HL-LHC Crab-Cavities Low Level RF (LLRF)

G. Hagmann on behalf of WP4

Acknowledgements on slides ♣ to P. Baudrenghien, T. Mastoridis,
Acknowledgements on slides♠ to Daniel Valuch, Michal Krupa, Tom Levens

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Overview

1) LLRF Overview

2) Infrastructure

3) Architecture

4) LLRF Cavity Controller

5) RF noise & CC noise feedback

7) RF conditioning

9) Conclusion

HL-LHC LLRF overview

Great challenges for LHC LLRF systems

- Synchronize a distributed RF system in multiple points
  - Point 4 Surface (SR4): Beam-Control[1], ADT
  - Point 4 underground (UX45): ACS Cavities
  - Point 1 underground (ATLAS) : RFD CC
  - Point 5 underground (CMS) : DQW CC

- Very low CC RF noise to limit EGR
- RF phase stability to keep the luminosity
- Crabbing voltage closure for machine protection
- Large and distributed LLRF infrastructure

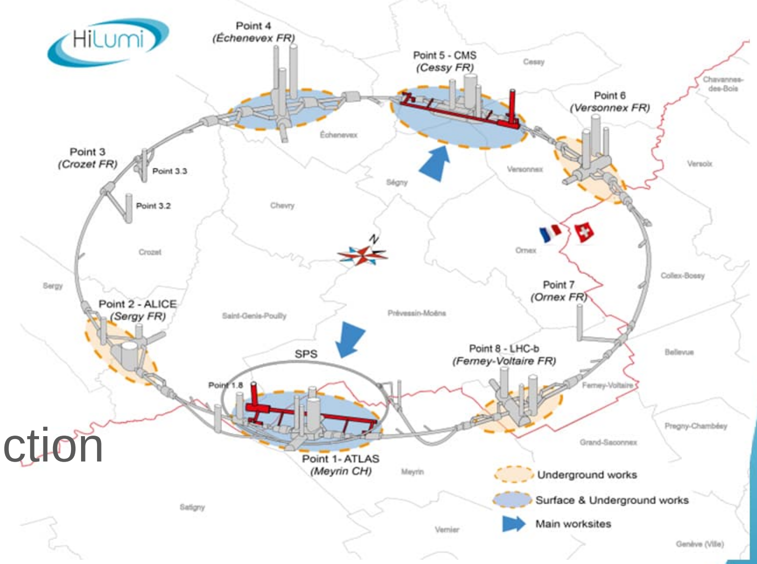

Fig – HL-LHC layout [2]

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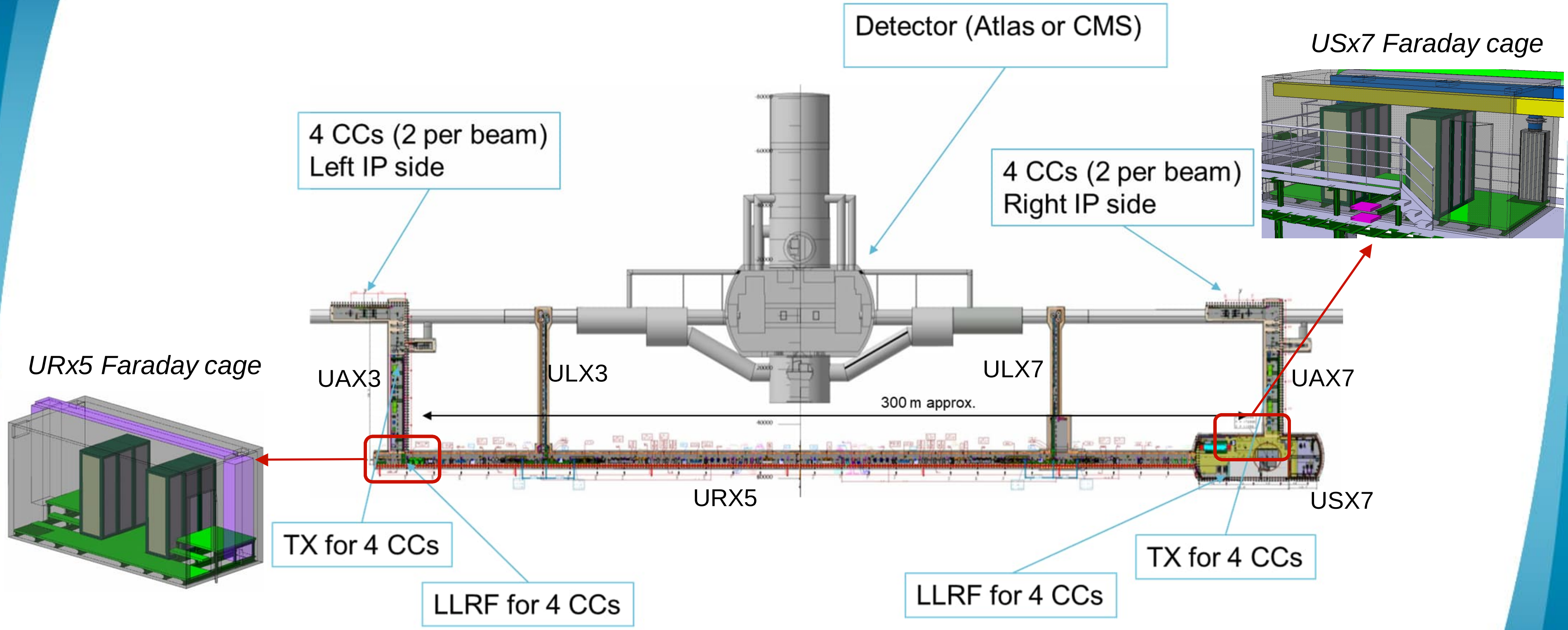
[1] *LHC Beam Controls Consolidation request EDMS 2956941*

LLRF Infrastructure (1/2)


Detector (Atlas or CMS)

