

# FemtoSynch: 100-fs, 5000-km clock synchronization



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For the LTE-IJCLab collaboration



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[Assemblée générale du GDR DI21](#) – June 2026 – LPSC, Grenoble

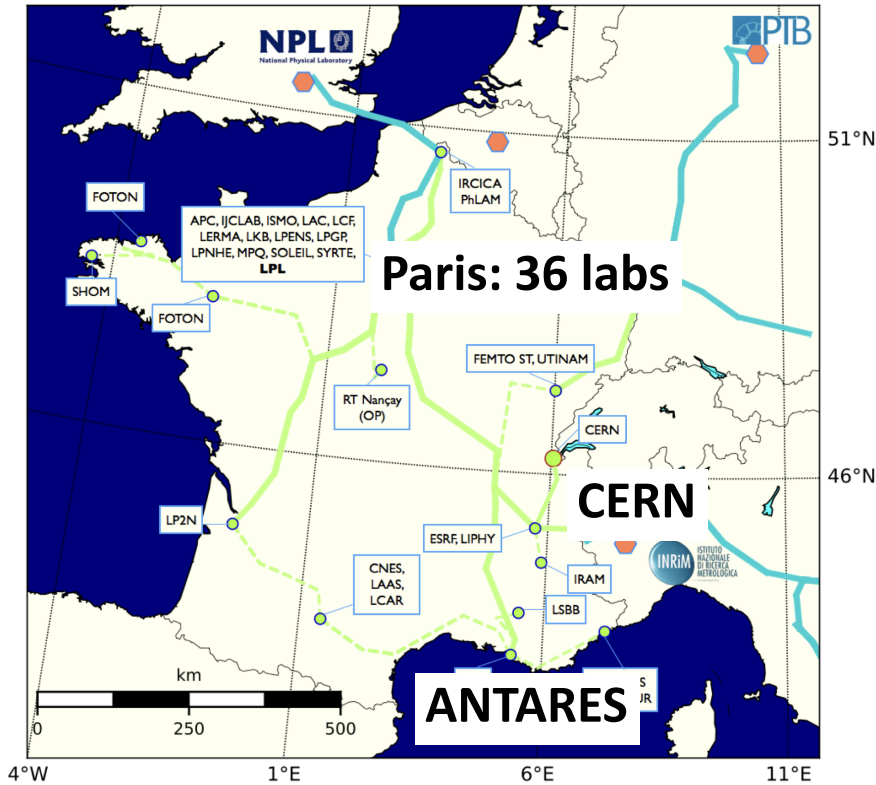
- Context: strong scientific and technical drivers
- Working base: improvement of the IDROGEN board through intermediate deliverables
- Resources: IN2P3 + INSU collaboration
- Summary and prospects

# Drivers

## Issue: signal time and phase shift due to propagation delay

Present off-the-shelf solution: clock synchronization with White Rabbit:

- 20-ps resolution with standard white rabbit switch
- at best 5+ ps with low-jitter switches over 10 km (1-s stability)
- Single clock frequency
- Timestamp: build in a White Rabbit node
- Connection to digitizer: expensive, integration development
- Accelerator synchronization and monitoring
  - **CERN DRD7.3b2: timing distribution techniques**
    - Bench-marking of the performance of COTS- or custom-based solutions
    - assess achievable timing precision and determinism.
    - Investigation of generic solutions to mitigate the observed limitations  
-> [CERN proposal](#)
  - **KEK upgrade: 5-ps jitter over 5 km**
    - frequency generation phased with a common 10-MHz clock
    - Synchronized Beam Position Monitoring signal digitization
    - ANR COMPO: laser synchronization
  - **PERLE: 150-fs jitter at 801.58 MHz**
    - Synchronized Beam Position Monitoring
- Instrumentation
  - CERN (LHCb: 10 ps)
  - CTAO: 10-ps correlation of 5-km separated telescopes
- Multi-messenger gravitational waves
  - World scale (5 000 km, < 1 ns)



The REFIMEVE frequency distribution network:  
4,000 km implemented, 6,000 km planned

## • Sensing:

- SENSEI European project (LTE, Exail company)
- internet optical fiber as large scale, low cost, permanent seismic sensor
- $< 100$  fs,  $> 1000$  km

