Noise feedback system for Crab Cavities in Large Hadron Collider

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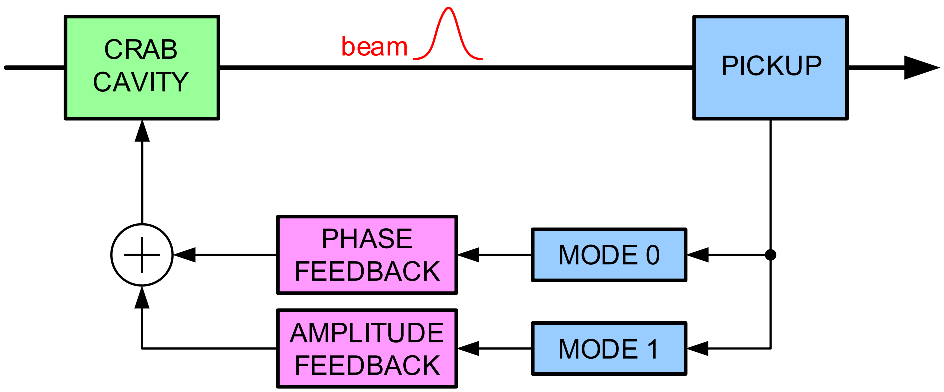
Crab cavity noise feedback

- In order not to blow-up the beam emittance, RF system of crab cavities must be very low noise (both LLRF and power).
- It is not possible to achieve only by the electronics itself, an active “noise” feedback is necessary.

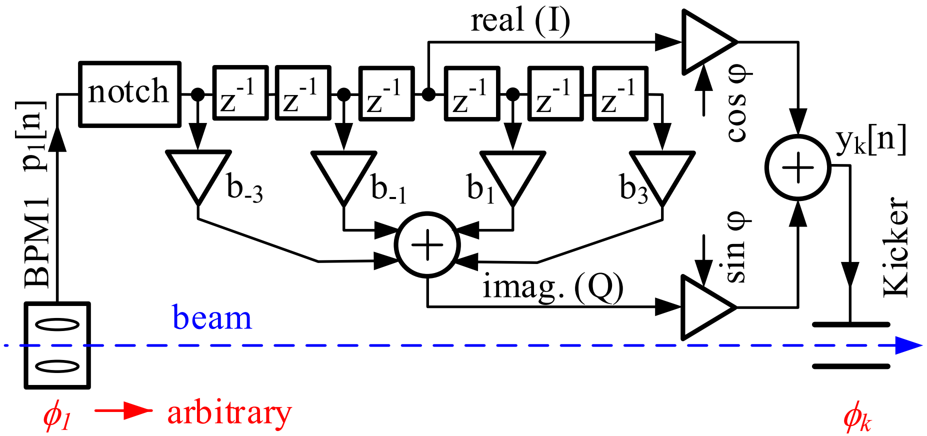


Baudrenghien, P. and Mastoridis, T.: Transverse emittance growth due to rf noise in crab cavities: Theory, measurements, cure, and high luminosity LHC estimates. 10.1103/PhysRevAccelBeams.27.051001

How do we close the feedback loop?

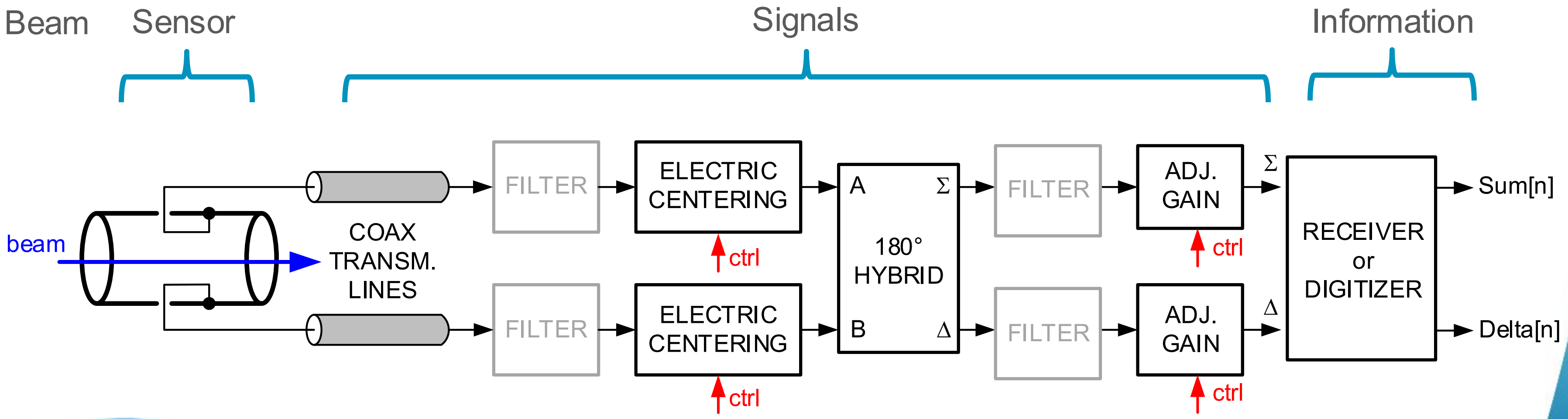
Single pickup feedback

- Single pickup at arbitrary betatron phase advance is sufficient
- Hilbert phase-shifter calculates the kick from the past turns (e.g. 7)
- Notch filter extracts the oscillatory part from beam motion
- Notch filter also suppresses all constant errors/artifacts (highly desirable)
- The correction is applied back to the beam via the crab cavity



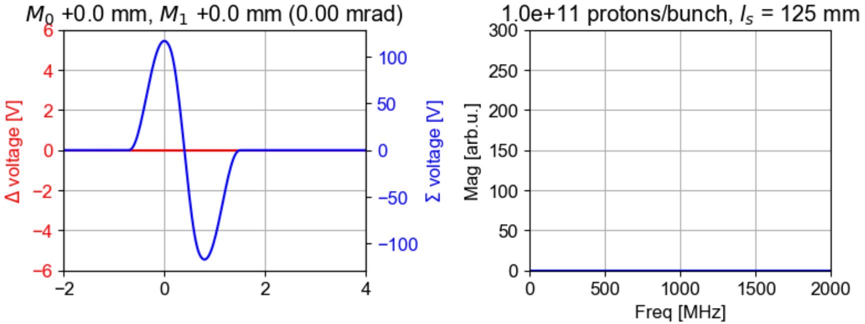
Bunch position and tilt measurements

- Most critical components for performance are the 180° hybrid and the digitizer
- Full signal path must have a very clean impulse response (not to mix bunches)

