Beam motion measurement subsystem for the Crab-Cavity noise feedback

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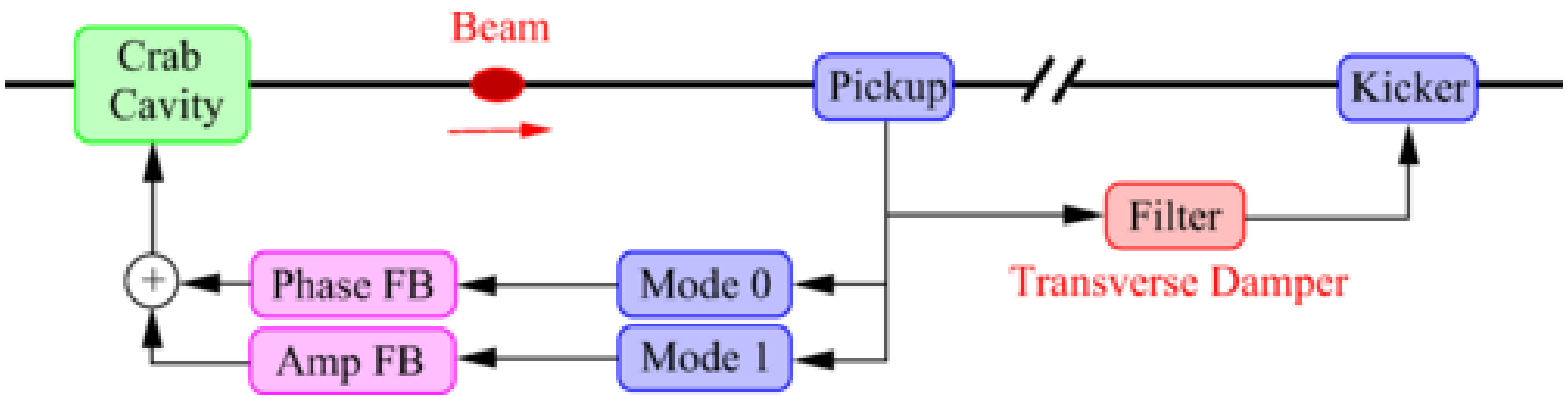
15.1.2025

Crab Cavity noise feedback system

- **Feedback system proposed to mitigate the emittance growth due to the residual amplitude and phase noise of the Crab Cavities**



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

Crab Cavity noise feedback system

Performance requirements for the feedback system beam position measurement units:

- **The measurement noise thresholds are thus σ_0 < 320 nm and σ_1 < 8.3 μrad. These are bunch-by-bunch measurement levels**
- **The above measurement noise thresholds require extremely high precision measurements. Fortunately, the closed loop bandwidth of the crab cavity with LLRF field regulation will only extend to 136 kHz. As a result, the noise bandwidth will also be limited to 136 kHz. In addition, the bunches are spaced every 25 ns and the measurement noise is uncorrelated from bunch to bunch.**
- **Filtering the data with a low-pass filter matching the signal spectrum will scale the measurement noise power by a factor of about 12 (linear) improvement in signal-to-noise ratio.**
- **This increases the actual single bunch resolution threshold to σ_0 < 3.9 μm rms and σ_1 < 100 μrad rms. This is a tight, but achievable specification.**

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Crab Cavity noise feedback system

- **Evaluation of viable options for the feedback system hardware started In a broad collaboration**

