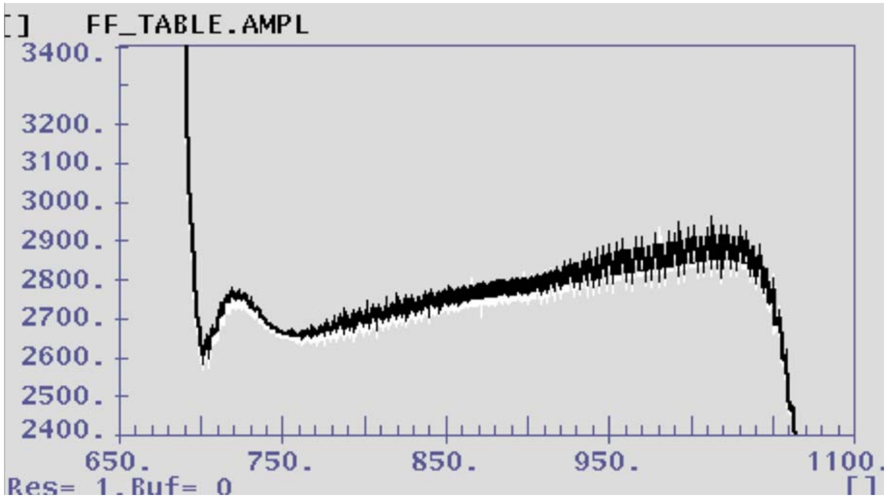
-11=Data inconsistency (bandwidth out of range, signal too noisy, ...)

-12=Adaptive feedforward algorithm itself returned an error message (very unlikely)

-21=Config-file not found

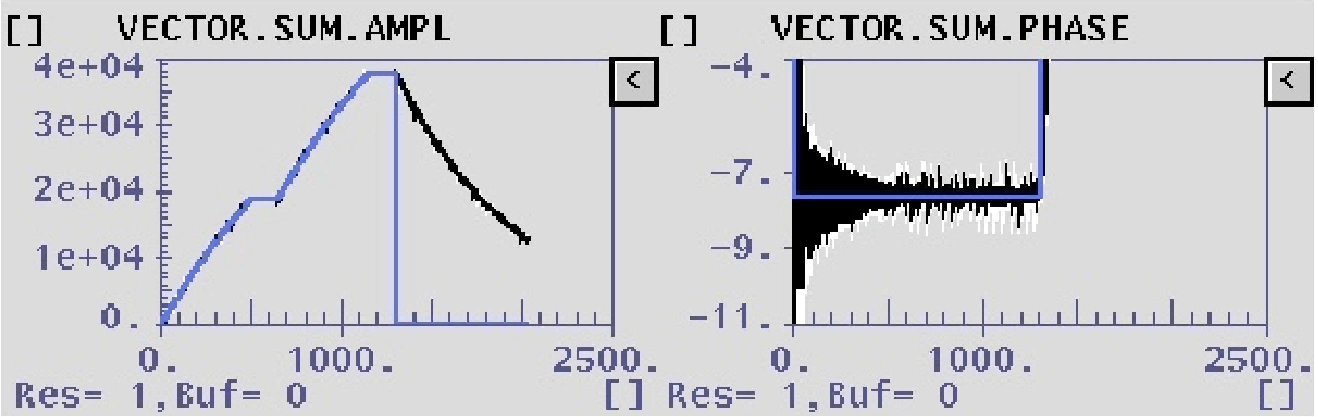
IMPACT

Adaptive Feedforward

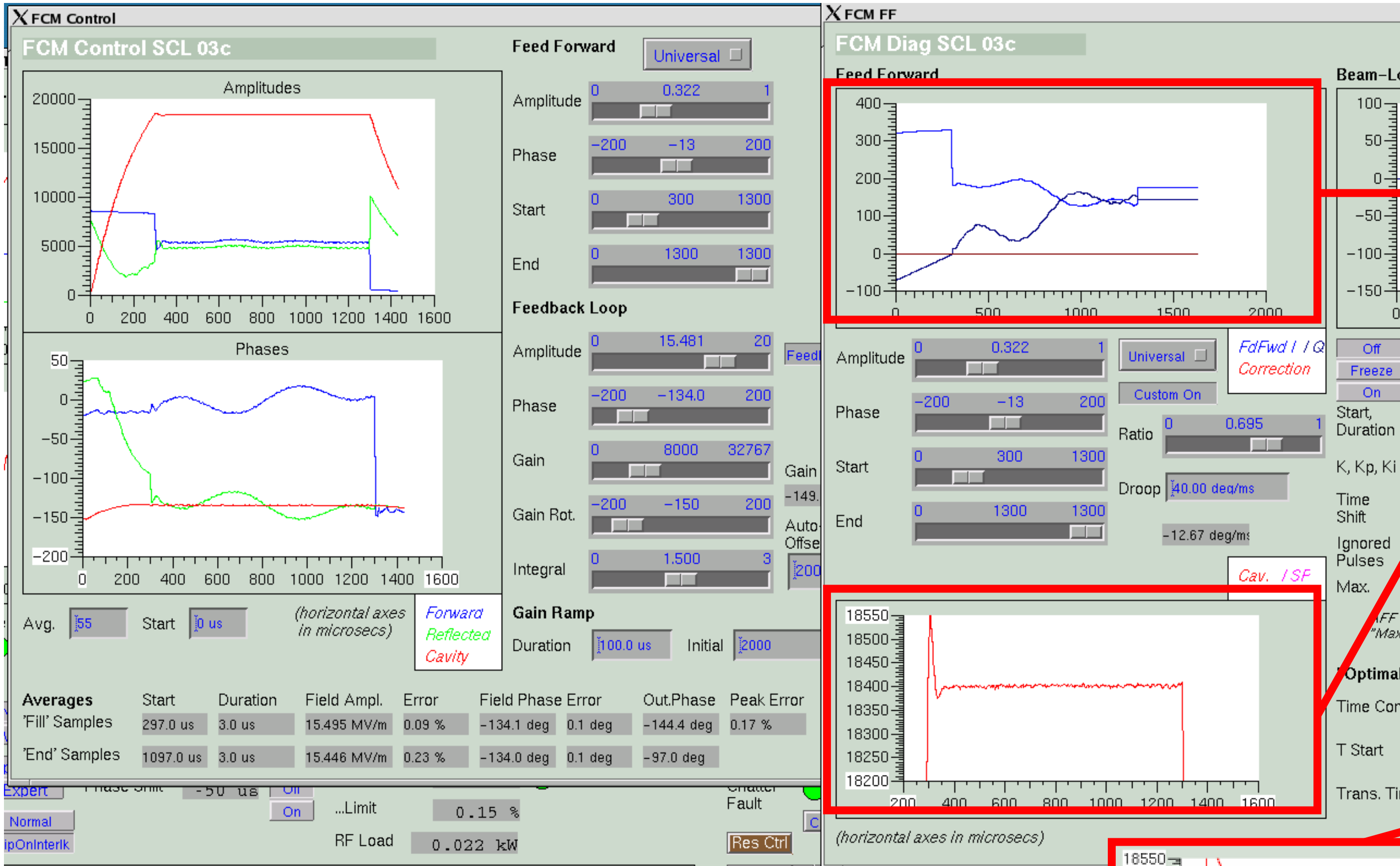


Adaptive FF w/ beam load (ACC2/3, 30us, ~1nC)
Remember, this is just the FF contribution!
E-Log 10/3/2006, 14:15

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



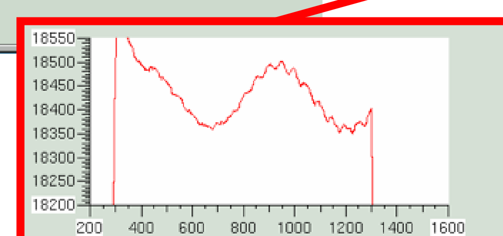
Adaptive Feedforward



Feedforward-Table

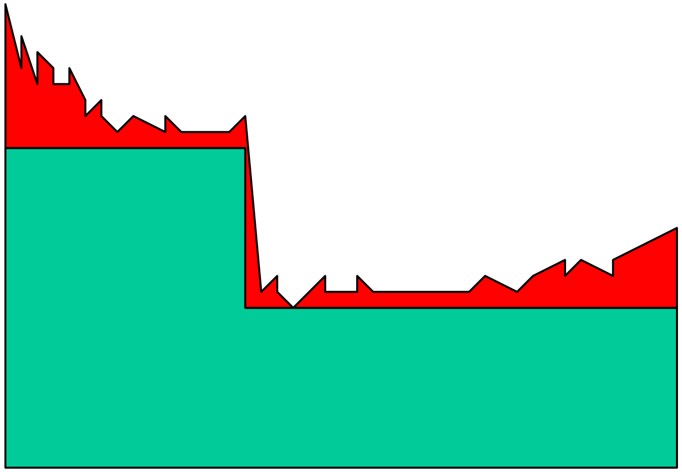
Flattop w/ Adaptive FF (3 Iterations)

Flattop w/o Adaptive FF



SNS LLRF Control Panel

Adaptive Feedforward



1st idea: $FF_{new} = FB_{last} + FF_{last}$ ***…is instable :(***

2nd idea: $FF_{new} = LP(FB_{last}) + FF_{last}$ ***…is even worse :(***

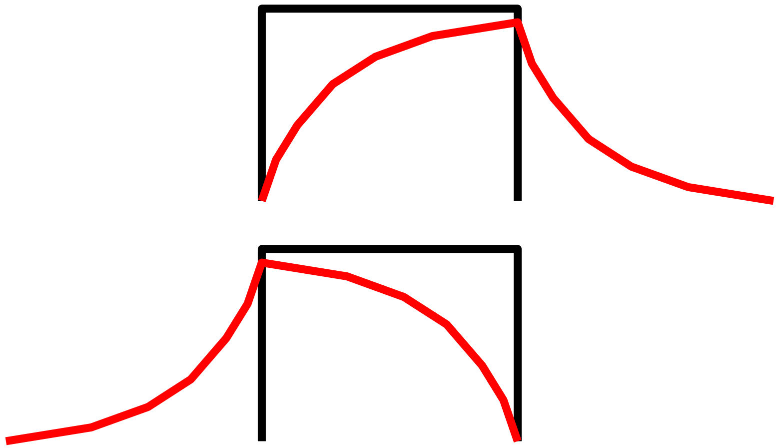
low-pass

Adaptive Feedforward

3rd idea: Instead of a low-pass use a "time-reversed low-pass":

Lowpass:

Time-reversed lowpass:



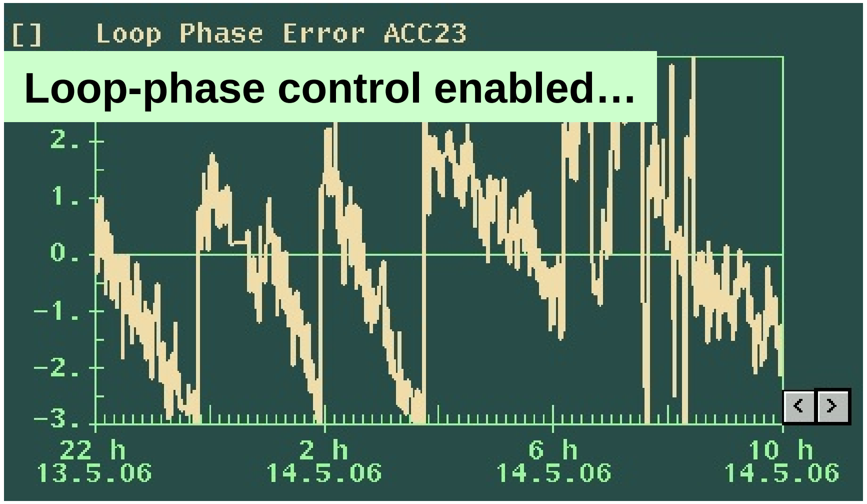
$$FF_{new} = TRLP(FB_{last}) + FF_{last}$$ ***...is surprisingly stable :)***

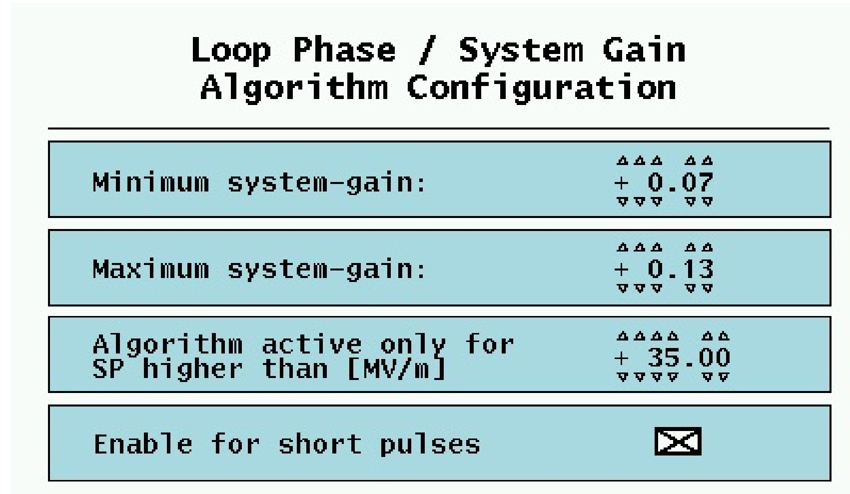
time-reversed low-pass

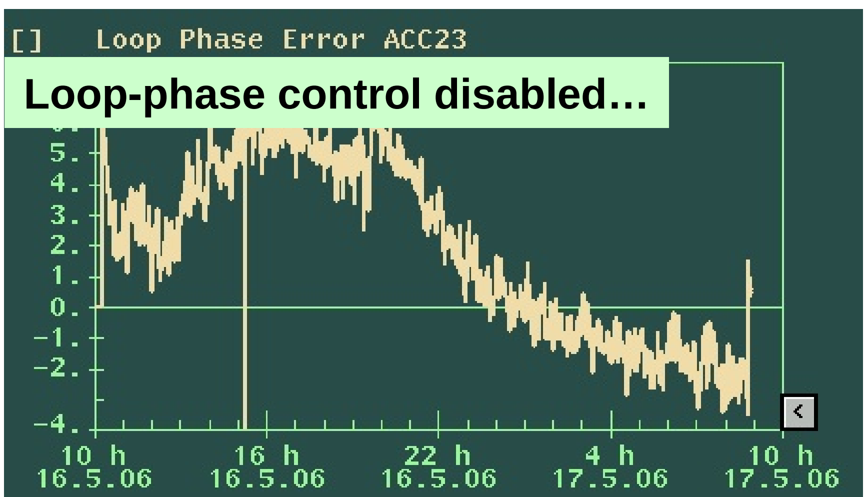
Adaptive Feedforward

- **Currently used: time-reversed lowpass at 2.5kHz (just 3 lines Matlab code!)**
- **Good results after 2-3 iterations**
- **However: exception handling most important!**

Loop Phase Correction







Config File

/home/abrandt/development/doocs/source/server/ttf/fsm/llrf_fsm_applications/confi

