LLRF Control: Operational Issues

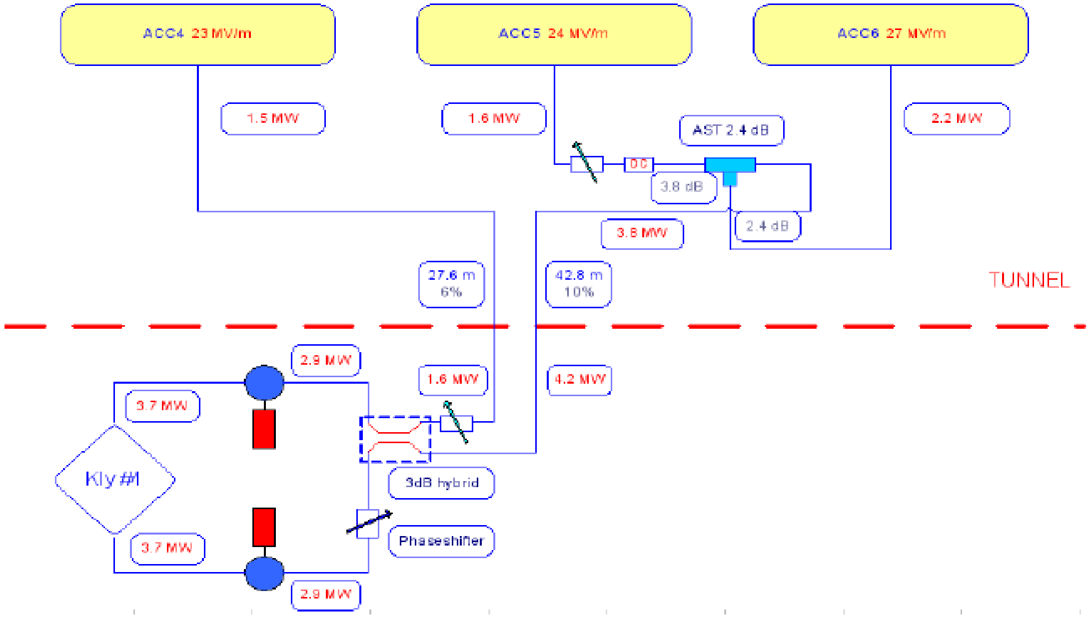
Wojciech Cichalewski, Boguslaw Koseda, Wojciech Jalmuzna TUL-DMCS;
Valeri Ayvazyan, Crystian Schmidt, Stefan Simrock, DESY

Agenda

- 1GeV operation (V. Ayvazyan)
- Beam based vector sum calibration (V. Ayvazyan)
- Klystrons operation in FLASH (W. Cichalewski)
- Close to limit operation (W. Cichalewski, V. Ayvazyan)
- Linearization tool evaluation (W. Cichalewski)
- Feedback loop delay study (W. Cichalewski, W. Jalmuzna)
- Automation (B. Koseda)
- Detuning and Ql measurement (C. Schmidt)

Waveguide Distribution System for ACC4-6 (10MW klystron)

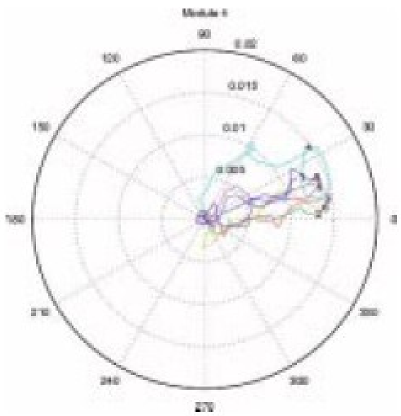
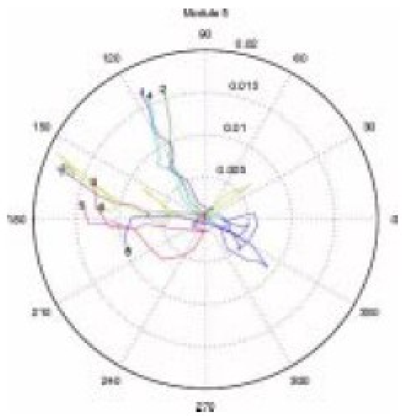
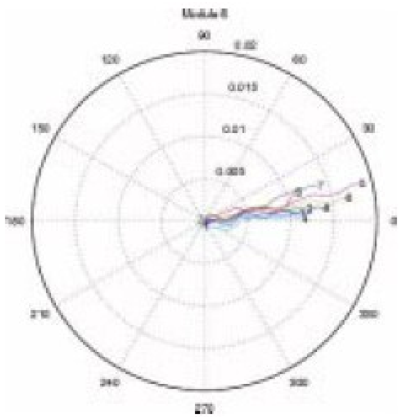
- New XFEL type cryo-module (ACC6)
- Different type of waveguide distribution system
- 24 cavities in one feedback loop



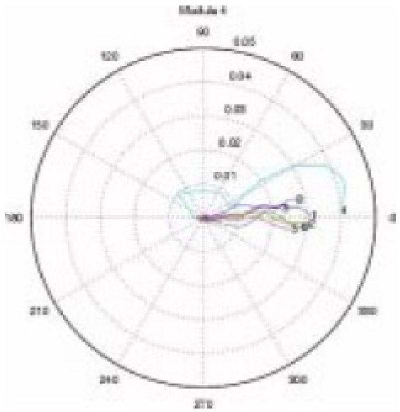
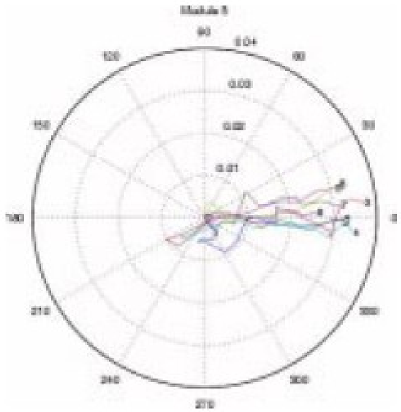
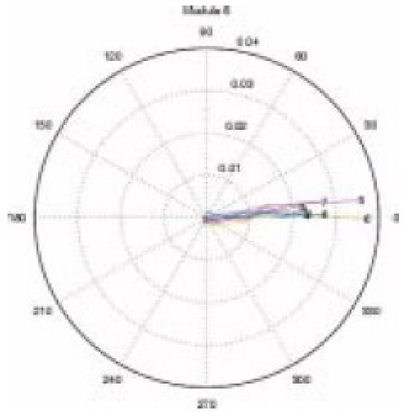
DESY
HELMHOLTZ GEMEINSCHAFT

Phase Adjustment (at ACC4/5/6)

Initial Measurement:

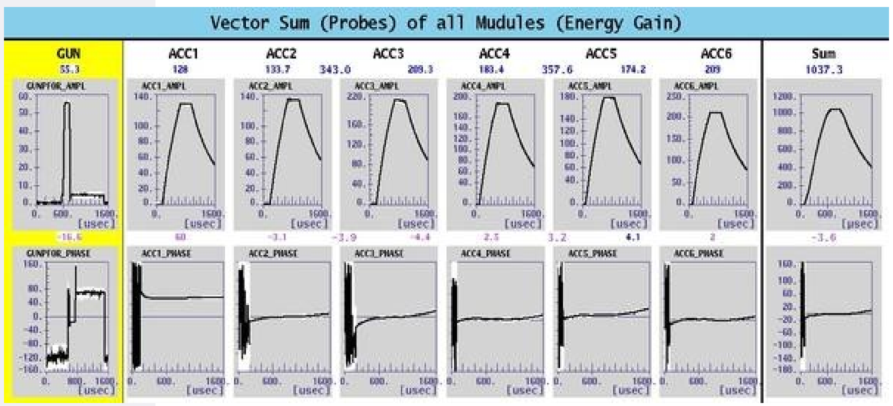




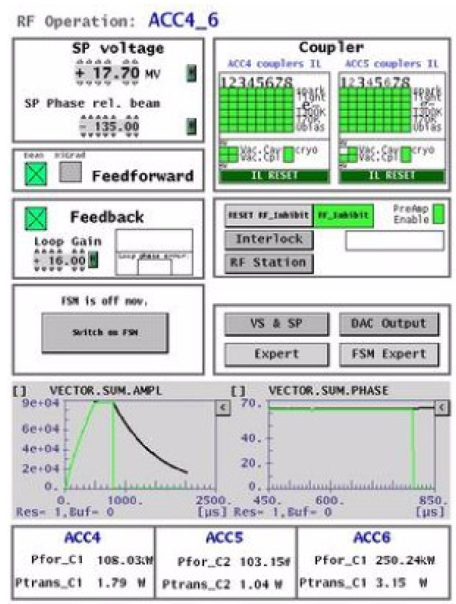
After Adjustments:

Vector Sum Control of 24 Cavities

- 24 cavities in one loop within significant spread in gradients between the modules
- ACC1: cav. 1-4 at 12MV/m, cav. 5-8 at 20MV/m
- ACC6: cav. 1-4 at 32MV/m, cav. 5-8 at 21-31MV/m

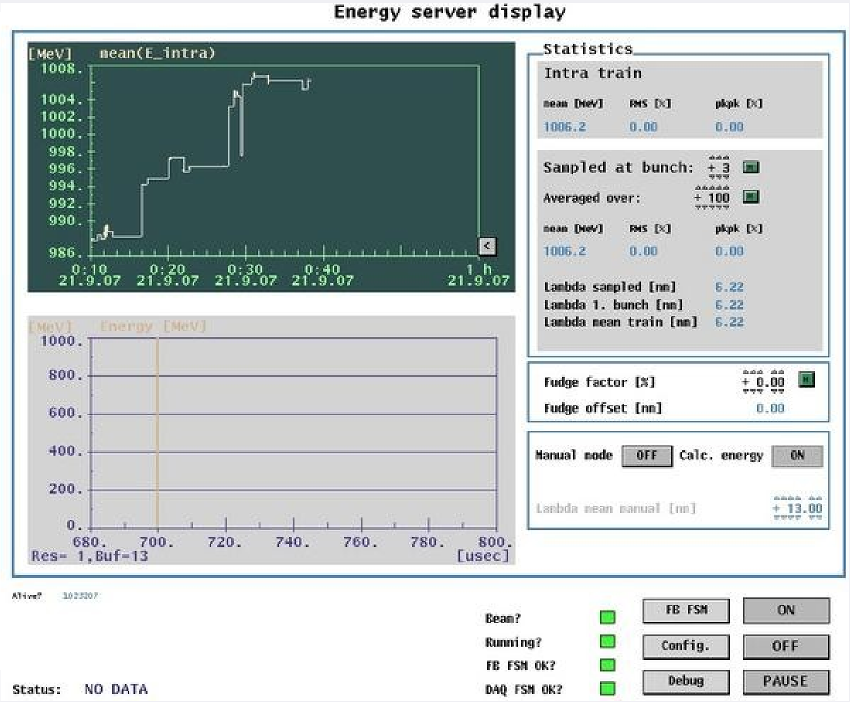




1 GeV operation

FLASH: Gradient Calibration (Achieved Gradients)

Energy (MeV)	ACC1	ACC2	ACC3	ACC4	ACC5	ACC6	
Cavity 1	13.2	16.7	25.6	21.0	20.5	29.1	
Cavity 2	12.9	13.4	25.8	20.6	19.8	28.9	
Cavity 3	12.6	19.2	25.7	21.3	19.9	30.3	
Cavity 4	13.1	18.6	25.9	20.1	20.0	29.0	
Cavity 5	19.2	18.7	25.7	21.1	20.5	20.0	
Cavity 6	20.0	15.0	25.3	21.1	20.7	20.5	
Cavity 7	13.3	18.5	25.3	20.6	20.2	23.4	
Cavity 8	19.9	19.4	26.0	20.4	19.7	23.5	
sum	124.2	139.5	205.3	166.2	161.3	204.7	1001.2



DESY HELMHOLTZ GEMEINSCHAFT

The current operating point for FLASH klystrons

- Klystron 3 – 5 MW tube:
  - Supplies RF-gun
  - operating HV: 124 kV
  - LLRF controller: Simcon 3.1
  - current operating point (peak value):
    - Klystron output: about 3.15 MW
    - Controller output: about 112000 counts (out of 131k)

86% of full scale

DESY HELMHOLTZ GEMEINSCHAFT

The current operating point for FLASH klystrons

- Klystron 2 – 5 MW tube:
  - supplies ACC1 (8 cavities with different gradients),
  - operating HV: 122 kV
  - LLRF controller: Simcon 3.1
  - current operating point:
    - Klystron output: about 1 MW (max. 1.7 MW)
    - Controller output amplitude: about 45.2k counts
      34.5 % of full range

The current operating point for FLASH klystrons

- Klystron 5 – 5 MW tube:
  - supplies ACC 2 & 3: ACC2 – 8 cav, ACC3 – 8 cav, each module has different operating gradient.
  - operating HV: 128.78 kV
  - LLRF Controller: DSP system
  - current operating point (data from 10-11.09.07):
    - Klystron output: about 2.98 MW (max. about 3.10MW) (max. Acc2C5 = 134 kW, Acc3C1 = 252 kW) Controller output amplitude: about 1.7k counts (out of 2^13)