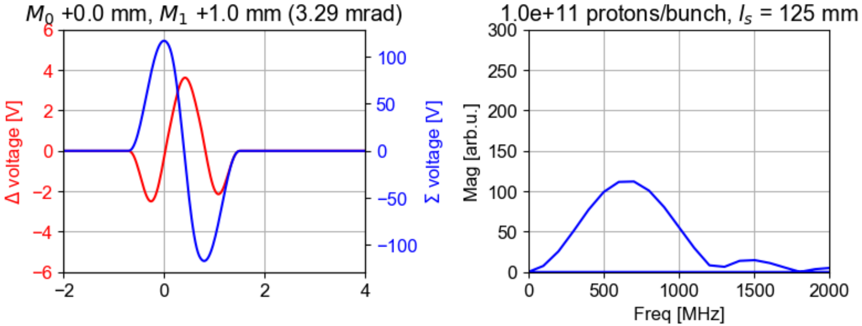


Example pickup signals

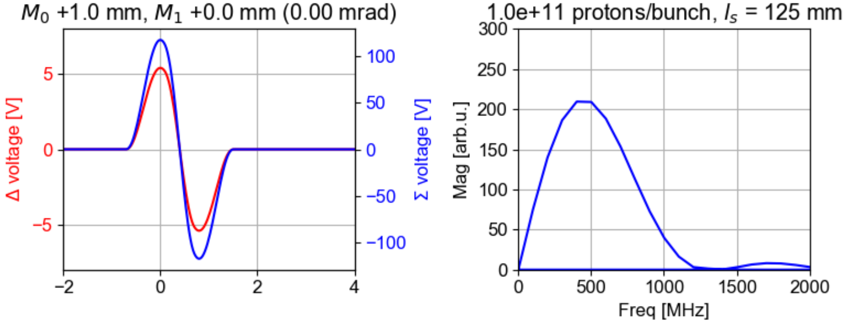
Centered



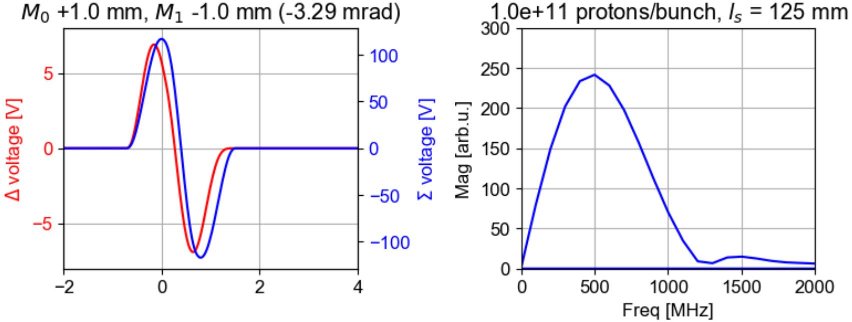
Tilt (m_1)



Displacement (m_0)

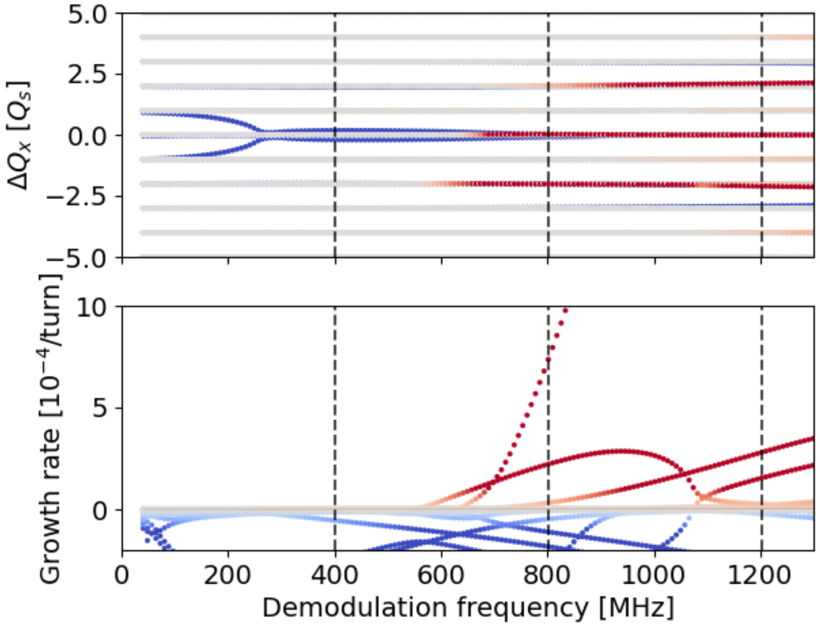


Displacement + Tilt (m_0 + m_1)



Measurement frequency selection

- Technically, we can process the signal at any frequency. Proposed stripline pickup has a peak sensitivity at 600 MHz…
- However, beam dynamics studies show a presence of two-node head-tail mode in a vicinity of 600 MHz, with a risk to be driven by the noise feedback if the position and tilt measurement will be done above 500 MHz.
- Therefore we need to measure between 400 and 500 MHz

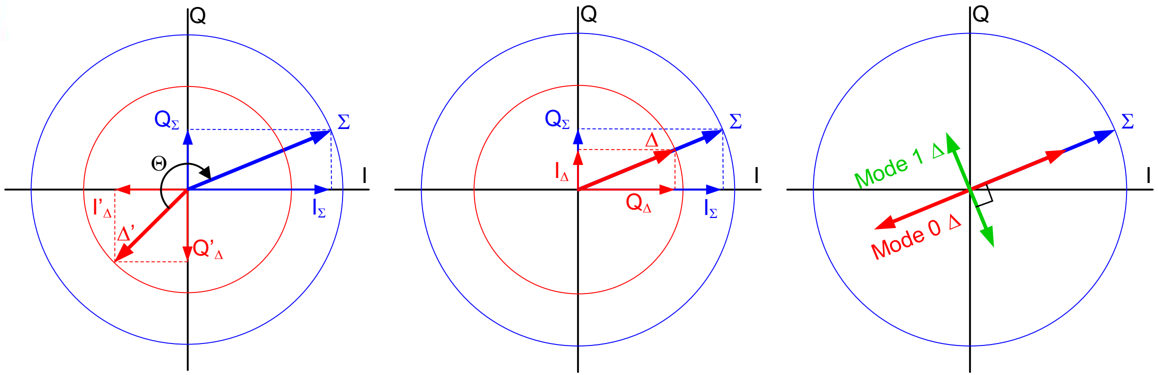


Buffat X: Update on stability from the amplitude feedback - Impact of RF curvature and quality factor. HL-LHC WP2 meeting 05.04.2022 https://indico.cern.ch/event/1144197/

Extraction of m_0 and m_1 motion from pickup signals

- Both position (m_0) and tilt (m_1) motion can be extracted from a pickup signal measured at the same frequency

