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

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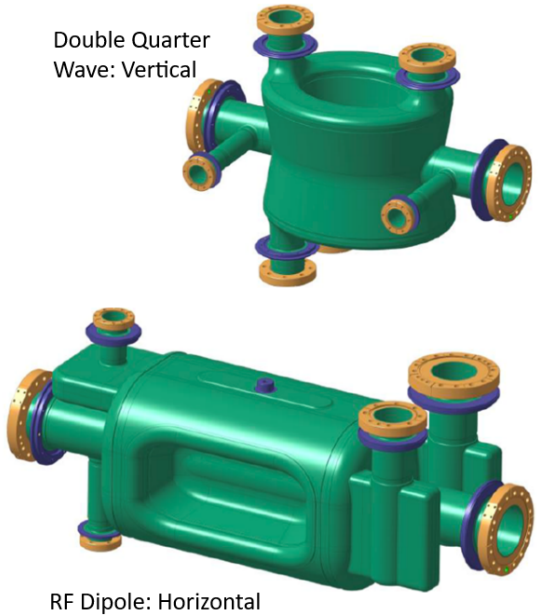
HL-LHC: Introduction

Upgrading the LHC

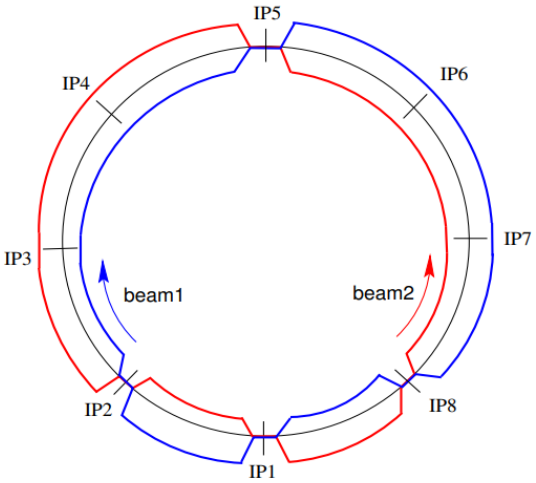
	Unit	LHC	HL-LHC
Energy	[TeV]	7	7
p/bunch	[10^{11}]	1.15	2.2
Bunch Spacing	[ns]	25	25
ϵ_n (x,y)	[µm]	2.5	2.5
σ_z (rms)	[cm]	7.55	9.0
$IP_{1,5}$ β^*	[cm]	55	20
Betatron Tunes	-	64.31, 59.32	62.31, 60.32
X-Angle: $2\phi_c$	[µrad]	300	590
Piwinski Angle	$\frac{\sigma_z}{\sigma^*}\phi_c$	0.65	3.14
RF Frequency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

