



RF Beam Noise Feedback System for the High-Luminosity LHC Crab Cavities

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Slovenia. 14.10.2026



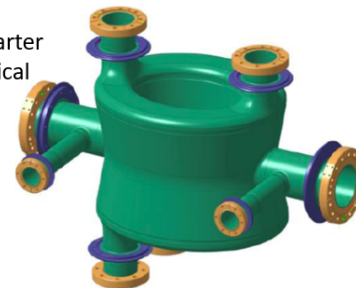
HL-LHC: Introduction

Upgrading the LHC

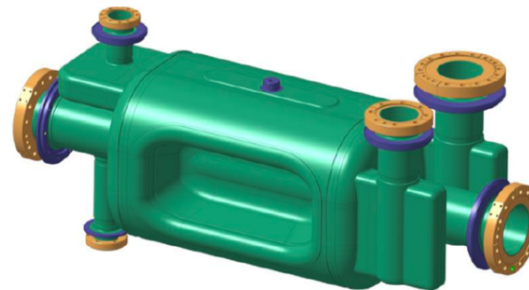
	Unit	LHC	HL-LHC
Energy	[TeV]	7	7
p/bunch	[10^{11}]	1.15	2.2
Bunch Spacing	[ns]	25	25
ϵ_n (x,y)	[μm]	2.5	2.5
σ_z (rms)	[cm]	7.55	9.0
IP _{1,5} β^*	[cm]	55	20
Betatron Tunes	-	64.31, 59.32	62.31, 60.32
X-Angle: $2\phi_c$	[μrad]	300	590
Piwinski Angle	$\frac{\sigma_z}{\sigma^*} \phi_c$	0.65	3.14
RF Frequency	[MHz]	400.79	
Peak luminosity	[$10^{34} \text{cm}^{-2} \text{s}^{-1}$]	1.0	7.2

[1] CRAB CAVITIES FOR THE HIGH-LUMINOSITY LHC

Double Quarter
Wave: Vertical

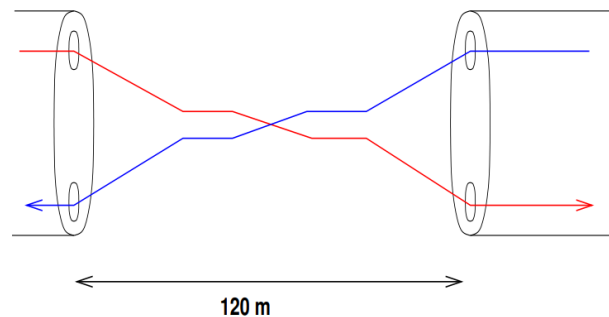
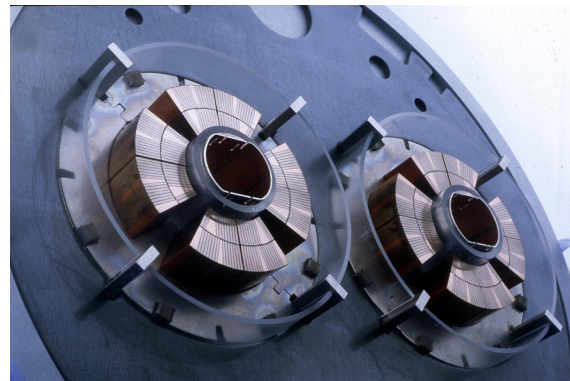
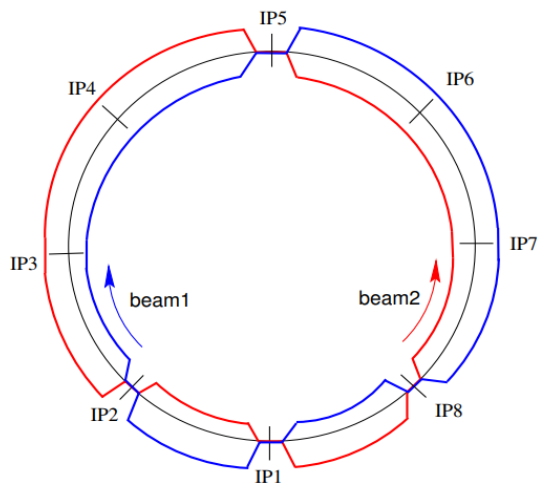


RF Dipole: Horizontal



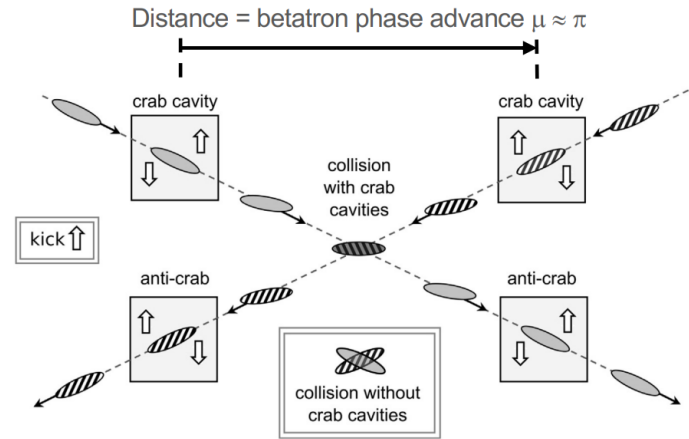
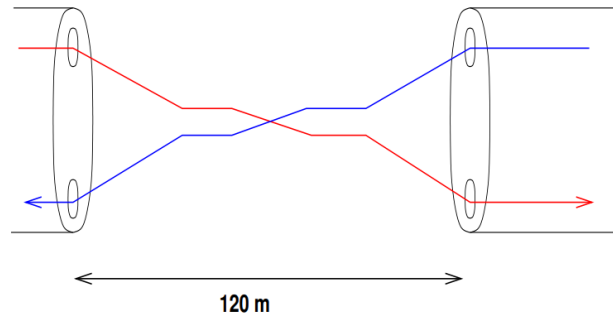
HL-LHC: Crossing Angle

LHC Beam Crossing



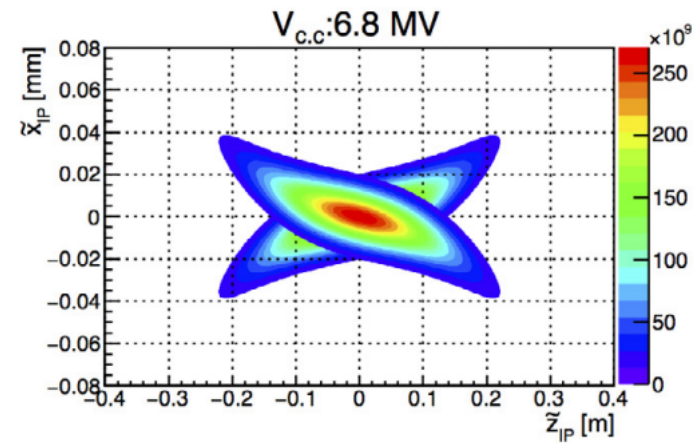
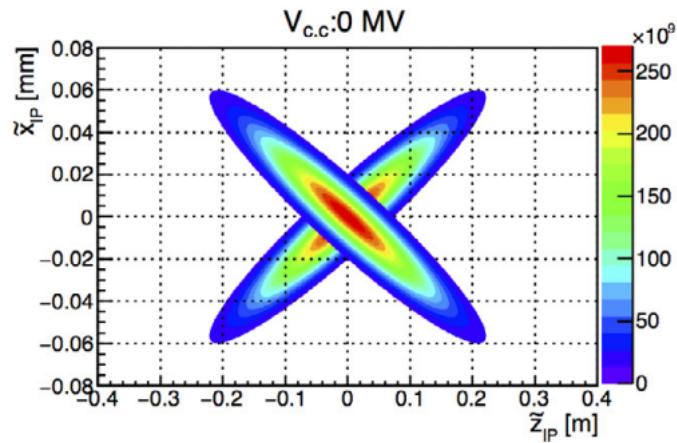
HL-LHC: Crab Cavities (1)