1. Raw Σ, Δ signals
2. Phase aligned Σ, Δ signals
3. Effect of m_0 and m_1 motion



$$\frac{\Delta}{\Sigma} = \frac{I_\Delta + iQ_\Delta}{I_\Sigma + iQ_\Sigma}$$

$$Position = \Re\frac{\Delta}{\Sigma} = \frac{I_\Delta I_\Sigma + Q_\Delta Q_\Sigma}{I_\Sigma^2 + Q_\Sigma^2}$$

$$Tilt = \Im\frac{\Delta}{\Sigma} = \frac{Q_\Delta I_\Sigma - I_\Delta Q_\Sigma}{I_\Sigma^2 + Q_\Sigma^2}$$

Kotzian et al.: Sensitivity of the LHC Transverse Feedback System to Intra-Bunch Motion DOI 10.18429/JACoW-IPAC2017-TUPIK093

Required noise feedback performance

- Noise performance requirements for the feedback system beam position measurement units are **σ_0 < 320 nm** and **σ_1 < 8.3 µrad** (bunch-by-bunch measurement levels).
- The above measurement noise thresholds require extremely high precision measurements.
- Closed loop bandwidth of the crab cavity with LLRF will only extend to 136 kHz. As a result, the noise bandwidth will also be limited to 136 kHz.
- This relaxes the actual single bunch resolution threshold to **σ_0 < 3.9 μm_{rms}** and **σ_1 < 100 μrad_{rms}**. Works only for beam pattern without gaps.
- **It is a tight, but achievable specification.**

Baudrenghien, P. and Mastoridis, T.: Transverse emittance growth due to rf noise in crab cavities: Theory, measurements, cure, and high luminosity LHC estimates
DOI 10.1103/PhysRevAccelBeams.27.051001

Required noise feedback performance

- *“The measurement noise thresholds are thus σ_0 < 320 nm and σ_1 < 8.3 µrad. These are bunch-by-bunch measurement levels”*
- How good our signal processing needs to be?

$$Pos = f(I_\Sigma, Q_\Sigma, I_\Delta, Q_\Delta) \tag{5}$$

Sensitivity of the function 5 to small changes in the input values (due to noise) can be calculated as

$$\Delta Pos = \left(\frac{\partial Pos}{\partial I_\Sigma}\right)\Delta I_\Sigma + \left(\frac{\partial Pos}{\partial Q_\Sigma}\right)\Delta Q_\Sigma + \left(\frac{\partial Pos}{\partial I_\Delta}\right)\Delta I_\Delta + \left(\frac{\partial Pos}{\partial Q_\Delta}\right)\Delta Q_\Delta \tag{6}$$

As long the uncertainties (noise) on the input signals are random and independent, variance of the output value will be

$$\delta_{Pos}^2 = \left(\frac{\partial Pos}{\partial I_\Sigma}\right)^2\sigma_{I\Sigma}^2 + \left(\frac{\partial Pos}{\partial Q_\Sigma}\right)^2\sigma_{Q\Sigma}^2 + \left(\frac{\partial Pos}{\partial I_\Delta}\right)^2\sigma_{I\Delta}^2 + \left(\frac{\partial Pos}{\partial Q_\Delta}\right)^2\sigma_{Q\Delta}^2 \tag{7}$$

and the standard deviation

$$\sigma_{Pos} = \sqrt{\left(\frac{\partial Pos}{\partial I_\Sigma}\right)^2\sigma_{I\Sigma}^2 + \left(\frac{\partial Pos}{\partial Q_\Sigma}\right)^2\sigma_{Q\Sigma}^2 + \left(\frac{\partial Pos}{\partial I_\Delta}\right)^2\sigma_{I\Delta}^2 + \left(\frac{\partial Pos}{\partial Q_\Delta}\right)^2\sigma_{Q\Delta}^2} \tag{8}$$

20 steps later…

$$\sigma_{ReqPosData} = \frac{\sigma_{0single}}{\sqrt{2}} = 226\ nm \tag{25}$$

$$\frac{full\ scale}{rms\ requirement} = \frac{4.0\ mm}{226\ nm} = 17699\ codes,\ i.e.\ 14.1\ bits \tag{26}$$

Using results from chapter 3.2 we can calculate that a front-end configured for ±2 mm position range, will generate same amplitude full scale signals for a tilt of 9.44 *mrad*. Required input data standard deviation for tilt measurement

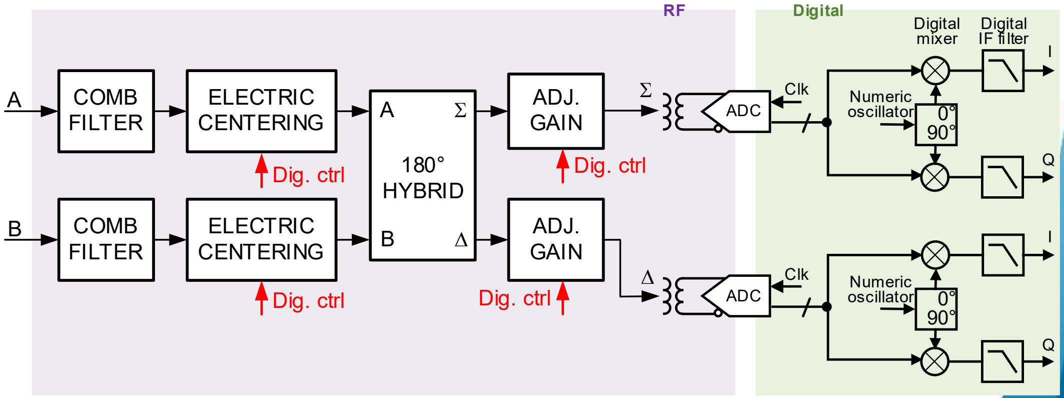
$$\sigma_{ReqTiltData} = \frac{\sigma_{1single}}{\sqrt{2}} = 5.86\ \mu rad \tag{27}$$

$$\frac{full\ scale}{rms\ requirement} = \frac{9.44\ mrad}{5.86\ \mu rad} = 1611\ codes,\ i.e.\ 10.7\ bits. \tag{28}$$

The noise floor is therefore dominated by position measurement requirements.