File Edit Text Cell Tools Debug Desktop Window Help

```
% Adress definitions, some constants
addr_vsi = 'TTF2.RF/LLRF.DSP/ACC1/VECTOR.SUM.IPARAM';
addr_vsq = 'TTF2.RF/LLRF.DSP/ACC1/VECTOR.SUM.QPARAM';
addr_vsa = 'TTF2.RF/LLRF.DSP/ACC1/VECTOR.SUM.AMPL';
addr_vsm = 'TTF2.RF/LLRF.DSP/ACC1/VECTOR.SUM.MIX';
addr_dri = 'TTF2.RF/LLRF.DSP/ACC1/TOTAL.OUT.DAC.IPARAM';
addr_drq = 'TTF2.RF/LLRF.DSP/ACC1/TOTAL.OUT.DAC.QPARAM';
addr_ffi = 'TTF2.RF/LLRF.DSP/ACC1/FF_TABLE.IPARAM';
addr_ffq = 'TTF2.RF/LLRF.DSP/ACC1/FF_TABLE.QPARAM';
addr_spi = 'TTF2.RF/LLRF.DSP/ACC1/SP_TABLE.IPARAM';
addr_spq = 'TTF2.RF/LLRF.DSP/ACC1/SP_TABLE.QPARAM';
addr_sg  = 'TTF2.RF/LLRF.DSP/ACC1/GT_SYS_GAIN';
addr_lg  = 'TTF2.RF/LLRF.DSP/ACC1/GT_LOOP_GAIN';
addr_lop = 'TTF2.RF/LLRF.DSP/ACC1/LOOP_PHASE.PHASE';
addr_del = 'TTF2.RF/LLRF.DSP/ACC1/SP_DELAY_TIME';
addr_sfd = 'TTF2.RF/LLRF.DSP/ACC1/SP_FF_DELAY_TIME';
addr_fil = 'TTF2.RF/LLRF.DSP/ACC1/SP_FILL_TIME';
addr_dur = 'TTF2.RF/LLRF.DSP/ACC1/SP_FLAT_TOP_DUR';
addr_buf = 'TTF2.RF/ADC/GUN.PFOR/CURRENT';
addr_ofi = 'TTF2.RF/LLRF.DSP/ACC1/FF_I_OFFSET';
addr_ofq = 'TTF2.RF/LLRF.DSP/ACC1/FF_Q_OFFSET';
addr_ffm = 'TTF2.RF/LLRF.DSP/ACC1/FF_TABLE.MIX';
addr_fb  = 'TTF2.RF/LLRF.DSP/ACC1/OPEN_CLOSE_LOOP';
addr_ff  = 'TTF2.RF/LLRF.DSP/ACC1/FF_MODE';
addr_rat = 'TTF2.RF/LLRF.DSP/ACC1/FF_RATIO';
addr_bcmp= 'TTF2.RF/LLRF.DSP/ACC1/BEAM_COMP_ON_OFF';
addr_sp  = 'TTF2.RF/LLRF.DSP/ACC1/SP_VOLTAGE_MV';
addr_fam = 'TTF2.RF/LLRF.DSP/ACC1/FF_AMPL_CAL_MV_HV';
addr_fab = 'TTF2.RF/LLRF.DSP/ACC1/FF_AMPL_CAL_HV_BIT';
addr_spp = 'TTF2.RF/LLRF.DSP/ACC1/SP_PHASE_REL_BEAM';
addr_po  = 'TTF2.RF/LLRF.DSP/ACC1/SP_PHASE_OFFSET';
addr_ffp = 'TTF2.RF/LLRF.DSP/ACC1/FF_SP_PHASE_OFFSET';
addr_fri = 'TTF2.RF/LLRF.DSP/ACC1/REF_FF_TABLE.IPARAM';
addr_frq = 'TTF2.RF/LLRF.DSP/ACC1/REF_FF_TABLE.QPARAM';
addr_frm = 'TTF2.RF/LLRF.DSP/ACC1/REF_FF_TABLE.MIX';
addr_fru = 'TTF2.RF/LLRF.DSP/ACC1/REF_FF_TABLE.USR';
addr_ta3 = 'TTF2.DIAG/TIMER/MASTER/CH01.DELAY';
addr_ta6 = 'TTF2.DIAG/TIMER/MASTER/CH04.DELAY';
addr_dsd = 'TTF2.RF/TIMER/DSP1/CH01.DELAY';
addr_add = 'TTF2.RF/TIMER/ACC1/CH02.DELAY';
addr_igctstop = 'TTF2.RF/TIMER/KLY5DSP/CHANNEL.6.DELAY';
addr_spd = 'TTF2.RF/LLRF.DSP/ACC1/SP_DELAY_TIME';
addr_bed = 'TTF2.UTIL/LASER/GUN/T_DELAY12';
addr_nbu = 'TTF2.UTIL/LASER/GUN/PULSE_NUM';
addr_lat = 'TTF2.UTIL/LASERLINE/LASER.ATTENUAT/MOTOR.POS.SETPOINT';
addr_tor = 'TTF2.DIAG/TOROID/3GUN/CH00.DIFF.TD';
```

config_acc1 Ln 228 Col 23 OVR

…all RF-stations have <u>identical</u> algorithms with <u>individual</u> config-files.

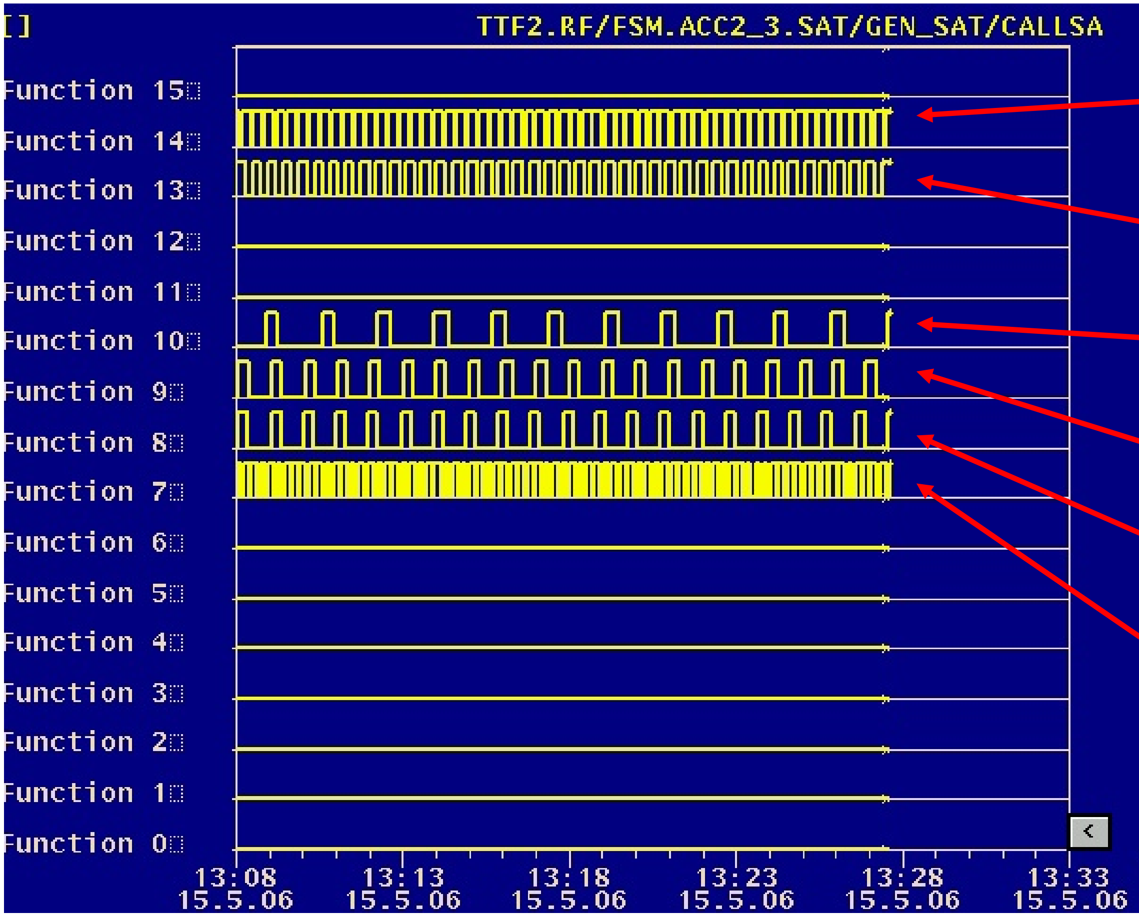
Procedure Server

``Stateless Procedures''-Server

Hist 0-15
Hist 16-31

	Configuration	Timeout	Short Description	Human-Readable Result	Numerical Res.		
FUN0	llrf/runDummy.csh out0.dat llrf/out0.dat	1500		Operation Successfull!	0	1.96	0.28
FUN1	/h…da/doocs/solaris2/obj/server/ttf/kly4 fsm/run_fsm llrf/out1.dat	1500		Script execution error.	-99	0	0
FUN2	llrf/runOffCal.csh out2.dat llrf/out2.dat	1500	Correcting Offsets.	Script execution error.	-99	0	0
FUN3	llrf/runSetSGandLP.sh out3.dat llrf/out3.dat	1500	Correcting loopphase.	Corrected loop phase.	2	-3.84	0.12
FUN4	llrf/runOneStepAFFDSP.csh out4.dat llrf/out4.dat	1500	Adapting Feedforward (DSP-par.).	Applied zero Feedforward (Feedforward was off)	0	0	0
FUN5	llrf/runOneStepAFF.sh out5.dat llrf/out5.dat	1500	Adapting Feedforward	Feedback is off. No FF-adaption possible.	0	0	0
FUN6	llrf/runDefaultFF.csh out6.dat llrf/out6.dat	1500	Applying default Feedforward.	Successfully set default feedforward.	0	0	0
FUN7	llrf/runCouplerRst7.sh out7.dat 1 llrf/out7.dat	1500	Checking coupler interlocks.	Executing...	-98	0	0
FUN8	llrf/runSetSGandLP.sh out8.dat 1 llrf/out8.dat	1500	Checking loopphase.	No drive from llrf is applied.	0	0	0
FUN9	llrf/runFieldQuality.sh out9.dat llrf/out9.dat	1500	Checking data quality.	FB=0 or FF=0! Data quality is unacceptable.	9	inf	117.42
FUN10	llrf/runCheckNetwork7.sh out10.dat llrf/out10.dat	1500	Checking network.	Network works fine.	0	0	0
FUN11	llrf/runRampFB.csh out11.dat llrf/out11.dat	1500	Ramping Feedback.	Successfully ramped FB to target value!	0	0	0
FUN12	llrf/runSetSPVal.csh out12.dat llrf/out12.dat	1500	Setting amplitude and phase.	Successfully ramped SP to target value!	0	0	0
FUN13	llrf/runOperatorAction.sh out13.dat llrf/out13.dat	1500	Looking for operator action.	Executing...	-98	0	0
FUN14	llrf/runKathLaser.sh out14.dat llrf/out14.dat	1500	Checking cathode laser settings.	Executing...	-98	0	0
FUN15	llrf/runGetDSPCalData.csh out15.dat llrf/out15.dat	1500	Retrieving DSP calibration-data.	Script execution error.	-99	0	0
FUN16	llrf/runEvalDSPCalData7.csh out16.dat llrf/out16.dat	1500	Evaluating DSP-Cal-Data.	Script execution error.	-99	0	0
FUN17	llrf/runSignalCalib7.sh out17.dat llrf/out17.dat	1500	Calculating cavity signal calibration.	There is no drive at all!	2	0	0
FUN18	llrf/runGetDetunings.csh out18.dat llrf/out18.dat	1500	Calculating detunings.	Calculating detuning done.	0	0	0
FUN19	llrf/runSetSPVal.csh out19.dat llrf/out19.dat	1500	Setting amplitude and phase (slowly).		0	0	0
FUN20	llrf/runKlyIsDown.sh out20.dat llrf/out20.dat	1500	Looking if Klystron is alive.	Executing...	-98	0	0
FUN21	llrf/runFindFancyPulses.sh out21.dat llrf/out21.dat	1500	Looking for fancy pulses.	Feedforward is off.	0	0	0
FUN22	offCal ACC456 out22.dat out22.dat	0		Script execution error.	-99	0	0
FUN23	setSGandLP ACC456 out23.dat out23.dat	0		Calculated bandwidth out of range. (Maybe there is no drive signal at all!)	[illegible]	0	0
FUN24	llrf/runRippleLoad.sh out24.dat llrf/out24.dat	500	Applying ripple-correction.	Script execution error.	-99	0	0
FUN25	llrf/runRippleLoad.sh out25.dat 0 llrf/out25.dat	500	Restoring zero ripple-table.	Script execution error.	-99	0	0
FUN26	defaultFF_ACC456 out26.dat out26.dat	0		Script execution error.	-99	0	0
FUN27		0			0	0	0
FUN28	./runfsmkly4 out28.txt out28.txt	0		Script execution error.	-99	0	0
FUN29	./runfsmkly5 out29.txt out29.txt	0		Script execution error.	-99	0	0

Procedure History



Check Cathode Laser

Check Operator Action

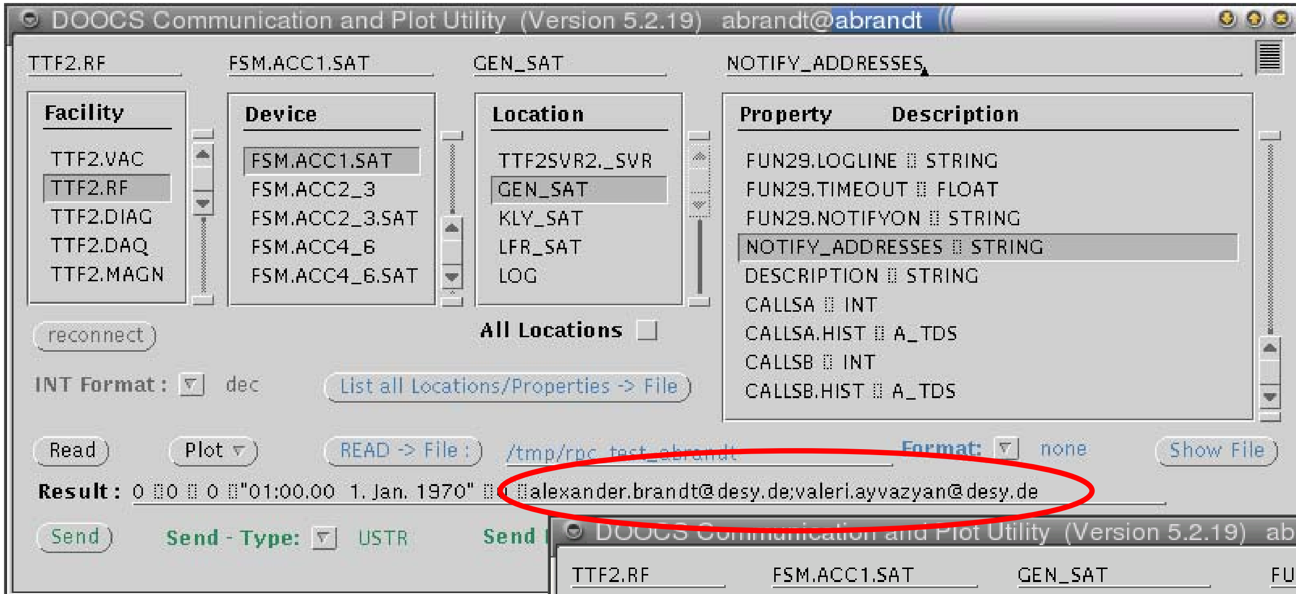
Check config file (network availability)