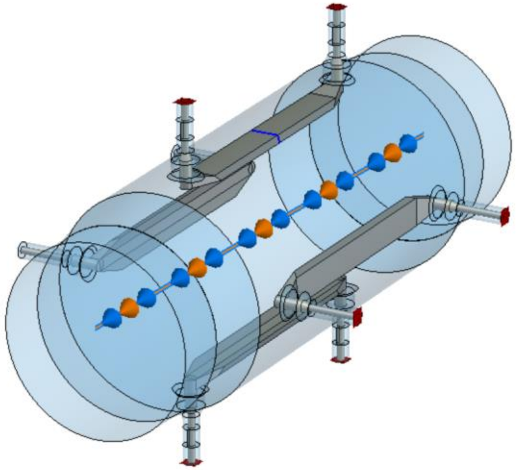
- **ABP:**
  - Optics scenarios, expected position range etc.
  - Possible contraindications
  - Discussion about options to measure at Ips 1/5, and/or at point 4…
- **BI:**
  - Pickup design
  - Detailed numeric simulations providing sensitivity to mode 0 and 1 motion
- **RF:**
  - Analytic model providing sensitivity to mode 0 and 1 motions
  - Mathematical analysis and detailed modelling of the beam position measurement signal processing chain to identify critical points and calculate the noise budget
  - Evaluation of digitizer performance.

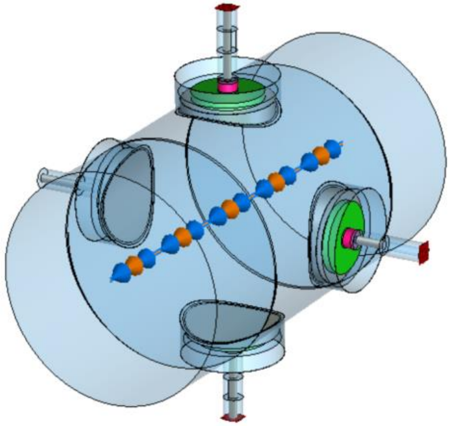
Crab Cavity noise feedback system

- **A set of pickups installed next to the CC**

- **Pickup functional specifications *Hofle, Calaga: Conceptual Specification - BPTQR Crab Cavity RF Pick-up System*. EDMS 3069868 v.0.1 LHC-BPM-ES-0015 v.0.1**