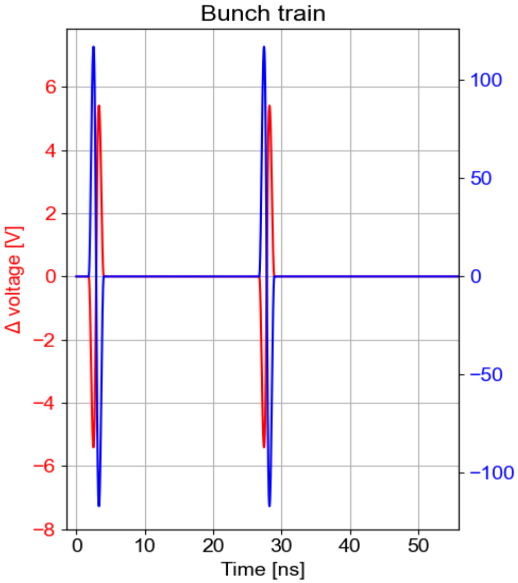
m_0 and m_1 measurement system architecture

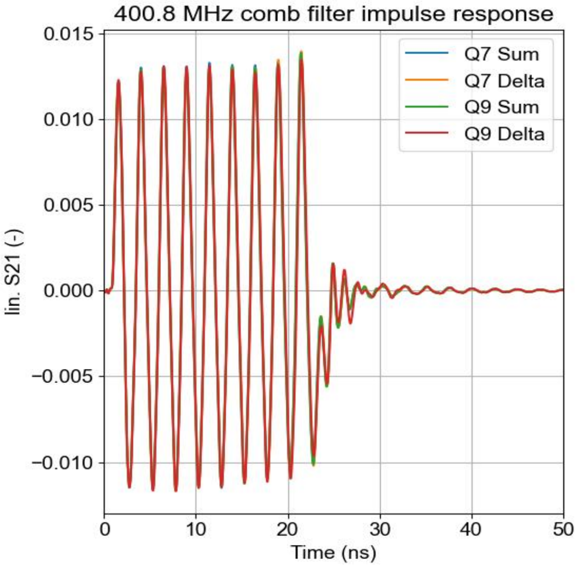
- We can not use the proven LHC very low noise BPM receiver architecture due to system architecture decisions…
- **Perhaps, would the direct RF sampling architecture be suitable?**
- No noisy or drifting analogue RF components in the signal chain…
- Gain setting, el. centering, all signal conditioning in RF domain e.g. 400±40 MHz
- Output signal is still in the RF domain
- Requires fast digitizer (~5 Gsps) with good ENOB (~10+) and many samples per bunch passage (10-100)

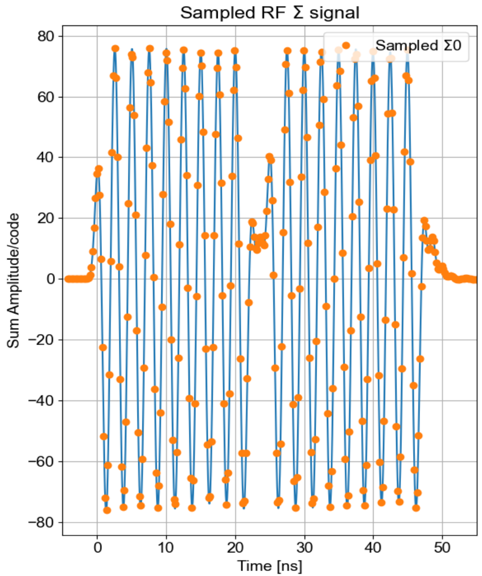


Pickup RF signal preparation for sampling

- Bunch spacing in LHC is 25 ns, pickup signal from one bunch lasts <2.5 ns
- Special comb filter with rectangular impulse response to select desired center frequency and stretch signal for sampling
- At 5 Gsps we can get about 110 samples per bunch passage

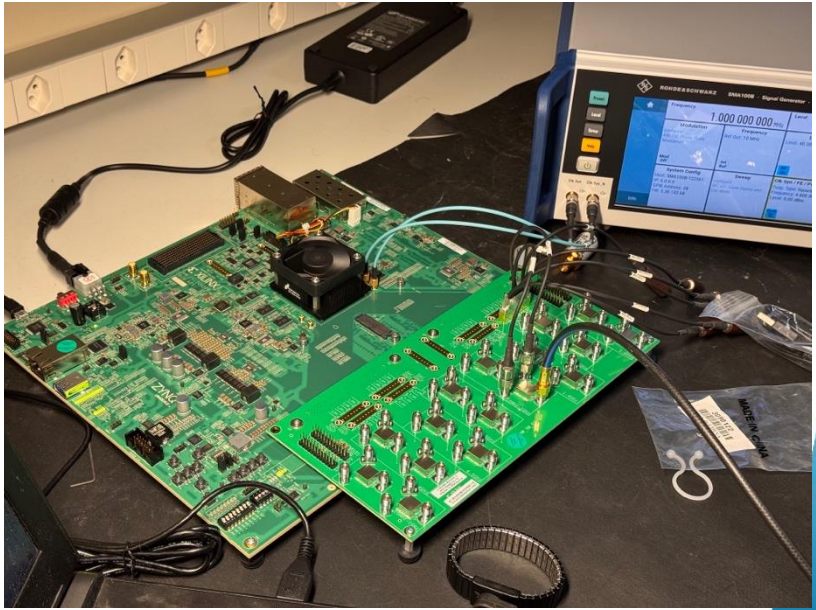




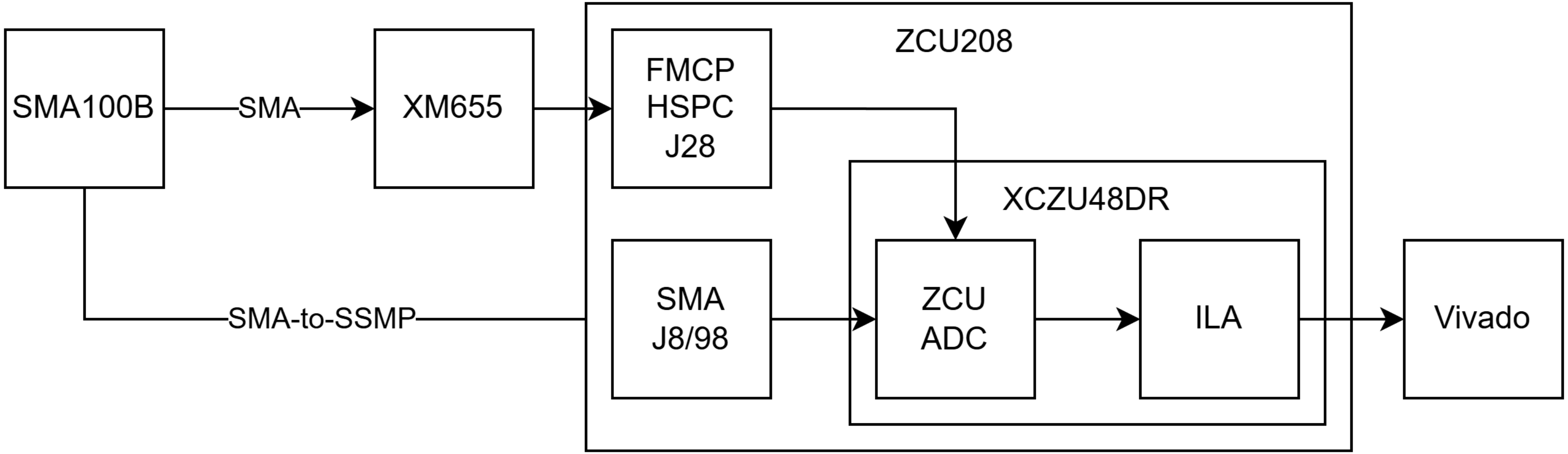


We need a good digitizer – is RF SoC suitable?

