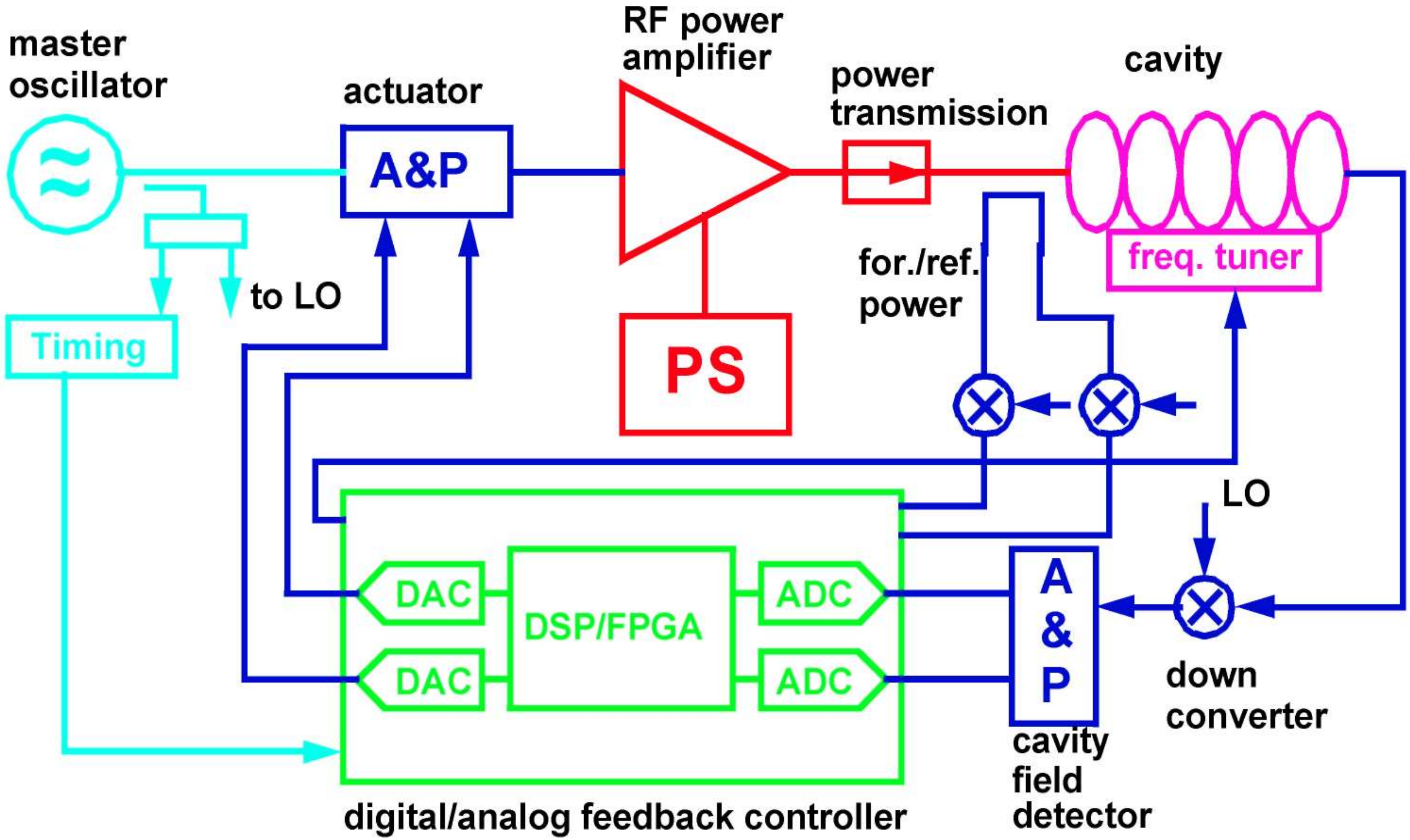
Amplitude and Phase Stability

S. Simrock, DESY

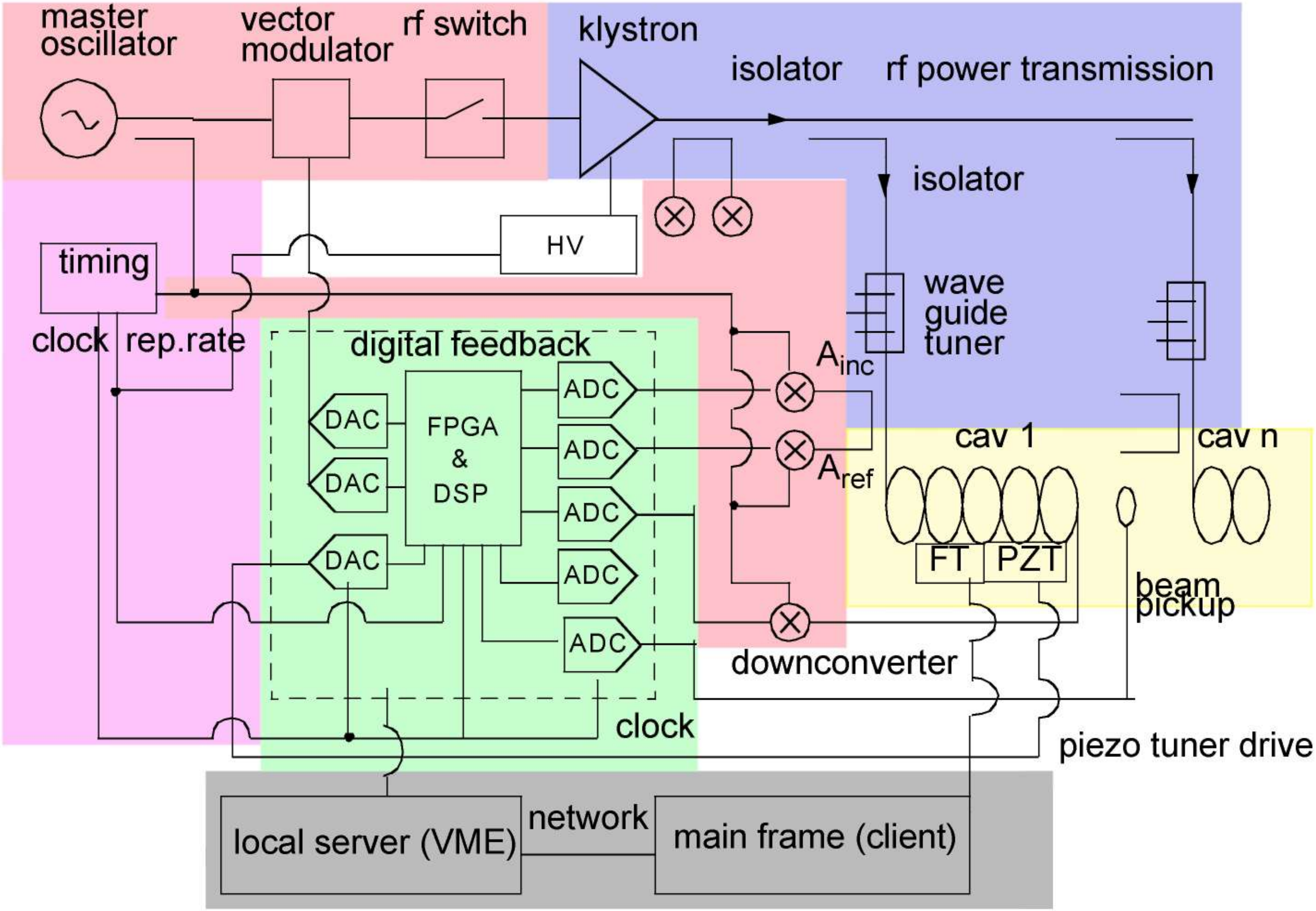
Outline

- Principle of RF Control
- Sources for Field Perturbations
- Noise Sources in LLRF System
- Choices of RF Control
- Choices for phase reference
- Limitation of RF Control
- Performance of RF Control at FLASH

RF System Architecture



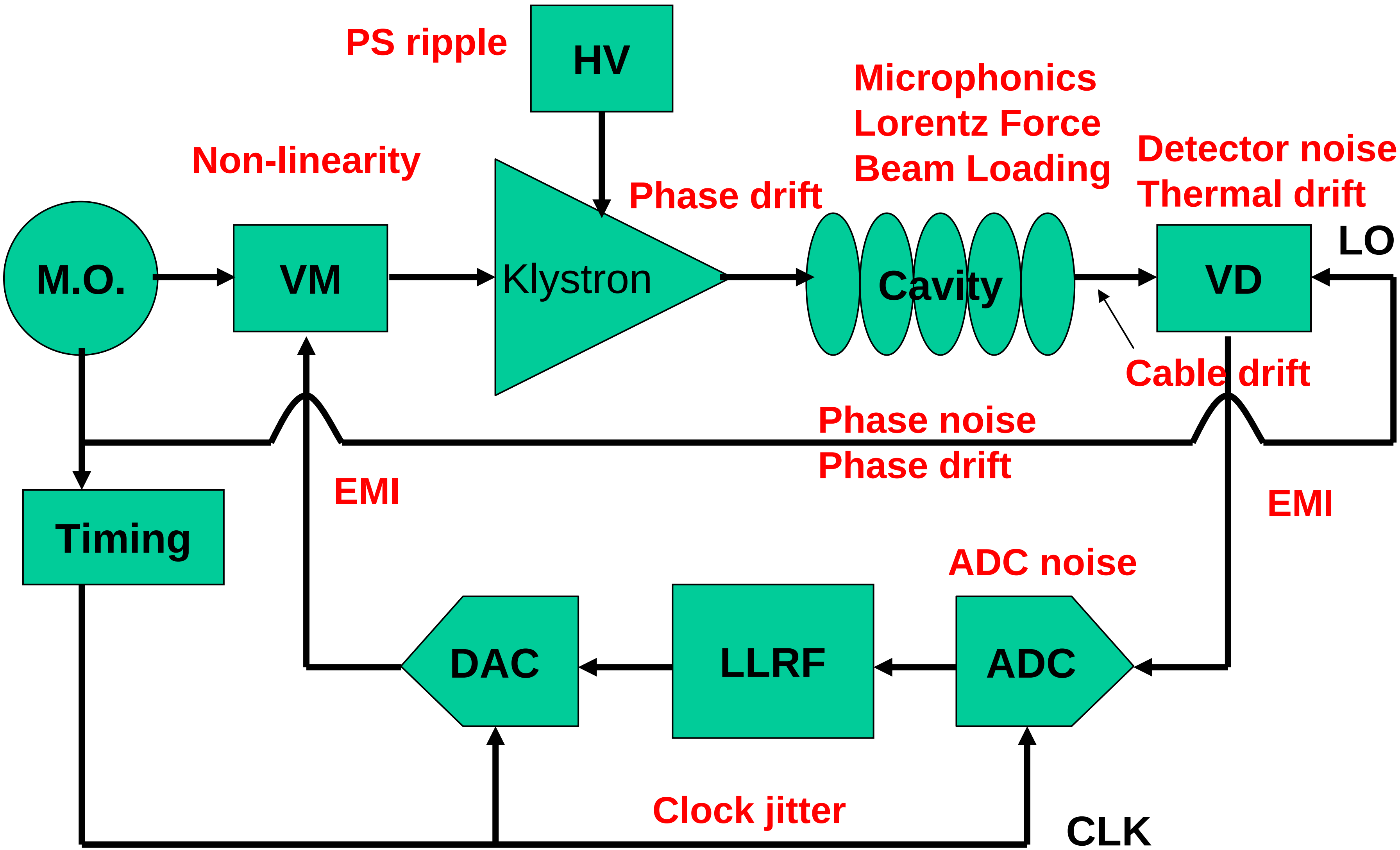
System Architecture Details



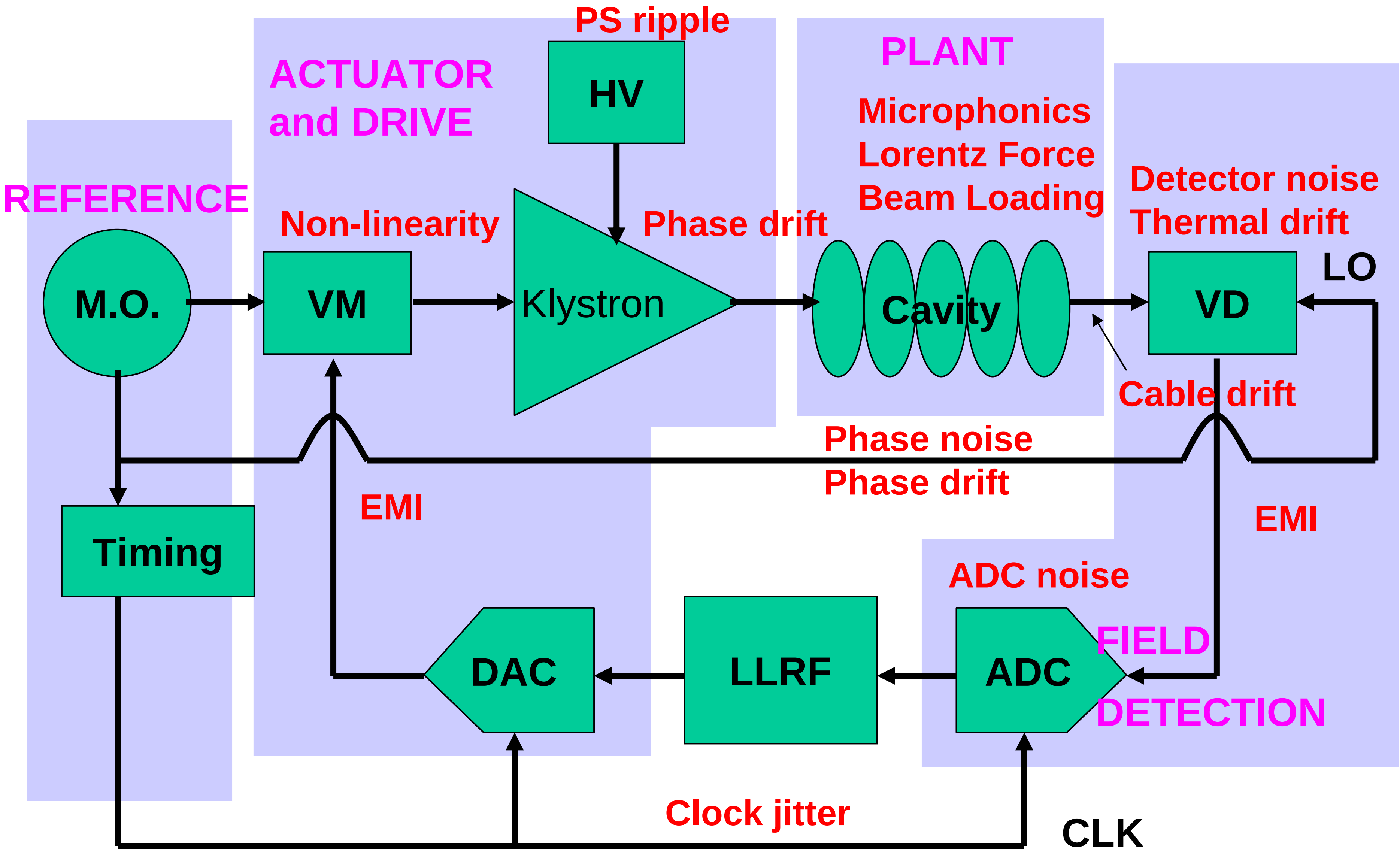
Sources of Field Perturbations

o **Beam loading**	o **Cavity dynamics**
- Beam current fluctuations	- cavity filling
- Pulsed beam transients	- settling time of field
- Multipacting and field emission	
- Excitation of HOMs	o **Cavity resonance frequency change**
- Excitation of other passband modes	- thermal effects (power dependent)
- Wake fields	- Microphonics
	- Lorentz force detuning
o **Cavity drive signal**	
- HV- Pulse flatness	o **Other**
- HV PS ripple	- Noise in electronics (mixer, ADC)
- Phase noise from master oscillator	- Thermal drifts (electronics, cables
- Timing signal jitter	- Interlock trips
- Mismatch in power distribution	- Response of feedback system

