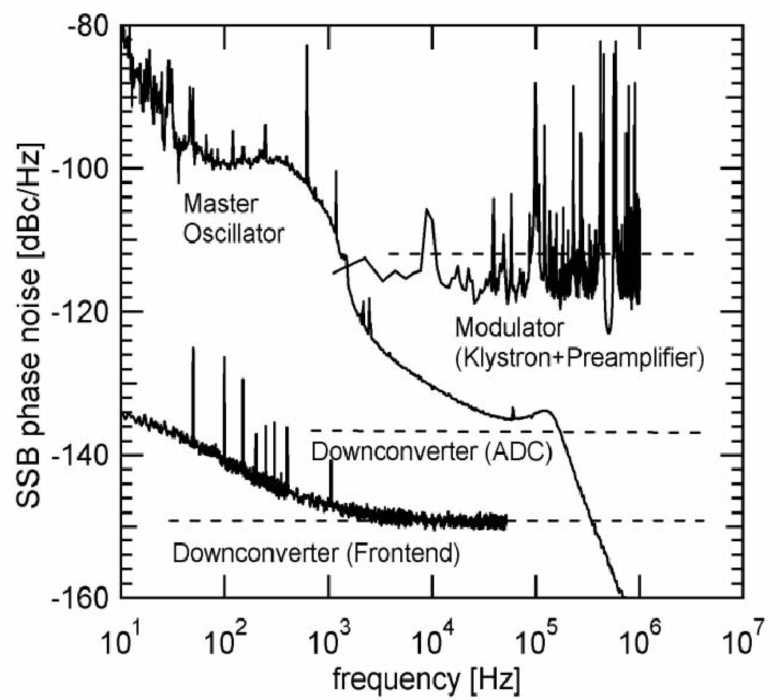
‚Results from tests of the new down-converter and field detection scheme at FLASH‘

- F.Ludwig, M.Hoffmann, K.Suchecki, C. Schmidt,
C. Gerth, W.Jalmuzna / DESY,ELHEP

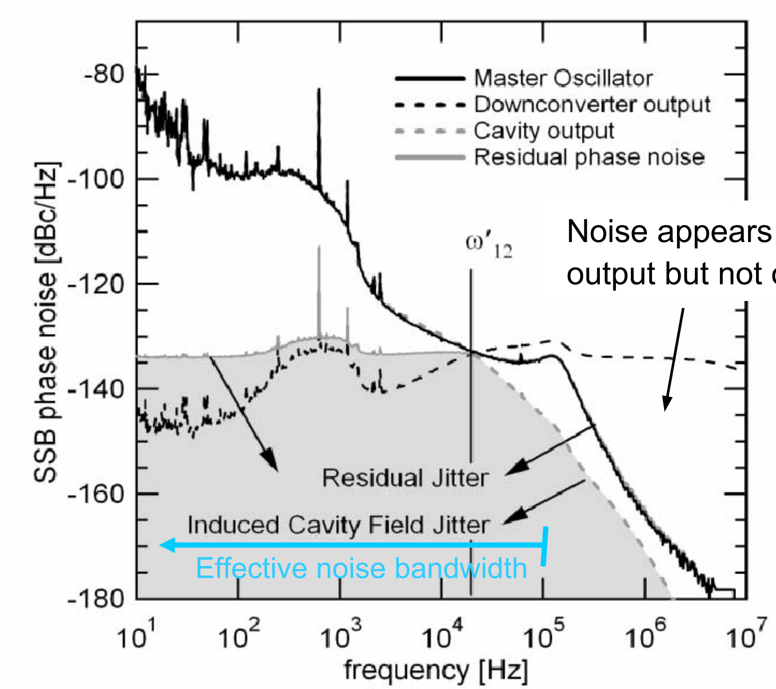
Content :

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

- **Phase noise measurements :**

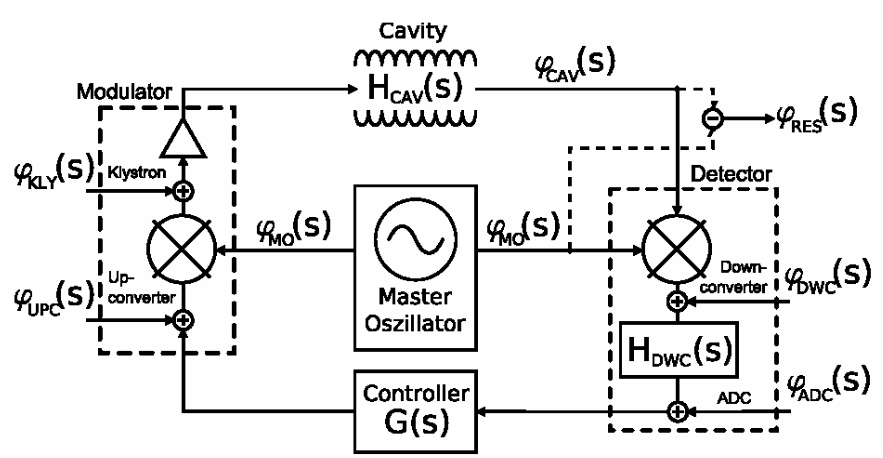


- **Contributions to cavity field jitter :**



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

Beam-based monitors



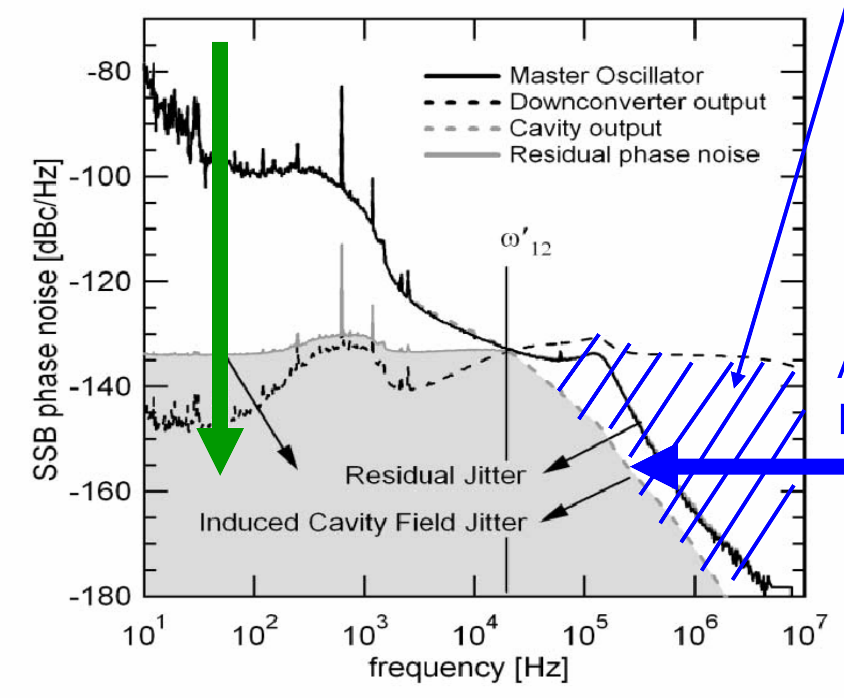
Subsystem	Phase noise [dBc/Hz]	Residual jitter [fs]	Induced jitter [fs]
MO	see Fig.3	14.1	5.5
DWC (Frontend)	−147	1.8	1.8
DWC (ADC)	−135	5.8	5.8
MOD	−110	1.2	1.2

(Complete ADC module)

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

„Beam performance“:
Increase SNR by
- Increasing input power
- Decreasing noise spectra density of the down-converter

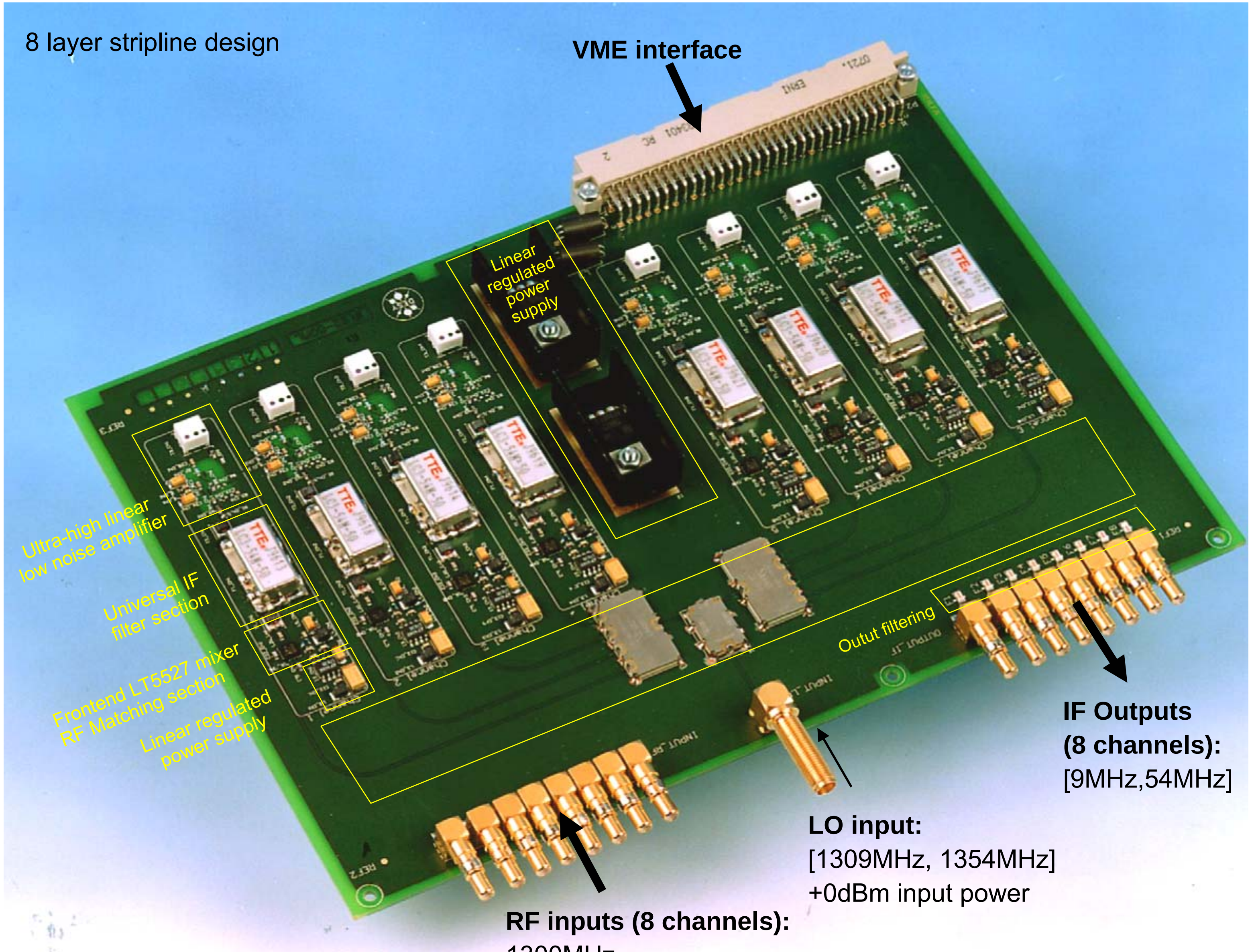
„Display property for the operator“:
Noise appears at the DWC output but not on the cavity field!



Averaging
Filtering

Effektive noise bandwidth for the beam jiter induced by the LLRF

?


8 layer stripline design
VME interface
Linear regulated power supply
Ultra-high linear low noise amplifier
Universal IF filter section
Frontend LT5527 mixer RF Matching section
Linear regulated power supply
Outut filtering
IF Outputs (8 channels):
[9MHz,54MHz]
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

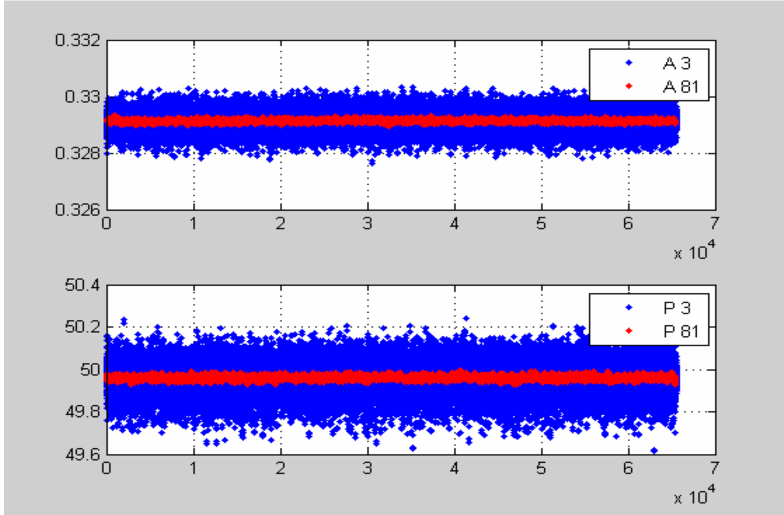
→ 1 IQ value

→ **~5 Hz through 10 minutes**

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

BW=27MHz

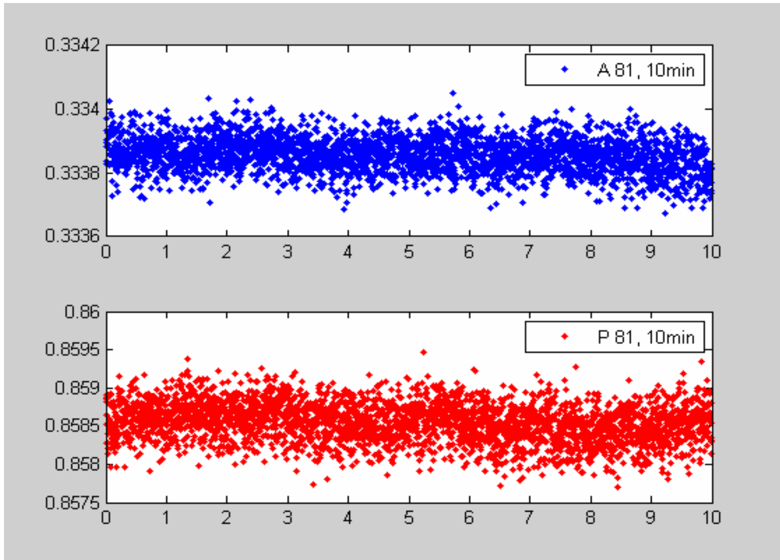
BW=1MHz



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

BW=1MHz

BW=1MHz



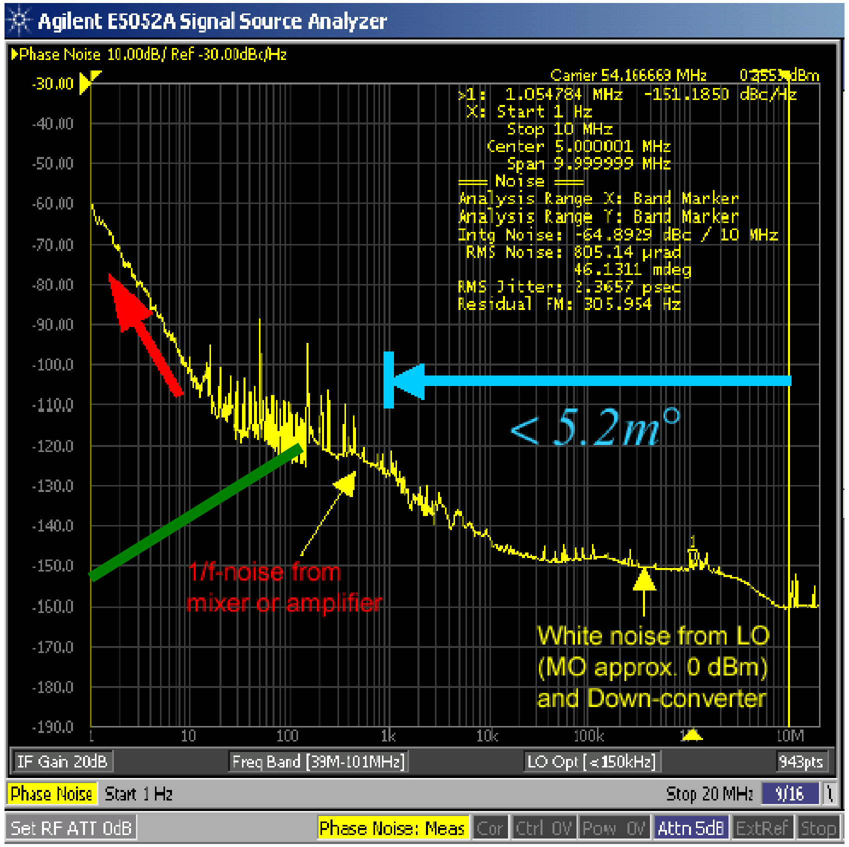
Single channel receiver performance at FLASH