Monitor data quality

Check for loop phase

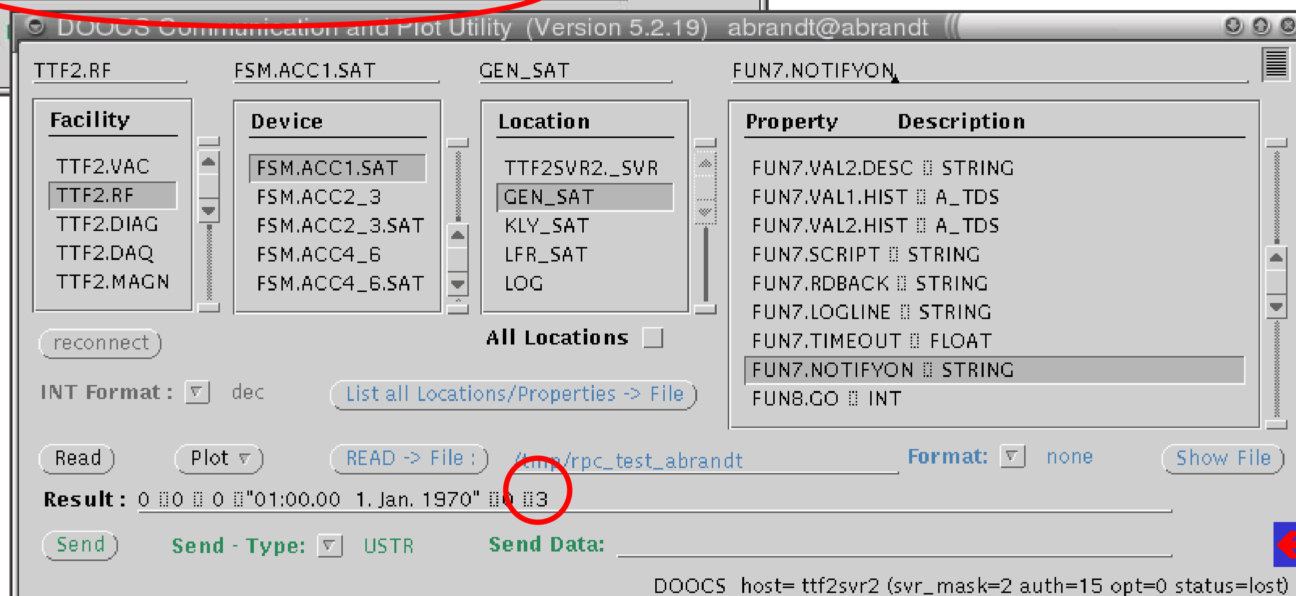
Check for coupler interlocks

Email-Notification



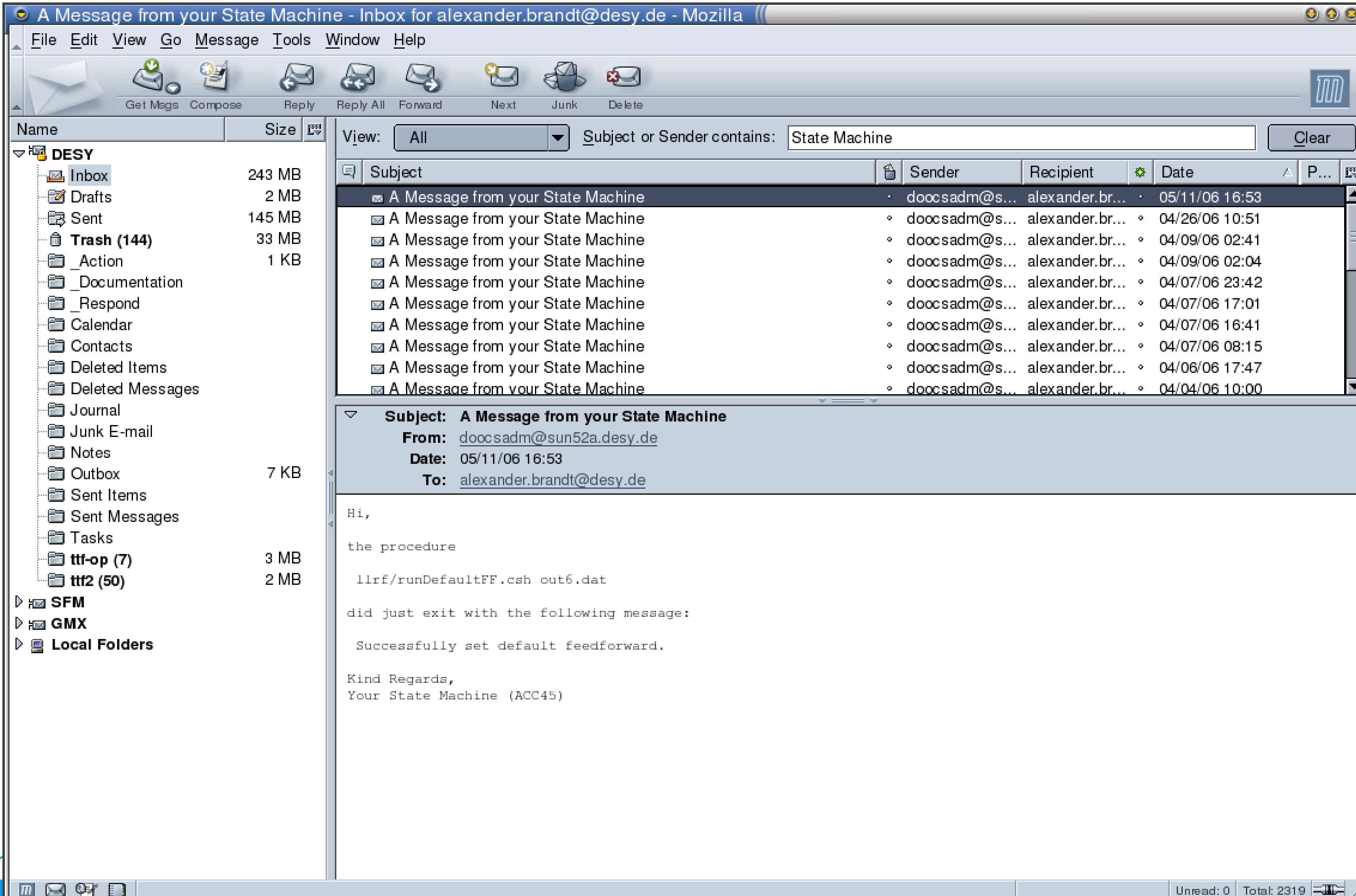
Email-adresses for this RF-station…

Example:



Notify-Condition for procedure in slot 7

Email-Example

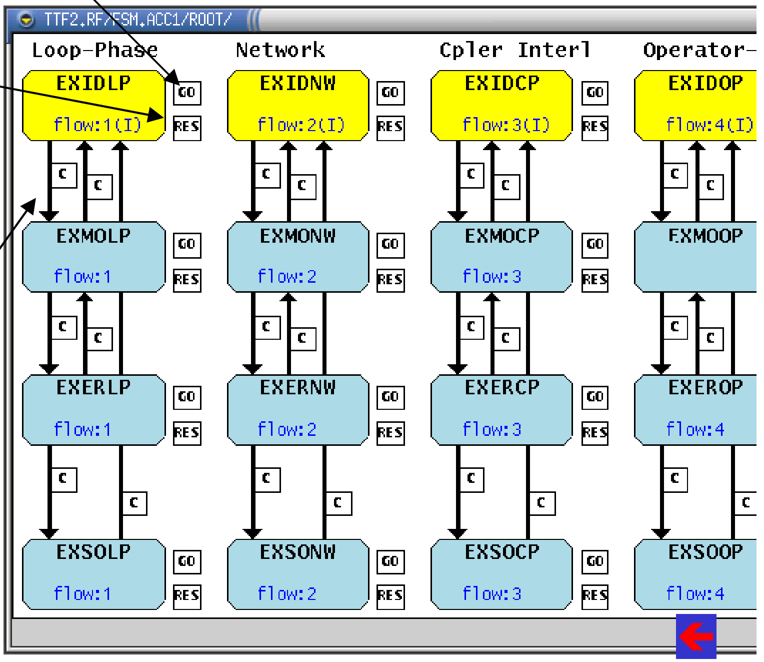


On-Line Reconfigurability

A click here defines what happens on enter…
- **can be a number (like ‘wait 25 pulses’),**
- **can be an event (make transition somewhere),**
- **can be a procedure**
- **can be a combination of them.**

Where to find the numerical result once the procedure (timer) has finished - can be any DOOCS-address!

Conditions, that the result is compared to (which lead to a transition)
- **can be (a list of) number(s)**
- **can be a ‘not’, ‘else’, ‘all’**



Off-Line Restructurability

emacs@

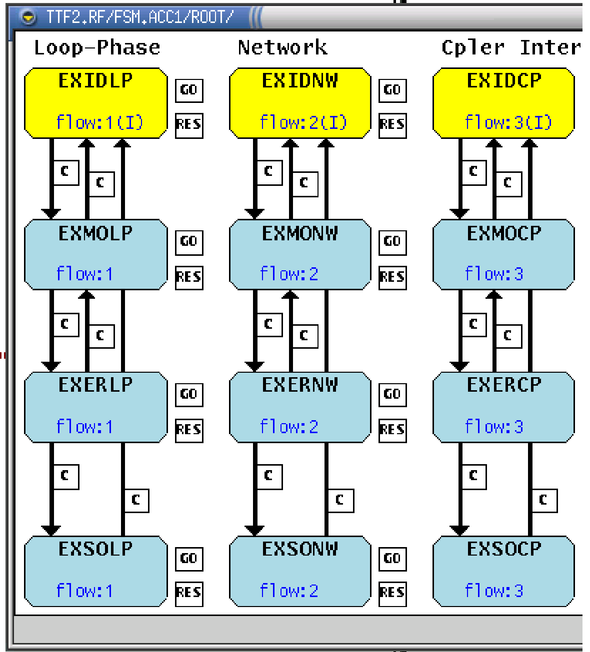
File Edit Options Buffers Tools C++ Help

```
//// DO NOT EDIT THIS AND NEXT TWO ROWS
// init function for state 'EXERDQ'
int     ROOT_EXERDQ_init_action(FSMstate *st_p_)
{

        fputs("ROOT_EXERDQ:: \"init\" event  procedure: ROOT_EXERDQ_init_action \n", stderr);

        TStateLogic* sd=TStateLogic::factory("EXERDQ");
        sd->set_go("ROOT_EXCEPTION.EXERDQ_GO");
        sd->set_res("ROOT_EXCEPTION.EXERDQ_RES");
        sd->add_event("EXERDQ", "exerdq_exmodq", "ROOT_EXCEPTION.EXERDQ_T1");
        sd->add_event("EXERDQ", "exerdq_exsodq", "ROOT_EXCEPTION.EXERDQ_T2");

        return ST_OK;
}

//// DO NOT EDIT THIS AND NEXT TWO ROWS
// enter function for state 'EXERDQ'
int     ROOT_EXERDQ_enter_action(FSMstate *st_p_)
{

        fputs("ROOT_EXERDQ:: \"enter\" event  procedure: ROOT_EXERDQ_enter_action \n"

        TStateLogic* sd=TStateLogic::factory("EXERDQ");
        sd->enter(st_p_);

        return ST_OK;
}

//// DO NOT EDIT THIS AND NEXT TWO ROWS
// during function for state 'EXERDQ'
int     ROOT_EXERDQ_during_action(FSMstate *st_p_)
{

        fputs("ROOT_EXERDQ:: \"during\" event  procedure: ROOT_EXERDQ_during_action \n", stderr);

        TStateLogic* sd=TStateLogic::factory("EXERDQ");
        sd->during(st_p_);

        return ST_OK;
}
--:** llrf_fsm_panel_ROOT.cc      (C++ Abbrev)--L1949--94%--------------------------------
```