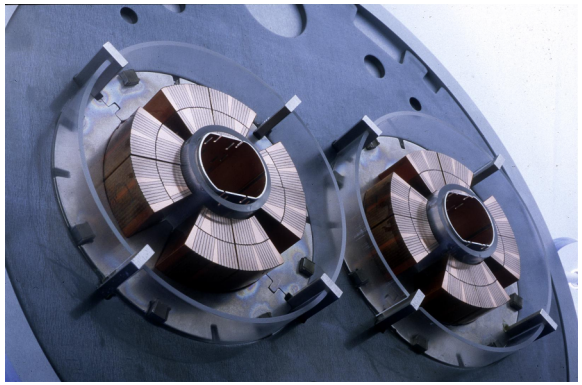
[1] CRAB CAVITIES FOR THE HIGH-LUMINOSITY LHC

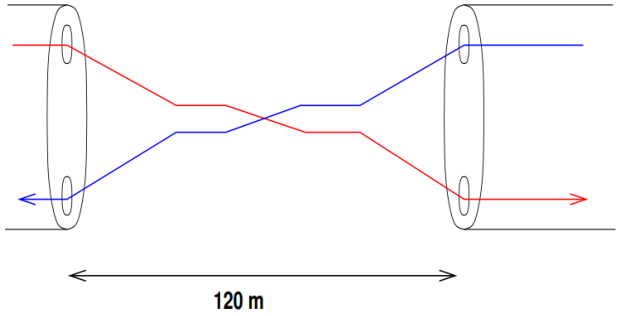


HL-LHC: Crossing Angle

LHC Beam Crossing

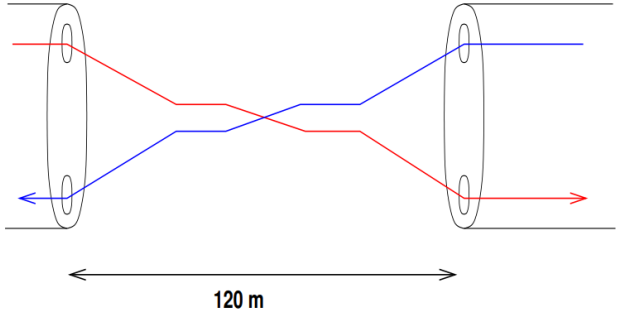


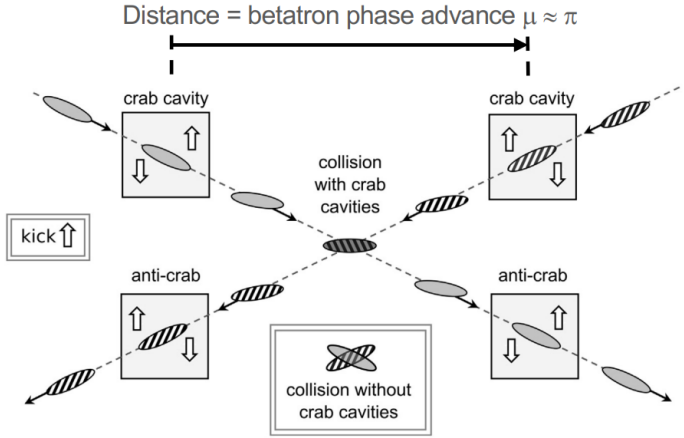




HL-LHC: Crab Cavities (1)

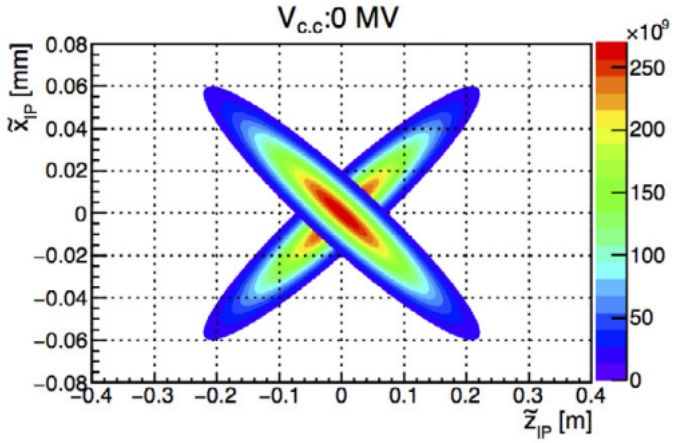
- Pivoting the bunch to increase the collision surface

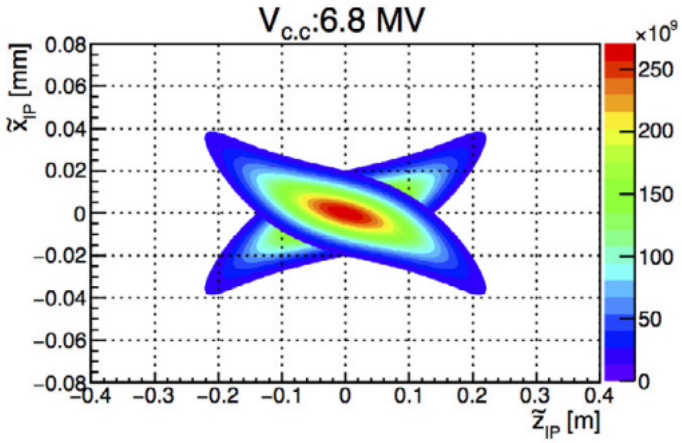




[2]Luminosity reduction caused by phase modulations at the HL-LHC crab cavities

HL-LHC: Crab Cavities (2)





