Introduction to White Rabbit protocol

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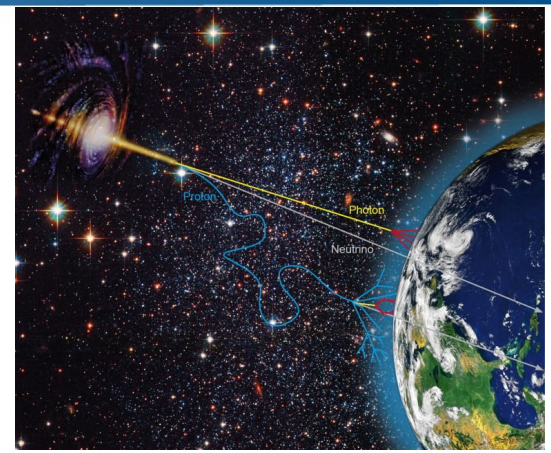
Outline

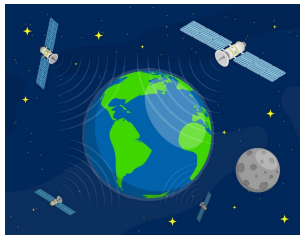
- The new challenges of synchronization and time distribution
- White Rabbit protocol
- White Rabbit implementation and evaluation
- White Rabbit additional features
- Conclusion

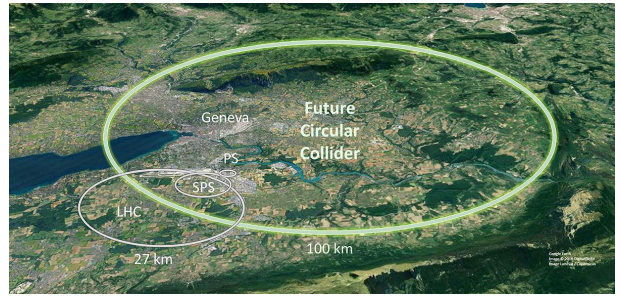
The issue of synchronization in modern large detector arrays

Motivations for time and frequency dissemination

- Large instruments, array of detectors
  - Large Accelerators (LHC, SuperKEKB), Einstein telescope
- Multi-messenger Astronomy
- Fundamental Scientific applications
  - Definition and variation in fundamental constants
- Earth science and climate change
  - Fiber sensing, geodesy, chronometric leveling
- Sensing/Defense
  - Positioning, navigation and timing
- Dissemination of time and frequency
  - Atomic clocks, telecom, network synchronization

