# HL-LHC Crab-Cavities LLRF project

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# Overview

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# HL-LHC project - Introduction

- The High-Luminosity LHC (HL-LHC) upgrade planned operation from 2029 onwards [4]

- Upgrade goal of tenfold increase of the integrated luminosity:
  - Expected cumulative LHC integrated luminosity by end 2024: 350 fb-1
  - HL-LHC integrated luminosity: 250 fb-1 per year, 3000 fb-1 (12 years)

- Increasing the luminosity by
  - Doubling the intensity per bunch (2.2 x $10^{11}$ p+ per bunch)
  - Reducing the transverse beam size at the IP (β* reduction)

- Issue with the beam current increase
  - Long range beam-beam interaction at the collisions Intersect Points
  - Reduced by increasing the full crossing angle from 320 urad to 500 urad

- key upgrades for increasing luminosity
  - LHC triplet magnet upgrade
    - Current triplet aperture limits the potential β* Low β inner triplet quadrupoles installed
  - Super-conducting Crab-cavities for LHC Point 1 (P1 - ATLAS) and LHC Point 5 (P5 - CMS)
    - Recovers part of the luminosity lost by crossing angle, via a 380 urad full crabbing angle.

# HL-LHC luminosity

- The reduction factor **R** (number of collisions) caused by the crossing angle $\theta_c$ depends on the ratio of bunch length ($\sigma_z$=7.55 cm) to transverse bunch size ($\sigma$= 7 μm).
- The transverse bunch size will be much smaller than to-day (reduced β*)
- The reduction of beam size and increase in crossing angle (to limit beam-beam effects) results in a reduction of factor R:
  - LHC[1]: $\theta_c$ = 320 μrad, β*=0.3 → R=0.6
  - HL-LHC[2]: $\theta_c$ = ~500 μrad, β*=0.15 → R= 0.35
- → losing up to 65% in peak luminosity due to the crossing angle!

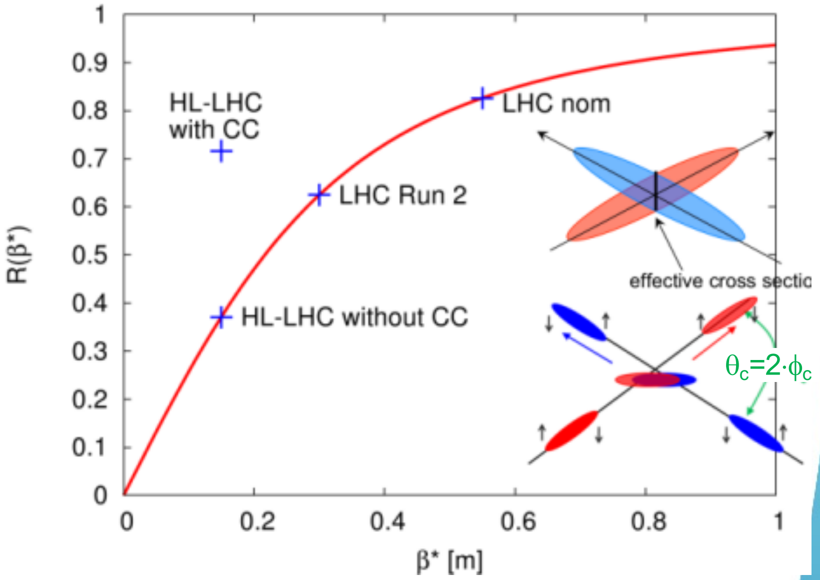



Fig – Variation of the geometrical luminosity reduction factor with β* [4]

$$L = \gamma \frac{n_b N^2 f_{rev}}{4\pi\, \beta^*\, \varepsilon_n} R \qquad R = \frac{1}{\sqrt{1+\phi^2}} \qquad \phi = \frac{\sigma_z}{\sigma_x}\phi_c$$

1. End of β* levelling Run 3 [Ref 18, Table 5]
2. End of β* levelling [Ref 5, Table 2-1]

# HL-LHC Crab-Cavities

- To recover head-on collision we want to apply a rotation to the bunch
  → crab-cavities in LHC point 1 and point 5
  - head and tail receive transverse kicks in opposite directions
  - nominal bunch centroid receives no kick (zero voltage)
- We use 380 urad crabbing angle, only partly compensating for the 500 urad crossing angle.

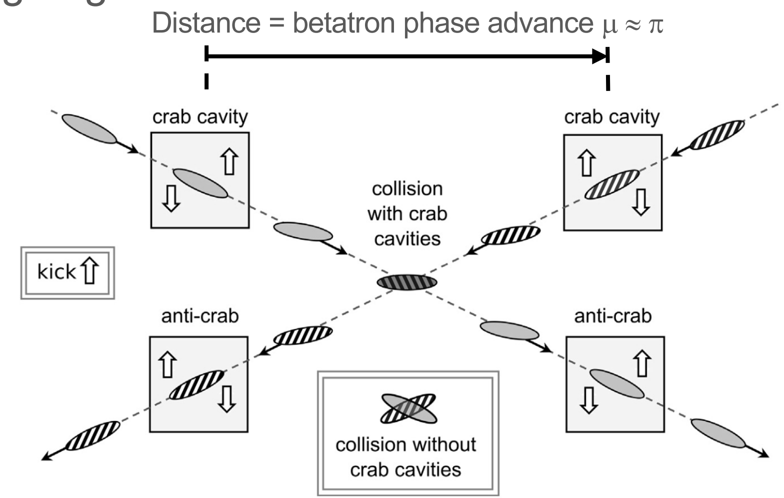



Fig – Simplified diagram of the collisions at the IP with and without crab cavities [1]

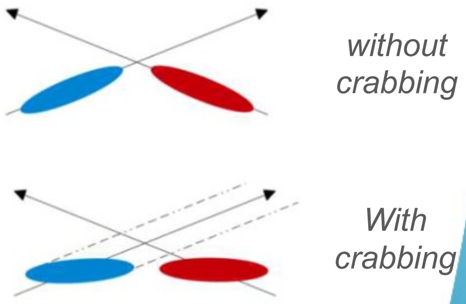
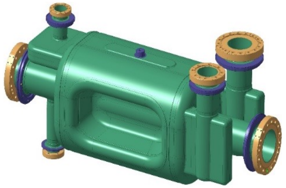



Fig – Schematic of the bunch crossings at the IP with (bottom) and without (top) crab cavities [8]