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

HL-LHC: RF Beam Noise Feedback System

Data Acquisition

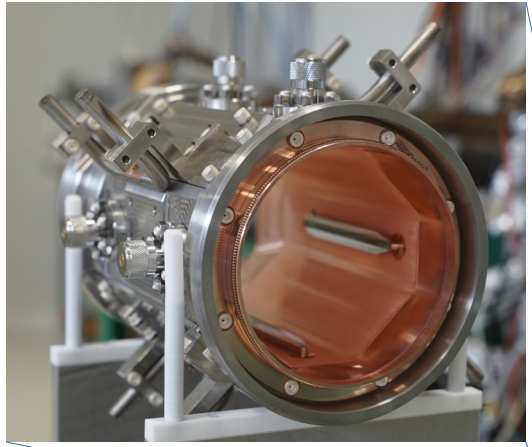
Required ENOB

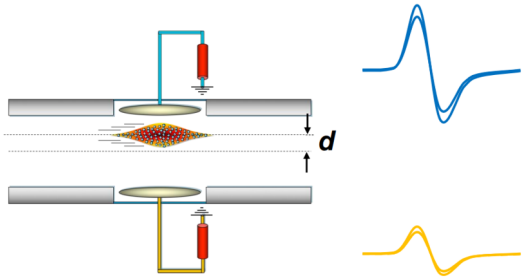
- Position:14.1-bits

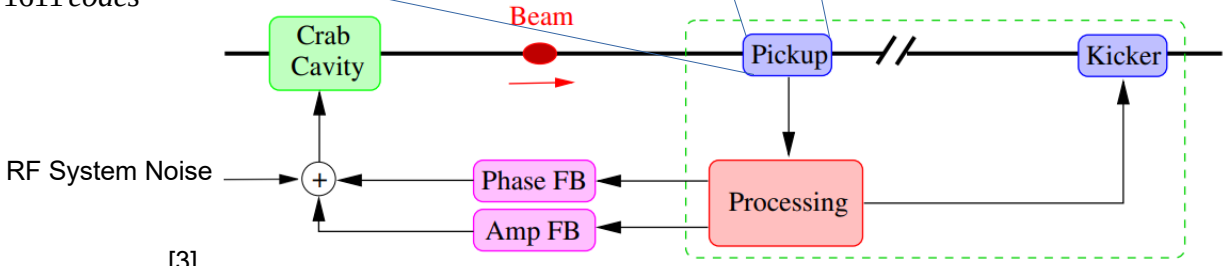
$$\frac{max\ distance}{resolution} = \frac{4\,mm}{226\,nm} = 17699\,codes$$

- Tilt: 10.7-bits

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







[3]

