

# From femtosecond to attosecond RF field control.

IPAC 2026, 17th International Particle Accelerator Conference

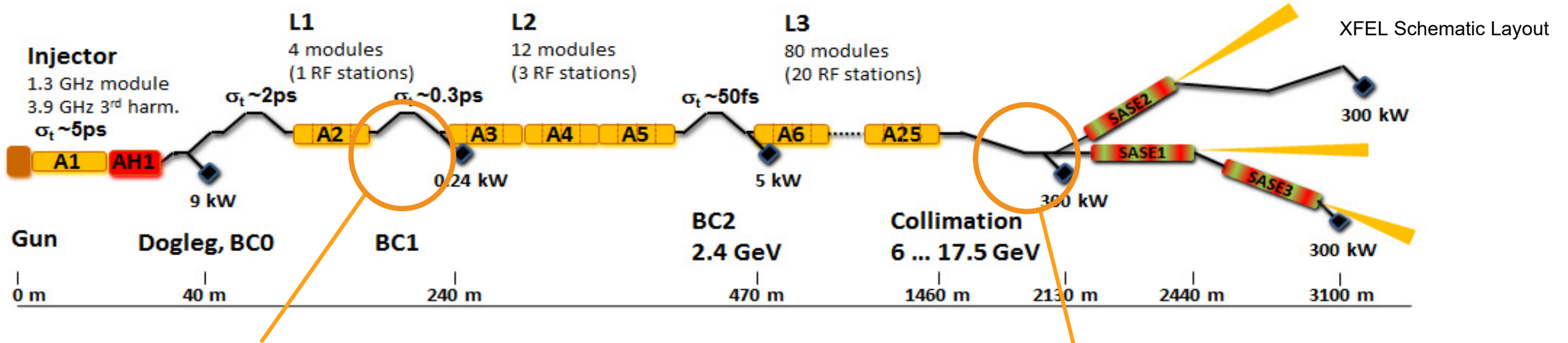


Dr. Frank Ludwig on behalf of the LLRF, LbSync, Special Diag. team at DESY  
Deauville, Normandy, France, 22.05.2026

HELMHOLTZ RESEARCH FOR  
GRAND CHALLENGES



# Source of timing jitter for accelerators / FELs



- RF acceleration fields define arrival time:

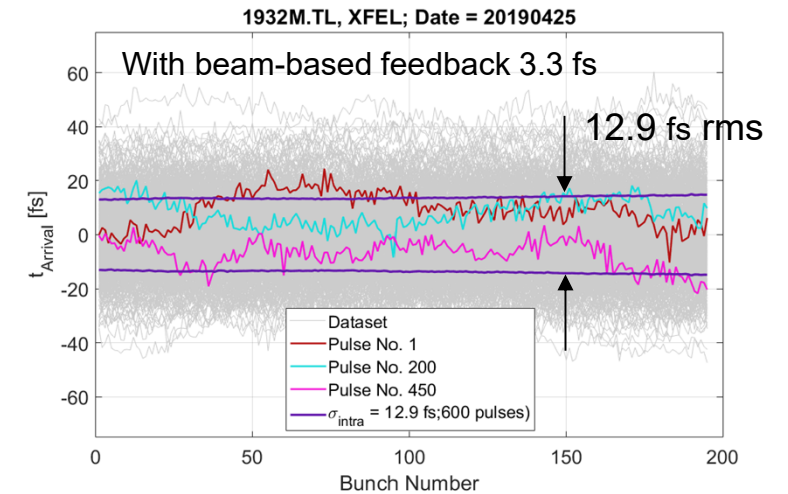


Bunch Compressor BC1

$$t_{j,out}^2 \approx \underbrace{\left(\frac{R_{56}}{c_0} \frac{\sigma_A}{A}\right)^2}_{\text{Amplitude}} + \underbrace{\left(\frac{C-1}{C}\right)^2 \left(\frac{\sigma_\phi}{c_0 k_{rf}}\right)^2}_{\text{Phase}} + \underbrace{\left(\frac{1}{C}\right)^2 t_{j,in}^2}_{\text{Init. arrival}}$$

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

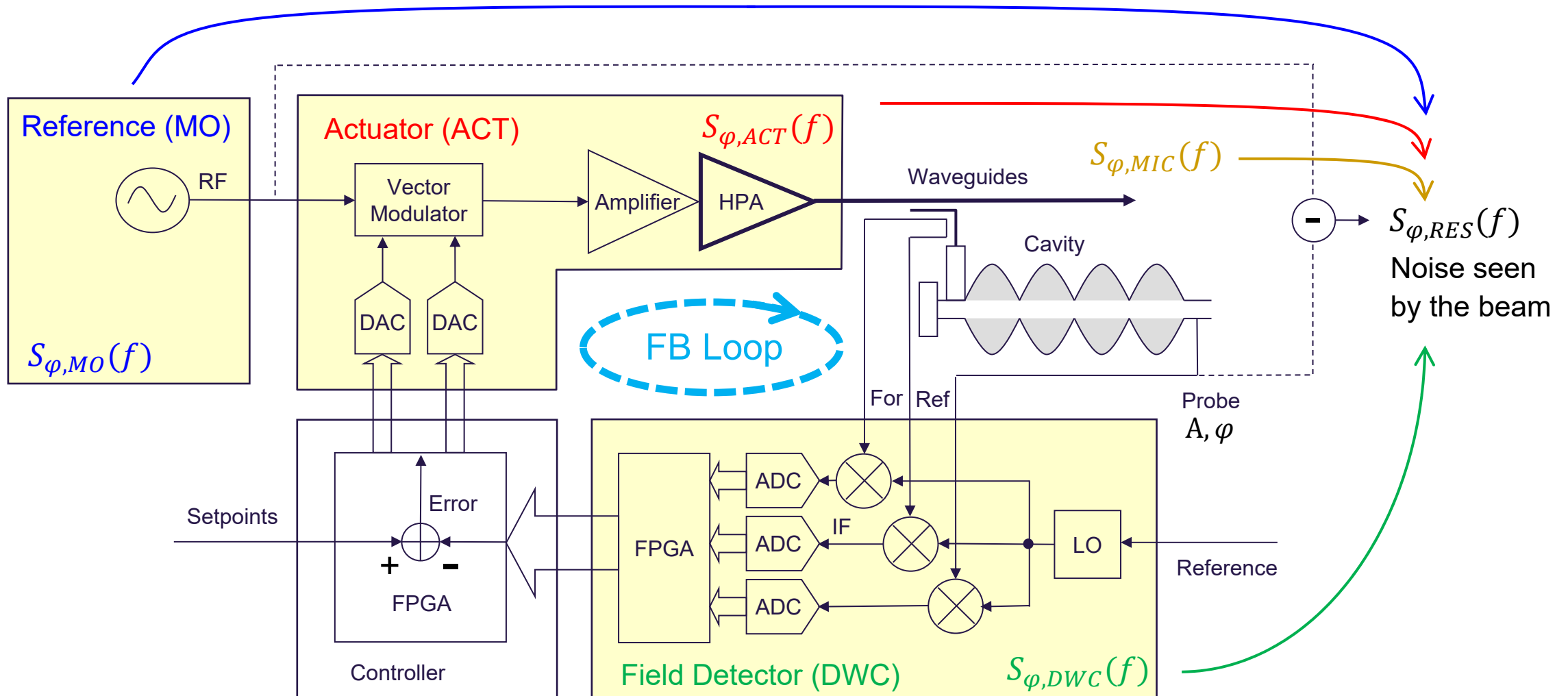


Courtesy of H.Schlarb

# Low-Level-Radio-Frequency (LLRF) Control



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



# Low-Level-Radio-Frequency (LLRF) Control



- Concept of envelope approach for AN, PN modelling (simplified):

$$S_{\varphi,RES}(f) = \underbrace{\left| \frac{s}{s + \omega'_{12}} \right|^2}_{\text{high-pass}} S_{\varphi,MO}(f) + \underbrace{\left| \frac{\omega'_{12}}{s + \omega'_{12}} \right|^2}_{\text{low-pass}} \left( S_{\varphi,DWC}(f) + \frac{1}{g_0^2} S_{\varphi,ACT}(f) \right) + \underbrace{\left| \frac{s + \omega_{12}}{s + \omega'_{12}} \right|^2}_{\text{high- and low-pass}} S_{\varphi,MIC}(f)$$

Cavity effective noise bandwidth  
 $\omega'_{12} = g_0 \omega_{12}$

↪ Cavity field phase fluctuations \*:

$$\sigma_{\varphi,RES}^2 \approx K_{MO} \ln(2) + \underbrace{\left( g_0 S_{\varphi,DWC} + \frac{1}{g_0} S_{\varphi,ACT} \right)}_{\text{Optimal gain}} \underbrace{\frac{\pi}{2} f_{12} + \frac{2}{(g_0 f_{12})^2} S_{\Delta f,MIC} \Delta f_{MIC}}_{\text{Optimal cavity bandwidth}}$$



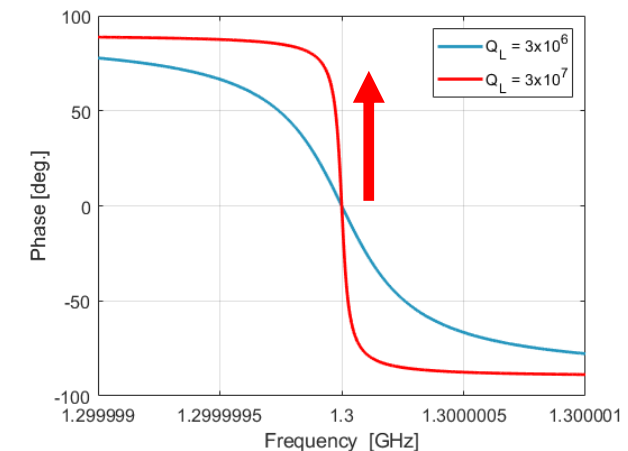
- The actuator and microphonic noise can be reduced by increasing the gain \*\*.
- But the field detector noise must be very low.

Microphonics:

Detuning to phase conversion

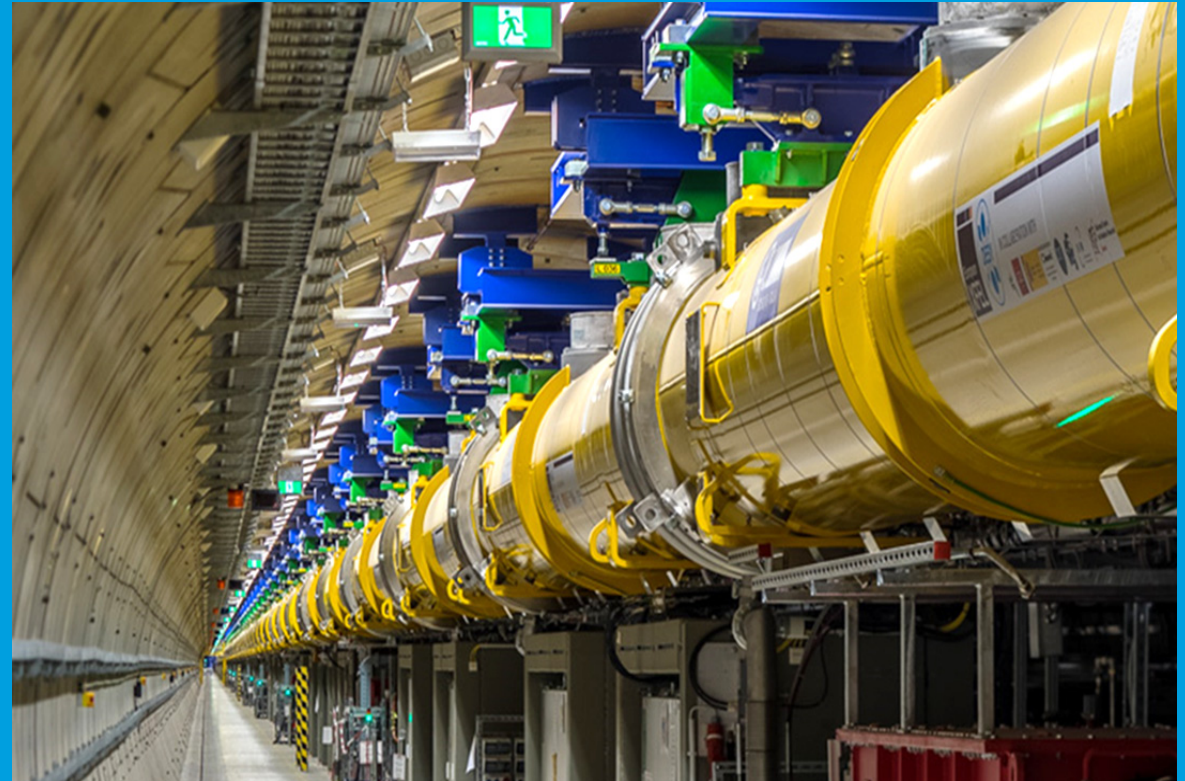
$$S_{\varphi,MIC}(f) = \left( \frac{2Q_L}{f_0} \right)^2 S_{\Delta f,MIC}(f)$$

$$S_{\varphi,MIC}(f) = \left( \frac{1}{f_{12}} \right)^2 S_{\Delta f,MIC}(f)$$



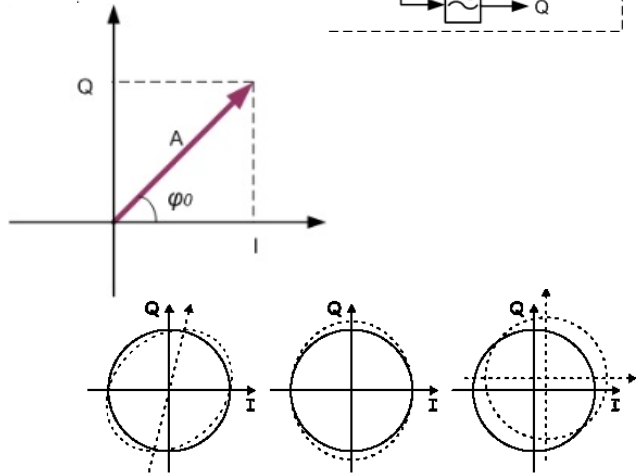
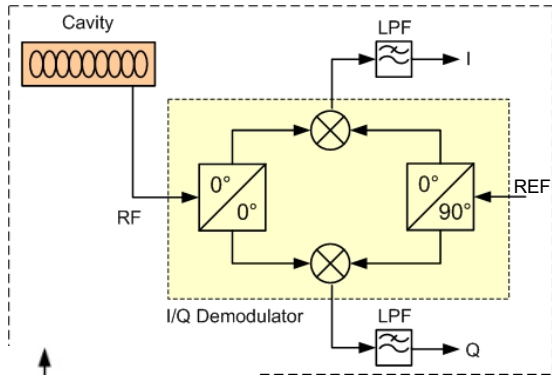
\* MO with 1/f, DWC, ACT, MIC white noise behavior., \*\* limited by the system latency

