Next generation RF field detection with the carrier-suppression interferometer

LLRF22 Workshop

Presentation ID #41

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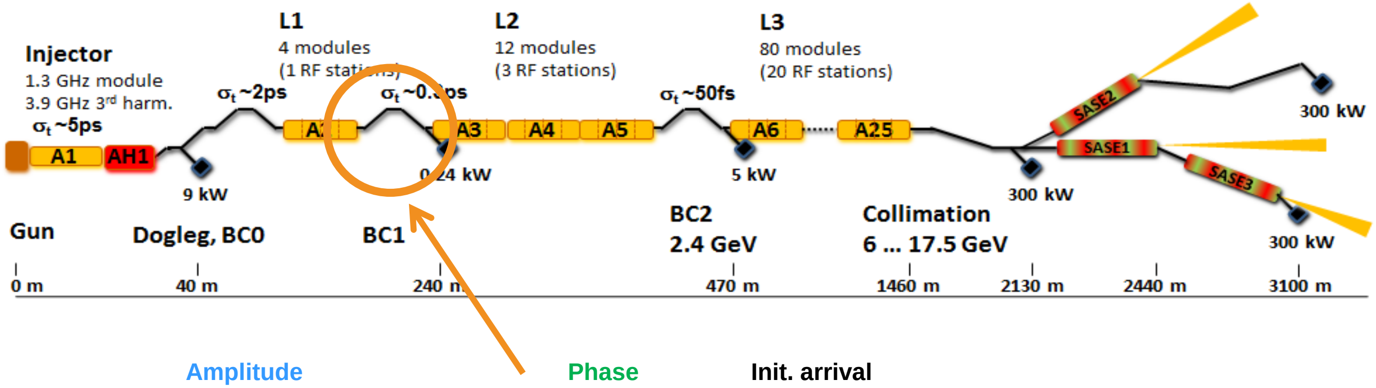
Agenda

- Introduction
- Motivation (present limitations, alternatives)
- Carrier suppression interferometer (principle, implementation)
- Calibration methods
- Automatic carrier suppression (course tuning)
- Measurements (setup limits)
- Evaluation of various actuators and their limits
- Proposal for a CSI-based RF detector as part of a LLRF system

*CSI – Carrier Suppression Interferometer

Introduction



Amplitude — Phase — Init. arrival

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

EuropeanXFEL: 1.5ps/%
FLASH: 7.0ps/%

2 ps/deg
L-band

0.05 ps/ps
C=20

Arrival time strongly depends on the amplitude and phase stability of accelerating RF fields.

In a LLRF system there are several sources of disturbances which affect the RF field stability.

$$S_{\varphi,\mathrm{RES}}(f_m) = \left|\frac{s}{s+\omega'_{12}}\right|^2 S_{\varphi,\mathrm{MO}}(f_m) + \left|\frac{\omega'_{12}}{s+\omega'_{12}}\right|^2\left[S_{\varphi,\mathrm{DWC}}(f_m) + \frac{1}{g_0^2}S_{\varphi,\mathrm{MOD}}(f_m)\right]$$

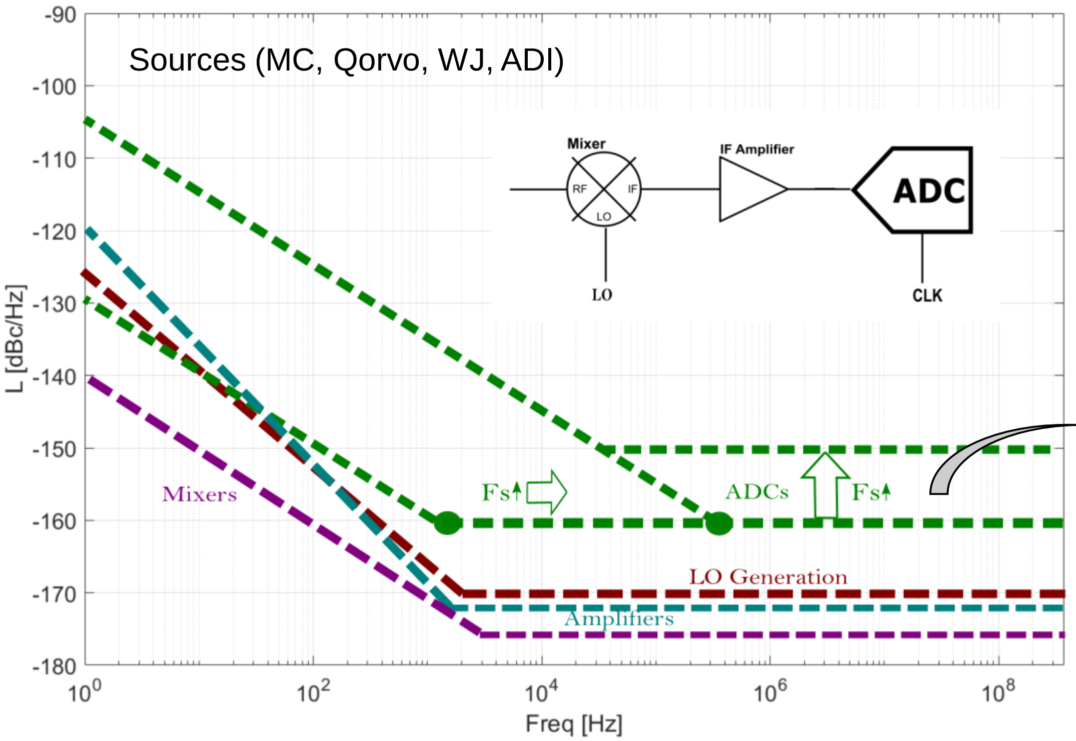
See Ref [1]

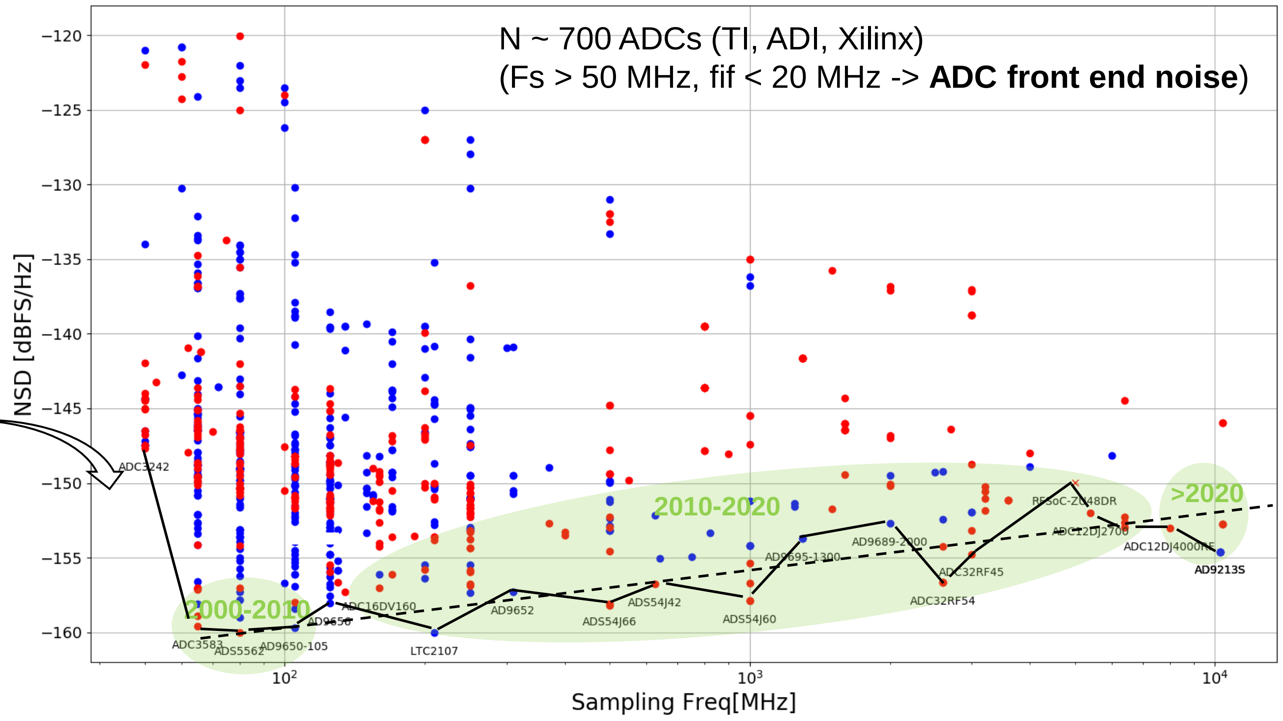
Disturbances in the field detectors translate directly to the differential disturbances between beam and cavity RF field.

This talk will focus on the limitations on the small signal side of the dynamic range.

Limitations in standard field detectors

What is available off-the-shelf (2022)?





Assumptions:

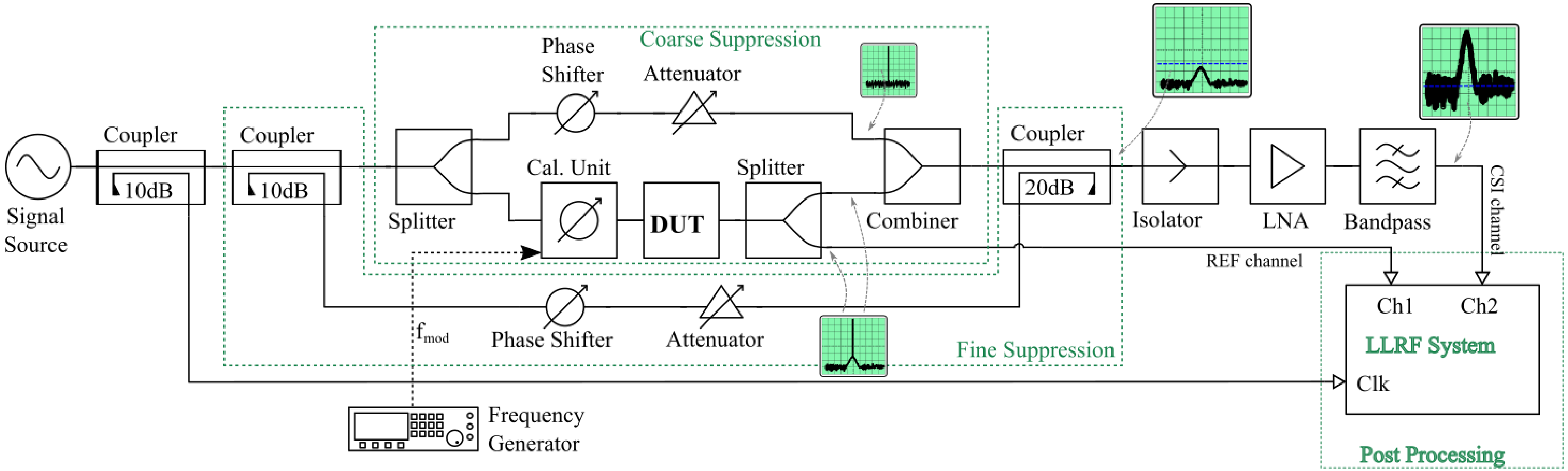
- Standard RF detector configuration.
- Standard manufacturers considered.
- Enough input power (>+10 dBm).

