Status of 3.9 GHz LLRF
FLASH Upgrade 2009/2010 Seminar

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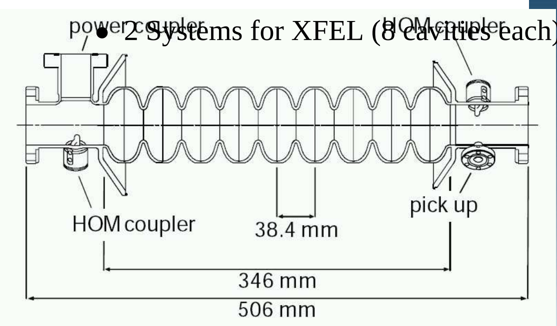
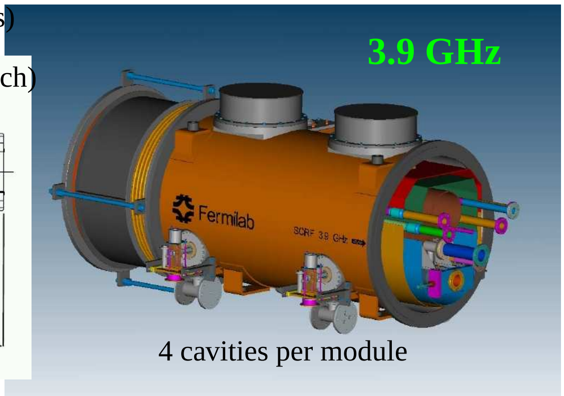
4. Status & Outlook

2 Third Harmonic System

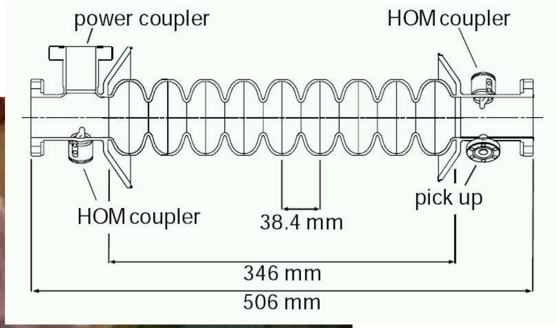
- To improve **Bunch Compression**,
- A **peak current** of >2kA can be realized within >200 fs.
- New possibilities: pre-requiste for all **seeding** schemes.
- The System for FLASH (4 cavities)
- 2 Systems for XFEL (8 cavities each)





TESLA type cavities have been scaled down in size to fit the 3.9 GHz.
All auxiliaries like coupler, HOM coupler, frequency tuner, etc..., are scaled as well.
Most of this work was done by H.Edwards et al. / FNAL.

3 3.9 GHz Cavity



4 FLASH Module ACC39

1. The Field Controller
How well must we do?

5 Global Requirements

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given from physics, from SASE, from the users

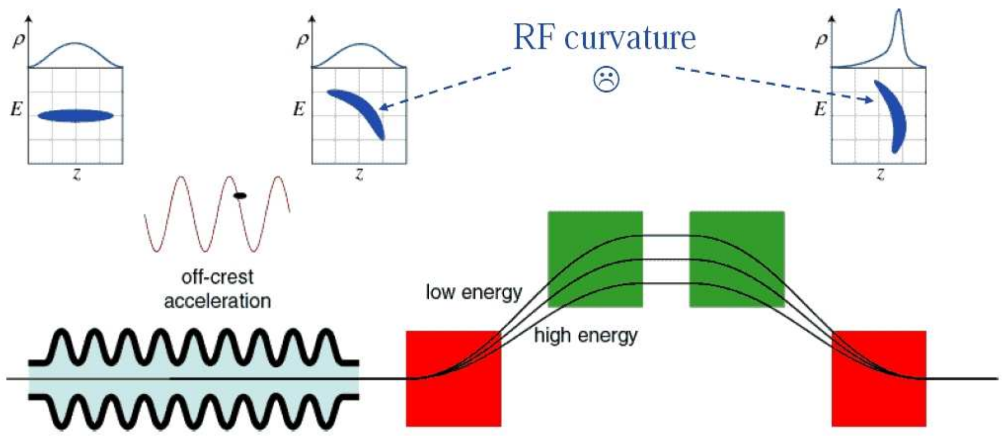
1. Final **energy spread** $\frac{\Delta E}{E} \leq 5 \cdot 10^{-5}$
2. Final bunch **peak current** $I_{\text{peak}} \geq 5$ kA (1nC)
3. **current variation** $\frac{\Delta I}{I} < 10\%$ (because of SASE)
4. Final **arrival time** jitter $\Delta t < 30$ fs.

- 1 and 4 are directly influenced by the **phase (and amplitude) stability** of all RF components
- 2 and 3 influenced by Electron Gun and Photocathode Laser and **bunch compressors**.
- bunch compressor operation required highly stable beam parameters **before** passing the BC. Therefore stability at low energy is more critical.

Now lets look at the consequences...

6 Bunch Compressor

How to produce high **peak currents** and short bunches.



- Apply energy differences of particles in front and in the tail of the bunch. ⟶ Off-crest acceleration in one cavity.
- No difference in velocity (almost c anyway) but different path length in magnetic chicane.

7 Requirements on RF control (Injector)

From Bunch-Compression:
$\Delta z = R_{56}\frac{\Delta p}{p}$ momentum compaction: $R_{56} = 100$ mm
Required:

$$\text{fluctuations} \quad \boxed{\Delta z \overset{!}{<} \sigma_z \approx 20\mu\text{m}} \quad \text{bunch length}$$

- $\longrightarrow \frac{\Delta p}{p} < 2 \cdot 10^{-4}$ before BC (ACC1, 67 MeV).
- **energy spread**: $\frac{\Delta E}{E} = \frac{\Delta p}{p} < 2 \cdot 10^{-4}$
- **time jitter**: $\Delta t = 70$fs ($\widehat{=} 20\mu$m from Δz)
- Energy-drift compensation with Feedback on Energy-Measurement at Bunch Compressor possible.

RF amplitude stability: $\leq 10^{-4}$ required
RF phase stability: $\Delta\phi = 0.03^\circ$ at 1.3 GHz.