21 % of full range

The current operating point for FLASH klystrons

- Klystron 4 – 10 MW tube:
  - supplies ACC 4 & 5 & 6: 8 cav. in each module
  - operating HV: 110 kV
  - LLRF controller: DSP system
  - current operating point (data from 11.09.07):
    - Klystron output: about 5.3 MW (max. 5.4 MW) (max. Acc4C1=170kW, Acc5C2=150kW, Acc6C1=350kW)
    - Controller output amplitude: about 3.2k counts (out of 2^13)

40 % of full range

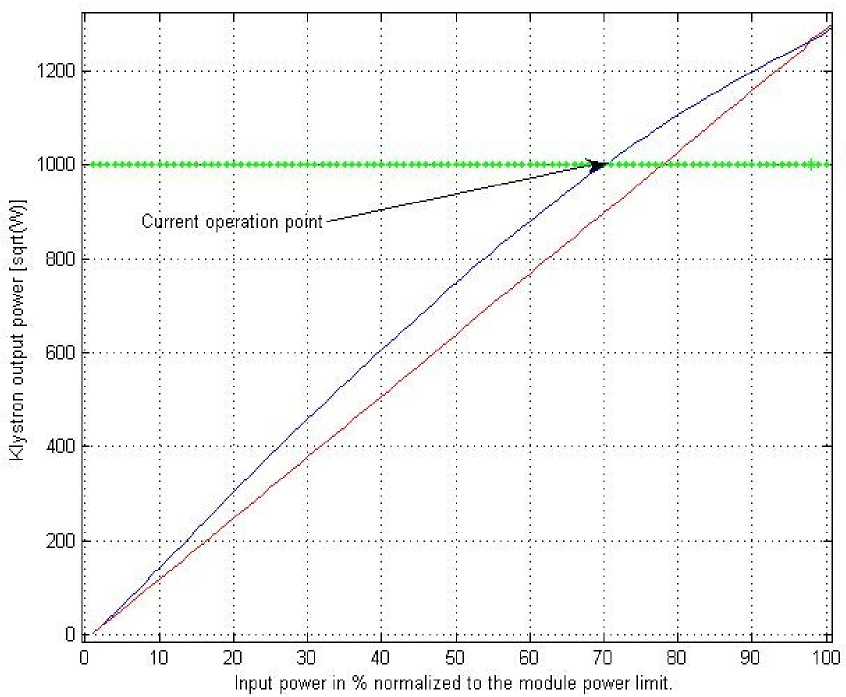
FLASH status (12.09.2007)

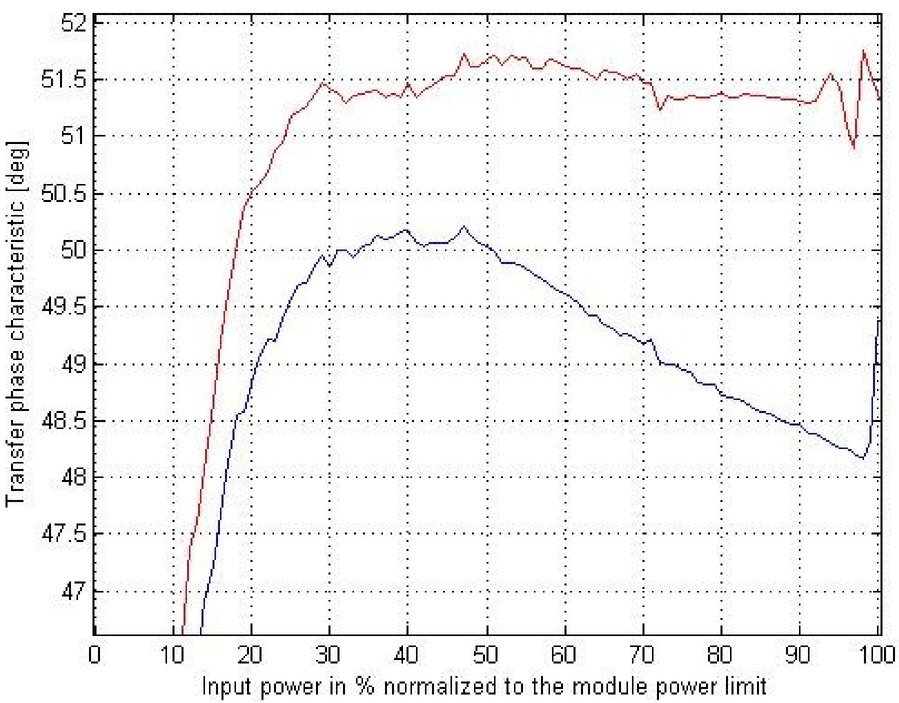
- Current FLASH RF stations operating points are far from the operational limits:
  - K2 ~ 20% of 5MW, - K3 ~ 62% of 5 MW,
  - K4 ~ 53% of 10MW, - K5 ~ 60% of 5 MW.
- Current OP already are placed in the region where transfer characteristics of High Power Chain are non-linear
- The output power margin is well balanced concerning the LLRF field controller range and HV level in most of the RF systems.
- For current OP levels the LLRF controller has sufficient output signal range to provide (non-saturated) operation of the modules even for the feedback gain that corresponds to operation near to the loop instability.
- In case of the ACC2&3 (21% of LLRF controller full scale) and ACC4&5&6 (40% of LLRF controller full scale) one can consider the controllable attenuator in the HPC path (after the VM for instance) in order not to lose controller resolution.

Klystron 2 – characteristics

(and current OP)

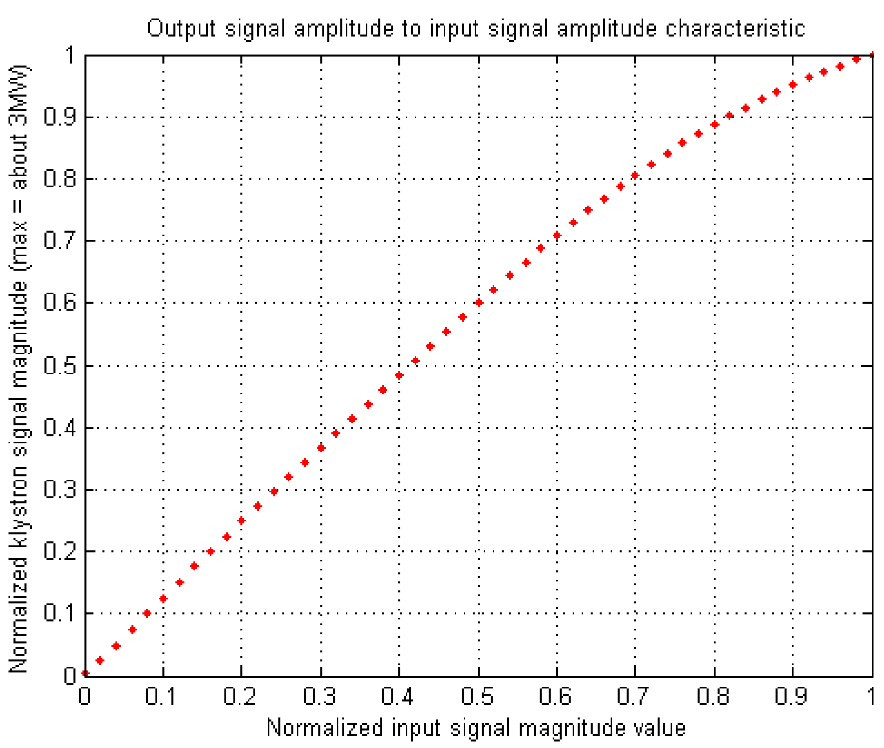
- The amplitude (left) and phase (right) transfer characteristic for the klystron operation with HV level 122kV.
- Blue curve – nonlinear amplitude transfer characteristic
- Red curve – transfer characteristic after linearization

