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APPLICATIONS

LLRF and synchronization system

Luca Piersanti – 8th EuPRAXIA@SPARC_LAB TDR review committee 25-26/11/2024

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Outline

- EuPRAXIA@SPARC_LAB RF stability requirements
- Synchronization system baseline
- Updates on the LLRF system definition and procurement
- Experimental activity at SPARC_LAB and TEX facility
  - Upgrade of the LLRF system and Reference Master Oscillator
  - Upgrade of the intra-pulse phase feedback
  - RF stability measurements at TEX
- Conclusions

EuPRAXIA@SPARC_LAB stability requirements

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AMPLITUDE stability

- The amplitude jitter values required are routinely achieved in other facilities using solid state modulators + saturated klystron tubes (e.g. SwissFEL)
- Unfortunately we don't have measurements on solid state modulator driven klystrons at LNF (we only have 2 and they do not operate in saturation yet)
- We will perform some dedicated measurements both at SPARC and TEX on C and X band power stations to validate this requirement, but we are confident it will not represent a showstopper

RF Gun (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.02	*deg*
S-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.02	*deg*
X-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.10	*deg*
Cathode Laser System		
Charge [ΔQ] (max)	± 1	%
Laser time of arrival [Δt] (rms)	± 20	fs
Laser Spot size [Δσ]	± 1	%

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PHASE stability

- The jitter added by the reference distribution system must be included in the budget of the BD requirements
- The final jitter of each client is given by the quadratic sum of client's intrinsic jitter and the distribution system

$$\sigma_{BD\ spec} = \sqrt[2]{\sigma_{Distr}^2 + \sigma_{Client}^2}$$

- Depending on the reference distribution technology, the added jitter can **range from <8 fs** (RF over Fiber transmission) **to <1 fs** (pulsed optical system). **The price to pay is increased complexity, cost and maintenance of the system**

General remarks

Considering the scale of the EuPRAXIA@SPARC_LAB project and the critical role of the synchronization system in ensuring optimal machine operation, our approach focuses on the **adoption of commercial solutions**, reserving the development of **custom systems exclusively for areas where substantial improvements can be achieved** (e.g. intra-pulse feedback)

The content of **the presentation summarizes the experimental work** carried out over the past three months **and the information exchanged during the «LLRF Topical Workshop - Timing, Synchronization, Measurements and Calibration»** organized by our group at the LNF (https://agenda.infn.it/event/42239/).
As a result, the TDR chapter is not fully aligned with the information I am about to present

Reference distribution system

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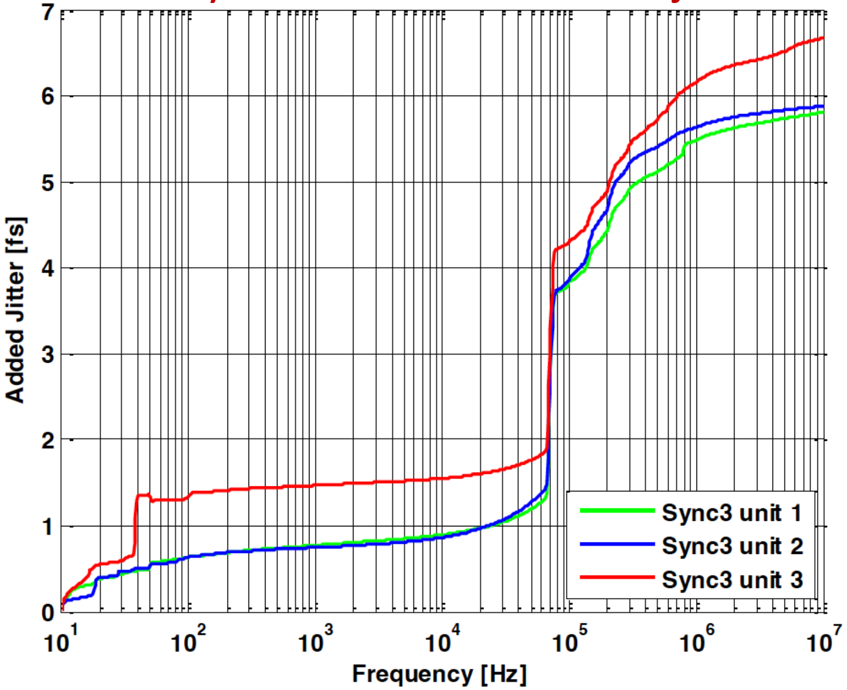
RF Over Fiber working principle

- CW amplitude modulation of an optical carrier transmitted along an optical fiber backbone
- 2 fibers for each link: one used to correct drifts, the other for the RF reference transmission/reconstruction
- Robust, reliable system, easy to implement, with very good performance.
  It is **used in many FEL facilities worldwide**: PSI-SwissFEL, PAL-XFEL, SLAC-LCLS-II, SINAP-SXFEL, STFC-CLARA FEL …
- Considering the BD requirements, assuming a client stability of 15 fs, the impact on the final jitter can be estimated to be **only ≈2 fs worse wrt pulsed laser system**

$$\sigma_{BD\ spec} = \sqrt[2]{8^2_{RFOF} + 15^2_{Client}} = 17\ fs$$

$$\sigma_{BD\ spec} = \sqrt[2]{1^2_{Pulsed} + 15^2_{Client}} = 15.03\ fs$$

RFOF system measured added jitter



P. Orel et al. in *Proc. IPAC’14*, TUPRI079, pp. 1751-1753

Synchronization system baseline

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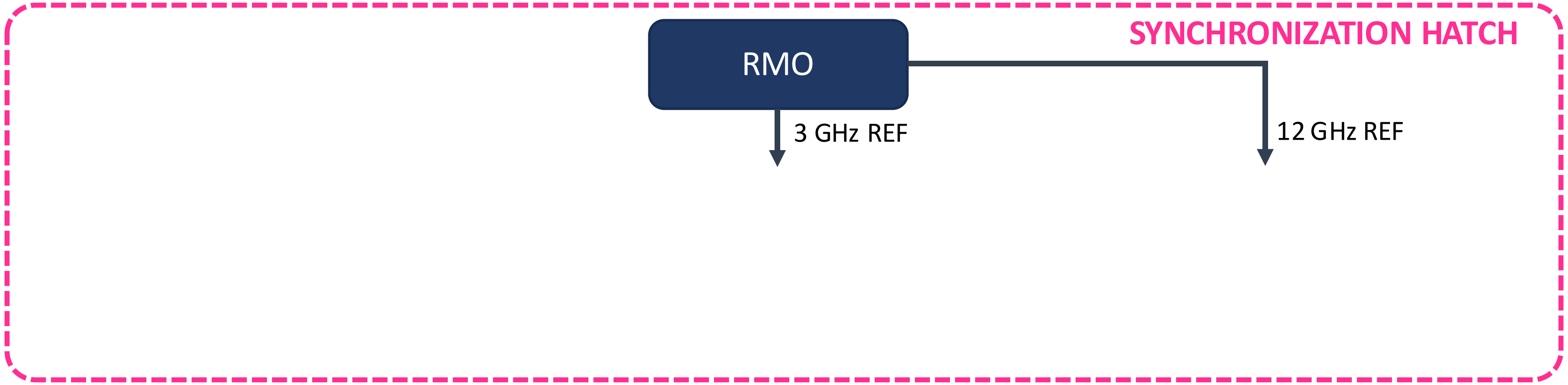
- EuPRAXIA@SPARC_LAB synchronization system baseline has been defined:
  - RF synthesizer or microwave OCXO ultra-stable reference master oscillator (RMO):
    Typical integrated absolute jitter <20 fs 10 Hz - 10 MHz)
    2 coherent output frequencies (3 and 12 GHz)



