Timing and synchronization experience and future plans at LNF

M. Bellaveglia

on behalf of the Timing and Synchronization groups at INFN - LNF

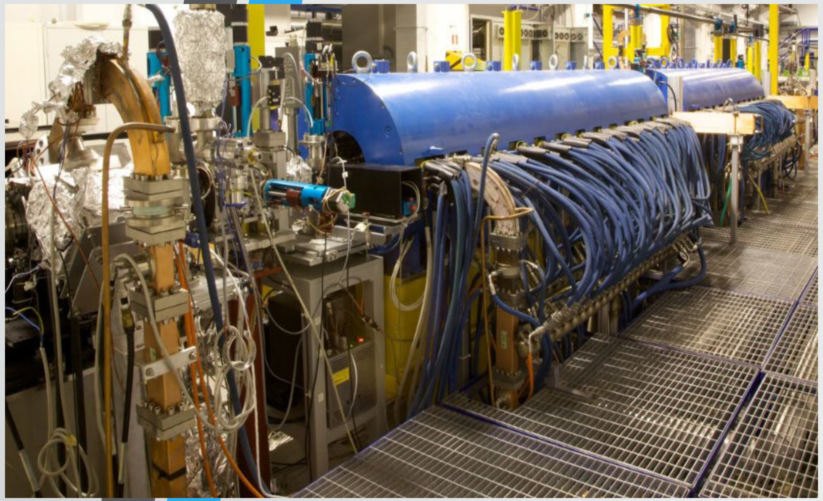
30 October 2024

Overview

- Requirements for a reliable plasma acceleration
- SPARC_LAB
  - Overview
  - Synchronization system: description and recent developments
  - Timing system: description and recent developments
- EuPRAXIA@SPARC_LAB
  - Overview
  - Synchronization system design
  - Timing system design
  - TEst stand for X-band (TEX): overview and stability performance
- Conclusion and open points

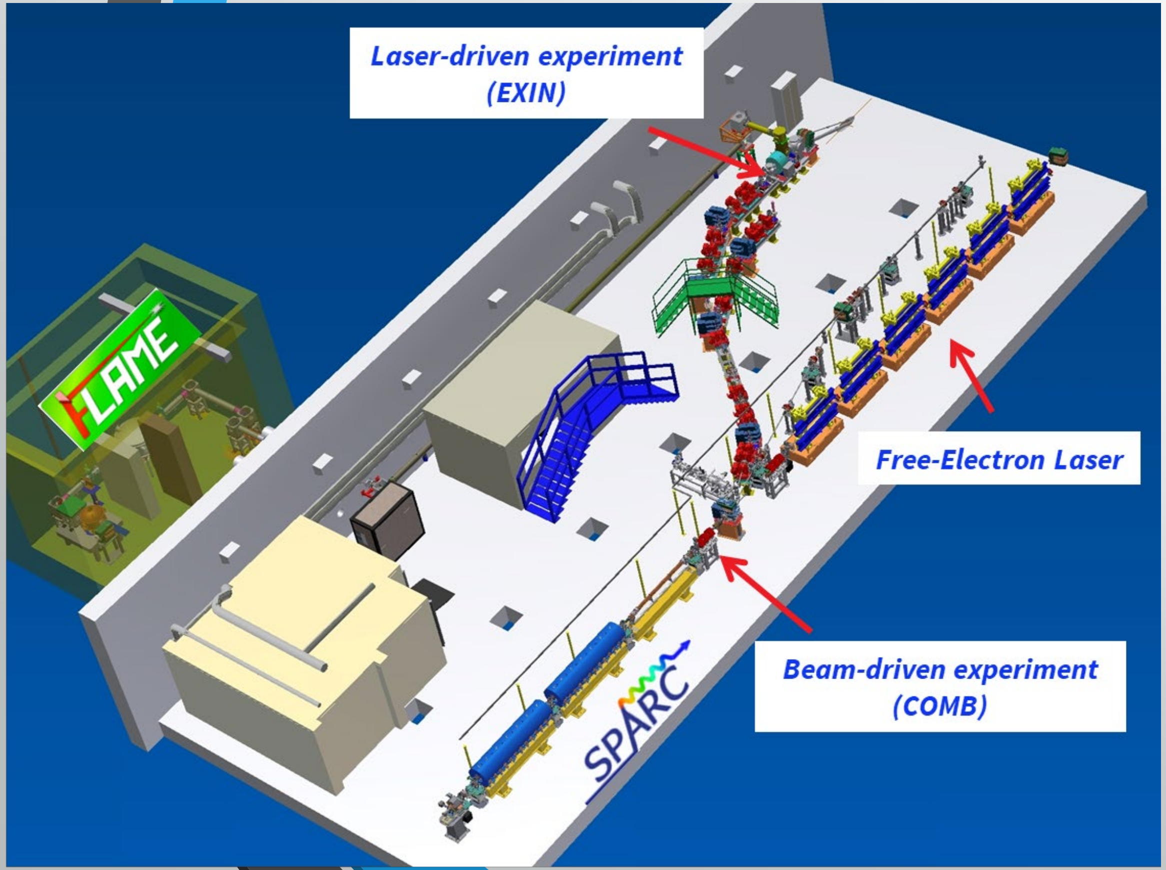
PWFA-LWFA requirements

- The R&D towards the plasma acceleration needs very strict requirement for the synchronization system
- The timing system could be designed using state-of-the-art technology and should not incur in particular issues. Timing precision < 30 ps can be obtained, as already tested in SPARC_LAB
- We are presently exploiting the SPARC linac for a PWFA experiment. We have multiple bunches inside the same RF bucket and their relative phase (that leads to time of arrival in the plasma chamber) must be very stable shot-by-shot to obtain a reliable acceleration
- The requirement in relative longitudinal positioning of the bunches translates in **< 10 fs_{RMS}** between photo-cathode laser pulse arrival time and accelerating field phase, that, again, leads to a relavite jitter < 10 fs_{RMS} between the involved sub-systems (RF and laser) and the RMO.
- Even a stricter specification can be requested in case of particular machine working points and for LWFA with external injection



SPARC_LAB overview

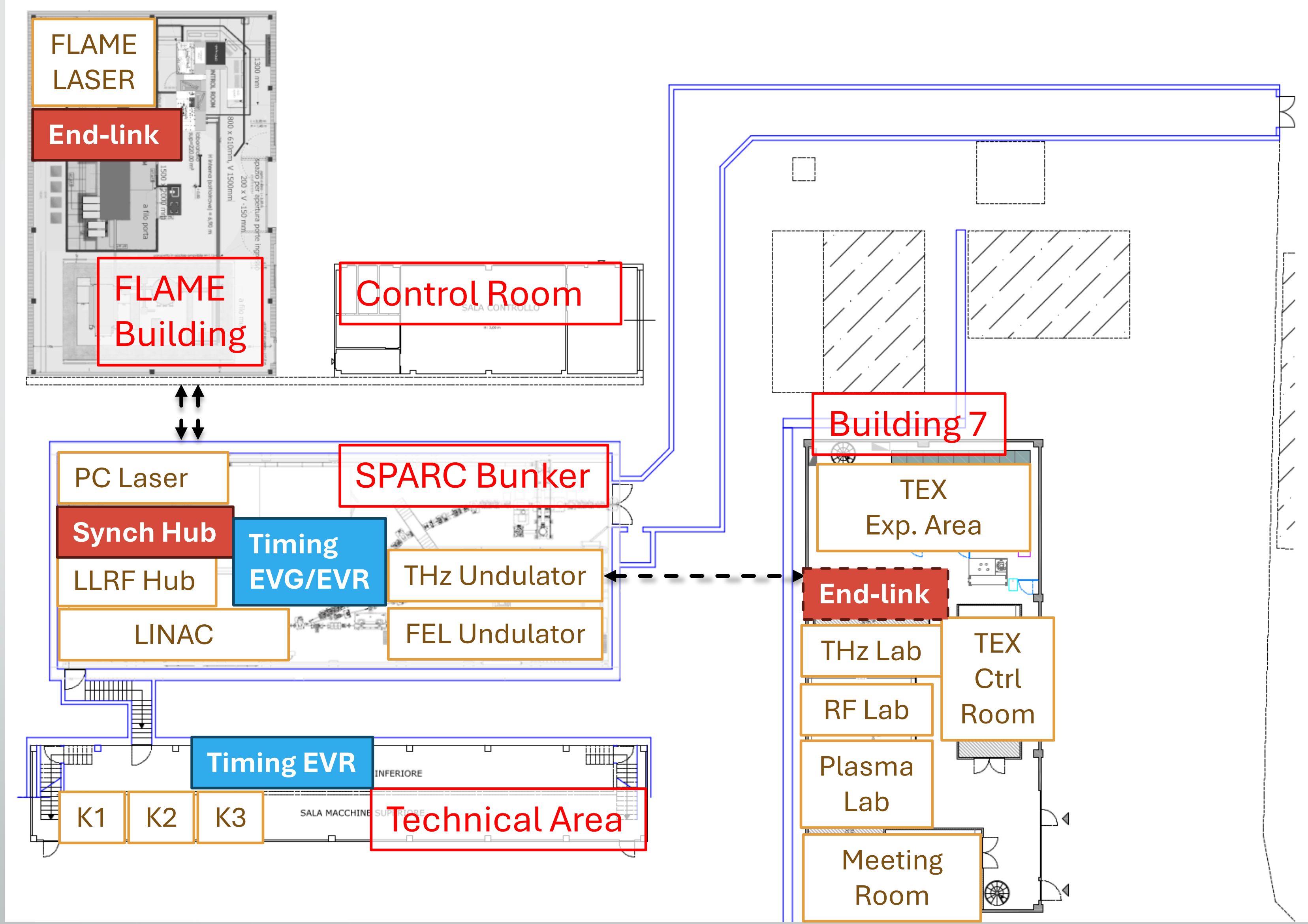
- SPARC_LAB facility was born in early 2000s as an R&D activity to develop a high brightness e^- photo-injector aimed to perform FEL experiments
- Presently, it is composed by
  - 150 MeV electron photo-injector (2 S-band and 1 C-band power stations)
  - a TW class laser (FLAME)
  - 2 undulators (for FEL and THz radiation)
- An intense R&D program has been carried out performing many experiments:
  - SASE and seeded FEL
  - Thomson back-scattering
  - THz radiation
  - Plasma focusing and acceleration
  - Laser-matter interaction