## • REFIMEVE: European network (ESFRI) INSU, INSIS, IN2P3, CERN

## • Radioastronomy

## • Quantum technologies

- signal propagation time measurement to discriminate signal from noise

- **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).**

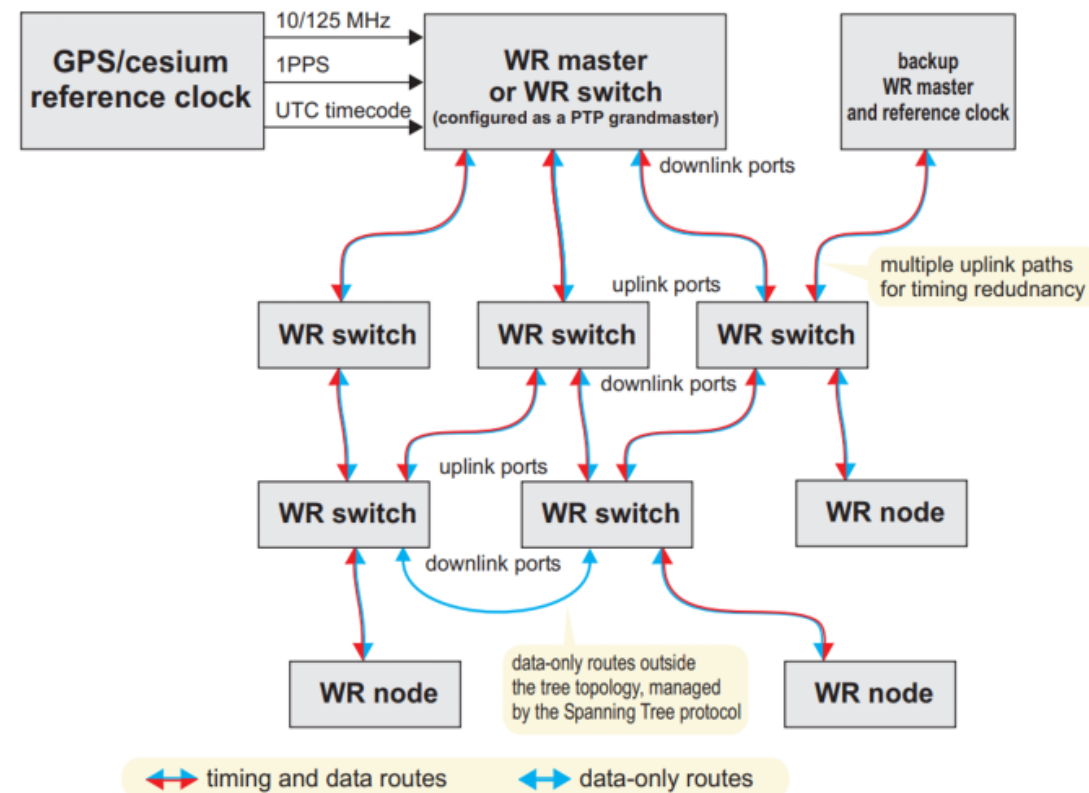
**Deterministic network.**

**Provides:**

Synchronisation,

Timestamp and

Pulse-Per-Second (PPS) signal.



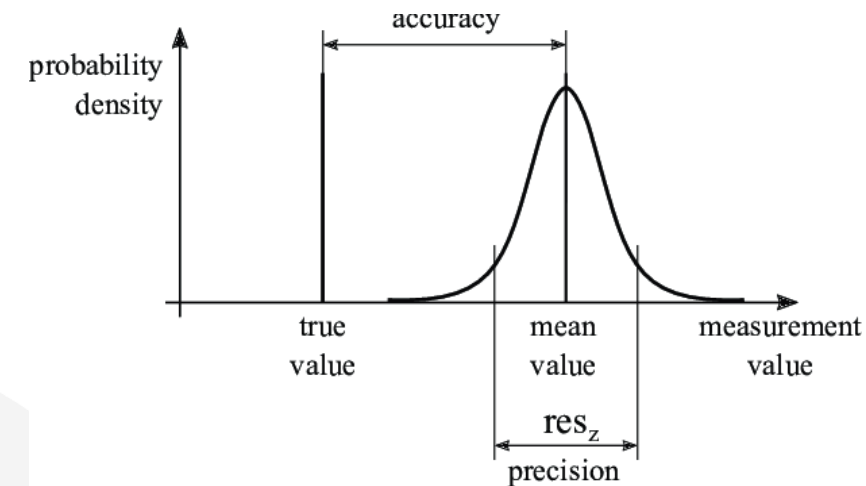
White Rabbit network topology <sup>(1)</sup>

- **Extend White Rabbit performance**

- **Precision** < 100 fs (Accelerator, fiber sensing,...)
- Long time phase stability on frequency generation (accelerator, ..)
- **Distance of uses versus precision** > 10km → 1000km ( Interferometer,..)
- Associated data acquisition performance :
  - Numbers of high precision nodes > 256 (high energy detectors) (today: 17 max)
  - WR 1Gb/s to 10 Gb/s Ethernet (MAN et WAN network,..)

- **Improve performance**

- **Porting WR on new ALTERA platforms ARRIA 10 → AGILEX 3/5/9**
- Associated data acquisition performance
  - Data acquisition Frequency > 1GSPS → 3GSPS 14bit
  - Data transfer rate 20Gb → 40Gb → 100Gbs



# Working base

*Modular picosecond clock synchronization system for accelerators and data acquisition*

- **Versatility – modularity**

- Motherboard and daughterboards with standard connectivity and expansion options (FMC, RTM,  $\mu$ TCA, SFP+, QSFP)
- Automatic configuration
- Layered architecture (hardware to software)

- **Performance**

- Synchronization with 1 ps RMS jitter thanks to White Rabbit
- Data transfer at 20 Gb/s (up to 40 Gb/s)

Standard WR: 20 ps  
Low-jitter WR: 5 ps  
IDROGEN: 1 ps

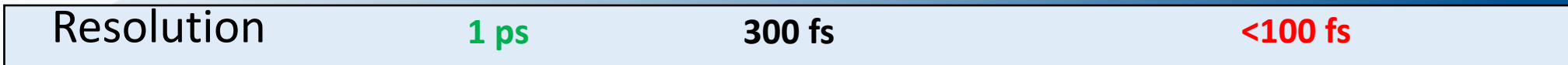
See poster GDR DI2I, 2025 - [hal-05120726](https://hal.archives-ouvertes.fr/hal-05120726)

## Initiated by IN2P3 R&T projects

- DAQGEN:
  - CPPM, IJCLab, LPSC
  - Generic data acquisition (PCIe40 for LHCb)
- TIMED:
  - IJCLab, LPSC, LPCC, LP2IB + INSU (SYRTE -> LTE)
  - White Rabbit implementation