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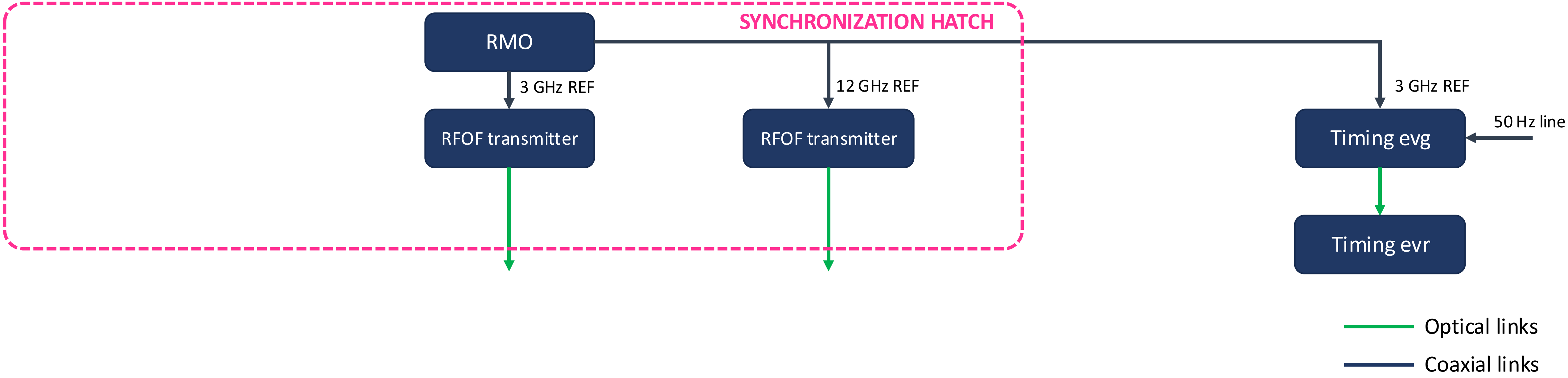

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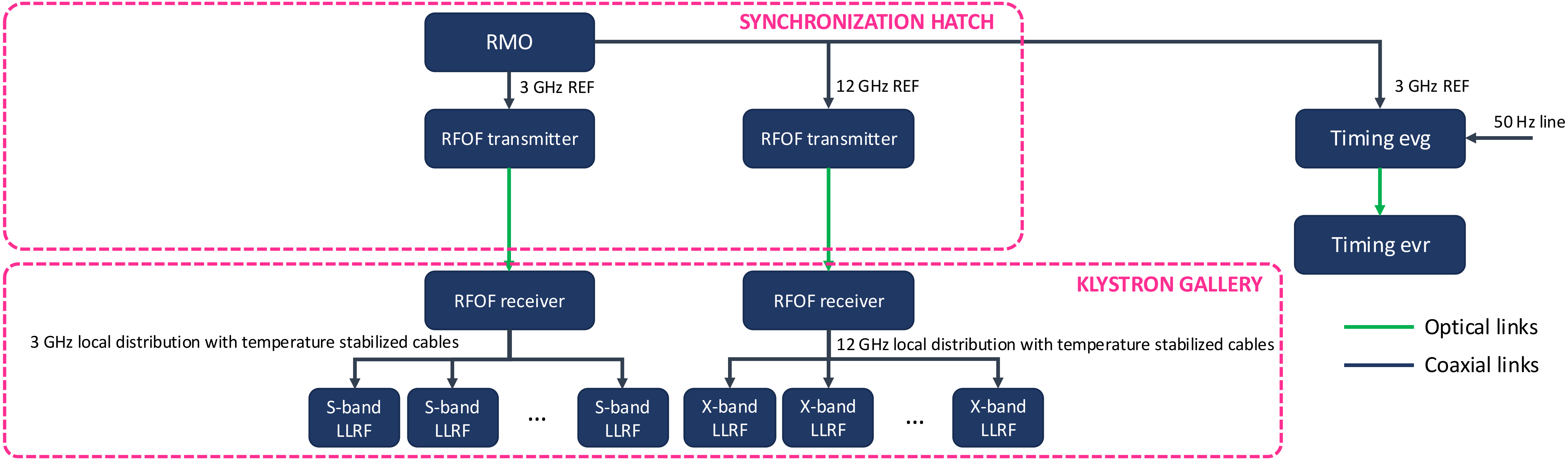

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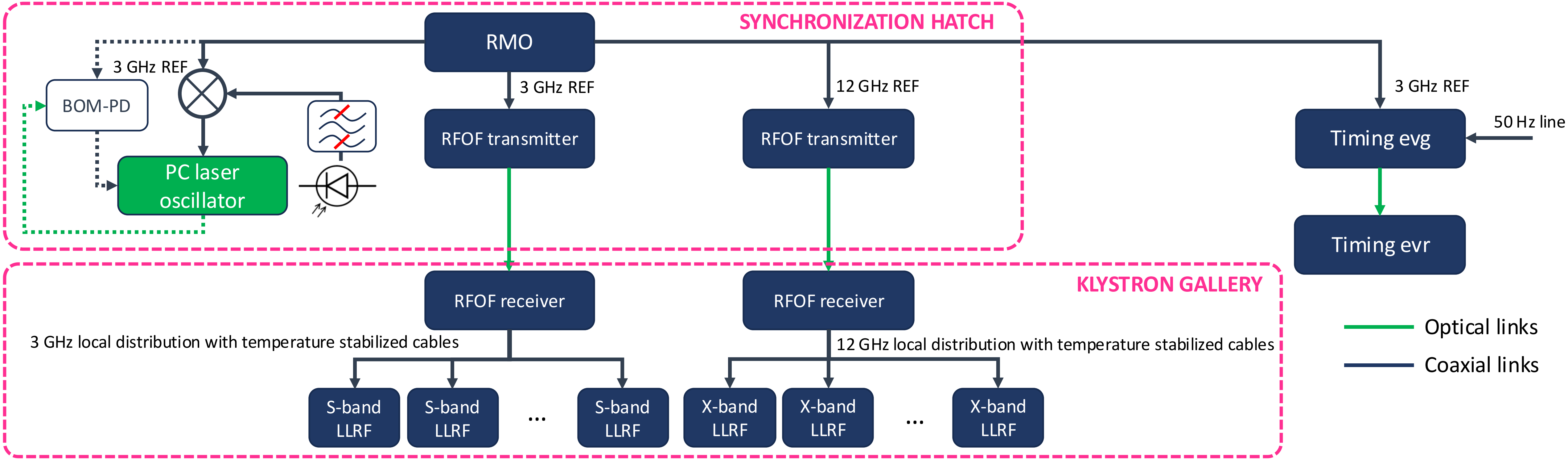
  - Local RF distribution by means of temperature stabilized coaxial cables (e.g. Andrew FSJ2-FSJ1)
  - PC laser oscillator locking system with **RF mixer** as phase detector (**best residual jitter < 20 fs**) or **BOM-PD** (**< 10-15 fs**)

