RF synchronization and phase recovery using a White Rabbit network for the Large Hadron Collider at CERN

A. Spierer, T. Gingold, G. Hagmann - 28th October 2024 | LLRF Topical Workshop

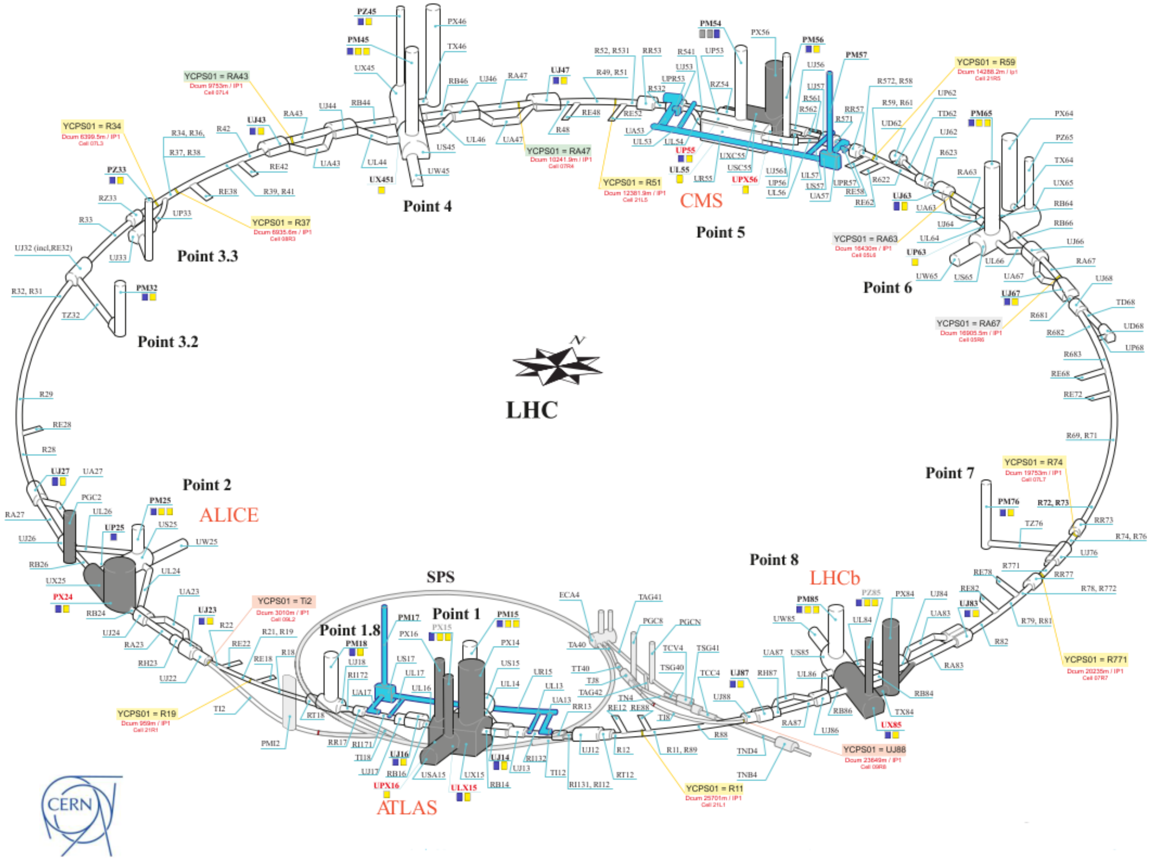
Overview

Context of the upgrade → Require-ments → Solutions → Example → Timeline → Conclusion & Outlook

Context of the LLRF upgrade (Phase 0)

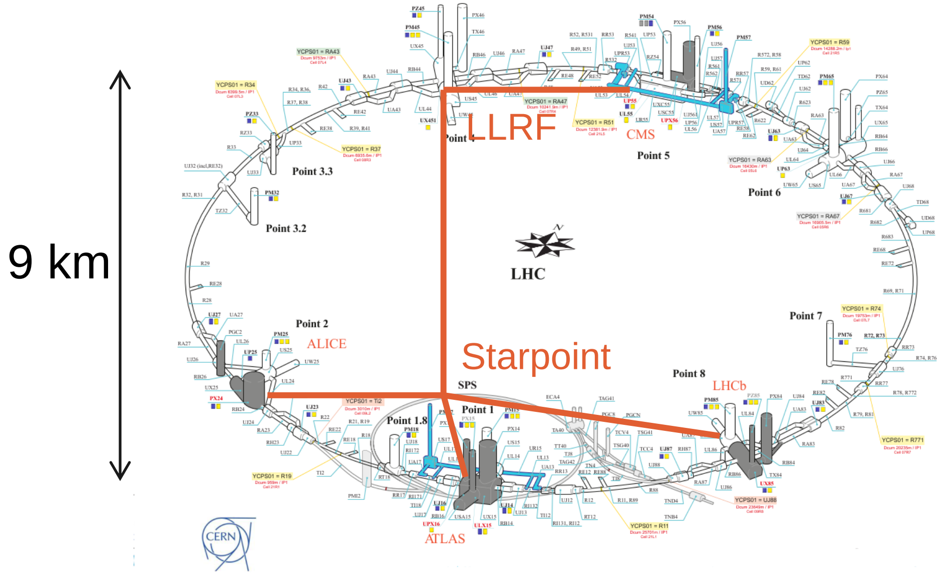
- **High-Luminosity LHC (HL-LHC)**
  - Increase of the integrated luminosity
    - Beam intensity increase : Injectors upgrade
    - Increased focusing : New quadrupoles
    - Beam orientation : Crab cavities
  - Planned for restart in 2030, operation until 2040+