## Applications to...

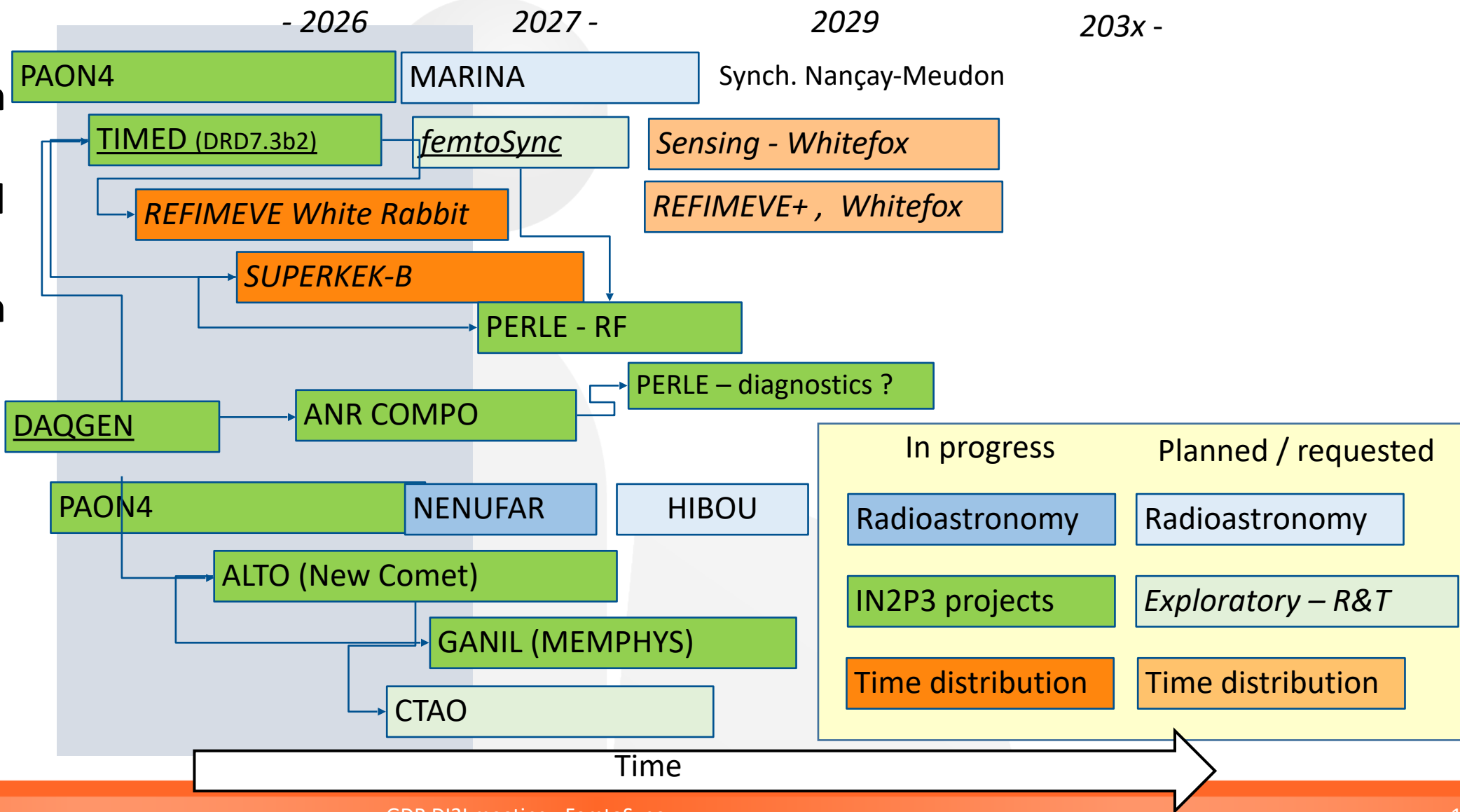
- IDROGEN
- PCIe400
- OXIGEN



**Cross-Site  
synchronization**

**Accelerator and  
detectors  
synchronization**

**Data  
acquisition +  
continuous  
calculation**



- IN2P3 labs

- Subatech, IPHC, IPNL , IJCLab, LP2IB, CPPM, LAPP, LPLC

- IN2P3 projects

- IJCLab : PERLE (accelerator), CTAO (Astronomy), Belle II (ANR COMPO), PAON IV (Astronomy), PICMIC (Detector), NewComet (Detector), PCIe400 (acquisition), GANIL-MEMPHYS (accelerator R&D), LPSC(Faster3)

- INSU

- NENUFAR (astronomy), T+REFIMEVE(timing distribution)

- Other

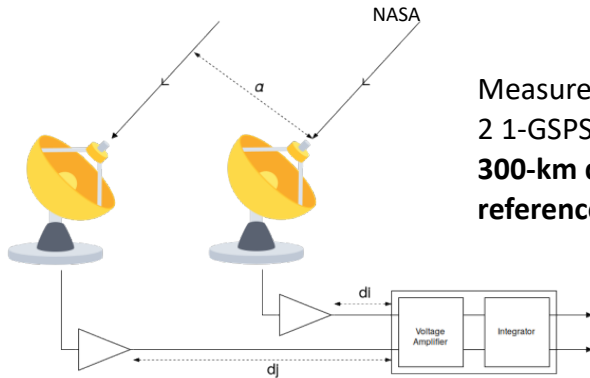
- SUPERKEK-B, SENSEI

- Requests

- MARINA(Time distribution), HIBOU (Radio astronomy), QUASAR (University Geneve Astronomy)