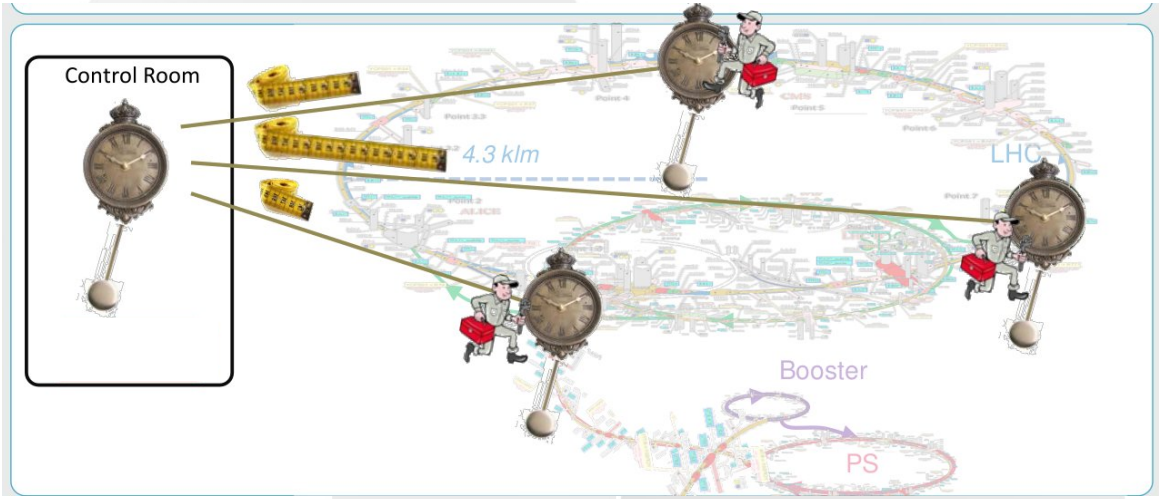




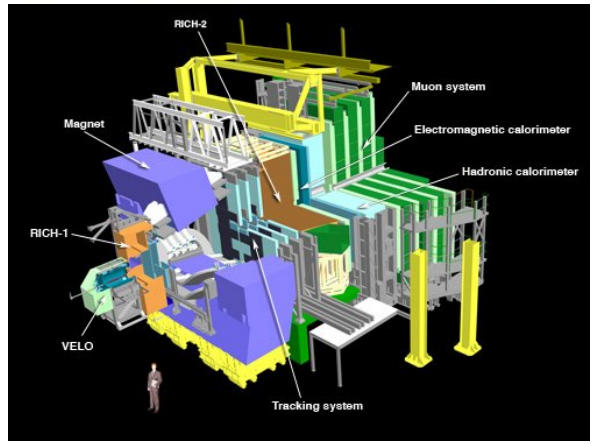


Accelerators: Master oscillator distribution

- Increasing requirements for timing precision and stability O(1ps) for:
  - Real-time communication system;
  - Monitoring;
- Needs scalable system:
  - Long distances between nodes (> 1km);
  - Large numbers of nodes;
- Currently realized with expensive optical systems or electronics.

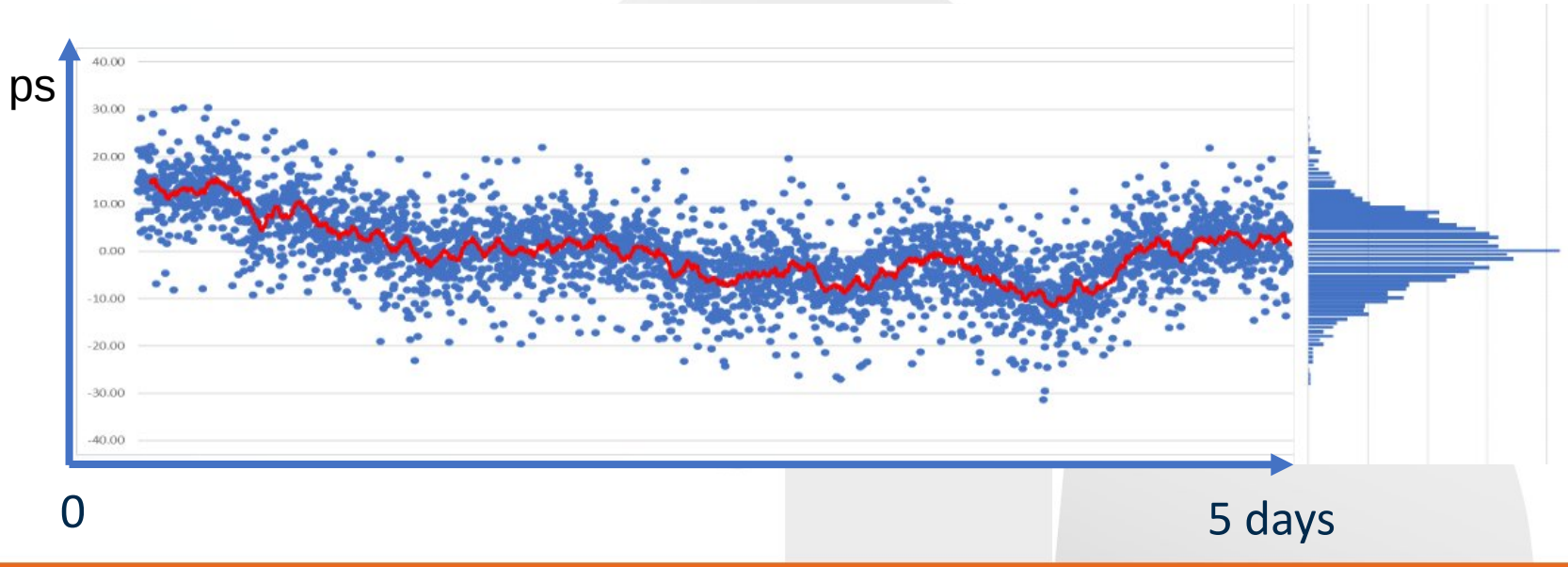


Multi detectors: clock drift example



Large detector calibration:

- Clock drift ±25ps over 5 days in LHCb RICH detector;
- Regular calibrations are mandatory.



