‚Precision low-noise field detectors‘

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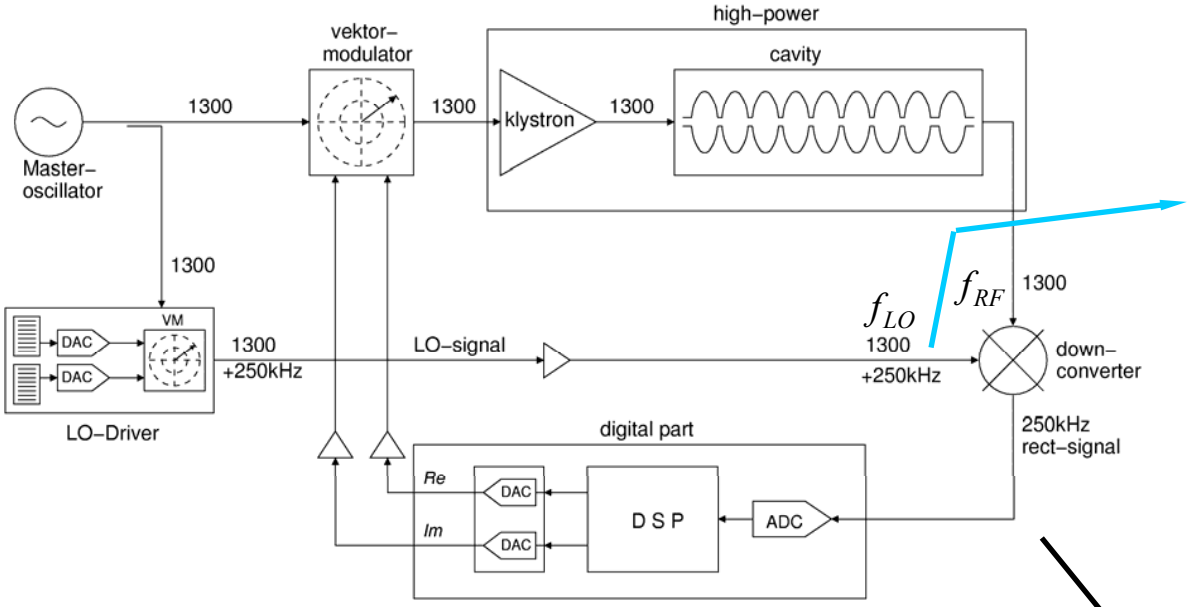
T. Filipek, R. Romaniuk / Warsaw University

Content :

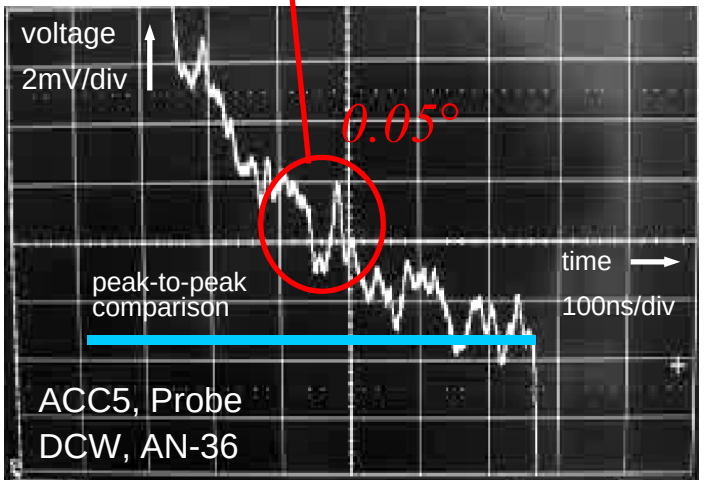
Stability requirements on phase and amplitude for the XFEL

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



- Rotation of the LO-signal in four 90° steps using a squared LO-Signal.
- Bandwidth for transforming the squared LO-signal : $\Delta f \approx 10 MHz$

$$\delta U_{TTF2} \approx 10 \times \delta U_{XFEL}$$



- **Stability requirements of the cavity field vector sum :**

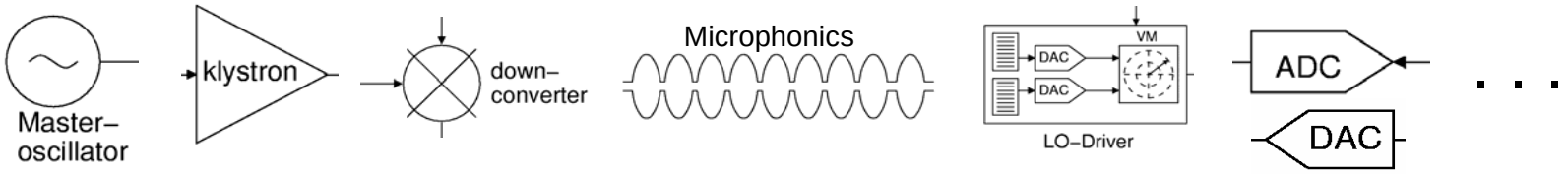
Amplitude stability : $\frac{\delta A}{A} < 5 \cdot 10^{-5}$

Phase stability : $\delta\varphi < 0.01°$

$$\delta U_{XFEL} < 50 \mu V_{rms}$$
(normalized to A=1V)

- 86dB dynamic range of signal-to-noise.

Where comes the noise from and what
do we measure after the down-converter ?

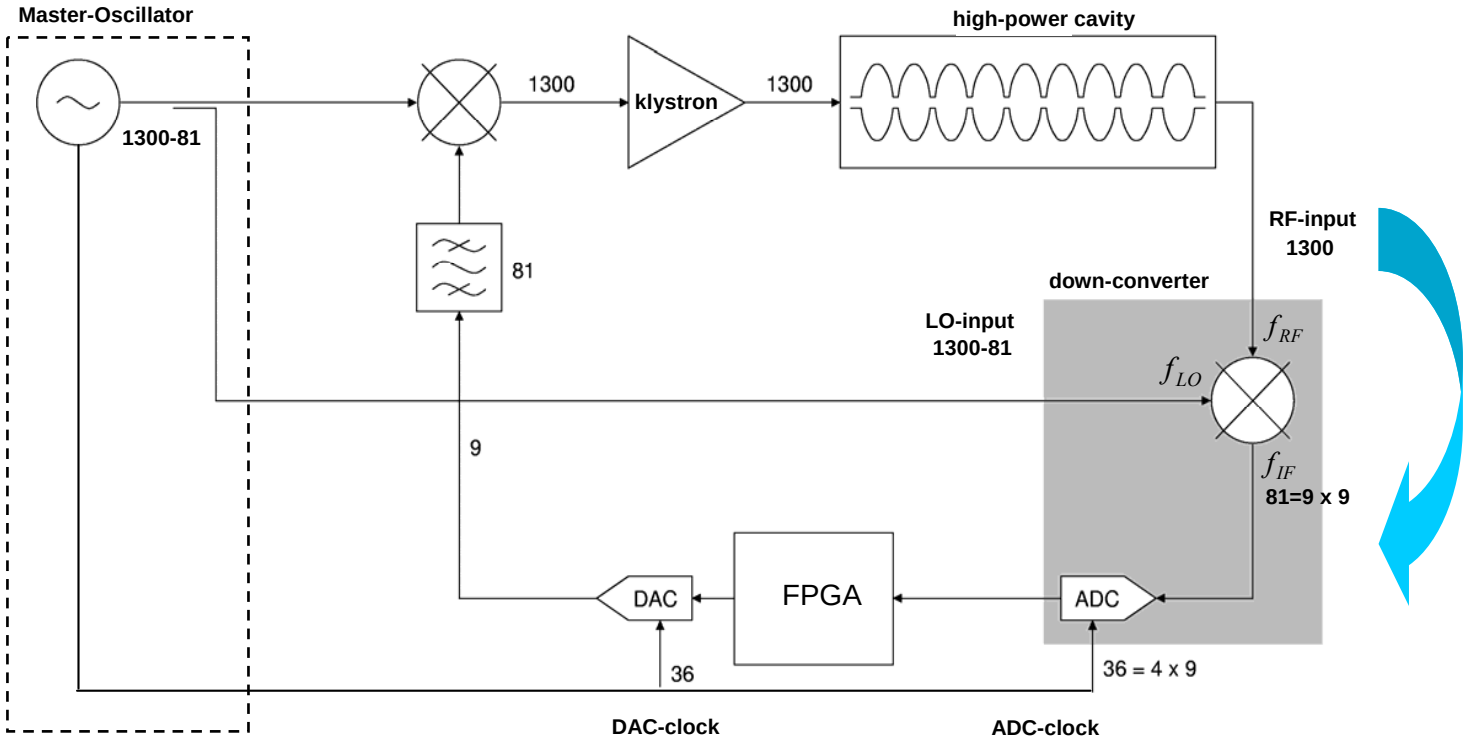


We measure all noise sources of the loop for a finite gain,
but not the residual jitter between beam and reference!