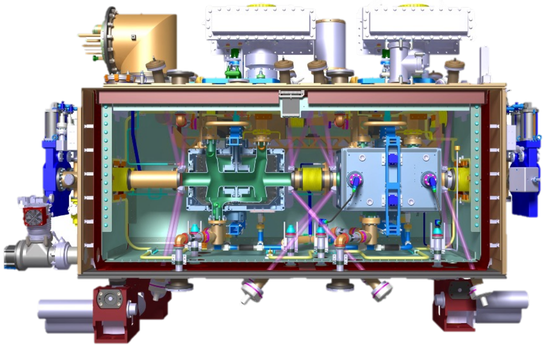
# HL-LHC Crab-Cavities

- Two types of Crab-Cavities

**D**ouble **Q**uarter **W**ave (DQW) resonator,
Crabbing in vertical plane
(IP5, CMS)



**RF D**ipole (RFD),
crabbing in horizontal plane
(IP1, ATLAS)



$$f_0 = 400 \text{ MHz}$$
$$\mathrm{V_T} = 3.4 \text{ MV/cavity*}$$
$$(\mathrm{E_p}, \mathrm{B_p} < 40 \text{ MV/m}, 70 \text{ mT})$$
$$\text{Beam aperture} = 84 \text{ mm}$$
$$\text{RF power} = 50 \text{ kW-CW**}$$
$$\text{Operating Temp} = 2 \text{ K}$$

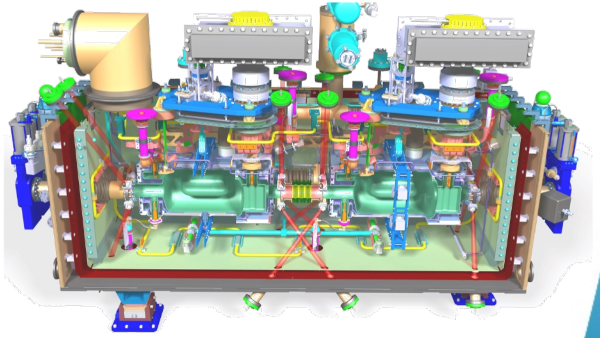


Fig – DQW Cavity and cryomodule (vertical crabbing)

Fig – RFD Cavity and crymodule (horizontal crabbing)

*Engineering spec: 4.1 MV dressed for 20% margin
** Required for for beam off-centred by 1 mm

# HL-LHC RF overview

- Point 4 Surface (SR4)
  - Beam-Control
    (WR frame master)
- Point 4 underground (UX45)
  - Accelerating cavities (ACS)
- Point 1 underground (ATLAS)
  - RFD Crab-cavities
- Point 5 underground (CMS)
  - DQW Crab-cavities

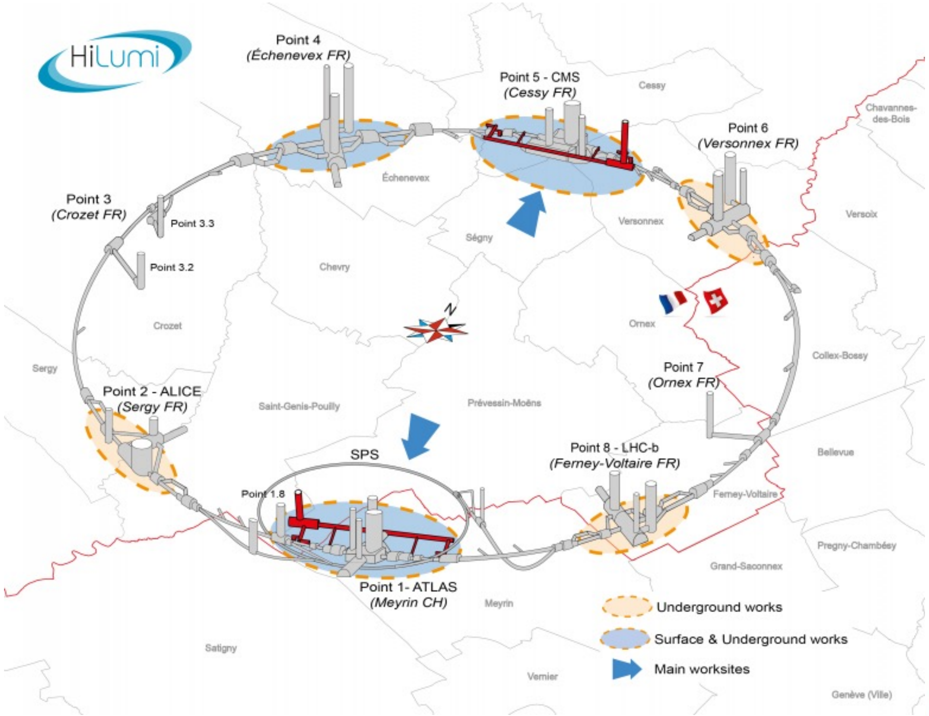
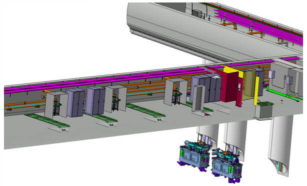
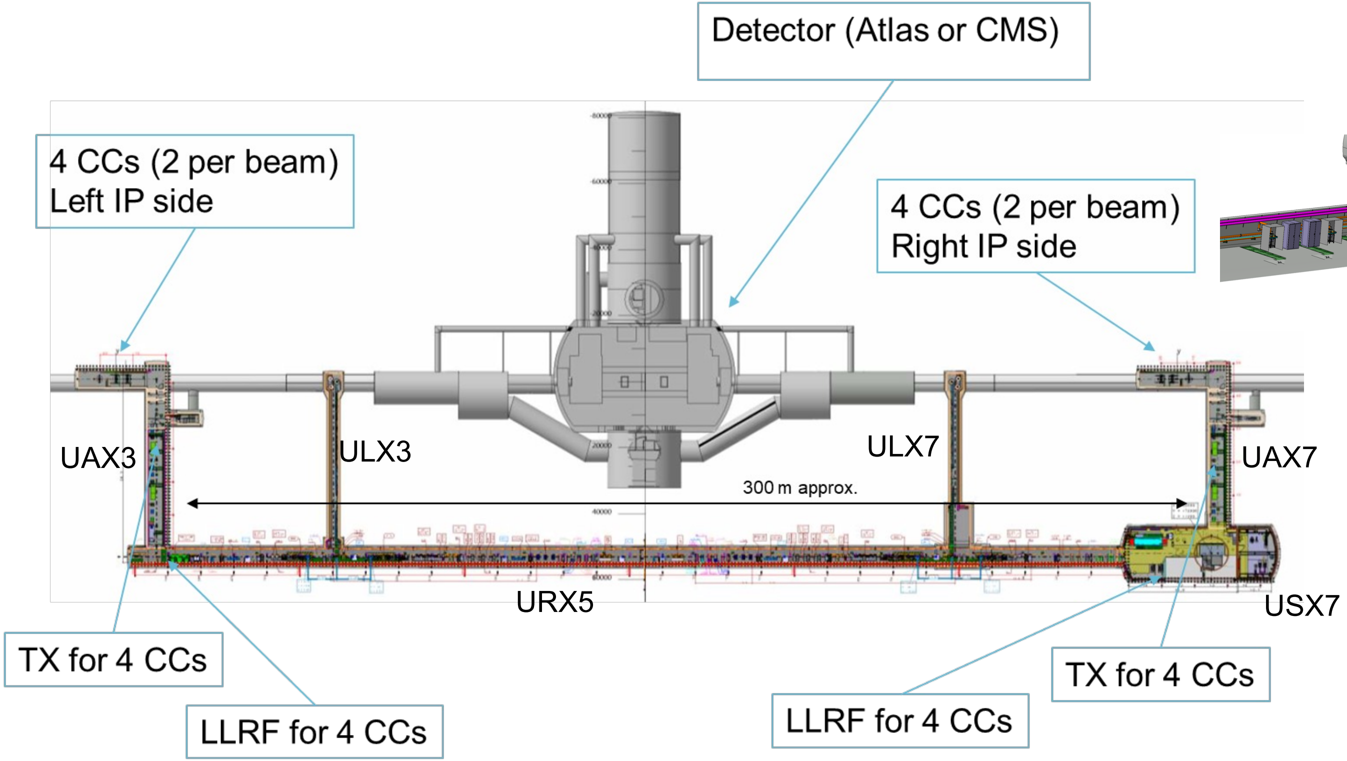