USx7 Faraday cage

4 CCs (2 per beam)
Left IP side

4 CCs (2 per beam)
Right IP side

URx5 Faraday cage

TX for 4 CCs

LLRF for 4 CCs

LLRF for 4 CCs

TX for 4 CCs

Fig – HL-LHC point 1 or 5 underground layout. Top view,
Courtesy S. Maridor

LLRF Infrastructure (2/2)

- RF integration being finalized
    - FC & Cabling layout finalized
    - Technical details Q4 2024
- Four Faraday-cages
    - Technical spec by Oct 2024, Ordering Q1 2025
- Cabling & Fibers
    - Requests & routing finalized (682 cables / ~100 fibers)
- Cable temperature sensitivity (ΔT=8K, 7/8’’
    - Phase shift of ~ 3.1 RFdeg, Budget 2 RFdeg
    - → **Beam phase tracking**
- Joint GMT & RF White-Rabbit network

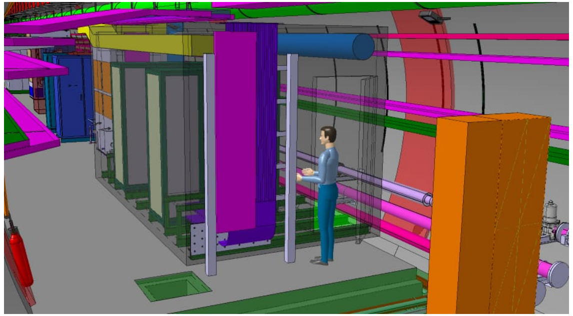


Fig – HL-LHC URx5 Faraday cage, Courtesy S. Maridor

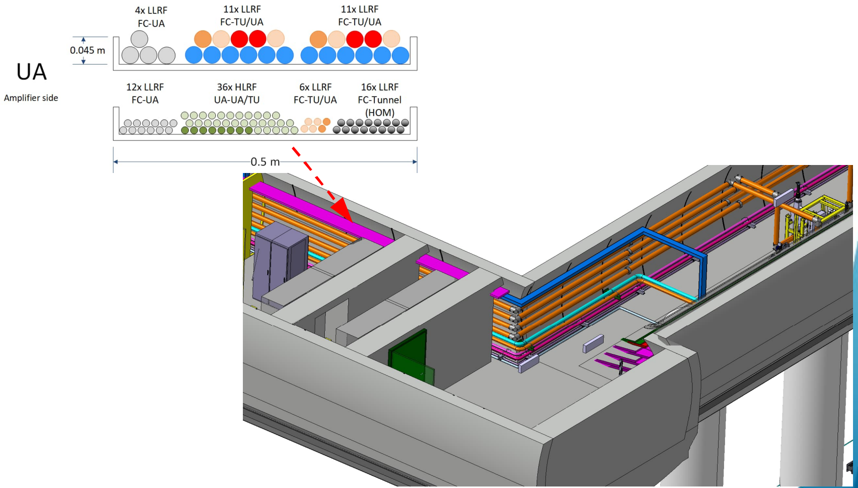
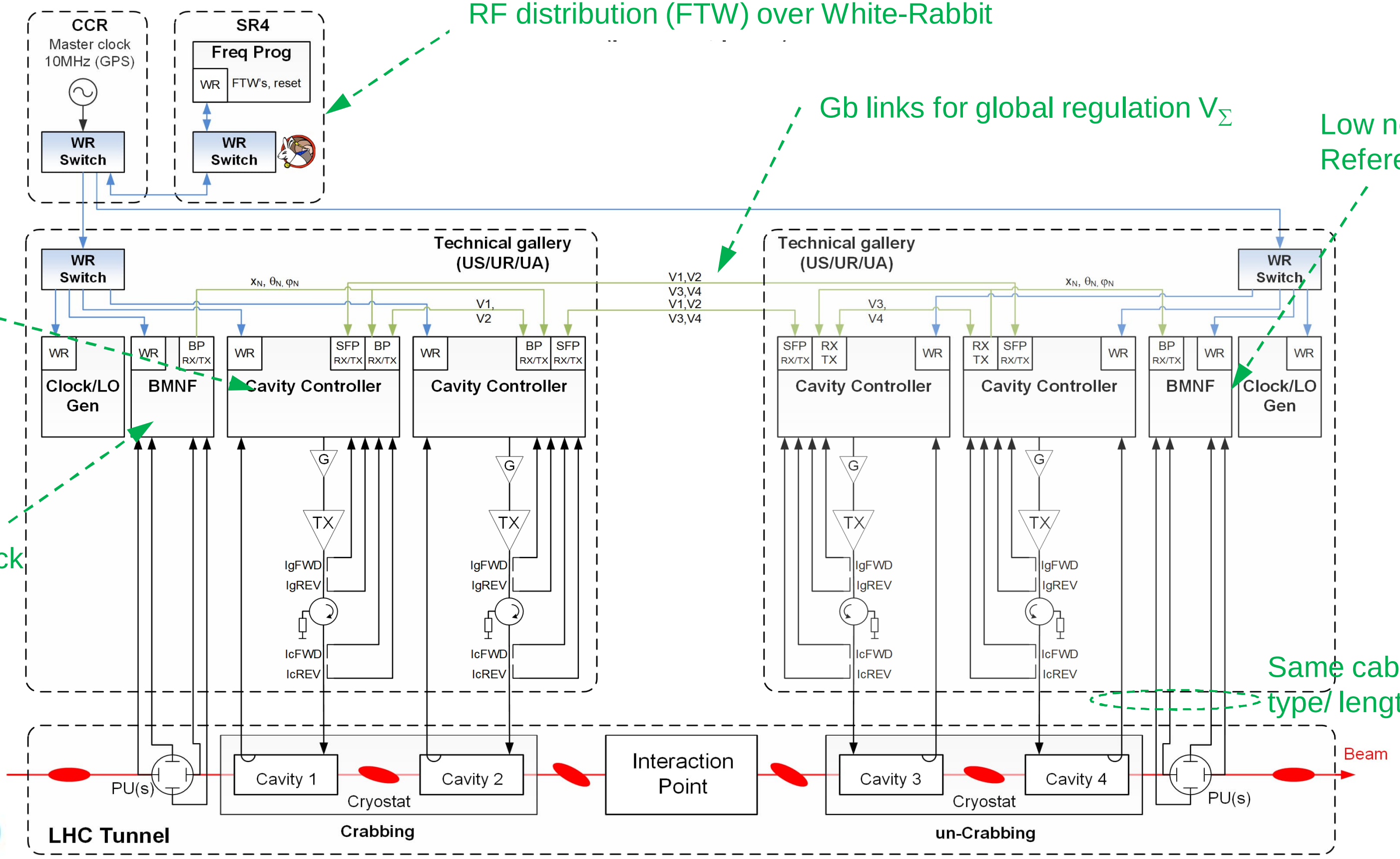