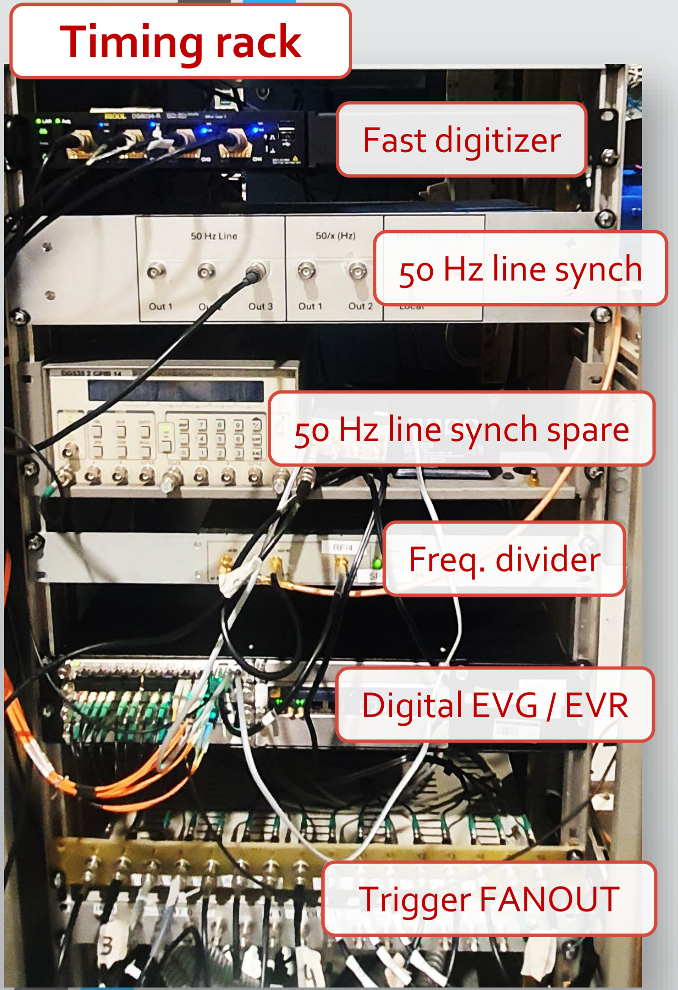
SPARC_LAB overview - Present status

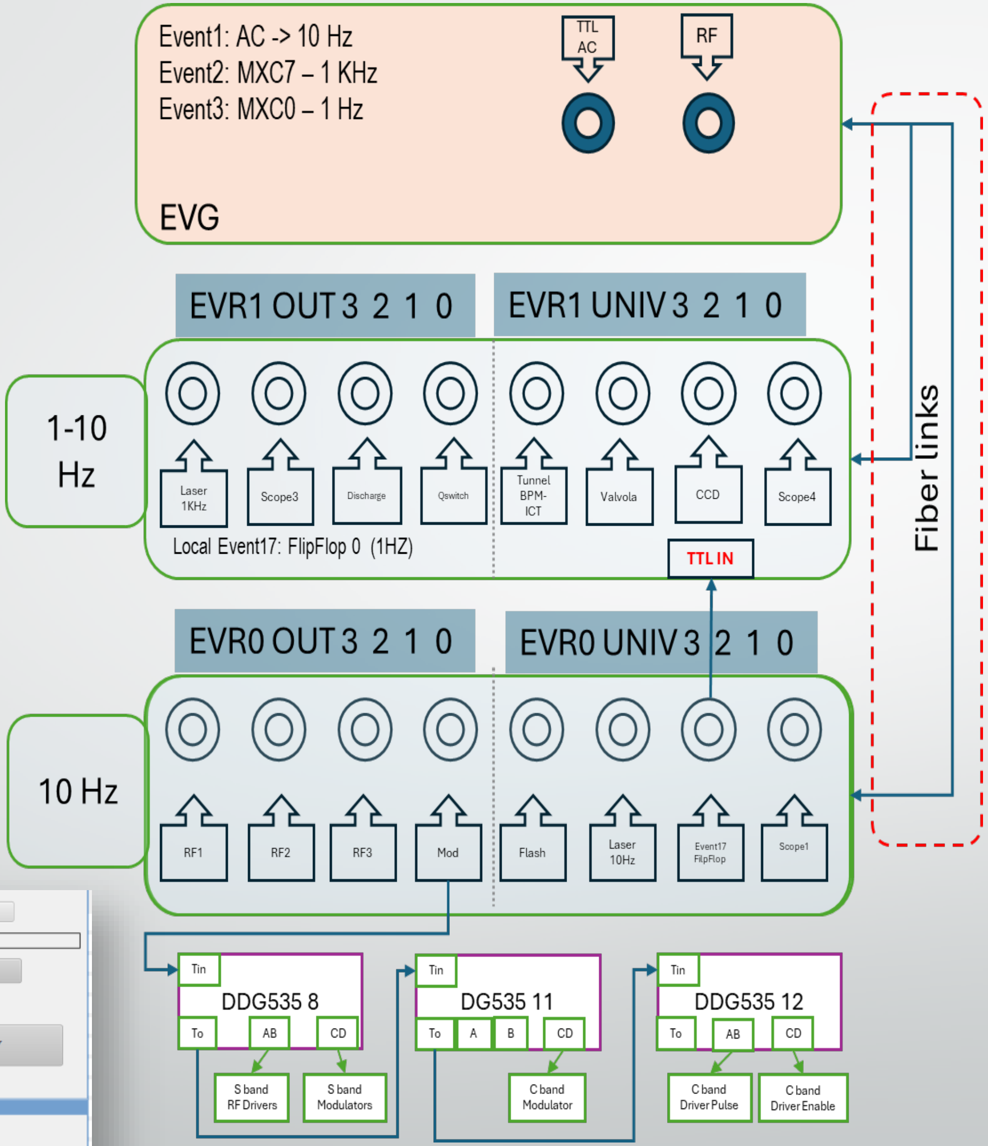
- The machine went through many upgrades during its period of activity
- The most recent, spreaded over the last 3 years, was a major upgrade that involved the whole facility
- The **synchronization** and **timing** systems experienced major changes as well:
  - The old **LLRF system** has been completely dismantled and installed from scratch passing from an analogue to a digital architecture
  - The **reference signal** generation and distribution for the whole facility has been renewed
  - The **phase stabilization** systems for both the photo-cathode laser oscillator and klystrons have been upgraded
  - The **timing system** has begun its transition from analogue (digital delay gen.) to digital (event generator/receiver) architecture