External perturbations effects on optical fibers

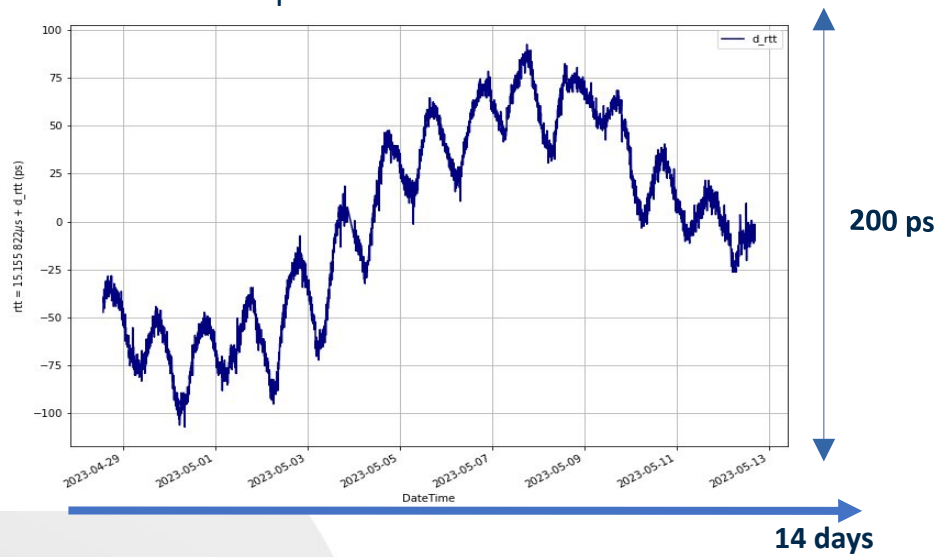
Optical fiber is the natural media for data transfer.

- Fibers are very sensitive to externals conditions:
  - Temperature;
  - Movements...
- Affect the time propagation delay.

Example for 14 km fiber:

- **Time propagation delay dispersion ~ 200ps**

Time propagation delay (ps) in a 14km optical fiber over time



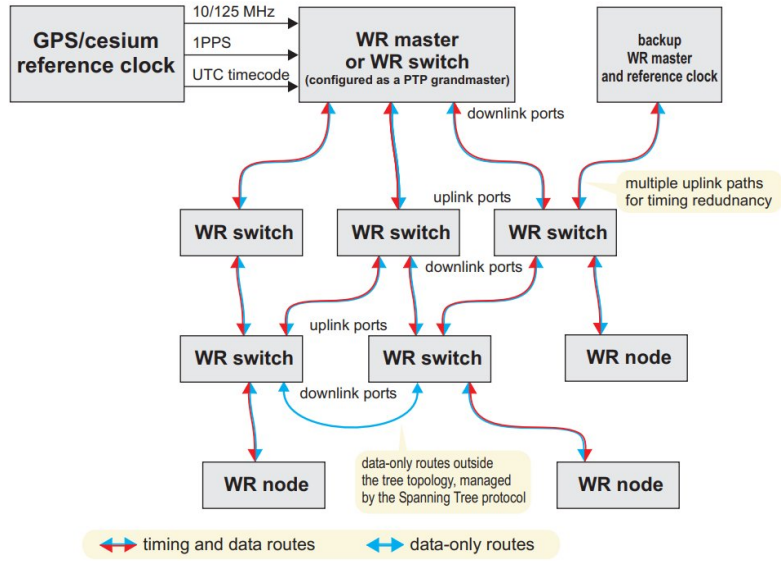
White Rabbit protocol

White Rabbit protocol

Project initiated by CERN and GSI for sub-nanosecond accuracy time transfer.

- Gigabit Ethernet network based on:
  - Precision Time Protocol (IEEE1588);
  - Synchronous Ethernet;
  - DDMTD Phase tracking (Digital Dual Mixer Time Difference).
- Time propagation compensation.
- Large area and node number (+1000).
- Deterministic network.

Provides: Synchronisation, Timestamp and Pulse-Per-Second (PPS) signal.



White Rabbit network topology (1)

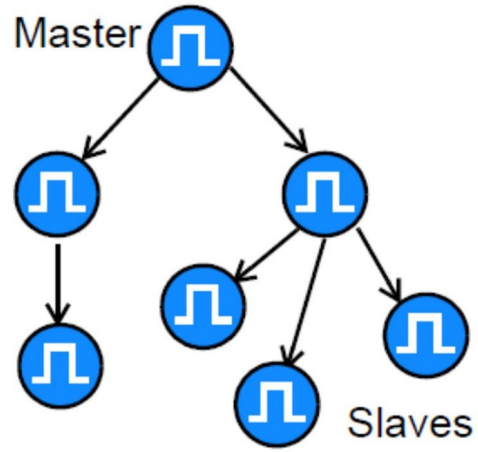
(1) Precise time and frequency transfer in a White Rabbit network, *T. Wlostowski*

White Rabbit protocol: Synchronous Ethernet

Synchronous Ethernet (Sync-E): Clock transfer throughout Ethernet network

- Hierarchical master – slave architecture;
- Recover master clock from data stream in slave node;
- Allows sub-nanosecond synchronisation.