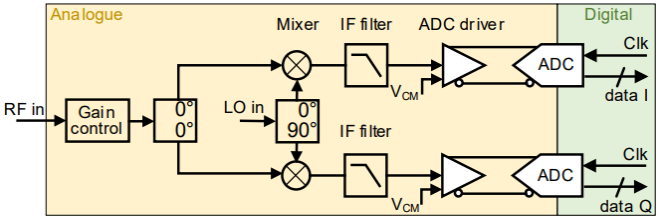
Architecture: IF vs Direct RF Sampling

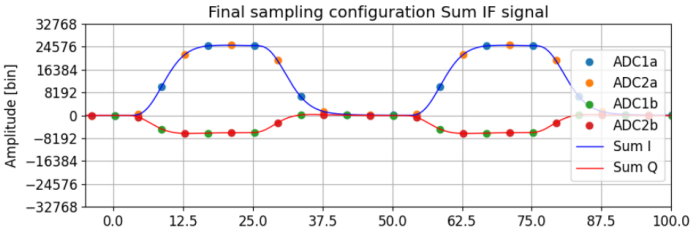
Architectures

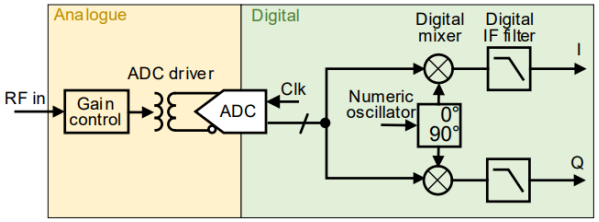
- IF Design
- Direct RF Design

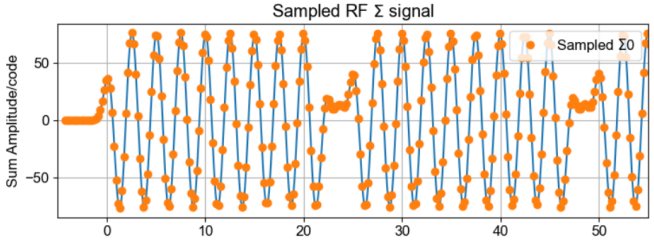
Solutions

- AMD RFSoC
- TI 12DJ





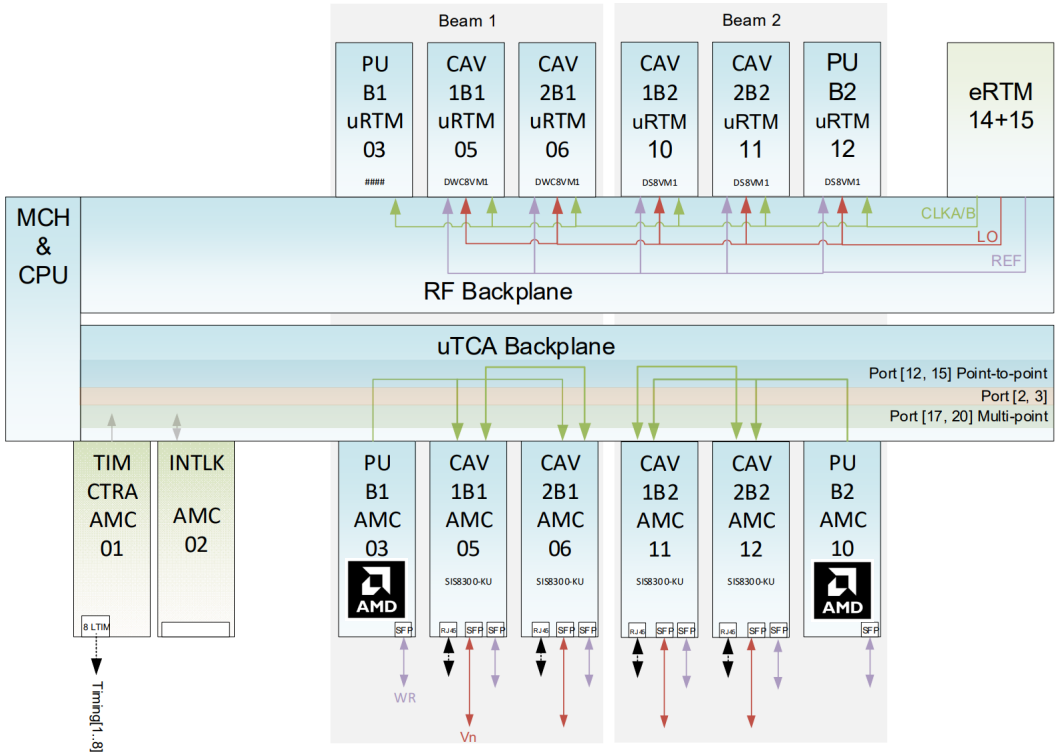




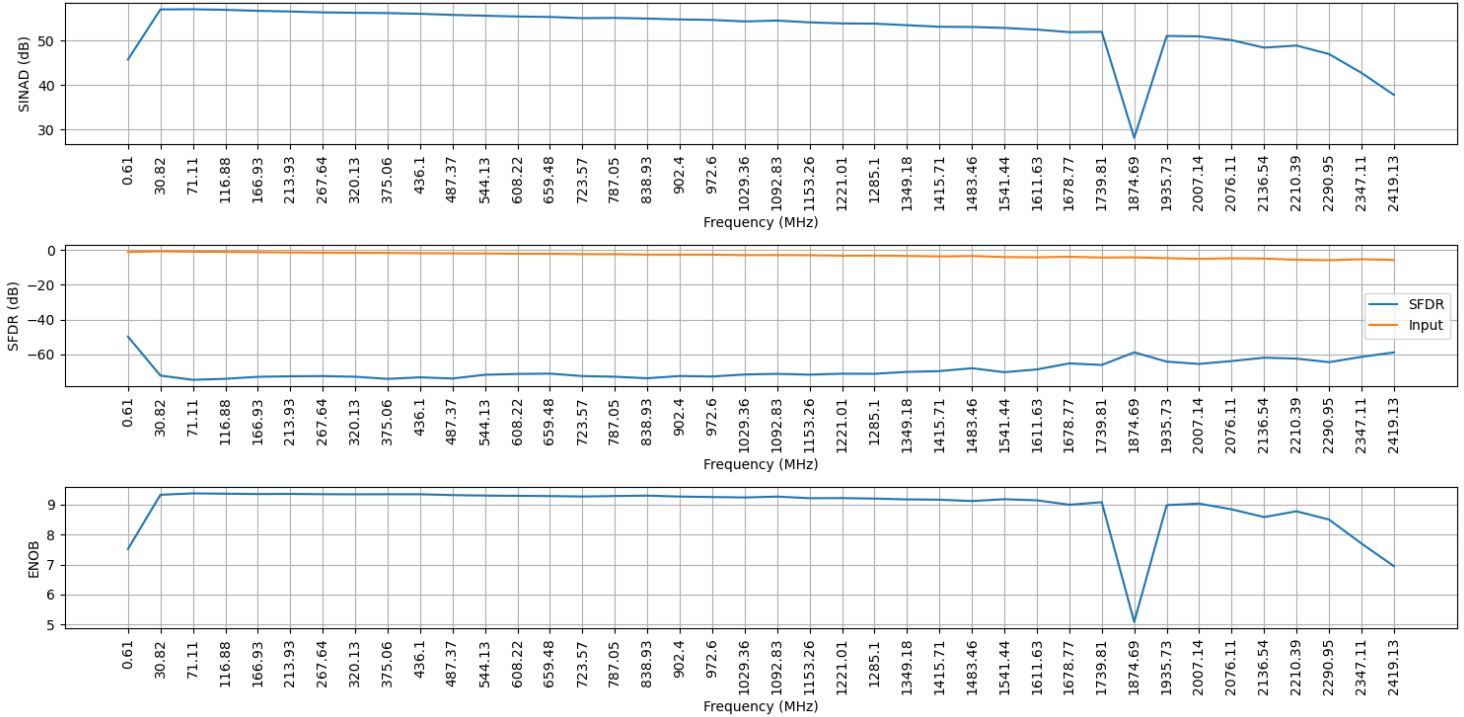
[4] Performance evaluation of CC Noise feedback subsystem variants

