Upgrade of the fast analogue intra-pulse phase feedback at SPARC_LAB

L. Piersanti, M. Bellaveglia, A. Gallo, R. Magnanimi, S. Quaglia, M. Scampati, G. Scarselletta, B. Serenellini, S. Tocci INFN-LNF

Outline

- SPARC_LAB facility at Frascati National Laboratories of INFN
- Plasma acceleration experiments in view of EuPRAXIA@SPARC_LAB project
- The SPARC_LAB RF system
- Main RF constraints on plasma acceleration stability
- First development of intra-pulse phase feedback (“klystron loop”) and RF phase stability improvements
- Upgrade of klystron loop error amplifier and first tests at SPARC_LAB

SPARC_LAB facility at LNF

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

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

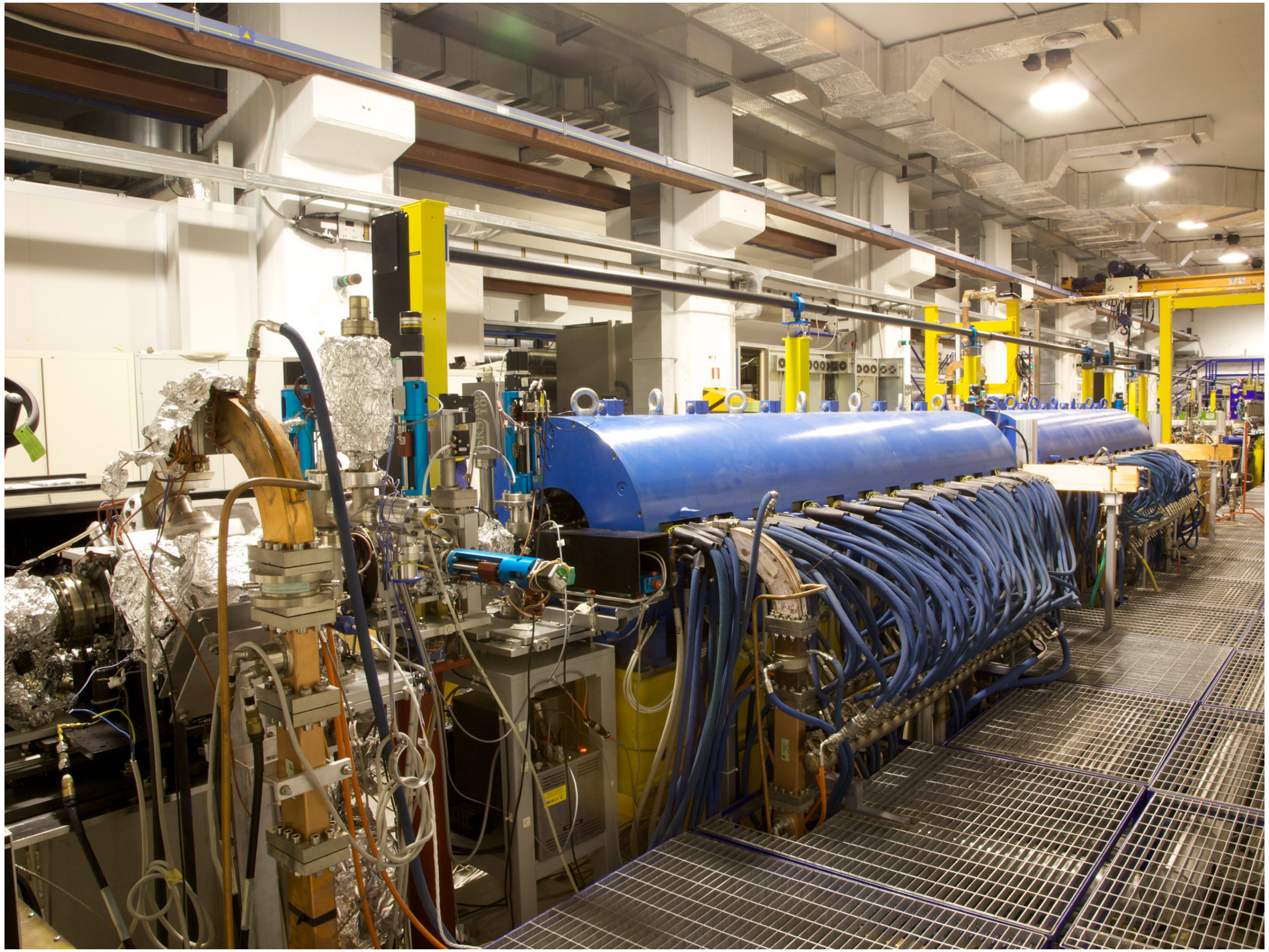
» An intense R&D program has been carried out performing many experiments:

  » **SASE and seeded FEL**

  » **Thomson back-scattering**

  » **THz radiation**

  » **Plasma focusing and acceleration (Particle WakeField Acceleration - PWFA)**



SPARC_LAB facility at LNF

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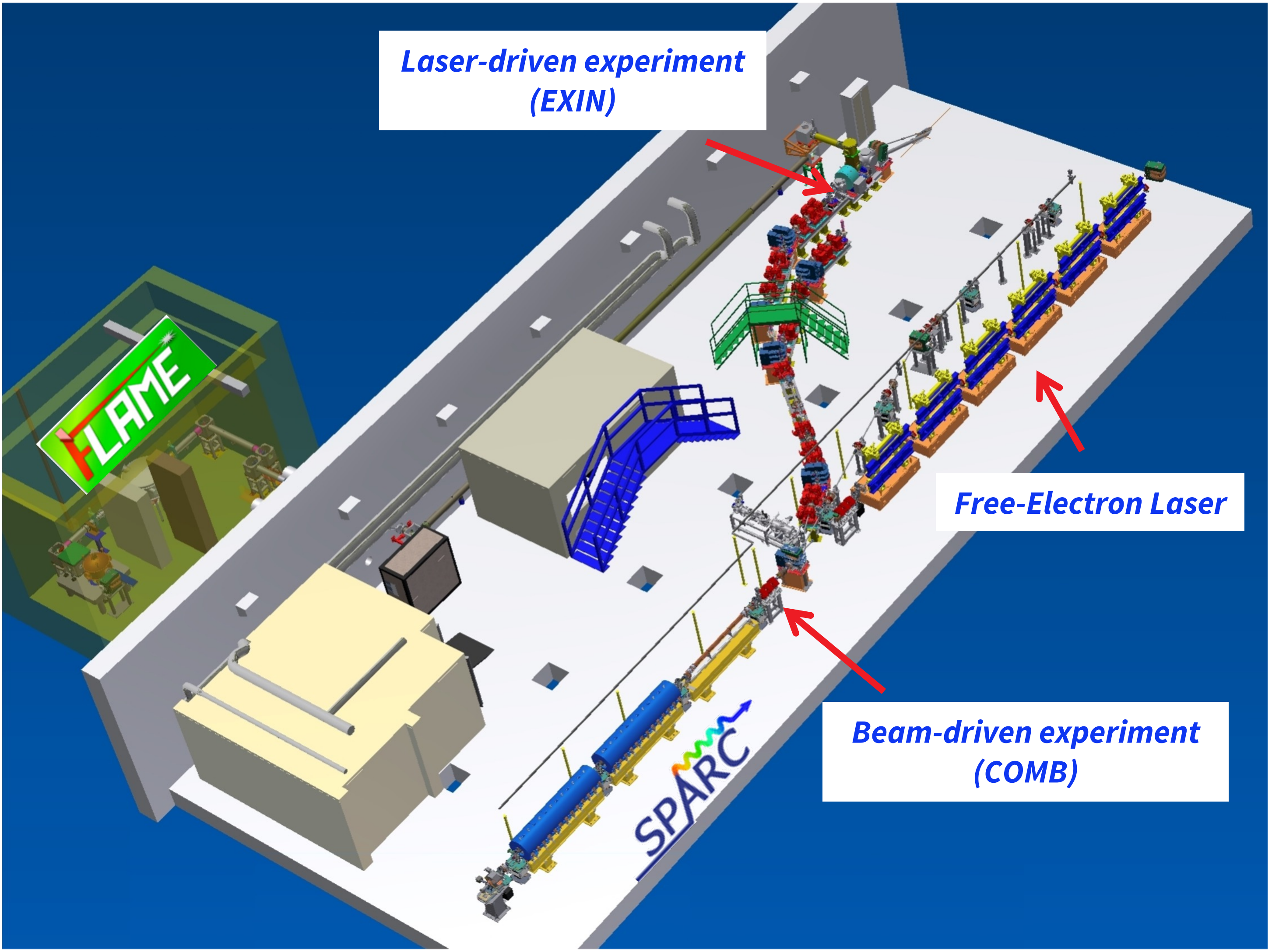
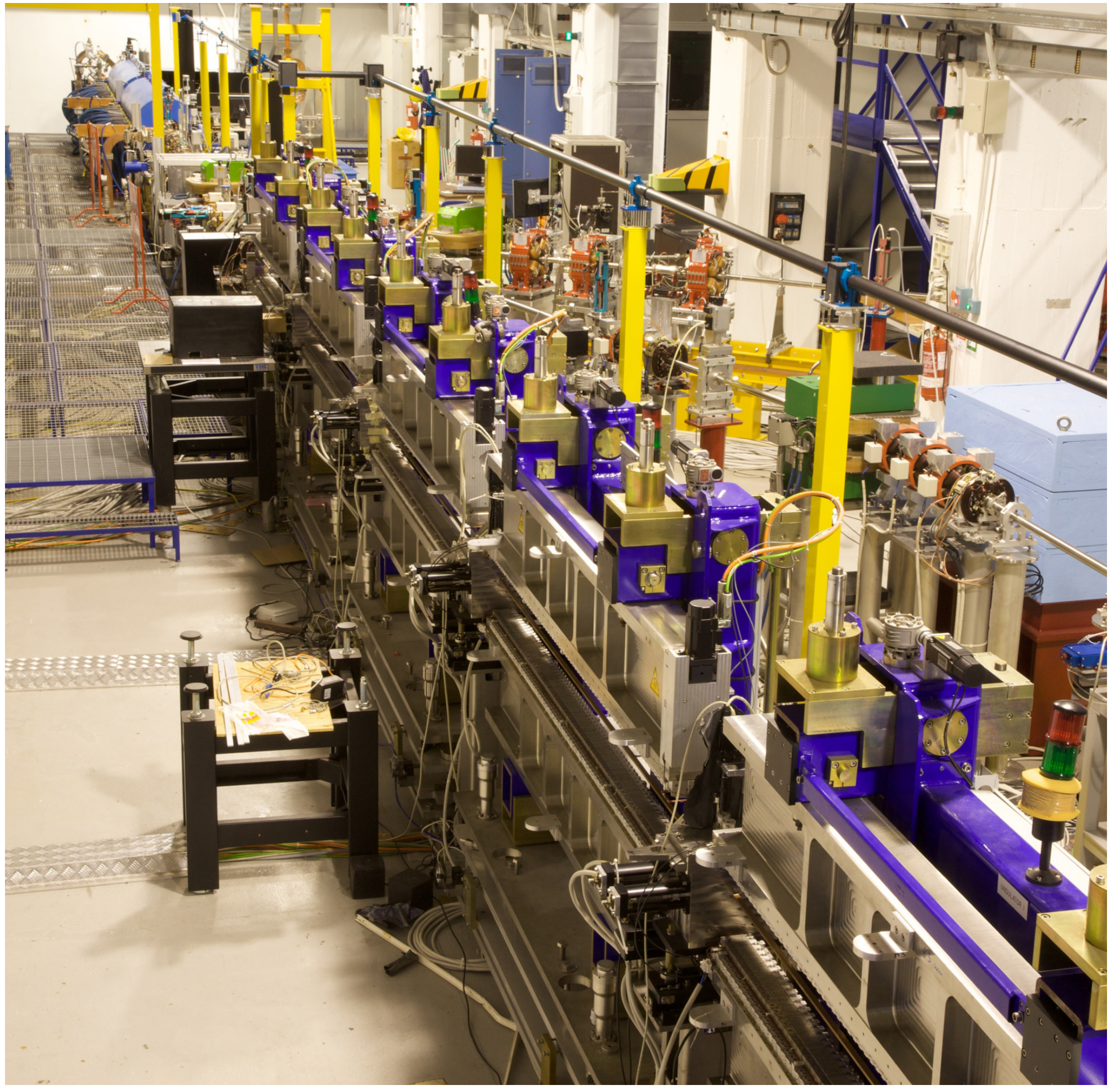




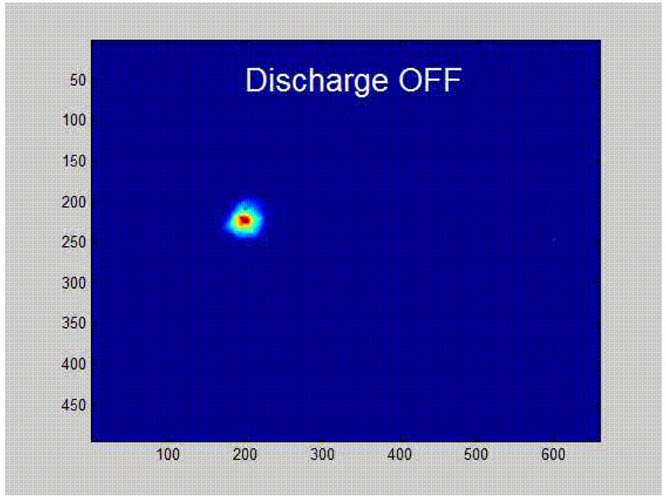
M. Ferrario et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

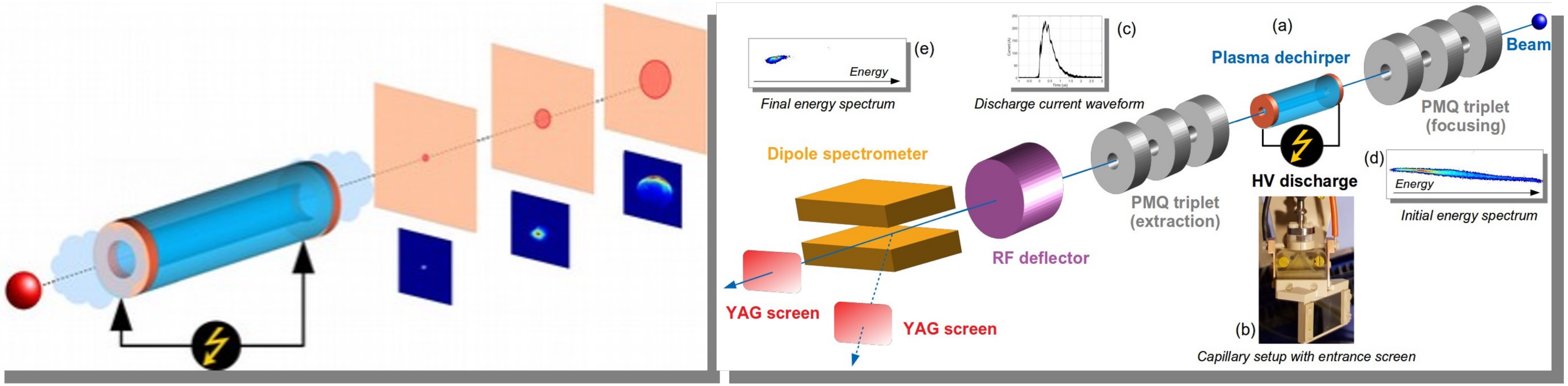
SPARC_LAB facility at LNF

- Today SPARC_LAB is a multi-disciplinary experimental facility that combines:
  - **High brightness** S-band **photo-injector**;
  - **'Conventional' booster linac**: 2 S-band SLAC-type TW structures + 1 C-band CI structure (up to 150 MeV e- on crest);
  - Plasma acceleration stage for PWFA experiments (and a brand new plasma lab. for capillary R&D);
  - 12 m undulator for FEL (both SASE and seeded);
  - 200 TW (5J, 25 fs, 10 Hz rep. rate) class laser for LWFA and interaction laser-matter experiments
- The R&D activities in the last 3 years have been devoted to plasma acceleration and beam focusing with plasma lenses -> **EuPRAXIA@SPARC_LAB new LNF facility**

