Published by IOP Publishing for Sissa Medialab

Received: *November 4, 2024*
Accepted: *December 3, 2024*
Published: *December 23, 2024*

Topical Workshop on Electronics for Particle Physics
University of Glasgow, Scotland, U.K.
30 September–4 October 2024

Phase stability compliancy testing of a White Rabbit based solution for the LHC RF and Timing Distribution Backbone upgrade

---

P. Hazell,[a,*] S. Baron,[a] E. Gousiou,[a] G.Hagmann,[a] J. Gill,[b] M. Lipinski,[a] Q. Genoud,[a] T. Gingold[a] and T. Wlostowski[a]

[a] *CERN,*
Espl. des Particules 1/1211, 23 Genève, Switzerland
[b] *Mercury Systems International,*
Avenue Eugène-Lance 38, Grand-Lancy, Geneva, Switzerland

E-mail: philippa.kay.hazell@cern.ch

Abstract: The LHC RF and Timing Distribution Backbone is being upgraded for the HL-LHC. A White Rabbit technology solution for the generation and the distribution of the RF, similar to the system currently employed in SPS, is being considered. To verify its suitability from a phase stability perspective, an investigation was conducted on a proof-of-concept system. The requirement for the end-nodes is ± 1 degree of the 200 MHz SPS RF frequency. The key figure of merit to check compliancy is peak-peak phase variation which must be < 28 ps. The compliance tests campaign will be described and results presented.

Keywords: Hardware and accelerator control systems; Trigger concepts and systems (hardware and software)

2024 JINST 19 C12019

---

[*] Corresponding author.

https://doi.org/10.1088/1748-0221/19/12/C12019

Contents

1 Introduction

1.1 Background

The unidirectional Timing, Trigger and Control (TTC) backbone network distributes orbit clocks and bunch clocks from Point 4 (P4) of the Large Hadron Collider (LHC) to the experiments via cables and optical fibres [1, 2]. Aging hardware with obsolete components necessitates upgrading this Timing Distribution Backbone and provides an opportunity to optimize network operations for the LHC High Luminosity (HL) upgrade.

Two additional criteria, which the TTC backbone replacement must provide for the HL-LHC, are: the ability to compensate for phase drift (e.g. those linked to environmental temperature fluctuations); and replaying the RF signal generated at P4 for the crab cavities being installed at ATLAS and CMS [3]. An RF and Timing Distribution Backbone utilising current and redesigned White Rabbit (WR) [4] based hardware was proposed to replace the TTC backbone and address both these criteria.

1.2 White Rabbit

WR technology is based on IEEE standards. WR switches and nodes are interconnected via Ethernet (IEEE 802.3) into Bridged Local Area Network (IEEE 802.1Q) and synchronised using the WR extension to the Precision Time Protocol (PTP, IEEE 1588) [5].

WR-based hardware was chosen for this infrastructure upgrade because it can automatically and continuously compensate for fiber link delays and align phase of specially distributed devices with required precision. This has been demonstrated in the WR-based RF distribution solution implemented for the Super Proton Synchrotron (SPS) [6, 7] that could be adapted and scaled for the HL-LHC. Finally, a WR-based timing distribution solution is the official solution for the operations side of the accelerator, enabling the RF and timing distribution network to become part of a unified WR-timing distribution network, thus simplifying future maintenance and reducing costs.

2024 JINST 19 C12019

1.3 WR-based RF and Timing Distribution Backbone

The proposed HL-LHC WR-based RF and Timing Distribution Backbone will be a combination of WR switches and WR2RF (after being redesigned) modules [8], the latter are currently employed by the SPS to locally generate RF and Bunch Clock and orbit clock signals [9].

WR2RF boards connected to a WRS will be present at each Experiment. These will be connected, via a cascade of WR switches, to a Grandmaster (GM) WR switch (WRS) which will be (and thus the whole system) synchronised to a Global Navigation Satellite System (GNSS), which provides a precise timing and frequency reference to the network [10].

