FemtoSynch:
100-fs, 5000-km clock synchronization

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For the LTE-IJCLab collaboration

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Groupement De Recherche
Détecteurs et Instrumentation pour les 2 Infinis

Assemblée générale du GDR DI2I – June 2026 – LPSC, Grenoble

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

Drivers

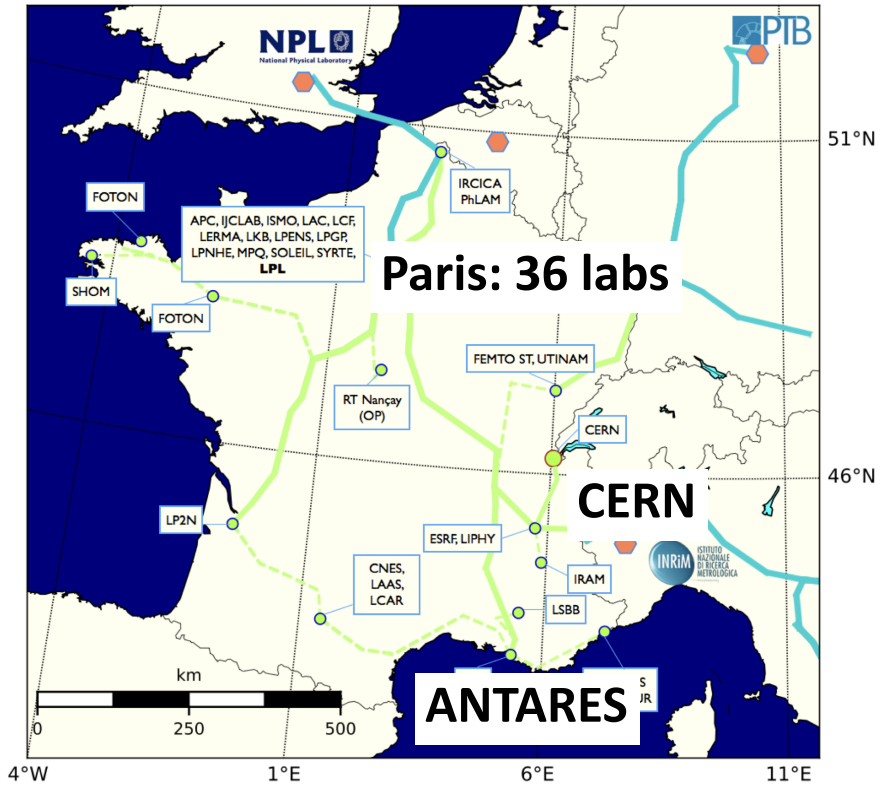
Issue: signal time and phase shift due to propagation delay

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 Postion Monitoring signal digitization
    - ANR COMPO: laser synchronization
  - PERLE: **150-fs jitter at 801.58 MHz**
    - Synchronized Beam Postion 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**)

Clock synchronization beyond IN2P3



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 sismic 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

Goal: from White Rabbit…

- **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).

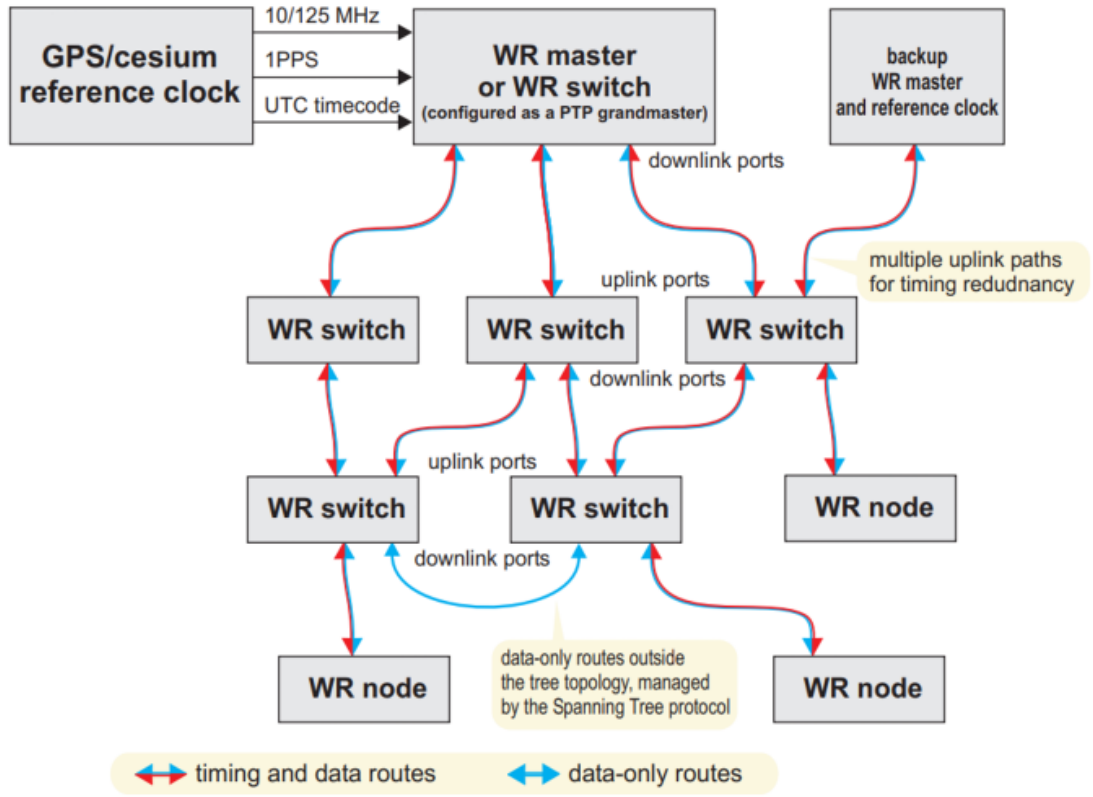
Deterministic network.