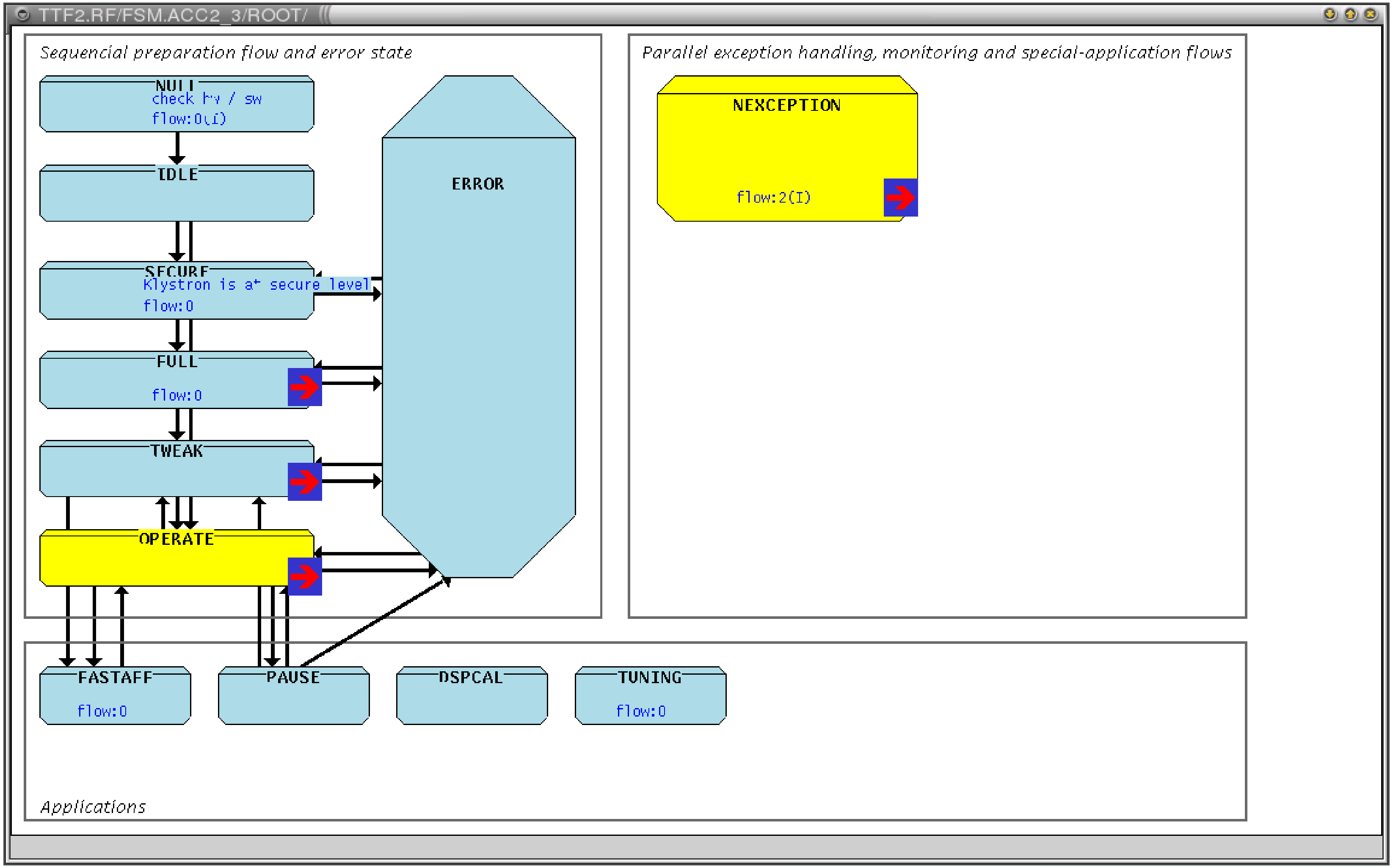
init

enter

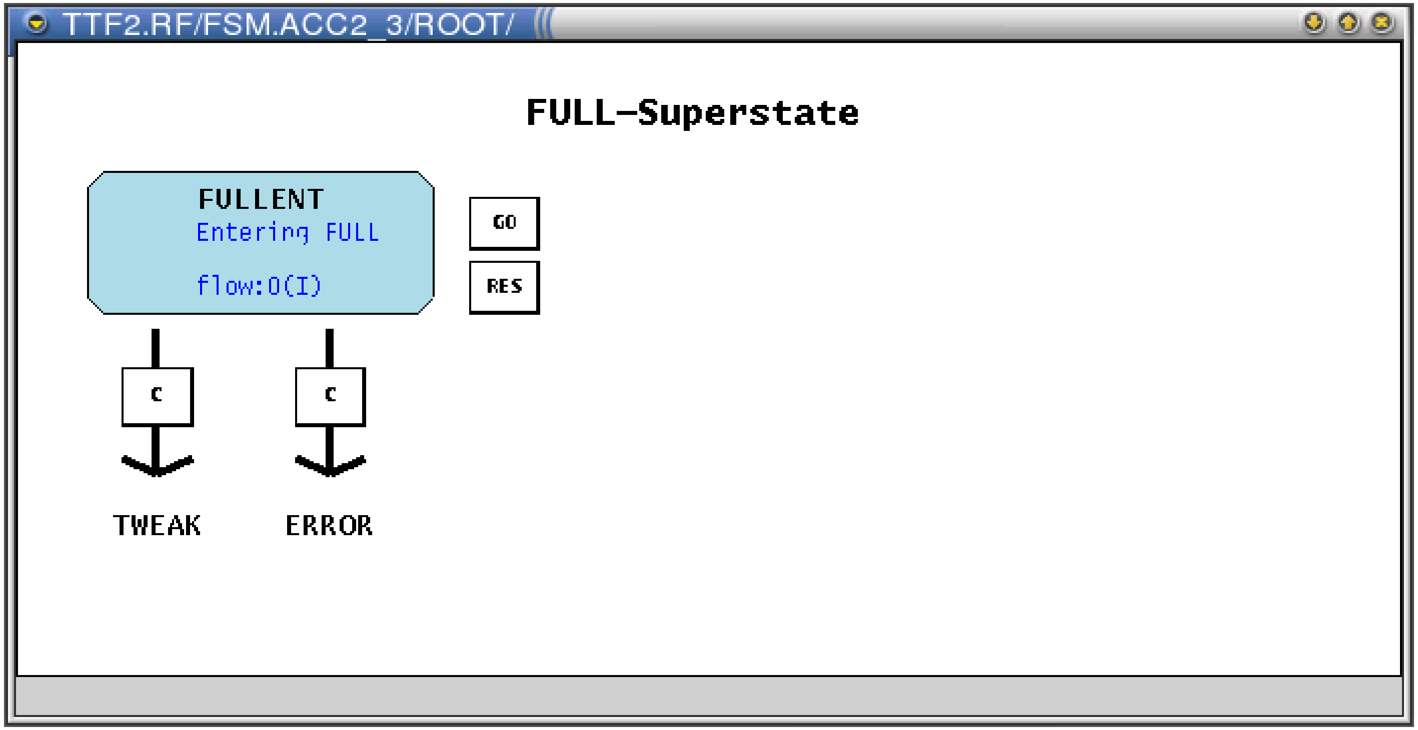
during



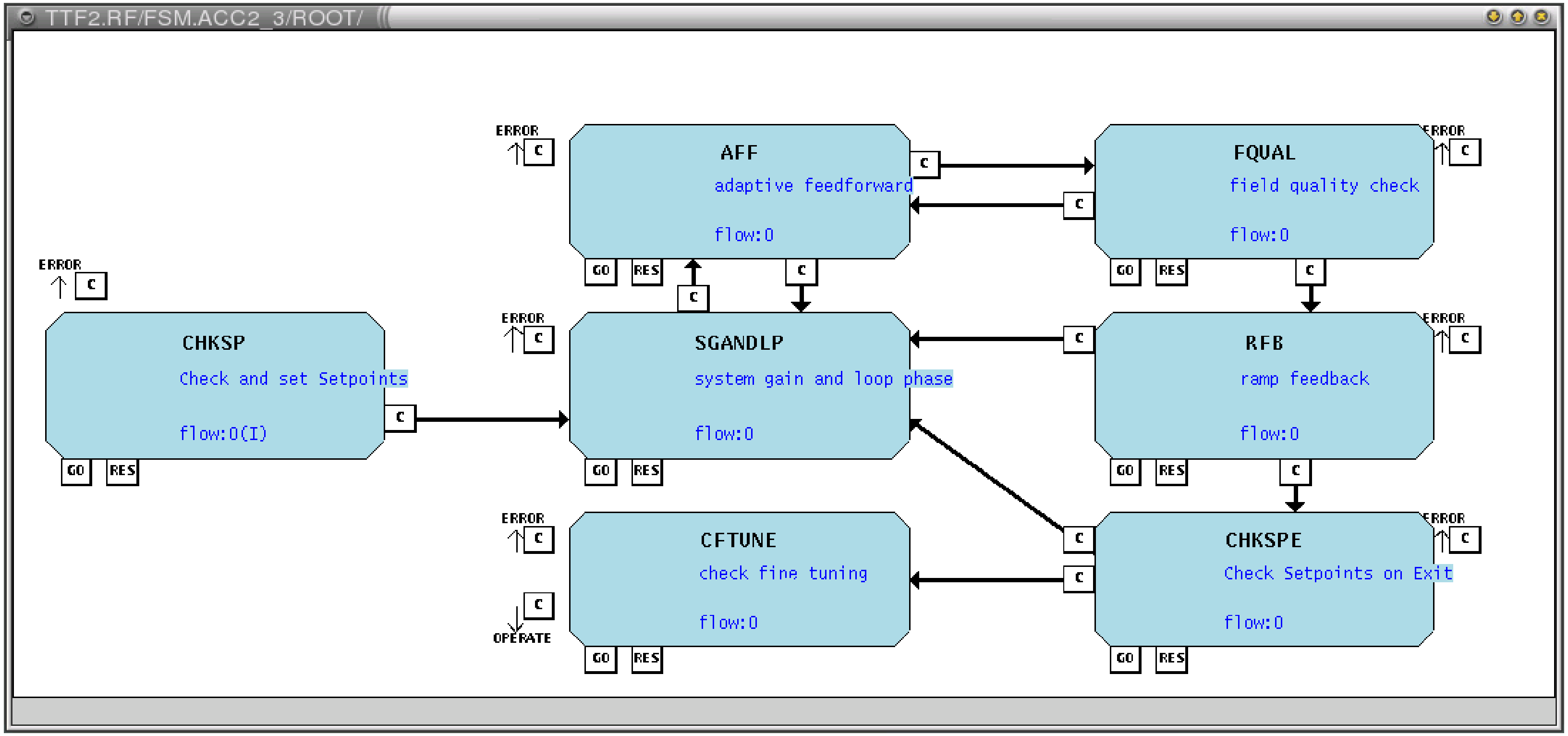
FSM Top Level View



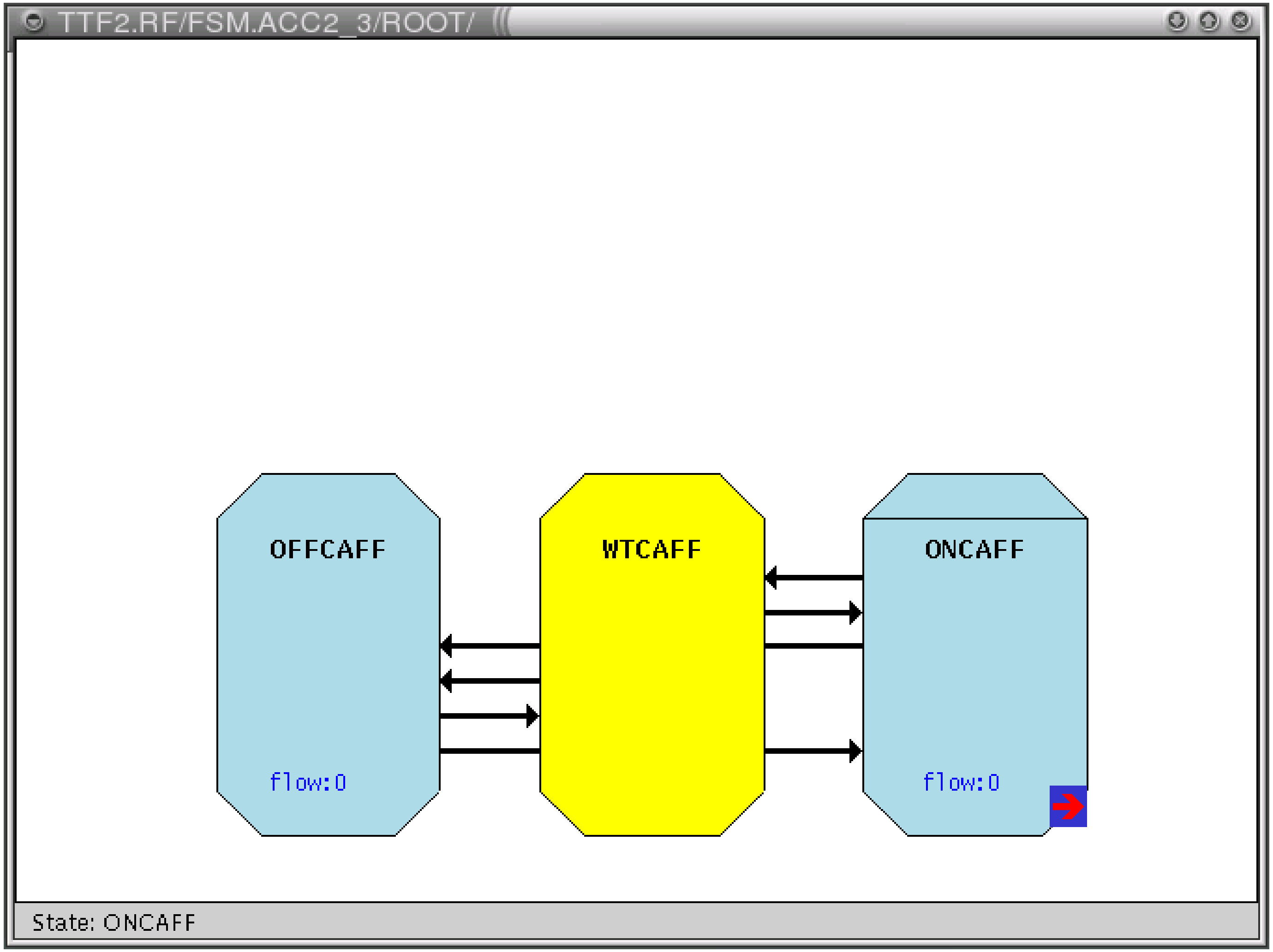
FSM Full State



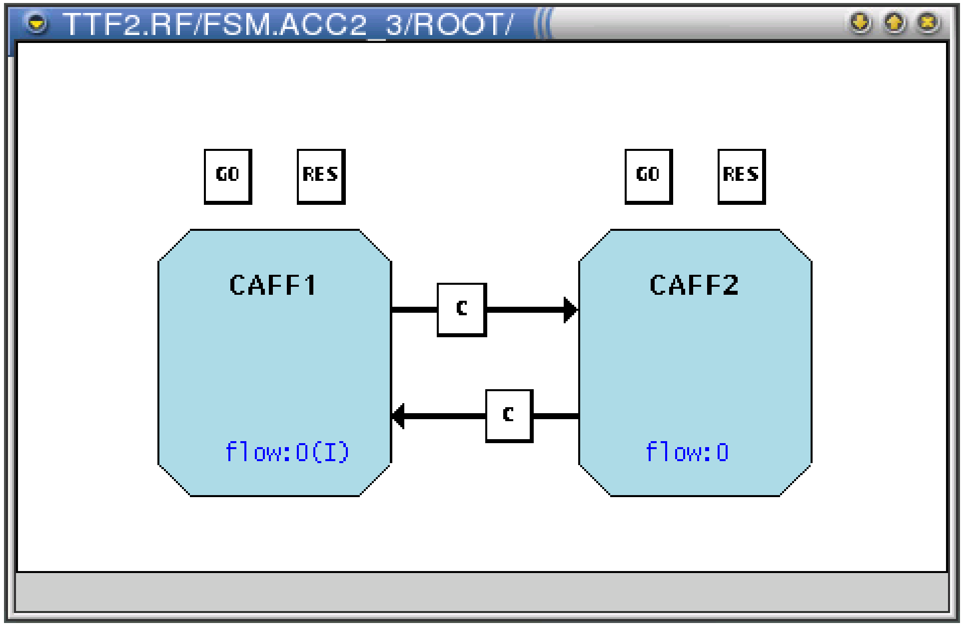
FSM Tweak State



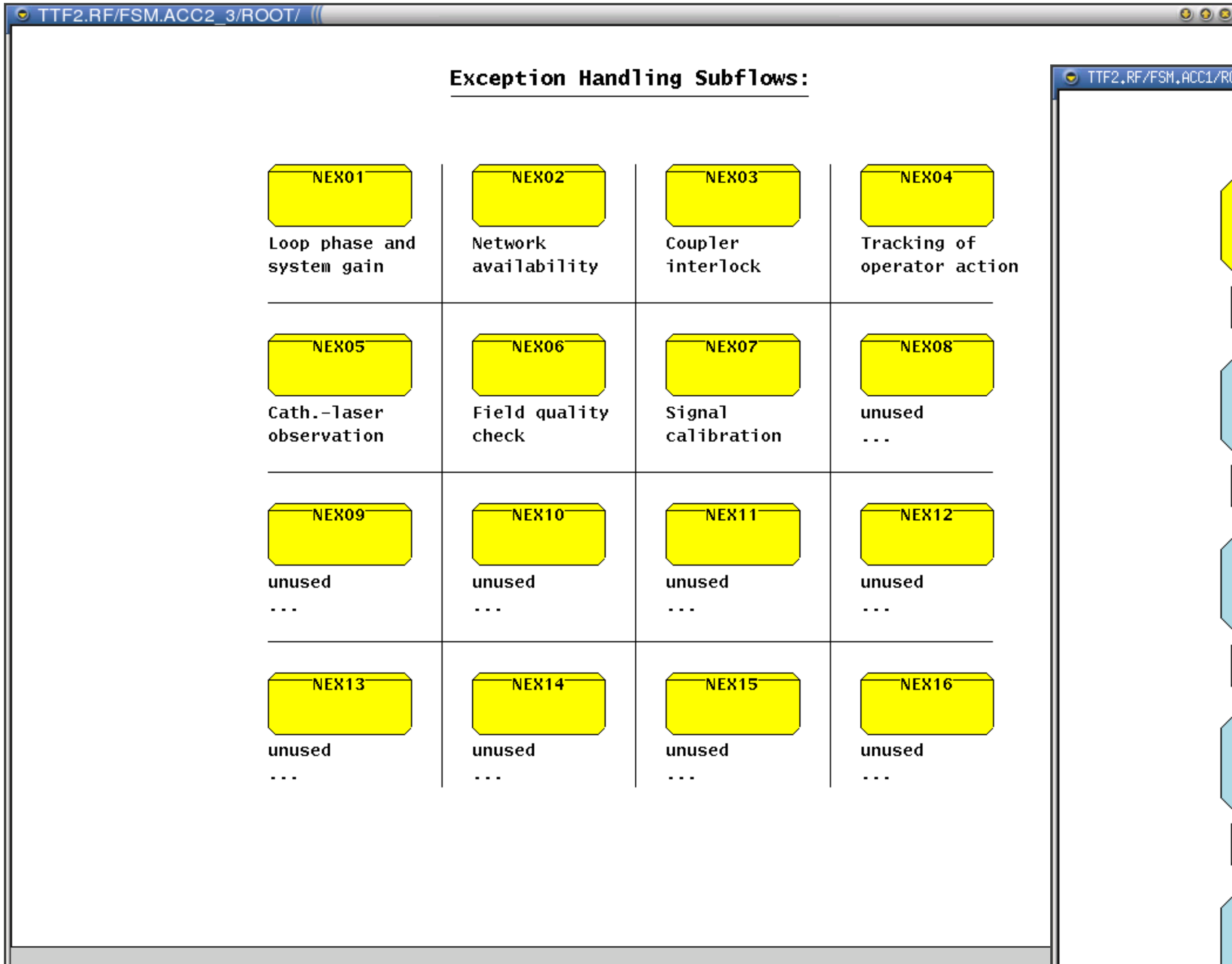
FSM Operate State

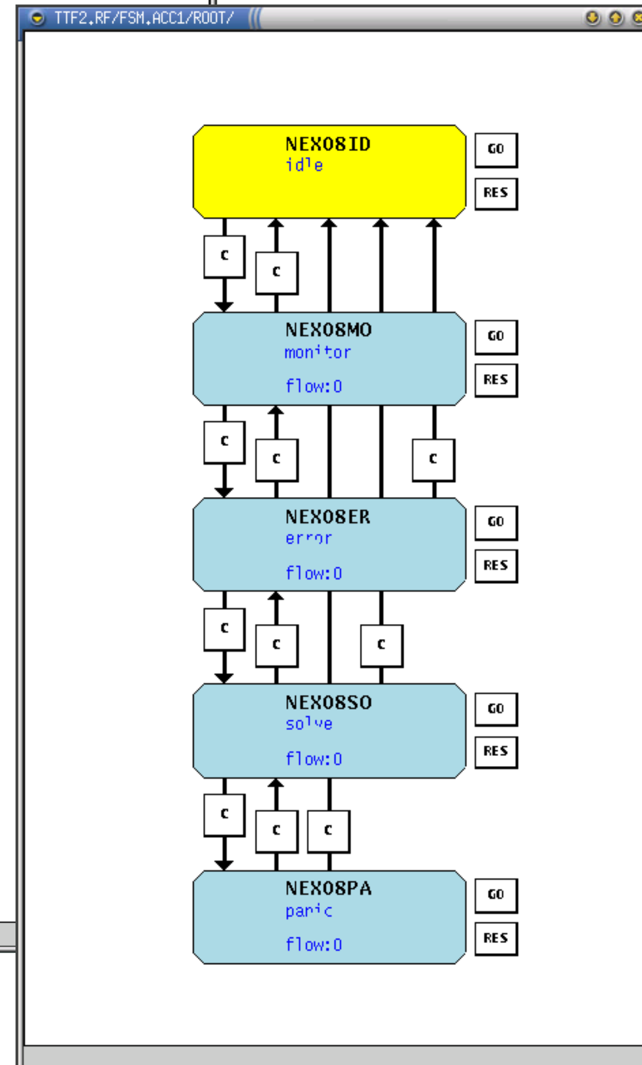


FSM ONCAFF State



FSM Exception State



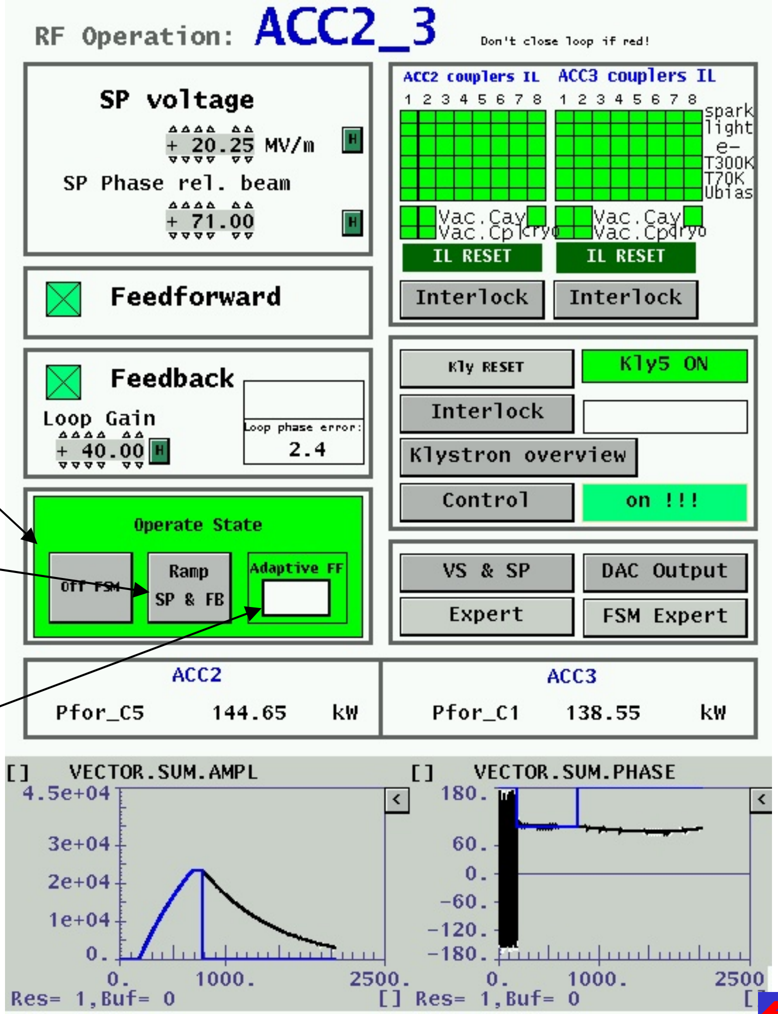


Simple Operators View

Switch off FSM

Ramp RF to the target values (…)

Enable adaptive FF



FSM-Expert View

Checkboxes determine the behavior of the algorithms (and the algorithms determine the behavior of the FSM).

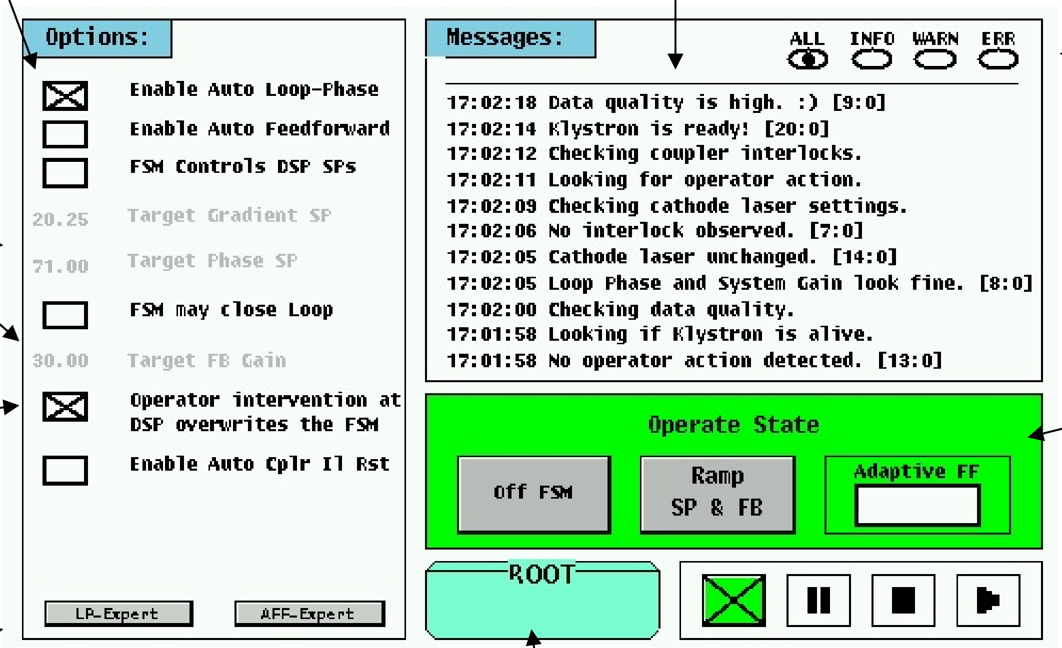
Scrolling messages from all procedures

Target values are automagically updated while operator is working with the DSP!

Debug level

…but only as long as this is desired!

Simple operators view



Algorithm expert settings

Access to FSM-structure (for on-line reconfig)

Operation Experience

- “Permanent features”
  - Loop phase running with <1 error/week (fixed usually the next day)
  - Adaptive feedforward (rarely used) with ~1 error/week (fixed next day)
  - Few things run without operator awareness (signal calibration, operator-tracking)
- “Occasional features”
  - DSP ramp up after down: tested but not used
  - DSP ramp down after klystron trip: tested but not used
- “Optional Features”