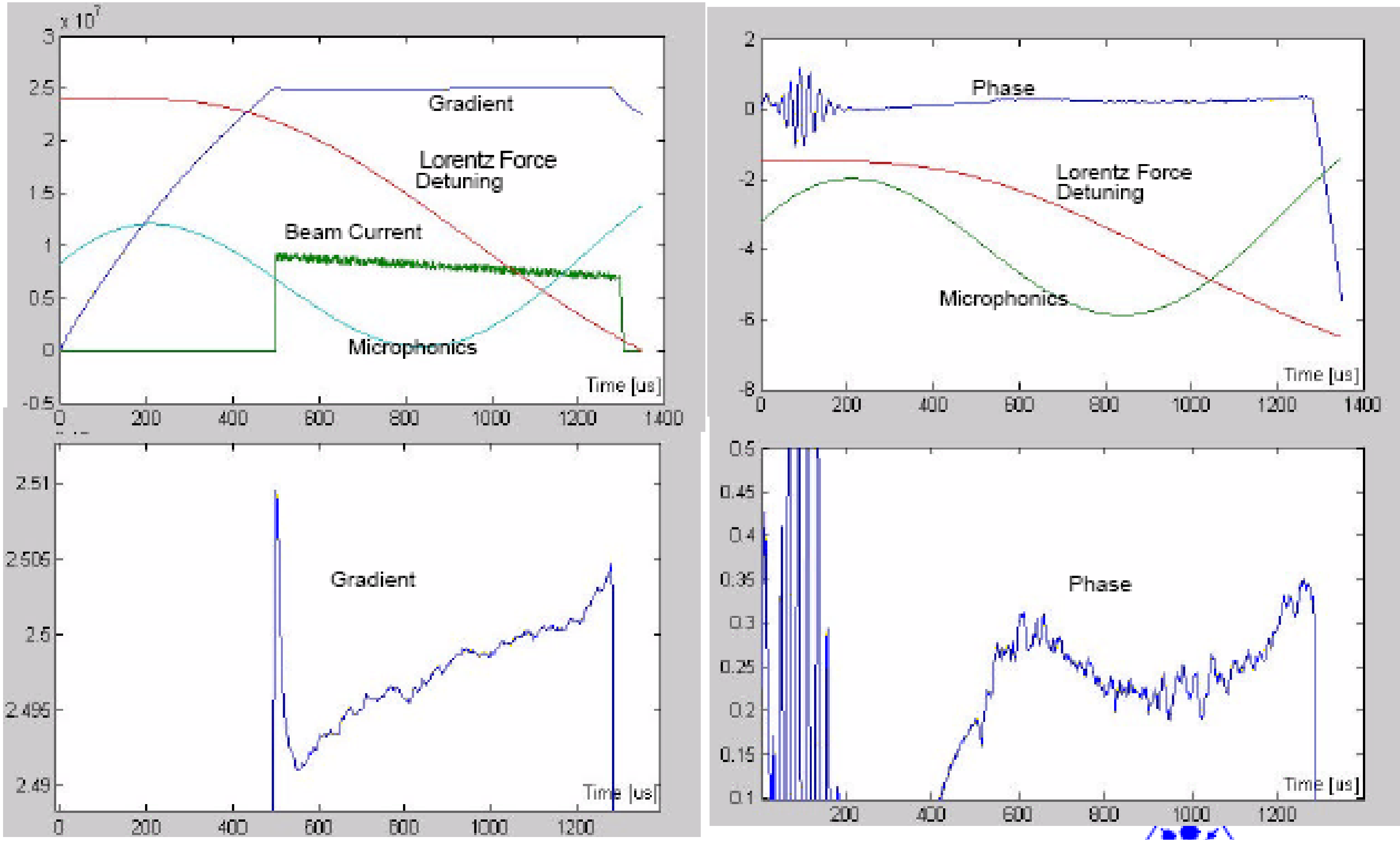
Noise Sources in LLRF Systems



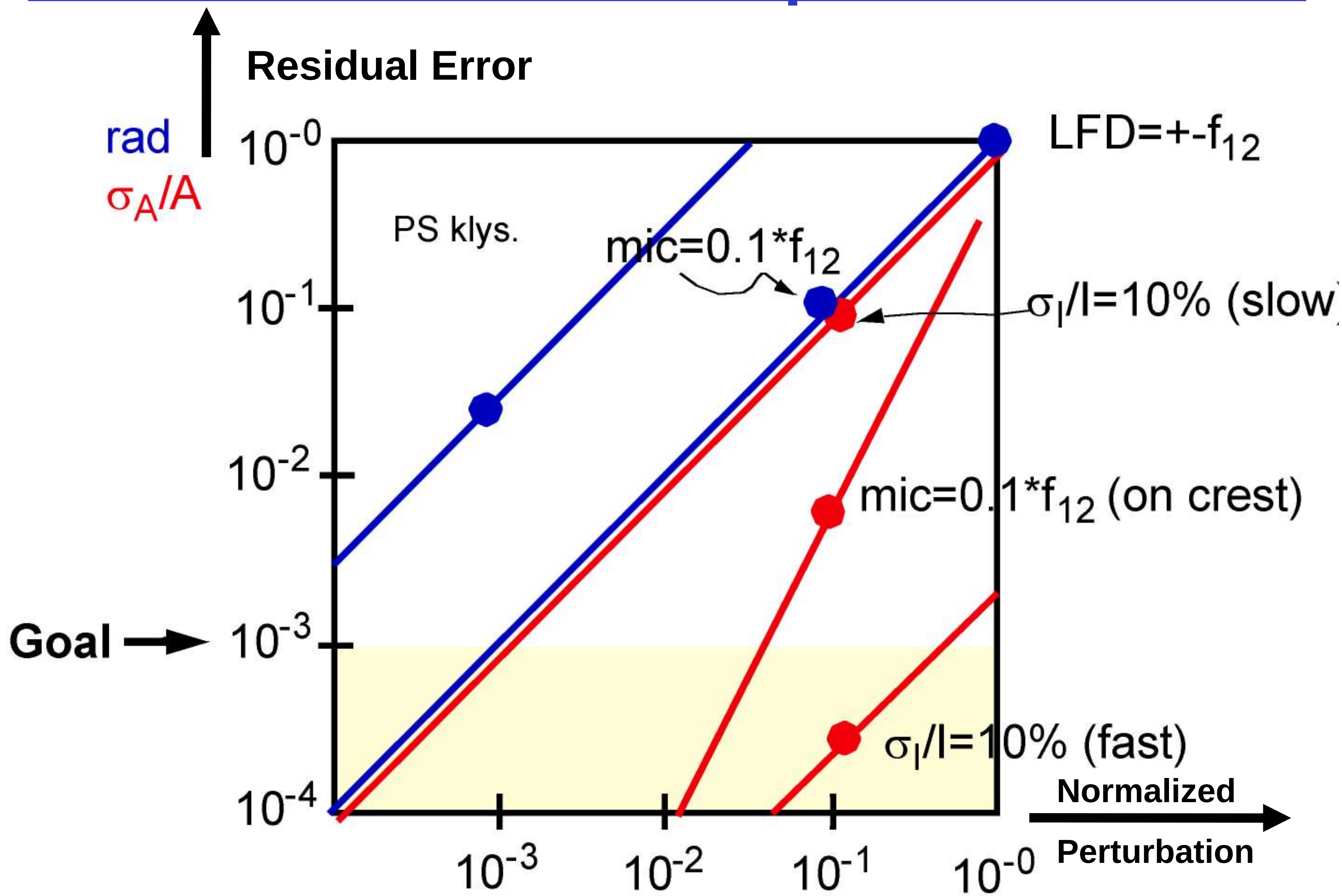
Grouping of Sources of Perturbations and Noise



Noise Sources at Flash (Simulation)

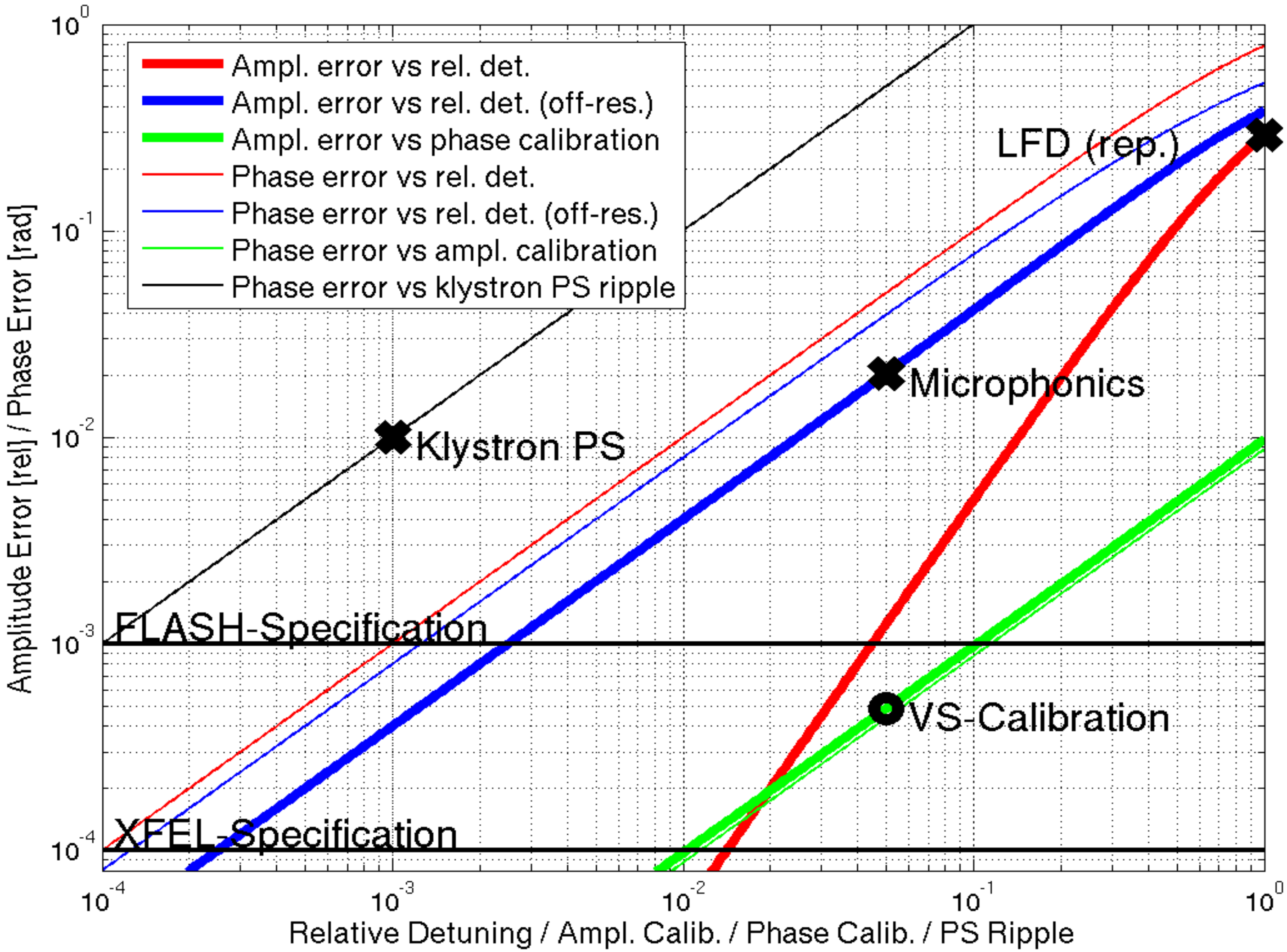


Error Map



Residual Error
rad
σ_A/A
10^{-0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
Goal
PS klys.
mic=0.1*f_{12}
LFD=+-f_{12}
σ_I/I=10% (slow)
mic=0.1*f_{12} (on crest)
σ_I/I=10% (fast)
10^{-3}
10^{-2}
10^{-1}
10^{-0}
Normalized
Perturbation