Conclusions:

- The two manufacturers are concentrating on high Fs ADCs since 2010.
- The front end noise floor (the ultimate limit) of the ADCs is getting worse with higher Fs.

We need alternative methods.

Carrier suppression interferometer



see Ref [2,3,4,5]

Challenges:

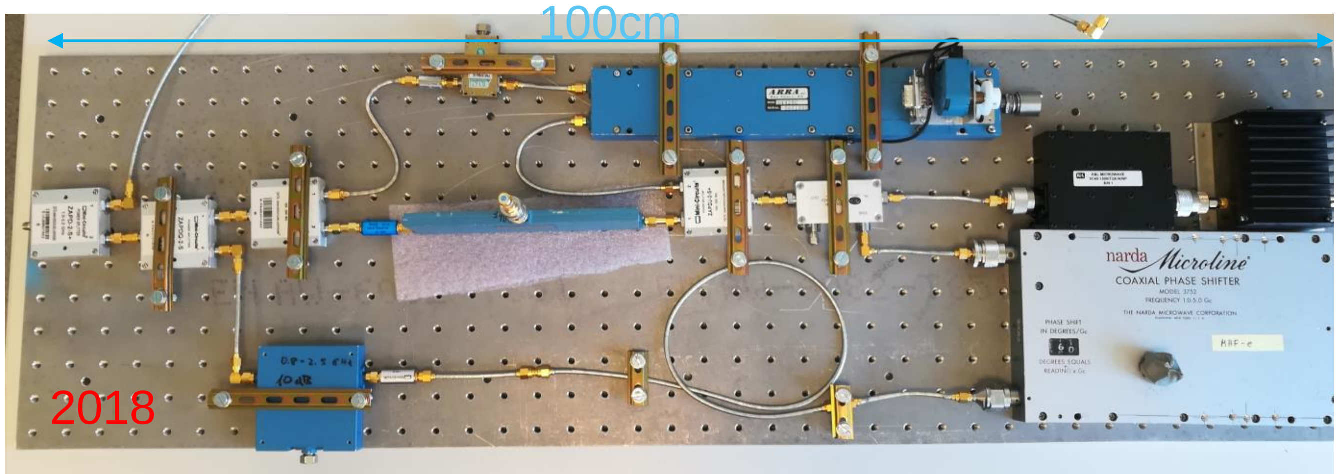
- No carrier – how to calibrate for phase or for amplitude?
- Keeping a high suppression over a longer time.
- Finding actuators (variable phase shifters and attenuators) with low additive noise.

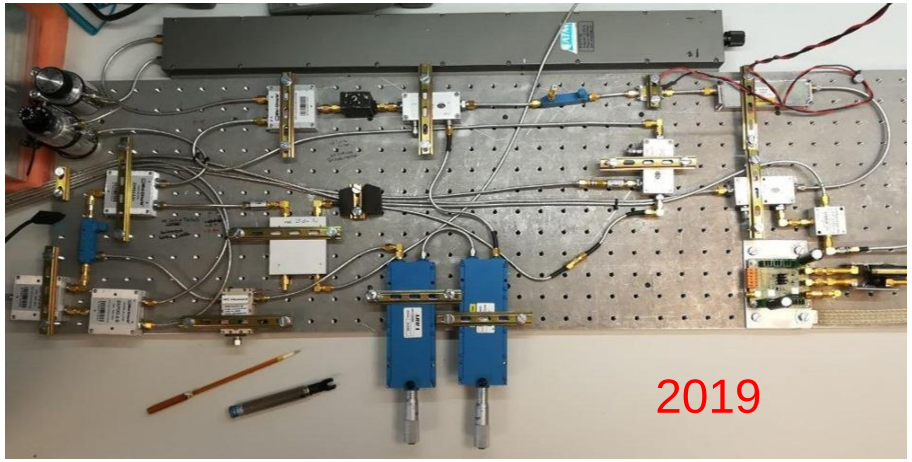
(+) Additive 1/f noise of the amplifier is small (no carrier).

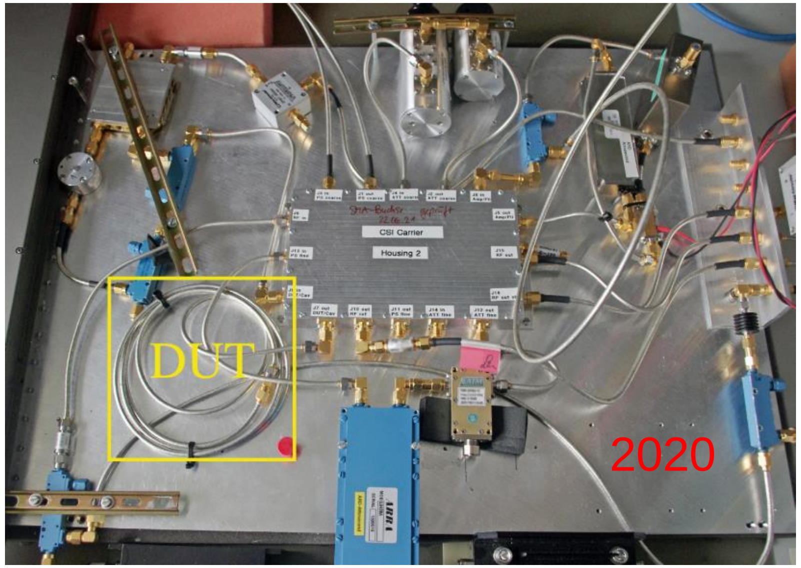
(+) Amplitude noise of the source is subtracted.

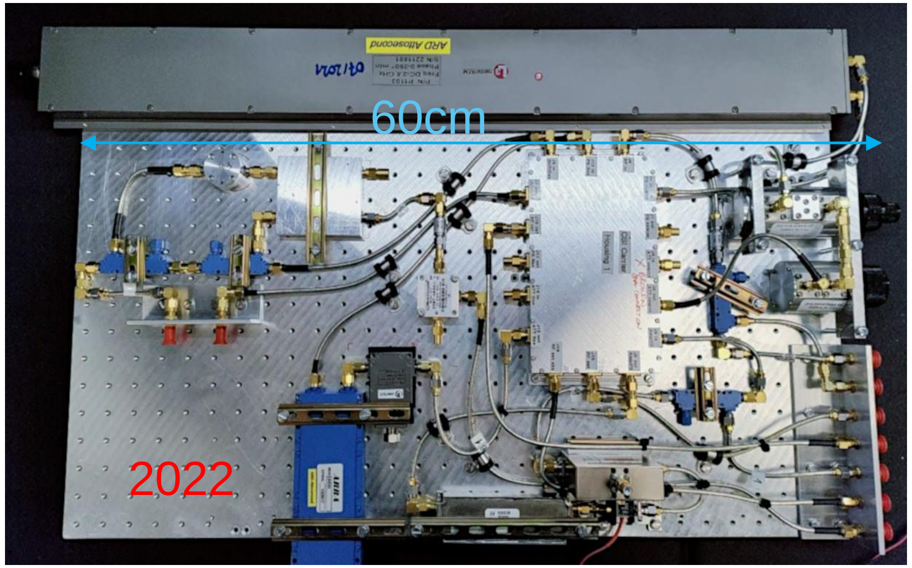
(+) Operation at RF frequency (lower risk of EMI).

Carrier suppression interferometer - implementation





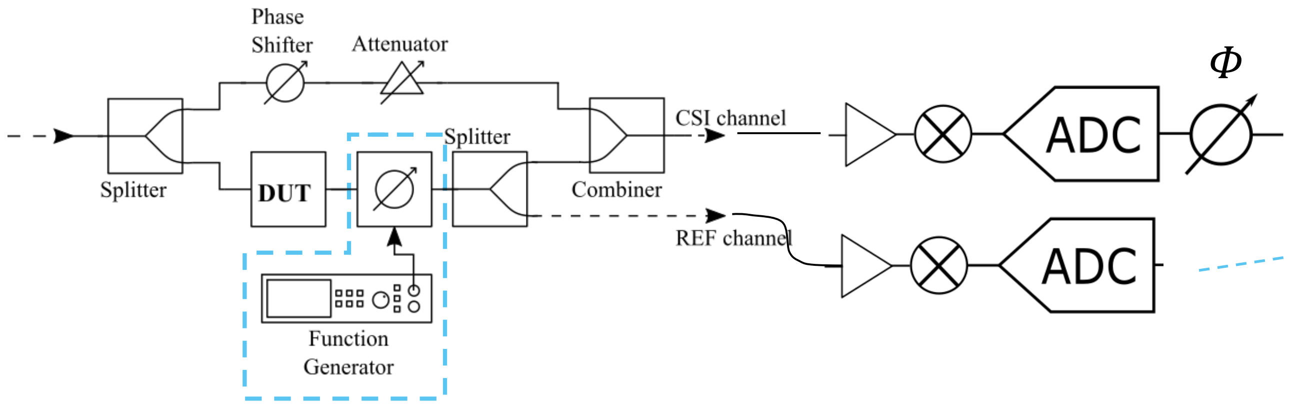


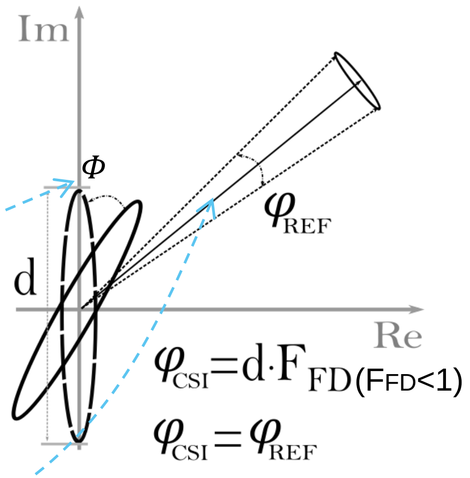


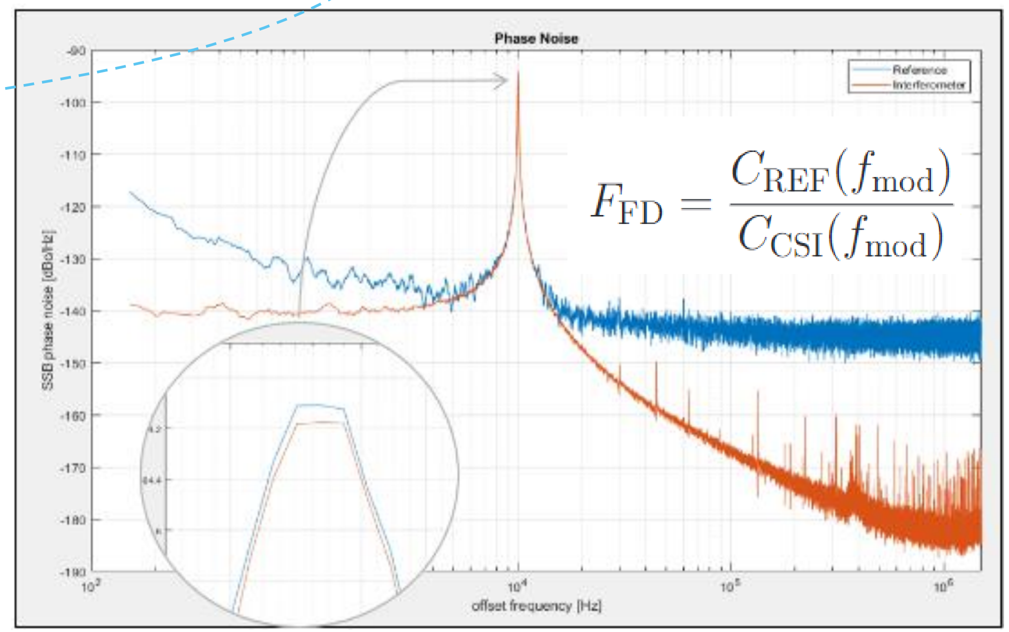
- Improvements in long term supression stability.
- Improvements in speed in finding a good supression.
- Better EMI immunity.
- Better Vibration immunity.