How can we improve this ?

- Conceptional improvements using noise reduction methods, e.g. filtering and averaging.
- Sort the priorities: low noise, low drift, high linearity, absolute accuracy.
- Improve each component.
- Minimize residual jitter by increasing or decreasing the loop gain.

- **Proposed LLRF control system operating with a CW LO-signal :**



Measuring bandwidth :

$$\Delta f \approx 1MHz$$

Jitter transformation :

$$\Delta t = 10\,fs$$

$$\Downarrow$$

$$\Delta T = \frac{f_{RF}}{f_{IF}} \Delta t$$

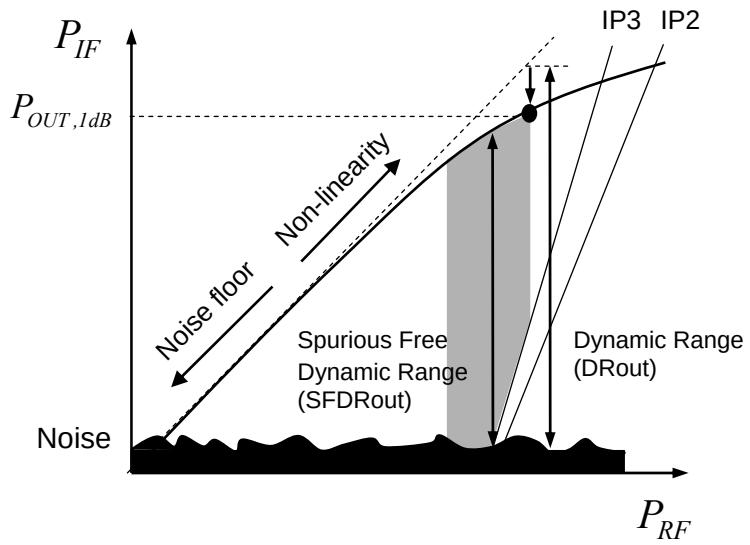
$$\Downarrow$$

$$\Delta T \approx 160\,fs$$

+ *Higher harmonics and disturbancies using bandpass filters can be suppressed.*
+ *Narrowband filtering the IF-signal reduces distortions from mixer non-linearities.*
+ *Averaging reduces ADC-noise and no aliasing effects.*
+ *No noise from LO-driver.*
- *Precise synchronization system.*

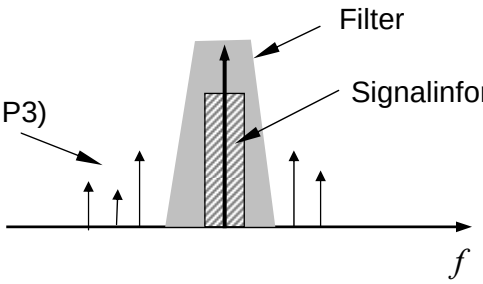
Down-converter limitations from noise and non-linearity

- **Compromise between noise and linearity :**



- **Filtering of distortions :**

Signal distortions :
- intermodulation effects (IP3)
- higher harmonics (IP2)



- **Active Gilbert-mixers:**

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

- **Passive Mixer + FET:**

+ High linearity
+ Low NF
- Large LO drive needed (additional phase noise)
- High LO/RF crosstalk

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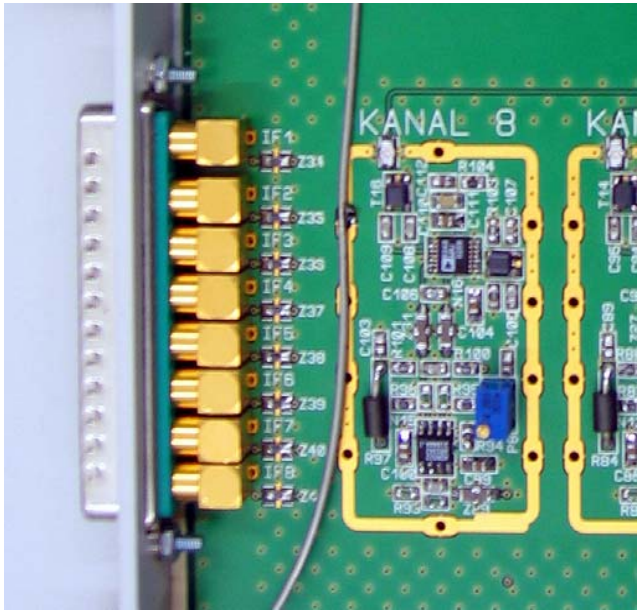
P(LO)	dBm	-5	4	-3	21	21	-10
P(IF)	dBm	-7,4			18,5	-18,5	-4,9
NF	dB	13,2	6	12,4	8,5	10,5	14,1
OIP3	dBm	23	20	27,5	23,5	25,5	23,6
out,1dB	dBm	8,1	11	10,3	13,5	14,5	8,9
Gain	dB	-0,4	-6	2,3	-8,5	-8,5	7,1
i. RF to IF	dB		22		24	24	29
i. LO to RF	dB	50	15	55	24	24	52
i. LO to IF	dB	49	21	70	30	30	54
IF(min)	MHz	0,1	200		10	10	0
B=10MHz							
MDSin	dBm	-87,78	-94,977	-88,577	-92,5	-90,48	-86,88
DRin	dB	96,28	111,98	96,577	114	113,5	88,68
MDSout	dBm	-87,38	-88,977	-86,277	-84	-81,98	-79,78
DRout	dB	95,48	99,977	96,577	97,5	96,48	88,68
SFDRout	dB	73,58	72,651	75,851	71,7	71,65	68,92

