RF Controls Towards Femtosecond and Attosecond Precision.

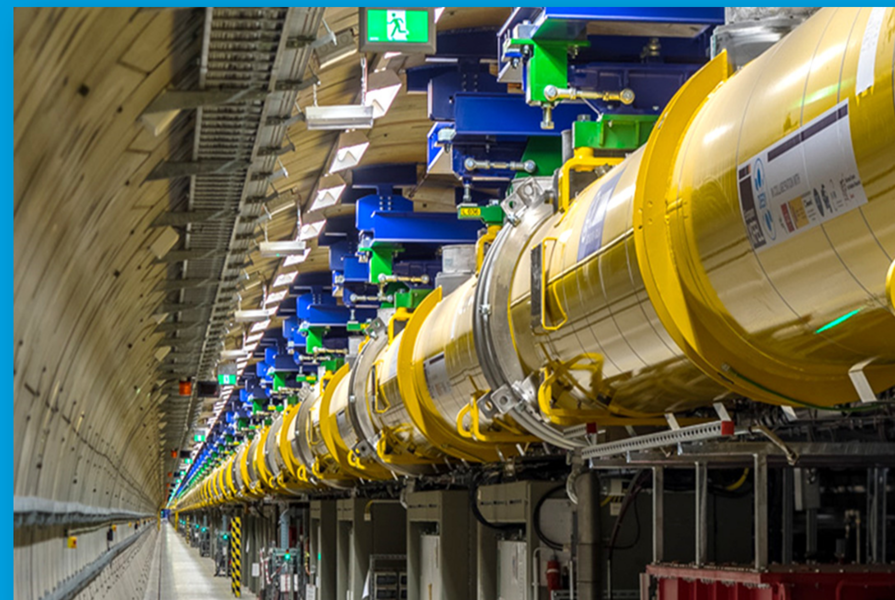
IPAC 2019, 10th International Particle Accelerator Conference

Dr. Frank Ludwig on behalf of the LLRF, LbSync, Special Diag. team at DESY
Melbourne, Australia, 23.05.2019

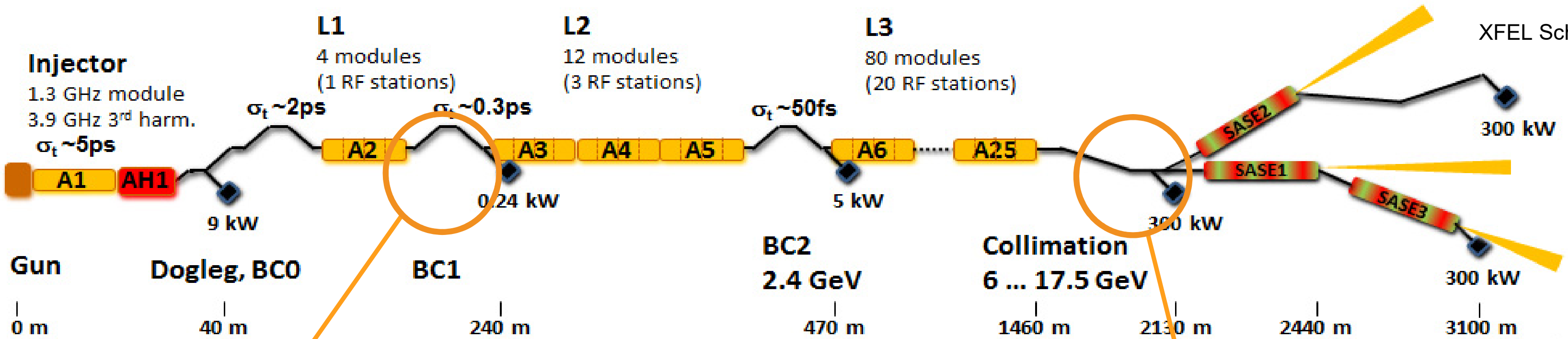
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

RF-Controls
with fs-Precision



Source of timing jitter for accelerators / FELs



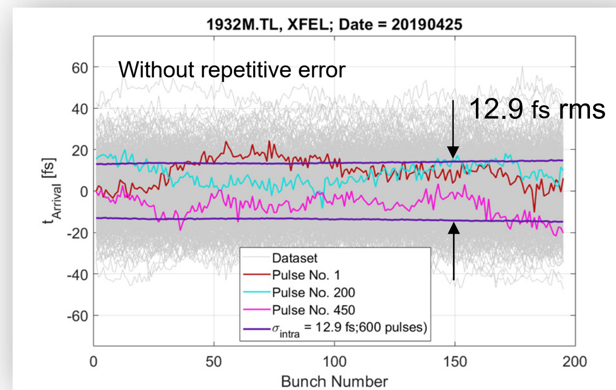
- RF acceleration fields define arrival time:

Amplitude **Phase** **Init. arrival**

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

XFEL: 1.5ps/% — 2 ps/deg — 0.05 ps/ps
FLASH: 7.0ps/% — L-band — C=20

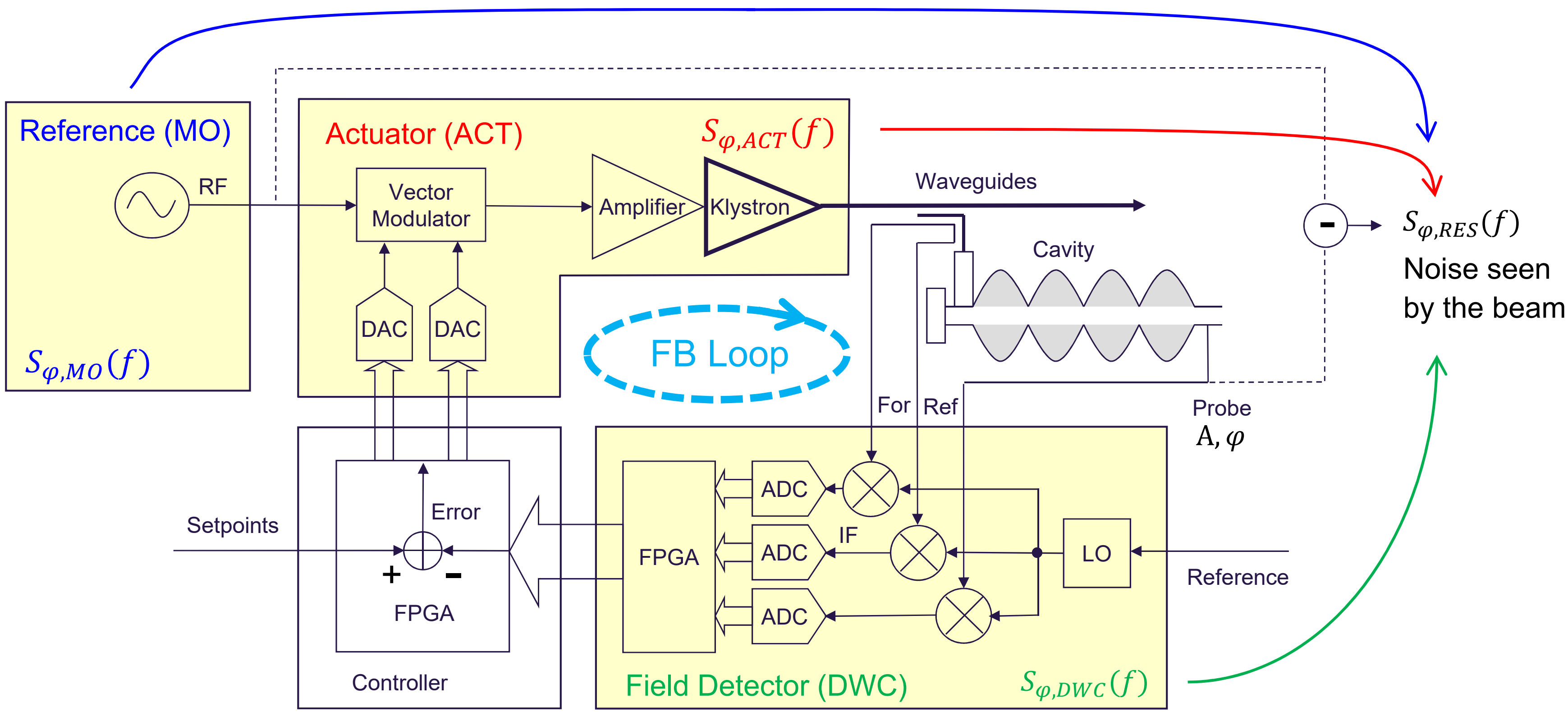
Conclusions for 10fs bunch arrival time:
RF field control and reference distribution is critical <0.01%, <0.01deg @ 1.3GHz