  - DSP calibration, detuning display, … just used by me from time to time

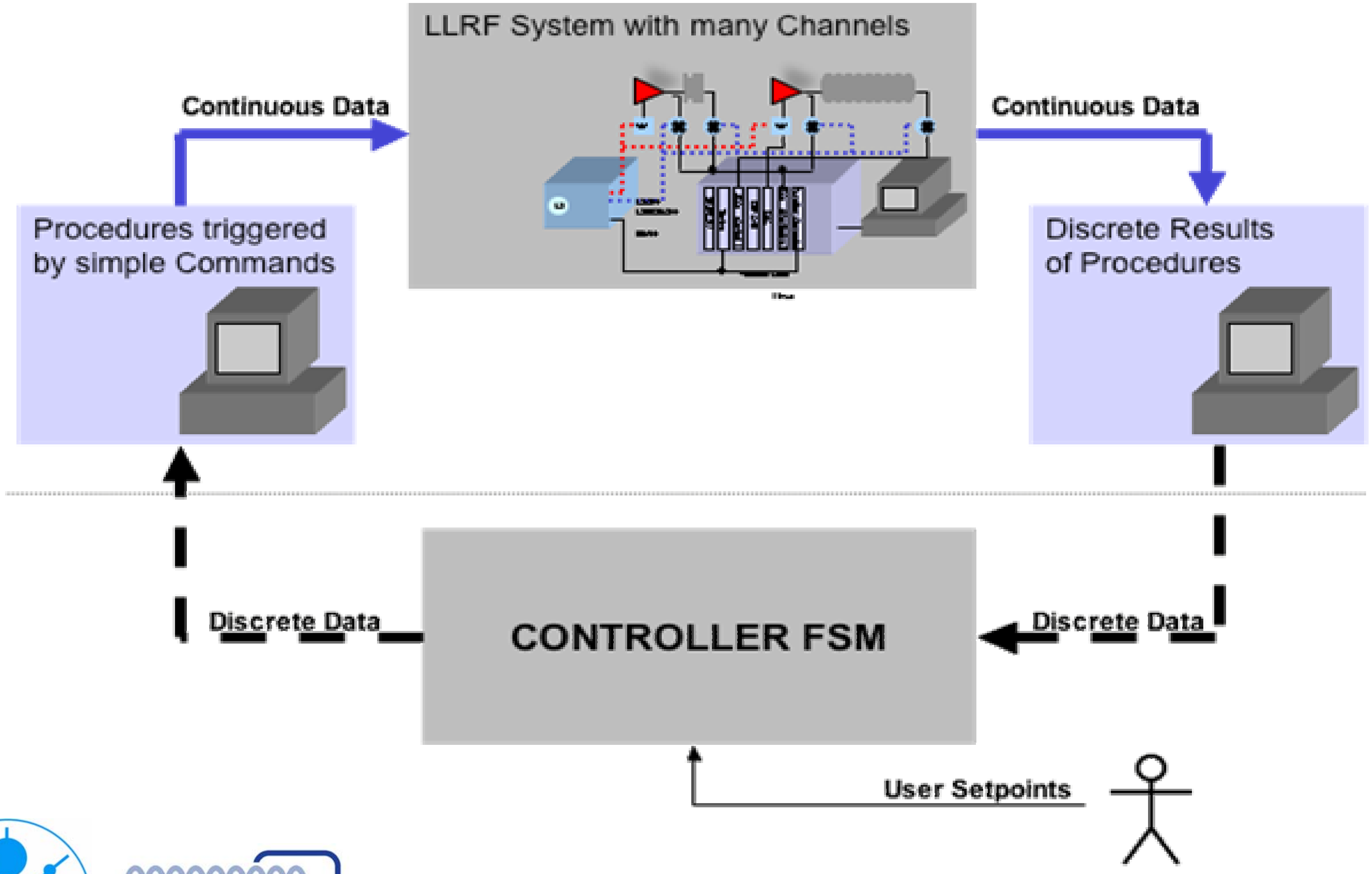
DDD FSM Framework

- Nice, but probably to unflexible
- That's why my implementation extended it by
  - Procedure server (with features like timeout and email notification)
  - Factory-classes for a simple reconfiguration (still needs compilation)
  - Parser that interprete online configuration ("go", "res" and "c" - buttons)
- Re-working the automation should be as easy as re-designing a panel
- Extension of the DDD FSM Framework is in progress…

Finally…

- **FSM is in permanent commissioning - Valeri and I are activating features and testing them**
- **Adaptive Feedforward is**
  - **available at FLASH**
  - **tested at SNS (to be implemented in August)**
  - **on it's way into the FPGA**
- **Still: there is a lack of operator acceptance / cooperation**
- **Good experience made with the flexibility of this approach (fast bug-fixing, adaptation to operator needs)**

...



LLRF System with many Channels
Continuous Data
Continuous Data
Procedures triggered by simple Commands
Discrete Results of Procedures
Discrete Data
Discrete Data
CONTROLLER FSM
User Setpoints

Operation at Alternating Gradients

Goal

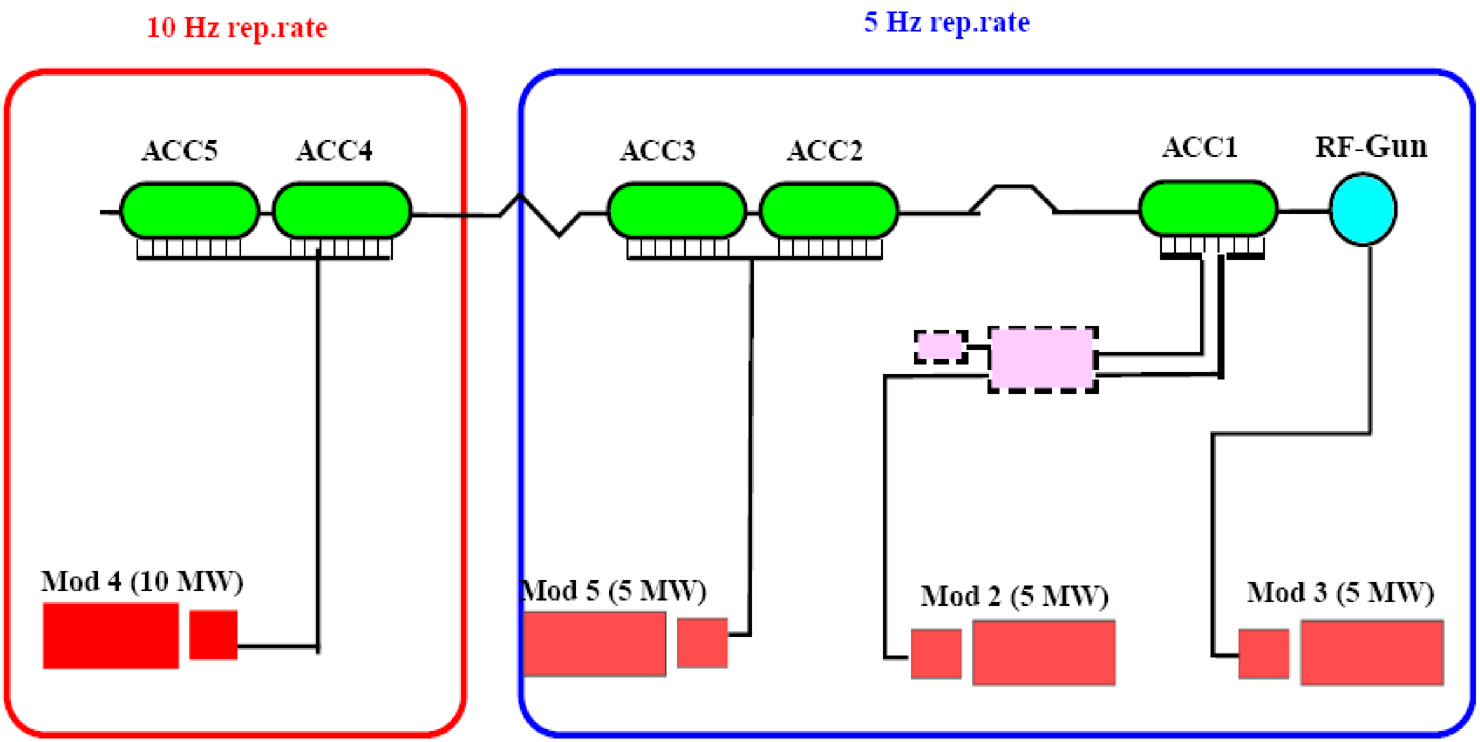
- Establish the possibility of operating the cavities with two gradient levels (pulse to pulse and intra pulse) so that they can be run at high gradient along with (during) SASE operation.