Provides:

Synchronisation,

Timestamp and

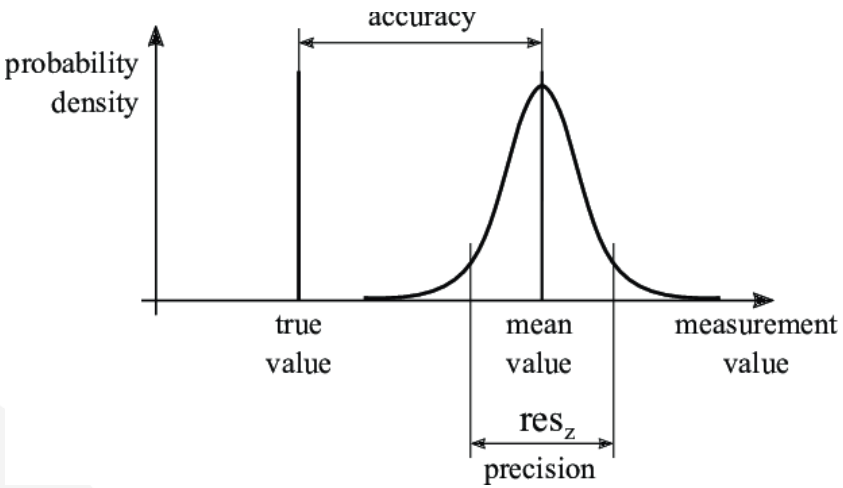
Pulse-Per-Second (PPS) signal.



White Rabbit network topology (1)

… to FemtoSynch (White Fox)

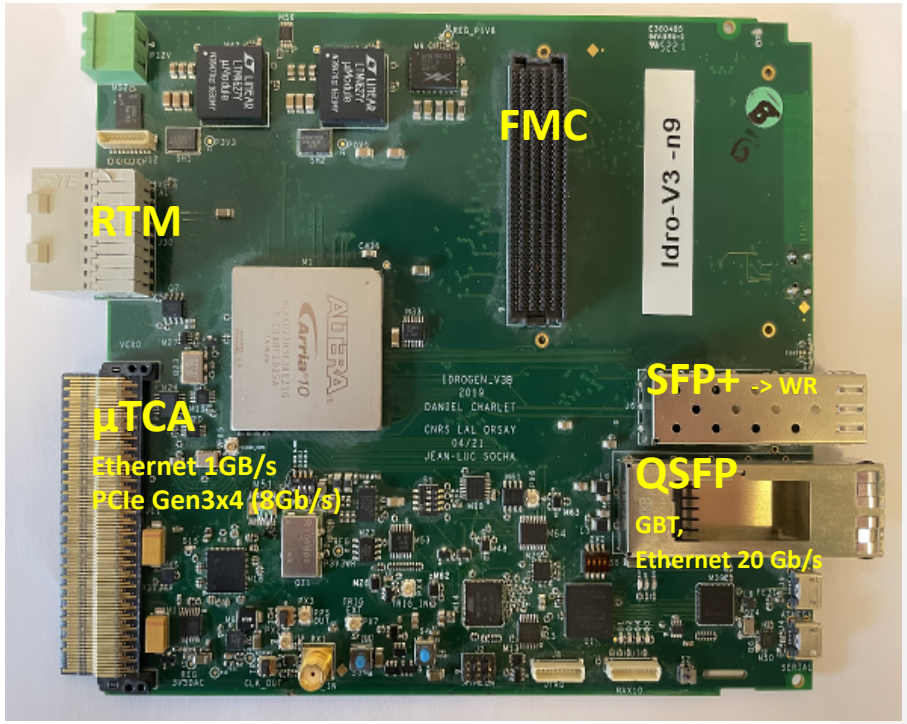
- **Extend White Rabbit performance**
  - **Precision < 100 fs** (Accelerator, fiber sensing,...)
  - Long time phase stability on frequency generation (accelerator, ..)
  - **Distance of uses versus precision > 10km → 1000km** (Interferometer,..)
  - Associated data acquisition performance :
    - Numbers 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

The IDROGEN system

Modular picosecond clock synchronization system for accelerators and data acquisition



- Versatility – modularity
  - Motherboard and daughterboards with standard connectivity and expansion options (FMC, RTM, µTCA, 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)