- **A combined button + stripline pick-up proposed**

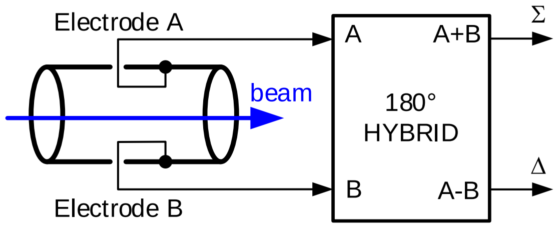


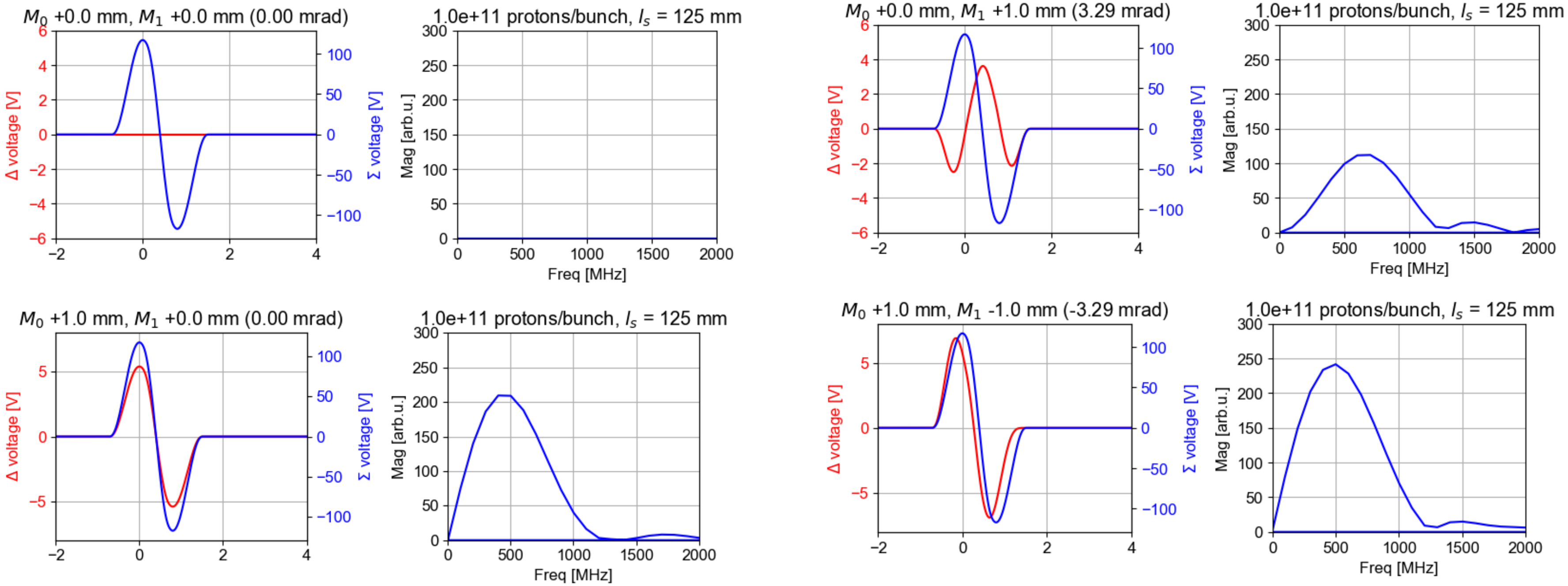


Simulations and models: M. Krupa

Pickup type selection

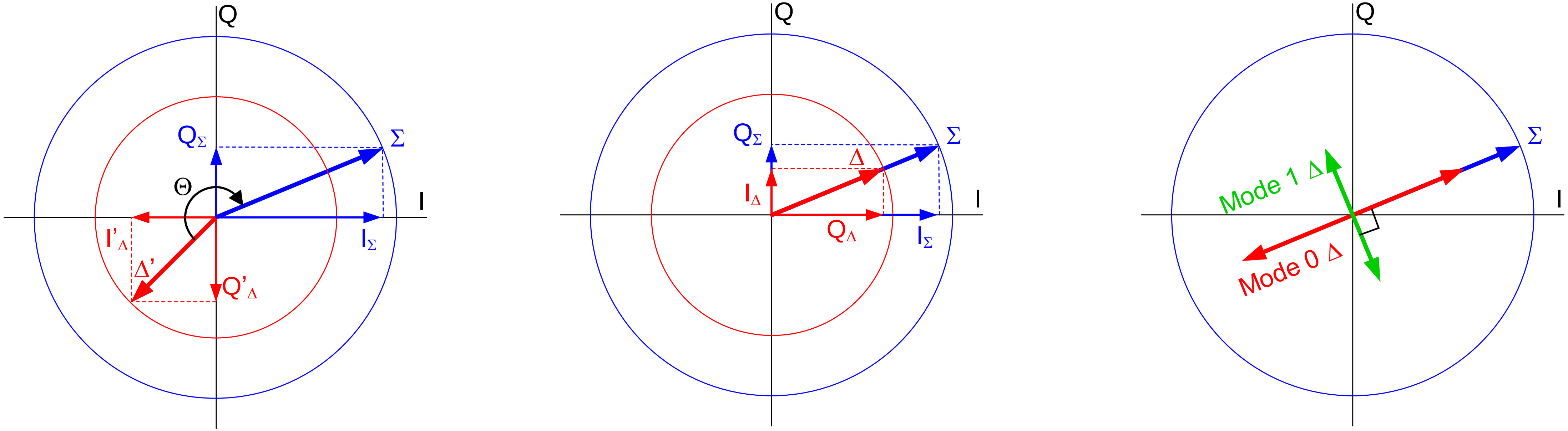
- **After extensive comparison of the two technologies, we have converged to use the strip-line pickup for the feedback**
- **Length 125 mm (peak response at 600 MHz), diameter 86.5 mm**
- **Expected beam displacement in operation up to ±2 mm (slow and fast)**





m_0 and m_1 motion detection

- **Both m_0 and m_1 motion can be extracted from a measurement at the same frequency**