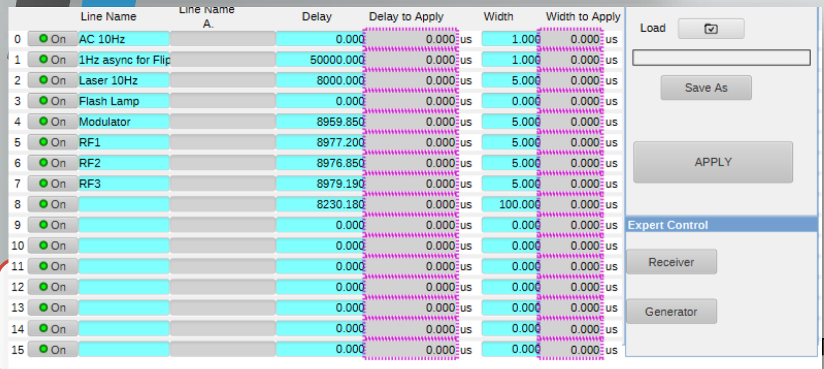
SPARC_LAB overview – Facility layout



SPARC_LAB overview - Timing





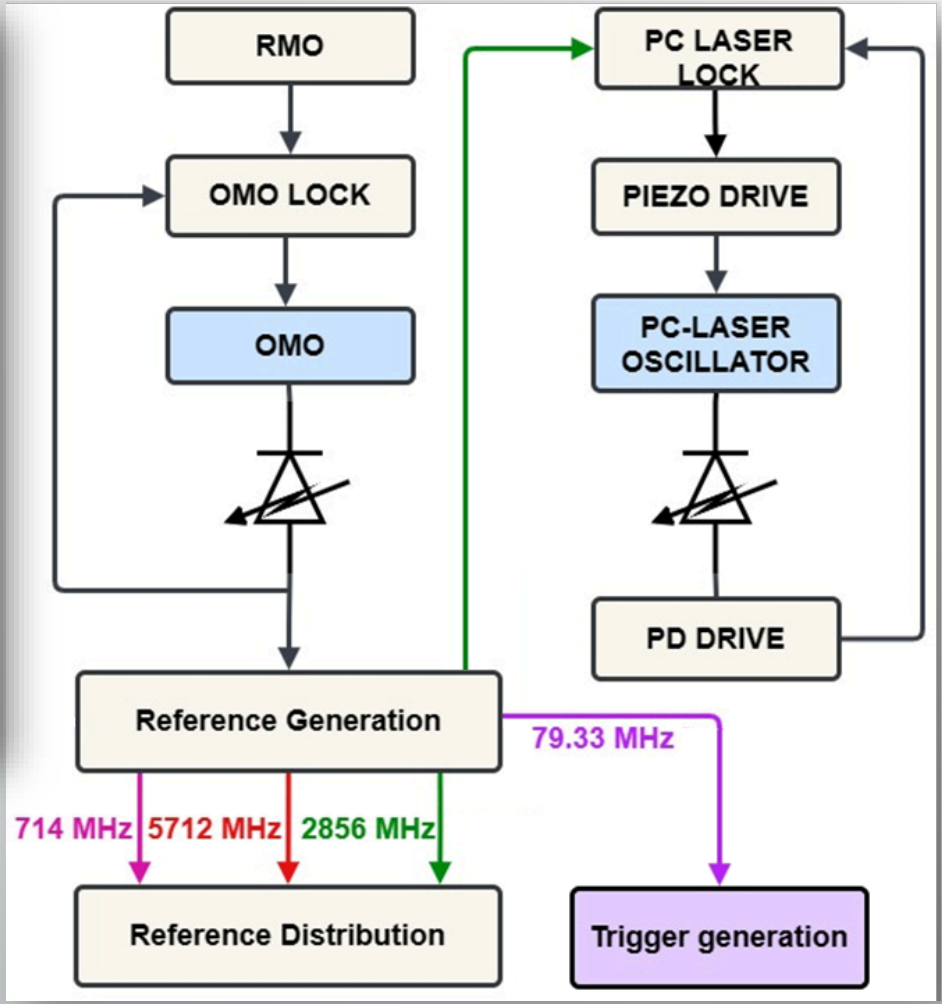


		Line Name	Line Name A.	Delay	Delay to Apply	Width	Width to Apply
0	On	AC 10Hz		0.000	0.000 us	1.000	0.000 us
1	On	1Hz async for Flip		50000.000	0.000 us	1.000	0.000 us
2	On	Laser 10Hz		8000.000	0.000 us	5.000	0.000 us
3	On	Flash Lamp		0.000	0.000 us	0.000	0.000 us
4	On	Modulator		8959.850	0.000 us	5.000	0.000 us
5	On	RF1		8977.200	0.000 us	5.000	0.000 us
6	On	RF2		8976.850	0.000 us	5.000	0.000 us
7	On	RF3		8979.190	0.000 us	5.000	0.000 us
8	On			8230.180	0.000 us	100.000	0.000 us
9	On			0.000	0.000 us	0.000	0.000 us
10	On			0.000	0.000 us	0.000	0.000 us
11	On			0.000	0.000 us	0.000	0.000 us
12	On			0.000	0.000 us	0.000	0.000 us
13	On			0.000	0.000 us	0.000	0.000 us
14	On			0.000	0.000 us	0.000	0.000 us
15	On			0.000	0.000 us	0.000	0.000 us

Load
Save As
APPLY
Expert Control
Receiver
Generator

- Transition of the timing system to a digital architecture in ongoing
- Event generator and receiver from MRF Oy has been installed and configured during last upgrade
- It replaced the old analog triggering system made by pulse generators
- Presently the system is in a «hybrid» configuration since the last event receiver is installed, but is not operational yet (some delay generators are still running)
- The system meets the requirements and no major issues have been reported
- EPICS IOCs and CSS Phoebus are used as software interface

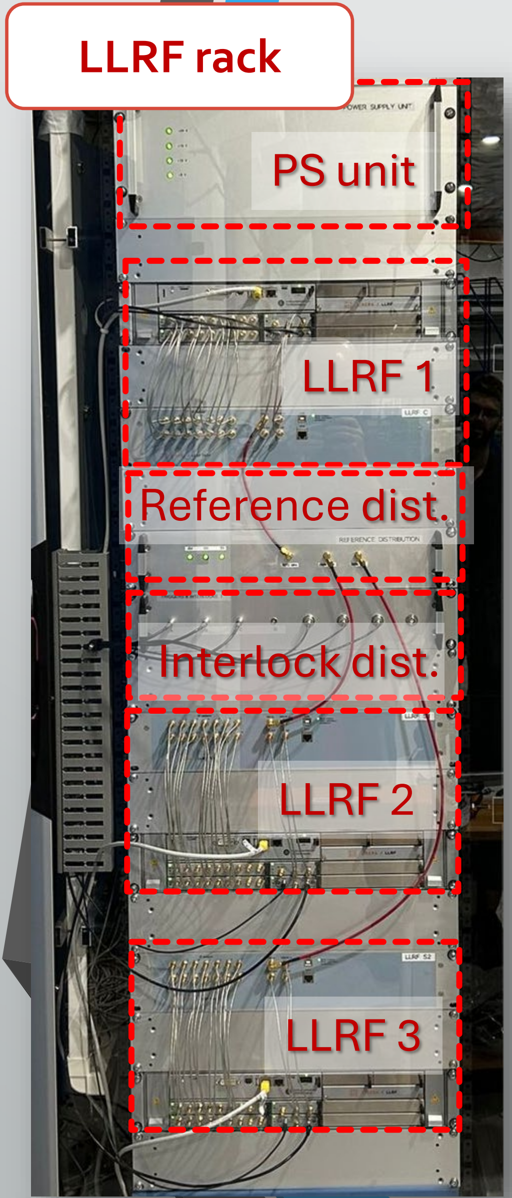
SPARC_LAB overview - Synchronization



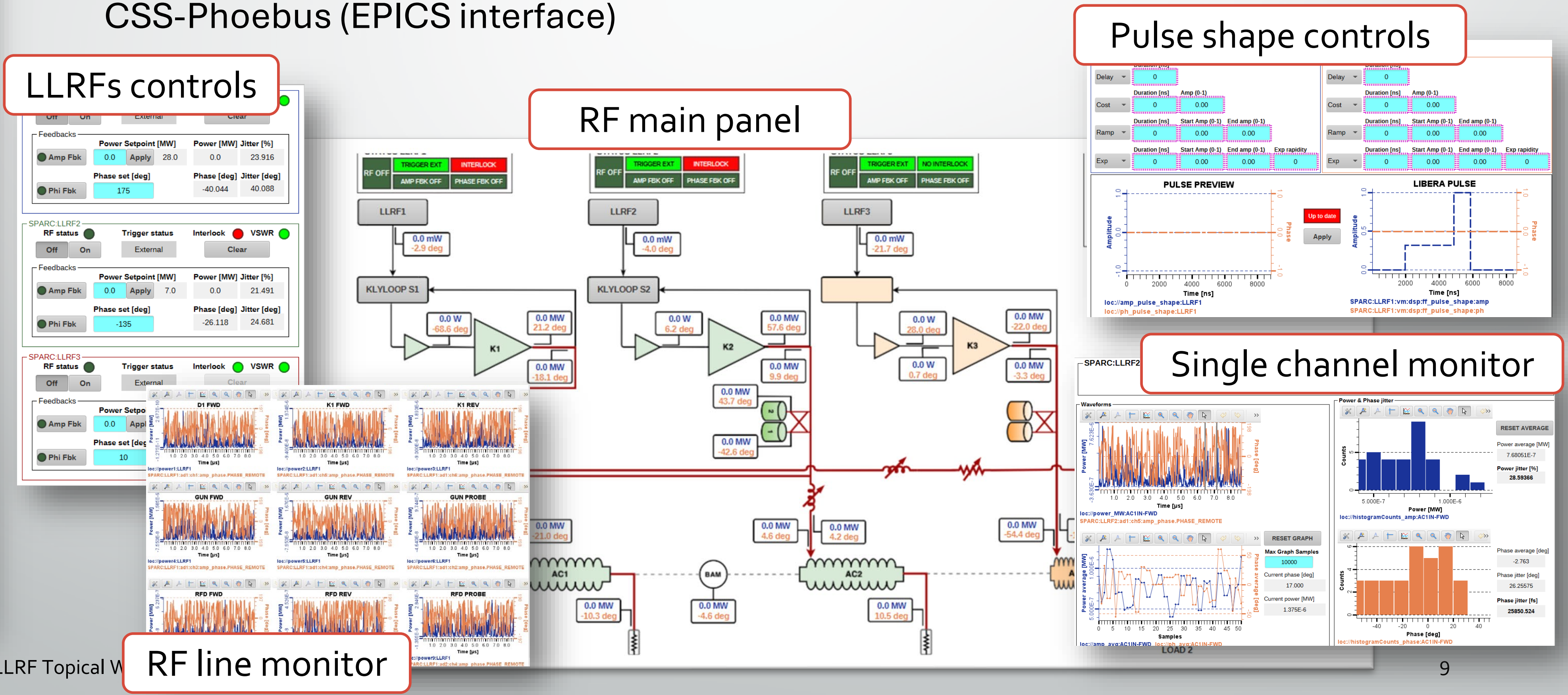
Courtesy of B. Serenellini

- **RMO** is a 2856MHz oscillator from Instrumentation Technology d.o.o. with < 20 fs_{RMS} absolute jitter (SSB: 10 Hz -10 MHz)
- **OMO** is 79.33 MHz fiber laser from Menlo systems GMBH < 10 fs_{RMS} (SSB: 1 kHz – 10 MHz)
- Transition towards optical architecture has a big delay due to an OMO major fault. It has been sent back for assistance and it is still under repair
- The system foresees two **optical links**
  1. Towards the FLAME laser oscillator: link already installed, but to re-commission after OMO repair
  2. Towards THz lab in building 7: planned, but still not purchased
- **Four main frequencies** are generated and distributed through (temp. stabilized) coaxial cable FSJ2-50:
  1. S- band for RF line 1 and 2
  2. C-band for RF line 3
  3. 714->2142 MHz for diagnostic purpose
  4. 79.33 MHz for timing system reference