Courtesy of H.Schlarb, CLEO2019

Low-Level-Radio-Frequency (LLRF) Control

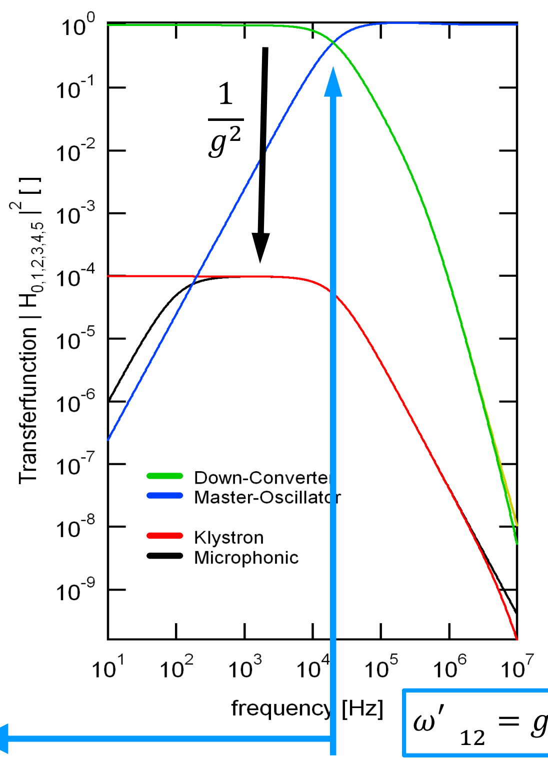
- High-frequency regulation – main noise sources: ACT, DWC, MO



FIL

Noise Contributions from LLRF-Subsystems

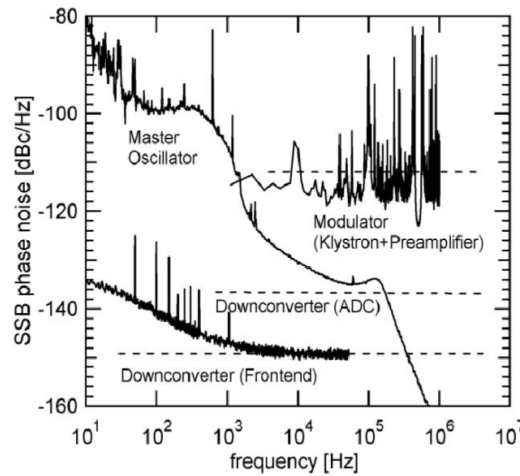
- Noise Transfer Functions:



$\omega'_{12} = g\omega_{12}$

Cavity effective noise bandwidth

- Real sub-systems:



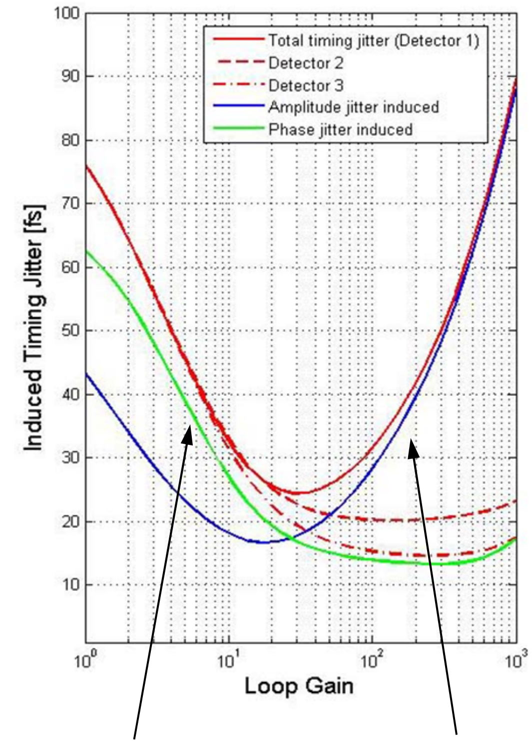
Residual cavity phase and amplitude jitter

Bunch compressor

-> Energy fluctuation

-> Beam arrival time jitter

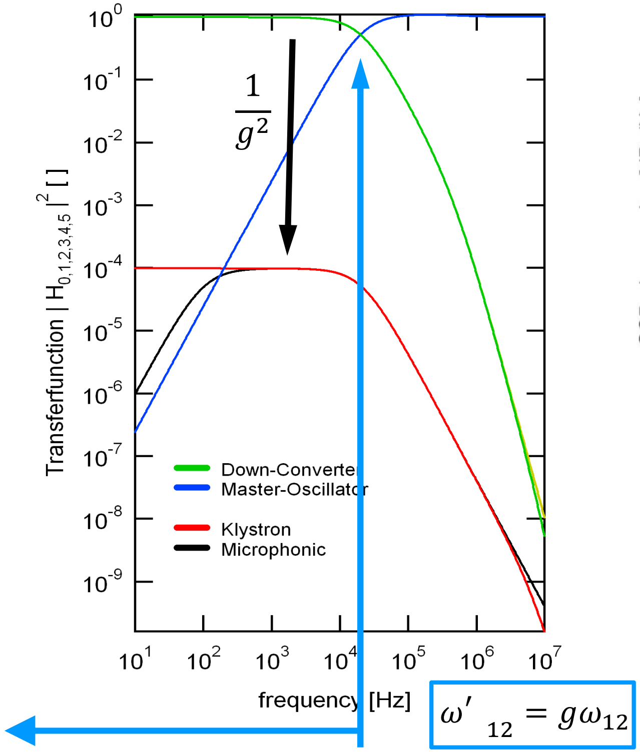
- Beam timing Jitter:



Actuator chain phase noise ↔ Field detector amplitude noise

Noise Contributions from LLRF-Subsystems

- Noise Transfer Functions:



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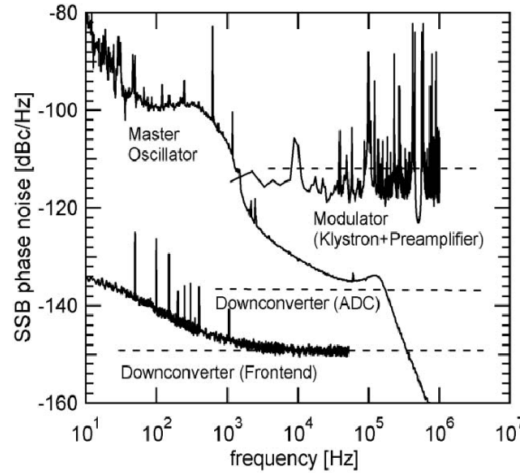

Residual cavity phase and amplitude jitter

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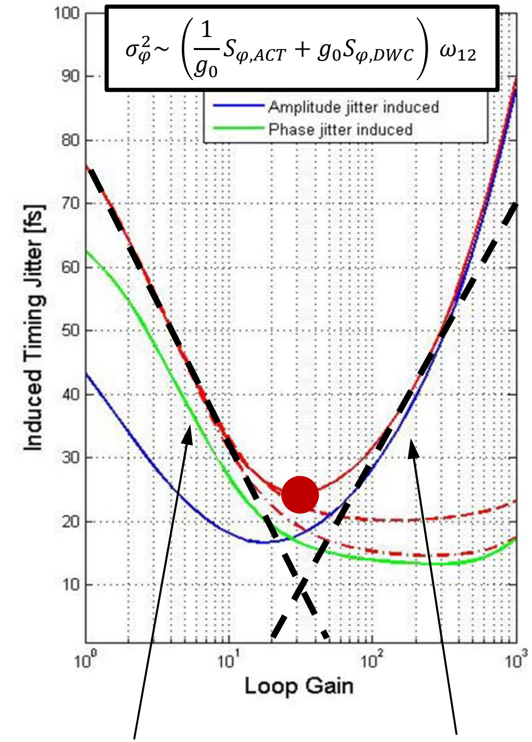


Actuator chain phase noise ↔ Field detector amplitude noise

LLRF-Systems – European XFEL

- XFEL 48-channel LLRF station:

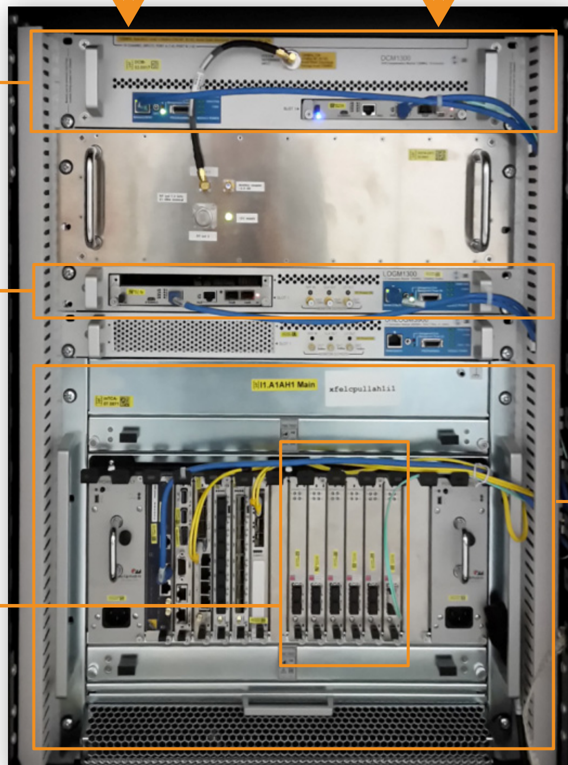
Cavity patch panel

Drift Compensation (DCM, 2U 19")

