Achieving ultra-stable RF control for plasma acceleration at LNF-INFN

Advancements in RF stability at the SPARC_LAB facility

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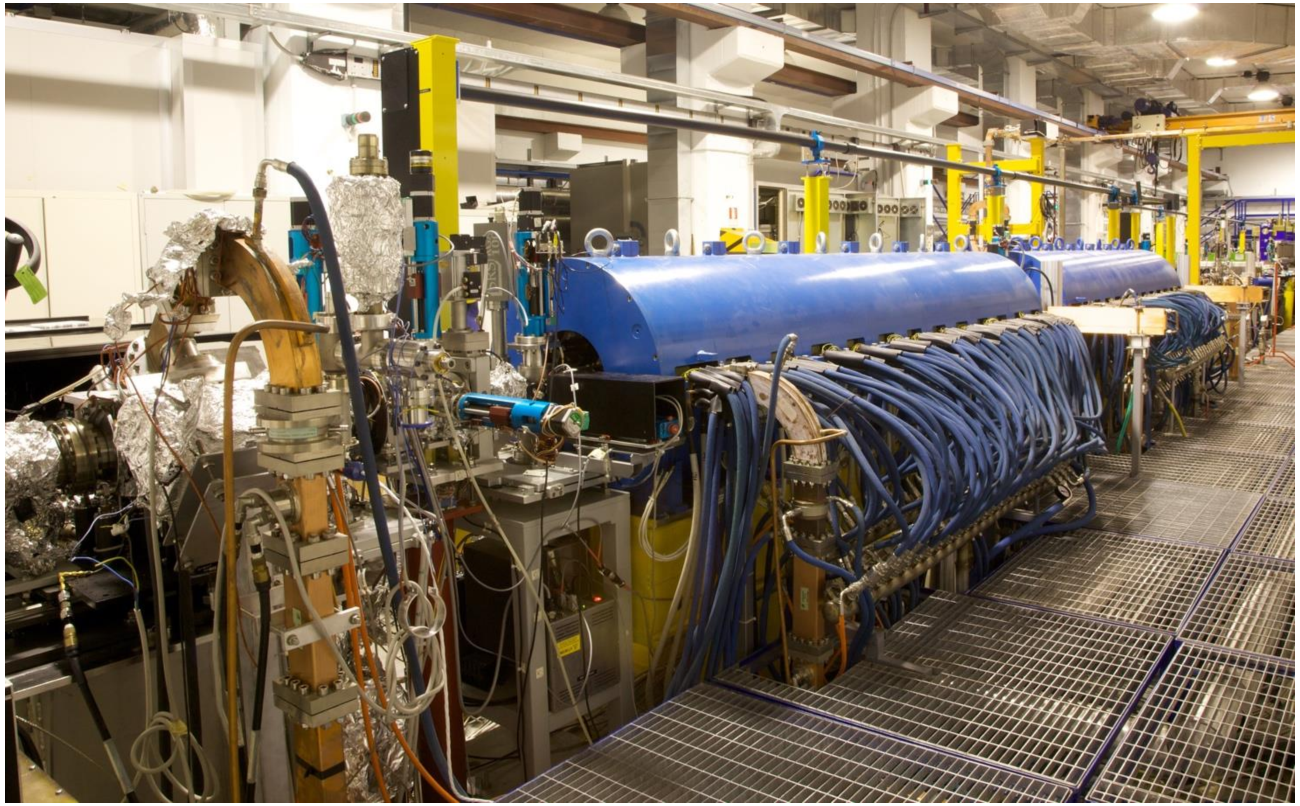
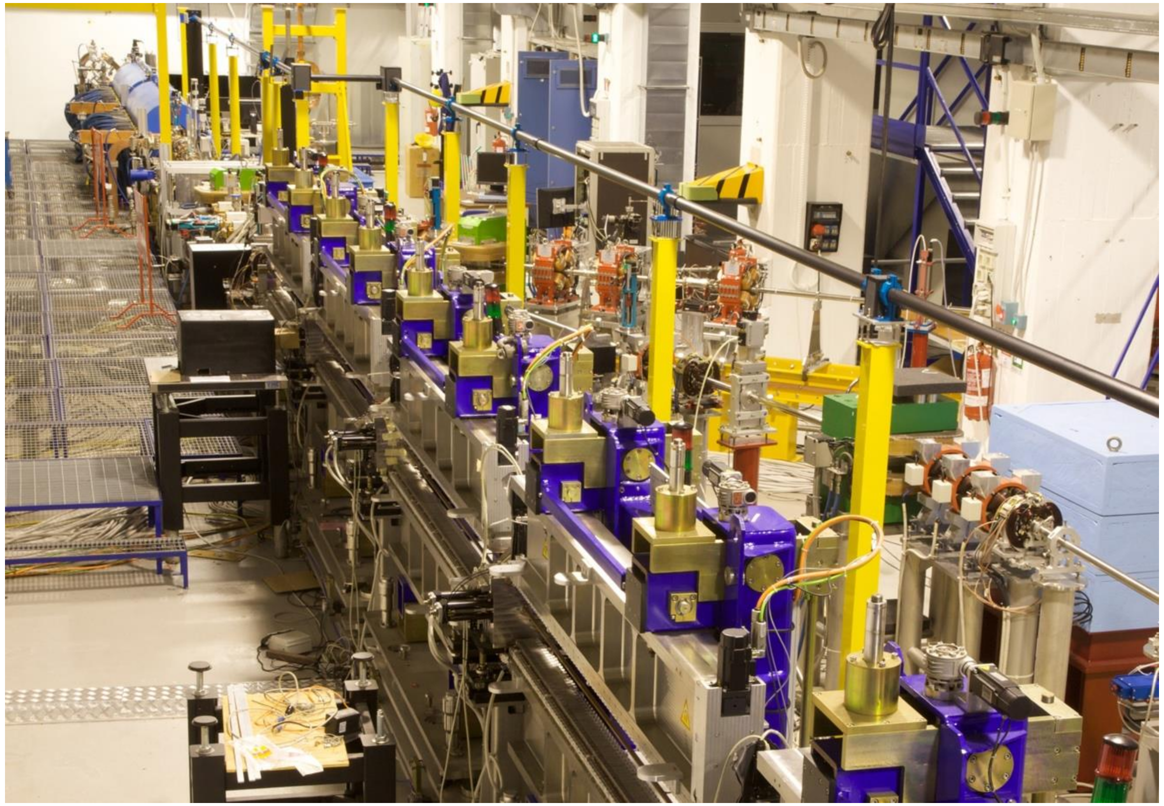
SPARC_LAB facility at LNF

» SPARC_LAB facility was born as an R&D facility to develop a high brightness **e-** photo-injector for SASE-FEL experiments

» The installation at LNF began in 2004. The first tests on the RF gun and measurement of beam parameters started in 2006

» Many experiments have been carried out over the years:
- SASE and seeded FEL
- Thomson back-scattering, THz radiation generation
- **Plasma focusing and acceleration (Particle Wake-Field Acceleration - PWFA)**

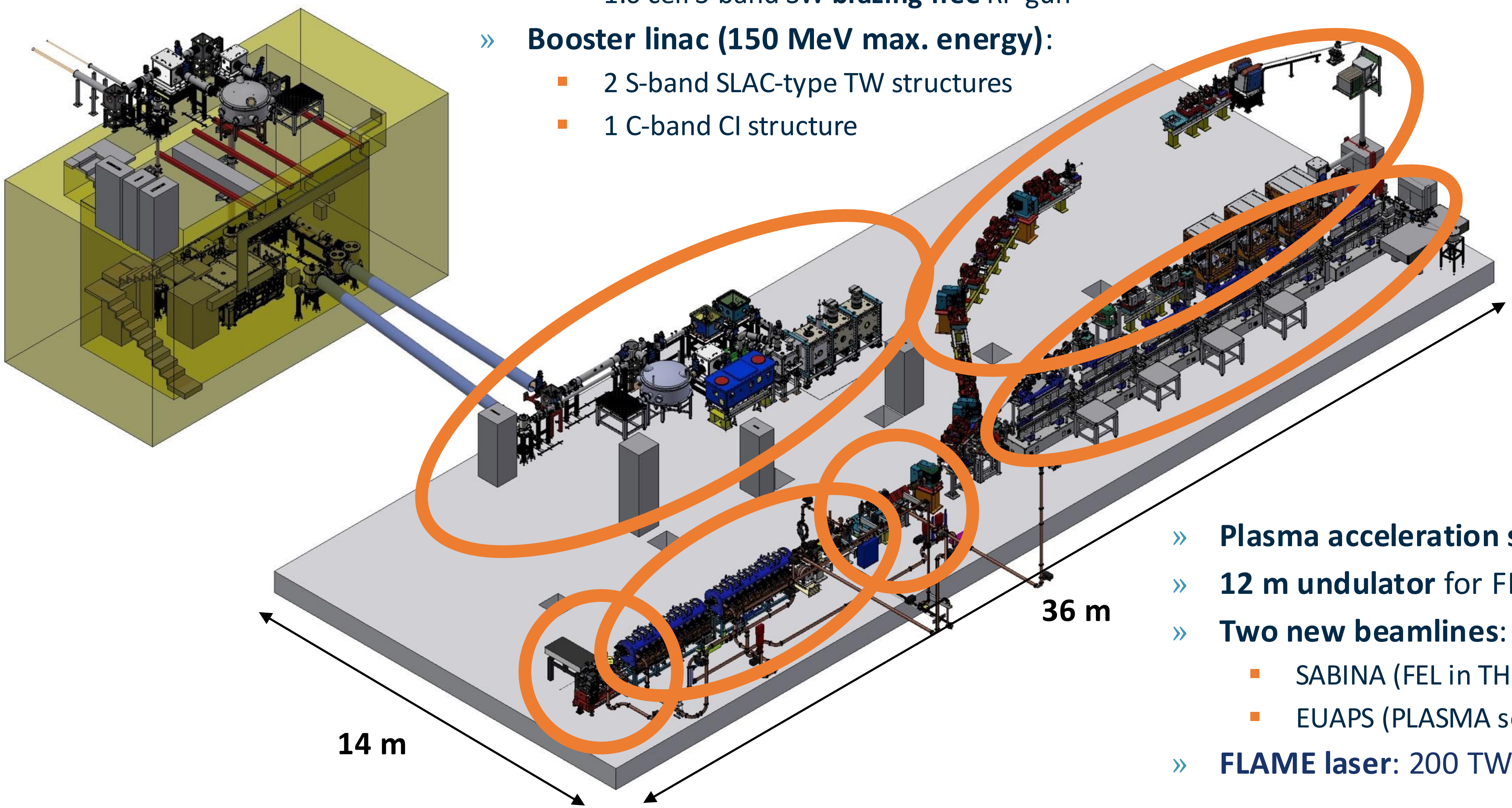




SPARC_LAB facility at LNF

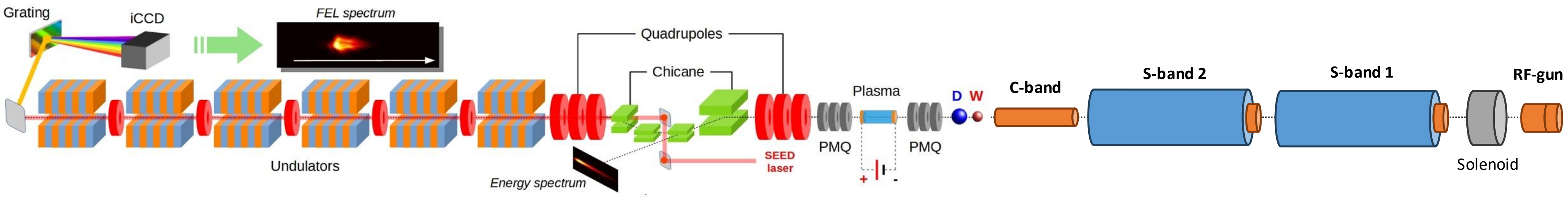
Today SPARC_LAB is a multi-disciplinary experimental facility that combines:

- **High brightness photo-injector:**
  - 1.6 cell S-band SW **brazing-free** RF-gun
- **Booster linac (150 MeV max. energy)**:
  - 2 S-band SLAC-type TW structures
  - 1 C-band CI structure



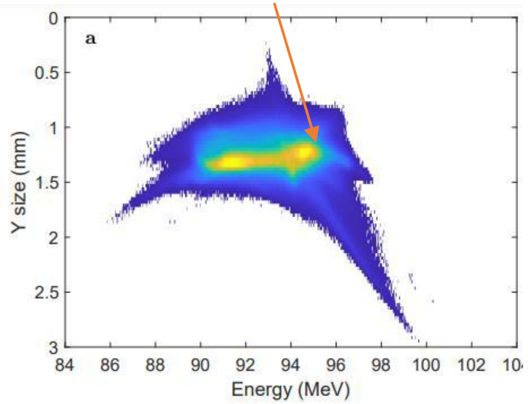
- **Plasma acceleration stage** for PWFA experiments
- **12 m undulator** for FEL experiments (SASE or seeded)
- **Two new beamlines**:
  - SABINA (FEL in THz range)
  - EUAPS (PLASMA source of betatron radiation)
- **FLAME laser**: 200 TW (5J, 25 fs, 10 Hz)

Over the past decade, R&D has focused on plasma acceleration

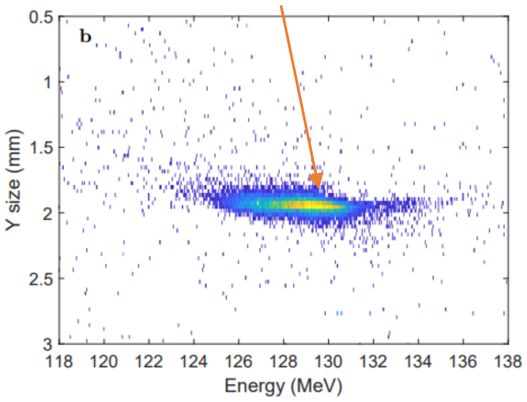


Plasma acceleration experiment at SPARC_LAB: Energy gain > 30 MeV in 3 cm > 1 GV/m gradient!

Witness beam before acceleration



Witness beam after acceleration



First FEL lasing from plasma accelerated beam

nature

Free-electron lasing with compact beam-driven plasma wakefield accelerator

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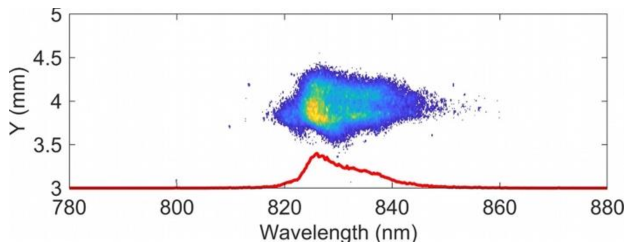
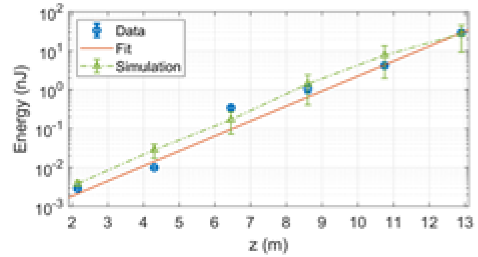
Single-shot spectrum of FEL radiation at 830 nm



Exponential gain of FEL radiation energy

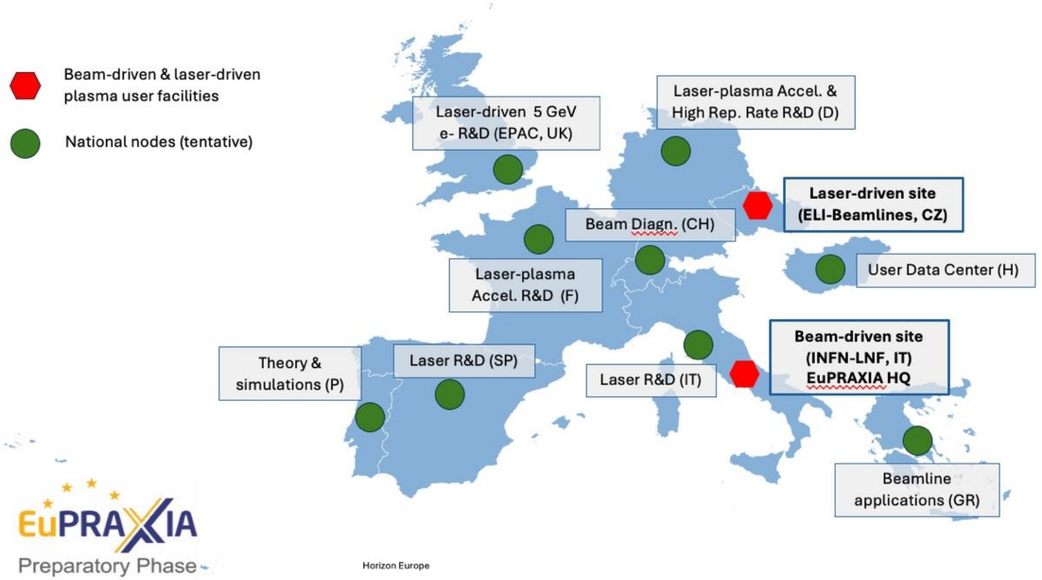


Courtesy of R. Pompili and M. Galletti

LNF future facility: EuPRAXIA@SPARC_LAB

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

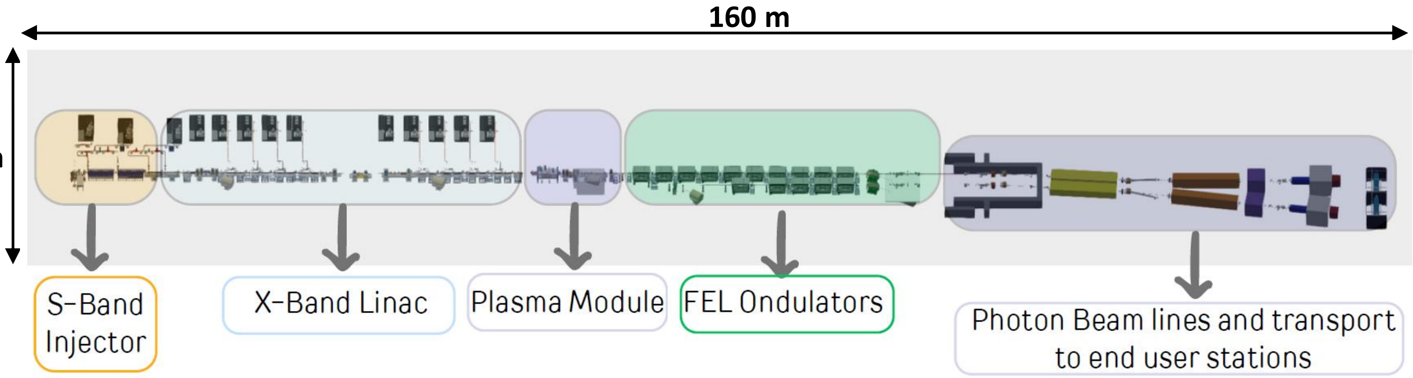
European consortium of excellence labs, 2 sites selected for LWFA (ELI Prague) and PWFA (LNF-INFN)



EuPRAXIA Preparatory Phase

LNF future facility

- 1 GeV electron linac with a plasma acceleration module to drive 2 FEL Lines:
  - ARIA (180 nm) - recent funding from Regional Government through ERDF Eu Program
  - AQUA (water region, around 4 nm)
- It includes a brand-new building and ancillary utilities
- Major investment (≈130 M€) and flagship project of INFN-LNF
- Technical Design Report in the approval phase (end of the year)
- Building tender to be issued soon (hopefully Oct. 2025) - exp. completion end of 2029



Courtesy of A. Falone

SPARC_LAB RF system history

The requirements on **RF stability (especially EM field phase)** tightened from **< 2 ps** (RF gun characterization) to **< 10 fs** (PWFA)

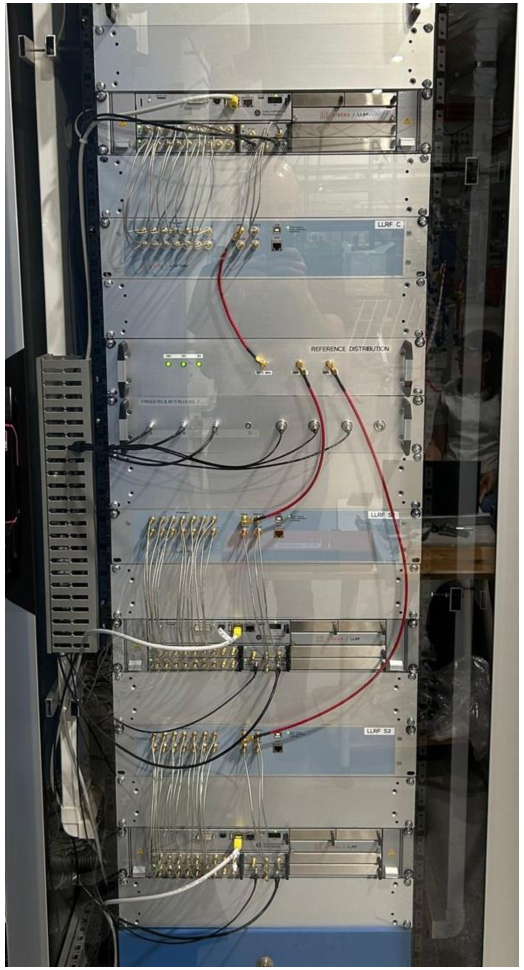
Multiple upgrades to RF and synchronization systems, to follow the evolution of the facility over the years:

- **Low noise RMO**
- **Electronic phase shifters for RF stations working point fine tuning**
- **New photocathode laser locking electronics**
- **Low-drift cables for reference and RF signals distribution**
- **Fast intra-pulse phase feedback** (klystron phase stabilization within the 4.5 μs RF pulse)

In 2024 a huge RF upgrade took place: **new RMO**, **new digital LLRF systems**, **R&D on intra-pulse phase feedback**