Focusing with active-plasma lenses

Longitudinal phase-space manipulation





R. Pompili et al., Physical review letters 121.17 (2018): 174801.

V. Shpakov et al. Phys. Rev. Lett. 122, 114801 (2019)

R. Pompili et al., Applied Physics Letters 110.10 (2017): 104101.

Courtesy of R. Pompili

The plasma acceleration experiment at SPARC_LAB

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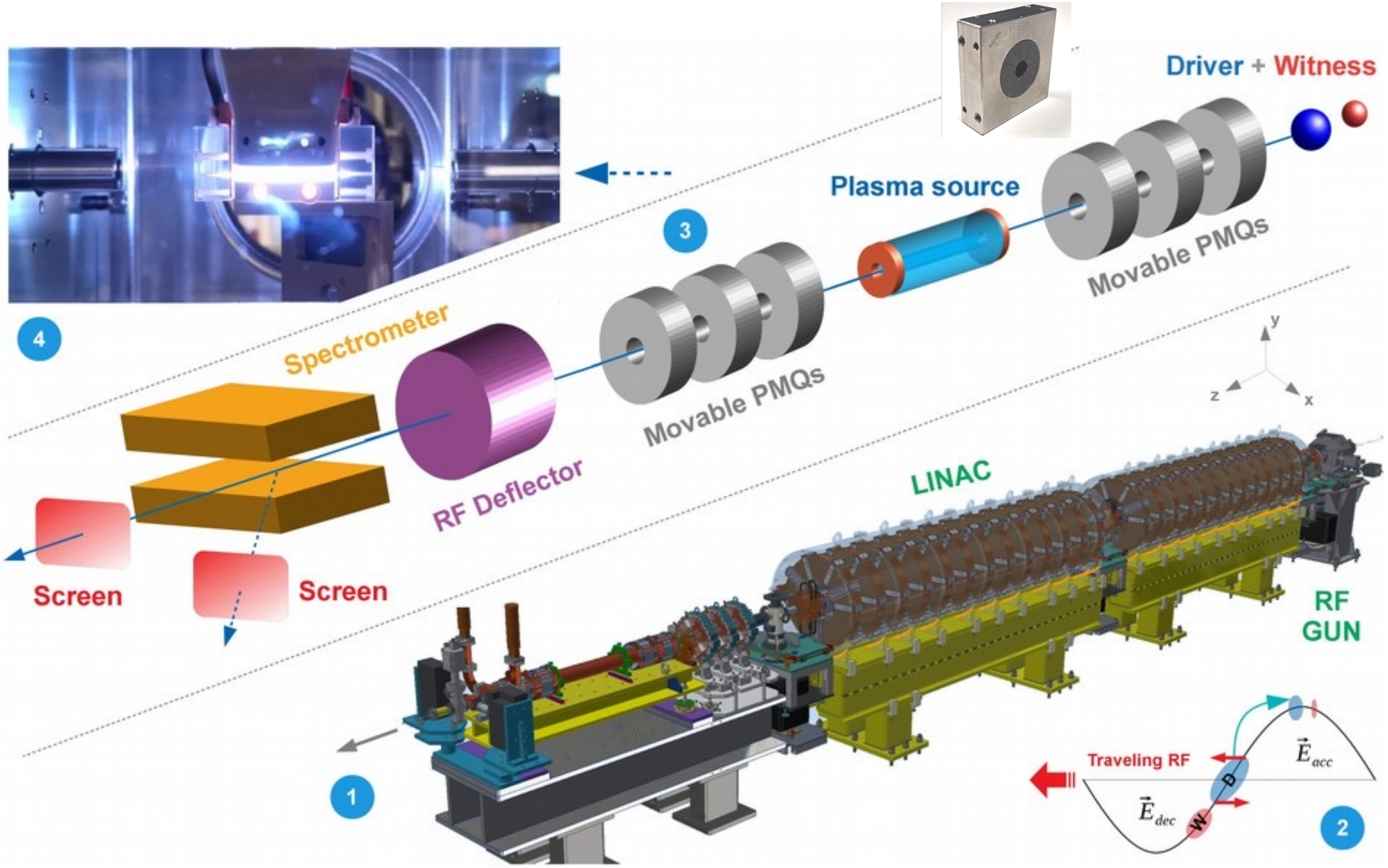

First plasma acceleration at SPARC_LAB: 4 MeV gain in 3 cm plasma (133 MV/m)

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]

Courtesy of R. Pompili and A. Giribono

The plasma acceleration experiment at SPARC_LAB

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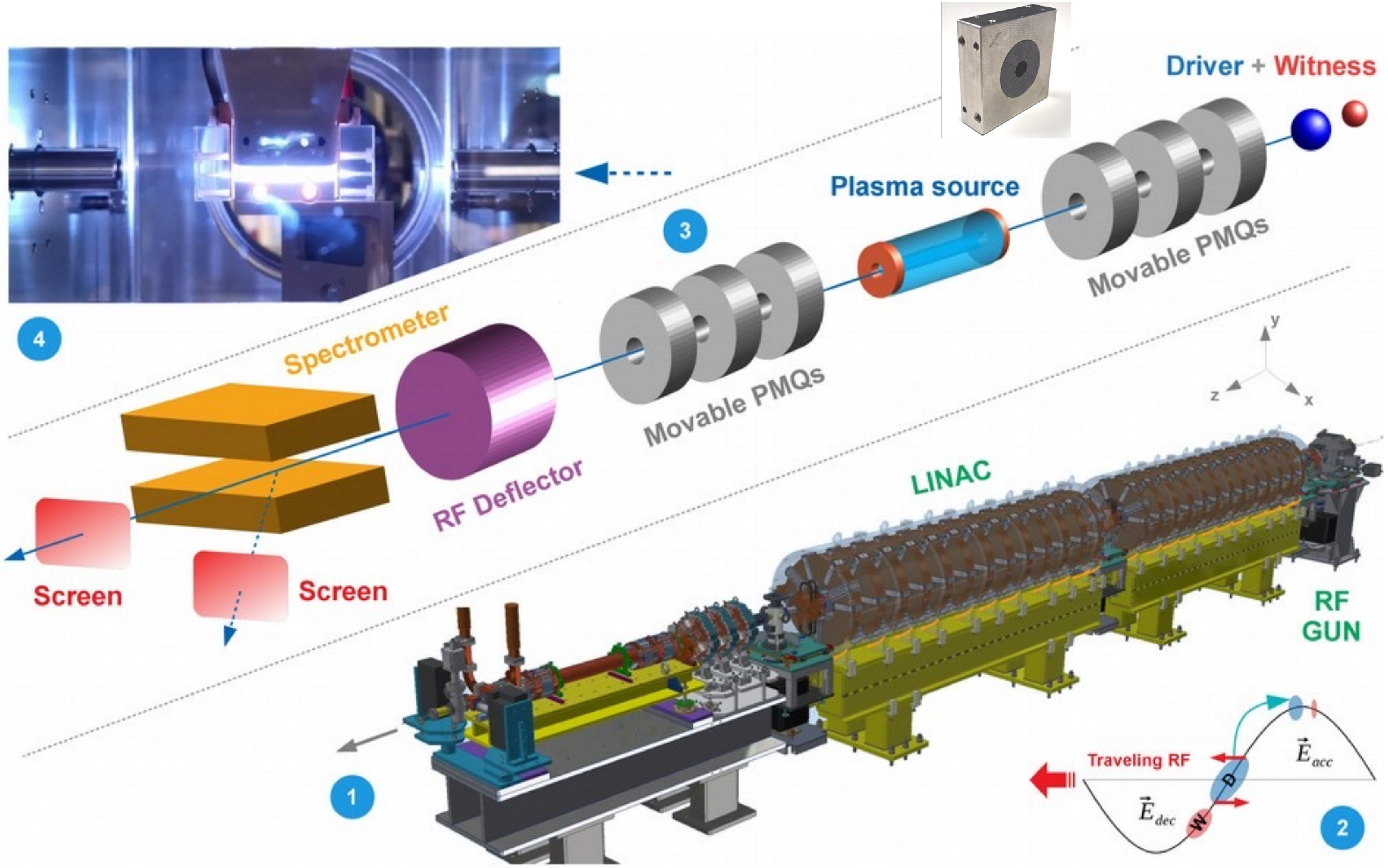
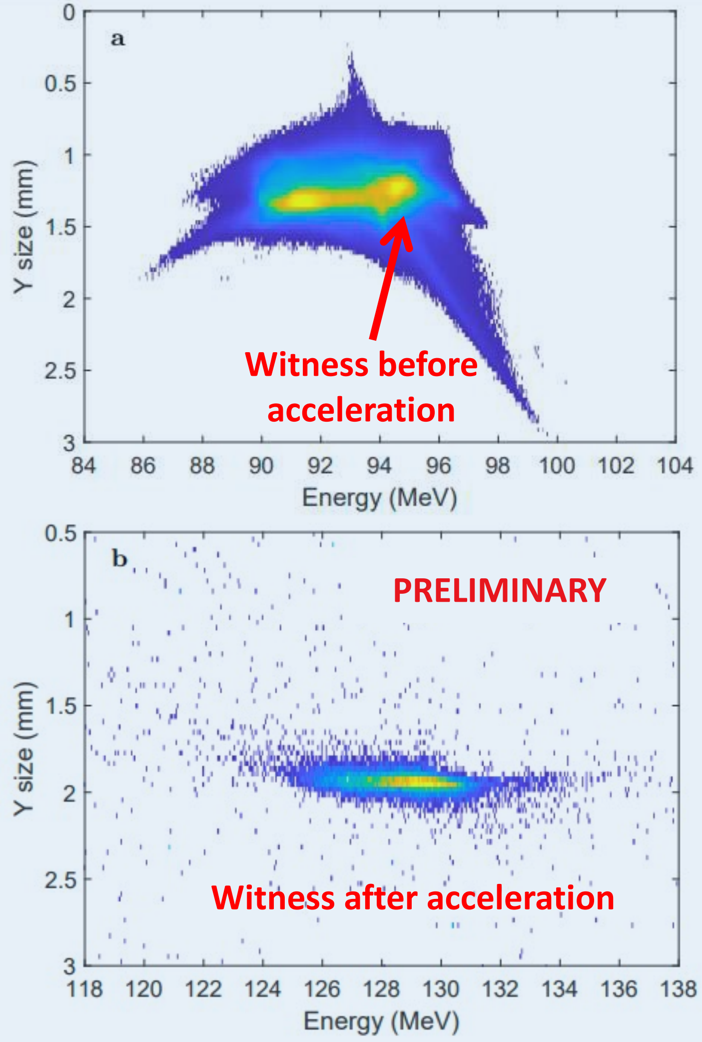


Nov. 2022

>30 MeV gain in 3 cm **>1 GV/m gradient!!!**

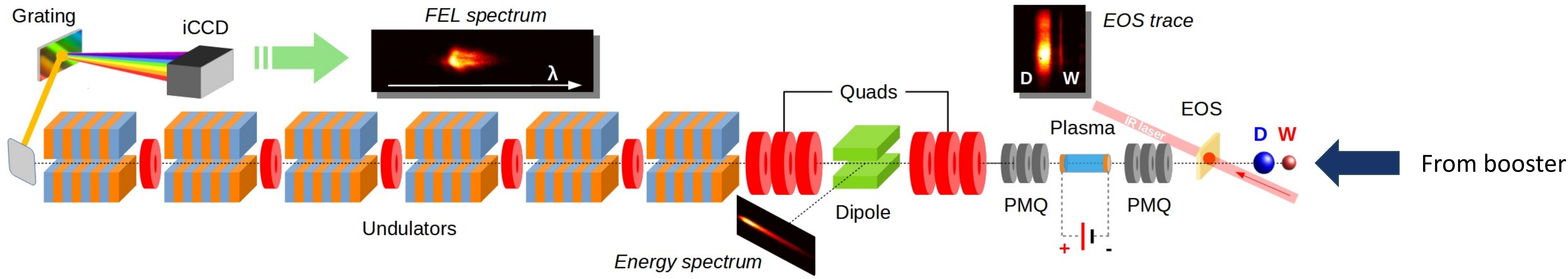


Courtesy of R. Pompili and A. Giribono

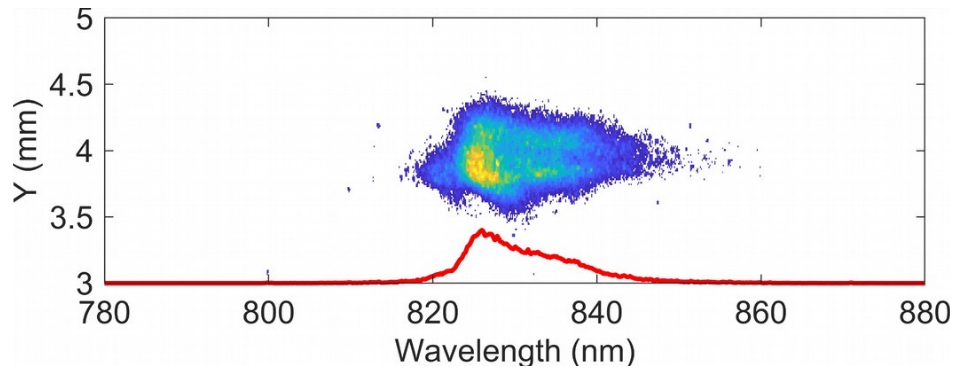
Proof of principle of SASE FEL driven by PWFA

» Proof-of-principle experiment to demonstrate high-quality PWFA acceleration able to drive a Free-Electron Laser

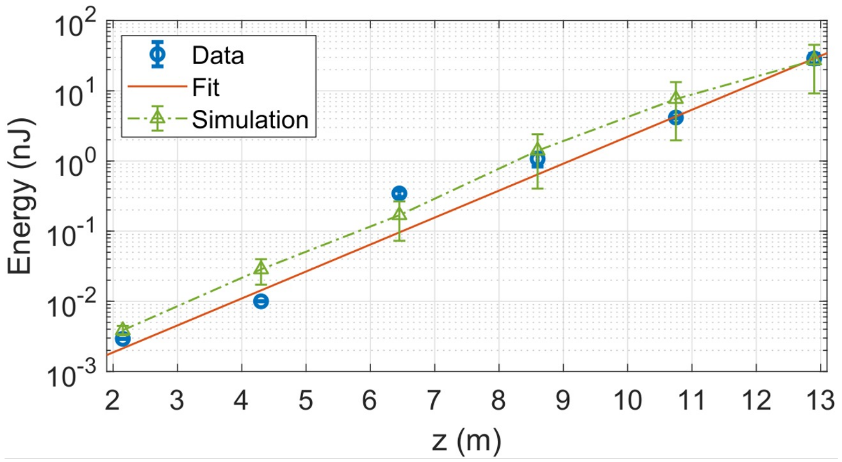
» Witness is completely characterized (energy, spread, X/Y emittance) allowing to match it into the undulators beamline



Single-shot spectrum of SASE FEL radiation at 830 nm



Exponential gain of FEL radiation energy

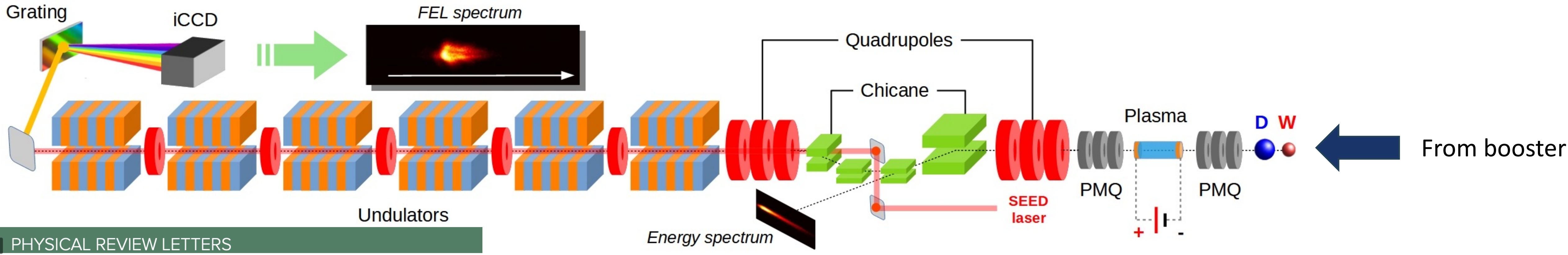


Courtesy of R. Pompili

Proof of principle of seeded FEL driven by PWFA

» Proof-of-principle experiment to demonstrate high-quality PWFA acceleration able to drive a Free-Electron Laser

» Witness is completely characterized (energy, spread, X/Y emittance) allowing to match it into the undulators beamline

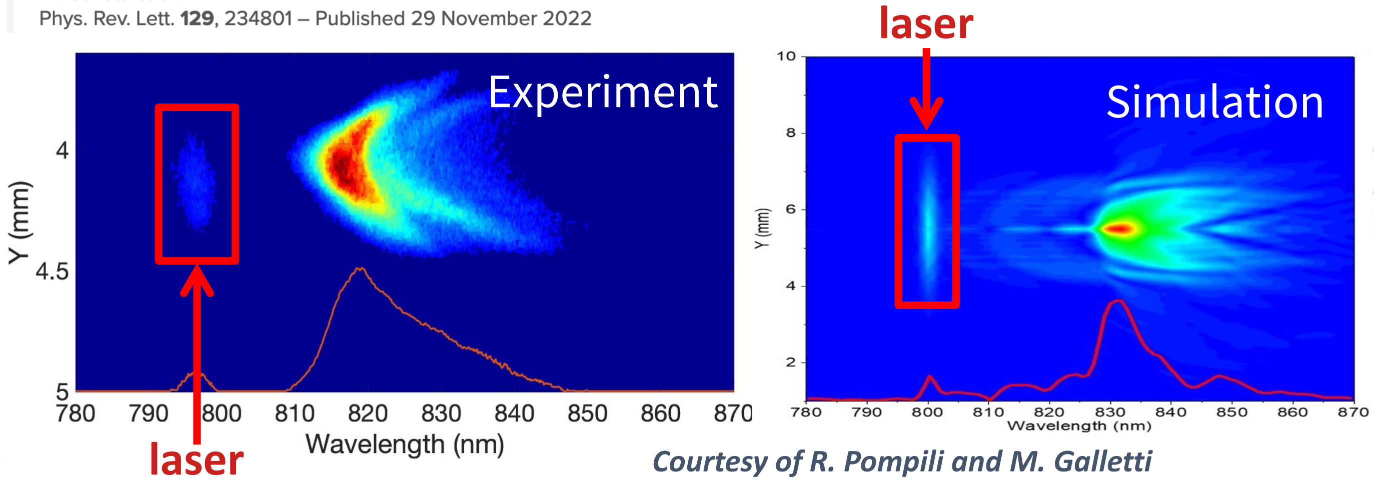


PHYSICAL REVIEW LETTERS

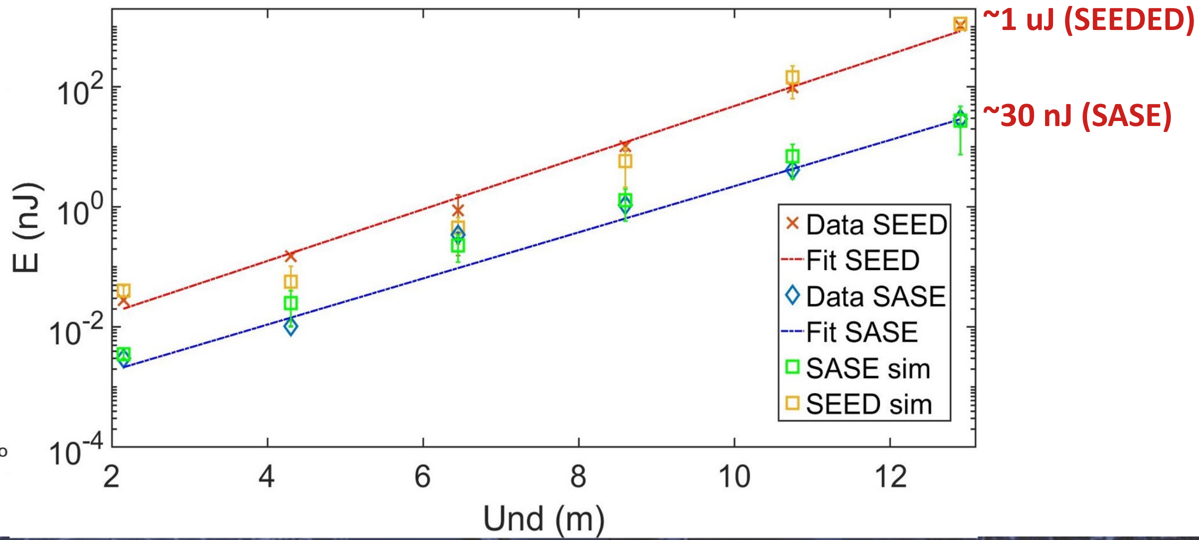
Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator

