The IDROGEN System

A high data rate acquisition system synchronized by an enhanced White Rabbit node

- IJCLab : Scientific themes : Astroparticles, Astrophysics & Cosmology, Nuclear physics, High Energy Physics, Accelerator Physics, Theory, Heath, Energy
  - Daniel Charlet, Antoine Back, Nawal Belouchrani, Cédric Esnault, Christophe Joly, Christelle Soulet, Monique Taurigna, Chafik Cheikali, *Gaetan Seuillot, *Mathias Vecchio, *Sid Ali Cherrati
- Paris Observatory : Scientific themes : Time and frequency metrology, time and frequency transfer, inertial sensors, space-time reference frames, theory, epistemology
  - LTE : Paul-Eric Pottie, Michel lours
  - Obs Nancay : Cédric Viou
- LPSC: Olivier Bourrion

Agenda

- Introduce the White Rabbit technology and how it works
- Role of the IDROGEN board
- Some projects examples

White Rabbit and its areas

White Rabbit is a sub-nanosecond timing and frequency distribution technology developed by CERN & GSI, with a range of applications in distributed systems where timing precision is critical

Synchronizing thousands of nodes in accelerators chains (eg CERN, FAIR …)

Precise coordination of antenna and sensor networks

Time synchronization in critical transaction networks

Infrasturctures like REFIMEVE for distributing Time & frequency references

Particle accelerators & high-energy physics	Astronomy	Advanced Radar	Quantum networks	Financial sector	Telecomunications	Metrology & National timing

Timing for widely distributed detector arrays

Tests for synchronized quantum nodes & secure communications

Precision time for critical communication infrastructure

Technical Principles

White Rabbit is a high precision synchronization technology based on Ethernet.
It synchronizes multiple devices on a network with sub-nanosecond precision.

White Rabbit Operation (Key concepts)

- SyncE (Synchronous Ethernet):

shares a common frequency clock

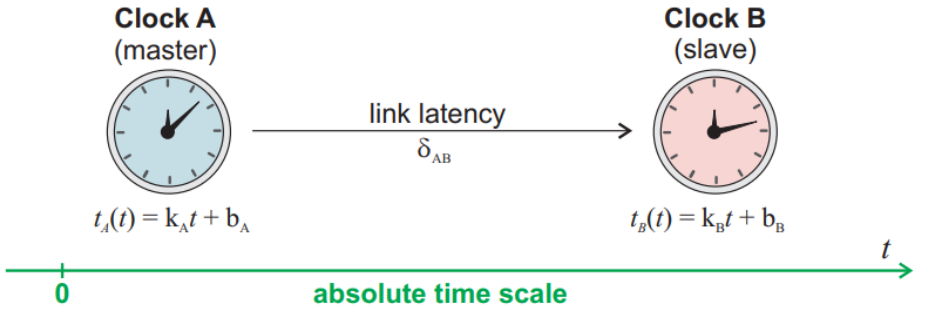
- PTP (Precision Time Protocol IEEE1588)

Message exchange to measure/deduce delays

- Ultra-fine phase measurement:

Extremely precise phase alignment between clocks via DDMTD Phase tracking (Digital Dual Mixer Domain)

Delivering synchronous clock and 1PPS via optical link



Tomasz Włostowski : Precise time and frequency transfer in a White Rabbit network

Delivering synchronous clock 10 MHz, 1PPS and timestamping via optical link

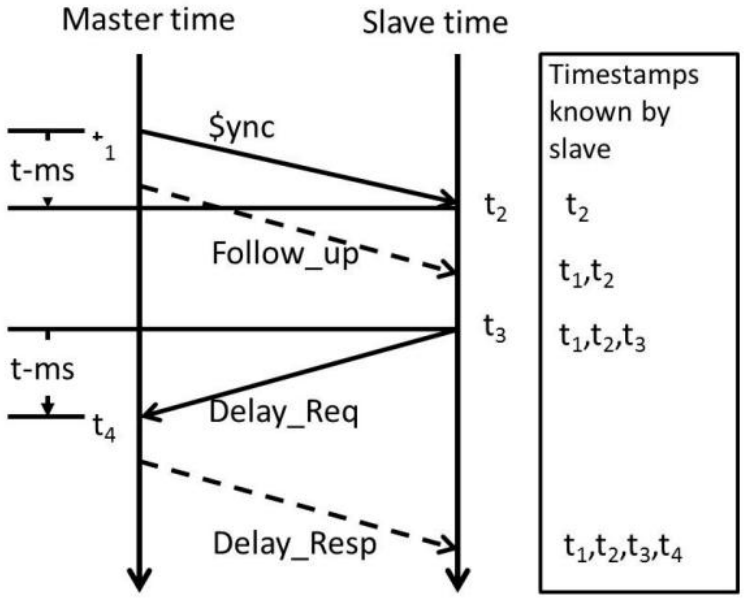
Precision Time Protocol (IEEE 1588):

Protocol that allows devices to align their local clocks to a master clock by exchanging timing information.

Devices send timestamps (send and receive times), which allows calculation of propagation delays and clock offset

Key points:

- Measures and corrects clock offset
- Uses timestamps in exchanged messages
- Enables deduction of propagation delay
- Better precision than standard networks, but insufficient alone for sub-ns accuracy targeted by White Rabbit



PTP clock synchronization process

White Rabbit: Sub-Nanaosecond Timing over Ethernet P.P.M. Jansweijera , H.Z. Peeka , E. de Wolfb,a,

TECHNOLOGY OVERVIEW : Synchronous Ethernet (Sync-E)

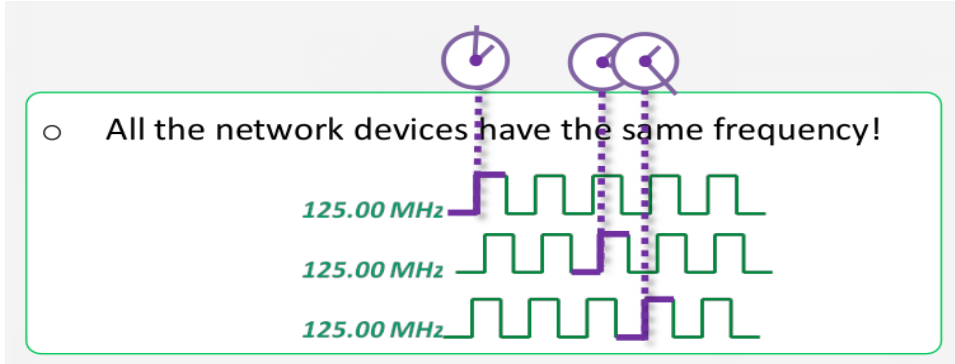
SYNTONIZATION => SAME FREQUENCY

SyncE:

A method that allows all devices on a network to share the same clock frequency over Ethernet.

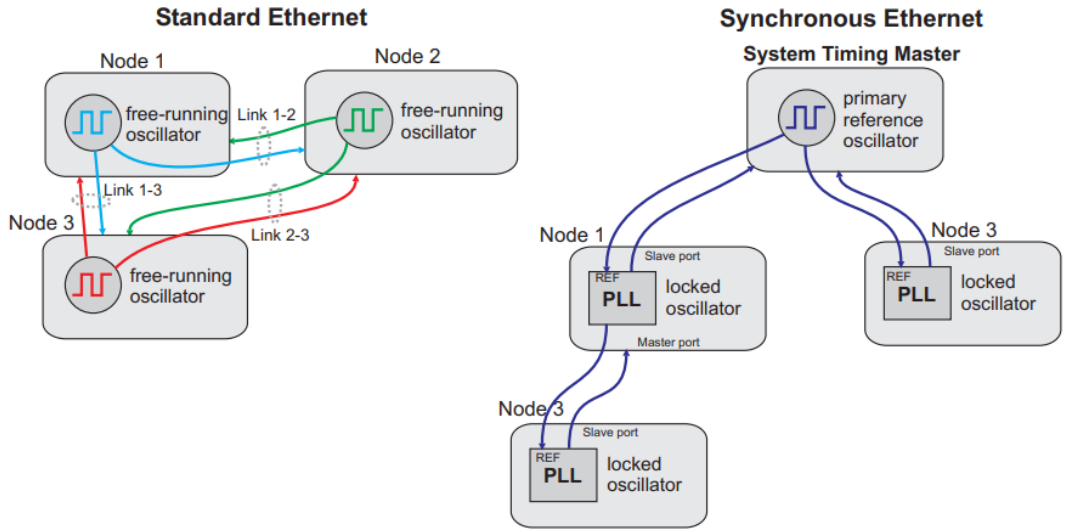
The receiver recovers the clock from the incoming signal, so all nodes “tick” at the same rate.

