CERN High luminosity LLRF project Crab-Cavities

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Overview

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   RF Modulation
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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**

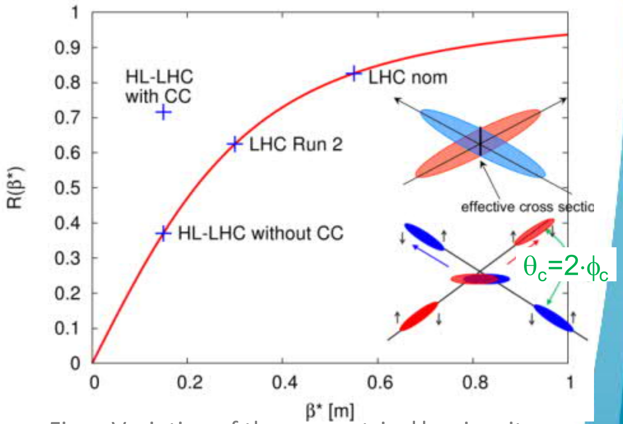


Fig – Variation of the geometrical luminosity reduction factor with β* [4]

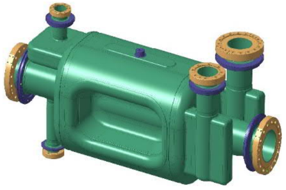
- key upgrades for increasing luminosity
  - LHC triplet magnet upgrade
    - Current triplet aperture limits the potential β* Low β inner triplet quadrupoles installed
  - Super-conducting Crab-cavities for LHC Point 1 (P1 - ATLAS) and LHC Point 5 (P5 - CMS)
    - Recovers part of the luminosity lost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

See LLRF23 talk for more introduction on the HL-LHC project. [18]

HL-LHC project - Crab-Cavities

- Two types of Crab-Cavities

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



RF Dipole (RFD),
crabbing in horizontal plane
(IP1, ATLAS)

$f_0 = 400$ MHz

$V_T = 3.4$ MV/cavity*

$(E_p, B_p < 40$ MV/m, 70 mT$)$

Beam aperture = 84 mm

RF power = 50 kW-CW**

Operating Temp = 2 K

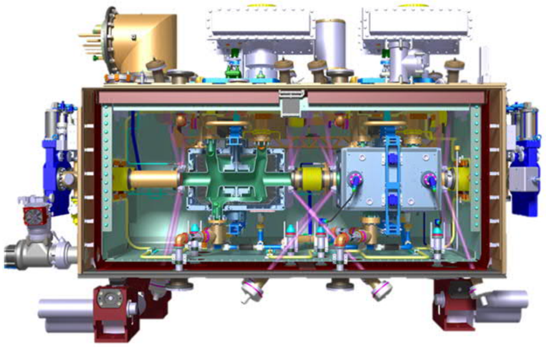


Fig – DQW Cavity and cryomodule (vertical crabbing)

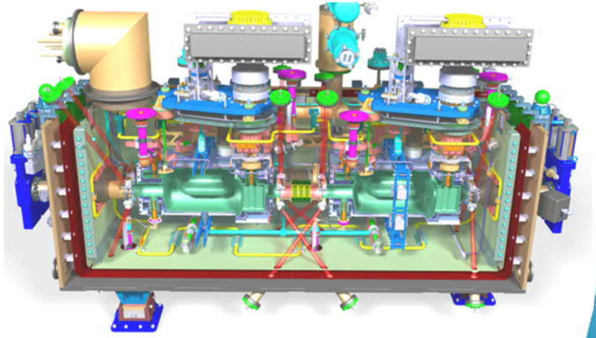


Fig – RFD Cavity and crymodule (horizontal crabbing)

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

HL-LHC project - layout

- 16 Crab-Cavities (SR4)
  - 4 cavities on each IP side (2 per beam)
- RF frequency sweeping
  - Acceleration ramp
  - RF distribution from point 4
- Based on White-Rabbit network
  - RF over White-Rabbit (fiber optics)
  - Master REF locked on WR