M. Galletti *et al.*

Phys. Rev. Lett. **129**, 234801 – Published 29 November 2022



Courtesy of R. Pompili and M. Galletti

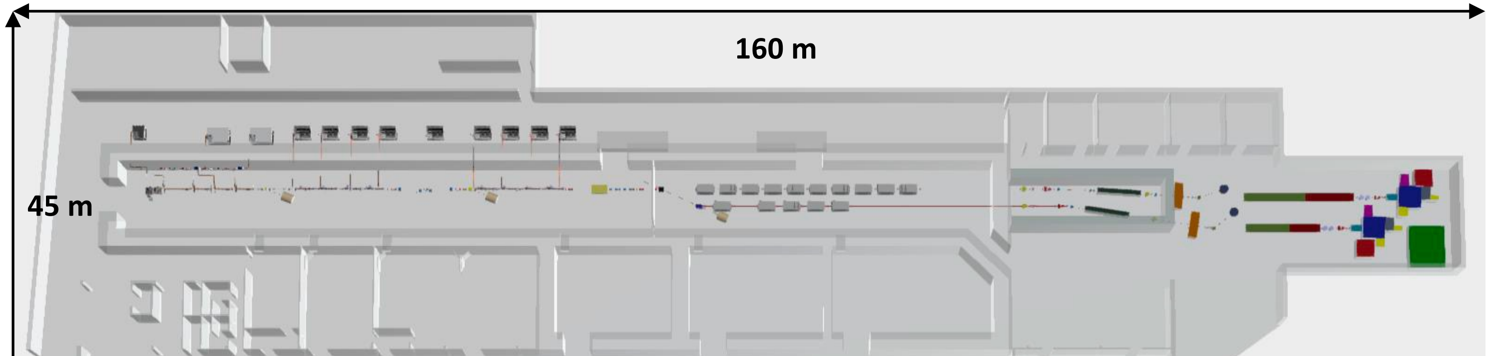


LNF future facility: EuPRAXIA@SPARC_LAB

Credits: INFN & Mythos – consorzio stabile s.c.a.r.l.

LNF future facility

- > 130 M€ invest funding
- FEL user facility with plasma accelerator booster
- X-band technology in collaboration with CERN
- Executive project approved by the Italian Ministry



Courtesy of F. Cioeta, E. Di Pasquale, A. Ghigo, A. Falone

SPARC_LAB RF system

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- In all these years the request on **RF stability (in particular EM field phase)** went from **< 2 ps** (RF gun characterization) down to **< 10 fs** (particle driven plasma acceleration)

- To meet the evolving demands of the facility, many upgrades of the original RF and synchronization systems have been made:
  - **Low noise RMO (50 fs residual jitter 10 Hz – 10 MHz)**
  - **Electronic phase shifters added for working point fine tuning**
  - **Photocathode laser new locking electronics**
  - **Fast intra-pulse phase feedback**
  - **Low drifts cables for reference and RF signals distribution**

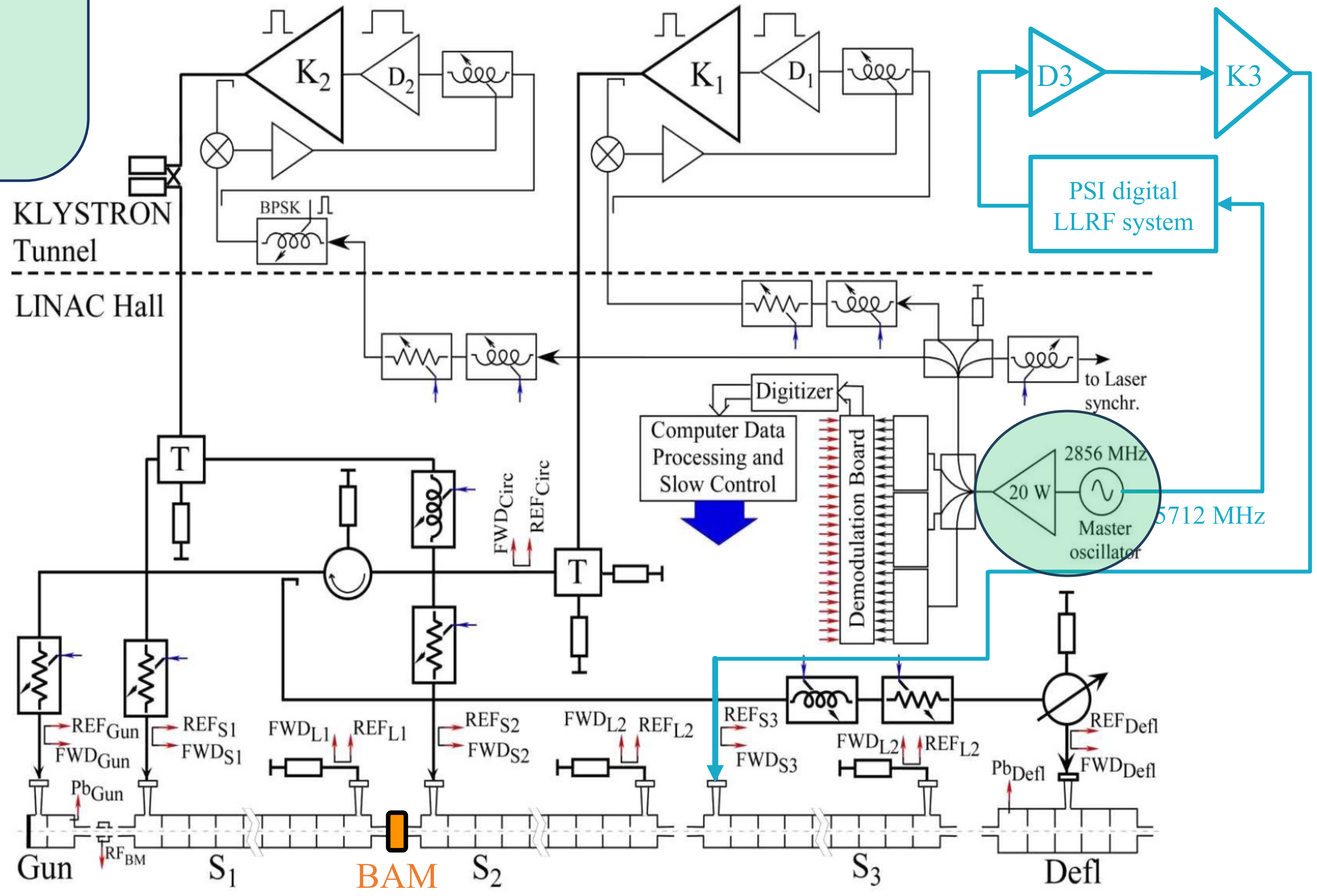
- And a big one is coming: new RMO + upgrade of all LLRF systems -> digital FPGA-based (**B. Serenellini's** poster ID #69)

SPARC_LAB RF layout: reference generation

Reference Master Oscillator:

Laurin A.G. low phase noise OCXO provides the reference to:

- S-band and C-band klystrons
- Laser systems (Photo-cathode & FLAME)
- LLRF front-end and back-end



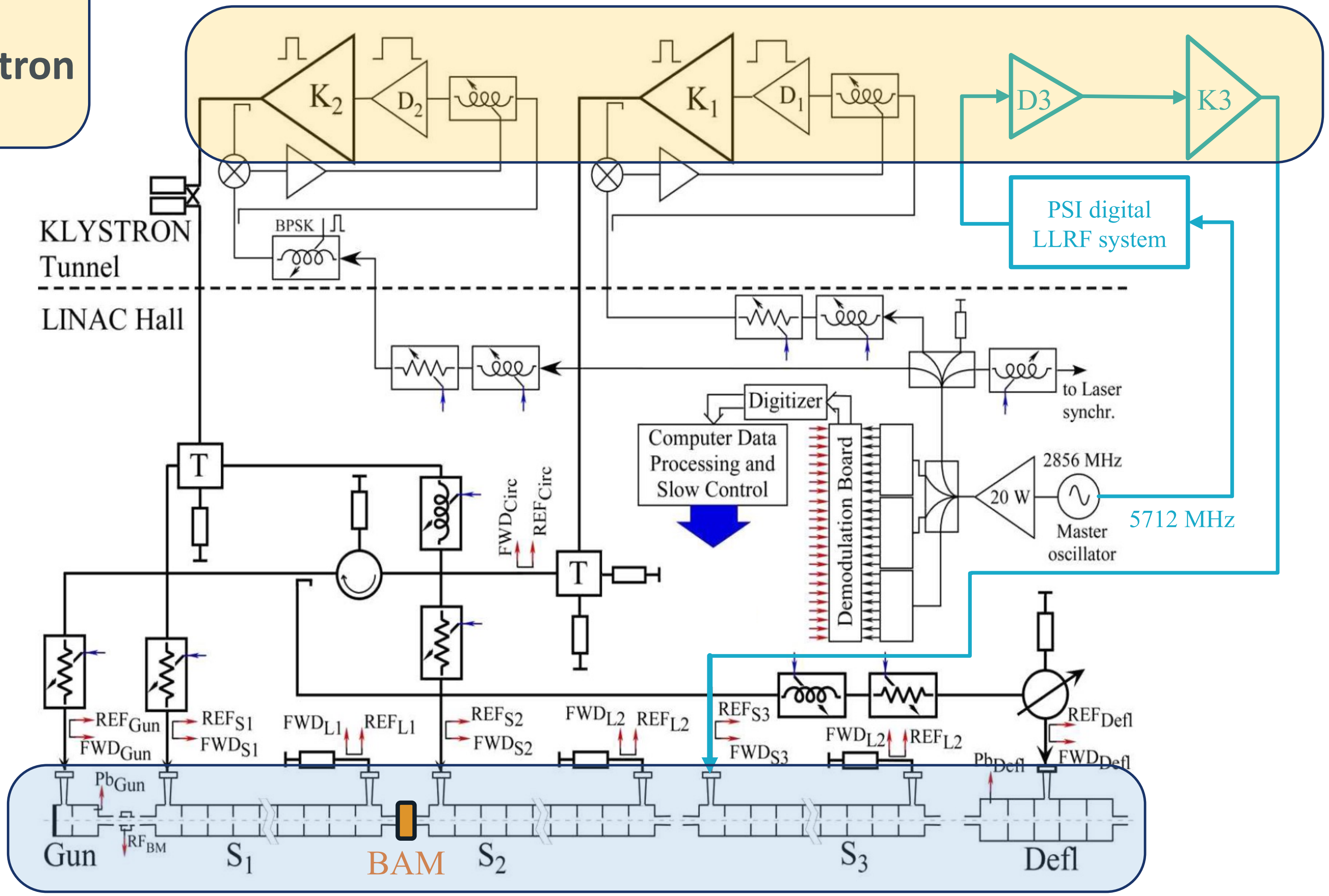
SPARC_LAB RF layout: RF power plants and accelerator

RF power plants:

- 2x PFN modulators (PPT) + **45 MW S-band klystrons** (Thales TH2128C)
- 1x SS modulator (ScandiNova) + **50 MW C-band klystron** (Canon E37202)

Accelerating structures:

- 1x SW RF-gun
- 1x SW RF deflector
- 2x TW S-band SLAC type CG structures (S1-S2)
- 1x TW C-band CI structure (S3)
- 1x passive Beam Arrival Monitor (BAM) cavity

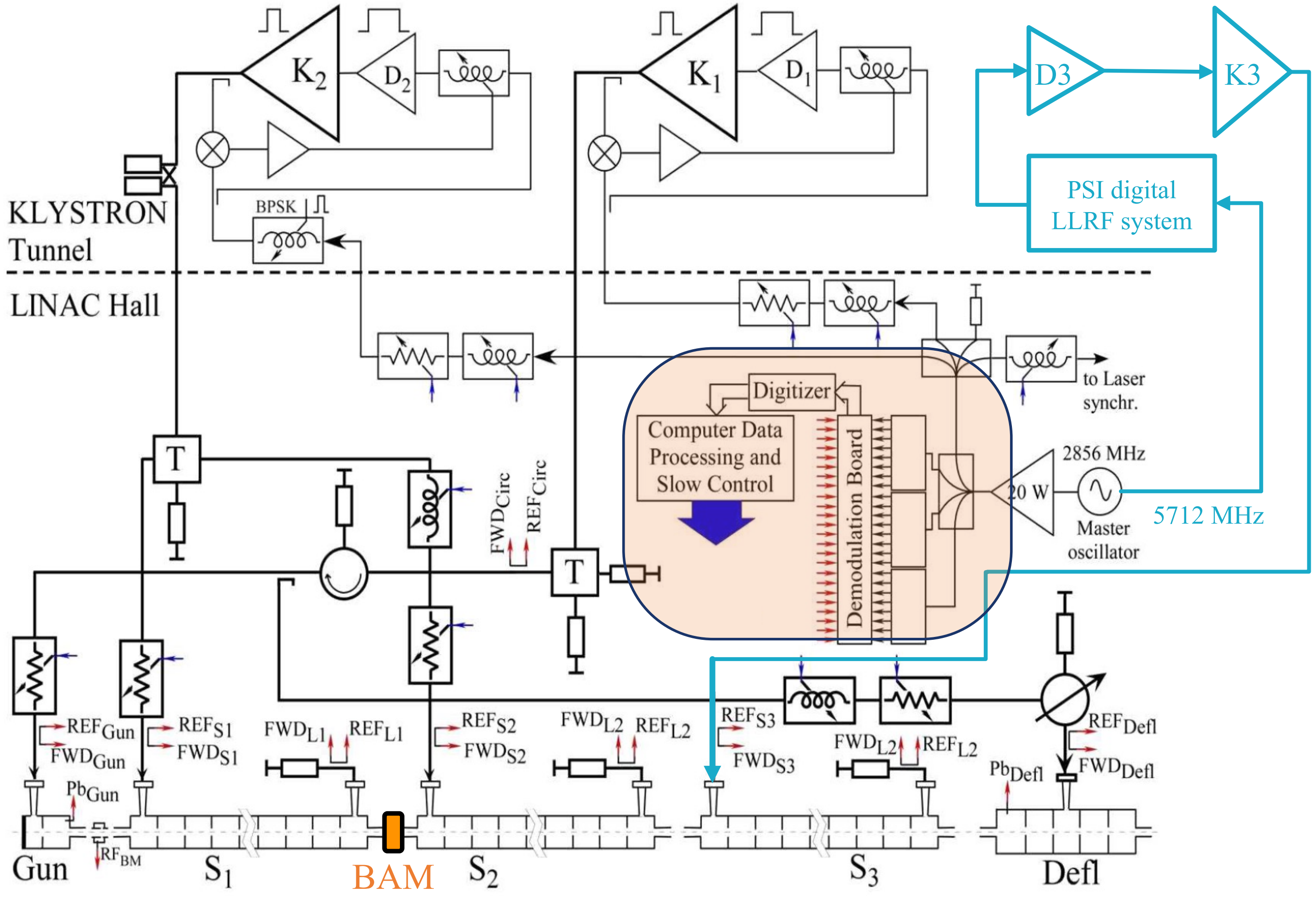


SPARC_LAB RF layout: S-band LLRF system

» S-band LLRF has been developed in 2006 at LNF by RF-group using commercial RF components for signal manipulation (attenuation, phase shift, pre-pulse generation, BPSK,…) and ADCs for signal acquisition:

Analog front end: 24 ch. level 27 Pulsar I/Q mixers, **direct conversion**;