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

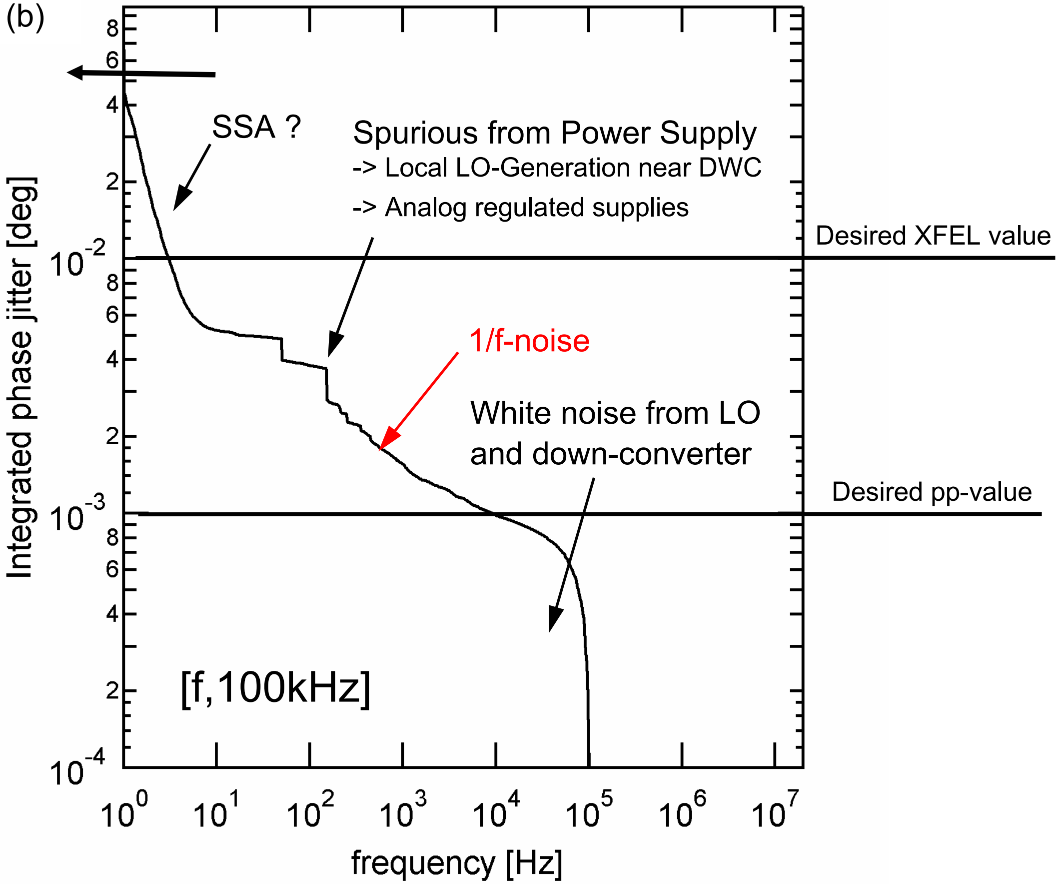
- Analog Receiver has 0.0052 deg [1kHz,10MHz].
- IF[9,54MHz] works also with a lowpass
- Powerful diagnostic using the CW modulation scheme!
- Drift calibration <100Hz is needed!
  (Injector door effect on LO) e.g. injected, reflected or
  LO or Beam-based feedbacks

Biased by MO reference :

(a)



(b)



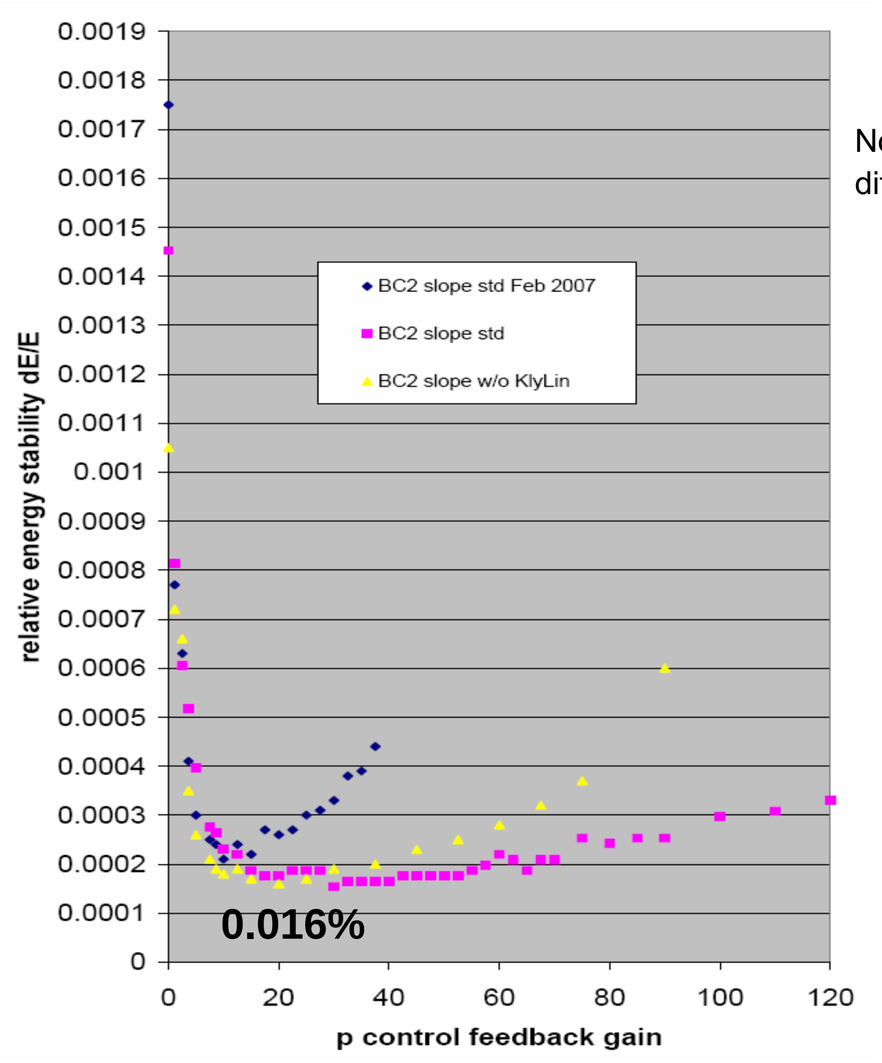
Main Parameters Table

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$

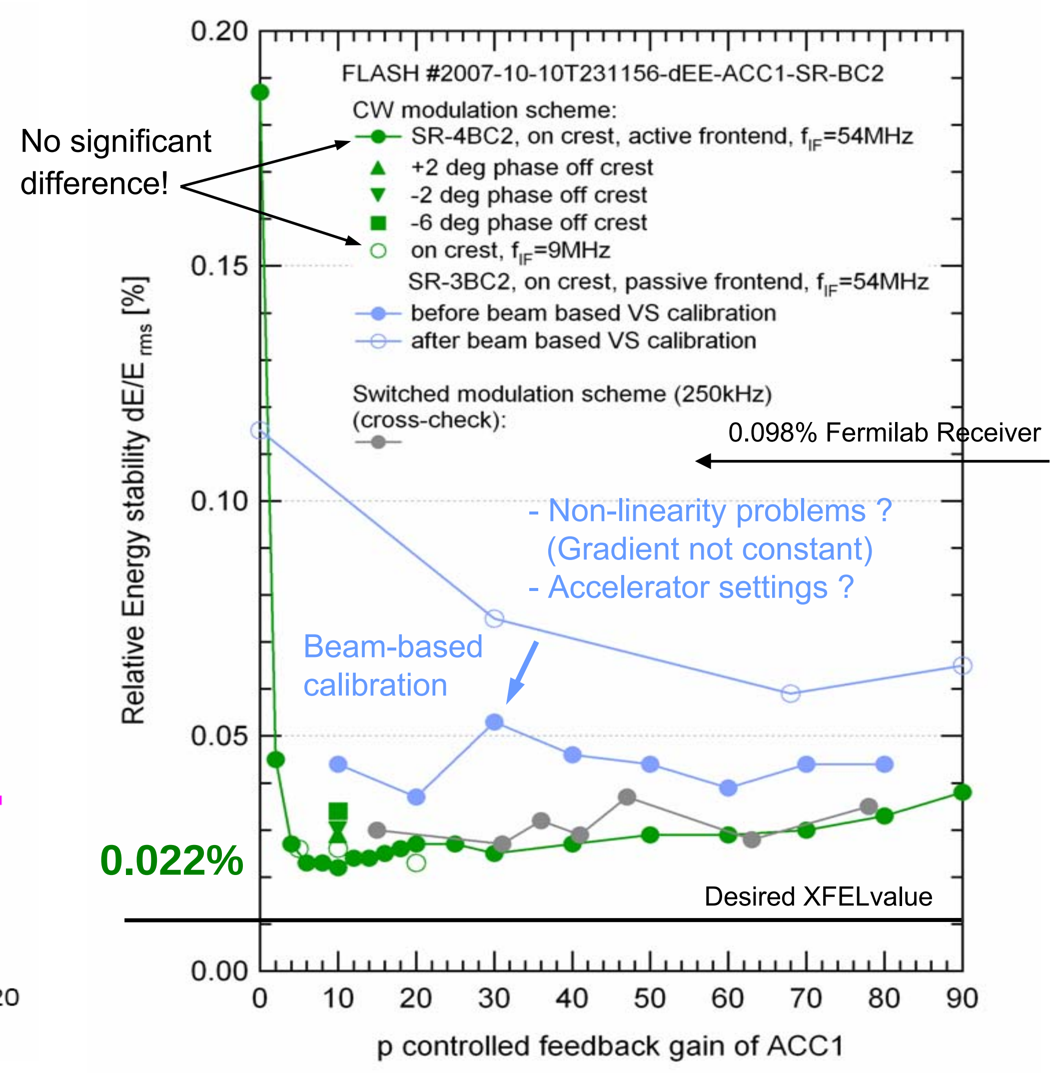
LLRF07 Fermilab

Courtesy of U.Mavric, B.Chase / FNAL

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

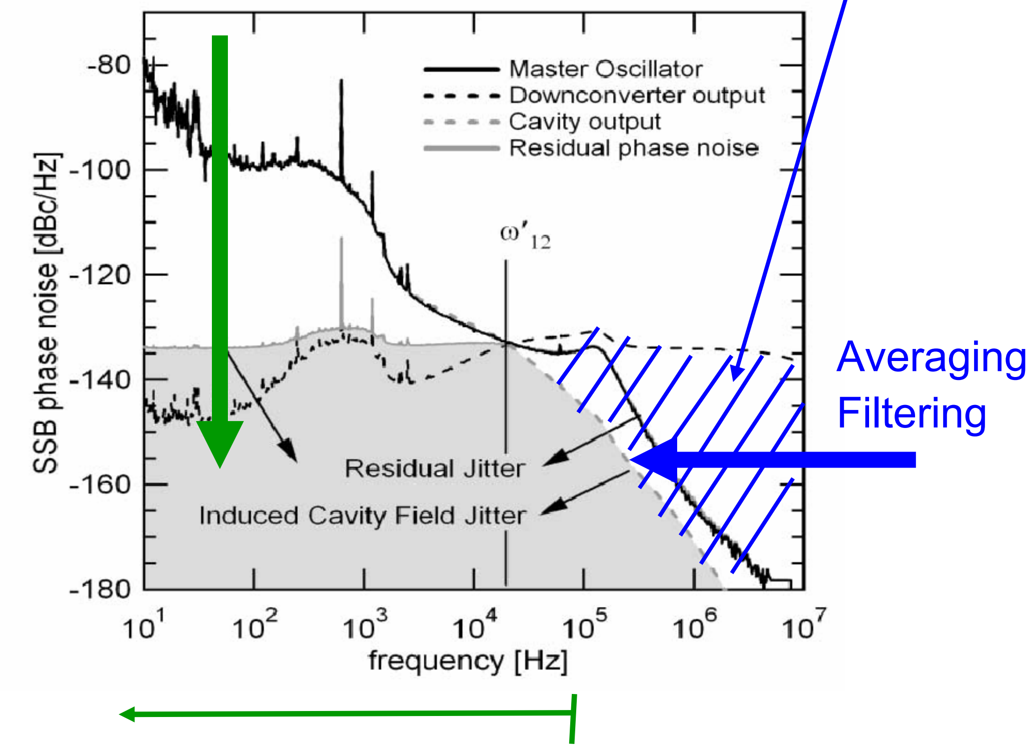


- **IF sampling down-converters (9,54MHz):**



„Beam performance“:
Increase SNR by
- Increasing input power
- Decreasing noise spectra density of the down-converter

„Display property for the operator“:
Noise appears at the DWC output but not on the cavity field!

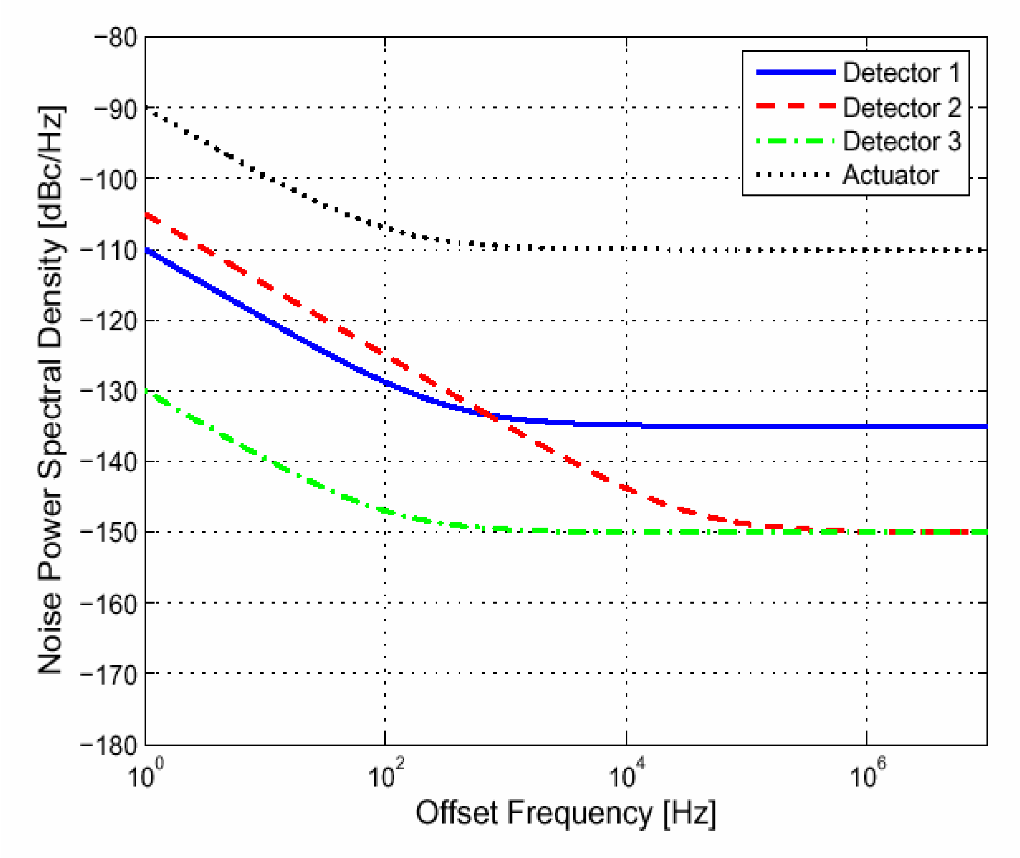


Effektive noise bandwidth for the beam jiter induced by the LLRF

- Automated beam-based calibration and fixed machine parameters

?

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



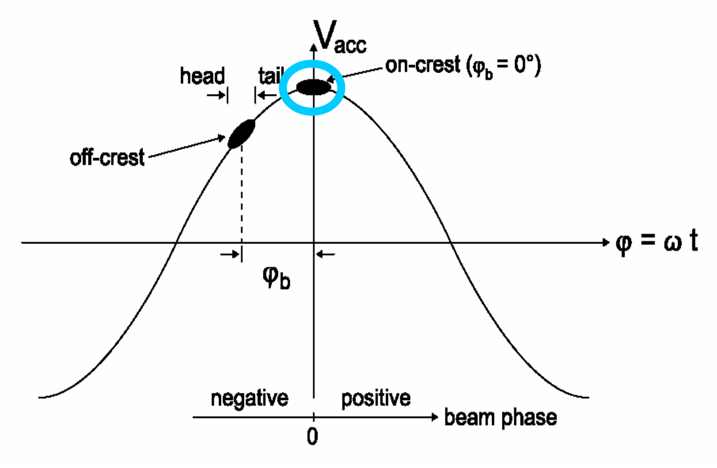
Detector 1 / FLASH:
- IQ Sampling 250kHz method
- Gibert-Mixer active AD8343
- ADC-boards (14-bit, 1MHz) + DSP System

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

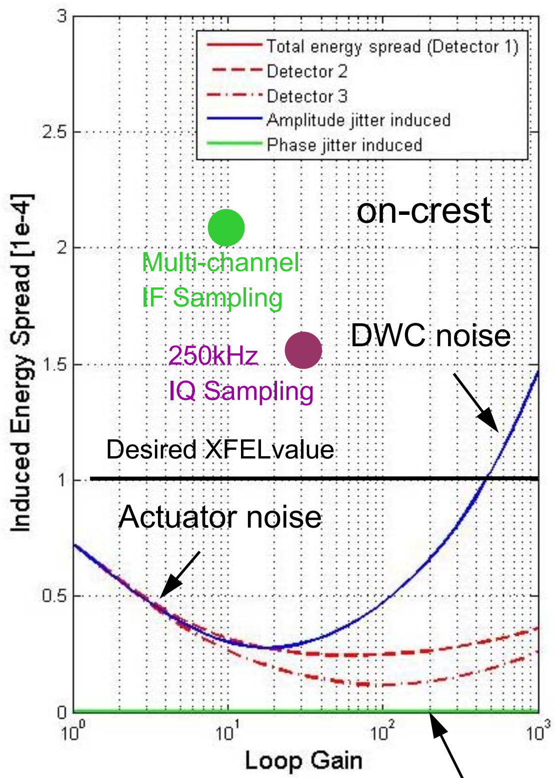
$$S_R(f) = b_{r,0} + b_{r,-1} \cdot f^{-1}$$
$$S_A(f) = b_{a,0} + b_{a,-1} \cdot f^{-1}$$