- Performance with direct sampling by high speed ADC might be in reach. We have more thoroughly evaluated Zynq™ UltraScale+™ RFSoC chip ZCU208
- Contains 8x 14-bit, 5.0 Gsps RF-ADC
- Must be in uTCA format
- Very good candidate uTCA board DAMC-DS5014DR from DESY (should be available in 1 year time)
- Currently we have an evaluation board with the same chip for developments and testing concepts



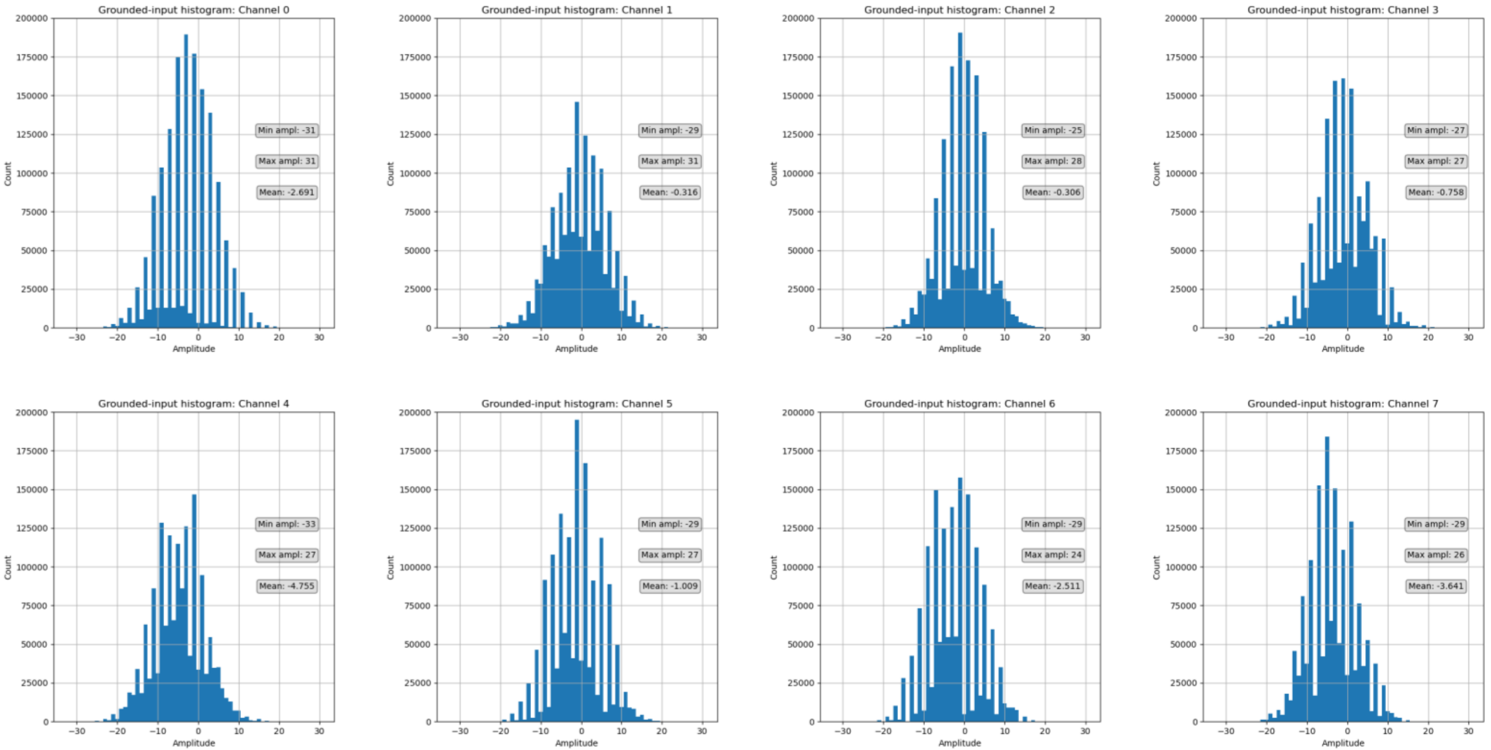
RF SoC evaluation



- Clock and Signal Generator: Rohde Schwarz SMA100B, ultra low noise opt.
- Analog Signal Interface: XM655
- Evaluation Board: ZCU208
- User Interface: Vivado