# RF-Controls with fs-Precision



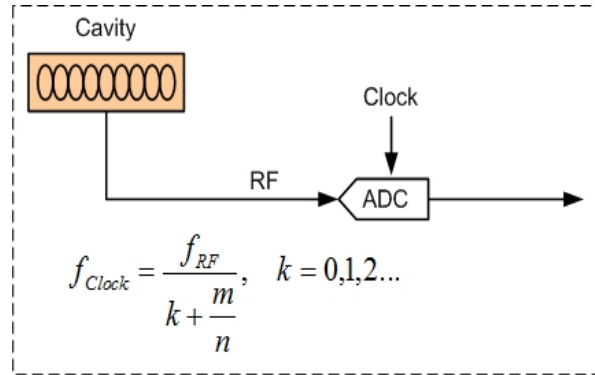
# Field Detectors – Modulation Schemes

## ■ IQ-baseband Sampling:



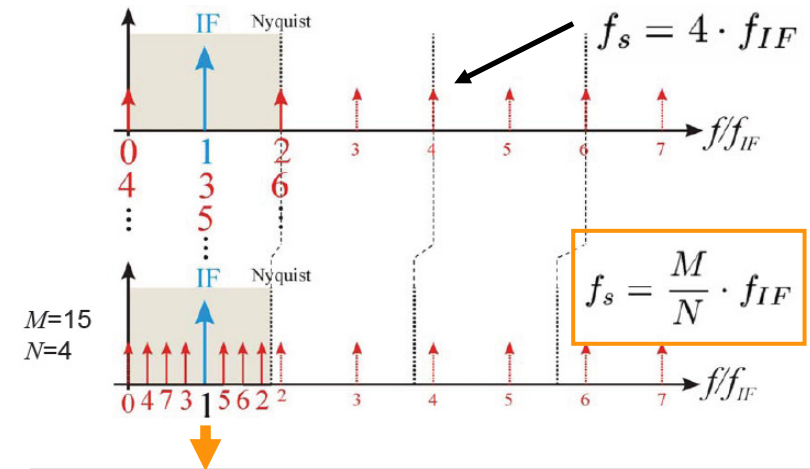
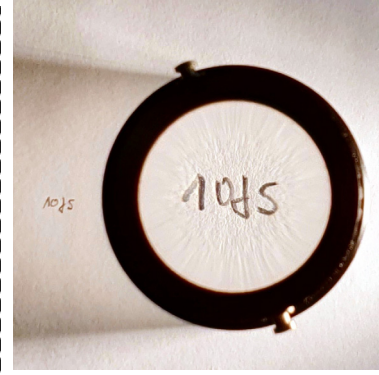
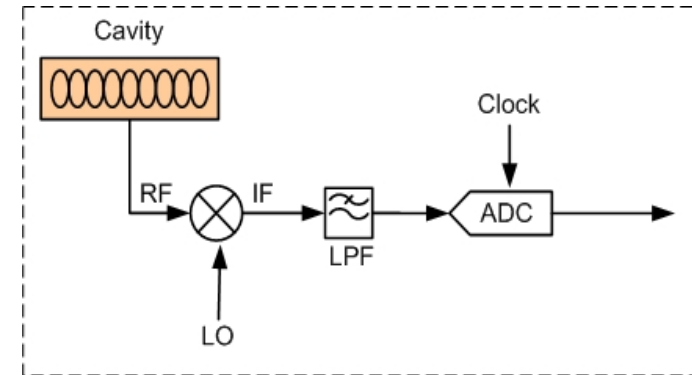
- (+) No LO-Generation
- (-- ) IQ-Errors in the % range
- (-- ) PM to AM effects
- (-- ) IQ-Calibration is needed

## ■ Direct Sampling:



- (+) Wideband, flexible use
- (+) AM <0.01% @ 1.3GHz
- ( ) SNR sensitive to CLK jitter due to high input frequency

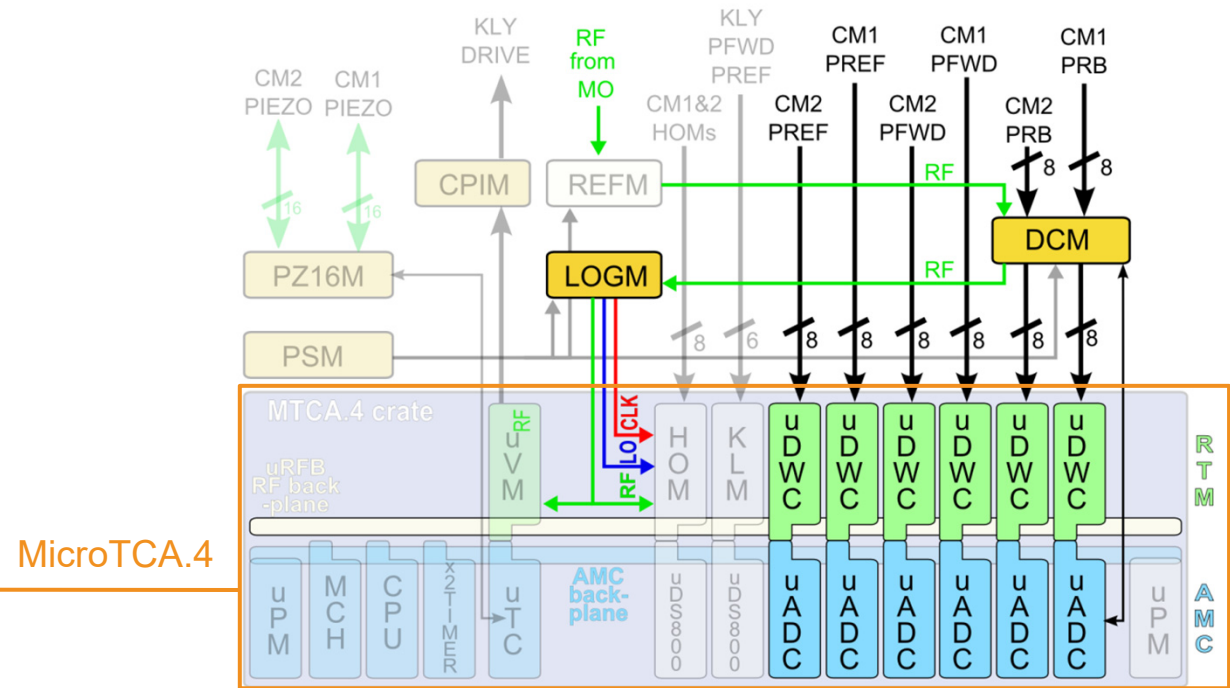
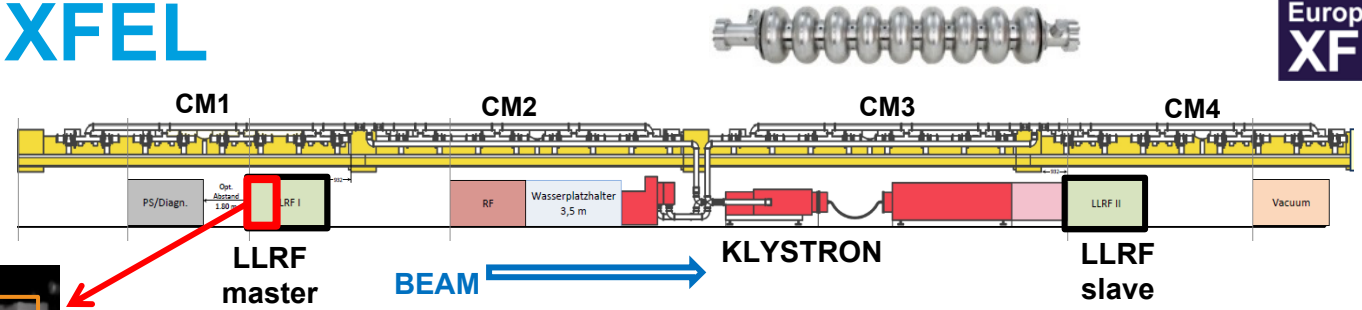
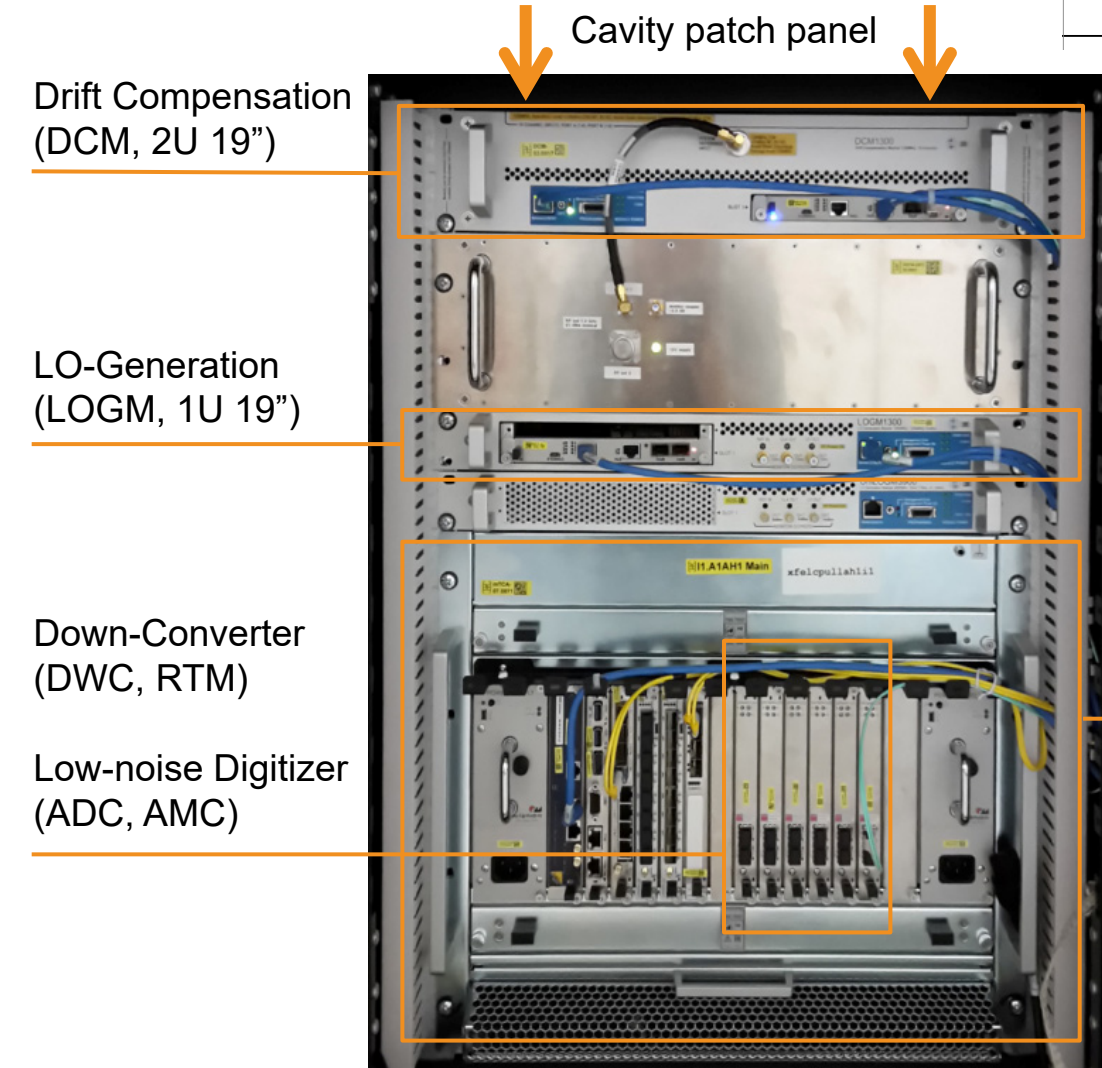
## ■ Non-IQ Sampling (gold standard):



- (+) Most harmonics do not alias into the signal
- (+) No PM to AM effects
- (+) Analog mixer 'magnifies' the RF time jitter
- (-- ) Requires mixer and LO-Generation

# LLRF-Systems – European XFEL

## ■ XFEL 48-channel LLRF station:



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

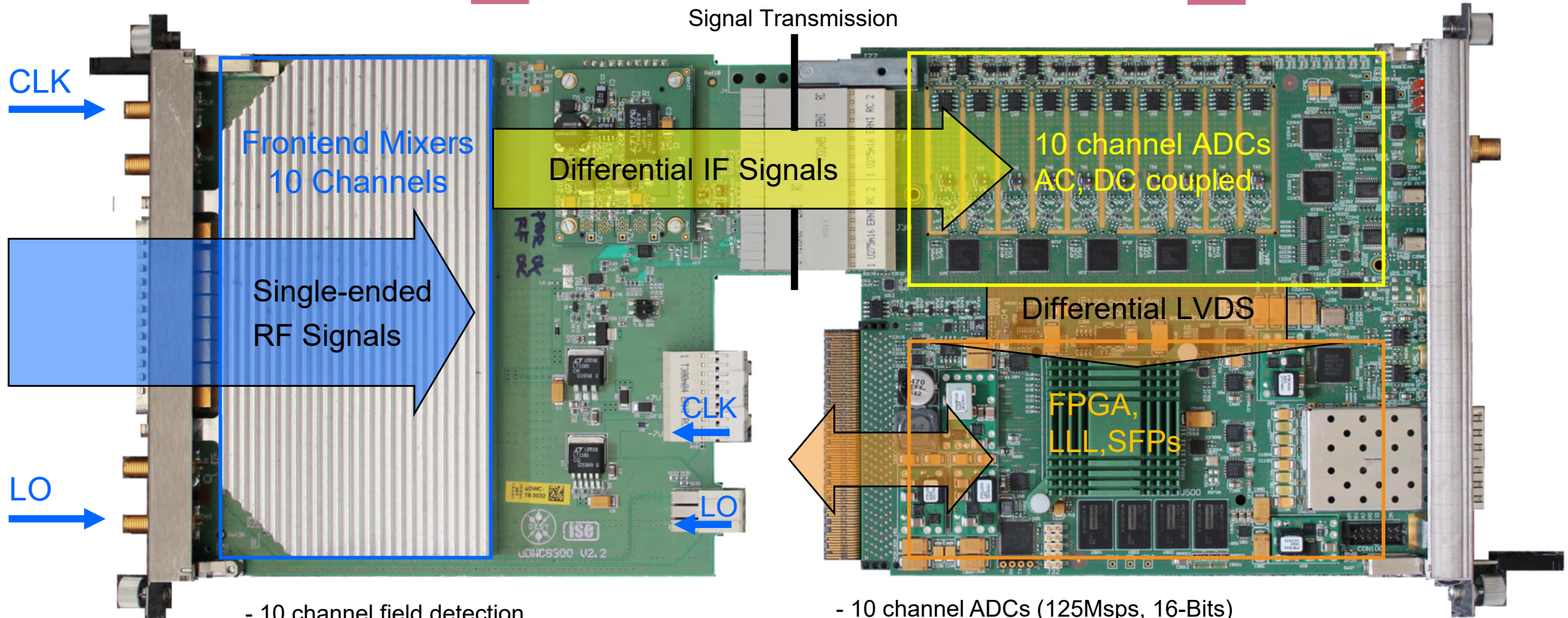
# LLRF-Systems – Signal Conditioning, Digital Processing