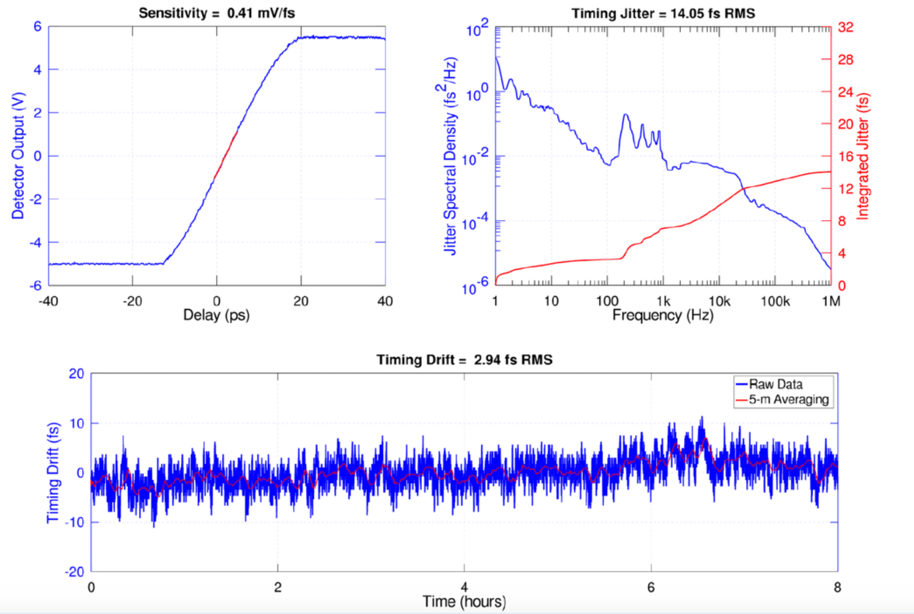


PC-laser locking to RF reference

- Decision still to be finalized, 2 options under consideration:
  - Laser pulse train converted in electrical domain with a photodiode, band-pass filtered to extract the desired RF frequency and phase compared with the reference by means of an **RF mixer**.
    Not expensive, relies on RF components, sensitive to AM/PM conversion, already in operation at SPARC
    (**best measured residual jitter <20 fs**)
  - **Balanced Optical-to-Microwave Phase Detector** + locking electronics + piezo and delay stage motor control
    More expensive, exceptional sensitivity (0.2 mV/fs) and resolution, lowest jitter (**< 15 fs**), amplitude invariant

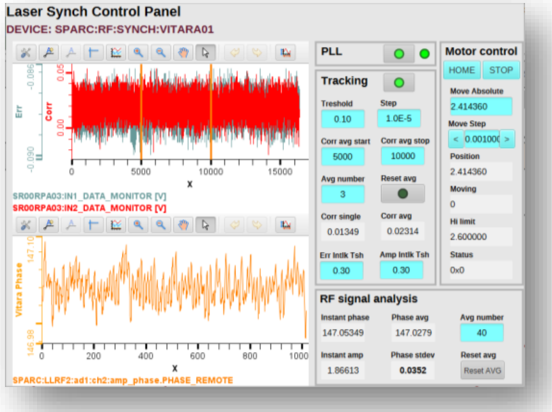
BOM-PD spec. performance

Out-of-loop timing jitter and drift a Ti:Sa laser locked to a RF master oscillator at 5712 MHz.



RF mixer based locking electronics @ SPARC

After the upgrade of the PC laser oscillator and of the locking electronics we still need to optimize the system to recover the optimal jitter performance (currently < 40 fs)



Laser Synch Control Panel
DEVICE: SPARC:RF:SYNCH:VITARA01

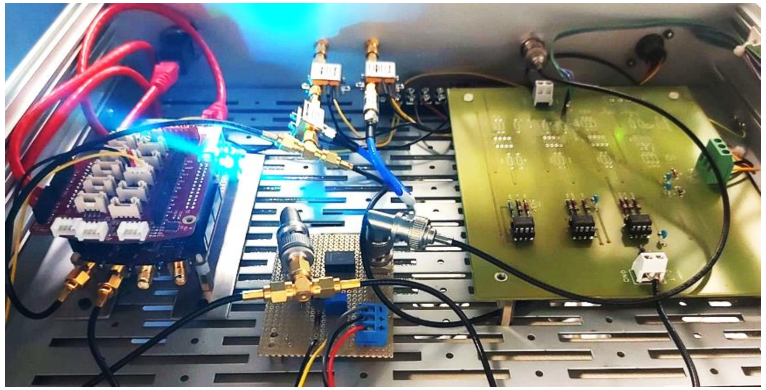
SR00RPA03:IN1_DATA_MONITOR [V]
SR00RPA03:IN2_DATA_MONITOR [V]
SPARC:LLRF2:ad1:ch2:amp_phase.PHASE_REMOTE

PLL

Tracking
Treshold: 0.10
Step: 1.0E-5
Corr avg start: 5000
Corr avg stop: 10000
Avg number: 3
Reset avg
Corr single: 0.01349
Corr avg: 0.02314
Err Intlk Tsh: 0.30
Amp Intlk Tsh: 0.30

Motor control
Move Absolute: 2.414360
Move Step: 0.001000
Position: 2.414360
Moving: 0
Hi limit: 2.600000
Status: 0x0

RF signal analysis
Instant phase: 147.05349
Phase avg: 147.0279
Avg number: 40
Instant amp: 1.86613
Phase stdev: 0.0352
Reset avg



X-band LLRF updates

- Currently, there aren't any "off-the-shelf" systems available on the market
- All laboratories that use X-band power plants have developed custom systems, almost never with stringent specifications on RF stability
- They are very often based on the adaptation of existing LLRF systems at lower frequencies (typically 3 GHz) with up/down converters for frequency translation
- From the perspective of a user facility, the R&D effort and manpower required for the development, large-scale production, and maintenance of a LLRF system, over the project's timeframe, is not sustainable by the LNF RF group -> **commercial solution**
- Since 2022 we are contacting private companies that could be interested in such R&D – we got 2 positive answers (Instrumentation Technologies, Safran)
- The technical specifications of the LLRF system have been drafted and are on constant review
- The budget for the whole supply has been granted from INFN management (≈ 2M Euro for 16 systems: 4 S-band, 12 X-band including spares) and we are ready to start the administrative procedure for the tender