The accelerating 400 MHz RF frequency generated at the LHC point 4 (SR4) will be encoded in a Frequency Tuning Word (FTW) and transmitted via the WR network to the WR2RF boards. These boards will use the FTW to replay the RF signal, as well as locally generating the bunch clocks and orbit clocks for the Experiments.

The unknown baseline performance of this proposed system necessitated testing to be performed on a Proof of Concept system. This paper presents the findings from test campaigns undertaken to verify the feasibility of using WR technology for distributing the RF and the Bunch Clock to experiments. The objectives of this work were to:

- *Understand the system and its constraints*, by assessing the system under a variety of conditions and exploring how it responds to different disturbances introduced into the network.
- *Assess the performance of the system*, by measuring the jitter of the generated signals and analyse their phase stability with respect to the number of WR switches.
- *Collaborate with the maintainers and the users* of the RF and Timing Distribution Backbone to understand their constraints and needs.

2 Specifications

The WR-based RF and Bunch Clock distribution system's specification included: compensating for phase drift; having phase variation over time between WR nodes within ± 1 degree of the SPS 200 MHz RF frequency (equates to a peak-peak phase variation, denoted as θ_{pkpk}, of less than 28 ps); having a signal jitter rms < 5 ps for Experiments; maintaining good phase determinism after any disturbances occur in the network; and assessing the technical hard limit of the system.

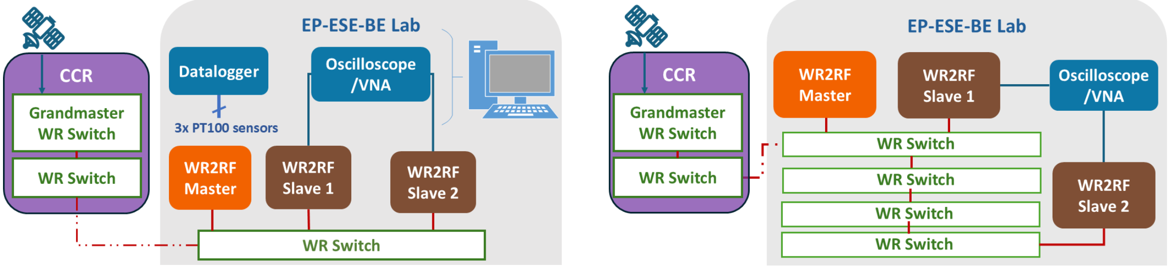
Physically measuring the phase difference between the RF signal generated at P4 and where it will be regenerated on the LHC was not possible. Thus, the Proof of Concept system was employed for assessing feasibility the RF and Bunch Clock distribution system for the HL-LHC, before redesigning the SPS WR2RF boards for this application. The main figure of merit employed to assess the system was θ_{pkpk}.

3 Tests and findings

Testing the Proof of Concept system was split into three key test campaigns, each detailed in the subsections below. These tests and the Proof of Concept system started relatively small and simple, before increasing in size and complexity. The focus will mostly be on the Bunch Clock signals performance, as that of the RF signals were similar.

3.1 WR2RF boards phase determinism

This testing stage assessed the phase variation over time between signals generated by different WR2RF boards did not exceed 28 ps. The Proof of Concept system employed comprised two WR2RF slave boards and one master WR2RF board all connected to a WRS (see figure 1(a)). This system is referred to as the Single Switch system. The Master WR2RF board was responsible for transmitting a FTW that the WR2RF slave boards employed to replay RF signals at the same timestamp. The WRS in the lab received timing and diagnostic information from the GM WRS (referred to as layer 0) via another switch layer, and the whole system was synchronised to GNSS.



(a) Single Switch System.

(b) Cascaded Switches System.

Figure 1. Block diagrams of the two Proof of Concept System Variants.

Two types of tests were executed to assess the WR2RF board performance. Firstly, the *normal operation test*, which repeatedly measured the phase between like signals generated by the two WR2RF slave boards. Secondly the *WR2RF slave board reset test*, which involved resetting a WR2RF slave board between phase measurements.