- Filtering of distortions
- Linearization during beam pauses

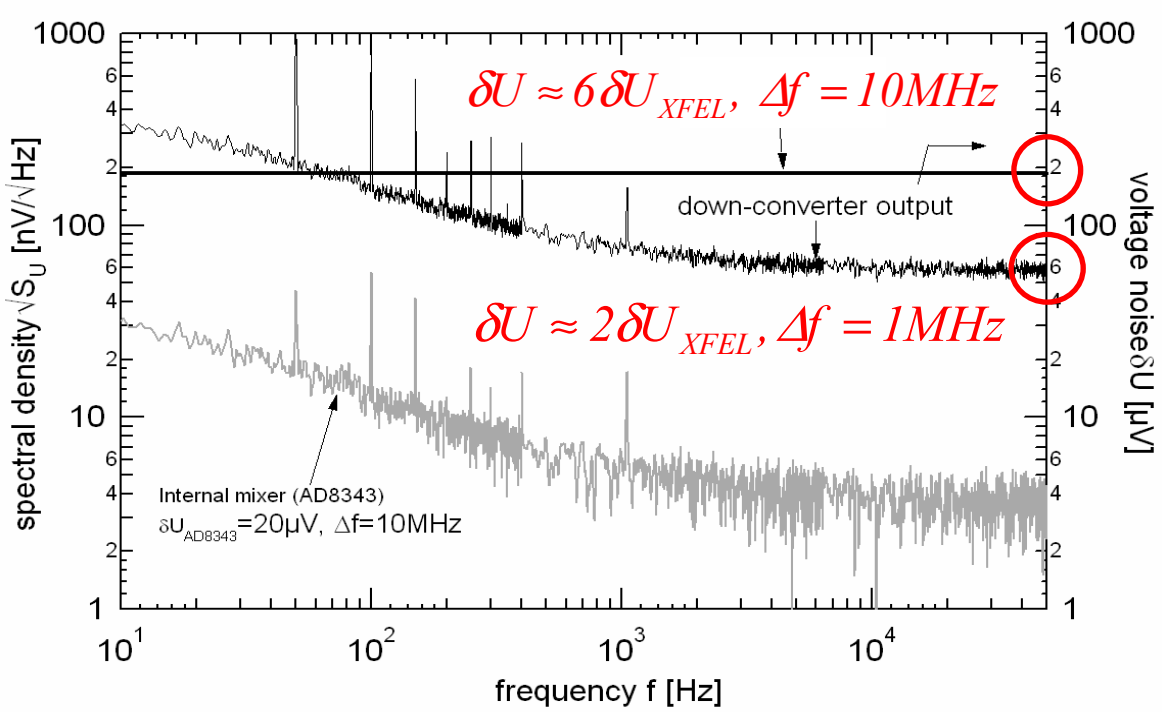
Multi-channel detector board :
- Gilbert cell mixer

Actual down-converter



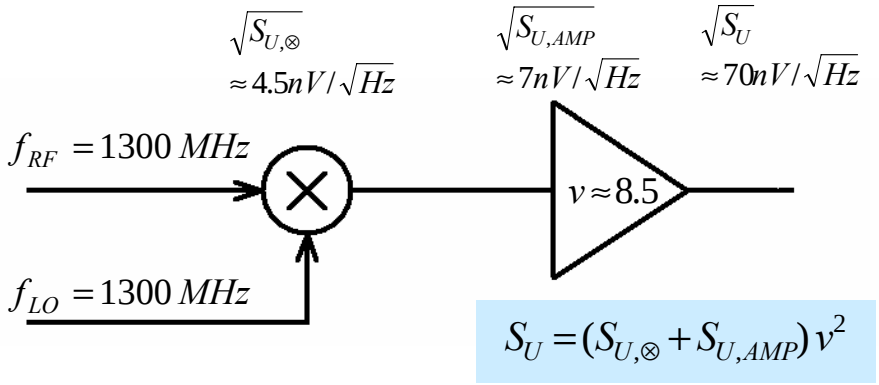
LLRF05: G.Möller, [43] Multichannel down-converter board for cavity field detection at the TTF.

- **Noise from actual down-converter :**

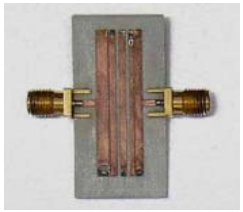


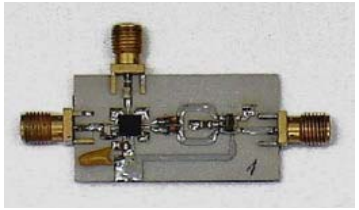
- First mixer stage determines the noise performance.
- Actual down-converter performance:

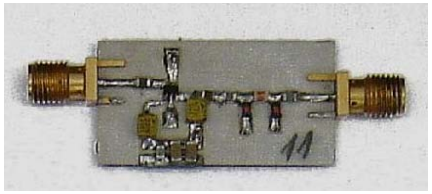
$\delta U \approx 6\delta U_{XFEL},\ \Delta f = 10MHz,$ (Switched LO-Signal)
$\delta U \approx 2\delta U_{XFEL},\ \Delta f = 1.0MHz,$ (CW-LO-Signal)
$\delta U \approx 0.6\delta U_{XFEL}, \Delta f = 0.1MHz,$ (Cavity filtered)