ADC: NI-5105 **60 MHz, 12 bit, 8 ch./module**



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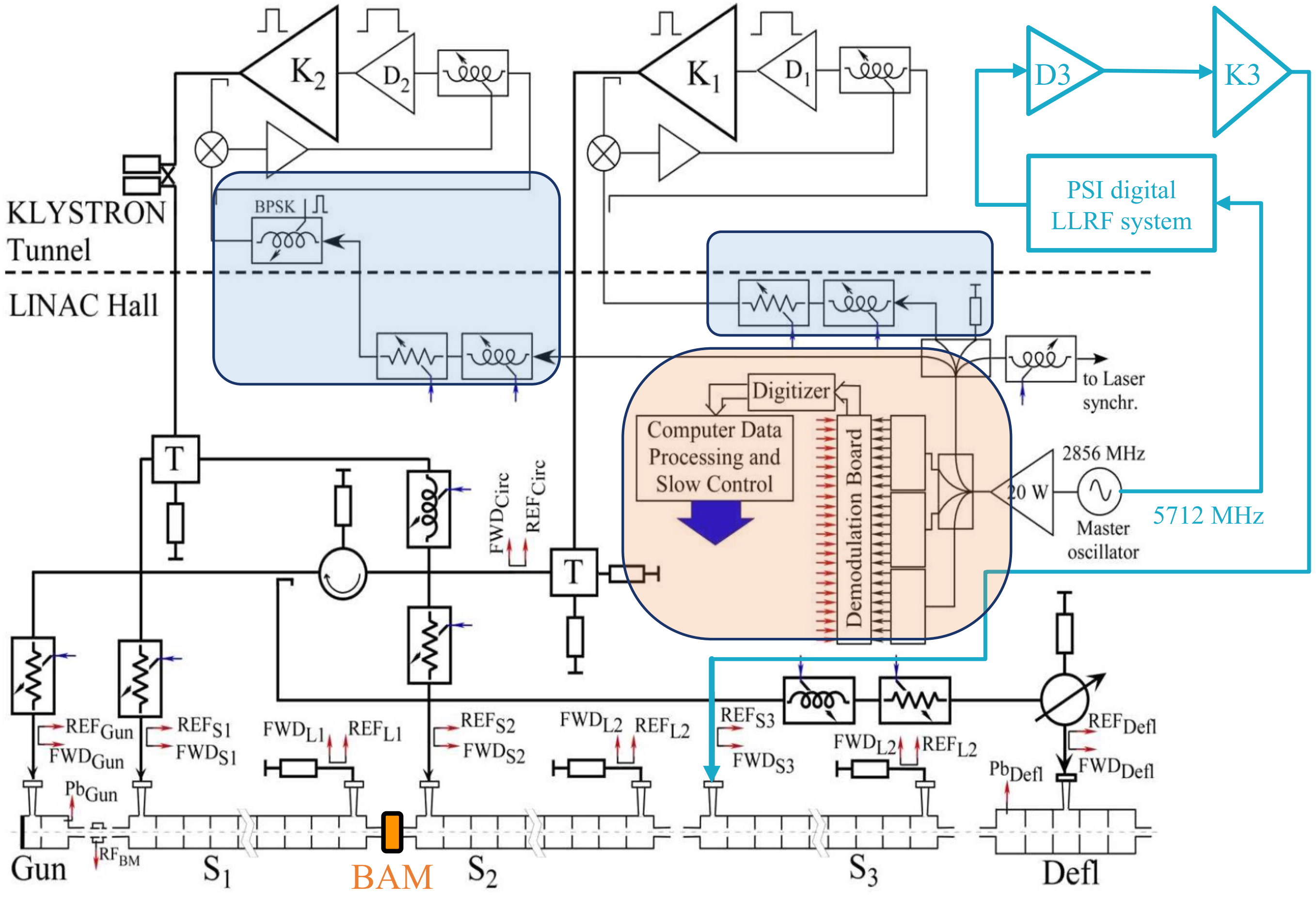
Analog back-end:

RF switch, voltage controlled attenuators, motorized phase shifters (coarse tuning), electronic phase shifters (fine tuning), BPSK;



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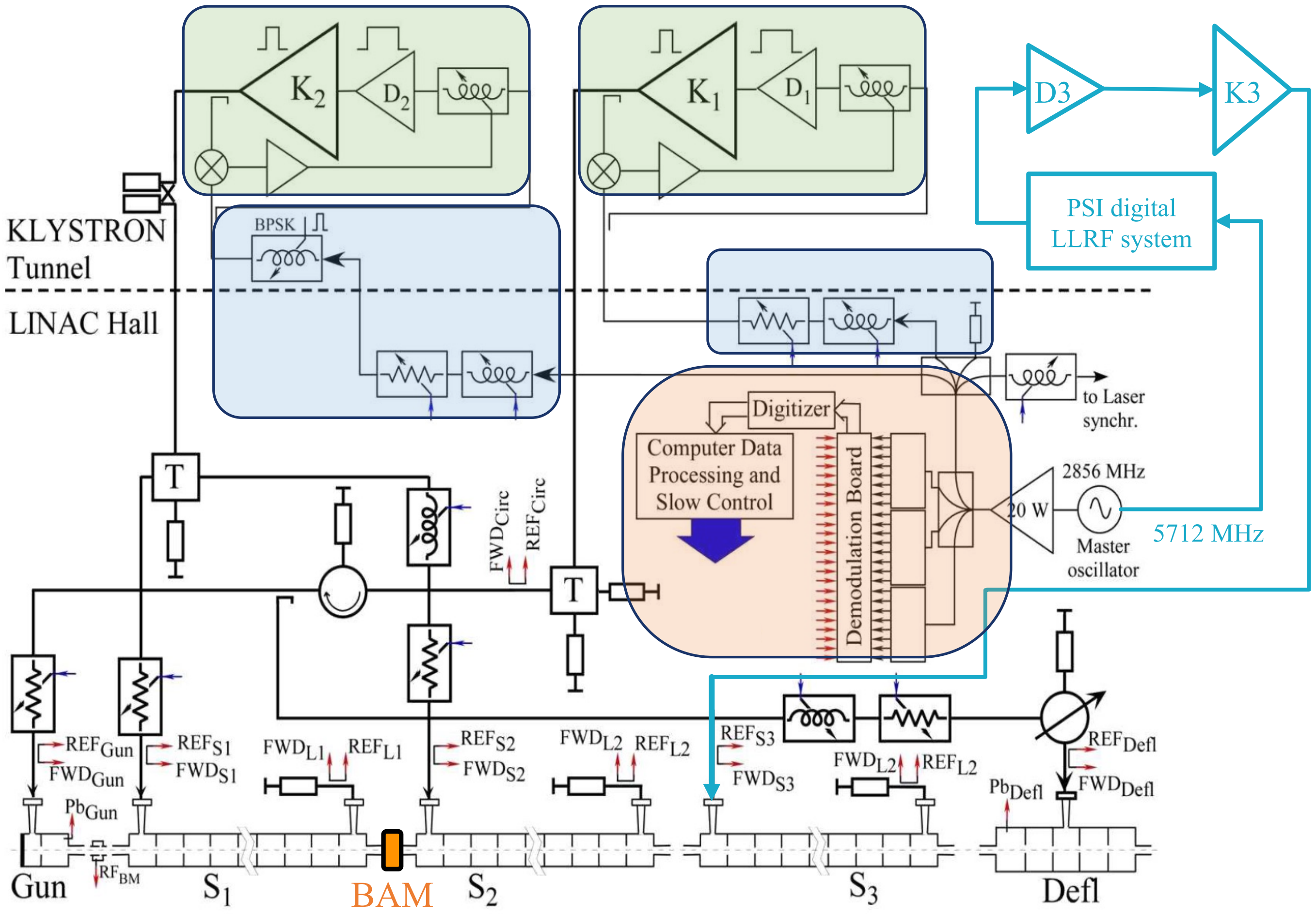
RF switch, voltage controlled attenuators, motorized phase shifters (coarse tuning), electronic phase shifters (fine tuning), BPSK;

Fast klystron phase feedbacks

» Slow A, φ feedbacks via software (control system)

» No pulse shaping, (only pre-pulse generation for fast klystron 1 phase feedback)

» Front-end noise limits the achievable resolution (e.g. RF phase ≈ 50 fs, amplitude ≈ 0.15%)



SPARC_LAB RF layout: C-band LLRF system

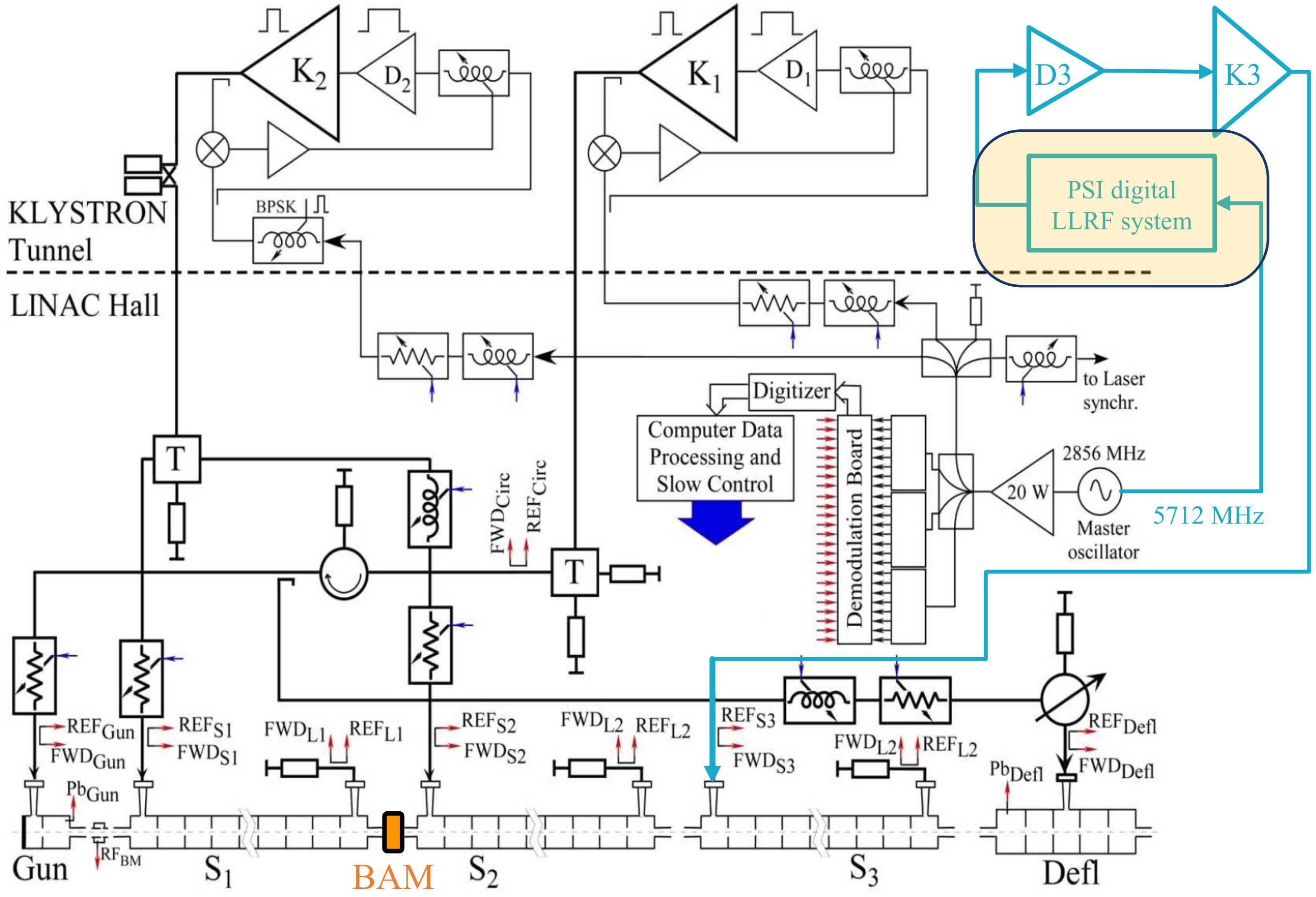
C-band LLRF developed at PSI (Tiara project FP7), digital system with RF pulse mask, **only amplitude and phase detection** (phase error < +/- 0.05 deg, amplitude <0.1%) **feedback implemented in the control system**

» <u>Front end:</u>

- up to 16 inputs (RF in max -15 dBm)
- ch. isolation > 80 dB
- conversion to IF (39.667 MHz), BW >30 MHz
- ADC-DAC: 16-bit; 238-476 MS/s respectively

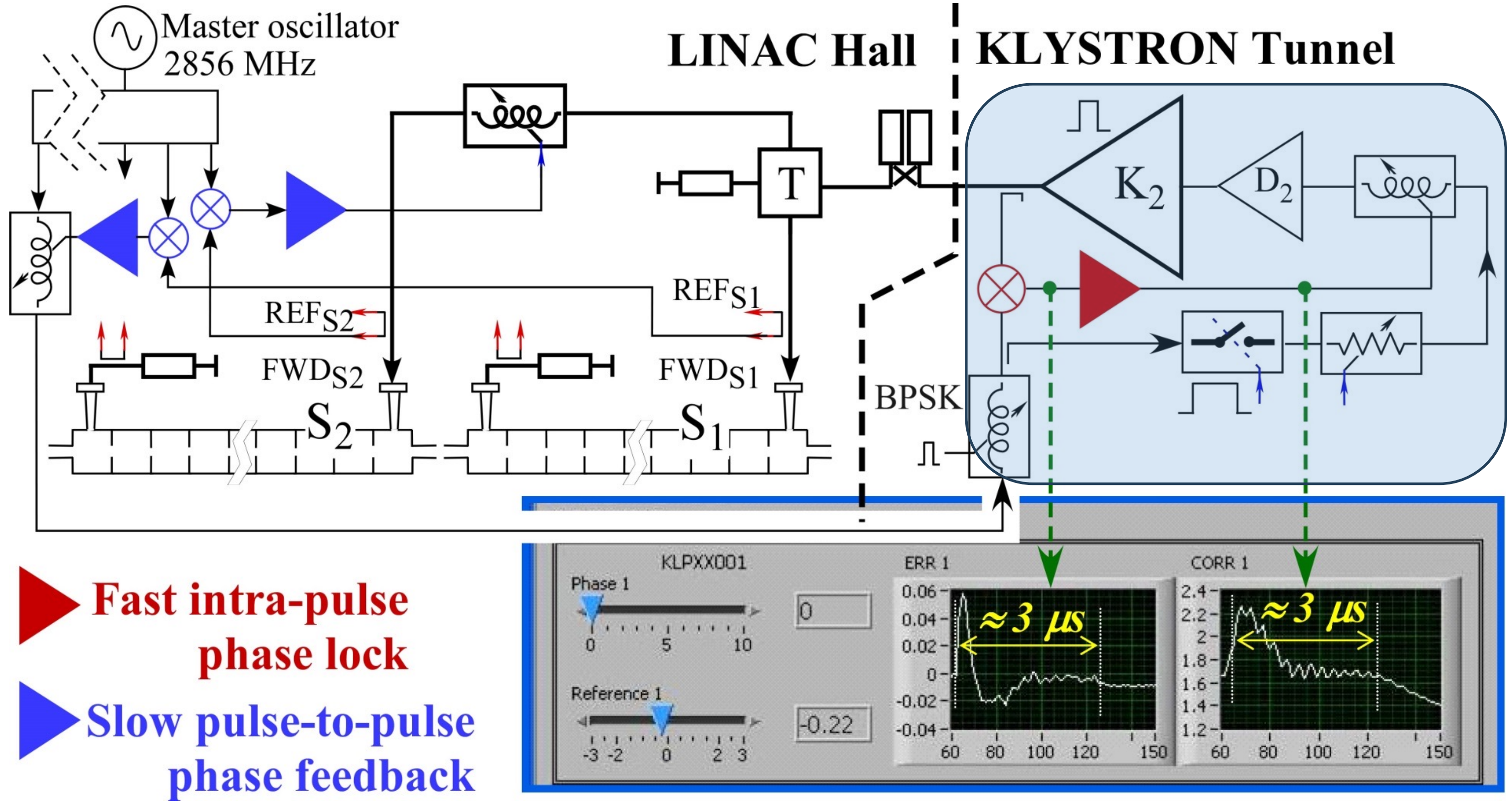
» <u>Back end:</u>

- I/Q differential VM
- output BW >40 MHz, **added jitter <10 fs**
- PSI upgraded its LLRF systems to a new architecture → support and spare parts no longer availabile



First implementation of fast-phase feedback at SPARC_LAB

- HV jitter of pulsed modulators directly affects the phase jitter of the klystron output RF signal
- The phase noise introduced at the RF power generation level can be reduced by phase locking the klystron output to the RF reference with an analog loop
- Same concept as phase loops in CW machines
- Very short time available to reach steady state (≈ 1 μs); wideband loop transfer function (≈ 1 MHz required)