uTCA Infrastructure

- 2 Systems per experiment
- RTM:
  - RF input conditioning
- Clocking
  - System clocks
  - ADC clocks
- White Rabbit
  - Over QSFP



RFSoC Measurements: Spectrum



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

RFSoC Measurements: ENOB

ENOB Figures

- 9.34 bits from the ADC (at 400MHz)
- 1 bit from channels averaging
- 3.377 from sample averaging (108 samples)
- Total: 13.71 ENOBs!
  - 14.1 Required!

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

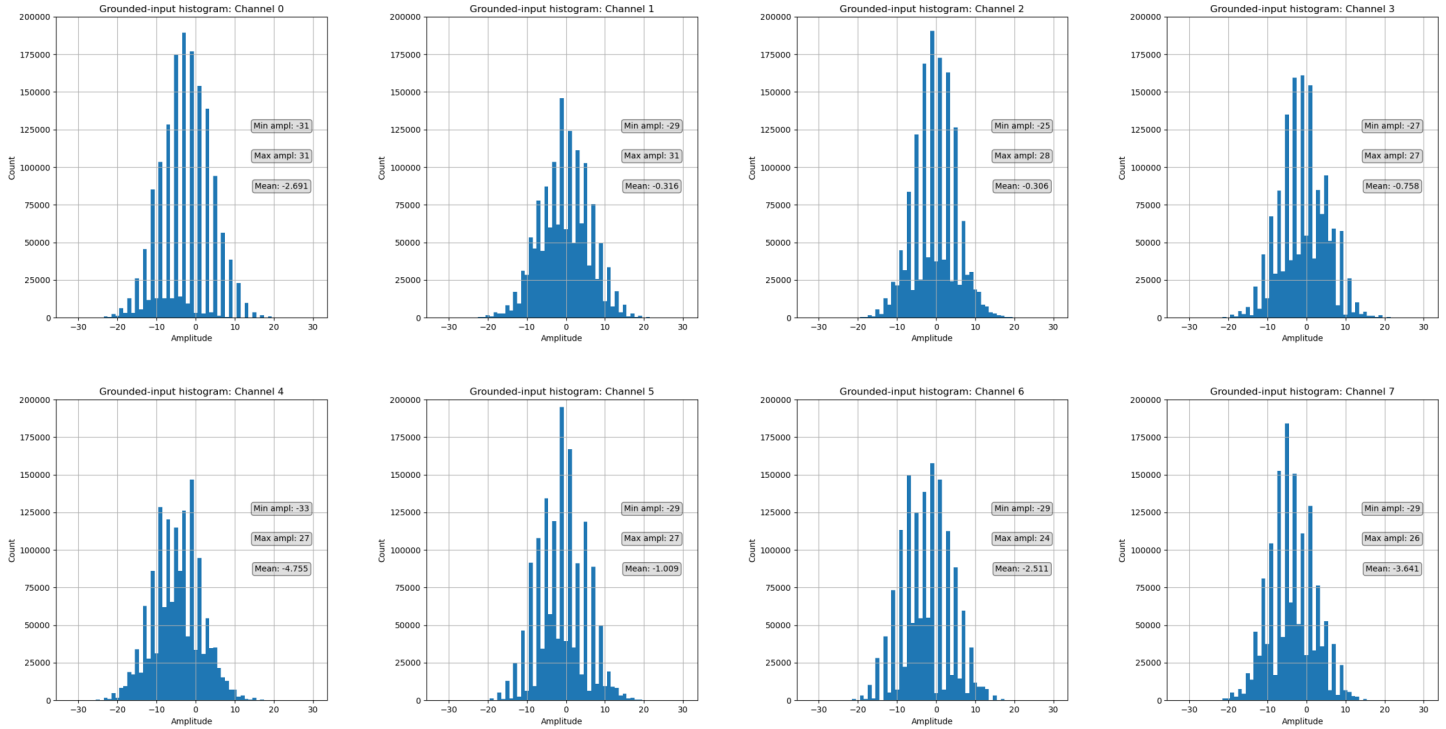
[3] "Crab Cavity RF Noise Feedback and Transverse Damper Interaction", P.Baudrenghien (CERN), T.Mastoridis (California Polytechnic State Univ. (US)), B.Miller Nicholas