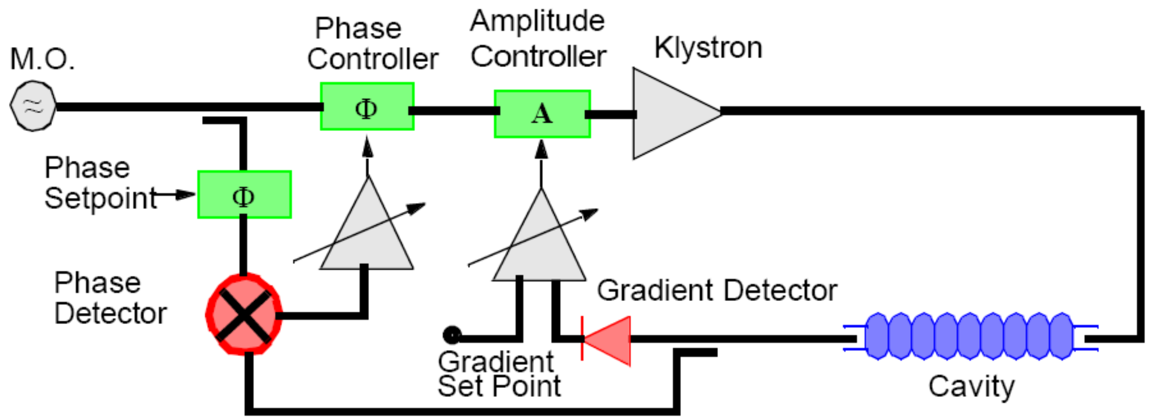
Sources of field perturbation



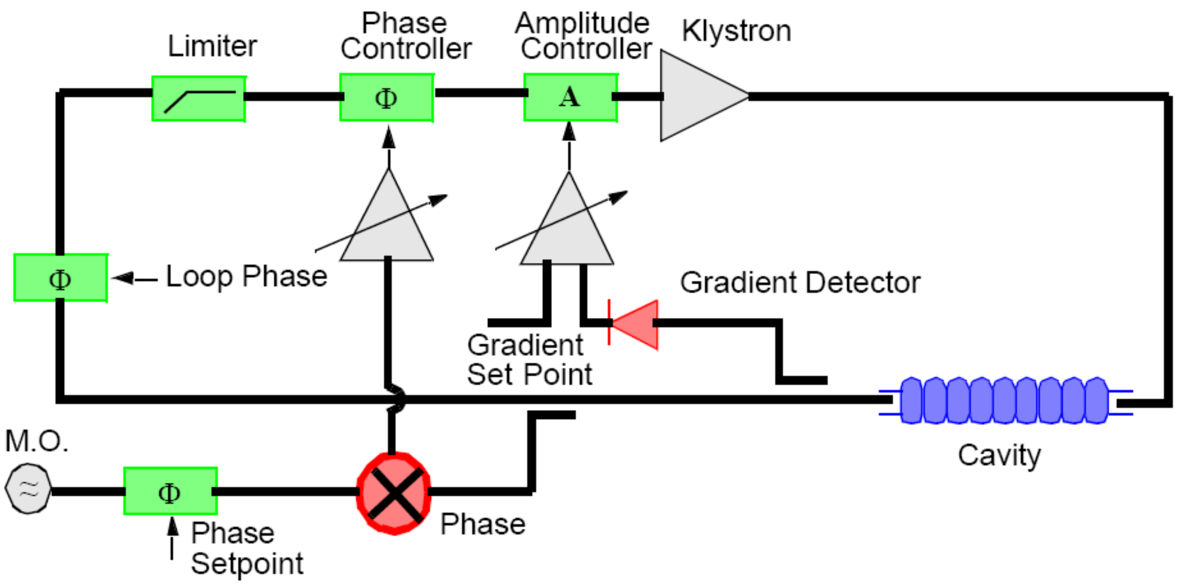
Control Choices (1)

- Self-excited Loop (SEL) vs Generator Driven System (GDR)
- Vector-sum (VS) vs individual cavity control
- Analog vs Digital Control Design
- Amplitude and Phase (A&P) vs In-phase and Quadrature (I/Q) detector and controller

Control Choices (2)

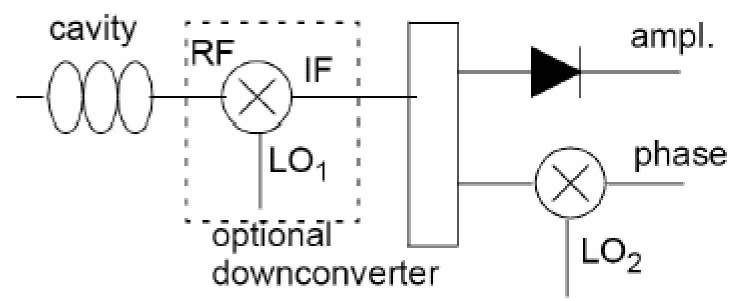


Generator Driven Resonator

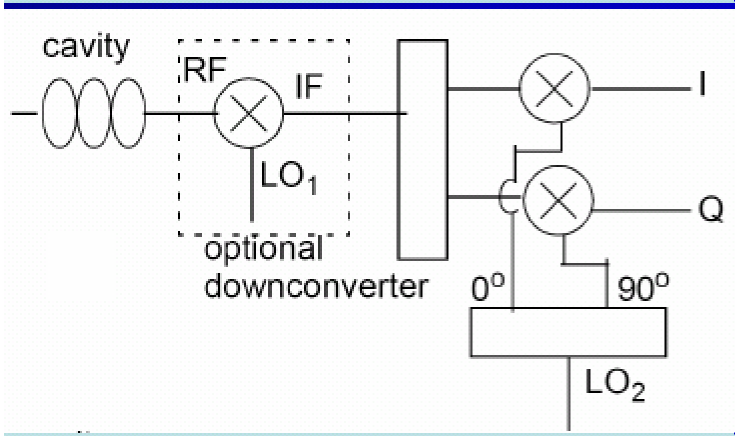


Self Excited Loop

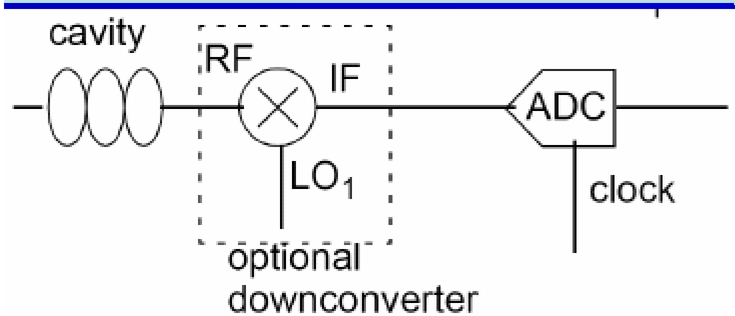
Choices of field detectors



- Traditional amplitude and phase detection
- Works well for small phase errors

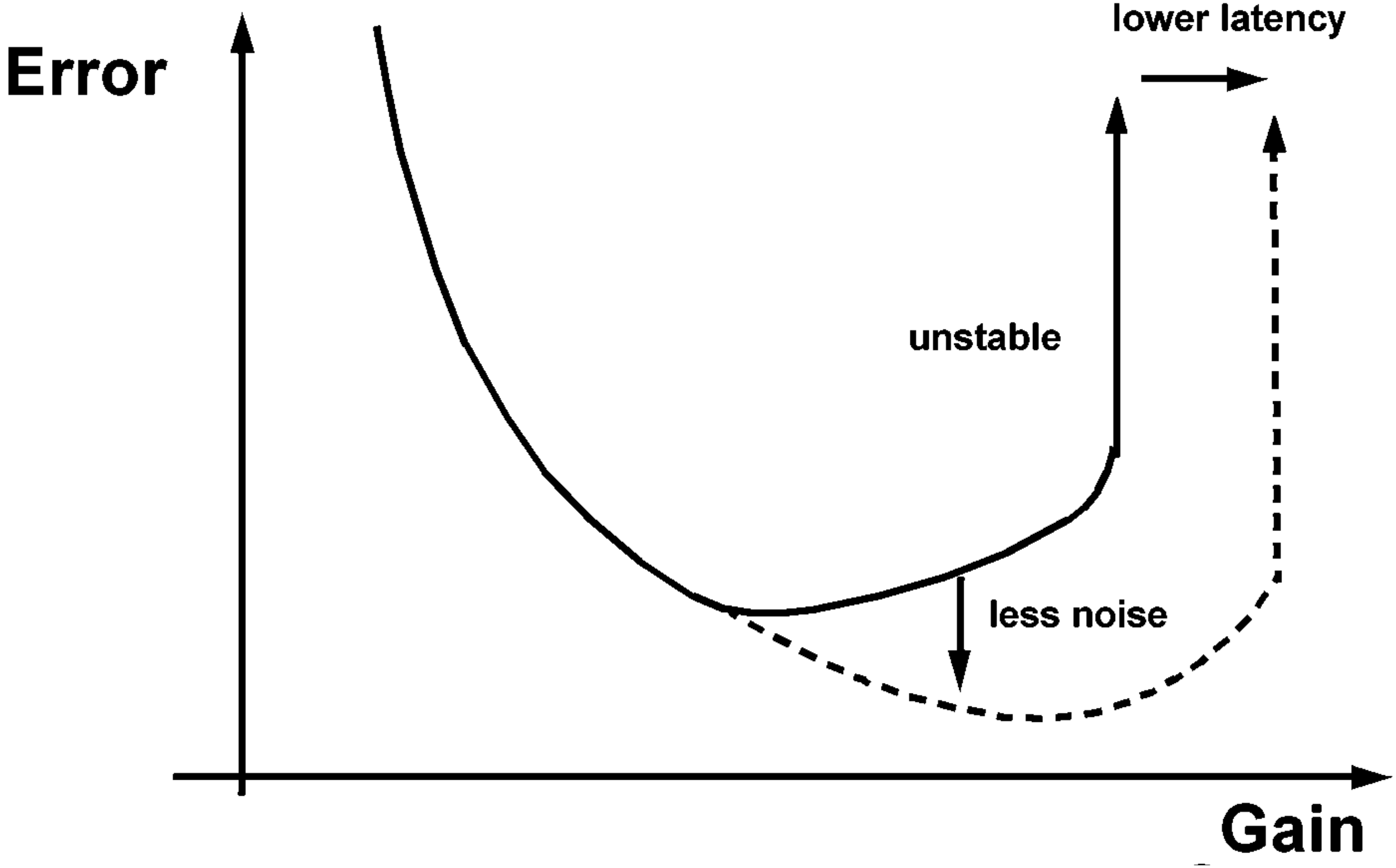


- I /Q detection: real and imaginary part of the complex field vector
- Preferable in presence of large field errors

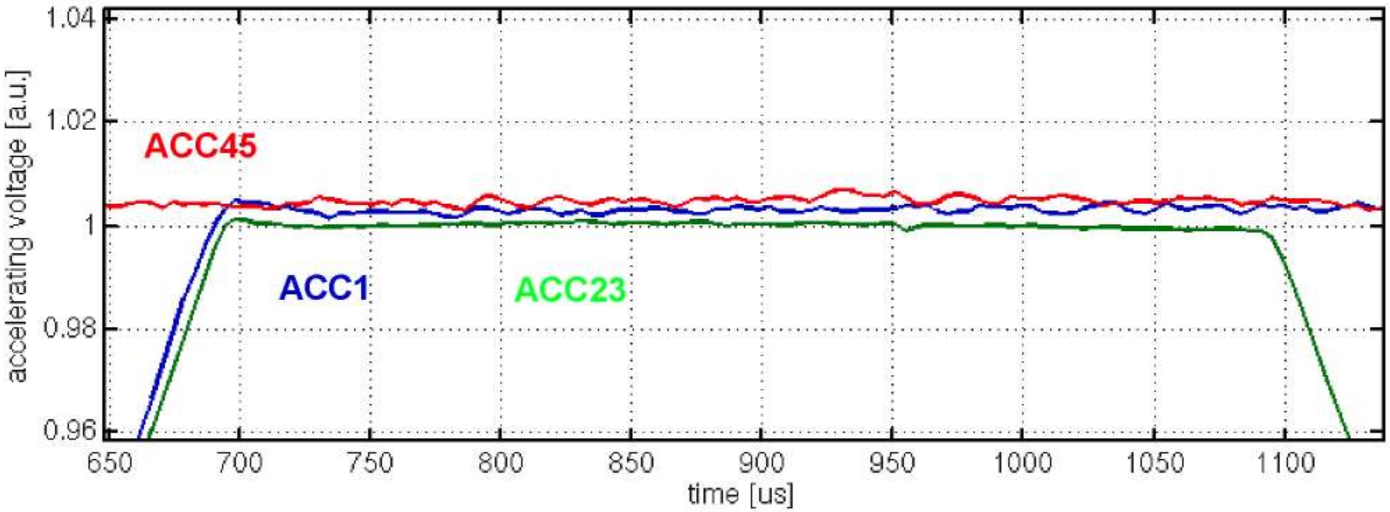


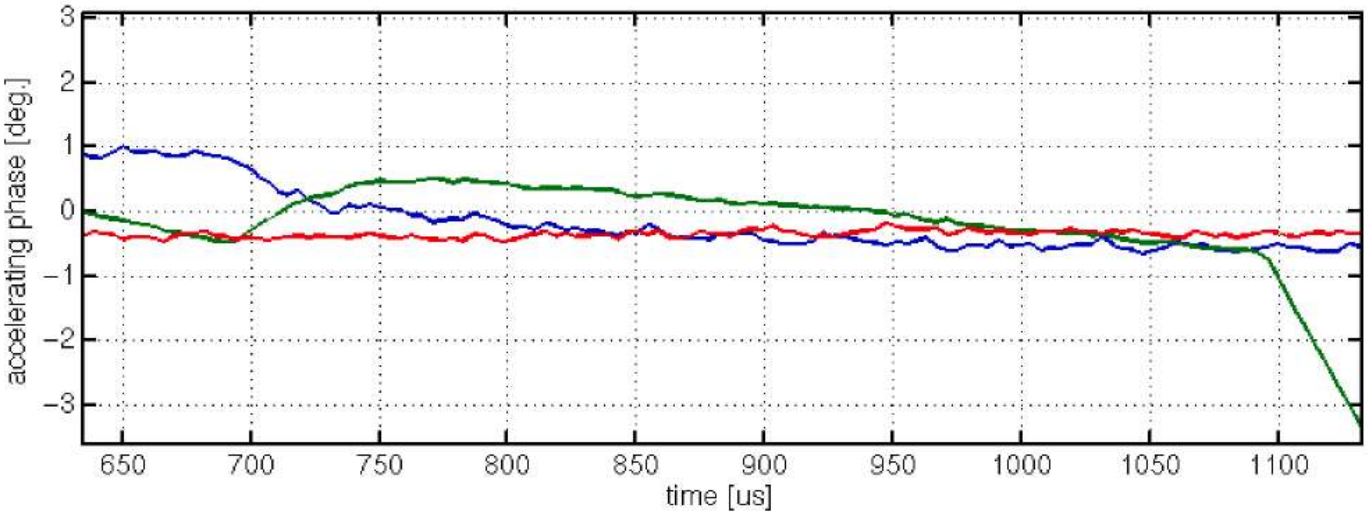
- Digital I / Q detection
- Alternating sample give I and Q component of the cavity field