Fig – HL-LHC layout [2]

# HL-LHC Crab-Cavities underground layout [1]





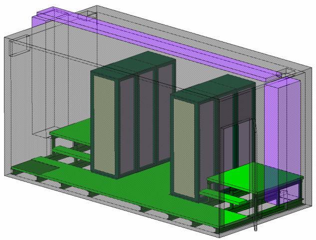



Fig – HL-LHC point 1 or 5 underground layout [1] . Top view

# Specifications for LLRF: Cavity Impedance [5]

- Crab-Cavities add a strong transverse impedance at the fundamental:

| | |
|---|---|
| Shunt impedance | $R_\perp$ = 0.9024 G$\Omega$m$^{-1}$ |
| Loaded Quality factor | $Q_L = 5{\cdot}10^5$ |
| Fundamental frequency | $f_r$ = 400.789 MHz |

  - Four cavities per plane, per beam → $4{\cdot}10^9$ $\Omega$/m
  - With a correction factor of $\beta_{CC}/\beta_{avg} \approx 9 \rightarrow 3.6{\cdot}10^{10}$ $\Omega$/m
- That can lead to transverse Coupled-Bunch instabilities [5].
- Closest betatron side-band at 3kHz offset from revolution lines.
- The transverse damper has no effect on head-tail oscillations.
- Landau damping available from octupoles but limited.
- Requirement: **Crab-cavities Impedance reduction at fundamental by 1000 [5].**

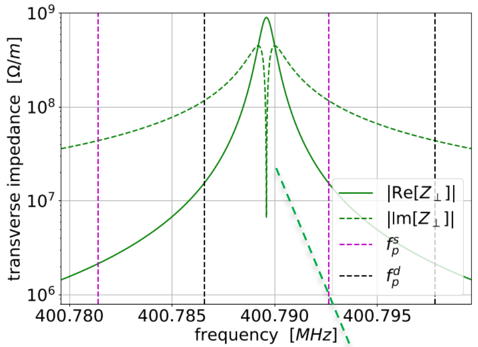



Fig – Beam coupling impedance of the a crab-cavity fundamental mode [5].

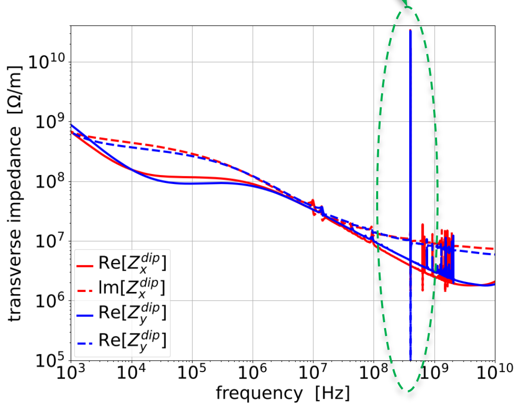



Fig – HL-LHC transverse impedance including crab-cavities fundamental mode [5] .

# Specifications for LLRF: RF noise

- Crab-cavities acts as transverse deflector.
- RF noise will increase the transverse emittance, thus reducing the luminosity.
- **RF noise budget:** 2%/hour emittance growth rate with $\beta^*$=15 cm, (0.05 $\mu$m/h for $\varepsilon_n$=2.5 $\mu$m) [14]
- **Requiremements**: phase/amplitude noise reduced to **-151 dBc/Hz** at 3 kHz offset from carrier (400 MHz) [11].
- Too challenging?
  - **Requirements:** :**-143 dBc/Hz** @ 3 kHz offset [11]
    → 7.6 %/hour emittance growth rate > 2% target
  - **Requirements:** Mitigation via CC phase/amplitude feedback for the extra factor 10 [7]

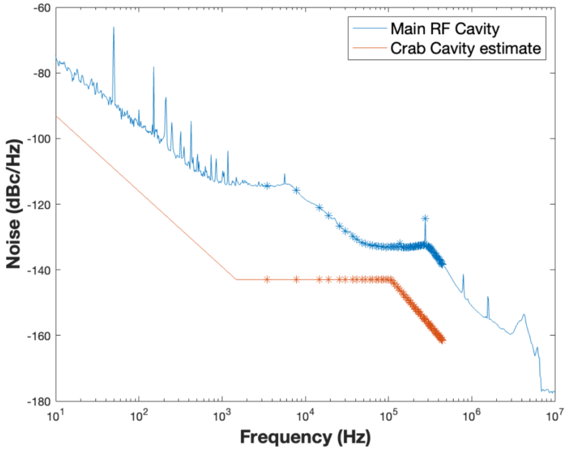



Fig – LHC ACS cavities and Crab-cavities SSB phase noise [11]

# Specifications for LLRF: Crabbing closure

- Cavity phase locked on the bunch core
  - CC phase offset → transverse displacement (Δx or Δy) of bunch core
  - 1 deg RF phase (7 ps) leads to $\Delta x$ =0.4 μm (6% transverse $\sigma_t$ rms beam size)
  - Two situations:
    - Same phase shift on both beams (**coherent**) This is the case if the phase offset is caused by transient beam loading.
      - The transverse displacement is identical for both beams → **Small impact on luminosity** caused by RF curvature: -1.9 %/100 ps offset [1]
    - Different phase shift on both beams (**incoherent**). This is the case if the phase offset is caused by Low and High Level RF.
      - Transverse misalignment of the colliding beams → **Significant impact on luminosity:** -5.7 %/100 ps offset [1]