Parameter	Desired value
Mode of operation	Pulsed
Carrier frequency	11.994 GHz
Back-end BW	> 80 MHz
Back-end output level	> 10 dBm
Front-end BW	> 25 MHz
Front-end max. input level	20 dBm
Sampling rate	≥ 250 MS/s
Time window	≥ 3 us
RF pulse max. repetition rate	≥ 400 Hz
Min. pulse-to-pulse detectable amp. jitter (front end)	< 0.05% rms
Min. pulse-to-pulse detectable phase jitter (front end)	< 0.015 deg rms (@ 11.994 GHz)
VM pulse-to-pulse added amp. jitter	< 0.05% rms
VM pulse-to-pulse added phase jitter	< 0.015 deg rms (@ 11.994 GHz)
n. RF input ch.	16
n. RF output ch.	2
Pulse shaping (amp. & phase) of VM output	Arbitrary (from spreadsheet)
Amplitude and phase pulse to pulse feedback	Yes
Interlock + post-mortem analysis	Threshold + VSWR

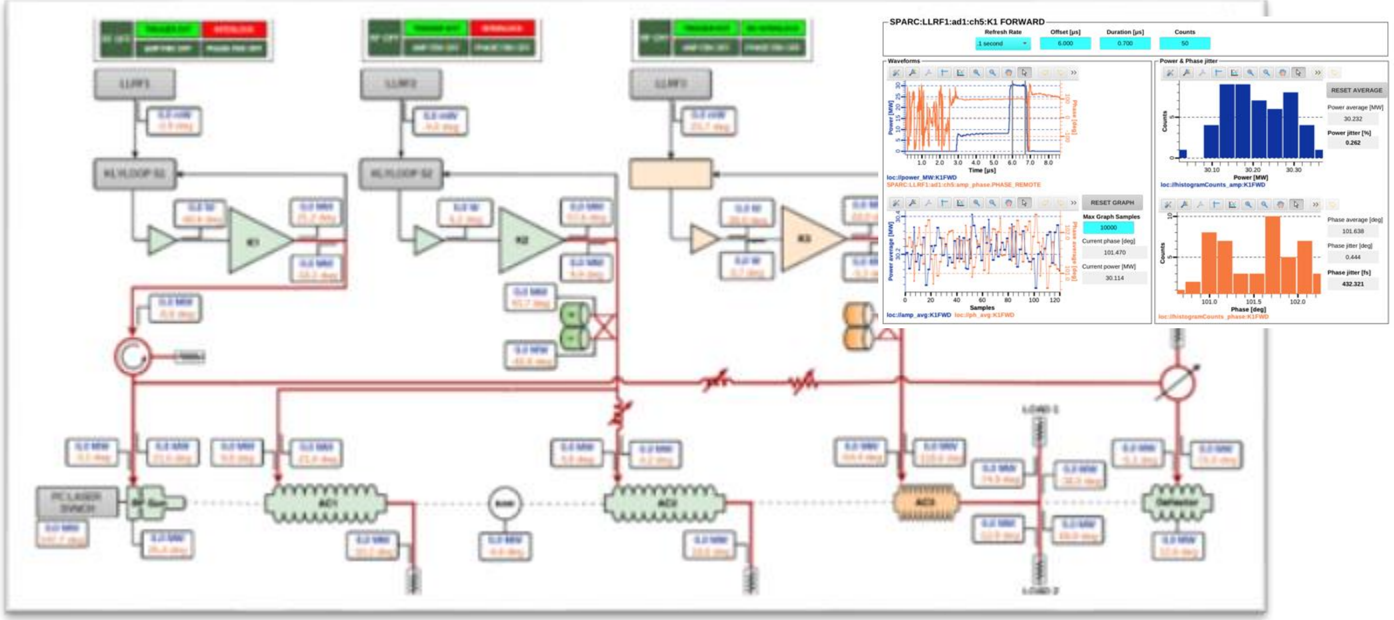
Recent experimental activities at SPARC_LAB: SABINA project

Funded by the European Union

- Thanks to the SABINA project the whole LLRF system and RMO have been updated
    - 3x digital LLRF (ITech) with temperature stabilization, arbitrary pulse shape, and low noise front-end installed and successfully commissioned in July 2024
    - New CSS-Phoebus control interface developed for RF systems setup and diagnostics
    - Ultra low noise reference master oscillator has been acquired and installed
    - New reference generation and distribution system developed exploiting an optical master oscillator (Menlo)