SPARC_LAB Synchronization - LLRF

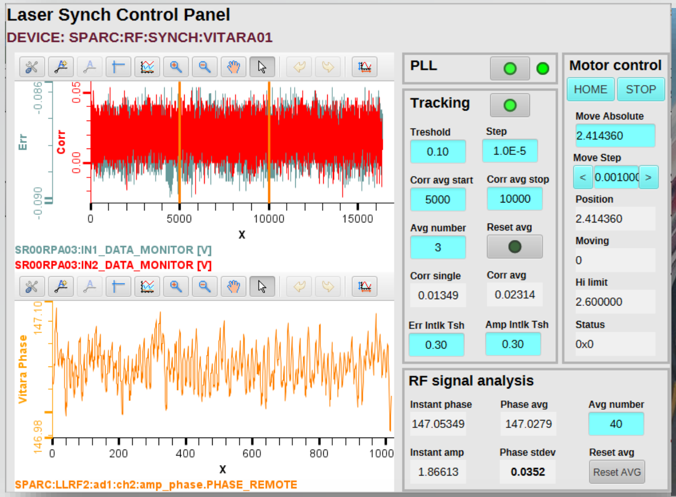


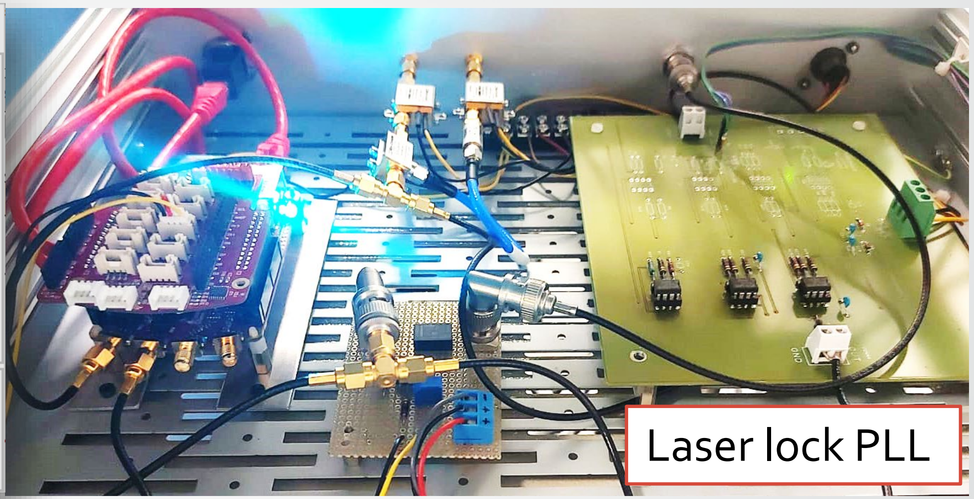
- LLRF system has been fully replaced with a **new digital system** composed by three modules from Instrumentation Technologies, d. o. o.
- The **system** allowed us to achieve the following **performances**:
  - <u>Amplitude resolution</u>: < 0.01% RMS
  - <u>Phase resolution</u>:< 0.01° RMS (0.02° for C-band)
  - <u>Added jitter</u>: < 10 fs RMS
- The **control system user interfaces** have been designed and programmed at LNF in CSS-Phoebus (EPICS interface)

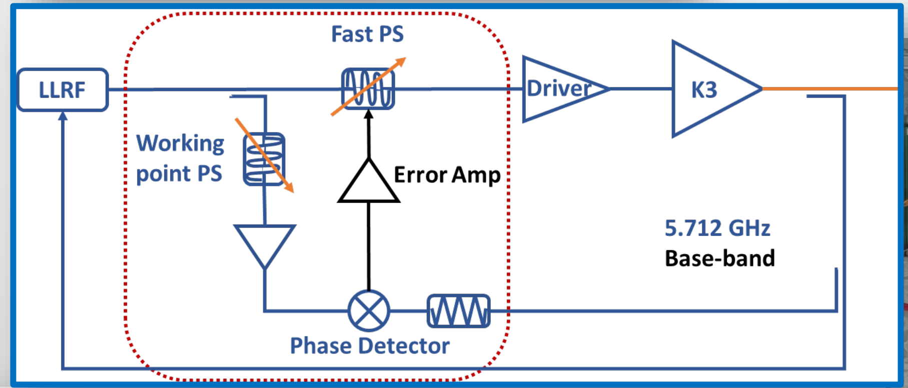


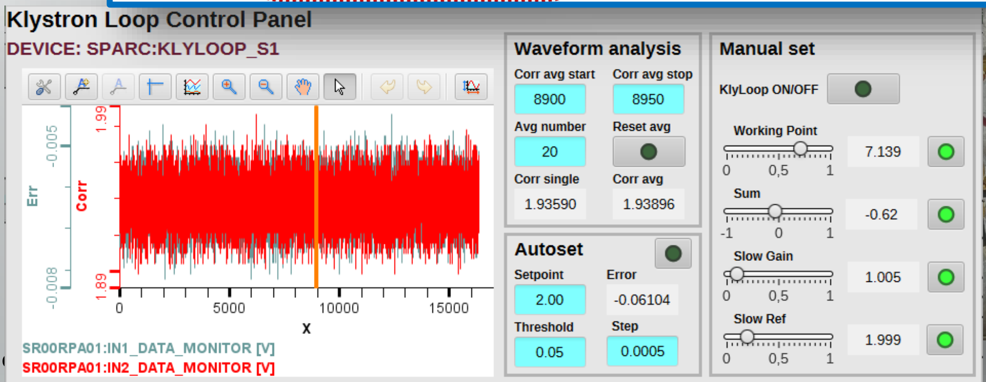
SPARC_LAB recent upgrade – Locking electronics

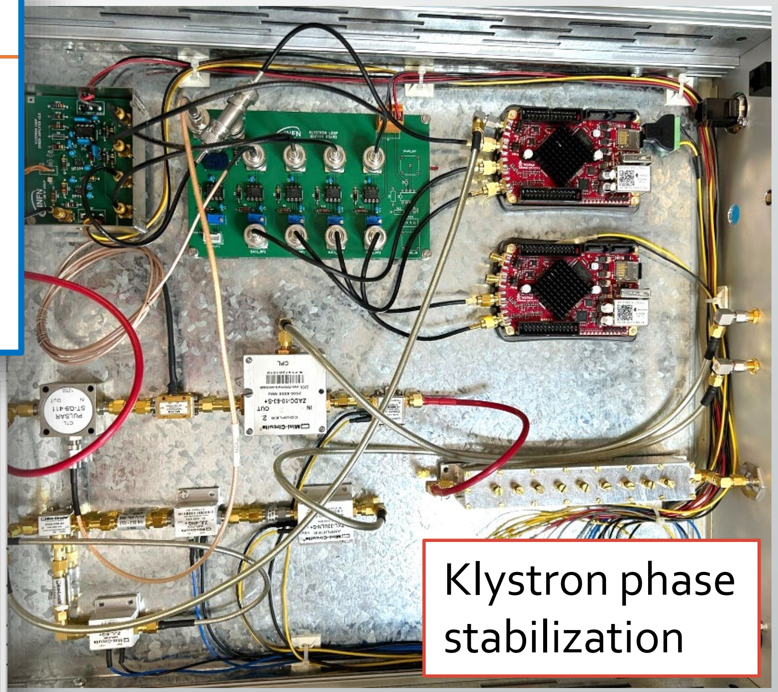
- Hardware and software of **laser repetition rate locking** system and **klystron phase stabilization** system have been upgraded
- **Control hardware** has been embedded in the electronic board (© Red Pitaya)
- **New control panels** in EPICS+CSS environment have been developed