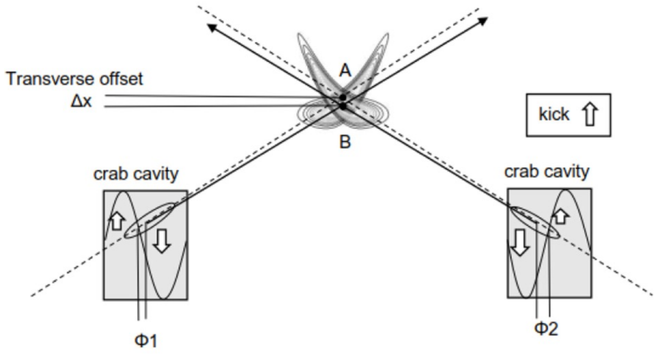
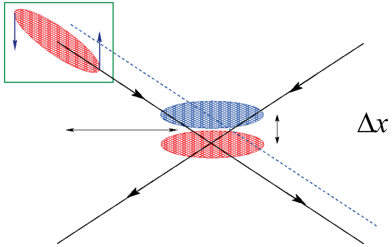



Fig – Identical phase shift for colliding bunches $\phi_1$=$\phi_2$ Partial crabbing [1]



$$\Delta x = \frac{c\phi}{\omega_{RF}} \delta\varphi_{RF}$$

Fig – Phase offset leading to transverse displacement on one beam only [16]

# Specifications for LLRF: Crabbing closure

- Coherent phase shift:
  - Same transverse offset for both beams
  - Full-detunning of the main accelerating cavities
    - ~Same filling pattern for both beams
  - **Requirement: <100ps phase error** (14.4°) [1] (2% peak luminosity reduction)
- Incoherent phase shift:
  - Different transverse offset for both beams
  - Static phase offset or drifts (calibration, clock distribution,..)
  - **Requirements: <15ps phase error** (2°) [1] (1% peak luminosity reduction)

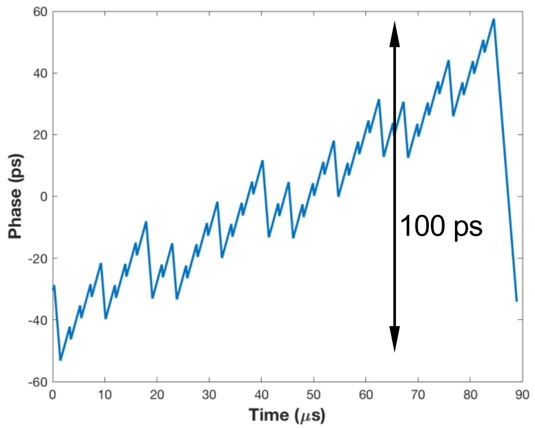



Fig – Phase modulation of LHC ACS cavities along the batch for $2.2{\cdot}10^{11}$ [9]

# Specifications for LLRF: Crabbing closure

- Precise crabbing-uncrabbing voltage ($V_{\Sigma}$)
  - Crabbing must be strickly limited in the ± 150 m on each side of IP1 and IP5.
  - Counter-phasing on both side of the IP during filling/ramping ($V_{\Sigma}$=0)
  - **Requirements:**
    - Voltage amplitude error = t.b.d
    - Global quality control
- Single-cavity failure
  - Amplifier trip, quench/breakdown, multi-packting.
  - Large and global head-tail oscillation along the ring
  - Stored energy decay time $\tau \approx 400$ $\mu$s
    (can be dominated by quench dynamics)
  - **Requirements**:
    - Beam dump within 3 turns (~270$\mu$s)
    - Compensation in the other cavities to track the uncontrolled voltage and limit the damage during the 3 turns till dump.

# LLRF Solutions: Cavity-Controller

- Power amplifier: IOT
- Self-Excitation Loop
- Tuning loop
  - We must 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

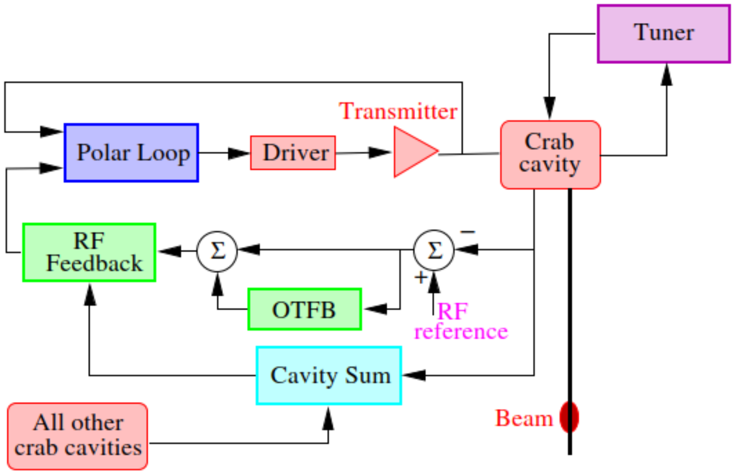



Fig – Crab Cavity Low-Level RF block diagram [11]

# LLRF Solutions: Cavity Impedance [11]

- Direct feedback (proportional)
  - Expected open-loop latency <1.3μs.
  - Gain of 150 (43dB).
- Betatron comb filter (OTFB)
  - The cavity impedance requires evaluating it only a discrete set of frequencies (Vlasow equation [5]) → betatron frequencies.
  - Mitigation: Reduce the impedance at these frequencies by a factor 10 linear (Gain of 20dB) [11]

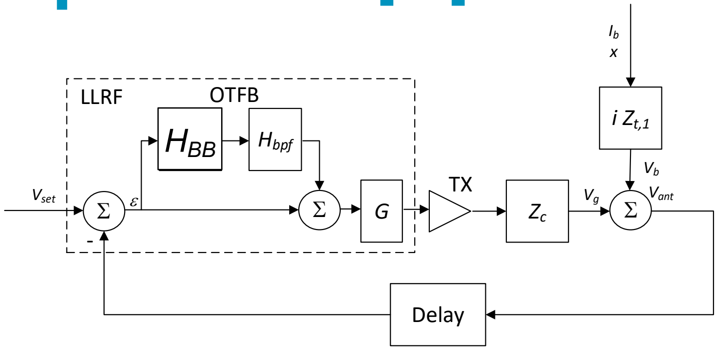
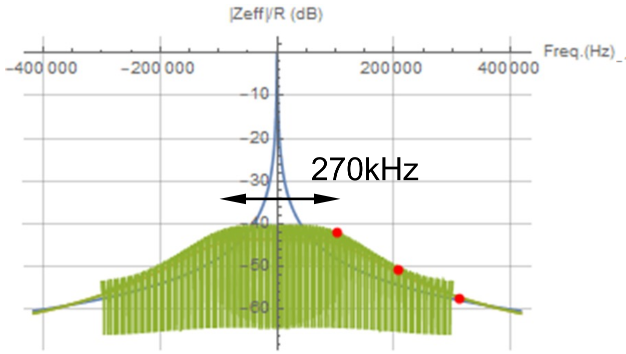