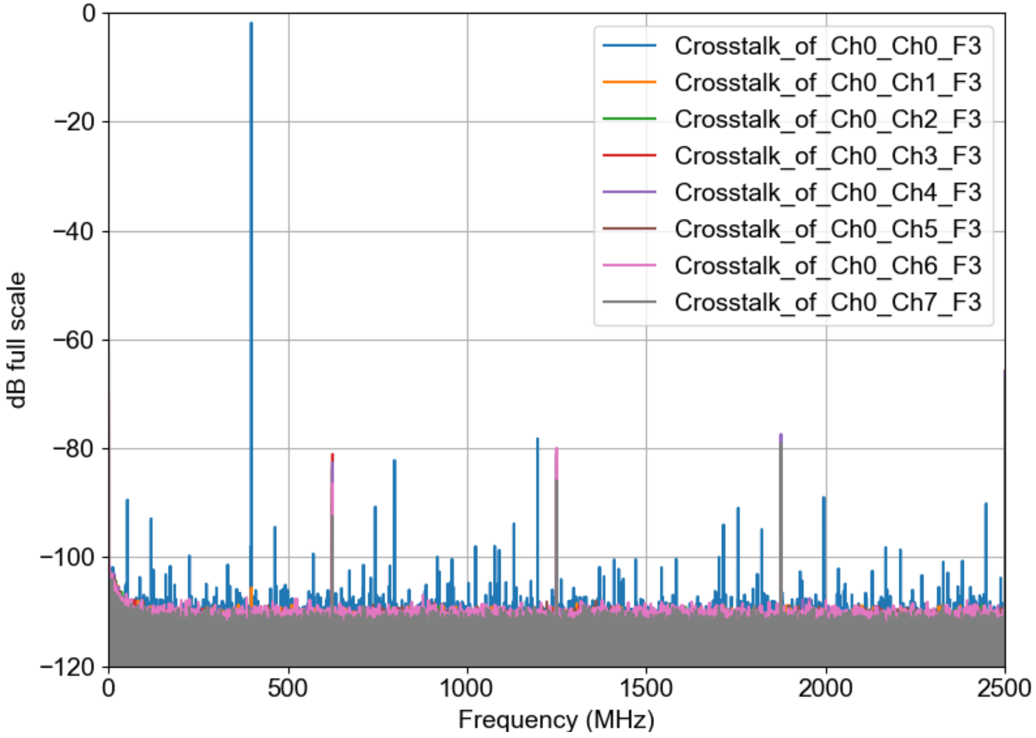
RF SoC evaluation, noise floor 5 Gsps

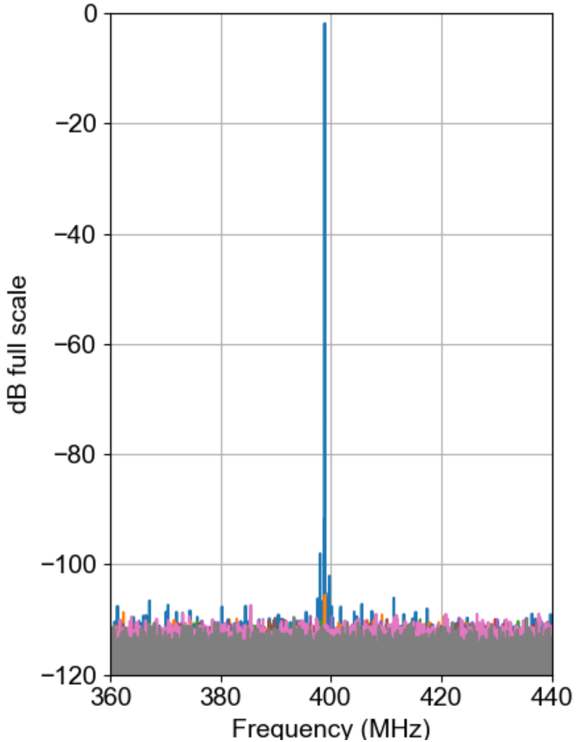
Observation of systematic LSB latching…



RF SoC evaluation, crosstalk and spurs

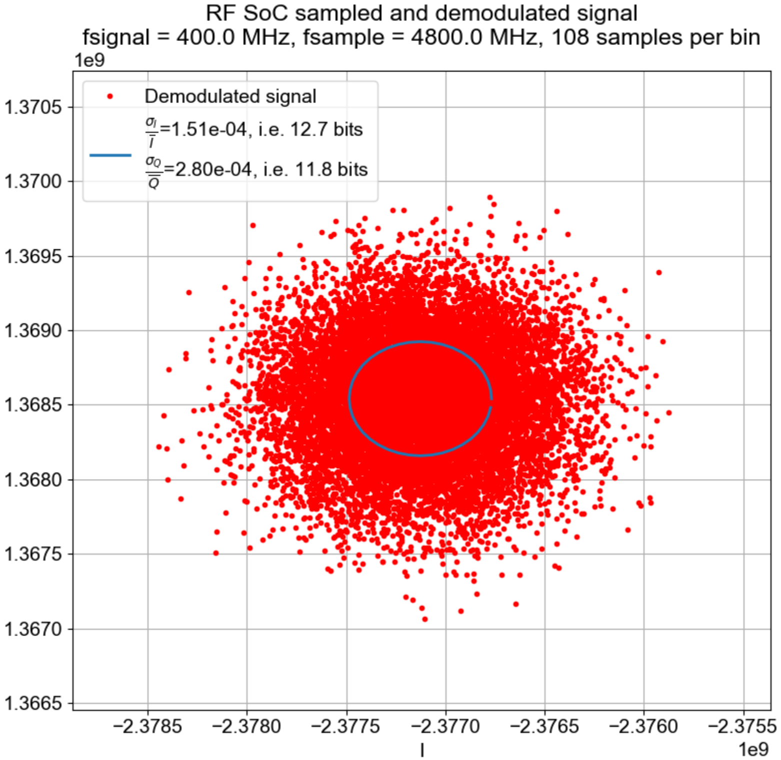
Sampling 398 MHz at 5 Gsps, no spurs in our band of interest. Promising…





RF SoC evaluation, synchronous acquisition

- Demodulated signal quality from RF SoC data, signals like in the machine
- “Beam synchronous” sampling
- f_{signal} = 400 MHz
- f_{sample} = 4800 MHz
- 9 periods of RF signal (108 samples) used for each ’bin’
- We plan to use 2 channels for Σ (+0.5 bit) and 4 channels for Δ (+1 bit)
- Two channels for cavity pickup (beam phase)



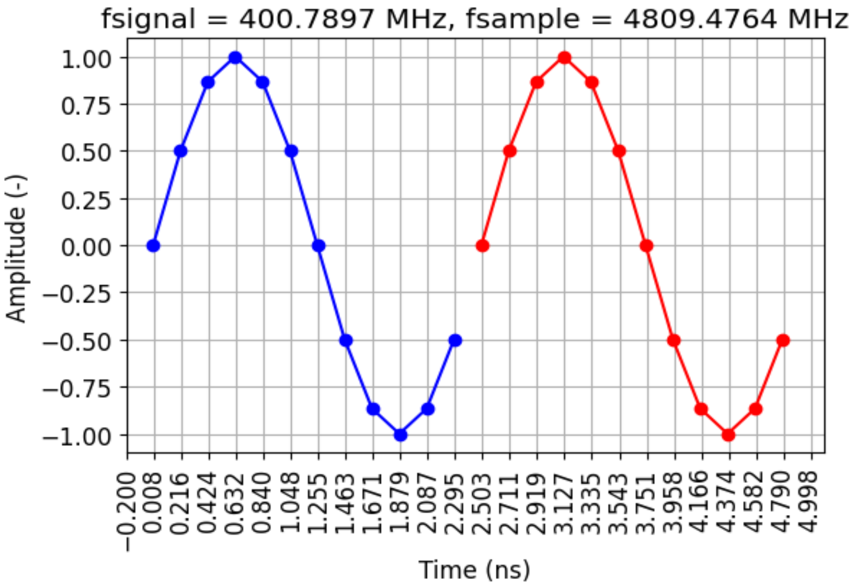
RF SoC evaluation

- But ENOB is not the only important thing.
- When aiming at the best possible noise performance, we need to meticulously analyze all potential noise contributors. For example…