SyncE does not provide absolute time (like UTC), but ensures local clocks do not drift from each other



Key points:

- Frequency synchronization, at the physical network layer
- Provide a stable base for DDMTD



TECHNOLOGY OVERVIEW : Digital Dual Mixer Time Domain

SYNCHRONISATION=> SAME PHASE

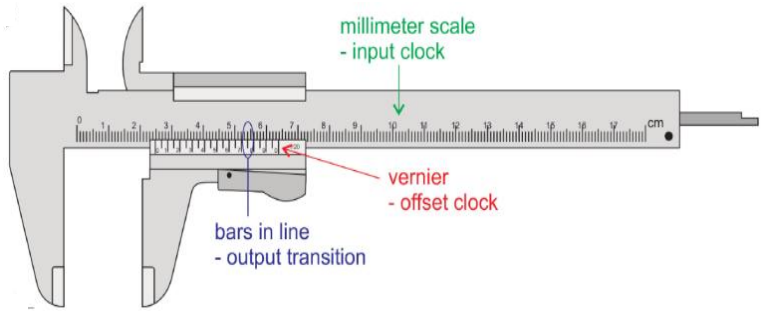
- DDMTD (Digital Dual Mixer Time Difference):

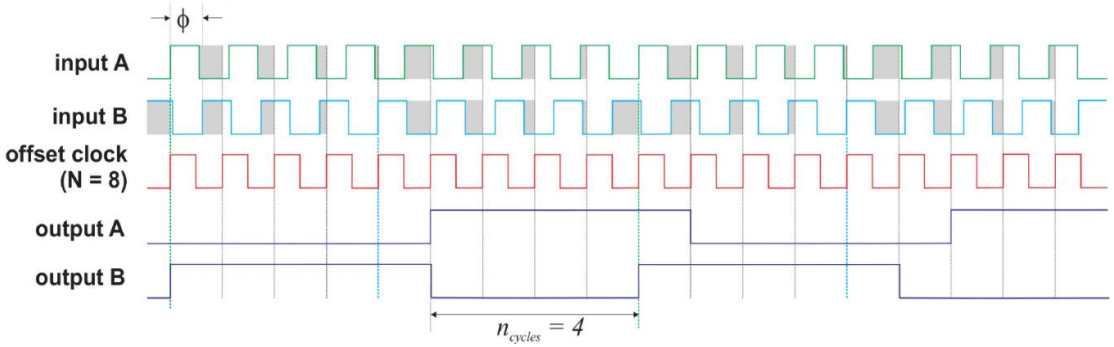
A technique for measuring the phase difference between two clock signals with extremely fine resolution.

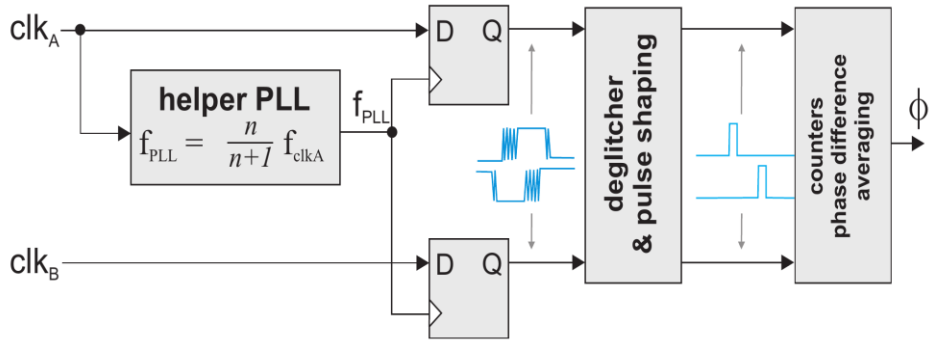
In WR, DDMTD allows very precise alignment to a master clock's phase.

Key points:

- Very high-precision phase measurement
- Resolution better than timestamp alone
- Complements PTP to reach sub-nanosecond
- Essential for demanding applications like LLRF







On the shelf White Rabbit solution

https://safran-navigation-timing.com/solution/white-rabbit-solutions/

Safran technology ensures deterministic Ethernet performance across large networks, making it ideal for applications, such as FinTech and Data Centers, that require real-time data transfer. With Wavelength Division Multiplexing (WDM), our solutions provide scalability and efficiency in synchronization.

White Rabbit Z16

- Sub-nanosecond Time Accuracy
- Multi-Source Time References
- 16 Optical Timing Ports for WR, PTPv2 and NTP

White Rabbit ZEN TP-FL

- Sub-nanosecond Time Accuracy
- 4x1PPS expansion / 8x1PPS expansion boards
- Remote configuration and monitoring

White Rabbit ZEN TP-32BNC

- Sub-nanosecond Time Accuracy
- Robustness & Redundancy
- 32 BNC configurable outputs

WROX

- Adds White Rabbit interface to SecureSync
- PTP: Compliant with IEEE1588v2
- 1 G and 10 G configurations

High Accuracy Timing IP Core (HATI)

- Sub-Nanosecond Time Accuracy
- Easily Integrable and Compatible with Multiple FPGA Families
- Deterministic Delivery of Timing Information

White Rabbit PTP License

- WR to PTP Protocol Interoperability
- Synchronize Network Via WR & PTP Timing Protocols
- Sub Nano Second Accuracy

White Rabbit Switch – Low Jitter

- Sub-Nano Second Time Accuracy
- Time & Frequency Distribution
- Improved Clock Jitter and Phase Noise

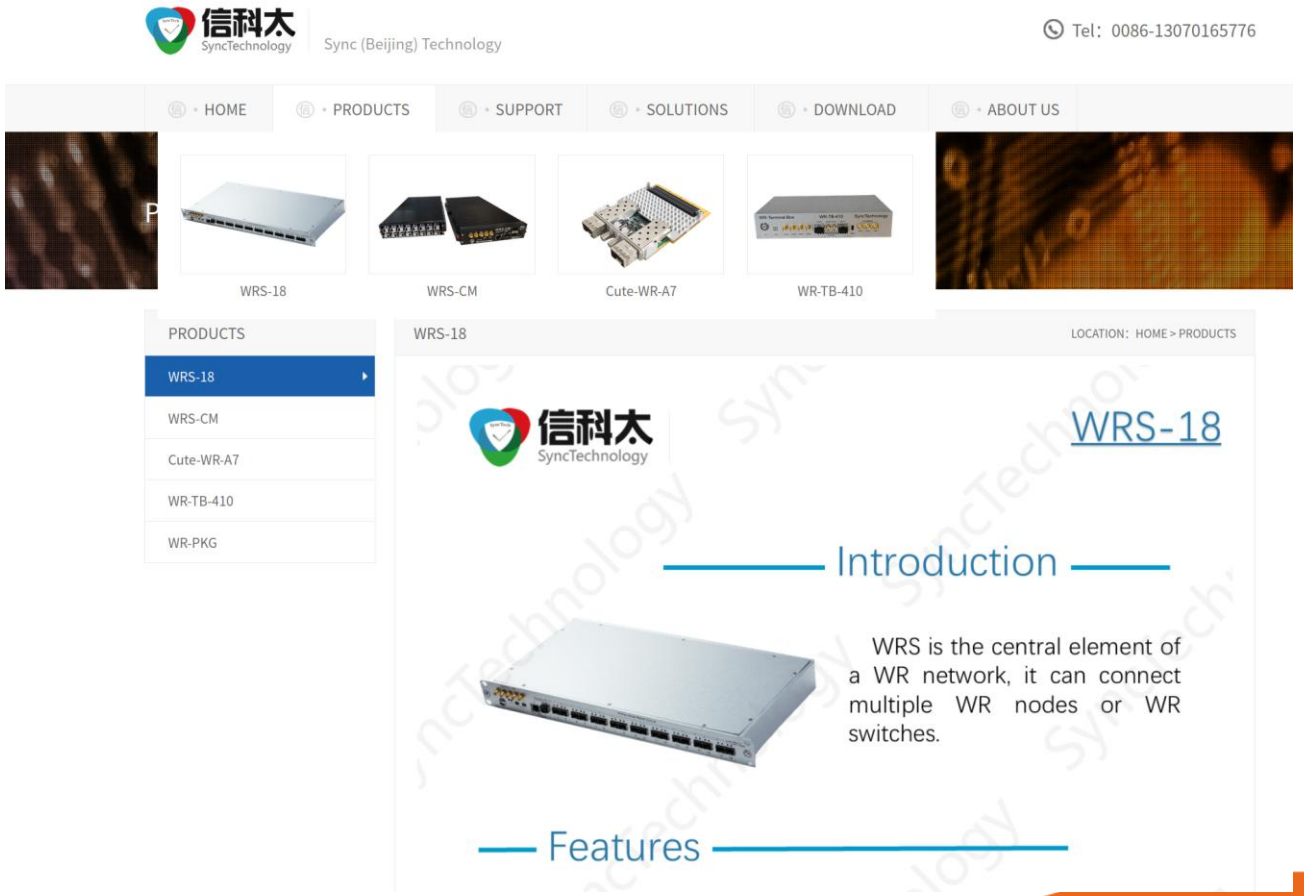
White Rabbit Switch v3.4.