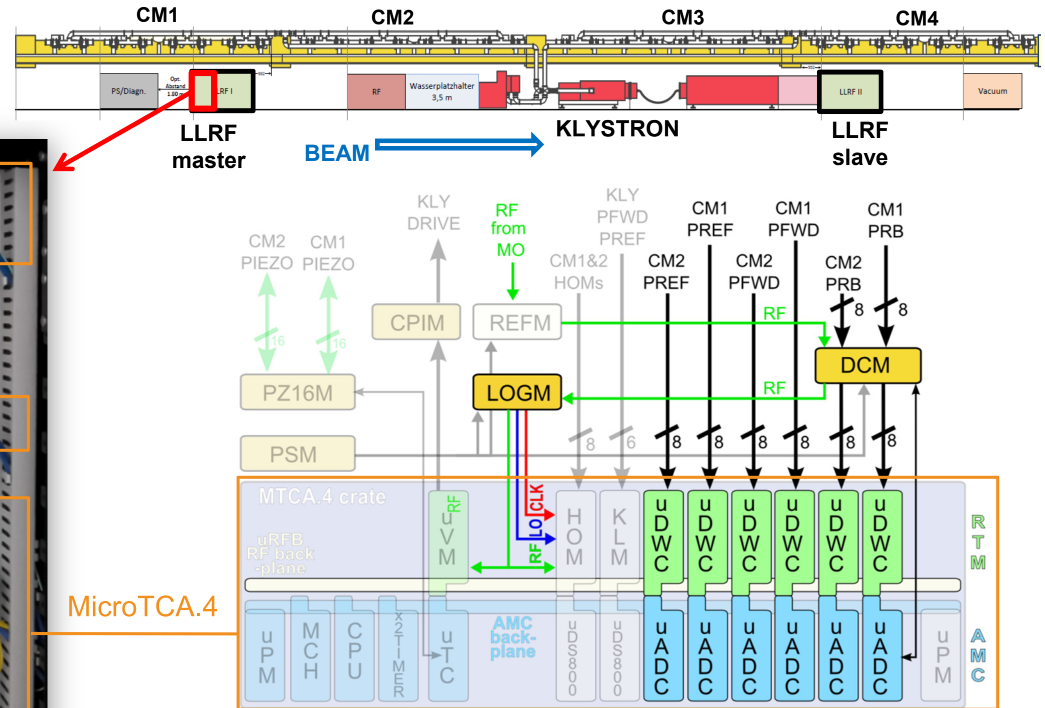
LO-Generation (LOGM, 1U 19")

Down-Converter (DWC, RTM)

Low-noise Digitizer (ADC, AMC)



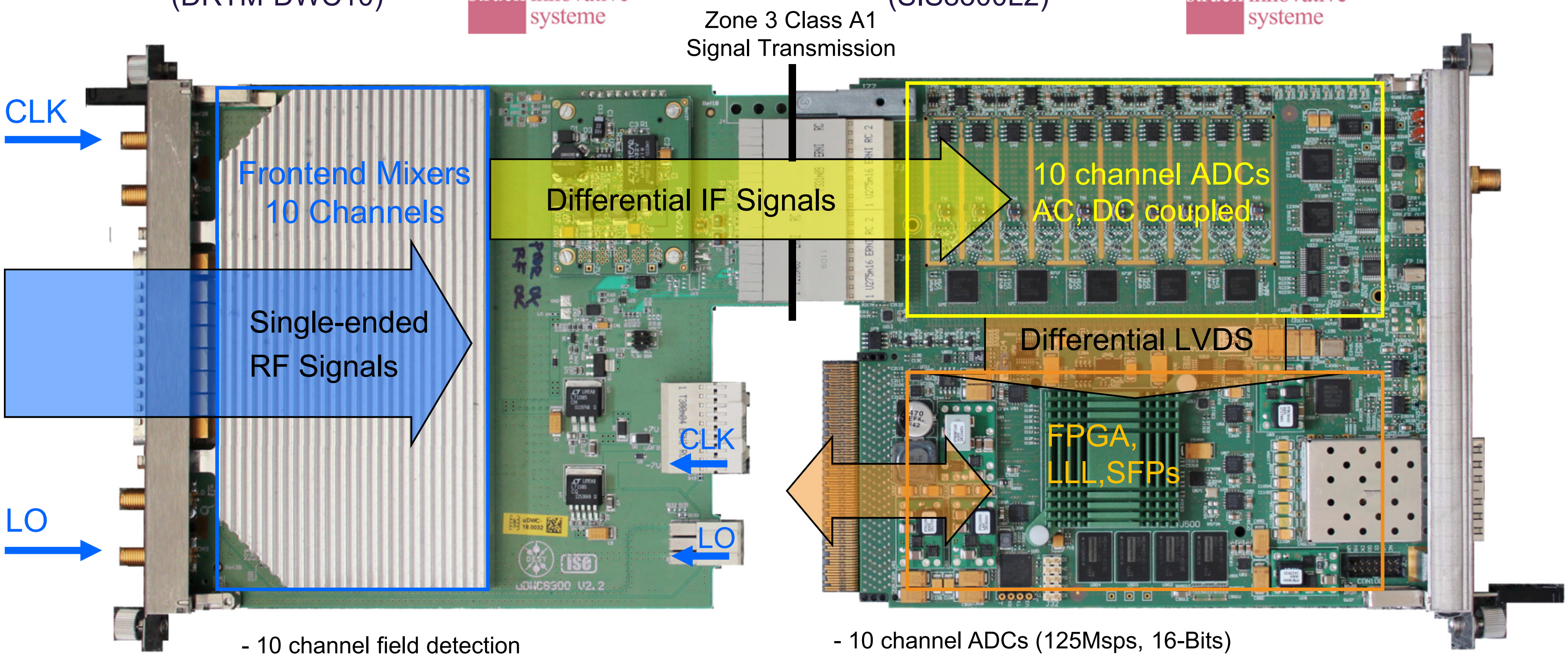
MicroTCA.4



- MicroTCA.4 complete suite: LLRF/Diag./Interlocks/HOM
  Challenges:
- Total: 27 RF station / 800 cavities / >3000 RF signals
- Stability requirements < 0.01% & 0.01deg

LLRF-Systems – Signal Conditioning, Digital Processing

- High frequency Down-Converter (DRTM-DWC10) struck innovative systeme
- Multi-Channel fast ADC Digitizer (SIS8300L2) struck innovative systeme



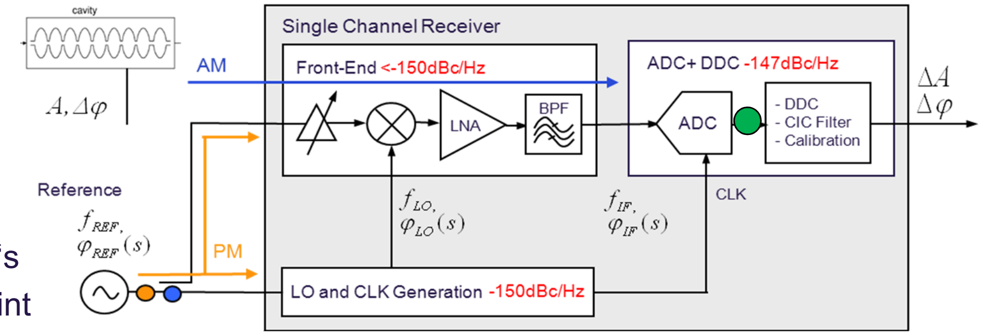
- 10 channel field detection
- S-band (700MHz - 4.0GHz)
- Resolution, 0.004%, < 10fs

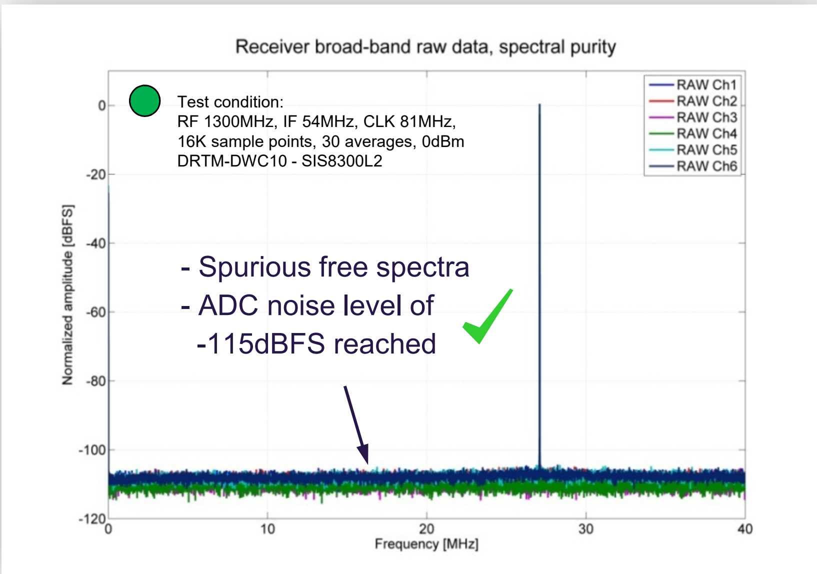
- 10 channel ADCs (125Msps, 16-Bits)
- FPGA (Virtex6) pre-processing partial cavity vectors
- Low latency links via MTCA-backplane