- Higher measurement resolution and lower noise floor
- Push to the limit the klystron induced phase jitter (GOAL: < 10 fs rms)

SPARC_LAB new LLRF rack

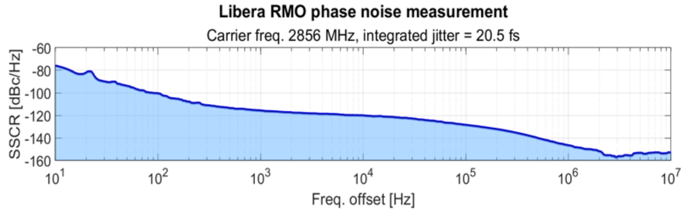


Upgrade motivations:

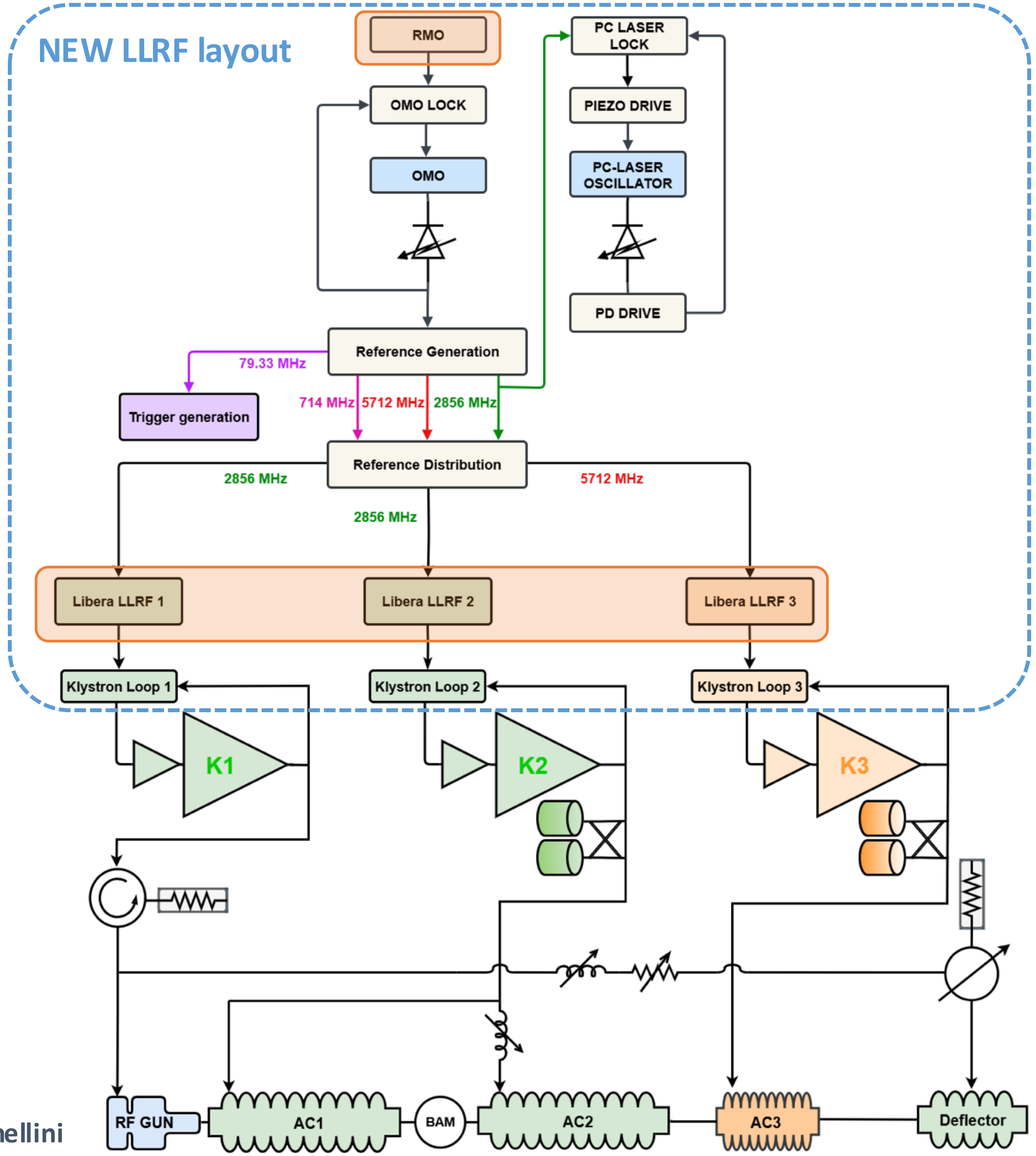
- » Custom RMO degraded performance + support discontinued
- » LLRF front-end noise limited the achievable phase resolution (50 fs rms)
- » Signal acquisition with general purpose ADC – non negligible fault rate
- » Fully analog system (w. connectorized components) – no pulse shaping for beam induced effects compensation

New RMO and LLRF system – Instrumentation Technologies:

- » Improved RMO stability (10 Hz-10 MHz integrated jitter: **20.5 fs @ 2.856 GHz**)



- » Front-end: temperature stabilized, 16-bit ADC @ 119 MS/s, 5 MHz BW
- » Independent pulse-by-pulse A and Φ feedback, long term stability (24h): < 100 fs rms
- » Back-end: fully customizable pulse shape, analog VM driven by FPGA, 14-bit DAC, 16 MHz analog BW
- » New LLRF control system developed with EPICS (**see next talk by B. Serenellini**)
- » Required resolution:
  - Amplitude: < 0.1% rms
  - Added phase jitter < 10 fs rms



Courtesy of B. Serenellini

Intra-pulse feedback motivation and evolution

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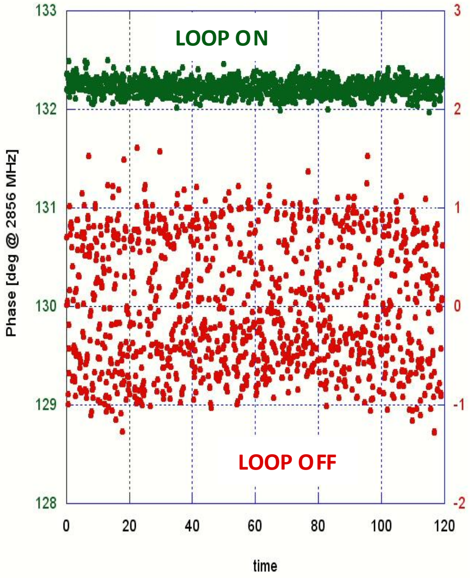
2008

Intra-pulse feedback v1

FEL experiments demanded major improvements in RF stability.
First implementation adapted from CW circular machines phase feedback



	Loop On
Minimum	131.97
Maximum	132.5
Points	1196
Mean	132.21993
Median	132.22
RMS	132.21996
Std Deviation	0.077561417
Variance	0.0060157733
Std Error	0.0022427463
Skewness	0.070226863

	Loop Off
Minimum	-1.2826609
Maximum	1.6096886
Points	1306
Mean	-2.9379256e-16
Median	-0.092634891
RMS	0.63517579
Std Deviation	0.63541911
Variance	0.40375745
Std Error	0.017582826
Skewness	0.19770408

2021

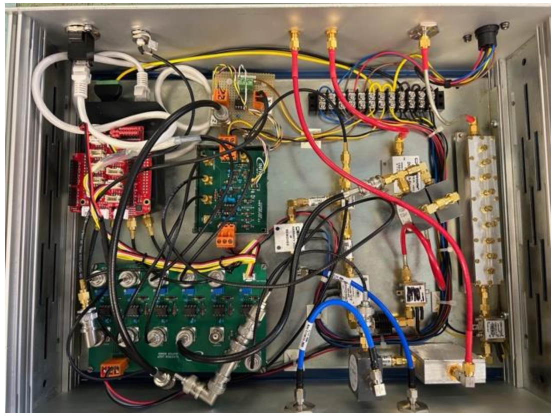
Requirement for improved RF stability

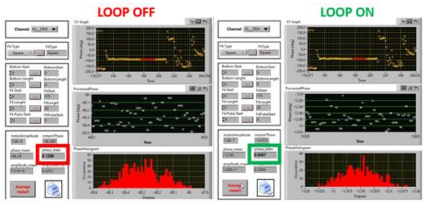
First PWFA experiment showed the need for phase jitter below a few tens of fs

2023

Intra-pulse feedback v2

Prototype with larger BW, successfully tested [1] on SS modulator + klystron at SPARC_LAB





5 MW K3 FWD (not saturated)	loop OFF	loop ON
K3 jitter (deg) RMS	0.12	0.0307
K3 jitter (fs) RMS	58.4	14.9

2024 - today

Boosting S-band stability with intra-pulse feedback v3

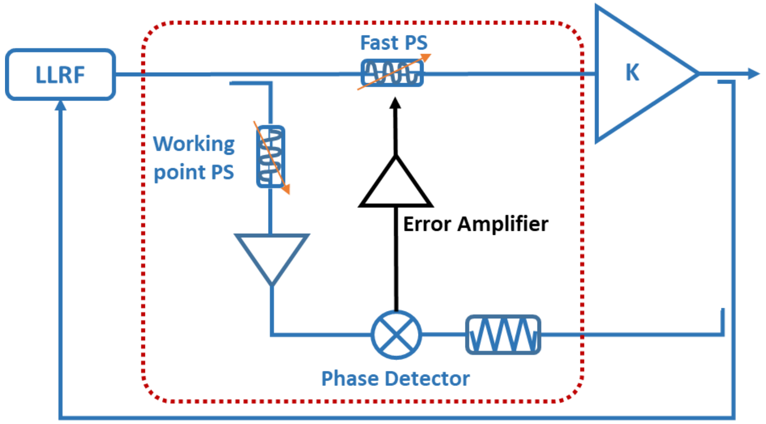
- New feedback electronics
- Red Pitaya integrated signal readout
- Remotely controlled feedback gain
- Slow loop to reduce phase transients
- Succesfully tested on S-band PFN modulators + klystrons at SPARC_LAB

[1] L. Piersanti et al. Photonics 11 p.413 (2024)

Intra-pulse feedback v3

Upgrade motivations:

- **RF phase comparison stage optimized** (reduced sensitivity to variations in the LLRF drive level)
- Only **one Red Pitaya ADC/DAC module** used to achieve a more compact architecture
- **Remote interface for feedback gain fine tuning** from control room
- Prototype chassis 1:1 copy of working system -> easier deployment at SPARC_LAB facility

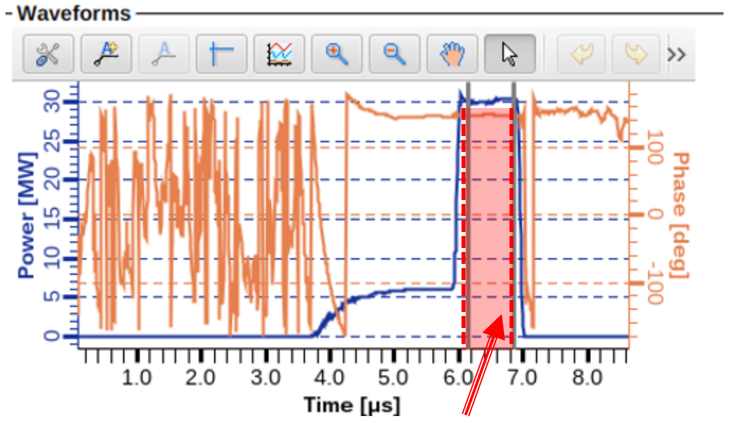


System deployment at SPARC_LAB:

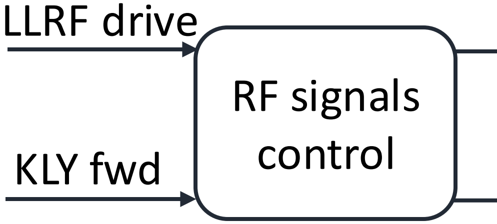
- Prototype of S-band intra-pulse feedback v3 developed, validated in lab, and installed at SPARC_LAB for beamline tests (late 2024 – early 2025)
- New electronics tested on both S-band RF stations **driven by PFN modulators**

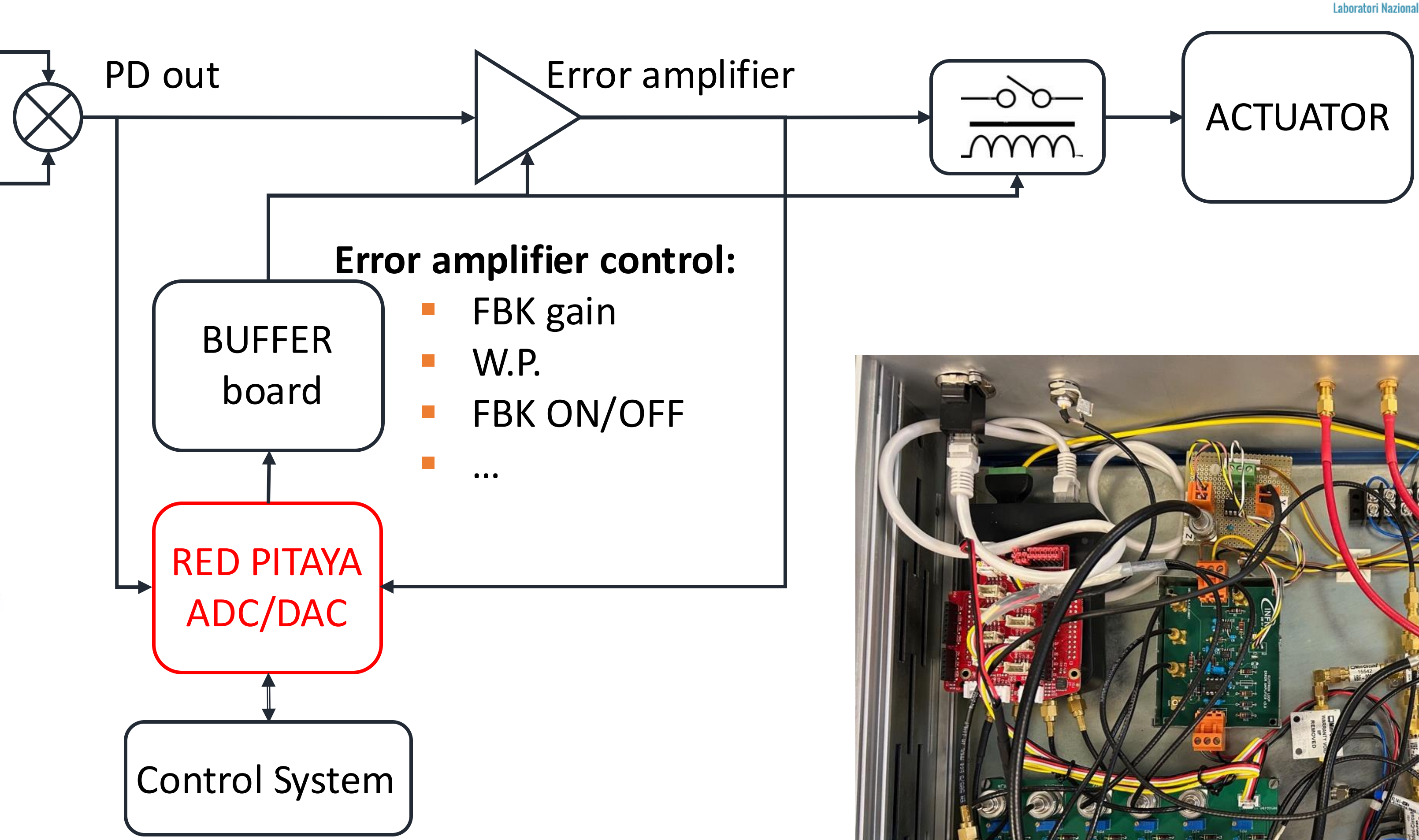
Measurement description

- RF pulse phase evaluated averaging the waveform within a configurable window
- 30 consecutive pulses acquired (5 Hz rep. rate – 6 seconds acquisition)
- Phase jitter quantified as the RMS of the 30-pulse dataset

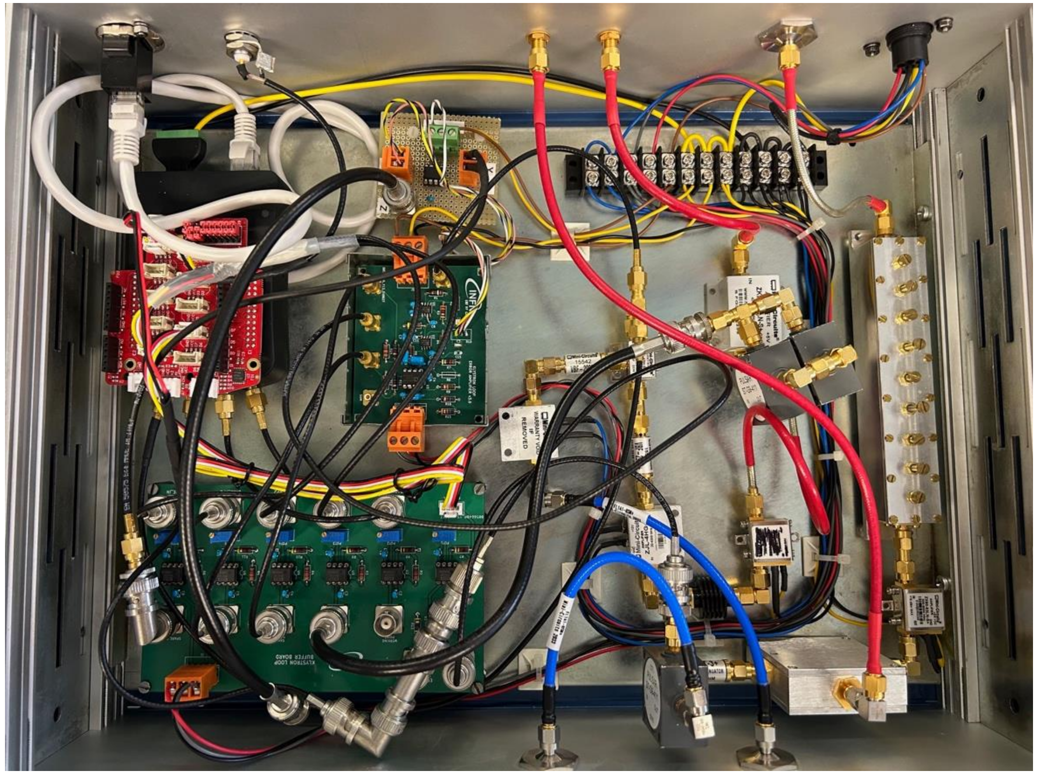


Intra-pulse feedback v3 block diagram





STEMLAB 125-14



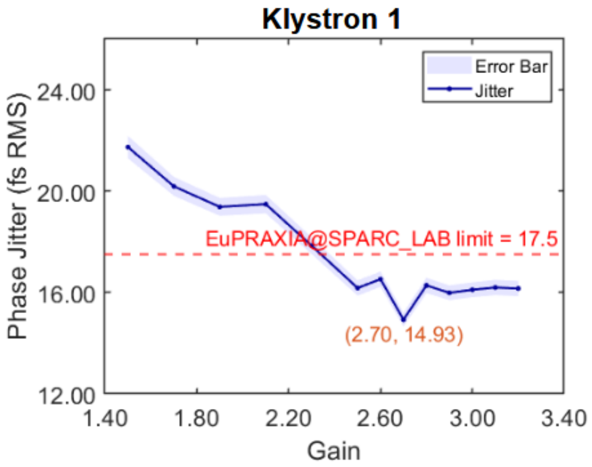
2x 14-bit 125 MS/s ADC
2x 14-bit outputs
Xilinx Zynq 7010 FPGA, Ethernet remote access

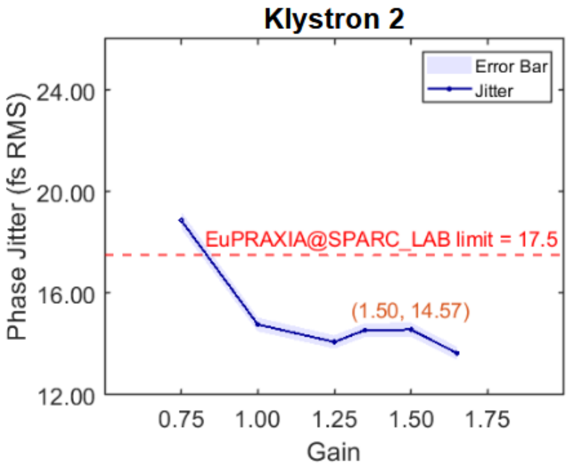
Intra-pulse feedback v3 gain scan

Gain scan

- For both RF plants, a fine scan of the feedback gain was performed
- For each gain value 5 minutes of data acquisition were recorded and the average jitter computed
- Both plants show wide regions were the jitter stays below the project stability limit

For EuPRAXIA@SPARC_LAB, the total jitter of the S-band RF plant should be < 20 fs RMS
Including the reference distribution jitter (10 fs RMS, worst case), the klystron jitter should be < $\sqrt[2]{20^2 - 10^2} \approx 17.5$ fs RMS