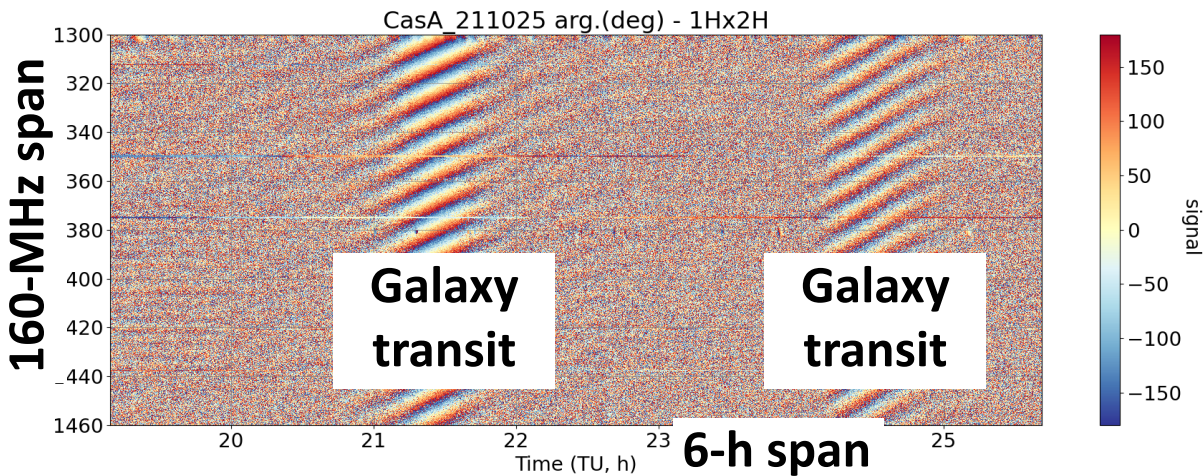
- **Inter-site synchronization**
  - PAON-4: **DAQ 1-GSPS synchronization - 300 km** - Nançay-LTE clock (2025) – publication forthcoming
- **Accelerator and detector synchronization**
  - LTE tests:
    - Phase drift – communication workshop
    - Synchronization of a ps laser with an electronic board costing less than €10k – whereas previously required equipment costing €50-100k [Accepted by IEEE Transactions on Instrumentation & Measurement](#)
  - KEK, ATF: Study of **laser-beam** arrival time synchronization towards **sub-picosecond stability** level, [LCWS 2025](#)
  - Synchronization to **1 ps of a repeating laser at 800 MHz, 100 km** (*Laser Synchronisation Over One Hundred Kilometers With Stability at Picosecond Scale*, accepted by IEEE Transactions on Instrumentation & Measurement)
- **Data acquisition, embedded computing**
  - PAON-4: FFT software
  - CTAO: continuous acquisition principle, 50% of the transfer rate (2025)

\*



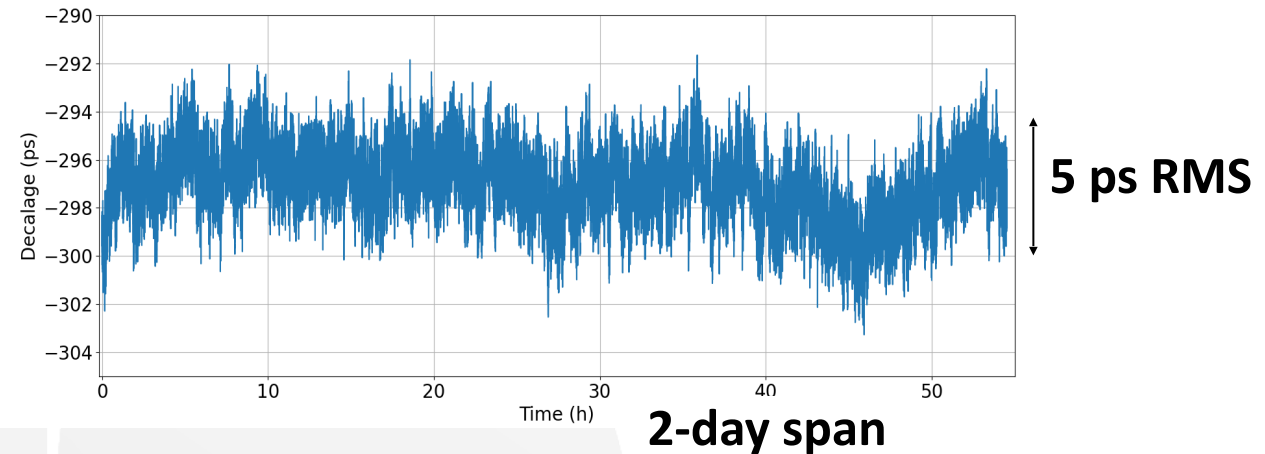
Measurement at Nançay – Oct. 2025  
2 1-GSPS FADC **synchronized with the**  
**300-km distant Paris Observatory**  
**reference clock**

Interference fringes of source signal  
Phase difference depending on source direction