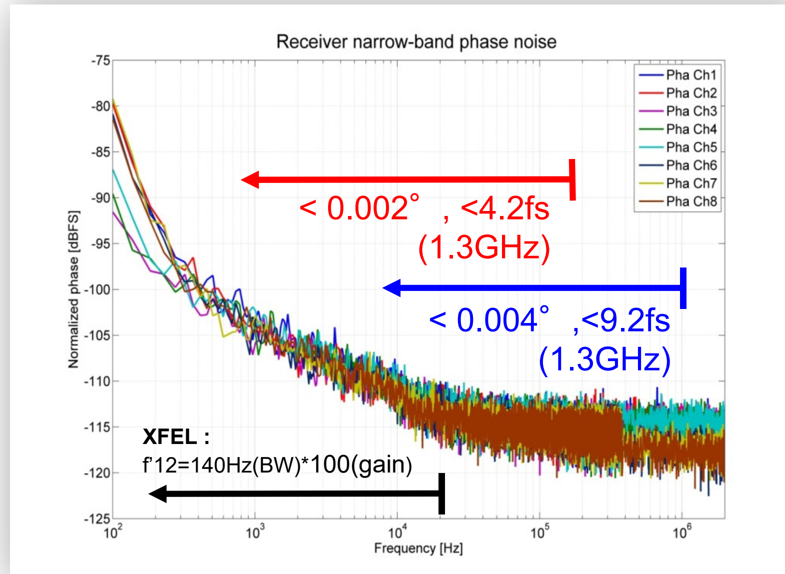
LLRF-Systems Channel Performance

- Spectral purity : (non-IQ Sampling scheme)
  - Mainly ADC limited

System's Fingerprint

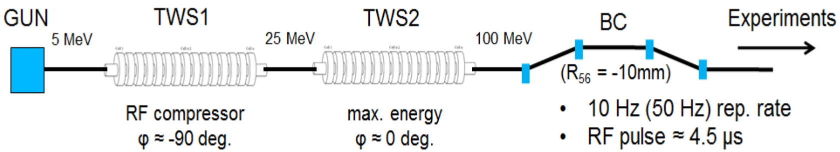






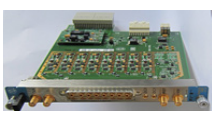
LLRF-Systems – Actuator Noise

TWS Structure (3GHz, f_{12}=500kHz BW) :



- 10 Hz (50 Hz) rep. rate
- RF pulse ≈ 4.5 μs
- Bunch charge few pC

VM+PA+KLY Stability (additive jitter):



-> MOD/KLY @850V (20ppm), 10MW

REGAE, XFEL TDS (PM, AM)

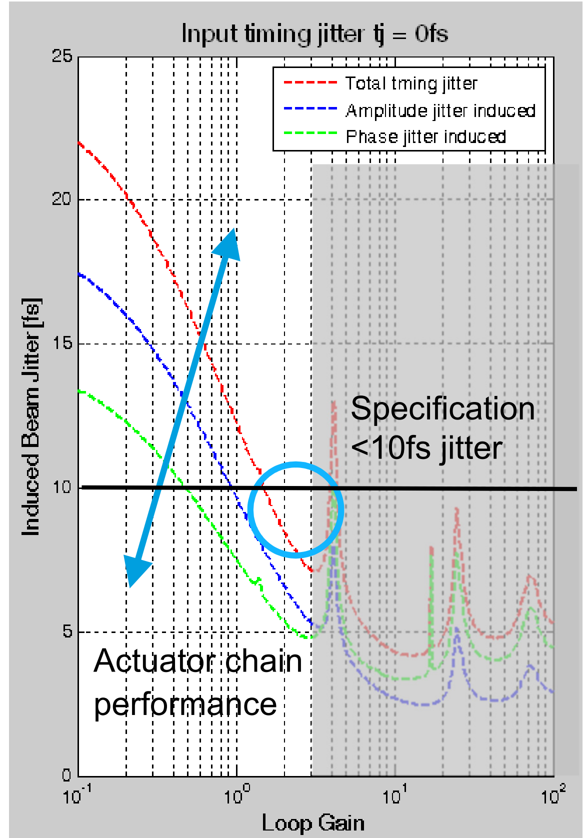
1. KLY MOD
1/f-noise : 13.79fs, ~0.049%, [min,1MHz]

2. Power Amplifier
1/f-noise : 3.4fs, ~0.0039%, [min,1MHz]

3. Vector-Modulator
1/f-noise : 2.9fs, ~0.0063%, [min,1MHz]

High-power chain : ✓
-> 14.5fs, 0.049%, -165dBc/Hz

Beam timing Jitter :



Gain Limitation :

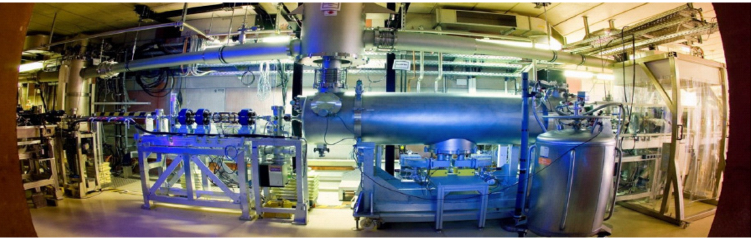
$$g_{max} = \frac{1}{4 t_D f_{12}} \approx 2 \dots 5$$

Latency Budget t_D	[ns]
RF-cables (5.5ns/m)	280
Field detection	80
LLRF Controller	300
High-power chain	100

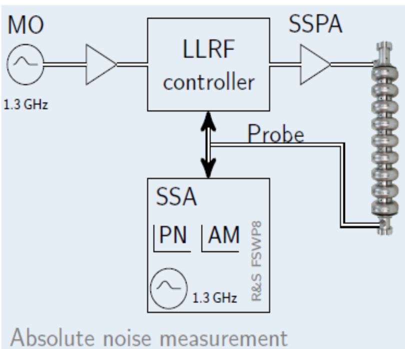
↷ In NC RF-Controls the stability is limited by the actuator chain (mainly modulator) and latency.

Courtesy of M.Hoffmann

LLRF-Systems – CW-Operation with an SRF-Cavity

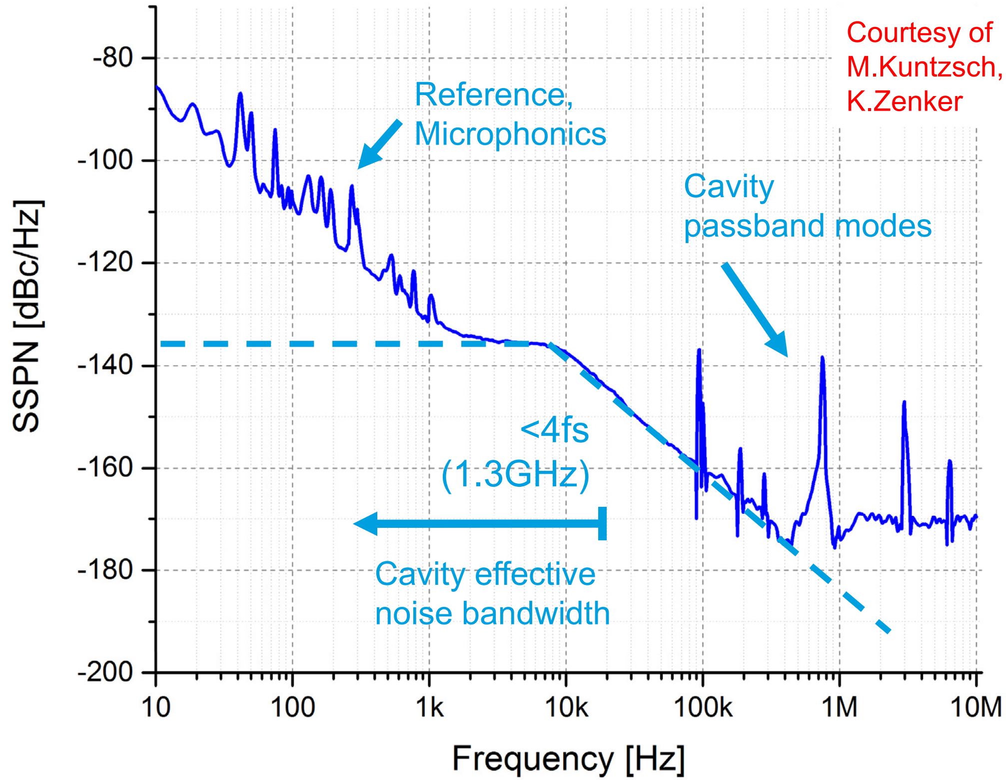


■ Absolut/Residual noise measurements :

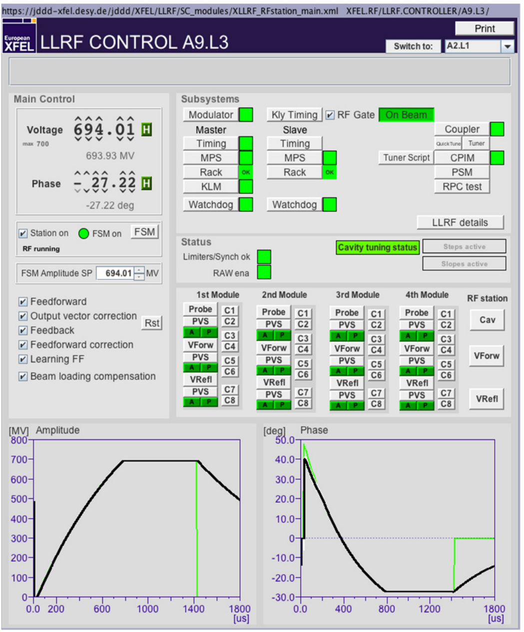


- High precision **out-of-loop measurement** PN/AN using signal source analyzers
- Direct investigation of noise sources

Out-of-loop absolute phase noise spectrum (FSWP)