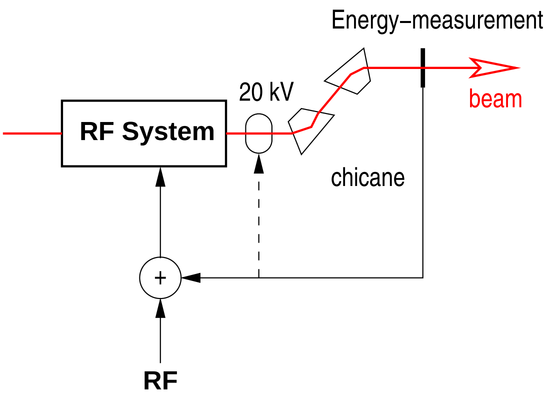
($1^\circ \widehat{=} 2$ps, 1μm $\widehat{=} 3$fs)

8 Req. on 3rd Harmonic System (Injector)

Stabilities are strongly dependant of the operational setpoints of these systems. This is non-trivial! Critical for optimal bunch compression!

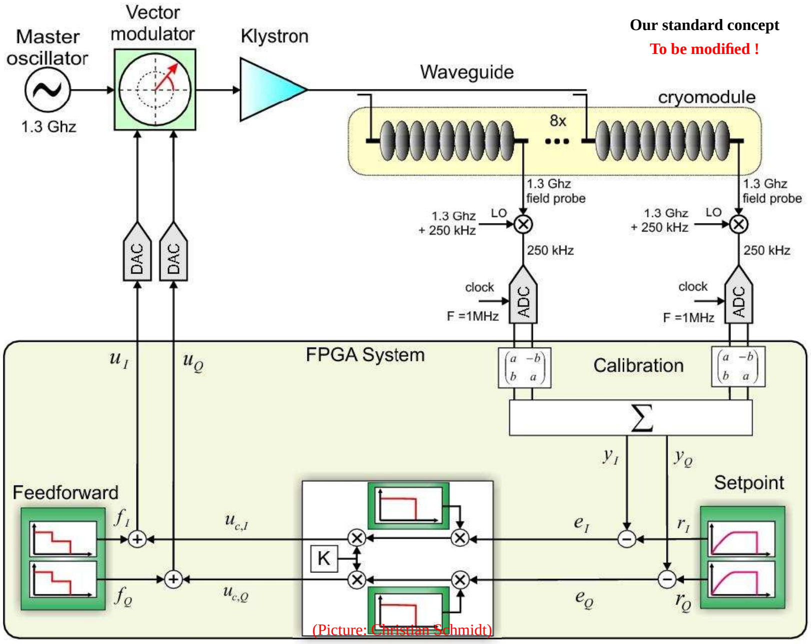
RF amplitude stability: $1 \cdot 10^{-4}$
RF phase stability: $\Delta\phi = 0.03^\circ$ (at 3.9 GHz).

- better have some safety margin.
- the phase translates 1:1 to final arrival time jitter.



Although there are particular setpoints where the RF stability is not critical, a **beam based feedback** looks necessary in any case, not to be limited.

9 RF Field Control



(Picture: Christian Schmidt)

10 3.9 GHz Challenges

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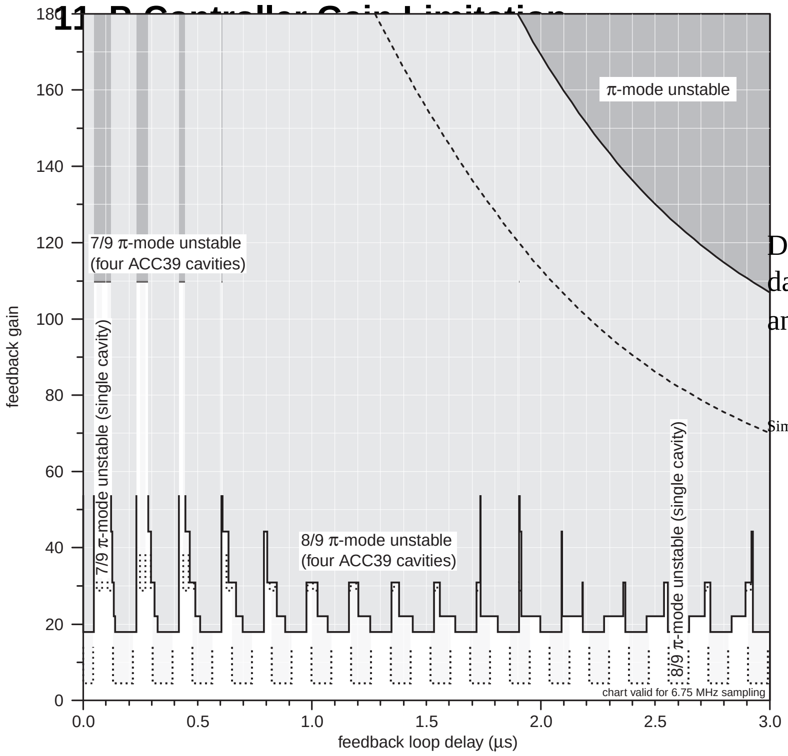
1. **Higher frequency (3.9 GHz):**
   - Extra LO frequency generation.
   - Downconverter hardware.
   - Higher crosstalk.
   - More sensitive to timing/drifts.
2. **Higher bandwidth (4 kHz):**
   - *more noise* in the detector **!**
   - *limit* in gain (for a p-controller) is lower
   - usage of next order stable gain areas or **higher order (complex) controller** (MIMO) necessary!
3. **Operation:**
   - Operation together with *ACC1* and together with the beam based feedbacks **!**

11 P-Controller Gain Limitation



Due to next (two) fundamental order modes $\frac{8}{9}\pi$ and $\frac{7}{9}\pi$.

Simulation by Elmar Vogel 2008

12 Realization

LLRF control for the 3.9 GHz system is **in principle identical** to the 1.3 GHz concept:

- VME based with as many as possible standard hardware boards
- SIMCON DSP based
- 1.3 GHz RF-field detection (downconverters) **plus** converter box
- Standard Controller Algorithm **plus** modifications necessary for overcoming gain limitations

We face additional developments in:

- **LO-Generation** hardware (3.9 GHZ out of 1.3 GHz with low noise)
- Downconverters hardware (new IF-scheme, **drift-calibration**)
- New **controller algorithm**! (MIMO)
- FPGA firmware and DOOCS server modifications.
- Operation experience to be gained in machine studies.