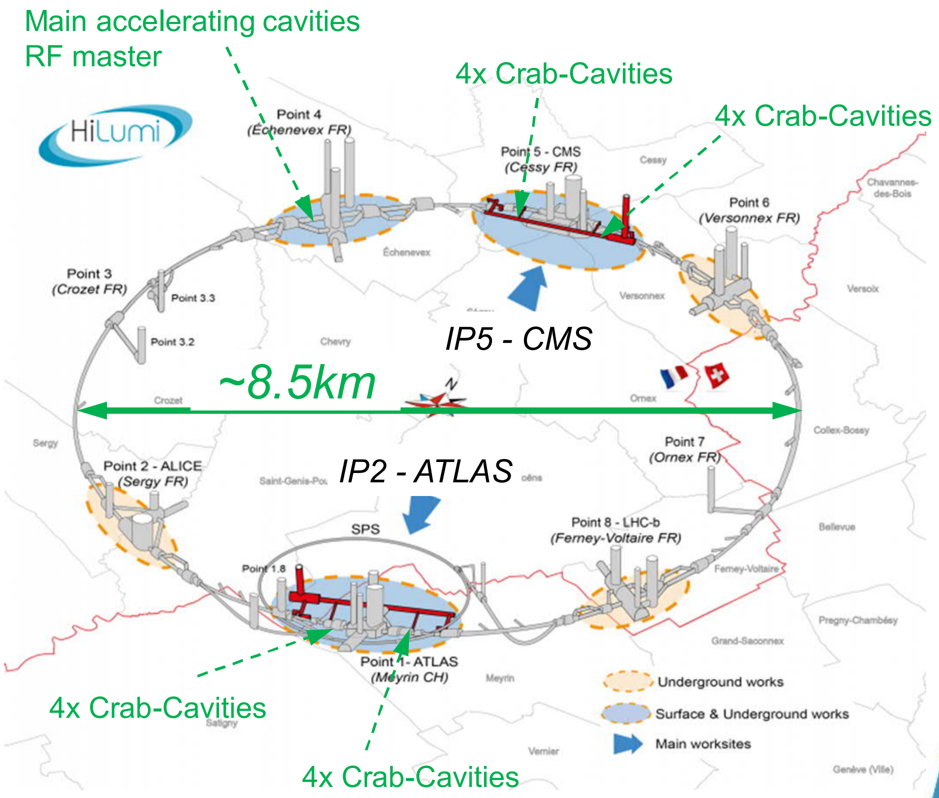
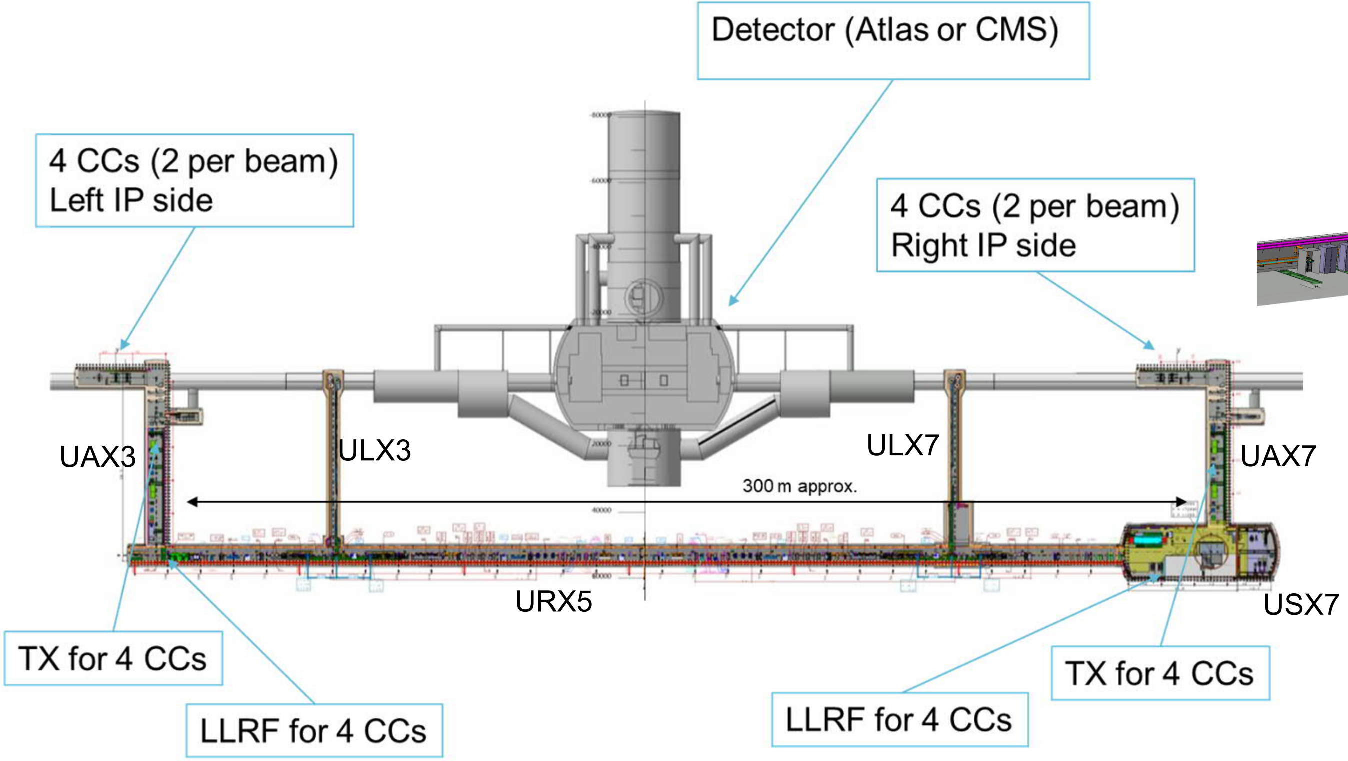
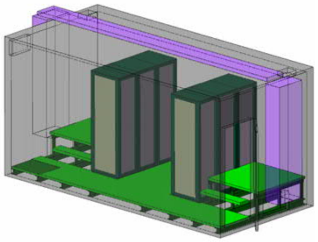


Fig – HL-LHC layout [2]

HL-LHC project - layout





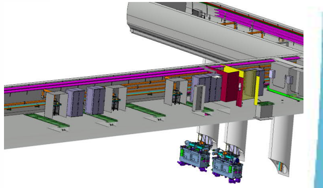


Fig – HL-LHC point 1 or 5 underground layout [1] . Top view

Specifications for LLRF

- Cavity Impedance [5]:
  - Strong transverse impedance at the fundamental:
  - Four cavities per plane, per beam → $4{\cdot}10^9\ \Omega/m$
  - **Impedance reduction at fundamental by 1000 [5]**

- RF noise
  - Increases the transverse emittance (luminosity reduction). **Budget:** 2%/hour EMG[1] [14]
  - **Requirements**: phase/amplitude noise reduced to **-151 dBc/Hz** at 3 kHz offset from carrier (400 MHz) [11].
  - **Target:**
    - **-143 dBc/Hz** @ 3 kHz offset [11] → 7.6 %/hour EGR[1]
    - Mitigation via CC phase/amplitude fdbk for the extra factor 10 [7]

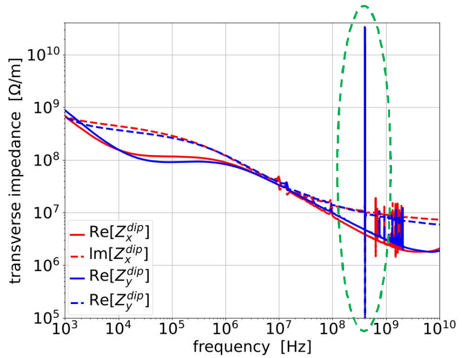


Fig – HL-LHC transverse impedance including crab-cavities fundamental mode [5] .