Fig – RF feedback and OTFB block diagram [11]

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

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



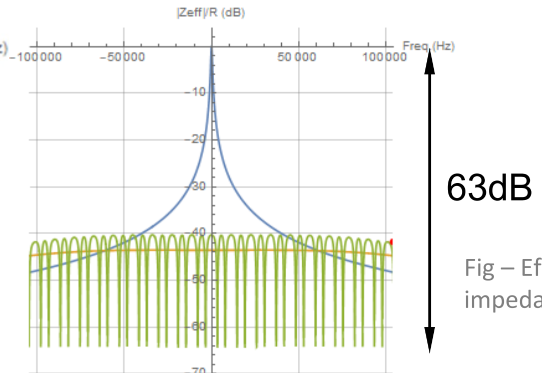




Fig – Effective transverse cavity impedance with w/o feedback [11]

# LLRF Solutions: RF noise

- Low noise Master Reference
  - Based on 100MHz OCXO, locked on WR
  - Frequency multiplier + DDS
  - → Preliminary study looks feasible
- Same LO for down & up conversion
  - RF frequency sweeping
  - IQ demod, SSB Transmitter
- ADC 16bits
  - Expected: ~77dB SNR @125MSPS
    → ENOB ≈ 12.5bits
  - Considering white-noise PSD:
    → $L_N(f)$≈-152 [dBc/Hz]
  - 1/f noise? Hardware to be evaluated…

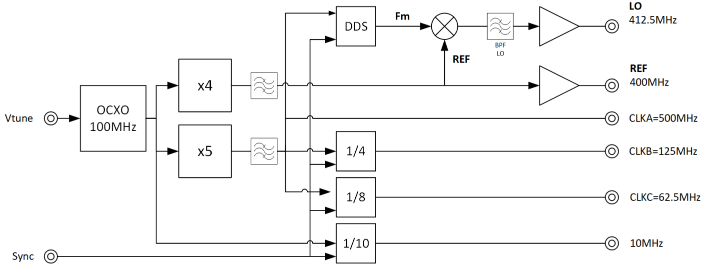



Fig – Master Reference block diagram

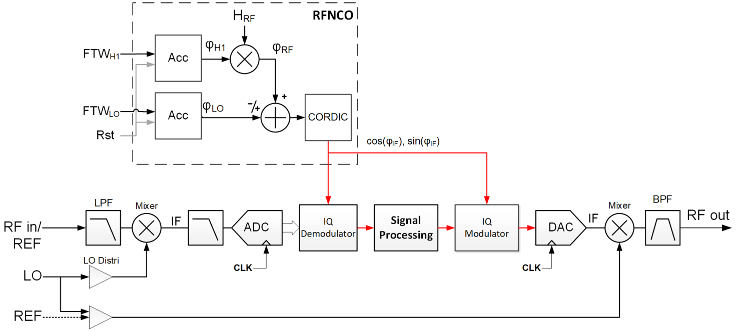



Fig – RF demodulation/modulation block diagram

# LLRF Solutions: RF noise

- RF feedbacks only:
  - $S_{\Delta\phi,eff}(f)$ = 0.141 µrad²/Hz , $L_N(f)\approx$-143 [dBc/Hz]
  - → 16.6%/h total emittance growth rate (EGR) [7]
- Dedicated feedback system to counteract crab cavity noise:
  - Provide additional factor 10 reduction
  - Measure bunch displacement (mode 0) and tilt (mode 1)
  - Process to achieve 90 degrees phase shift in betatron oscillation.
  - Use CC as kicker: Apply correction to CC set point amplitude/phase.
  - **Promising simulations: <2%/h EGR [10].**
  - Efficiency limited by the pickup measurement noise. Under study.
  - Will operate in conjunction with the transverse damper (ADT), Gain=50 turns.

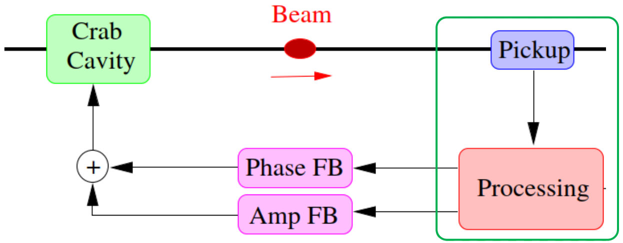



Fig – Crab-cavity noise feedback [10]

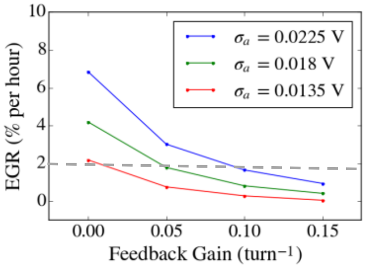



Fig – EGR for different amplitude noise vs fdbk gain [10]

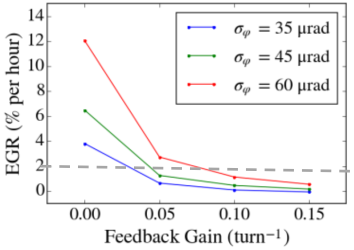



Fig – EGR for different phase noise vs fdbk gain [10]

# LLRF Solutions: crabbing closure

- Bunch phase/noise feedback will also keep the crab-cavity phase locked on the bunch core.
  - One PU per beam and IP side
  - “Differential measurement” (Same Pickup & ANT cables) will compensate for:
    - Cables length variation with temperature (same cable type, length, routing)
    - Clock phase shift (White-Rabbit, distribution)
    - Drifts between main accelerating cavities (ACS) and Beam-Control (WR master)
- MIMO feedback (combining the 4 CCS per IP per beam) for global control
  - GB link to distribute the voltage measurement (latency $\approx 2\mu s$)
  - LQR

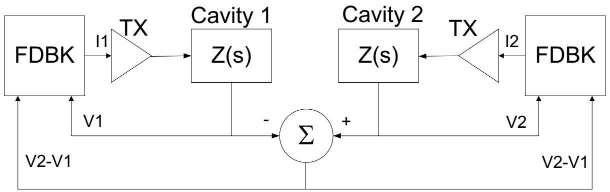



Fig – Crab-cavity noise feedback [12]