Fig – HL-LHC US galleries, Courtesy L. Ciampo

LLRF architecture



RF distribution (FTW) over White-Rabbit

Gb links for global regulation V_Σ

Low noise Master Reference (Clock, LO)

Cavity field regulation

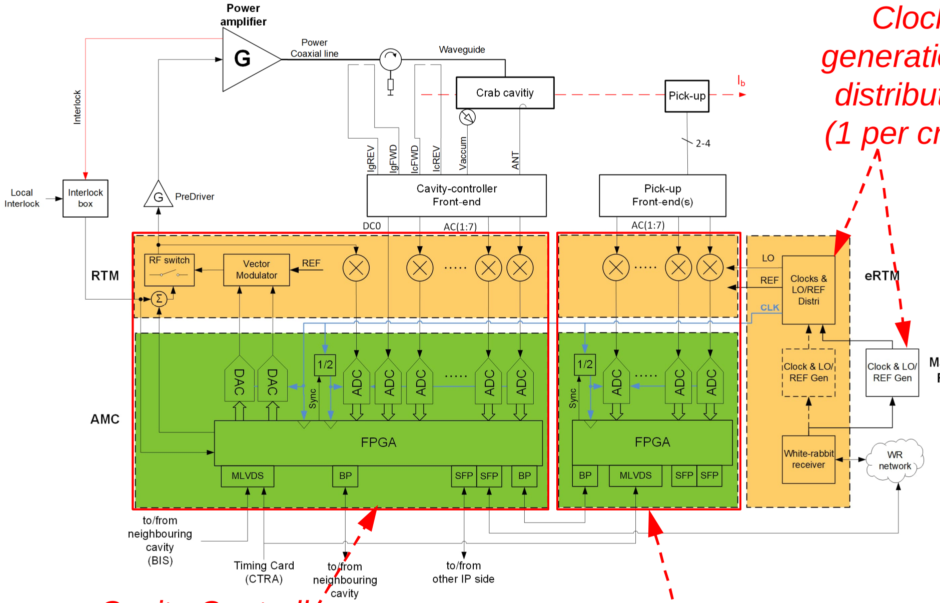
Beam phase and RF noise feedback

Same cable type/ length

Fig – HL-LHC Crab cavities LLRF architecture, per IP, per beam

LLRF architecture - Hardware

- Inspired by SPS LLRF upgrade
- White-Rabbit network
  - RF over WR
  - Master REF locked on WR
- MTCA platform
- Cavity-Controller
  - RF feedback (direct + Comb)
  - Global control for crabbing closure
- Beam Measurement
  - Bunch phase & tilt
  - Crab-cavity noise feedback
- COTS and in-house designs (baseline scenario)



Clock generation & distribution (1 per crate)

Cavity-Controller (1 per acvity)

Beam measurement (1 per beam, IP side)

Fig – HL-LHC Crab cavities controller HW diagram

LLRF Cavity-Controller

The Cavity-Controller is in charge of

- Self-Excitation Loop (SEL)
- Tuning loop
  - keep the cavity on-tune the entire LHC fill (filling/rampling/collision)
- Polar-loop
  - Slow regulation around the amplifier (Gain&phase drift, reduce amplifier noise)
- RF feedback
  - Control cavity field + Impedance reduction
  - Fast loop around cavity-amplifier
  - Slow global loop regulating the vector sum: crabbing-uncrabbing voltages
- RF conditioning

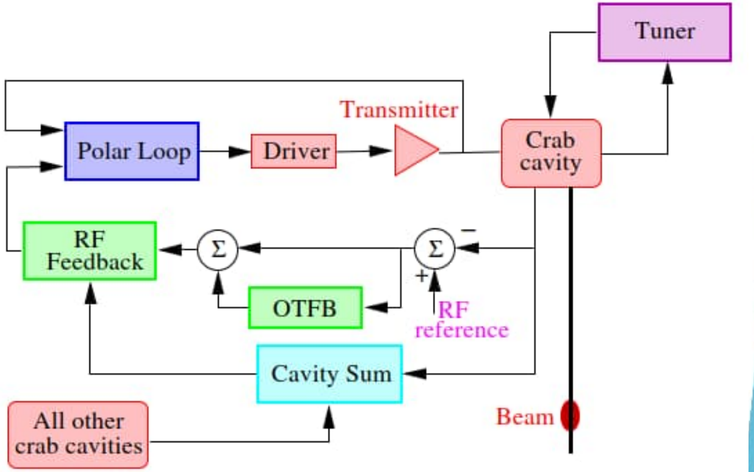


Fig – Crab Cavity Low-Level RF block diagram [11]

LLRF Cavity-Controller

- One Cavity-Controller per Cavity → 16 total
  - Pair of AMC and RTM cards:
    - AMC: Digital processing (ADC, DAC; FPGA)
    - RTM: Analog processing (RF mixer, etc.)