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

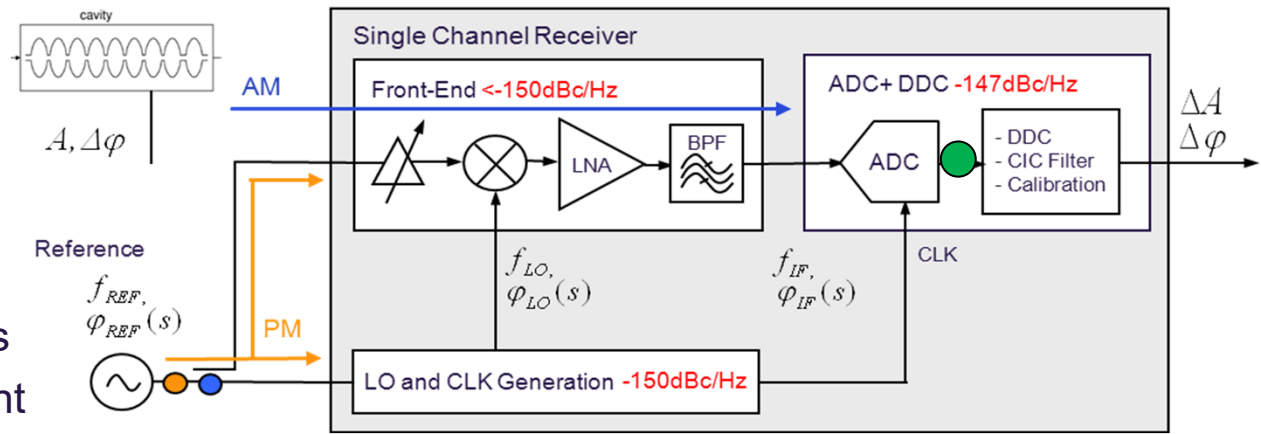
# LLRF-Systems (<10fs) Channel Performance

- Spectral purity :  
(non-IQ Sampling scheme)

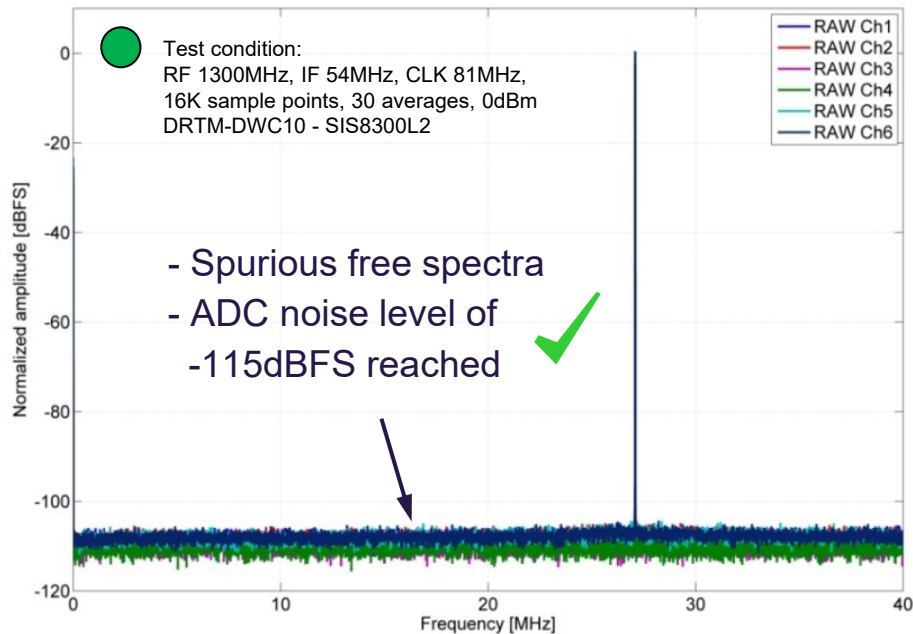
- Mainly ADC limited



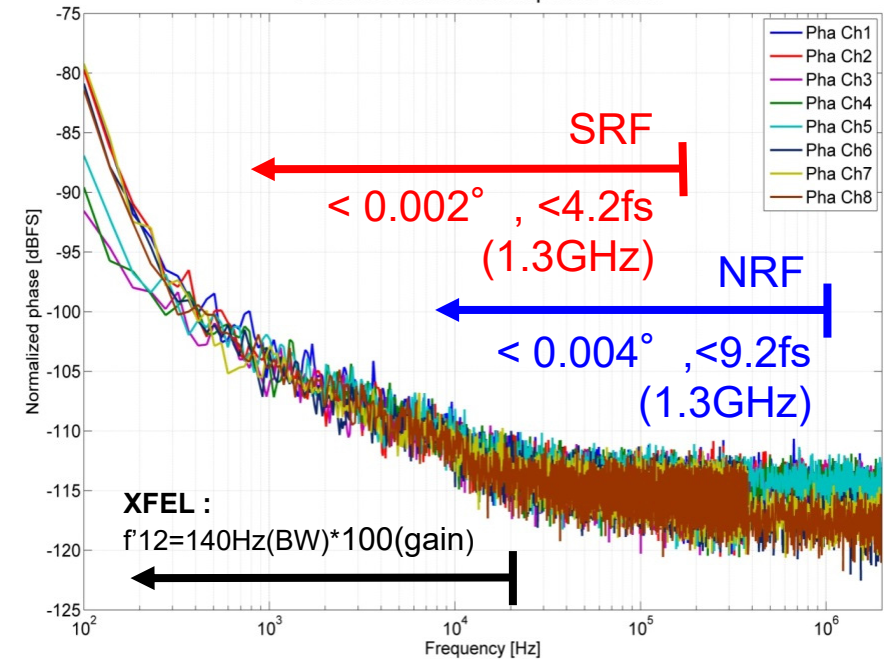
System's  
Fingerprint



Receiver broad-band raw data, spectral purity



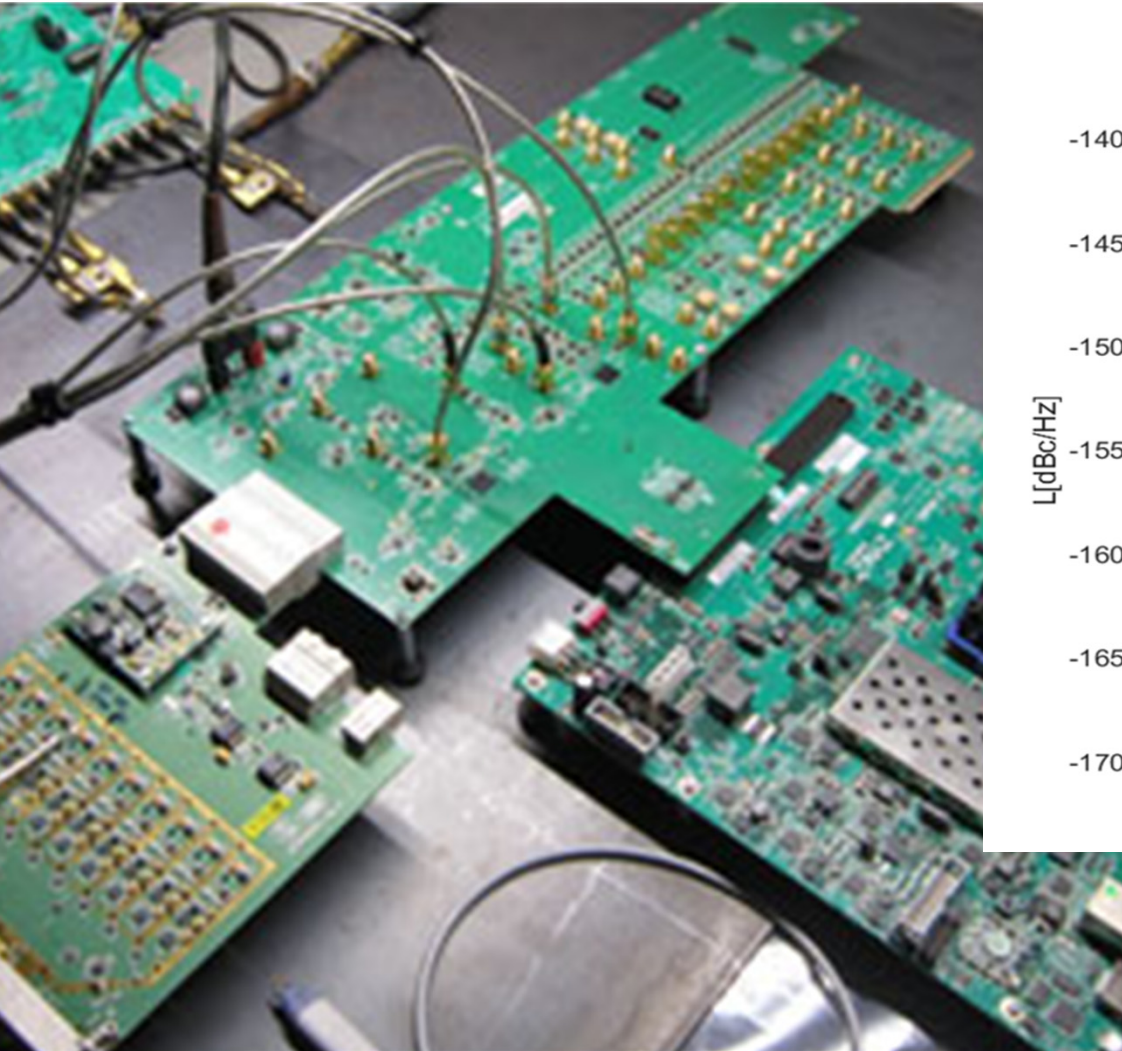
Receiver narrow-band phase noise



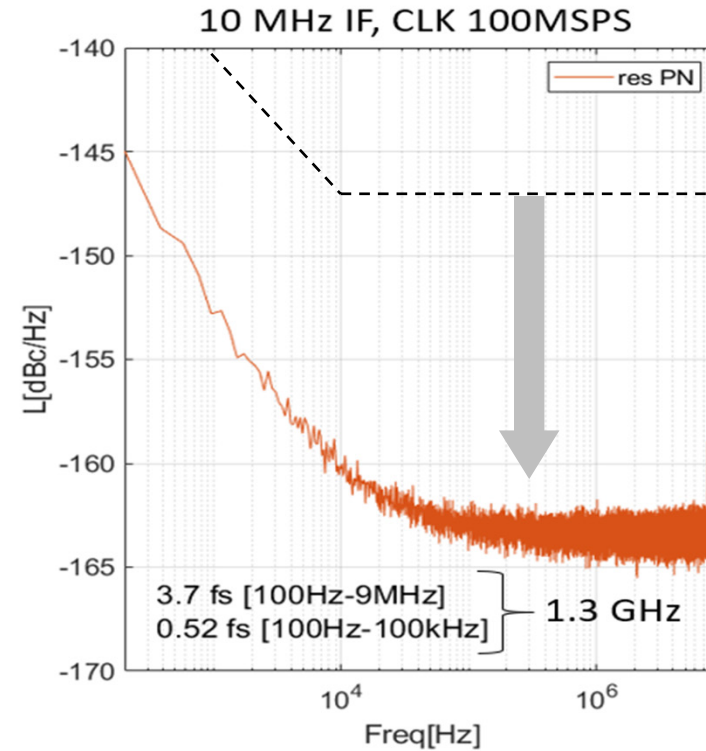
# Next Generation – Field Detection – Non IQ Sampling (<1fs)

- Distributed heterodyne receiver in evaluation phase (2026):