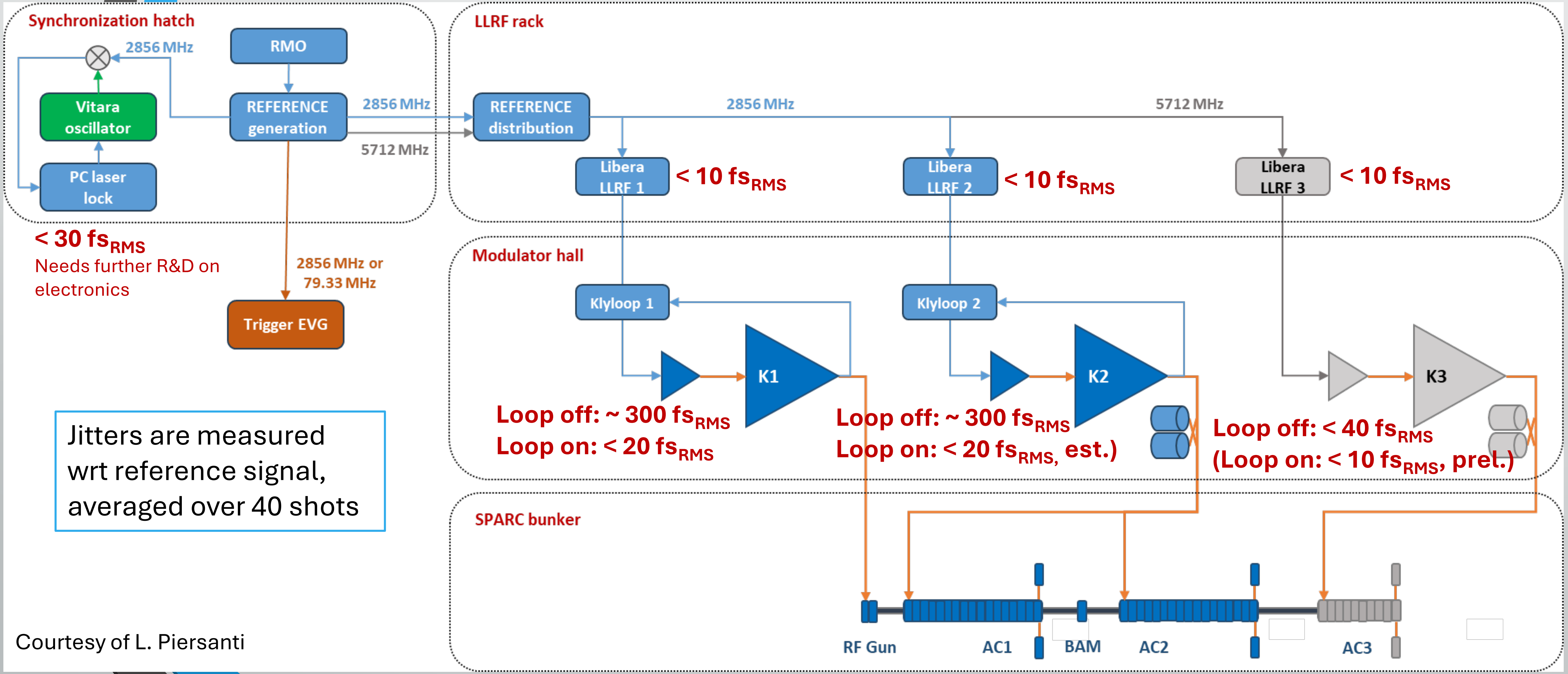








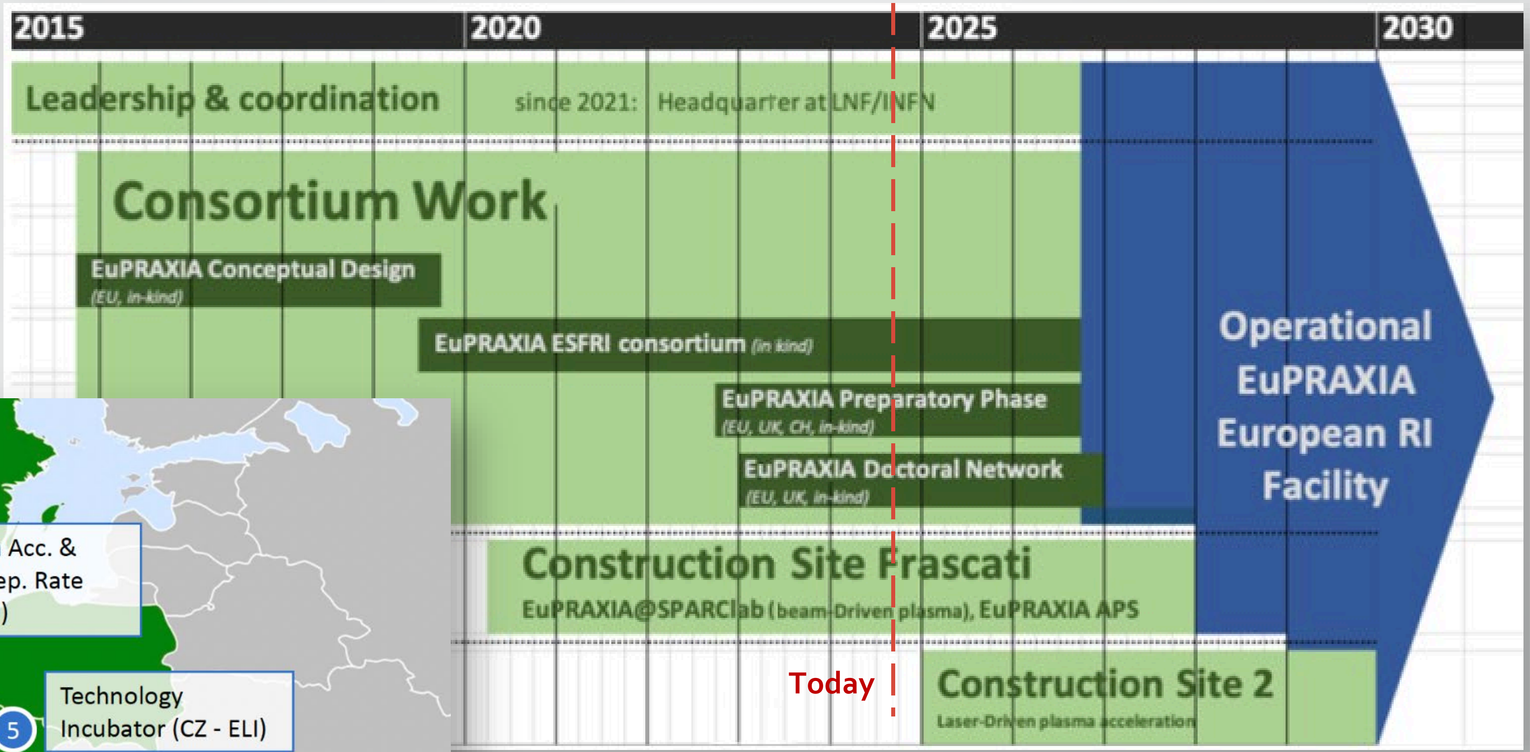
SPARC_LAB Synchronization – Residual jitters



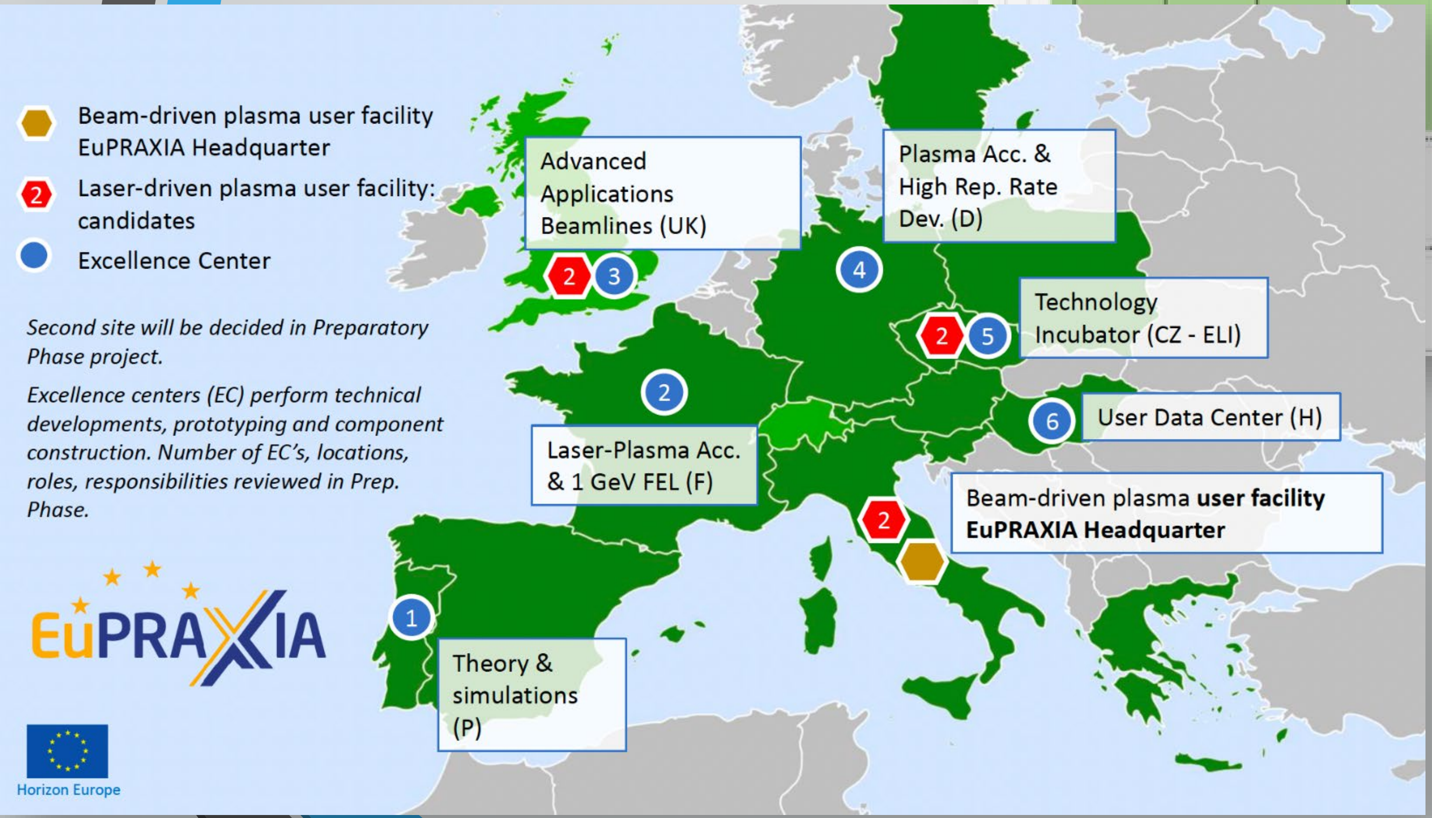
Jitters are measured wrt reference signal, averaged over 40 shots