13 SIMCON DSP

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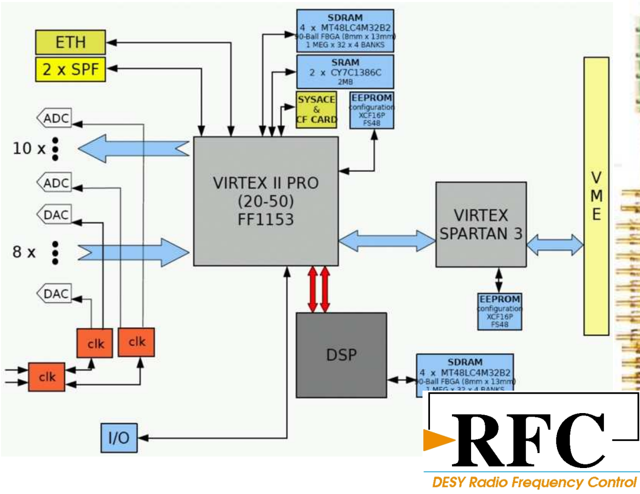
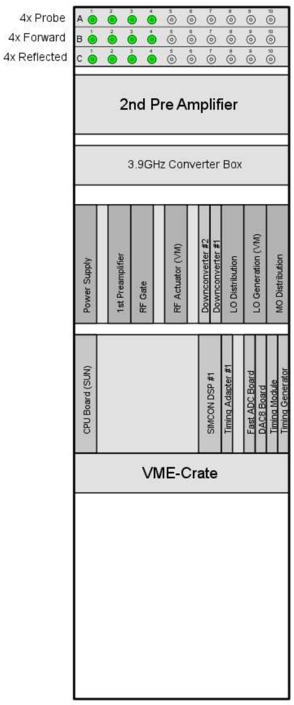
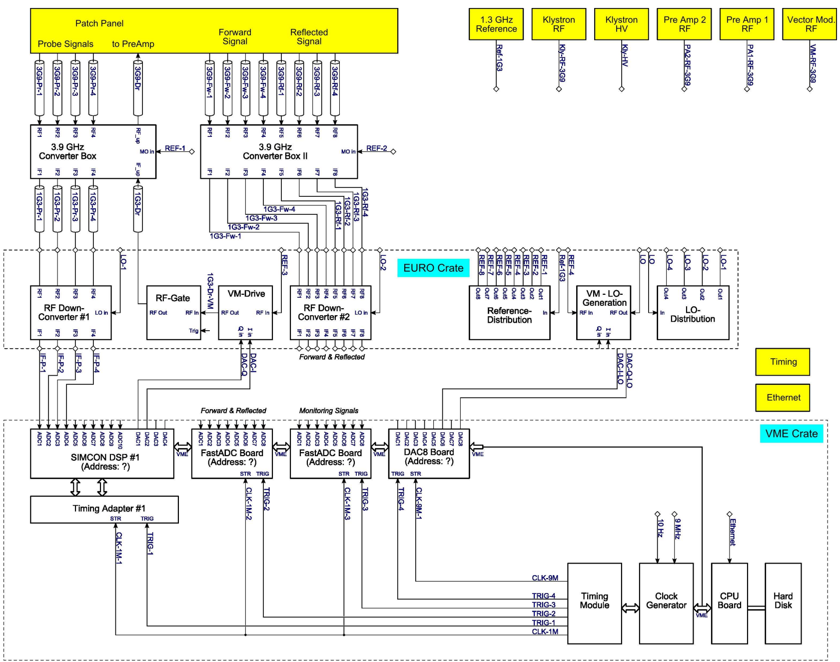
10 ADCs 14bit 105 MS/s
FPGA + DSP



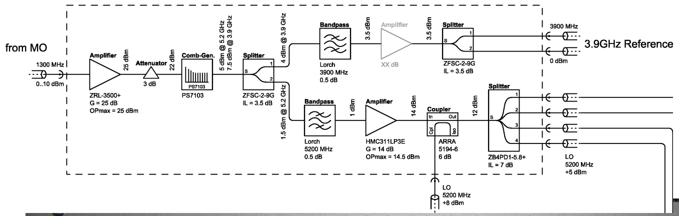
14 Hardware used in CMTB

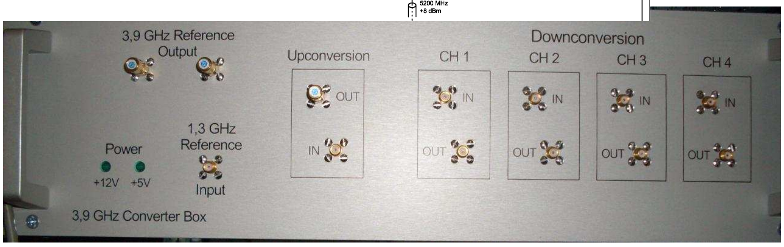




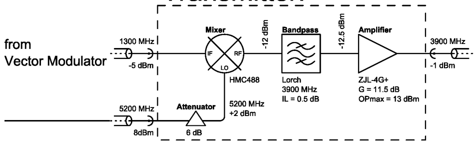
15 3.9 GHz Converter Box

LO and Reference Generation:

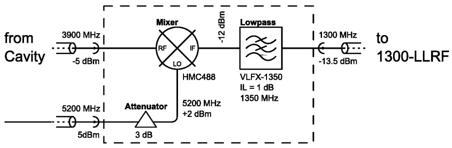




Transmitter:



Receiver:



16 3.9 GHz Downconverter (IF=54MHz)