- This will allow for
  - Gaining operating experience at high gradient over long periods of time
  - The possibility of working on the second ramp during FEL runs (needs to be shown that we can do this without disrupting experimental program)

Other Goals

- Establish 10 Hz operation on Klystron 4
- Establish existence proof that SASE is not affected by the second ramp level
- Look at and compare amplitude and phase regulation with standard behavior

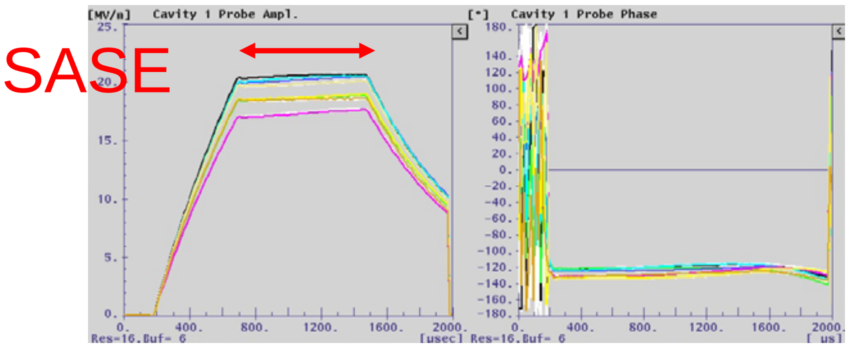
FLASH RF System



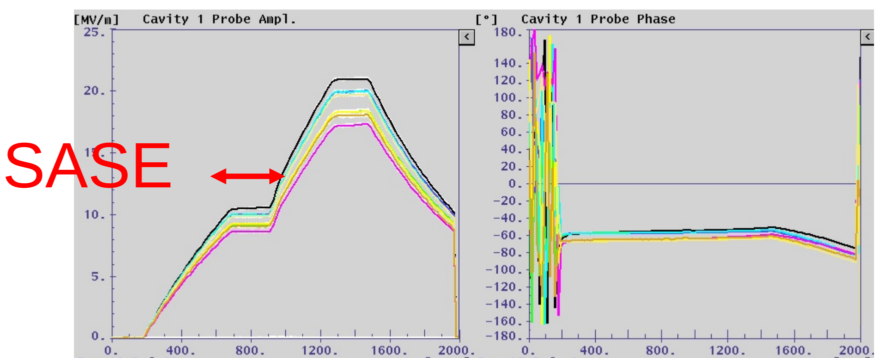
Two Ramp Modes

- Alternate SASE (lower gradient ramp) with a high gradient ramp
- Have a ramp with two levels, 1st for SASE, then going to higher gradient on the same pulse (but usually shorter flat time)
- Possibility of combining both of these (though not clear would want to)

Two Ramp Modes (2)



Alternate SASE, standard mode of operation



Ramp with two levels, 1st for SASE

Variable RF pulse length

Requirements

- The second (hi gradient) ramp must be set up so that making an adjustment to the lower (SASE) ramp does not affect the hi gradient ramp.
- This is so that operators can adjust the level with beam without worry of tripping on the high gradient level

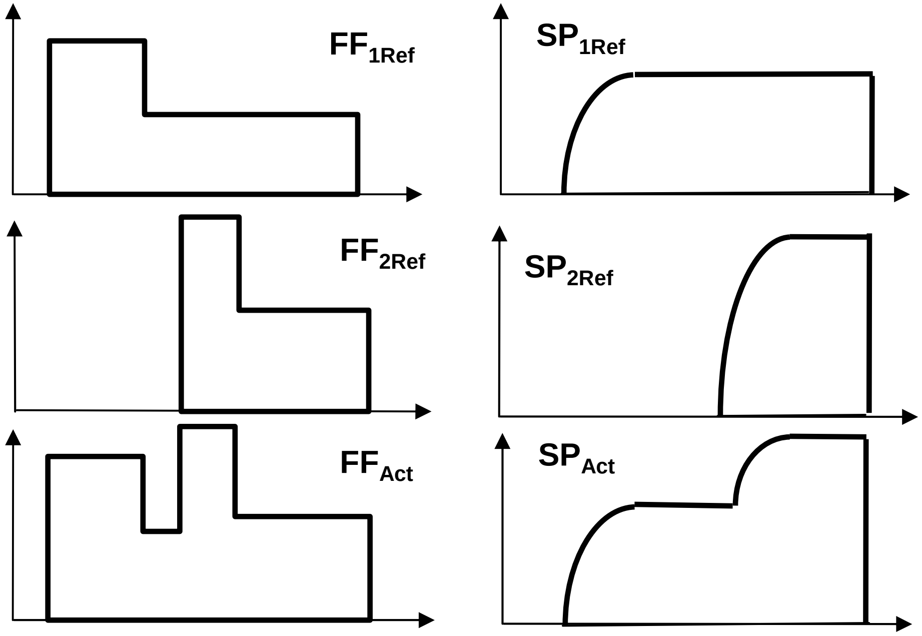
Technical Implementation

DSP server creates two reference SP and FF tables for alternate pulses

Actual tables are superposition of both reference tables

$$SP_{Act} = \max(SP_{1Ref}, SP_{2Ref})$$

$$FF_{Act} = \max(FF_{1Ref}, FF_{2Ref})$$



06.08.2006 22:37Ayvazyan, Edwards, Petrosyan, Simrock,Pchalek

Alternating Gradients – shift summary

Implementation and full test with beam bi-modal RF gradient operation at ACC4/5 is successfully completed.

It has bi-modal function with two features in it:

a) Alternate RF pulses have different gradients on ACC4/5, ramps 1 and 2 and beam can be run on ramp 1.

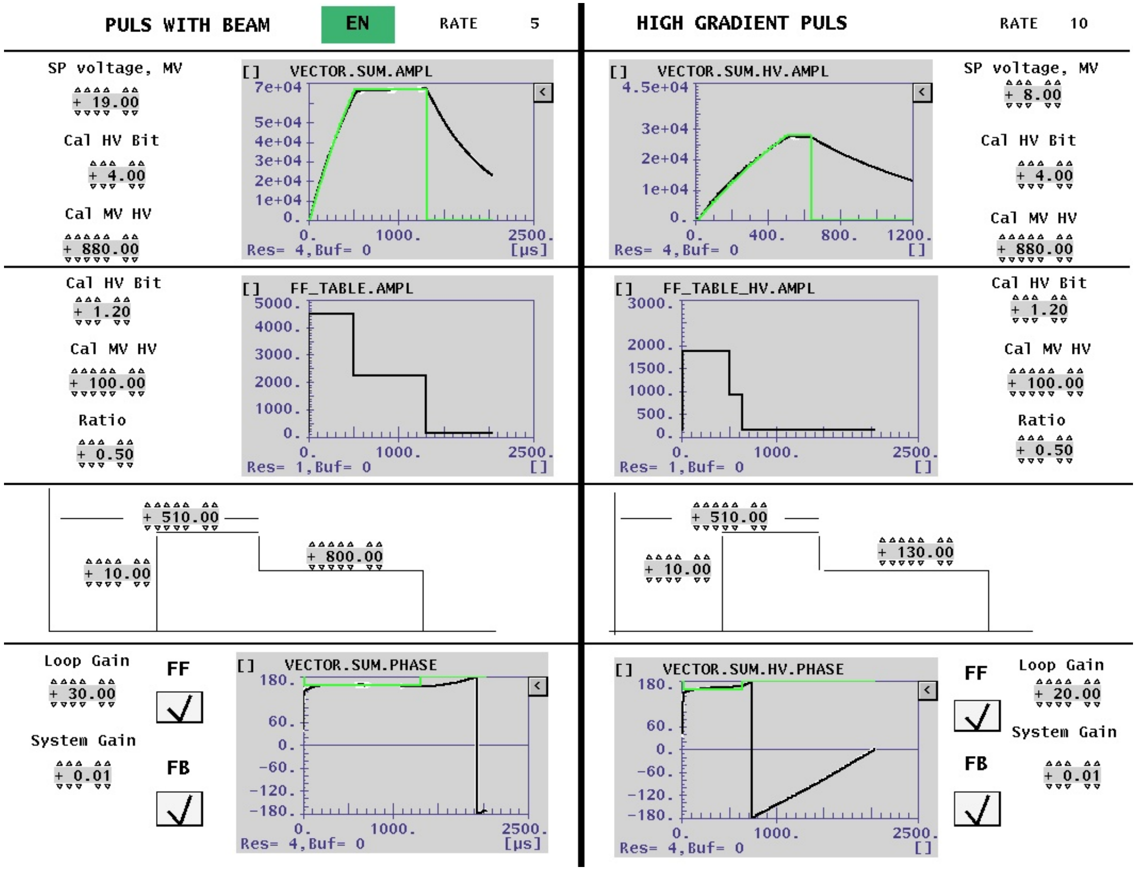
b) Ramp 2 has two gradient levels within the same pulse.

ACC4_5 runs at 10Hz rep. rate stable with average gradient close to 20MV/m. Rest of RF and beam runs at 5Hz rep. rate.

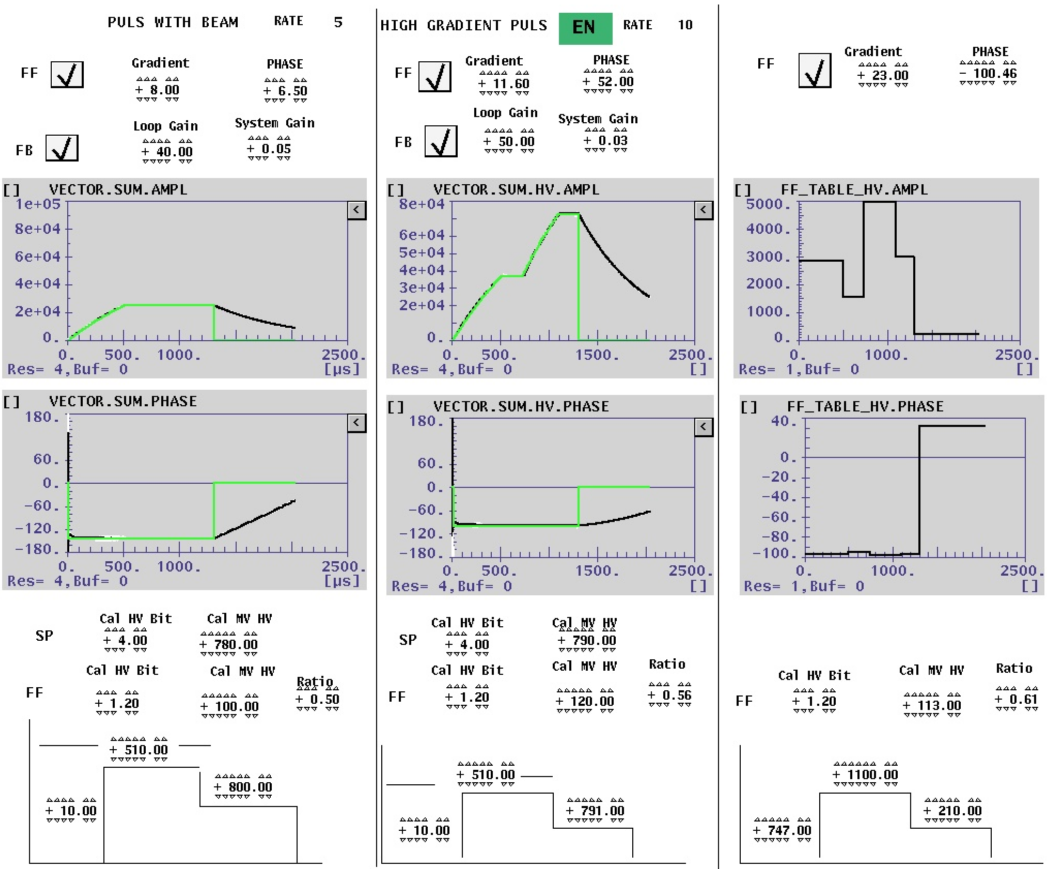
We got full transmission in both cases:on Ramp 1 and Ramp2 on low part of gradients.

Control performance for high alternating gradient is as good as for single pulse mode. Additional shift are required to test with SASE.

Tow Ramps (each one level)



Two Ramps, 2nd with 2 levels

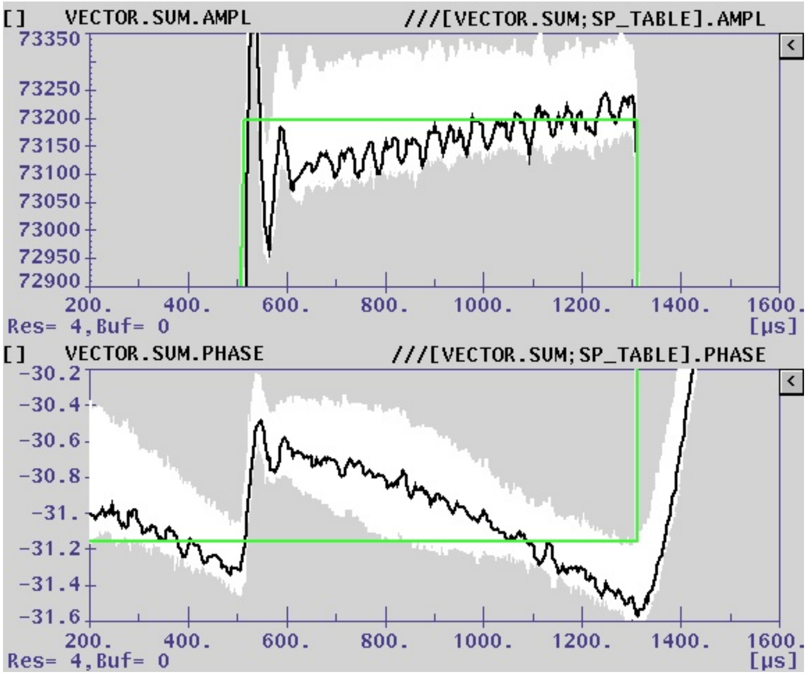


Regulation

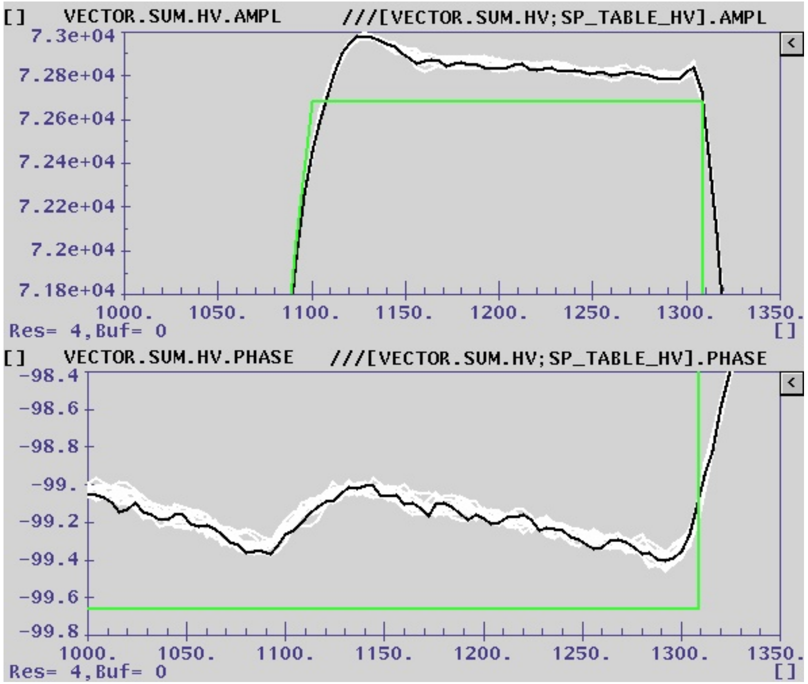
Gradients are close to 20Mv/m. Feedback gain is 50.

Control performance for high gradient part is the same as one pulse mode operation, except pulse length is shorter.