SPARC_LAB Klystron 2 RF block diagram

First implementation of fast-phase feedback at SPARC_LAB

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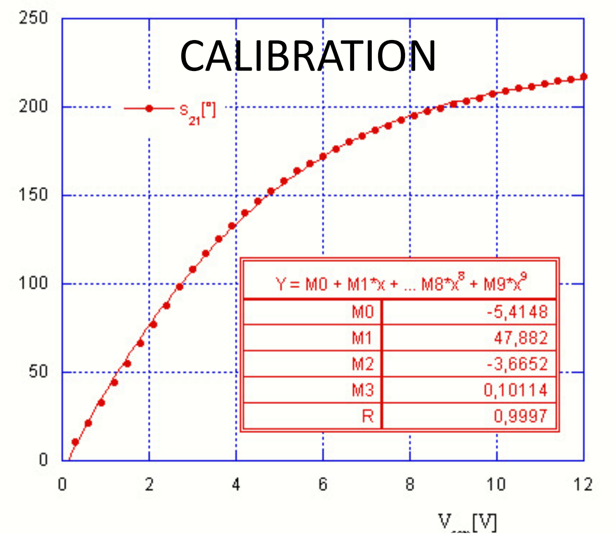
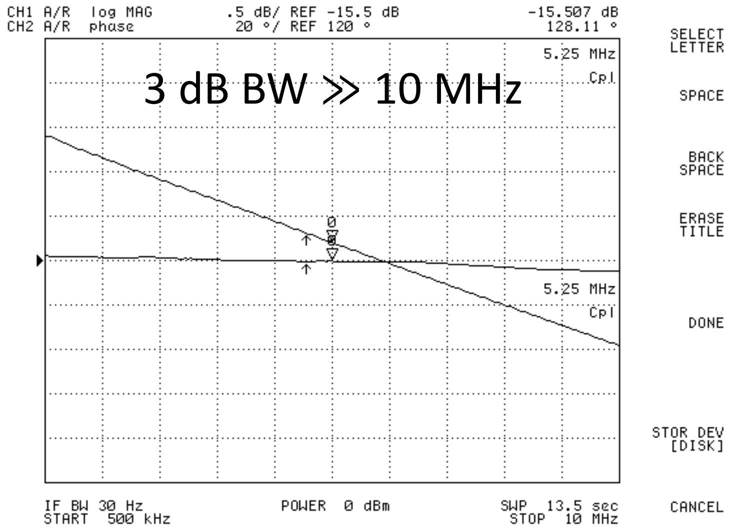
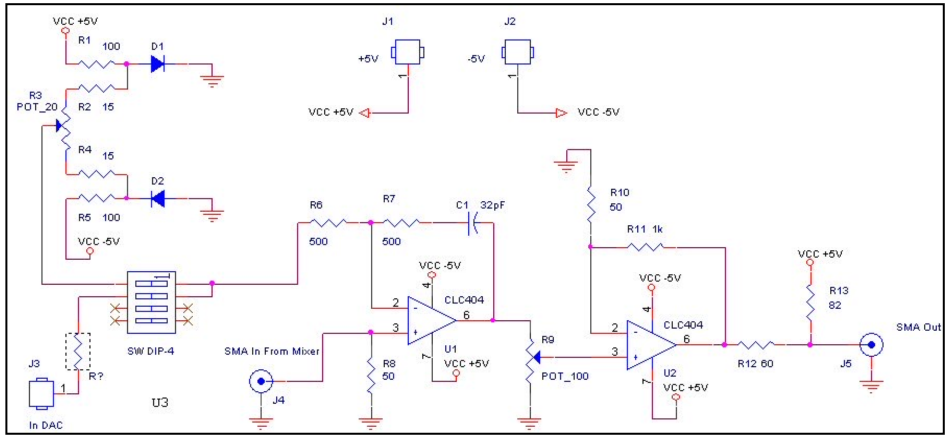
Actuator: PULSAR ST-G9-411 Phase Shifter

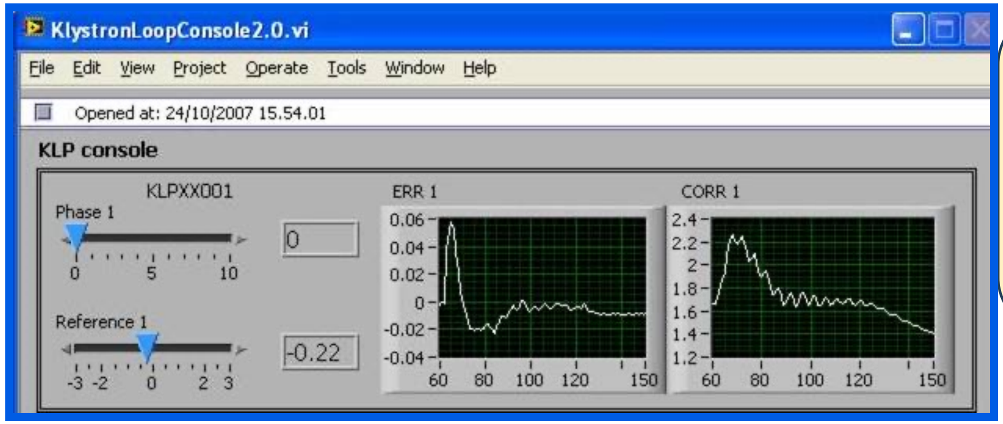




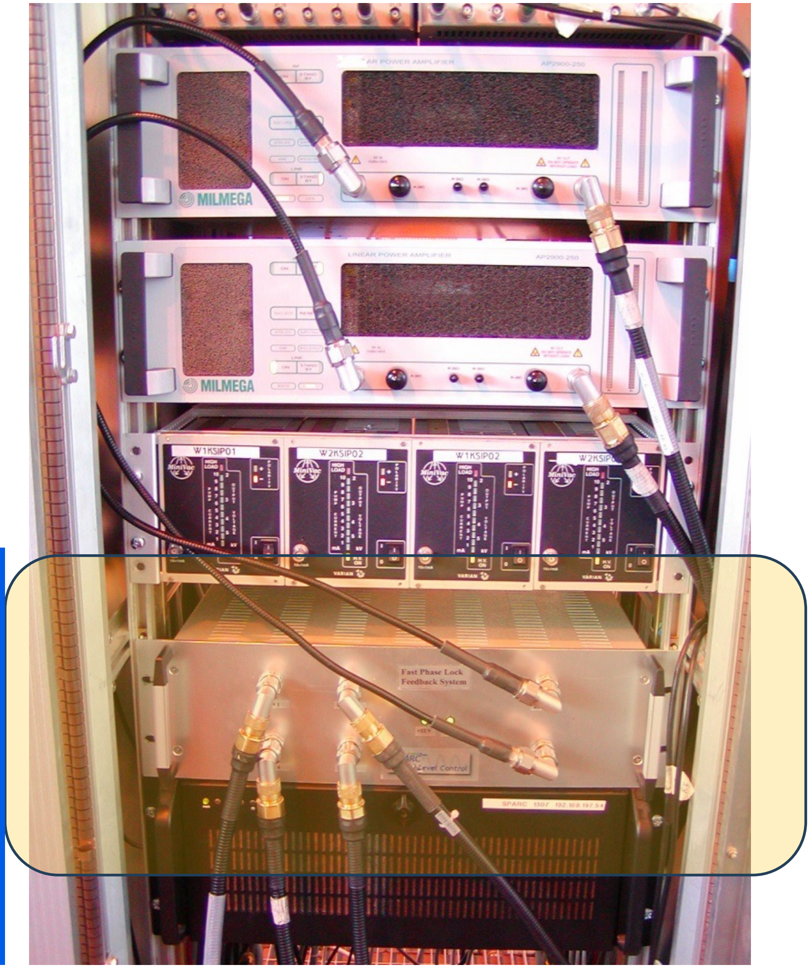
Error amplifier



Intra-pulse feedback control panel



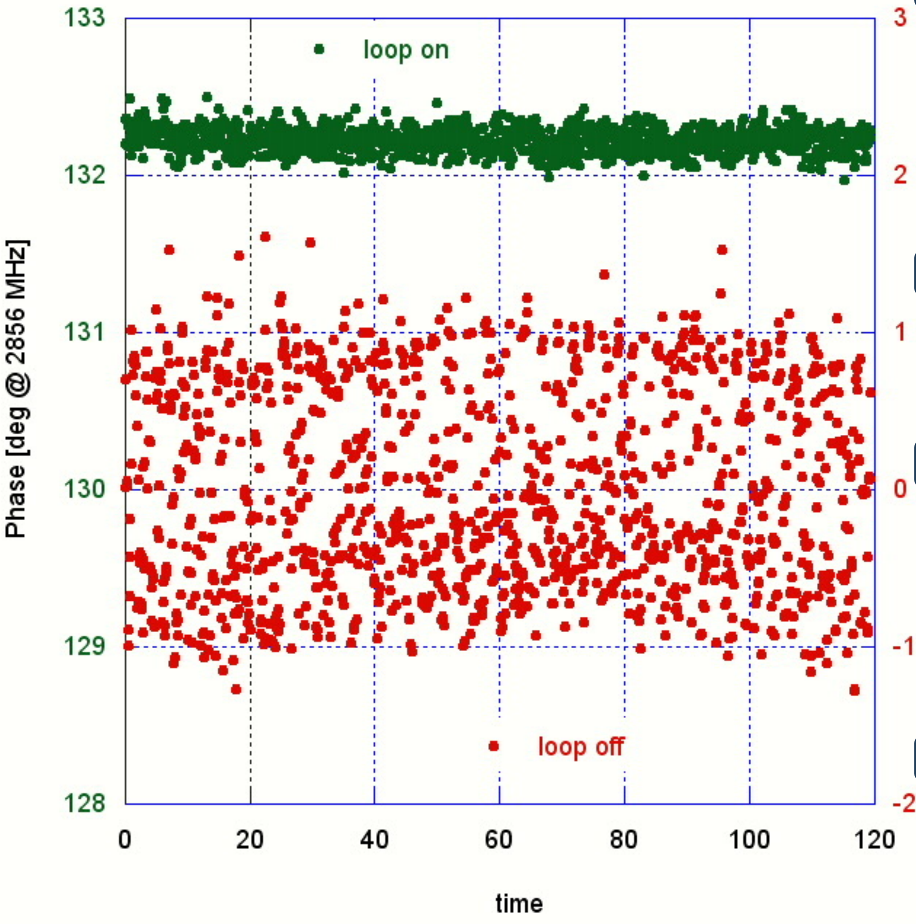
Klystron loop electronics installed at SPARC_LAB in the LLRF rack in the modulator hall



Klystron loop v1.0 performance

First results after intra-pulse feedack deployment in 2008

Almost 1 order of magnitude phase jitter compression!

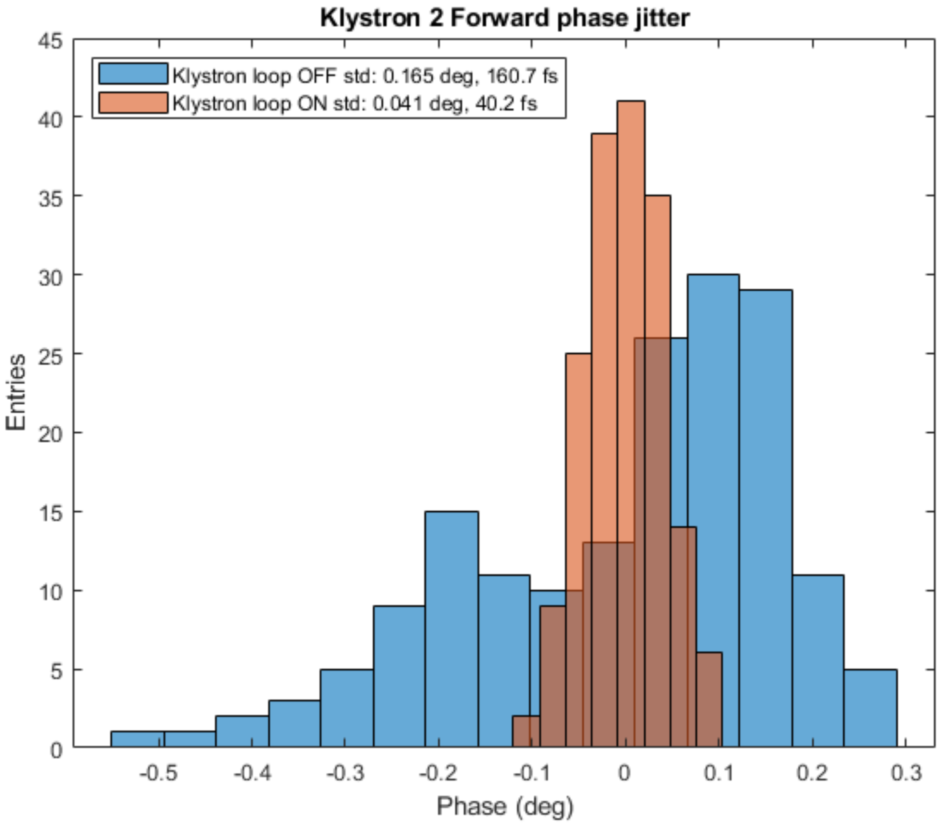


LOOP ON	
Minimum	131.97
Maximum	132.5
Points	1196
Mean	132.21993
Median	132.22
RMS	132.21996
Std Deviation	**0.077561417**
Variance	0.0060157733
Std Error	0.0022427463
Skewness	0.070226863

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

Recent measurements with low noise front-end electronics and after modulator upgrade:

RF phase jitter of 0.041 deg RMS*



*the performance is ≈2 times worse after 180 deg phase jump of BPSK

Klystron loop v2.0 motivation

- The actual RF phase stability is not sufficient for a stable and repeatable acceleration with plasma: **< 10 fs RMS required***
- For this reason a new version of klystron loop has recently been realized and tested at LNF
- We decided to realize this upgrade on the C-band system:
  - Minimize the impact on the experimental activity at SPARC_LAB (C-band booster phase jitter has a lower impact on beam stability -> perform parasitic measurements during the experiments)
  - C-band power plant is based on a solid state modulator -> test if the «native» higher pulse stability could be combined with our intra-pulse feedback performance
  - The architecture of the LLRF system is such that upgrading the S-band klystron loop would have been much more difficult and time consuming
- If successful, this proof of principle could easily be extended to the S-band power plants (either «as they are» or after their upgrade to solid state in the next years)

*at least for the accelerating structure that performs the RF compression → **0.01 deg RMS** (S-band)

Klystron loop v2.0

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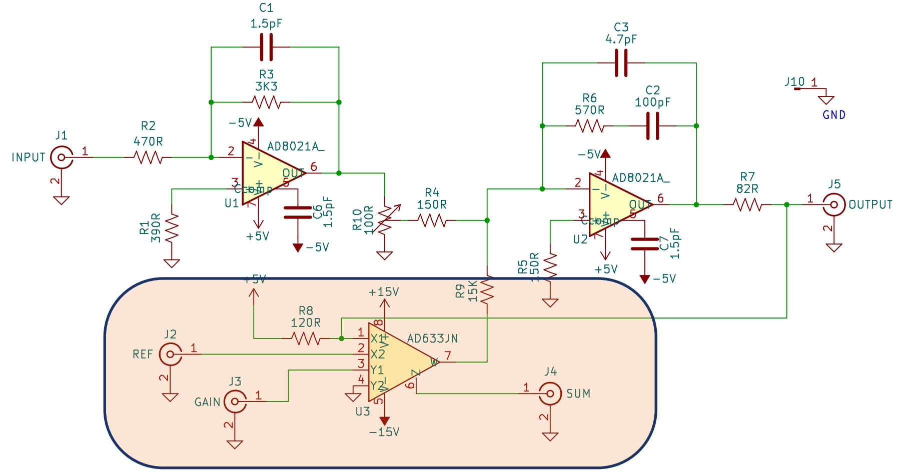
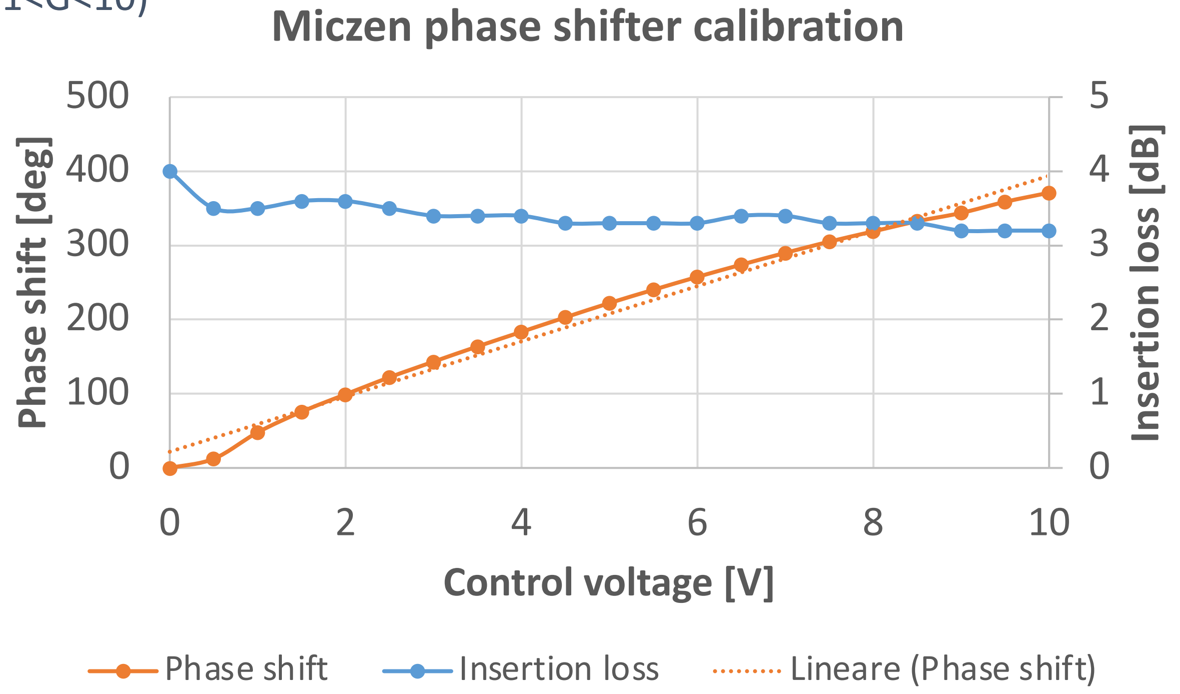
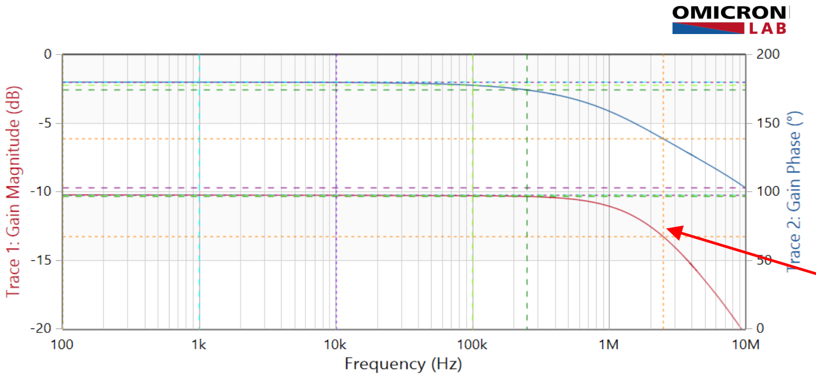
» A new version of error amplifier has been designed.