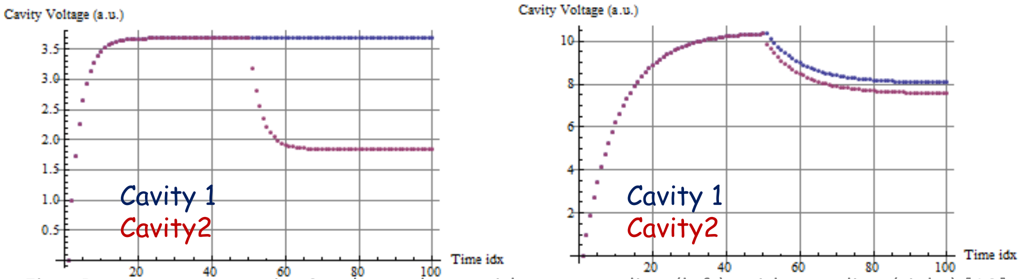



Fig – Response to a cavity 2 voltage drop, withtout coupling (left), with coupling (right) [12]

# HL-LHC LLRF architecture

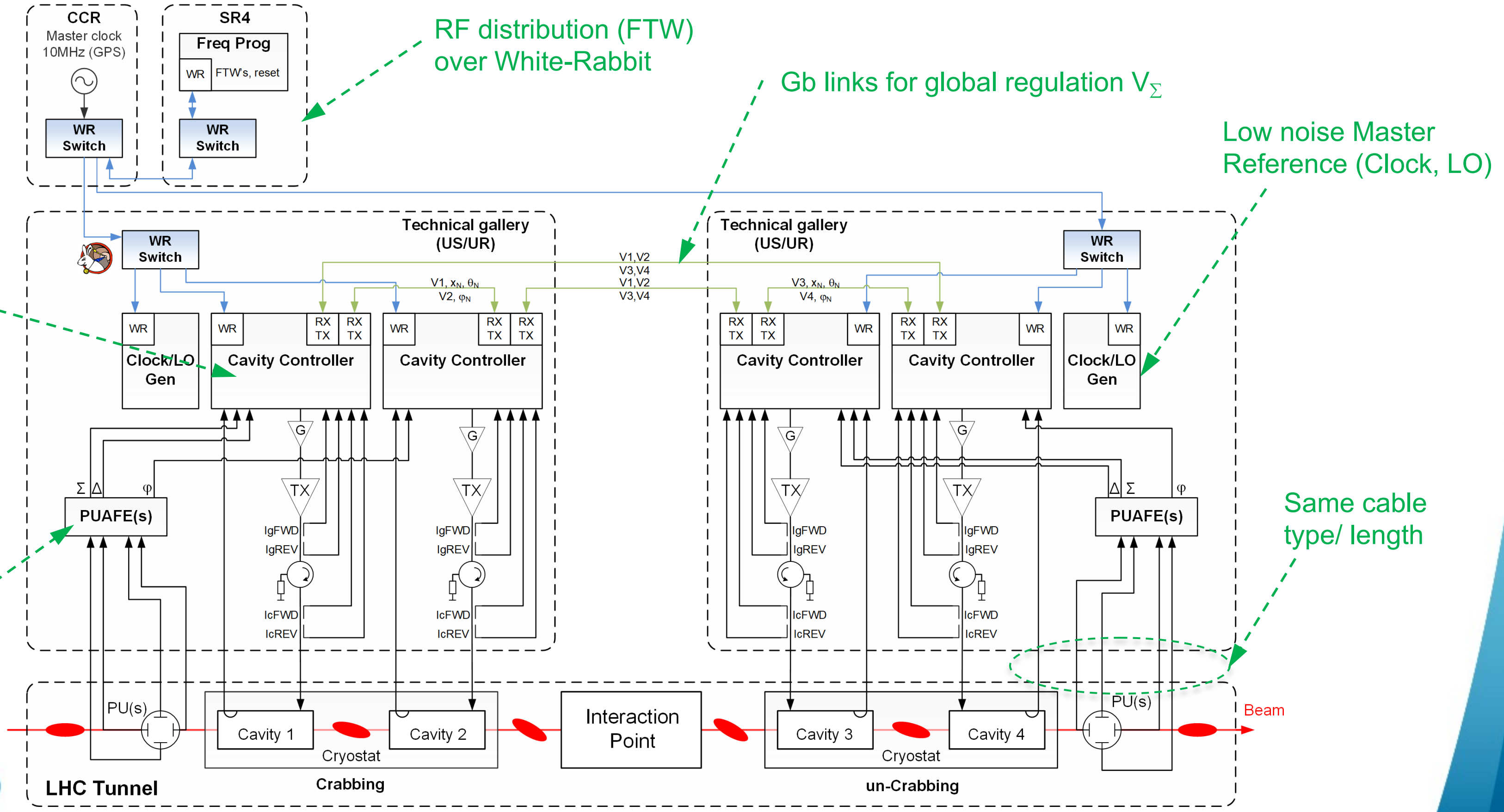



Fig – HL-LHC Crab cavities LLRF architecture, per IP, per beam

# HL-LHC LLRF Cavity-Controller HW

- Inspired by SPS LLRF upgrade
- Based on White-Rabbit network
  - RF over WR
  - Master REF locked on WR
- MTCA platform
- Analog RF front-end
  - Calibration, Remote diag
  - RF distri to interlock system
- Pickup front-end
  - Analog pre-processing for Bunch phase/tilt
- Dedicated AMC possible for CC noise feedback