See poster GDR DI2I, 2025 - hal-05120726

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

Previous IN2P3 R&T

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

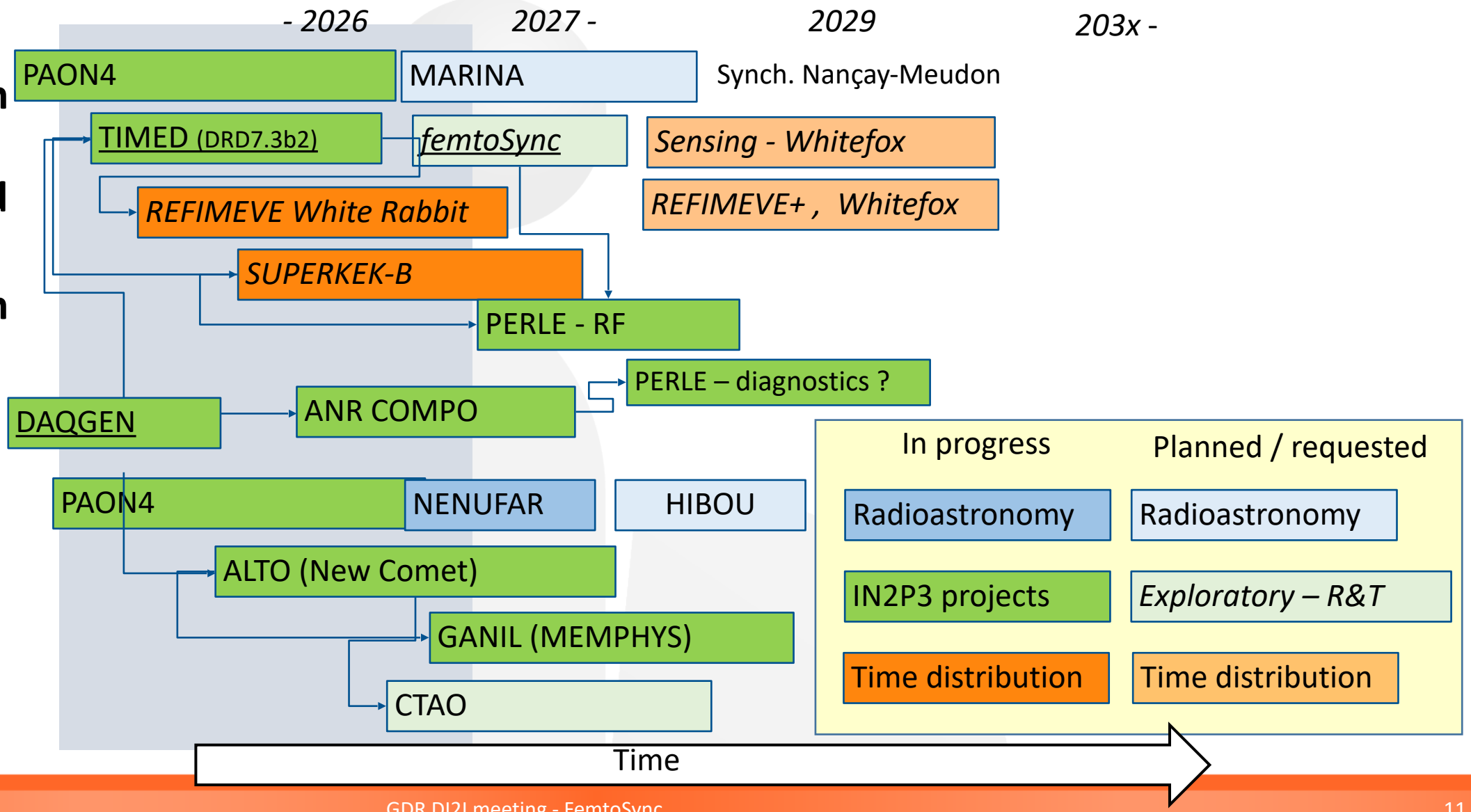
Driving projects

Resolution: 1 ps | 300 fs | <100 fs

Cross-Site synchronization

Accelerator and detectors synchronization

Data acquisition + continuous calculation



Involvements: present and requested

- 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)

Results

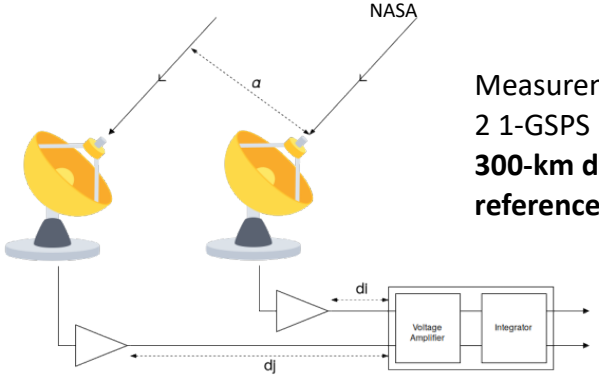
- **Inter-site synchronization**
  - PAON-4: **DAQ 1-GSPS synchronization - 300 km** - Nançay-LTE clock (2025) – publication forthcoming

- **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)