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

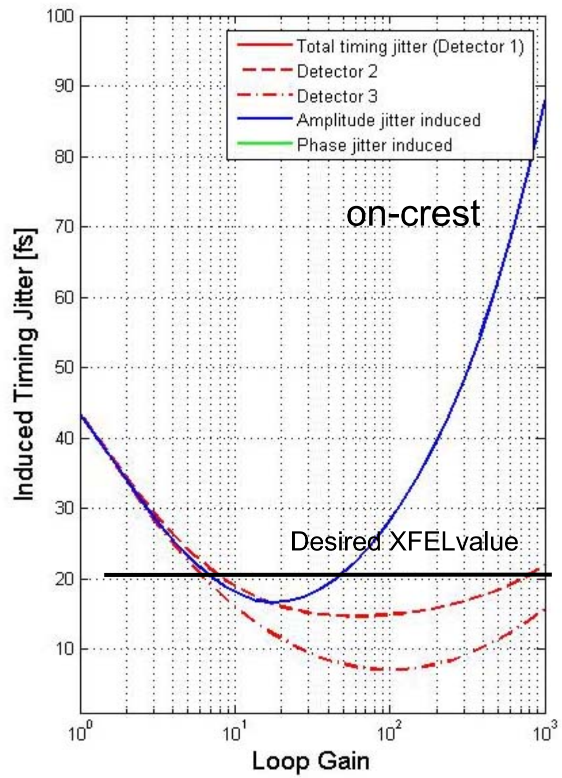
Simulation results



- **Beam energy spread :**



- **Beam timing jitter:**



No phase noise contribution

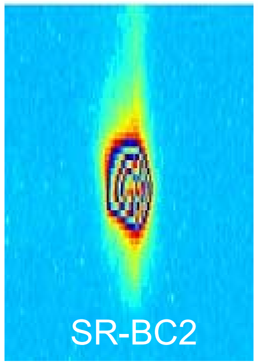
Residual cavity amplitude jitter

Beam phase

Energy spread :

$$\left(\frac{\sigma_E}{E}\right)^2 \cos^2\varphi_b = \frac{1}{2}(1+\cos 2\varphi_b)\left(\frac{\sigma_A}{A}\right)^2 + \frac{1}{2}(1-\cos(2\varphi_b))\,\sigma_\varphi^2 + \frac{1}{4}(3\cos(2\varphi_b)-1)\,\sigma_\varphi^4$$

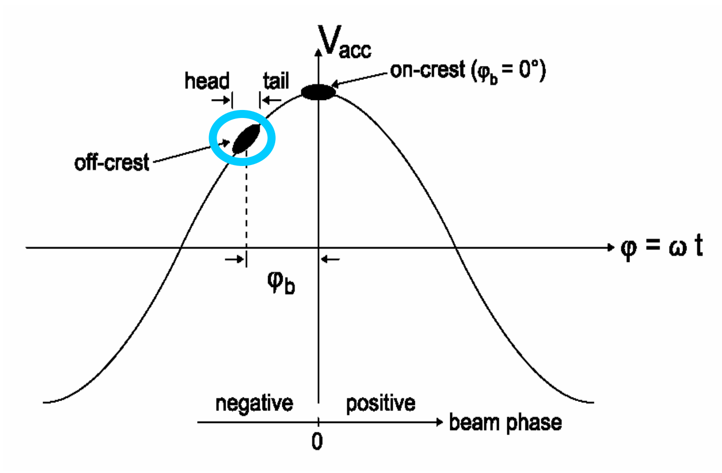
Residual cavity phase jitter



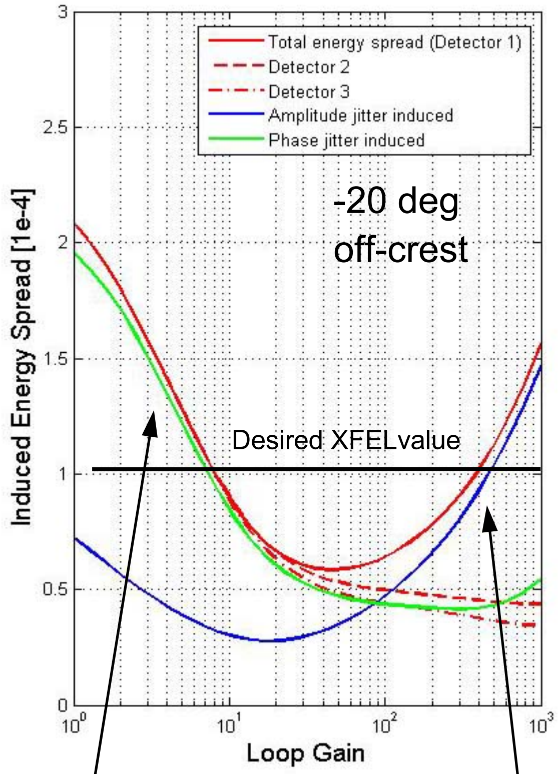
Arrival timing spread :

$$t_{j,\mathrm{out}}^2 \approx \left(\frac{R_{56}}{c_0}\frac{\sigma_A}{A}\right)^2 + \left(\frac{C-1}{C}\right)^2\left(\frac{\sigma_\varphi}{c_0 k_{\mathrm{rf}}}\right)^2 + \left(\frac{1}{C}\right)^2 t_{j,\mathrm{in}}^2$$

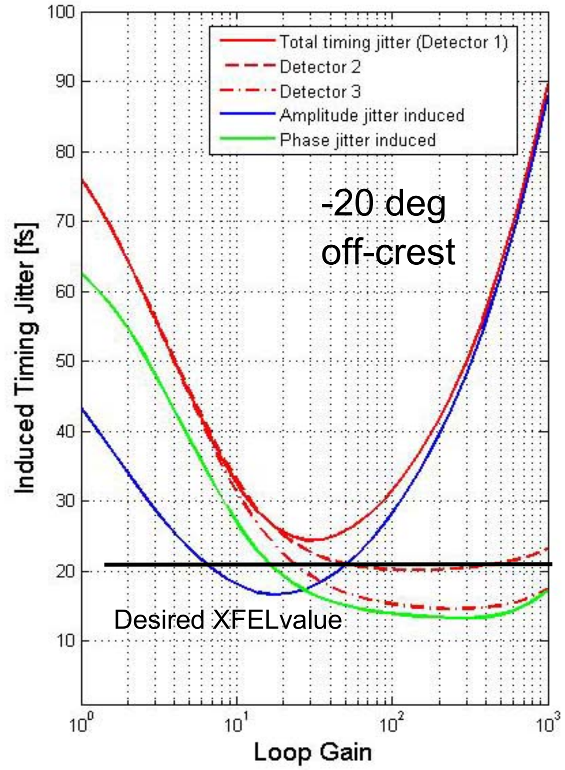
Sources of field perturbation



- **Beam energy spread :**

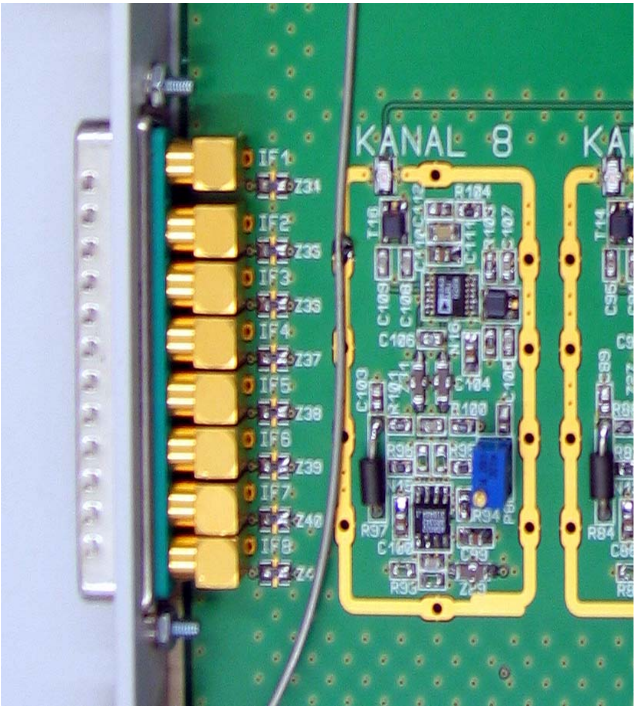


- **Beam timing jitter:**

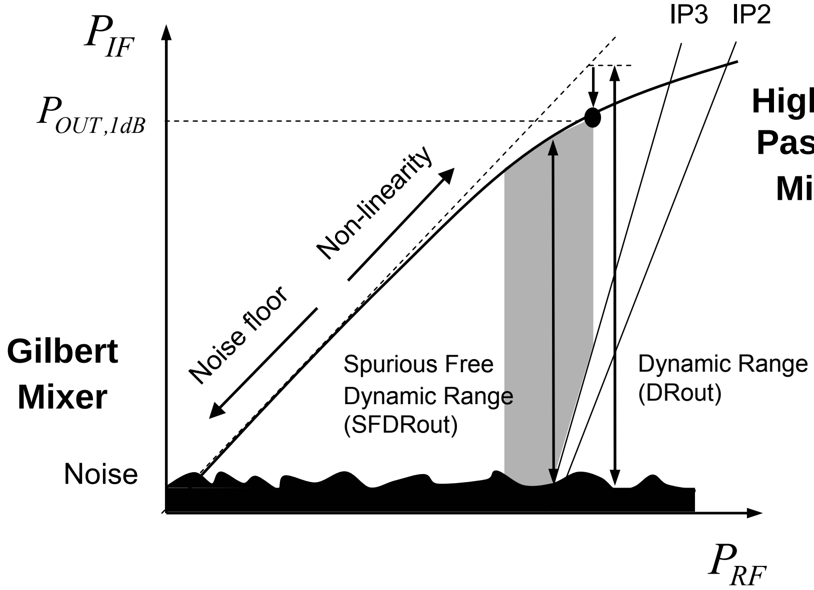


Actuator phase noise ⟷ Down-converter amplitude noise (Mainly caused by ADC)

- 1/f-noise and white noise level of the down-converter have to be improved with low latency
- For off-crest operation, phase noise is much more critical than amplitude noise.



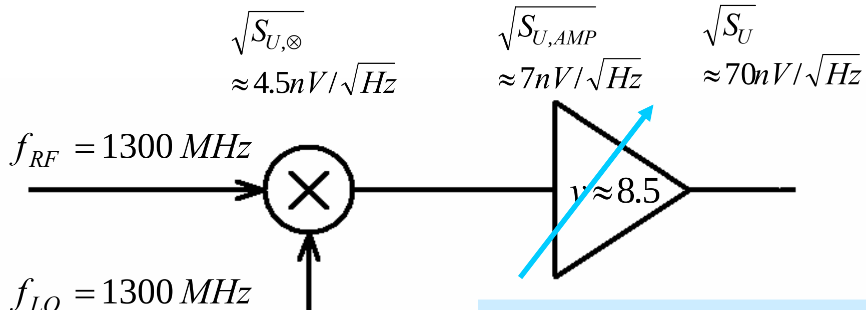
● **Compromise between noise and linearity :**



- 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)

$\Delta f = 100kHz,$

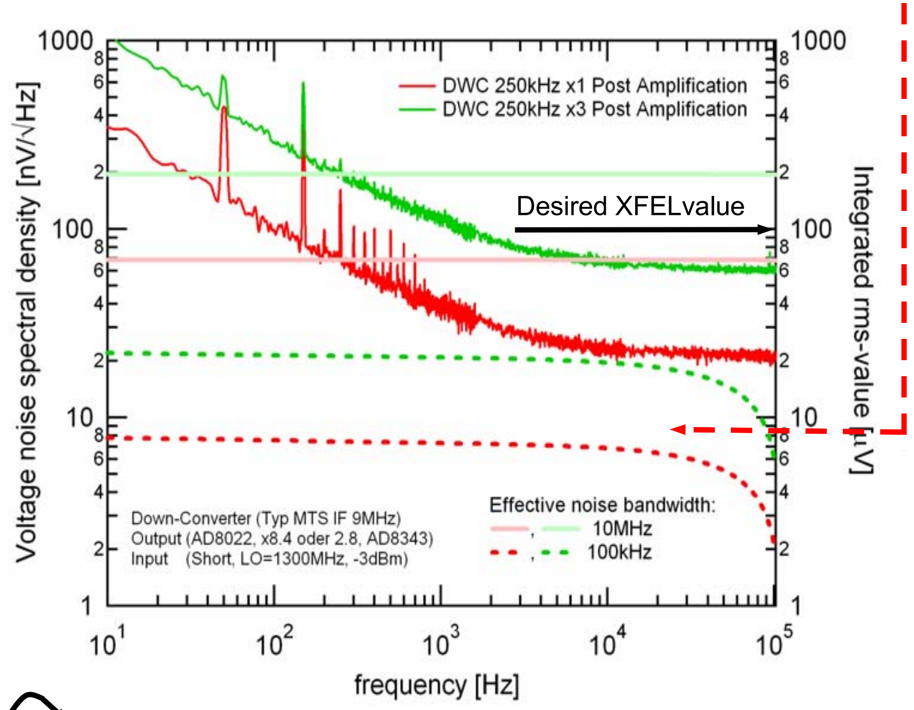


$$S_U = (S_{U,\otimes} + S_{U,AMP})\, v^2$$

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

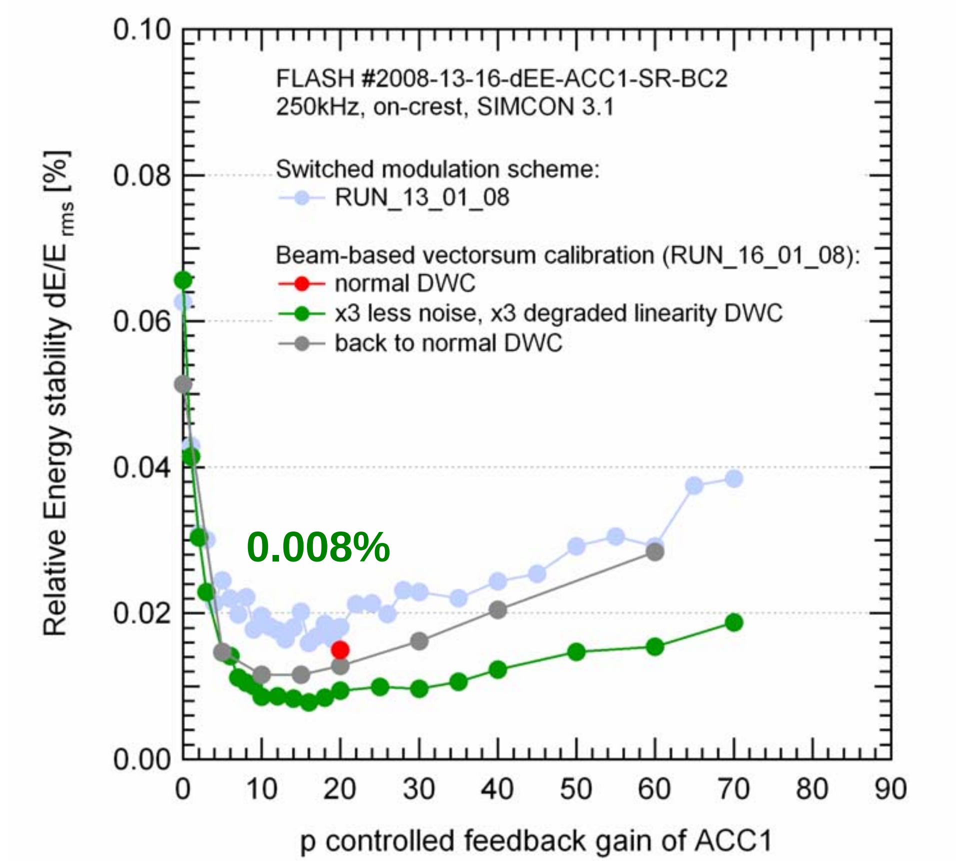
- **Modified DWC performance :**

  - 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%



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

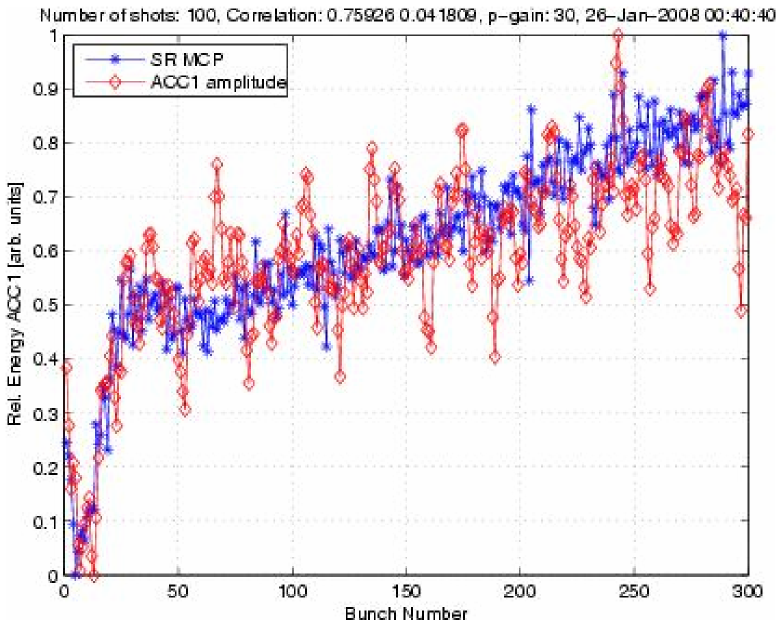
- **Pulse-to-Pulse Beam Stability :**

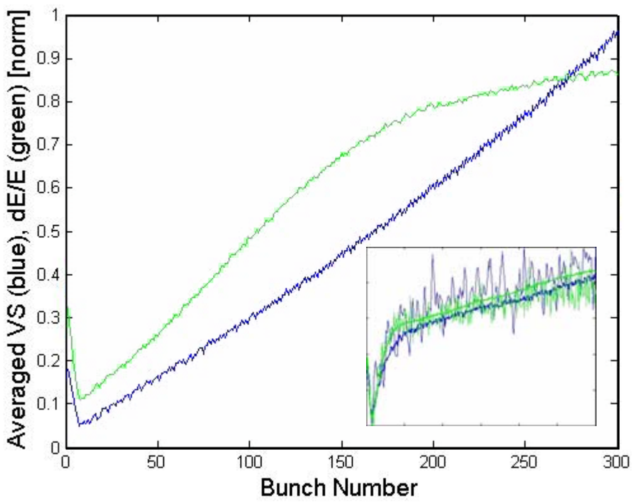


- 0.008% on-crest beam stability is achieved.
- The DWCs non-linearity has no influence on beam stability for fixed machine parameters.
- DWC is not the limiting factor.