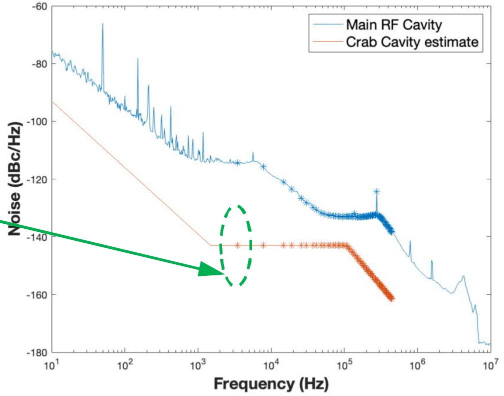


Fig – LHC ACS cavities and Crab-cavities SSB phase noise [11]

[1] Emittance Growth Rate

Specifications for LLRF

- Crabbing closure
  - Cavity phase on bunch core. Phase offset → transverse displacement (Δx or Δy) of bunch core
  - **Coherent phase shift Requirement: <100ps phase error** (14.4°) [1] (2% peak luminosity reduction)
  - **In Coherent phase shift Requirement : <15ps phase error** (2°) [1] (1% peak luminosity reduction)
  - Precise crabbing-uncrabbing voltage (V_Σ)
  - Counter-phasing on both side of the IP during filling/ramping (V_Σ=0)
  - **Requirements:**
    - Voltage amplitude error = t.b.d

- Single-cavity failure
  - Amplifier trip, quench/breakdown, multi-packting → uncontrolled voltage
  - **Requirements**:
    - Beam dump within 3 turns (~270μs)
    - Compensation in the other cavities to track the uncontrolled voltage and limit the damage during the 3 turns till dump.
    - Global quality control (MIMO)

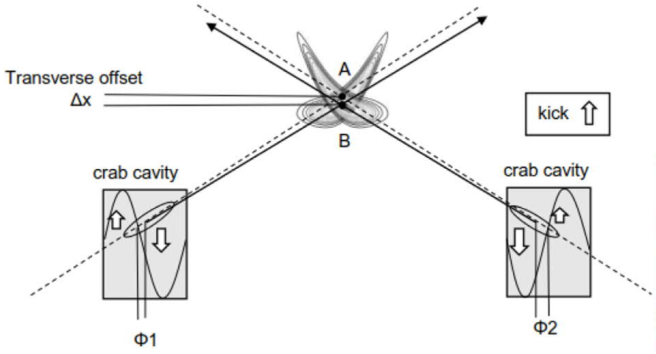
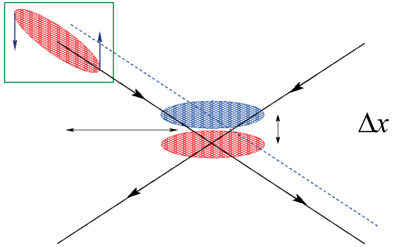


Fig – Identical phase shift for colliding bunches $\phi_1=\phi_2$
Partial crabbing [1]