Calibration – part 1

1. Inject a large phase or amplitude modulation on the carrier.
2. Two types of calibration:
   - Calibration of angle (Φ) to measure amplitude or phase noise.
   - Calibration to transform a carrier-less CSI signal into phase sensible units [deg, dBc / Hz,…].







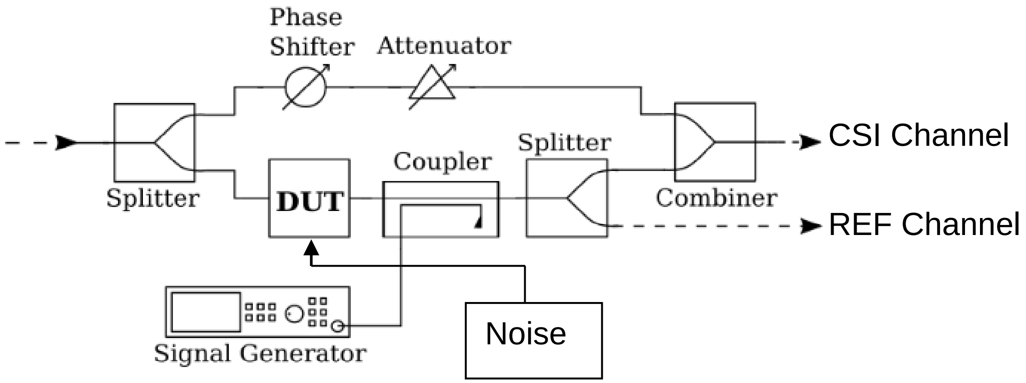
(-) Needs a var. phase shifter or attenuator in the main branch. This can limit power and performance.

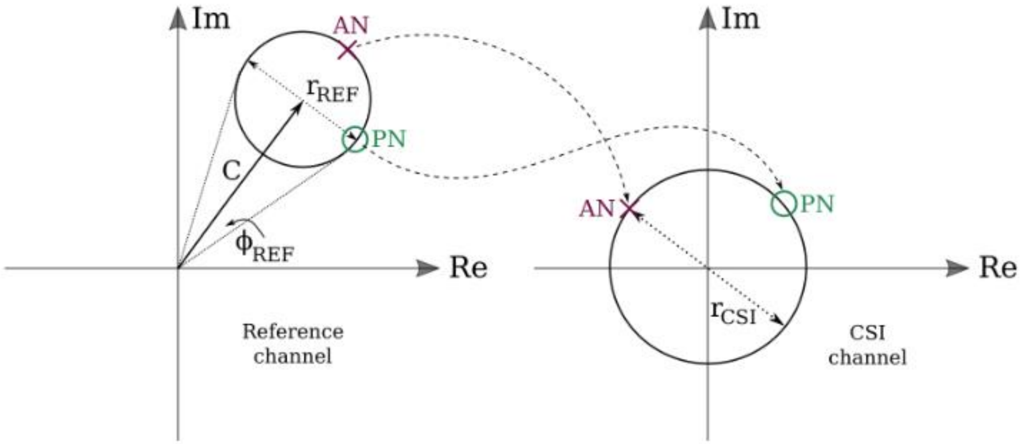
(-) AN and PN need a different actuator.

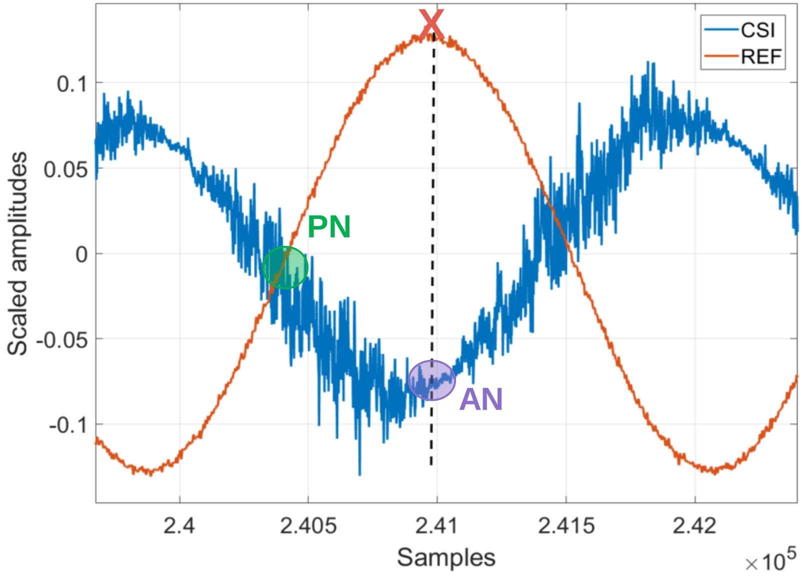
Calibration – part 2

Injection of a pilot with f0 +/- df frequency.

- The method is noninvasive and allows for calibration of amp and pha at the same time.





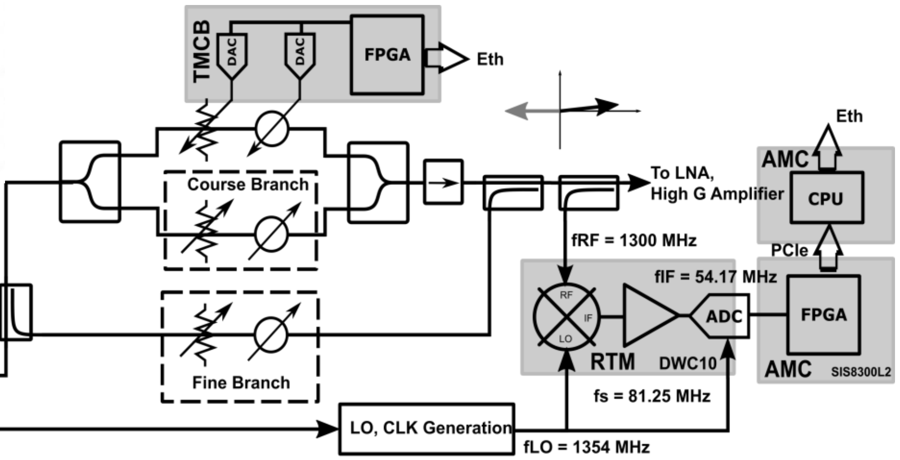


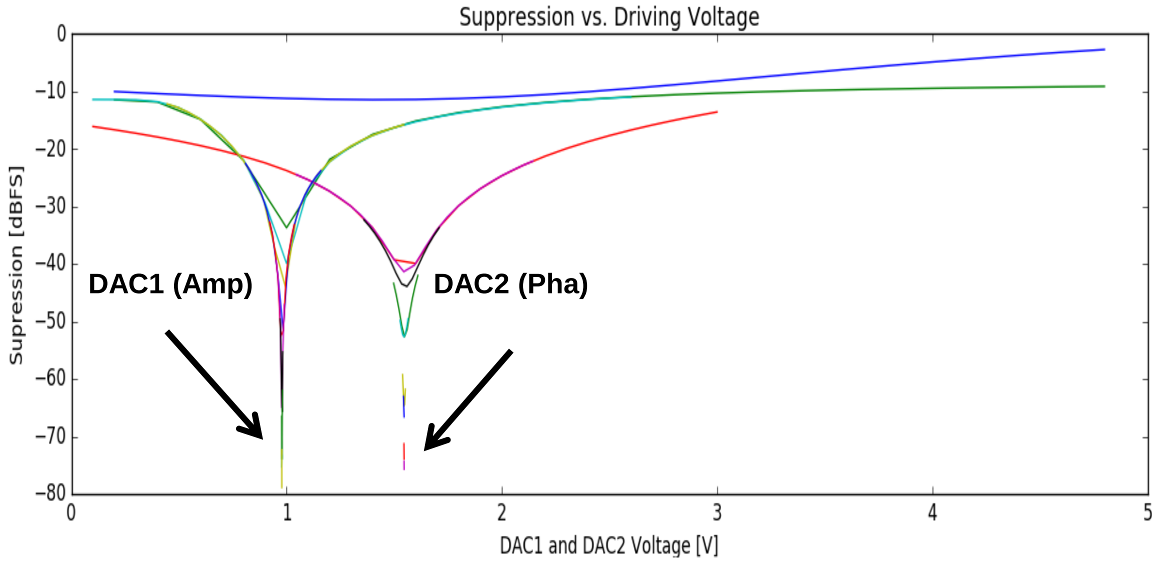
Calibration steps:

1. Turn the pilot ON.
2. Find points for AN and PN on the reference signal (with carrier).
3. Find same time points on the CSI signal.
4. Rotate angle (FPGA) to move AN on Re axis and PN on Im axis.
5. Switch the pilot OFF.