- Hardware currently under evaluation in lab
  - RF receiver noise is the most critical issue
  - Baseline scenario: COTS similar to SPS 200MHz
    - Reusing same AMC from SPS LLRF
    - **New RTM now supported** (COTS, RF mixer)
    - Additional FPGA Firmware+Gateware developed in 2024
  - Detailed noise measurement on-going→ Q4 2024

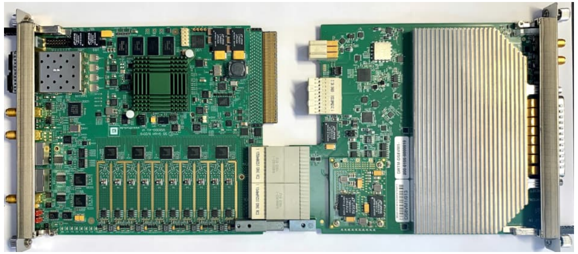


Fig – Example of the SPS Cavity-Controller, AMC (left), RTM (right) [20]

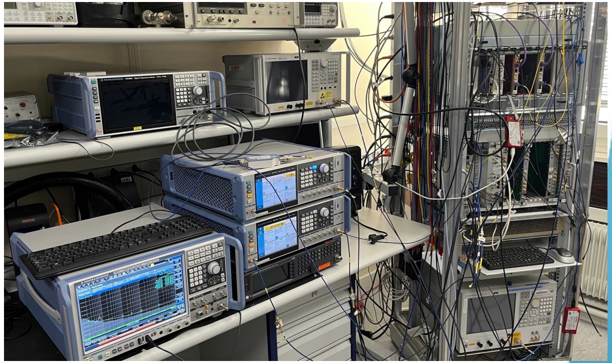


Fig – LLRF lab test

LLRF Cavity-Controller

- Scenarios for MTCA development
  - **A) Baseline:** COTS similar to SPS
  - **B)** If required study possibility for HW modifications with manufacturer (only if minimal)
  - **C)** Else evaluation of different COTS or **D)** in-house design
    → new cost and resources evaluation will be required.
  - **Strategy**:
    - (in)validation of the baseline scenario by Q4 2024
    - pre-series only with HL-LHC performances achieved

- Integration in SM18 or SPS (BA6)
  - With baseline scenario A), feasible end 2025
  - With B) tentative in 2026
  - With C) or D) late 2026 or beyond

Fig – LLRF lab test stand for HL-LHC LLRF Cavity-Controller [20]

LLRF Cavity-Controller: RF Feedback ♣

- Direct feedback (proportional)
  - Gain of 150 (43 dB) limited by the latency (<1.3μs).
- Betatron comb filter (OTFB)
  - The cavity impedance requires evaluating it only a discrete set of frequencies → betatron frequencies [5].
  - Adding narrow band gain peaks of 10 (20dB) at these frequencies with the betratron comb filter [11].

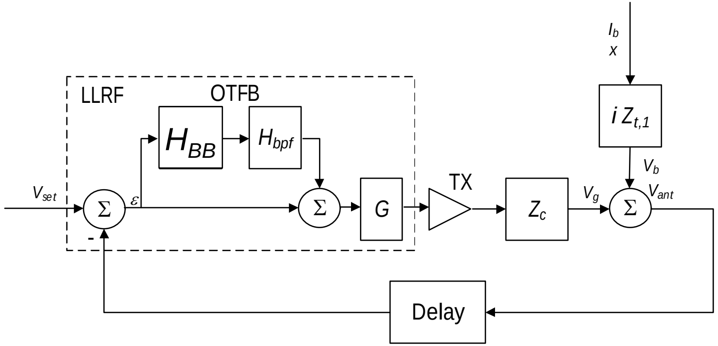


Fig – RF feedback and OTFB block diagram [11]

$$f_p^s = (p + \nu_*) f_0 \qquad f_p^d = (p + (1 - \nu_*)) f_0, \quad \forall p \in \mathbb{N}$$

$$H_{BB}(\omega) = K(1-a)\left[\frac{e^{i\,2\pi Q}\,e^{-i\,T_{rev}\,\omega}}{1-a\,e^{i\,2\pi Q}e^{-i\,T_{rev}\,\omega}} + \frac{e^{-i\,2\pi Q}\,e^{-i\,T_{rev}\,\omega}}{1-a\,e^{-i\,2\pi Q}e^{-i\,T_{rev}\,\omega}}\right]$$

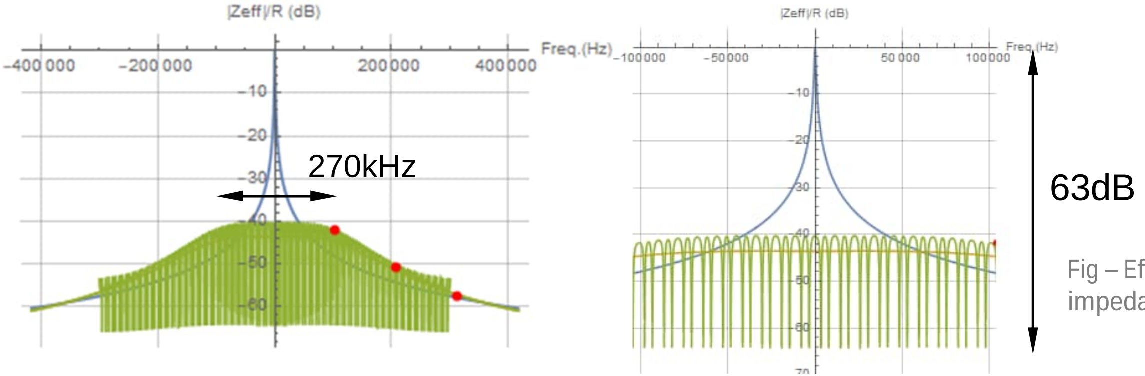


Fig – Effective transverse cavity impedance with w/o feedback [11]

Cavity-Controller: RF Feedback ♣ [11]

- The optimal OTFB gain is inversely proportional to the bandwidth.

$$G \simeq \frac{f_{rev}}{6\,\pi\Delta f}$$

- For the nominal OTFB gain of 10 linear, the 3dB bandwidth would be 50 Hz.
- This bandwidth has to cover the tune spread and tune shifts.
- Any required increase in bandwidth would come at the expense of impedance reduction, as shown below → **keep highest gain**.