## • Radioastronomy:

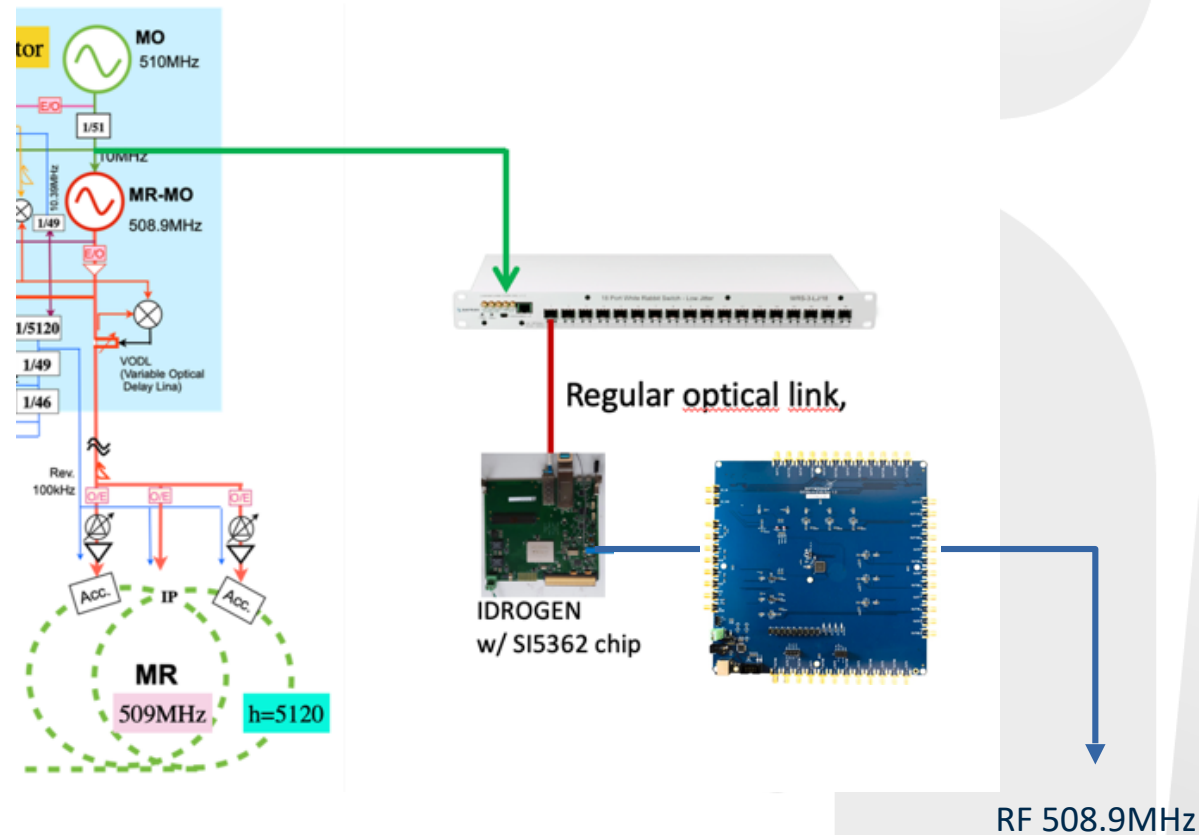
- 5-ps jitter over 5 km
- frequency generation phased with a common 10-MHz clock



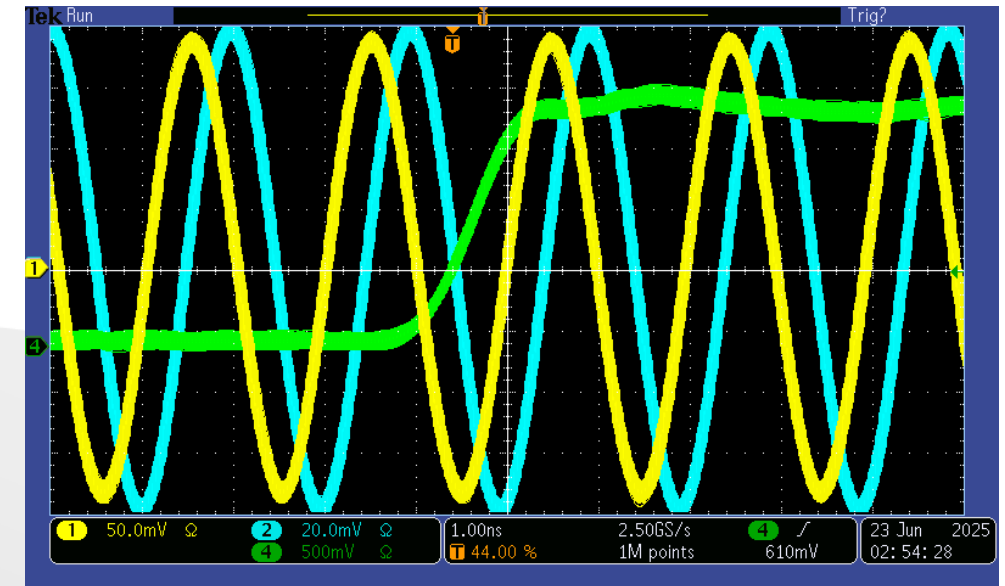


# Clock synthesis for accelerators: 508.9 MHz for SUPERKEK B

Last result of Super KEK B clock synchronization with IJCLab IDROGEN board.



Comparison of SKB and Idrogen clocks  
10h persistency, at scope resolution limit





- 
- The diagram illustrates the experimental setup for the White Rabbit clock distribution system, divided into three main functional areas:
- White rabbit clock distribution:** This section includes the RF Oscillator (Rohde & Schwarz SMB100A option B1H), the Idrogen Master (MIB), the Idrogen Slave (SIB), and the SIC (Skyworks SI5362-EVB). The MIB and SIB are connected via an optical fiber using the WhiteRabbit protocol, with a distance of up to 50km. The SIB is connected to the SIC via a 4.FO signal.
  - Laser lock scheme:** This section includes the Laser (Menhir Photonics Menhir-1030), the PhD (Alphas UPD-70), the PID (TEM Messtechnik Laselock), and the PZTs. The Laser is connected to the PhD via 1 μm light. The PhD is connected to the PID via a 15nH inductor. The PID is connected to the Laser via PZTs.
  - Diagnostics:** This section includes the 50Ω Splitter, the Minicircuits SLP-15 + BLP-1.9 LPF, the Minicircuits ZX05-43H LPF, the Femto DHPVA-201 Amp, the Minicircuits SLP-15 + BLP-1.9 LPF, the Minicircuits ZX05-43H LPF, the Minicircuits VLF-320 + BLP-1.9 LPF, and the Rohde & Schwarz RTO2044 Oscilloscope. The 50Ω Splitter is connected to the Minicircuits SLP-15 + BLP-1.9 LPF, which is connected to the Femto DHPVA-201 Amp. The 50Ω Splitter is also connected to the Minicircuits ZX05-43H LPF, which is connected to the Minicircuits SLP-15 + BLP-1.9 LPF, which is connected to the Minicircuits ZX05-43H LPF, which is connected to the Minicircuits VLF-320 + BLP-1.9 LPF, which is connected to the Rohde & Schwarz RTO2044 Oscilloscope.