- Sub-Nano Second Time Accuracy
- Time & Frequency Distribution
- 18 SFP 1GbE ports

White Rabbit LEN

- Sub-Nano Second Time Accuracy
- Distance Range: Over 80km Using Fiber
- Dynamic Calibration

http://www.synctechnology.cn/en_detaile.aspx?ClassID=1



Courtesy : Daniel Charlet

Accuracy system comparison

Wide user community

Best performance

System	accuracy	Note
GPS	10ns -200ns	Propagation in non-stationary disruptive environment. Problem of the multi-way.
GPS-IPPP	2 – 3 ns	Resolution of phase ambiguities using RIMEX data. More complex implementation
On the shelf WR switch without calibration	500ps - 100ns	Tested with WR switch SAFRAN in master configuration
On the shelf WR switch with calibration	200ps – 2 ns	Tested with WR switch SAFRAN in master configuration
IDROGEN enhanced WR node	13 ps	Tested with WR switch SAFRAN in grand master configuration
IDROGEN enhanced WR node	1 ps	2 IDROGEN boards on the WR switch configured in Grand Master and synchronized by T+ REFIMEVE fiber from Paris Observatory (SYRTE)
In development : IDROGEN & external functions	< ps	Aim of T+REFIMEVE

Courtesy : Daniel Charlet

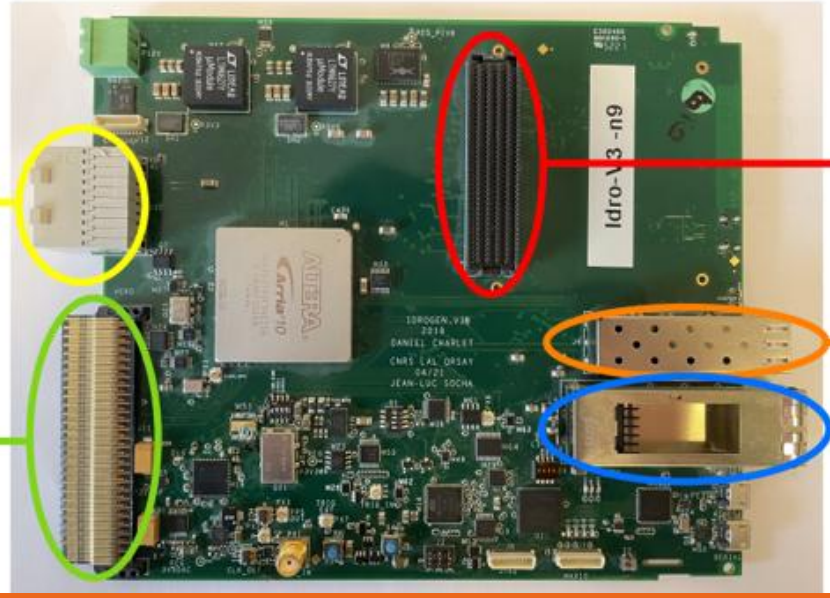
THE IDROGEN BOARD

The IDROGEN board:

- **Full White Rabbit node designed for precision synchronization (based on CERN schematic) and high performance data acquisition by IJCLAB.**
- It integrates WR mechanism (PTP, SyncE, DDMTD) in FPGA hardware, allowing it to act as a synchronized endpoint in a WR network

Key points:

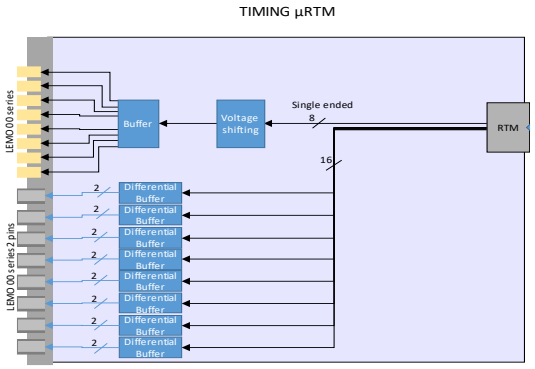
- Integrate WR core
- Can operate as slave node or a local grand master
- Integrate with high-speed data acquisiton using standard procole
- Fully re-configurable