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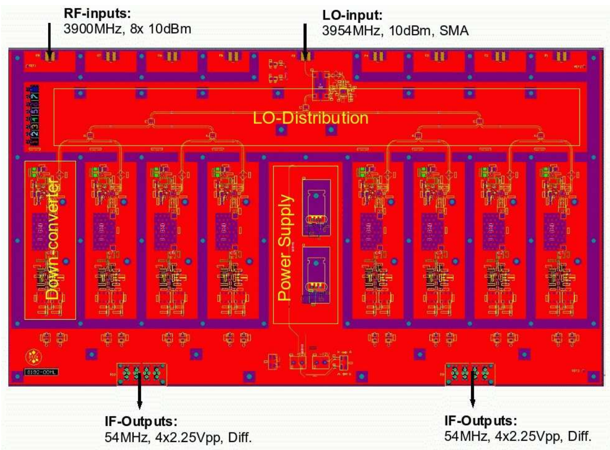
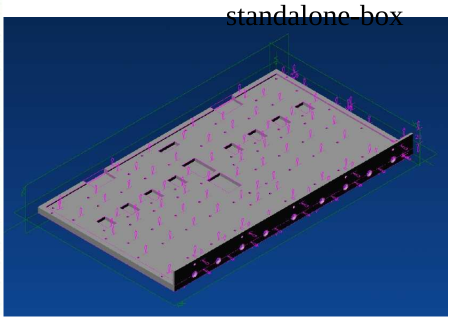
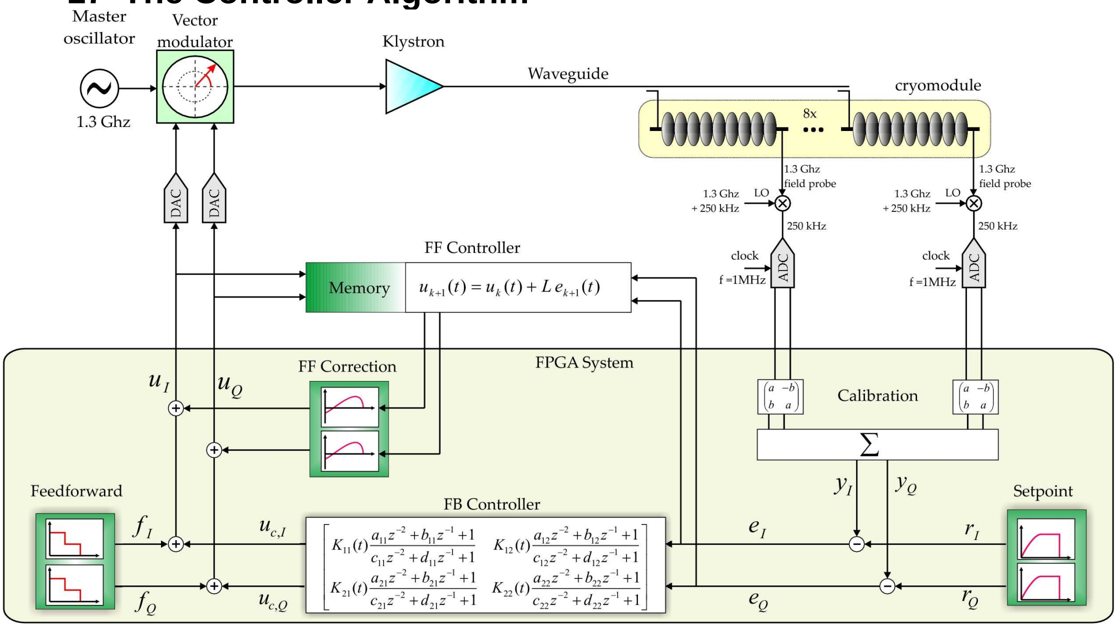