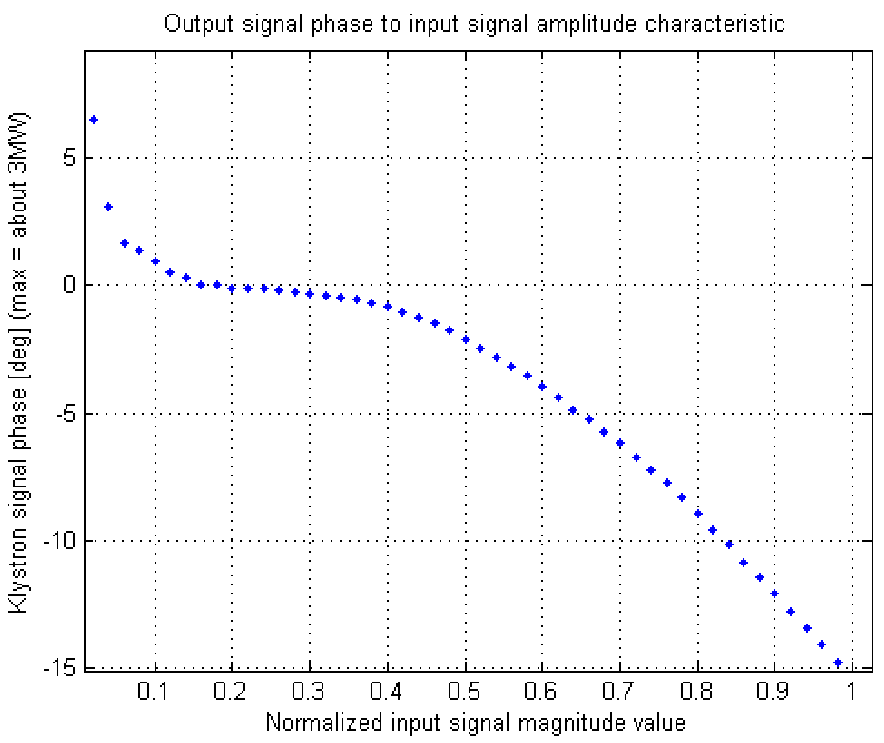




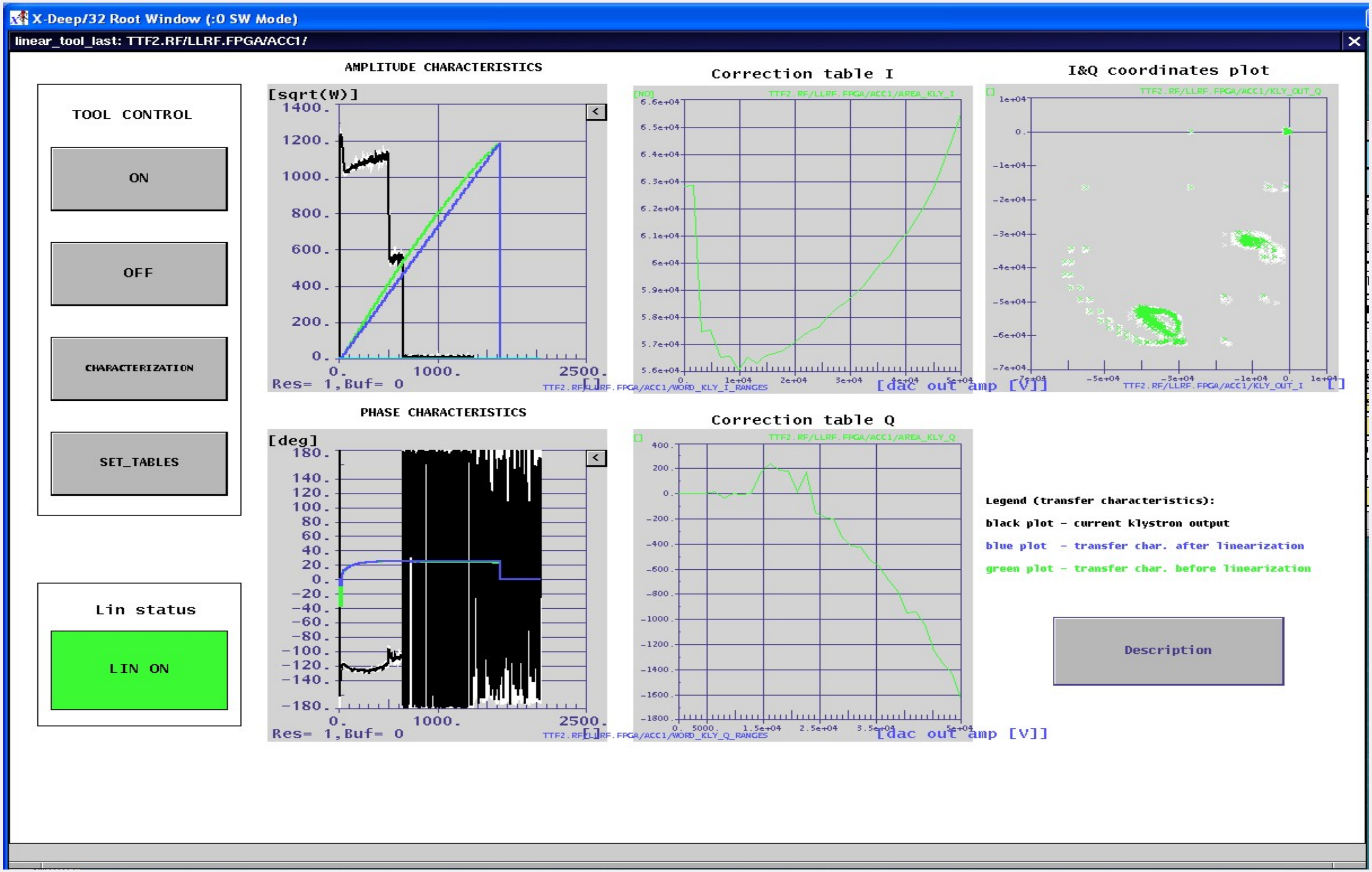
Klystron 5 – characteristics
(up to the OP)

- The amplitude to amplitude (left side) and phase to amplitude (right side) characteristics for klystron 5 (HV=121kV, Simcon 3.1 operation).