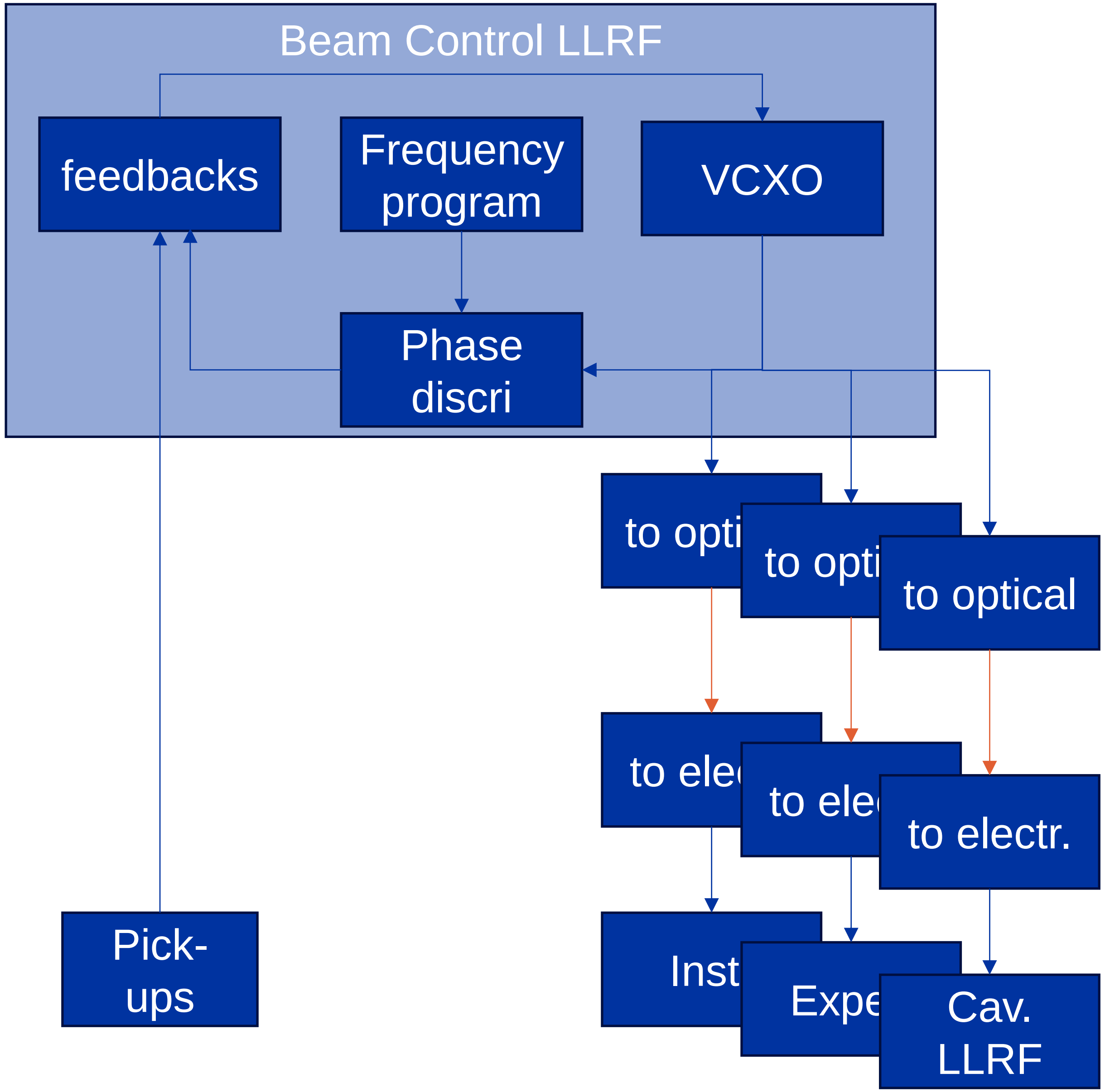
- **LLRF upgrade motivation**
  - Obsolescence of the LHC beam control hardware (frequency program, reference RF generators)
  - Modernization of the clock distribution, requested by users
  - Need for an RF distribution to the Crab cavities
  - Parallel upgrade of the machine timing to White Rabbit



Current distribution

- **Analog RF distribution over fibers (uncompensated): 40-400 MHz, pulses**
  - To cavity controllers
  - To instrumentation
  - To experiments



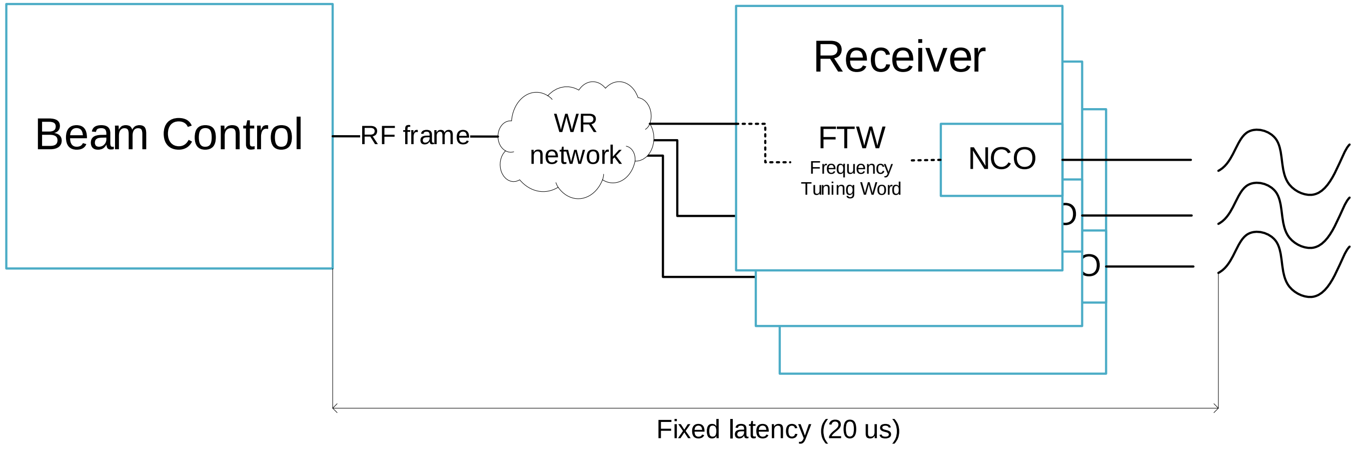


Requirements

- Providing glitch-free clocks for experiments triggers, FPGAs, …
- Phase locked in all locations
- Phase recovery after the power cycle of an endpoint
- Scalability - Limiting the number of optical fiber links
- Phase noise, thermal drift and reproducibility - described in the WR2RF poster
- Reliability - 24/7 operation