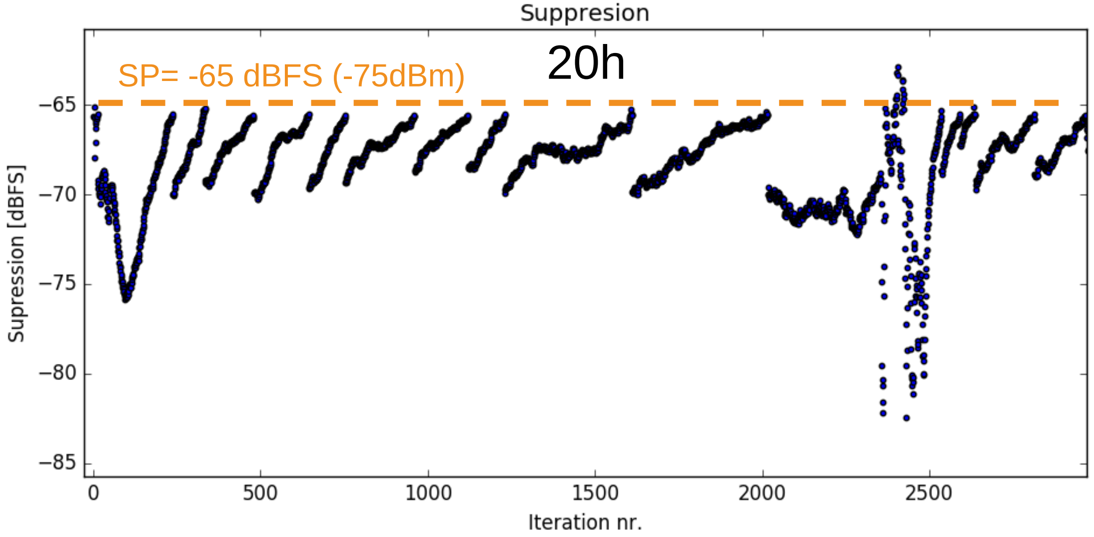
Note : assumption is that the phase change on a ~1-10kHz signal between the 2 branches is negligible.

Automatic carrier suppression





Work in progress. Not used for measurements yet.

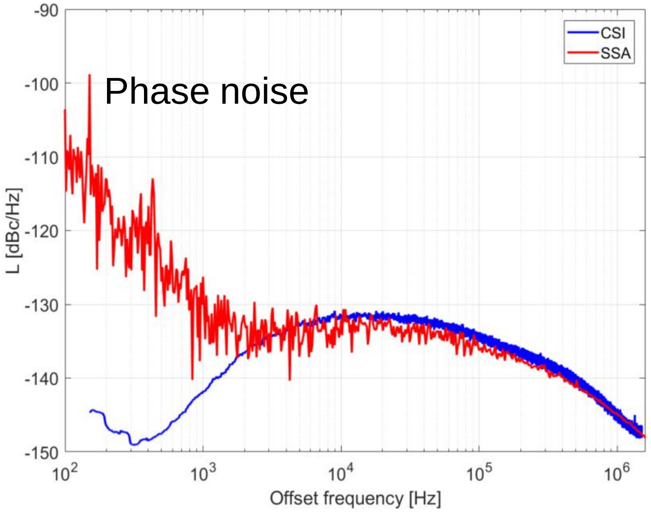


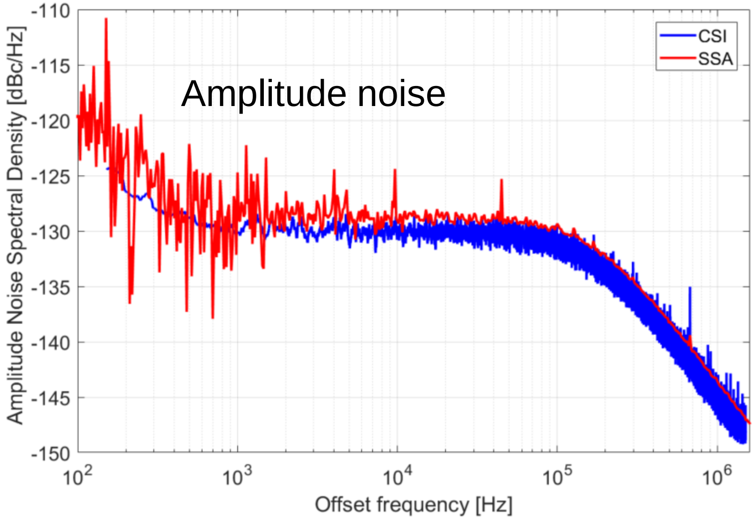
Some lessons learned:

- Assumed decoupled amplitude and phase behavior is a good approximation.
- Adjustments on fine and course branches are needed.
- 18 bit DAC is OK for -80 dBc supression.
- Main challanges are *r*eflections and low SNR.

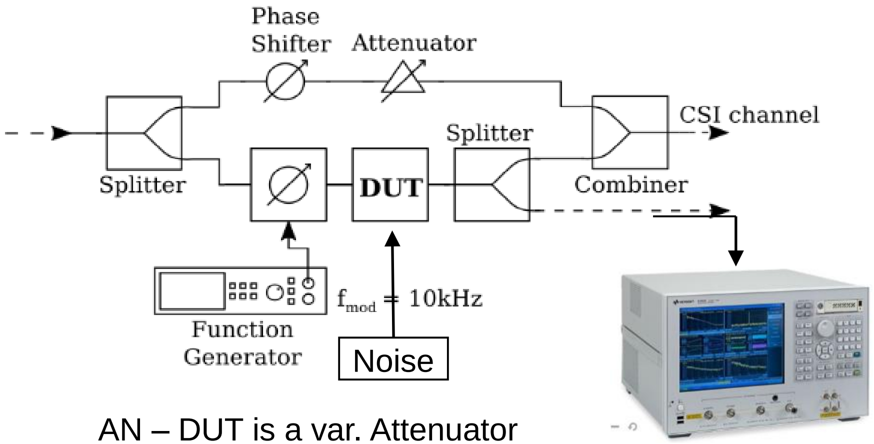
Verification of carrier supression interferometer measurements

Comparison with a commercial instrument (E5052B).





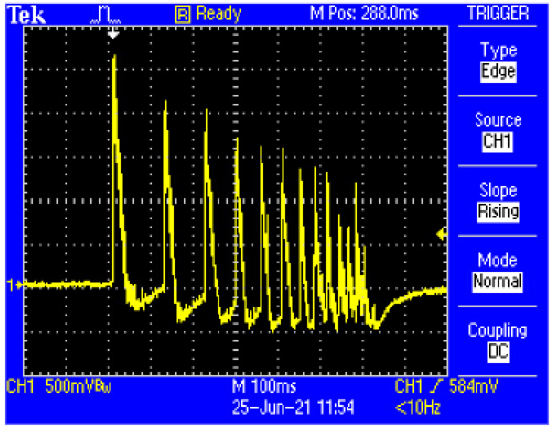
The DUT is phase or ampltiude modulated with a noise source.



AN – DUT is a var. Attenuator

PN – DUT is a var. Phase shifter

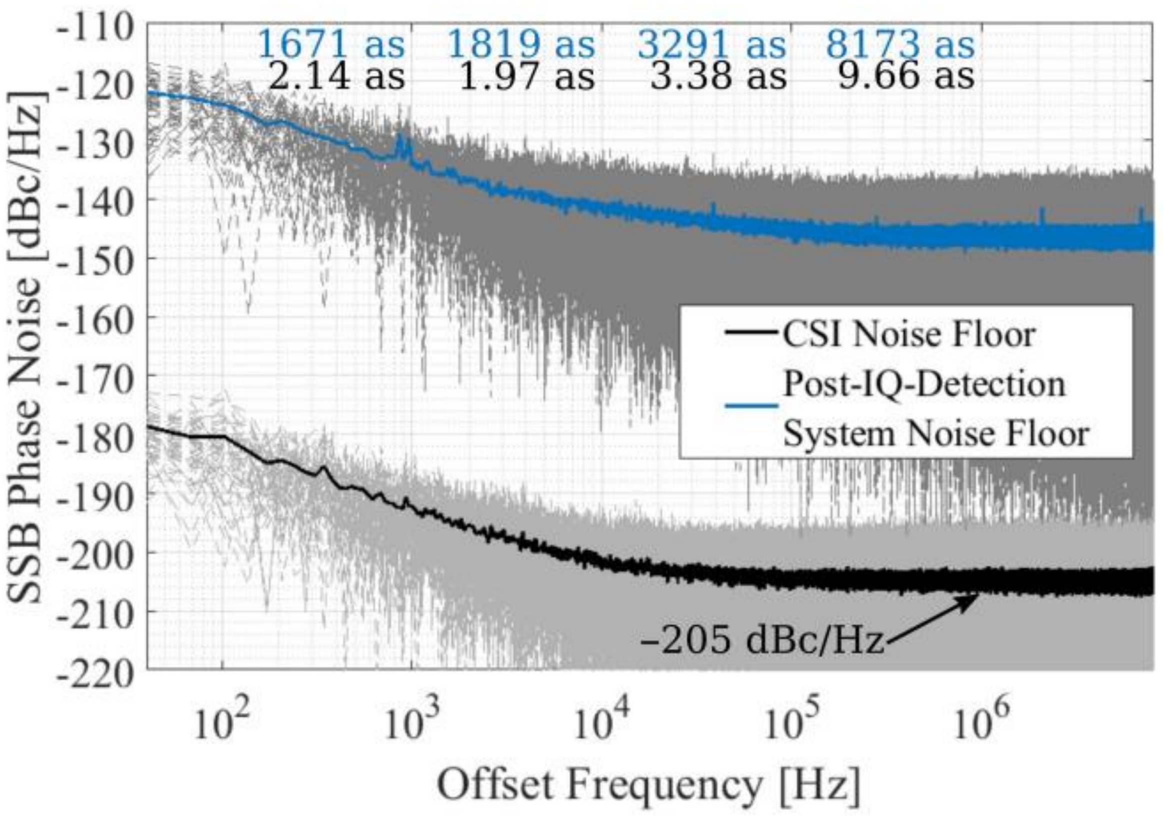
Sensitivity measurements of the setup.



1. Measured phase when droping a plastic screw driver on the main plate.

Performance

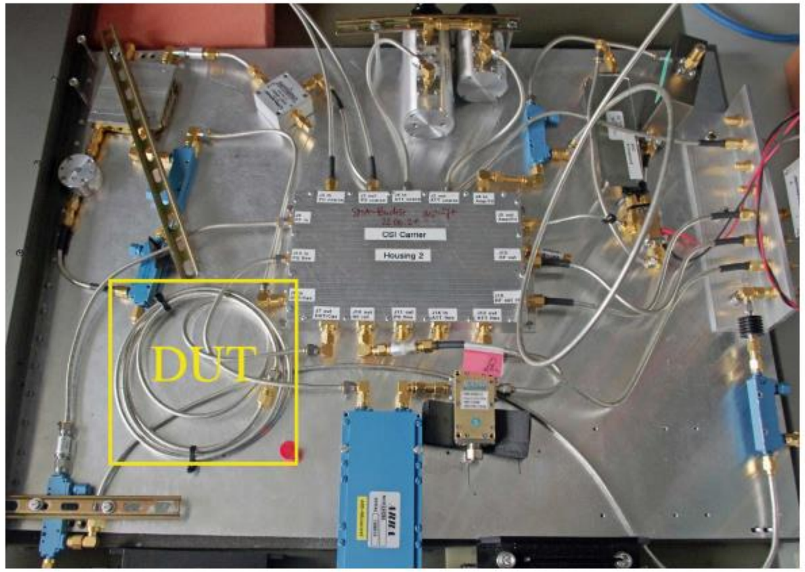
- The sensitivity limit of the setup was checked by increasing the carrier power to the DUT.
- In order to avoid any additional noise contributions the DUT was a short cable.