- A slow loop ($G_{slow}/G_{fast} \approx 10^{-3}$) has been added to keep the phase close to the desired level also when the RF pulse is OFF (avoiding strong phase modulations at the beginning of each RF pulse)
- High bandwidth operational amplifier: AD8021A (200 MHz BW for 1<G<10)





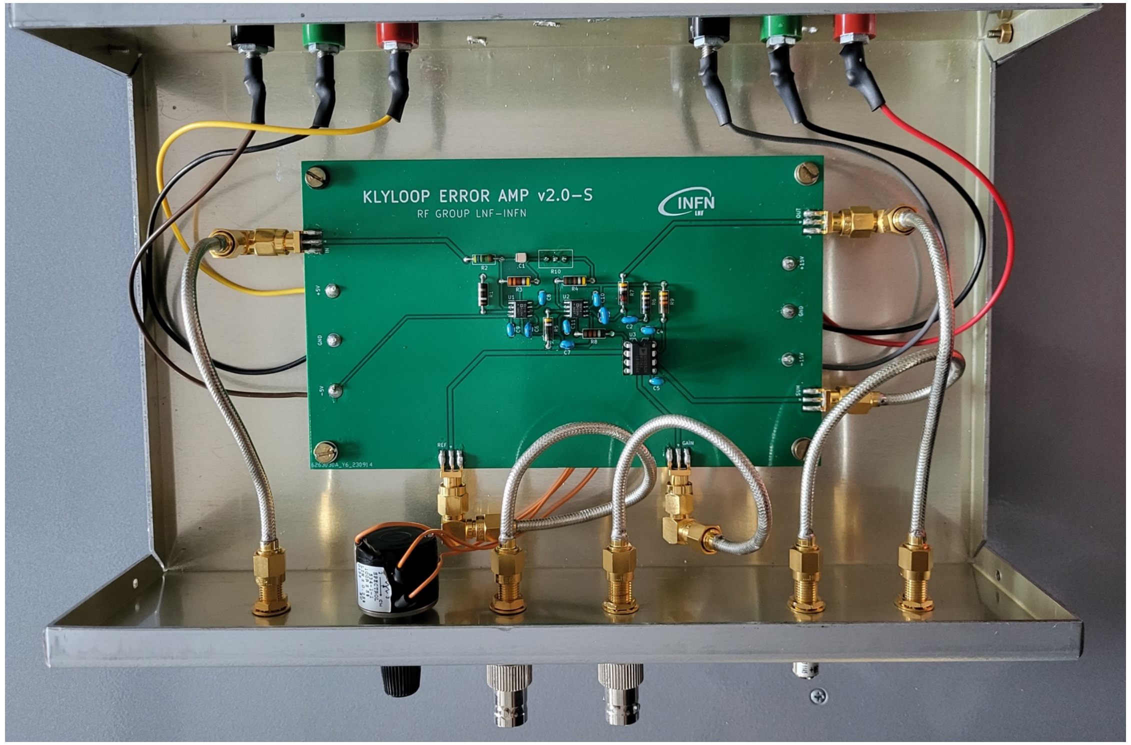
» Actuator: phase shifter Miczen VPH0506GA360Z

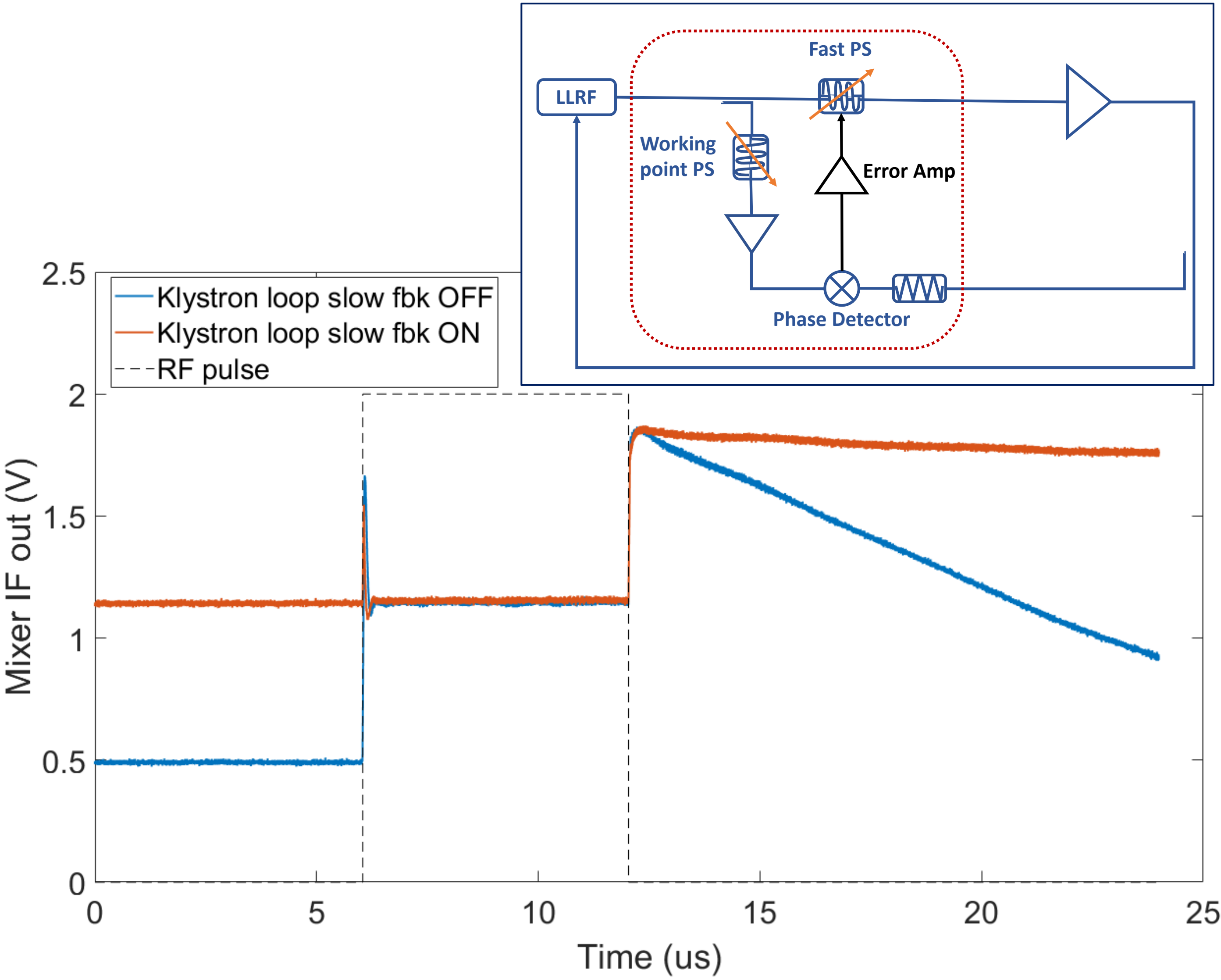


3dB BW 2.5 MHz, compensated with a zero in the error amplifier

Klystron loop v2.0: experimental setup

» The setup used for the evaluation of the intra-pulse feedback is similar to the one already in operation for the S-band





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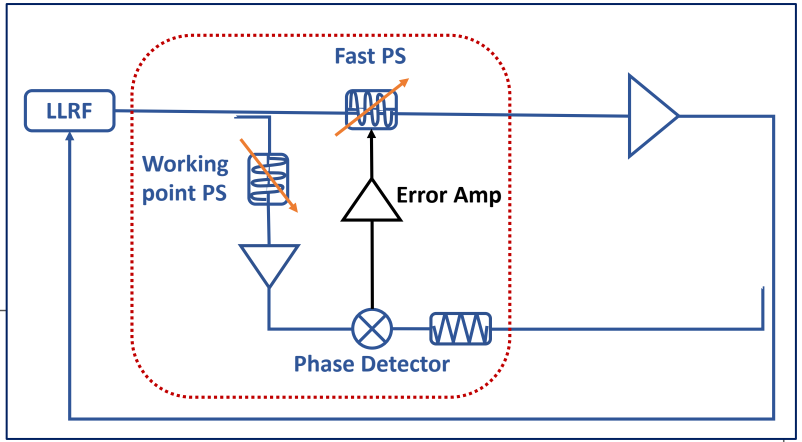
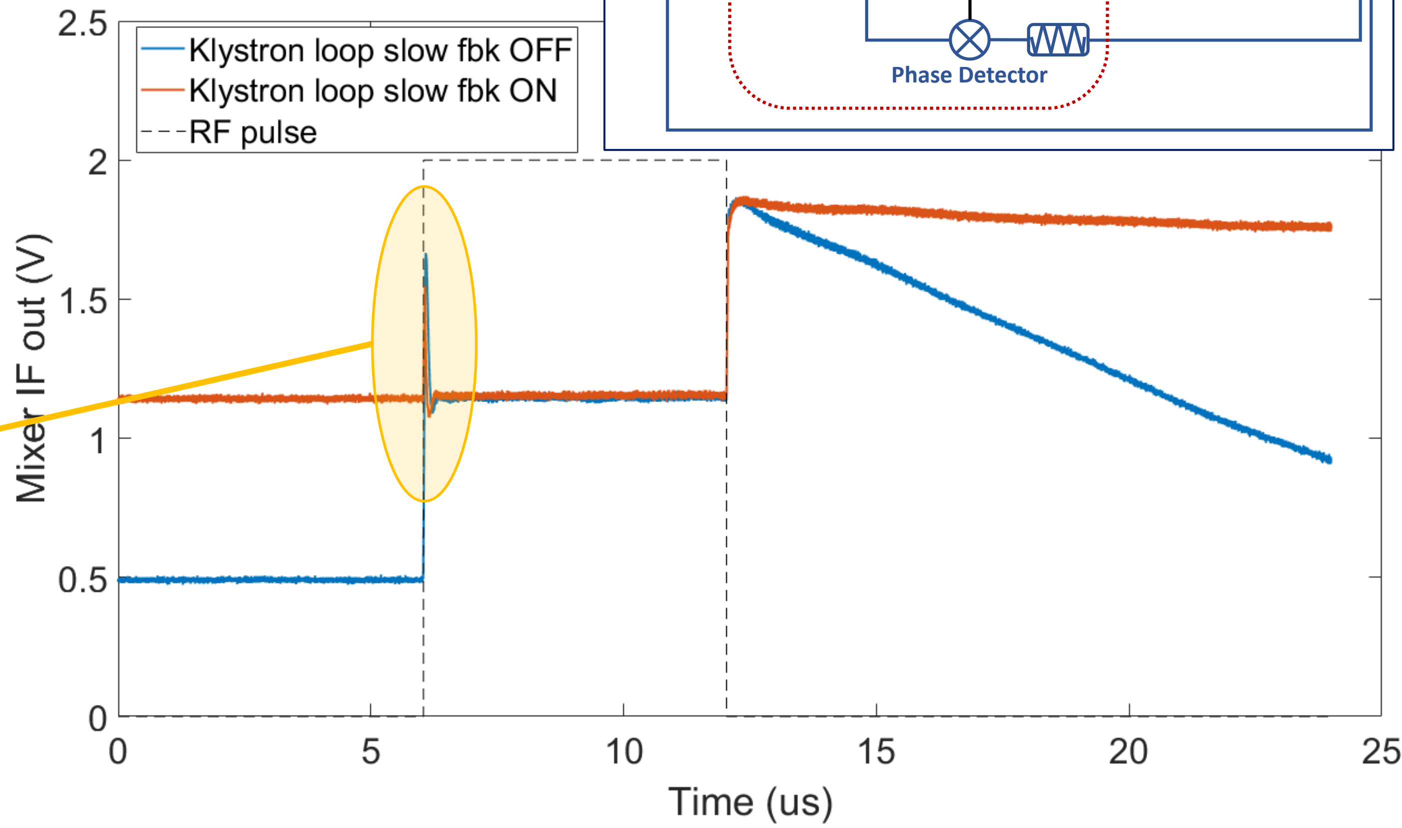
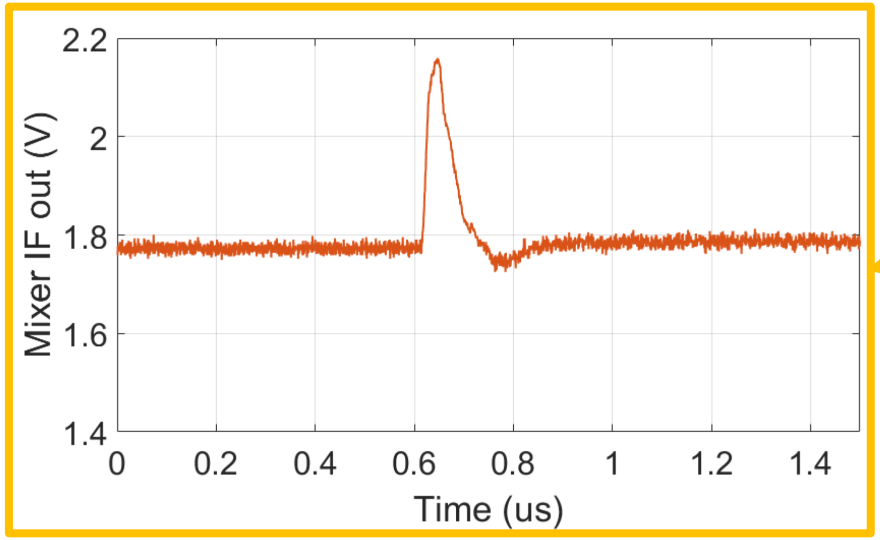
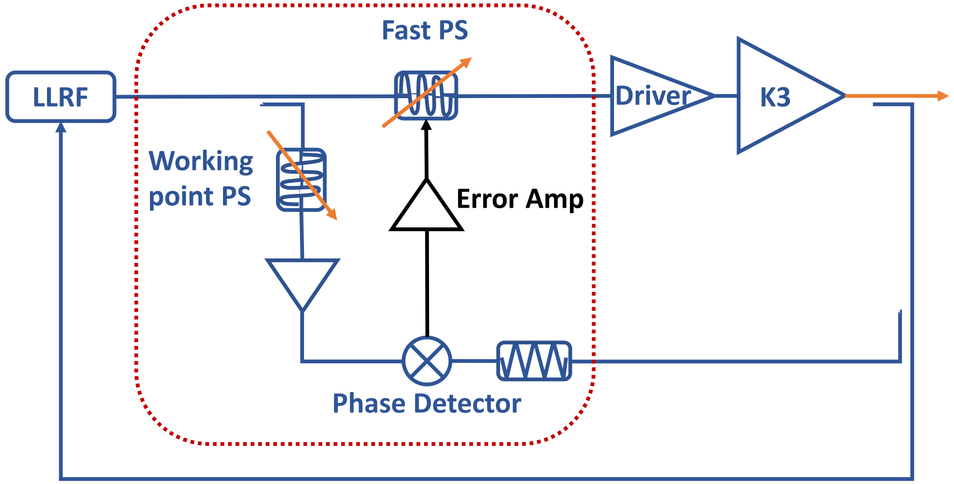




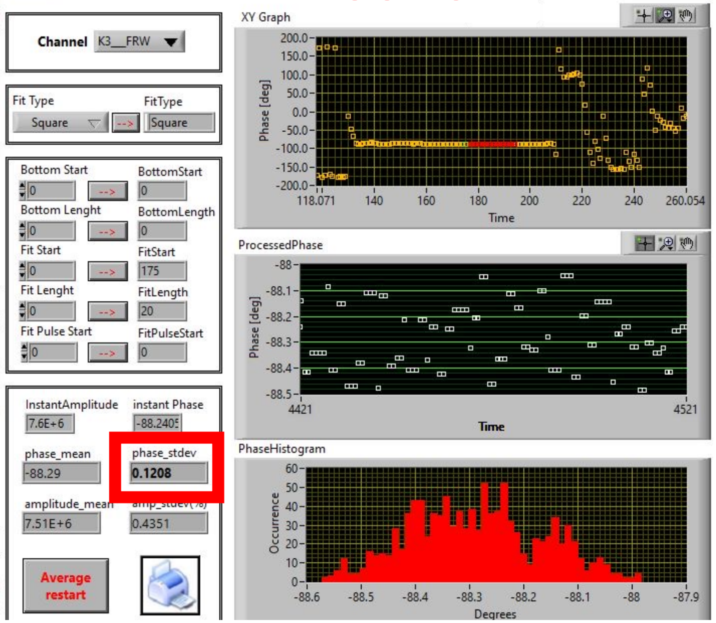


Klystron loop v2.0: experimental setup

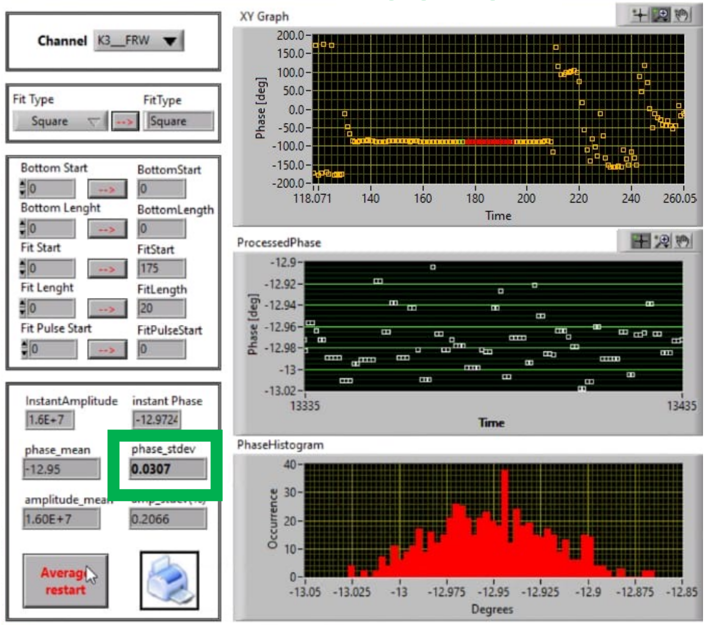
- Due to a late restart of the machine and some HW faults, the final error amplifier has not been tested yet at SPARC_LAB
- Some preliminary measurements done with a prototype (**without the slow loop**) show nice results, but there are still some open points to be addressed (and hopefully some more fs to gain…)



LOOP OFF



LOOP ON



OPEN POINTS:

- Klystron response not well modelized in lab tests
- Excessive delay added in the measurement
- Frequency response of fast phase shifter
- EM/ground noise perturbing the measurement
- Test the functionality of the slow loop

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**

Conclusions

- Stable plasma acceleration requires RF plants stability beyond the current state of the art (**< 10 fs RMS**)

- At SPARC_LAB a fast intra-pulse phase feedback has been successfully tested, installed and is in operation since 2008

- This system allowed to have a phase jitter of PFN driven RF sources of the order of **40 fs RMS**

- In order to meet the plasma acceleration requirements an upgrade of the feedback electronics has been performed

- Preliminary measurements on a prototype show promising results: phase jitter **reduction from 0.12 deg to 0.031 deg RMS**

- A huge R&D on this system is still required to solve the open points: a dedicated Ph.D. position MSCA (Eupraxia DN) will be opened soon…

Thank you for the attention!