- Implementation plan:
  - Design based on SPS LLRF
  - Only on the working pre-series (MTCA platform)
  - Tentative end 2025 for baseline scenario (A)

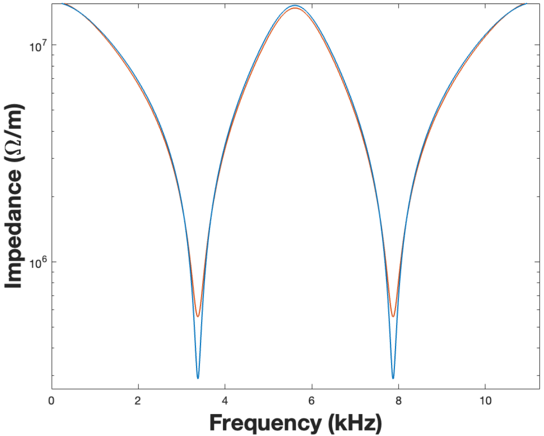


Fig – Impedance reduction at the betatraon frequencies wrt to comb bandwidth, Courtesy T. Mastoridis

RF noise: Recap (1/2) ♣

- The CC deflecting field will suffer from small phase and amplitude fluctuations (PM and AM) called RF noise

- The RF noise depends on the LLRF and HLRF architecture

- The RF noise will therefore be dominated by the LLRF receiver noise (demodulation, ADC) of the CC voltage
  - Identical PM and AM noise spectra are expected identical (I/Q demodulation).

- The CC LLRF includes a strong RF feedback [11] to reduce the cavity impedance at fundamental, required to prevent CBI[1] [5]
  - Expecting flat RF noise spectrum from ~1 kHz to the RF feedback BW (136 kHz) [11]

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[1] *CBI: Coupled Bunch Instability*

RF noise: Recap (2/2) ♣

- Emittance growth is due to the excitation that overlaps the betatron tunespread (red asterisks)
- With a realistic improvements planned for the CC LLRF compared to the ACS system:
  - noise plateau at 5 10^{-3} (μ rad)^2/Hz, that is -143 dBc/Hz
- Using analytical expressions [6] we can calculate the emittance growth, in physics conditions (at lowest β^*=15 cm), caused by the red noise spectrum. We assume β_{cc}=3620 m
  - 23.7 %/h EGR due to PM and 9.0 %/h due to AM with the four cavities per beam and plane [7]
  - Budget is 1% integrated luminosity loss caused by CCs. That corresponds to 2 %/h EGR at flat top and lowest β^*[14]
- We must therefore **find a mitigation to further reduce the emittance growth by factor 25 for phase and 10 for amplitude**

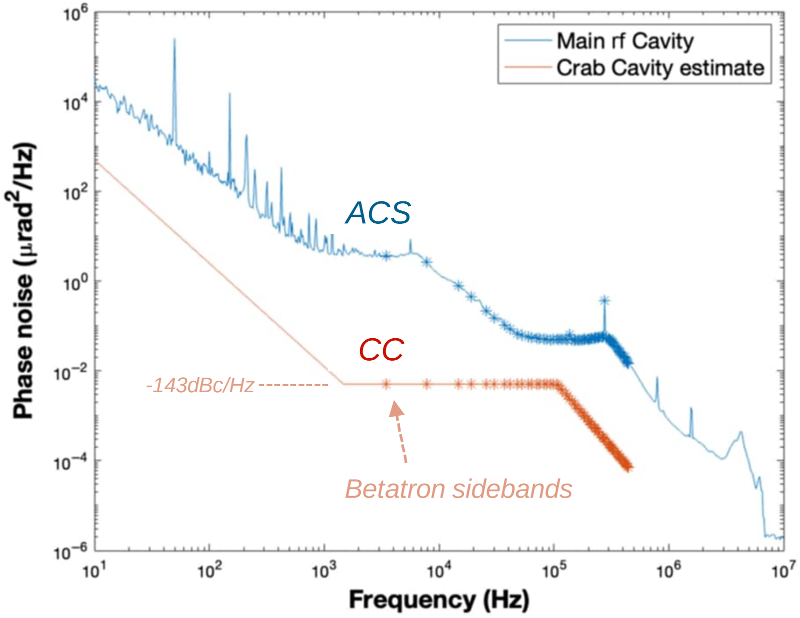

Fig – LHC ACS cavities and Crab-cavities SSB phase noise [11]

RF noise feedback (1/3) ♣

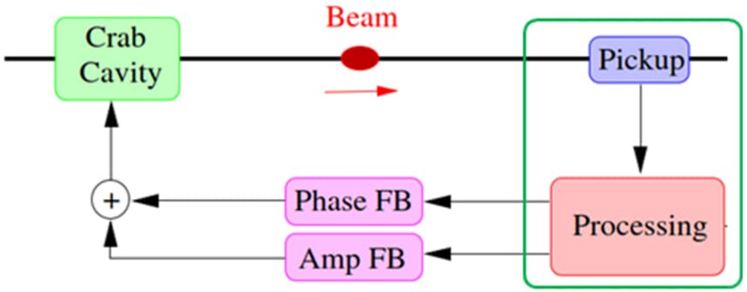

Fig – Crab-cavity noise feedback diagram [10]

- Emittance growth caused by crab cavity RF noise is a two-step process:
    - 1) Noise excites a bunch oscillation.
    - 2) This oscillation results in emittance growth through decoherence due to the betatron tunespread
- A feedback system can mitigate this degradation:
    - Damping the oscillation before decoherence has significantly impacted the emittance
    - Using Crab cavities as kickers to mitigate rf noise effects
    - Extracting both the dipole (mode 0) and head-tail (mode 1) signals from Pickup + LLRF
    - Feeding back signals on the CC phase and the head-tail (tilt) signal to modulate the CC amplitude in quadrature with the measurement, thereby achieving damping [7].