RMS Error as Function of Gain

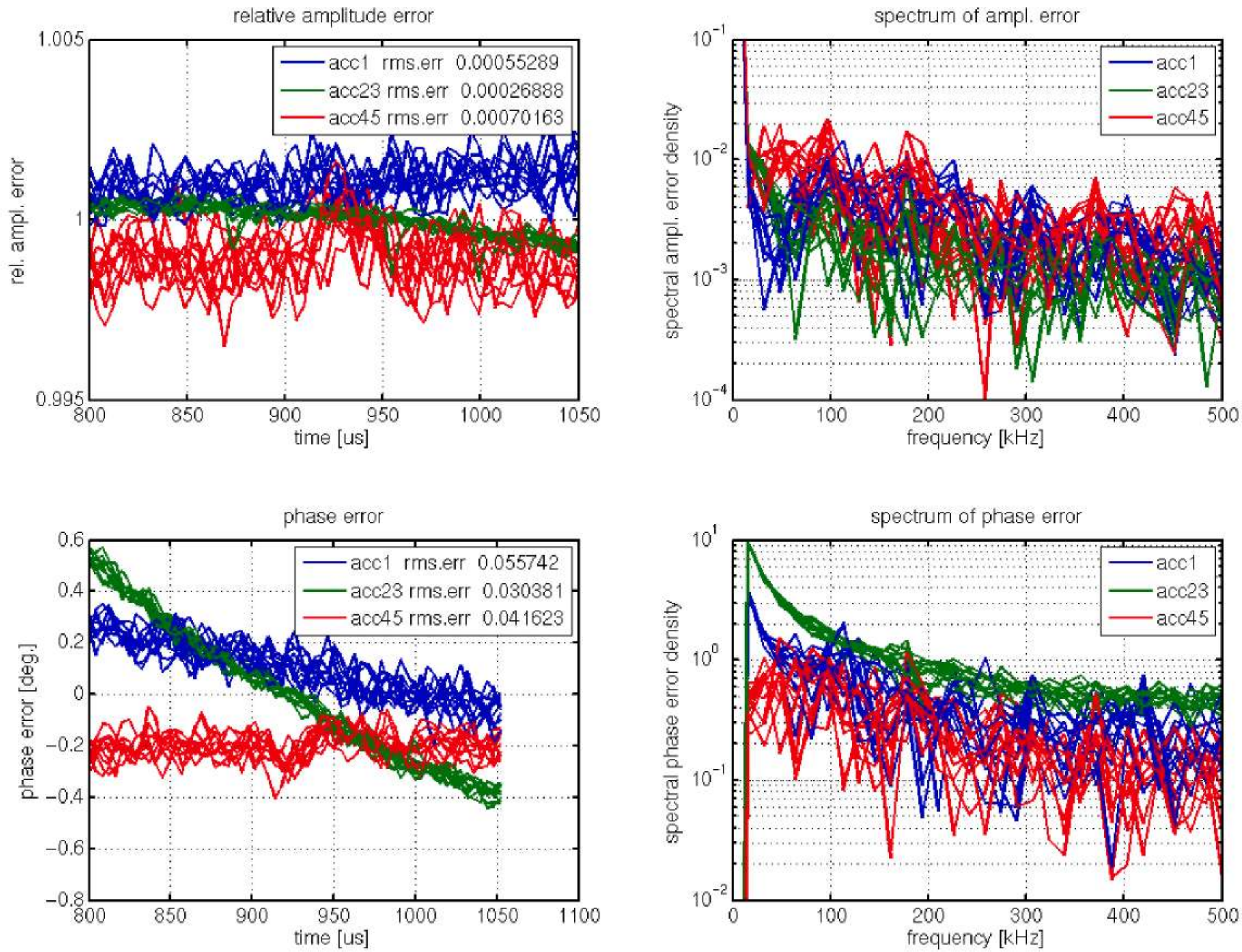


Field Regulation at FLASH

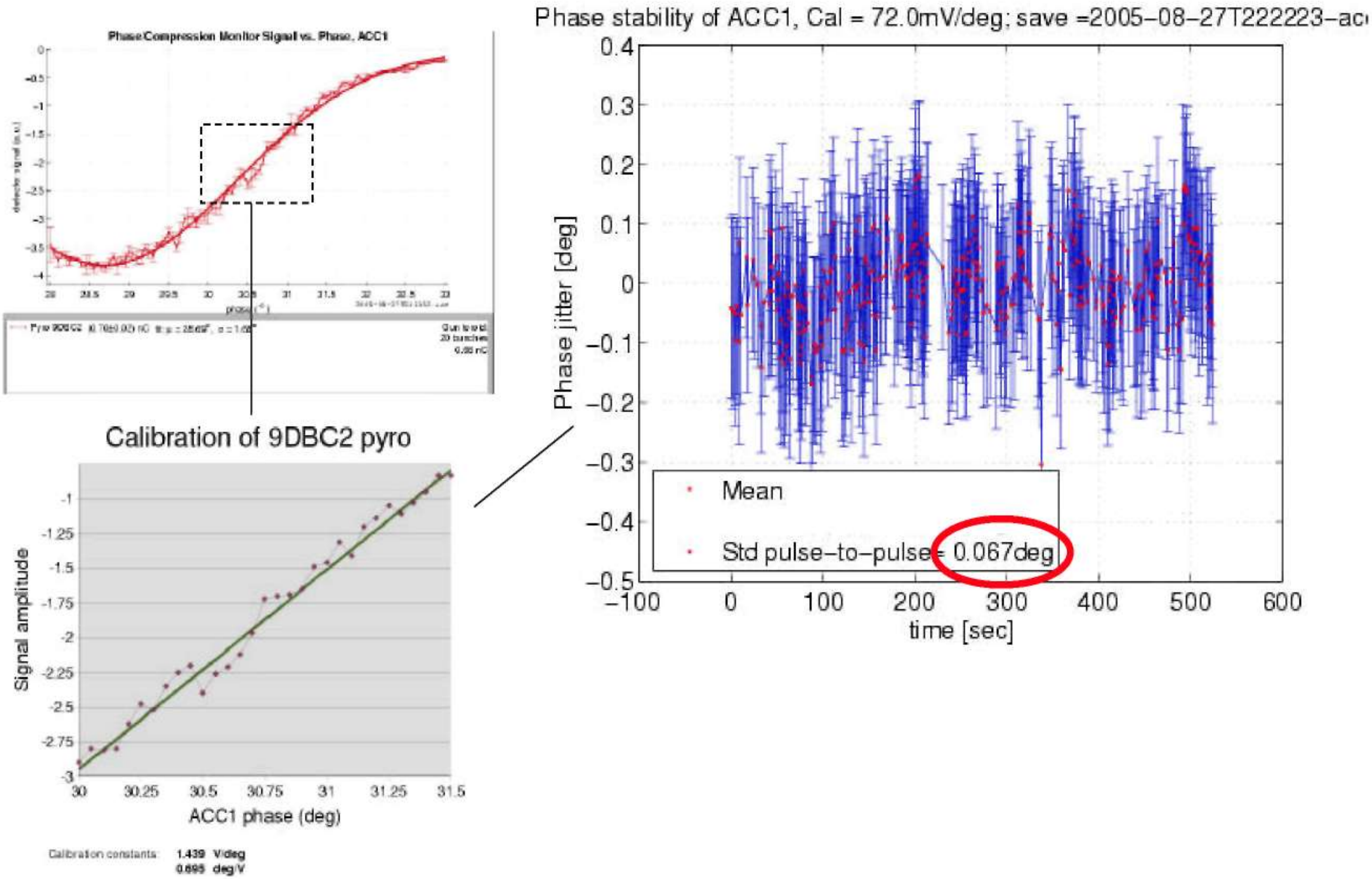




Field regulation at FLASH



Field Regulation at FLASH



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

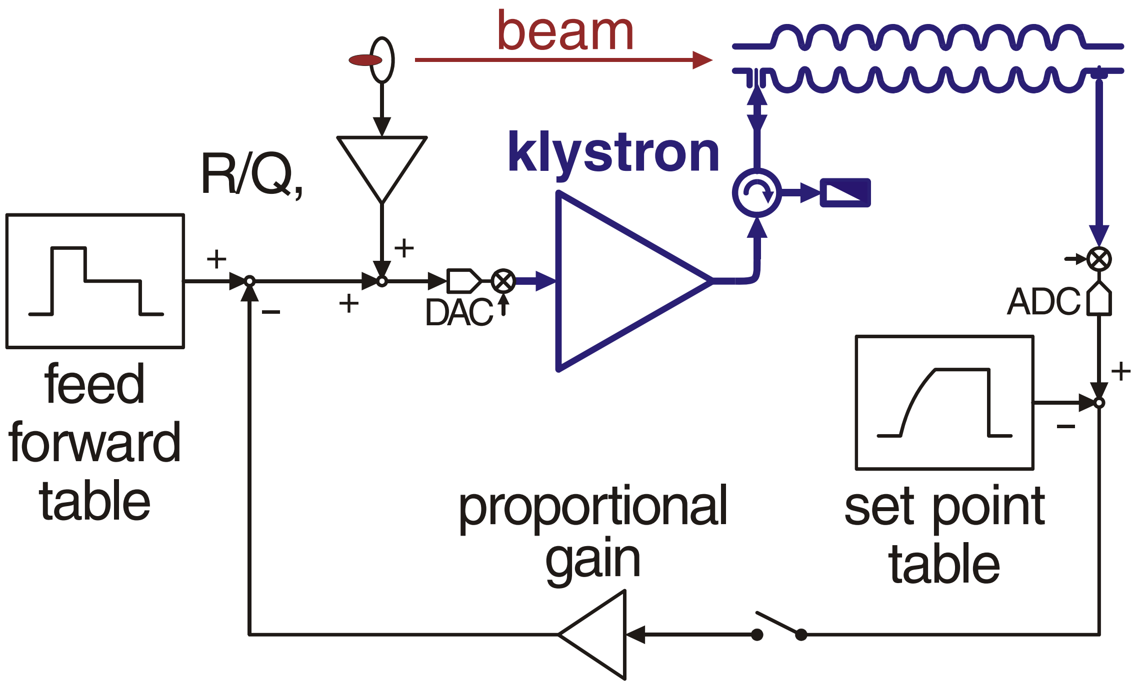
Problem:

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

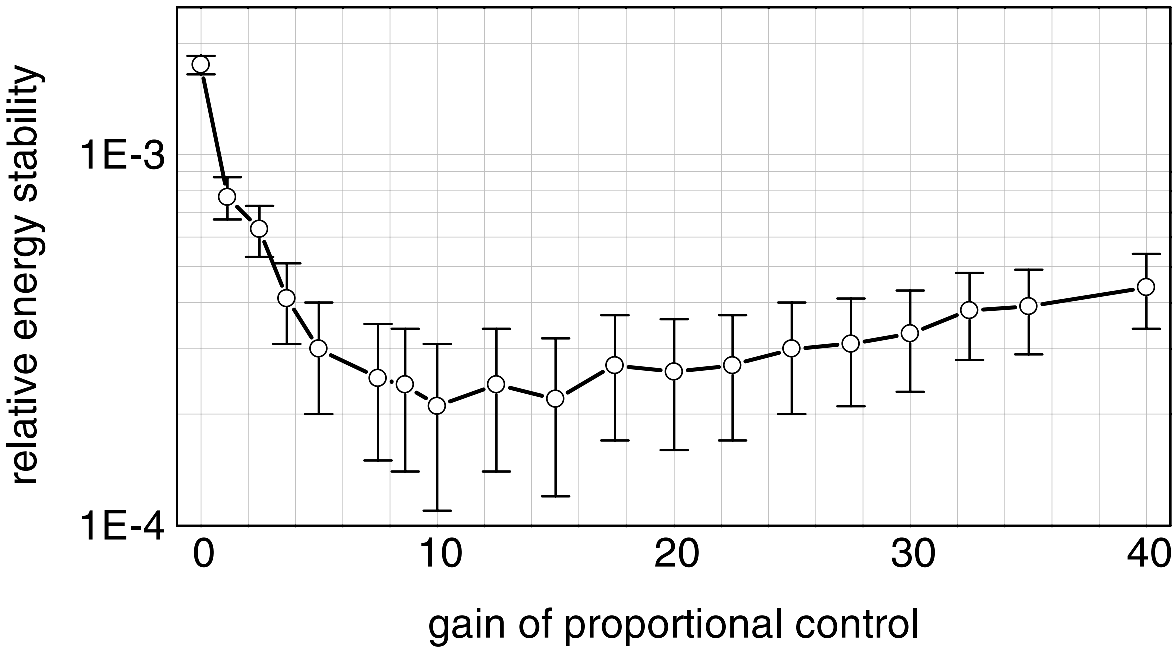
Countermeasures:

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

Scheme implemented for ACC1 at FLASH:



'Ideal' gain for proportional rf control at ACC1



Gain limitations:

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

Plus points:

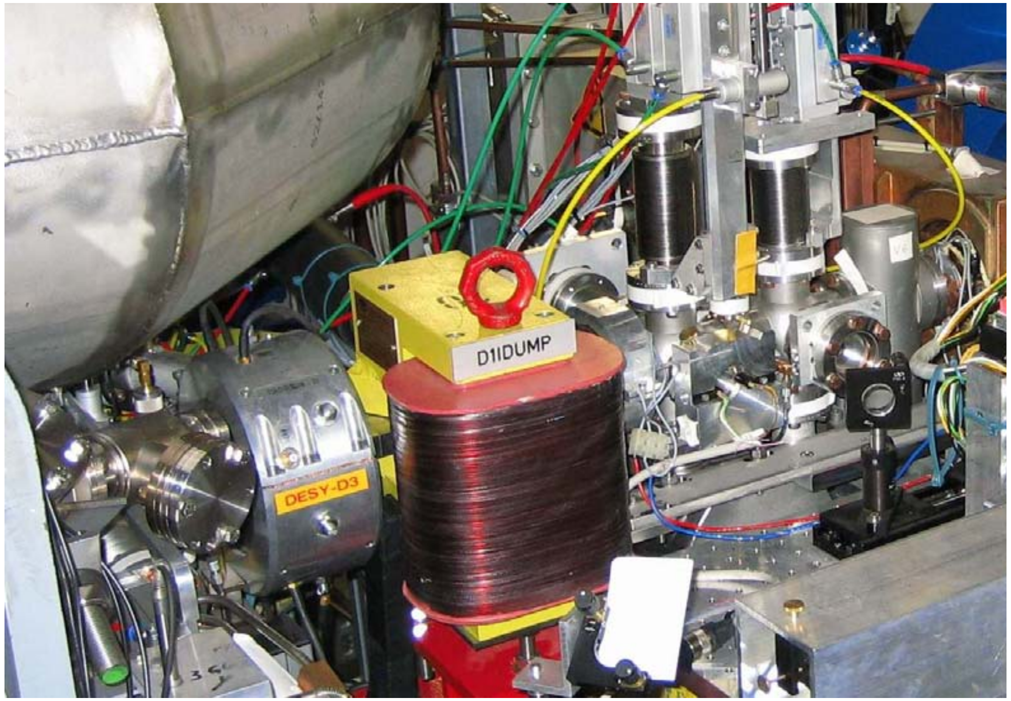
- XFEL requirement: $\Delta E/E = 10^{-4}$
- we controlled only 7 cavities (one pick up makes trouble)
- XFEL injector has four instead of only one module