Solution

- **RF distributed digitally over a White Rabbit network**
- **Generated locally, at the endpoint**

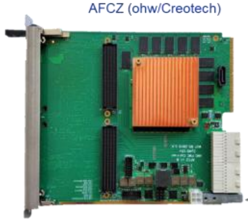


Solution

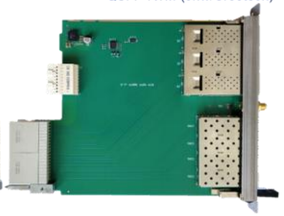
- **Based on the Super Proton Synchrotron (SPS) experience**
  - Same/similar hardware uTCA+VME (eRTM for clocks, WR2RF modified for 400MHz, AFCZ, WR switches)
  - New: RF over ethernet (RoE) instead of streamers, lightweight and generic
  - New: Glitch-free operation
- **Towards a more generic approach**
  - Shared networks with general timing and other accelerators
  - Opportunity to connect and synchronize with the up/downstream machine

WR Switch

AFCZ (ohw/Creotech)



QSFP-RTM (ohw/Creotech)

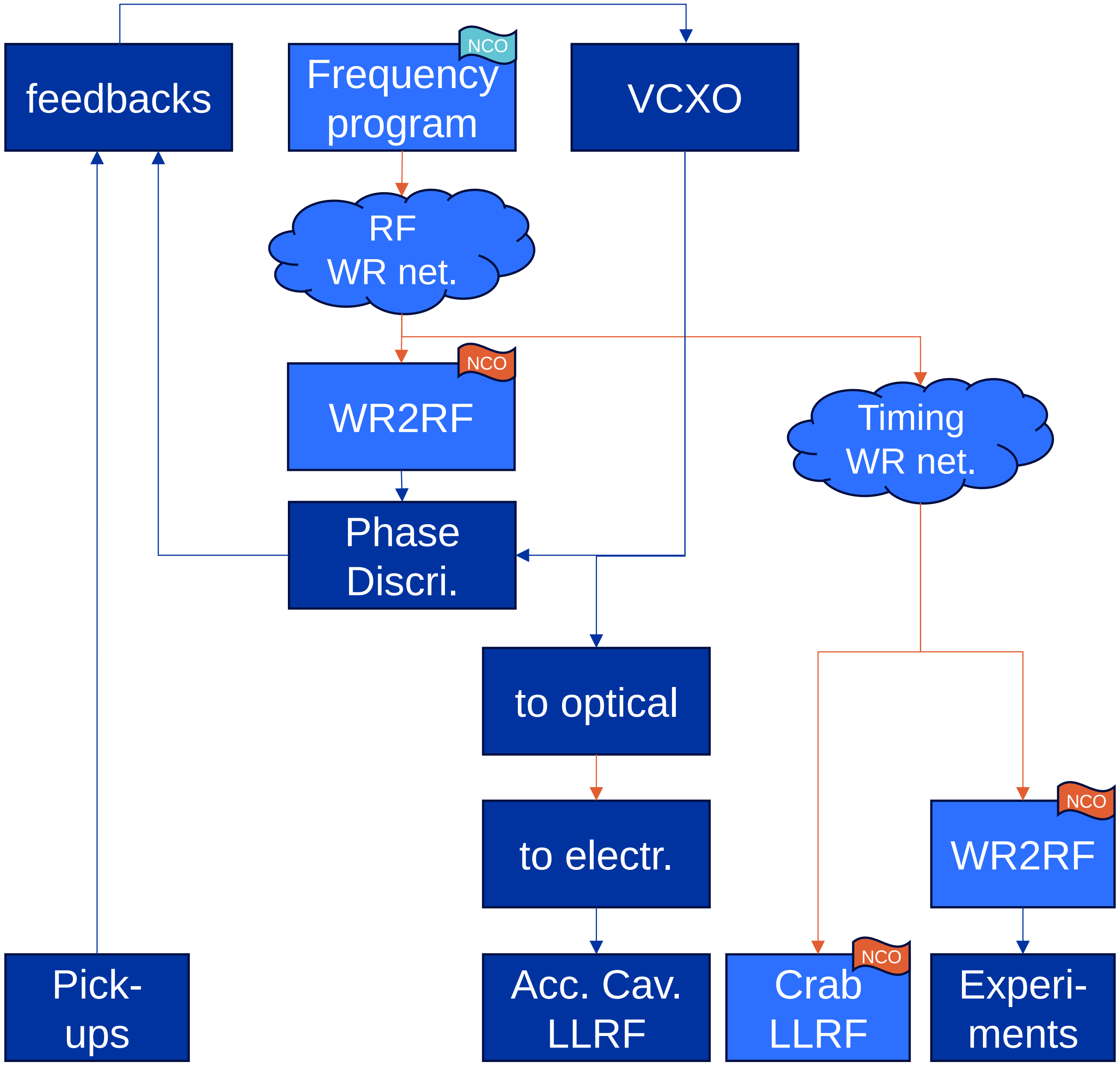


eRTM14/15 (CERN)

WR2RF (VME)