L. Springer et al., "Phase Noise Measurements for L-Band Applications at Attosecond Resolution," in IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1-7, 2022

Where does the remaining 1/f come from?

L = **-205 dBc/Hz (1 MHz), -180 dBc/Hz (100Hz)**
Time jitter : **10 as [40 Hz – 1MHz]**
Measured with +33 dBm, 1.3 GHz at DUT.

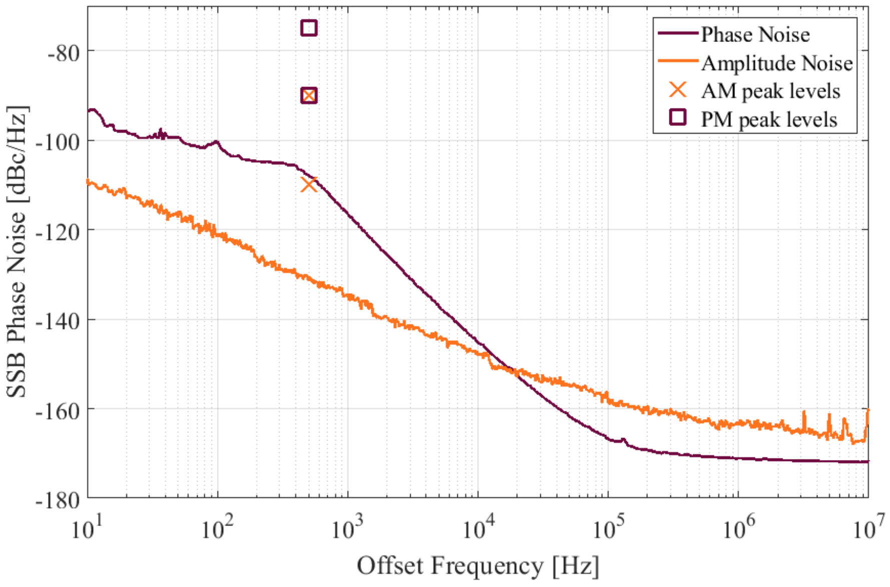


Why not increasing the power even further?

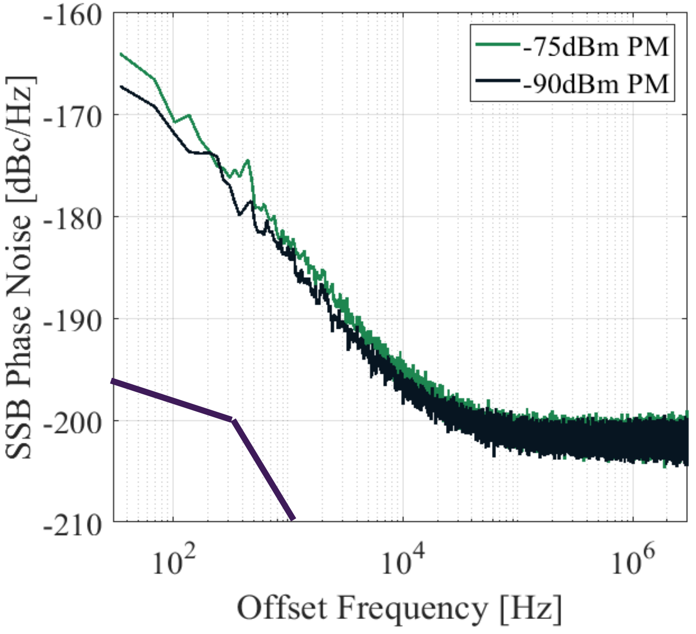
- Manual carrier supression becomes chalenging (unpractical).
- Input amplifier with the required parameters is not easy to find.

Possible sources of noise residuals

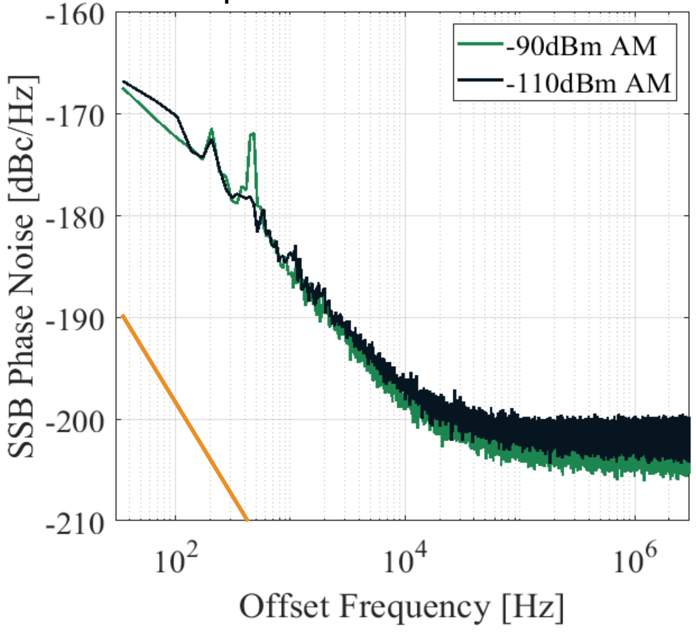
Residual from the source?



Phase modulated source.



Amplitude modulated source.

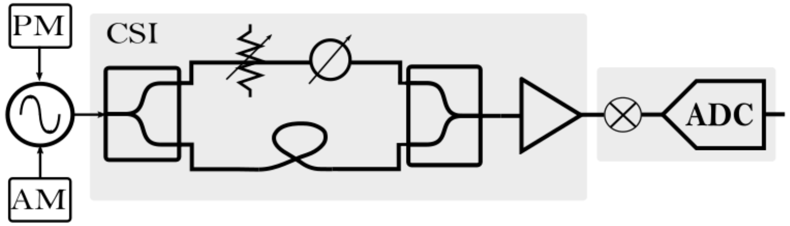


Phase modulated source:

- 17 dB and 32 dB at 500 Hz above the RF source phase noise floor.
- High suppression (app. -100 dB). The RF source PN does not influence the results.

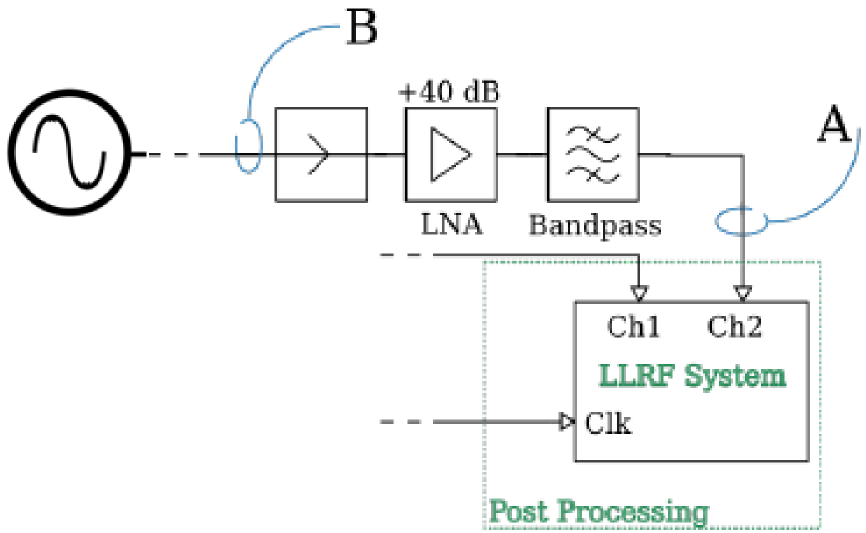
Amplitude modulated source:

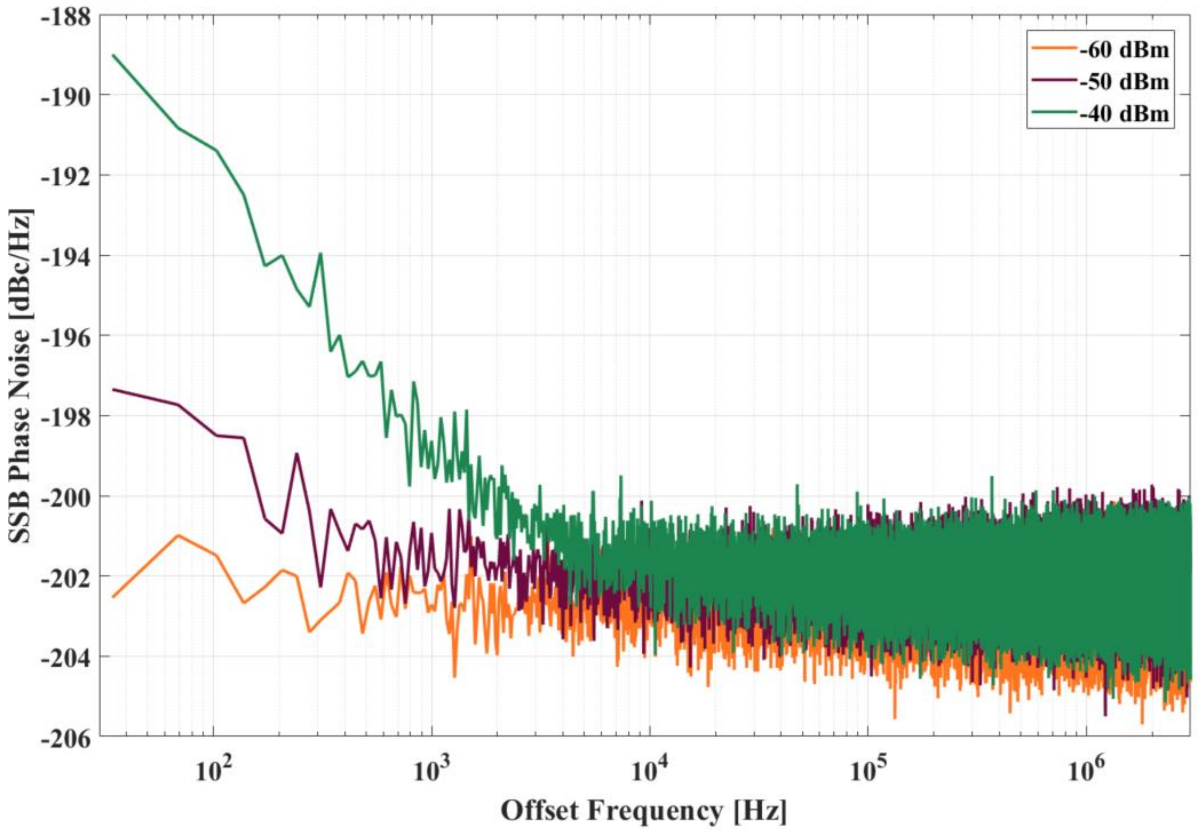
- 20 dB and 40 dB at 500 Hz above the input source amplitude noise floor.
- High suppression (app. -80 dB). The RF source AN does not influence the results.