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

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

m_0 and m_1 motion detection

- **Both m_0 and m_1 motion can be extracted from a measurement at the same frequency**

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

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

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

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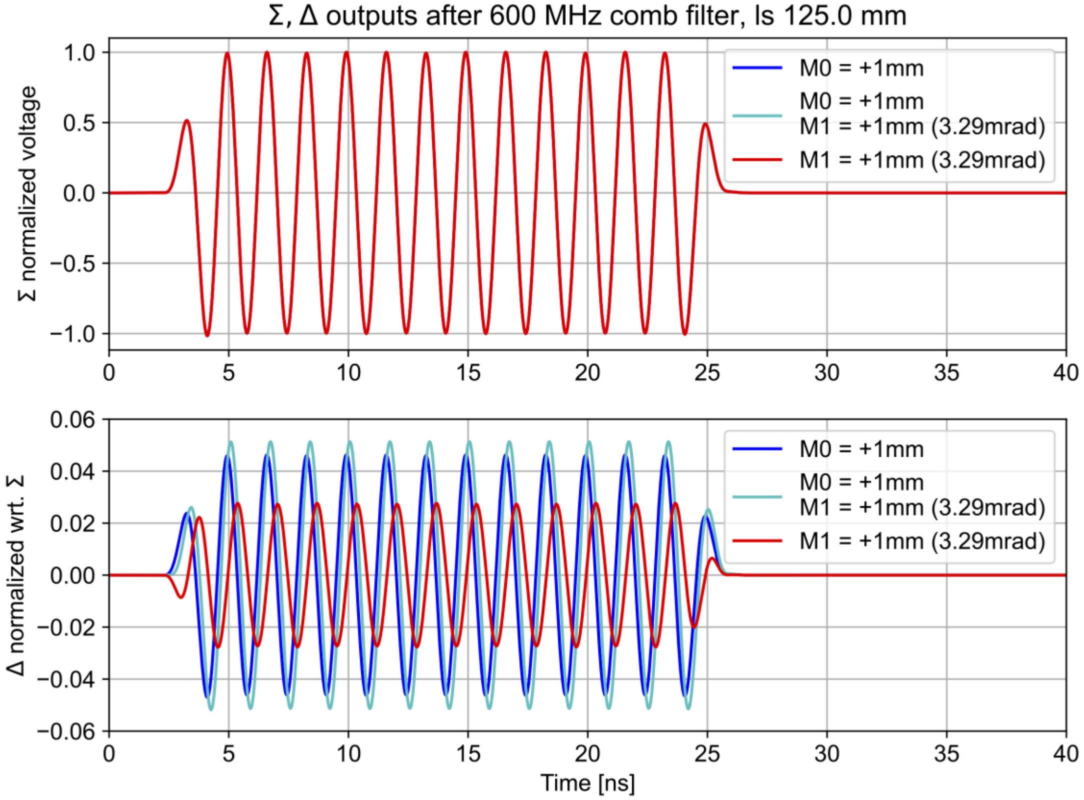
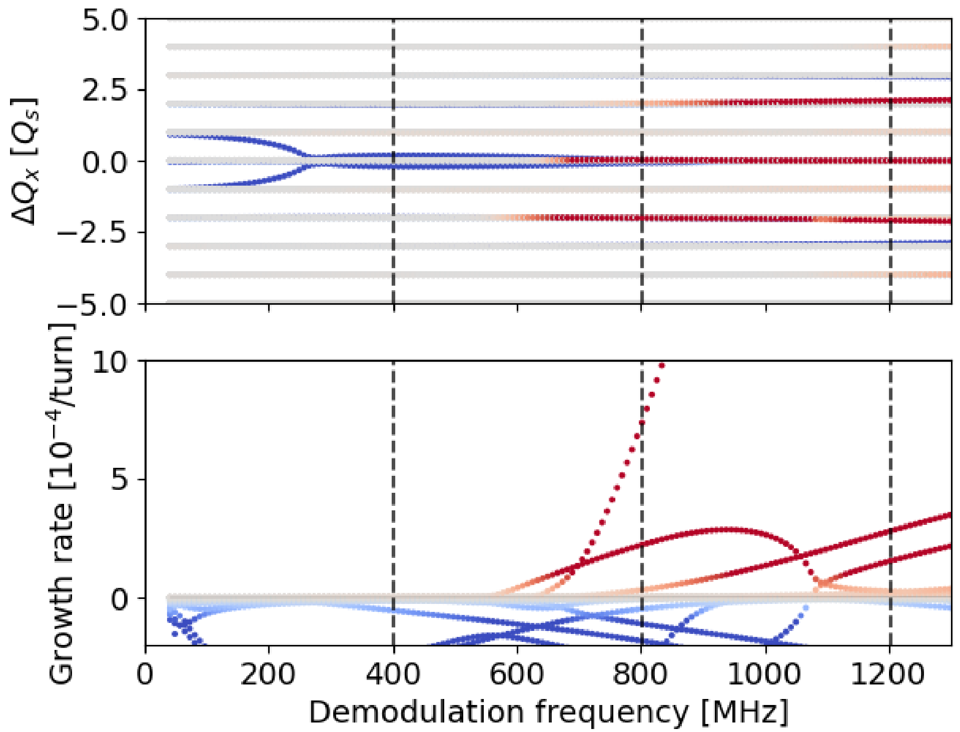
Measurement frequency selection