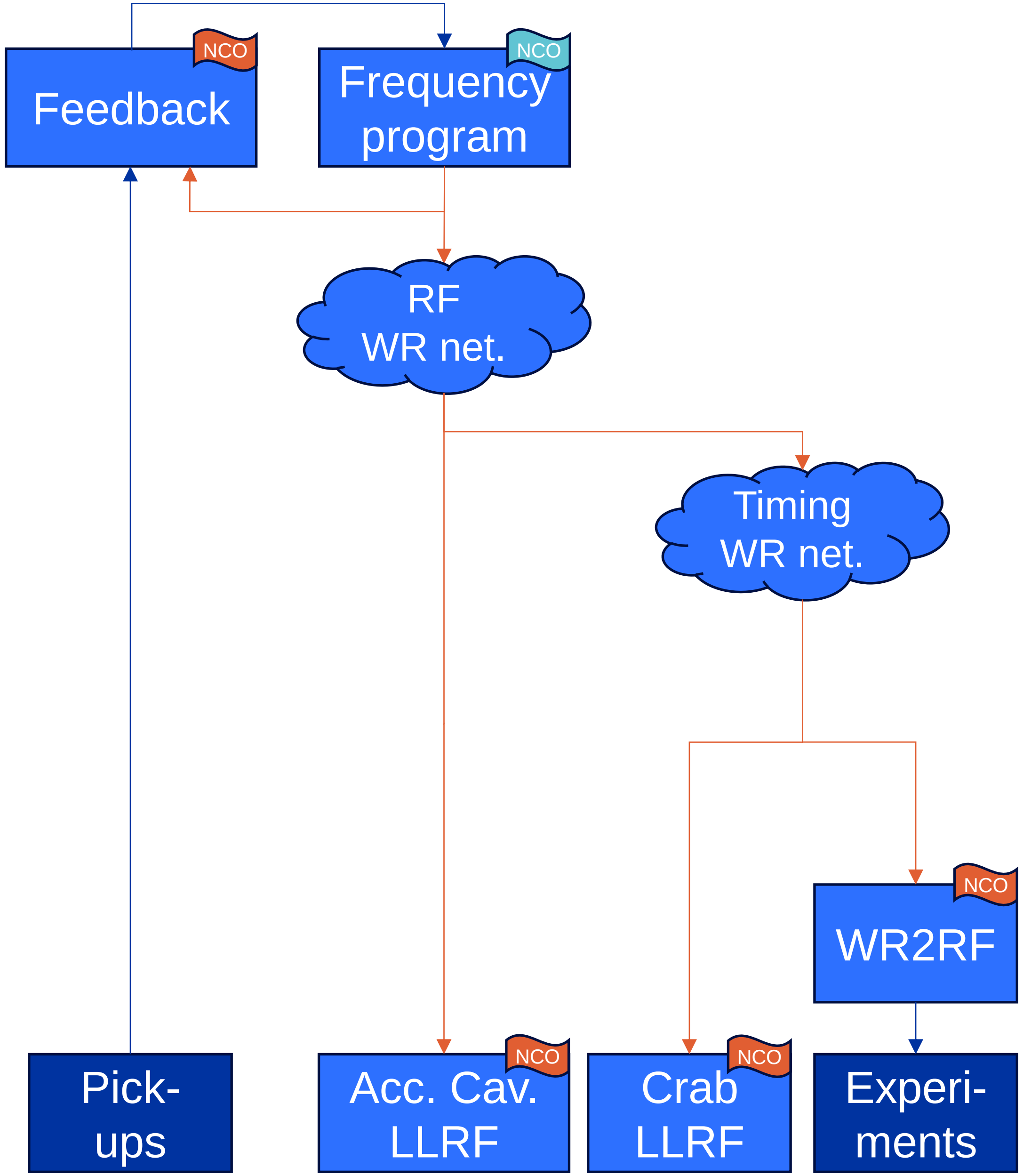
Solution (Phase 0)

- **Replacement of the frequency program**
  - WR capable
- **WR2RF to generate reference RF for loops and accelerating cavities**
- **Dedicated low-latency network (~20 us)**
  - Accelerating cavities LLRF, Beam Control LLRF
- **Injection of RoE in the machine timing WR network (~200 us)**
  - For experiments, Crab cavities, instrumentation



Solution (Phase 1+)

- **Update of the cavities and Beam control LLRF**
  - Long shutdown 4, ~2033
  - nodes are all WR-enabled