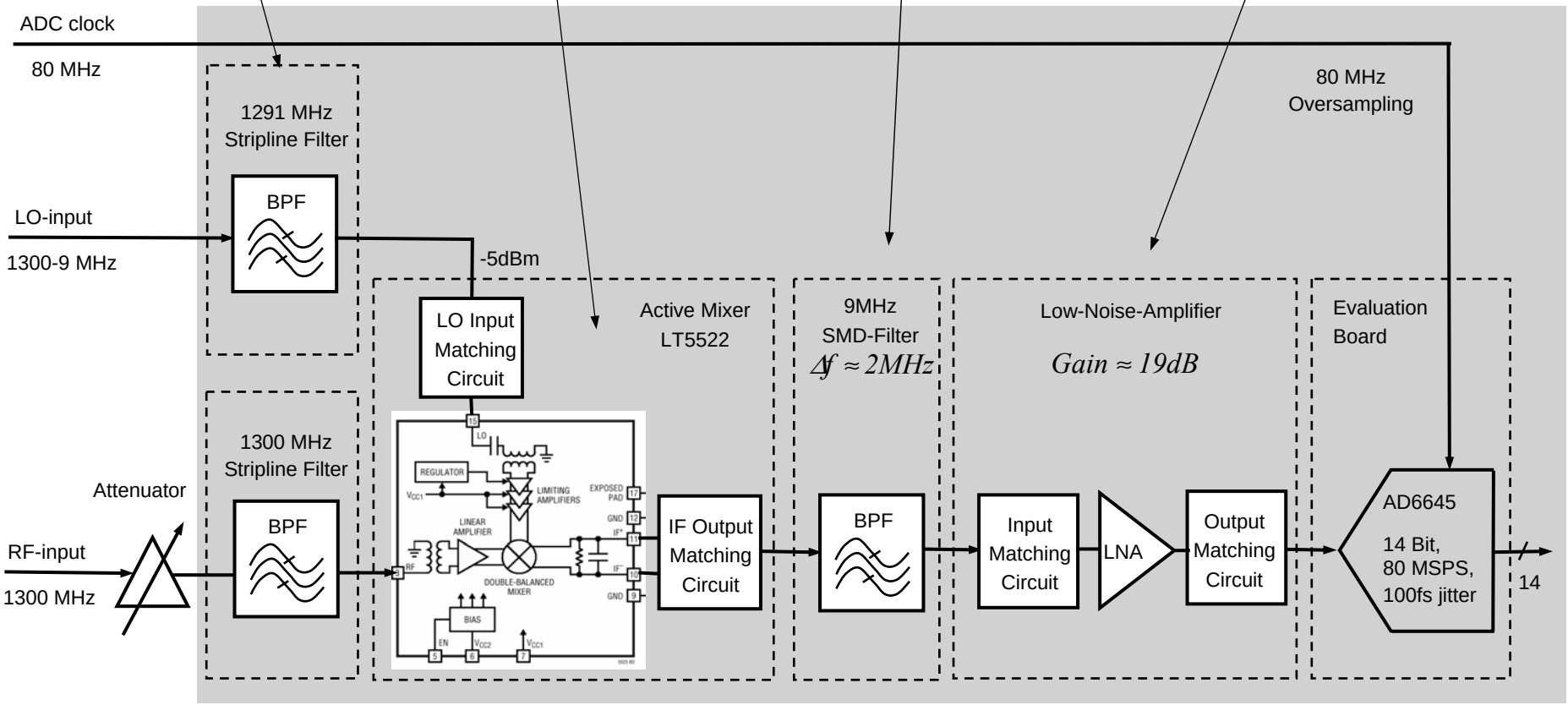


Down-converter prototype for CW-modulation scheme



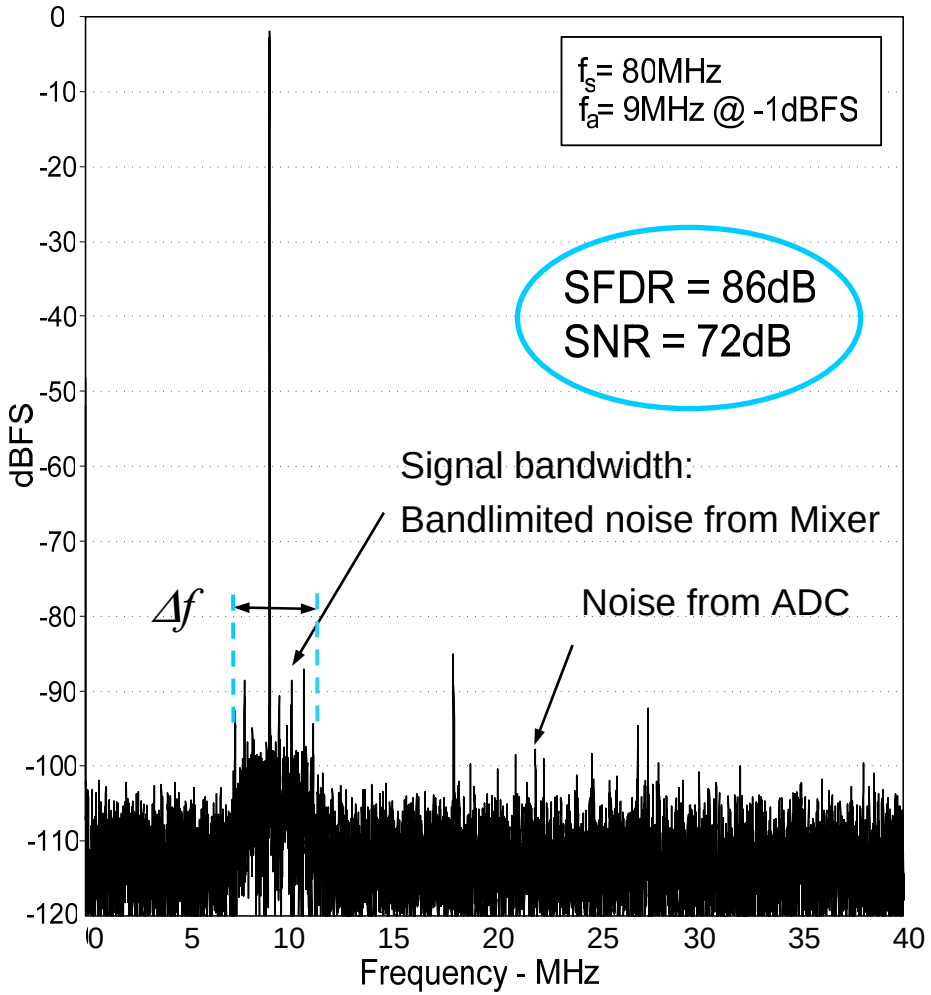




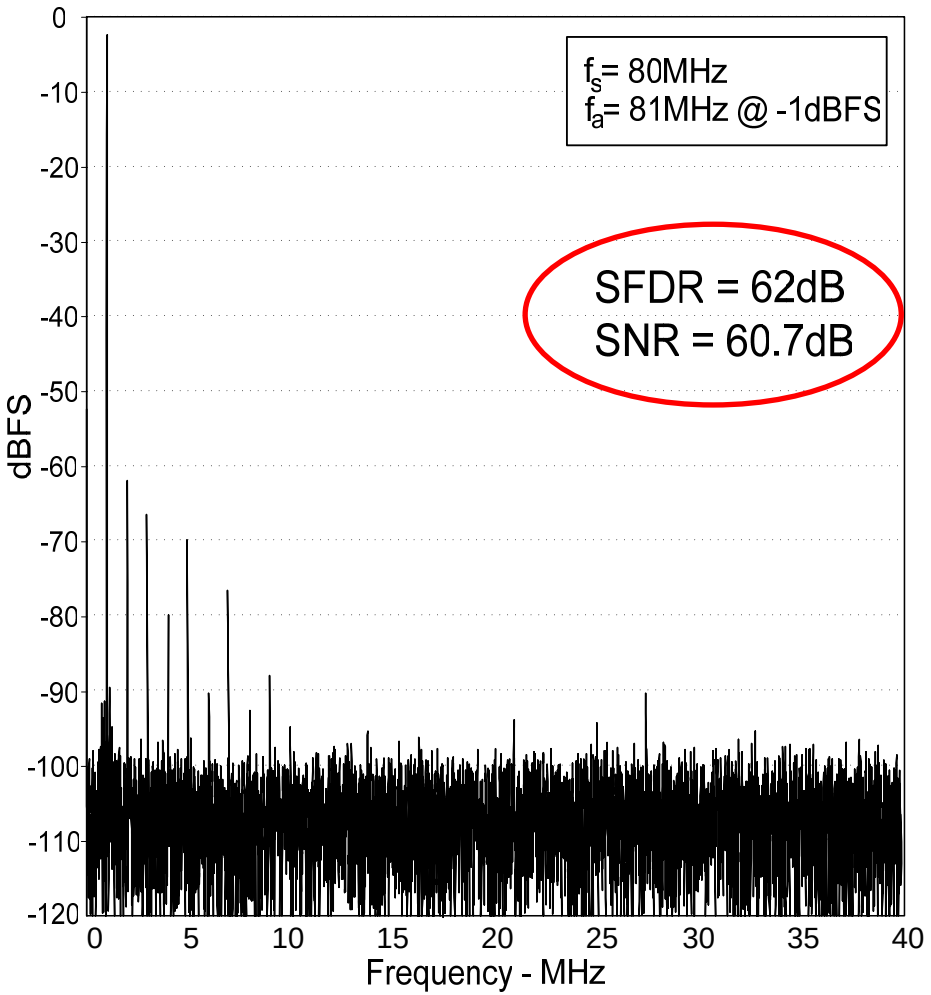


Down-converter prototype for CW-modulation scheme

- **Oversampling :**



- **Undersampling :**

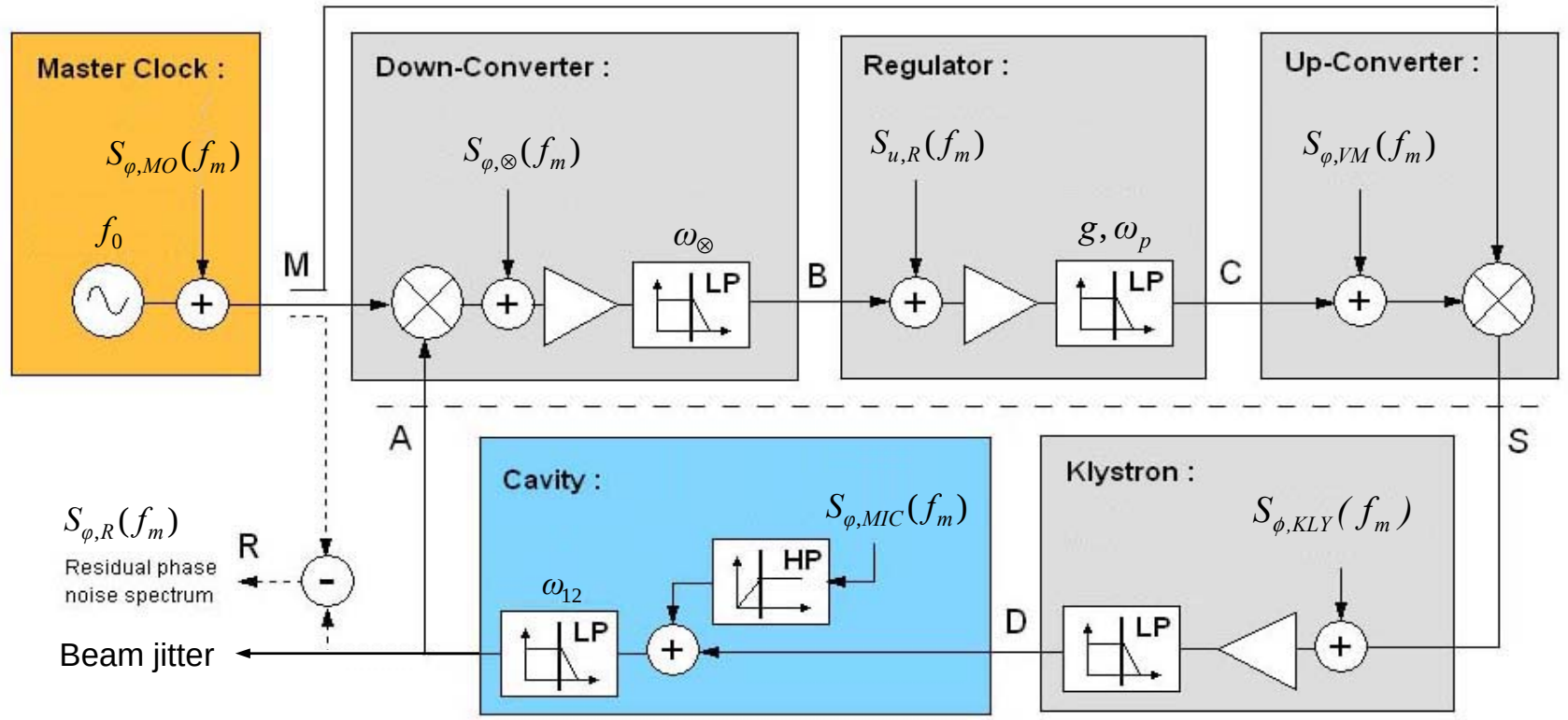


Oversampling promises better SNR than undersampling.

ADC-noise, oversampling, clock phase noise requirements

LLRF05: T.Filipek, Frequency Conversion in Field Stabilization System for Application in SC cavity of linear accelerator.

LLRF phase noise budget – Residual jitter



(simplified)