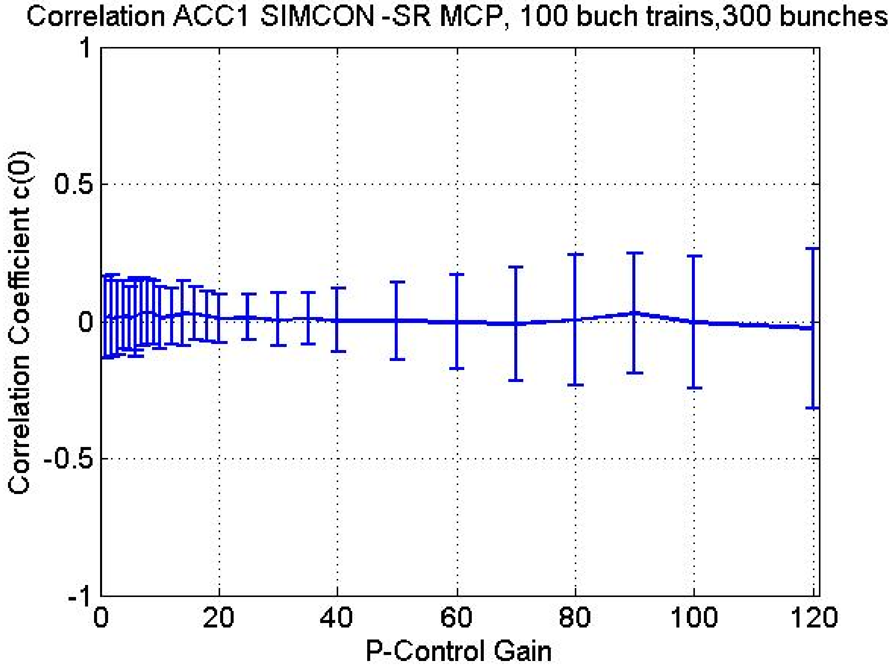
Correlation measurements between vectorsum and beam fluctuations

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





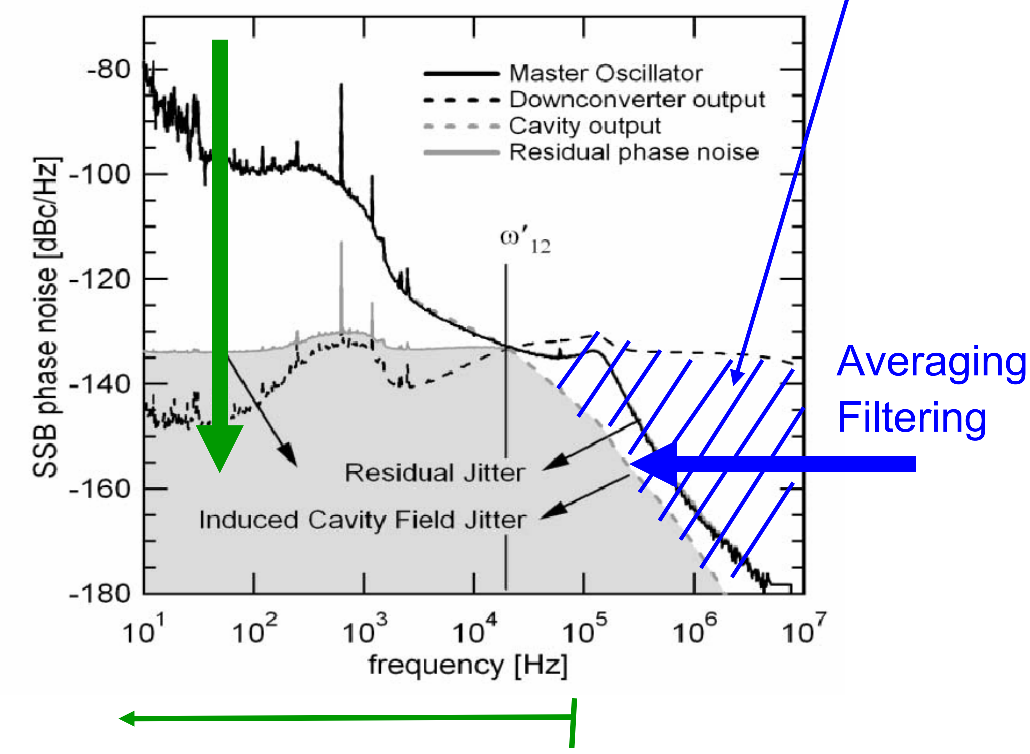
- **Feedback gain dependent correlation :**



- 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.

„Beam performance“:
Increase SNR by
- Increasing input power
- Decreasing noise spectra density of the down-converter

„Display property for the operator“:
Noise appears at the DWC output but not on the cavity field!



Effektive noise bandwidth for the beam jiter induced by the LLRF

- Imrove monitor resolution (SR 3E-5 (fine), MCP ?, BAM ?)
- Automated beam-based calibration (ok)
- Accurate waveguide adjustment
- Passive High IP3 mixers (1.3GHz, 3.9GHz)
- 1/f-noise and drifts from LO, IQ Driver
- Drift calibration (LO, injected or reflected)
- ADC limitation -> Multiple IF (KEK)
  -> bypass the ADC/P/DAC

- Further test at FLASH:
- ACC1 RF-phase, gradient sweep
- DWC, LO characterization biased by MO
- DWC, LO lab characterization biased by MO

- 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

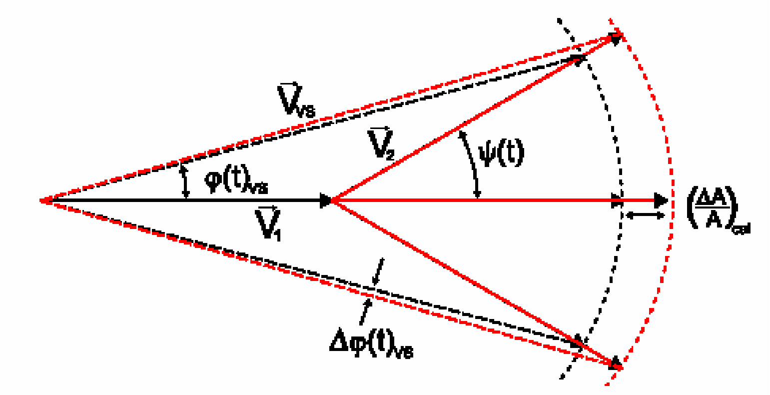
Thanks for your attention!

* Linearity requirement for multi-cell cavity structures

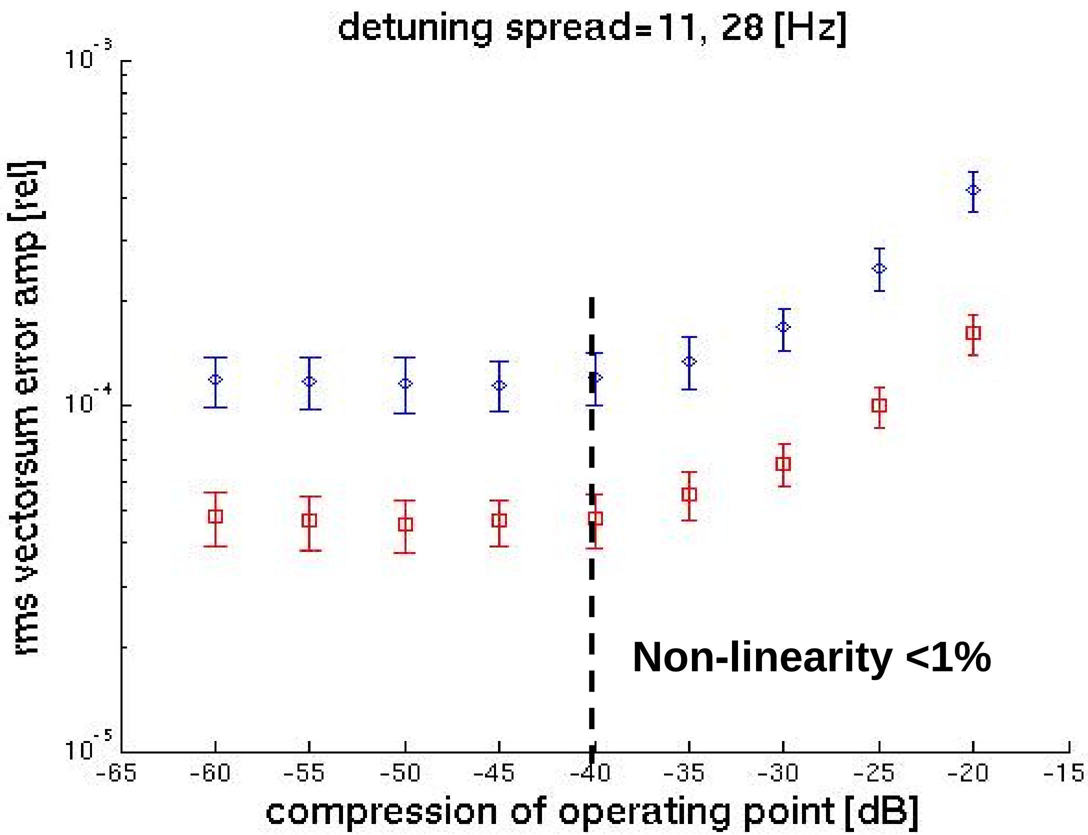
End of Discussion

Backup Slides

- **Effect on the vectrorsum:**



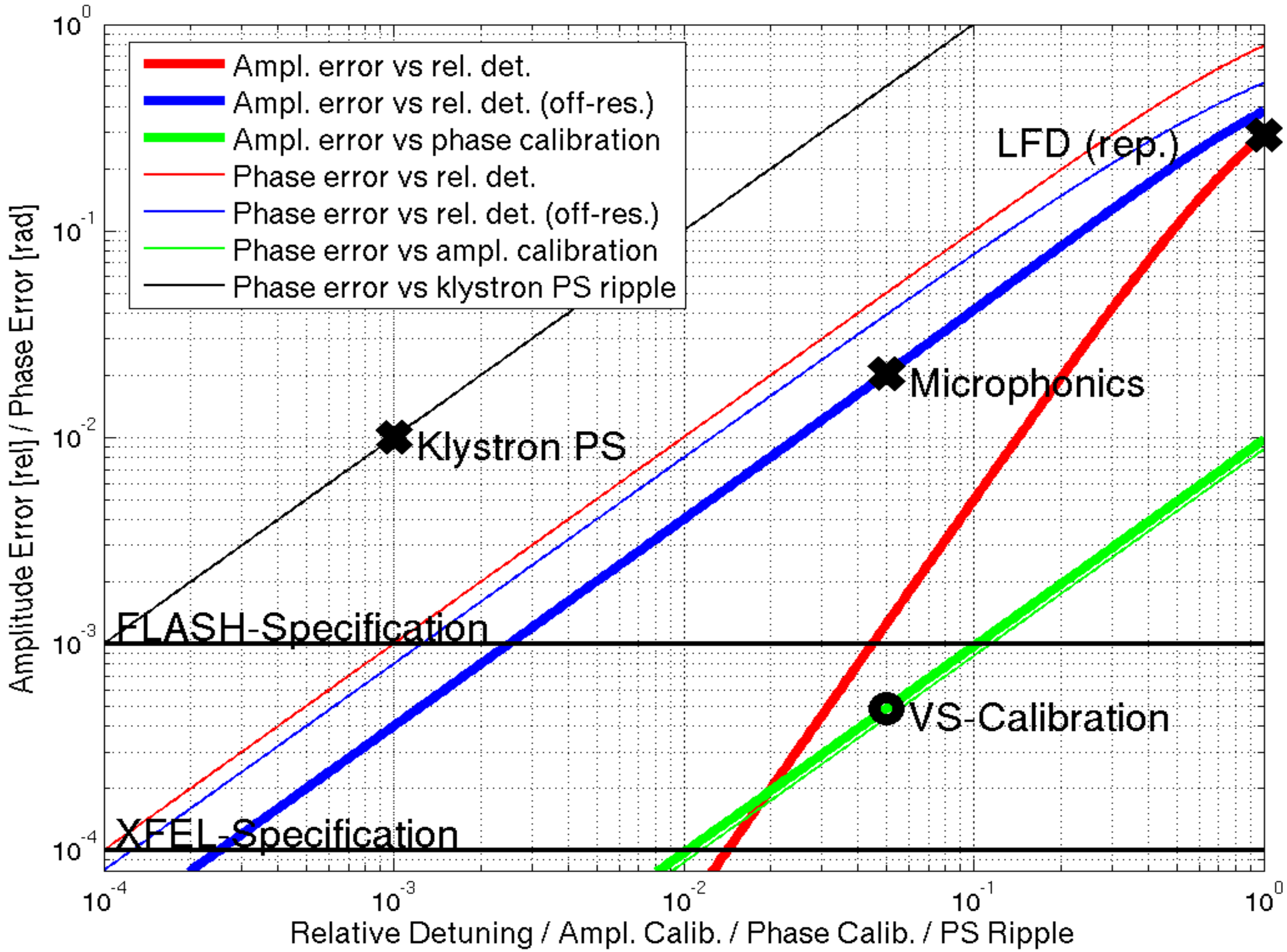
Number of cavities: 32, Predetuning: 50 Hz,
Detuning-Spread: 11 Hz, 28 Hz
Amp. cal. error: 0.005, Phase cal. err.: 0.5°



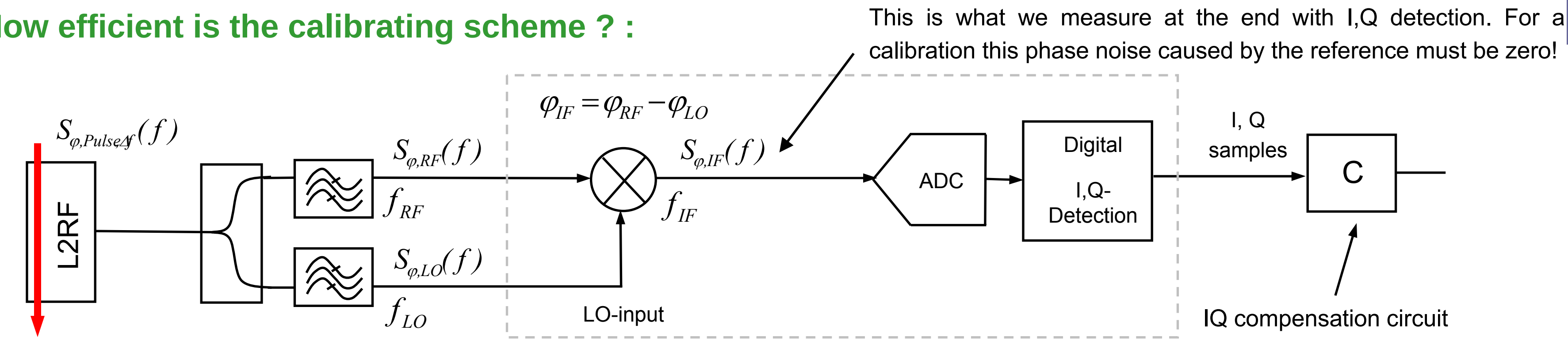
In presence of a vectorsum calibration error microphnics induces additional noise.

Courtesy of A.Brandt / DESY

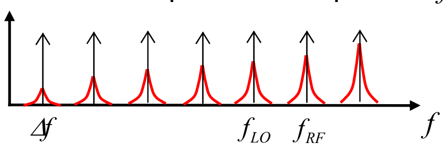
Sources of field perturbation



How efficient is the calibrating scheme ? :



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



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

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

Operation of mixer (down-converter) :

$$\varphi_{IF}(t) = \varphi_{RF}(t) - \varphi_{LO}(t),\quad f_{IF} = f_{RF} - f_{LO}$$

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

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

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

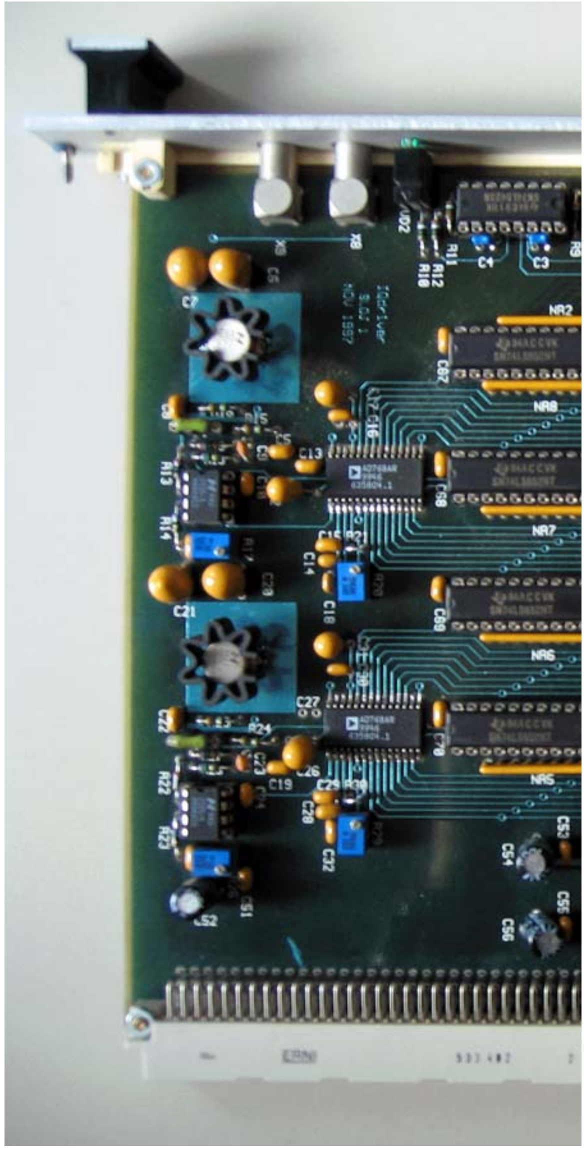
$$S_{\varphi,IF}(f) = S_{\varphi,LO}(f)\left(\frac{f_{RF}}{f_{LO}} - 1\right)^2 = S_{\varphi,LO}(f)\left(\frac{f_{IF}}{f_{LO}}\right)^2 \overset{!}{=} 0$$

For a perfect calibration!