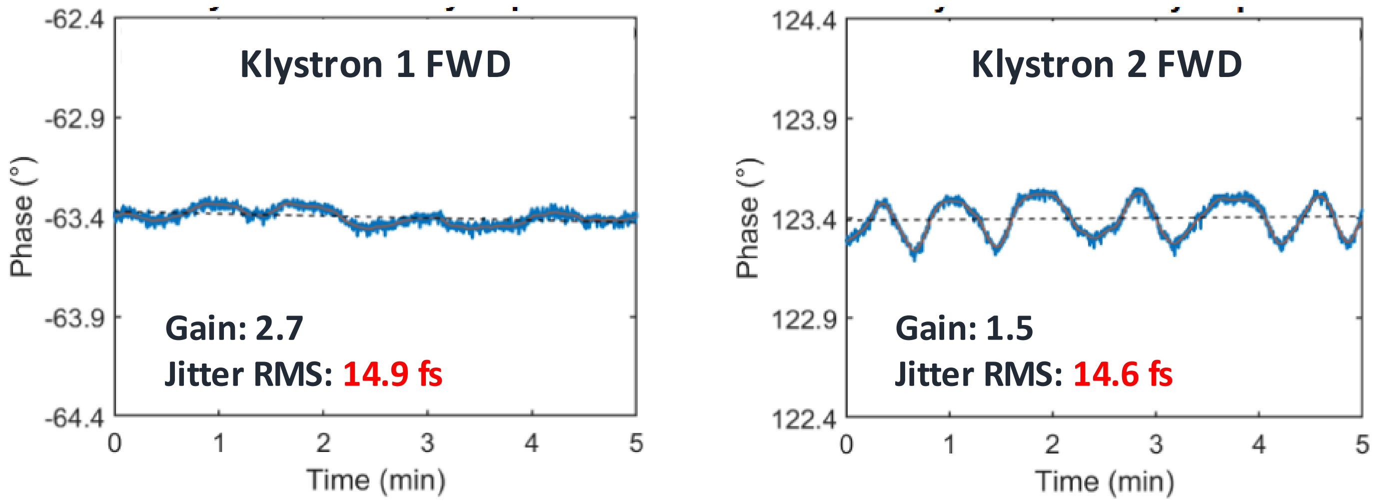


- The same scan would have been much more time consuming in the previous releases (variable resistor in the RF chassis in the modulator hall)

Intra-pulse feedback v3 short-term measurements

Example of phase measurement with optimized gain

- Comparable performance for both RF plants
- Oscillations on klystron 2 still to be addressed (PI gain too high?)



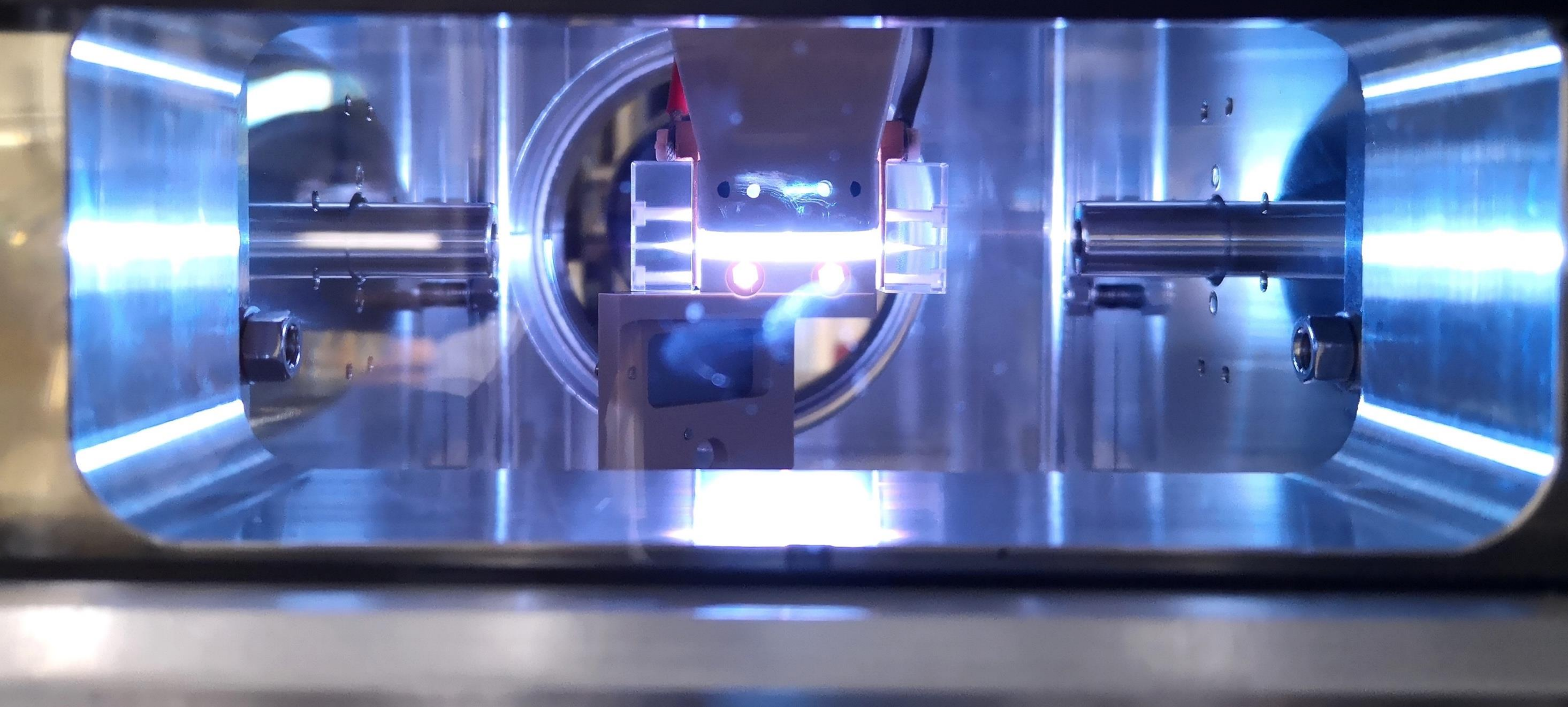
RF power plant	Intra-pulse feedback release		
	v1	v2	v3
Kly1 RMS jitter	≈ 70 fs	≈ 20 fs	**≈ 15 fs**
Kly2 RMS jitter	≈ 100 fs	≈ 35 fs	**≈ 15 fs**

Gain remote control

Conclusions

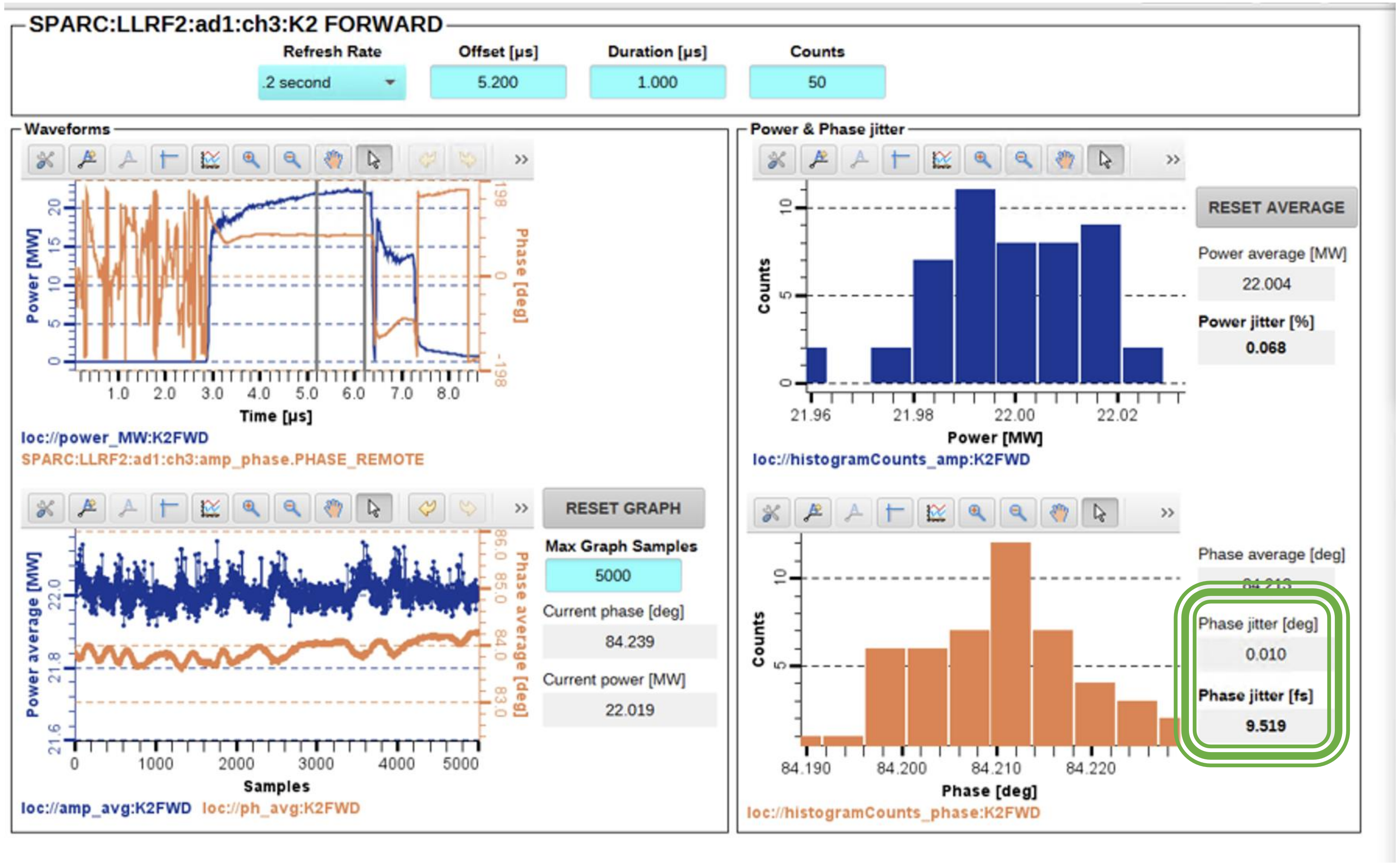
- RF stability is a key challenge for plasma acceleration experiments at INFN-LNF
- After a major upgrade of the RF system, the sensitivity to phase and amplitude jitters has significantly improved, enhancing the quality of measurements performed during operation
- In parallel, continuous R&D on intra-pulse phase feedback is being carried out to push the stability of the RF power plants to their limits
- Currently, we have succeeded in reducing the klystron phase jitter from hundreds of femtoseconds down to 15 fs, effectively **"transforming" old PFN modulators into state-of-the-art solid-state ones** in terms of phase stability
- Reaching the **10 fs limit** now seems feasible, pushing the feedback performance even further

Thank you for your attention



Spares

SPARC_LAB best 10 seconds…



Plasma acceleration experiments

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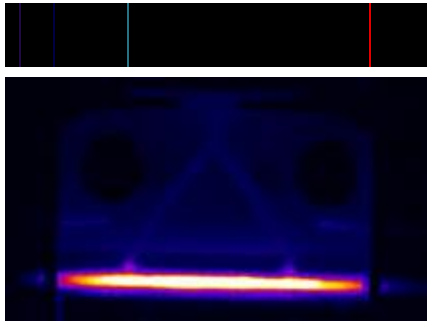
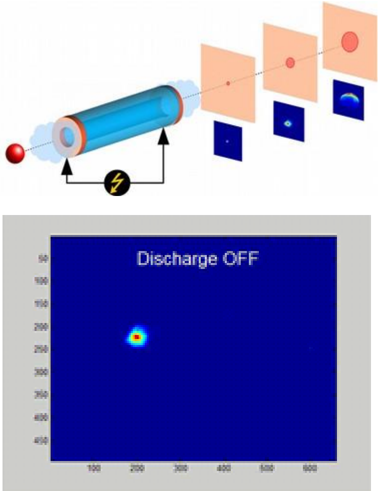
Over the past decade, R&D has focused on plasma acceleration and beam focusing with plasma lenses-> **EuPRAXIA@SPARC_LAB new LNF facility**