- Pivoting the bunch to increase the collision surface



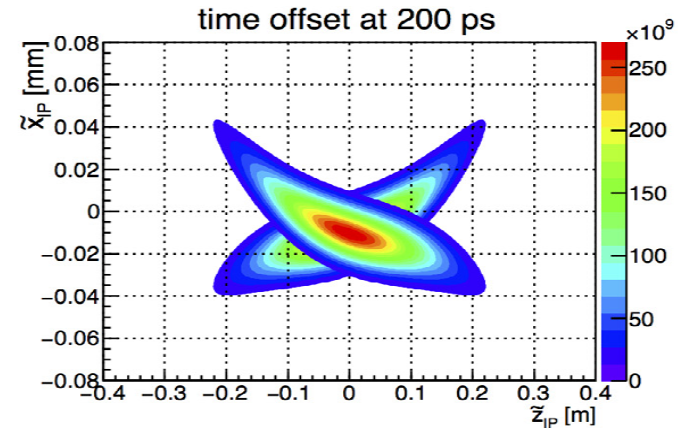
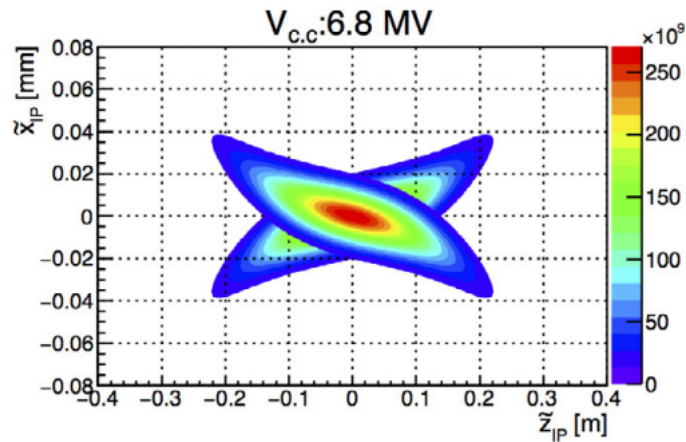
[2] Luminosity reduction caused by phase modulations at the HL-LHC crab cavities

HL-LHC: Crab Cavities (2)



[2] Luminosity reduction caused by phase modulations at the HL-LHC crab cavities

HL-LHC: Crab Cavities (3): Phase Noise Crabbing Effect



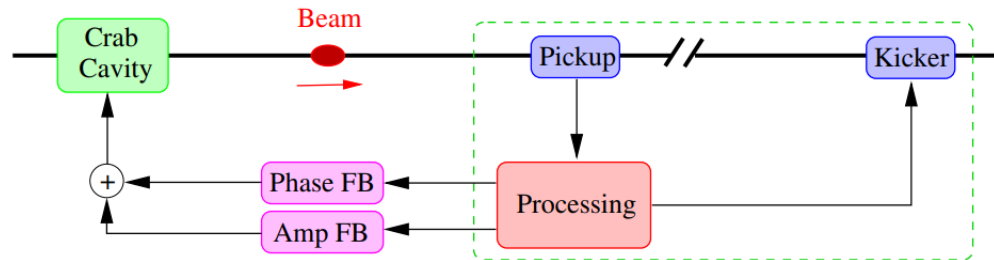
[2] Luminosity reduction caused by phase modulations at the HL-LHC crab cavities

HL-LHC: RF Beam Noise Feedback System

Emittance Growth: 16.6(32.7)%/h [3]

- Due to Amplitude Noise: 7.6(23.7)%/h
- Due to Phase Noise: 9%/h

Emittance Target: 2%/h



Architecture: IF vs Direct RF Sampling

Architectures

- IF Design
- Direct RF Design

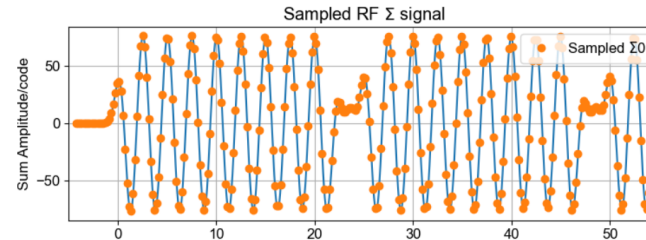
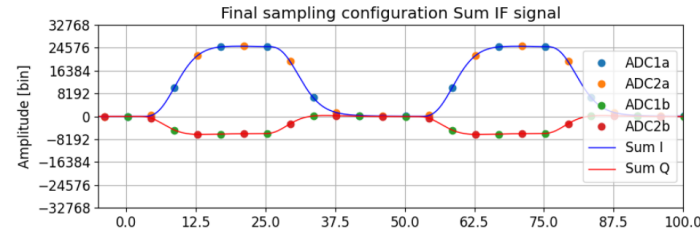
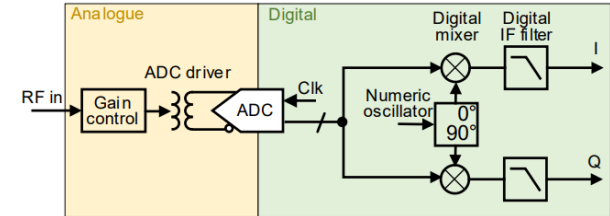
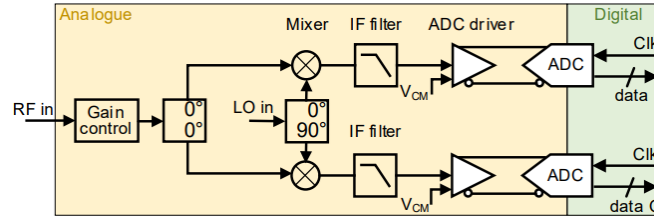
Required ENOB

- Position: 14.1-bits

$$\frac{\text{max distance}}{\text{resolution}} = \frac{4 \text{ mm}}{226 \text{ nm}} = 17699 \text{ codes}$$

- Tilt: 10.7-bits

$$\frac{\text{max tile}}{\text{resolution}} = \frac{9.44 \text{ mrad}}{5.86 \text{ urad}} = 1611 \text{ codes}$$



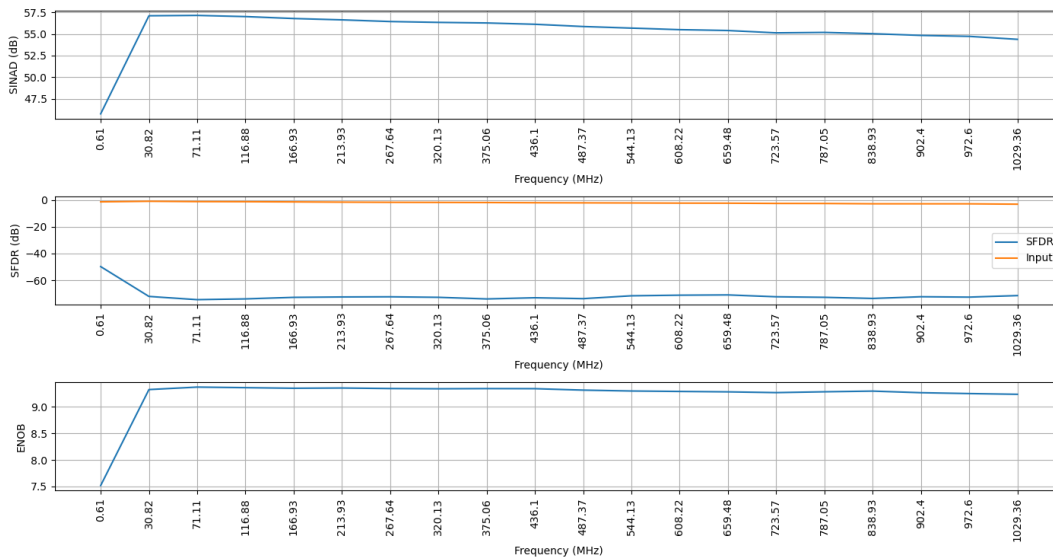
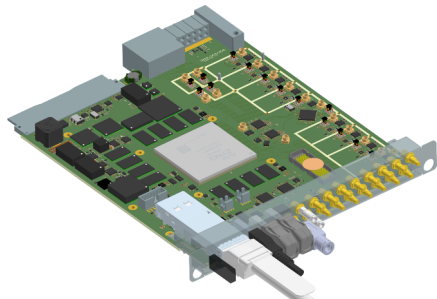
RFSoc Measurements: ENOB