standalone-box

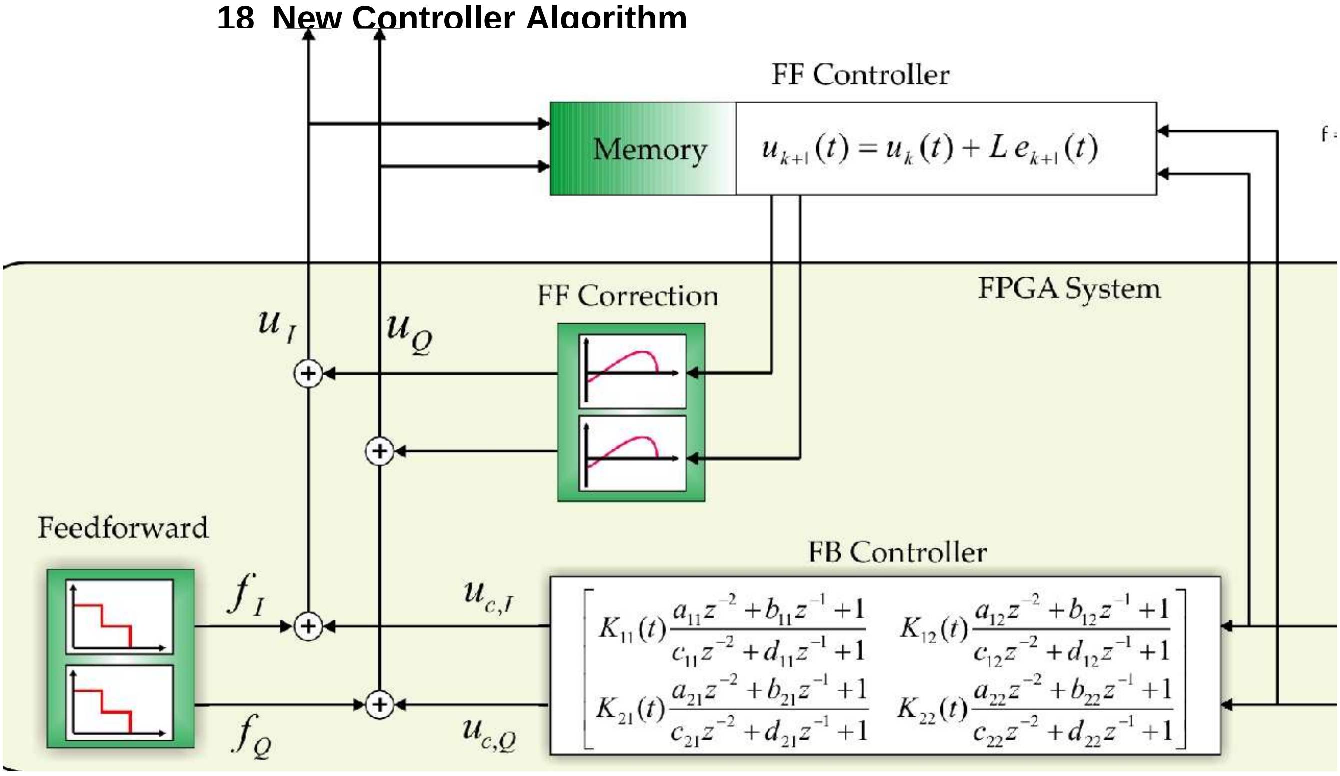


RFC
DESY Radio Frequency Control

17 The Controller Algorithm



18 New Controller Algorithm



19 Software

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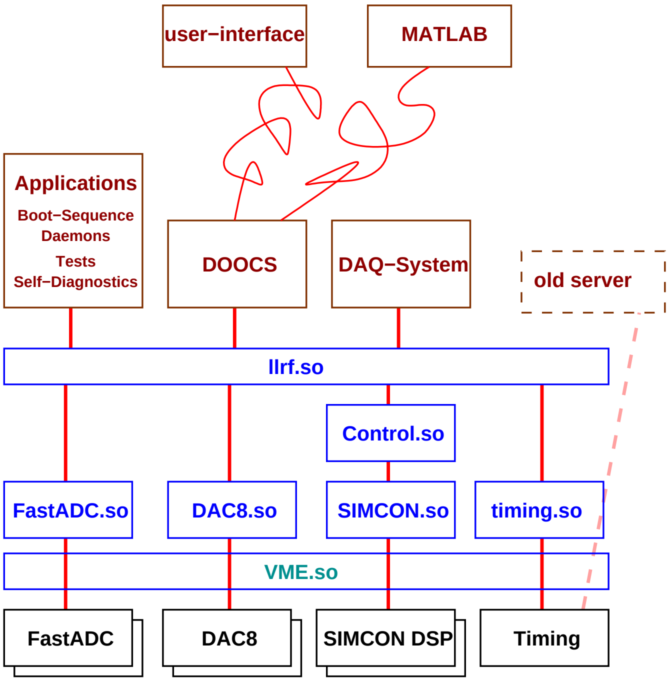

- Cooperation with MCS is essential!
- The interfaces need to be defined and worked out.
- This is new! And a lot of work.

20 User Interface

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21 Performance

- The performance is determined by the **analog frontend electronics** and the quality of the **ADCs**,
- plus the quality of the 3.9 GHz **reference** signal,
- also the I/Q **detection scheme** is important.
- But: We dont really know, **how well (?)** we must stabilize the RF-field in the cavities. Our answer: -157 dBc/Hz.

⟶ Simulations and Measurements

1. longitudinal beam dynamics
2. RF field regulation, controller and analog components

3. Measurements

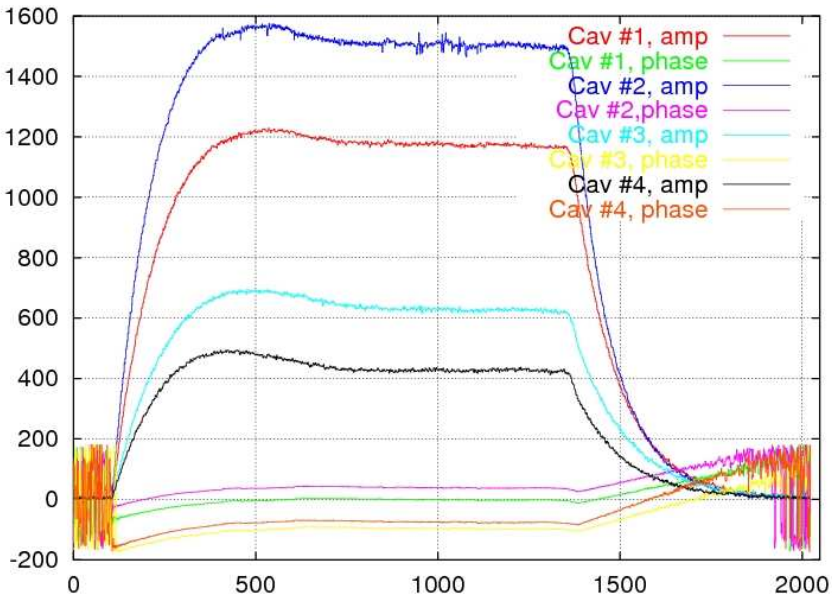
Nov 2009

22 Measurements

- The **setup** consisted of a SIMCON 1.3 GHz LLRF system with 3.9 GHz converter box and with MIMO firmware to regulate the vector sum of 4 probe signals. The 250 kHz IQ field detection scheme was used.
- **Configuration** was done with the standard DOOCS server.
- **Data aquisition** was done with MATLAB and special server-like applications.

- a Markoni RF generator was used as a **Master Oscillator**.
- We measured **long term stability** of detuning, Loaded Q, Amplitude, Phase, the RMS of amplitude and phase during the flattop and from pulse to pulse.
- 2 Hz Pulse repetition rate.

23 The Pulse



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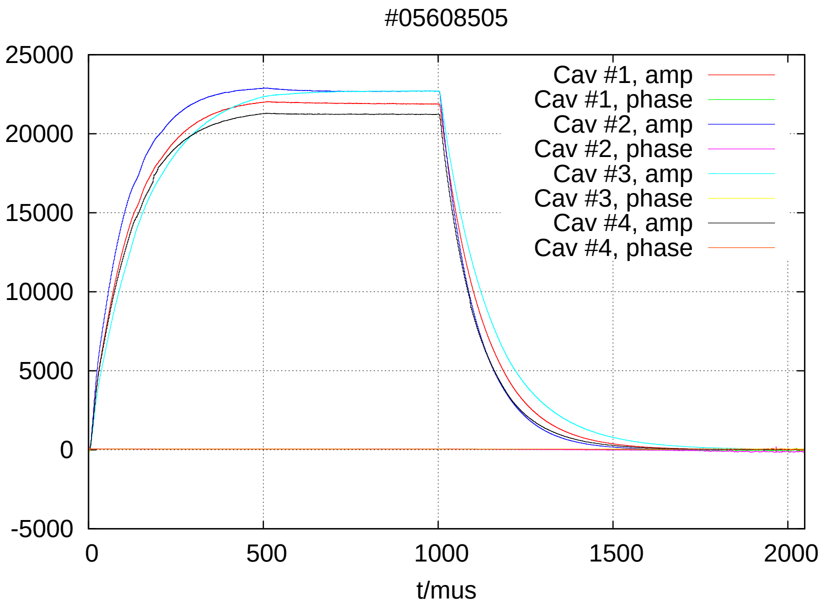
open loop