RF noise feedback (2/3) ♣

- Feedback limitations:
  - Gain α_O limited by the latency (processing) (expecting <5 turns , $\alpha_O<5.3$)
  - Measurement noise
- Requirements emittance growth reduction:
  - $R_0=1/25$ for phase
  - $R_1=1/10$ for amplitude
- The intersection with an analytical curve indicates the maximum measurement noise over RF noise ratio $\sigma_0/\sigma\Delta\phi$ (R_0 = 1/25).
- With lower measurement noise level (yellow curve), we can get higher reduction (R_0=0.03, mode 0 case plotted here) with same gain.

Max gain α_O=5.3 (mode 0)

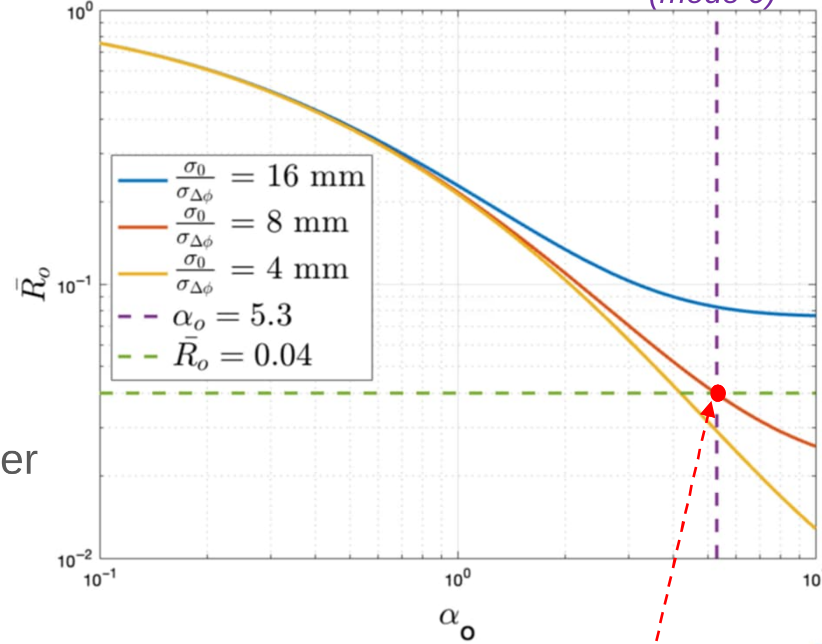

Fig – Emittance growth reduction factor with varying mode 0 measurement error to phase noise ratios. HL-LHC case (Ncc = 4) [7]. s

Max allowed measurement noise

RF noise feedback (3/3) ♣

- The acceptable RF noise levels are now defined, setting the LLRF specifications [7].

- To achieve the luminosity goal (reduction of total e-growth to 2 %/h), a dedicated noise feedback is required.
- The noise feedback specifications call for a pickup single bunch measurement noise rms below $\sigma_0 < 320$ nm and $\sigma_1 < 8.3$ µrad [7] → **Challenging!**

- Fortunately, the CC RF noise spectrum is limited to 136 kHz, so we could average over multiple bunches.
- The requirement for bunch-per-bunch measurement can be relaxed by 12 (linear) to **$\sigma_0 < 3.9$ µm rms and $\sigma_1 < 100$ µrad rms** [7], assuming:
  - 25 ns bunch spacing
  - independent measurement noise from bunch to bunch
  - Averaging the measurements over 144 bunches (approx.) = 3.6 us

RF Noise feedback – Design status ♠

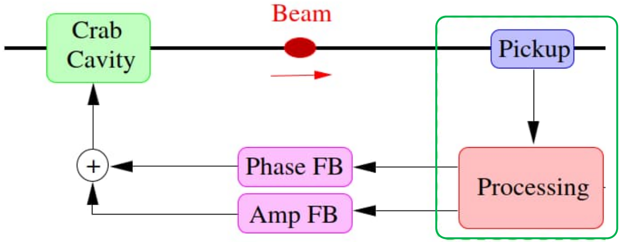

Fig – Crab-cavity noise feedback diagram [10]

- Beam interaction side – PICKUP
  - Conceptual specification of the pickup now finalized [18]
  - Joint Pickup analysis and simulation between BI and RF (set of position and angular displacements) → almost completed
  - Existing LHC Pickup measurement foreseen end run 2024 → validation of BI simulation and RF analytic model
  - Preliminary BI & RF analysis indicates the need of the stripline pickup for crab-cavity noise feedback.
- LLRF Hardware - Signal processing
  - Analysis of expected signal at LLRF input finalized (Pickup, Cables)
    - Further analysis with real RF device parameters (cables, hybrids, etc) required
  - Analysis on-going of the beam motion sensitivity to be measured (mode 0 and mode 1). Current models confirm it will be very challenging to measure (very carefully electronics design and cabling required)
  - Similar hardware architecture with MTCA AMC+RTM
    - AMC: On-going analysis with available digitizers (COTS from SPS LLRF)
    - RTM: In-house design required → design starting Q4 2024, for tests in SPS in 2025

Clock generation & distribution

- Clocks generation synchronized on WR
  - Fixed frequency sampling & processing clocks for noise optimization (thanks to SPS experience)

- Low noise Master Reference
  - Generates clocks and LO for RF receivers
  - New standalone module (3U, 19'')
  - Based on very low noise OCXO, locked on WR
  - Development outsourced to industry

- enhanced RTM (eRTM)
  - Distributes clocks and LO in the MTCA shelf
  - Control the Master Reference (phase lock)
  - Collaboration with BE-CEM for Développent (eRTM15)

- Design schedule (Master REF, eRTM)
  - Specification by Q1 2025
  - Prototyping end 2025