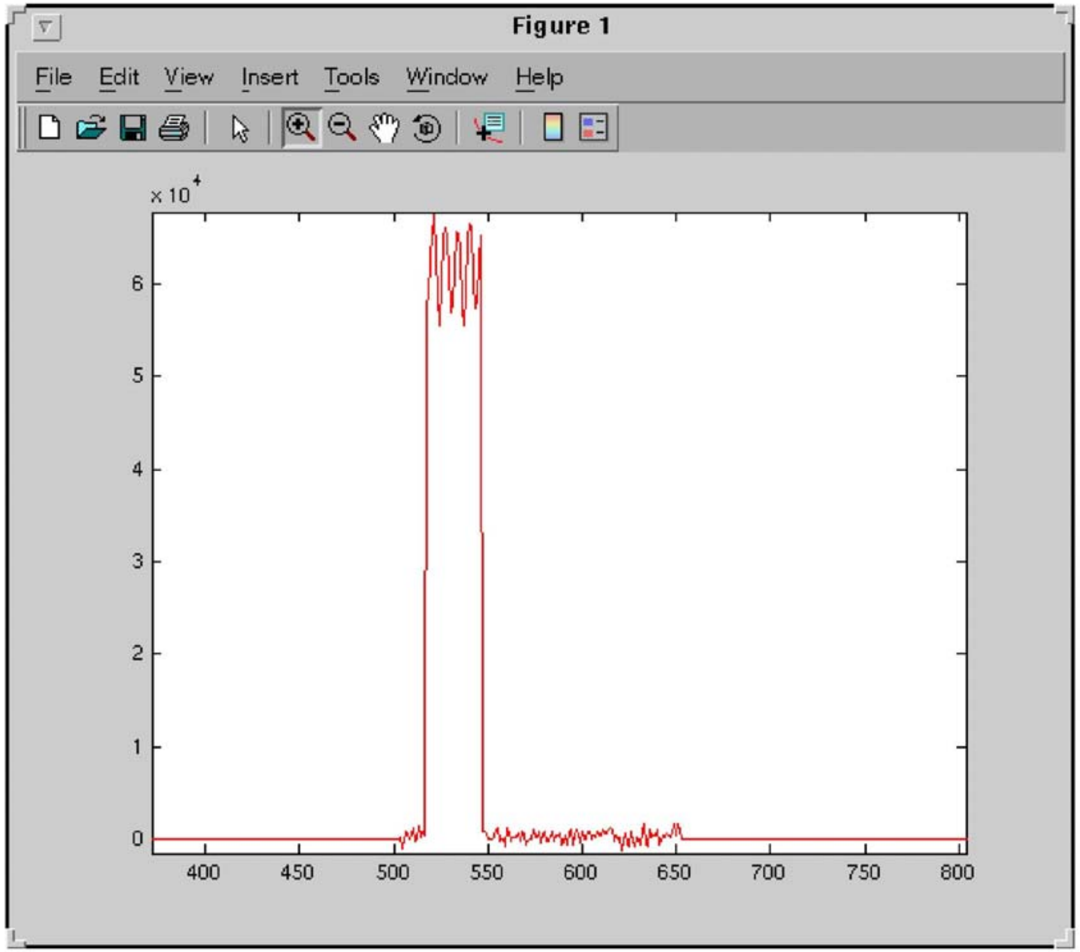
Gain resulting in most stable beam:

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

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





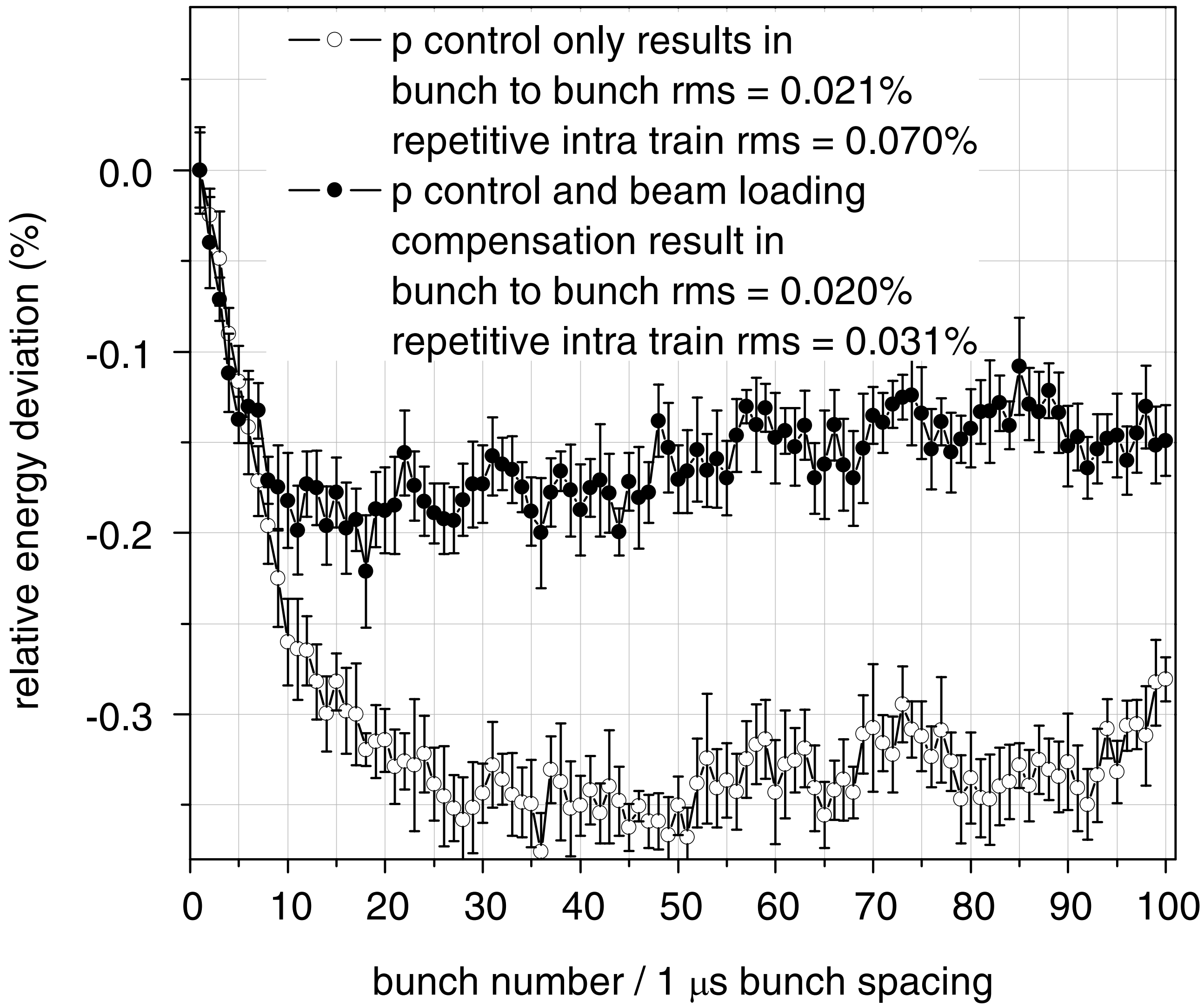
Actual status of the ACC1 beam loading compensation

Status:

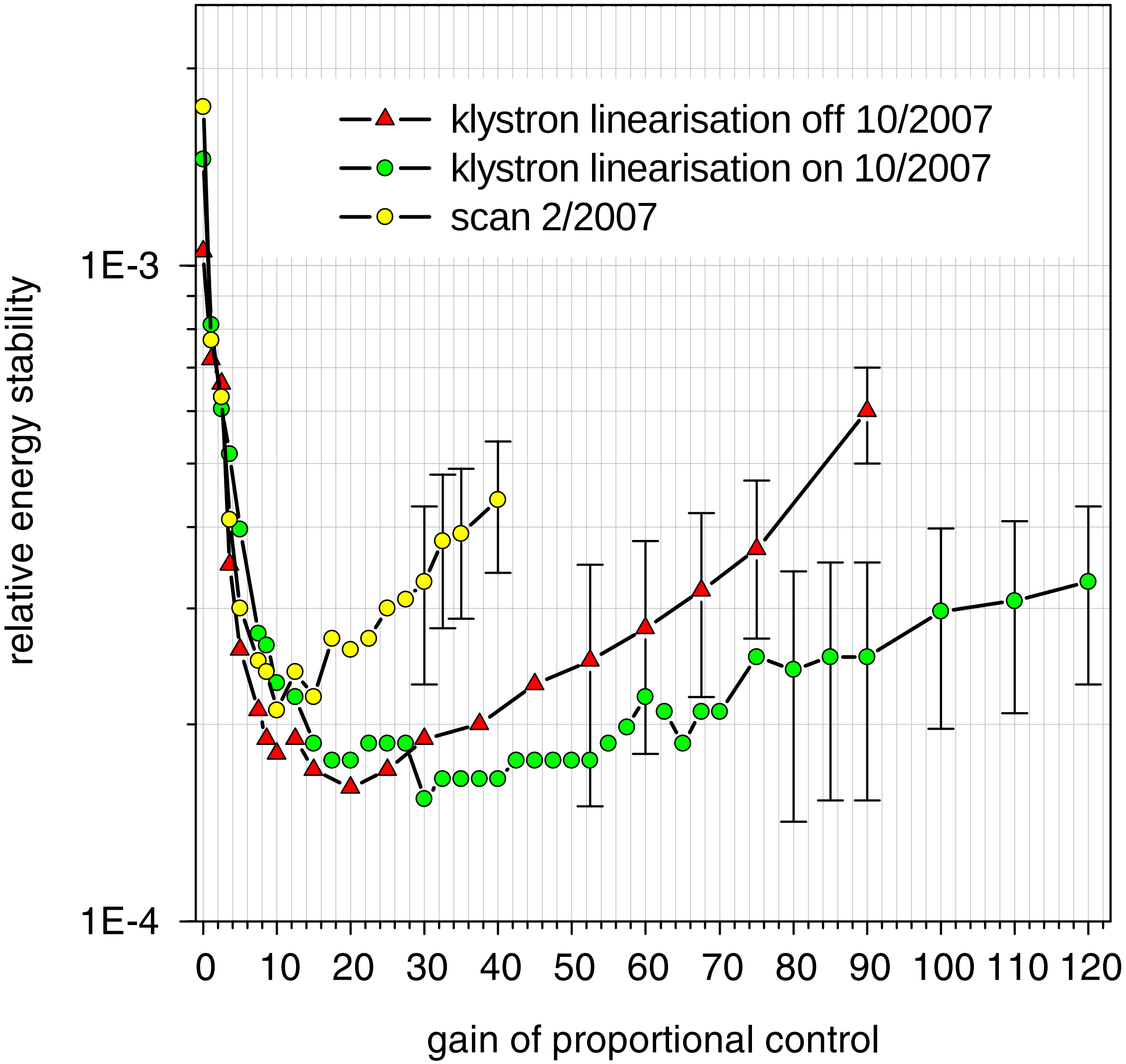
- not yet ideal, but…
- sufficient for SASE with more than 400 bunches

Next steps:

- improvement of calibration
- further qualification by beam measurements



'Ideal' gain for proportional rf control at ACC1



Gain giving most stable beam:

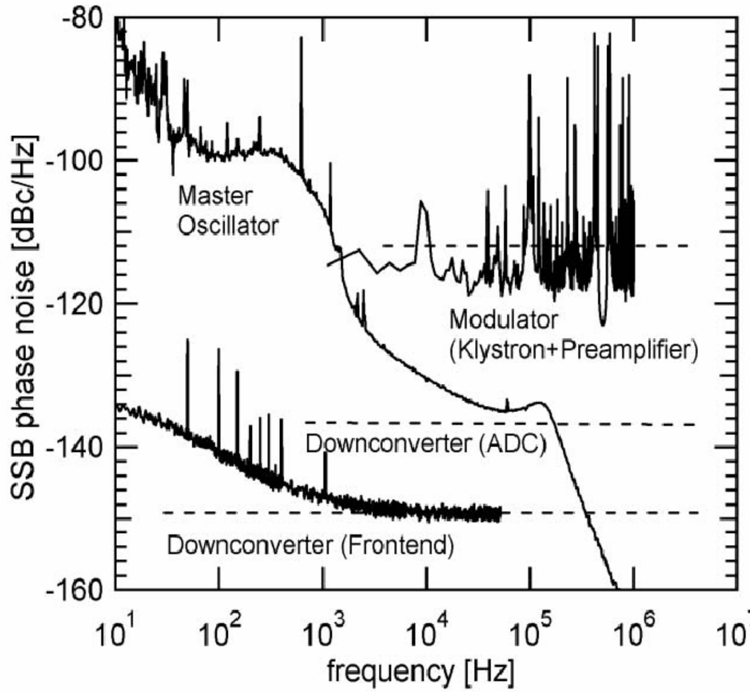
- small gain: error suppression
- large gain: noise amplification
- best single bunch stability: $\Delta E/E = 1.6 \times 10^{-4}$

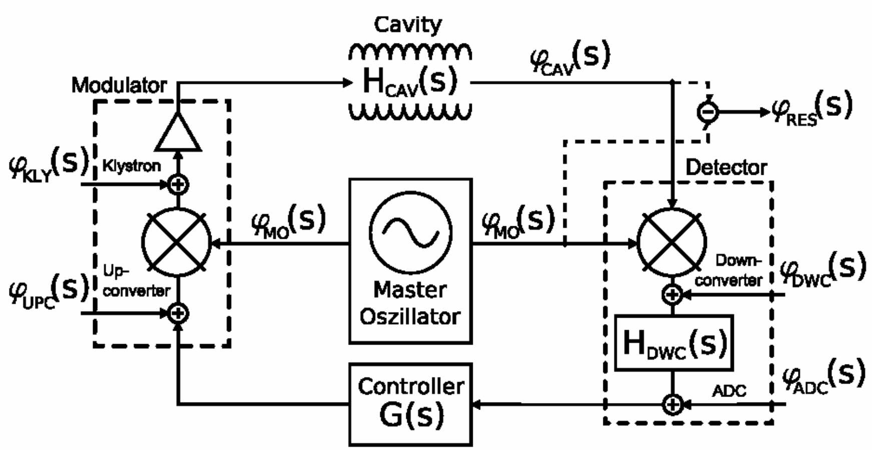
Gain limitations:

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

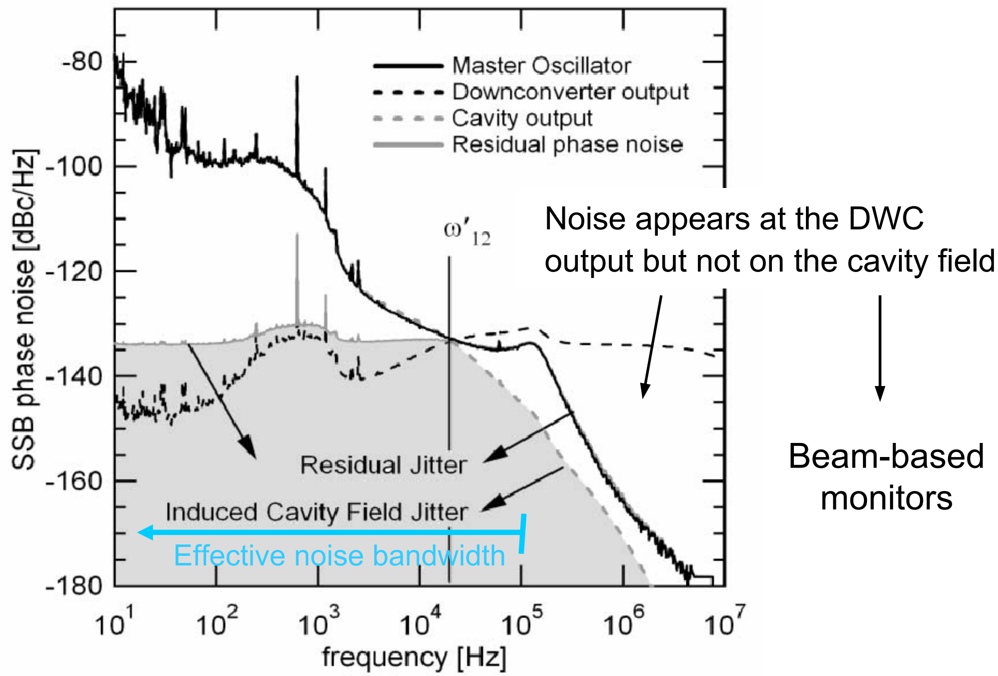
Phase noise budget at FLASH (Switched LO, single cavity)