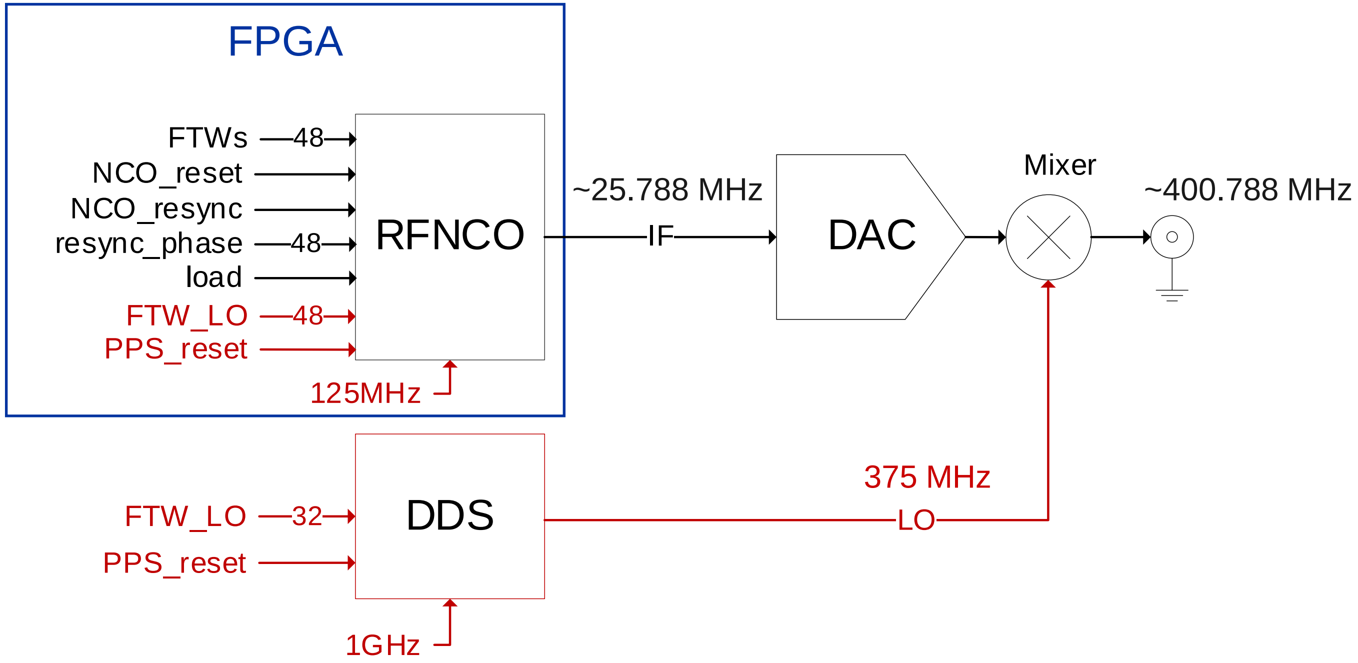
Synchronization example: WR2RF

Recovering the relative phase between two distant nodes

RF generation

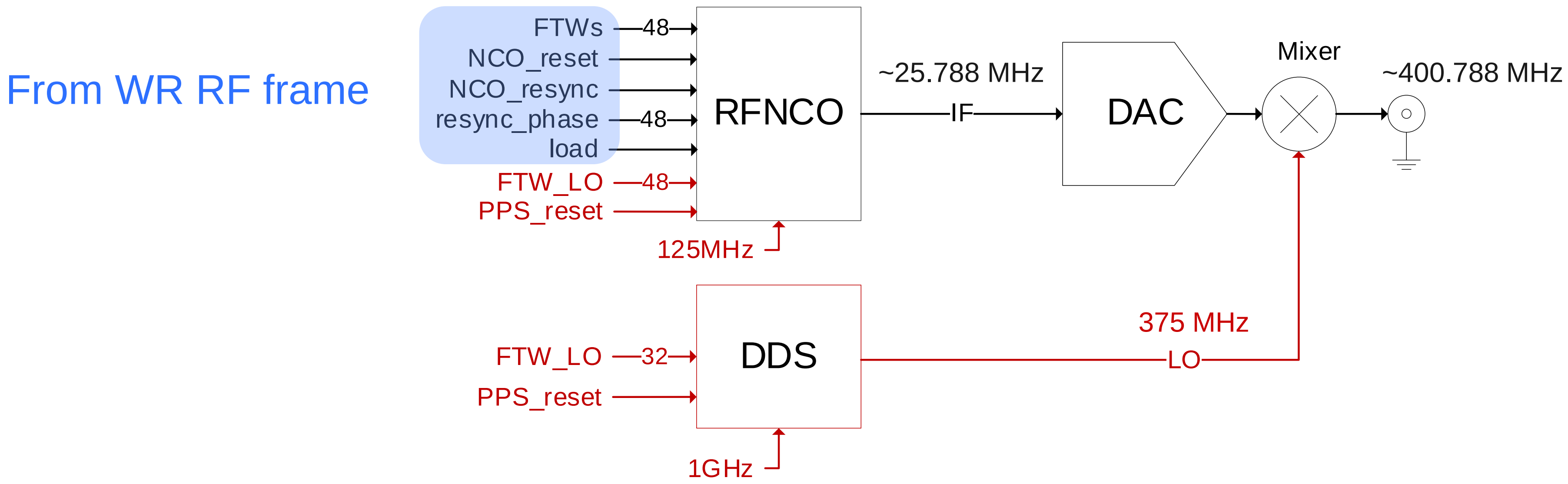
- **The WR2RF contains two types of oscillators**
  - The clocks and analog LOs are at constant frequency (in red)
  - The IF that sweeps during acceleration

WR2RF (VME)



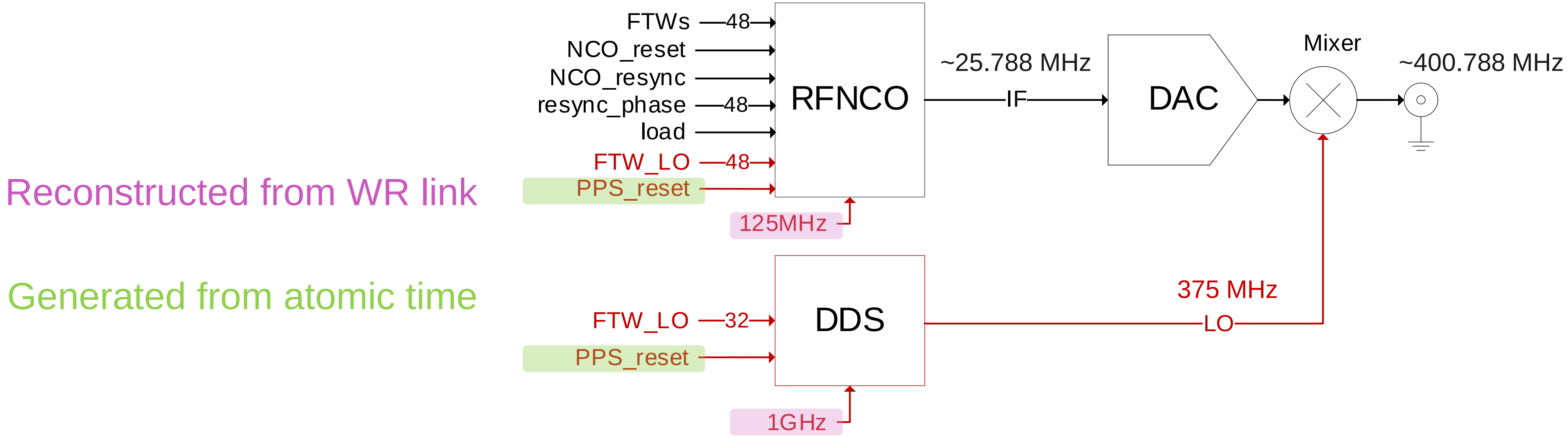
RF generation – tracking the sweeping RF

- **The frame is sent once per beam revolution (~90 microseconds) by the beam control**
- **It is received and applied to the RFNCO with a fixed delay set at the receiver side***



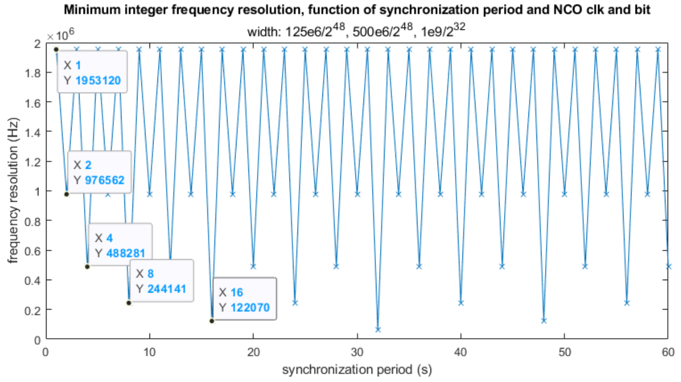
RF generation – Locking fixed frequency DDS