- **Technically, we can process the RF 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.



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/

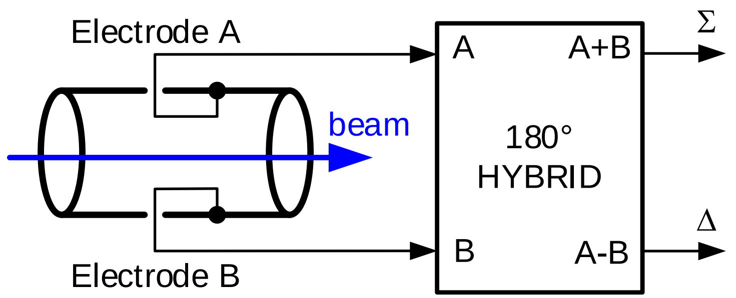
Critical component – the 180° hybrid

Major complications:

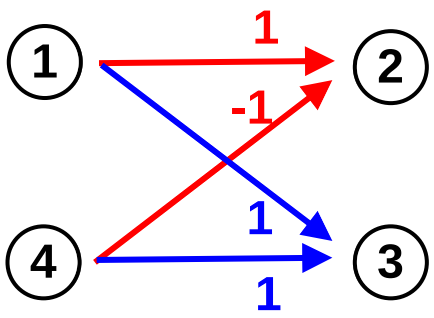
- **With such a large pick-up, the expected Δ signals will have about the same magnitude than the 180° hybrid crosstalk (isolation)**
- **Standard phase unbalance between Σ and Δ ports of H-9 hybrid ~5°**

Implications:

- **Loss of dynamic range, the output will be always close to the full scale**
- **Mixing of m_0 and m_1 signals, or cross-generation of false motion signals**