- **Phase noise measurements :**





- **Contributions to cavity field jitter :**



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]

Available technologies and selection of the detector concept

• Passive Mixer + GaAs FET:

+ High linearity
+ Low NF
- Large LO drive needed
- Low LO/RF isolation

• Active Mixer (Gibert cell):

+ High conversion gain
+ Low LO drive needed
+ High LO/RF isolation
- Normal NF
- Additional 1/f-noise

• Other detectors :

HMC439: phase detector SiGe

+ Low NF, - Limited to 1.3GHz

AD8347 : quadrature demodulator

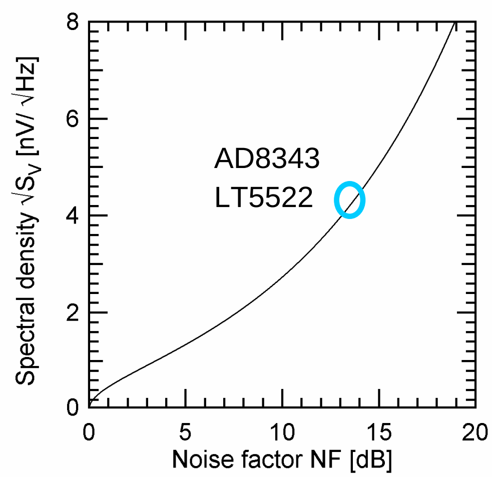
- to be tested in ‚parallel‘

AD8302 : gain, phase monitor

+ good temperature stability

- worse NF

		down	up	down	down	down	down	down	down	down	down	down
		LT5522	LT5521	LT5526	MC1502	CDB-9050	DBM-182	MBA-15L	HMJ7	HMJ7-1	IAM-92516	AD8343
P(RF)	dBm	-7		-15	-10	-5	-10		-10	-10	-10	-12
P(LO)	dBm	-5	-5	-5	7	-5	7		21	21	-3	-10
P(IF)	dBm		-7									
NF	dB	13,2	12,5	12,3	7,5	15	8,5		8,5	10,5	12,5	14,1
IP3	dBm	25	24,2	16,5	12	-3			34	34	27	16,5
1dB	dBm	10,8	11	5			0		23	23	9	2,8
MS11	dB											
PS11	deg											
MS22	dB											
PS22	deg											
MS33	dB											
PS33	deg											
Gain	dB	-0,4	-0,5	0,5	6	6	-7,5	-6,5	-8,5	-8,5	-5,5	7,1
RF to IF	deg											
isol IF RF	dB											
iso LO RF	dB	50	38	55	30	33	25		24	24	34	
iso LO IF	dB	49	59	55	25	35	20	14	24	30	56	54
IF(min)	MHz	0,1	10	0,1	0	30	0	0			0	0

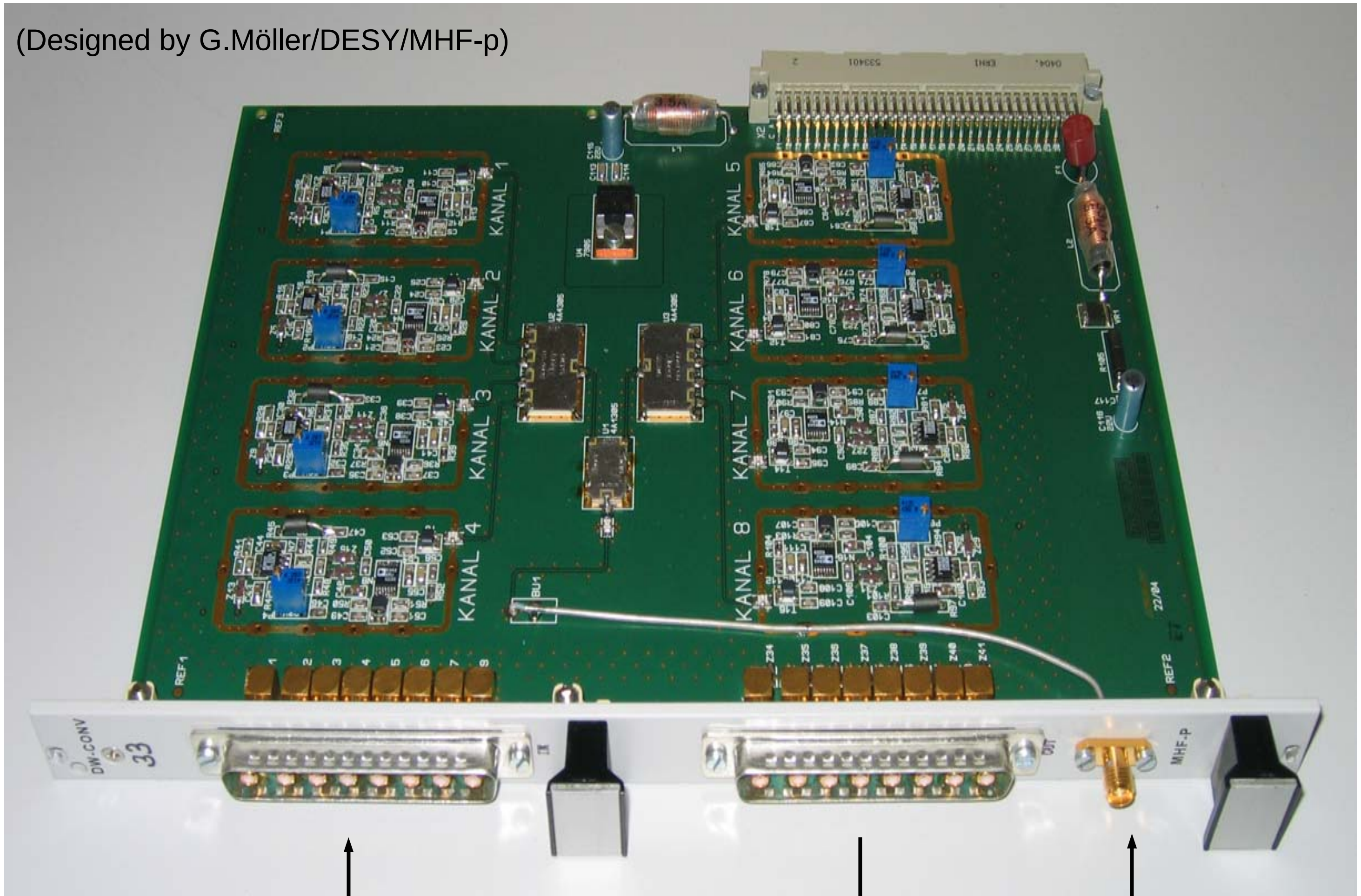


Multi-channel detector :

Gilbert cell mixer

Frank Ludwig, DESY

Actual down-converter (AD8343+OPAmp) operating at 1.3GHz



+ High LO/RF isolation

- RF-range [DC-2.5GHz]

- Mixing into baseband caused additional noise

8-channels from cavity probe :

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

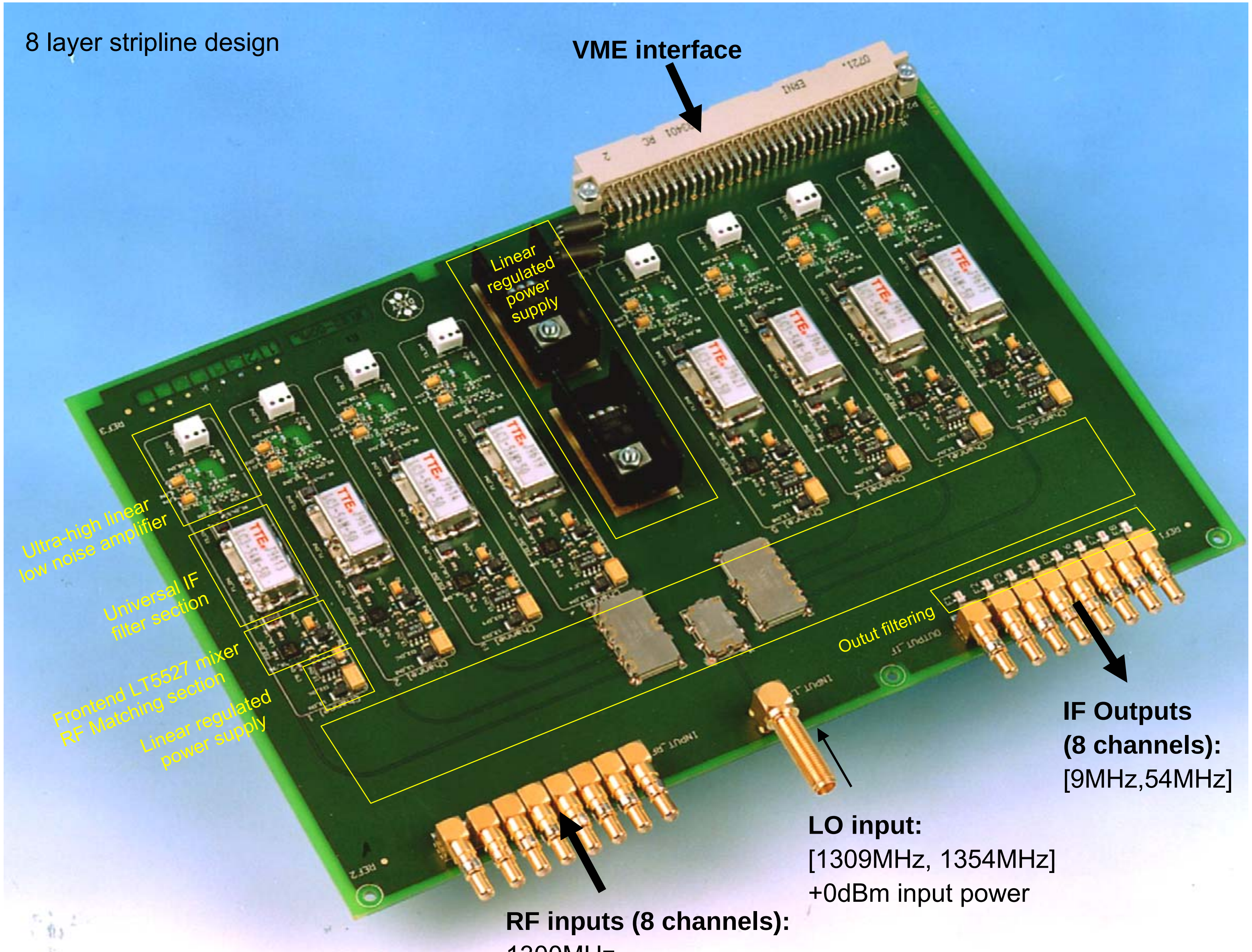
$-70dB \ \ linearity$

8-channels to ADC-Board :

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

LO-Input :

$P_{LO} \approx -5dBm$



LO input:
[1309MHz, 1354MHz]
+0dBm input power

RF inputs (8 channels):
1300MHz
+0dBm input power / channel

- **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

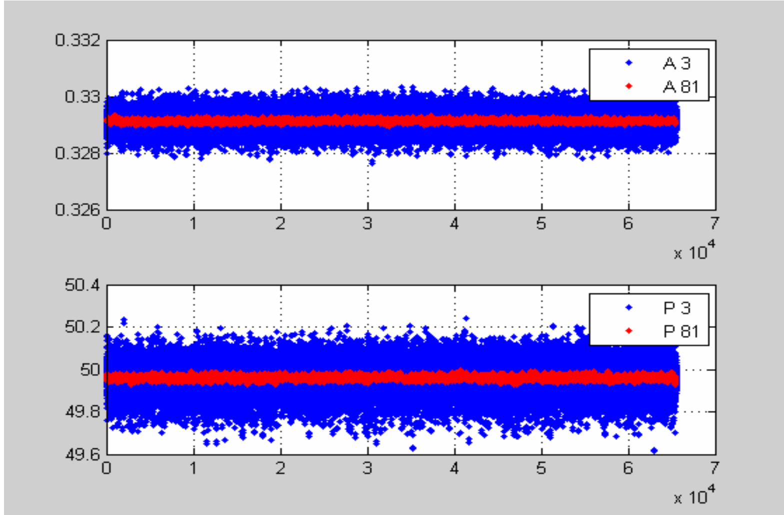
Parameter :

- 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**

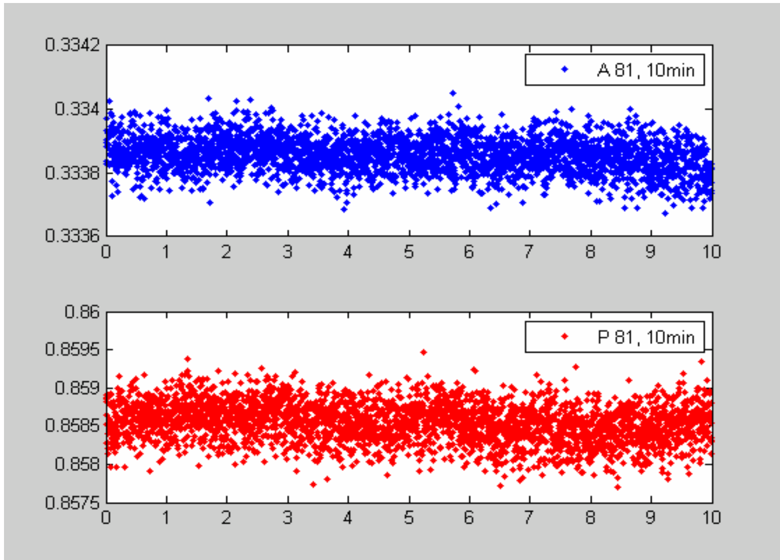
- **Shortterm stability 800us (bunch-to-bunch):**