The signals of interest were the 200 MHz RF and the 40 MHz Bunch Clock. A Keysight MXR254A oscilloscope measured the phase between Bunch Clock signals (using its *Edge-Edge function*), whilst a Keysight E5061B VNA acquired the phase between the sinusoidal RF signals. A Keysight 34970A Datalogger and several PT100 sensors acquired the temperature at various spots within the set-up.

Assessing the phase stability of the system involved taking multiple phase measurements, where each phase measurement was the average computed over a consistent period of 12.5 ms for the oscilloscope, and a varying 0.5 ms to 6 ms for the VNA, during a single trigger. This process was automated using python scripts. To determine the phase stability, the average phase value per single trigger were plotted over time and the variation in these phase values analysed. The θ_{pkpk} was determined by computing the difference between the minimum and maximum of the plotted phase values (a smaller value equates to better phase stability).

Figure 2 presents the phase versus sample number for the Bunch Clock signals. The leftmost plot presents the phase variation during normal operation. Meanwhile, the middle plot shows the phase variation when the WR2RF Slave 1 was reset between phase measurements, whilst the rightmost plot was when the WR2RF Slave 2 board was being reset. The teal points in the scatter diagram in figure 3 present the θ_{pkpk} values for these three test runs.

The θ_{pkpk} values for the normal operation test (1000 consecutive measurements over a duration of about 14 hours 15 minutes) were < 28 ps. Comparable results were also observed with the WR2RF slave board reset, although less measurements were acquired (250 over a duration of about 12 hours and 20 minutes) for these two test runs.

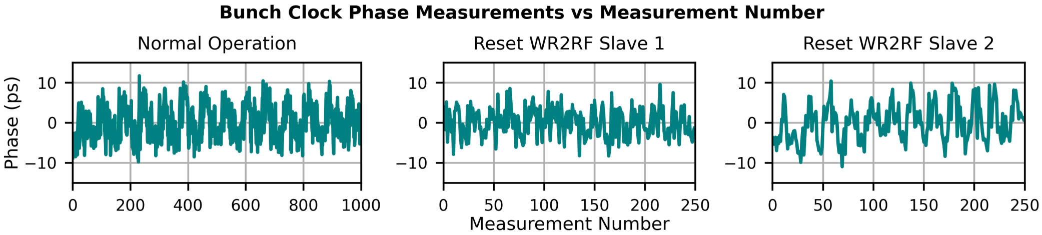


Figure 2. Phase vs sample number from WR2RF boards Phase Determinism Testing.

With the WR2RF slave board reset tests, several challenges were encountered and resolved. This included developing a "mock reset" procedure as the WR2RF boards had no reset functionality and finding solutions to fix phase jumps observed during initial rounds of testing. This latter point was mainly resolved through firmware upgrades for the WR2RF boards, but one type of phase jump required a change in the reinitialisation process that affected the whole system (not just the WR2RF slave board being reset). This finding has led to more strigent requirements being added to the HL-LHC WR2RF-VME redesign specifications.

3.2 Distribution network phase determinism

This test campaign scaling up the Proof of Concept system to more accurately resemble the system which will be employed in the HL-LHC. The single WRS was replaced with a cascade of four WR switches (resulting in a total of six cascaded switches, as shown in figure 1(b)). This "Cascaded Switches" system had the timing and diagnostic information from the GM WRS, the Master WR2RF board and the WR2RF Slave 1 board connected to the most upstream WRS in the lab (layer 2). The WR2RF Slave 2 board was connected to the most downstream WRS (layer 5).

To assess the RF and timing distribution network's phase determinism, the two tests presented in section 3.1 were repeated on the Cascaded Switches system (the number of phase measurements was reduced to 100 for the WR2RF slave board reset tests, which ran for a duration of $\approx$ 5 hours). Two new tests were also performed. The *WRS Reboot Test* and the *WRS Link Down/Up Test* analysed the phase determinism when a WRS was rebooted or a WRS's link temporarily disabled respectively between phase measurements.