Possible sources of noise residuals

Noise added by the output section of the setup?





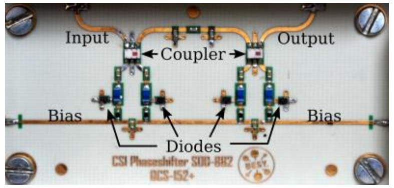
- A variable RF power was injected in front of the LNA.
- If the carrier is not well suppressed there is 1/f noise visible (green, magenta traces).
- The carrier is suppressed below -60 dBm during measurements.

The residuals are probably coming from resistive components and mechanical contacts in the actuators.

Investigation of phase shifters - part 1

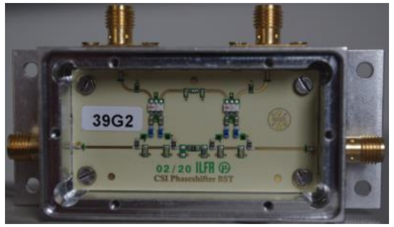
1. Varactor diodes

- Various varactor diodes tested through phase shifter.
- Many effects were observed which are not completely understood.



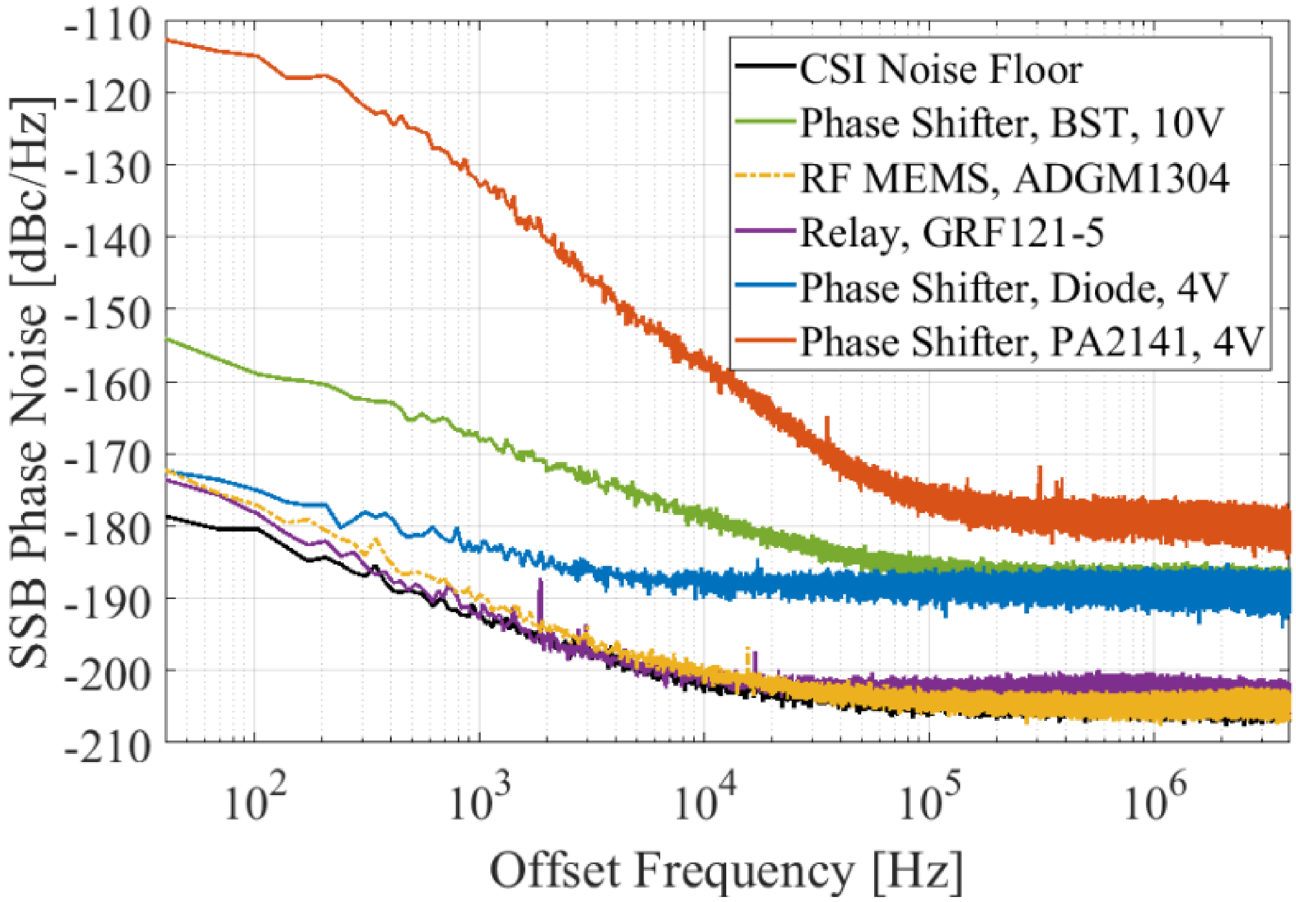
2. Barium Strontium Titanate varactors

- 2 different types tested by inserting them into a phase shifter structure.
- Effects visible in the 1/f region are not completely understood.
- Variations between varactor types.



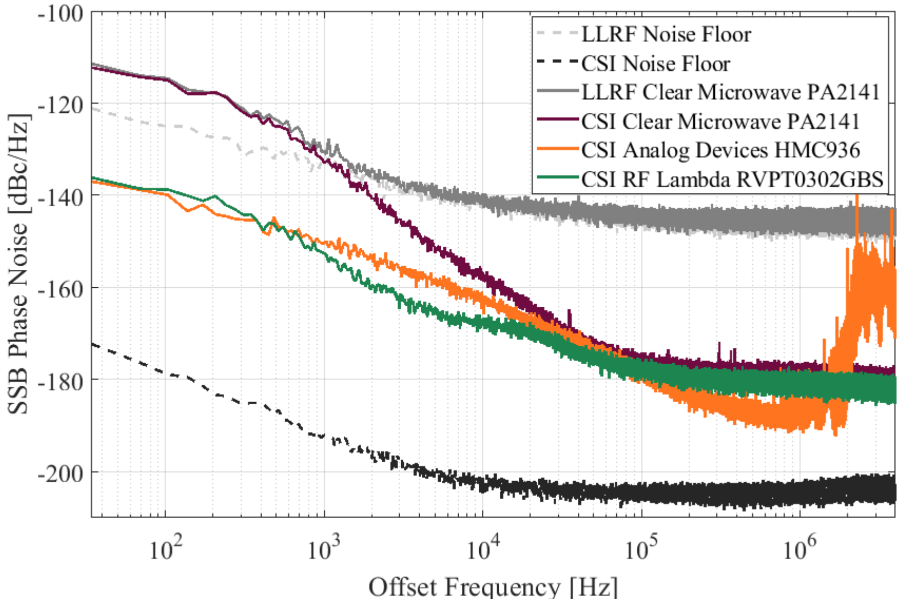
3. MEMS switches

4. Miniature magnetic relays

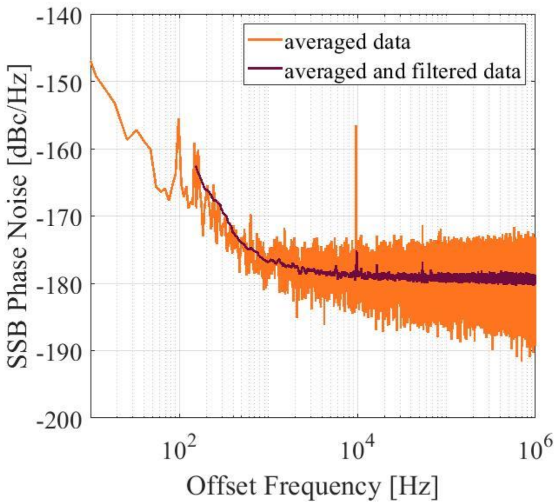


Investigations of phase shifters - part 2

4. Commercial phase shifters



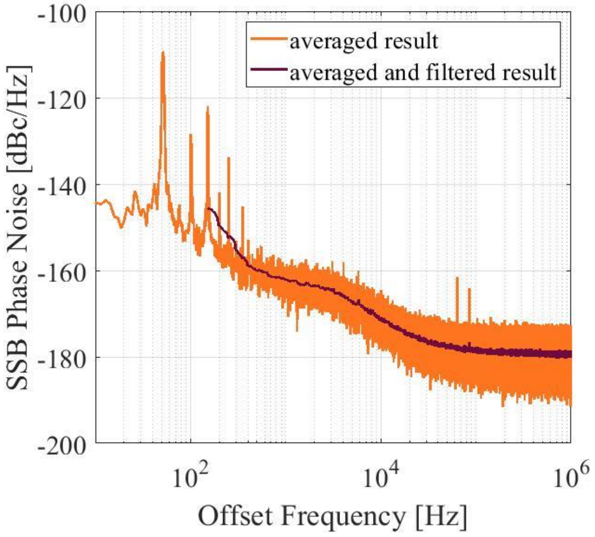
5. Manually tuned capacitors



6. Magnetic phase shifter

- Externally applied strong magnet on a ferromagnetic material changes the RF phase.
- The are several disturbances visible related to the ferrite material.

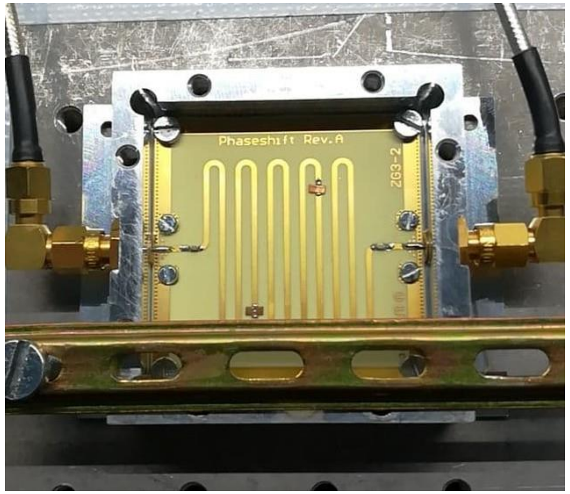
Courtesy of Laurin AG.