BW=27MHz
BW=1MHz



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

BW=1MHz
BW=1MHz



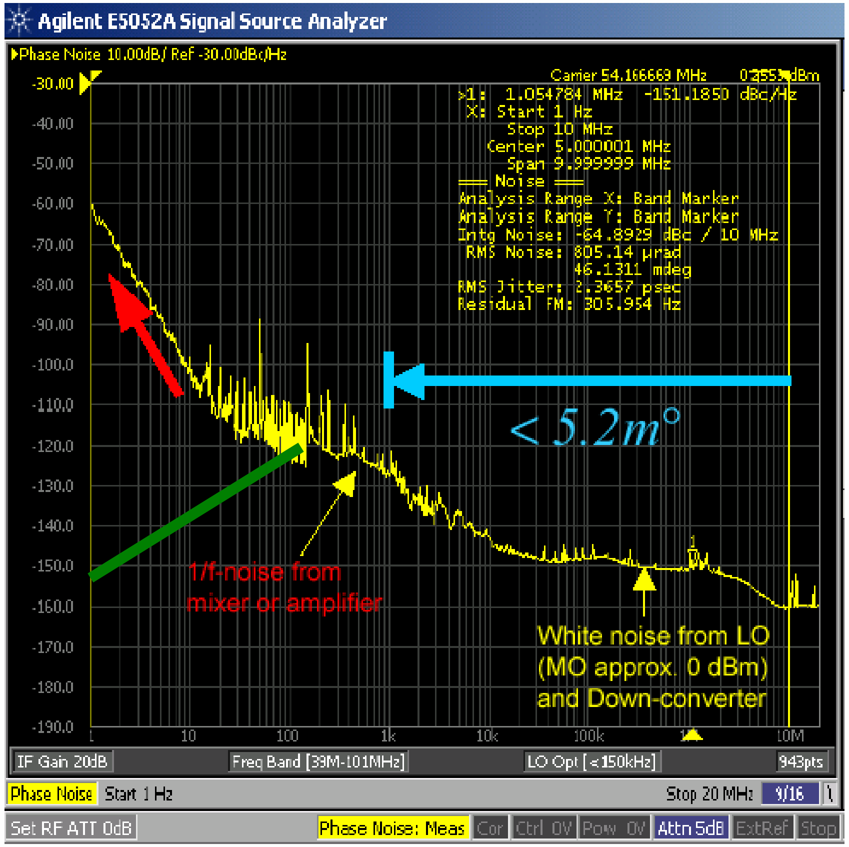
Single channel receiver performance at FLASH

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

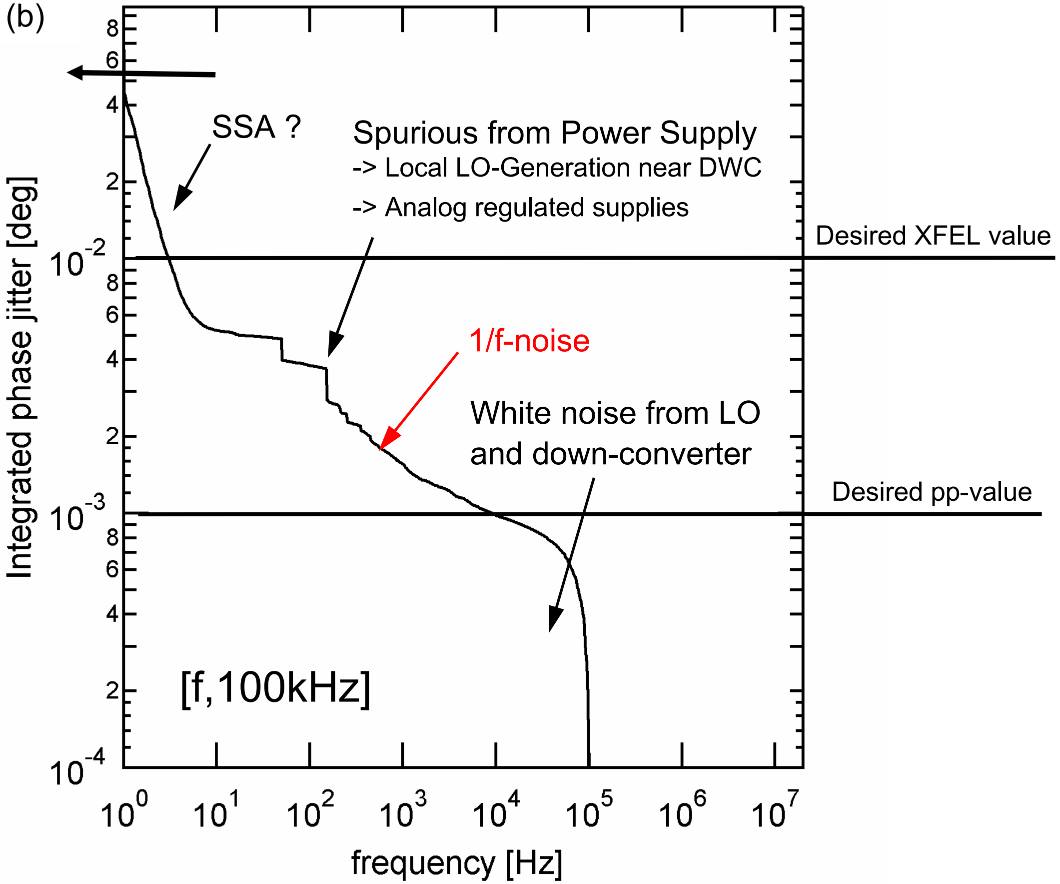
- Analog Receiver has 0.0052 deg [1kHz,10MHz].
- IF[9,54MHz] works also with a lowpass
- Powerful diagnostic using the CW modulation scheme!
- Drift calibration <100Hz is needed!
  (Injector door effect on LO) e.g. injected, reflected or LO or Beam-based feedbacks

Biased by MO reference :

(a)

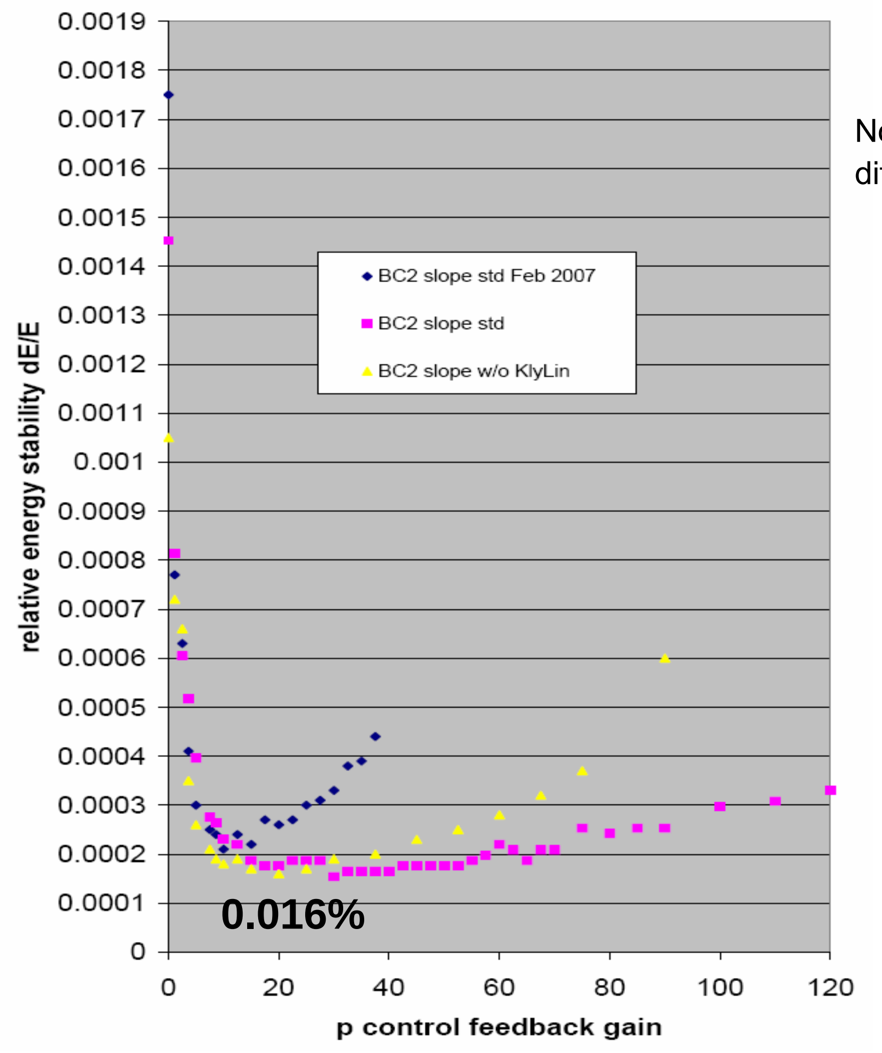


(b)

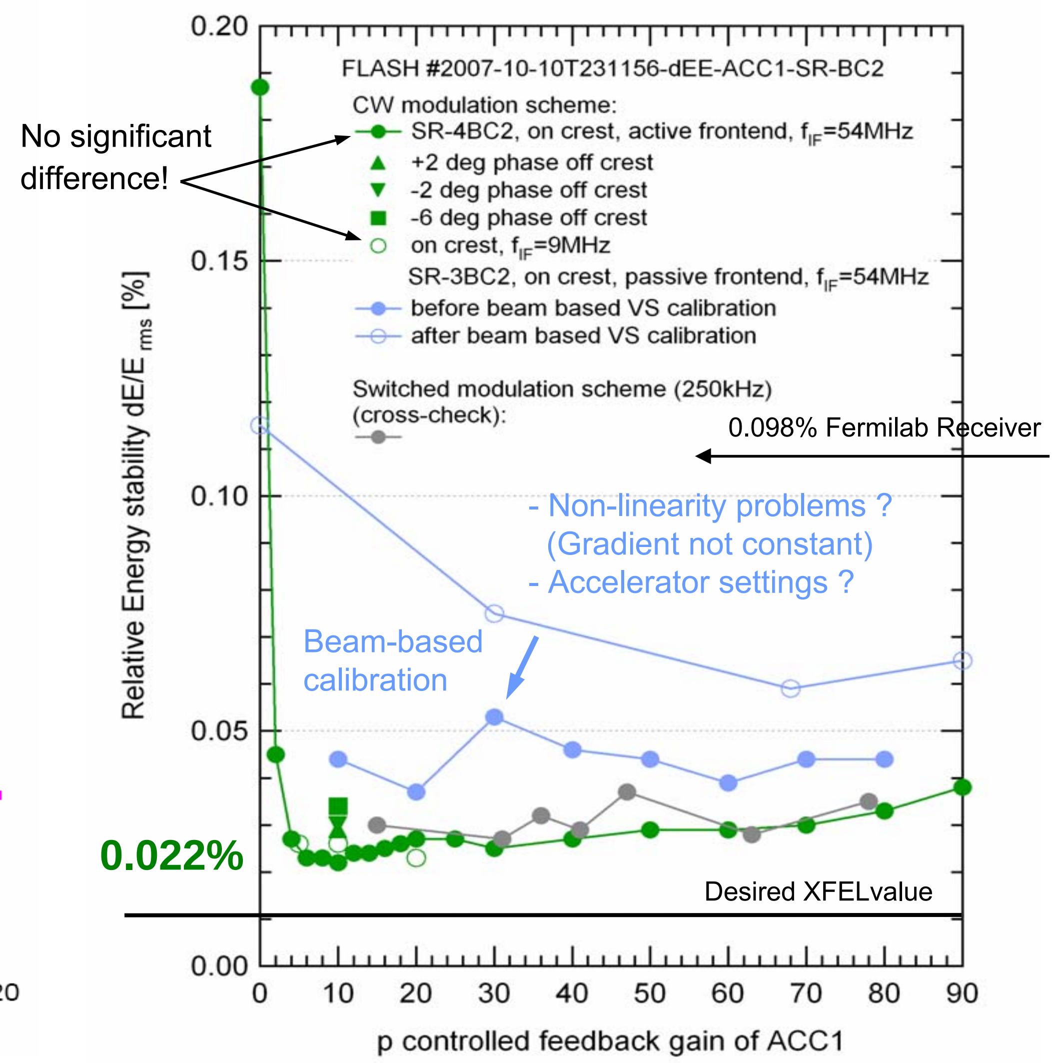


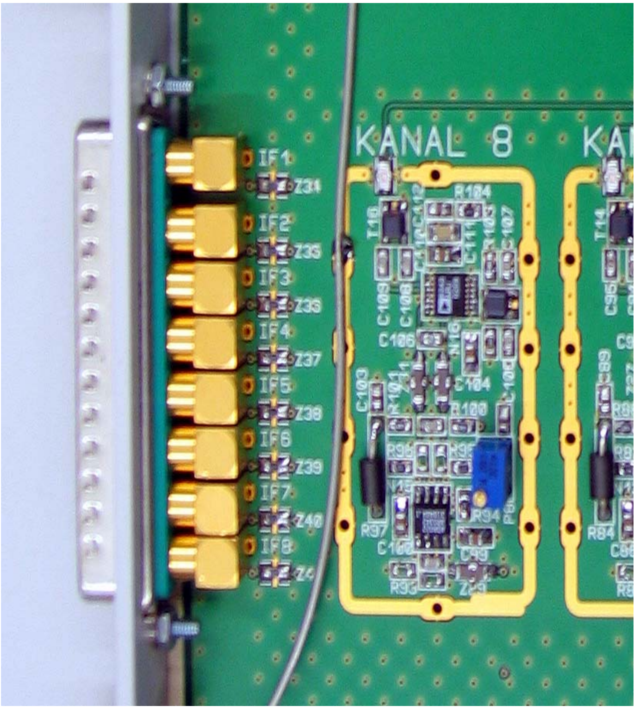
Summary of ACC1 beam stability at FLASH 09/07

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

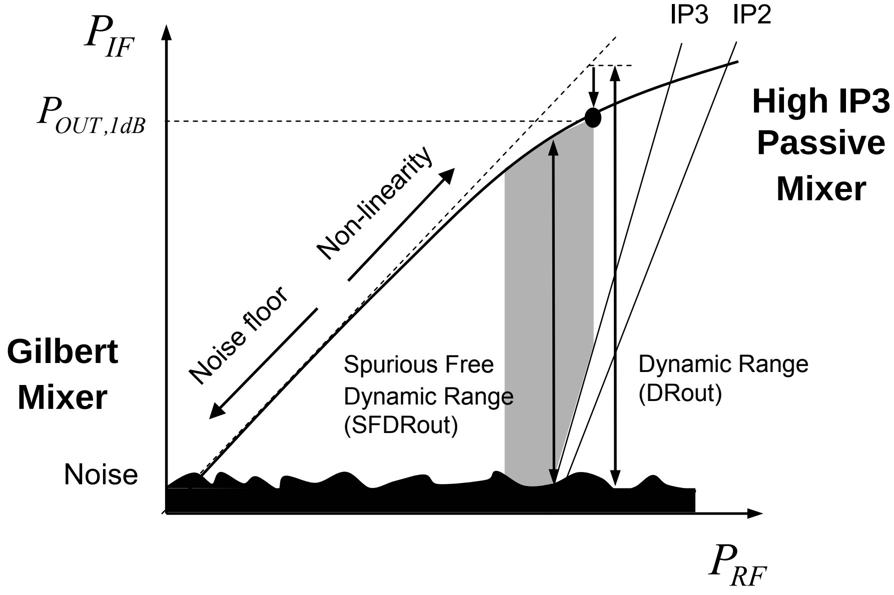


- **IF sampling down-converters (9,54MHz):**





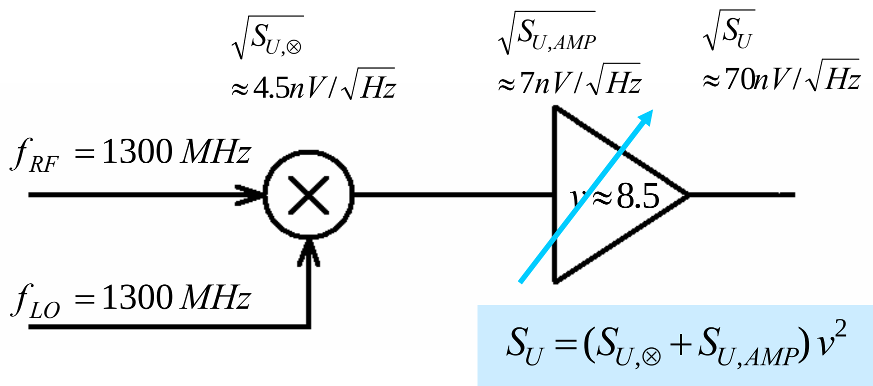
- **Compromise between noise and linearity :**