Plasma characterization



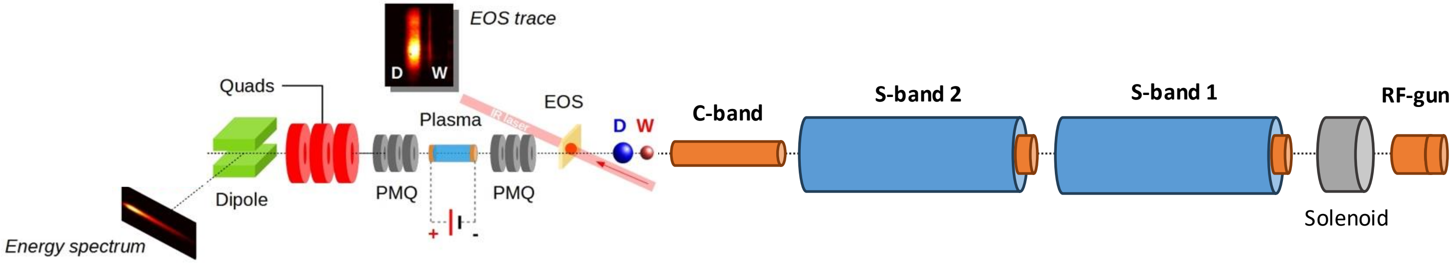
A. Biagioni et al., JINST 11.08 (2016): C08003

Focusing with active-plasma lenses



R. Pompili et al., PRL 121.17 (2018): 174801
R. Pompili et al., Appl. Phys. Lett. 110.10 (2017): 104101

Plasma acceleration



First plasma acceleration at SPARC_LAB:
Energy gain = 4 MeV in 3 cm (133 MV/m)

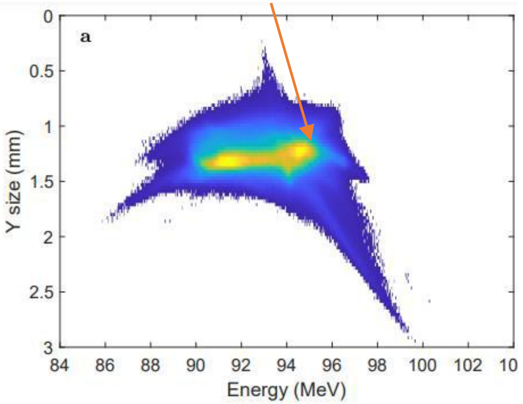
nature physics LETTERS
https://doi.org/10.1038/s41567-020-01116-9
Check for updates

Energy spread minimization in a beam-driven plasma wakefield accelerator

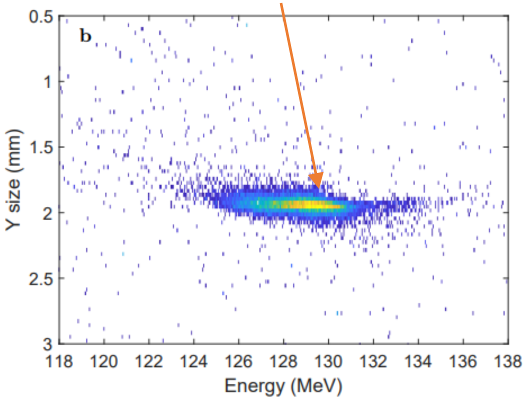
R. Pompili[1], D. Alesini[1], M. P. Anania[1], M. Behtouei[1], M. Bellaveglia[1], A. Biagioni[1], F. G. Bisesto[1], M. Cesarini[1,2], E. Chiadroni[1], A. Cianchi[3], G. Costa[1], M. Croia[1], A. Del Dotto[1], D. Di Giovenale[1], M. Diomede[1], F. Dipace[1], M. Ferrario[1], A. Giribono[1], V. Lollo[1], L. Magnisi[1], M. Marongiu[1], A. Mostacci[2], L. Piersanti[1], G. Di Pirro[1], S. Romeo[1], A. R. Rossi[4], J. Scifo[1], V. Shpakov[1], C. Vaccarezza[1], F. Villa[1] and A. Zigler[1,5]

Second plasma acceleration experiment at SPARC_LAB:
Energy gain > 30 MeV in 3 cm > 1 GV/m gradient!!!

Witness beam before acceleration



Witness beam after acceleration



Courtesy of R. Pompili and A. Giribono

First FEL lasing from plasma acceleration

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

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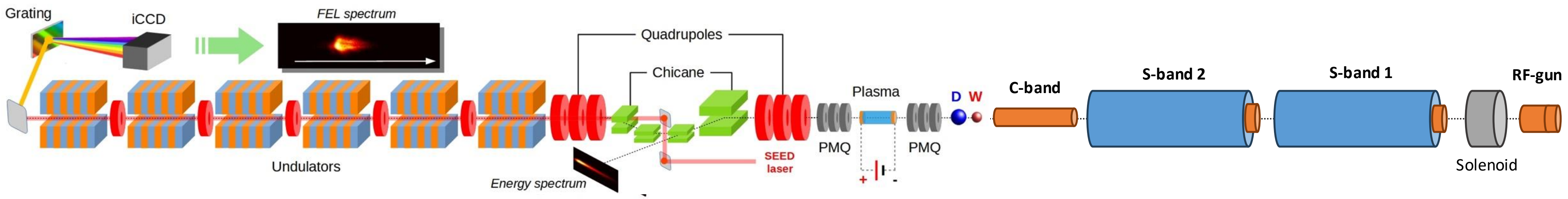
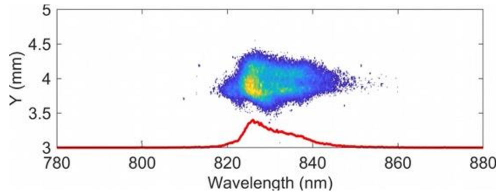
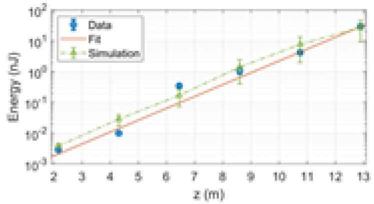
SASE-FEL driven by PWFA beam



Single-shot spectrum of SASE FEL radiation at 830 nm



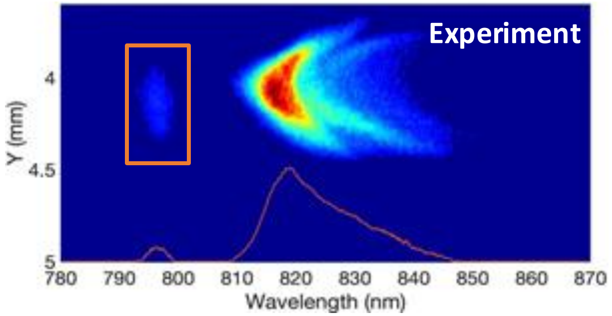
Exponential gain of FEL radiation energy

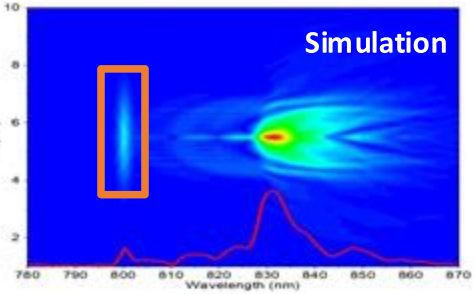


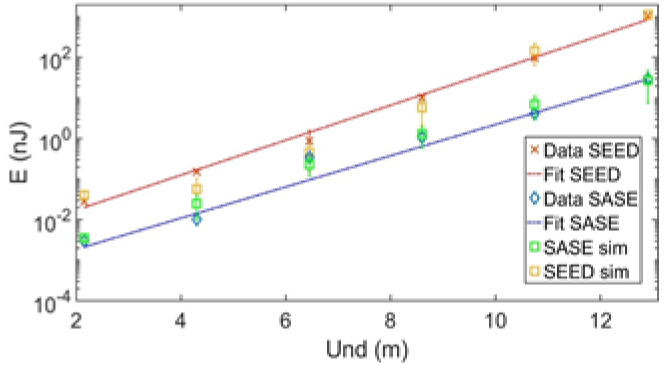
First FEL lasing from PWFA

Seeded FEL driven by PWFA beam

laser







~1 uJ (SEEDED)

~30 nJ (SASE)

Courtesy of R. Pompili and M. Galletti

Plasma synchronization: why we need fs stability

Fluctuations in the arrival time of electrons in the plasma reduce the efficiency of acceleration

$\lambda_P \cong 300\ \mu m$

$f_P = 1$ *THz (RF equivalent)*

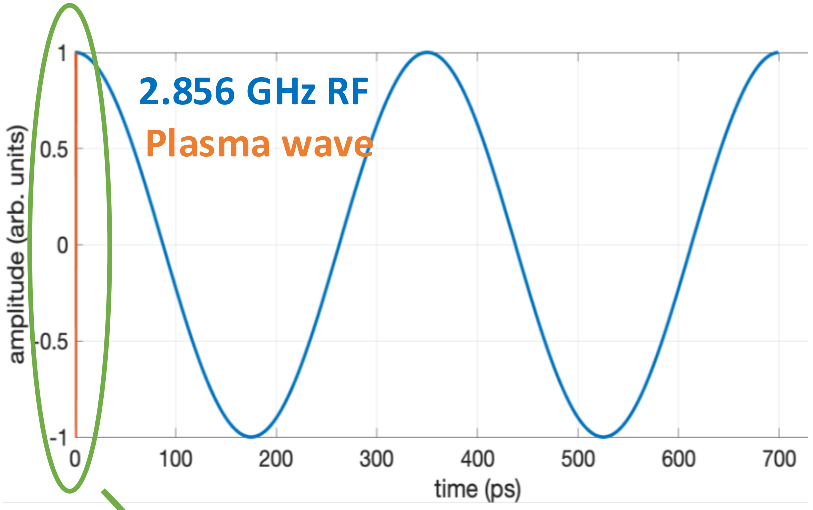
1 deg @ 1 THz $\cong$ ***3 fs***

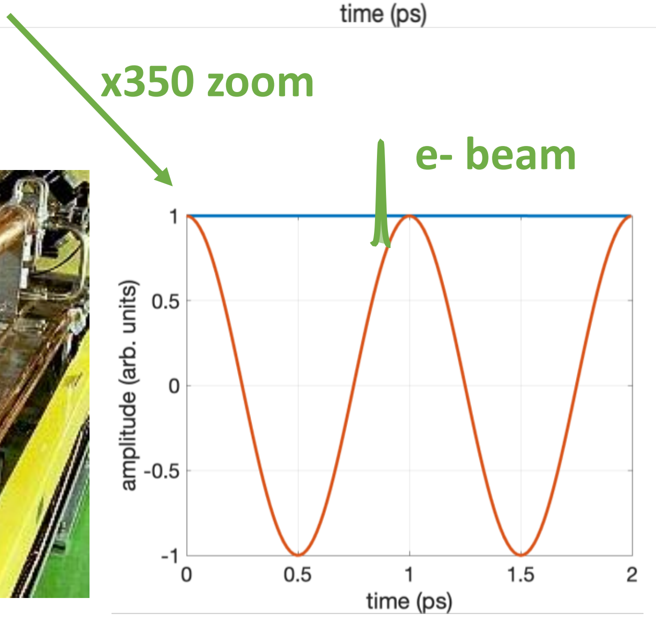
Unfortunately the key parameter for controlling the beam arrival time **on the plasma time scale** is the stability of the **3 GHz RF!**