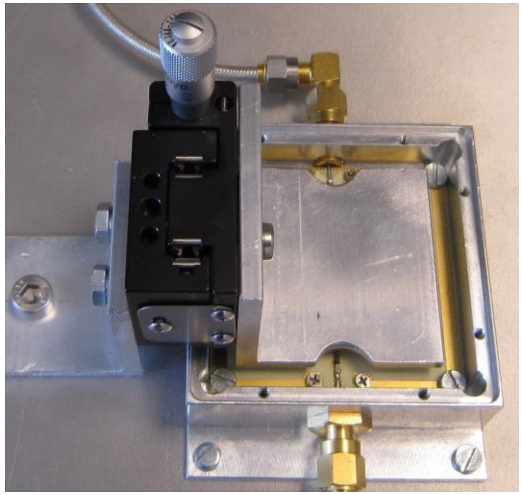


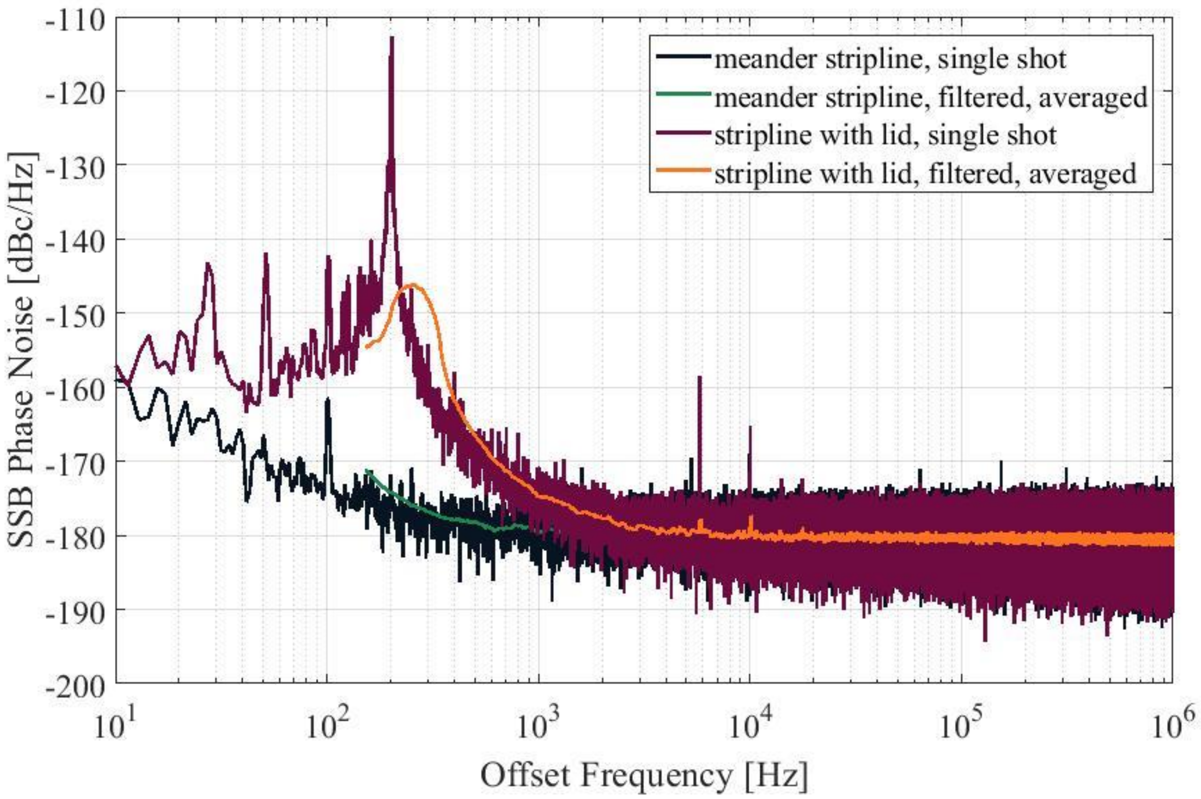
Investigations of phase shifters - part 3

7. Meander microstrip phase shifter

Distance of a metalic plate to a microstrip line can be used for adjusting signal phase.

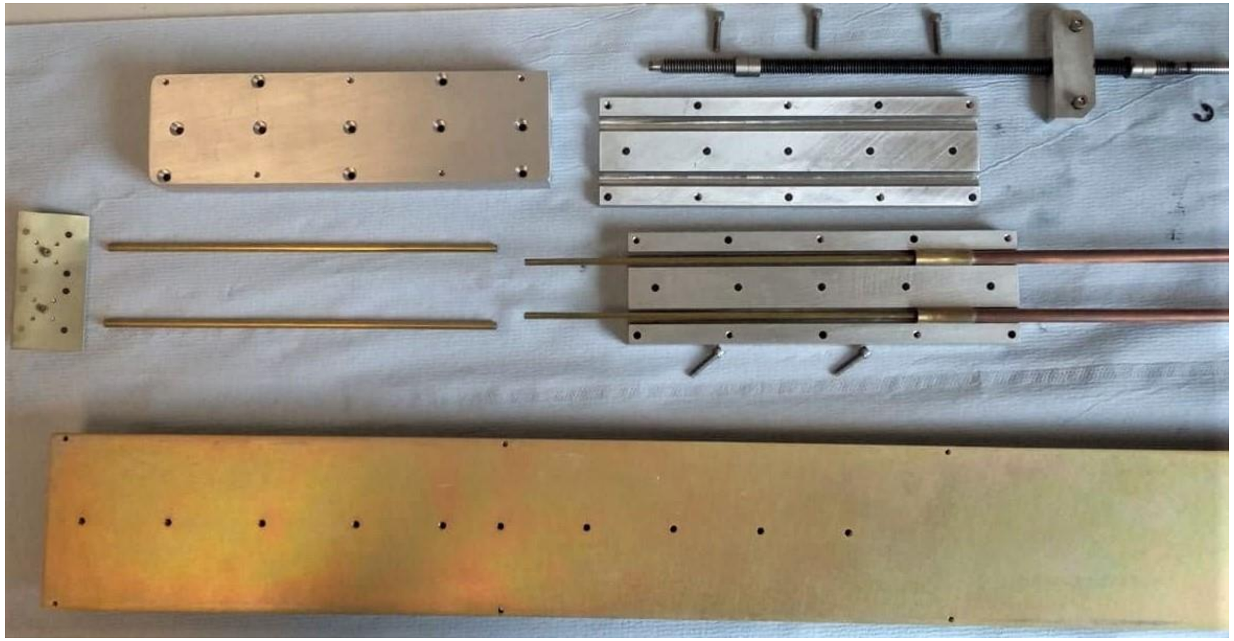




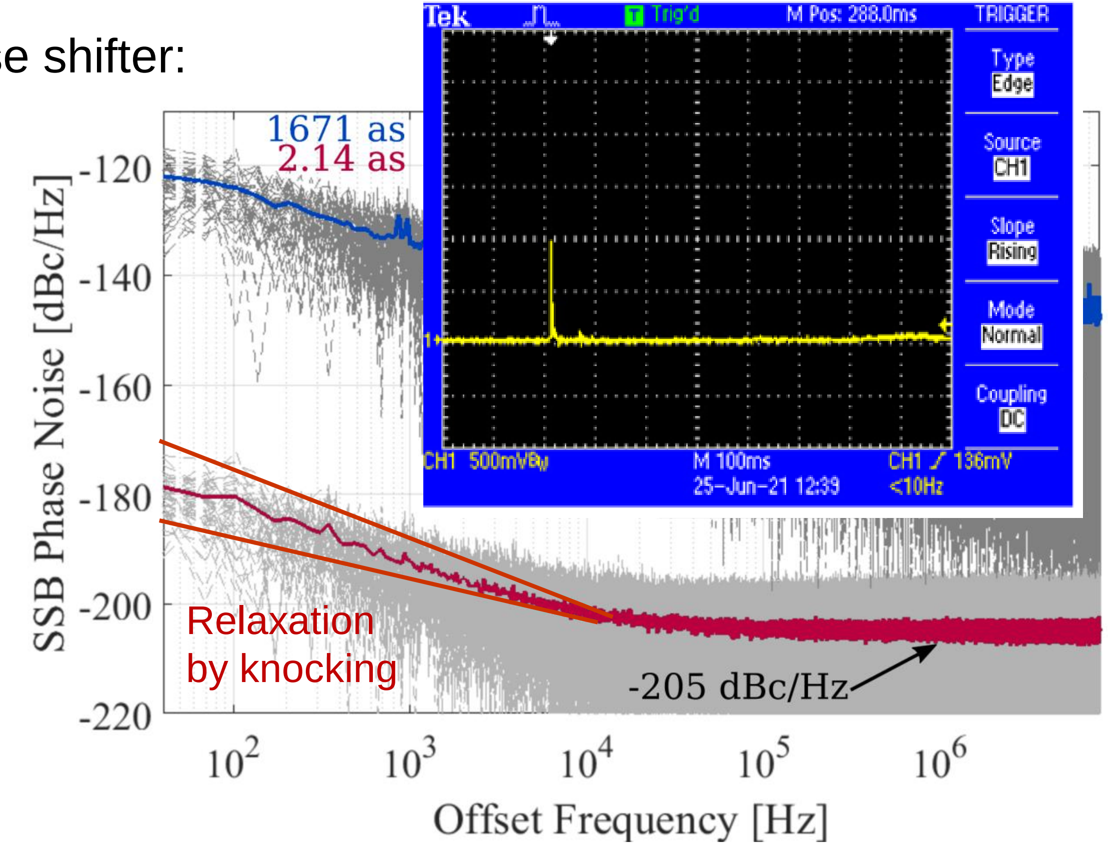


Trombone phase shifters

Micro-tensions and abrasion in a mechanical 360° - phase shifter:

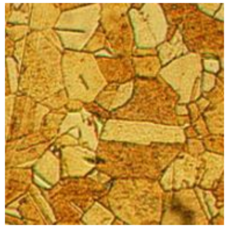


~60cm

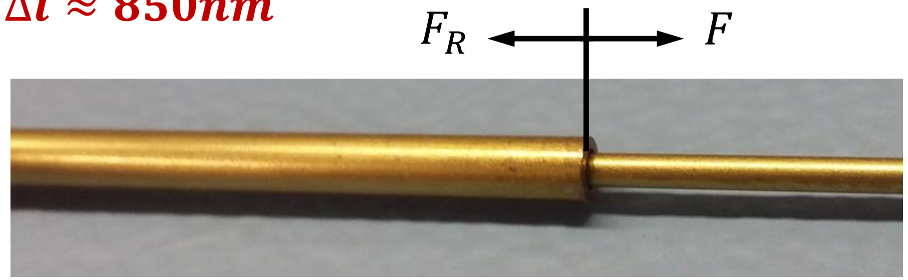


CSI measurement resolution:
10as, **≈3nm**, ≈ 4 lattice cells

Cu/Zn cell:
≈ 0.8nm



Extension, elastic micro-movement with friction:
$\boldsymbol{\Delta l \approx 850nm}$



$$\Delta l = \frac{F\, l_0}{A\, E}$$

$F = 3N,$
$l_0 = 20cm,$
$r = 1.5mm,$
$E = 100GPa$

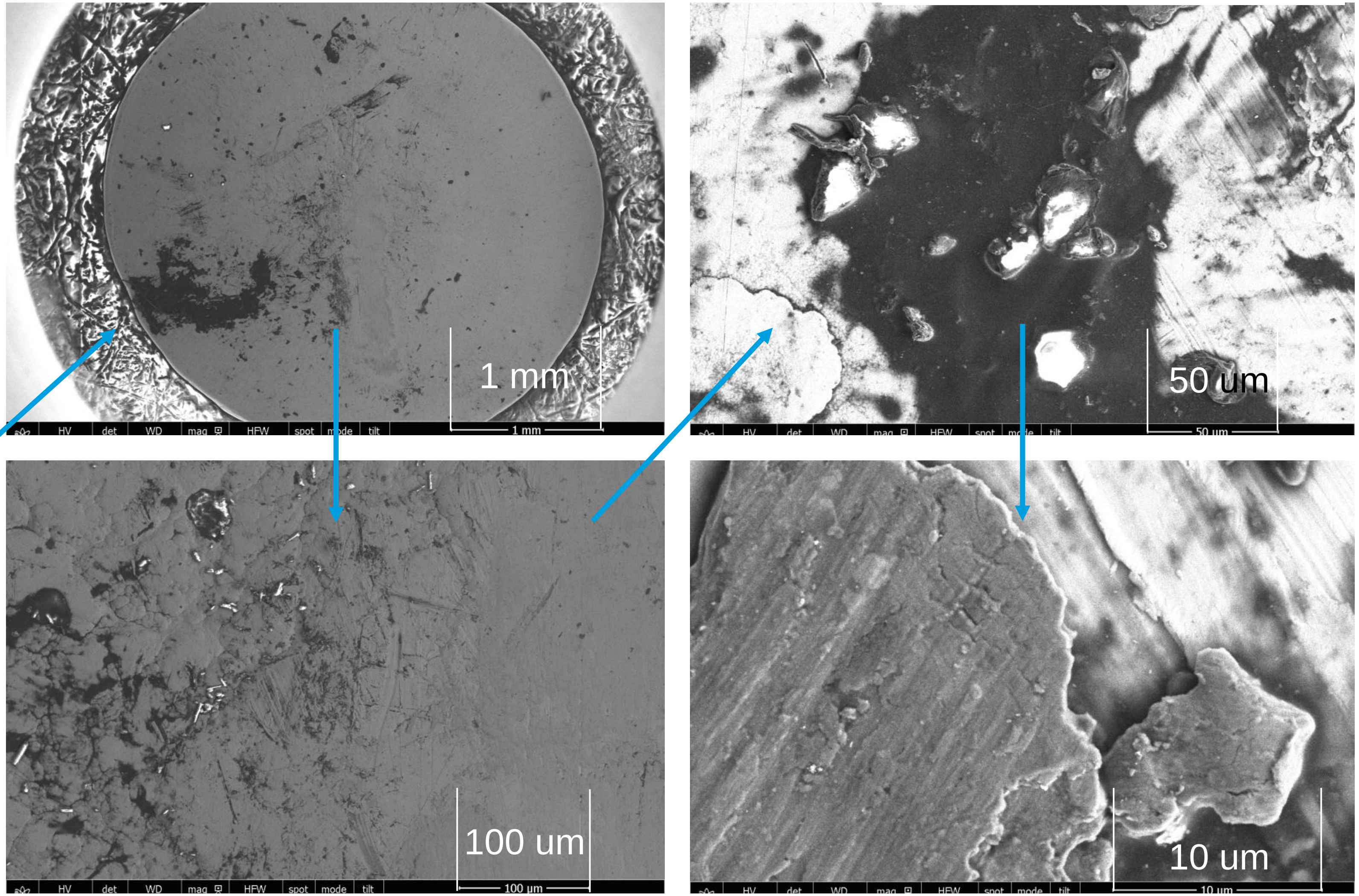
Remaining 1/f-noise in the mechanical CSI

Contact noise in a step attenuator:

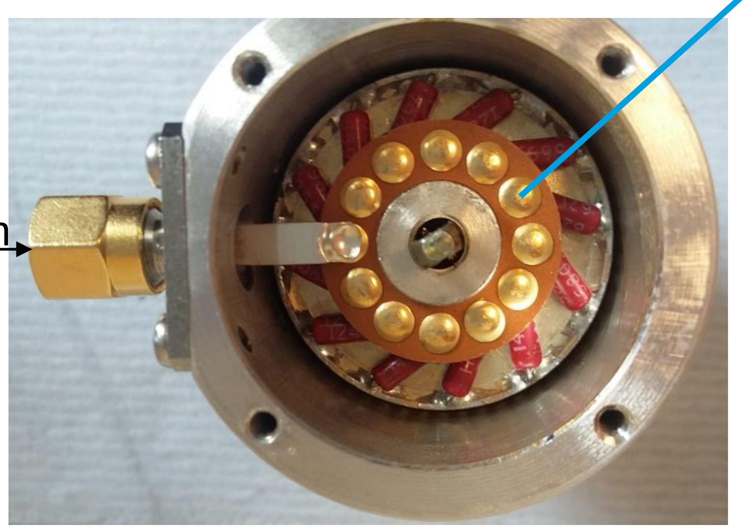
Courtesy of
DESY NanoLab

Surface inhomogenities lead to current inhomogenities, which lead to contact noise.

see Ref [7].

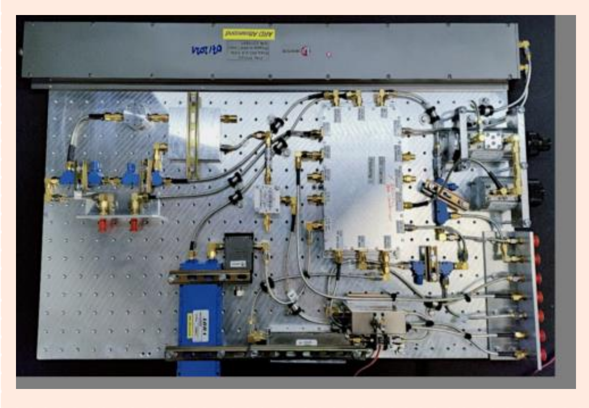


RF in

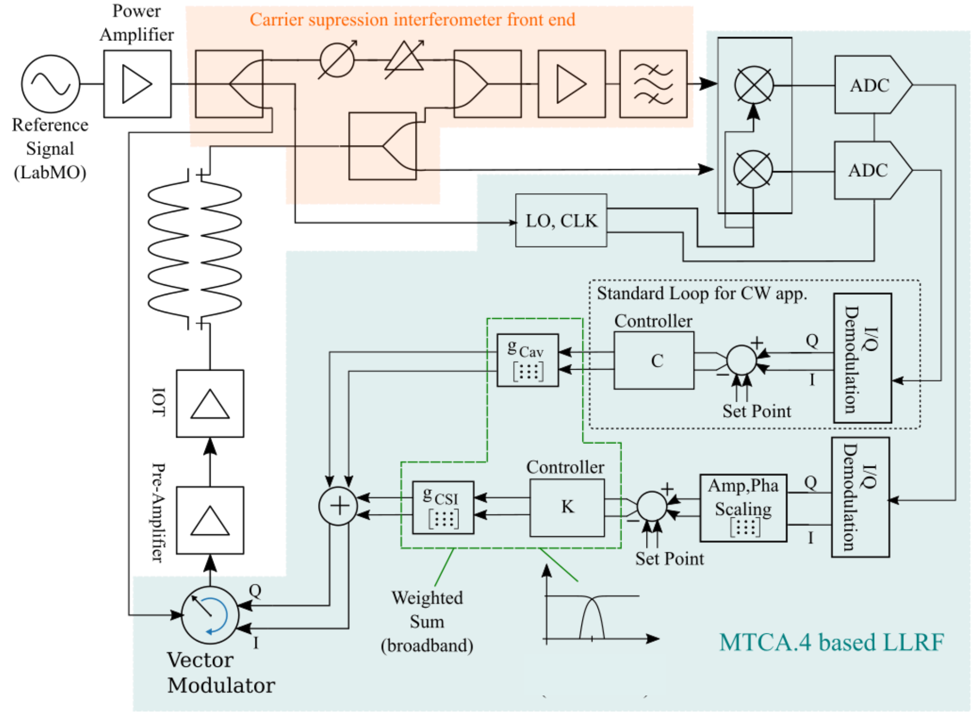


Future plans - using CSI as an RF detector in a LLRF system

- Foreseen tests:
  - Out of loop measurements.
  - Decouple the CSI and the „carrier“ branches through low/high pass filters.
  - Lock first the standard loop and by proper weighting gradually add the CSI loop.



CMTB (Cryo Module Test Bench) at DESY



Summary

- Carrier supression interferometer presents a possible alternative to the limitation in performance given by the current ADCs on the market.
- We investigated the automatic carrier supression and calibration methods.
- The presented setup can achieve -205dBc/Hz at 1 MHz and -190 dBc/Hz at 1 kHz (at 1.3 GHz and +33 dBm on DUT). This coresponds to 10 as [40Hz – 1MHz].
- The residual phase noise with 1/f behavior originates in the phase and amplitude actuators. A survey of various phase shifter architectures and their additive phase noise was presented.
- A proposal for a LLRF system based on carrier supression interferometer was presented.

References

[1] F. Ludwig et al., “Phase Stability of the Next Generation RF Field Control for VUV- and X-Ray Free Electron Laser”, presented at the EPAC 2006, Edinburgh.

[2] K. Sann, “The Measurement of Near-Carrier Noise in Microwave Amplifiers”, IEEE Transactions on Microwave Theory and Techniques, vol. 16, no. 9, pp. 761–766, Sep. 1968,

[3] C. Horn, “A Carrier Suppression Technique for Measuring S/N and Carrier/Sideband Ratios Greater Than 120 dB”, in 23rd Annual Symposium on Frequency Control, Atlantic City, USA: IEEE, 1969, pp. 223–235.

[4] E. Rubiola and V. Giordano, “A Low-Flicker Scheme for the Real-Time Measurement of Phase Noise”, IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control, vol. 49, no. 4, pp. 501–507, 2002.

[5] P. Buabthong and T. Berenc, “Interferometric Residual Phase Noise Measurement System”, 2013.

[6] A. C. C´ardenas-Olaya et al., “Noise characterization of analog to digital converters for amplitude and phase noise measurements”, Review of scientific instruments, voll. 88, no. 6, June 2017, doi: 10.1063/1.4984948

[7] F. Hooge and A. Hoppenbrouwers, “Contact Noise”, Physics Letters A, vol. 29, no. 11, pp. 642–643, Aug. 1969.

[8] L. Springer et al., “Phase Noise Measurements for L-Band Applications at Attosecond Resolution,” in IEEE Transactions on Instrumentation and Measurement, vol. 71, pp. 1-7, 2022

Thank you for your attention.

Contact

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