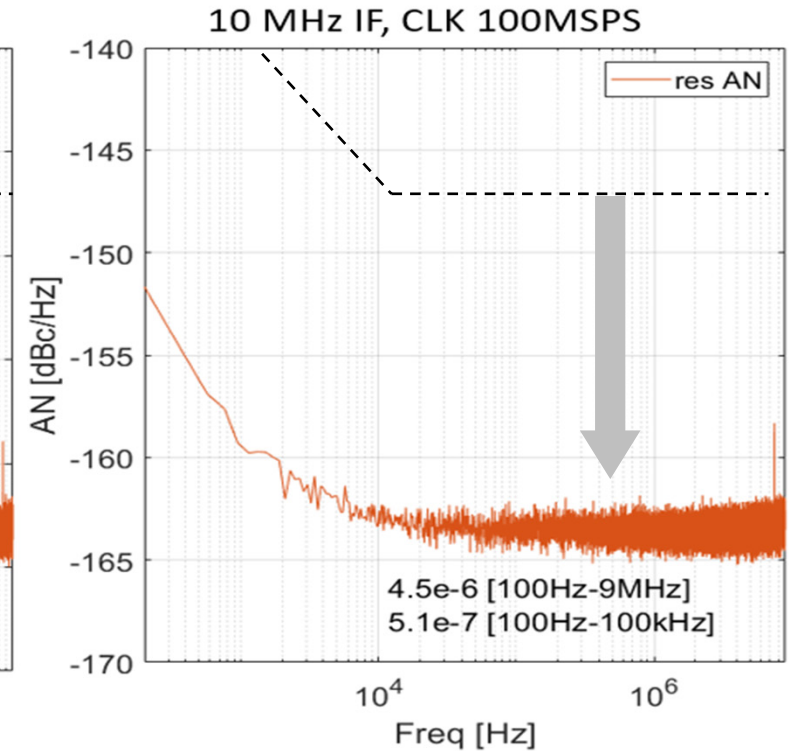
Courtesy of U.Mavric  
Preliminary



### Phase noise



### Amplitude noise

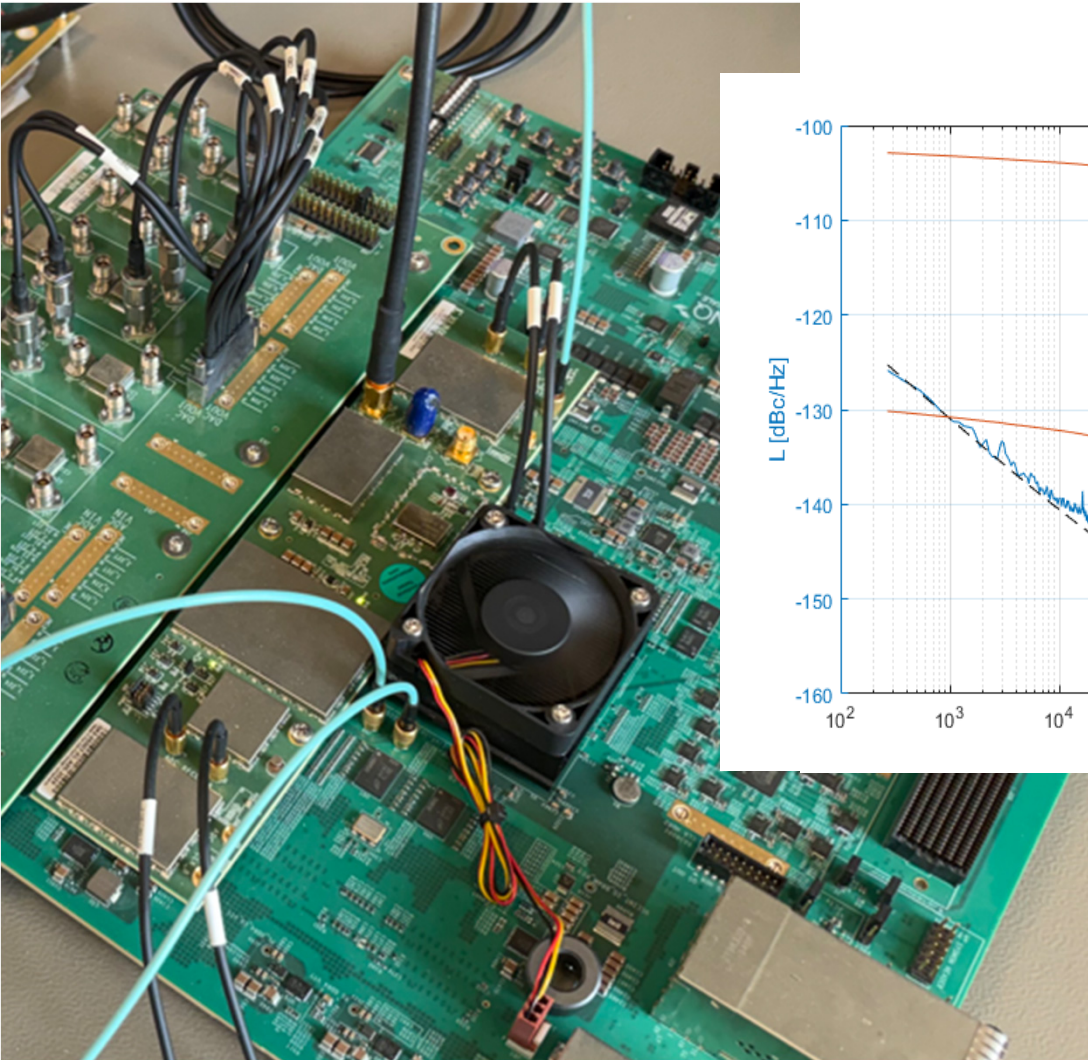


- ↪ - Expected improvement by 16dB to 0.6 fs [100 Hz, 100 kHz]
- Packaging in MicroTCA.4 and spur removal is a challenge.

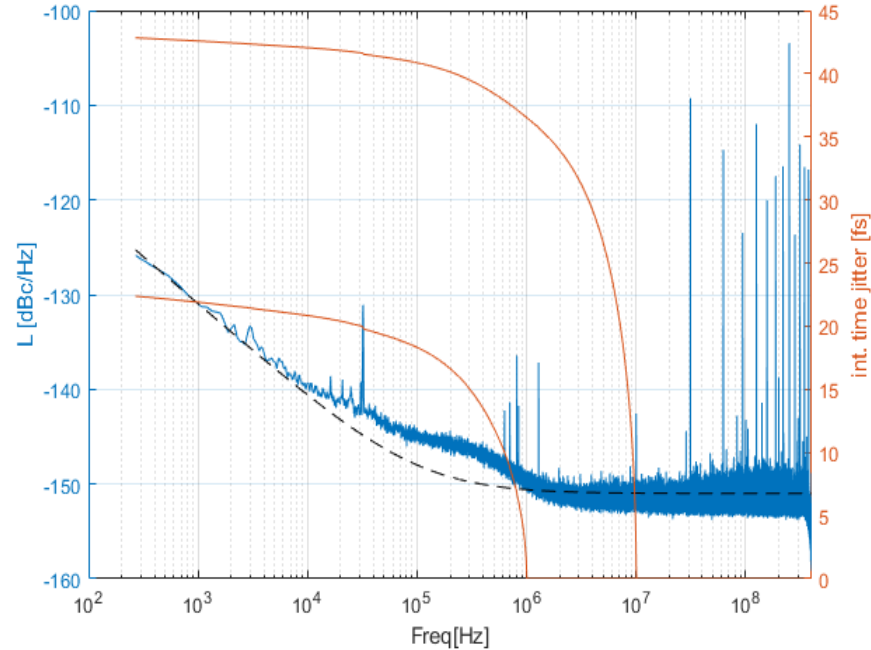
# Next Generation – Field Detection – Direct Sampling (fast)

■ Integrated receiver characterization and system integration (RFSOC 500MHz, 2.25Gbps):

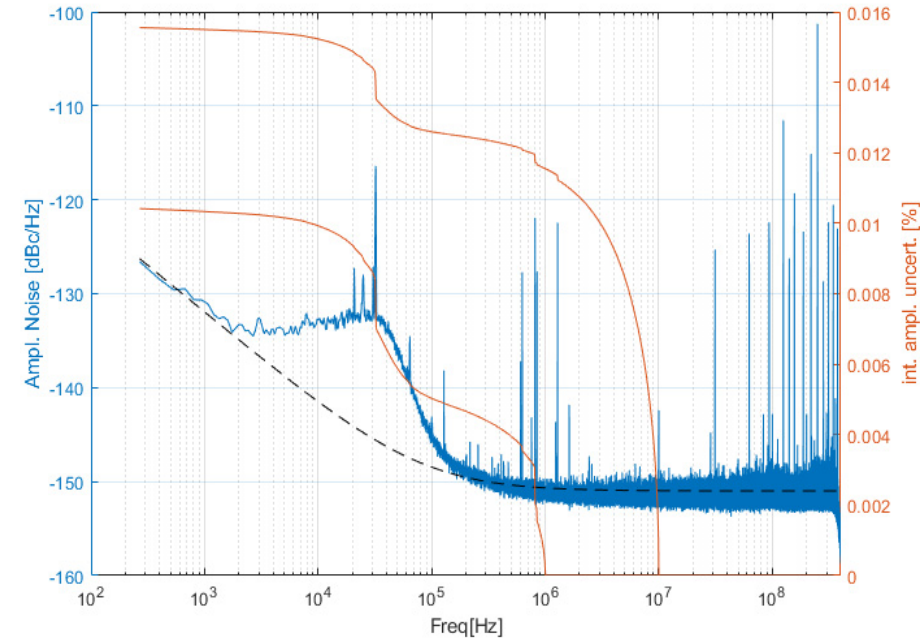
Courtesy of  
U.Mavric, B. Boghrati



Phase noise



Amplitude noise



Promising results of the RFSOC coming up in many form factors:

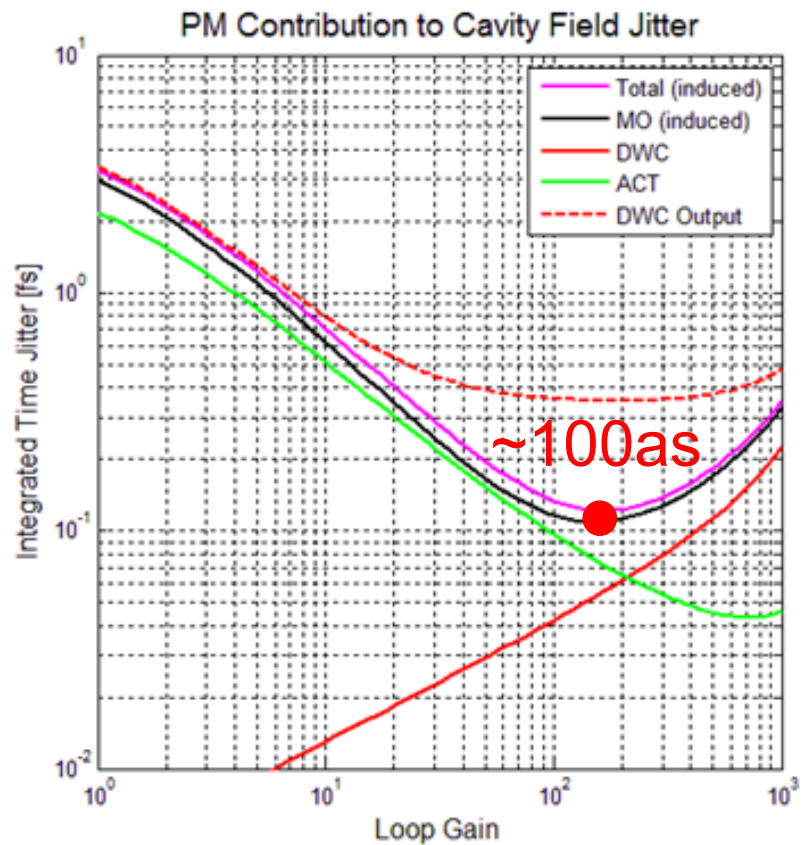
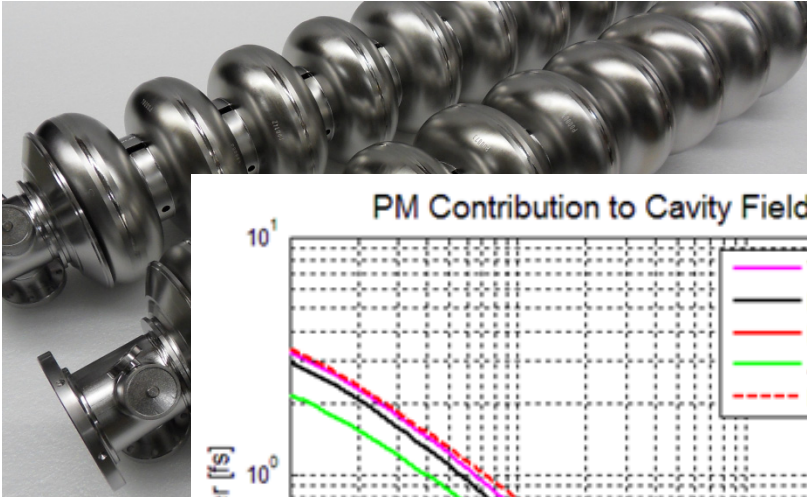
- Bandwidth : 6GHz bandwidth for many LLRF systems
- Phase noise : 22fs, 43fs (1MHz, 10MHz BW)
- Amplitude noise : 0.01%, 0.016% (1MHz, 10MHz BW)

# RF-Controls with as-Precision



# Towards as-Precision – LLRF Component Requirements

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

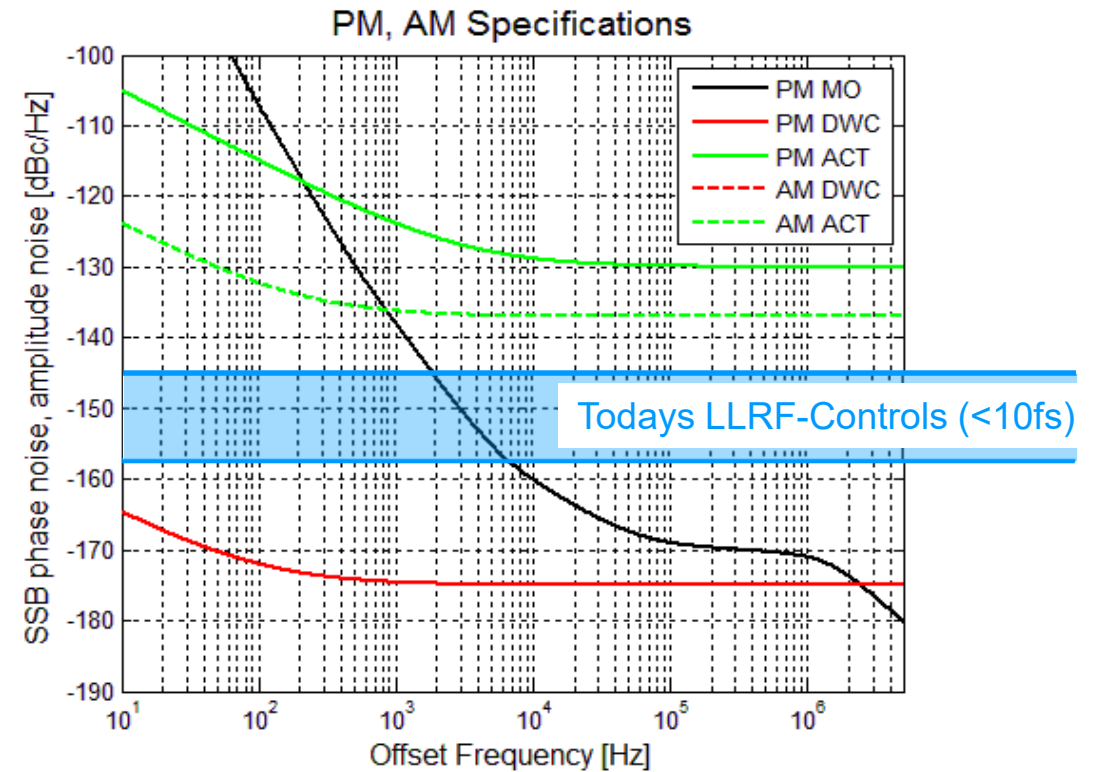


- LLRF Component Requirements :