RF main panel

Single channel monitor



SPARC:LLRF1:ad1:ch5:K1 FORWARD

Refresh Rate: 1 second

Offset [µs]: 6.000

Duration [µs]: 0.700

Counts: 50

Power average [MW]: 30.232

Power jitter [%]: 0.262

Max Graph Samples: 10000

Current phase [deg]: 101.470

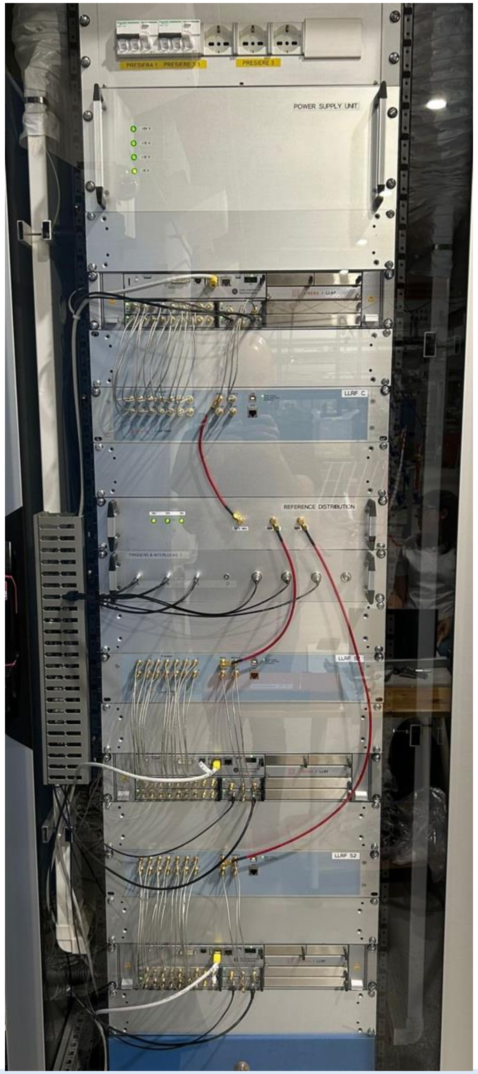
Current power [MW]: 30.114

Phase average [deg]: 101.638

Phase jitter [deg]: 0.444

Phase jitter [fs]: 432.321

New temperature controlled LLRF rack



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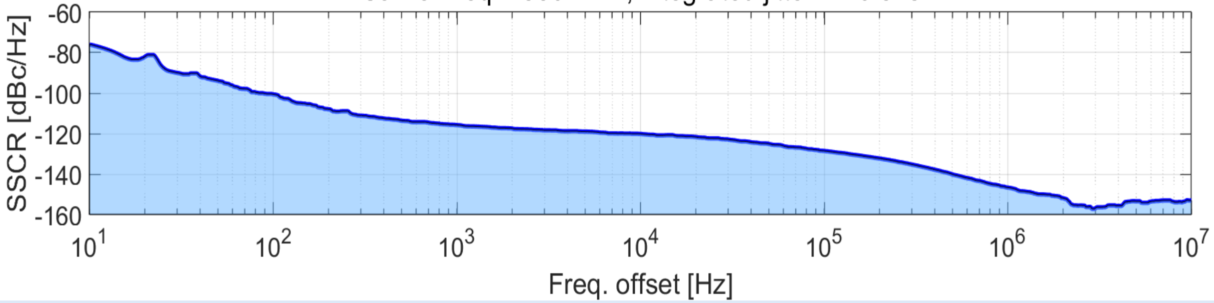
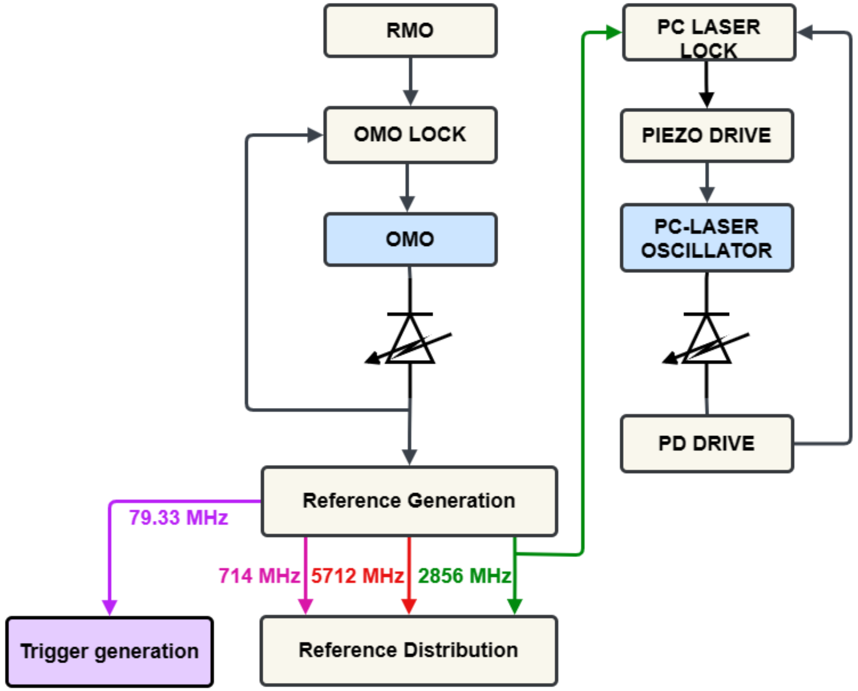
Libera RMO

Libera RMO phase noise measurement

Carrier freq. 2856 MHz, integrated jitter = 20.5 fs



New reference generation scheme at SPARC_LAB



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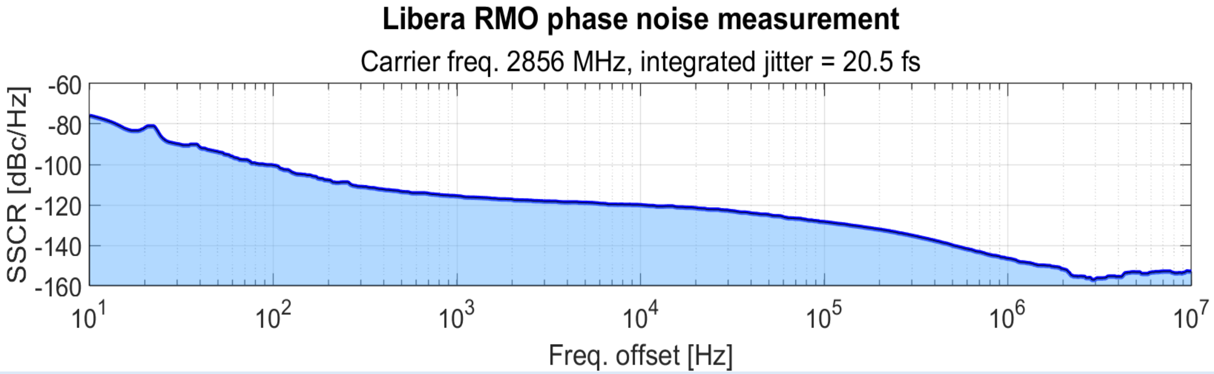

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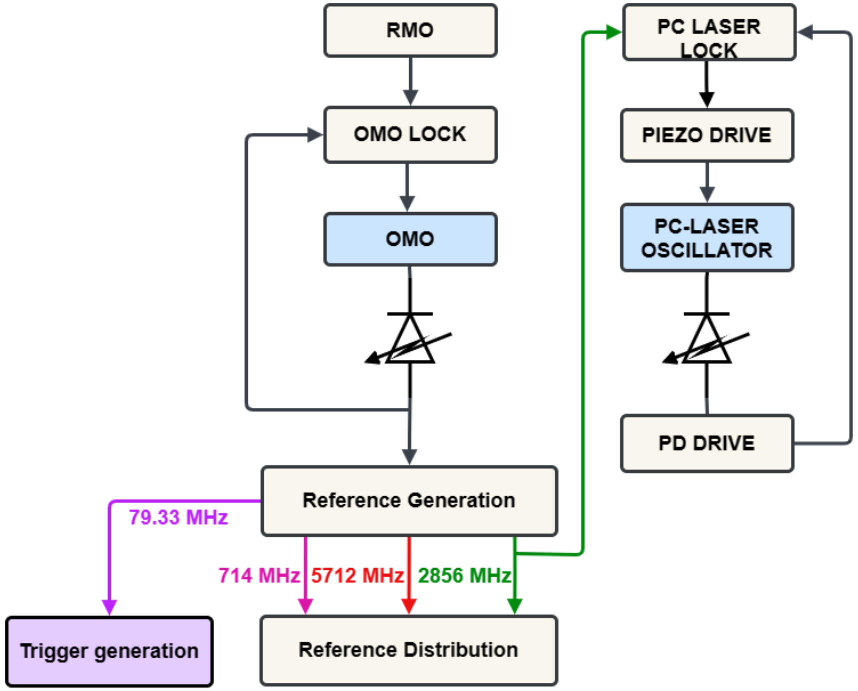
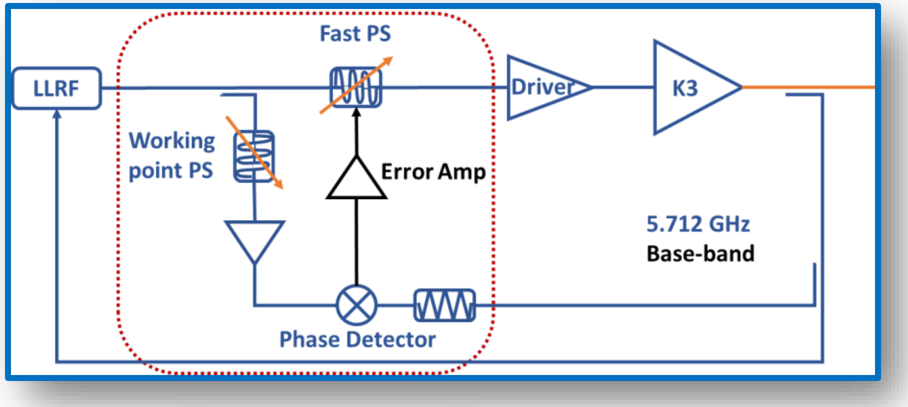