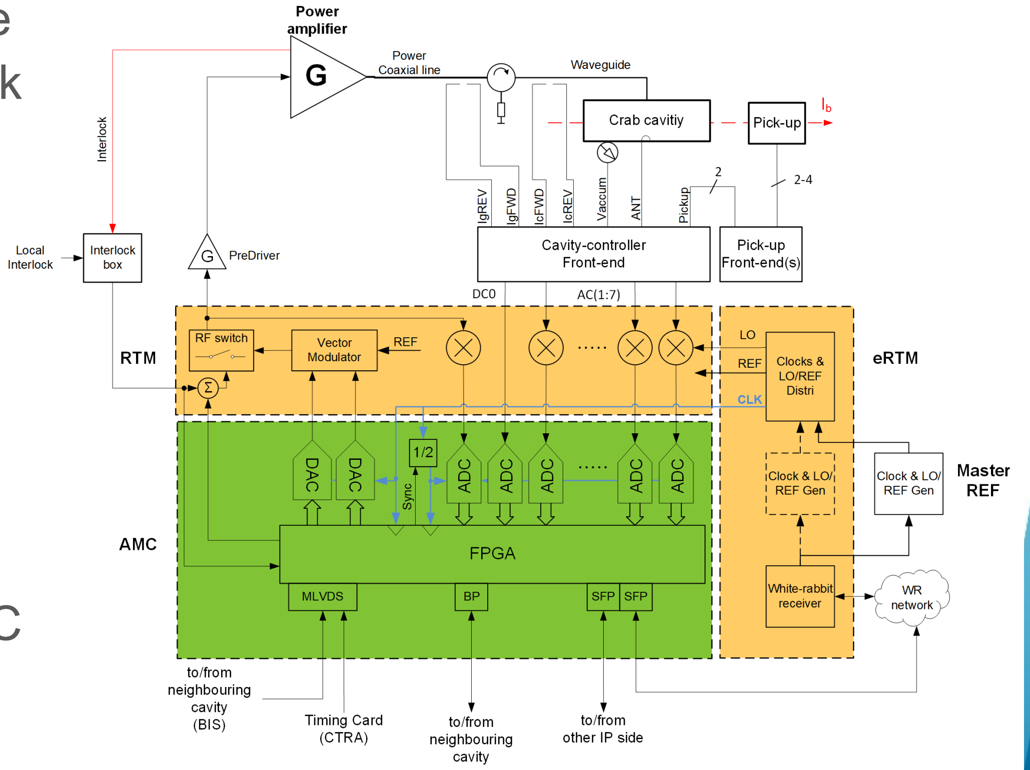



Fig – HL-LHC Crab cavities controller HW diagram

# Master plan

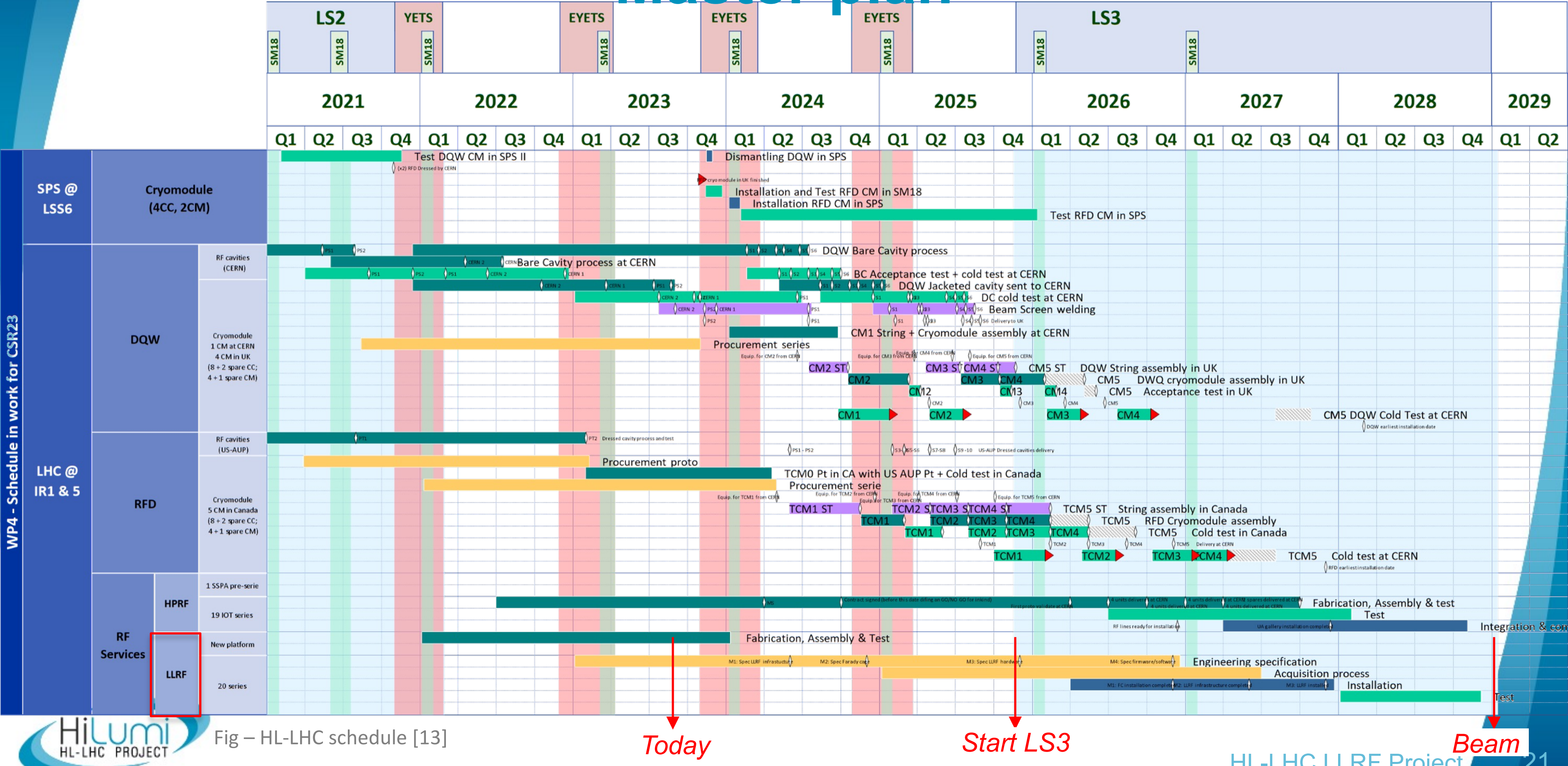



Fig – HL-LHC schedule [13]

# Conclusion

- HL-LHC targets a tenfold luminosity increase
- Crab-Cavities will recover the head-on collision from the large crossing angle (380 μrad vs. 500 μrad)
- Challenging LLRF specification
  - Transverse Impedance reduction: Direct feedback + Comb filter
  - RF noise: max 2 %/h transverse emittance growth,
    HW to be designed: low noise receiver + CC fdbk
  - Crabbing closure: Beam phase tracking, global regulation (crabbing-uncrabbing)
- Architecture
  - White-Rabbit based
  - MTCA platform

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# SPARE SLIDES

# HL-LHC low level RF architecture (SR4)

*Dual DDS* replaced by *WR2RF*

Phase 0

New *Freq Program* (RF train master)