Use high quality clock (GPS, Rubidium, atomic clock) as network reference clock



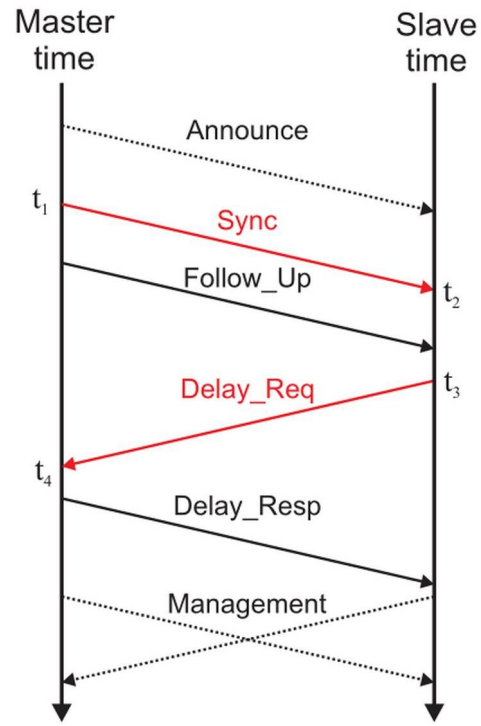
Sync-E network architecture

White Rabbit protocol: Precision Time Protocol

Precision Time Protocol (IEEE1588): Protocol for clock synchronisation throughout a network with high precision.

- Hierarchical master – slave architecture;
- Timestamped packets;
- Time delay measurement.

Measure delay introduced by physical link between nodes and frequency drift between clocks.



PTPv2 message exchange (1)

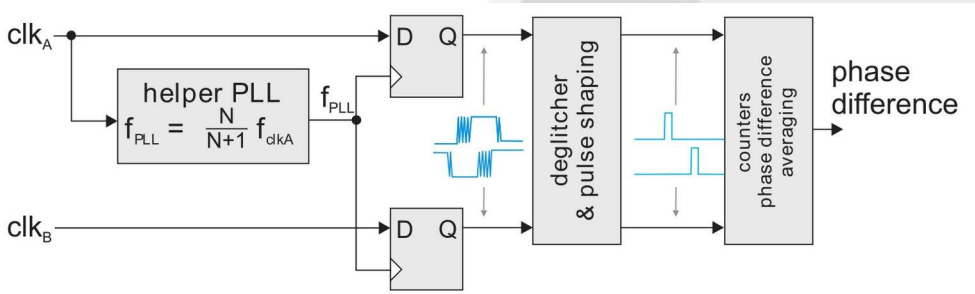
(1) **Precise time and frequency transfer in a White Rabbit network,** *T. Wlostowski*

White Rabbit protocol: Digital Dual Mixer Time Difference

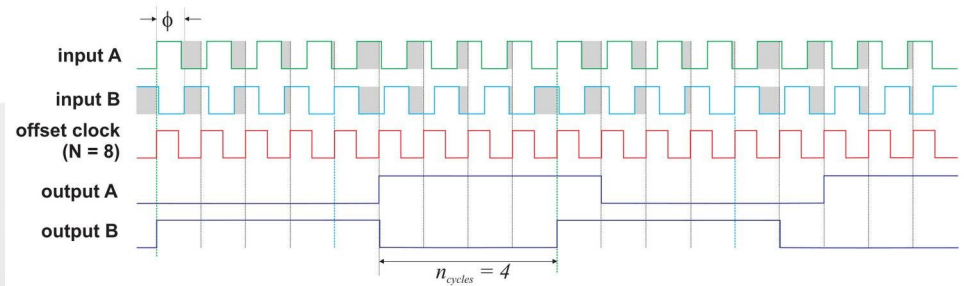
Digital Dual Mixer Time Difference (DDMTD):

- Converte a phase shift from a high frequency domain into a lower frequency domain.

Measure phase between local oscillator and recovered clock.