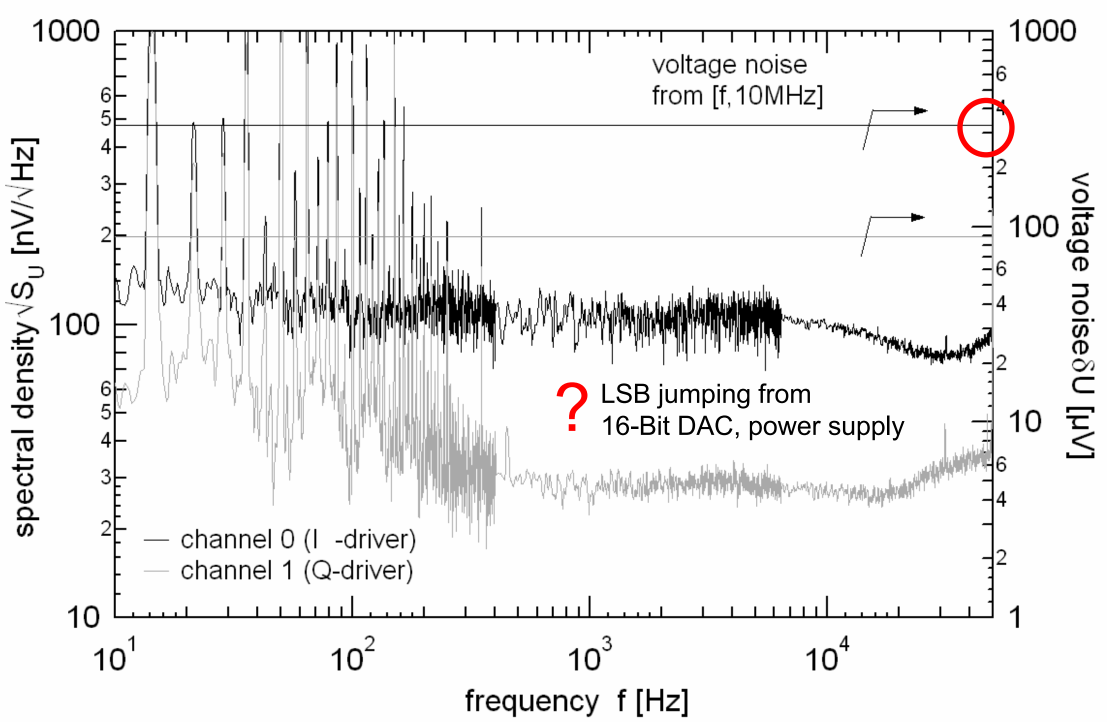
For the actual DWC structure a calibration is only possible in the baseband with $f_{IF} = 0$ .The drifts caused by the reference are reduced by a factor of f_{IF}/f_{LO}.

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.



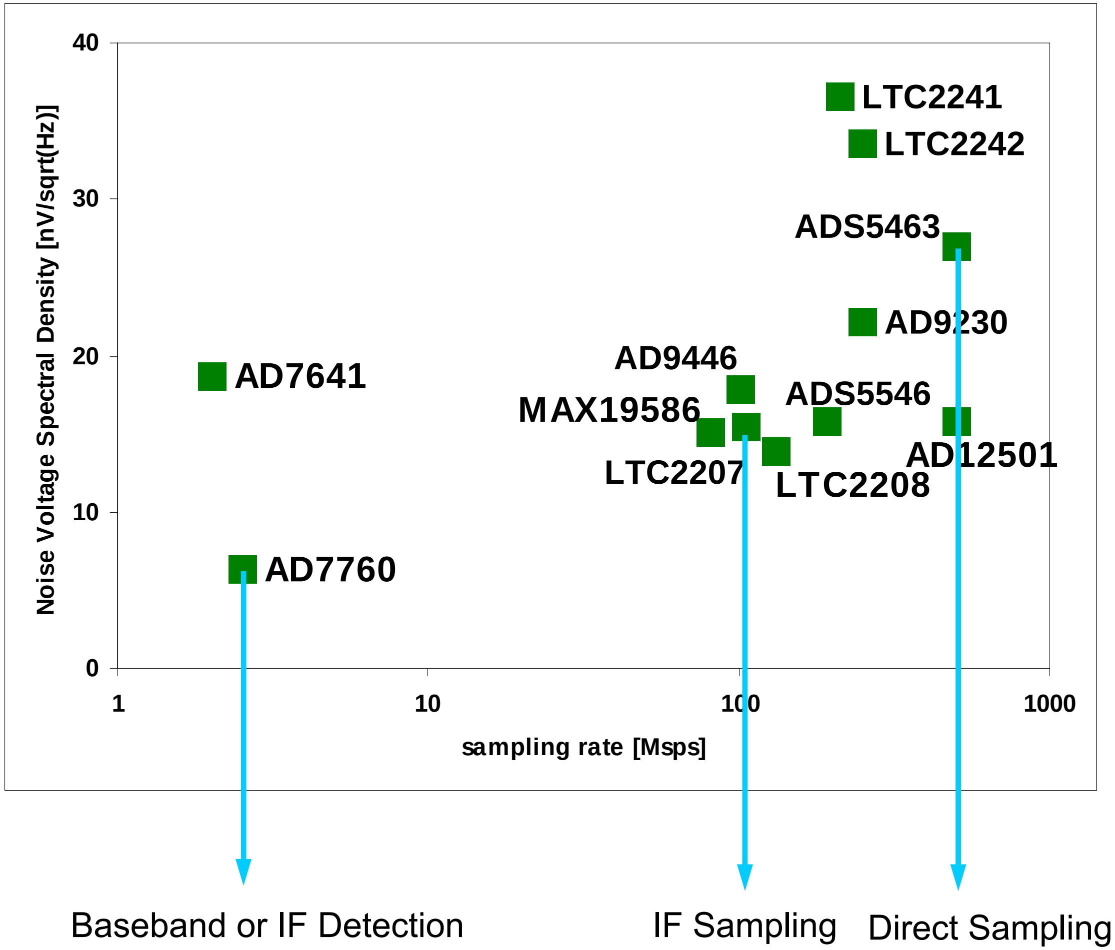
- **Noise from IQ-driver modul :**



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

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

- **ADC equilvalent noise spectral density :**



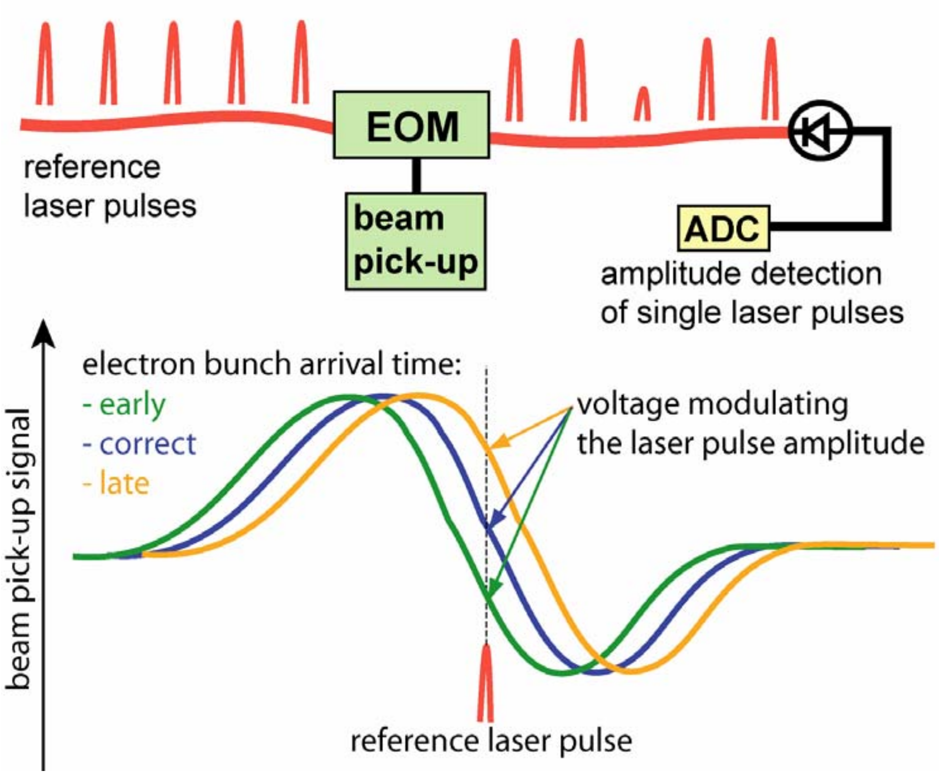
$$e_n = \frac{V_{FS,pp}}{\sqrt{8}} 10^{\frac{SNR(f_s,\varepsilon)}{20}} \sqrt{\frac{2}{f_s}}$$

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

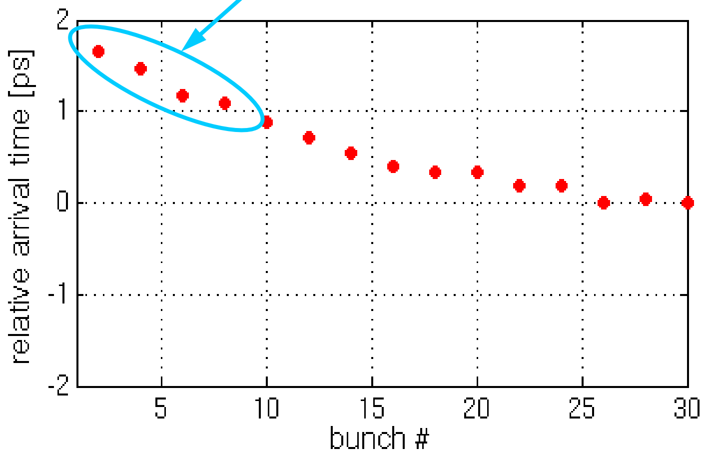
A lot of available ADCs have roughtly the same performance.

Bunch-to-bunch beam stability

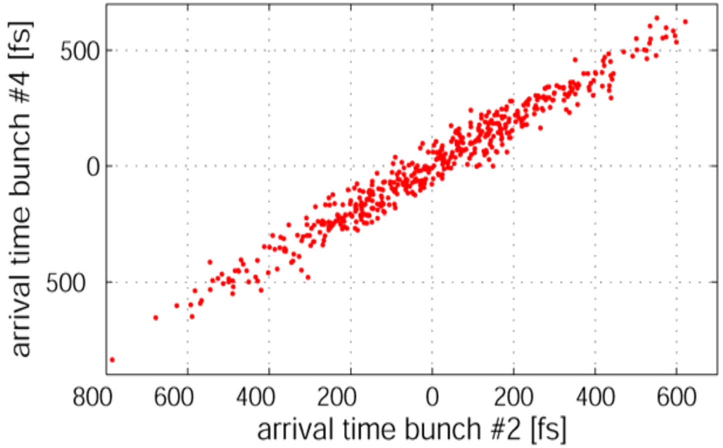
- **Bunch-Arrival Monitor :**



Short-term fluctuation
are filtered by the cavity.

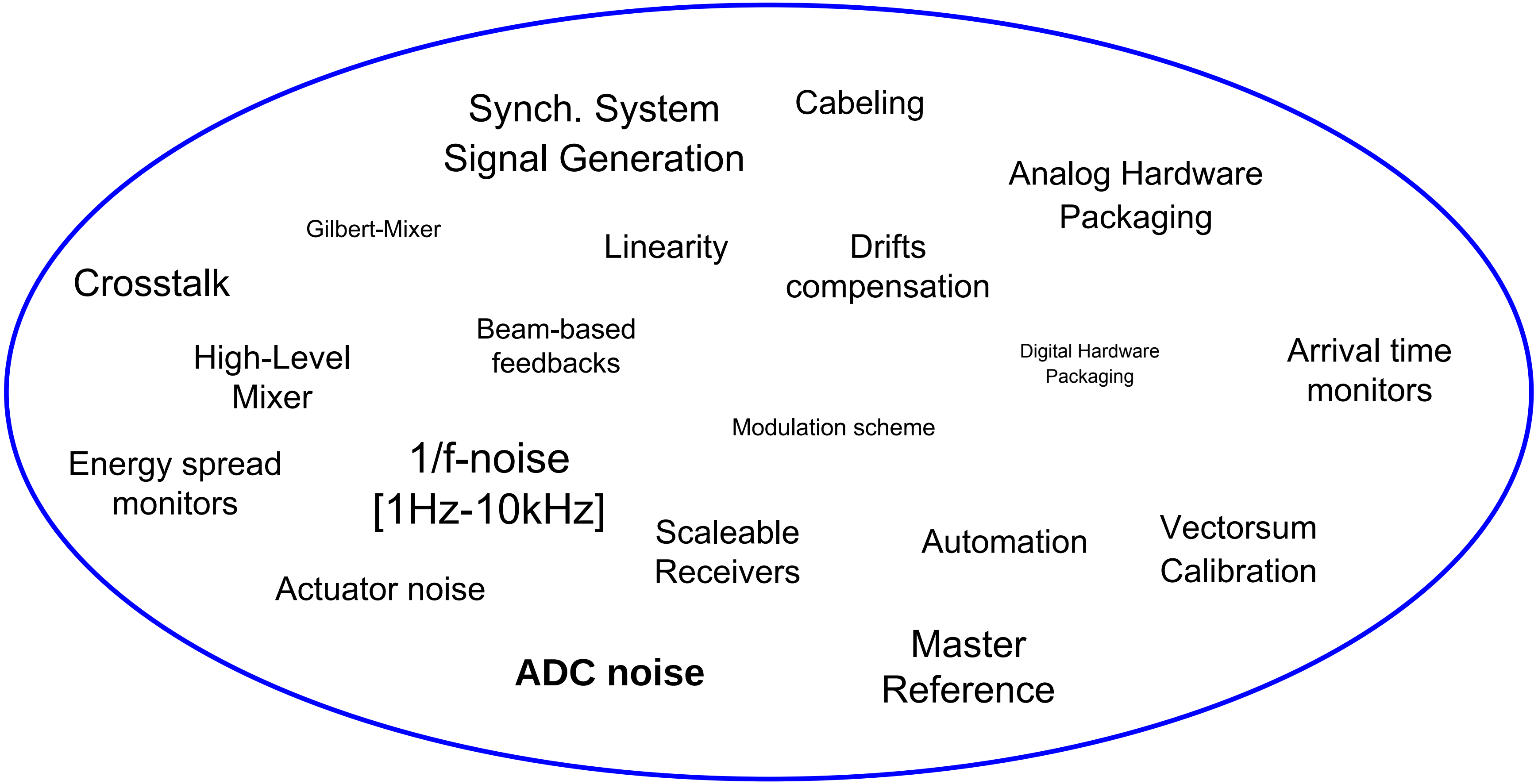


- Single bunch resolution better 30fs
- Synchronization problems



Courtesy of F.Loehl / DESY

Beam stability measurements

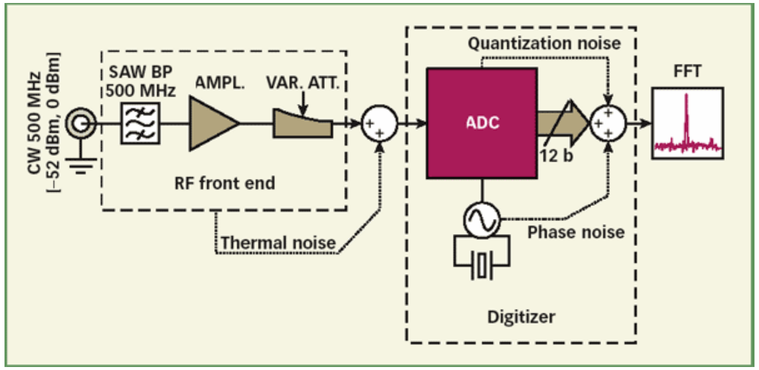


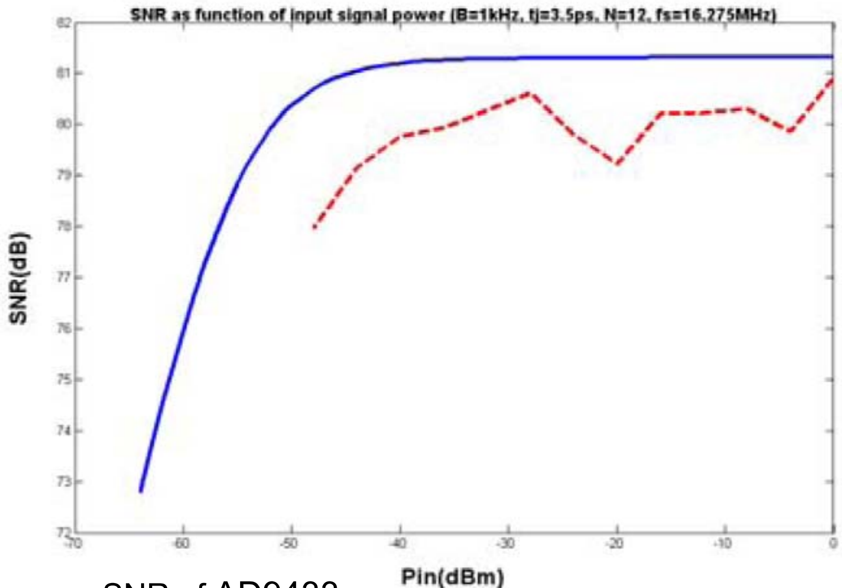
What is most important for a beam stability significantly lower than 0.01% ?