Courtesy of L. Piersanti

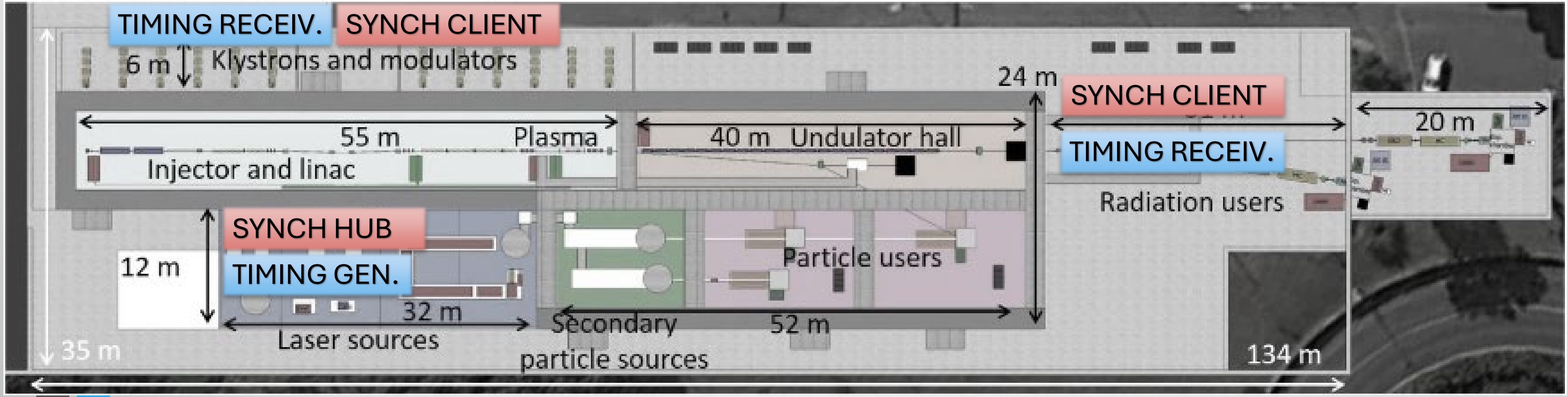
EuPRAXIA@SPARC_LAB - overview



Courtesy of A. Falone

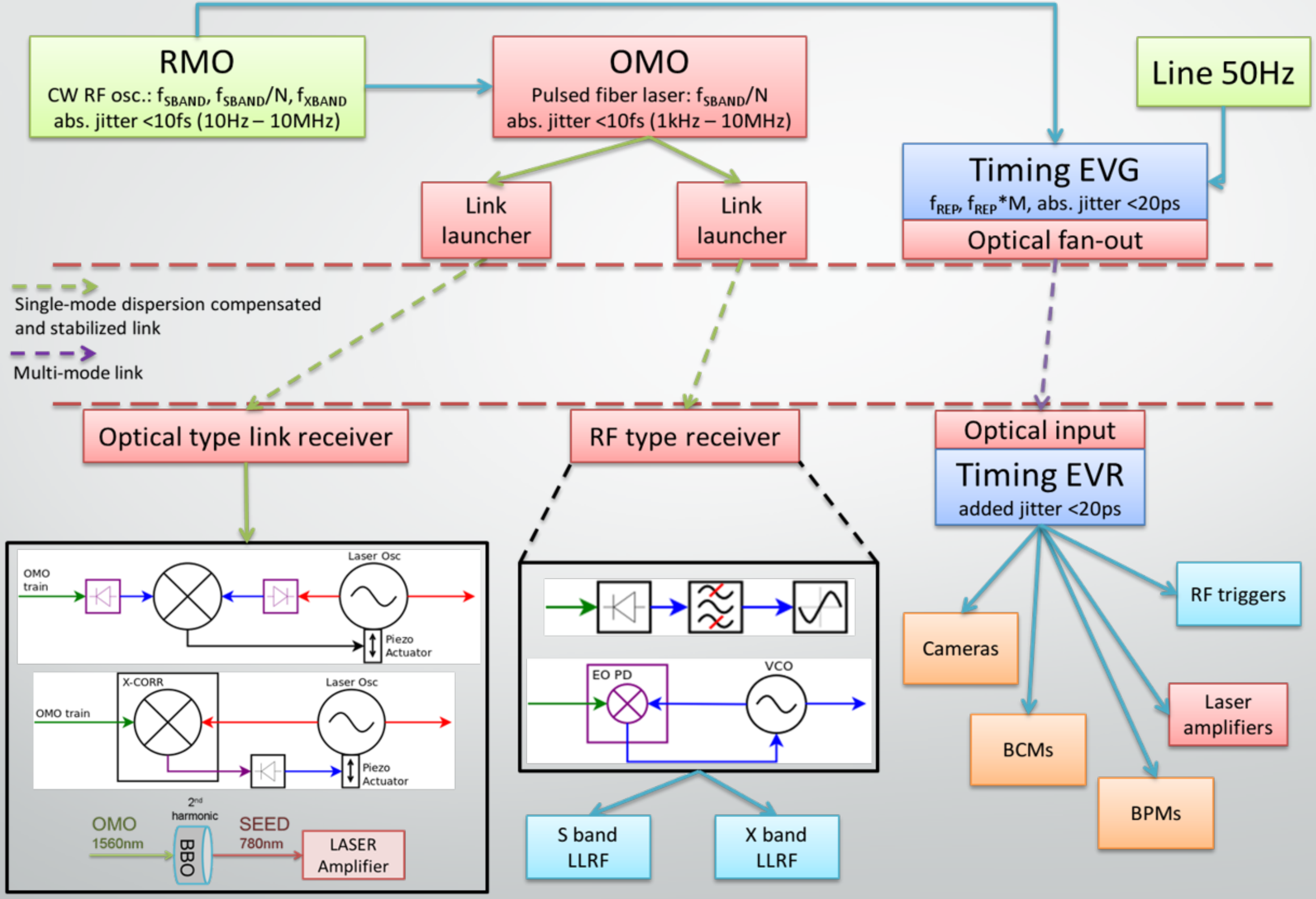


EuPRAXIA@SPARC_LAB layout - timing and synch



- Due to the facility scale, we foresee to employ
  - 2 fiber links for digital timing distribution
  - 2 stabilized fiber links for the master oscillator reference distribution

EuPRAXIA@SPARC_LAB layout - timing and synch



EuPRAXIA@SPARC_LAB – Timing system design

A possible path towards EuPRAXIA@SPARC_LAB

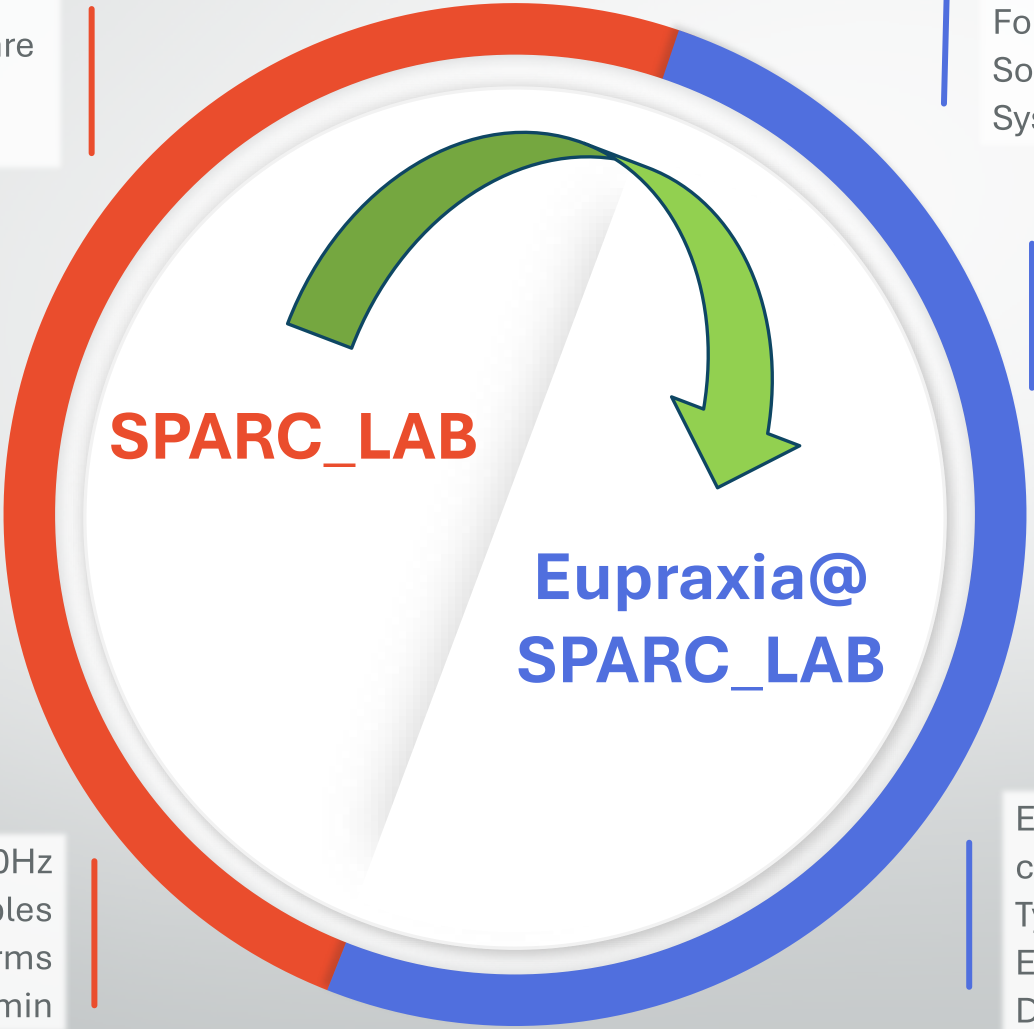
Single Event System (~2004)
In-house realization based on custom hardware
Form Factor: NIM Generator + delays module
Software: Labview