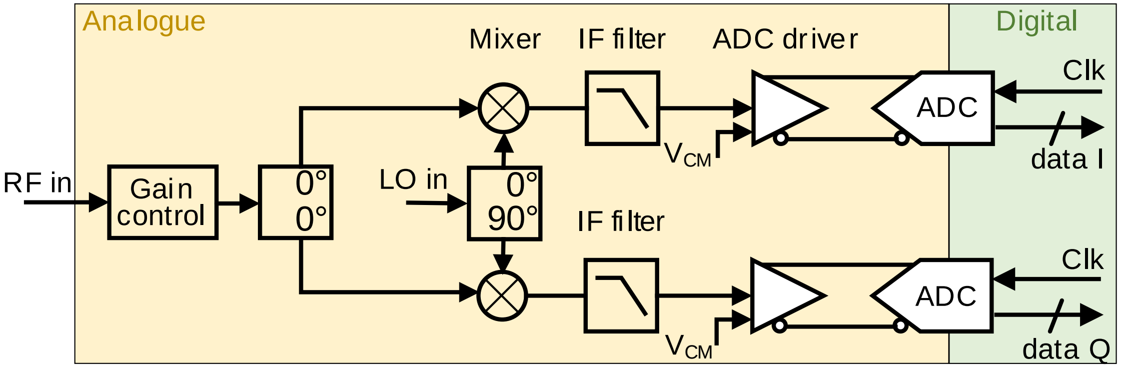
$$[S_{HYB180^\circ}] = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 & 1 & 1 & 0 \\ 1 & 0 & 0 & -1 \\ 1 & 0 & 0 & 1 \\ 0 & -1 & 1 & 0 \end{bmatrix}$$