ZCU208 ENOB Figures

- 9.34 bits from the ADC (at 400MHz)
- 1 bit from channels averaging
- 3.377 from sample averaging
- Total: 13.71 ENOBs!
 - 14.1 Required!

Solution

- AMD RFSoc: DAMC-DS5014DR



Signal Path (1): Analogue Processing

Comb Filter:

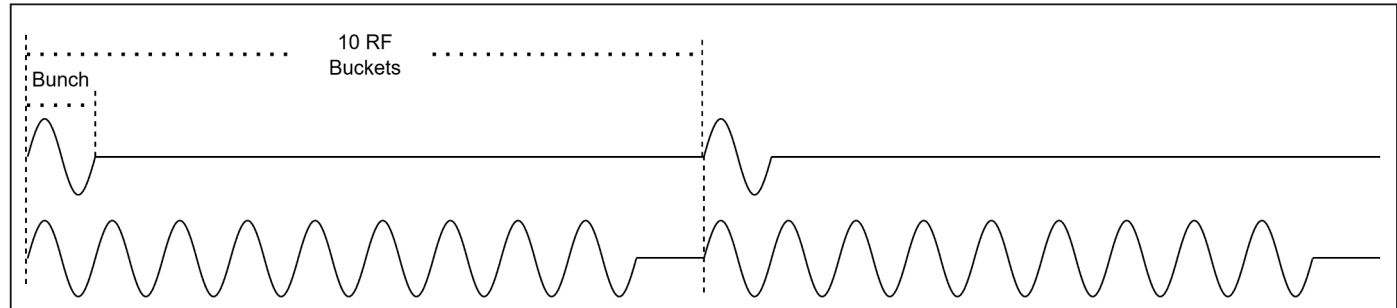
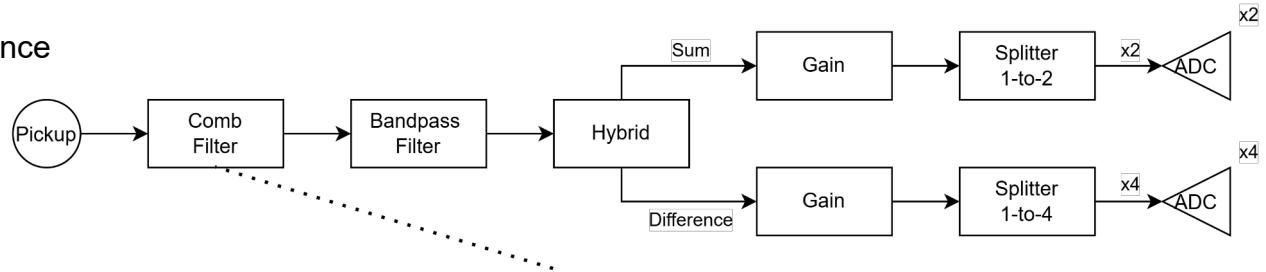
- Replicates the pickup signal

Hybrid:

- Derives the Sum and Difference

Signal Conditioning:

- Bandpass Filter
- Gain Control



Signal Path (2): Digital Processing

Bunch Frame Alignment

Baseband Mixing

Averaging

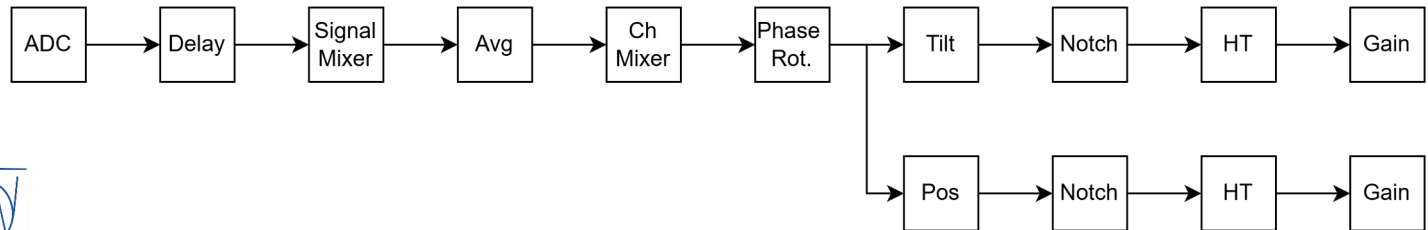
Channel Summing

Phase Rotation

Tilt and Position

Notch Filter

Hilbert Filter



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Baseband Mixing

Averaging

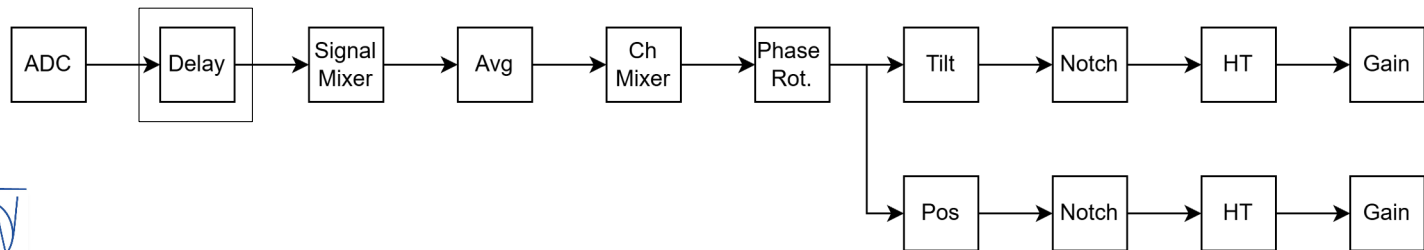
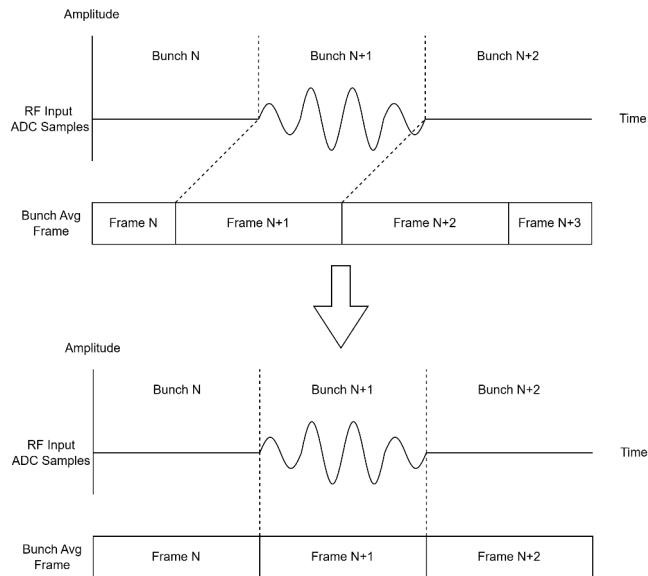
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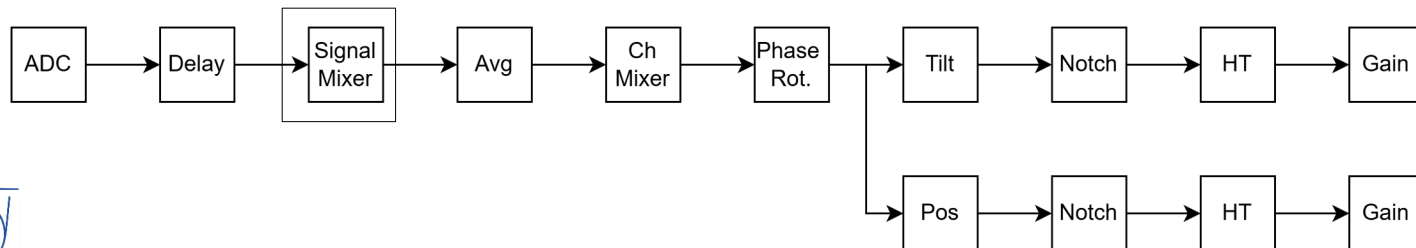
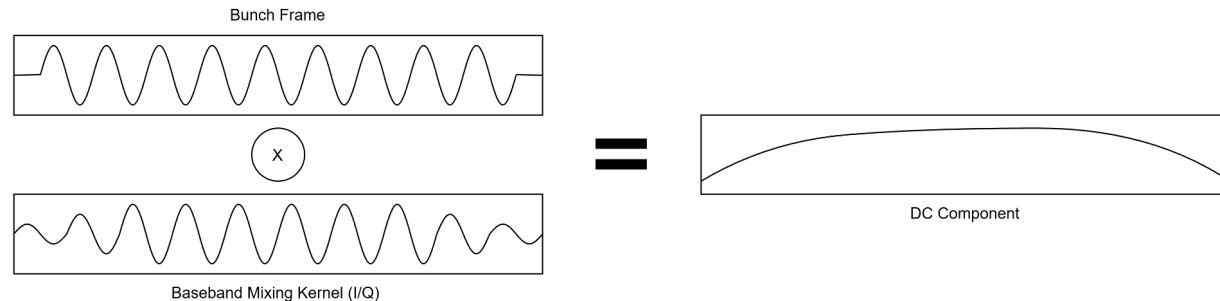
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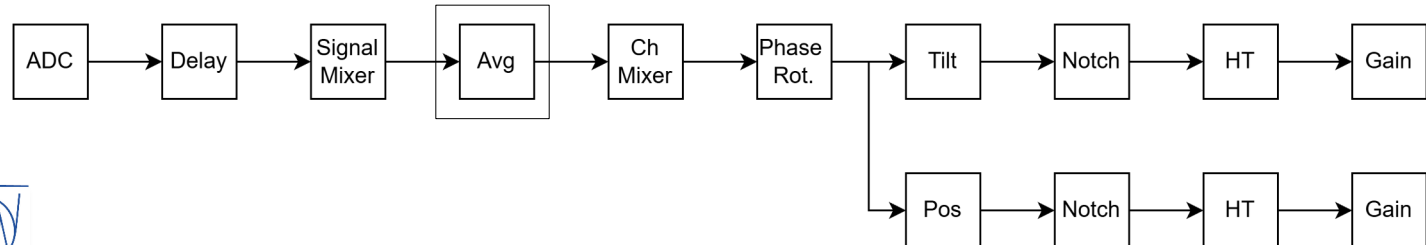
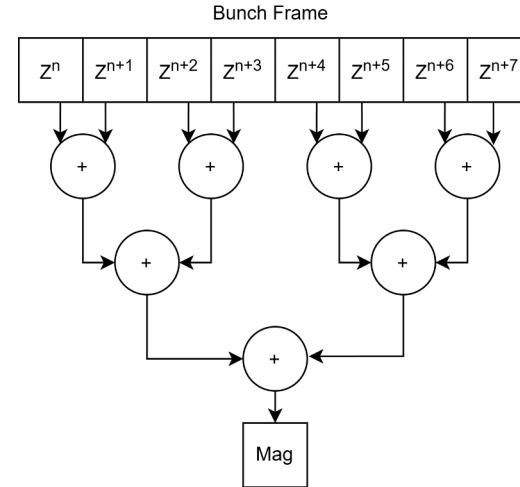
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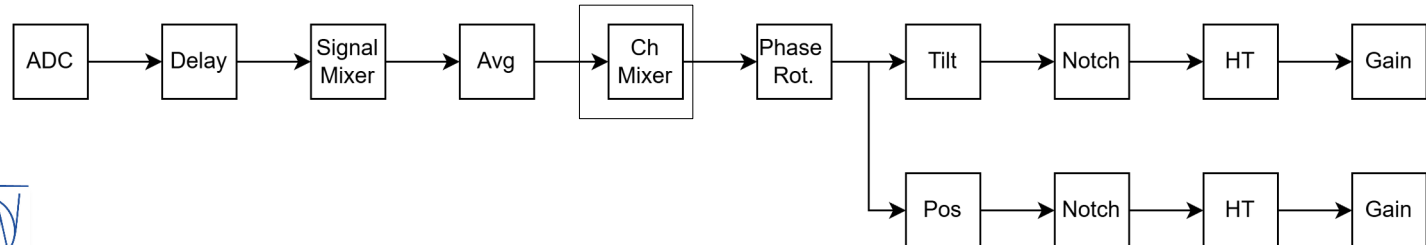
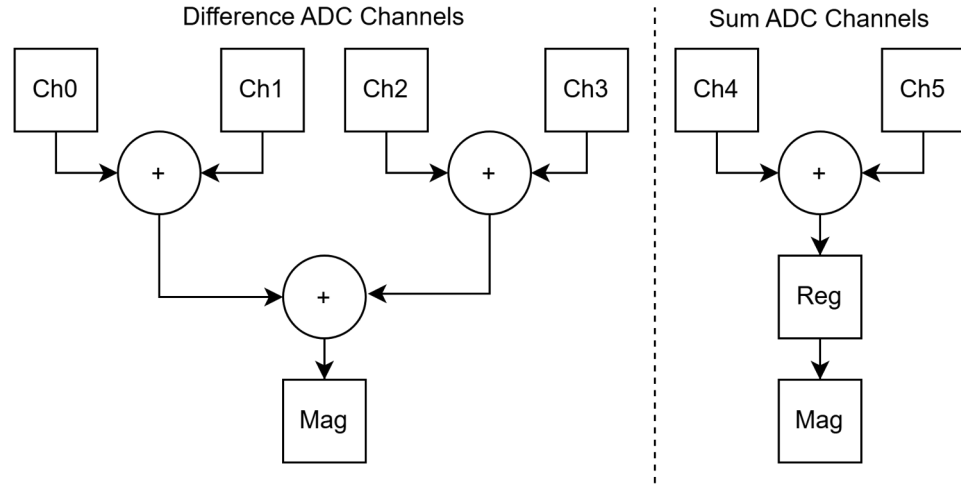
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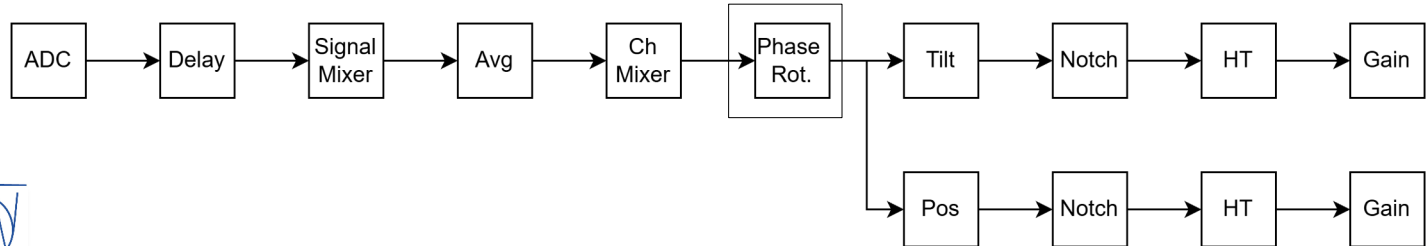
Tilt and Position