Clock precision and 5 ps over 2 days stability

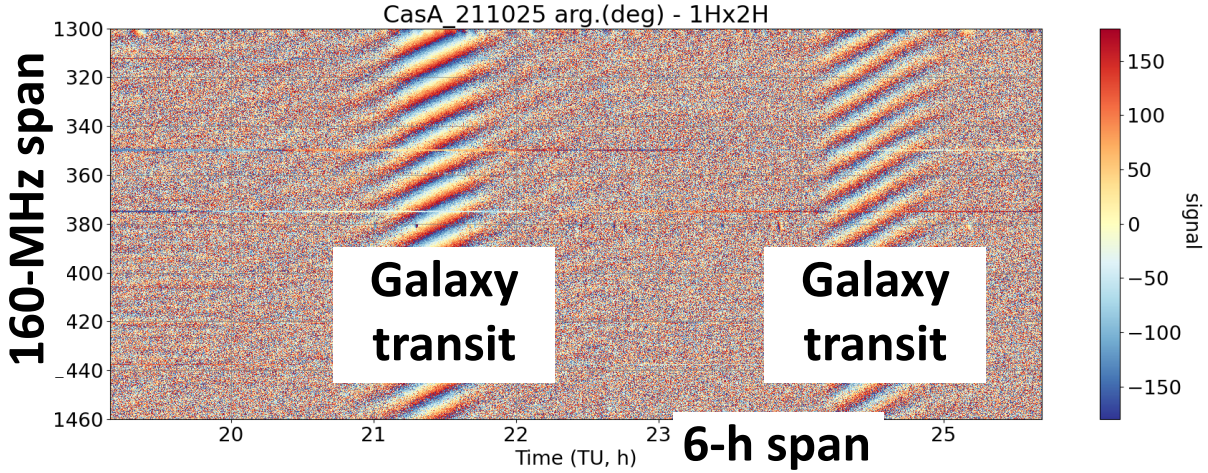
NASA

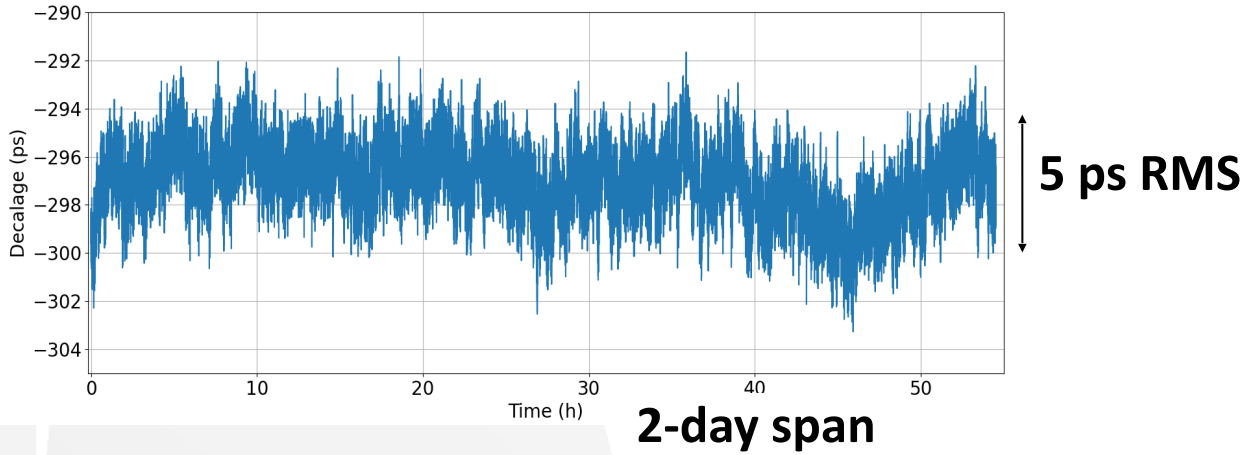


Measurement at Nançay – Oct. 2025
2 1-GSPS FADC **synchronized with the 300-km distant Paris Observatory reference clock**

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

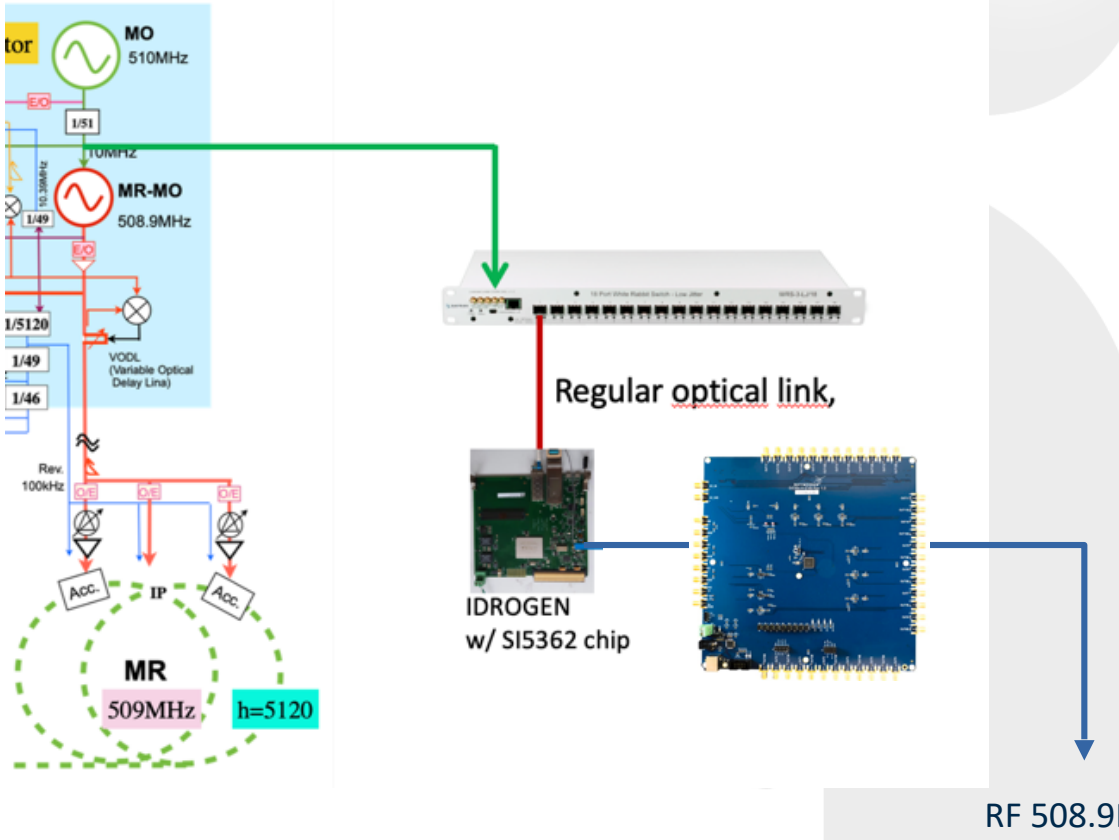
Interference fringes of source signal
Phase difference depending on source direction