- **The endpoints are locked to the atomic time (TAI) through the WR link**
- **After a power cycle, a pulse locked to the TAI second* is used to synchronize the DDS phase as well as RFNCO LO phase**
  - These oscillators must have an integer number of periods in N seconds

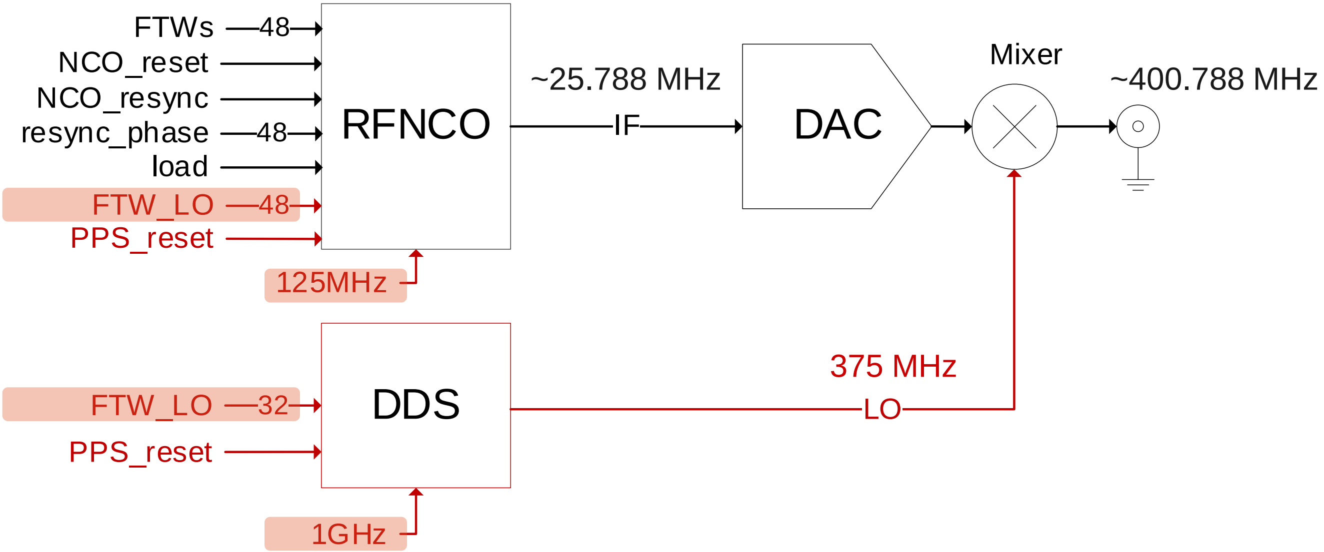


RF generation – Phase recovery

- **Higher synchronization period N*second => broader choice of LO frequencies**
- **The graph shows how the resolution improves when increasing N**

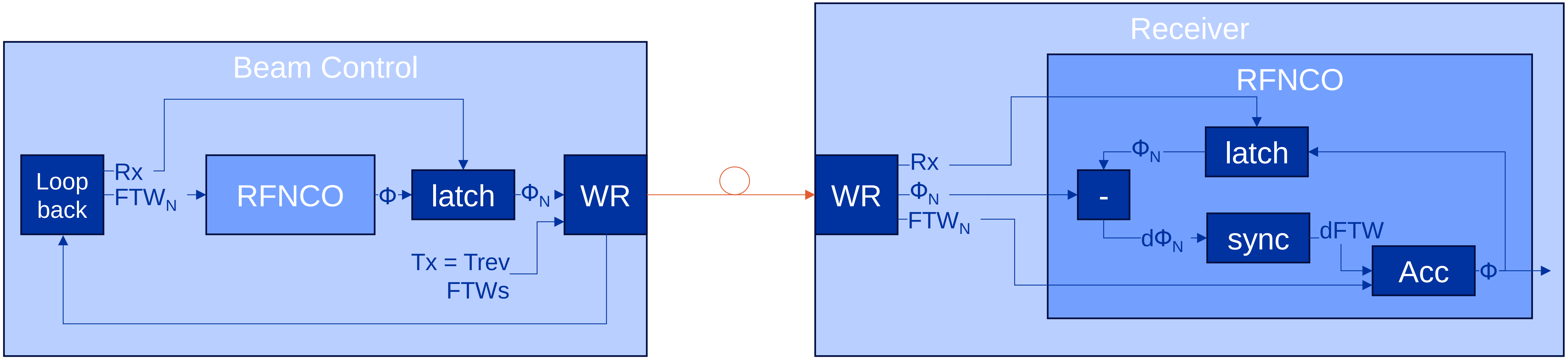


LO FTWs must match without rounding to avoid drift



RF generation – Reference phase recovery

- **The reference RFNCO phase (Beam Control) is transmitted over WR**
- **It is compared to the local RFNCO phase, if different triggers a re-sync.**
- **In case of re-sync., the phase difference is linearly ramped down**



Timeline

2024

- Hardware installation
- Parallel to the existing system

2025

- Parallel test and comparison with the existing system
  - Frequency locking
  - Reproducibility

2026-30

- Long Shutdown 3
- Replacement of the reference
- Stability tests without beam (with users)

2030

- Restart with the new frequency program as reference

Conclusion and outlook

- **We use a White Rabbit network and distributed NCOs to replace the obsolete RF generation and distribution in the LHC**
- **Based on the successful SPS system**
  - With a series of updates and modification to fit the LHC constraints
- **Installation ongoing and the restart with the new system planned in 2030**
- **In collaboration with our controls group, going towards a generalized transmission of the RF information together with the general timing**
- **Improvement of the received clock quality (Phase noise, drift)**
- **Easier network extensions/installations**

References

- **Workshop: G. Hagmann & al. Poster**
  - HL-LHC RF distribution over White-Rabbit, the WR2RF and eRTM modules
- **Workshop: G. Papotti & al. Presentation**
  - High-precision clocks and triggers for longitudinal beam measurements in high energy synchrotrons
- **Phase Stability Compliancy Testing of a White Rabbit Based Solution for the LHC RF and Timing Distribution Backbone Upgrade**
  - https://indico.cern.ch/event/1381495/contributions/5988793/
- **RoE**
  - https://roe-mapping.web.cern.ch/
- **WR**
  - http://white-rabbit.web.cern.ch/
- **SPS beam control**
  - https://cds.cern.ch/record/2845762?ln=en