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

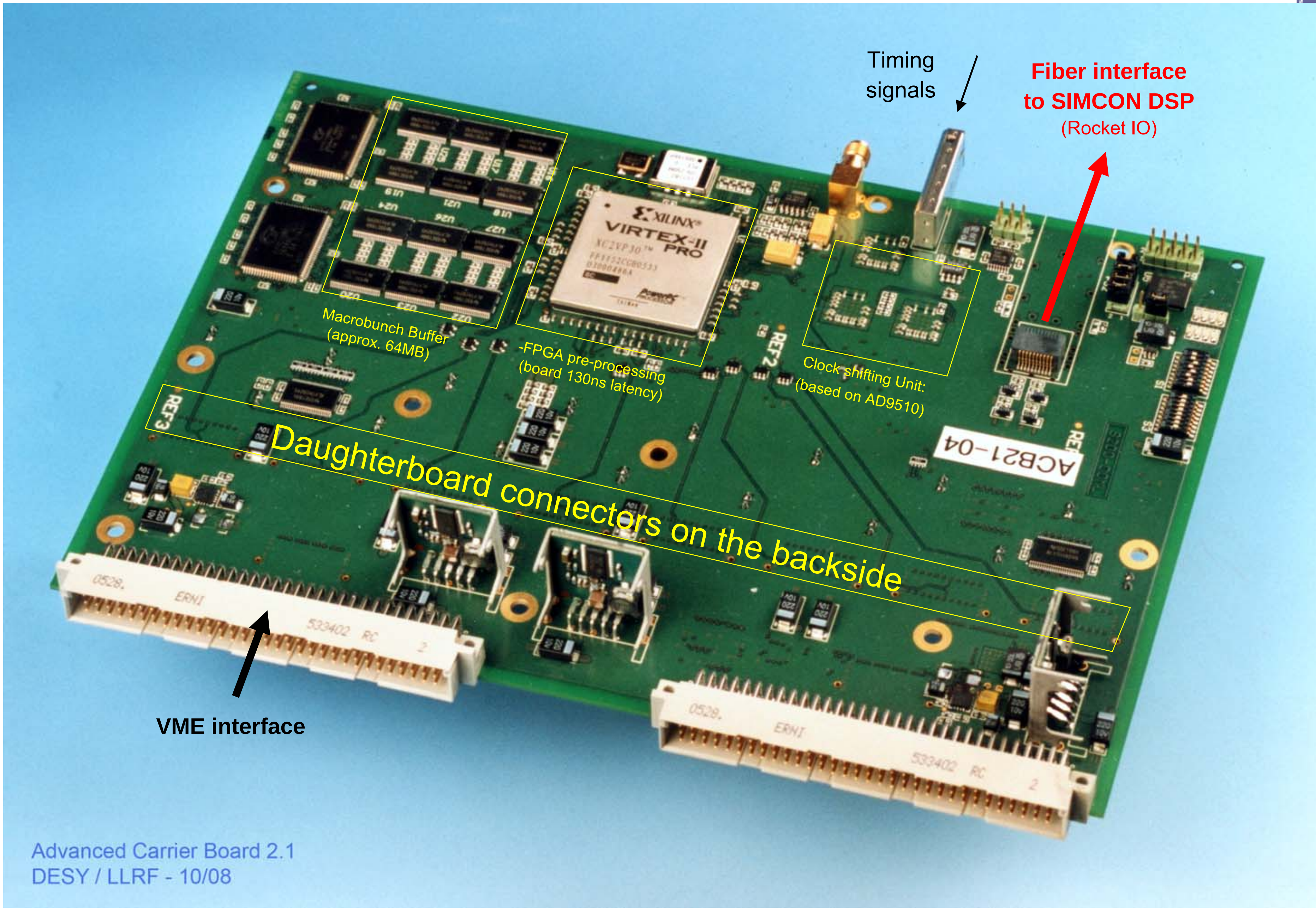
Courtesy of U.Mavric / FNAL





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

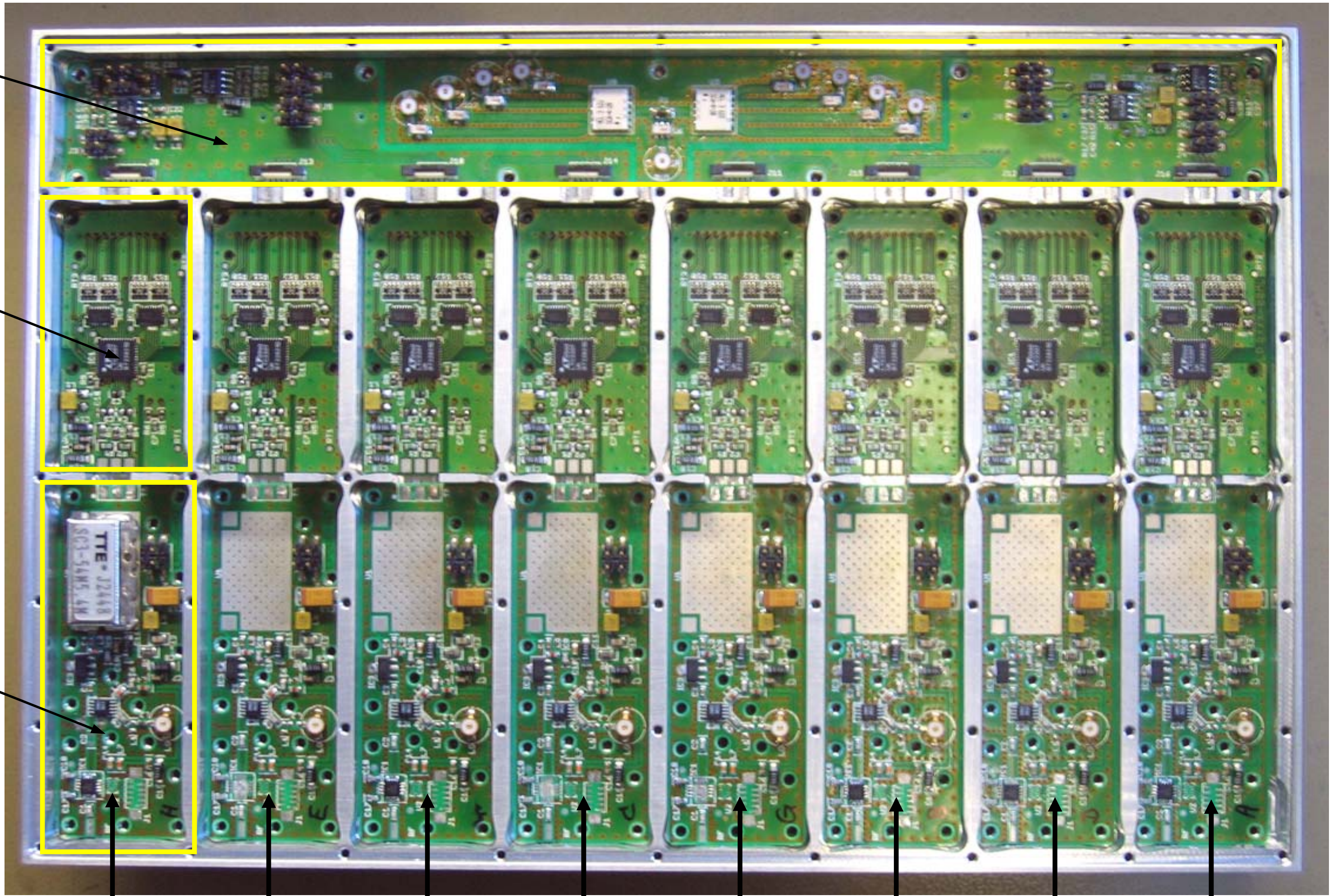
End of Discussion


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 Packaging and Preprocessing

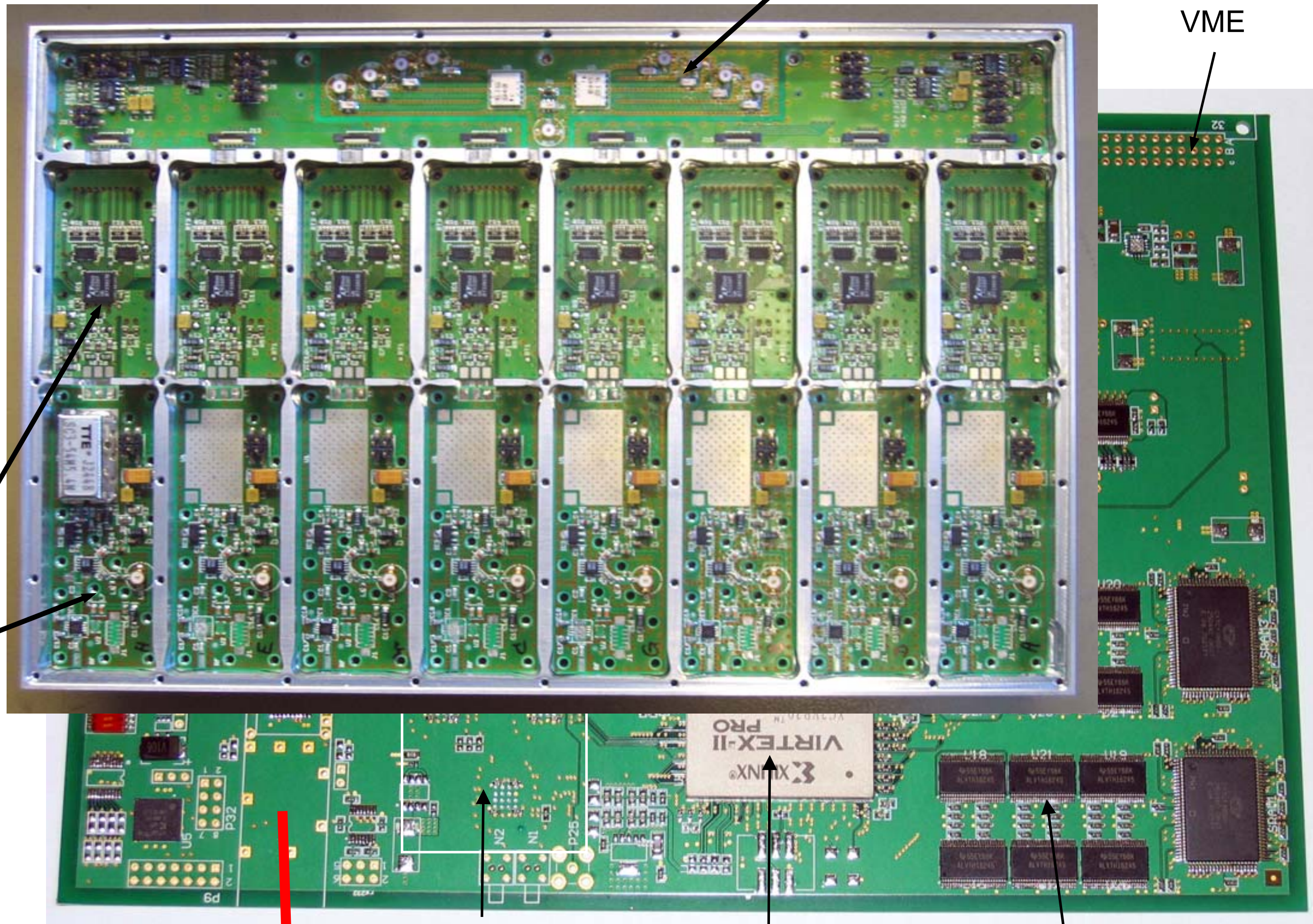
Multichannel Receiver frontend + fast ADC board for prototype testing :
(DWC2.0, BAM1.0)

- 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)

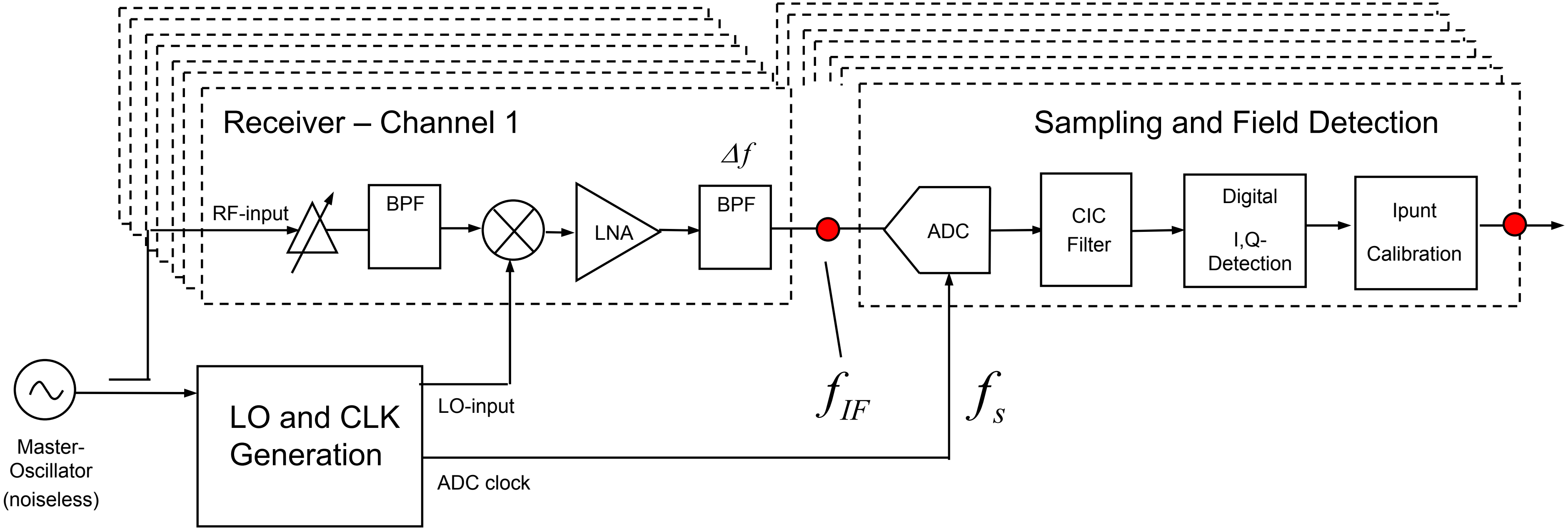
Fiber interface to SIMCON DSP (approx 400ns delay)

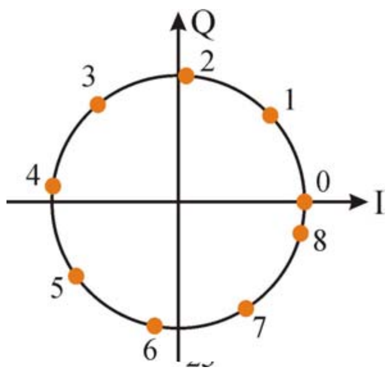
Clock shifting Unit:
(based on AD9510)

-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:

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

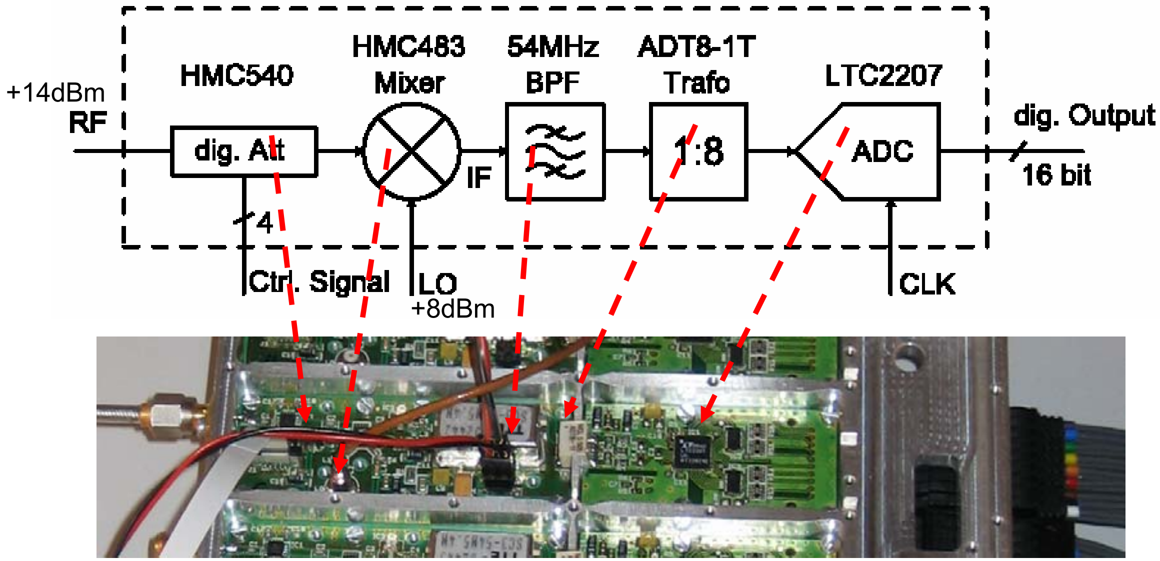
$$I = \frac{2}{N} \cdot \sum_{i=0}^{N-1} y_i \cdot \sin(i \cdot \Delta\varphi)$$

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

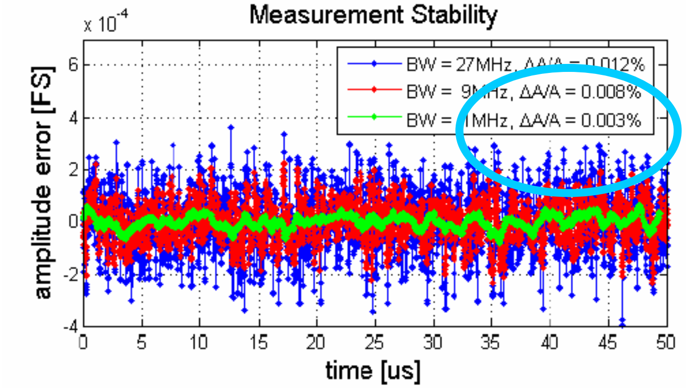
Single channel passive IF sampling down-converter

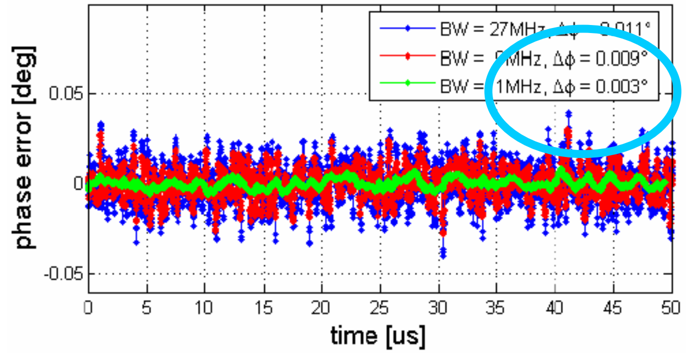
- **Laboratory performance :**

	Att.	Mixer	BPF	Trafo	ADC	System
NF [dB]	1	11	3	1	35	41
IIP3 [dBm]	48	36	35	35	/	36
G [dB]	-1	-11	-3	9	/	-6