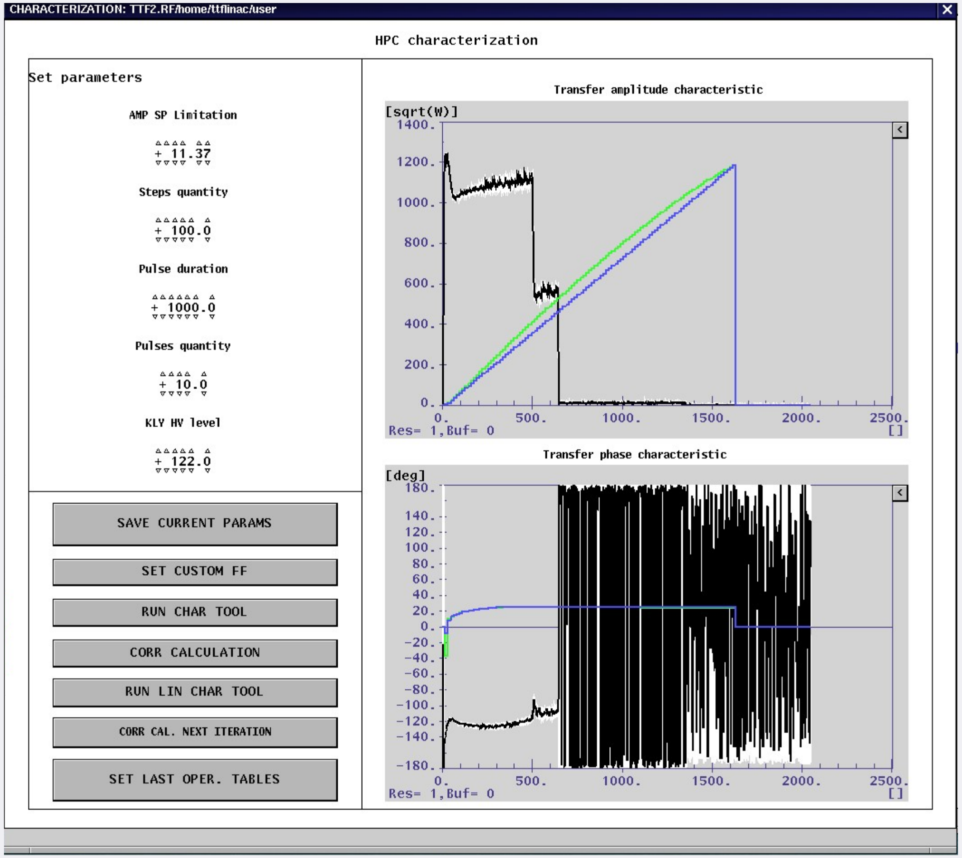




Linearization tool operation in ACC1



Linearization tool operation in ACC1



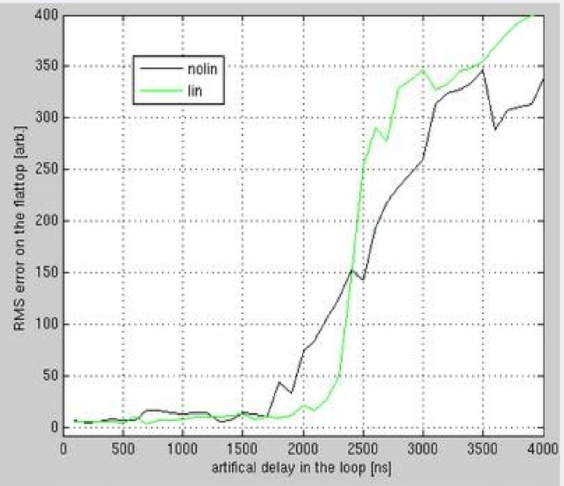
GUI for the HPC characterization and the correction coefficeints calculations.

Features:
-Customized FF tables generation,
-„Restore old settings" functionallity,
-HPA characterization before and after linearization,
-Digital predistorter coefficients adaptation,
-Characterization for different HV settings.

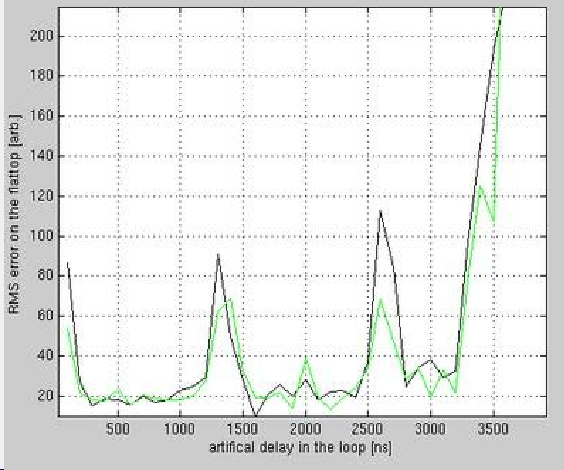
FLASH
Freie-Elektronen-LASer in Hamburg

Feedback loop delay study

•The artifically added delay in the LLRF feedback gain loop in ACC1 has been added in order to study loop stability issues.



- Loop delay scan for whole module (ACC1)
- Measurement for gain 200 and in case of linearized HPC gain = 234 due to the differences in the system gain. Measurements have been done for SP = 3.25 MV/m PH = 0 deg.



- Loop delay scan for one cavity (C8 ACC1)
- The Amp. RMSE on flattop in function of additional delay (expressed in ns) for the gain of 200 and SP = 3.25MV/m. During this measurement the 8 cavities was included in the vector sum.
- Peeks observed on the RMS error plot may correspond to the higher PI-modes excitation of the measured cavity [discussion with E.Vogel].

DESY HELMHOLTZ GEMEINSCHAFT

Existing algorithms for LLRF automation

Purpose – study the possibilities of automation components reusage

– Tool for estimation of field quality

– Tool for restarting cavity interlocks

– Tool for feed forward tables adaptation

– Tool for calculating/correcting the loop phase and the system gain

– Tool for forward and reflected power calibration

– DOOCS server hosting procedures (tools).