Lower synchronization rates

- 
- Overlapped allan deviation
- time [s]
- 5 km optical link  
50 km optical link  
100 km optical link
- A. Renaux, R. Chiche, A. Martens et al. (IJCLab)*

Laser Synchronisation Over One Hundred Kilometers With Stability at Picosecond Scale  
IEEE Transactions on Instrumentation & Measurement

## Talks at CERN's White Rabbit Workshop: [2024](#), [2025](#), [2026](#)

### Recognition of expertise

- Board sales + consulting requested by LTE, KEK, IPHC, Subatech
- Consulting requested by CPPM, LPSC, LAPP, LP2IB, LPC
- Use of the IJCLab **test bench to qualify WR** developments at the ps (CPPM on PCIe400, LPSC, LPC for FASTER3)
- Request to participate in the CERN consortium, then request to participate in the CNRS working group on the White Rabbit (DC, BG)
- Request from CERN (Sophie Baron) to participate in net-FELIX (DAQ card for ATLAS, CMS, LHCb)
- 40 boards produced

### Towards FemtoSynch

- WhiteFox board development
- Long distance
  - Accuracy test (800km) Paris to London
  - Precision test (200Km) Meudon to Nançay
- Jitter improvement : temperature stabilization and compensation

### Data acquisition improvements

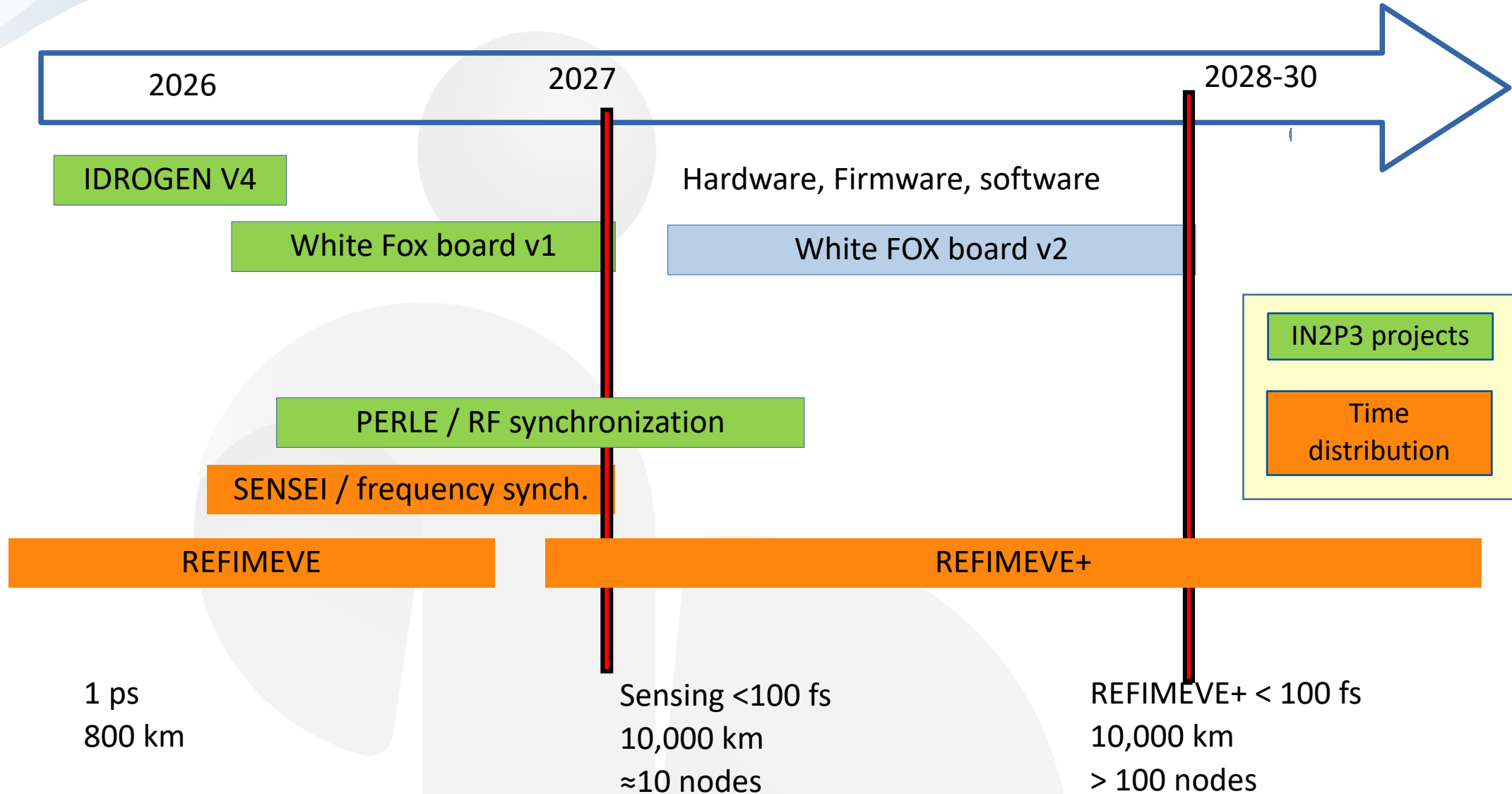
- 40Gb/s
- RDMA

# Implementation

FemtoSync's deliverables: prototypes

Major projects' deliverables: requirements, commissioning, production

Performance



| Financements      | 2026             | 2027             | 2028            | 2029            | Total            |
|-------------------|------------------|------------------|-----------------|-----------------|------------------|
| INSU - FemtoSync  | 64 484 €         | 40 434 €         | 17 934 €        | 13 451 €        | 122 852 €        |
| IN2P3 - FemtoSync | 40 000 €         | 8 500 €          | 6 000 €         | - €             | 54 500 €         |
| RP IJCLab Ventes  | 20 944 €         | 72 934 €         | 67 934 €        | 18 451 €        | 161 812 €        |
| <b>TOTAL</b>      | <b>125 427 €</b> | <b>121 868 €</b> | <b>91 868 €</b> | <b>31 901 €</b> | <b>339 163 €</b> |