Main reference (MO) :  $< -170\text{dBc/Hz}$

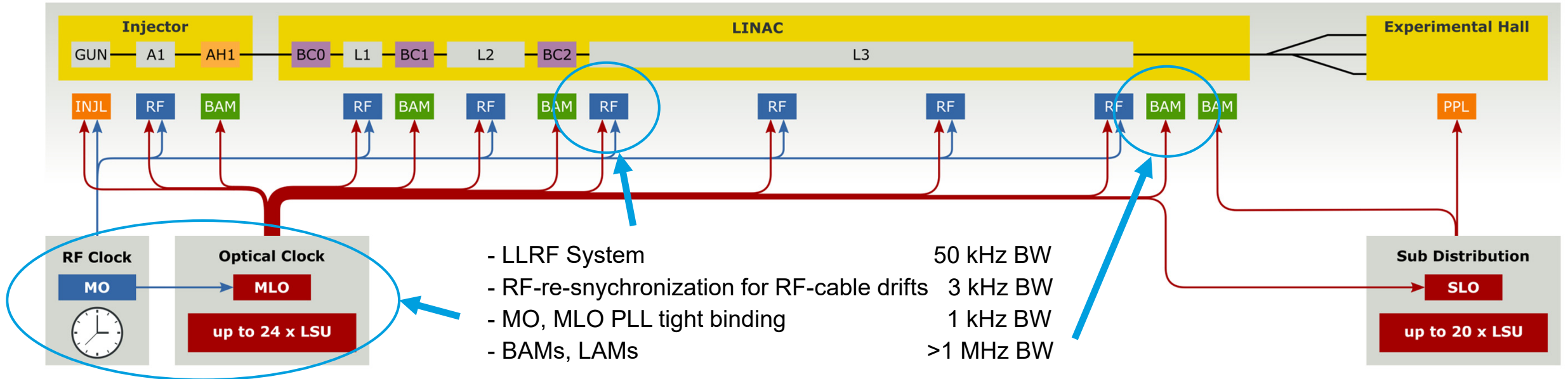
Actuator chain (ACT) :  $< -140\text{dBc/Hz}$

Field detectors (DWC) :  $< -175\text{dBc/Hz}$  ( $-150\text{dBc/Hz}$ )



# Main-Oscillators – Why do we need excellent sources ?

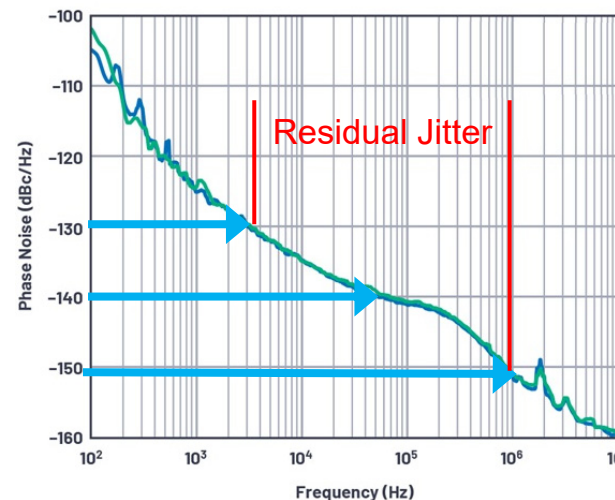
- e.g. RF-synchronization in combination with an optical synchronization:



- Sub-systems have different noise BWs :



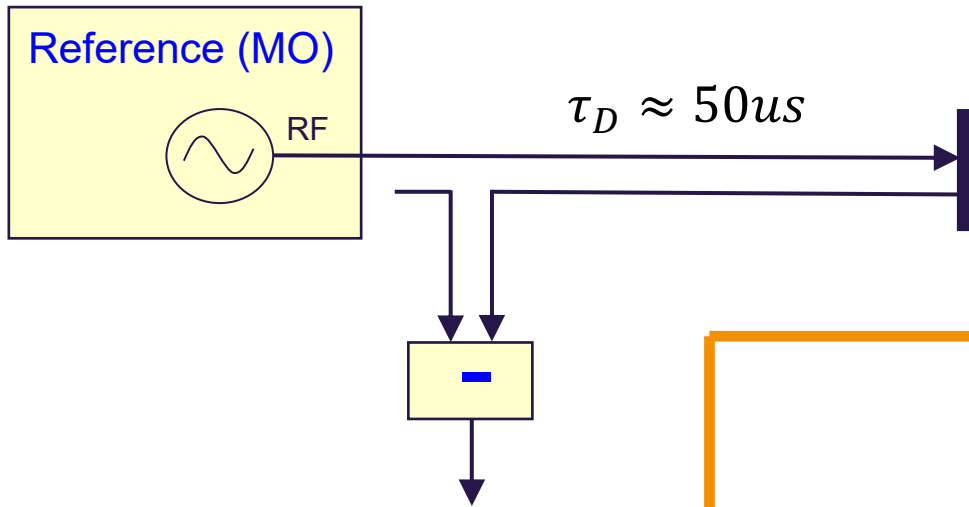
MO, MLO PLL  
REFM-OPT  
LLRF-System  
BAMs



- Low 1/f-noise Main-Oscillator
- Low noise MLO
- Relevant MO frequency range: Middle range [500Hz, 100kHz]

# Advances in Main-Oscillators for Accelerators (<1fs) – Links

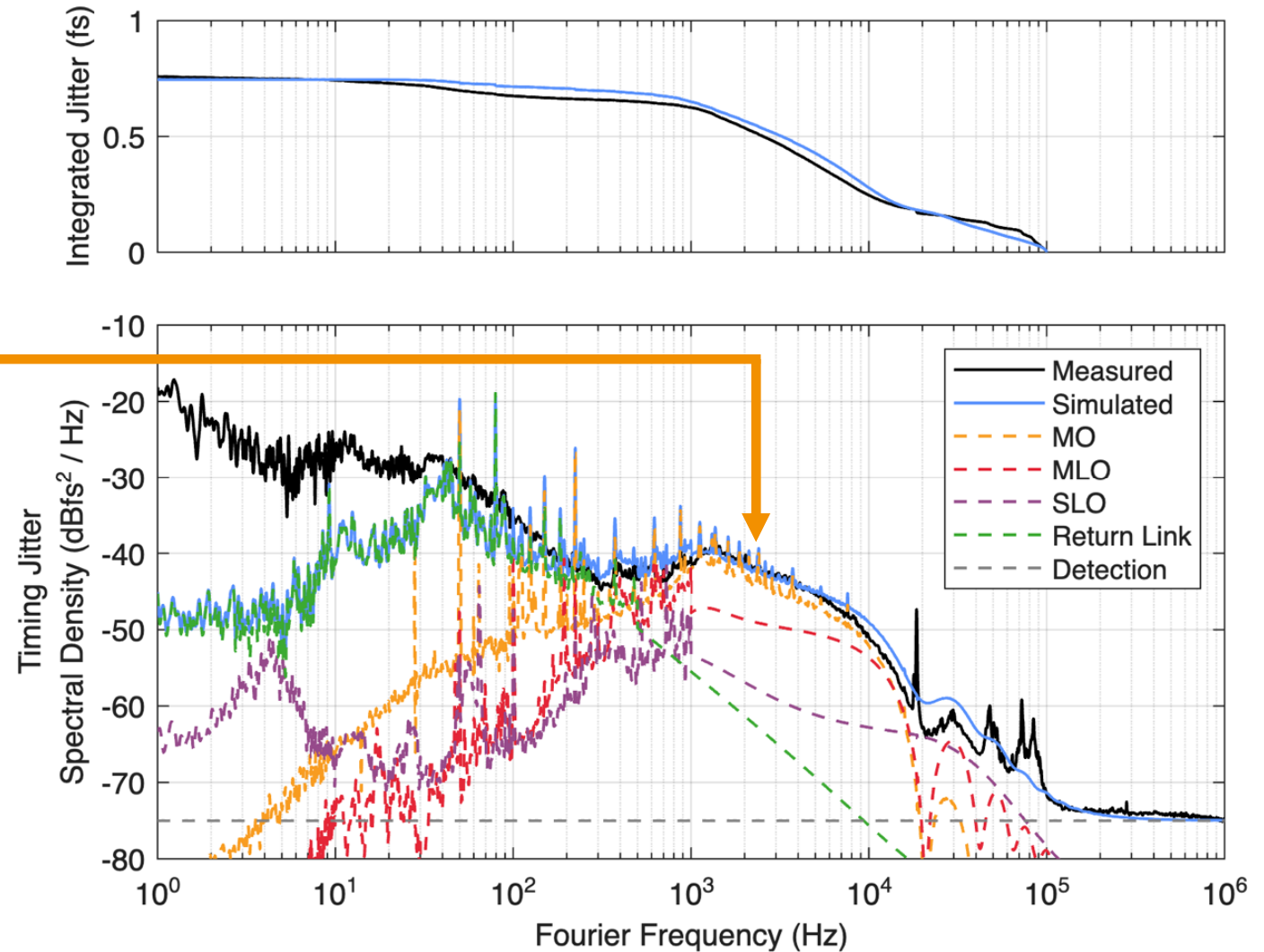
- Residual noise of 2 optical links (7km): (Simplified -> Discriminator)



$$S_{\varphi,RES}(f) = S_{\varphi,MO}(f) 4 \sin^2(\pi f \tau_D)$$

Delays or long links require low phase noise from main references in the middle frequency range

Courtesy of M.Schütte

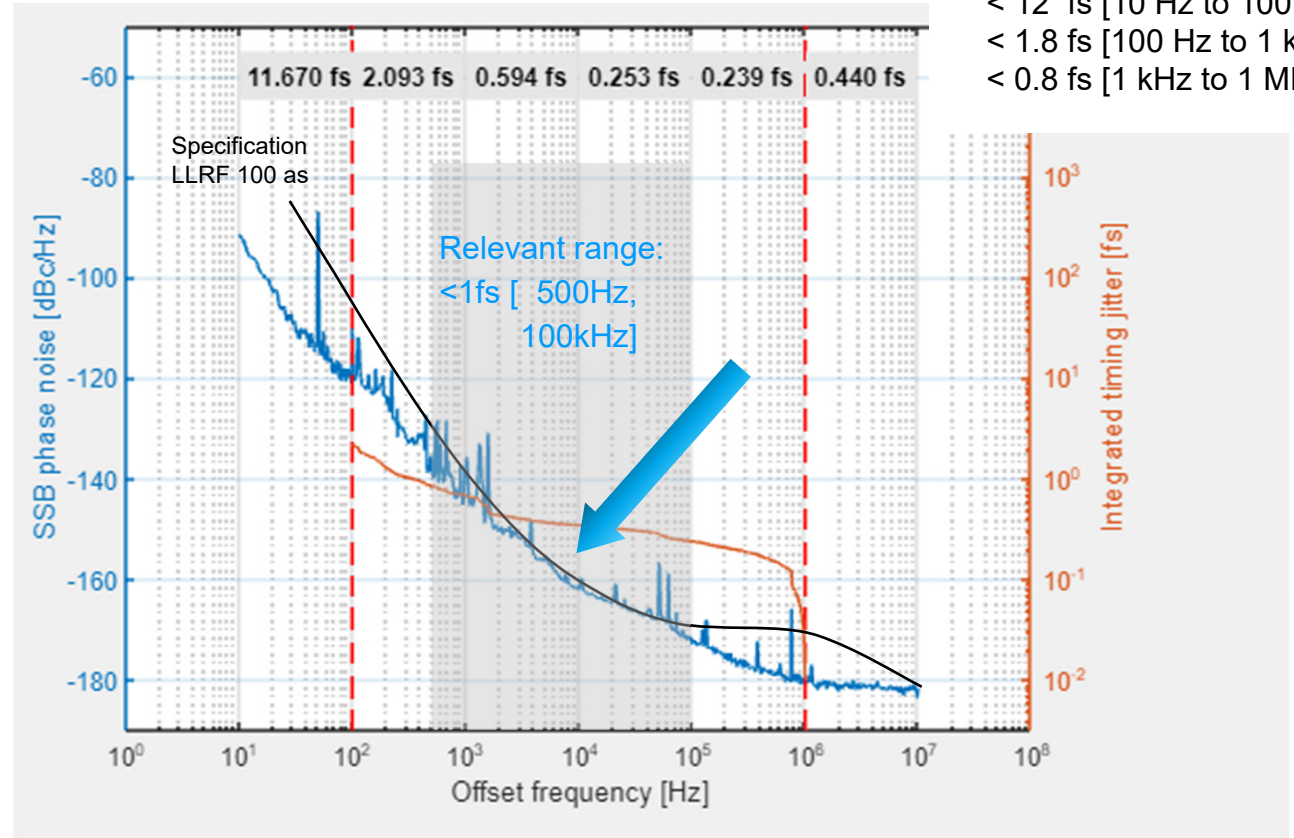


# Advances in Main-Oscillators for Accelerators (<1fs)

- XFEL, FLASH new Main Oscillators:  
1.3GHz (3.0GHz), +46dBm, Health monitoring



- Absolute Phase-noise:



Integrated Jitter:  
 < 12 fs [10 Hz to 100 Hz]  
 < 1.8 fs [100 Hz to 1 kHz]  
 < 0.8 fs [1 kHz to 1 MHz]

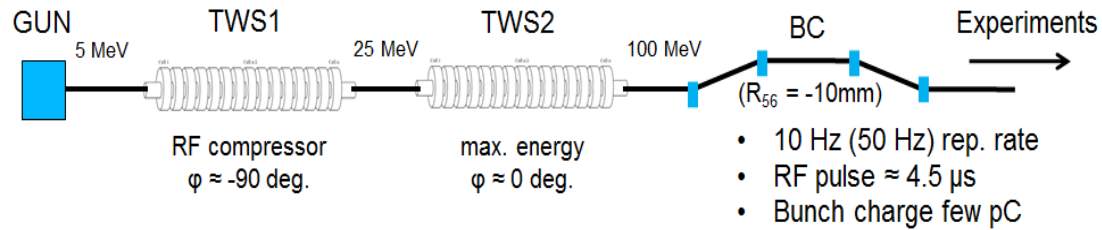
KVG Quartz Crystal  
Technology GmbH  
info@kvg-gmbh.de



- ↪ - Improvement of int. jitter from 40 fs to 0.8 fs [1kHz, 1MHz]
- fs-lasers locking to reference show improvement to <150as