Intra-pulse feedback R&D

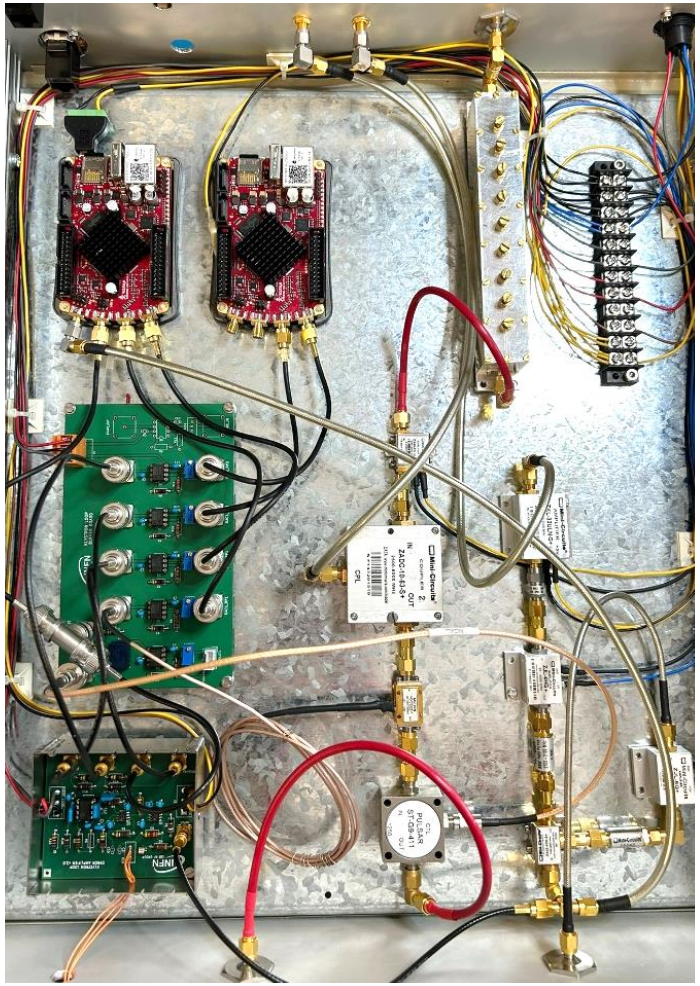
Funded by the European Union

- REMINDER: since 2008 the intra pulse feedback has been successfully operated at SPARC on K1 and K2 (driven by PFN modulators) with residual jitters of the order of 70 fs
- The R&D on the intra pulse feedback electronics to further reduce the RF plants phase jitter at SPARC_LAB is constantly ongoing since 2023
- **IDEA**: **correct the klystron phase within the same RF pulse with fast RF and baseband electronics**
  - High loop bandwidth required (> 10 MHz), klystron group delay limits the loop gain
  - This innovative approach triggered a commercial interest in industrializing and integrating such eletronics in a second generation LLRF chassis with a dedicated VM output with constant amplitude
- The new feedback electronics has been **tested on both PFN and solid-state driven klystrons**, to understand if the native higher stability of solid-state technology can further reduce the jitter

Intra-pulse feedback implementation at SPARC_LAB



New intra-pulse feedback electronics



Intra-pulse feedback R&D: preliminary results

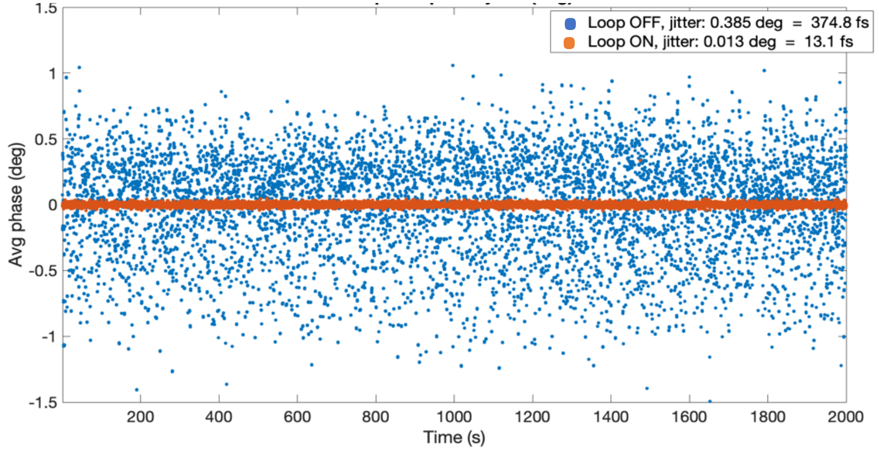
Funded by the European Union

Preliminary data have been parasitically collected during machine restart in Oct/Nov 2024 for the S-band power plants

S-BAND

RF-Gun phase jitter compression

from 0.385 deg down to **0.013 deg** (**13.1 fs**) rms



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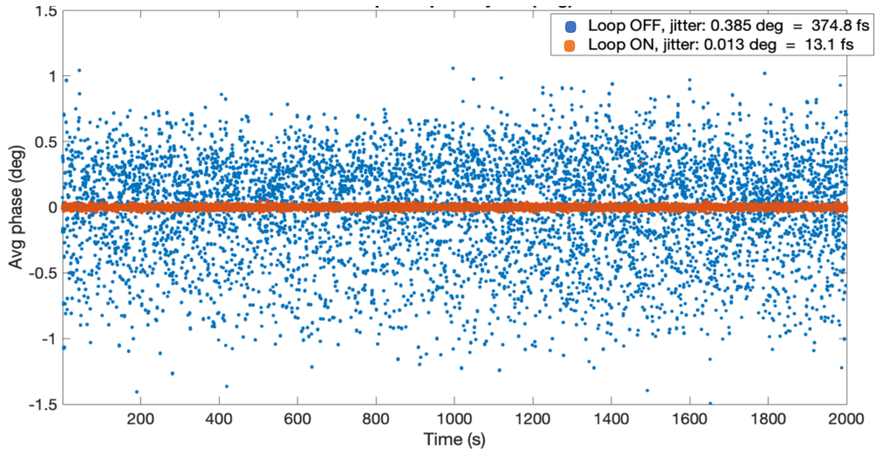
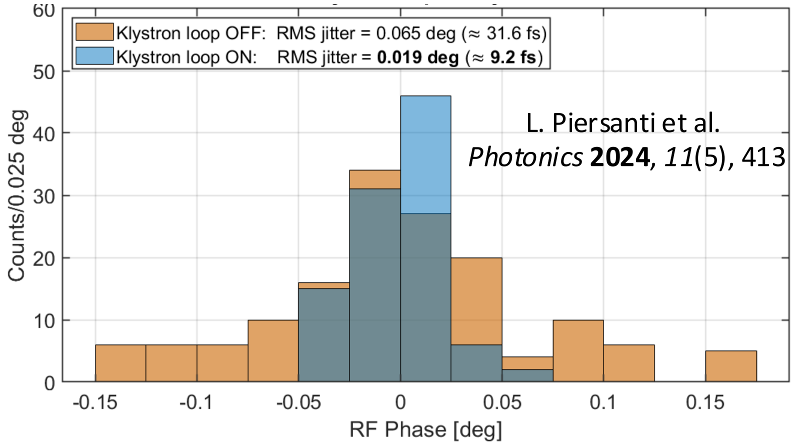