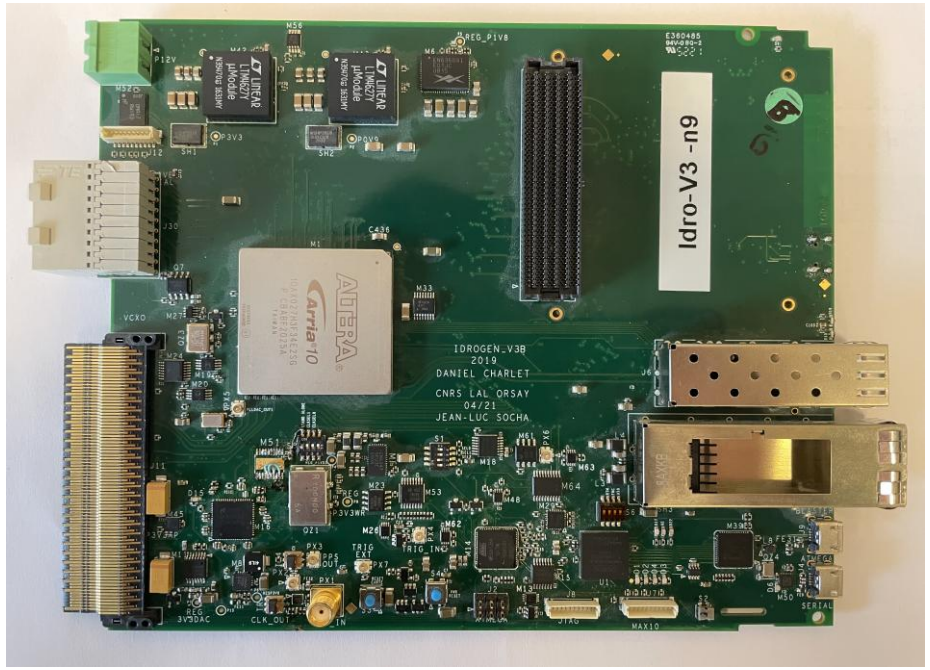


Courtesy : Antoine Back

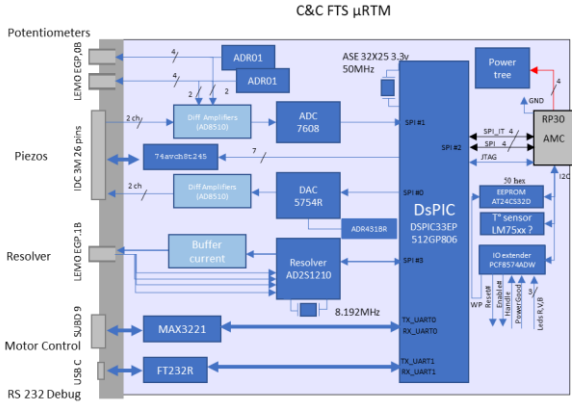
IDROGEN Eco-system

Timing disciplined by WR distribution µRTM





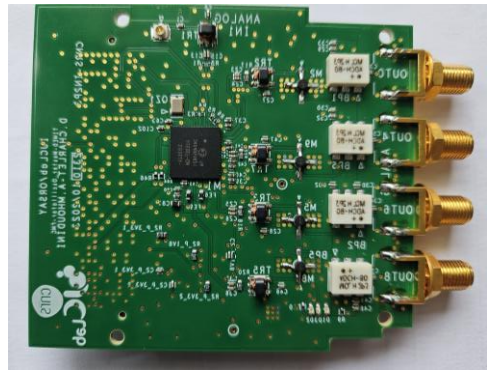
C&C Frequency Tuning system



Ongoing:
500 MSps 4 channels
3GSps 2 channels

ADC FMC

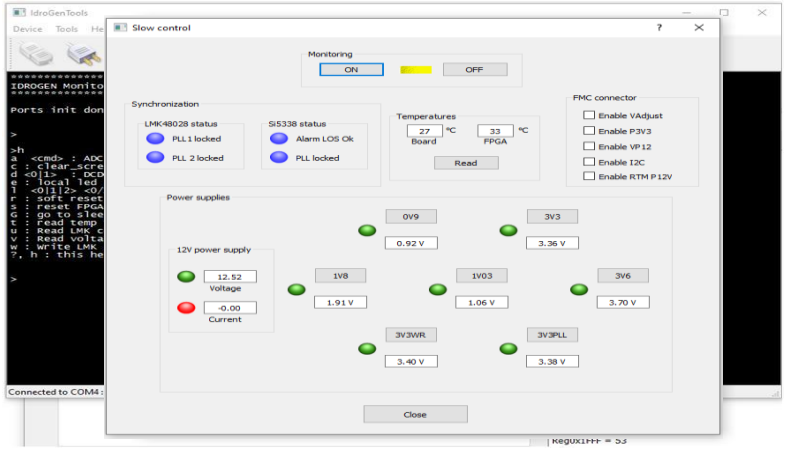
REFGEN FMC



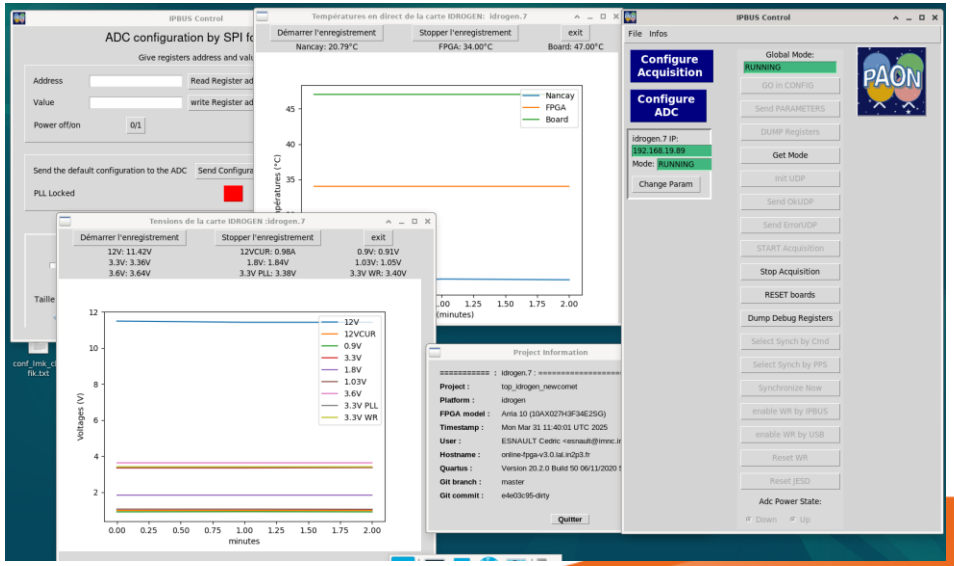
Acquisition board 16 channels

IDROGEN: softwares

- Configuration GUI tools over USB and Ethernet
  - Power, PLL, FMC, ADC configuration
  - Monitoring GUI for power supplies and temperature monitoring
- Slow control library and tools (I2C, SPI, WR diagnostic, …)
- Frame viewer
- Acquisition software



docker

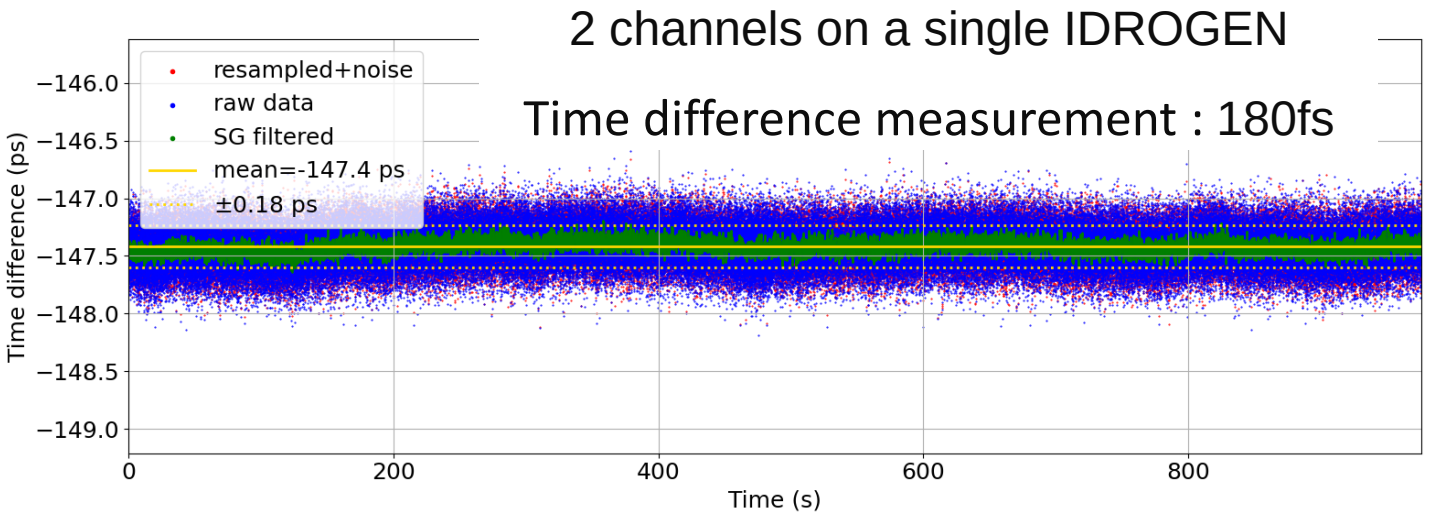


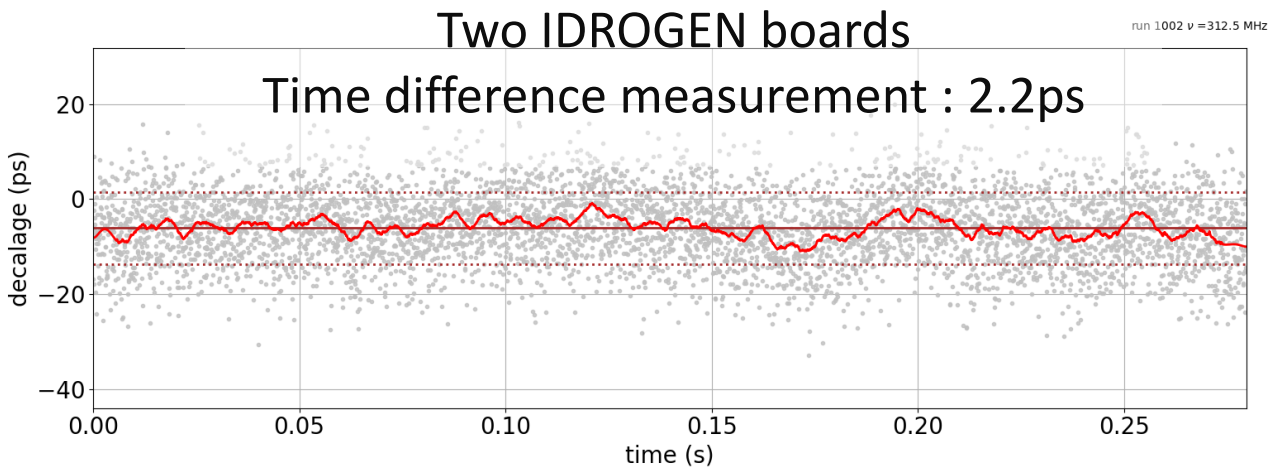
Courtesy : Daniel Charlet

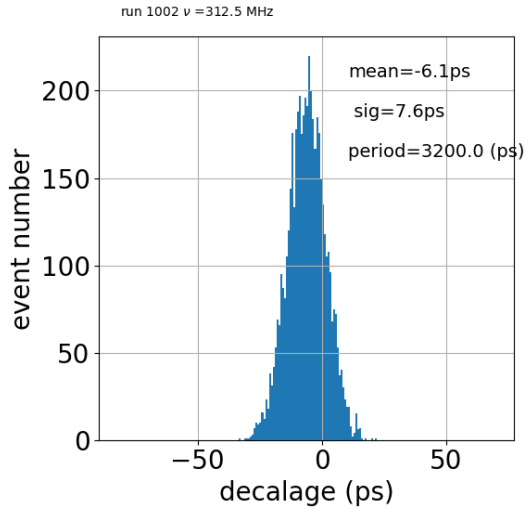
1GSPS ADC board: Synchronization performance

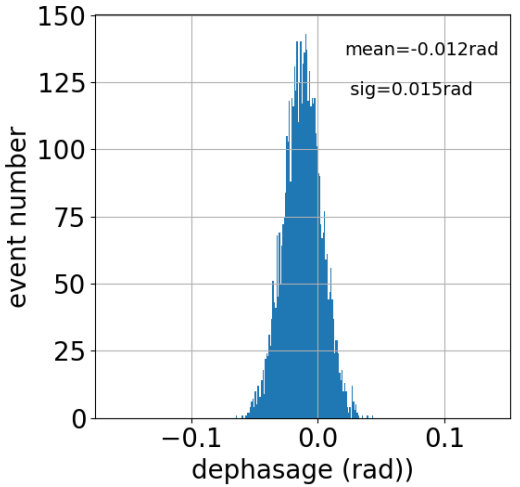
- Bandwidth (single board):
  ~500Mhz (1GHz → 1.5GHz)

- 2 IDROGEN boards synchronized by WR
- 2 channels 1GSPS 14b ADC
- Same RF signal (312.5MHz) split on boards
- FFT 8k point
- Cross correlation