One pulse mode
~1/1000 Amp, 0.9 deg per 700 micsec

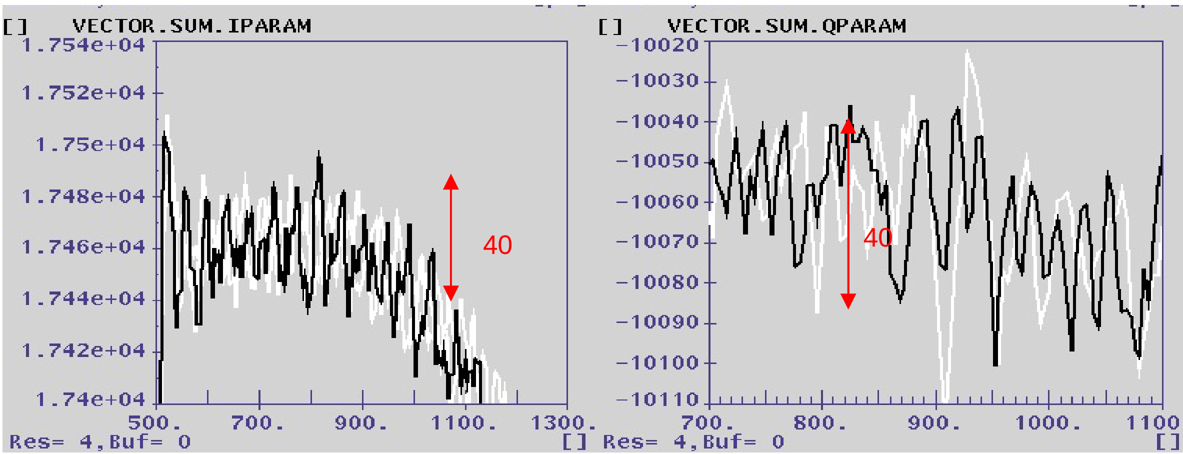


Alternating gradient mode
~1/1000 Amp, 0.3 deg per 150 micsec

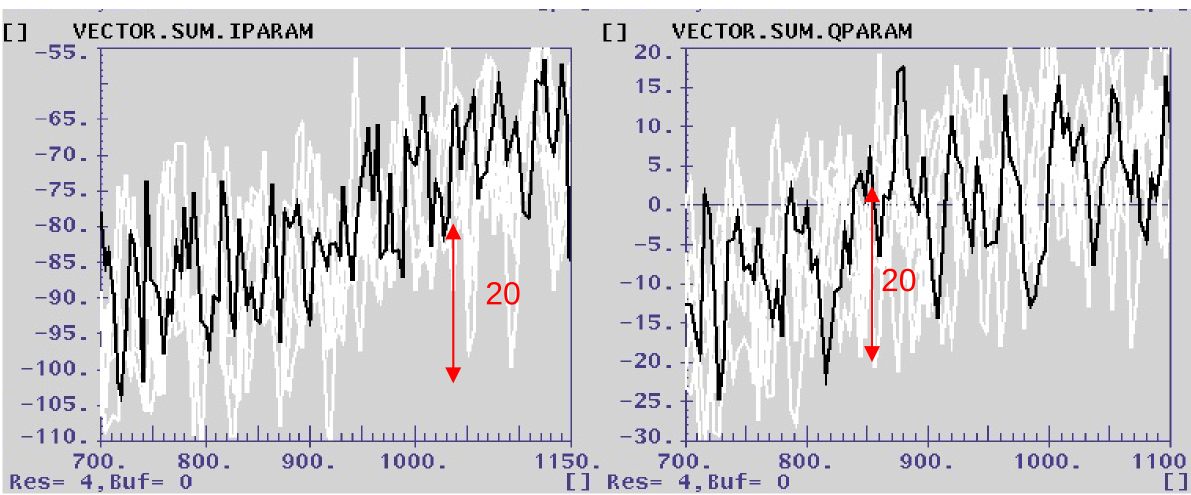


Noise investigation

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.

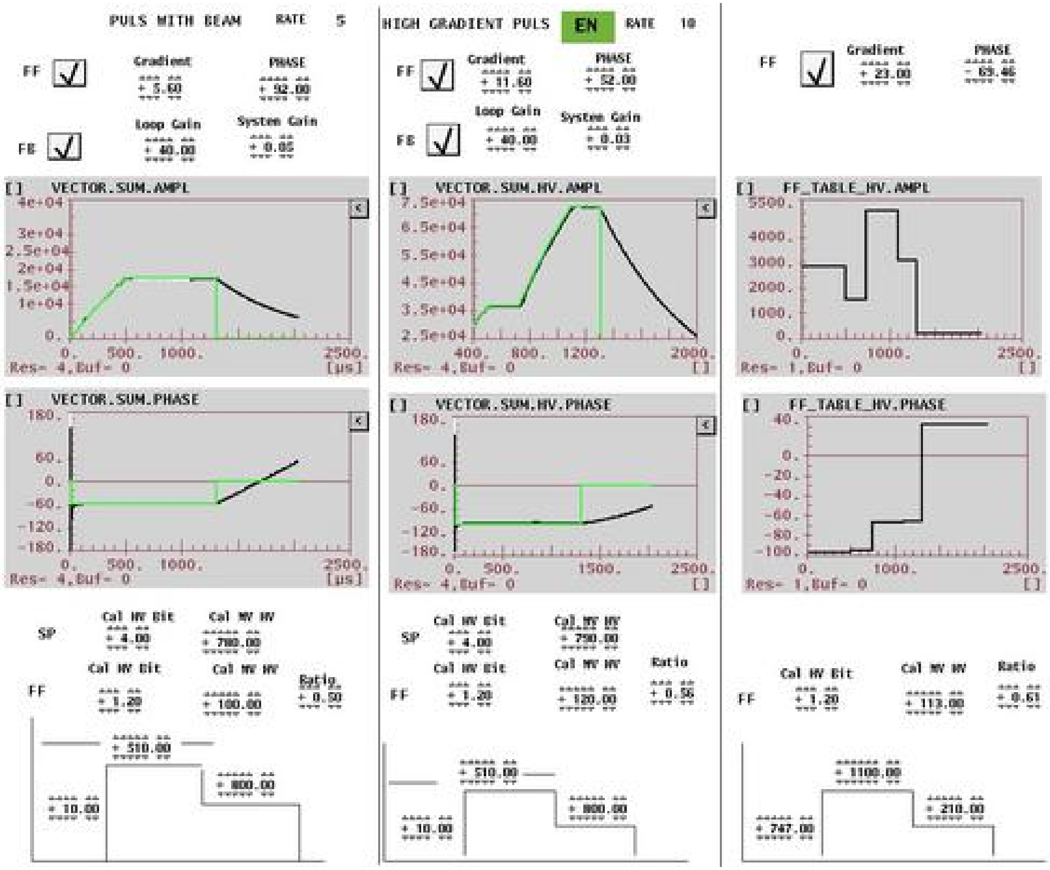


ACC4/5 with close to 20MV/m gradient.



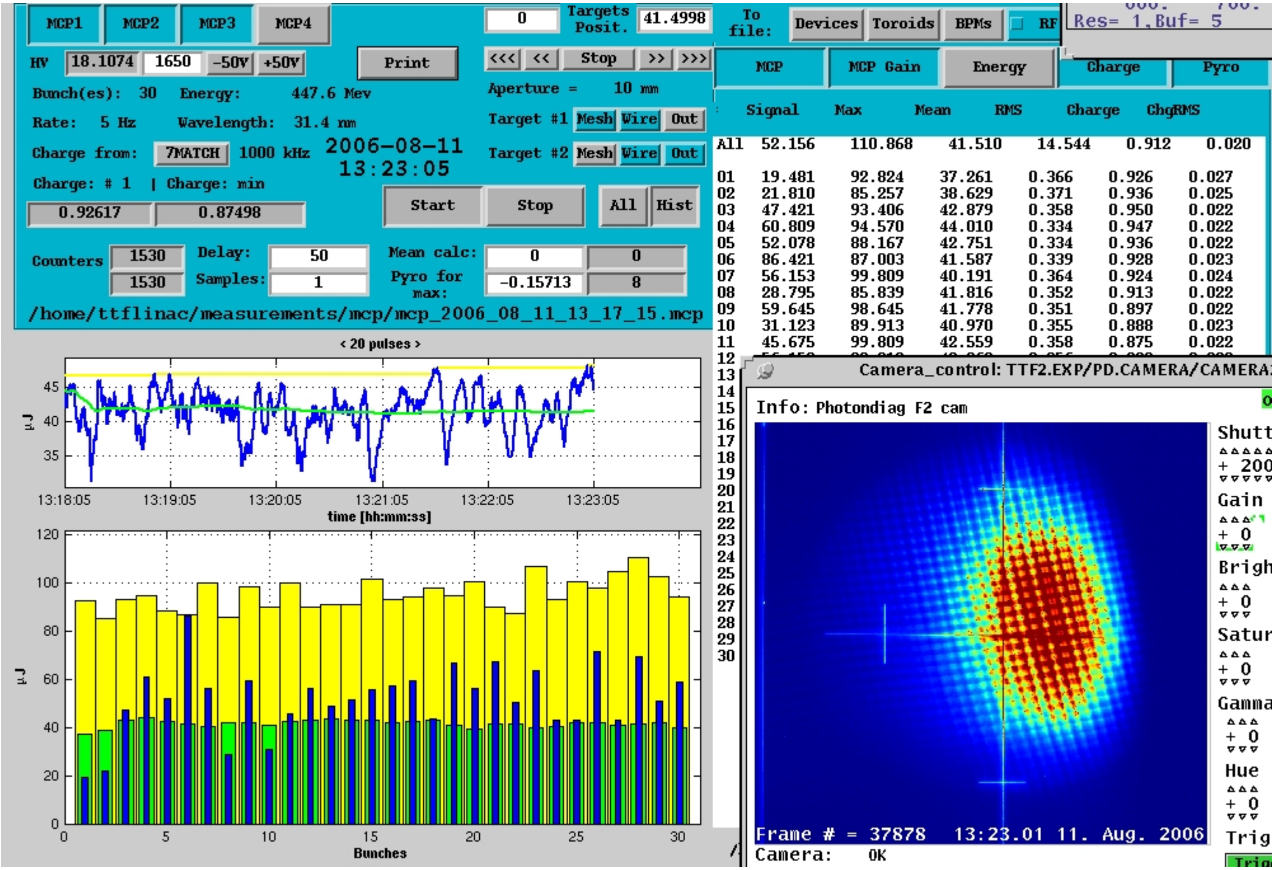
ACC4/5 with 0 gradient (no rf).

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

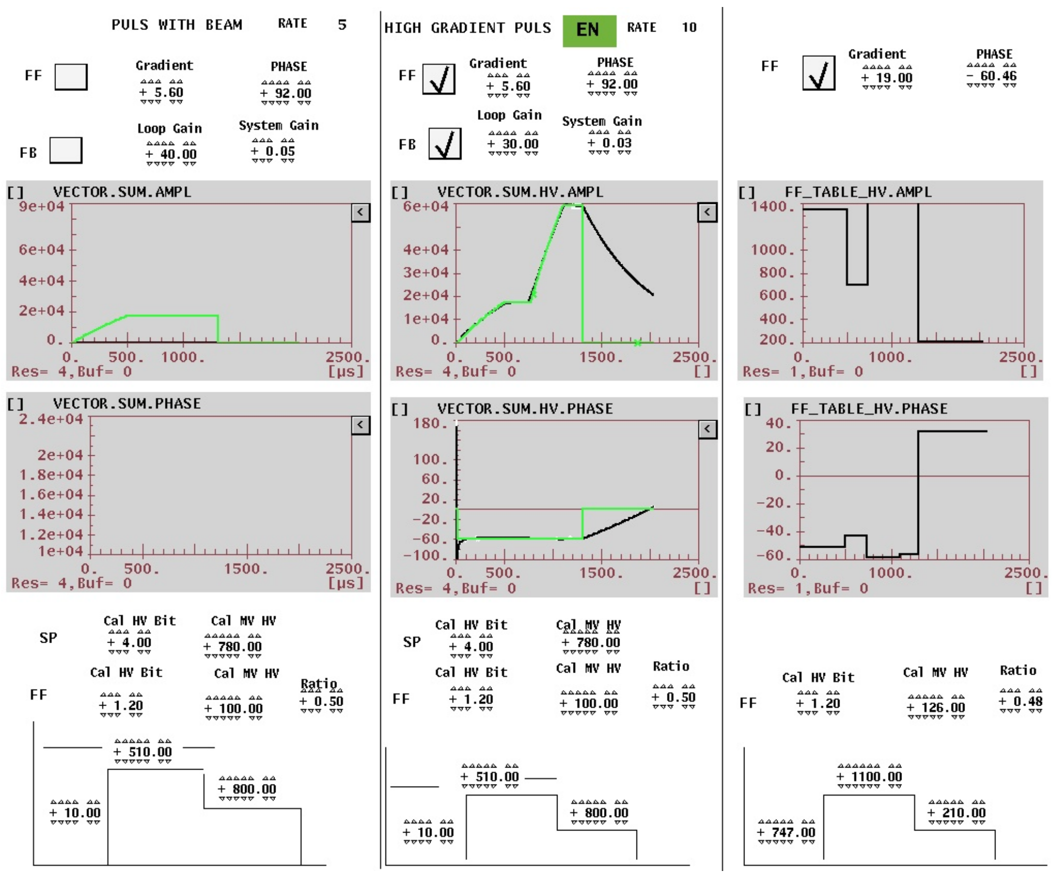


11.08.2006 12:59

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).

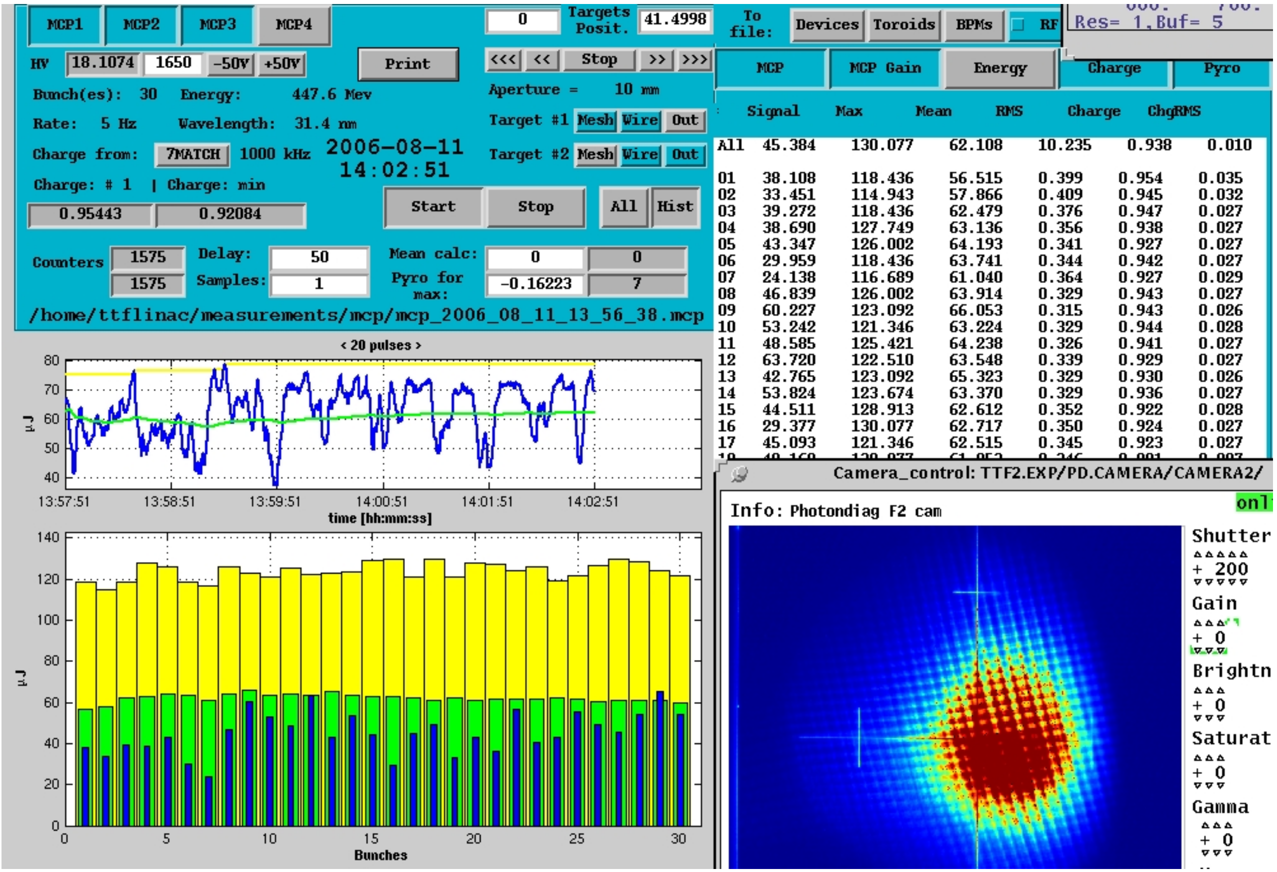


Now we switch off the first pulse for alternating gradient scheme and put the beam pulse on the first low level flat top of two levels of rf pulse.We see the same level of SASE.