Digital-Signal-Processing – In-loop Regulation Performance



RF field regulation

Repetitive disturbances

- Beam loading compensation
- Adaptive feed forward
- Set-point optimization
- Fundamental mode filters
- Loop gain/phase correction

Stochastic disturbances

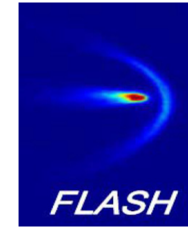
- MIMO controller
- Gain scheduling
- Drift compensation
- Intra-train beam based FB

Limitations and security thresholds

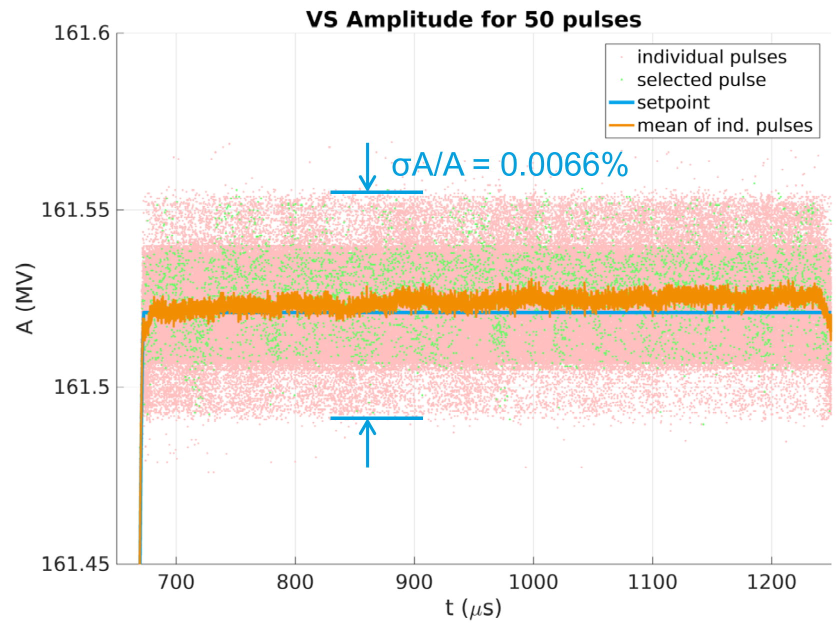
- Limiters on all control tables
- Final output limiter
- Individual cavity limiters
- Communication link error detection

Resonance control

- Slow motor tuners
- Fast Piezo tuners

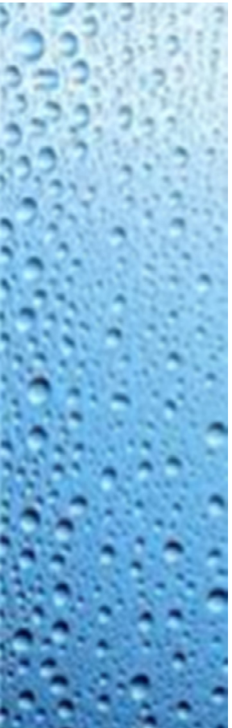


Regulation performance:
- In-loop within the specs (0.01%, 0.01 deg)
- Out-of-loop using BAMs ~25fs



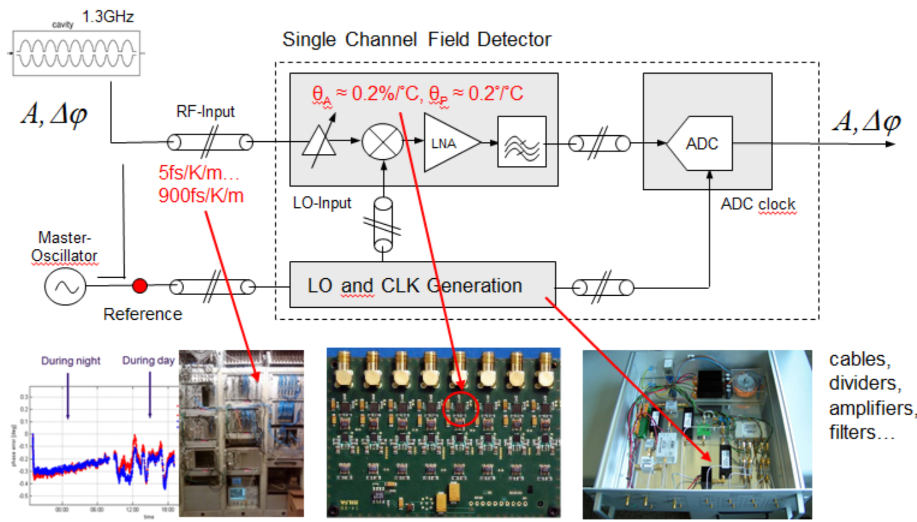
Courtesy of C.Schmidt

Long-term Stability – Depends on Temperature and Humidity



Why is this important ? -> Robust machine operation

- Distributed down converter (non-IQ-sampling scheme)

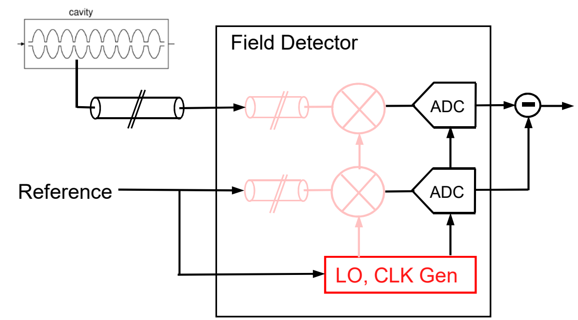


- Distortions are in the order of pico-seconds.
- Long-term stability depends on temperature and strongly on humidity.
  (Water penetrates slowly into the PCB/cable dielectric)

- No stabilization
  (+/-) Fully rely on beam-based feedbacks

- Passive stabilization
  (+) Simple method
  (--) Requires rack stabilization <0.2K_pp
  (--) Requires rf-packages with sealing

- Reference tracking



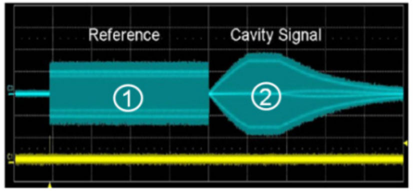
(+) Works quite good on PCB integrated detectors
(--) Depends strongly on external cable symmetry

- Reference injection (2nd-tone)

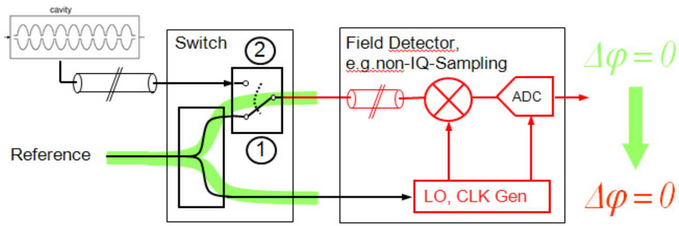
Long-term Stability – Drift-Compensation-Module

Courtesy of J.Piekarski

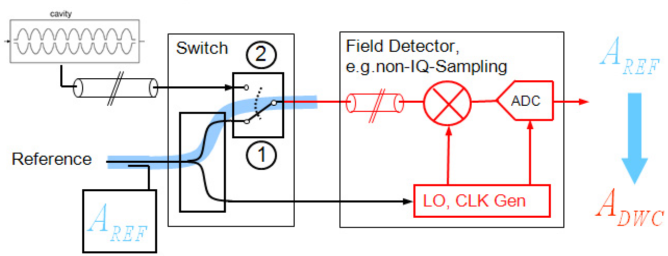
- Reference injection :
  (only for pulsed machines)



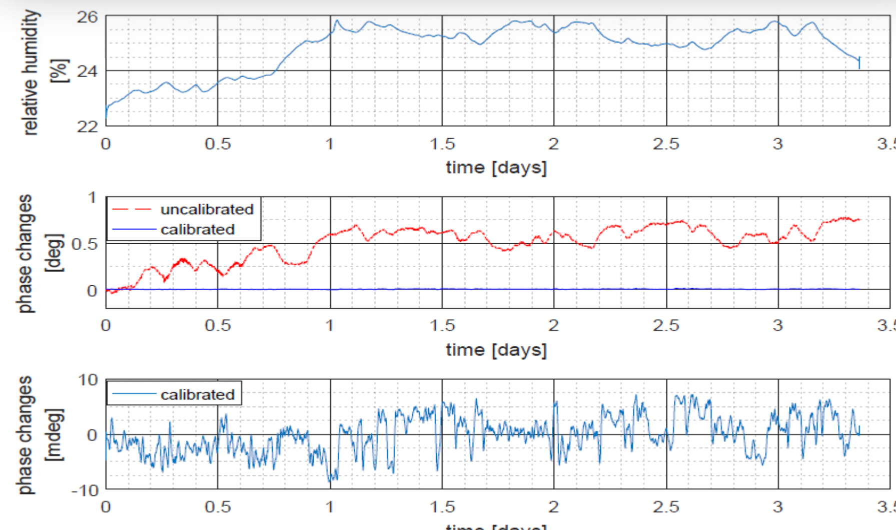
Relative Phase Calibration :



Absolute Amplitude Calibration :



Factor of phase and amplitude reduction >150
<40fspp over 3 days (1.3GHz)