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

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

LLRF Architecture

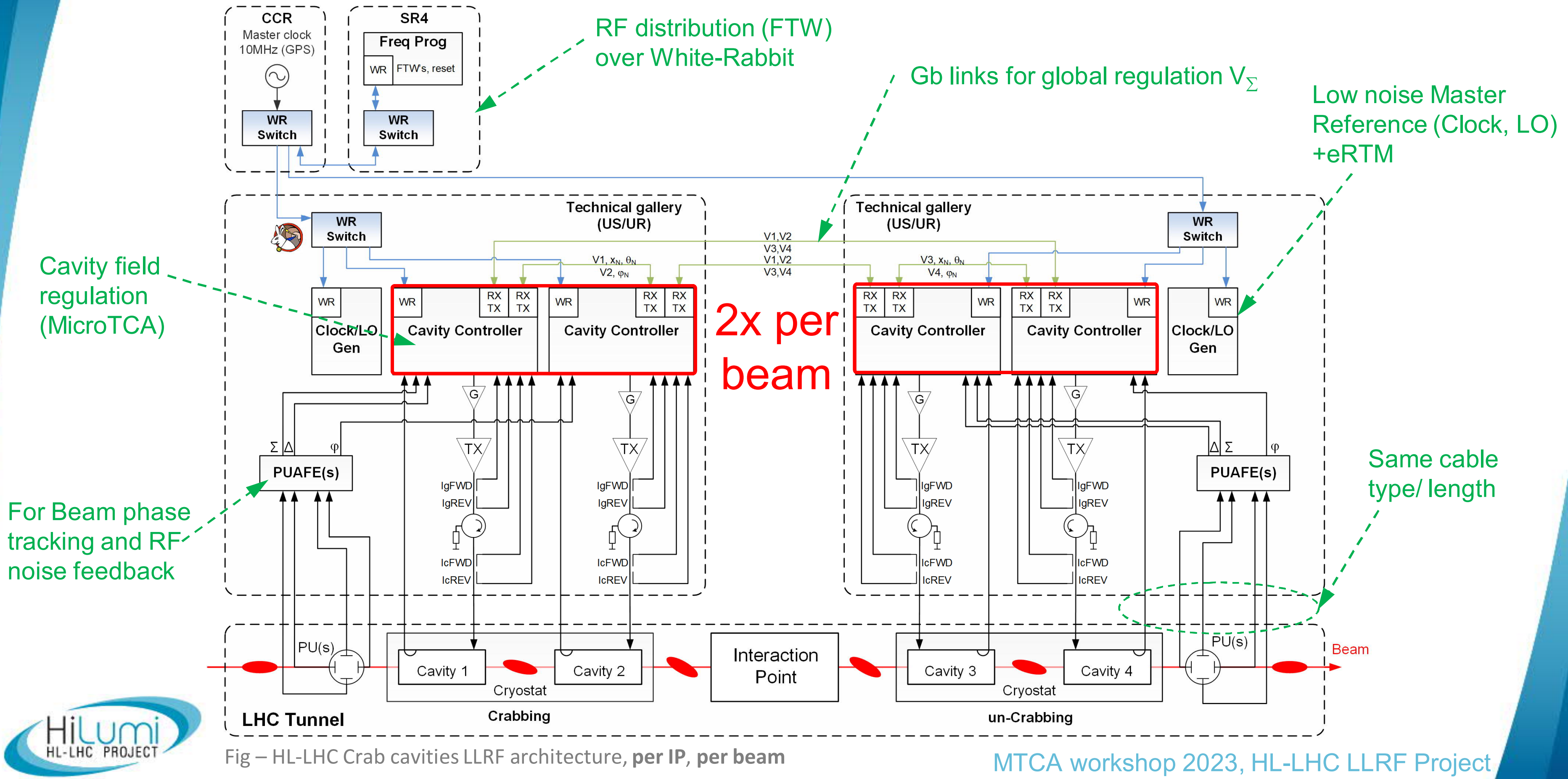


Fig – HL-LHC Crab cavities LLRF architecture, **per IP**, **per beam**

LLRF Architecture - Feedback loops

- 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, BW≈260kHz**
    - **Slow global loop regulating the vector sum: crabbing-uncrabbing voltages**
- Crab-cavity amplitude & phase noise feedback
  - Beam phase & tilt measurement
  - Cavity phase tracking bunch core

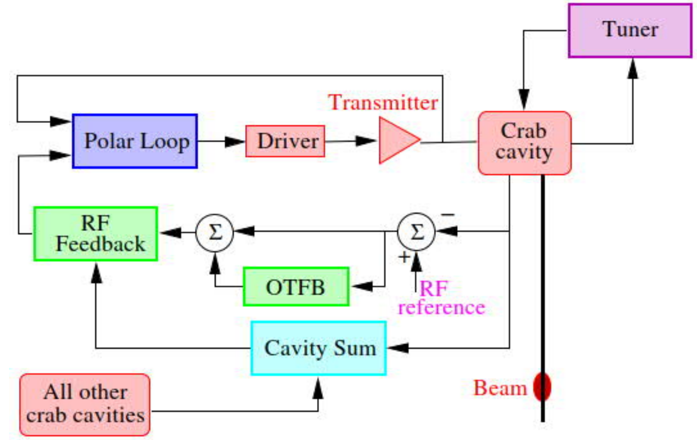


Fig – Crab Cavity Low-Level RF block diagram [11]

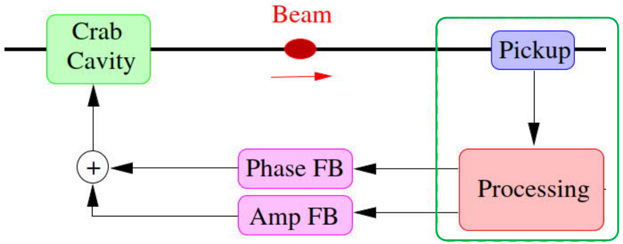


Fig – Crab-cavity noise feedback [10]

LLRF Architecture - Master Reference

- Low noise Master Reference
  - LO, REF, Clocks generation
  - Based on 100MHz OCXO, locked on WR
  - Frequency multiplier + DDS
  - → Preliminary study looks technically feasible