Sampling of a harmonic signal

Signal synchronous with the sampling clock

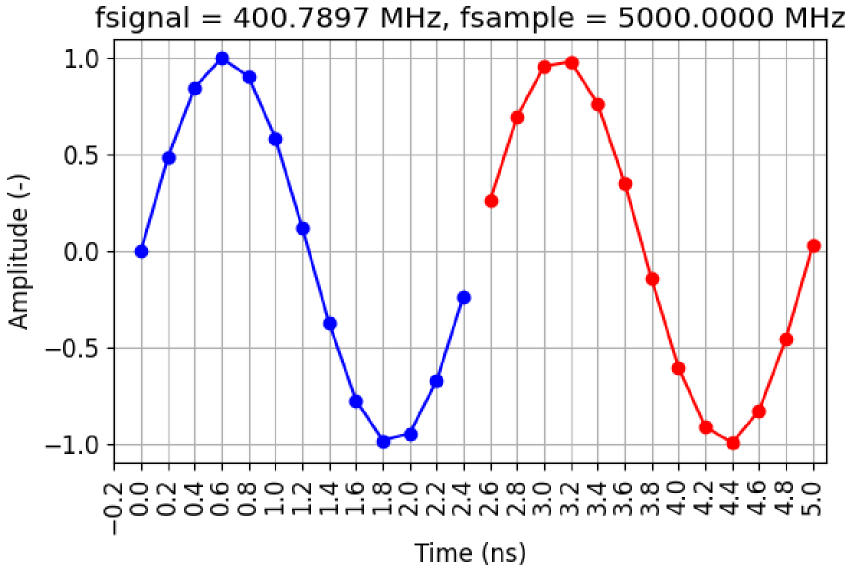
$$f_{sample} = k\ f_{signal}$$



Always the same acquisition

Signal asynchronous wrt sampling clock

$$f_{sample} \neq k\ f_{signal}$$



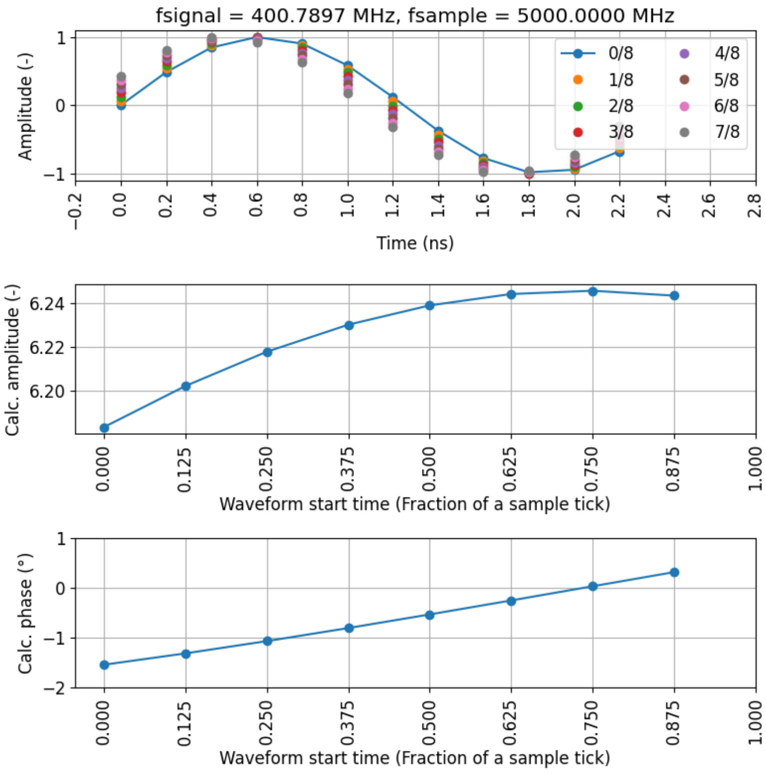
Every acquisition is different

Phase and amplitude of this sampled signal

Asynchronous sampling of signal, i.e.

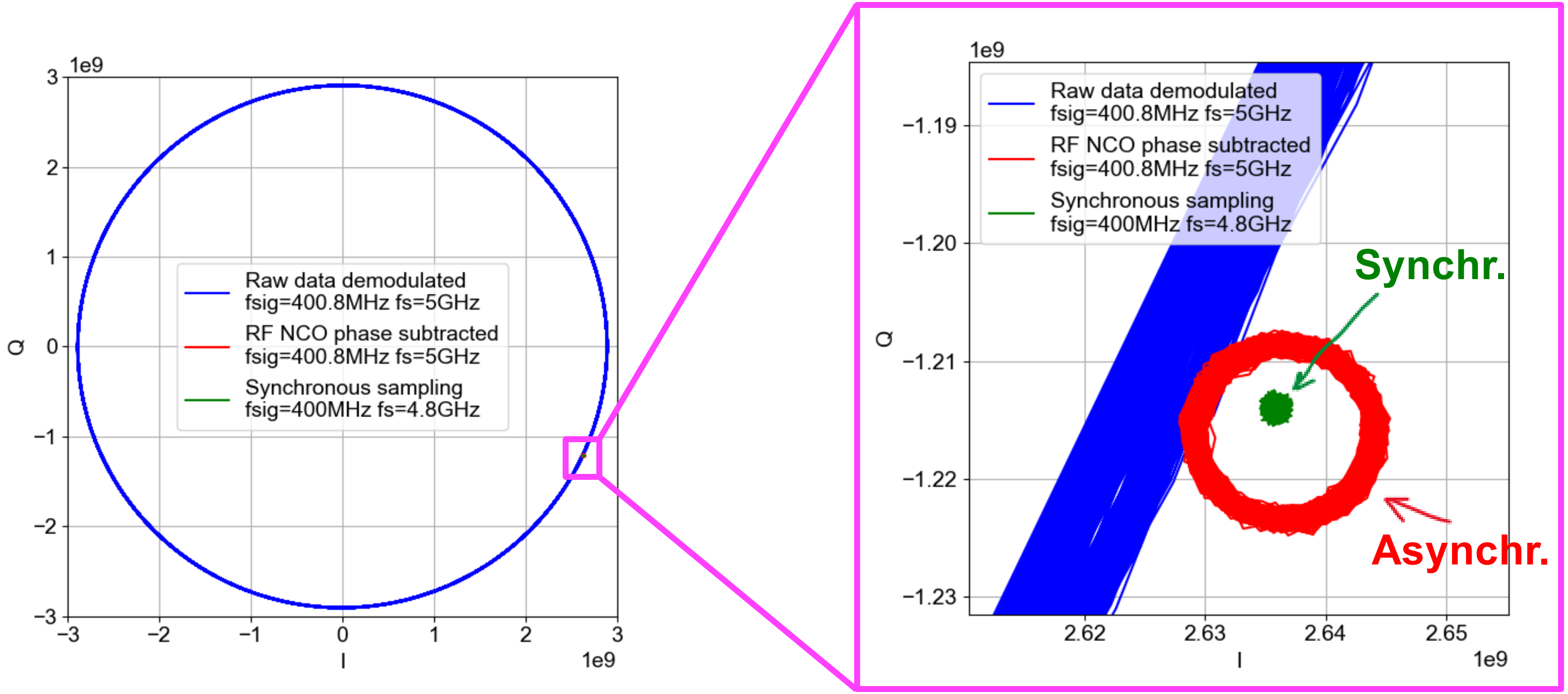
$$f_{sample} \neq k\, f_{signal}$$

means no two acquisitions are the same. It introduces a non-negligible additional phase/amplitude noise into the demodulated signal