# Advances in Actuators Klystrons (pulsed), SSPAs (CW)

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



## 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 :

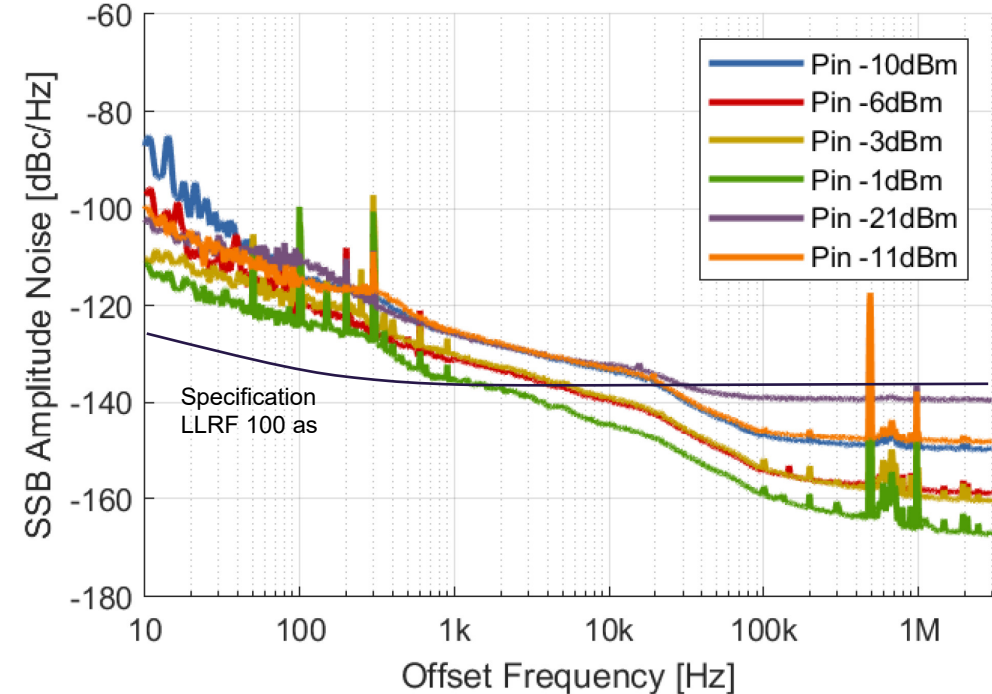
-> 14.5fs, 0.049%, -165dBc/Hz

-> Hidden middle f-range



## SSPA Stability (1.5GHz, 20kW):

Cryoelectra CRE-371C 1.5GHz SSPA Additive Amplitude Noise



Int. AN Jitter:  
 0.03% ...  
 0.007%

Integrated Jitter :

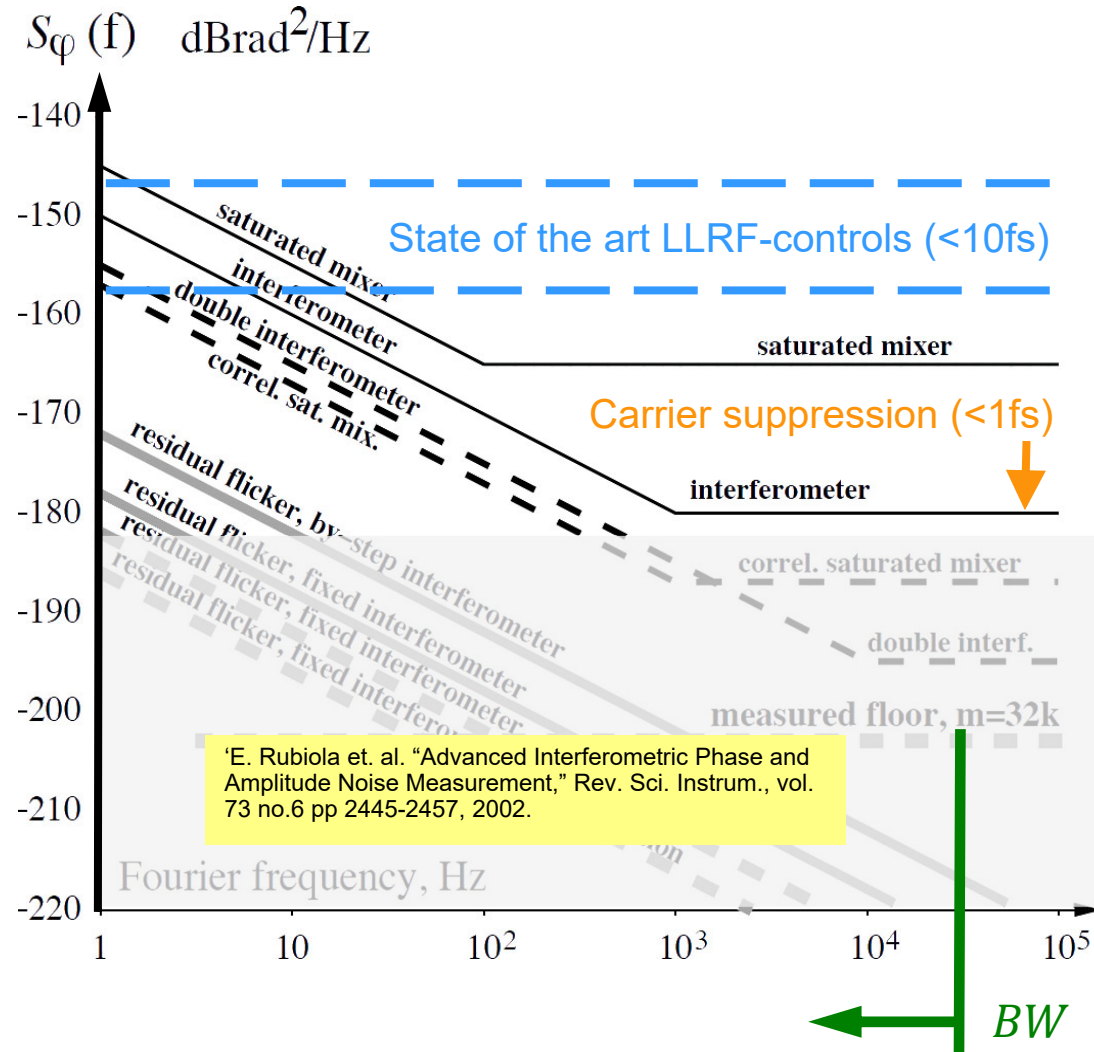
-> 8fs ...30fs depends on spurs

-> 0.01%...0.03% depends on spurs & power level



# Towards as-Precision – Options (Field Detection)

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



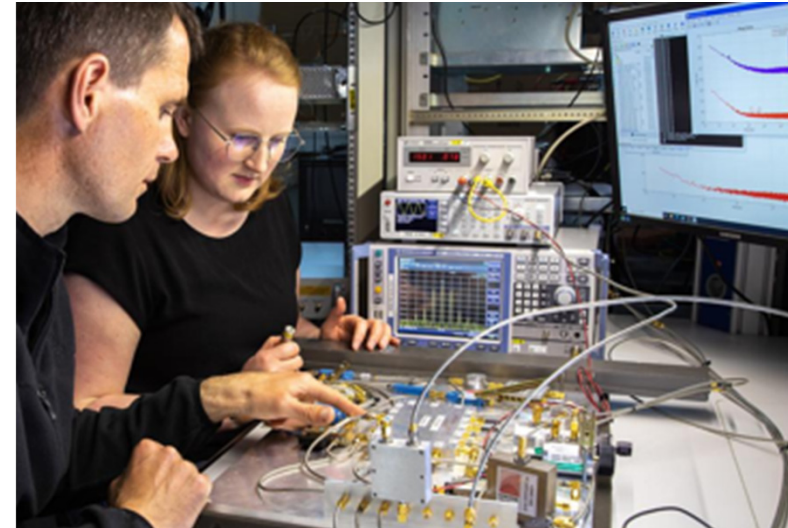
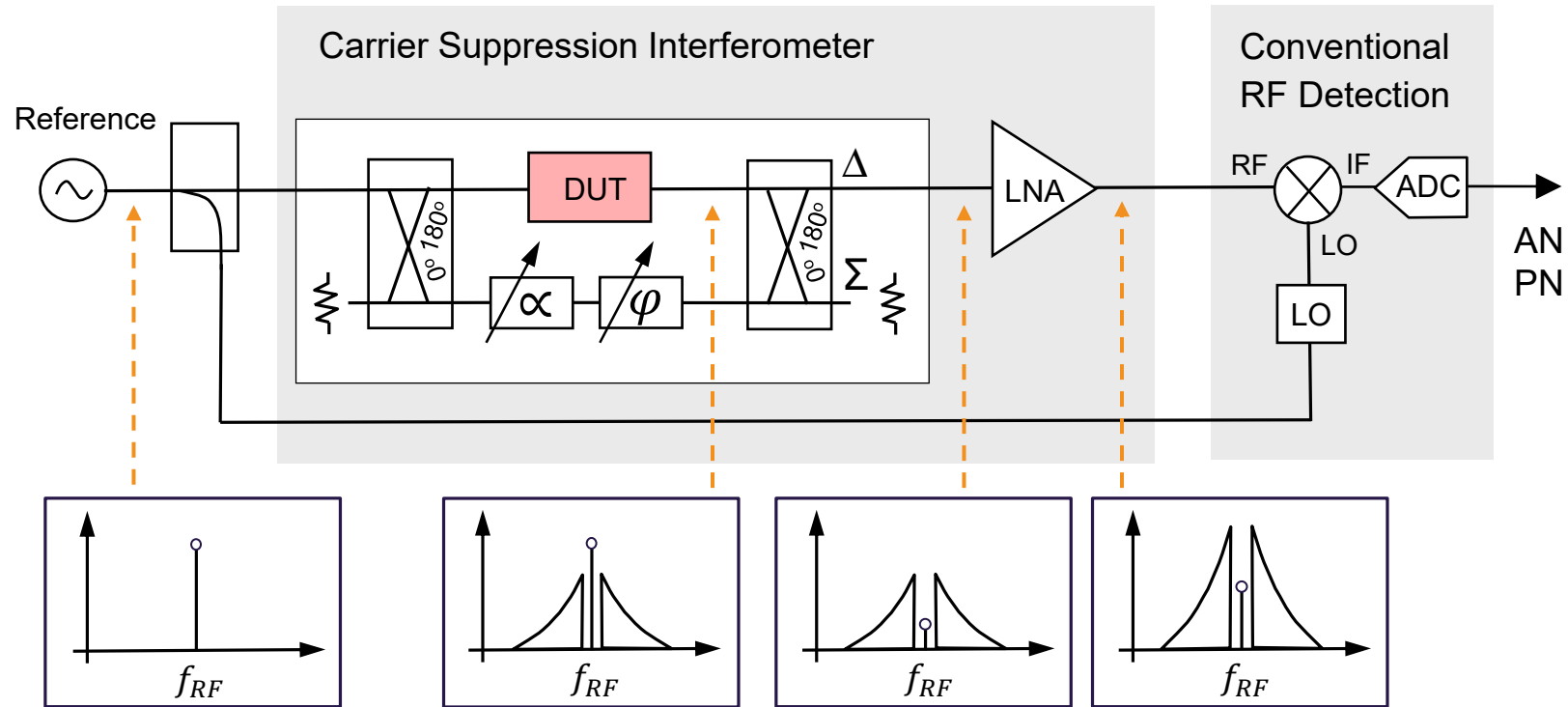
- ① Increase the RF-power:
  - PN, AN linear in RF-power
  - High level mixer
  - Carrier Suppression Interferometer
- ② Reduce the noise floor:
  - ADC/Channel parallelization,  $\sim\sqrt{N}$
  - Time correlation (no real time)

Correlation techniques

- ③ Reduce the cavity bandwidth:
  - Use >16-bit ADCs with better NSD
  - Microphonics increase

# Advances in Field Detection with as-Precision (<100as) – CSI

- Carrier-Suppression-Interferometer for residual AN, PN measurements (simplified):



L. Springer et al., "Phase Noise Measurements for L-Band Applications at Attosecond Resolution," in *IEEE TIM*, doi: 10.1109/TIM.2022.3170975.

Resolution 10as (realtime) :

- (+) PN, AN <-205dBc/Hz, @1.3GHz jitter
- (+) Low 1/f-noise -180 dBc/Hz @ 100Hz

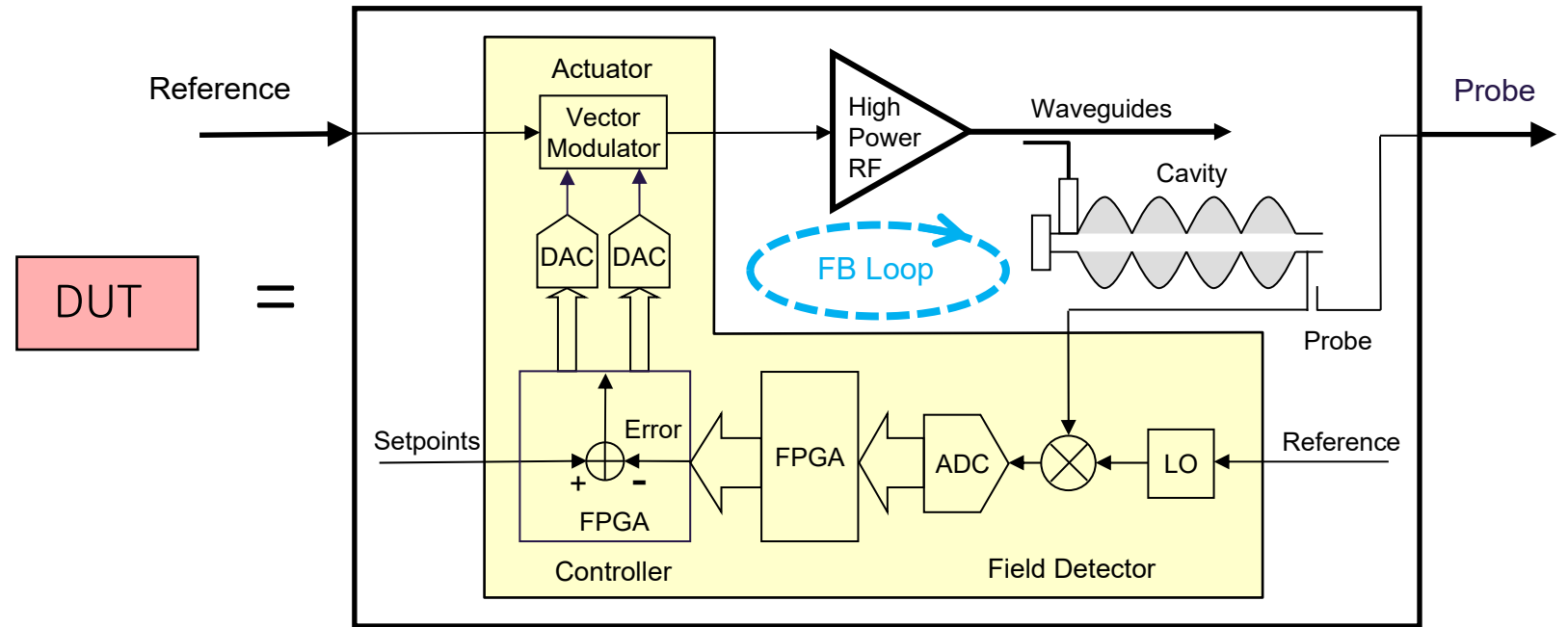
- (+) No carrier -> no 1/f-noise from LNA, DUT noise pass the system
- (+) PN, AN scales with RF-power
- (--) Needs a carrier tracking for destructive interference