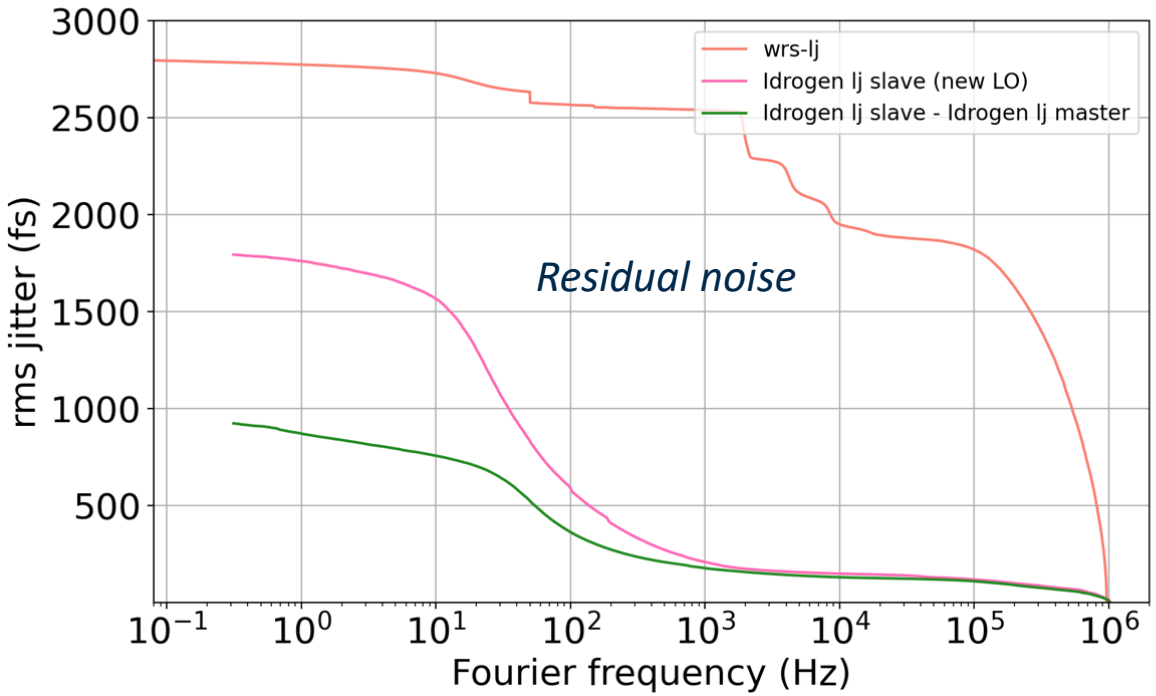






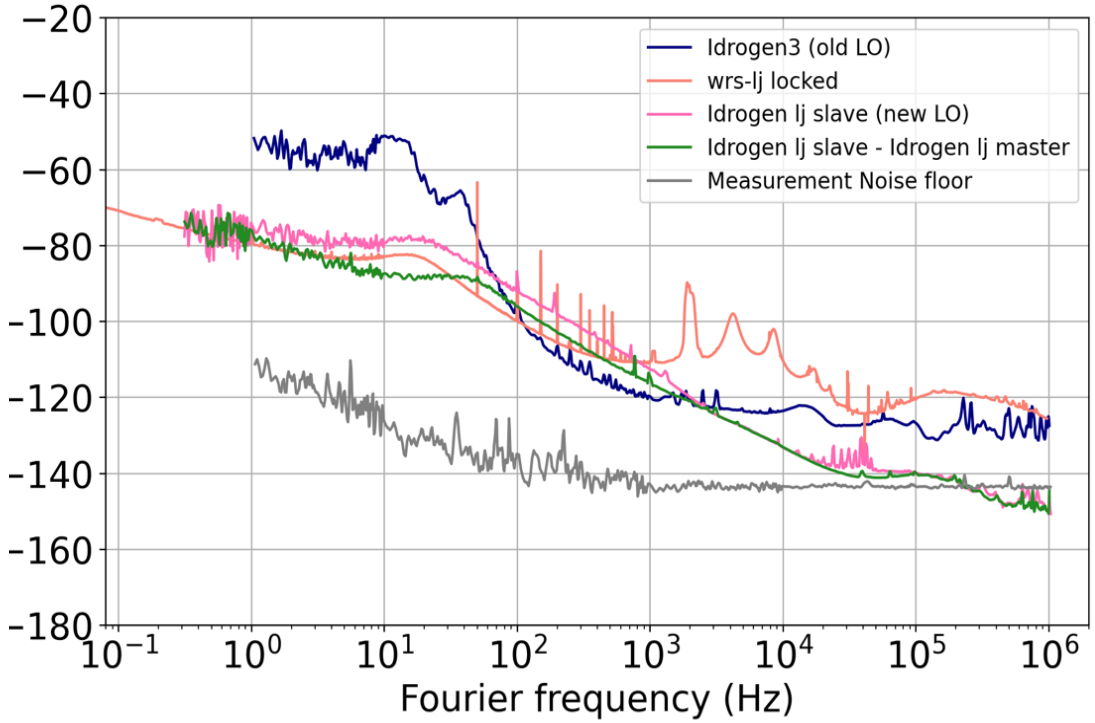
Phase noise measurement

Integrated jitter according to integration range



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

Absolute measurement

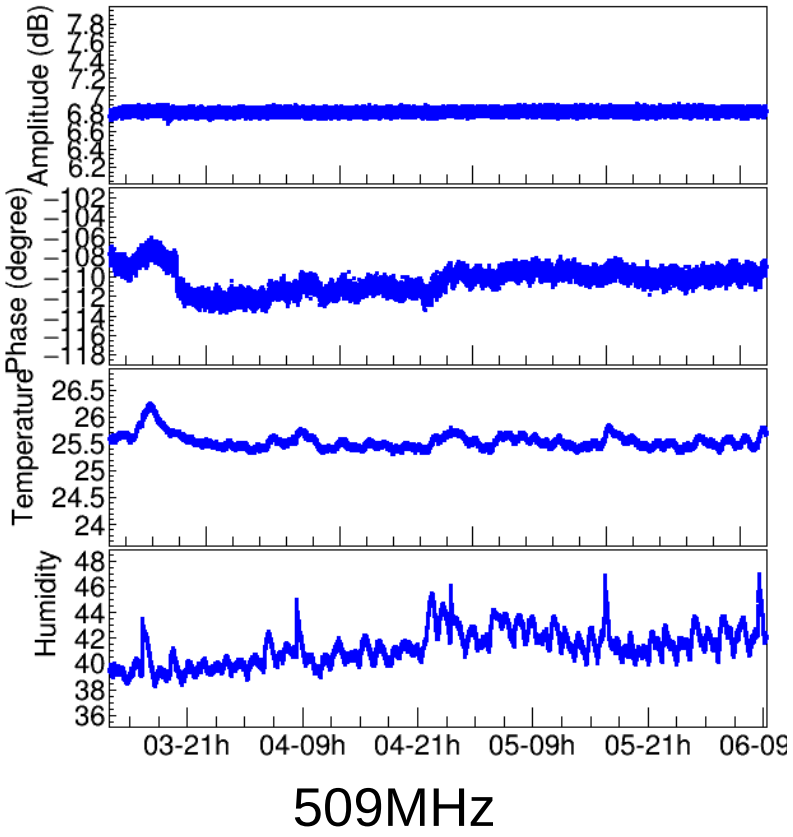


Jitter: [1Hz- 1MHz] : 580fs in slave mode
Jitter: [1Hz- 1MHz] : 260 fs in master mode