Notch Filter

Hilbert Filter

$$\Delta I' = \Delta I * \cos(\varphi) - \Delta Q * \sin(\varphi)$$

$$\Delta Q' = \Delta I * \sin(\varphi) + \Delta Q * \cos(\varphi)$$



Signal Path (2): Digital Processing

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Phase Rotation

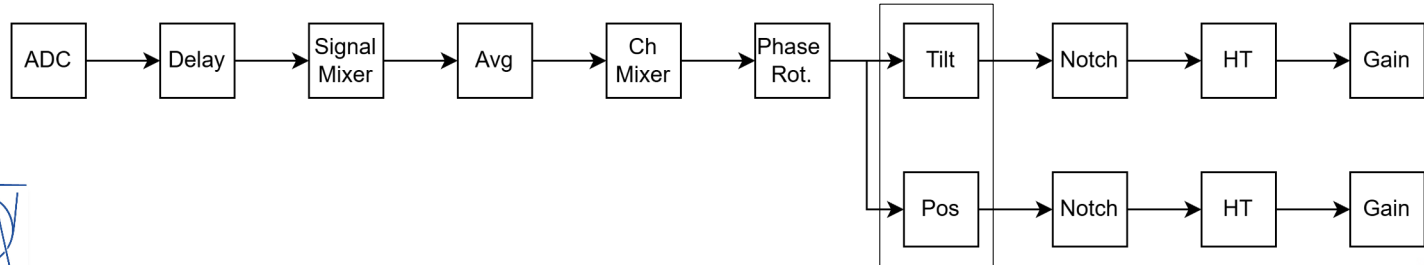
Tilt and Position

Notch Filter

Hilbert Filter

$$Tilt = \frac{\Delta Q * \Sigma I - \Delta I * \Sigma Q}{\Sigma I^2 + \Sigma Q^2}$$

$$Position = \frac{\Delta I * \Sigma I + \Delta Q * \Sigma Q}{\Sigma I^2 + \Sigma Q^2}$$



Signal Path (2): Digital Processing

Bunch Frame Alignment

Baseband Mixing

Averaging

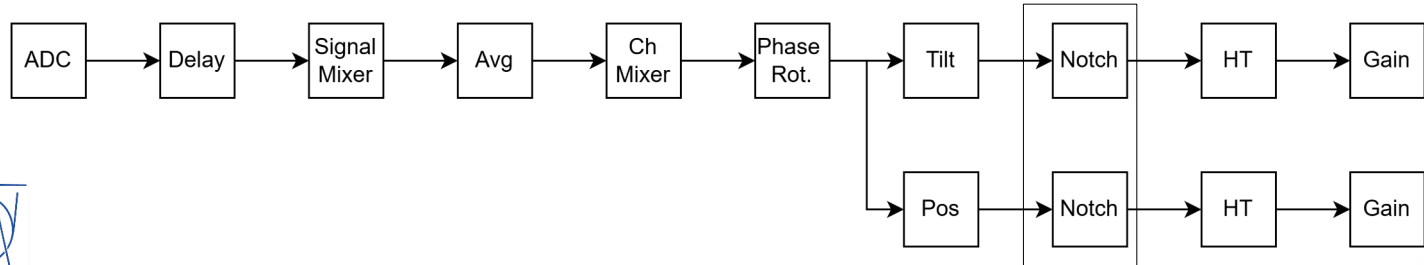
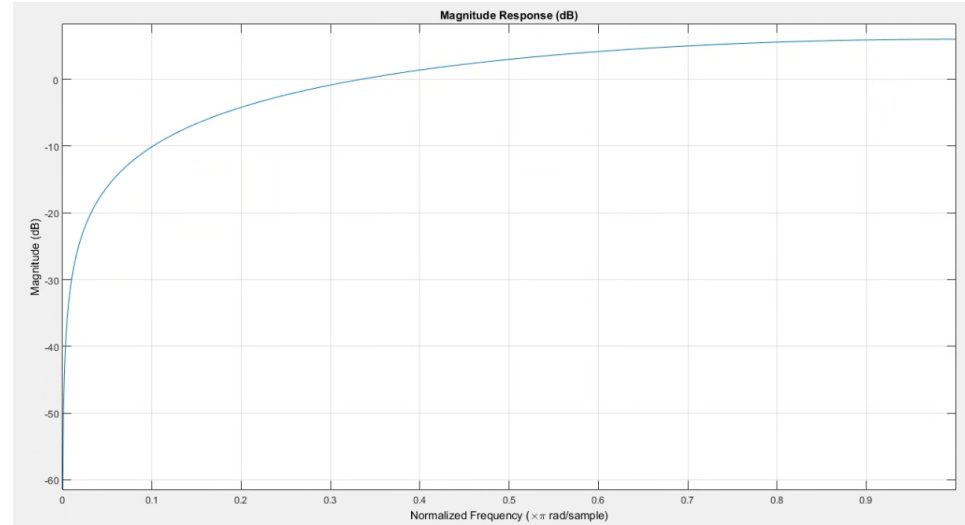
Channel Summing

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Tilt and Position

Notch Filter

Hilbert Filter



Signal Path (2): Digital Processing

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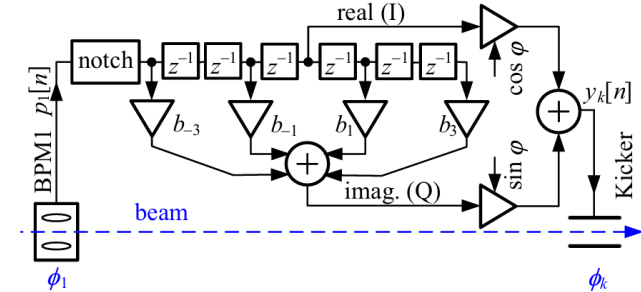
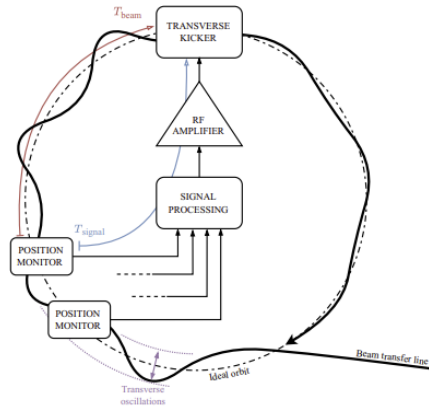
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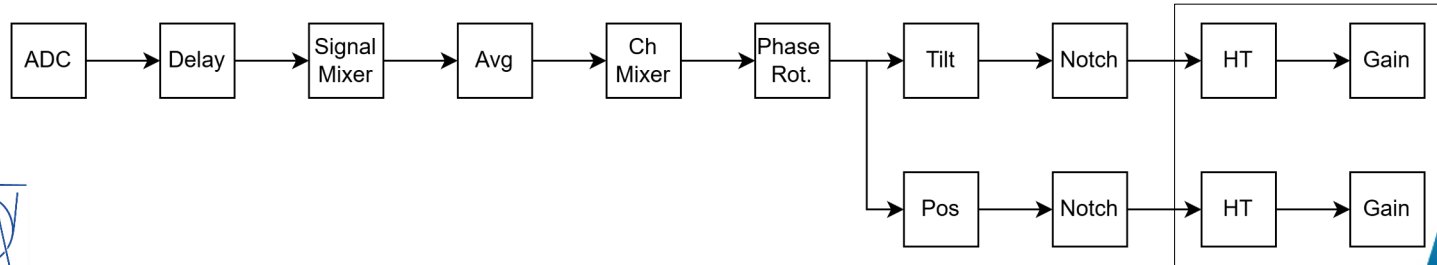
Tilt and Position