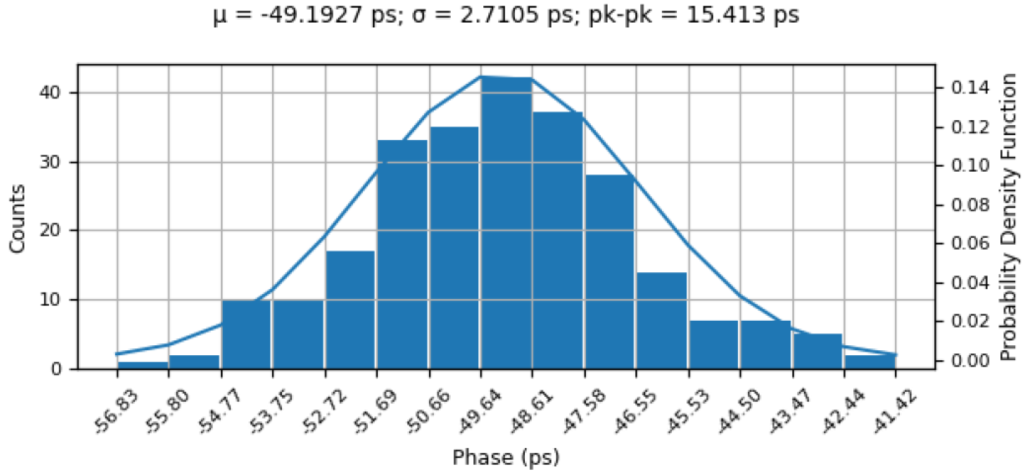
CERN

Clock & LO generation

Temperature range (degC):

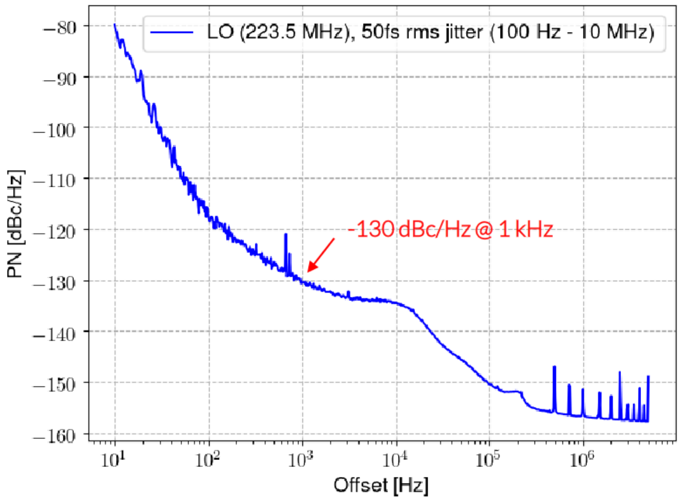
- **crate:** 26.45 – 28.74 (Δ 2.29)
- **lab:** 24.89 – 26.68 (Δ 1.80)
- **WRS rear:** 26.14 – 27.84 (Δ 1.70)

- **RF Phase variation over time between two WR clients with resets**
  - Clock phase reproducibility = WR reproducibility
  - Full characterisation ongoing with WR switches in cascade

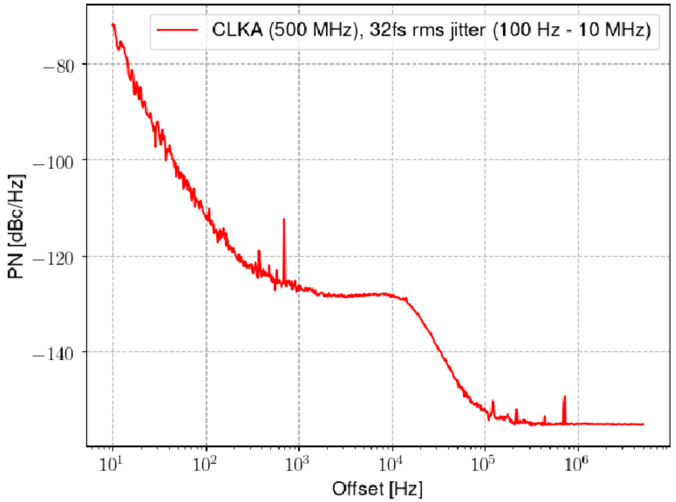


- **eRTM 14/15 phase noise performance**

LO (front panel) @ 223.5 MHz

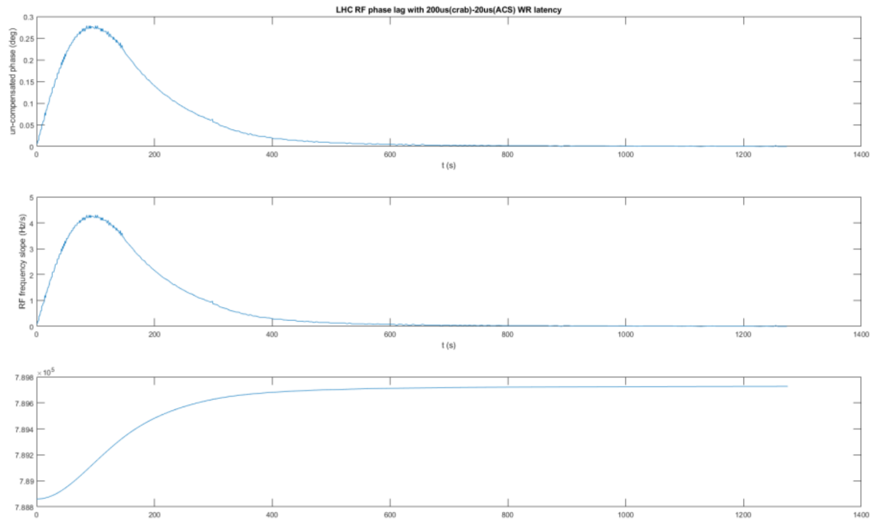


CLKA (front panel) @ 500MHz



Effect of WR delay

- **Requires cable length compensation for sweeping frequencies**
- **Introduces a lag in phase for distant devices (200us)**
  - OK for experiments as they are working only at flat top frequency
  - OK for Crab cavities for the same reason