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

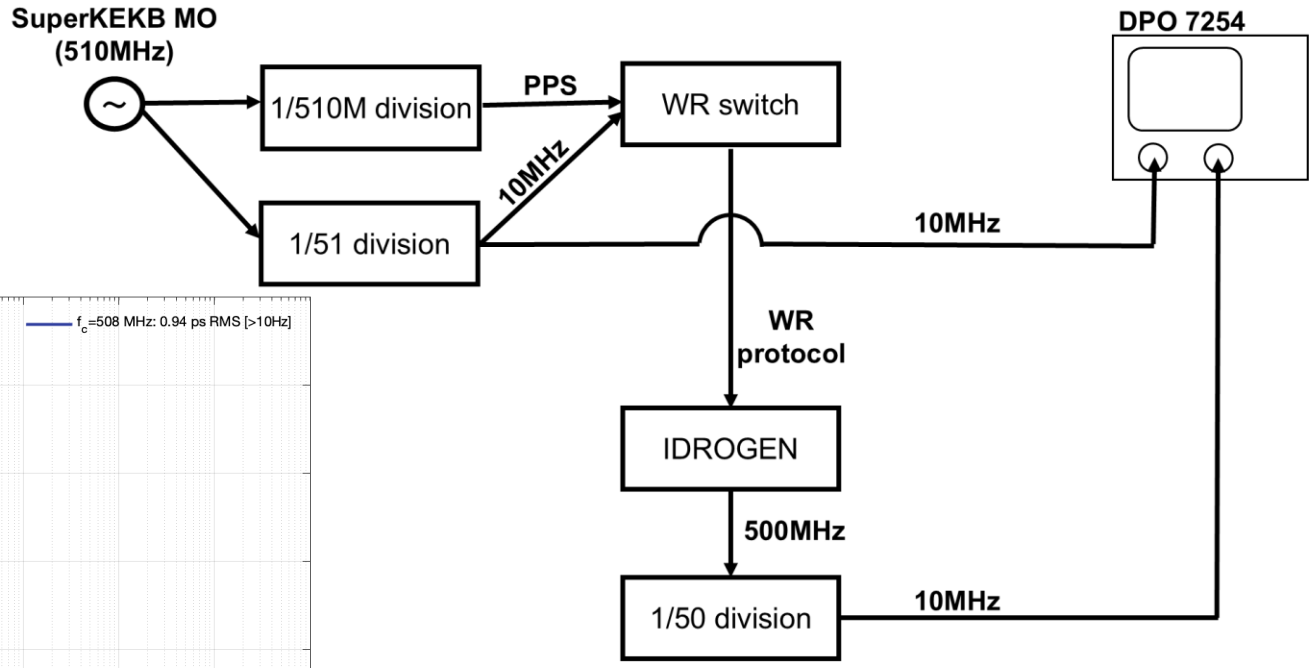
Courtesy : Daniel Charlet

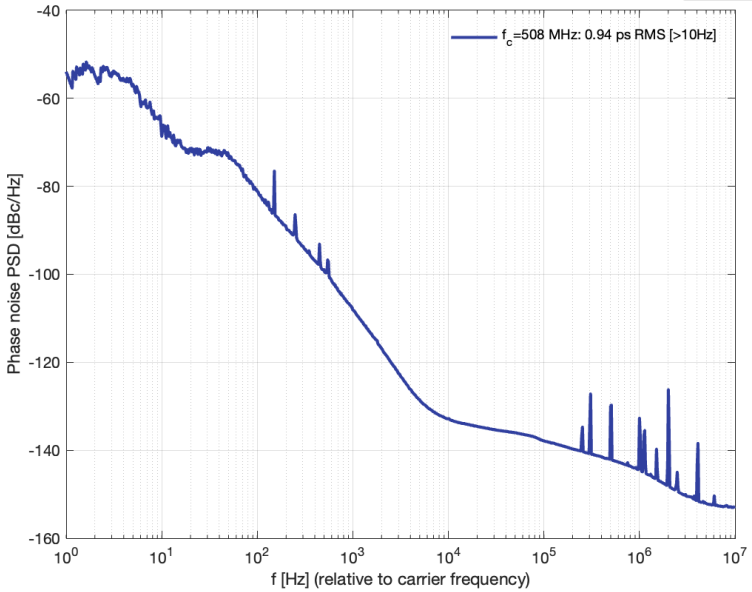
SuperKEKb : Master oscillator distribution



509MHz

IDROGEN synchronization setup





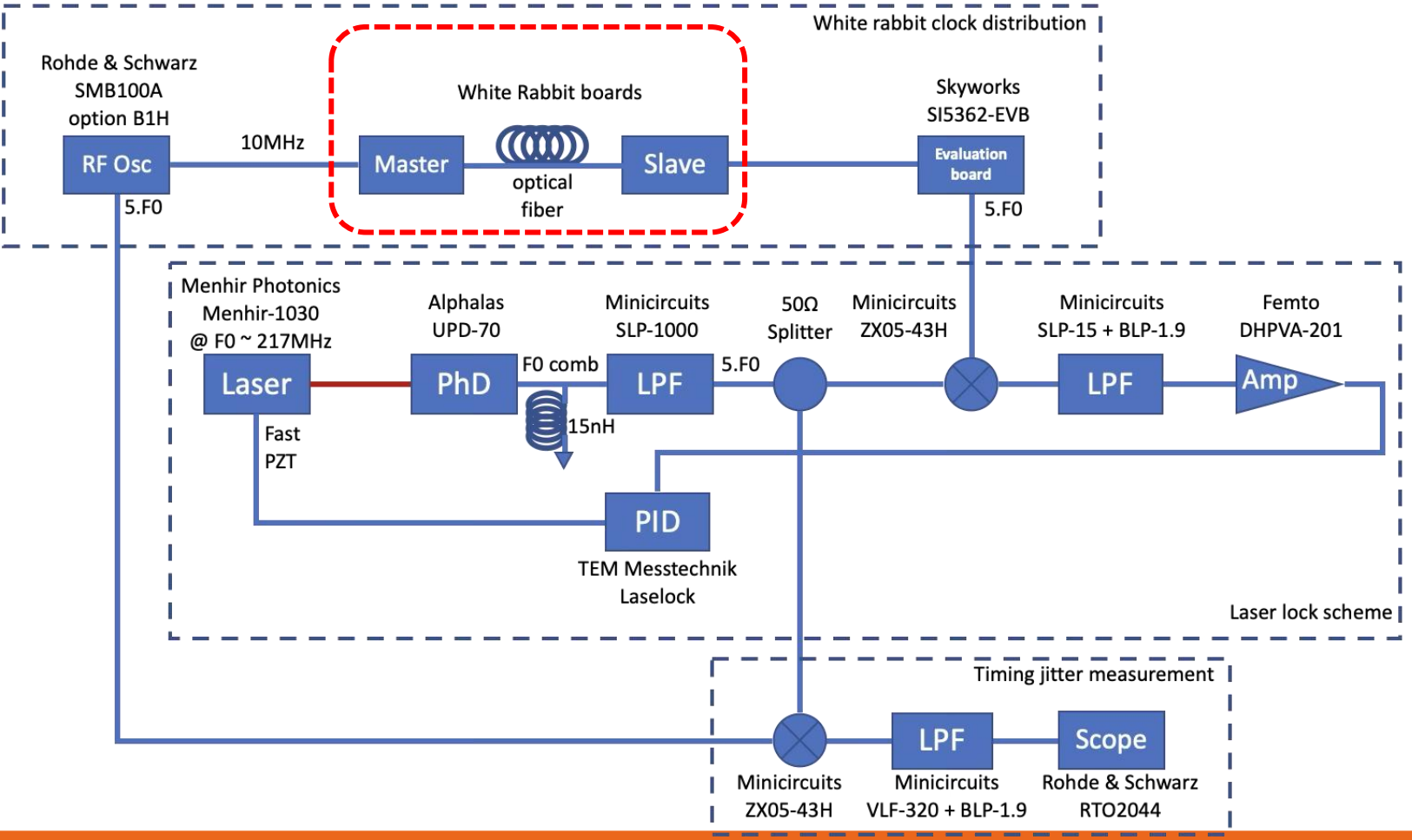
Data taken from Sep22 19:10 to Sep24 12:00