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Hilbert Filter

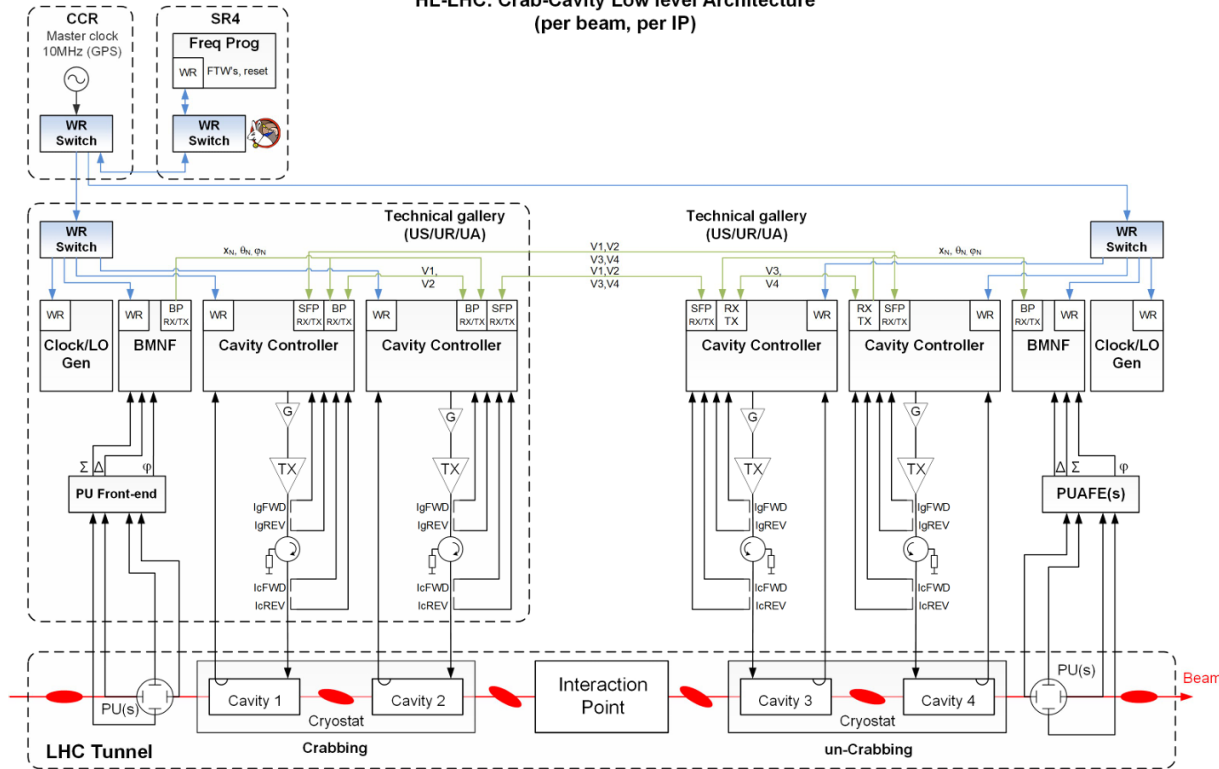


[4]