Clock synthesis for accelerators: 508.9 MHz for SUPERKEK B

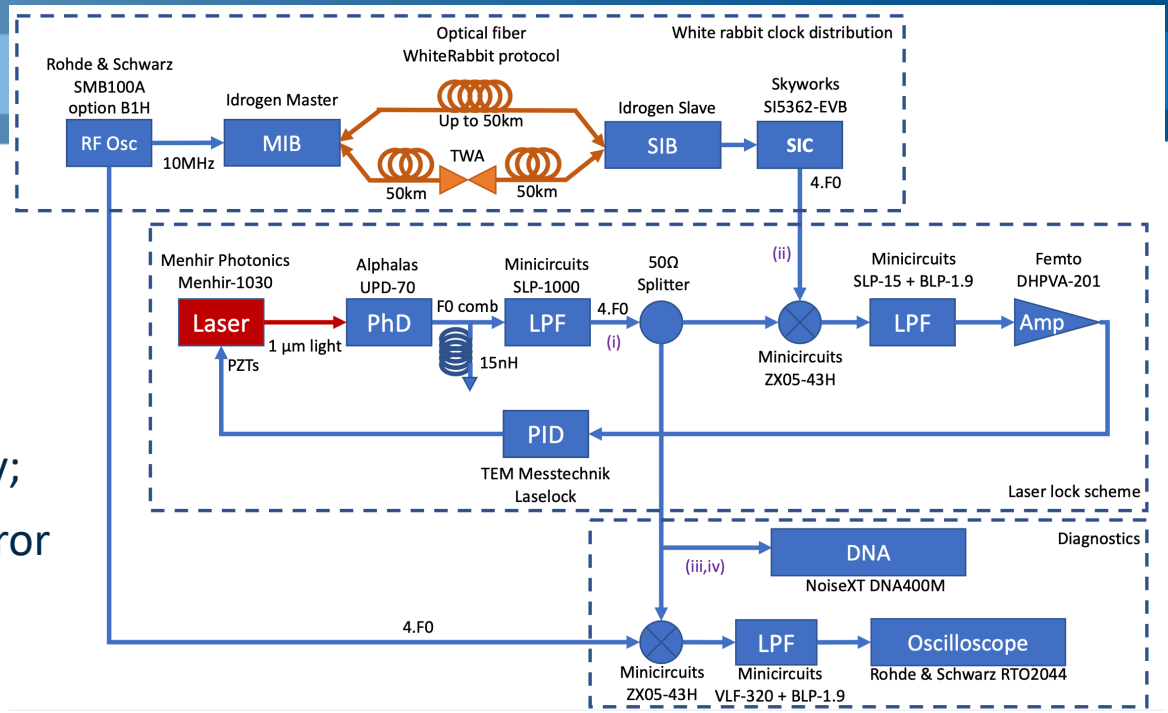
Last result of Super KEK B clock synchronization with IJCLab IDROGEN board.



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

ps, 100-km distant laser synchronization

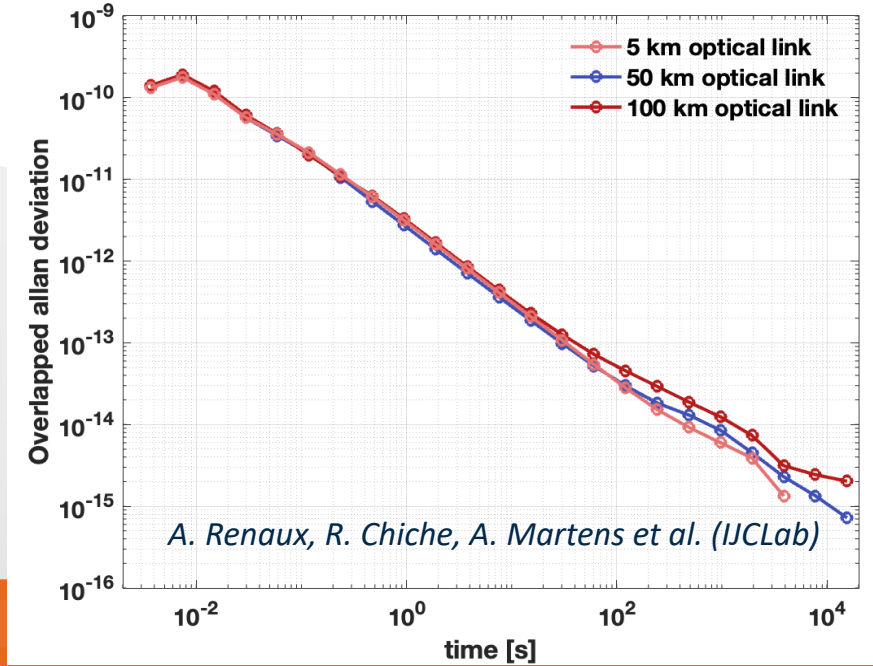
- SMB100A-B1H used as RF oscillator;
- Two Idrogen boards used as White Rabbit Grand Master and slave;
- Slave board generates a 250MHz signal that is provided to a SI5362 PLL;
- PLL generates a clocks at the fourth harmonic of the laser frequency;
- Clock is mixed with the filtered signal from the laser, resulting an error signal for a PID driving the laser piezo transducer



Laser synchronisation setup

Phase noise power spectral density of the synchronized laser:

- Four difference optical fiber length: 10m, 5km, 50km and 100km;
- No modification of the phase noise when replacing it with a 5 km and 50 km fiber link;
- Significant difference with 100 km fiber link around 1Hz and above 300Hz mainly due to chromatic dispersion in the fiber



Ref.: Ms. No. TIM-26-02166R2
Laser Synchronisation Over One Hundred Kilometers With Stabilityat Picosecond Scale
IEEE Transactions on Instrumentation & Measurement

IJCLab White Rabbit Status and Prospectives

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

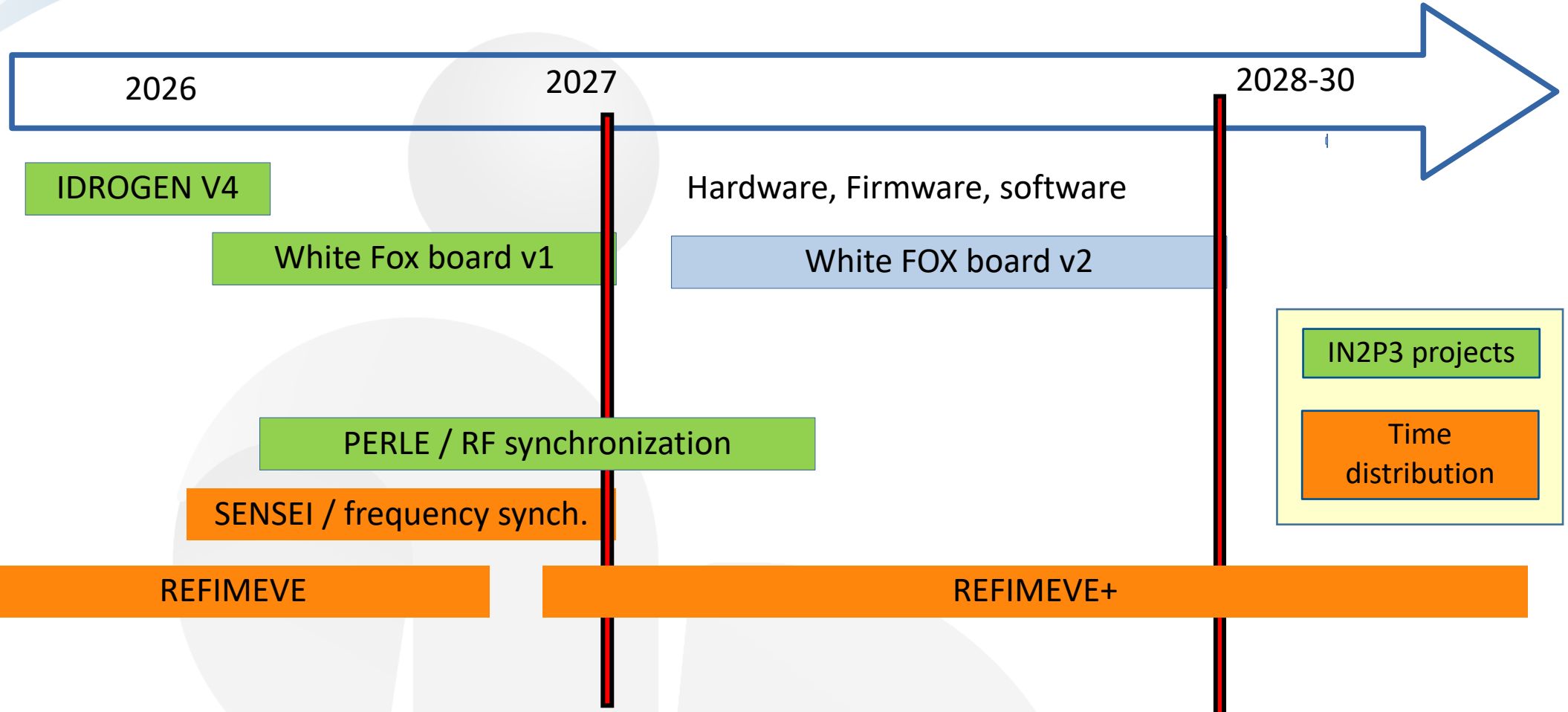
- WhiteFox board development
- Long distance
  - Accuracy test (800km) Paris to London
  - Precision test (200Km) Meudon to Nançay
- Jitter improvement : temperature stabilization and compensation

Data acquisition improvements

- 40Gb/s
- RDMA

Implementation

FemtoSync Timeline



FemtoSynch's deliverables: prototypes

Major projects' deliverables: requirements, commissioning, production

Performance	1 ps 800 km	Sensing <100 fs 10,000 km ≈10 nodes	REFIMEVE+ < 100 fs 10,000 km > 100 nodes

Resources: IN2P3 + INSU collaboration

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 €*
TOTAL	**125 427 €**	**121 868 €**	**91 868 €**	**31 901 €**	**339 163 €**

- 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

Persons involved

Nom des personnes	Statut	2026	2027	2028	Total (FTE)
IJCLab		**80%**	**50%**	**30%**	**1,60**
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
TOTAL (FTE)		**0,80**	**0,50**	**0,30**	**1,60**

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

Project organization

- 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

Summary and prospects

- 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 throuhg 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