24 The Pulse



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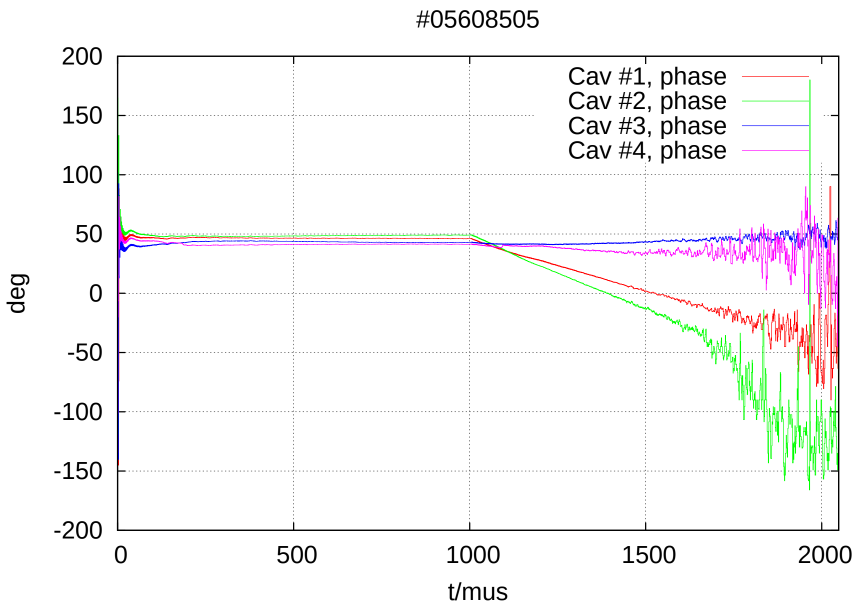
closed loop

25 The Pulse



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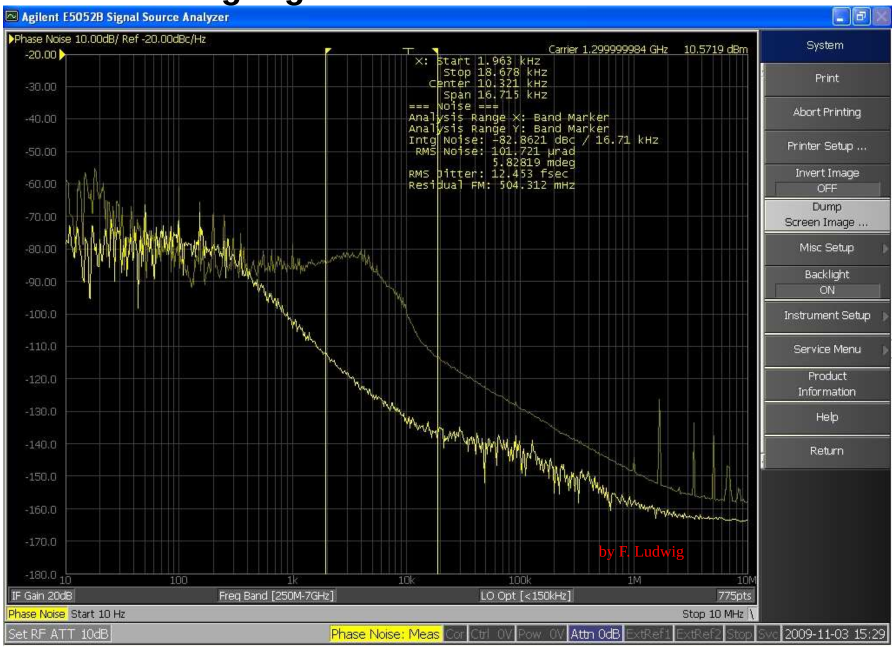
closed loop

26 Analog Signal Check



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Marconi 2032

contra

HP 8665B

27 Analog Signal Check

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- Analyzation of the refererence frequency signal
  (from **converter box**, relative to 1.3 GHz signal):

  Stability $\frac{dA}{A} < 10^{-4}$, $\Delta\phi < 0.02°$.

- Measuring with the RSA (real time spectrum analyzer) and making sure that it is triggered at the main RF pulse, one can see at 3.9 GHz a **modulation** on the amplitude. There is no signal from the $\frac{8}{9}\pi$-mode to be seen. That mode is only visible during the decay of the pulse.

- Looking at the **forward power** from the directional coupler at the cavity no modulation is found.

28 Cross-Talk

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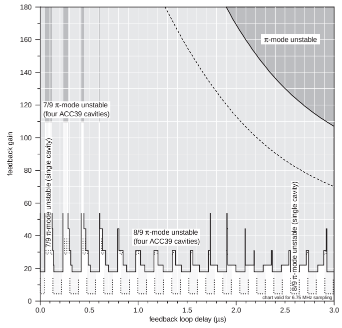
crosstalk	1	2	3	4
1	1	0.055	-	-
2	-	1	-	-
3	-	0.016	1	-
4	-	0.022	-	1

Closed Loop Operation



?

29 Loop Performance

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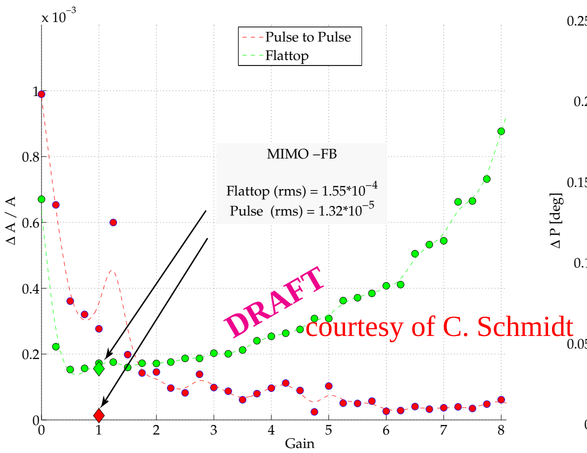