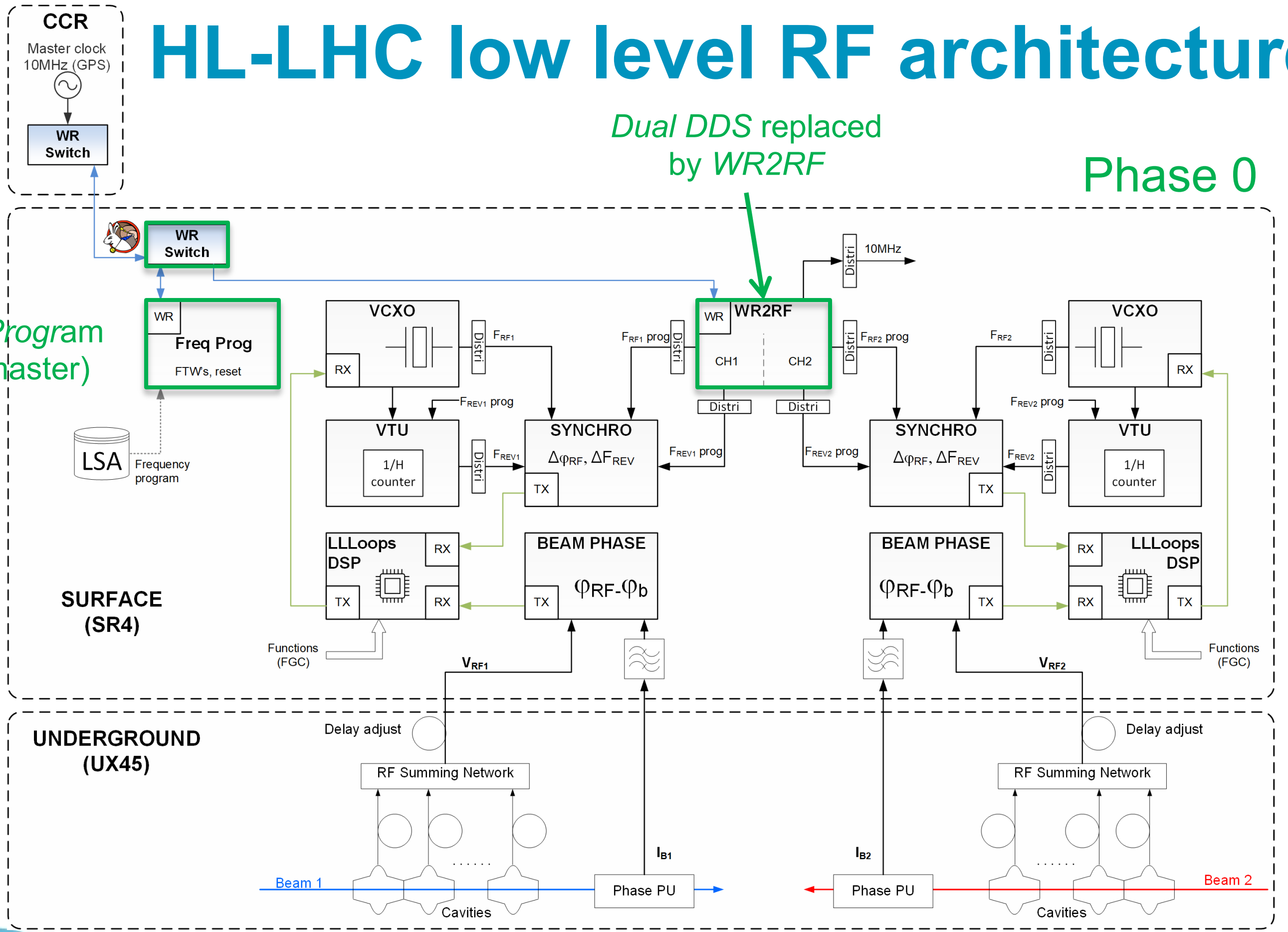


Fig – HL-LHC SR4 upgrade, phase 0

# RF over White-Rabbit

- Ethernet network with precision timing protocol
- Distributed Numerically Controlled Oscillators (NCO)
  - Accumulator adds Frequency Tuning Word (FTW)
  - Accumulator output = RF phase
  - LUT (or Cordic) computes sin/cos
- Fixed latency Ethernet links
  - Deterministic reset for NCO (absolute phase reference)
  - Deterministic FTW update
- Link stabilisation from WR
  - Reduces phase drifts (fiber)
- Scalable
  - Ethernet network

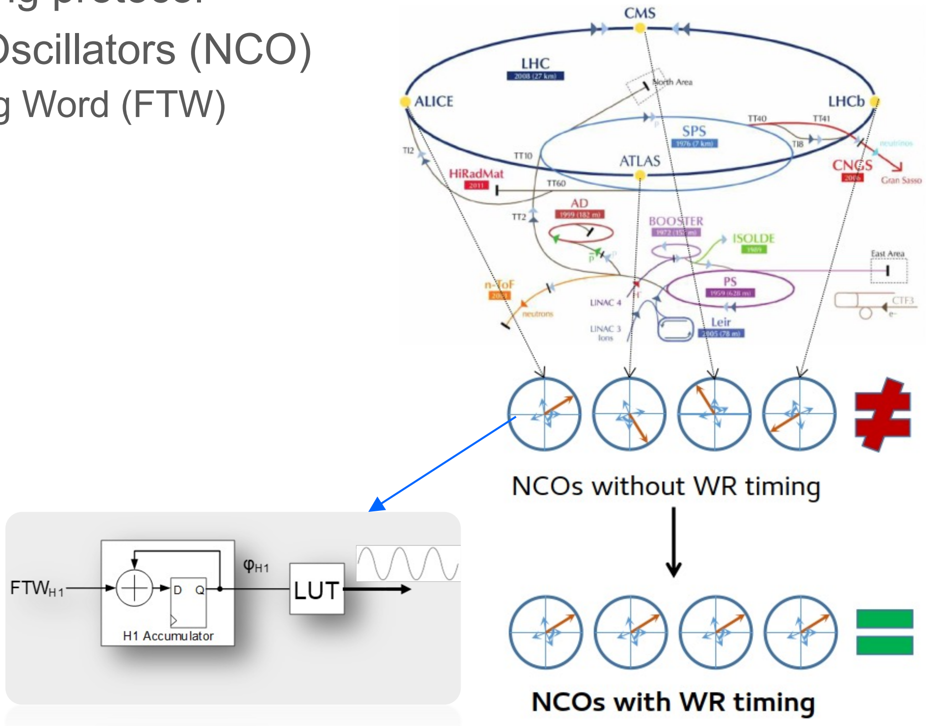


Fig John R. Gill, RF Signal Distribution over WR, J. Gill, Nov. 2019, BE [3]

# RF over White-Rabbit

- Digital RF frequency distribution
  - FTW's
    (frequency program, Master RF)
- NCO reset distribution
- Absolute time
  - Timestamps
- Beam-Control (SR4) is the Master
- Reconstruction of the RF anywhere in the accelerator