IDROGEN : timing transfer

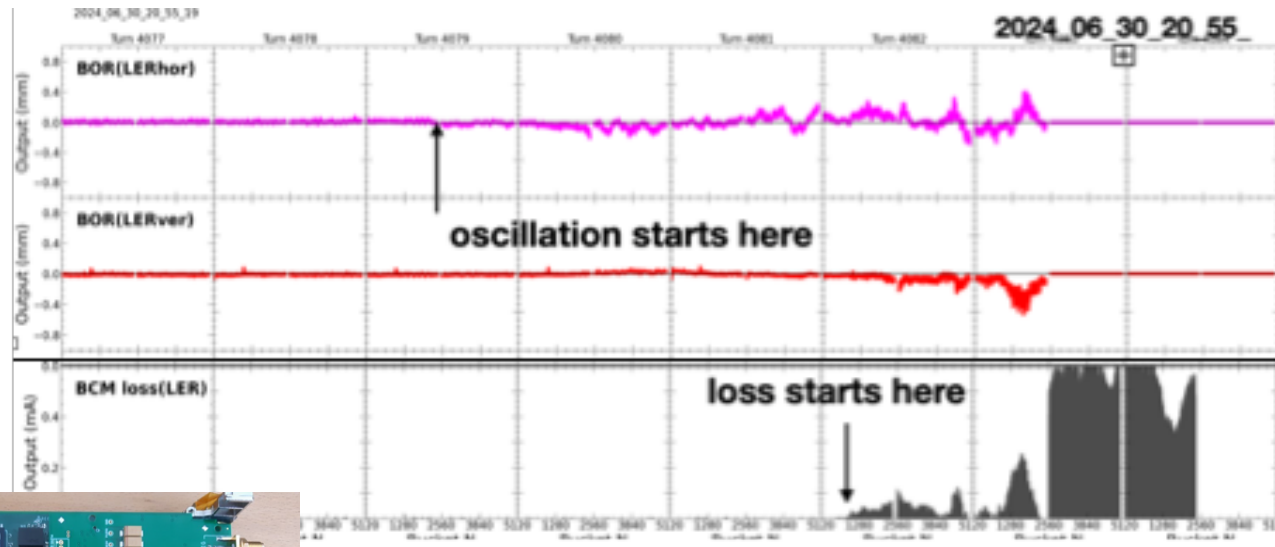
Accuracy performances between 2 reference clock at ≈800km (optical link).

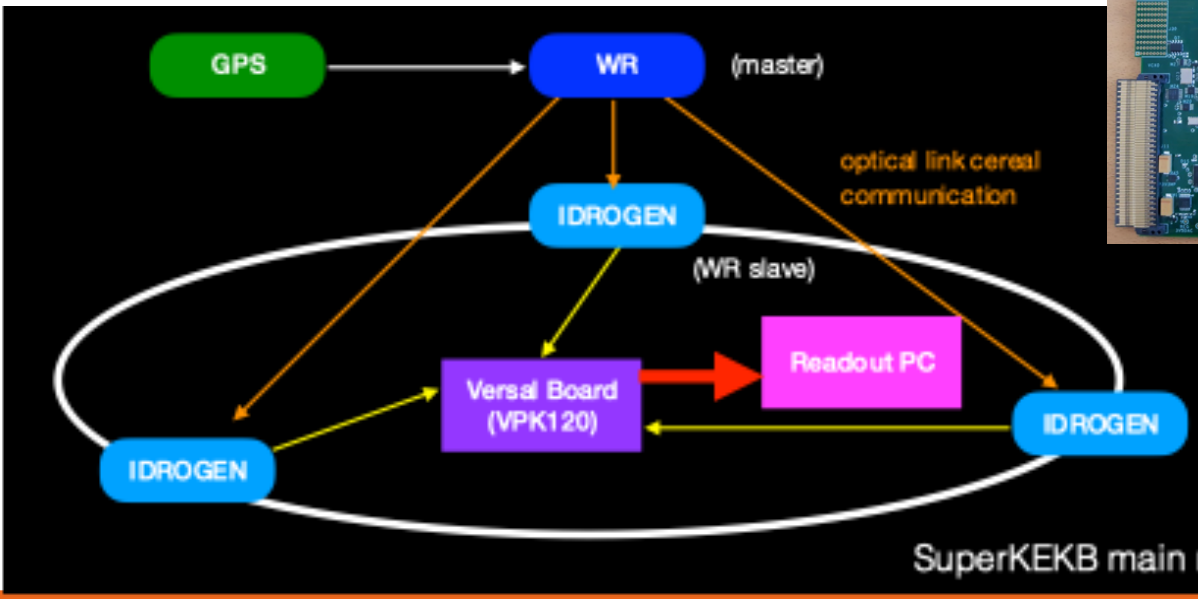
- LTE collaboratrion
- One master IDROGEN in Paris , one slave in London
- Comparison Reference clock (UTC OP) at Observatoire de Paris and Reference clock (UTC OP) at London 232km away;
- Synchronization through national RENATER (REFIMEVE) network and dedicated fiber in UK