[4] “Performance evaluation of CC Noise feedback subsystem variants”, D. Marinov, D. Valuch Progress report at HL-LHC LLRF meeting 24.9.2025 CERN.

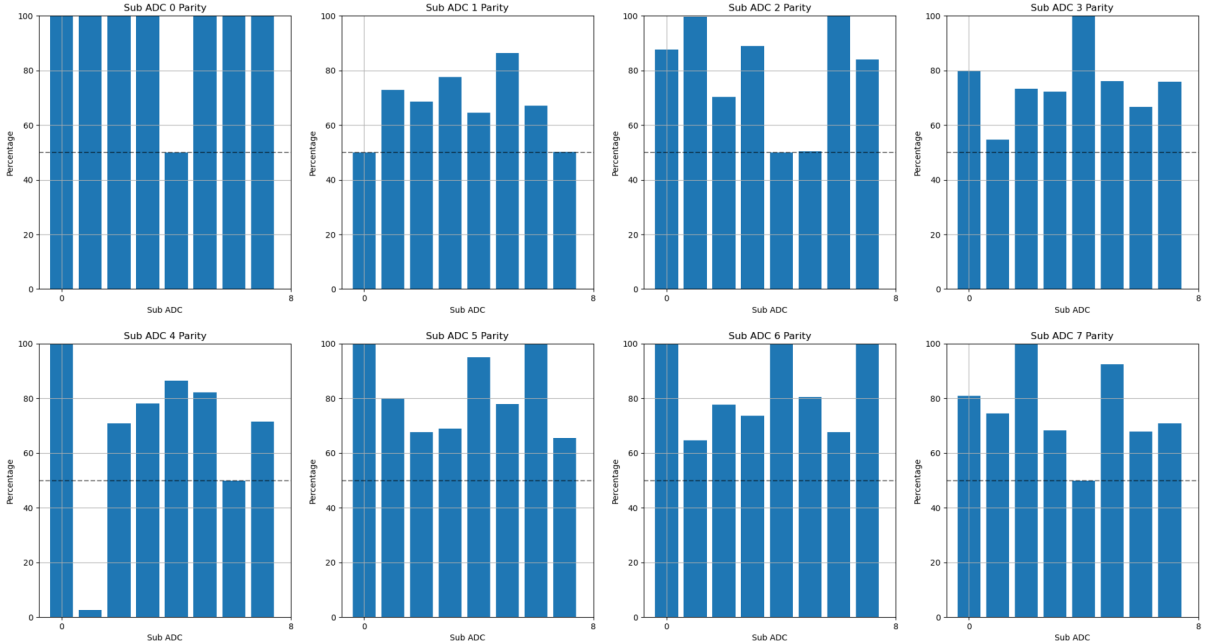
[5] "Transverse emittance growth due to rf noise in crab cavities: Theory, measurements, cure, and high luminosity LHC estimates" P.Baudrenghien (CERN), T.Mastoridis (Cal. Poly.). Physical Review Accelerators and Beams 27 (2024) 051001 DOI: 10.1103/PhysRevAccelBeams.27.051001