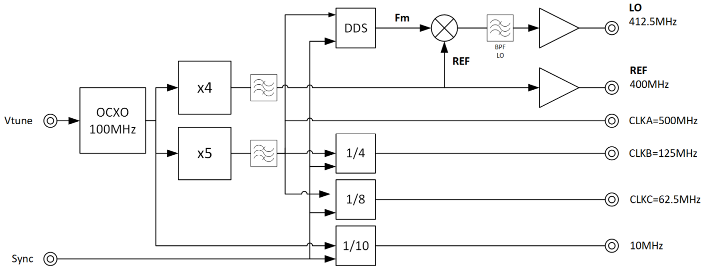

Fig – Master Reference block diagram

Fig – SPS eRTM (dual module eRTM14, eRTM15)

RF conditioning

- Obsolescence of the current RF conditioning system
  - SPS/CC: Limited nb of systems (2-3)
  - LHC: ~20years old, VME
- Migration of the RF conditioning inside the LLRF
  - Same HW than the Cavity-Controller
  - New FPGA firmware (IP core) being developed (GRAD), → by Q2 2025
  - Inspired from SPS and LHC algorithms
- Vacuum measurement required by the LLRF
  - Dedicated fiber optic link (from UAs to UR/US)
  - New HW interface being developed (GRAD) → series by Q4 2025
- Migration plan
  - Only on the working pre-series (MTCA platform)
  - late 2025 for the baseline scenario (A)

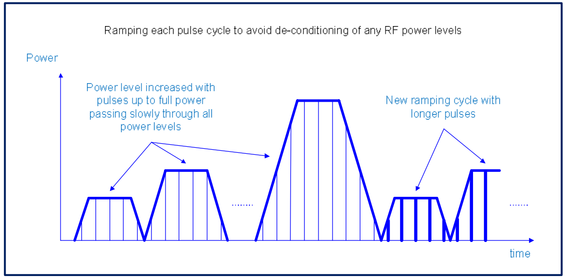

Fig – SPS Conditioning in pulse mode Courtesy E. Montesinos [12]

Conclusion

- LLRF Architecture is now well defined
  - White-Rabbit joint network with timing (GMT)
  - MTCA platform
  - Mixed of COTS and in-house designs, outsourcing is optimized
- Infrastructure is on track and well defined
- Challenging RF noise requirement
  - Now well defined specification available [7] → challenge for LLRF electronics
  - Crab-cavity noise feedback required
  - Hardware evaluation on going
- Strategy: priority on the development of HL-LHC LLRF hardware
  - MTCA Pre-series only with HL-LHC spec
  - Comb filter, RF conditioning on MTCA platform

References

[1] E. Yamakawa et al., Luminosity reduction caused by phase modulations at the HL-LHC crab cavities, NIMA 2018, https://www.sciencedirect.com/science/article/pii/S0168900218310325

[2] HL LHC layout, https://voisins.web.cern.ch/en/high-luminosity-lhc-hl-lhc

[3] J. Gill, RF Signal Distribution over WR, Nov. 2019, BE seminar https://indico.cern.ch/event/865008/attachments/1949767/3236439/BE_seminar_WR_Applications-RFoWR.pdf

[4] I. Béjar Alonso et al., **High-Luminosity Large Hadron Collider (HL-LHC)**, technical Design Report, CERN-2020-010, https://doi.org/10.23731/CYRM-2020-0010

[5] L. Giacomel et al., **Mitigation strategies for the instabilities induced by the fundamental mode of the HL-LHC crab cavities**, 2024 JINST 19 P05046, https://doi.org/10.1088/1748-0221/19/05/P05046

[6] P. Baudrenghien, T. Mastoridis, **Transverse emittance growth due to rf noise in the high-luminosity LHC crab cavities, Physical review accelerator and beams**, October 2015, https://doi.org/10.1103/PhysRevSTAB.18.101001

[7] P. Baudrenghien, T. Mastoridis, **Transverse Emittance Growth due to RF Noise in Crab Cavities: Theory, Measurements, Cure, and High Luminosity LHC estimates** [Phys. Rev. ST Accel. Beams 27, 051001 (2024), https://doi.org/10.1103/PhysRevAccelBeams.27.051001

[8] R. Calaga, "**Crab Cavities for the High-luminosity LHC**", in Proc. SRF'17, Lanzhou, China, Jul. 2017, pp. 695-699., https://doi.org/10.18429/JACoW-SRF2017-THXA03

[9] T. Mastoridis et al., **Cavity voltage phase modulation to reduce the high-luminosity Large Hadron Collider rf power requirements**, PRAB Oct 2017 Phys. Rev. Accel. Beams 20, 101003 (2017) - Cavity voltage phase modulation to reduce the high-luminosity Large Hadron Collider rf power requirements (aps.org)

[10] P. Baudrenghien, T. Mastoridis, **Crab Cavity RF Noise Feedback and Transverse Damper Interaction**, CERN-ACC-NOTE-2019-0006, CERN Feb 2019, https://cds.cern.ch/record/2665950

[11] P. Baudrenghien, T. Mastoridis, **HL-LHC Crab cavity Field Regulation and Resulting RF Noise**, CERN-ACC-NOTE-2023-0006, CERN May 2023, https://cds.cern.ch/record/2859258/

[12] P. Baudrenghien, **LHC & SPS RF Controls for Crab Cavities**, LHC-CC11, 5th Crab cavity workshop, CERN, Nov 2011, https://indico.cern.ch/event/149614

[13] R. Calaga, Status of WP4 crab cavities and RF, 13th HL-LHC Collaboation Meeting, Vancouver (CA), Sept 2023, https://indico.cern.ch/event/1293138

[14] E. Metral et al., **Update Of The HL-LHC Operational Scenarios For Proton Operation** , CERN-ACC-NOTE-2018-0002, CERN January 2018, https://cds.cern.ch/record/2301292