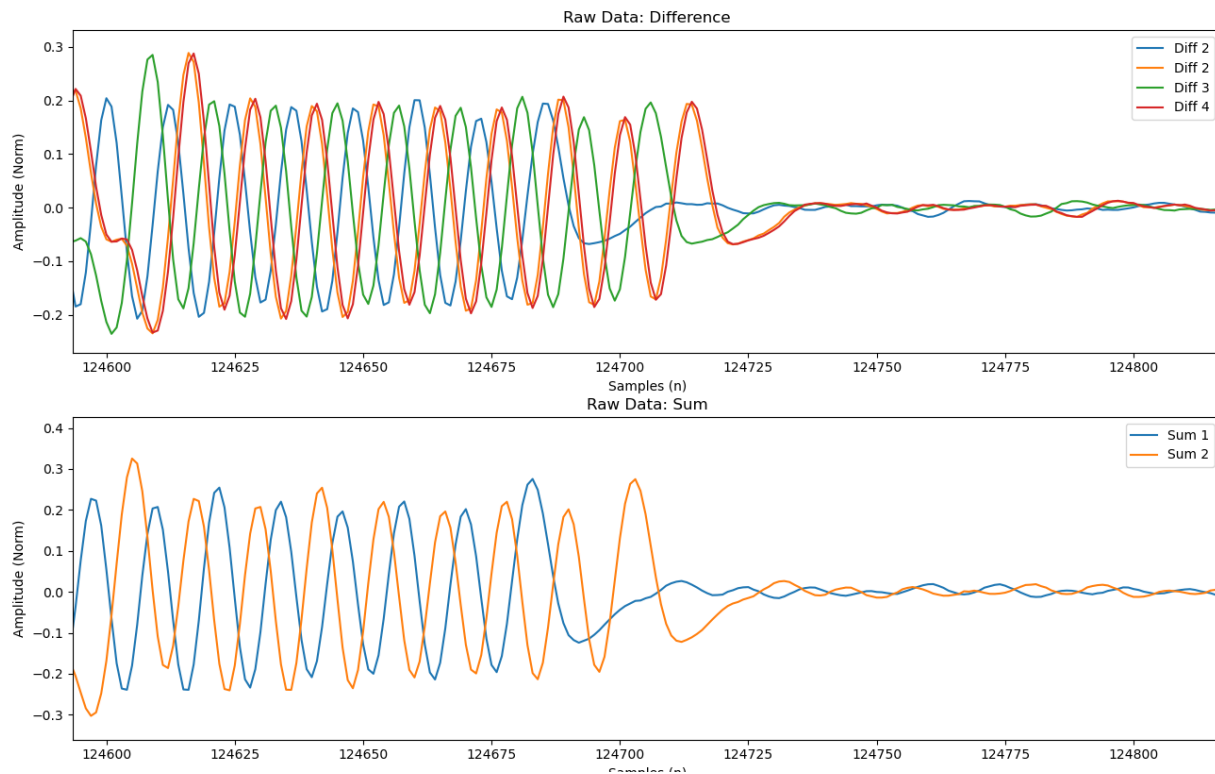


BMNF: Closing the loop

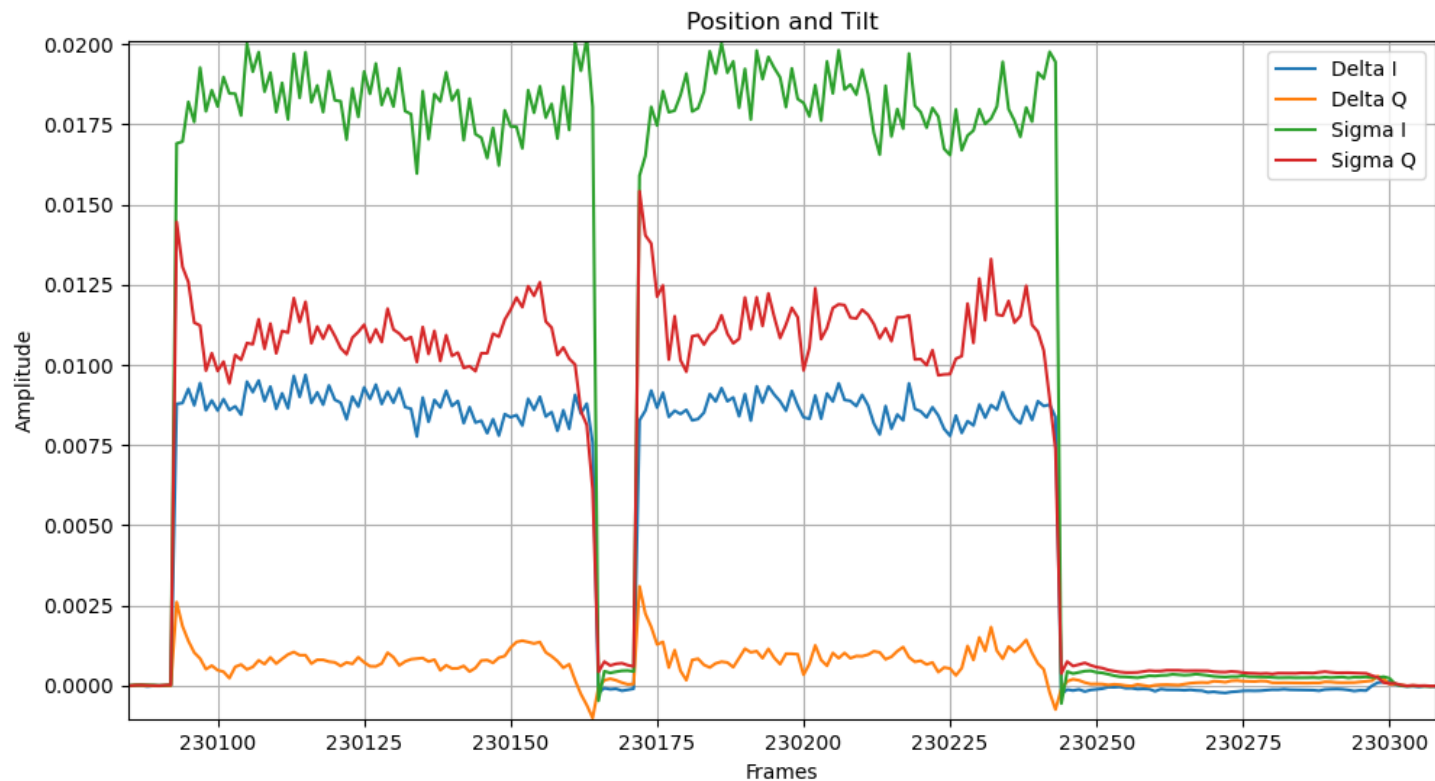
HL-LHC: Crab-Cavity Low level Architecture
(per beam, per IP)