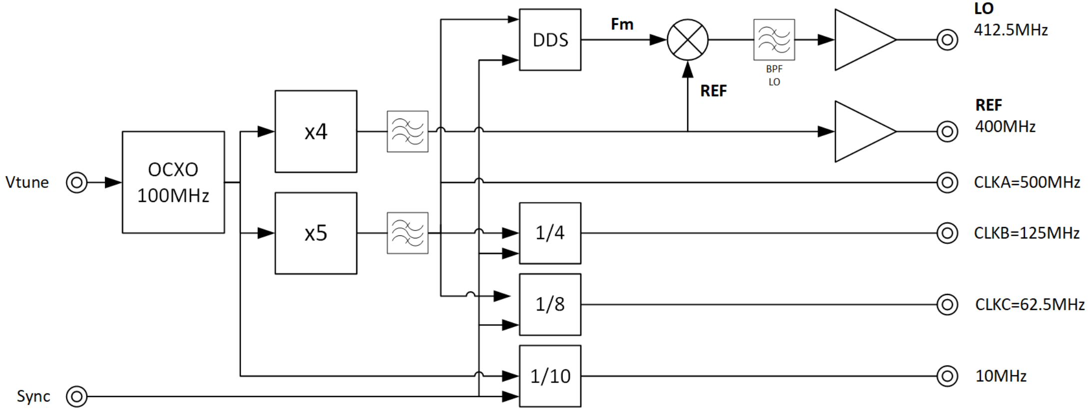


Fig – Master Reference block diagram

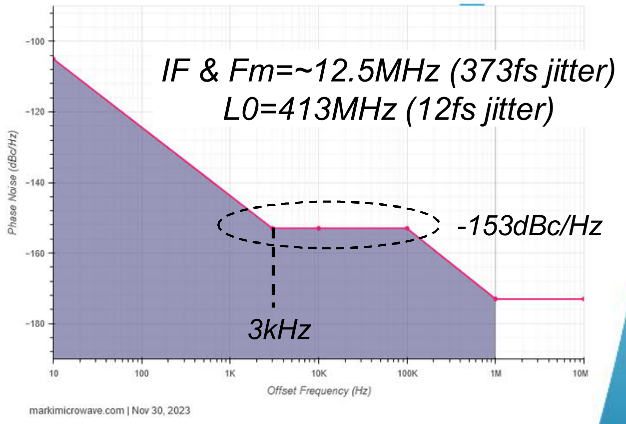


Fig – LO & IF Phase noise requirement

LLRF Architecture - RF Modulation

- Synchrotron → RF ramp
  - RF = 400.7842 to 400.7896MHz (+5.4kHz)
  - Feedback BW ≈ 260kHz
- Up/Down-mixing for RF input
  - Single-side band transmitter scheme
  - LO at fixed frequency, IF freq sweeping
  - LO=REF=RF-IF, **IF≈13MHz**
    - Optimized for IF aliasing, RF noise
  - **Clock=125MHz**
    - Optimized for latency
- LO leakage & images rejection
  - DAC’s (I&Q) calibration
  - External BPF (add latency)

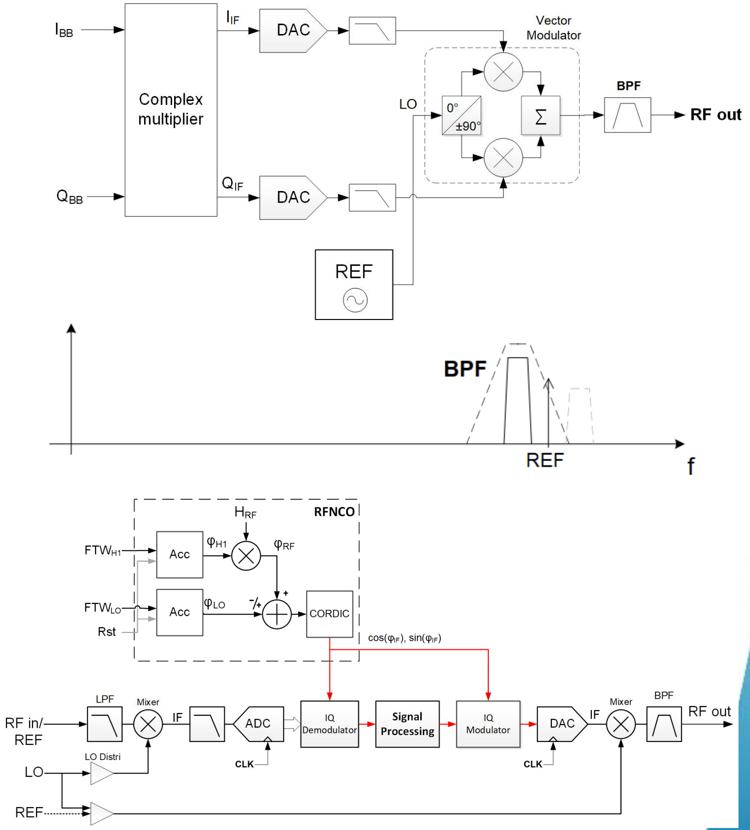


Fig – RF up/down modulation scheme

LLRF Architecture - Clock Distribution

new eRTM15 to be developed
(distribution only)

Standalone unit for
«Master REF»
(space, mechanical noise,
temperature stability)

reuse eRTM14
(EDA-03849)