- Funding contribution from LTE (INSU)
- Funding requests
  - Board developments
  - Test material
  - White Rabbit consortium fee
- People
  - Permanent FTE over 3 years : INSU = 0,75 FTE, IN2P3 = 3,5 FTE
  - 1 IN2P3 CDD
  - LTE's contracts fund between 2 to 3 CDD
  - Request to IN2P3: 1 technical PhD
  - Long-term: stabilize positions for board design to production

| Nom des personnes  | Statut | 2026        | 2027        | 2028        | Total (FTE) |
|--------------------|--------|-------------|-------------|-------------|-------------|
| <b>IJCLab</b>      |        | <b>80%</b>  | <b>50%</b>  | <b>30%</b>  | <b>1,60</b> |
| M. Daniel Charlet  | IR     | 20%         | 10%         |             | 0,30        |
| M. Donovan Kin     | AI     | 20%         |             |             | 0,20        |
| M. Antoine Back    | IR     | 10%         | 10%         | 10%         | 0,30        |
| M. Chafik Cheikali | IE     | 10%         | 10%         |             | 0,20        |
| M. Philippe Gauron | IR     | 10%         | 10%         | 10%         | 0,30        |
| M. Mattias Vecchio | IR     | 10%         | 10%         | 10%         | 0,30        |
| <b>TOTAL (FTE)</b> |        | <b>0,80</b> | <b>0,50</b> | <b>0,30</b> | <b>1,60</b> |

| Nom des personnes          | Statut | 2026        | 2027        | 2028        | Total (FTE) |
|----------------------------|--------|-------------|-------------|-------------|-------------|
| <b>LTE</b>                 |        | <b>25%</b>  | <b>25%</b>  | <b>25%</b>  | <b>0,75</b> |
| M. Paul-Eric Pottie (INSU) | IR     | 20%         | 20%         | 20%         | 0,60        |
| M. Michel Lours (INSU)     | IR     | 5%          | 5%          | 5%          | 0,15        |
| <b>TOTAL (FTE)</b>         |        | <b>0,25</b> | <b>0,25</b> | <b>0,25</b> | <b>0,75</b> |

- WP1 : Cartes - Daniel Charlet (IJCLab)
- WP1.1 : cartes (IDROGEN et WhiteFox)
- WP1.2 : firmware (stagiaire M2 E3A) 6 mois
- WP1.3 : software de contrôle-commande de banc de test : M. Vecchio, C. Cheikali (IJCLab)
- WP1.4 : software de contrôle-commande de production : M. Vecchio, C. Cheikali
- WP2 : Qualification - Paul-Eric Pottie (LTE)
- WP2.1 métrologie (LTE) Paul-Eric Pottie (LTE)
- WP2.2 fiabilité logicielle P. Gauron (IJCLab)

# Conclusion

- **Strong collaboration INSU-IN2P3**
  - **Framework agreement LTE IJCLab**
  - INSU (REFIMEVE + INSU) gave operational requirements, know-how and infrastructure in metrology, funding for early prototypes + coming evolutions, identified **industrial partners**
  - IN2P3 funded major R&T projects (DAQGEN, TIMED) for the technical implementation
  - IJCLab funded early production + « recettes » des cartes pour financements à venir
  - IN2P3 to play a major role with FemtoSync
  - INSU project funded CDD and interships, IN2P3
- **Technical goals**
  - Integrated Enhanced White Rabbit Node (<100 fs, > 10,000 km) + data acquisition interface + >10 Gb/s
  - White Rabbit enhancement required by major IN2P3 projects
  - The IDROGEN baseline ensures the development
- **Requests to IN2P3 for FemtoSync**
  - Funding through R&T program: 55 k€ over 3 years
  - Positions: technical thesis
- **Requested « competences » to reinforce**
  - High-speed electronic board (design, layout, test, production)
  - FPGA firmware for clock synchronization + rapid data transfer
  - Software: slow-control, automatic deployment, rugged user interface
  - Production follow-up
  - Administrative support (tender, juridical, technology transfer)

**CNRS's next membership in the CERN's White Rabbit consortium**



# Thank you!

# Backup



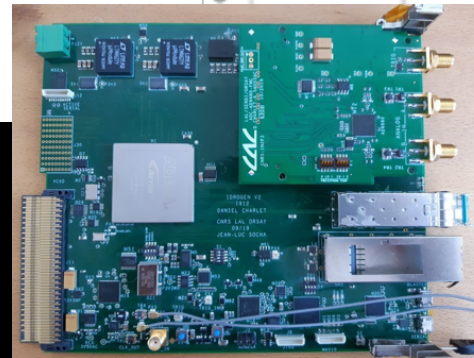
## Accuracy performances between 2 reference clock at $\approx 800\text{km}$ (optical link).