$$S_{\varphi,R}(f_m) \approx \left|\frac{\omega'_{12}}{s+\omega'_{12}}\right|^2 S_{\varphi,\otimes}(f_m) + \left|\frac{s}{s+\omega'_{12}}\right|^2 S_{\varphi,MO}(f_m) + \left|\frac{1}{g}\frac{\omega'_{12}}{s+\omega'_{12}}\right|^2 S_{\varphi,KLY}(f_m)$$

1st order LP (1st term) — 1st order HP (2nd term) — 1st order LP (3rd term)

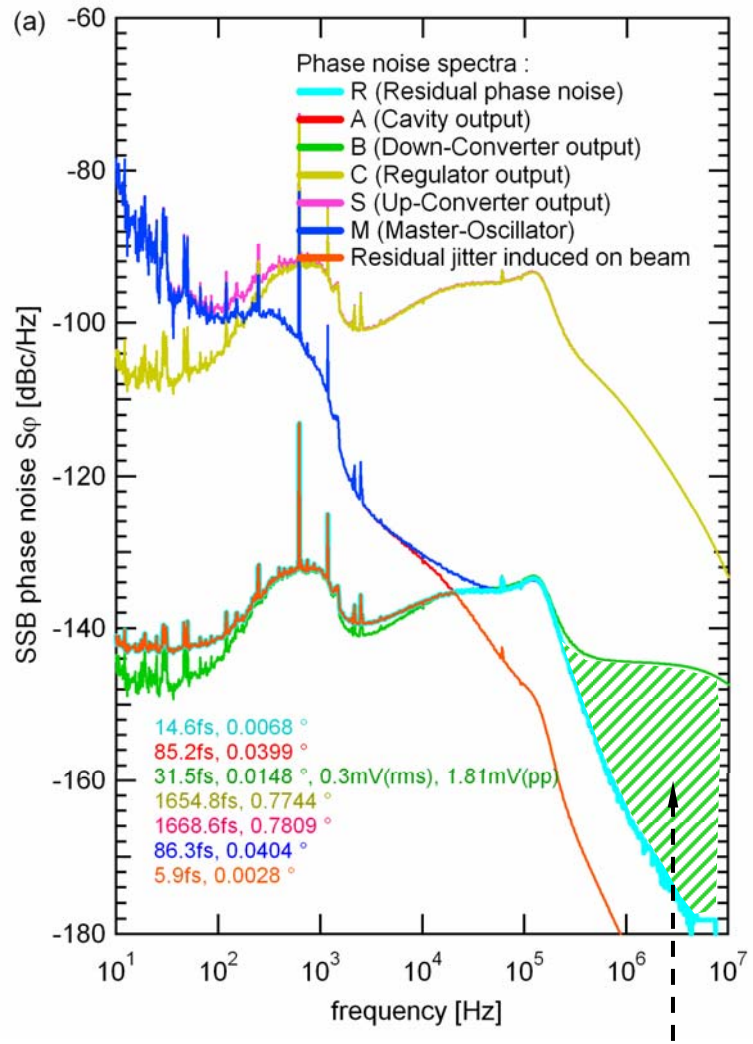
The effective noise bandwidth for the down-converter is given by : $\omega'_{12} = g\,\omega_{12}$

- MO and klystron contributions decreases with gain.
- Down-converter contributions increases with gain.

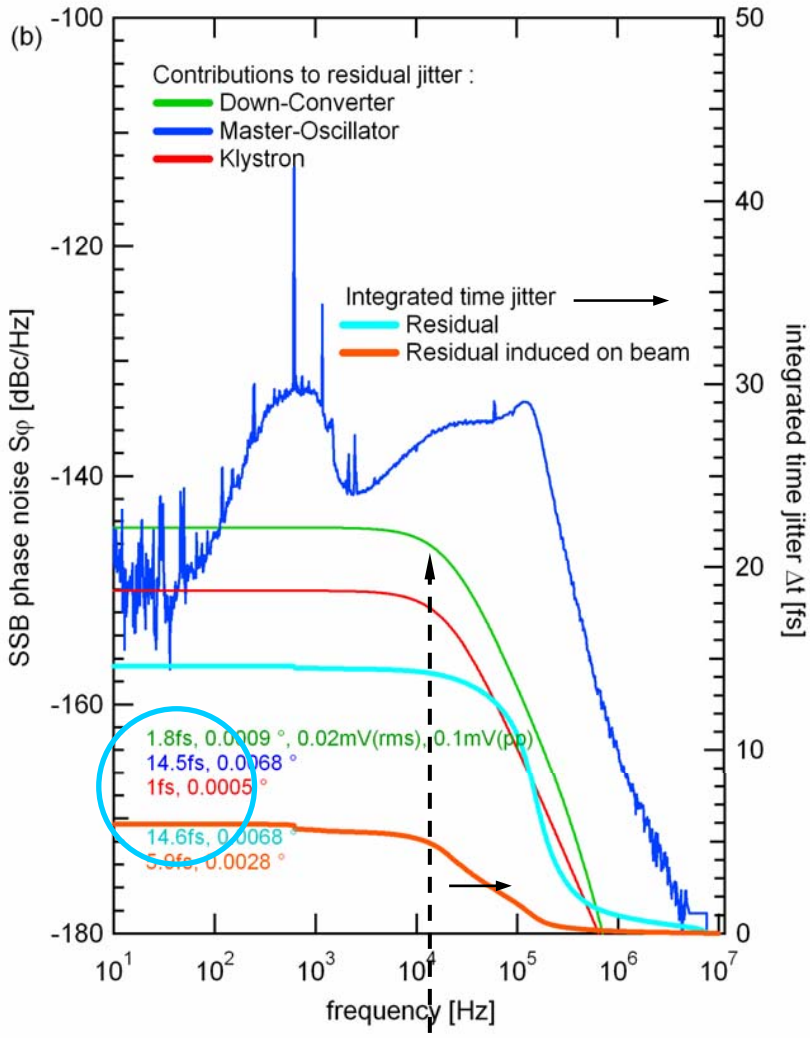
Phase noise budget (Switched LO, single cavity)