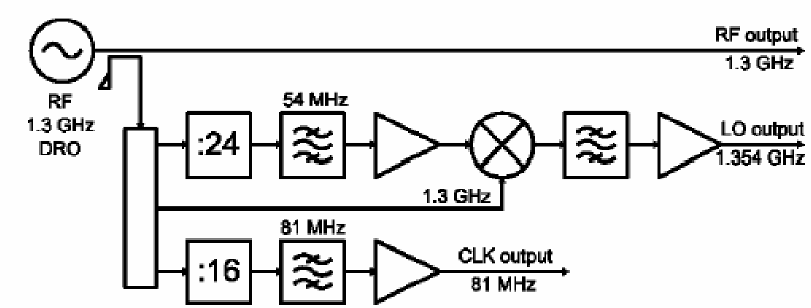


- **Shortterm stability :**





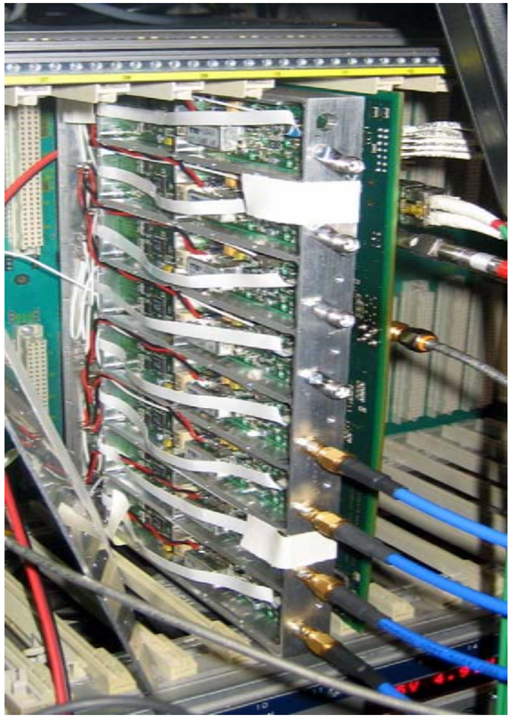
- **LO and CLK Generation setup :**



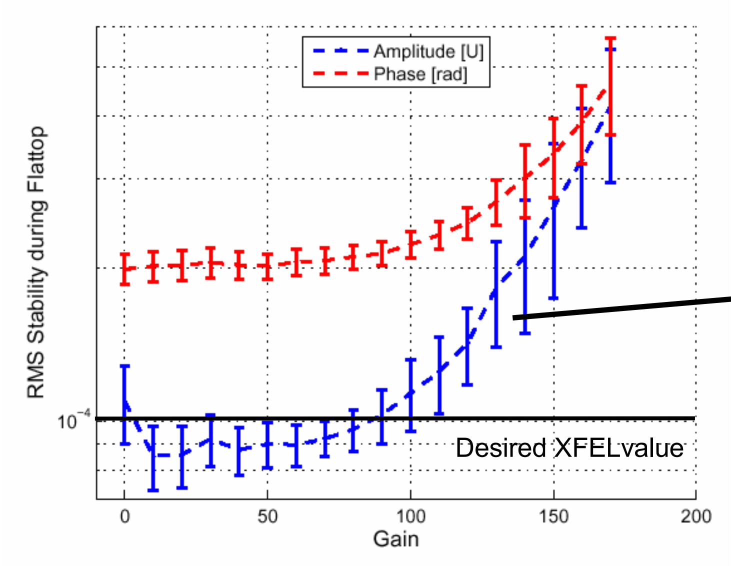
Shortterm stability (1MHz Bandwith) :
θ_A = 3E-3, θ_P = 3m°
Drift stability :
θ_A = 3e-3/°C, θ_P = 0.2°/°C

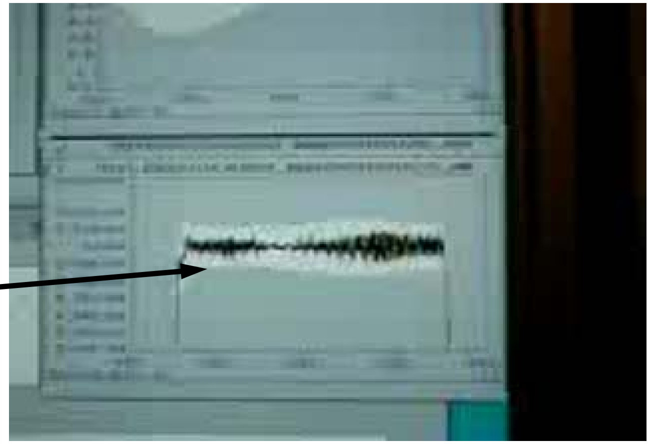
Receiver performance at FLASH

- **FLASH injector :**



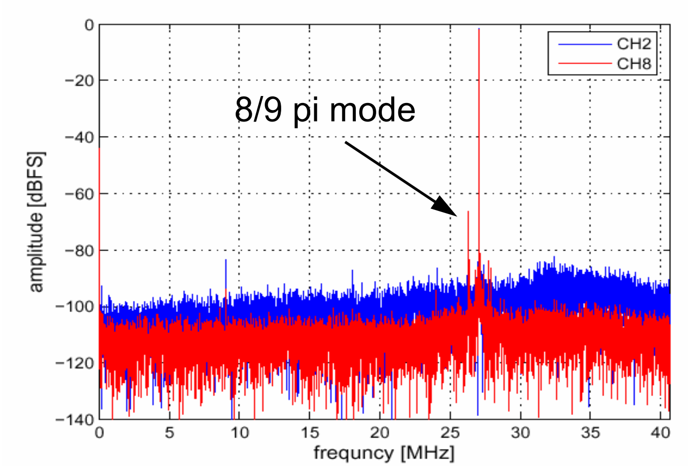
- **Vectorsum stability with closed control loop at ACC1:**





Instability caused by 8/9pi mode

Down-converter biased by Cavity pickup :

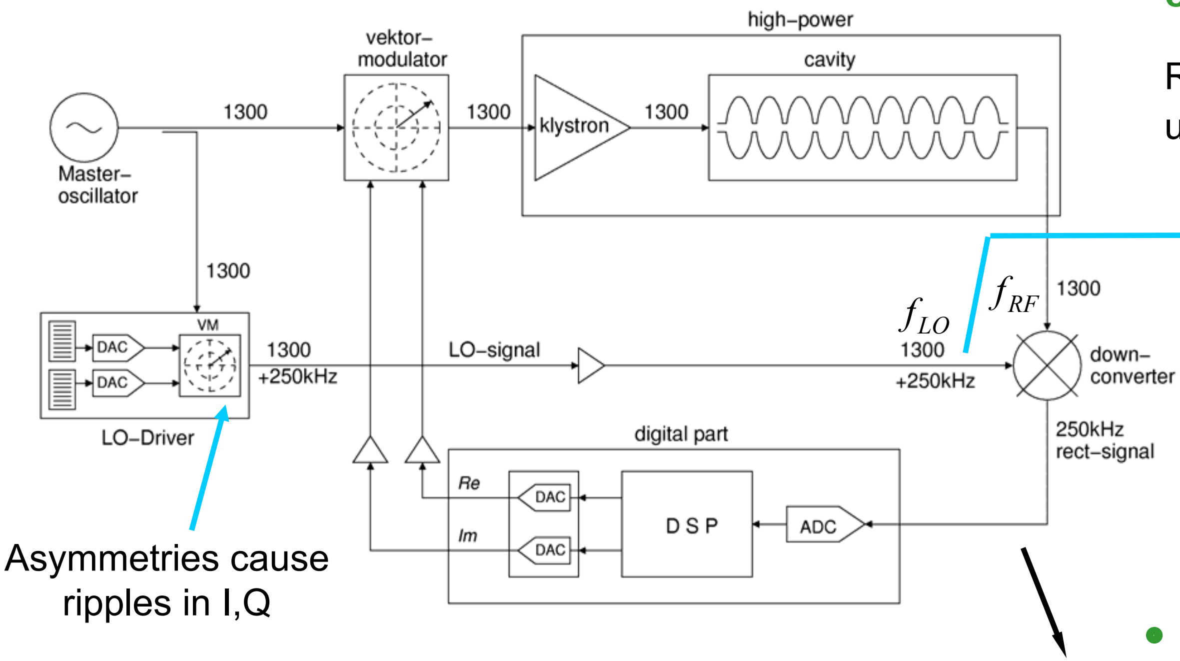


	CH1	CH2	CH3	CH4	CH5	CH6	CH7	CH8
$\Delta A/A\ [10^{-4}]$	3.8	5.8	5.1	4.1	2.8	4.1	2.1	3.6
$\Delta\varphi$ [deg]	0.028	0.038	0.035	0.033	0.025	0.032	0.022	0.032
$\Delta A/A\ [10^{-4}]$	2.1	2.5	1.9	1.6	1.0	1.5	0.9	1.5
$\Delta\varphi$ [deg]	0.016	0.019	0.018	0.021	0.016	0.020	0.015	0.019

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

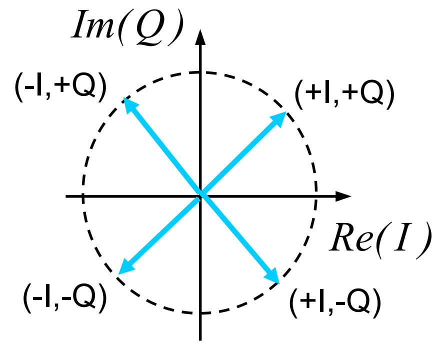
IQ sampling scheme in practice

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

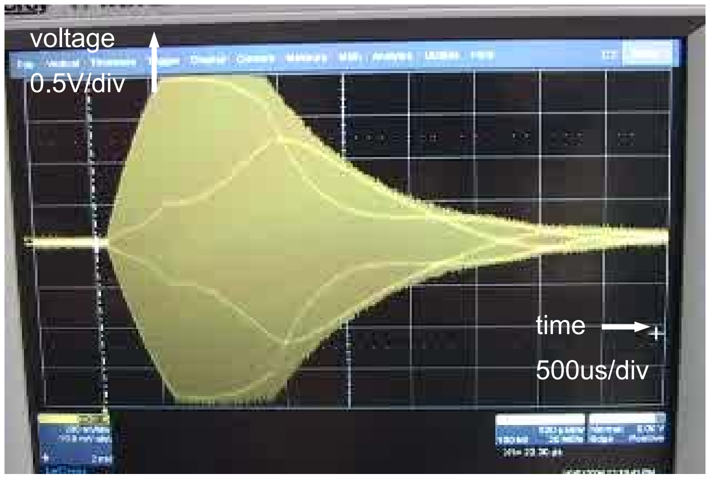


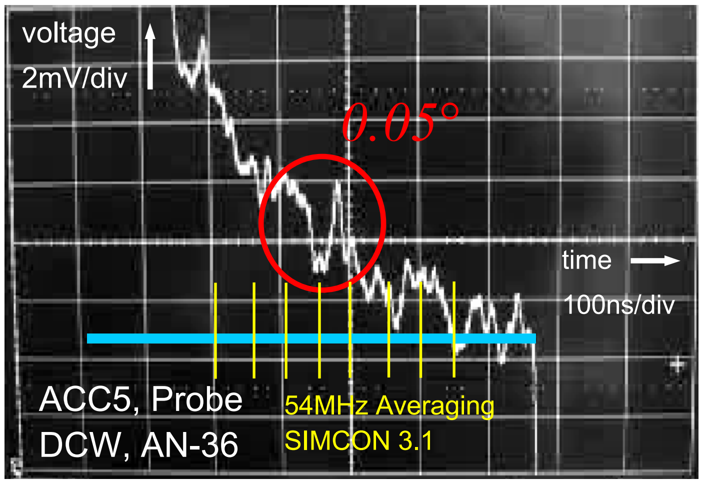
- **Phase and amplitude detection of the cavity field vector :**

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



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





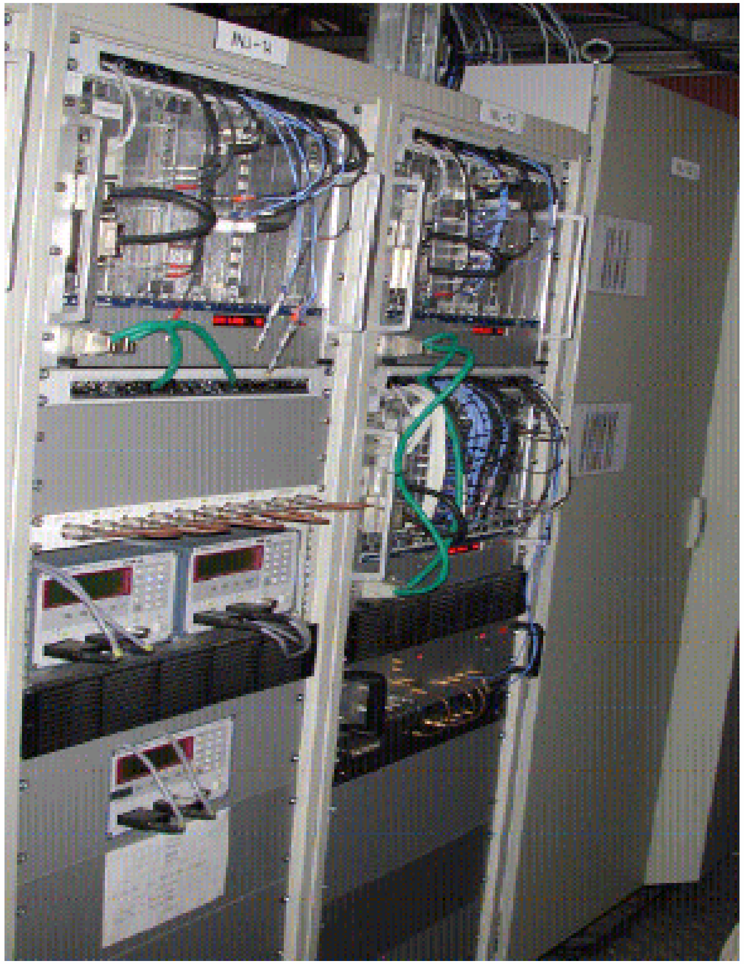
Bandwidth for transforming 250kHz squared pulses :

$\Delta f \approx 10 MHz$

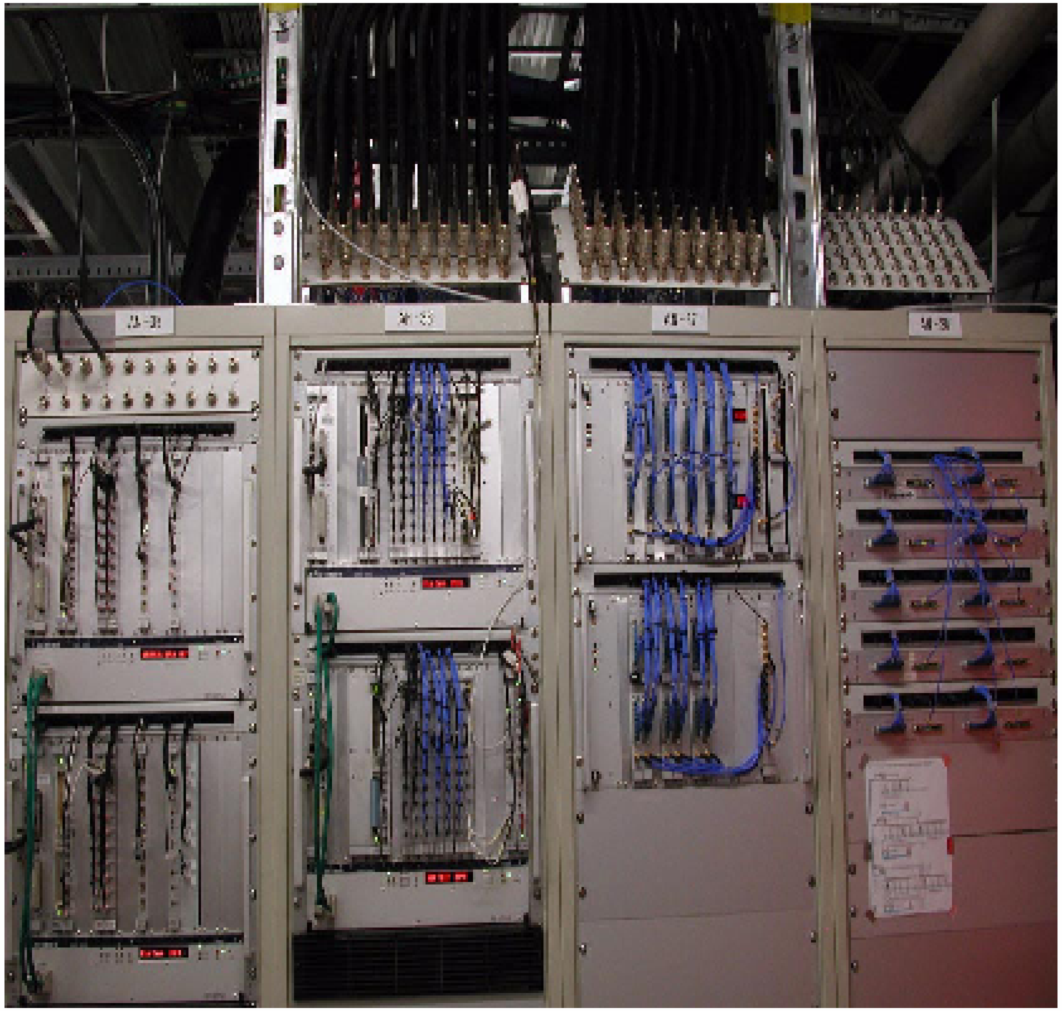
but required regulation bandwidth is only :