Frequency offset: [10Hz → 10MHz] ; RMS jitter: 940fs at 508 MHz

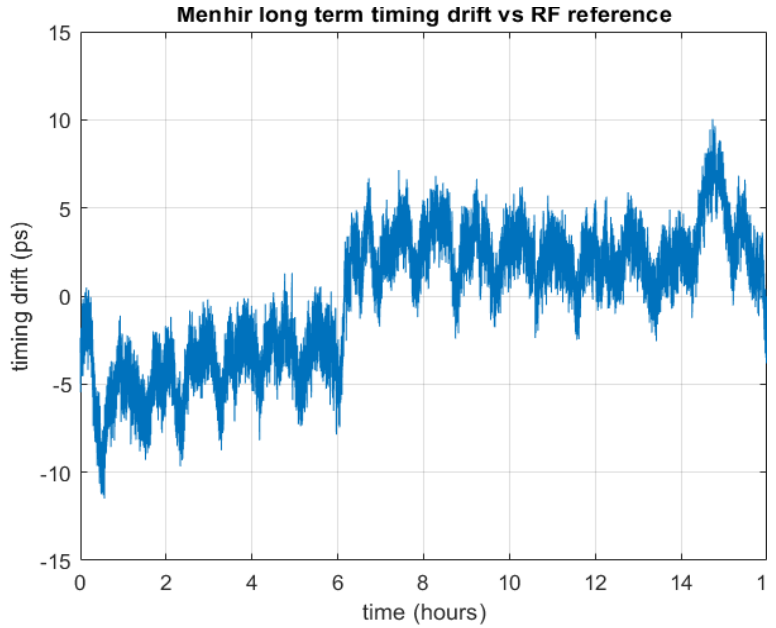
Courtesy : Daniel Charlet

Laser synchronization

IDROGEN 1 : GM → IDROGEN 2 slave
Fiber length 5Km → 100Km



Preliminary results

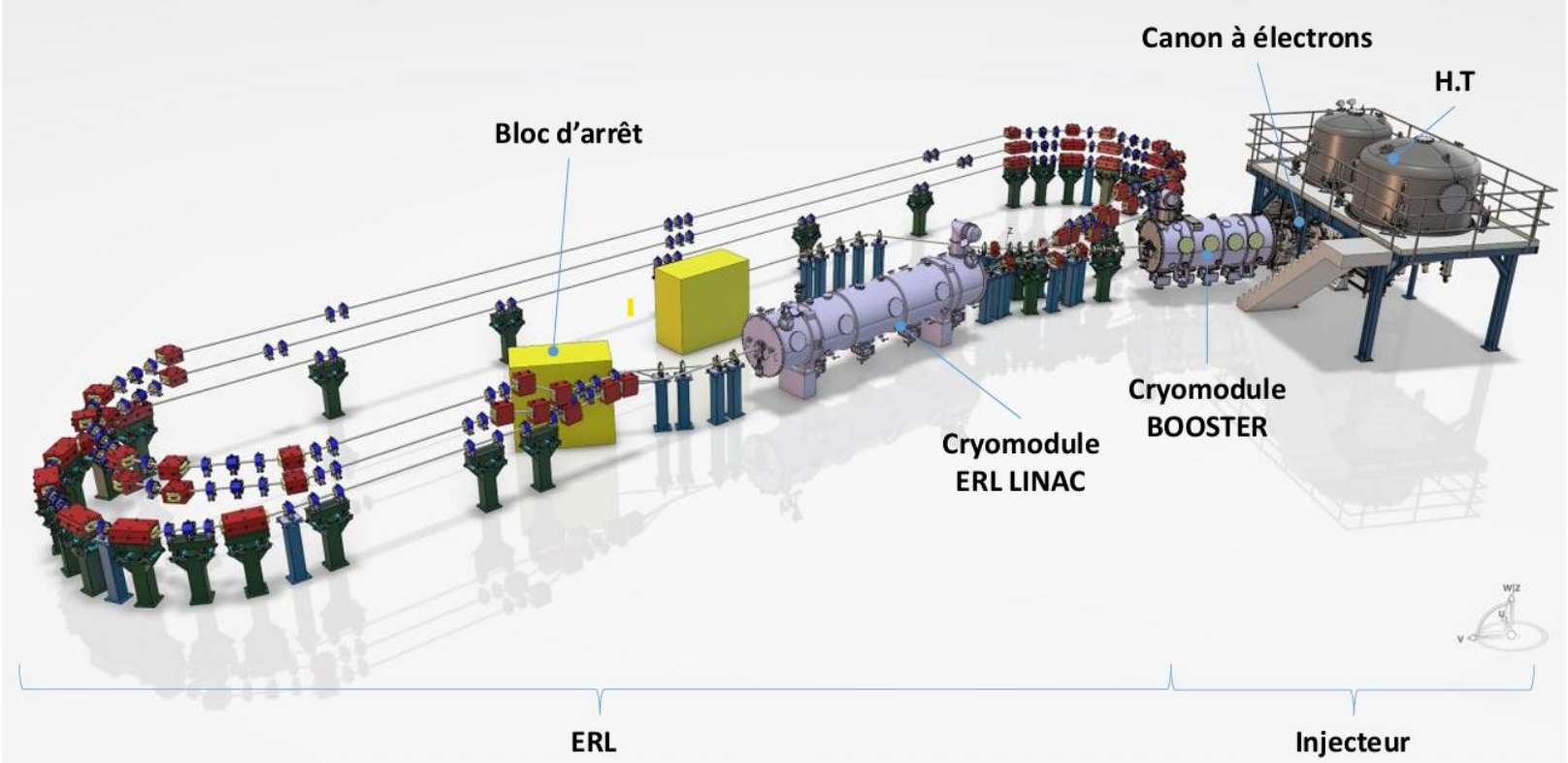


Courtesy : Aurélien Martens

Objectives

In systems like Low Level RF (LLRF) for accelerators, separate modules must share a coherent time and frequency reference

Poor synchronization lead to phase errors and performances loss
Standard networks cannot reach sub-nanosecond precision.

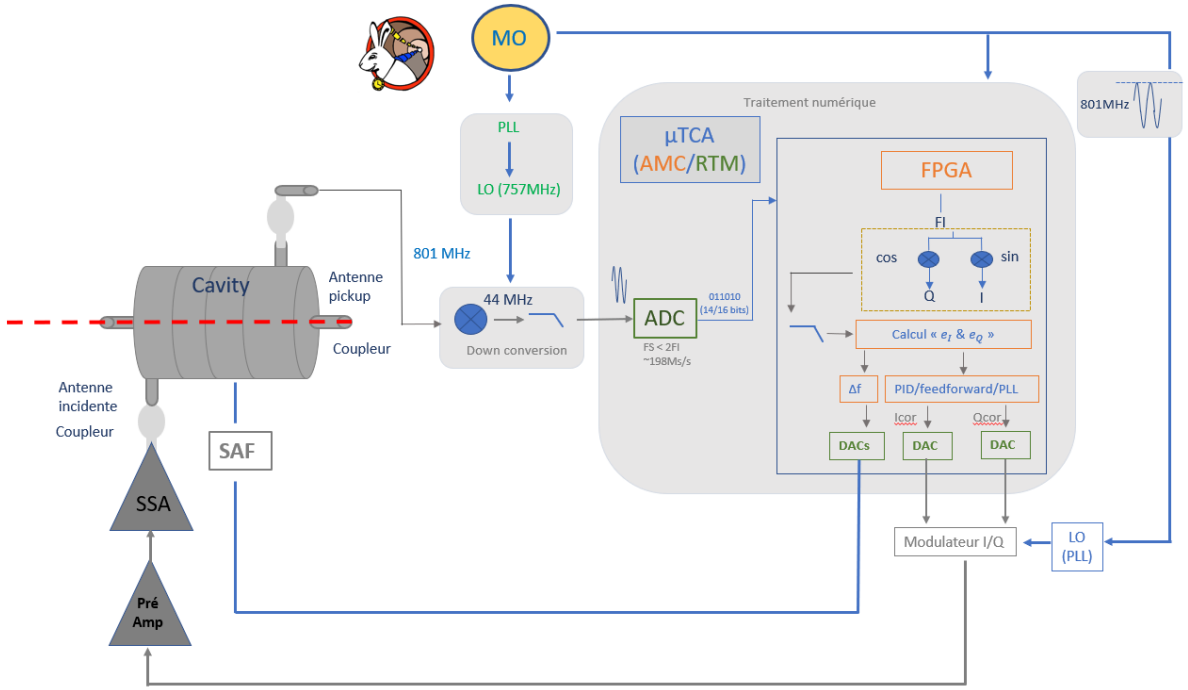


Context & Synchronization need

Low Level RF:

Real-time control and regulation system for RF cavities:

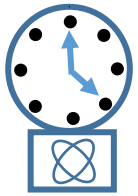
- Real-time measurement of the cavity (amplitude and phase)
- Real-time correction (feedback loop)
- Uses highly precise synchronization (White Rabbit)
- Stabilizes beam performance (field/beam)
- Controls the amplifiers for signal generation
- Operator interface: global synchronization



LLRF Requirements to be confirmed by beam dynamics: based on 0.1° (phase) & 0.1% (amplitude)

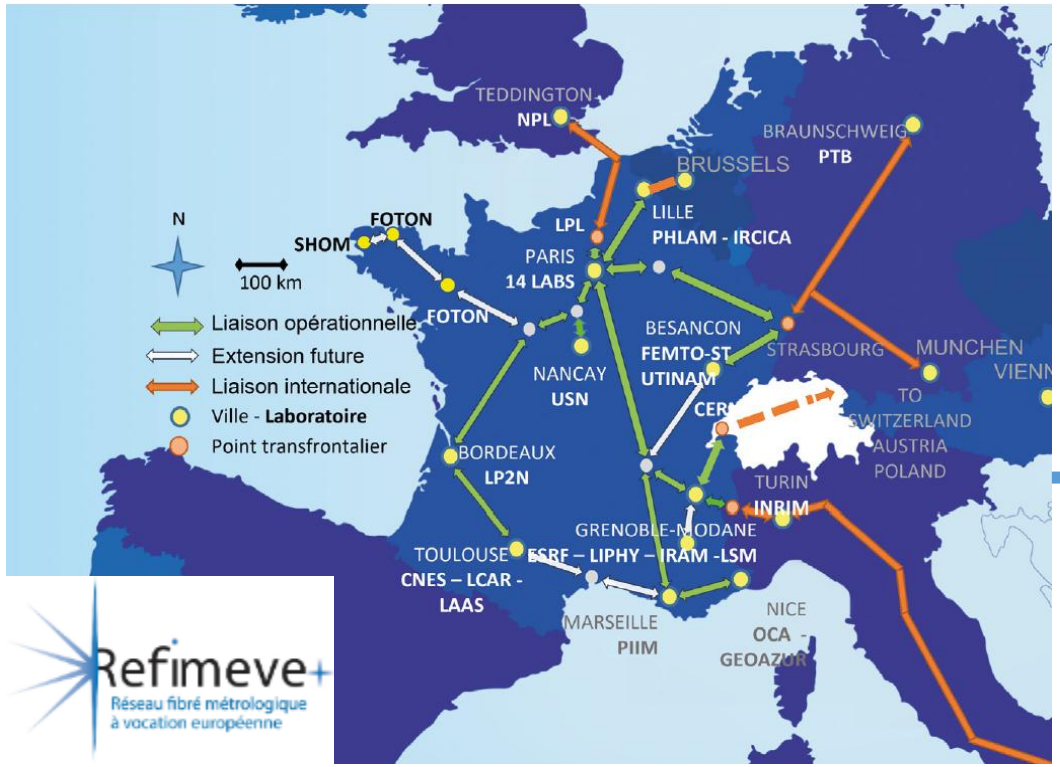
Distributed Master Oscillator (DMO)

Time and frequency



Atomic Clock

LTE
PARIS



Signal to be provided by T-REFIMEVE

		Stability or relative stab. @1s	Stability or relative stab. @1day	Uncertainty routine	Uncertainty dedicated
Radiofrequency	1st pillar - 10 MHz (White Rabbit)*	1,00E-12	1,00E-15	1,00E-14	1,00E-15
	2nd pillar - 1 GHz	1,00E-13	3,00E-16	1,00E-14	2,00E-16
Time	1st pillar (White Rabbit)*	1 ns	1 ns	10 ns	10 ns
	2nd pillar	20-50 ps	500 ps	10 ns	2ns to 100ps§
Optical frequency (194,5 THz/1542 nm)	Today	1,00E-15	3,00E-16	1,00E-14	2,00E-17
	Expected progress in 5 years	1,00E-16	2,00E-17	1,00E-14	1,00E-18

REFIMEVE: french network distributing time and frequency references over optical fiber.