- LTE collaboratrion
- One master IDROGEN in Paris , one slave in London
- Comparison Reference clock (UTC OP) at Observatoire de Paris and Reference clock (UTC OP) at London 232km away;
- Synchronization through national RENATER (REFIMEVE) network and dedicated fiber in UK



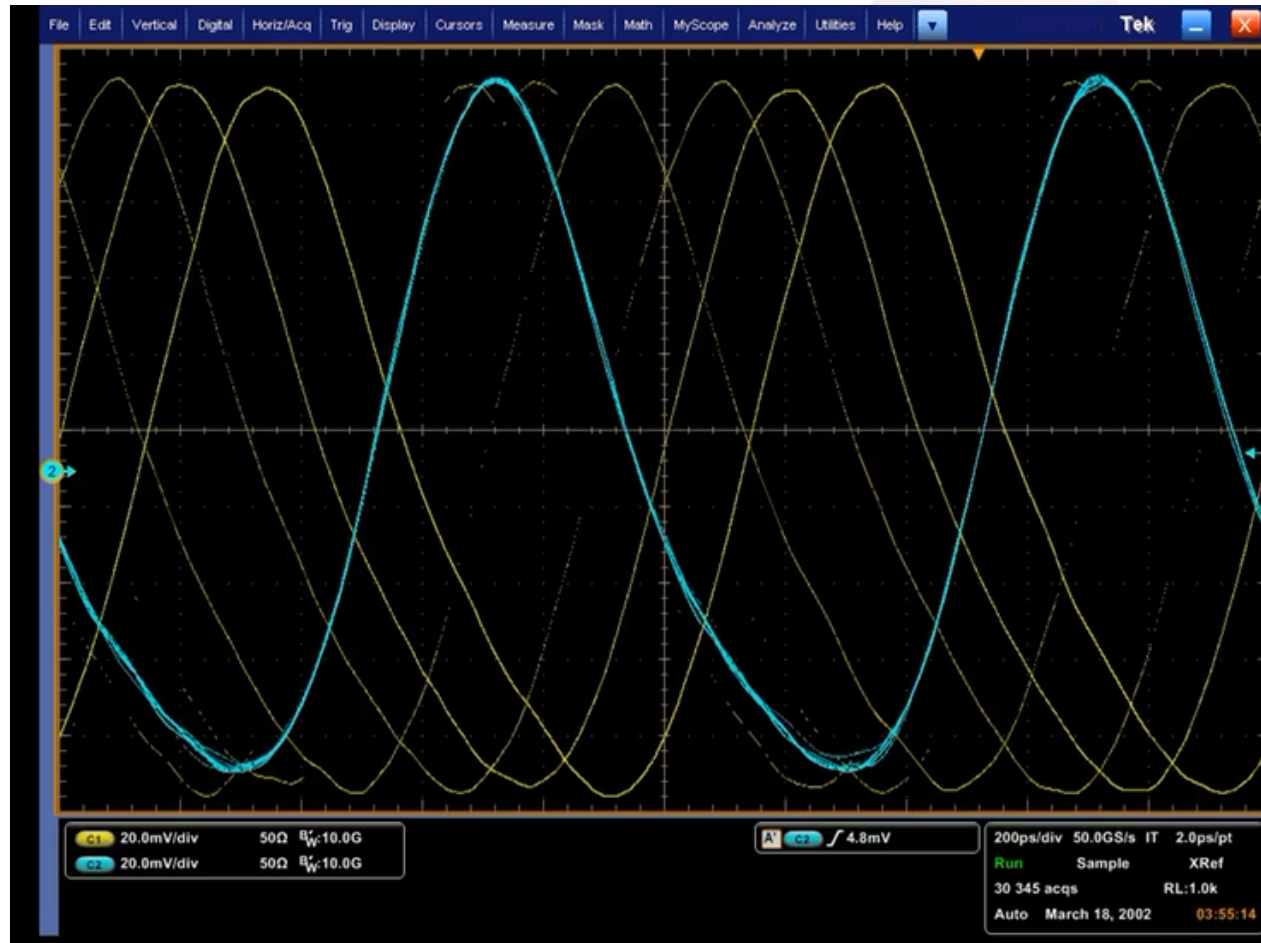


- SBL causes serious damage to the collimator/detector and prevent smooth operation of SuperKEKB
- Nano-second-Synchronisation of BOR can abort the beam before SBL! => IDROGEN boards, synchronized by White Rabbit (WR), acquire local bunch oscillations and send data to a Versal (VPK120) board.





# White Rabbit protocol



```
IDR0 WRPC Monitor wrpc-v5.0-pre1-1099-gfe3a2ee2 | Esc/q = exit; r = redraw
TAI Time: 2026-04-15-17:04:05 UTC offset: 0 PLL mode: BC state: Locked
-----+-----+-----+-----+-----+-----+
# | MAC | IP (source) | RX | TX | VLAN |
-----+-----+-----+-----+-----+
*0 | 22:33:03:e9:46:c2 | | 731801 | 233907 | 0 |

--- HAL ---|----- PPSI -----|
Itf | Frq | Config | MAC of peer port | PTP/EXT/PDETECT States | Pro
-----+-----+-----+-----+-----+
*wr0 | Lck | auto | 00:00:00:00:00:00 | DISABLED /IDLE /NONE | R-W
Pro(ocol): R-RawEth, V-VLAN, U-UDP

----- Synchronization status -----
Link down, master mode or sync info not valid
□
```

- Accord de collaboration IJCLab-LTE
  - Formalisation de ce qui était fait : expertise IDROGEN (IJCLab), moyens de test + REFIMEVE (LTE)
  - REFIMEVE : valorisation + visibilité internationale à long terme
- Collaboration White Rabbit du CERN (à venir)
  - Reconnaissance du travail fait avec TIMED
  - Autorité de certification et d'évolution de la norme White Rabbit
  - Intervient dans les relations avec les industriels pour les marchés du CERN
  - Possibilité de labellisation du banc de test pour prestations (certification pour entreprises vendant des cartes avec White Rabbit)