Comparison of demodulated synchronously/asynchronously sampled signal

Real data from RF SoC



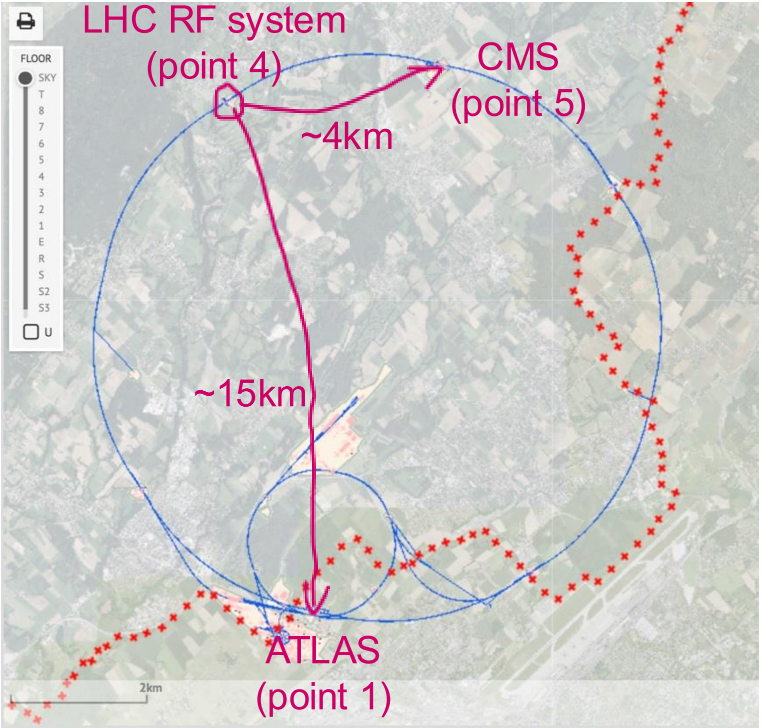
Phase and amplitude of this sampled signal

- To avoid creating additional noise, the sampling clock frequency must be an exact integer multiple of signal frequency (synchronous sampling).
- If the sampling clock is also beam synchronous, each turn will provide identical acquisition. We can profit from cancelation of many systematic errors by a notch filter.
- Chose wisely…

More options: transverse feedback in LHC

- LHC TFB has the required noise performance
- 4 pickups per beam per plane, we can reconstruct the full transverse phase space
- ~150 nm_{RMS} measurement noise
- Much smaller aperture pickups

- ...the required information is available there



More options: transverse feedback in LHC

An excerpt from the ADT beam position measurement module VHDL code

```
process(clk)
  begin
    if rising_edge(clk) then

      SumISquared <= signed(SumI) * signed(SumI);
      SumQSquared <= signed(SumQ) * signed(SumQ);

      SumDeltaI <= signed(SumI) * signed(DeltaI);
      SumDeltaQ <= signed(SumQ) * signed(DeltaQ);

      Divident <= SumDeltaI + SumDeltaQ;
      Divisor <= SumISquared + SumQSquared;

    end if;
  end process;
```

$$Position = \Re\frac{\Delta}{\Sigma} = \frac{I_\Delta I_\Sigma + Q_\Delta Q_\Sigma}{I_\Sigma^2 + Q_\Sigma^2}$$

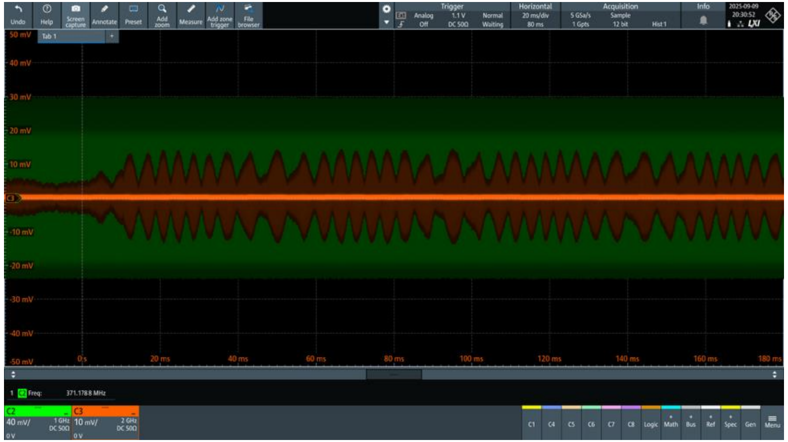
What if we add 3 lines of code to the already existing, very low noise LHC ADT BPM?

```
process(clk)
  begin
    if rising_edge(clk) then

      SumISquared <= signed(SumI) * signed(SumI);
      SumQSquared <= signed(SumQ) * signed(SumQ);

      SumDeltaI <= signed(SumI) * signed(DeltaI);
      SumDeltaQ <= signed(SumQ) * signed(DeltaQ);

      DeltaQSumI <= signed(DeltaQ) * signed(SumI);
      DeltaISumQ <= signed(DeltaI) * signed(SumQ);

      DividentPosition <= SumDeltaI + SumDeltaQ;
      DividentTilt <= DeltaQSumI - DeltaISumQ;
      Divisor <= SumISquared + SumQSquared;

    end if;
  end process;
```

$$Tilt = \Im\frac{\Delta}{\Sigma} = \frac{Q_\Delta I_\Sigma - I_\Delta Q_\Sigma}{I_\Sigma^2 + Q_\Sigma^2}$$

Testing with beam

- A number of sessions with real crab cavities in the SPS
- Preparing for a machine development session in LHC with crabbing induced by Head-On Beam-Beam Interaction. Very promising method, see Andrea Fornara's talk https://indico.cern.ch/event/1559978/contributions/6664927/
- Measurements by button pickups in SPS, W. Hofle et al. https://indico.cern.ch/event/1559978/contributions/6664925



Real pickup signals, high resolution R&S MXO58 scope used as 5 Gsps digitizer, 1e9 points. Offline position/tilt calculation by python.

Summary

- RF system of crab cavities must be very low noise (both LLRF and power). It is not possible to achieve only by the electronics itself, an active “noise” feedback is necessary.
- The work done so far indicates that the crab cavity noise feedback is feasible, however specifications are extremely demanding.
- Critical components are 180° hybrid and the digitizer.
- Preliminary tests confirm the RF SoC performance might be sufficient for LHC.
- We must meticulously analyze the performance and impact of every single component and every design decision

Fig. 1: A noisy crab preparing to ruin the HL-LHC luminosity