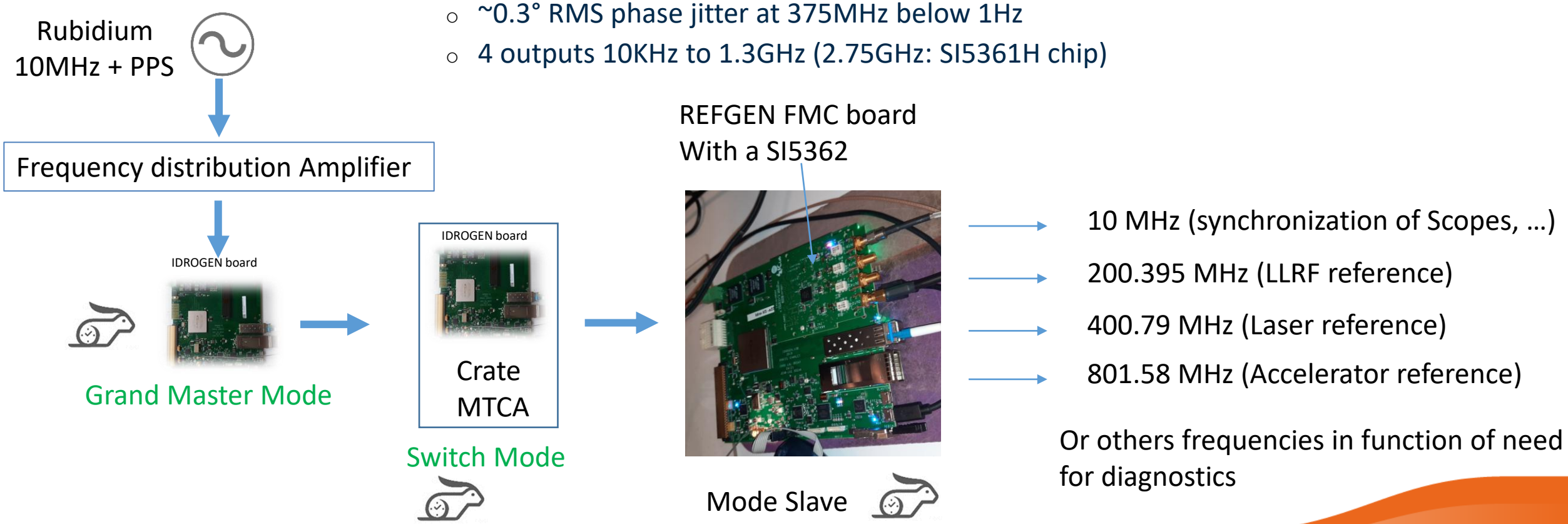
SYRTE (LTE): Paris Observatory, provides highly precise references

WR carries these references to end users

Distributed Master Oscillator (DMO)

Fractionnal PLL (FPLL) FMC (on test)

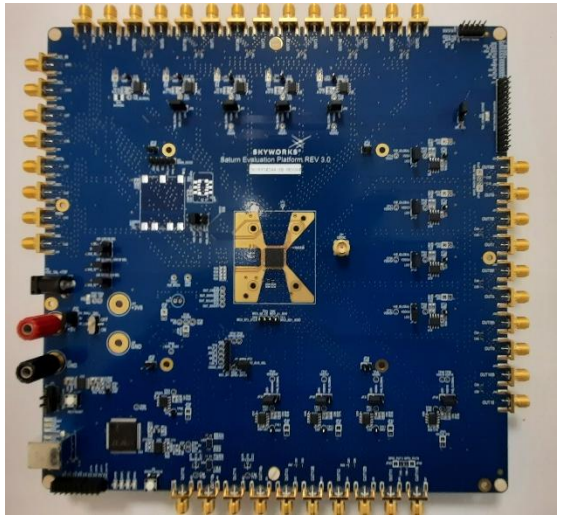
- Replace very expensive system with recent, 30€ component
- Generate arbitrary frequency disciplined by WR clock
  - Frequency resolution 1 Hz
  - Phase noise system: 1 ps (1 Hz, 10 MHz)
  - ~0.3° RMS phase jitter at 375MHz below 1Hz
  - 4 outputs 10KHz to 1.3GHz (2.75GHz: SI5361H chip)



Courtesy : Daniel Charlet

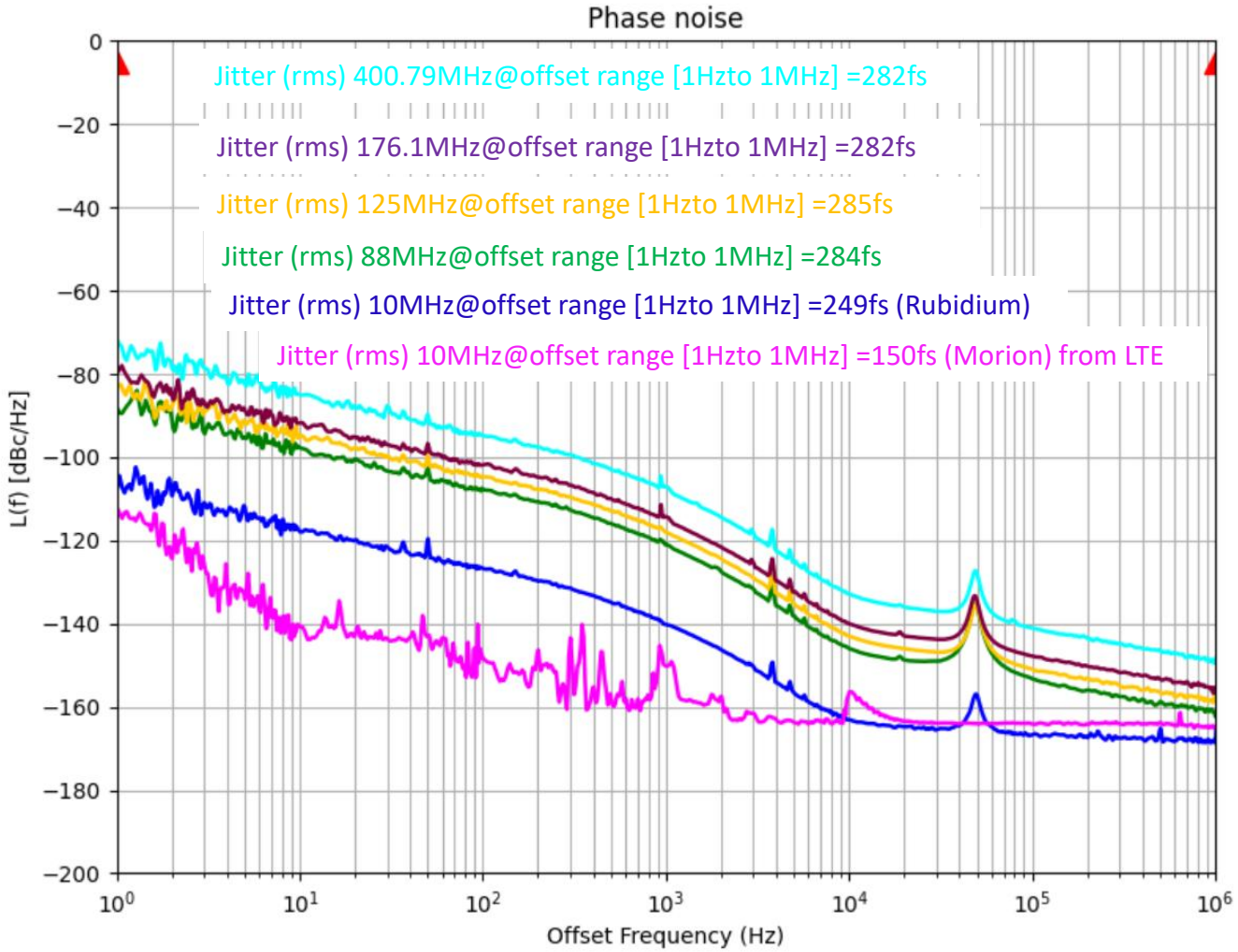
New PLL : preliminary results

SKY 63102



Rubidium
10MHz

Jitter (rms) 10MHz
@offset range [1Hzto 1MHz]
=150fs



-10fs better than Si5362 used on FMC REFGEN board in offset range [12kHz to 1MHz] → validated
- Need characterization in the offset range [1Hz to 1MHz]

IDROGEN: roadmap and future directions

- IDROGEN_V4
  - Development for Q4 2025, mass production mid 2026
  - Replacement of obsolete components
  - Versatility Improvement
- FMC-AD42JB69 (in development)
  - 4 channels 250MSPS 16bits
- FMC-ADC 3GSPS
- White Fox (Highly improved White Rabbit)
  - Development with LTE
  - Sub 100-fs performance (prototype in development)
- Improve short term performance (ongoing development)
- 10Gb/s White Rabbit firmware
- IDROGEN_v5
- New FPGA familly AGILEX

- PERLE:
- Improvements of slave IDROGEN jitter
- Improvements by PTPrate & SoftPLL

Courtesy : Daniel Charlet

Conclusion

- <u>IDROGEN:</u>
- Very promising results with IDROGEN board (sub-picosecond RMS jitter)
- New board version (v4) to be developed in Q1 of 2026
- Focus on essential hardware development
- <u>PERLE:</u>
- Timegen board to be finalised
- FTS board to be finalised
- Installation of WR testbench
- Bring WR switch

Courtesy : Daniel Charlet

Thank you for your attention