Prior to launching these latter two tests, manual testing indicated that an automated recovery plan required developing before testing could begin. The automated recovery plan ensured the WRS being tested, and all downstream switches, were back up and ready. Links to WR2RF boards in the network also had to be checked and if they had not come back up, the respective WR2RF board had to be reset. In most cases, all WR2RF slave boards in the network required their Bunch Clock generation circuitry re-initialising to ensure the Bunch Clock signals were synchronised. This recovery plan was automated using a combination of python and shell scripts.

The purple points in figure 3 presents the θ_{pkpk} values for the different test types executed on the Cascaded Switches Systems. With the WRS reboot test, four test runs occurred (one per lab WRS) each acquiring 100 phase measurements. Ten tests runs were performed for the WR Link Down/Up test (1 per utilised port on the lab WR switches) and again, each test run acquired 100 phase measurements.

Even during normal operation, the 28 ps threshold for θ_{pkpk} was occasionally exceeded with the Cascaded Switches system. For the Single switch system the θ_{pkpk} <22 ps, whilst for the Cascaded

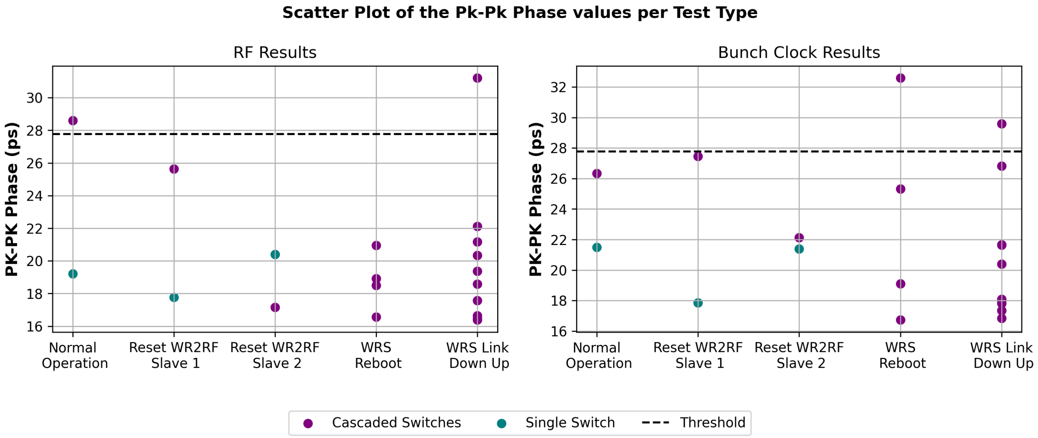


Figure 3. θ_{pkpk} values for all the different test types.

Switches system θ_{pkpk} <33 ps. This increase in phase variation was linked to the additional number of WR switches between the WR2RF Slave board nodes.

The results for the WRS reboot and WR Link Down/Up tests also suggested that, once the recovery plans were in place, these types of network disturbances did not introduce further fluctuations in phase (when comparing to the Cascaded Switches System normal operation test). However, compared to the normal operation tests, there were less statistics for each of the WRS disturbance test runs (a factor of 10 difference in the number of phase measurements acquired).

3.3 Phase noise and jitter performance

The third test campaign assessed the impact of the number of cascaded WR switches on the WR2RF phase noise and jitter. Phase noise analysis was performed, over a frequency offset band of 1 Hz to 5 MHz, on the WR2RF Slave 2 board, when it was connected to WR switches layers 2 to 5 in the Cascaded Switches System.

Figure 4 presents the Bunch Clock results, whose phase noise was nearly identical at higher frequency offsets. The phase noise quality decreased at frequency offsets <100 Hz when the WR2RF slave board was connected further down a cascade of WR switches, yet the integrated jitter continued to be below 5 ps rms.