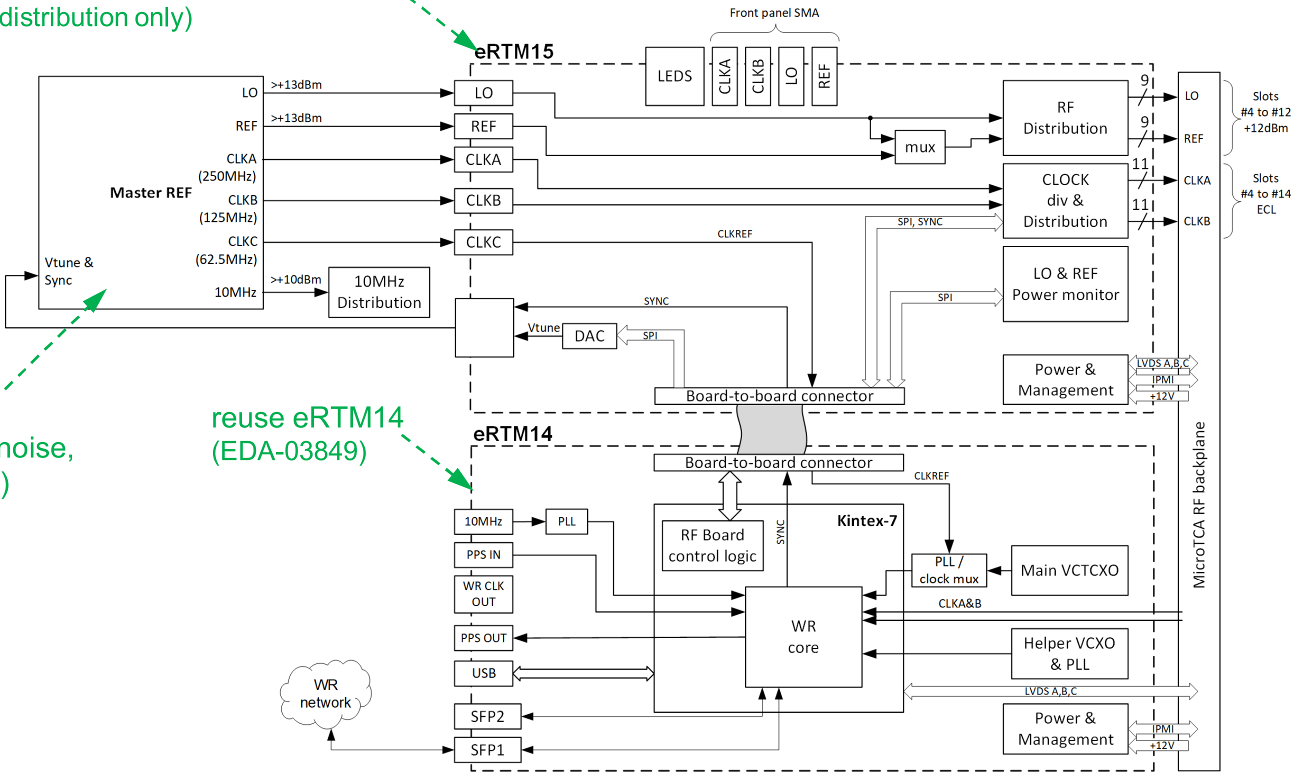


Fig – Master Reference & eRTM diagram

Cavity-Controller Proof of Concept (PoC)

- MTCA platform
- Analog RF front-end
  - Calibration, Remote diag
  - RF distri (Remote diag, interlock)
- Interlock Box
  - Fiber to copper
- Proof of Concept
  - Hardware evaluation required (Low noise receiver: demodulator+ADC)
  - ADC 16bits
    - Expected: ~77dB SNR @125MSPS → ENOB ≈ 12.5bits
    - Considering white-noise PSD: → LN(f) ≈ -152 [dBc/Hz]
    - 1/f noise?

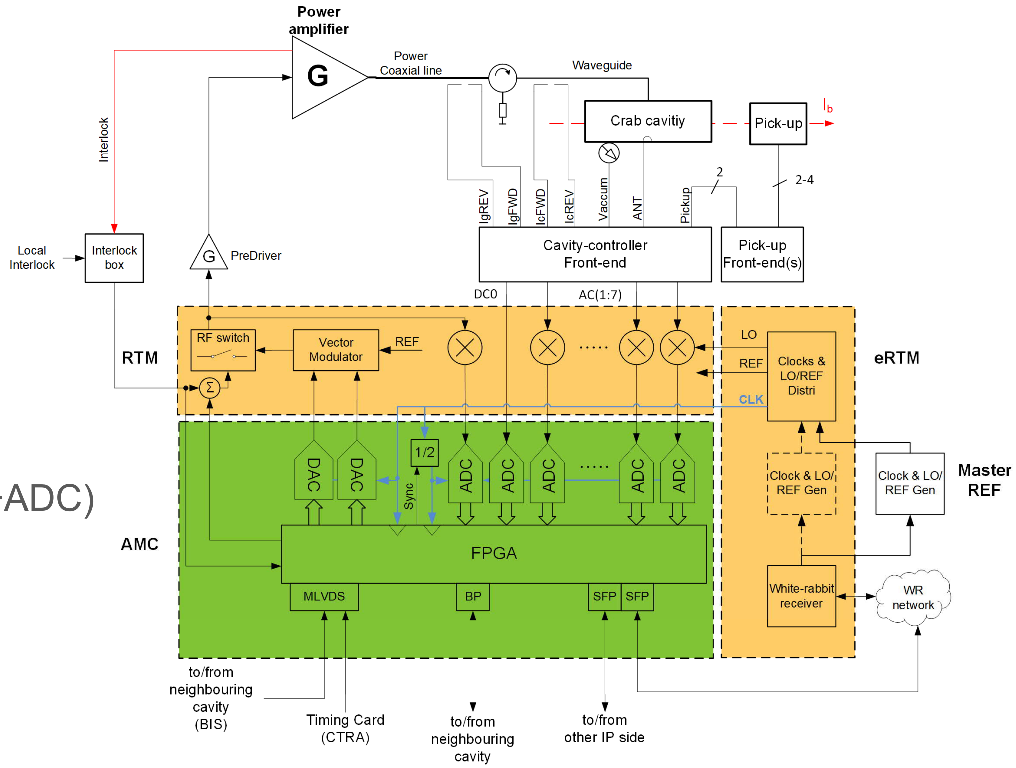


Fig – HL-LHC Crab cavities controller HW diagram

Crab-Cavity phase/Amplitude feedback (PoC)

- Pickup front-end
  - Analog pre-processing for Bunch phase/tilt
- Average bunches phase
  - Crab-cavity phase tracking bunch core
- Bunch-per-bunch phase & tilt measurement
  - Feedback to Crab-Cavity voltage setpoint (RF noise reduction)