C-BAND

K3 phase jitter compression

from 0.065 deg down to **0.019 deg** (**9.2 fs**) rms



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Photonics **2024**, *11*(5), 413

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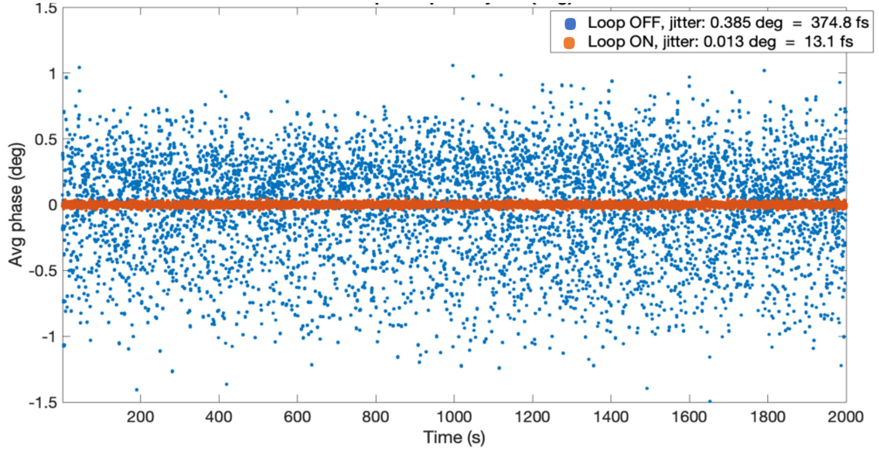

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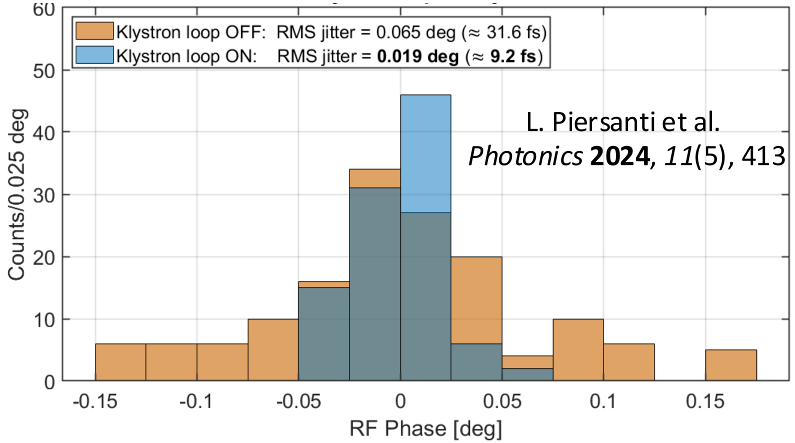

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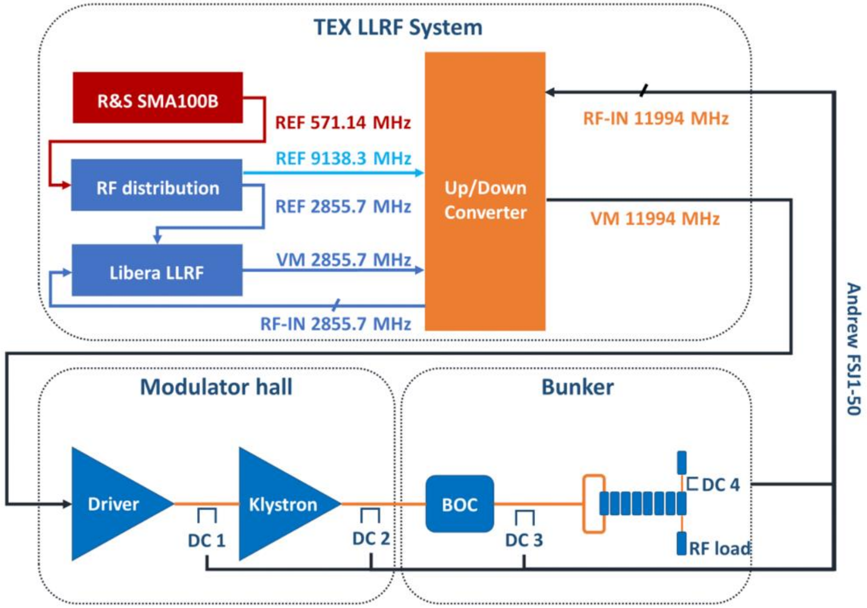
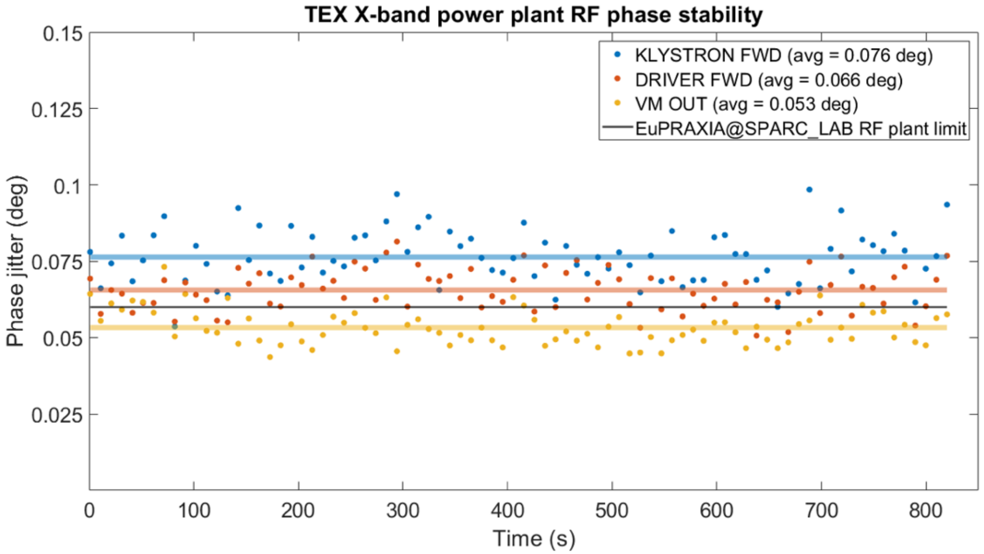
TO DO LIST:

- The **performance** achieved on both S and C band power plants are **very promising** but can be still optimized and consolidated:
  - Reach the same stability of K1 also on K2
  - Further optimize the intra-pulse feedback design (Xianghe Fang Ph.D. student from Eupraxia DN just started his activity on this topic)
- PC-laser locking electronics performance must be improved to meet again the EuPRAXIA@SPARC_LAB requirements
- Intra-pulse feedback system test on the X-band power plant at TEX