– FSM framework

DESY HELMHOLTZ GEMEINSCHAFT

Tool for estimation of field quality

Threefold classification of the field quality on the base of error = VS – SP during flat top

- High *rms(amp_hi) max(amp_hi) rms(phase_hi) max(phase_hi)*
- Medium *rms(amp_m) max(amp_m) rms(phase_m) max(phase_m)*
- Poor *rms(amp_p) max(amp_p) rms(phase_p) max(phase_p)*

If the error signal meets all the properties „rms(amp) max(amp) rms(phase) max(phase)" than the quality of the pulse belons to the corresponding category.

Tool for restarting cavity interlocks

Purpose: – to check status and restart couplers interlocks

Status: works – can be easily adapted.

Tool for feed forward tables adaptation

Principle: works it has been already implemented in the Matlab (DSP), C and FPGA (for SIMCON only).

Status: is already adapted to SIMCON based systems

DESY HELMHOLTZ GEMEINSCHAFT

Tool for calculating/correcting the loop phase and the system gain

Loop phase: phase change between the input and output signals of the LLRF controller in case of feedback off and system being in steady state.

Loop gain: the amplitude gain between the input and output signals in case of feedback off and system being in steady state.

Purpose: calculate the loop phase and loop gain.

Status: used now in the ACC23, can be used immediately.

Tool for calibration of forward and reflected power readouts in the GUN.

Purpose: Correct for crosstalk between the readouts of forward and the reflected power in the GUN.

Status: The algorithm was tested in ACC1. There were a problem with it because of wrong connection of the readouts of forward and reflected
power (diagnostics ADCs only). The conncetion has been corrected after the tests. Nevertheless the testers have belief that the tool can be used succesfully.

DOOCS server hosting procedures (tools).

Purpose: allow flexible connection between the supervisory logic and the procedures executed by it.

Status: works and is going to be adapted for future automation systems.

The FSM framework

Purpose: To implement supervisory logic of the automation.

Status: It is a modified version of the DOOCS FSM framework. Works for the automation of the DSP based systems, but future of the solution is unknown (new ddd is coming and the framework does not seem to be supported by any one now).

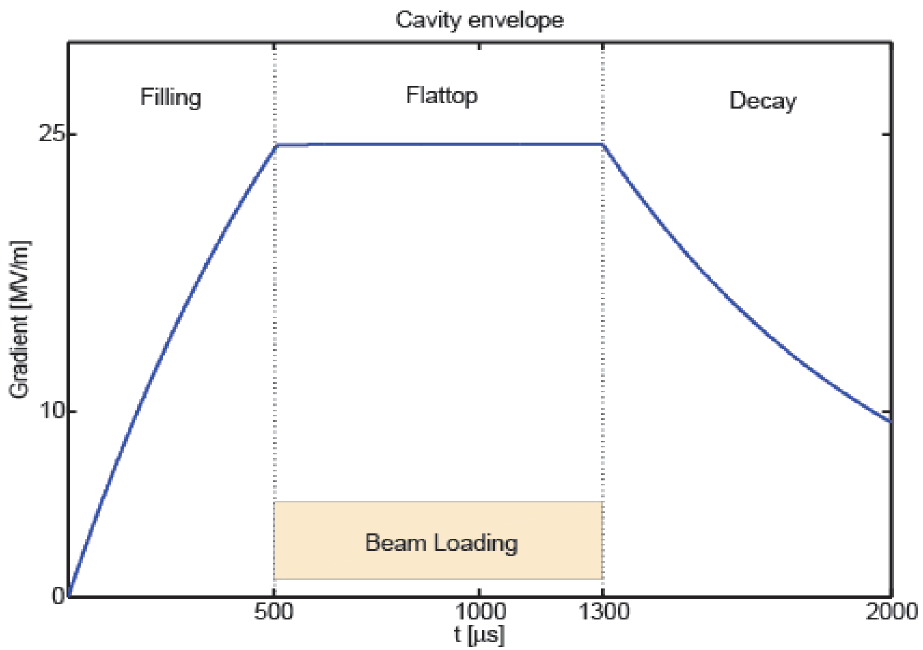
Physical system parameter identification

Motivation for measurements of following parameters:

- Detuning
  - Identification might lead to more accurate system modeling
  - predictable output due to deterministic parts (LF-detuning)
- Loaded Q
  - Quench detection and exception handling
  - Power distribution while adjusting Loaded Q
- Lorentz force detuning by piezo measurements
  - additional identification parameter for modeling
  - piezo actuator control

Pulsed distribution for data acquisition

Parameters are measured by the LLRF tool given in DOOCS

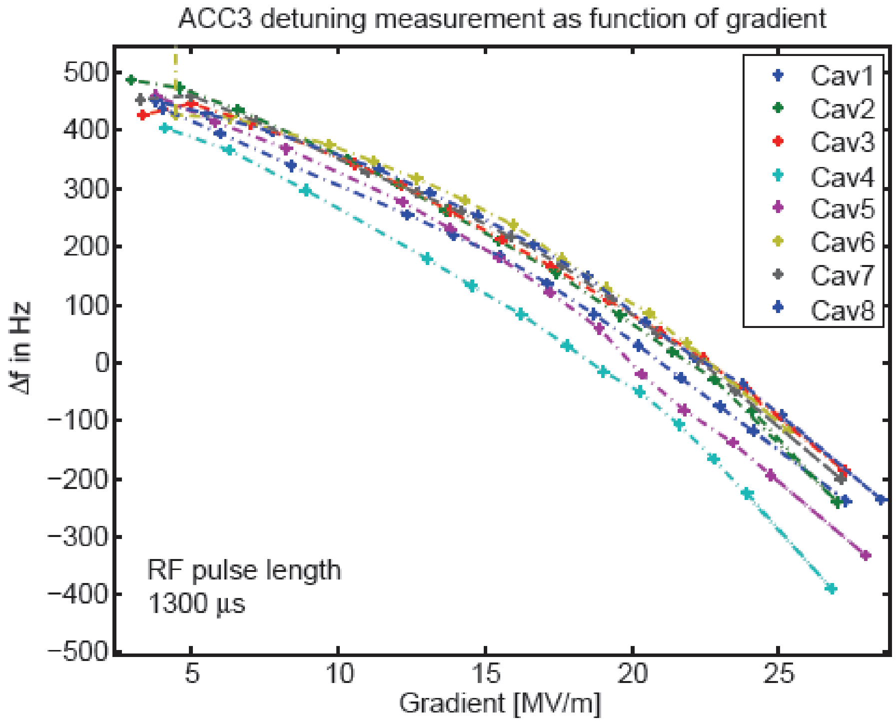


- Gradient at beginning of flattop averaging over first data points
- Loaded Q at beginning of decay while averaging time constant
- Detuning averaged but not as function of time

Measured detuning curves

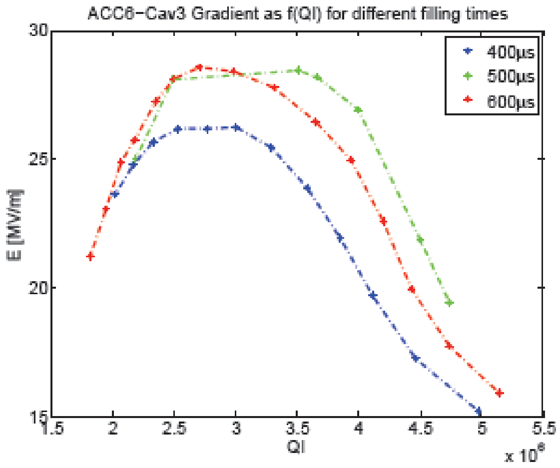
Task: The dependence of the detuning from the gradient of the field is to be analyzed.