Raw Data (3.1): NFB 2026-07-08 14.05.37_all8 N260096.txt



Averaged Data (2) NFB 2026-07-08 15.18.26_all8 N2000128.txt



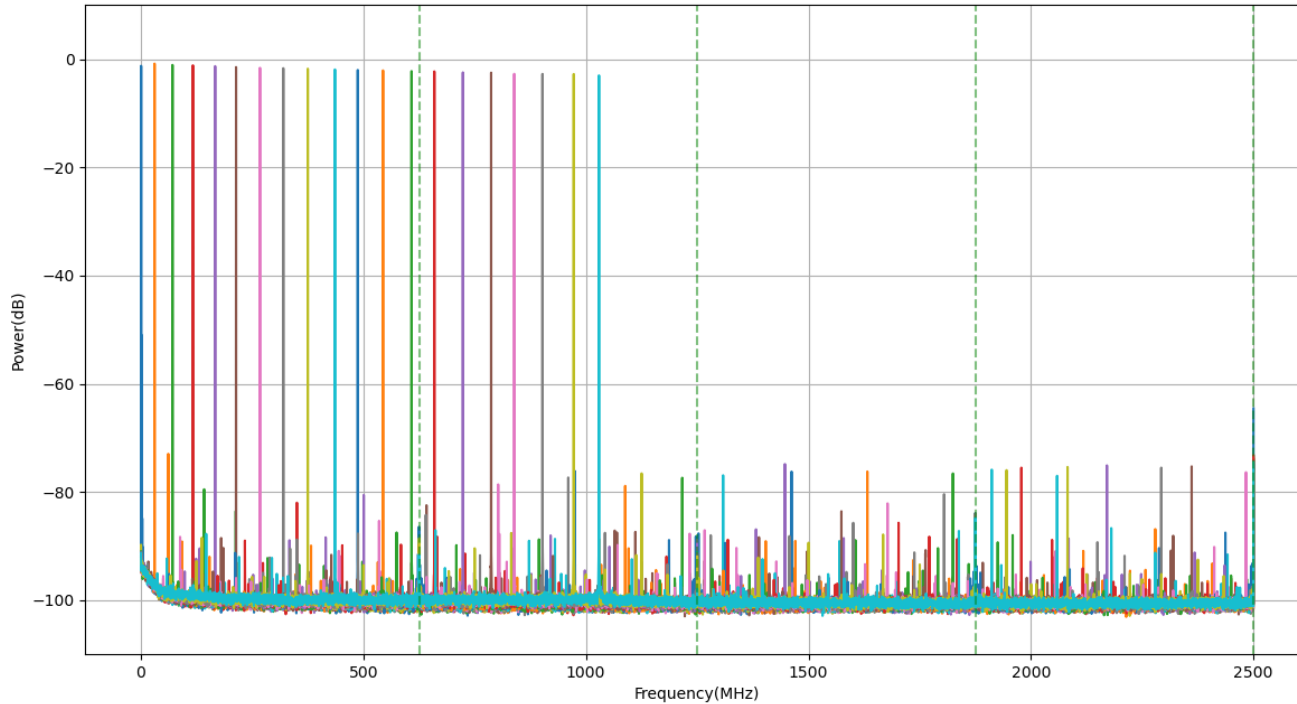
SPS Measurements: Setup



References

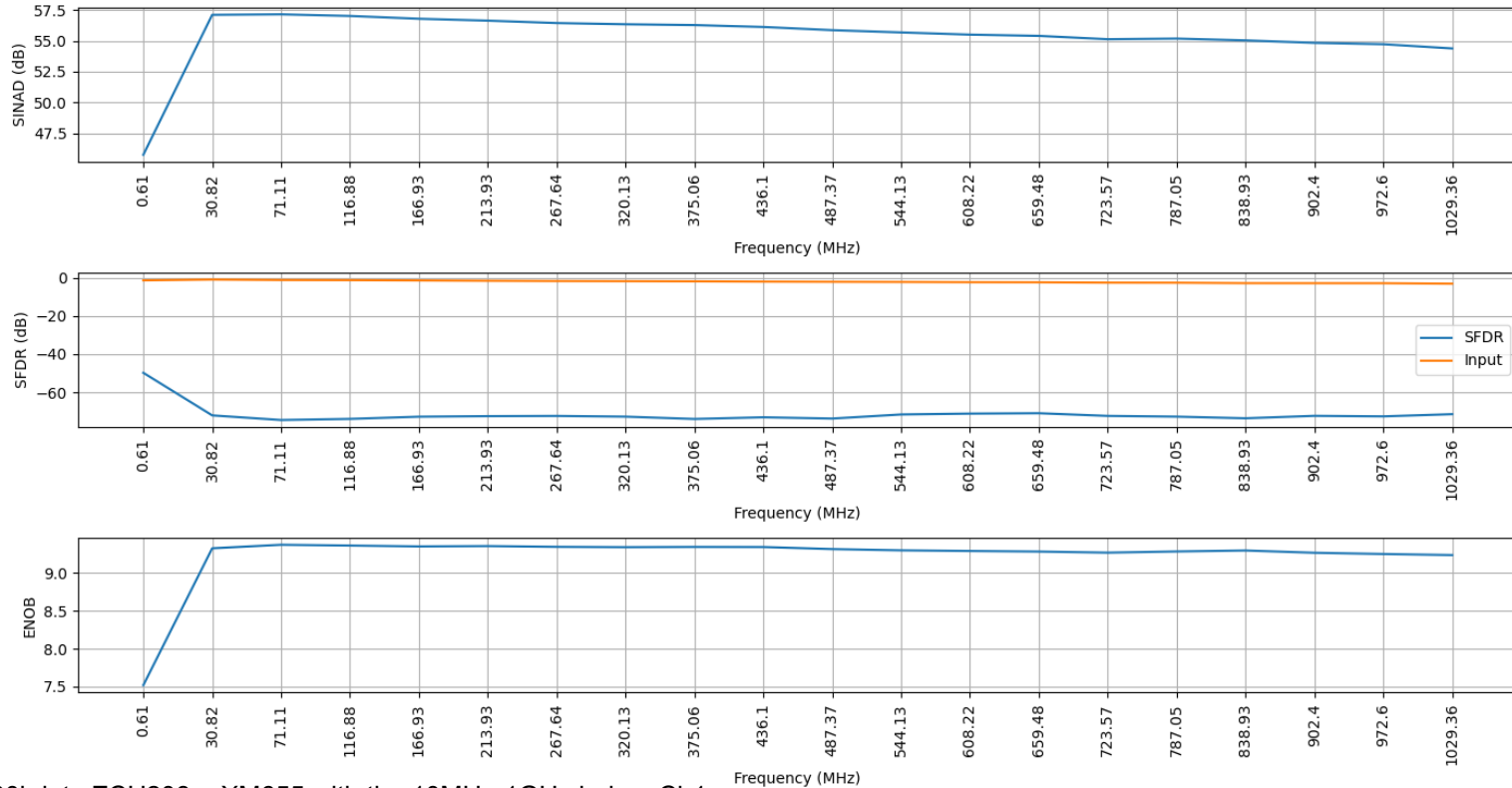
- [1] "CRAB CAVITIES FOR THE HIGH-LUMINOSITY LHC", Rama Calaga, CERN, Geneva, Switzerland. [18th International Conference on RF Superconductivity](#), Lanzhou, China, 17 - 21 Jul 2017, pp.THXA03. DOI: [10.18429/JACoW-SRF2017-THXA03](#)
- [2] "Luminosity reduction caused by phase modulations at the HL-LHC crab cavities", E.Yamakawa, R.Apsimon, P.Baudrenghien, R.Calaga. Nuclear Instruments and Methods in Physics Research Section A Accelerators Spectrometers Detectors and Associated Equipment 908 DOI:10.1016/j.nima.2018.08.074
- [3] "Transverse emittance growth due to rf noise in crab cavities: Theory, measurements, cure, and high luminosity LHC estimates" P.Baudrenghien (CERN), T.Mastoridis (Cal. Poly.). Physical Review Accelerators and Beams 27 (2024) 051001 DOI: 10.1103/PhysRevAccelBeams.27.051001
- [4] "Modern signal processing techniques for efficient transverse feedback systems operation in hadron accelerators", Gerd Kotzian, Xavier Buffat, Jani Komppula, Viera Stopjakova, Daniel Valuch. Phys. Rev. Accel. Beams 28, 102801 – Published 28 October, 2025 DOI: <https://doi.org/10.1103/szv9-nfd5>
- [5] "Crab Cavity RF Noise Feedback and Transverse Damper Interaction", P.Baudrenghien (CERN), T.Mastoridis (California Polytechnic State Univ. (US)), B.Miller Nicholas
- [6] "Performance evaluation of CC Noise feedback subsystem variants", D. Marinov, D. Valuch Progress report at HL-LHC LLRF meeting 24.9.2025 CERN.
- [7] "Noise feedback system for Crab Cavities in Large Hadron Collider", D.Valuch, D.Marinov, G.Hagmann, R.Calaga. Low-Level Radio Frequency (LLRF) Workshop 2025 <https://indico.jlab.org/event/939/contributions/17474/>

RFSoc Test Input Spectrum



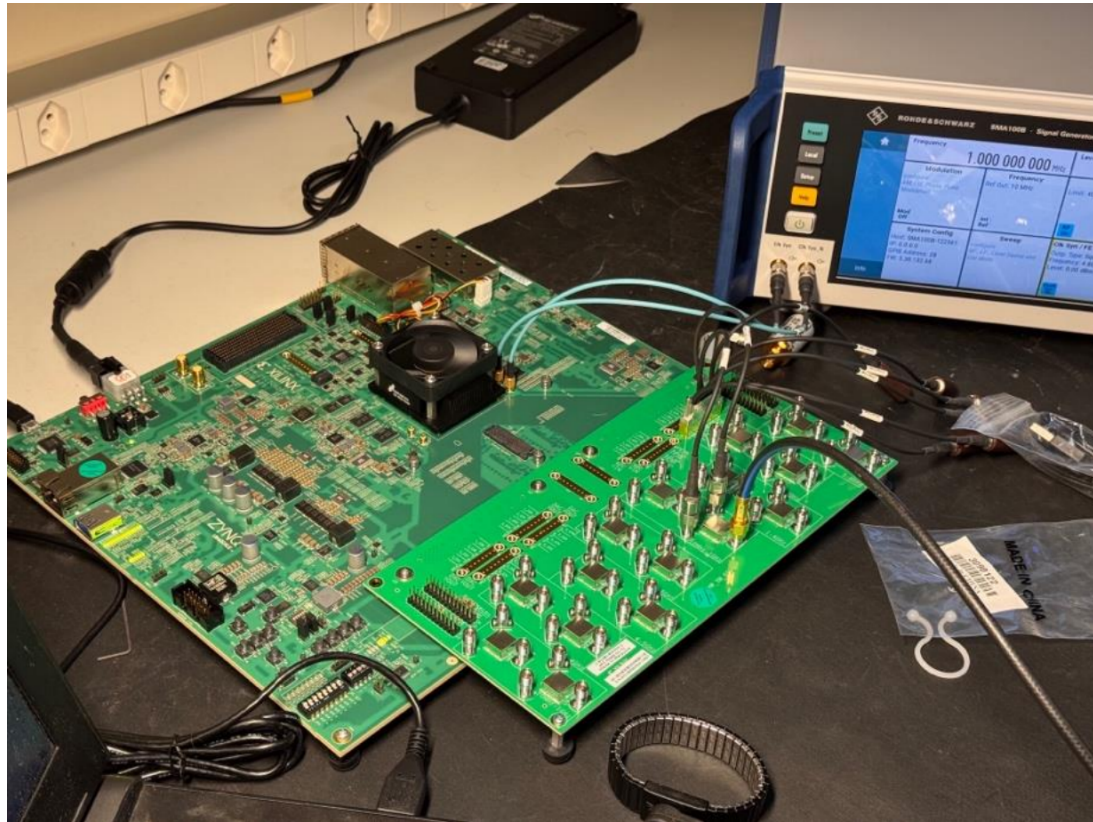
Note: SMA100b into ZCU208 + XM655 with the 10MHz-1GHz balun, Ch1

RFSoc: SINAD, SFDR and ENOB



Note: SMA100b into ZCU208 + XM655 with the 10MHz-1GHz balun, Ch1

Backup Slides: RFSoc Test Setup



Backup Slides: Double Quarter Wave (DQW) CC



- Backup Slides: RF Dipole



- Backup Slides: Crab Cavity Enclosure



- Backup Slides: HL-LHC Magnets