10Hz reference trigger is generated by counting a master clock @ 2.856GHz and synchronized with AC line 50Hz

~ 30 Total channels:
- 20 beam diagnostics
- 3 RF modulator
- 2 photocathode laser
- 3 Discharge circuits

- Bunch repetition rate 10Hz

Trigger Distribution: Coaxial Cables
- Typical Jitter 100ps rms
- Delays step: 5ps min



Based on commercial hardware (MRF)
Multiple Event Based System
Form Factor: uTCA
Software: EPICS + CSS Phoebus
System Layout: Master + Multiple Receivers

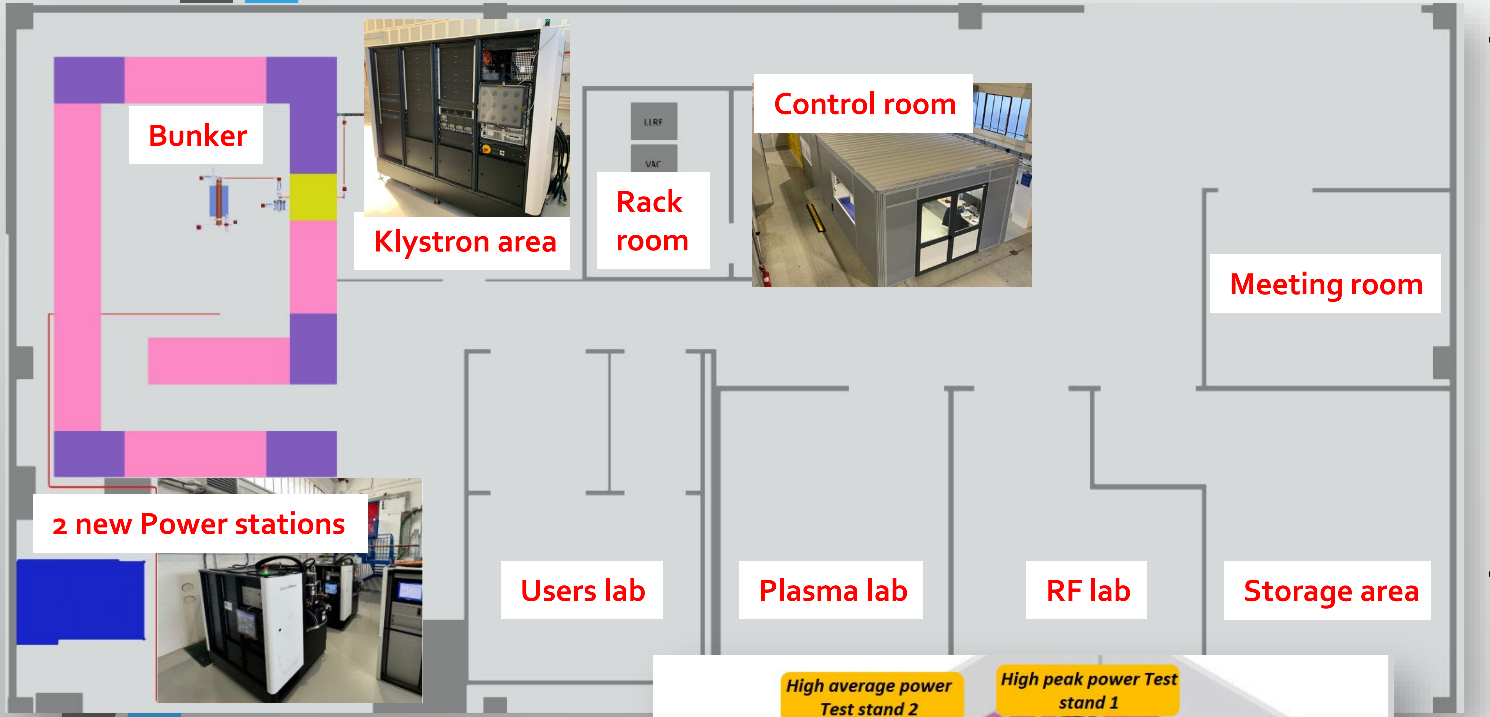
Up to 400Hz bunch rep rate
RF clock = 2856MHz
Bunch Rep rate decimation
Event Tagging
Possibility of delay compensation

100 Total channels between beam diagnostics , RF modulator + LLRF, photocatode laser, discharge circuits, external users

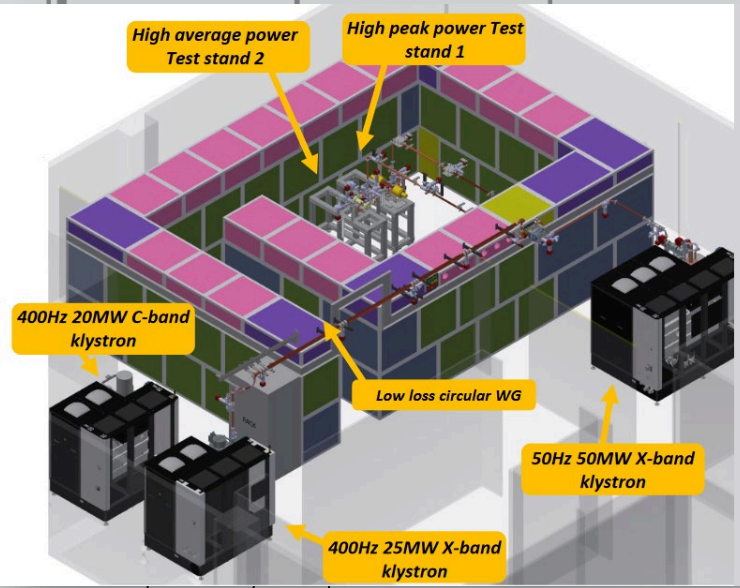
Event distribution: optical fibers + local coaxial cables
Typical Jitter ~30ps rms
Event clock: max 142MHz
Delays step: 1/EventClock