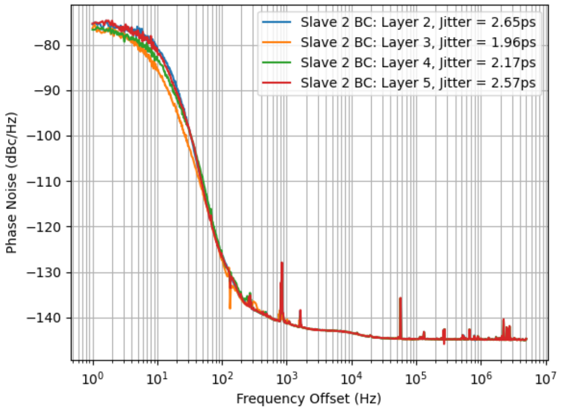


Figure 4. Phase noise and jitter values from WR2RF Slave 2 board Bunch Clock (BC) signals.

4 Summary

From this work, the baseline performance of the RF and Timing Distribution Backbone Upgrade at 200 MHz RF is known. This study has also enabled a more thorough specification to be drawn up for the HL-LHC (400 MHz) WR2RF redesign, as well as a set of test procedures to assess its performance. This repeat of testing will be necessary to ensure, amongst other things, that the θ_{pkpk} is within ± 1 to 2 degrees of the HL-LHC's 400 MHz RF frequency. Despite the promising results, it is advised to keep a monitoring system in place, for example to continuously measuring the phase of the reconstructed Bunch Clock with respect to the signal generated by Beam Pick Ups close to the experiments.

References

[1] S. Baron, *TTC challenges and upgrade for the LHC*, in the proceedings of the *11th Workshop on Electronics for LHC and Future Experiments (LECC 2005)*, Heidelberg, Germany (2005), p. 125–129 [`DOI:10.5170/CERN-2005-011.125`].

[2] B.G. Taylor, *Timing distribution at the LHC*, in the proceedings of the *8th Workshop on Electronics for LHC Experiments*, Colmar, France (2002), p. 63–68 [`DOI:10.5170/CERN-2002-003.63`].

[3] I. Zurbano Fernandez et al., *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*, CERN-2020-010 (2020) [`DOI:10.23731/CYRM-2020-0010`].

[4] M. Lipinski, T. Włostowski, J. Serrano and P. Alvarez, *White rabbit: a PTP application for robust sub-nanosecond synchronization*, in the proceedings of the *2011 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control and Communication*, Munich, Germany (2011), p. 25–30 [`DOI:10.1109/ispcs.2011.6070148`].

[5] M. Lipinski, *White Rabbit Official CERN website*, https://white-rabbit.web.cern.ch/ (2024).

[6] G. Hagmann et al., *The CERN SPS Low Level RF upgrade project*, in the proceedings of the *10th International Particle Accelerator Conference*, Melbourne, Australia (2019), p. 4005–4008, [`DOI:10.18429/JACoW-IPAC2019-THPRB082`].

[7] A. Spierer et al., *The CERN SPS Low Level RF: The Beam-Control*, in the proceedings of the *13th International Particle Accelerator Conference (IPAC 2022)* Muangthong Thani, Thailand (2022), p. 895–898, [`DOI:10.18429/JACoW-IPAC2022-TUPOST021`].

[8] WR2RF-VME, https://gitlab.cern.ch/be-cem-edl/chronos/wr2rf-vme/-/wikis/home (2024).

[9] T. Włostowski et al., *White Rabbit and MTCA.4 Use in the LLRF Upgrade for CERN's SPS*, in the proceedings of the *18th International Conference on Accelerator and Large Experimental Physics Control Systems (ICALEPCS 2021)*, Shanghai, China (2022), p. 847–852 [`DOI:10.18429/JACoW-ICALEPCS2021-THBR02`].

[10] T. Włostowski et al., *Trigger and RF Distribution Using White Rabbit*, in the proceedings of the *15th International Conference on Accelerator and Large Experimental Physics Control Systems*, Melbourne, Australia (2015), p. 619–623 [`DOI:10.18429/JACoW-ICALEPCS2015-WEC3O01`].

2024 JINST 19 C12019