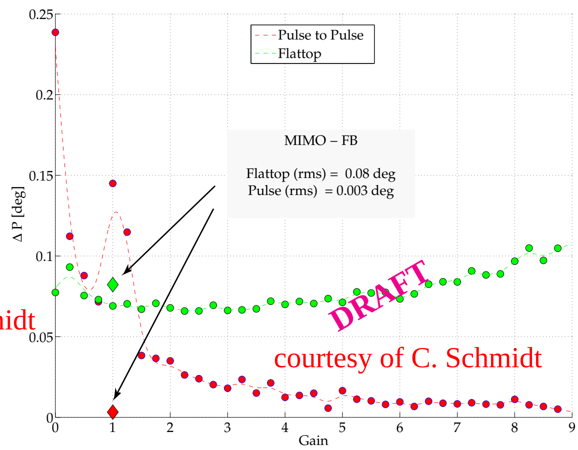

30 Performance

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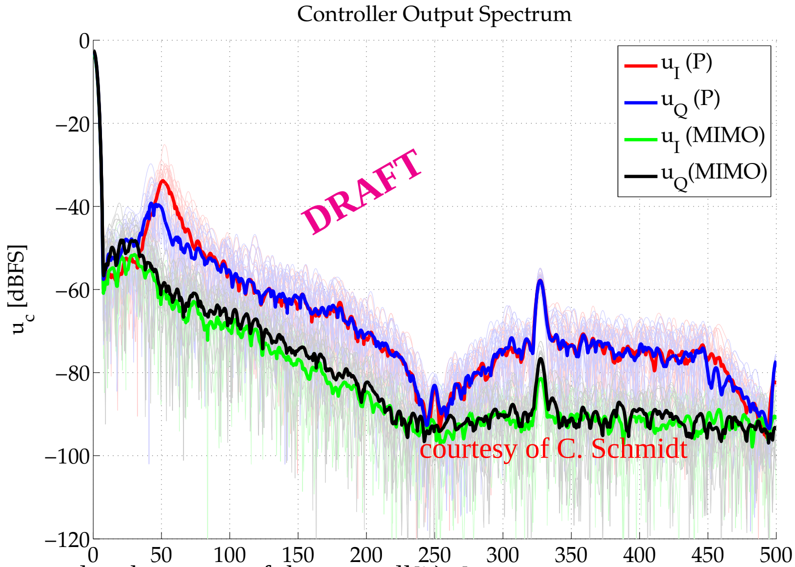

(measured at the output of the controller)

31 Done?

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ACC39	**required**	**measured**
$\frac{\Delta A}{A} =$	$1 \cdot 10^{-4}$	$1.3 \cdot 10^{-5}$
$\Delta\phi =$	$0.03°$	$0.003°$

The best values acheived with the MIMO-controller and 1.3 GHz cavities (ACC1) are $\frac{\Delta A}{A} = 5 \cdot 10^{-5}$ and $\Delta\phi = 0.003°$.
(see FLASH-Seminar Talk from C. Schmidt, 03.11.2009)

32 Loaded Q

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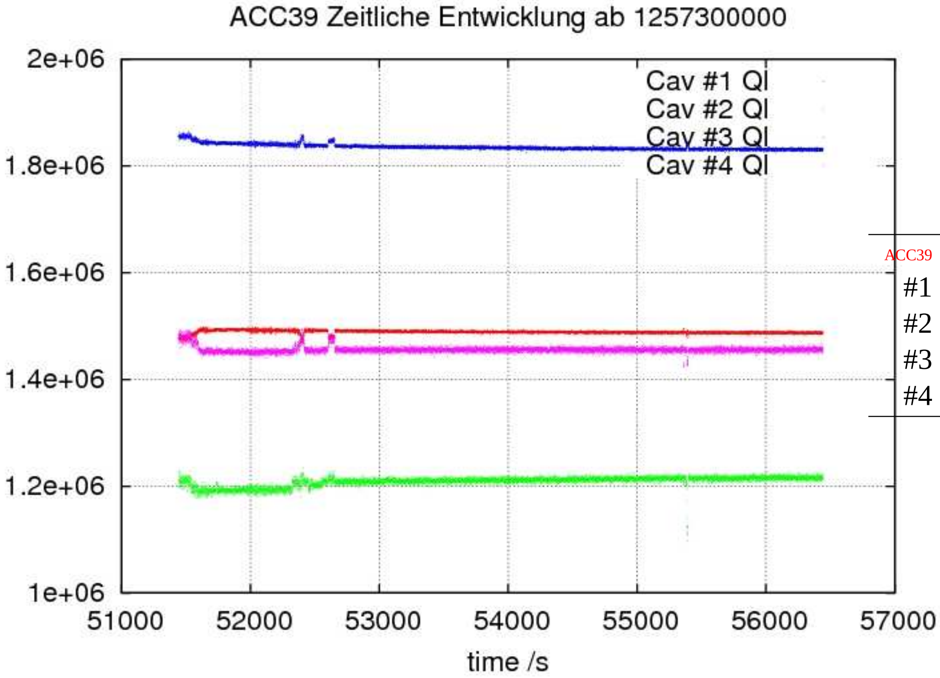
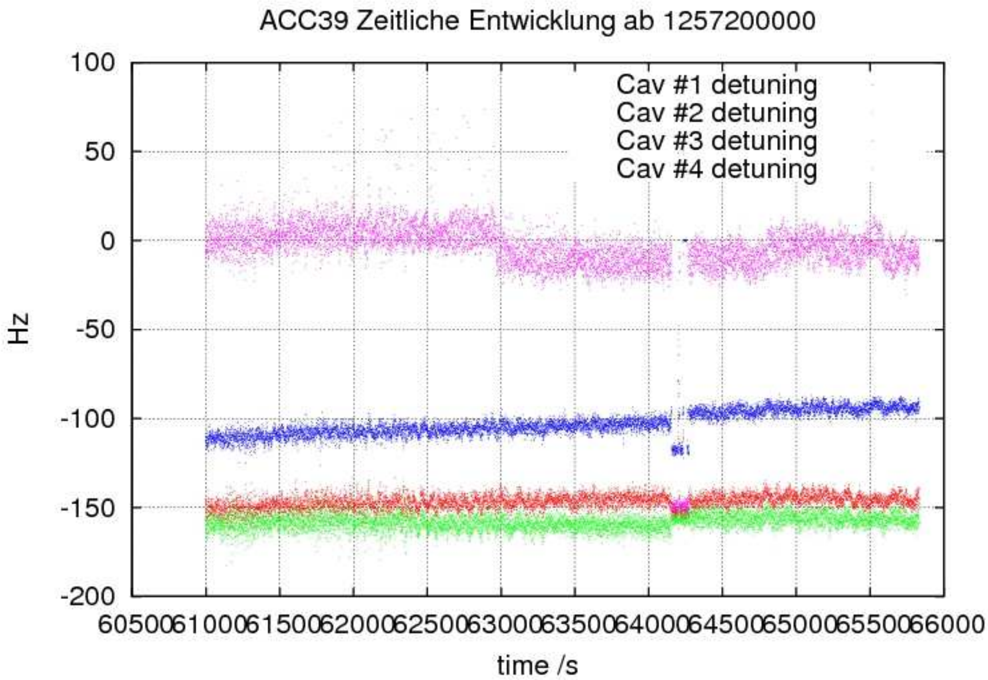
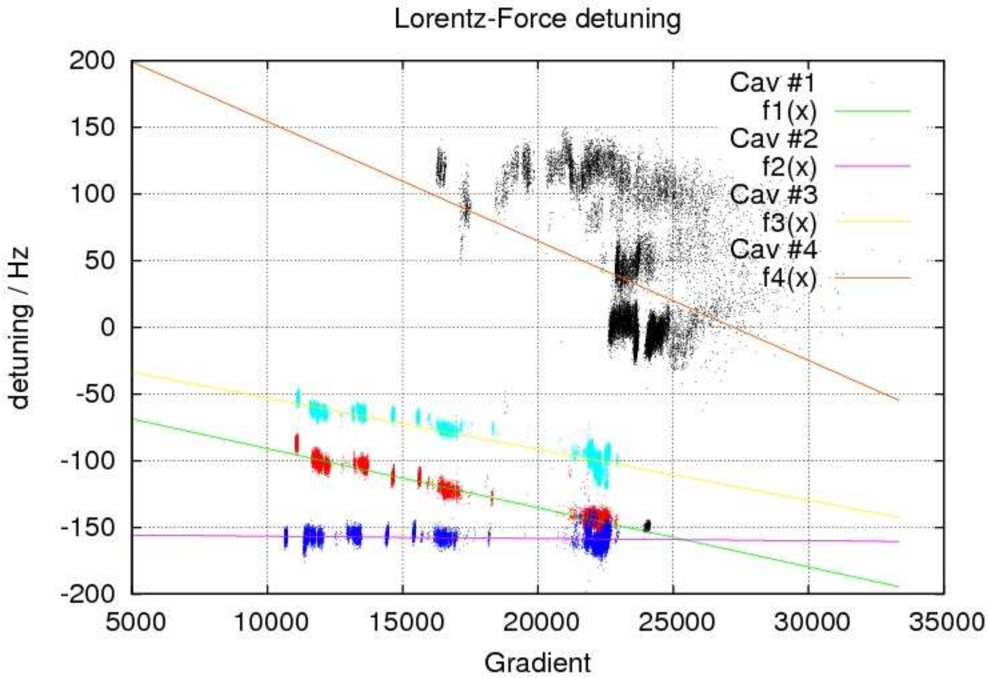