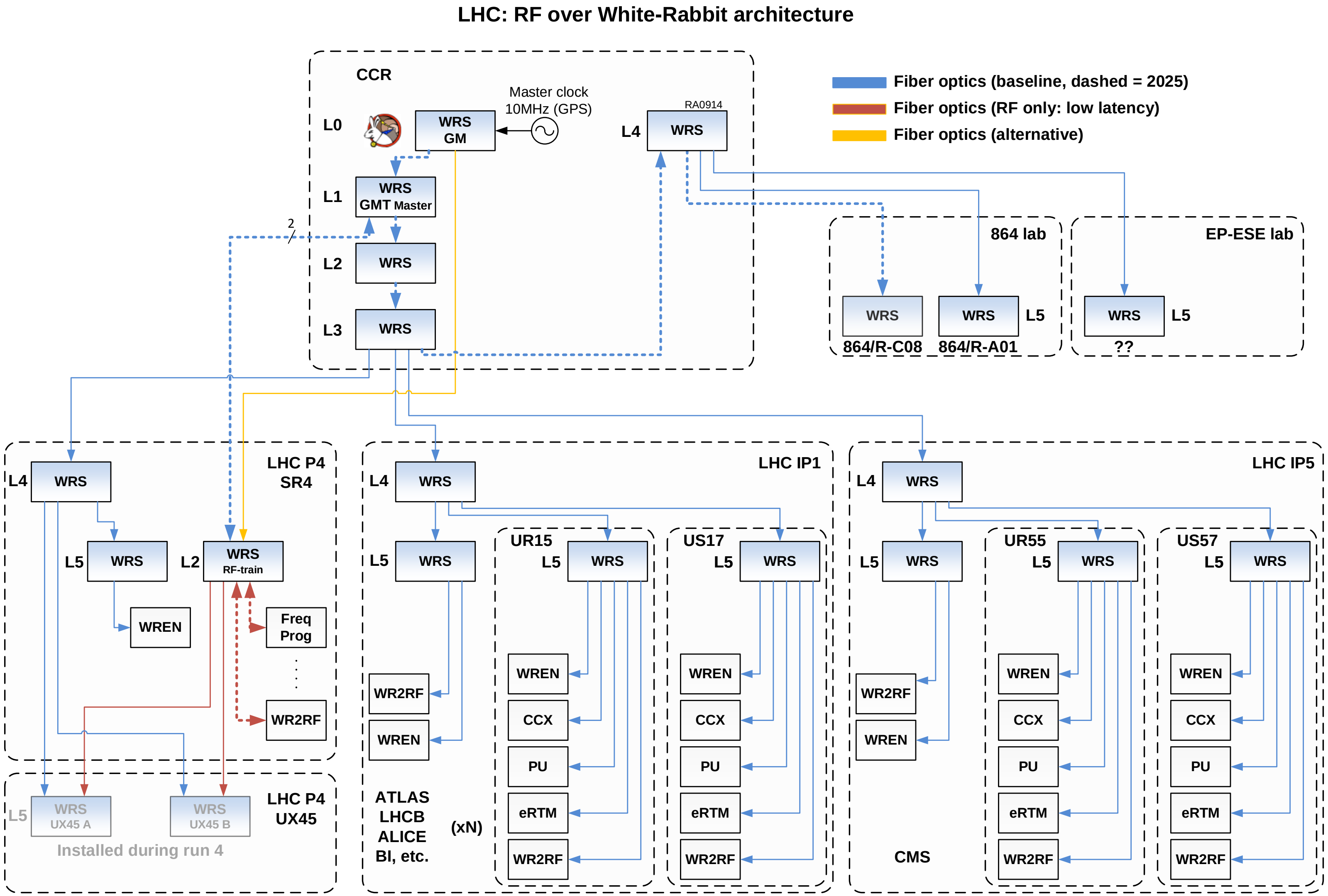


RF generation

- **Frame content**

Field	Type	Size	Comment
FTW_prog_b1 (1)	FTW	48 (2)	Includes radial_correction_b1 dFTW
FTW_prog_b2 (1)	FTW	48 (2)	Includes radial_correction_b2 dFTW
FTW_master_b1 (1)	FTW	48 (2)	FTW_prog_b1 + dFTW phase and synchro loop b1
FTW_master_b2 (1)	FTW	48 (2)	FTW_prog_b2 + dFTW phase and synchro loop b2
synchro_error_b1	phase	16	For phase 0, if VCXO drifts with temperature, receivers can take this offset in account.
synchro_error_b2	phase	16	
controls	bits	16	NCO_reset
			NCO_resync
			DDS_resync
resync_phase_prog_b1	phase	48	Used for glitch-free synchronization
resync_phase_prog_b2	phase	48	
resync_phase_master_b1	phase	48	
resync_phase_master_b2	phase	48	
Total Payload		432	(54 bytes)

WR Network



LHC: RF over White-Rabbit architecture
Fiber optics (baseline, dashed = 2025)
Fiber optics (RF only: low latency)
Fiber optics (alternative)
CCR
L0
WRS GM
Master clock 10MHz (GPS)
RA0914
L4
WRS
L1
WRS GMT Master
2
L2
WRS
L3
WRS
864 lab
WRS
WRS
L5
864/R-C08
864/R-A01
EP-ESE lab
WRS
L5
??
LHC P4 SR4
L4
WRS
L5
WRS
L2
WRS RF-train
WREN
Freq Prog
WR2RF
LHC P4 UX45
L5
WRS UX45 A
WRS UX45 B
Installed during run 4
LHC IP1
L4
WRS
L5
WRS
WR2RF
WREN
UR15
L5
WRS
WREN
CCX
PU
eRTM
WR2RF
US17
L5
WRS
WREN
CCX
PU
eRTM
WR2RF
ATLAS
LHCB
ALICE
BI, etc.
(xN)
LHC IP5
L4
WRS
L5
WRS
WR2RF
WREN
CMS
UR55
L5
WRS
WREN
CCX
PU
eRTM
WR2RF
US57
L5
WRS
WREN
CCX
PU
eRTM
WR2RF