DDMTD phase detector structure (1)

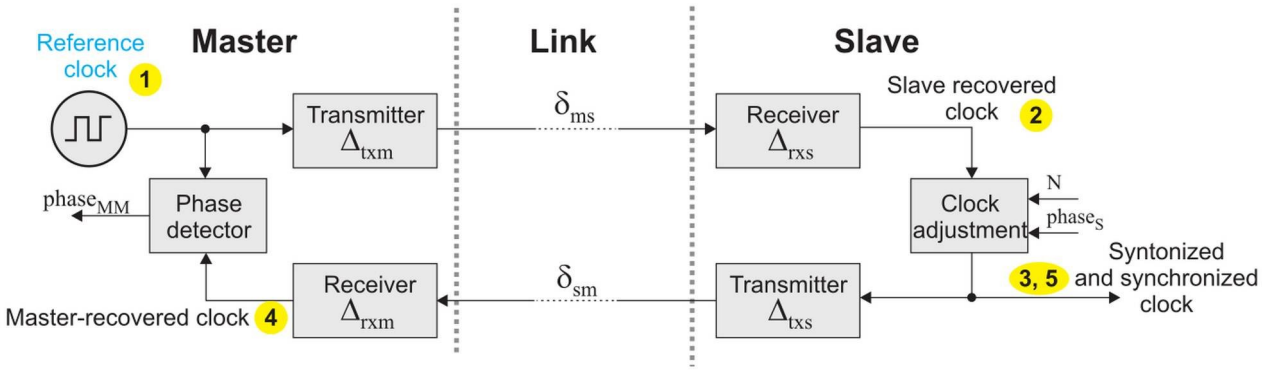


DDMTD signals (1)

(1) Precise time and frequency transfer in a White Rabbit network, *T. Wlostowski*

White Rabbit protocol

1) Reference clock transmitted by Master node and recovered on slave node (Sync-E);
2) Measure Master – Slave and Master – Master delay (PTP);
3) Measure phase difference between recovered and local oscillator clocks (DDMTD);
4) Local clock phase adjustment (VCXO controlled with a DAC).



White Rabbit link model (1)

(1) Precise time and frequency transfer in a White Rabbit network, *T. Wlostowski*

White Rabbit implementation and evaluation

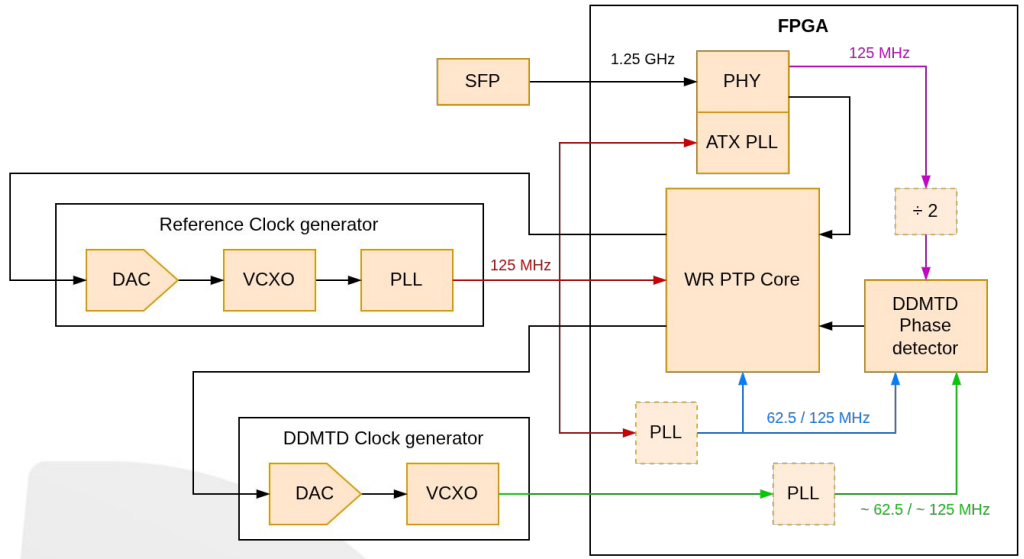
White Rabbit implementation

1) White Rabbit core implemented within the FPGA (PHY, DDMTD, PLLs, ...)

2) Two pairs of VCXO and DAC for local clock adjustment.