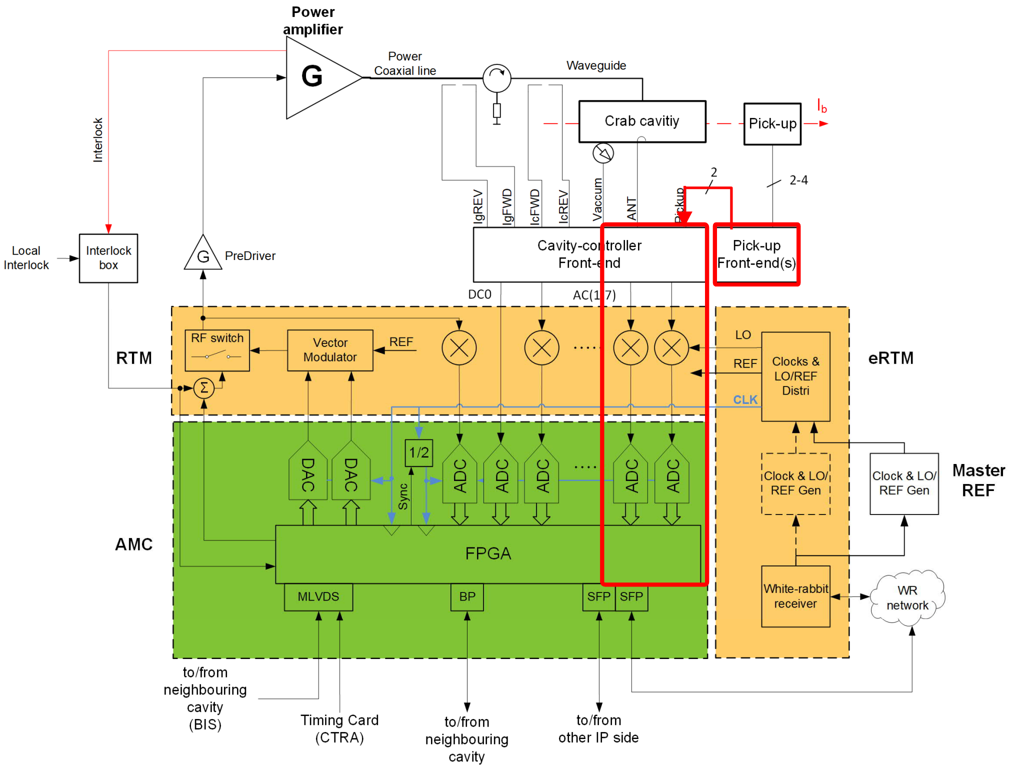


Fig – HL-LHC Beam phase & tilt measurement, alternative with dedicated AMC+RTM

Crab-Cavity phase/Amplitude feedback (PoC)

- Alternative solution with dedicated AMC & RTM
- MTCA backplane point-to-point Gbit link
- Inspired from the LHC Beam position measurement system [17]
- Requires new RTM