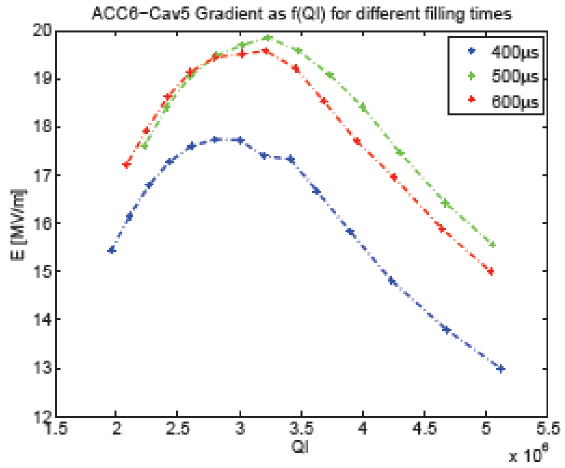
Method: Adjusting the loaded Q by arranging waveguide tuners (3 Stub tuners on ACC3)

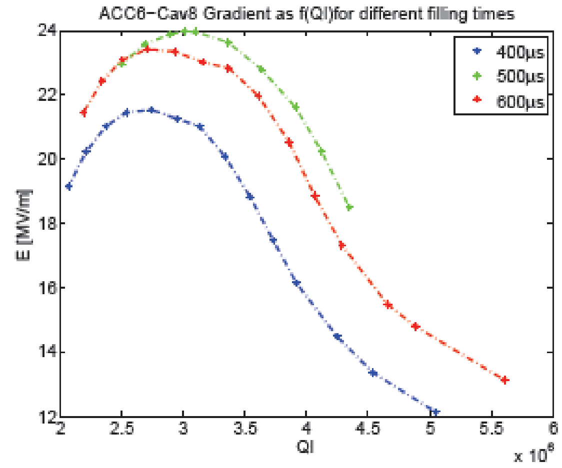


- comparable behavior for all cavities
- curves show assumed characteristics $\Delta\omega \approx E^2$
- pre-detuning causes max gradient for detuned cavities

E as function of Ql for different filling times

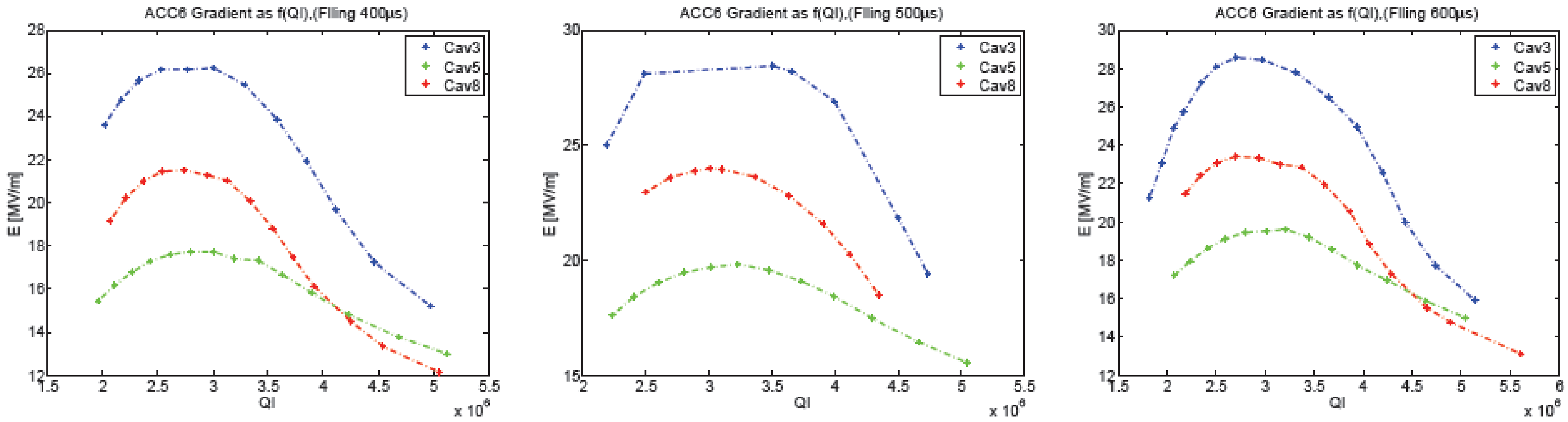






- **Method:** Adjusting the loaded Q by coupler position
- gradient variances caused by DAC restrictions for short time filling (ratio)
- sweeping loaded Q $\rightarrow$ max. Gradient differs for $400 - 600\,\mu s$

E as function of Ql for different cavities



- **Method:** Adjusting the loaded Q by coupler position
- gradient variances caused by max. gradient restrictions on different cavities
- comparable curves for different cavities due to E_{max}