3) Optional internal PLL (according to the FPGA brand/model)

WR core can also be fully implemented in an FPGA but the stability is reduced

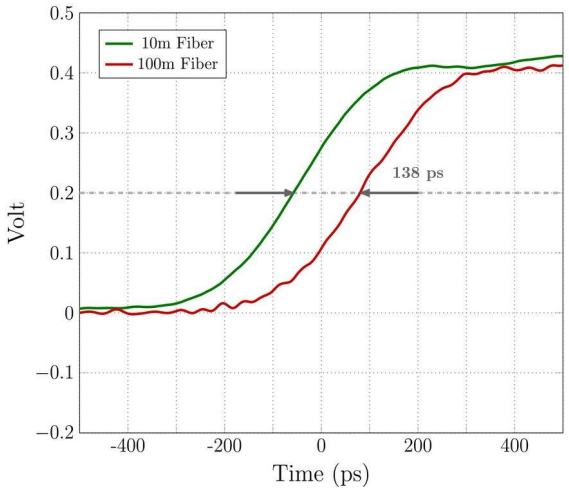


White Rabbit implementation

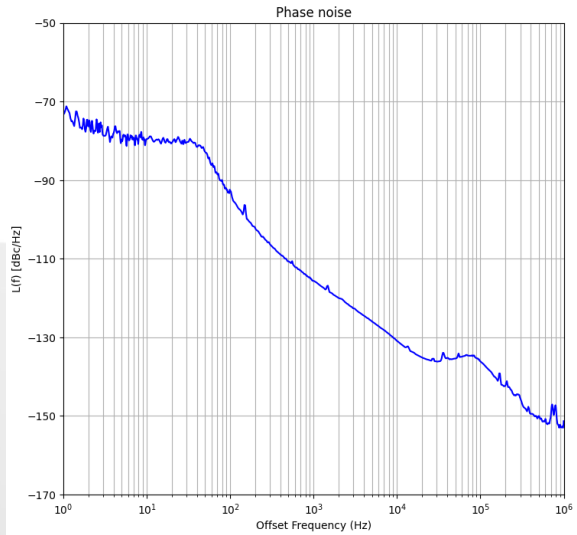
Evaluation criterion

Mainly two criterion : time and frequency precision.

- Time synchronisation: delay between Pulse-Per-Second (PPS) signals generated by each WR nodes.
- Phase noise (jitter): frequency-domain representation of random fluctuations in the phase of a signal (time-domain deviations from perfect periodicity).



PPS alignment between two WR nodes



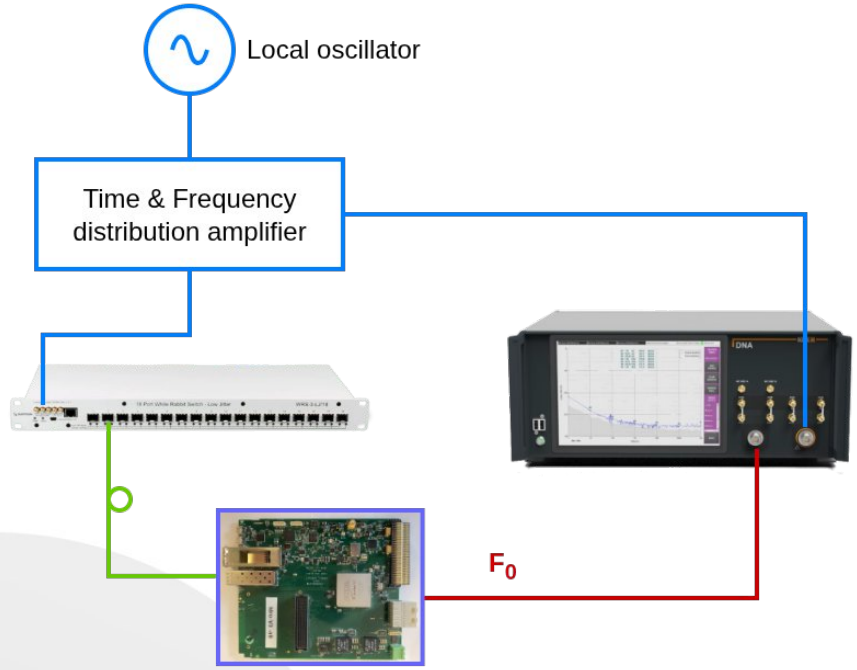
Phase noise measurement

White Rabbit evaluation

Phase noise measurement setup at IJCLab:

- Reference clock (GPS, rubidium);
- WR switch configured as Grand-Master;
- WR slave (Idrogen board);
- Digital Phase Noise and Frequency Analyzer (DNA)

DNA measure the phase noise of the WR slave local clock compared to its own oscillator or an external reference clock.