$\Delta f \approx 10MHz$

- **Phase noise spectra :**



- **Contributions to residual jitter :**



$f_{\otimes} = 10MHz$
$g = 100, f_{12} = 200Hz$
$f_p = 500kHz, f_0 = 1300MHz$
$S_{u,\otimes}(f_m) = 70nV/\sqrt{Hz}$
$S_{\phi,AMP}(f_m) = -110\,dBc/Hz$
$S_{\varphi,MO}(f_m) =$ TTF2 (new supply)

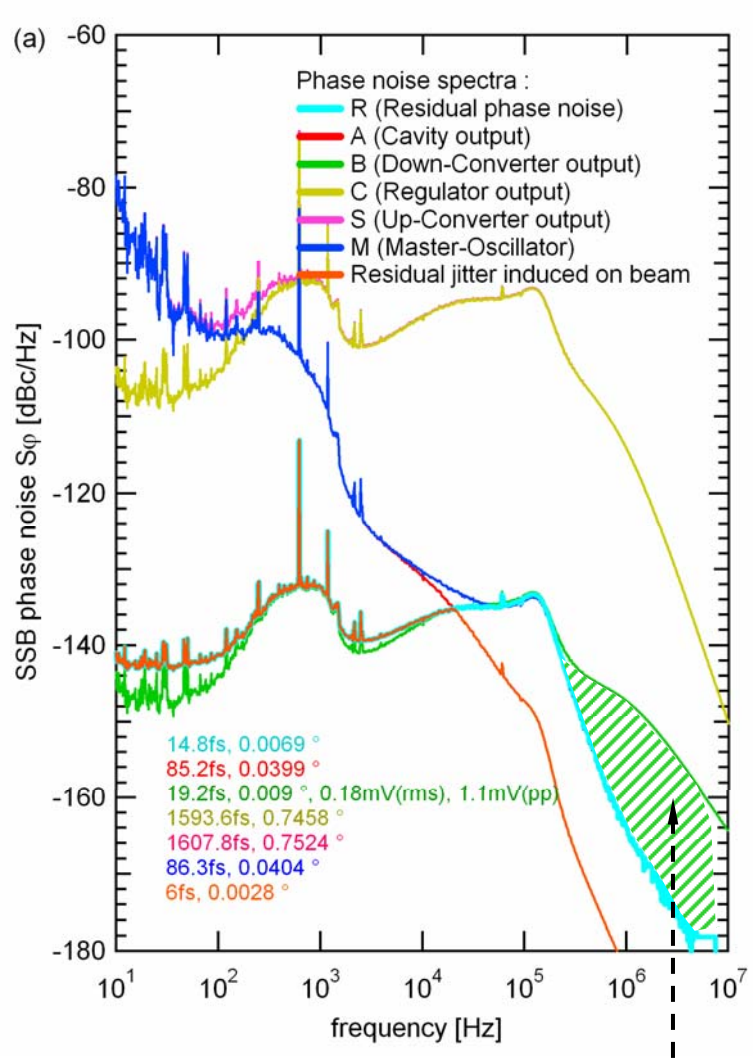
Measured down-converter noise is larger than residual noise and beam jitter.

- Noise is filtered by the cavity.
- The down-converter is not a good indicator for the residual jitter!

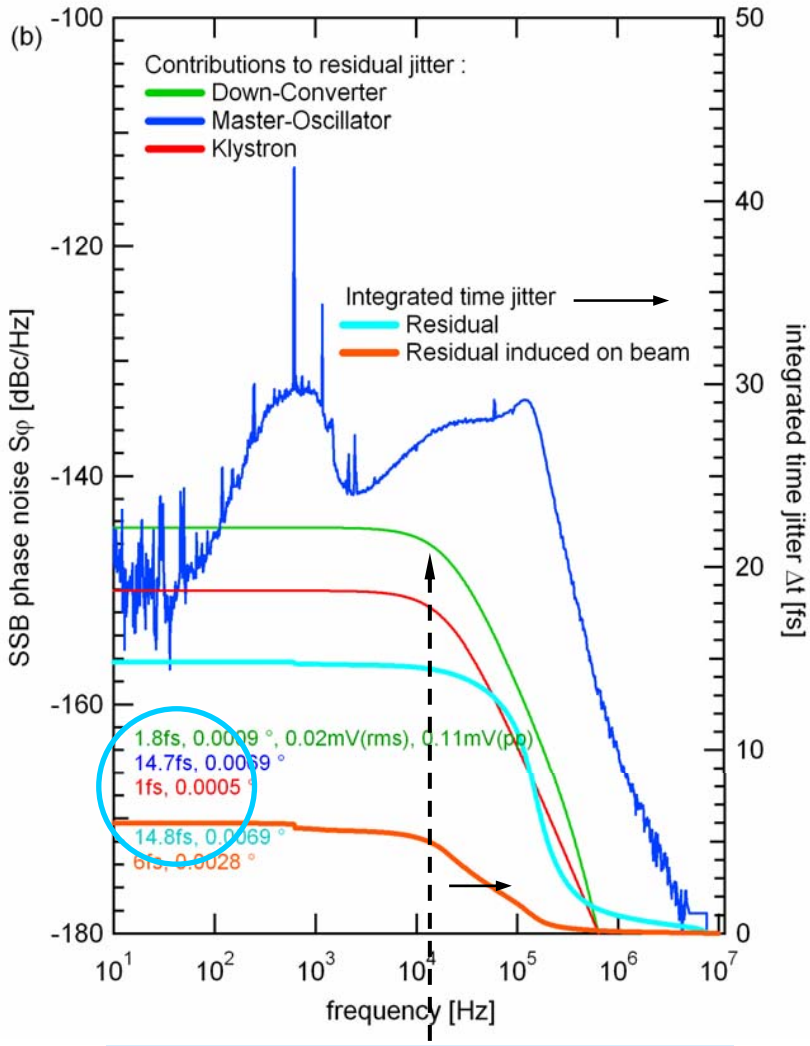
Phase noise budget (Switched LO, single cavity)

$\Delta f \approx 1MHz$

- **Phase noise spectra :**



- **Contributions to residual jitter :**



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Measured down-converter noise is larger than residual noise and beam jitter.

- Noise is filtered by the cavity.
- The down-converter is not a good indicator for the residual jitter!

Summary and Outlook

- **Summary :**
  - *The CW-modulation scheme combines many advantages, for example :*
    - *No aliasing effects and ADC-noise reduction.*
    - *Filtering of distortions, which allows a linearization with improved SNR.*
  - *For multi-channel systems Gilbert mixers are recommended.*
  - *Oversampling promises better SNR than undersampling.*
  - *The down-converters noise contribution to the beam jitter is reduced by the cavity transfer function.*

- **Outlook :**
  - *Design a multi-channel board and test within accelerator environment.*
  - *Beam jitter caused by LLRF should be measured with fs-resolution.*

- **Decrease mixers noise :**

- Passive front end structures.

- Parallel structures of detectors (VLSI prefered).

- pHEMT Gilbert mixers (promise higher gain and lower noise).

- Additional „Zero-Phase“ detectors.