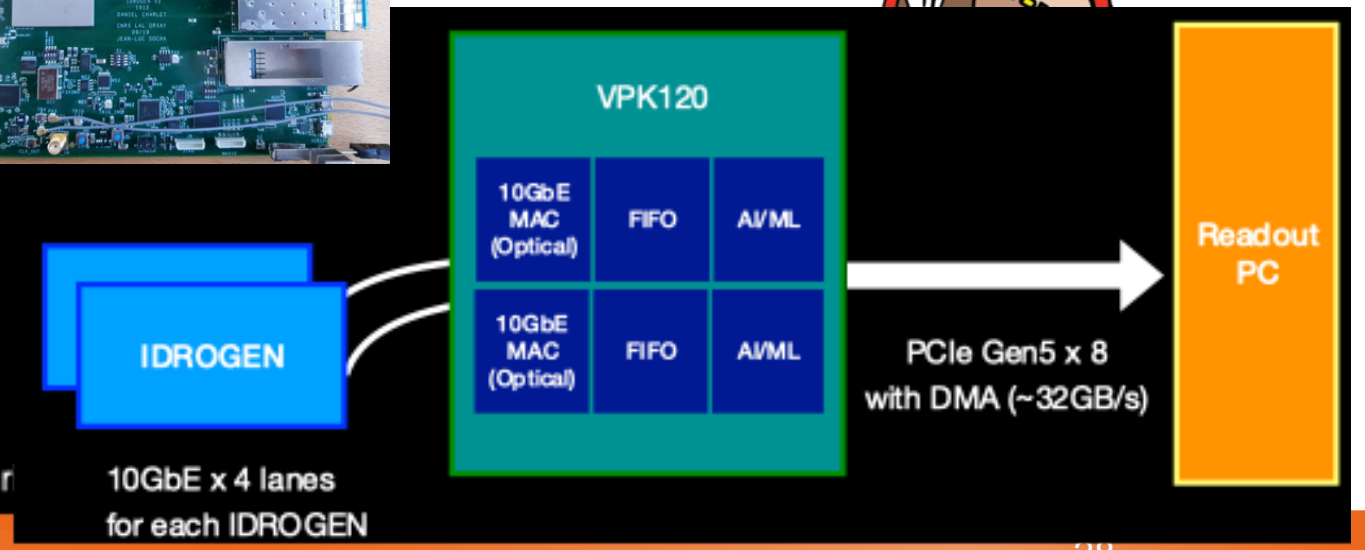
Accelerator application

Sudden Beam Loss (SBL) & Bunch Oscillation Readout (BOR)

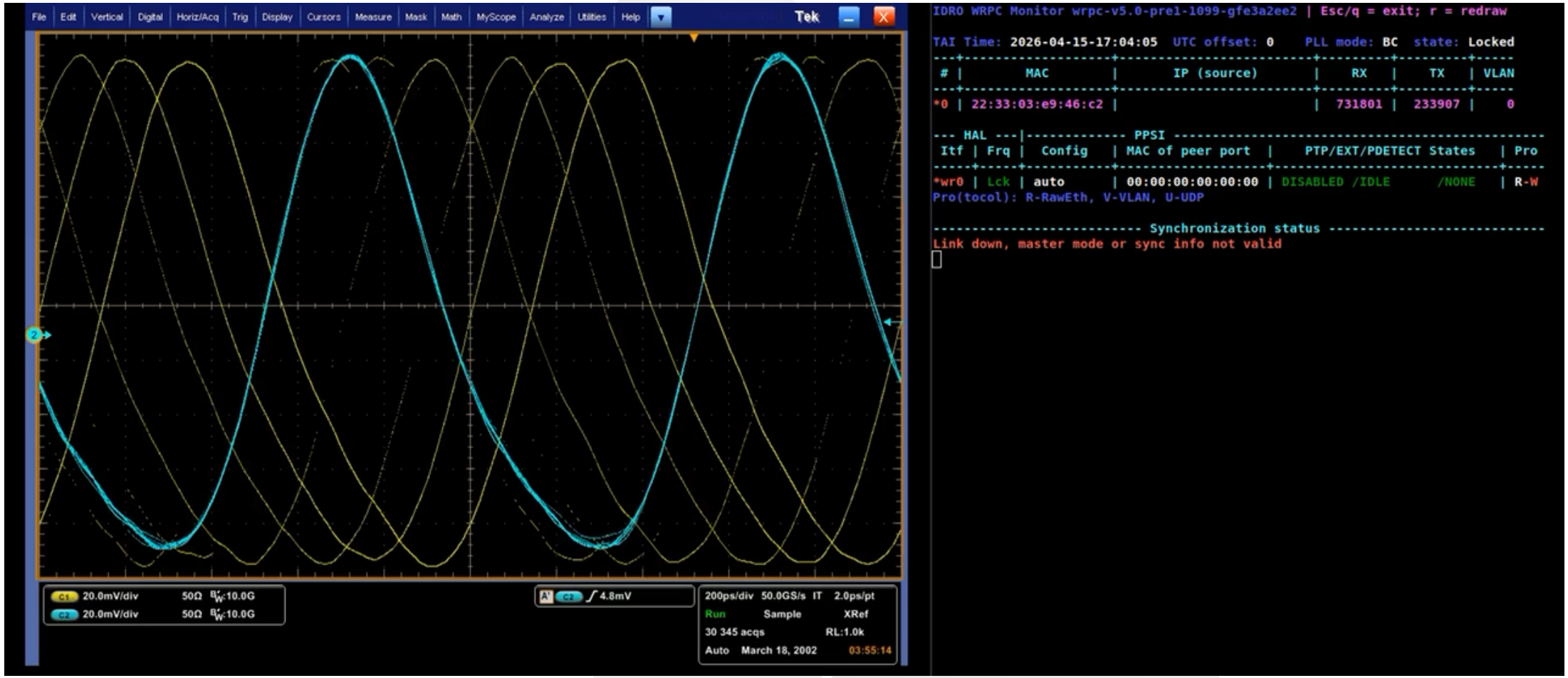
- SBL causes serious damage to the collimator/detector and prevent smooth operation of SuperKEKB
- Nano-second-Synchronisation of BOR can abort the beam before SBL! => IDROGEN boards, synchronized by White Rabbit (WR), acquire local bunch oscillations and send data to a Versal (VPK120) board.







White Rabbit protocol



- 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)