[15] S. Fartoukh et al., **LHC Configuration and Operational Scenario for Run 3**, CERN-ACC-2021-0007, CERN November 2021, https://cds.cern.ch/record/2790409

[16] P. Baudrenghien, **Cavity Control**, LHC-CC13 6th LHC Crab Cavity Workshop, CERN Dec 2013, https://indico.cern.ch/event/269322

[17] E. Montesinons, **Efficient Conditioning Method for High Power RF couplers**, CERN

[18] W. Höfle, R. Calaga, **BPTQR Crab Cavity RF Pick-up System**, CERN 2024, V0.1, EDMS Ref LHC-BPM-ES-0015,

[19] P. Hazell, **White-Rabbit performance**, Timing Distribution over WR for experiments - 2nd workshop, June 2024, CERN, https://indico.cern.ch/event/1414714/

[20] Struck Innovative system AG, SIS8300KU & DRTM-DWC8VM1, https://www.struck.de/

LLRF architecture - White-Rabbit network

- Joint WR network for GMT and RF validated
  - Design finalized
  - Max 6 layers of White-Rabbit Switches (WRS)
- RF-train injected on level 1
  - Available everywhere around LHC
- WR2RF module for RF users
  - SPS version qualification [19]
  - LHC Prototyping (400MHz)
    → Q1 2024

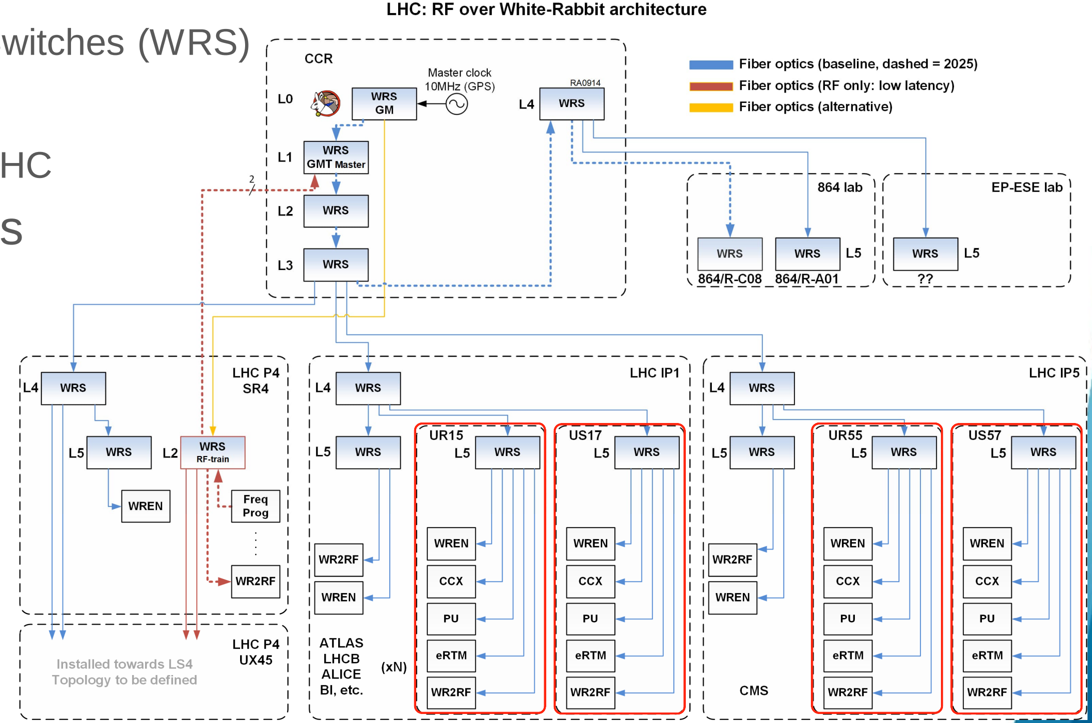
LHC: RF over White-Rabbit architecture

Fig – LHC RF-train White-Rabbit architecture

LLRF phase stability & Crabbing closure

- Coherent phase shift
  - Dominated by the full-detunning of ACS
  - ~ same transverse offset for both beams
  - **<100ps phase error** (14.4°) [1] (-2% peak luminosity)
- Incoherent phase shift (Static phase offset or drifts)
  - Different transverse offset for both beams
  - **<15ps phase error** (2° RF) [1] (-1% peak luminosity)
  - Beam phase tracking required (differential measurement)
- Precise crabbing-uncrabbing voltage ($V_{\sum}$)
  - Global control (slow MIMO fdbk) to be strickly limited crabbing around the IP
  - compensate a single-cavity failure) for at least 3 turns (~beam dump) in the other cavities
  - Design at the conceptual stage [12]

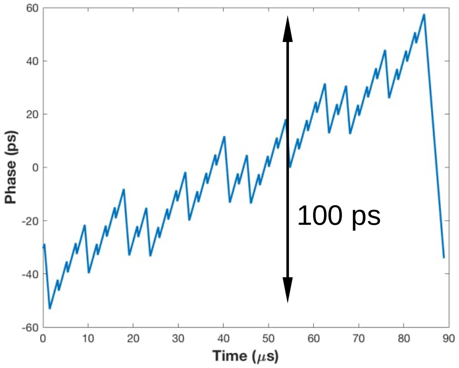

Fig – Phase modulation of LHC ACS cavities along the batch for $2.2{\cdot}10^{11}$ [9]

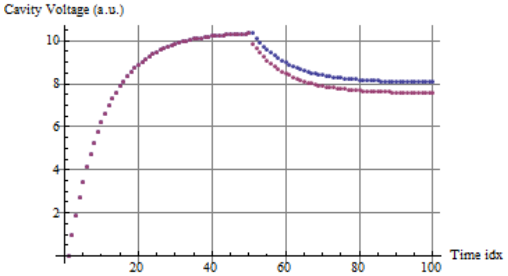

Fig – Response to a cavity 2 voltage drop, with coupling (right) [12]