Courtesy of A. Stella

EuPRAXIA@SPARC_LAB – TEX overview

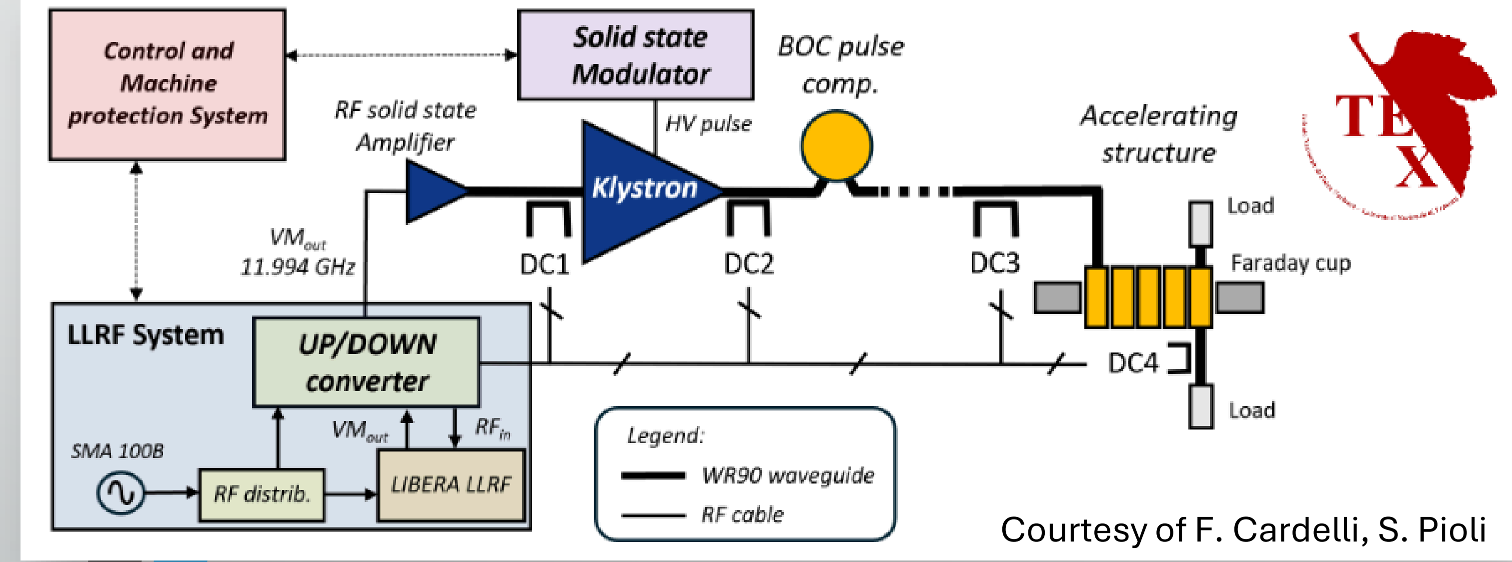


Courtesy of F. Cardelli, S. Pioli



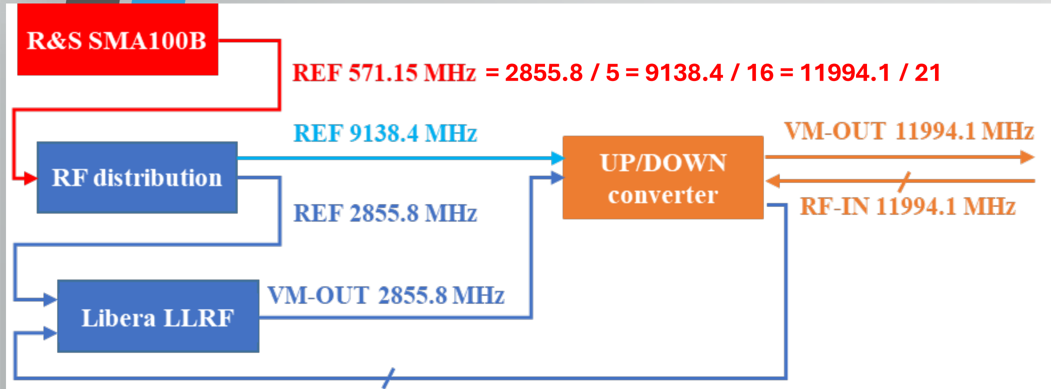
- The **TEst stand for X-band (TEX)** has been established in 2022 at Frascati National Laboratories of INFN in the context of LATINO (Laboratory in Advanced Technologies for INnOvation) and Rome Technopole Projects founded by Regione Lazio and NextGenerationEu and directly involved in the EuPRAXIA@SPARC_LAB flagship project to test accelerating structures
- The facility will also include a C-band (5.712 GHz) electron **linac** called Fringe to validate the RF technology and use the e$^-$-beam on targets (biological samples or electronic devices)
- **Three power stations** (with © Scandinova modulators) are present:
  - CPI X-band 50 MW peak power, 1.5 us RF pulses, 50 Hz rep. rate (operational)
  - Canon C-band 20 MW peak power, 2.5 us RF pulses, 400 Hz re. rate (installation)
  - Canon X-band 25 MW peak power, 1.5 us RF pulses, 400 Hz rep. rate (installation)

EuPRAXIA@SPARC_LAB – TEX LLRF

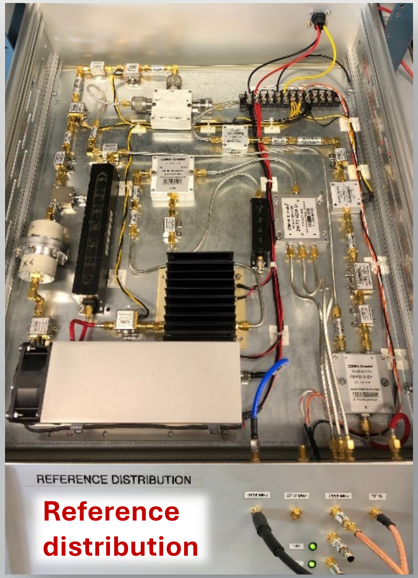


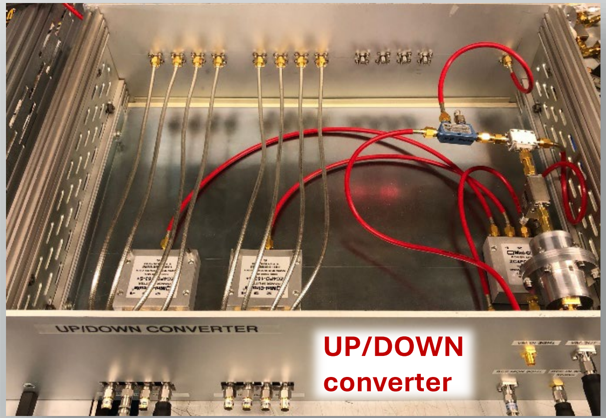
Courtesy of F. Cardelli, S. Pioli

- For now, one X-band power station is operational
- A commercial S-band LLRF system (ITech) has been adapted to work at 11.994 GHz developing at LNF:
  - up/down converter (8-12 ch. front-end, 1 ch. back-end)
  - reference generation and distribution
  - custom cavity band-pass filters (9.138 GHz and 11.994 GHz)
- Microwave Amplifier 1.3 kW solid state driver
- New LLRF prototype will be tested in 2025 (EuPRAXIA DN project)

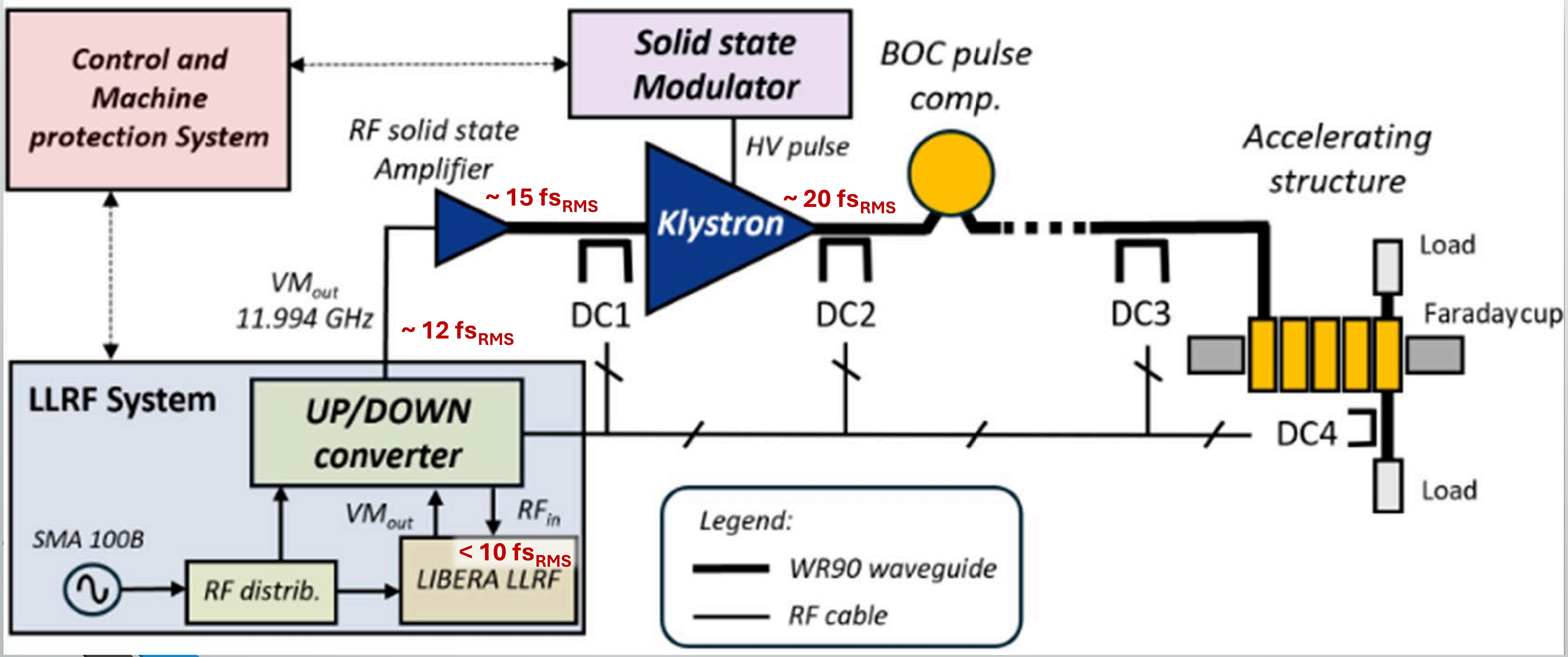


Courtesy of L. Piersanti





EuPRAXIA@SPARC_LAB – TEX residual jitters



Conclusion and open points

- SPARC_LAB
  - Synchronization and timing systems are up and running with good performances
  - Laser locking electronics has to be revised and upgraded
  - Klystron stabilization system exhibits good performances and further R&D is foreseen (contribution from EuPRAXIA DN fellow)
  - Timing system transition to full digital architecture is ongoing
- EuPRAXIA@SPARC_LAB and TEX
  - The design of synchronization and timing systems for EuPRAXIA@SPARC_LAB is ongoing
  - At TEX, we are characterizing the RF X-band power station in terms of residual jitters. A new X-band LLRF prototype will be tested in 2025 (contribution of EuPRAXIA DN project).
  - TEX new measurement campaigns on 400 Hz power stations will be performed in 2025