- **Increase mixer output :**

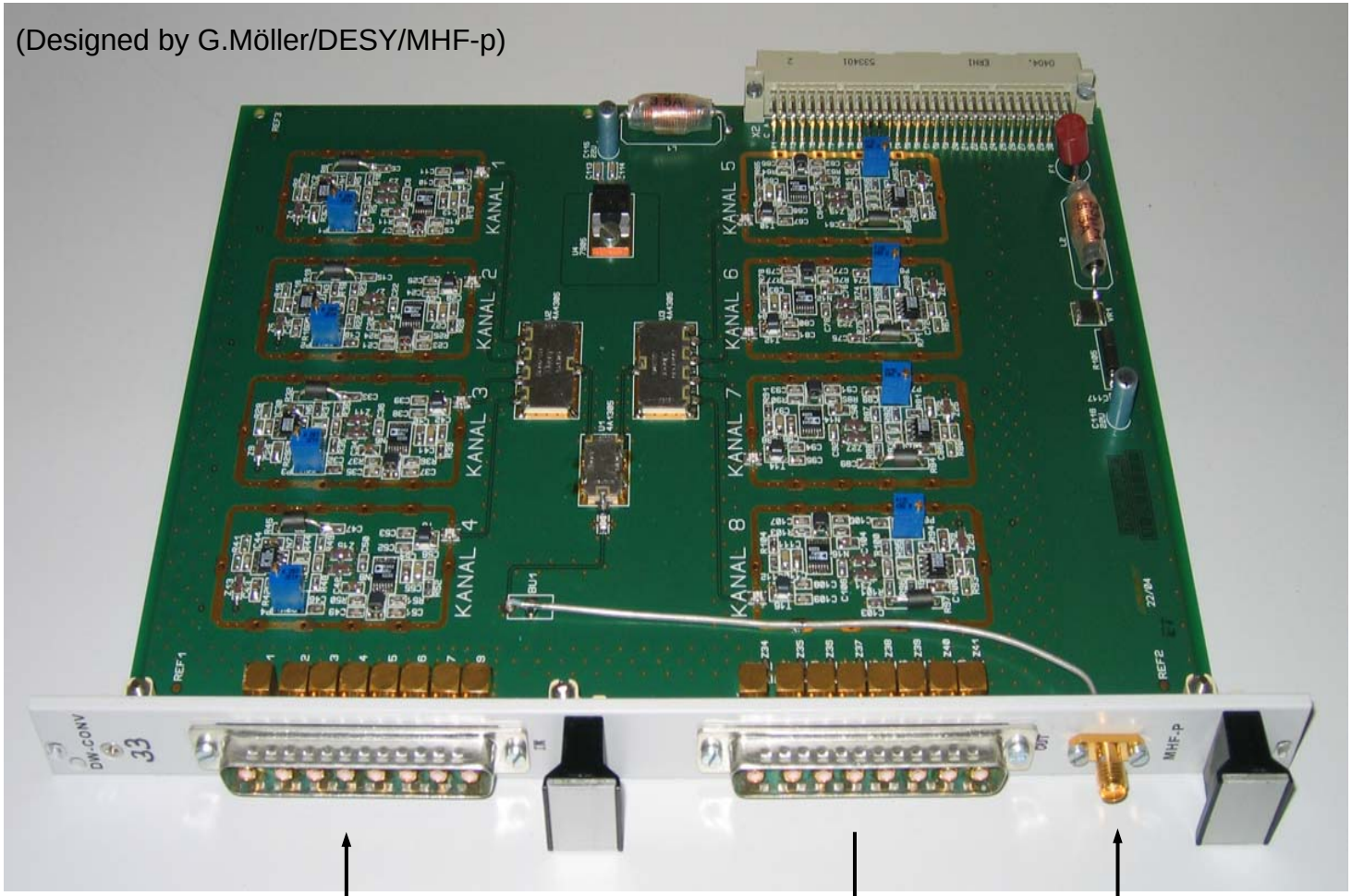
- Linearize the down-converters characteristic within the beam pause.

Thanks for your attention!

Backup Slides

Actual down-converter

(Designed by G.Möller/DESY/MHF-p)



+ High LO/RF isolation
- Mixing into baseband causes additional noise

8-channels from cavity probe :

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

8-channels to ADC-Board :

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

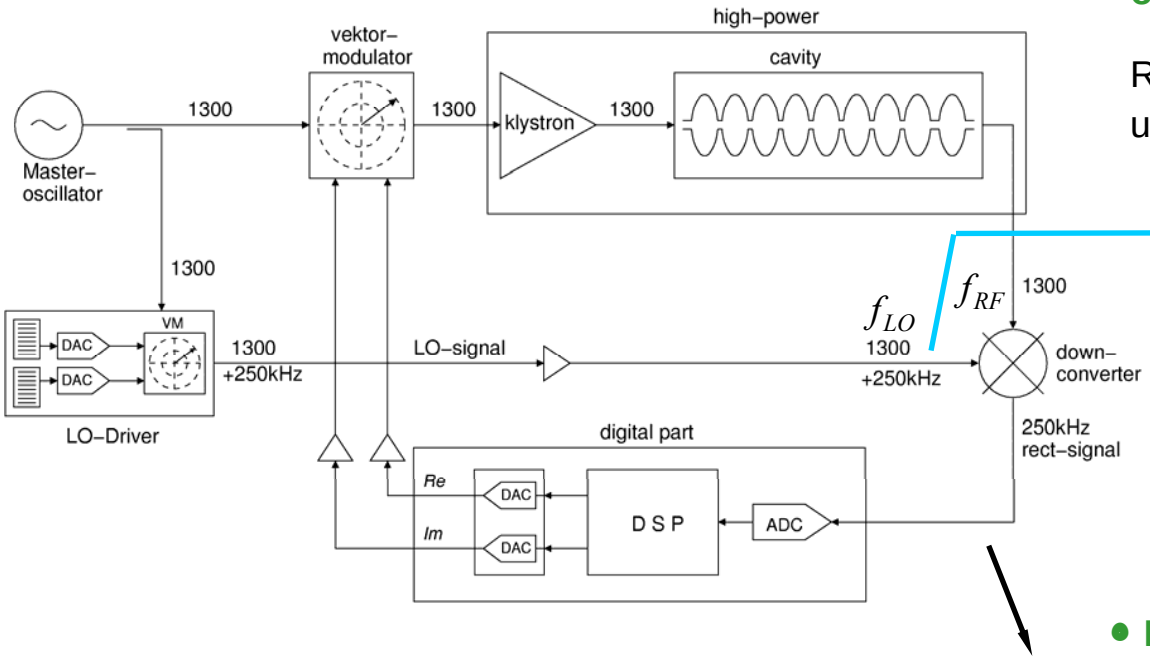
LO-Input :

$P_{LO} \approx -5dBm$

LLRF05: G.Möller, [43] Multichannel down-converter board for cavity field detection at the TTF.

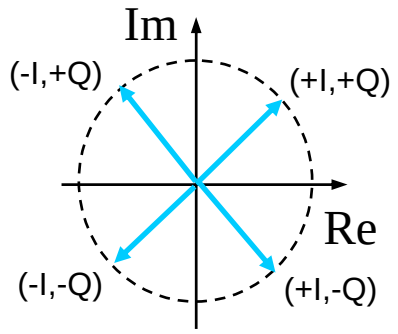
Choice of LLRF system for optimized detector operation