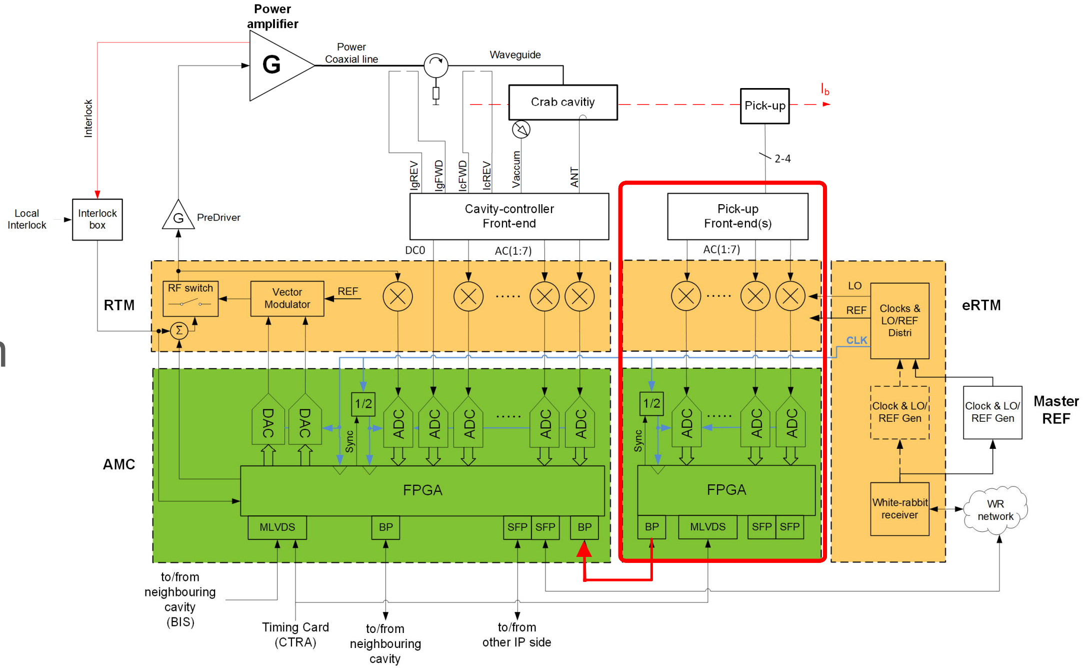


Fig – HL-LHC Beam phase & tilt measurement, alternative with dedicated AMC+RTM

Master plan

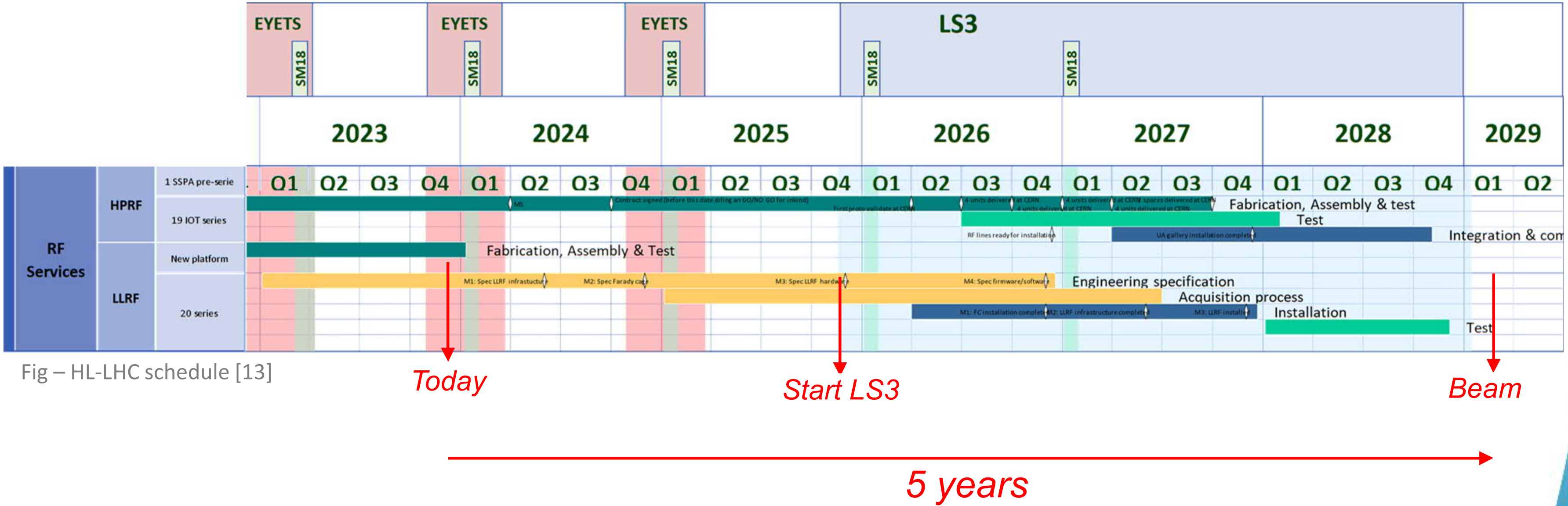


Fig – HL-LHC schedule [13]

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 specifications
  - Transverse Impedance reduction
  - RF noise: max 2 %/h transverse emittance growth,
    HW to be designed? (low noise receiver + CC fdbk)
- Architecture
  - White-Rabbit based
  - MTCA platform
  - Master Reference (clock, LO generation) + eRTM

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Clock Distribution - SIS8300KU+DWC8VM1 example

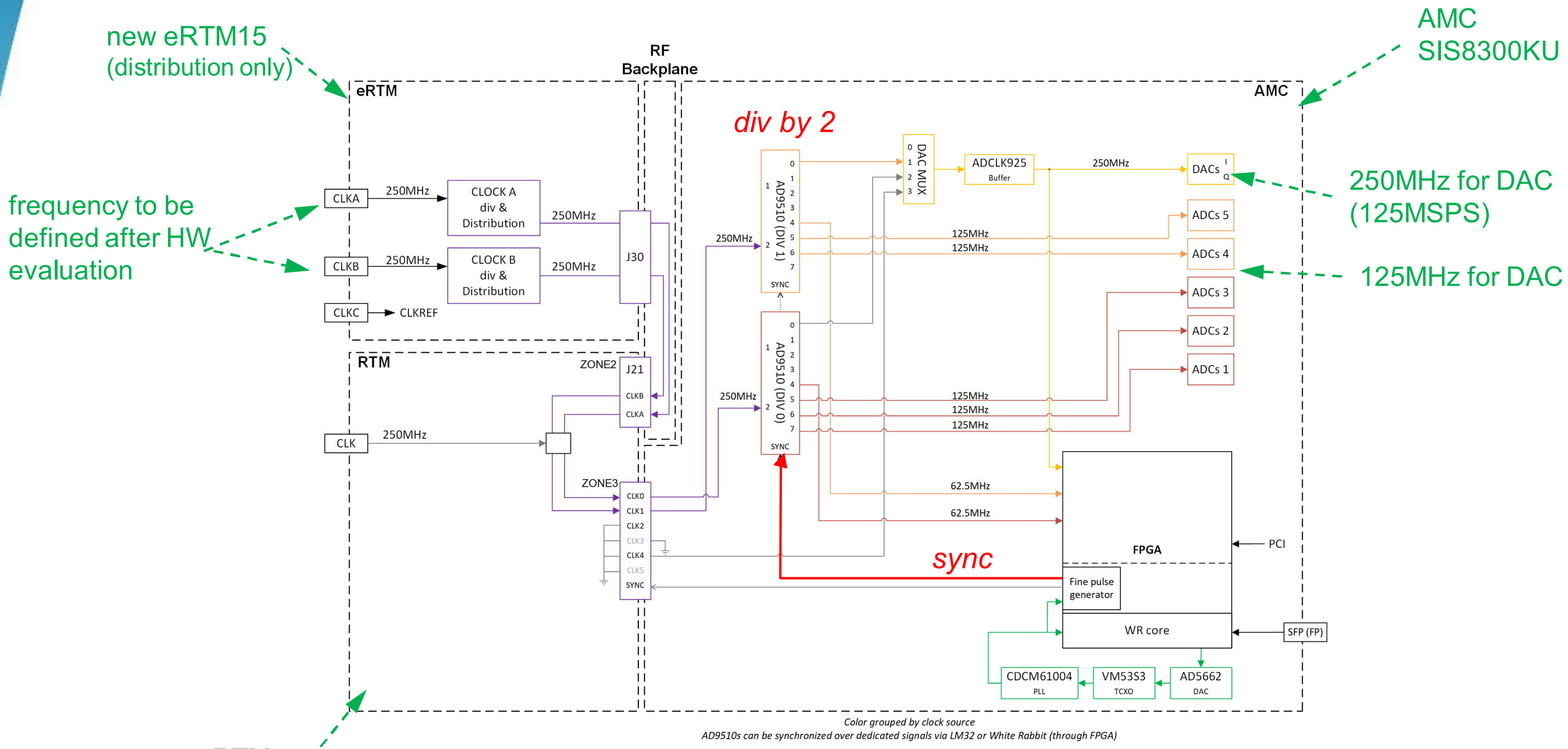

Fig – Clock distribution from eRTM to ADC& DAC on SIS8300KU