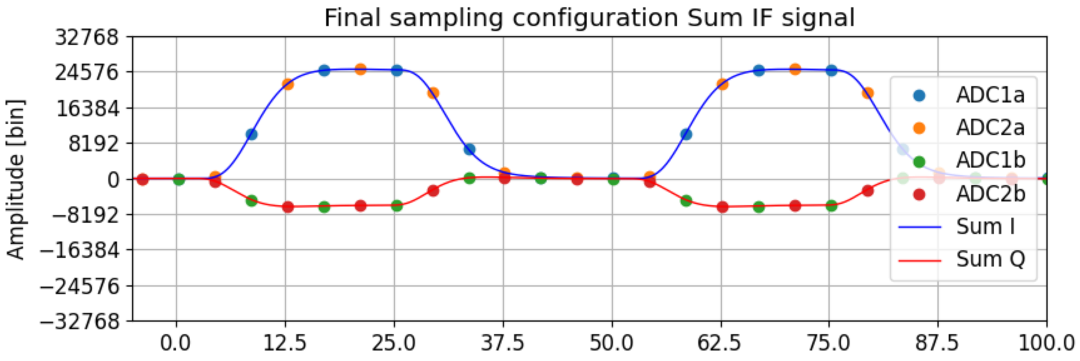


Receiver and digitizer performance requirements

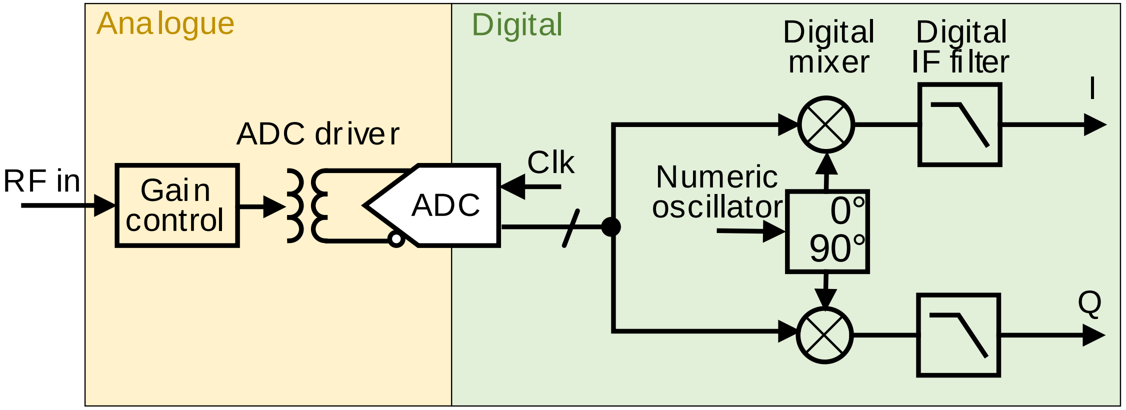
Typical receiver architectures

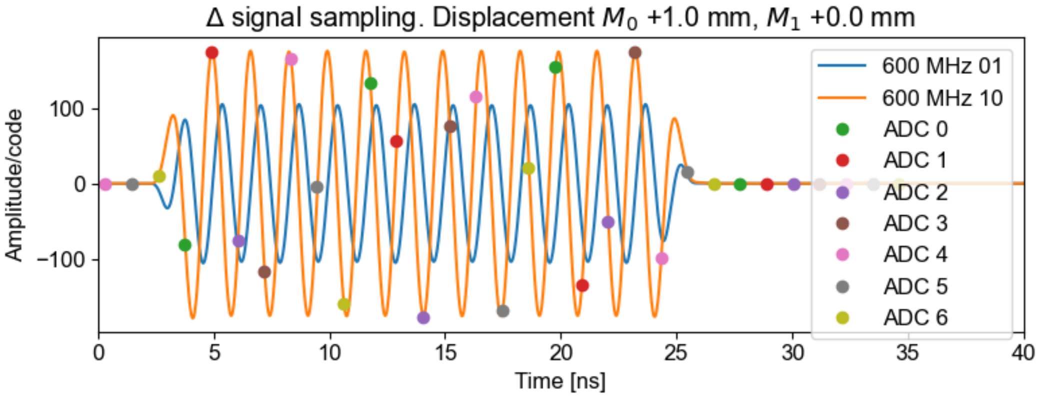
Super heterodyne receiver with analogue quadrature demodulation





Direct RF sampling with digital quadrature demodulation





Receiver and digitizer performance requirements

- ***"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?**

$$Pos = f(I_\Sigma, Q_\Sigma, I_\Delta, Q_\Delta) \quad (5)$$

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

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

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

$$\delta^2_{Pos} = \left(\frac{\partial Pos}{\partial I_\Sigma}\right)^2\sigma^2_{I\Sigma} + \left(\frac{\partial Pos}{\partial Q_\Sigma}\right)^2\sigma^2_{Q\Sigma} + \left(\frac{\partial Pos}{\partial I_\Delta}\right)^2\sigma^2_{I\Delta} + \left(\frac{\partial Pos}{\partial Q_\Delta}\right)^2\sigma^2_{Q\Delta} \quad (7)$$

and the standard deviation

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

20 steps later…

$$\sigma_{ReqPosData} = \frac{\sigma_{0single}}{\sqrt{2}} = 226\ nm \quad (25)$$

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

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

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

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

The noise floor is therefore dominated by position measurement requirements.

Receiver and digitizer performance requirements

- **Is the required ENOB of 14.1 bits needed for σ_0 < 320 nm and σ_1 < 8.3 µrad for a bunch by bunch mode easy or difficult to achieve?**

- **It depends…**

Receiver and digitizer performance requirements

- **Is the required ENOB of 14.1 bits needed for σ_0 < 320 nm and σ_1 < 8.3 µrad for a bunch by bunch mode easy or difficult to achieve?**