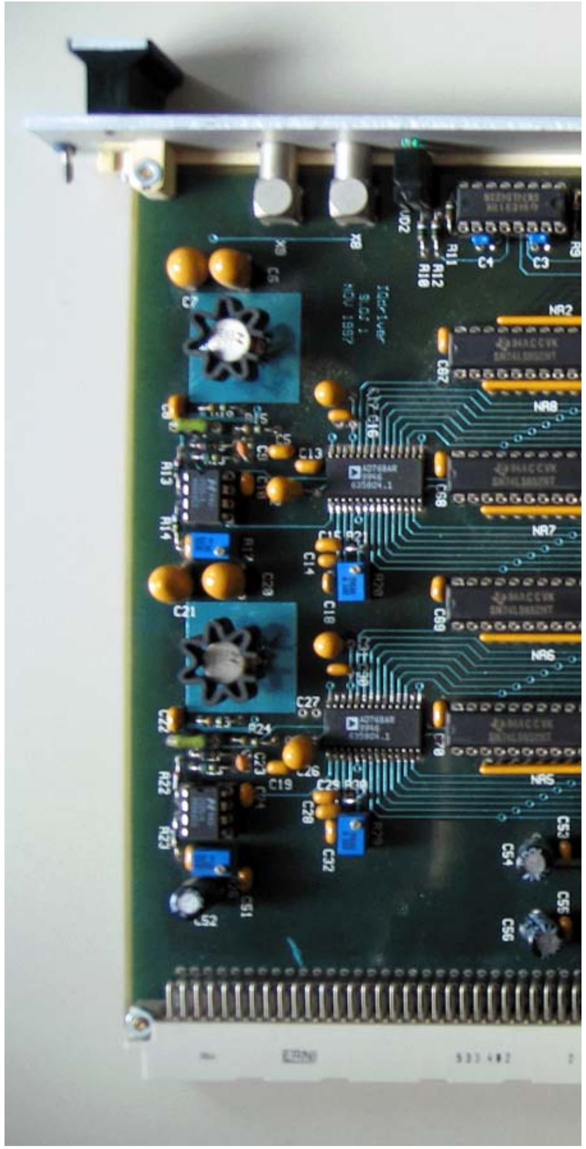


- Second amplification determines performance
- Expected down-converter performance from baseband measurements:

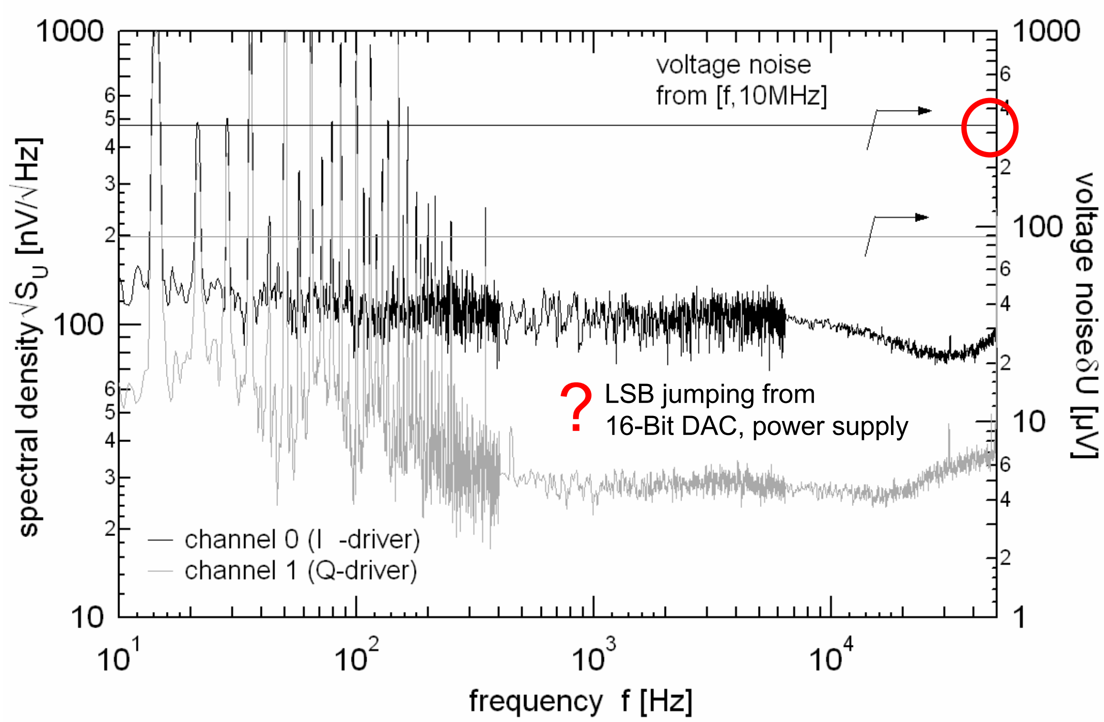
$$(\Delta A/A) \approx 0.2E-4 \approx 0.2\delta U_{XFEL},$$ (Cavity filtered)

$$\Delta f = 100kHz,$$





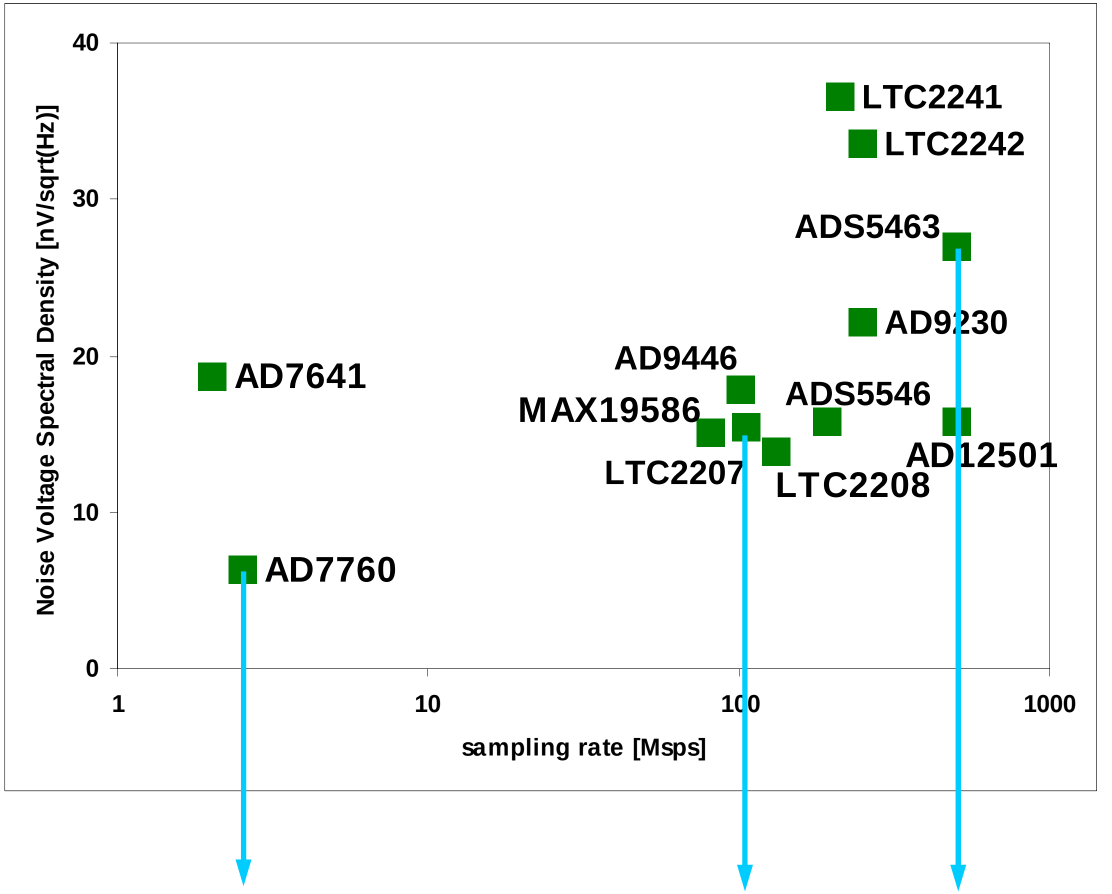
- **Noise from IQ-driver modul :**



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

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

- **ADC equilvalent noise spectral density :**



Baseband or IF Detection IF Sampling Direct Sampling

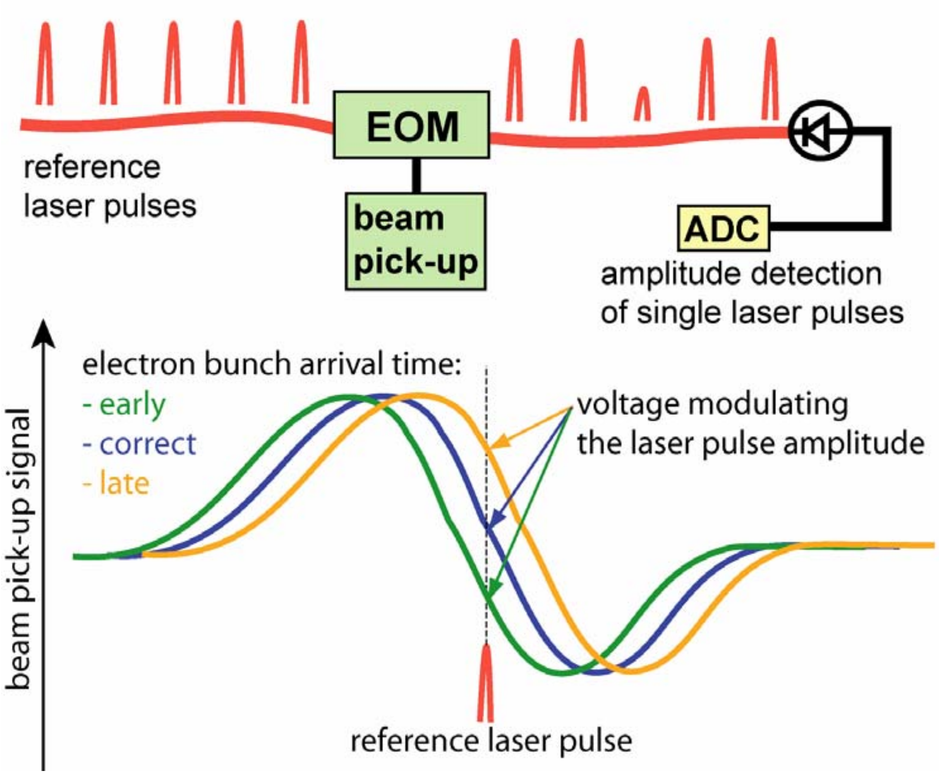
$$e_n = \frac{V_{FS,pp}}{\sqrt{8}} 10^{\frac{SNR(f_s,\varepsilon)}{20}} \sqrt{\frac{2}{f_s}}$$

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

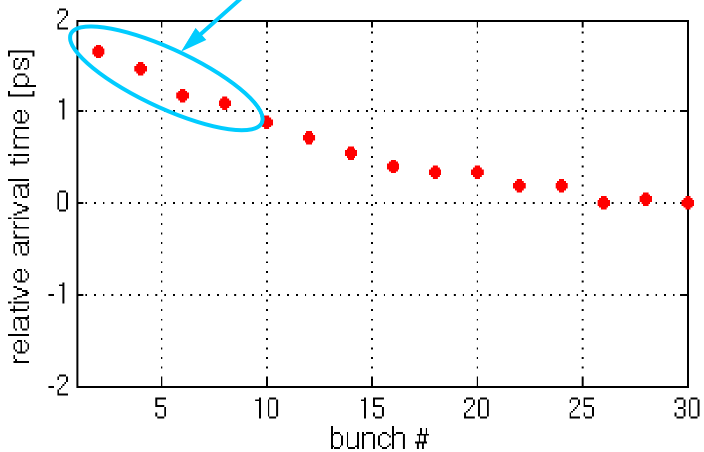
A lot of available ADCs have roughtly the same performance.

Bunch-to-bunch beam stability

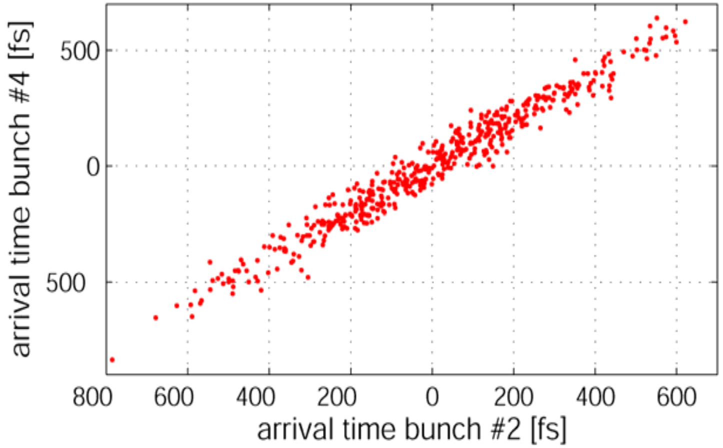
- **Bunch-Arrival Monitor :**



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% ?

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.

Conclusions (1)

- Field stability as required for crab cavities has been demonstrated at various places (JLAB, DESY, KEK, Cornell, …)
- Major challenge are beam loading variations as result of beam position fluctuations.
- Careful design of LLRF electronics, beam and rf diagnostics, and rf reference and calibration signals is required.

Conclusions (2)

- Field stability requirements for crab cavities are challenging but achievable if
  - Sources of perturbations and noise sources can be managed.
  - Combination of feedforward and feedback schemes are used and beam diagnostics is optimized for this purpose (beam position, beam current, etc.)
  - Phase reference and calibration signals are state of the art (combination optical and microwave)
  - Crab cavities must be individually controlled
  - 2 probes and independent phase monitoring (electro-optical detectors) desirable