[6] “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/

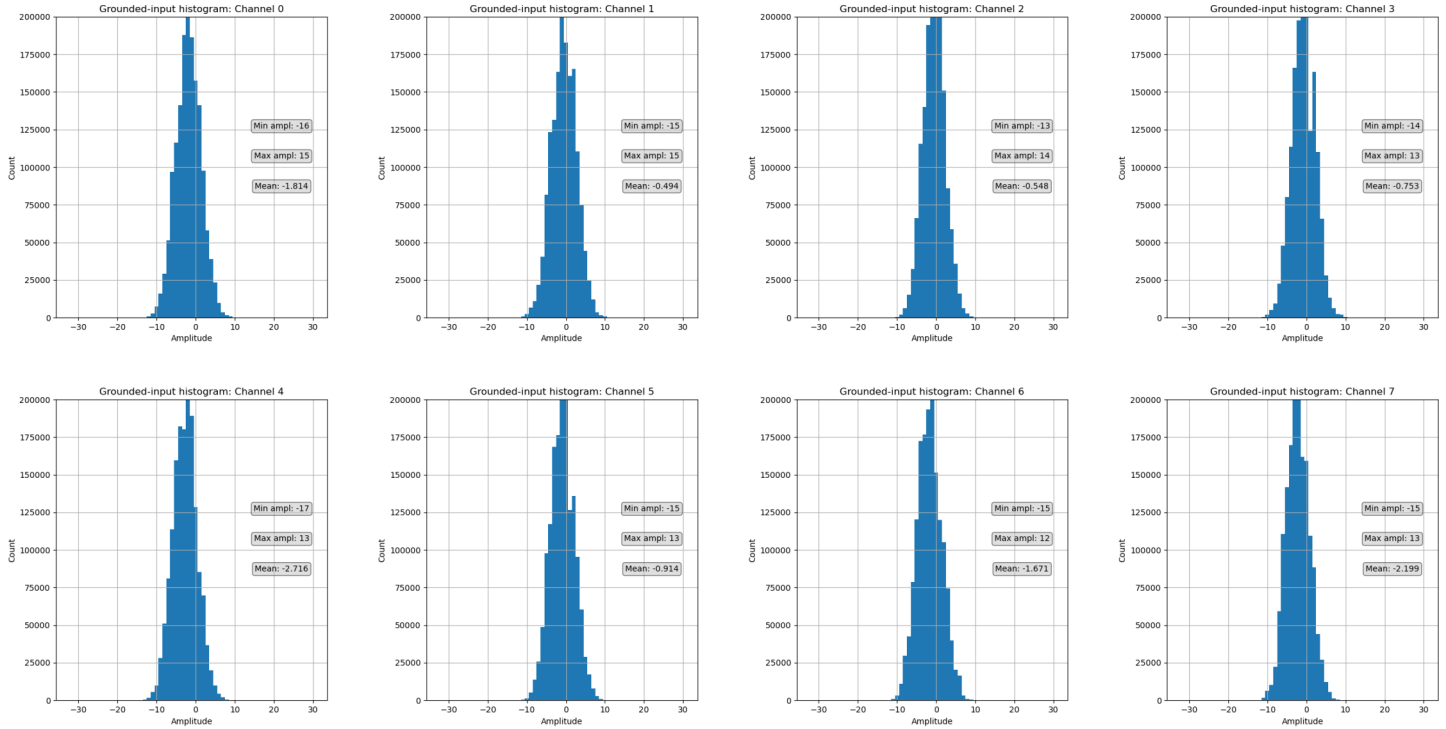
RFSoC Measurements: Noise (1), 14-bit data