RF stability experimental results at TEX facility

- In February 2024 RF stability measurements have been performed to assess phase jitter of the facility and LLRF performance
- LLRF system is a combination of 2.856 GHz Libera LLRF with custom U/D converter developed in-house
  - FE/BE limited bandwidth, low ADC sampling rate, FE dynamic range limited by U/D converter insertion loss and saturation
  - quotation requested for low noise Microwave Amp. driver for Canon klystron





Signal	Rms phase jitter (deg)	Rms time jitter (fs)
VM OUT	0.051	11.9
Driver FWD	0.068	15.8
Klystron FWD	0.076	17.6

Conclusions

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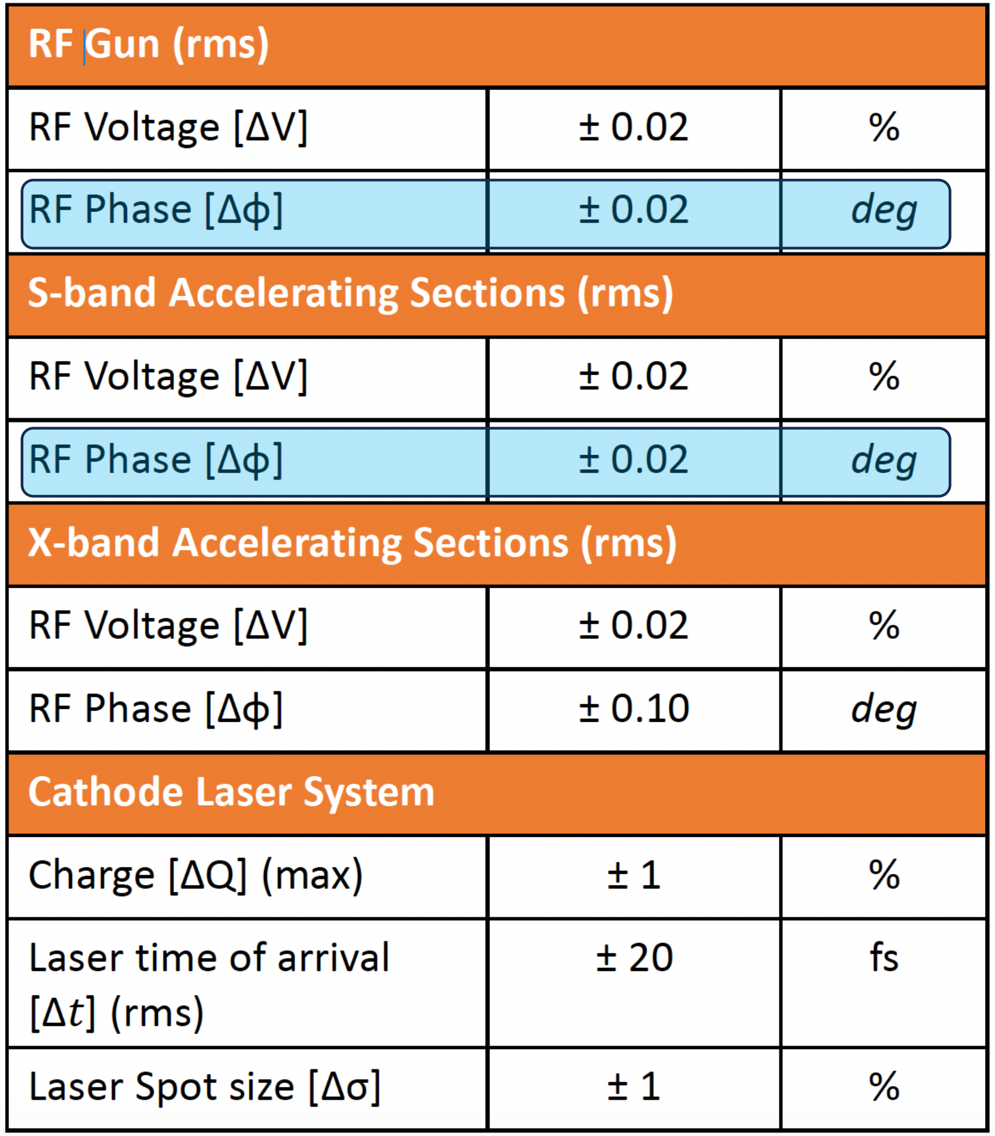
Laser time of arrival [Δ*t*] (rms)	± 20	fs
Laser Spot size [Δσ]	± 1	%

- Using solid-state modulators and saturated klystron tubes, we are confident in meeting amplitude jitter requirements, as other facilities achieve similar performance.
  Measurements at the TEX facility (with CPI and Canon klystrons) will be fundamental to confirm this statement.

Conclusions



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» With intra-pulse feedback for the S-band, we have already met the phase stability requirement (**moreover using PFN modulators**)

» In the past, we achieved a residual laser-RF jitter compliant with this value using RF mixers. Depending on the outcome of the optimization activity for the photocathode laser locking system in the coming weeks, we will define the locking technology.
We also have an agreement with one of the BOM-PD manufacturers to test a system directly at SPARC

Conclusions

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RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.02	*deg*
S-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.02	*deg*
X-band Accelerating Sections (rms)		
RF Voltage [ΔV]	± 0.02	%
RF Phase [Δϕ]	± 0.10	*deg*
Cathode Laser System		
Charge [ΔQ] (max)	± 1	%
Laser time of arrival [Δ*t*] (rms)	± 20	fs
Laser Spot size [Δσ]	± 1	%

- Using solid-state modulators and saturated klystron tubes, we are confident in meeting amplitude jitter requirements, as other facilities achieve similar performance.
  Measurements at the TEX facility (with CPI and Canon klystrons) will be fundamental to confirm this statement.
- With intra-pulse feedback for the S-band, we have already met the phase stability requirement (**moreover using PFN modulators**)
- In the past, we achieved a residual laser-RF jitter compliant with this value using RF mixers. Depending on the outcome of the optimization activity for the photocathode laser locking system in the coming weeks, we will define the locking technology.
  We also have an agreement with one of the BOM-PD manufacturers to test a system directly at SPARC
- We have **already met this minimal requirement** using a non-optimized LLRF system without intra-pulse feedback.
  However, we are **actively conducting R&D to implement intra-pulse feedback in the X-band for further minimization**

EuPRAXIA

EuPRAXIA-PP Consortium

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ENEA Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

SAPIENZA Università di Roma

Università di Roma Tor Vergata

Imperial College London

Queen's University Belfast

UKRI UK Research and Innovation

University of Liverpool

University of Oxford

University of Strathclyde Glasgow

CERN

DESY.

FBH Leibniz Ferdinand Braun Institut

Fraunhofer ILT

GSI

hhu Heinrich Heine Universität Düsseldorf

HZDR Helmholtz Zentrum Dresden Rossendorf

JÜLICH Forschungszentrum

LMU Ludwig-Maximilians-Universität München

Amplitude

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