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

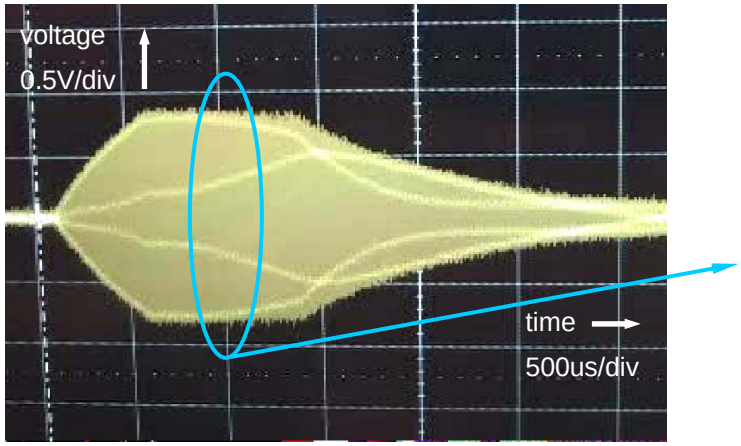


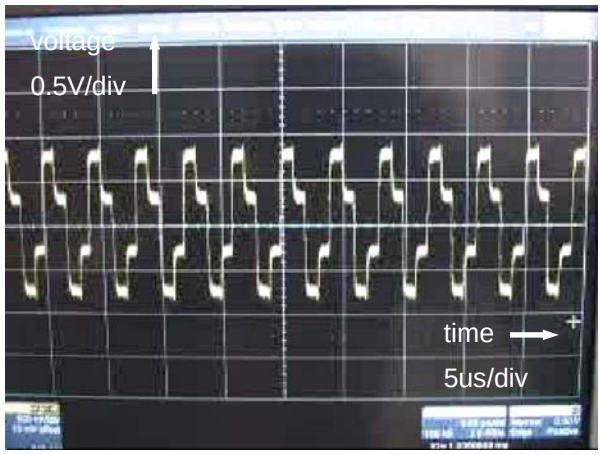
- **Phase and amplitude detection of the cavity field vector :**

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 :

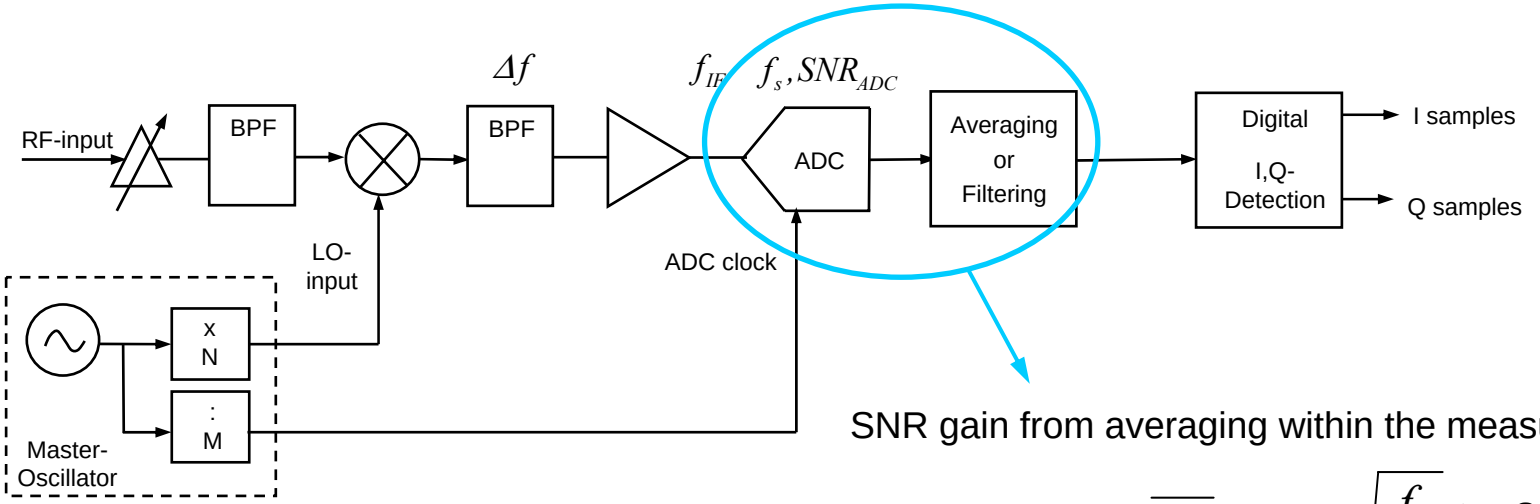
$$\Delta f \approx 10 MHz$$

but required regulation bandwidth is only :

$$\Delta f \approx 1 MHz$$

Down-converter prototype for CW-modulation scheme

- **SNR gain from ADC oversampling :**



SNR gain from averaging within the measuring time :

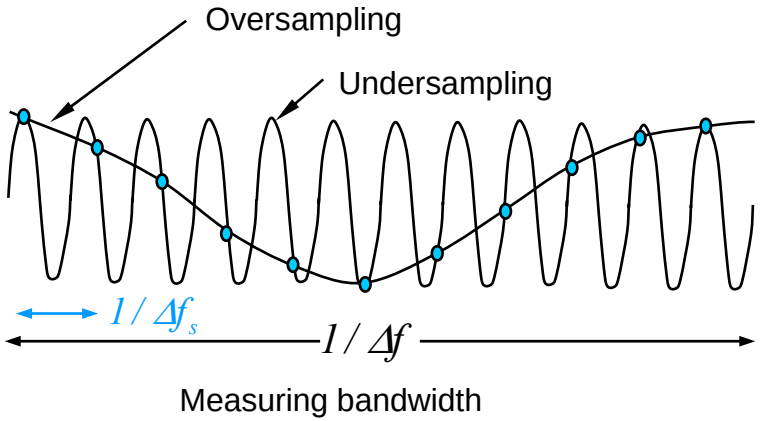
$$SNR = SNR_{ADC}(\overline{\Delta t_j^2}, \varepsilon, \Delta v)\sqrt{\frac{f_s}{\Delta f}}$$

f_s ← Sample frequency

Δf ← Measuring bandwidth

Clockjitter, Internal jitter — Quant. noise — Equiv. Input noise of ADC

- **Number of samples :**



- The signal within the bandbass filter, respectively noise from mixer stage will not be averaged.

Optimal IF frequency, clock phase noise requirements

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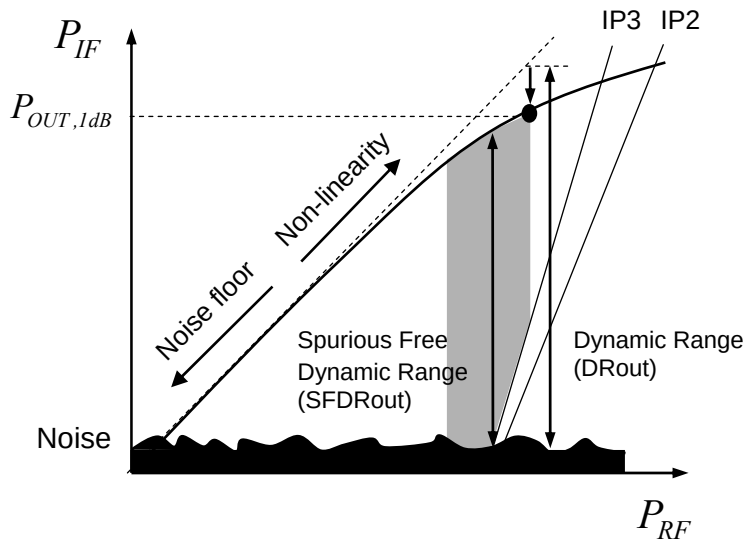
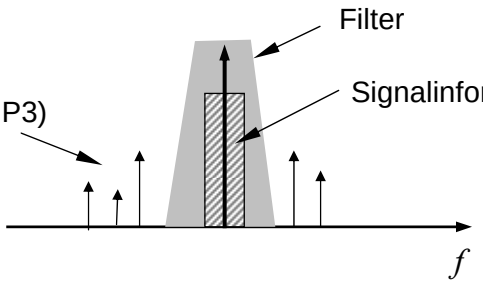
Down-converter limitations from noise and non-linearity

• Compromise between noise and linearity :



• Filtering of distortions :

Signal distortions :
- intermodulation effects (IP3)
- higher harmonics (IP2)



- Filtering of distortions
- Linearization during beam pauses

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Multi-channel detector board :
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