1° rms jitter in the plasma corresponds to ≅ 0.003° rms at 3 GHz
For RF structures at 3 GHz **the state of the art phase jitter is 0.01-0.02° rms**

R&D on multiple fronts:

- Reducing RF klystron jitter (**intra-pulse feedback**)
- Reducing RF-laser relative jitter
- Improving LLRF systems measurement sensitivity





Intra-pulse feedback v2 long-term measurements

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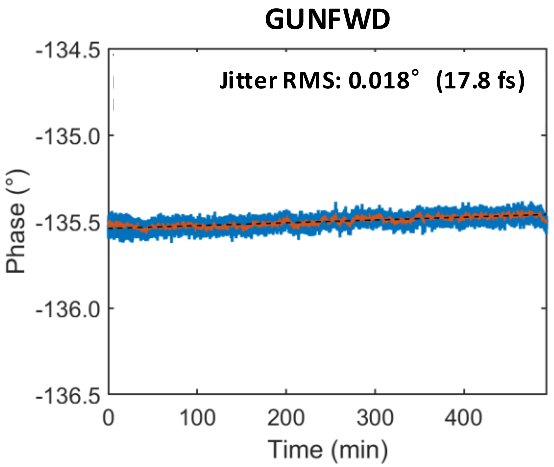
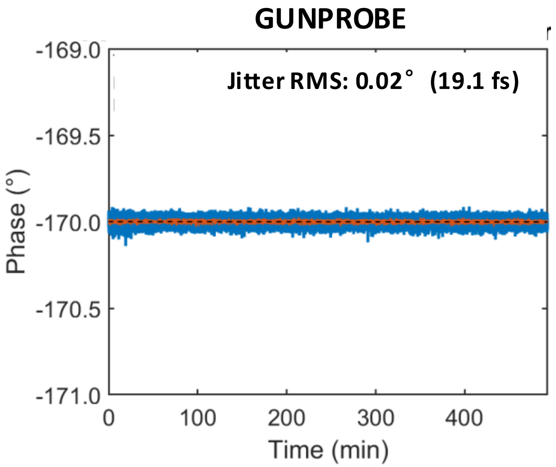
Long-term stability measurements – April 2025

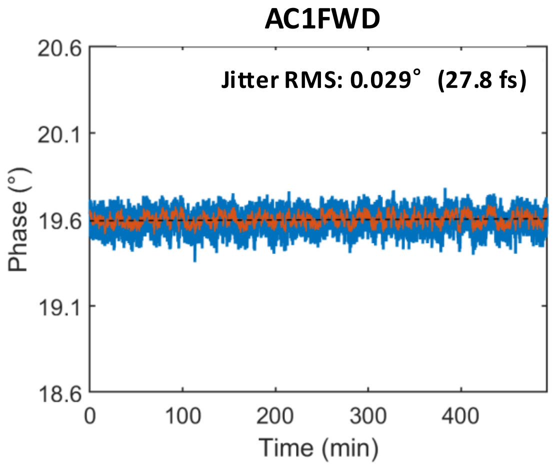
- Before deploying new feedback release, 8 hours stability measurements were conducted
- Drifts are minimized by slow feedback system
- Measured values are coherent with measurement uncertainty +/- 1.5 fs
- Overall larger jitter of line 2 due to non-optimized gain (manual variable resistor)
- The lack of remote gain control makes the optimization process time-consuming and nearly impractical during operation

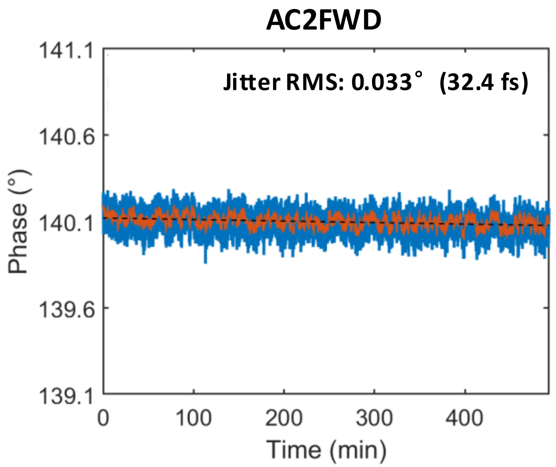
KLYSTRON 1





KLYSTRON 2



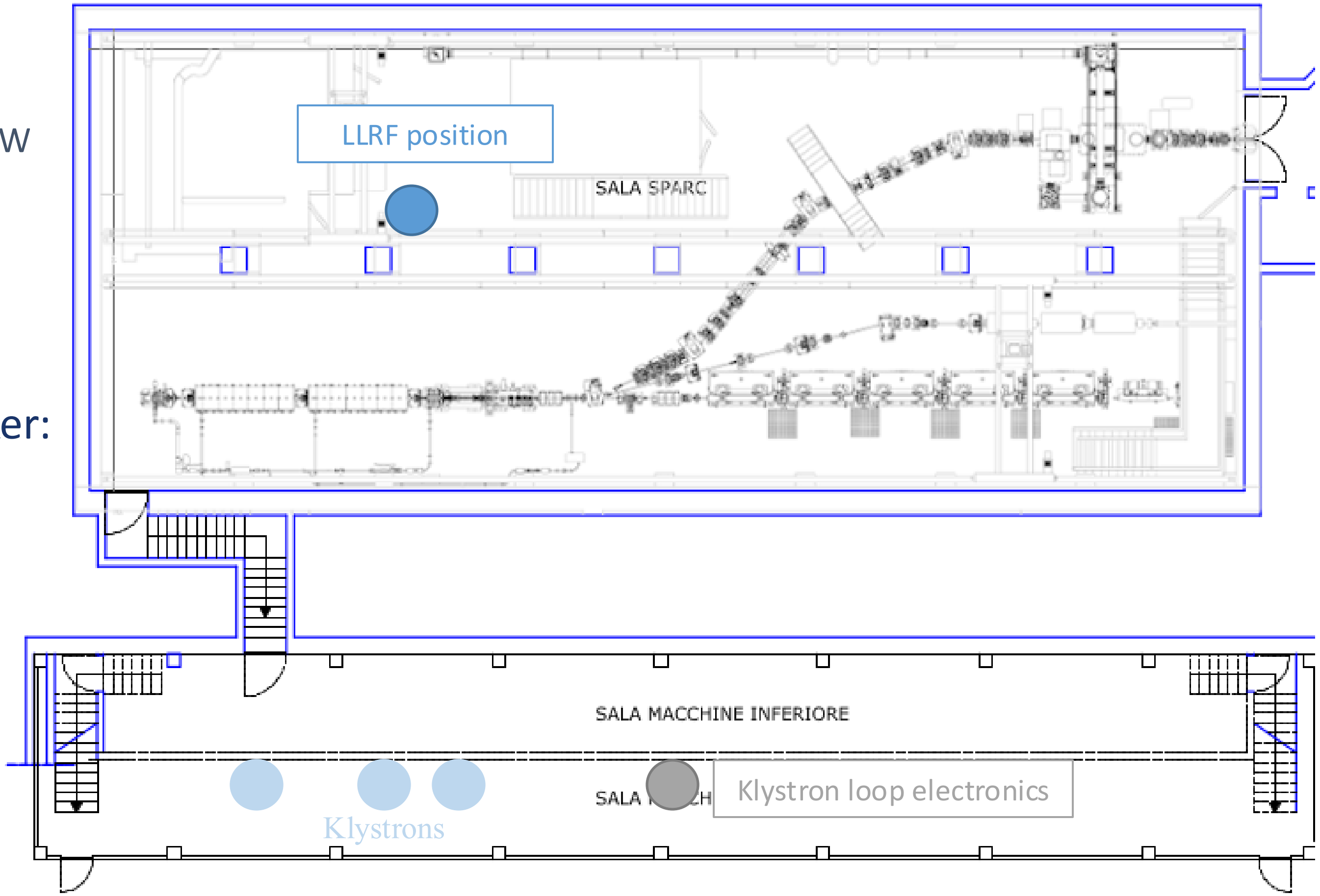


SPARC_LAB consolidation: the SABINA project

- In 2019 a 6.1 M€ regional project (SABINA – Source of Advanced Beam Imaging for Novel Applications) has been funded to consolidate the SPARC_LAB linac

- The RF systems involved in this machine refurbishment are:
  - 3x digital LLRF systems: 2x S-band, 1x C-band (ITech)
  - 1x RMO (ITech)
    - ifficulties with current manufacturer (potential issue in case of HW faults)
  - 1x C-band Solid State modulator (ScandiNova)

- New temperature stabilized LLRF rack in the SPARC bunker:
  - 3x LLRF systems
  - RF reference distribution from PC laser oscillator pulses

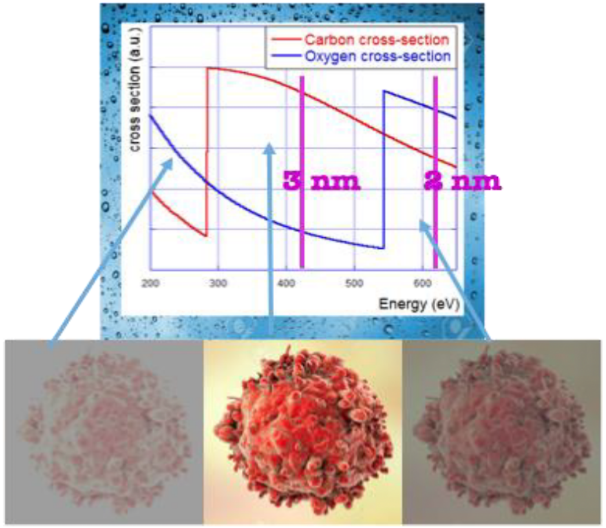


Expected SASE FEL performances

Radiation Parameter	**Unit**	PWFA	Full X-band
Radiation Wavelength	nm	**3-4**	4
Photons per Pulse	$\times 10^{12}$	**0.1-0.25**	1
Photon Bandwith	%	**0.1**	0.5
Undulator Area Length	m	30	
ρ(1D/3D)	$\times 10^{-3}$	**2**	2
Photon Brilliance per shot	$mm^2 mrad\ bw(0.1\%)$	$\mathbf{1-2 \times 10^{28}}$	1×10^{27}