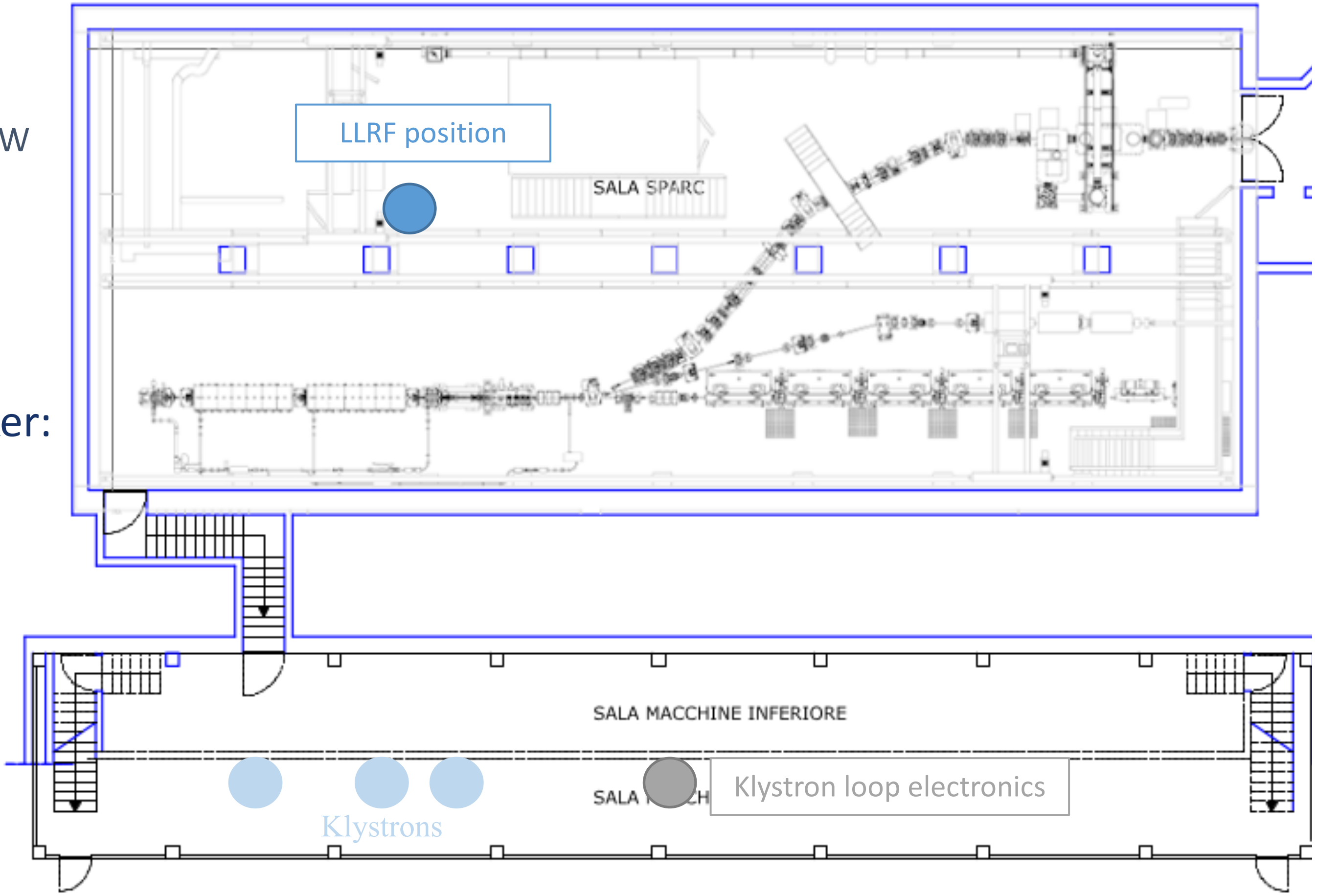
Spares

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



Experience with Libera LLRF systems at LNF

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

» Temperature stabilized LLRF front-end to compensate long-term thermal drifts (< 100 fs at 24 +/- 2 °C)

» Low noise front-end, high dynamic range (RF input from -10 up to 20 dBm)

» Required resolution: amplitude: 0.1 %; phase added jitter <10 fs

» Pulse-to-pulse amplitude and phase feedback on independent channels

» Arbitrary waveform pulse shaping

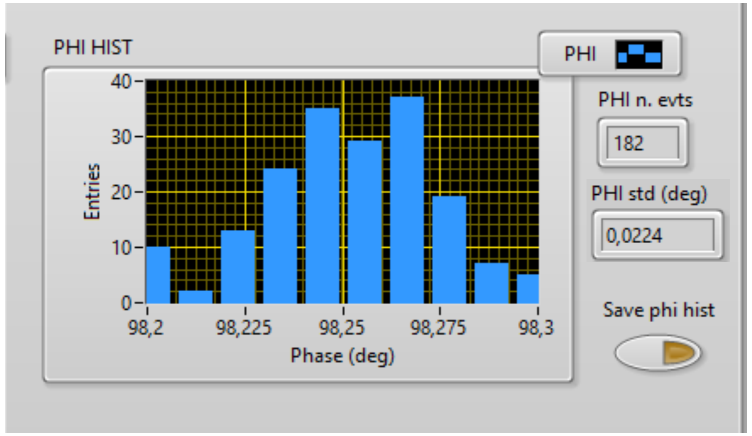
» Modular system (spare parts)

» Similar systems have been already procured from ITech for:
- ELI-NP project (13 systems, 3 S-band 10 C-band - calibrated, tested in lab but never installed in the facility)
- TEX (Test-stand for X-band) project (1 S-band system + up/down converter)

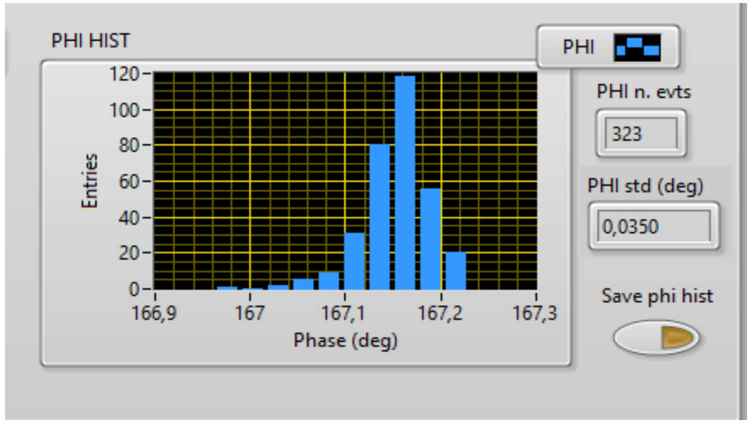
Experience with Libera LLRF systems at LNF

» Libera LLRF low noise front-end allowed to enhance the precision on the measured residual jitter at SPARC_LAB:

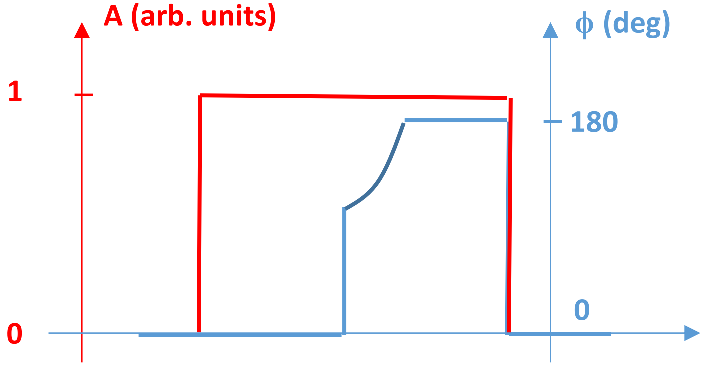
- RMO - Laser oscillator from 40 fs to 22 fs

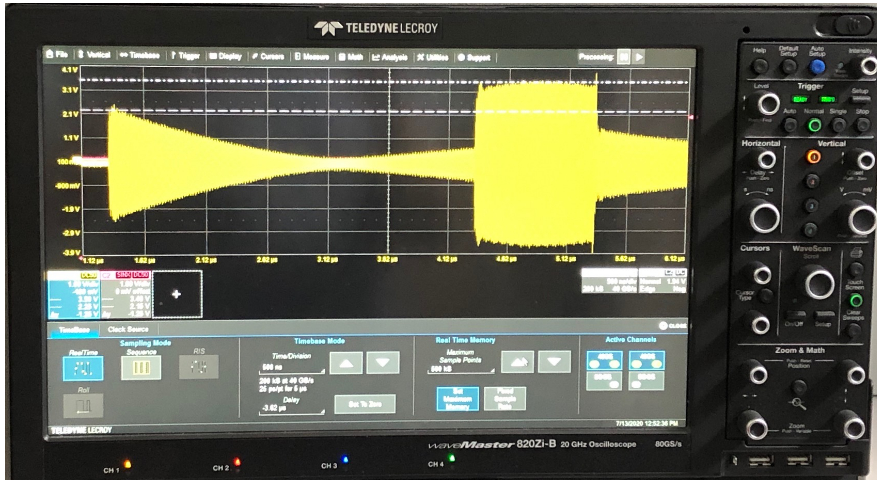


- RMO - K2 from 70 fs to 35-50 fs



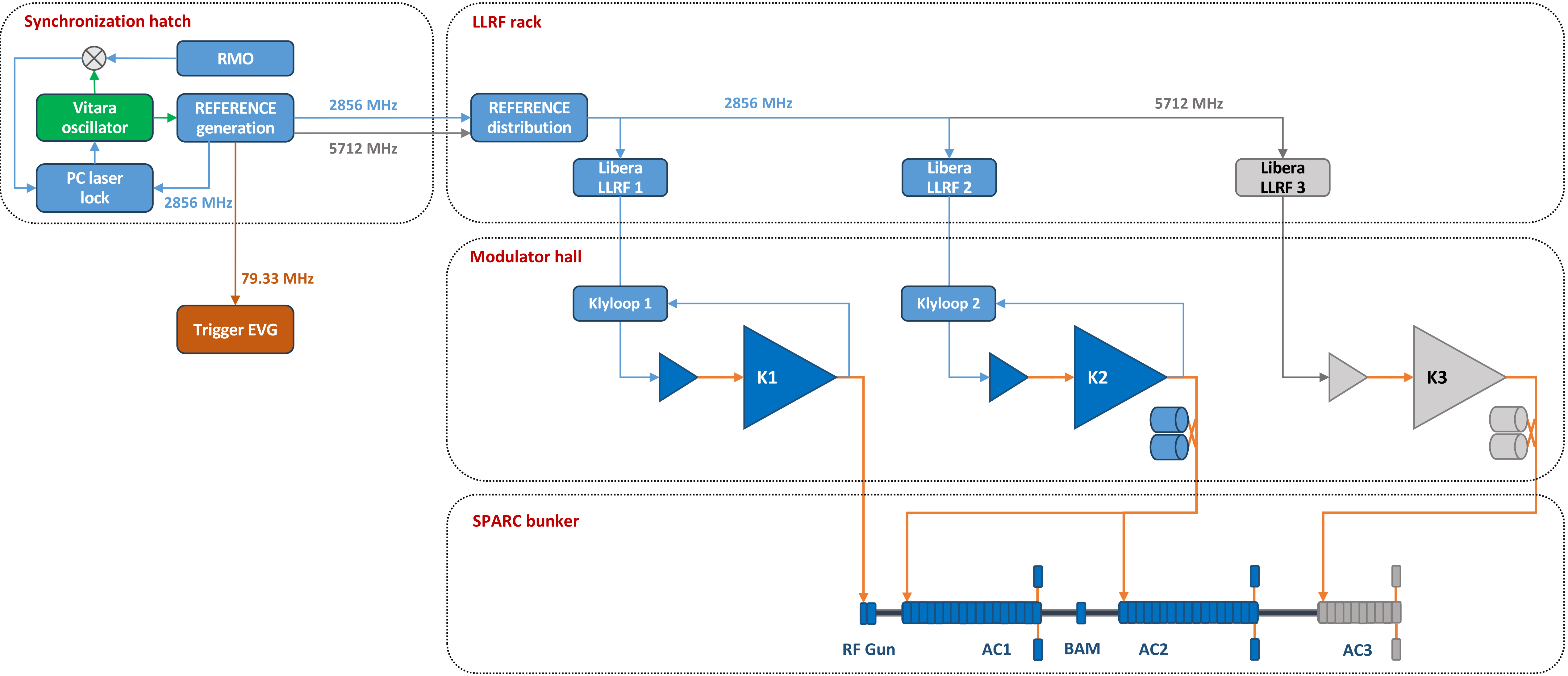
» SLED pulse shape optimization (at low RF power) by means of custom waveform mask (following PSI approach[1])





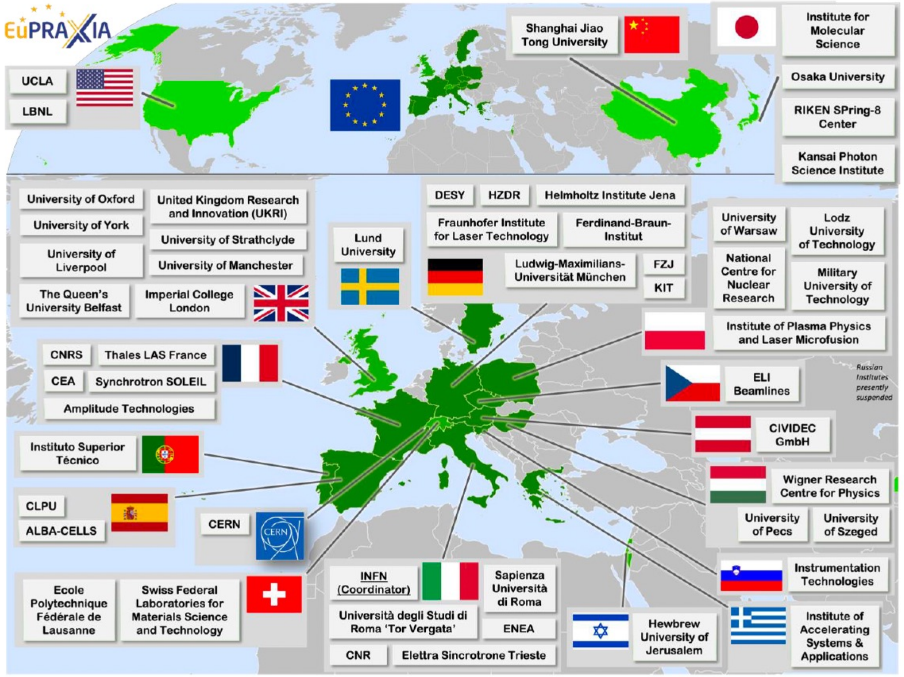
[1] A. Rezaeizadeh, et al.,in IEEE Transactions on Nuclear Science, vol. 63, no. 2, pp. 842-848, (2016)