Detuning due to Lorentz forces

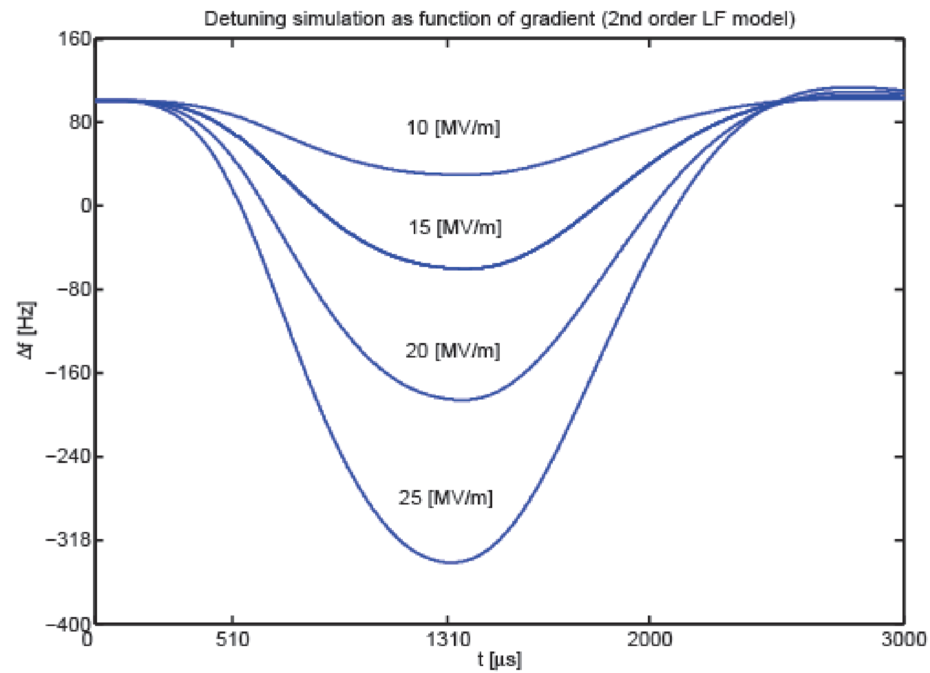


Figure: gradient depend detuning during acceleration pulse (cavity is pre-detuned with 100 Hz)

$$\ddot{\Delta}\omega = -\frac{1}{\tau_1}\dot{\Delta}\omega - \tau_2^2\,\Delta\omega - 2\pi\,\tau_2^2\,K\,V^2$$

$$\tau_1 = 125\,\mu s \qquad \tau_1 = 3608 s^{-1} \qquad K = 0.64\,Hz\,MV^{-2}$$

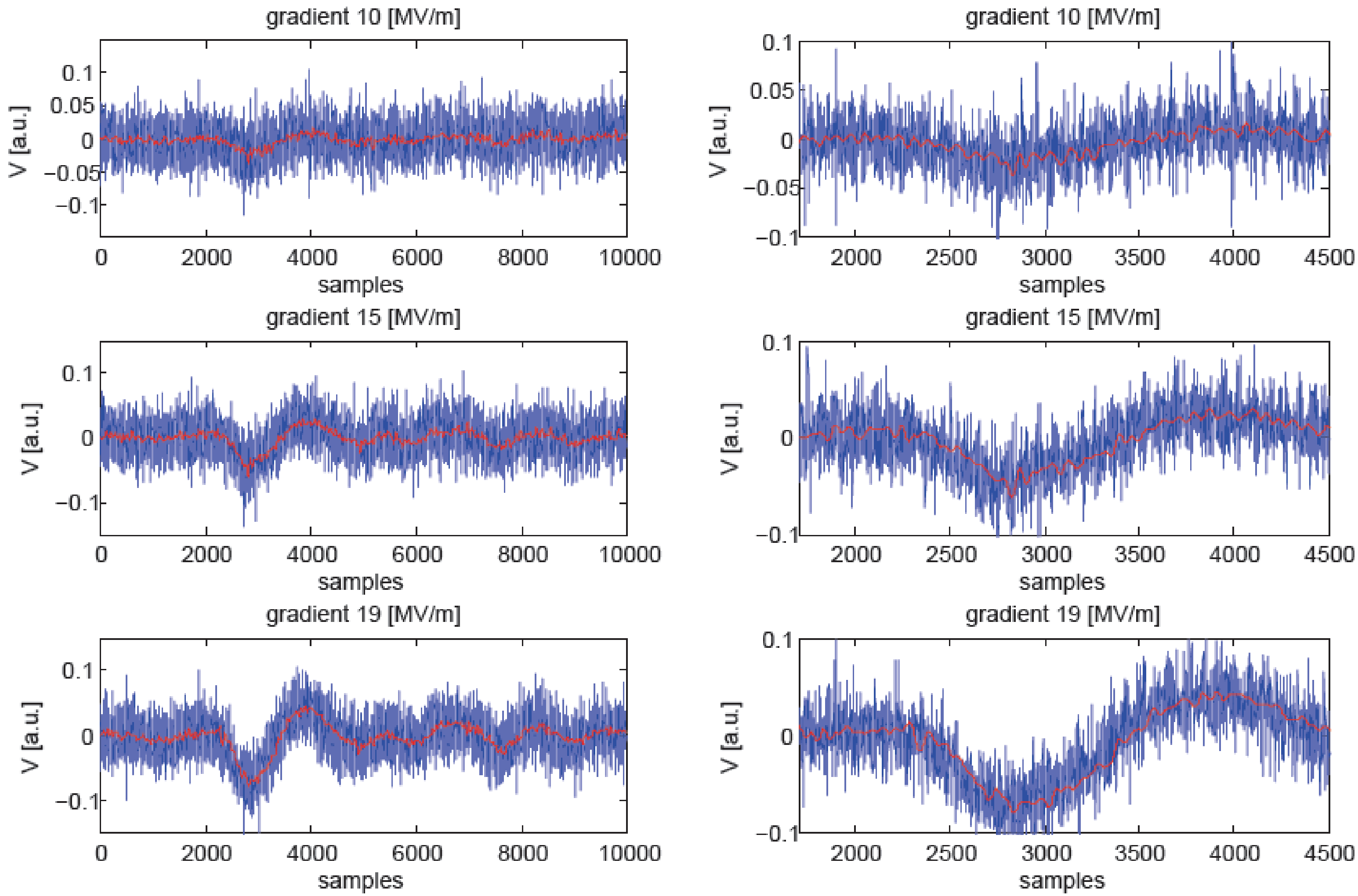
Piezo measurements on ACC6-Cavity 1

Problem:

- detuning is depending on the time interval (filling, flattop, decay)
- for system identification it might be feasible to have the detuning also provided in DOOCS
- piezo-sensors which are attached to the cavities but not "on-time" readable
- direct measurements and data acquisition can provide $\Delta f(t)$!
- stated that the detuning is proportional to the square of the gradient ($E \propto V^2$)

Execution: The piezo sensors are measured with the use of an oscilloscope for read-out.

Measured detuning curves



Summary & conclusions

- **Achievements:**
- 1GeV FLASH operation,
- Stable operation of three modules (ACC4/5/6) with significant cavities gradient spread by one LLRF system (world record!),
- Measured energy stability fulfil project requirements.
- Close to limits operation reveal current energy limits for the FLASH particular modules.
- Nonlinear characteristics measured of HPC in ACC1 (different HV settings),
- Linearization tool implemented in the ACC1 LLRF controller, DDD GUI available for operators
- **Conclusions:**
- Currently available algorithms (like Adaptive FeedForward, forward and reflected power calibration etc.) have been checked for usage in ACC1 automation.
- Work towards MIMO controller for the FLASH RF stations: measurement of the cavity gradients in function of Ql for the module ACC6 was done. Measurements for different cavities and different pulse lengths was performed
- The cavities detuning (in function of time) has been measured using piezo in the ACC6. Further studies are needed.

Thank You