WR phase noise measurement setup

White Rabbit additional features

White Rabbit additional features

WR core provides multiple access interfaces for additional features:

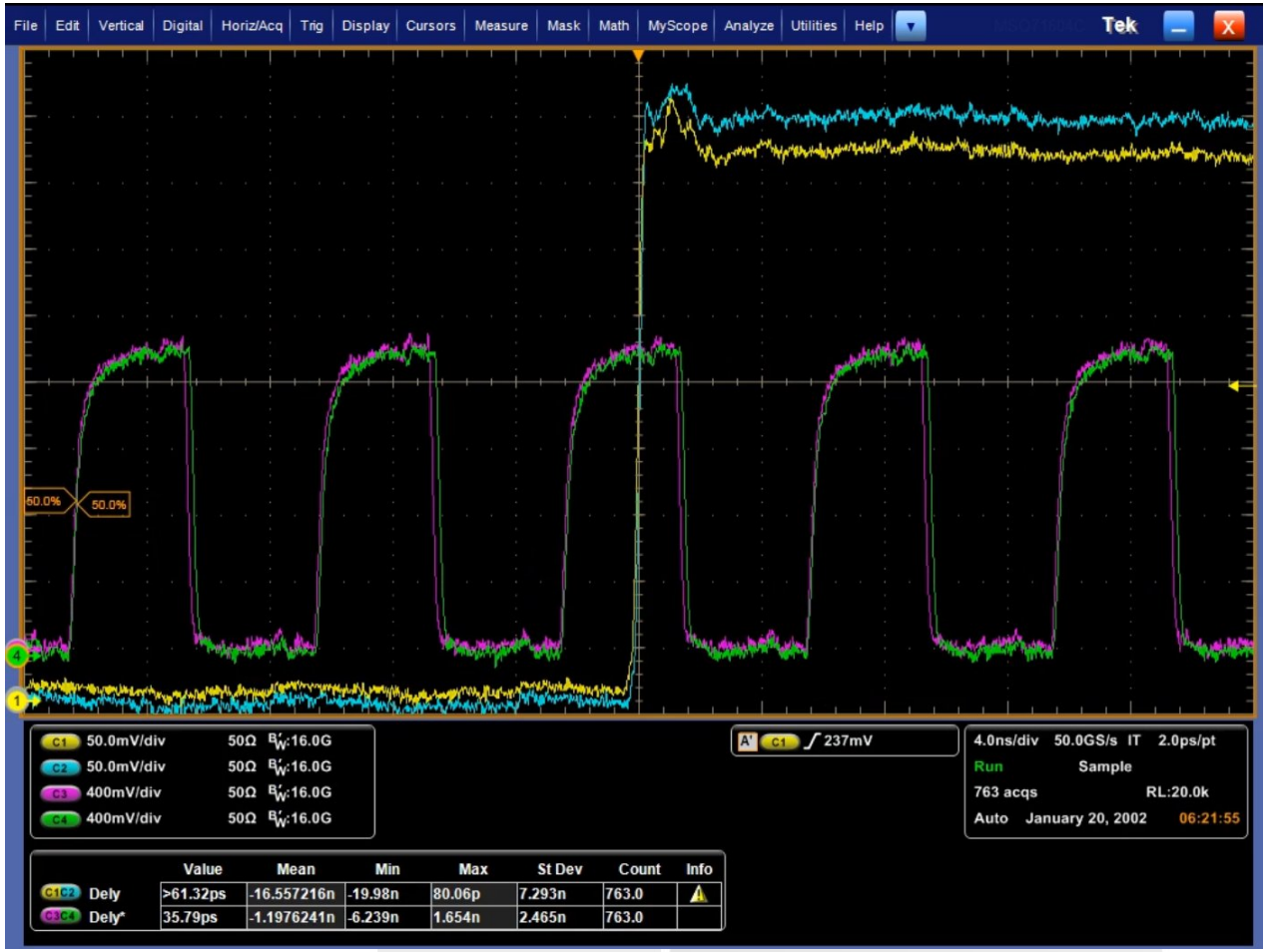
- Wishbone slave port:
  - External access to diagnostic registers or virtual UART;
  - Access for an external master like PCIe, Ethernet (IPBus, Etherbone, etc), embeded processor, …
- Wishbone master port:
  - Add peripherals to the WR core (needs WR software modifications);
- WR fabric interface:
  - Dedicated port to send and receive Ethernet packets.