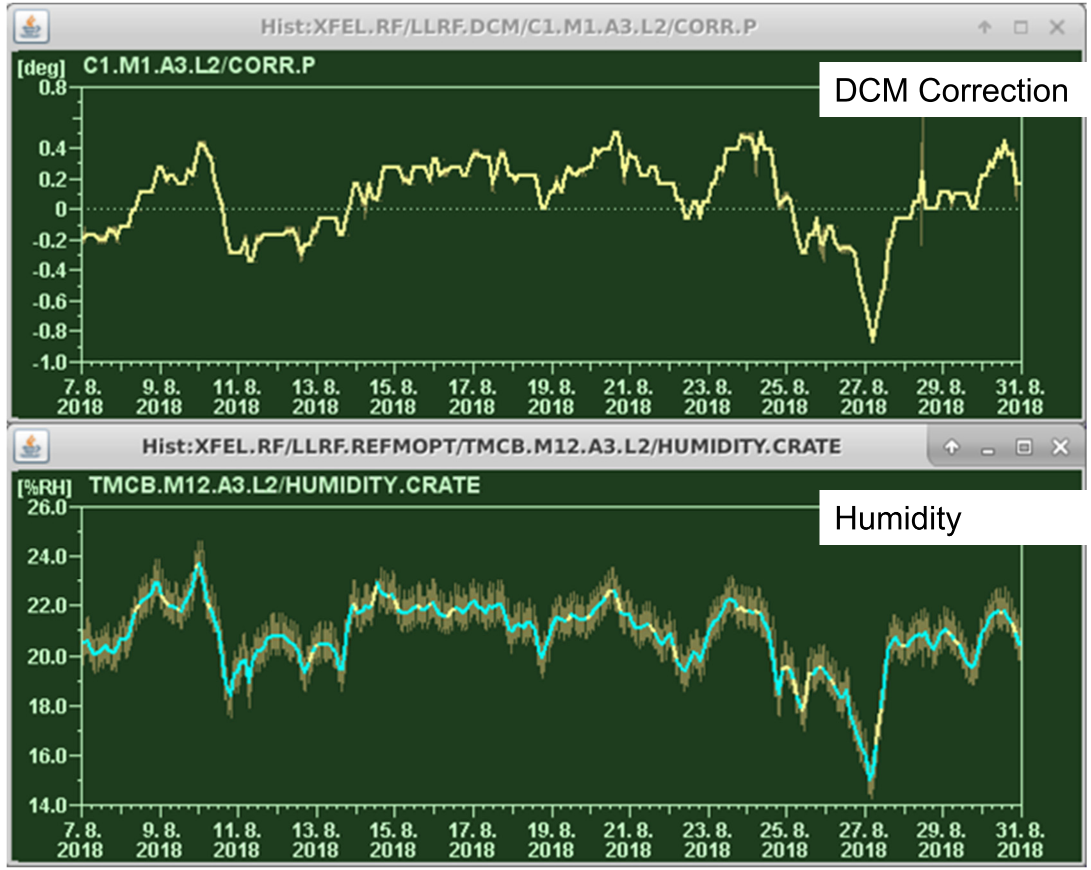


FLASH injector hutch ACC1' operation

Long-term Stability – DCM in Action

Humidity induced phase drifts dominates and compensated by using the injection reference.

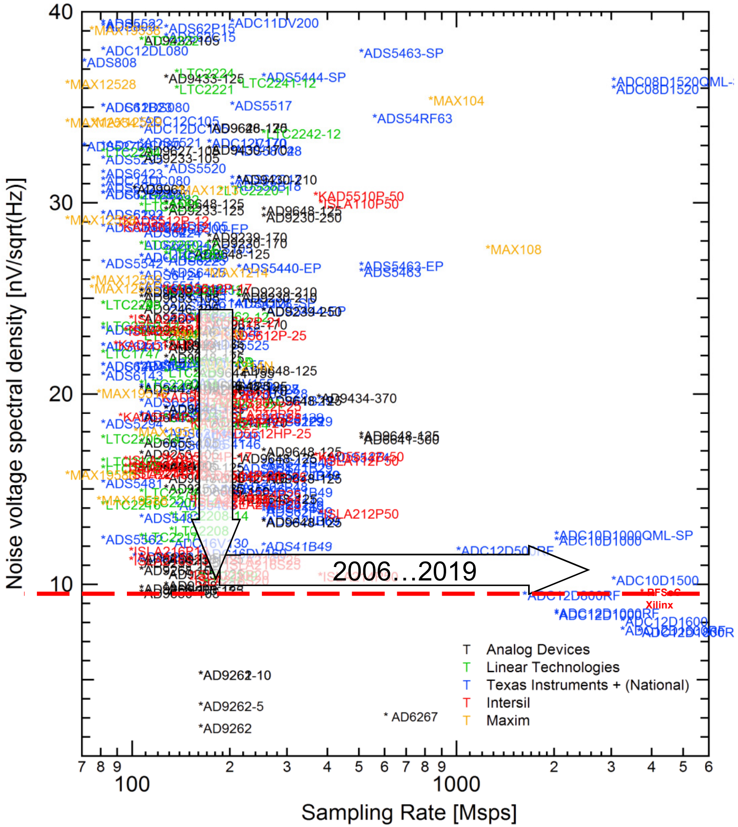
Rule of thumb @ 1.3 GHz:
1% Humidity change
~ 0.1deg Phase change



Courtesy of T.Lamb

fs-Precision – Limitations

- Commercial ADCs :



- Limited ADC Performance:

ADCs become faster, but no improvement in NSD since 2007

- ADC Parallelization (SRF):

Goal: 100 ADCs („IF-Sampling" type) + internal averaging:
<1nV/sqrt(Hz), 16-bit, ~150Msps, SNR >95dB, latency <100ns

-> OnChip
-> Chip Industry

-> in Standards
-> LLRF Community

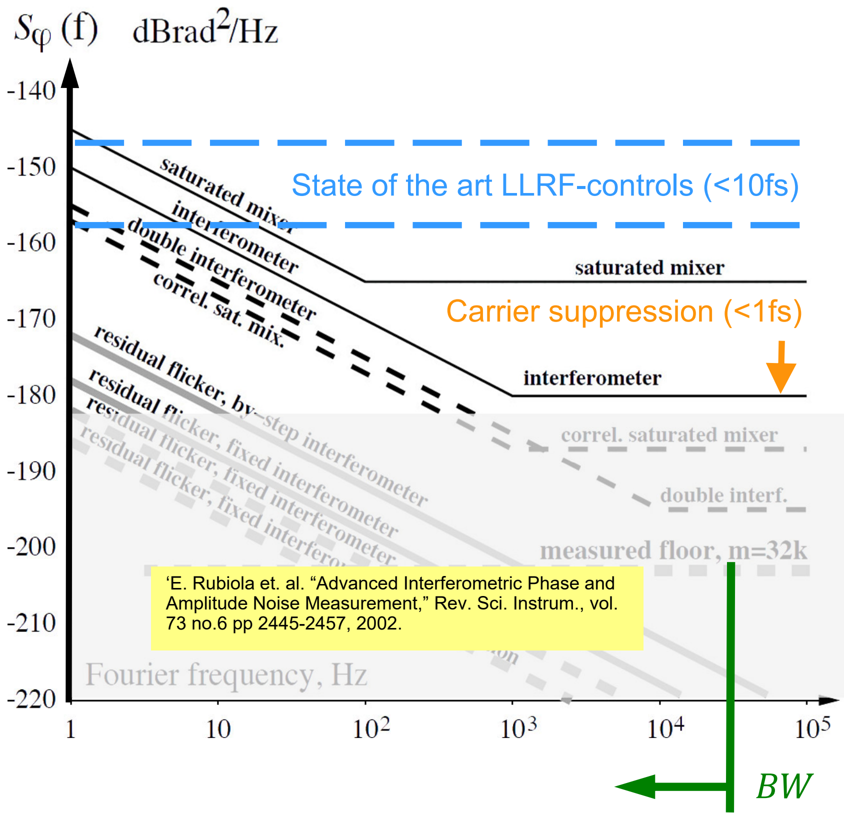
- High-power chain (NRF-pulsed):

- Modulator : Stability of power supplies
- Power Amplifier : 1/f-noise & spurs,
  Missing CW-diagnostic for internal stages

RF-Controls towards as-Precision

Towards as-Precision – Options (Field Detection)

- Options to increase the measurement resolution <100as (real time):



(1) Increase the RF-power:
- PN, AN linear in RF-power
- Carrier Suppression Interferometer
- High level mixer

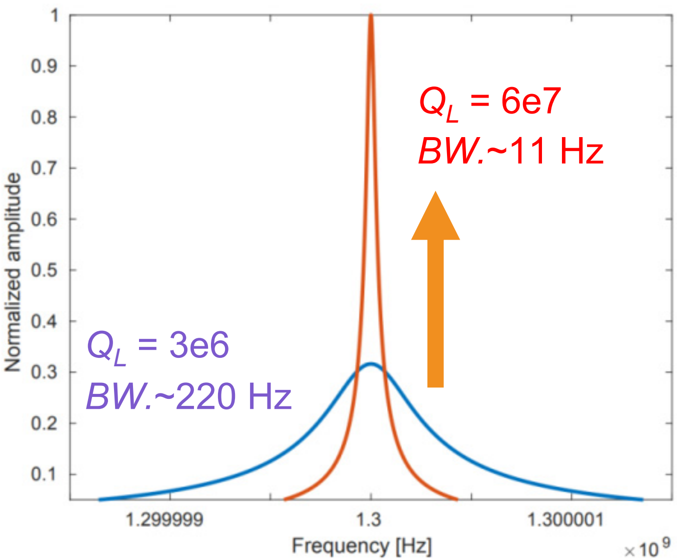
(2) Reduce the noise floor:
- ADC/Channel parallelization, ~\sqrt(N)
- ~~Time correlation (no real time)~~