ACC39	Q_l
#1	$1.487 \cdot 10^6$
#2	$1.218 \cdot 10^6$
#3	$1.830 \cdot 10^6$
#4	$1.455 \cdot 10^6$

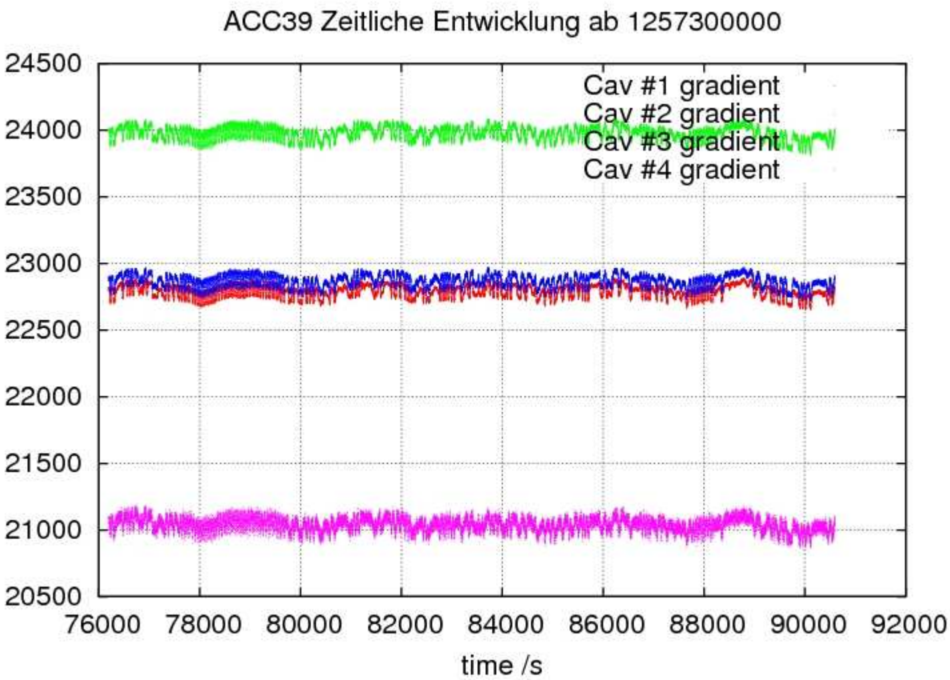
33 Detuning



34 Lorentz-Force-Detuning



35 Long Term Stability



4. Where are we now?

36 Status

1. We have assembled one **VME crate + SIMCON based hardware** including a 3.9 GHz **converter box** with a LLRF system capable of regulation of 4 (up to 8) 3.9 GHz Cavities and one RF station.

2. The **noise performance** of this system was characterized together with ACC39 in the cryomodule teststand.

3. With the new **MIMO controller** concept, this system fullfills the requirements, as we believe in.

4. Possible and planned improvements for the **FLASH** system:

   - **Hardware**
     - **16 bit:** better field detection. (future)
     - **passive frontends** (downconverters) for feld detection (in progress).
     - **injected calibration**: Automated driftcalibration (in progress).
   - **Software**

37 Status (2)

5. Possible and planned improvements for the **FLASH** system:

   - **Software**
     - **NON-IQ sampling** (54 MHz) for SIMCON
     - **Master-Slave-Betrieb** for two SIMCON-Boards (future)
     - **injected calibration** realised in firmware (in progress)
     - **Referenztracking** realised in firmware (in progress)
     - **Learning Feed-Forwards** realised
     - Anpassung des **DOOCS Servers**
     - Überarbeitung der Bedienoberfläche/**Panels**
     - Kopplung der Settings und ACC1-Arbeitspunkt durch **Automation**

6. Changes for the **XFEL** System:

   - 4 $\longrightarrow$ 8 cavities
   - common crate standard (ATCA?)
   - ...

38 To Be Done

7. **simulation software** need to be worked on to understand:
    - Impact of Field stability on beam parameters
    - The necessary requirements for LLRF control
8. **commissioning** procedure need to be worked out after FLASH upgrade. (in Progress)
9. We need to find a good way how to operate ACC1 and ACC39 simultanously.

The End

Further information to all LLRF related topics, progress and status of the projects can be found on `http://mskpc14.desy.de/wiki/`.