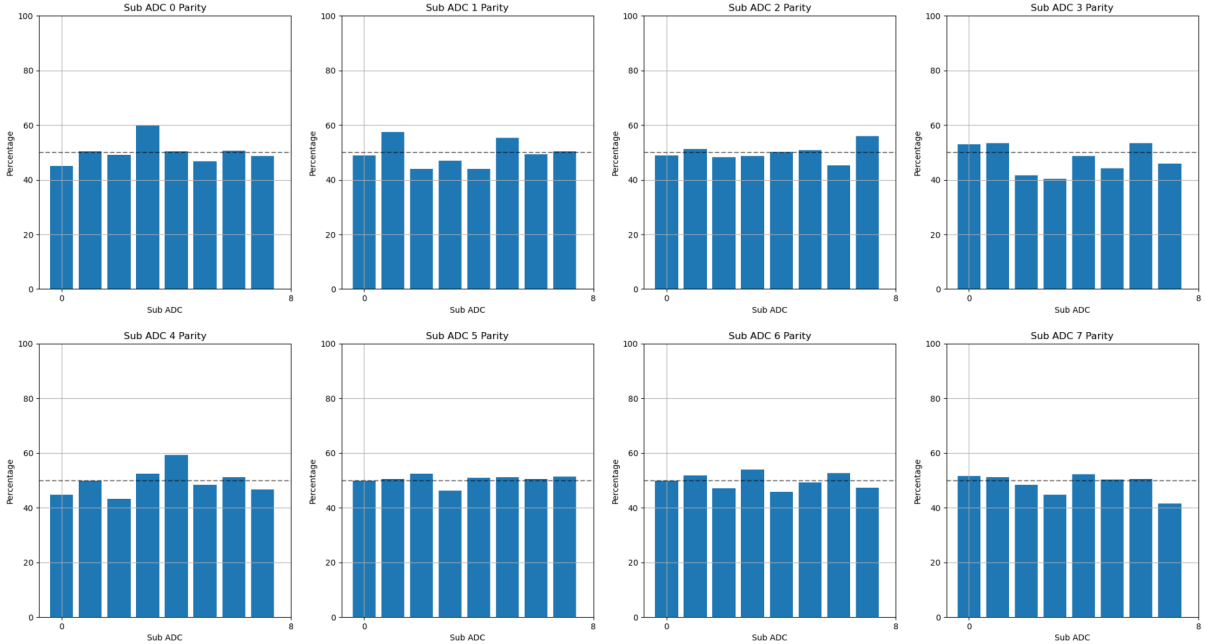
RFSoC Measurements: Noise (2), 14-bit data



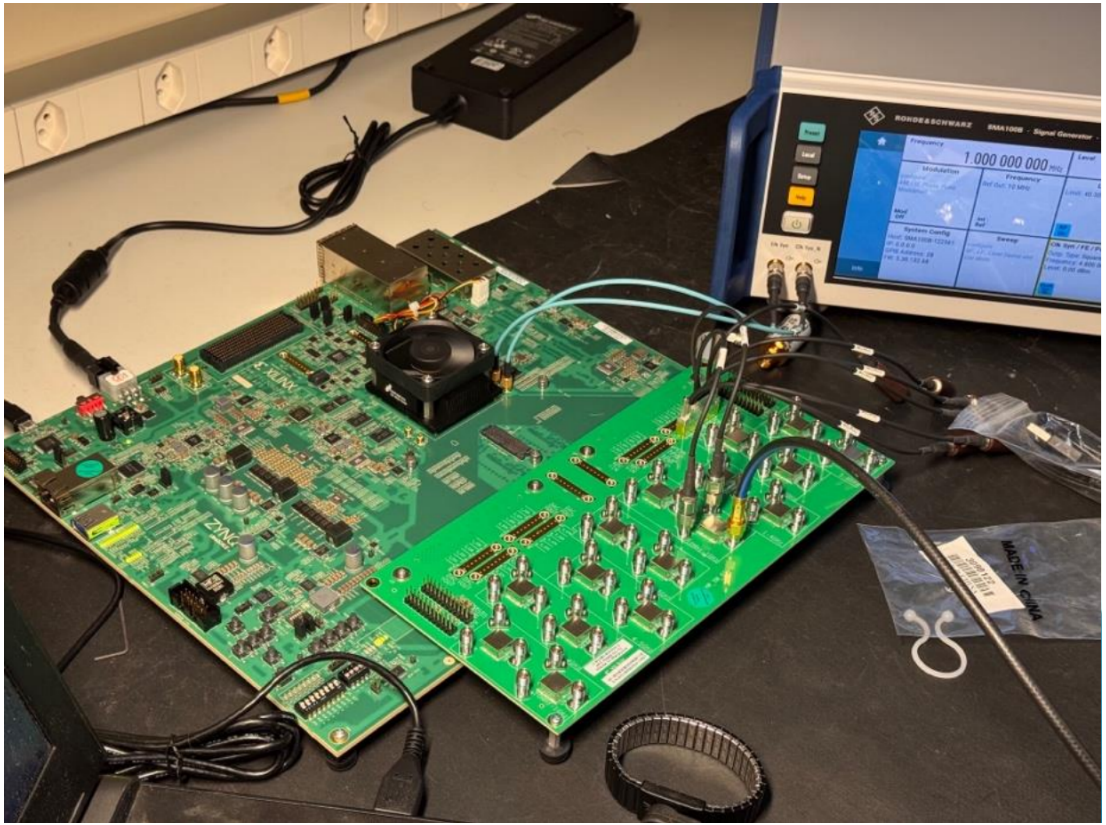
RFSoC Measurements: Noise (3), 13-bit data



RFSoC Measurements: Noise (4), 13-bit data



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