$\Delta f \approx 1 MHz$

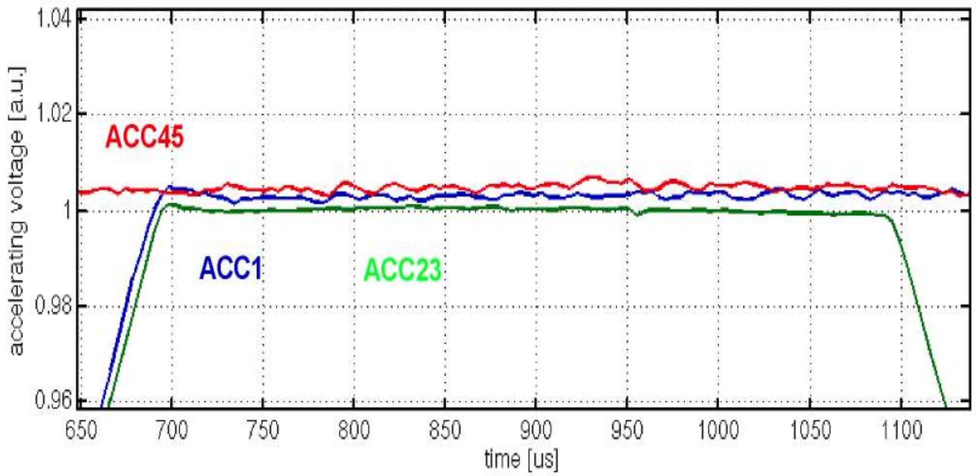
Gun and ACC1

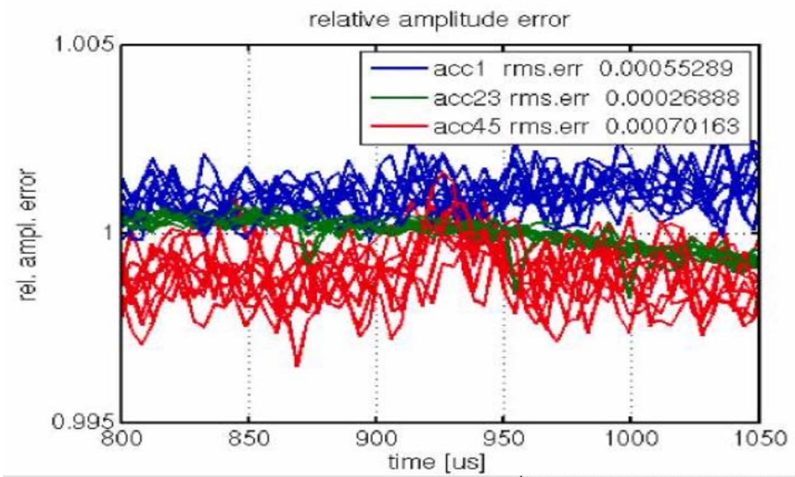


ACC2, ACC3, ACC4 & ACC5

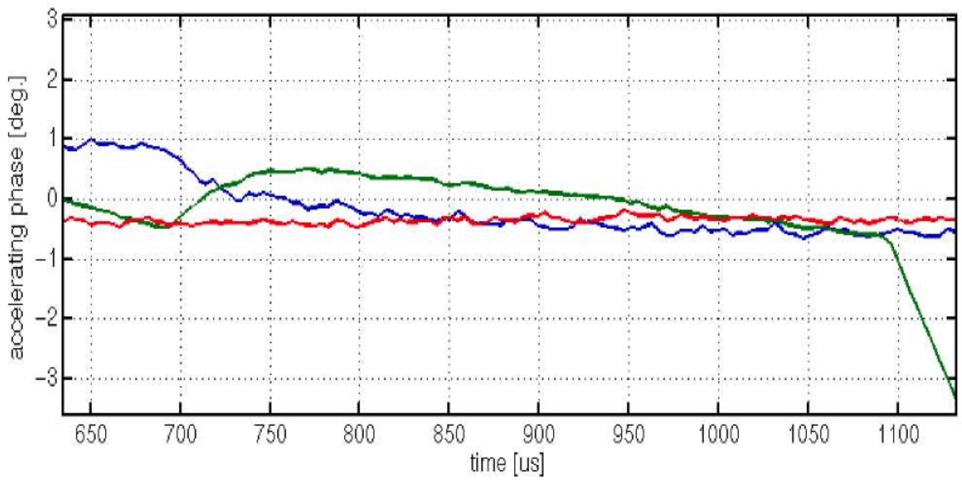


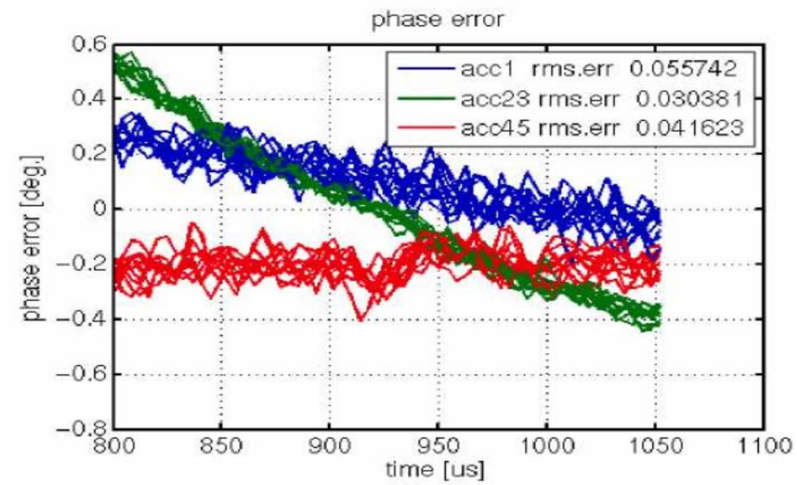
- **Performance of the 250kHz IQ Sampling scheme at FLASH :**





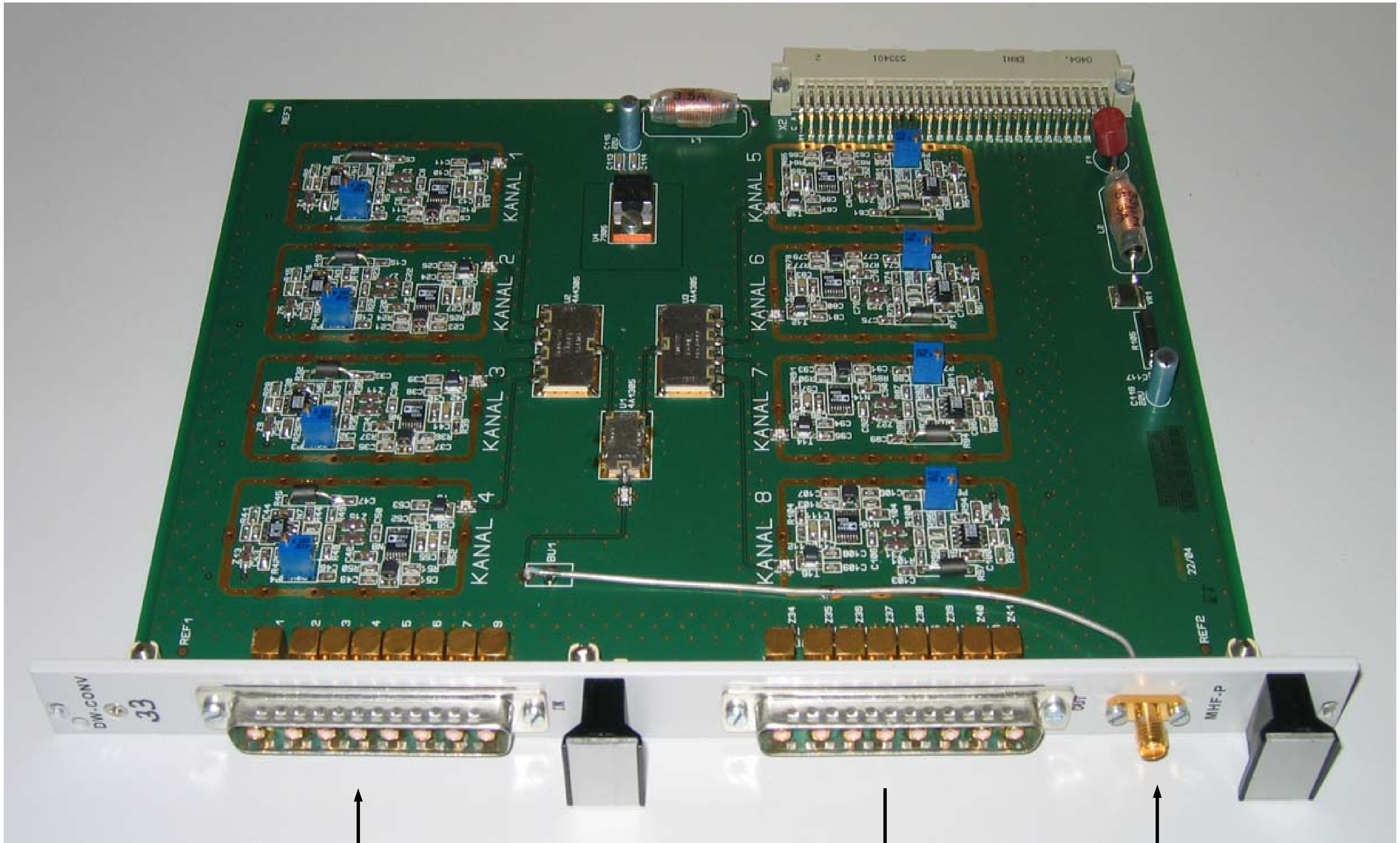
$\delta A / A \approx 2 \cdot 10^{-4} \ldots 7 \cdot 10^{-4}$





$\delta\varphi \approx 0.03 \ldots 0.05\,°$

IQ sampling multi-channel down-converter at FLASH



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 :

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

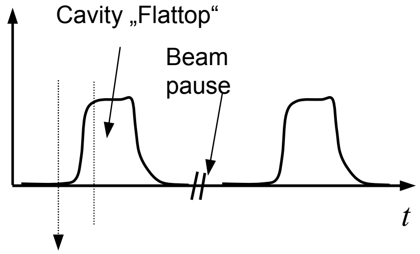
- **Why is this needed ? :**

A drift compensation is needed to compensate drifts and 1/f-noise from

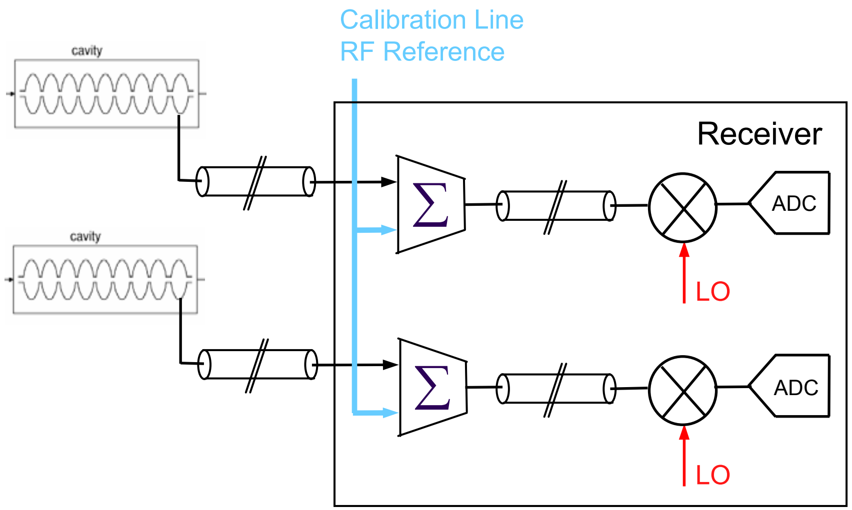
- Cavity pickup cables (4 module) $5\ fs\ m^{-1}K^{-1}, \pm 125 fs\ K^{-1}\ (\pm 25m), \Delta T \approx 1K$
- Downconverter (mixer) θ_A = 2e-3/°C, θ_P = 0.2°/°C (Injector)
- LO generation (dividers, amplifiers, filters)
- ADC CLK generation (timing system, less critical)
- Perfect separation to Synch.System

to have a robust machine operation.

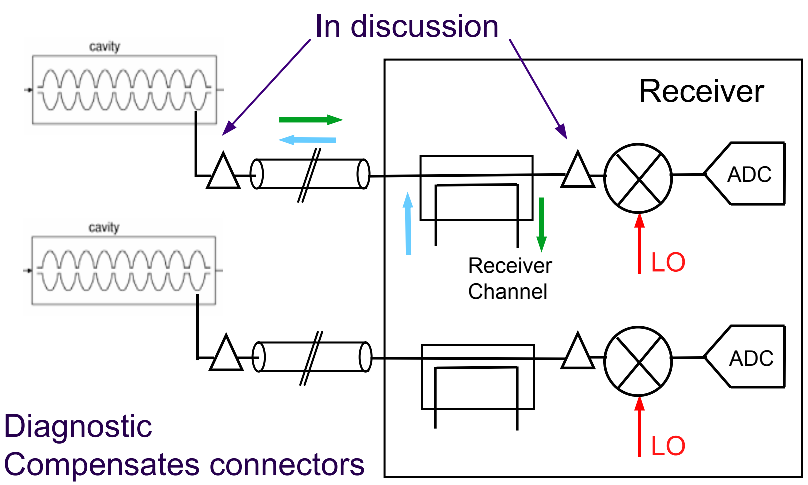
- **Off beam phase calibration :**



- **Injection of the reference signal :**



- **Reflection at the cavity :**

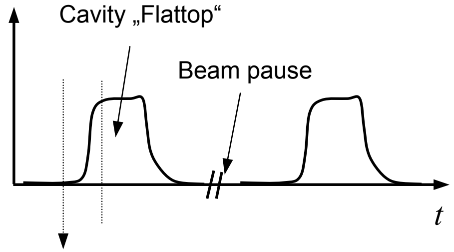


+ Diagnostic
+ Compensates connectors

- **Calibration of the LO-signal except the mixer :**

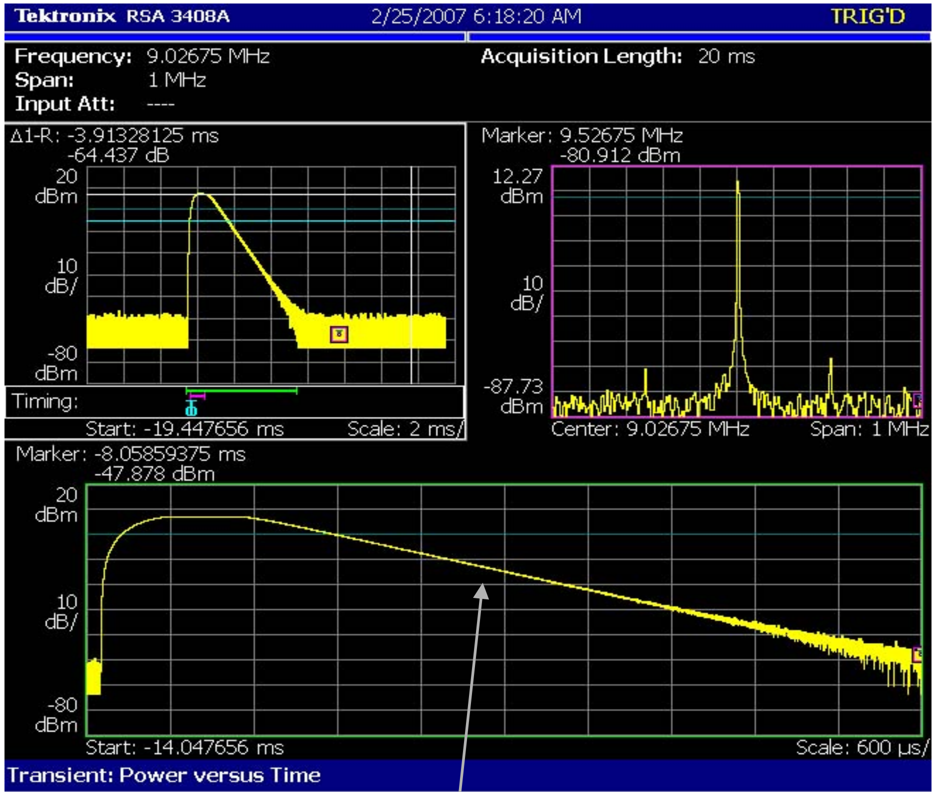
- Compenate drifts from down-converter LO, CLK Generation
- Separation from Synchronization System

- **Off beam phase calibration :**



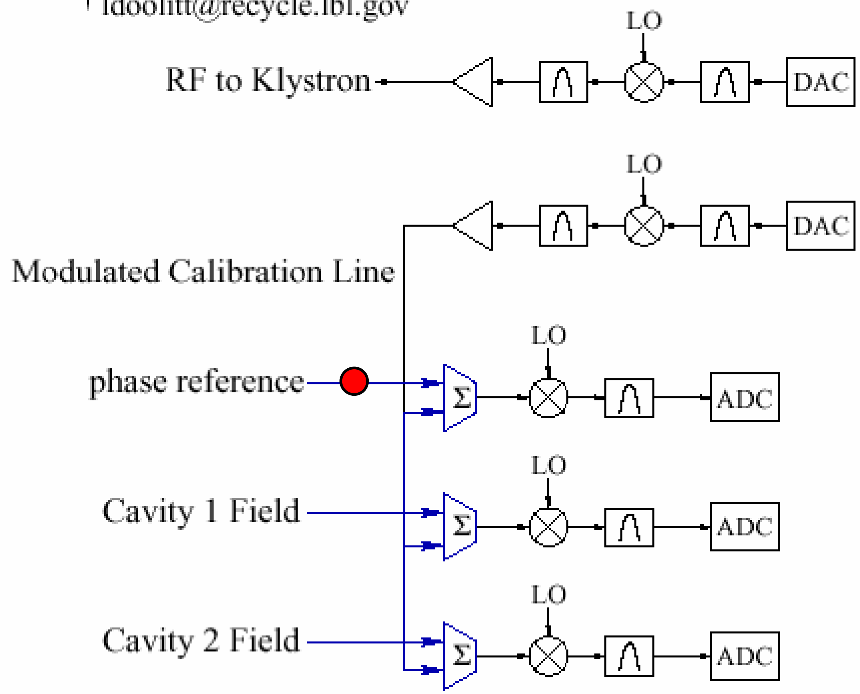
Calibration of the down-converter phase using a local rf-reference.

- **Linearization using the probe cavity decay:**



Quit good exponential decay
Possible hardware linearization of DWC's

Lawrence Doolittle†, LBNL, Berkeley, California
† ldoolitt@recycle.lbl.gov



Sources of field perturbation

- **Phase and Amplitude jitter contributions to the cavity field jitter for different subsystems:**