Conclusion

Conclusion

- Needs of very precise synchronisation for large facilities.
- White Rabbit protocol: an adaptative and scalable network for sub-nanosecond synchronisation using standard technologies (Synch-E, PTP, DDMTD).
- Achieve sub-nanosecond time synchronisation (PPS alignment) and sub-picosecond integrated phase noise (RMS jitter).
  Cf. Presentation from Daniel Charlet

White Rabbit protocol

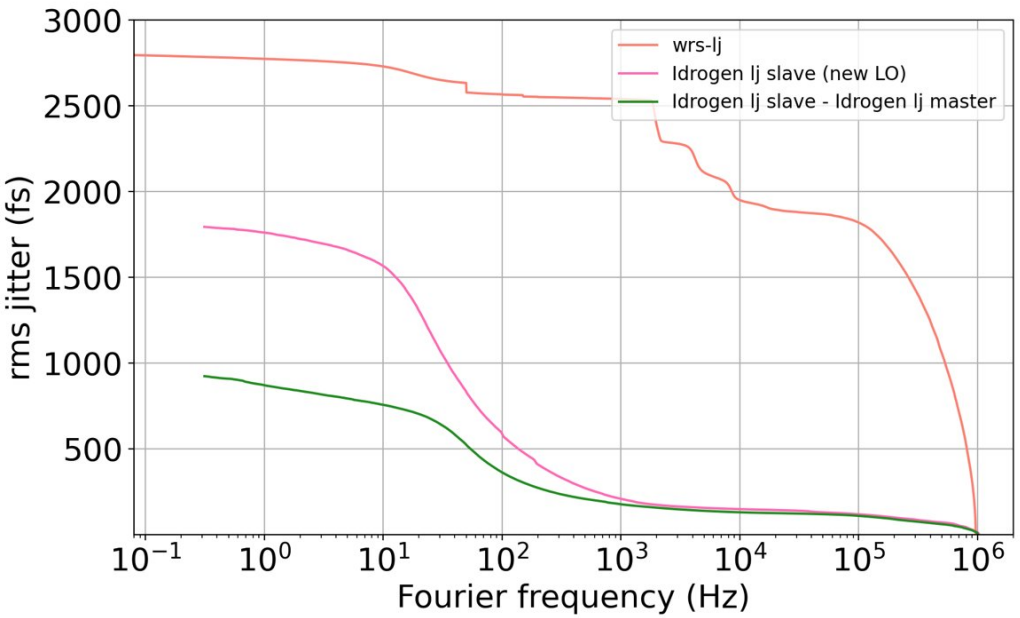


Spare

IDROGEN board performance

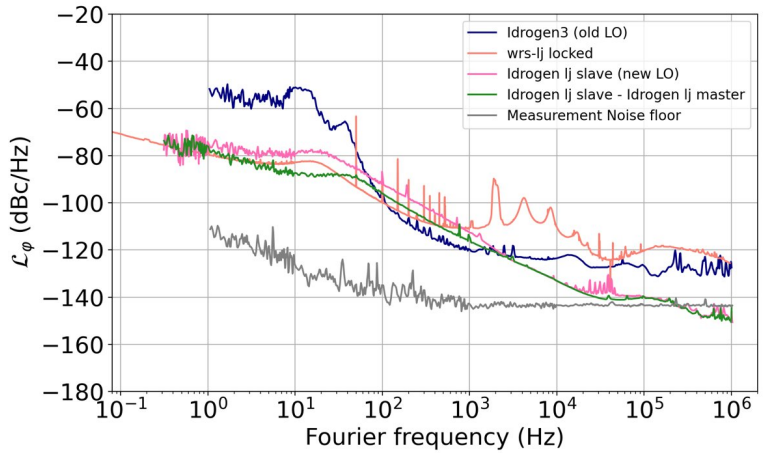
Phase noise measurement

Integrated jitter according to integration range



Variation of lower bound of integration range.
Upper bound fixed at 1 MHz

Phase noise measurement



	1	10	100	1,000	10,000
wrs-lj	2 246	2 191	1 984	1 075	1 075
S	1 757	1 557	563	110	110
S-M	866	751	351	94	94
GM	445	439	432	129	129

Table 1: Integrated rms jitter expressed in fs for Idrogen and a wrs-lj, for integration bandwidth up to 100 kHz

IDROGEN BOARD: 4x better than Switch
Low Jitter from Safran/Seven Solution