- **It depends…**

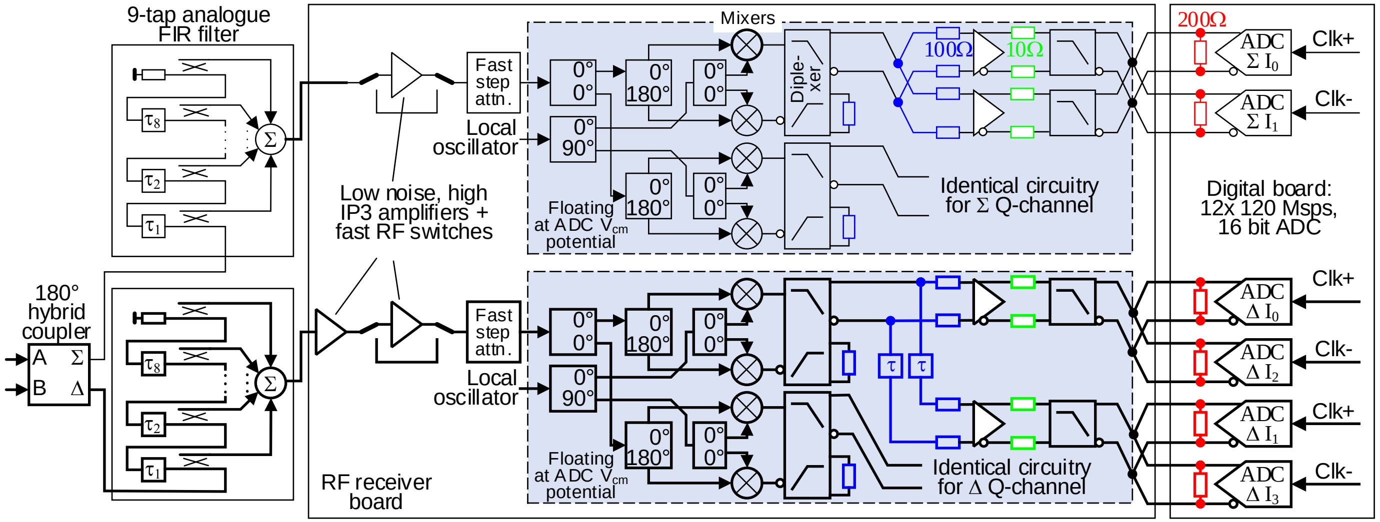
- **For bunch by bunch measurement we need ~80 MHz analogue bandwidth**

- **With a single, off the shelve uTCA SIS8300KU digitizer module with 10 ADCs, which is preferred for compatibility and synergy reasons it is out of reach.**
- **For operation with reduced bandwidth (with relaxed constraints) it is usable.**

- **Work is very advanced to select the best architecture (analogue receivers/direct sampling)**

Receiver and digitizer performance requirements

- **Is the required ENOB of 14.1 bits needed for σ_0 < 320 nm and σ_1 < 8.3 µrad for a bunch by bunch mode easy or difficult to achieve?**
- **LHC ADT was upgraded for low noise pickups during LS2. Estimation of achieved b-b-b performance σ_0 < 219 nm. Needs 4 Pickups, novel receiver architecture, 12 ADCs each…**



Valuch D. Stopjakova V.: New Generation of Very Low Noise Beam Position Measurement System for the LHC Transverse Feedback DOI 10.18429/JACoW-IPAC2022-TUPOST007

By the way, LHC ADT…

An excerpt from the ADT beam position measurement module VHDL code

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

      ThreshSquared <= signed(Threshold) * signed(Threshold);
      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;

  PositionOut <= FractionRemainder(15 downto 0);
```

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

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

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

```
process(clk)
  begin
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      ThreshSquared <= signed(Threshold) * signed(Threshold);
      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;

  PositionOut <= FractionRemainder(15 downto 0);
```

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

Current status and ongoing work

- Pickup specifications completed
- Selection which of the two pickups will be used completed
- Analytic model of pickup and calculation of expected signals for all modes completed
- Numerical modelling of pickup response to verify analytic model completed
- Analysis of required digitizer performance to obtain requested noise floor completed
- Evaluation of proposed uTCA digitizer module compatibility with performance requirements completed
- Evaluation of possibility to use the LHC ADT at point 4 to do the measurement ongoing
- Finding potential method to overcome the 180° hybrid imperfections ongoing
- Finding clever RF signal processing to allow for pickup electrical centering and crosstalk compensation ongoing

Current status and ongoing work

- **Detailed design of RF hardware prototype for tests in SPS/LHC not started yet**
- **Production of a prototype hardware for tests in SPS/LHC not started yet**
- **Preparation of MD(s) in LHC, using the prototype measurement hardware not started yet**
- **Definition of detailed digital signal processing using the CC fixed frequency LLRF architecture not started yet**
- **Clarification on interaction between the regular LHC transverse feedback and CC mode 0 feedback (section VI, paragraph F of the Baudrenghien/Mastoridis paper) ? or ?**

Thank you for your attention

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