Correlation techniques

(3) Reduce the cavity bandwidth:
- Use >16-bit ADCs with better NSD (higher latency, SAR, Sigma-Delta)

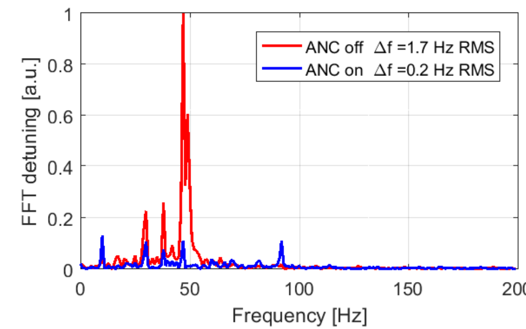
High-Q_L Cavity Operation – CW Operation

- Increasing the cavity external quality factor:
  - (+) Less power required to achieve same gradient
  - (+) Reduced effective noise bandwidth
  - (--) More sensitive to microphonics

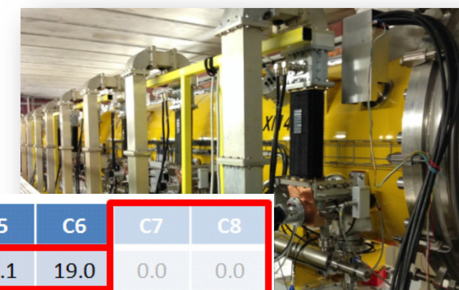


- Suppress microphonics:
  - Apply Active Noise Cancellation to notch measured frequencies
  - Suppression > 20 dB can be achieved

"FPGA-Based RF and Piezo controllers for SRF Cavities in CW Mode", R. Rybaniec et al. IEEE TRANSACTIONS ON NUCLEAR SCIENCE, VOL. 64, NO. 6, JUNE 2017



- Results for high Q_L, high gradient, vector-sum :
  - CW operation in vector sum
  - using piezo and RF feedbacks



	C1	C2	C3	C4	C5	C6	C7	C8
Eacc [MV/m]	20.0	20.5	20.3	20.6	20.1	19.0	0.0	0.0
QL [x1e7]	6.2	6.2	6.3	6.1	6.1	6.2	2.8	2.8

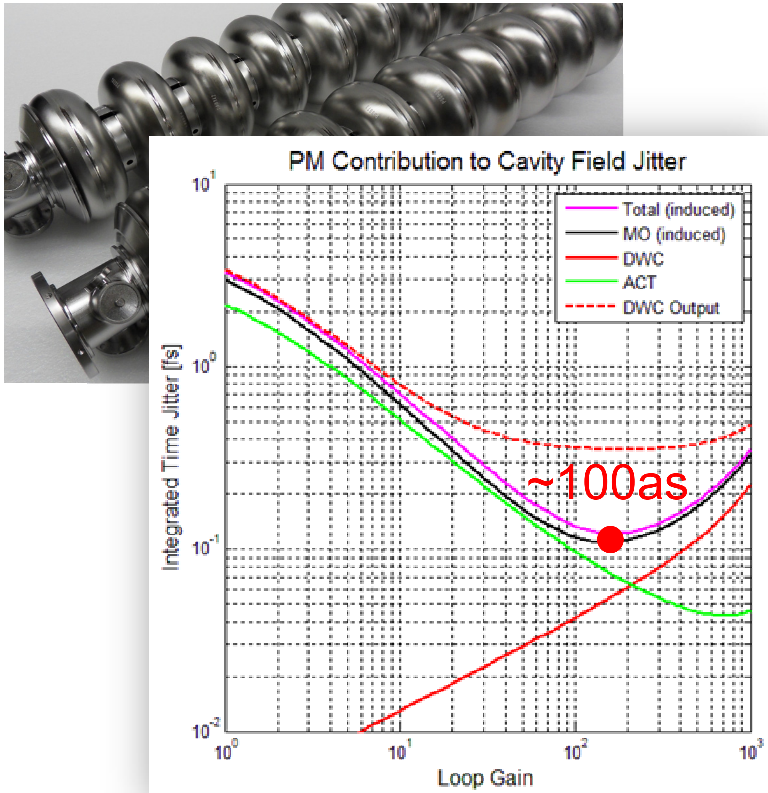
dA/A ~ 0.007%, dP ~ 0.015 deg.

Excluded from VS due to Ql max < 6e6

Courtesy of J.Branlard

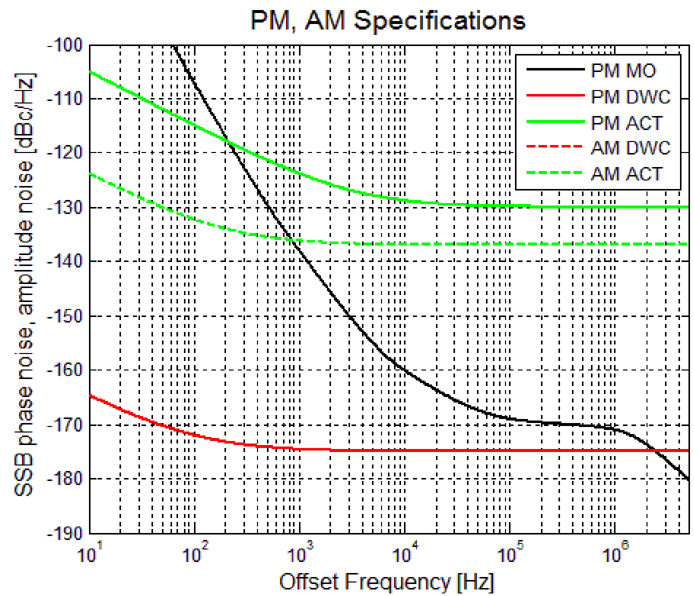
Towards as-Precision – LLRF Component Requirements

- SRF-Cavity (1.3GHz, Q_L $3 \cdot 10^6$, BW 200Hz) :



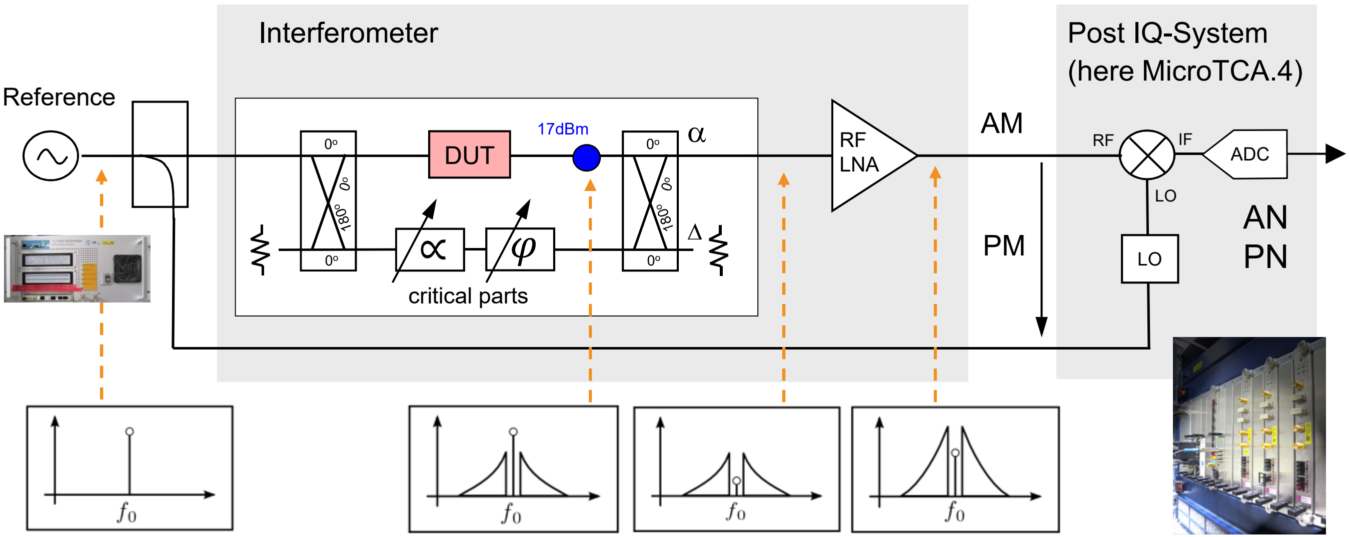
- LLRF Component Requirements :

Master reference (MO) : <-170dBc/Hz
Actuator chain (ACT) : <-140dBc/Hz
Field detectors (DWC) : <-175dBc/Hz (-150dBc/Hz)



Towards as-Precision – Carrier Suppression-Interferometer

- Carrier-Suppression-Interferometer Prototype :



(+) No carrier -> no 1/f-noise from LNA, DUT noise pass the system

(+) PN, AN scales with RF-power

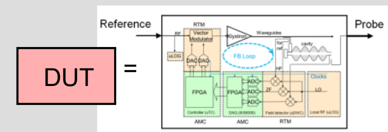
(--) Needs a carrier tracking for destructive interference