11.08.2006 14:02

SASE with alternating pulses



Things that could be improved

- Connection between Feed Forward table and Setpoint table
- Regulation
- Adaptive feed forward?

Success – in Use

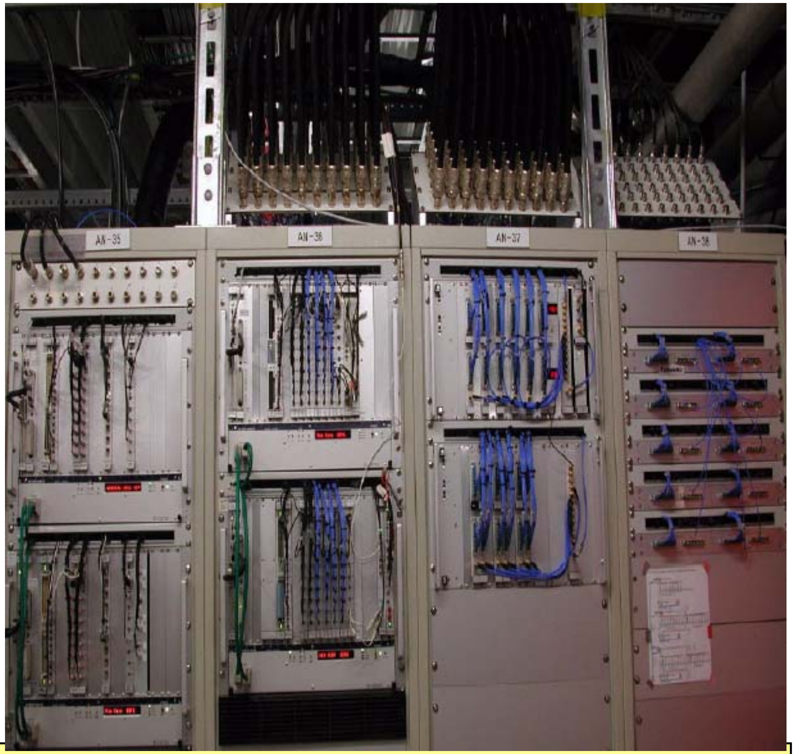
- Gain experience with high gradient operation, trips and reliability
- Explore gradient level can operate with and without feed back
- Work on regulation, Feedback, Feed Forward, Adaptive FF

Availability

XFEL LLRF System

LLRF Subsystems/Components Susceptible to Failure

o RF phase reference - from main driveline - LO for downconverter o Timing System o Vector modulator o Downconverter o Digital Control (Fdbck + FF) - ADC, DSP, DAC - includes exception handling - Redundant simple feedforward - Redundant monitoring system o Transient detection o Interfaces to other subsystems - includes interlocks	o Waveguide tuner and controls o Cavity resonance control - slow (motor) tuner - fast (piezo) tuner o CPU in VME crate o Network to local controls o Cabels and connectors o Power supply for electronics o Airconditioning in racks o Software - DSP (FPGA) code - Server programs - Client programs - LLRF Parameters - Finite State Machine



Work towards high availability started.

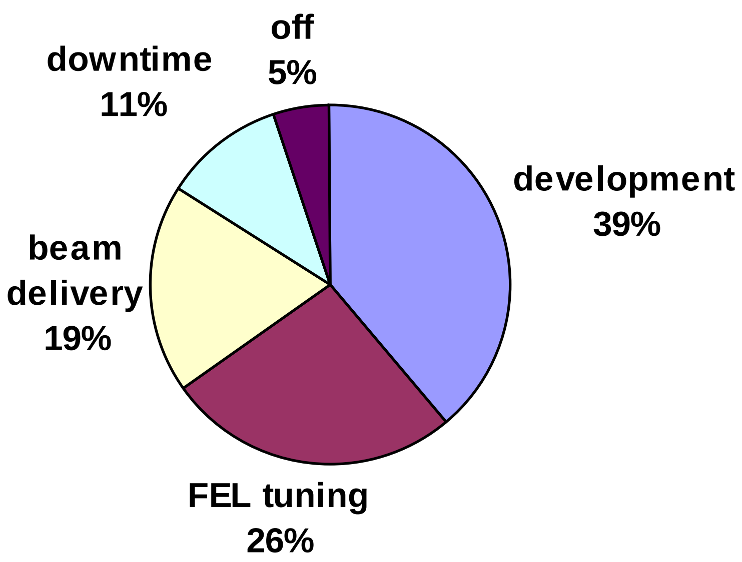
Each LLRF station consists of 9 crates from which 3 are critical. Here full and/or partial redundancy is planned with the aim to bring the actually estimated failure rate of 1 (of the 25) LLRF station failure / month down to one failure per 3 years.

This assumes 100,000 hours MTBF for each individual crate.

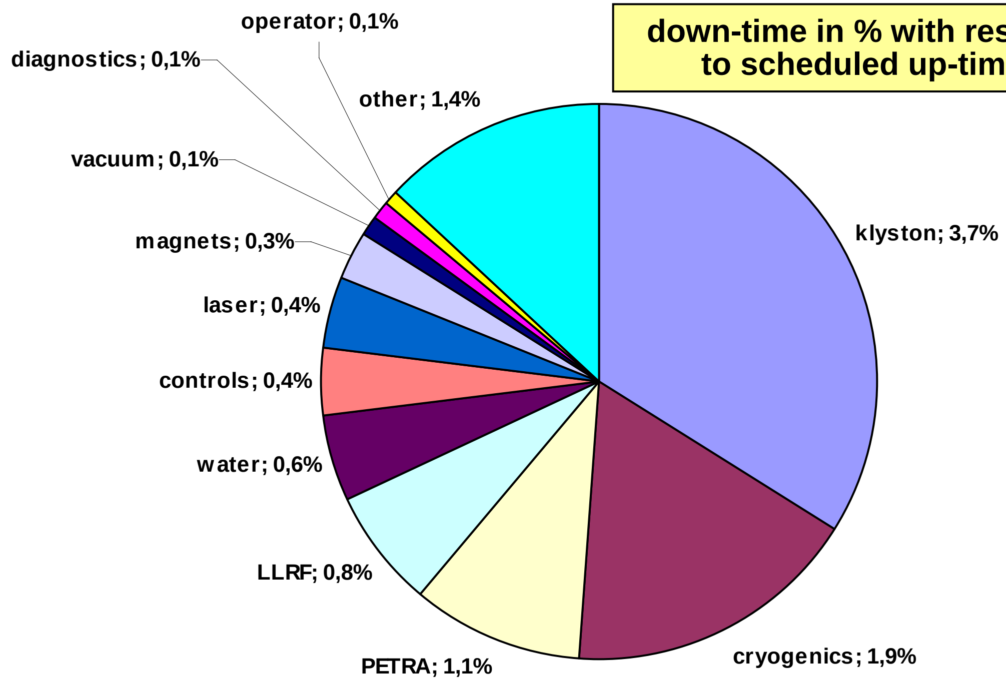
XFEL
X-Ray Free-Electron Laser

And now the truth… where are we?

TTF/VUV-FEL operation between
January 6th and November 1st, 2005



down-time in % with respect to scheduled up-time



The TTF/VUV-FEL downtime over 10 months was approx. 11%.

During this period we had

- user operation
- accel.studies
- system R&D.

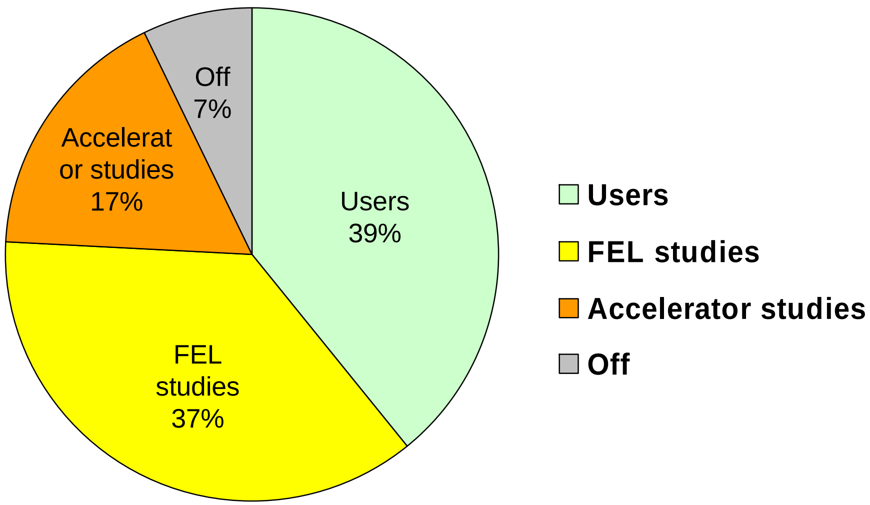
3.7% klystron	mostly problems with the prototype MBK
1.9% cryogenics	clearly dominated by one event connected with the use of the small/local refrigerator
1.1% PETRA	PETRA ramping disturbs the TTF/VUV-FEL operation
0.8% LLRF	clearly driven by system ‚improvements‘ since failures often shortly after R&D efforts

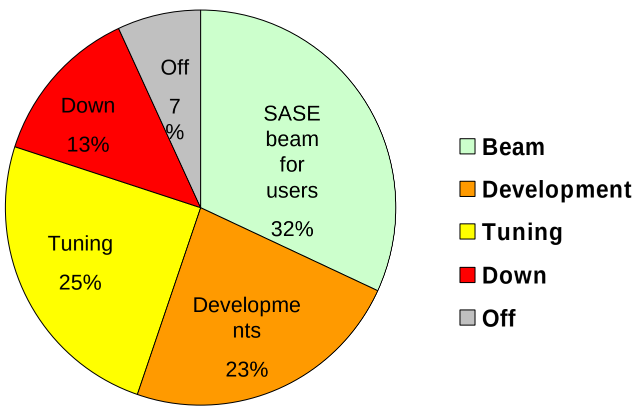
TTF2 / VUV-FEL (FLASH)

- Operation Statistics
  - July 2005 → Feb 2006: ~3600 hr (150 d). ~50% for users, 16% for FEL studies, the rest for acc studies and maintenance.

17-Apr-2006 to 13-Aug-2006 (weeks 16-32)

Total scheduled up-time: 2,648 h
Scheduled off-time (interlock tests + weekly maintenance): 208 h



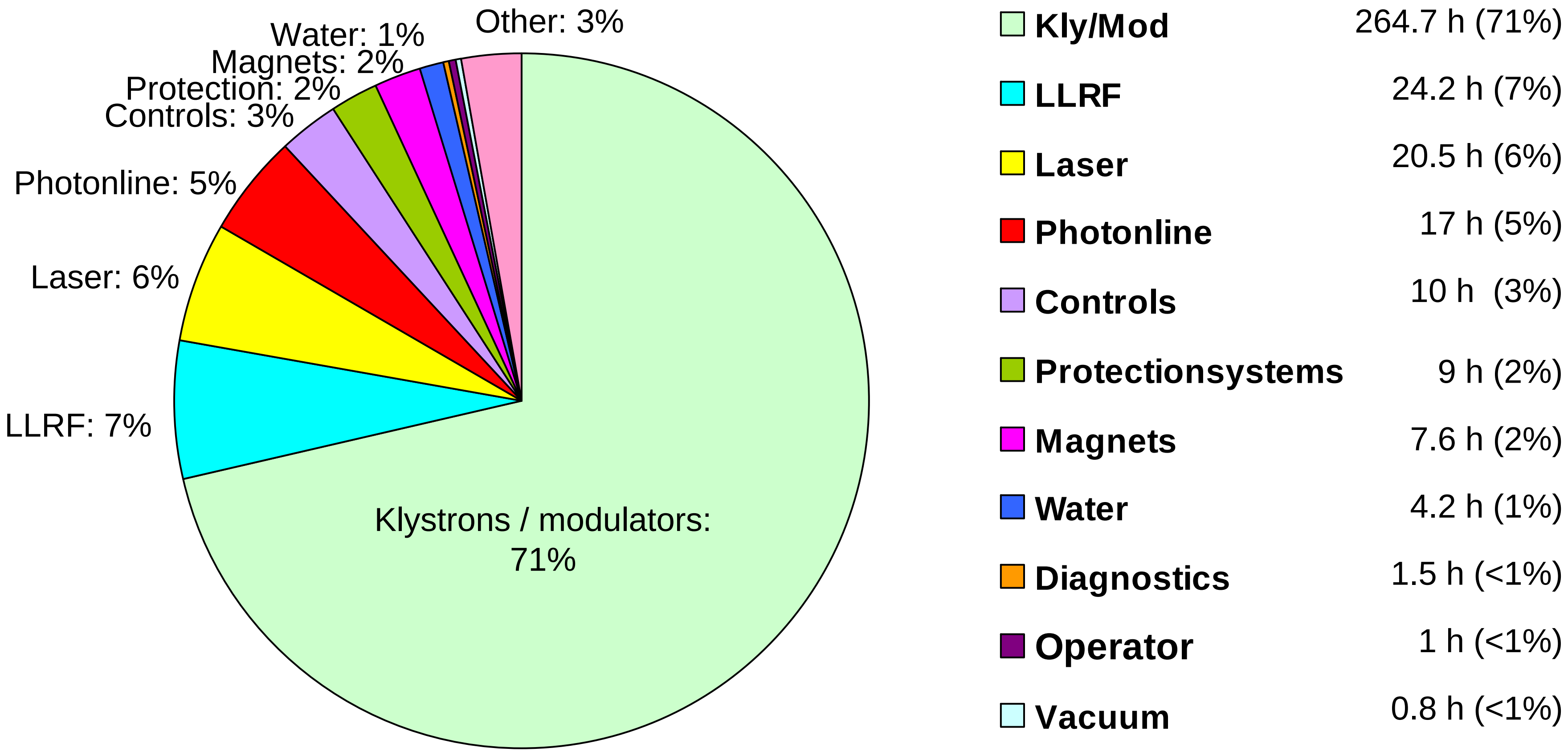


Total time: 2856 h (17 weeks, 7 days/week, 24 h/day)

Total up time: 2284.1 h (80%)

Down time weeks 16-32

Total downtime: 370.8 h (13%)



Klystrons / modulators is the sum of both plus waveguides, pre-amplifier, interlocks….

We urgently have to detail this; about 50% was one single event (bouncer circ. capacitor)

Kly / Mod. hardware failures weeks 16-32

	Weeks 16 to 35, 2006 only					
Summary categories	**Kly/Mod 3**	**Kly/Mod 2**	**Kly/Mod 4**	**Kly/Mod 5**	**Not defined**	**SUM**
Hardware failures	129,2	62,5	0	36,4	0,8	228,9
Resets required	7,2	10	2,3	8,7	1	29,2
Other failures	1,4	0	7	0,7	0	9,1
Wrong assignment	1	0	0	0	0,3	1,3
SUM	138,8	72,5	9,3	45,8	2,1	268,5

Hardware failures – an attempt to analyze the data…

no failure Kly/Mod 4, i.e. the MBK (at present every 2nd pulse at 6.5 MW)

Kly/Mod 3: all the 129 hours were caused by an oil leakage problem with the HV PS transformer, followed by some trouble with the regulation after replacing the transformer

Kly/Mod 2: 56 hours caused by a water leakage problem with a new 5 MW Thales tube (wrong material!)

Kly/Mod 5: approx. 25 hours caused by a defect capacitor in the bouncer