SPARC_LAB future RF layout



Wide International Collaboration

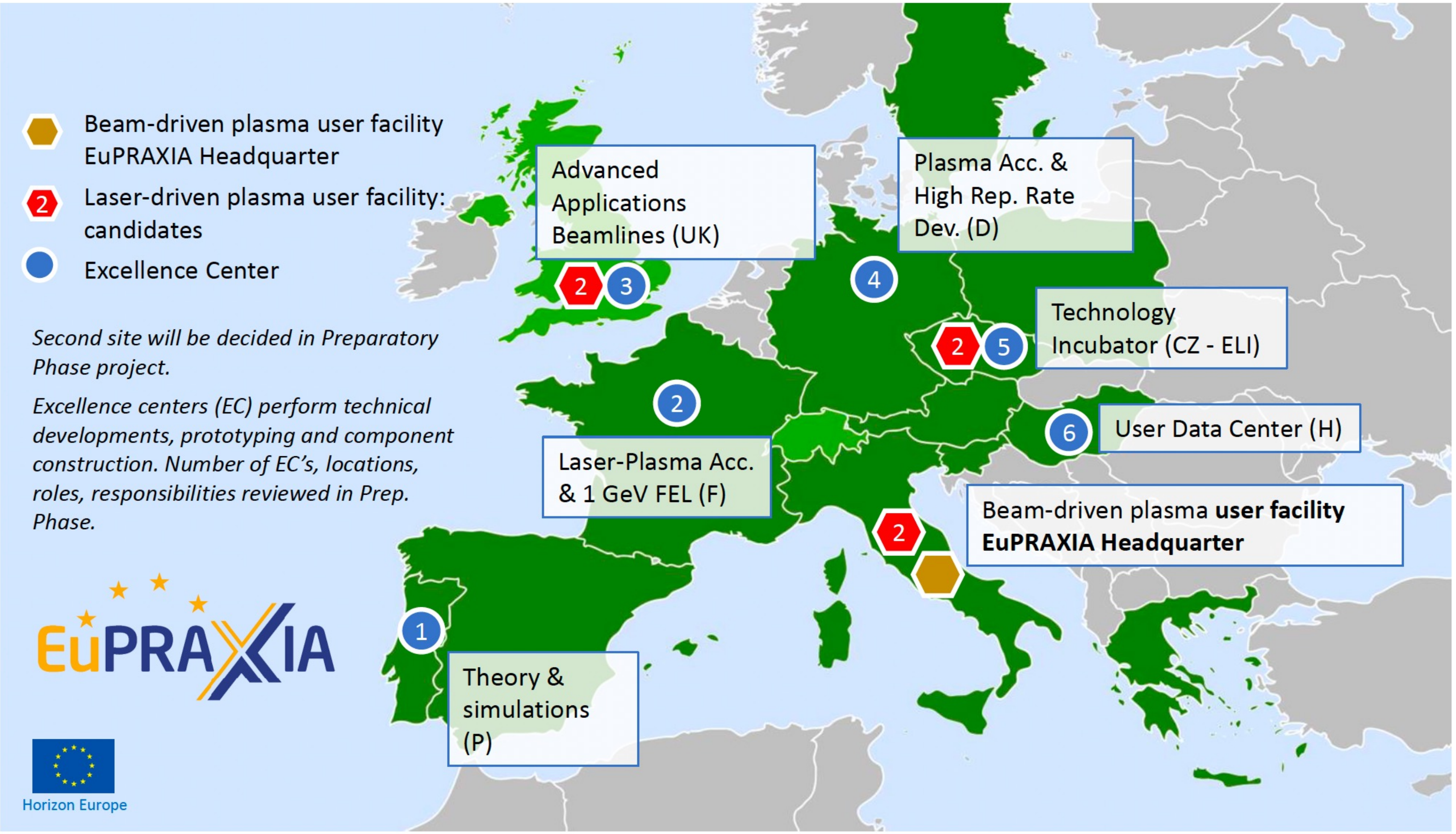
- The EuPRAXIA Consortium today: **54 institutes** from **18 countries** plus CERN
- Included in the **ESFRI** Road Map
- Efficient fund raising:
  - –**Preparatory Phase** consortium (funding EU, UK, Switzerland, in-kind)
  - –**Doctoral Network** (funding EU, UK, in-kind)
  - –**EuPRAXIA@SPARC_LAB** (Italy, in-kind)
  - –**EuAPS Project** (Next Generation EU)



EuPRAXIA

Distributed Research Infrastructure

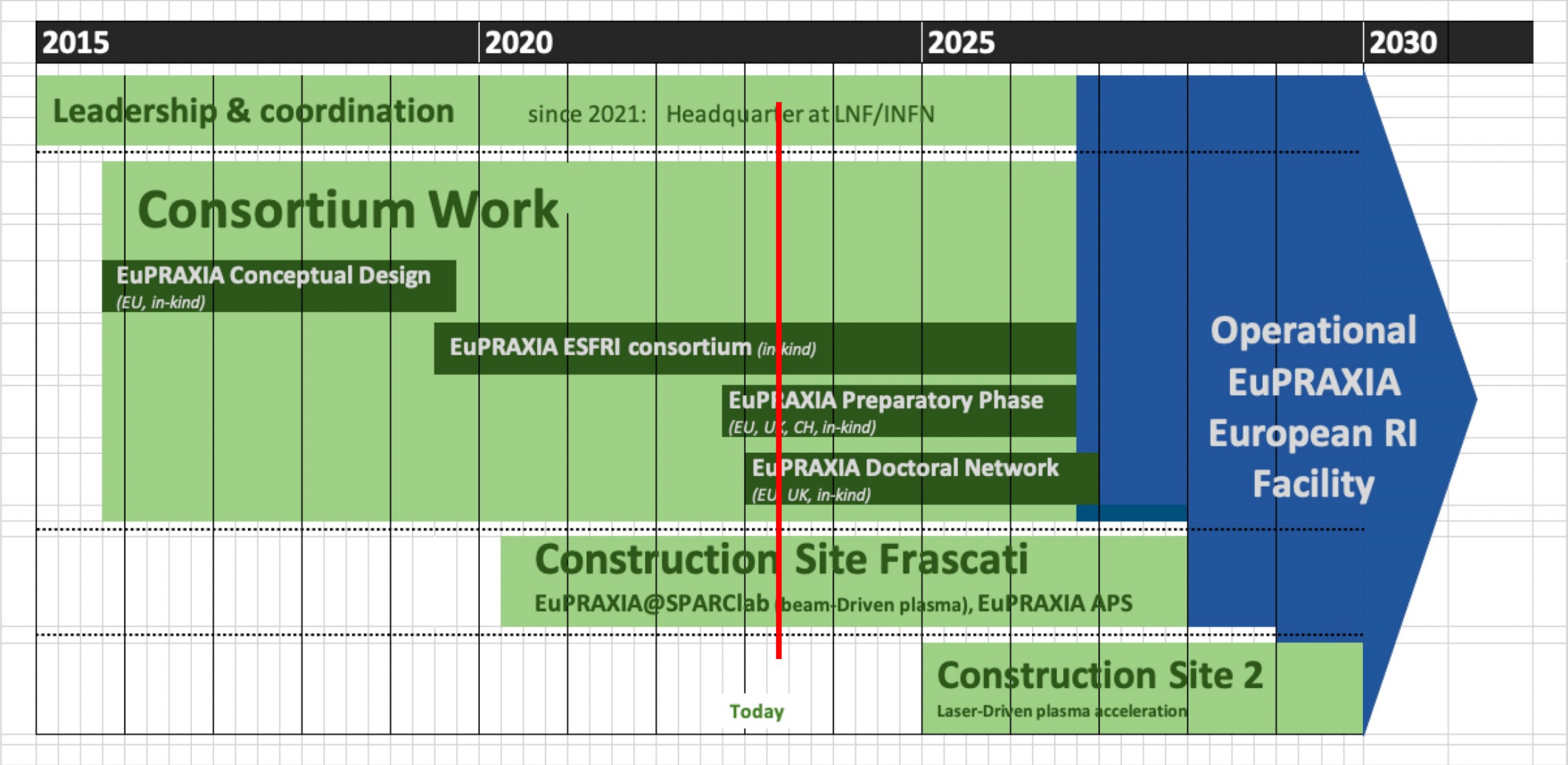
Funded by the European Union



Today`s status

- Excellence centers: several (6 – 10) assumed to be realized
- First site: EuPRAXIA@SPARC_LAB
- Second site: one to be selected
- Connect with WP´s to Horizon Europe and national funding lines

EuPRAXIA Project Timeline



Courtesy A. Falone

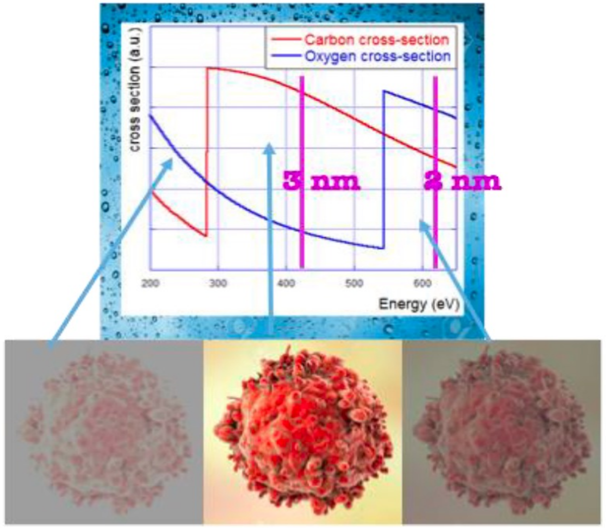
Expected SASE FEL performances

Funded by the European Union

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	$mm^2 mrad\ bw(0.1\%)$	$\mathbf{1\text{–}2 \times 10^{28}}$	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

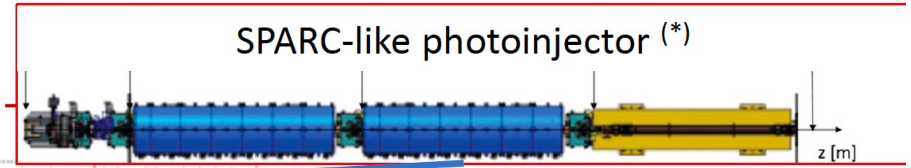
Courtesy F. Stellato (UniTov)

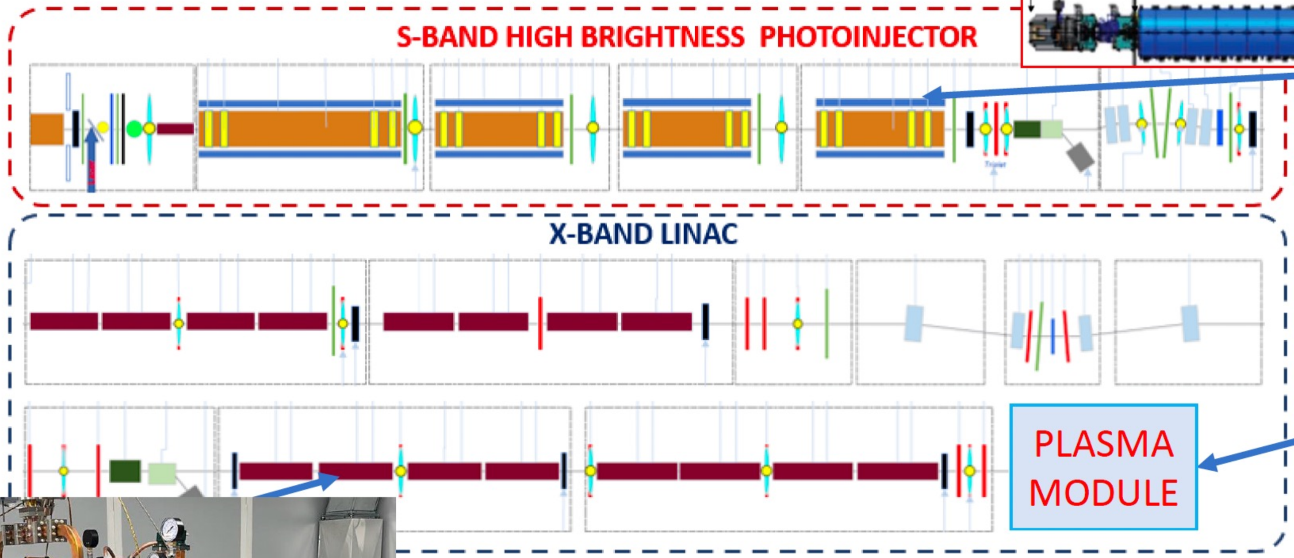
EuPRAXIA@SPARC_LAB: a high brightness PWFA

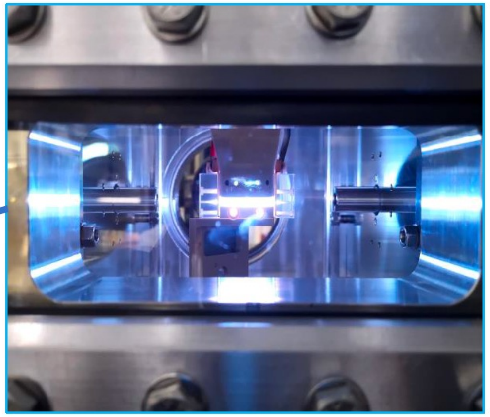
EuPRAXIA at SPARC_LAB

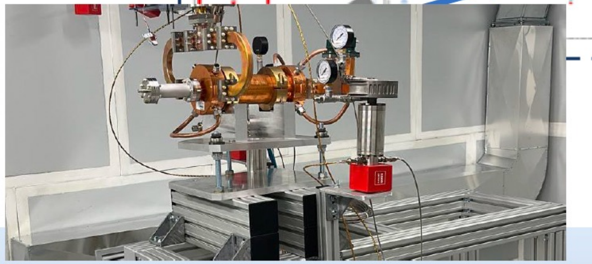
Funded by the European Union

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

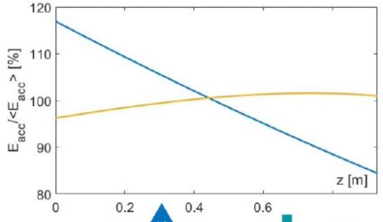


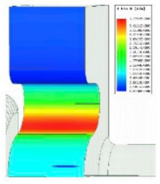


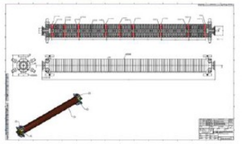


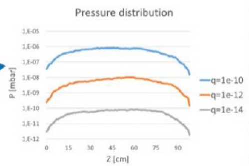


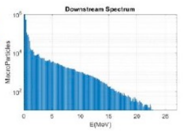
EuPRAXIA World`s Most Compact RF Linac: X Band





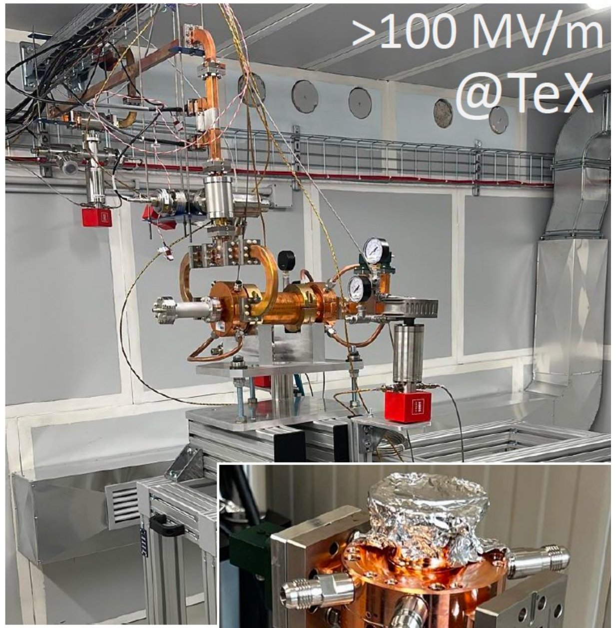


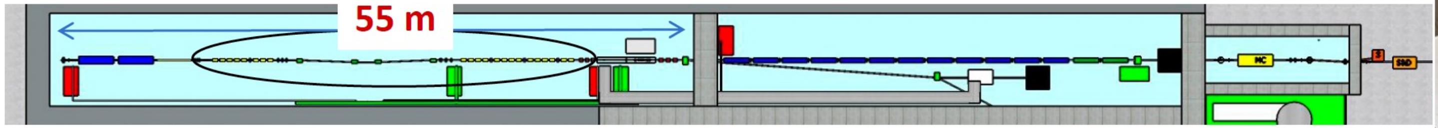




1. **E.m. design**: *done*
2. **Thermo-mechanical analysis**: *done*
3. **Mechanical design**: *done*
4. **Vacuum calculations**: *done*
5. **Dark current simulations**: *done*
6. **Waveguide distribution simulation with attenuation calculations**: *done*

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

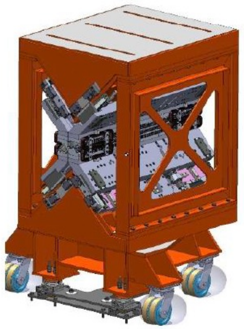
EuPRAXIA

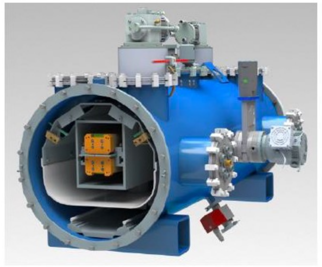
Radiation Generation: FEL

Two FEL lines:

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

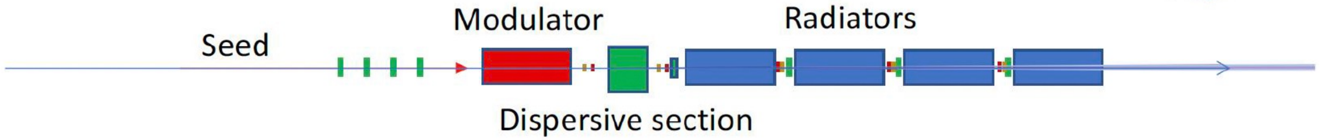
SASE FEL: 10 UM Modules, 2 m each – 60 cm intraundulator sections.
Two technologies under study: Apple-X PMU (baseline) and planar SCU.
Prototyping in progress





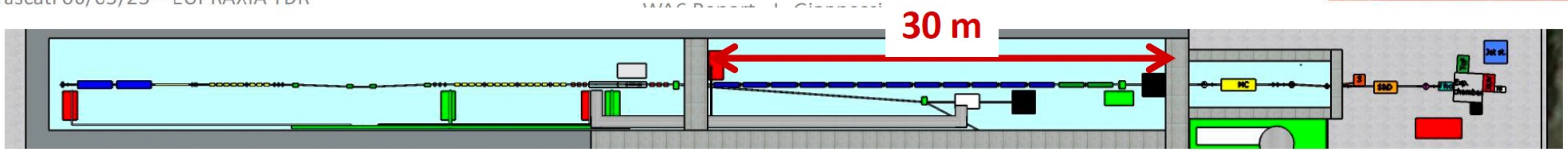
First *SABINA* undulator in FRASCATI March 29, 2023

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