Challenges for <100as:

- Tunable phase shifters
- Tunable attenuators

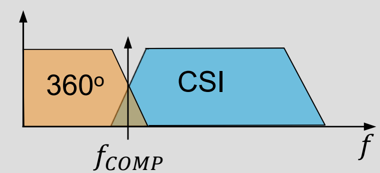
Replacement:

- DUT = LLRF System



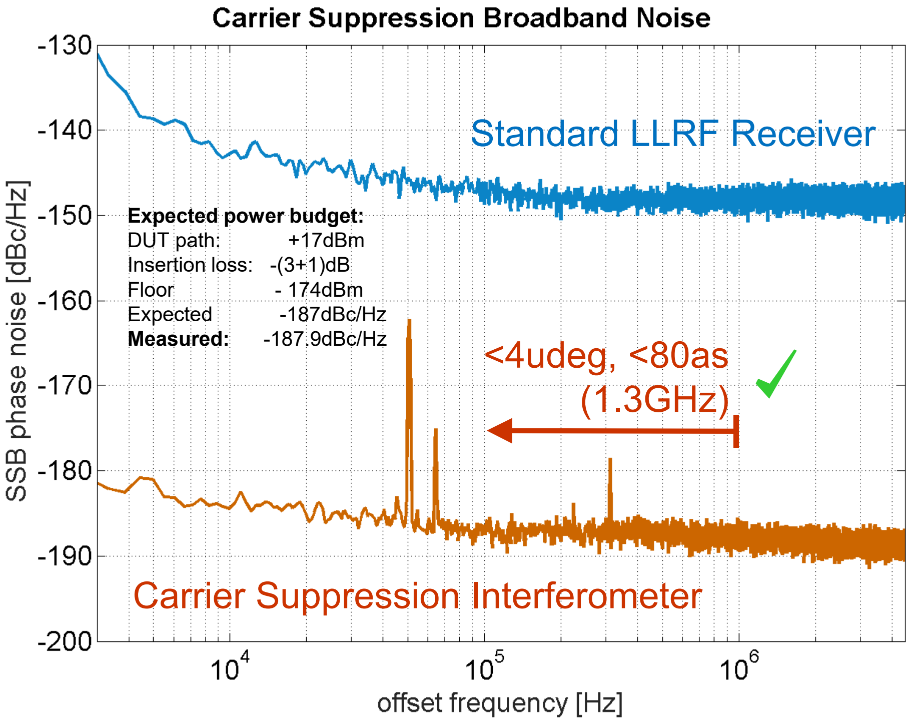
Large signal detector:

- Hybrid with non-IQ



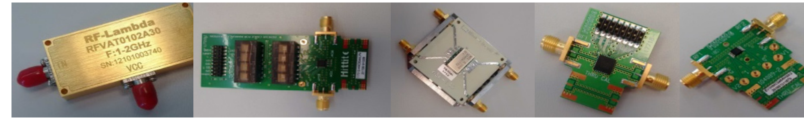
Towards as-Precision – Carrier Suppression Prototype

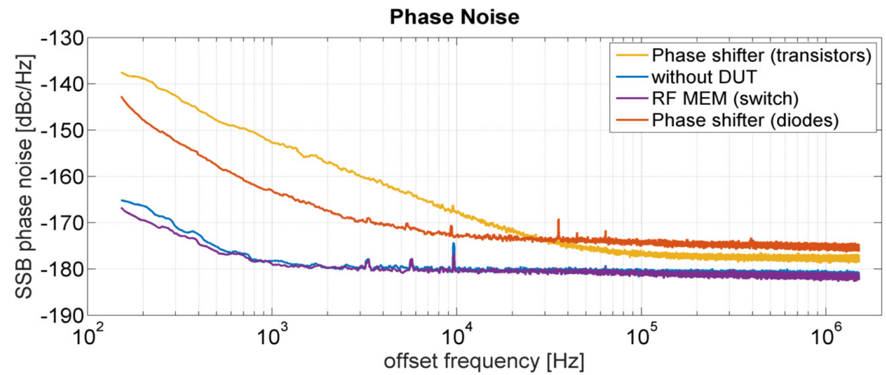
- Short-term performance @ +17dBm, 1.3GHz (uncorrelated):

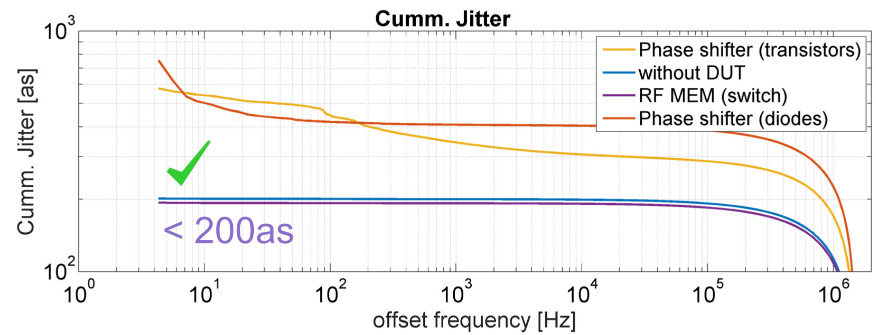


Courtesy of L.Springer

- DUT Tests in PN, AN below 1fs :



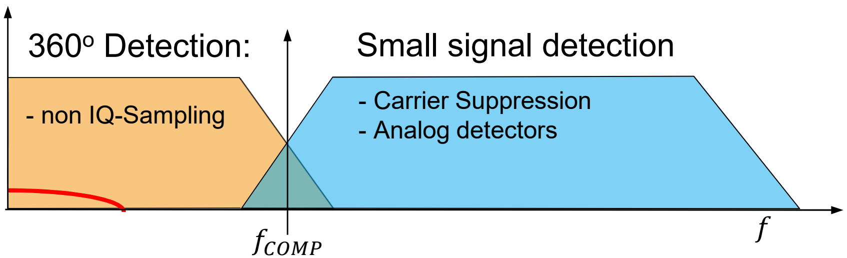




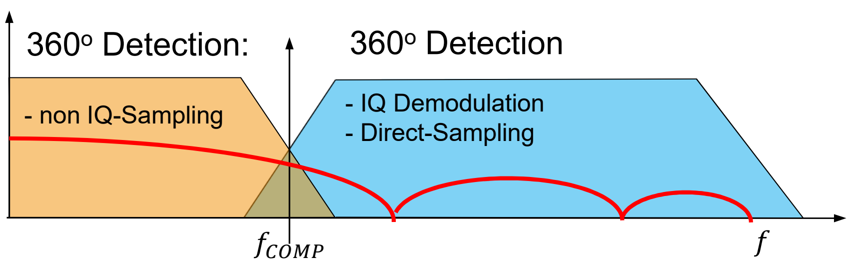
Low-noise Receiver Concepts – Hybrids and Parallelization

- Down conversion hybrid options :
  (not needed for SRF, high-Q, 10Hz)

Example: CW-operation

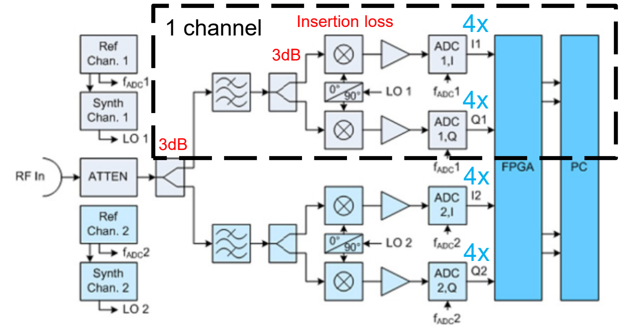


Example: Broadband 360° Operation



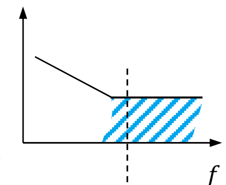
- Example : FSWP R&S

Courtesy of R&S

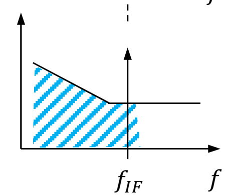


ADC vs. RF-channel parallelization
(+) No rf-power loss for splitting near baseband

Direct down-conversion (LO=REF)
-> High-offset spectral information
(+) No add. LO-noise contributions (>IF)
(+) IQ-Calibration removes IQ-90deg imperfections



Non-IQ IF down-conversion (IF>0)
-> Low-offset spectral information
(+) Avoids noise components from baseband
(--) LO-contribution, but bandlimited (<IF)
(+) Low IF minimize ADC CLK influence



https://www.rohde-schwarz.com/de/applikationen/1-mhz-bis-50-ghz-phasenrauschmessplatz-mit-direkter-abwaertsmischung-und-kreuzkorrelation-application-card_56279-231872.html

Summary and Outlook

- RF-Controls with spurious free short-term amplitude and phase detection below <10fs [1MHz BW] is available for the accelerator community in modern standards like MicroTCA.4 or proprietary systems.

- Having 10x better ADCs would be a big milestone for the community

- RF-controls with <100as field stability requires :

SRF: - High-Q_L cavity operation
- Hybrid field detectors
- Brute force parallelization, preferable in standards

NRF: - Low latency hybrids
- High-power chain stabilization loops
- High-power chains, RF-amplifiers below <1fs (better 1/f-noise, no spurs)

Thanks for your attention!