Electron Beam Parameter	**Unit**	PWFA	Full X-band
Electron Energy	GeV	**1-*1.2***	1
Bunch Charge	pC	**30-50**	200-*500*
Peak Current	kA	**1-2**	1-2
RMS Energy Spread	%	**0.1**	0.1
RMS Bunch Length	μm	**6-3**	24-20
RMS norm. Emittance	μm	**1**	1
Slice Energy Spread	%	**≤0.05**	≤0.05
Slice norm Emittance	mm-mrad	**0.5**	0.5

In the energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV) water is almost transparent to radiation while nitrogen and carbon are absorbing (and scattering)



Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state
Possibility to study dynamics
~10 ^{11} photons/pulse needed

Courtesy C. Vaccarezza

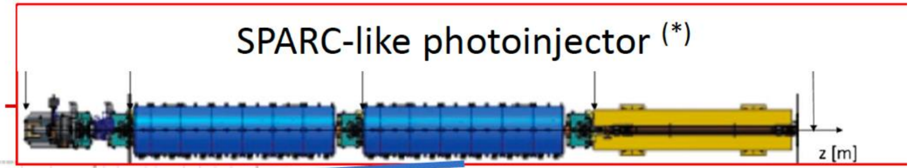
Courtesy F. Stellato (UniTov)

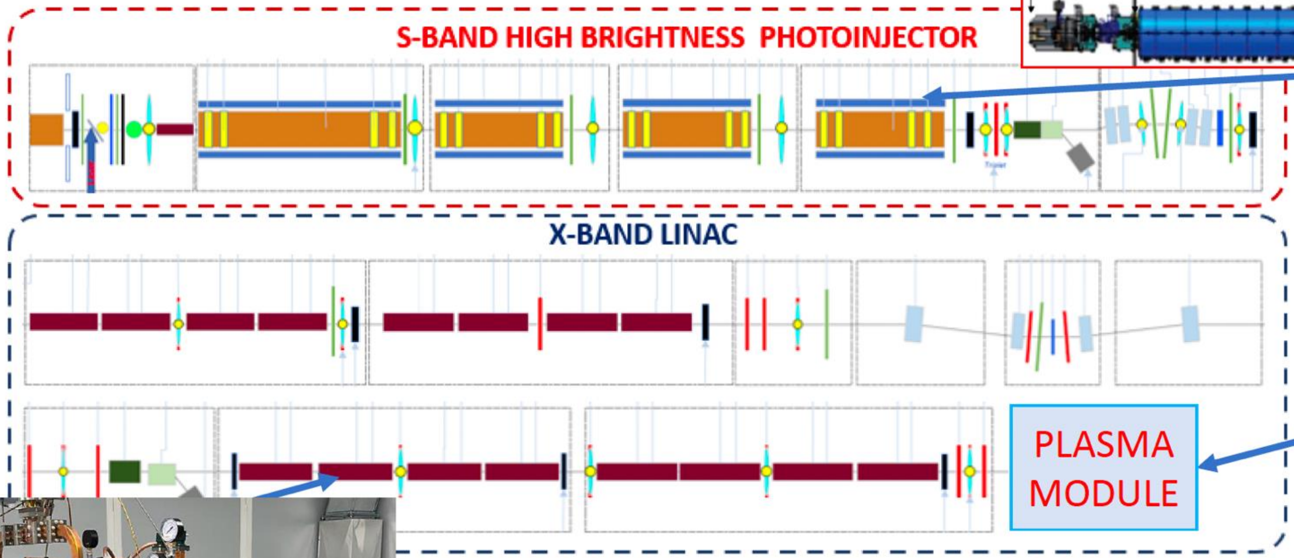
EuPRAXIA@SPARC_LAB: a high brightness PWFA

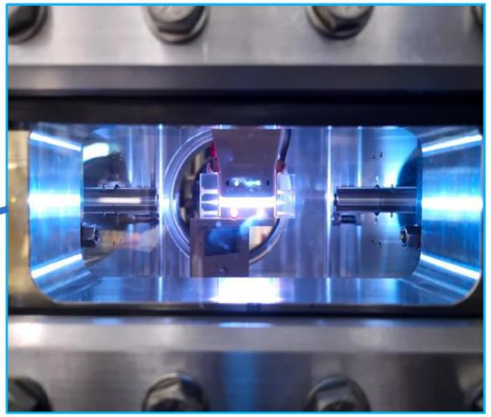
EuPRAXIA at SPARC_LAB

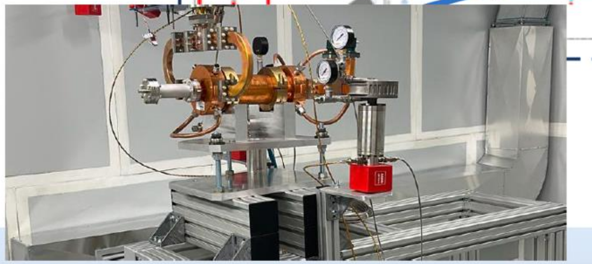
Funded by the European Union

The accelerator is based on the combination of a *high brightness RF injector* and a *plasma module*

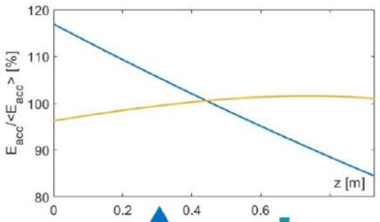


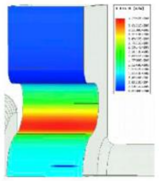




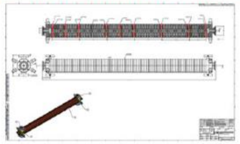


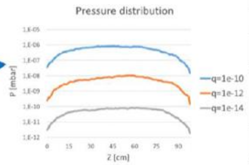
World`s Most Compact RF Linac: X Band

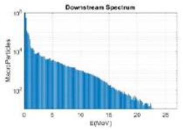




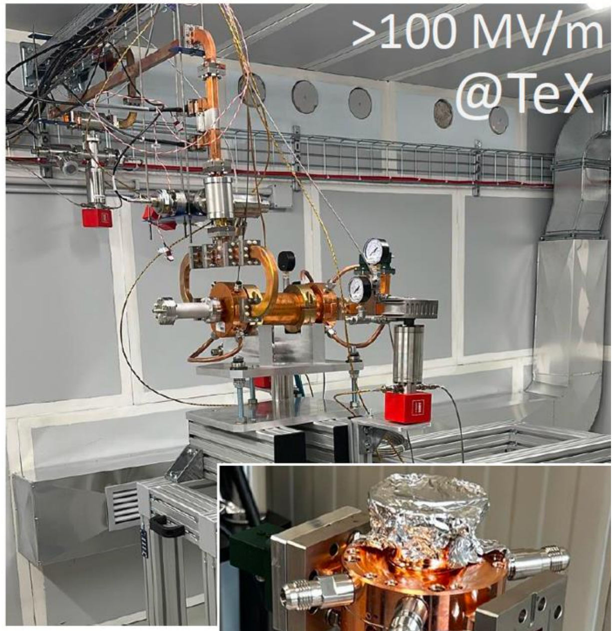
1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*

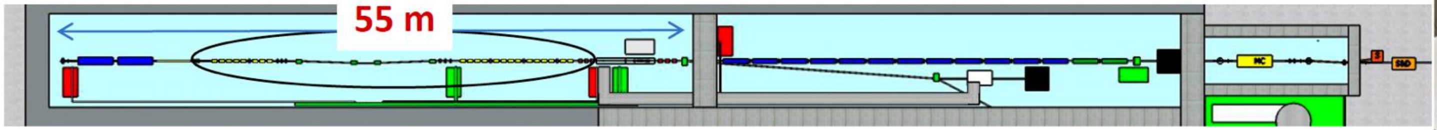






PARAMETER	Value	
	with linear tapering	w/o tapering
Frequency [GHz]	11.9942	
Average acc. gradient [MV/m]	**60**	
Structures per module	2	
Iris radius a [mm]	**3.85-3.15**	**3.5**
Tapering angle [deg]	0.04	0
Struct. length L_s act. Length (flange-to-flange) [m]	**0.94 (1.05)**	
No. of cells	112	
Shunt impedance R [MΩ/m]	93-107	100
Effective shunt Imp. $R_{sh\ eff}$ [MΩ/m]	350	347
Peak input power per structure [MW]	70	
Input power averaged over the pulse [MW]	51	
Average dissipated power [kW]	1	
P_{out}/P_{in} [%]	25	
Filling time [ns]	130	
Peak Modified Poynting Vector [W/μm²]	3.6	4.3
Peak surface electric field [MV/m]	160	190
Unloaded SLED/BOC Q-factor Q_0	150000	
External SLED/BOC Q-factor Q_E	21300	20700
Required Kly power per module [MW]	**20**	
RF pulse [μs]	**1.5**	
Rep. Rate [Hz]	**100**	





Courtesy D. Alesini, F. Cardelli

EuPRAXIA

Radiation Generation: FEL

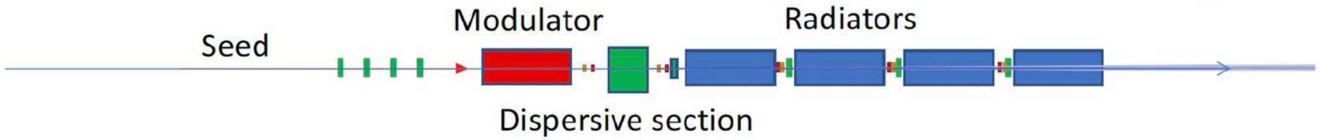
Two FEL lines:

1) *AQUA*: Soft-X ray SASE FEL – Water window optimized for 4 nm (baseline)

SASE FEL: 10 UM Modules, 2 m each – 60 cm intraundulator sections.
Two technologies under study: Apple-X PMU (baseline) and planar SCU.
Prototyping in progress

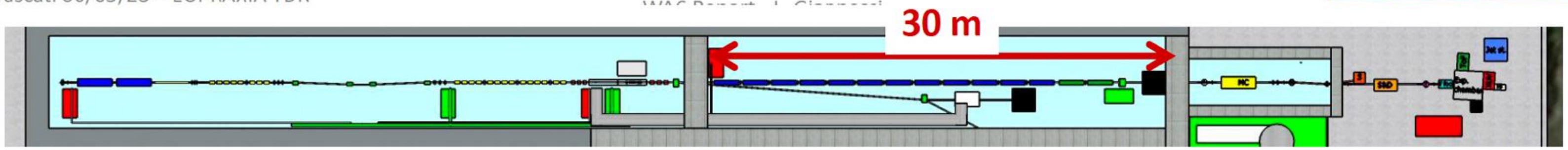
First ***SABINA*** undulator in FRASCATI March 29, 2023

2) *ARIA*: VUV seeded HGHG FEL beamline for gas phase



SEEDED FEL – Modulator 3 m + 4 Radiators APPLE II – variable pol. 2.2 m each – SEEDED in the range 290 – 430 nm (see former presentation to the committee and *Villa et al. ARIA—A VUV Beamline for EuPRAXIA@SPARC_LAB. Condens. Matter 2022, 7, 11.*) – Undulator based on consolidated technology.

Frascati 06/05/23 – EUPRAXIA TDR



Courtesy L. Giannessi