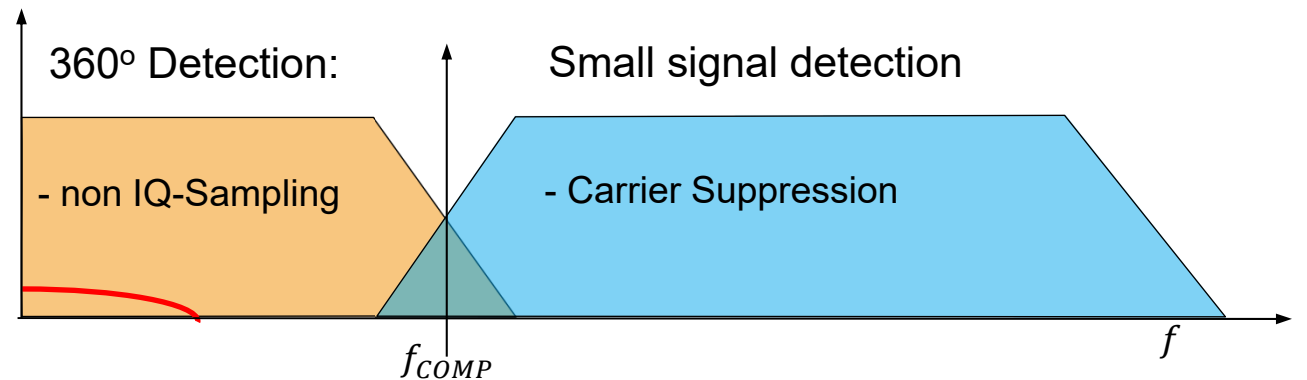
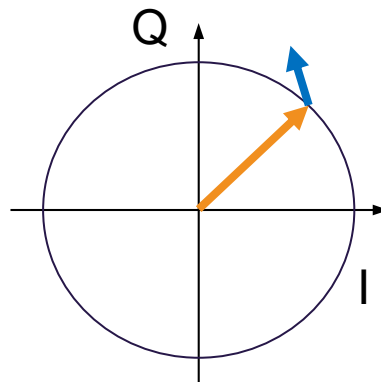
How to use this for RF control in accelerators ?

# Advances in Field Detection with as-Precision – CSI

- Replacement of the DUT as the complete RF Control: (for AN slightly different)

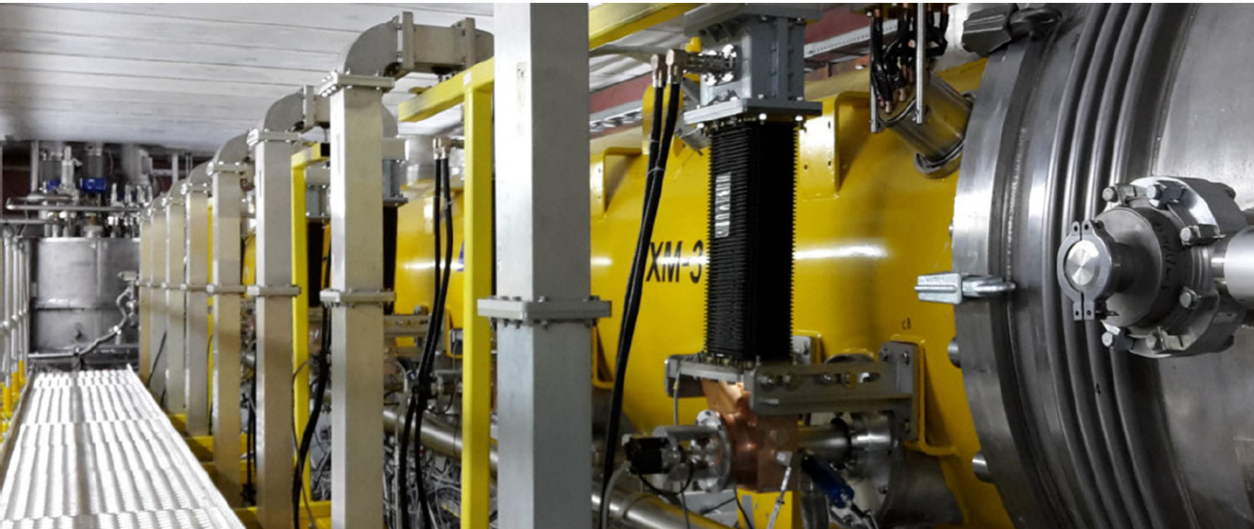


- Large signal detection - Hybrid with non-IQ: e.g. **CW-operation**



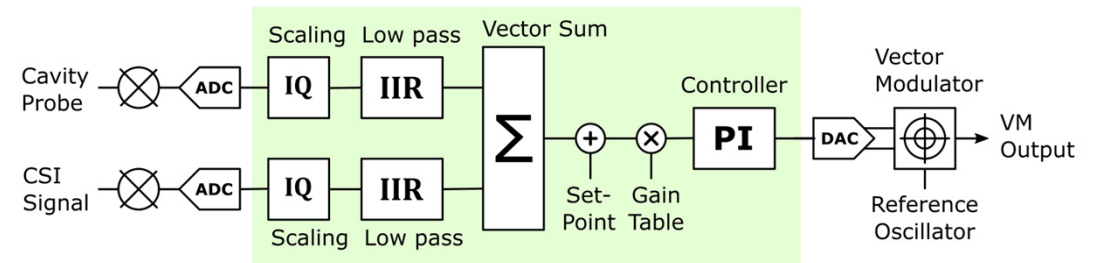
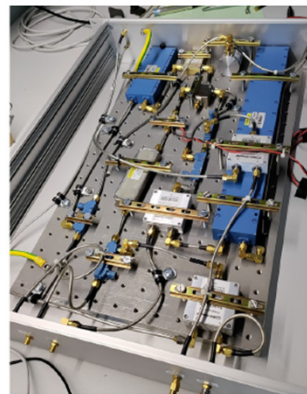
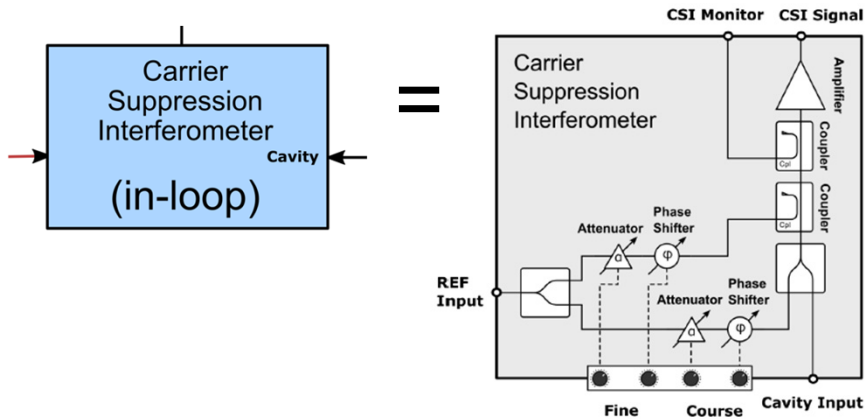
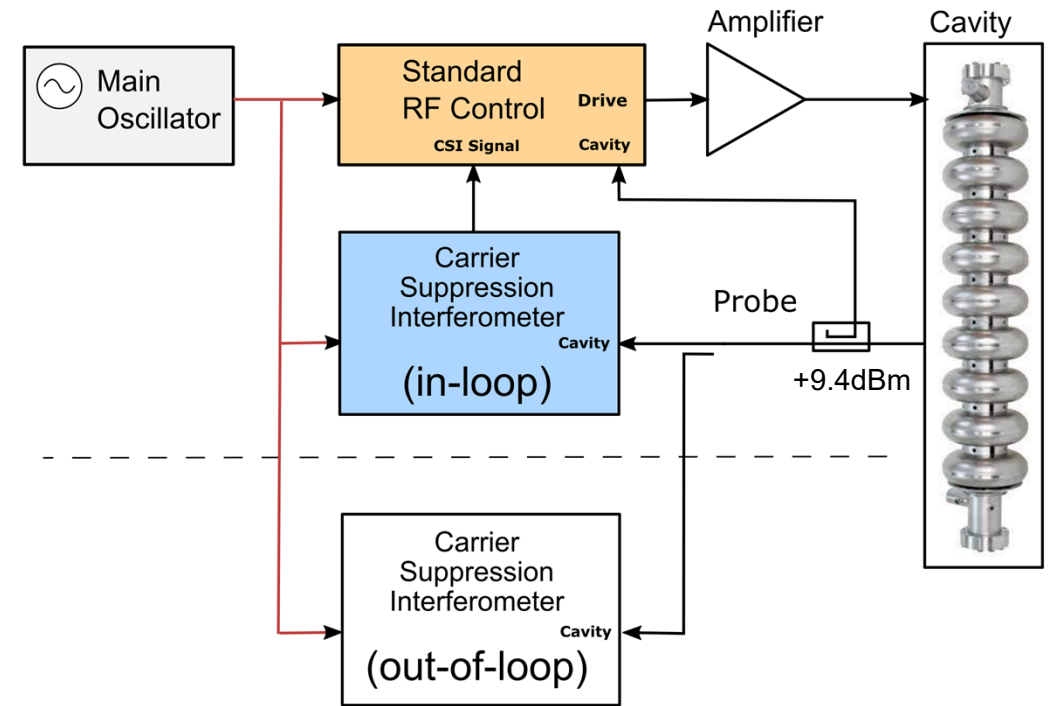
# Advances in Field Regulation with as-Precision – CMTB

- Cryo-Module-Test-Stand (CMTB) @ DESY:



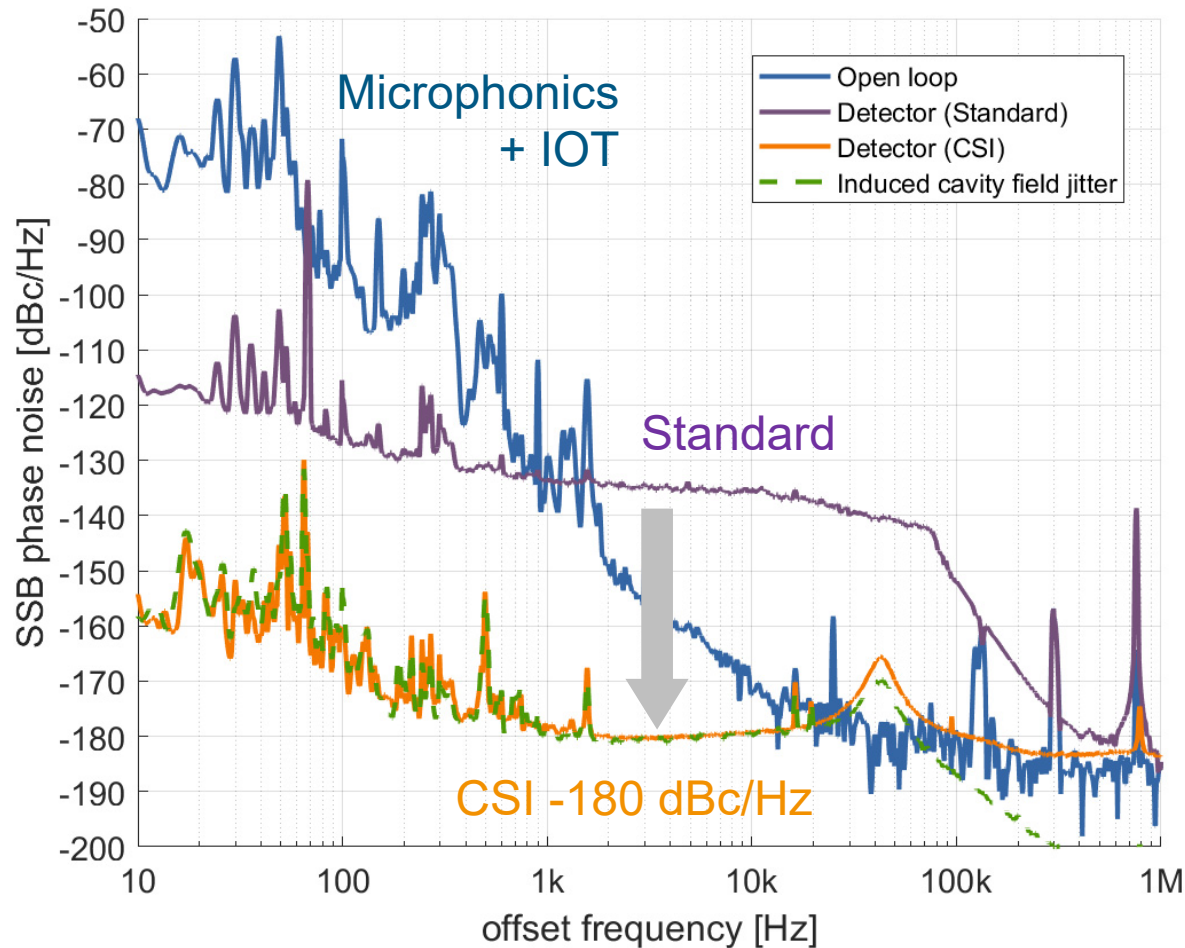
SRF 1.3 GHz, BW 65 Hz,  $Q_L=10^7$  at 8MV/m, IOT Amplifier, ANC off

- Hybrid system of a MicroTCA.4 LLRF system and a Carrier-Suppression Interferometer:

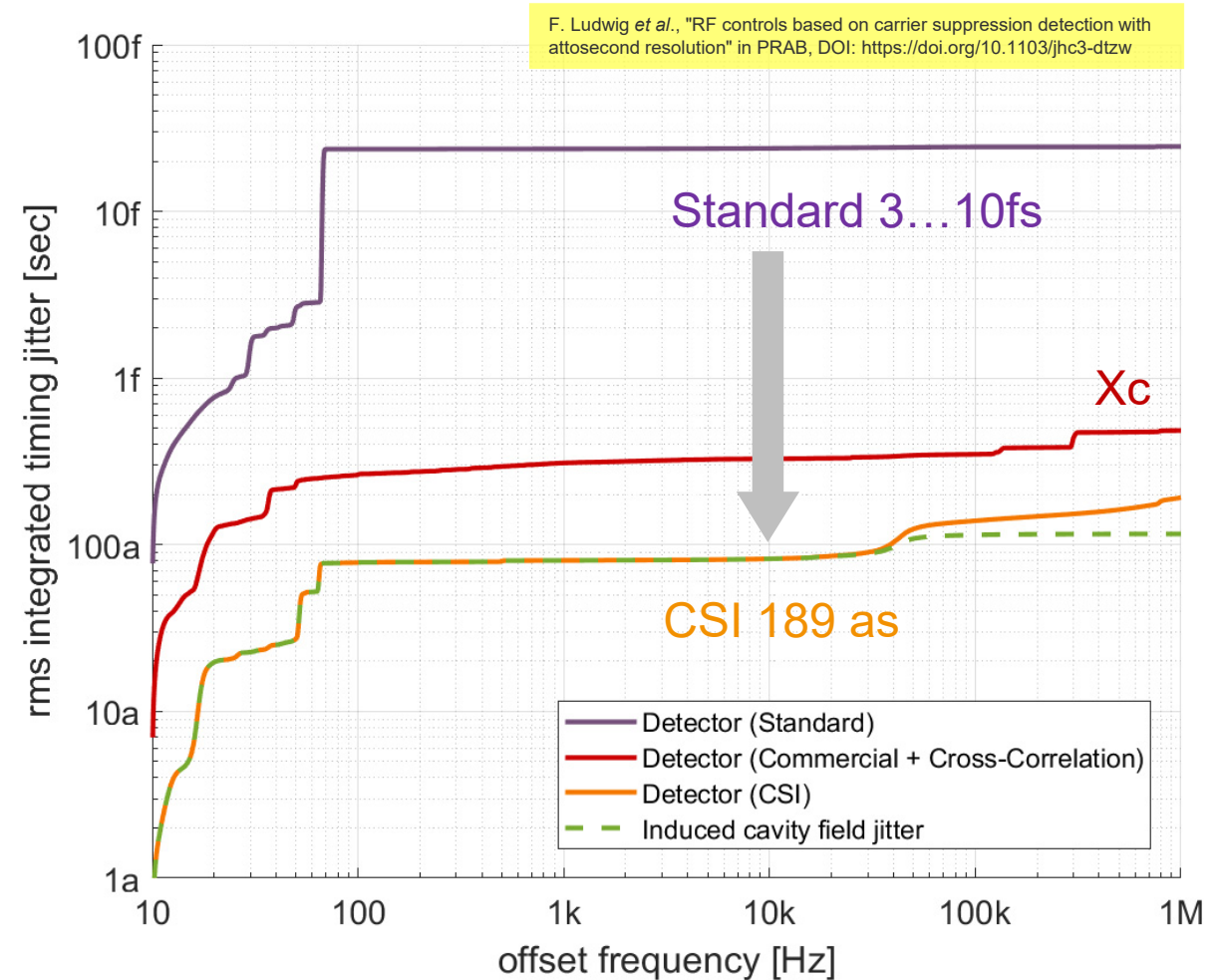


# Advances in Field Regulation with as-Precision – CMTB

## Phase noise measurements (out-of-loop):

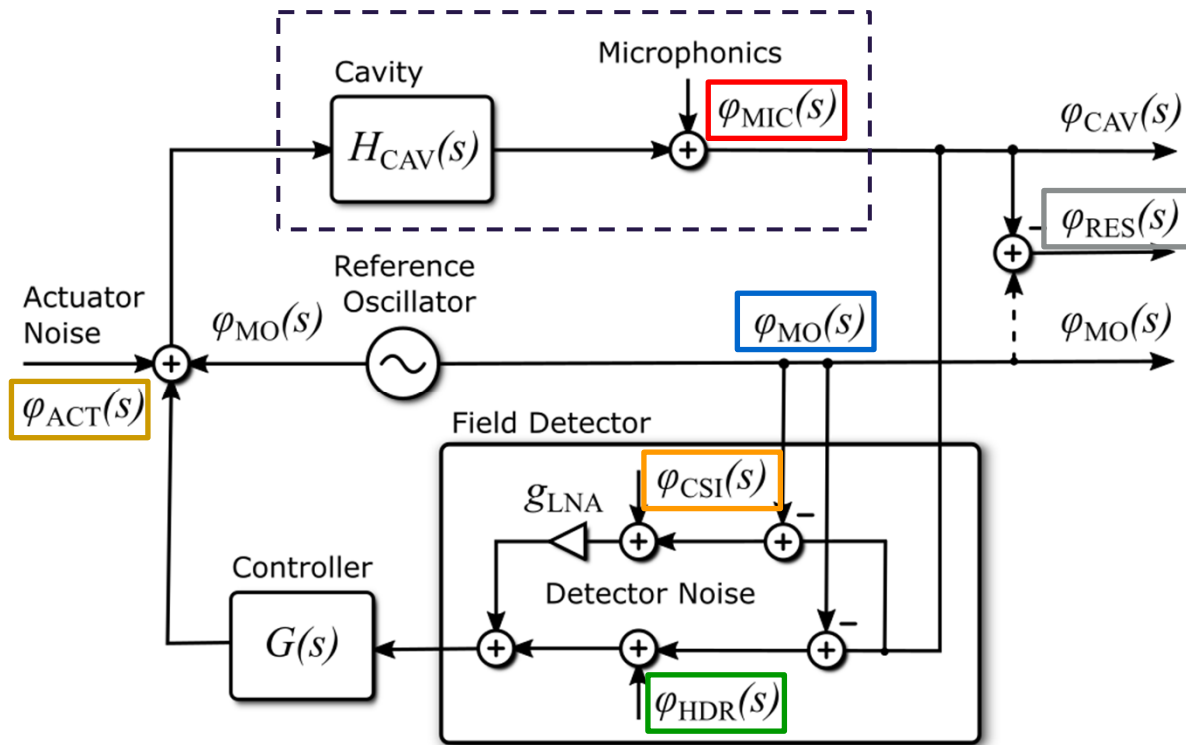


## Integrated time jitter (out-of-loop):



# Advances in Field Regulation with as-Precision – Modelling

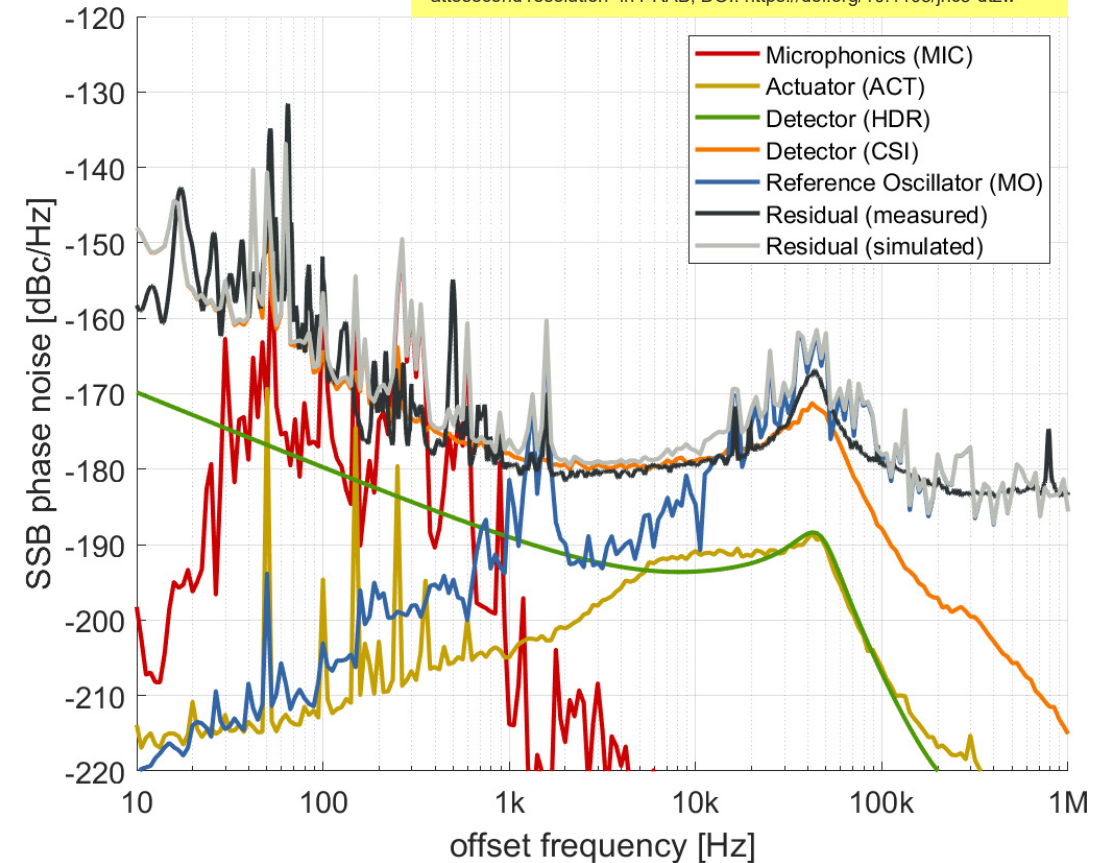
## Numerical simulation of the LLRF system:



$$S_{\varphi,RES,i}(f) = |K_i(f)|^2 S_{\varphi,i}(f)$$

- Determine all noise transfer functions from the model
- Measure each noise source individual
- Determine all noise contributions and total residual noise

F. Ludwig et al., "RF controls based on carrier suppression detection with attosecond resolution" in PRAB, DOI: <https://doi.org/10.1103/jhc3-dtzw>



- - Measurements and simulations fits quite well.
- Reference, Actuator, Microphonics are suppressed.
- Cavity RF-power limits the CSI.

# Advances in Field Detection with as-Precision – Challenges

## ■ Fundamental difference in closed-loop amplitude behavior:

- Cavity field phase is relative to the reference.
- Cavity field amplitude is absolute.

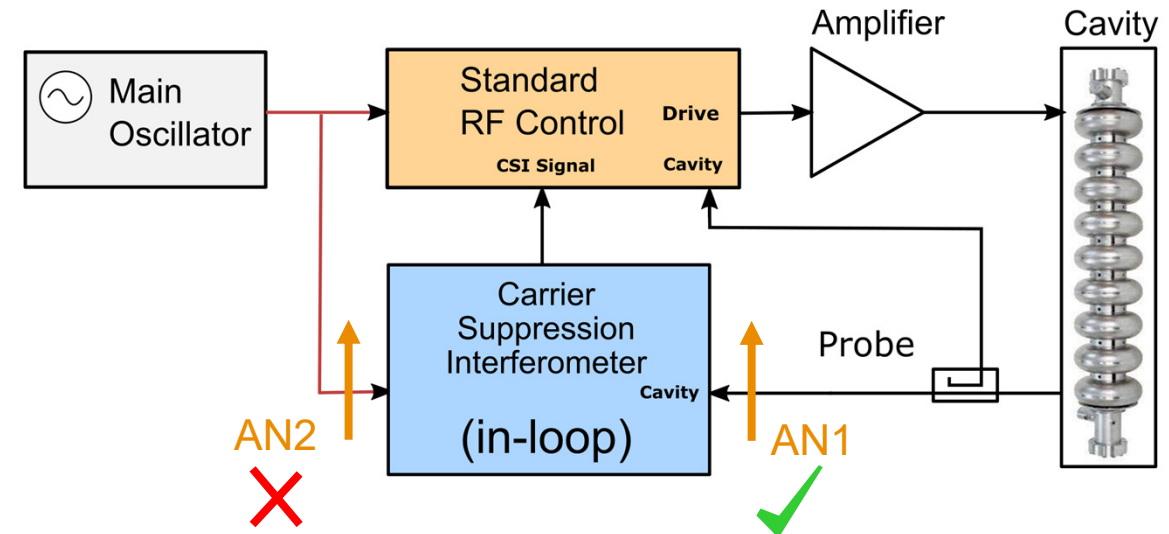
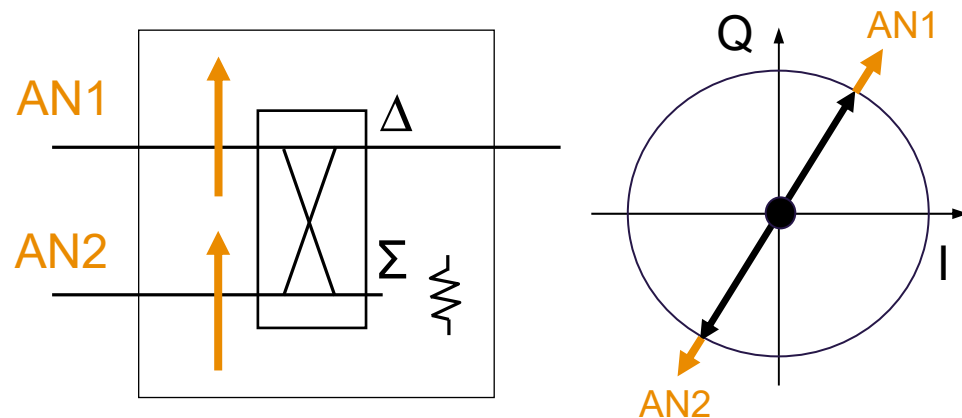
Amplitude

Phase

Init. arrival

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

## ■ CSI Detector: Amplitude difference:



- ↪ - The cavity field follows the phase **and** amplitude of the reference for the CSI detector..
- The amplitude noise of reference oscillators needs to be improved far below -180 dBc/Hz.

# Summary and Outlook

- RF-Controls with spurious free short-term amplitude and phase detection below  $<10\text{fs}$  [1MHz BW] is available for the accelerator community in modern standards like MicroTCA.4 or proprietary systems.
- RF-Controls with  $<1\text{fs}$  field stability is currently in preparation.
- RF-controls with  $<200\text{as}$  field stability is demonstrated in phase.  
To achieve amplitude stability at this level, the main references must be improved.

Thanks for your attention!