EuPRAXIA@SPARC_LAB

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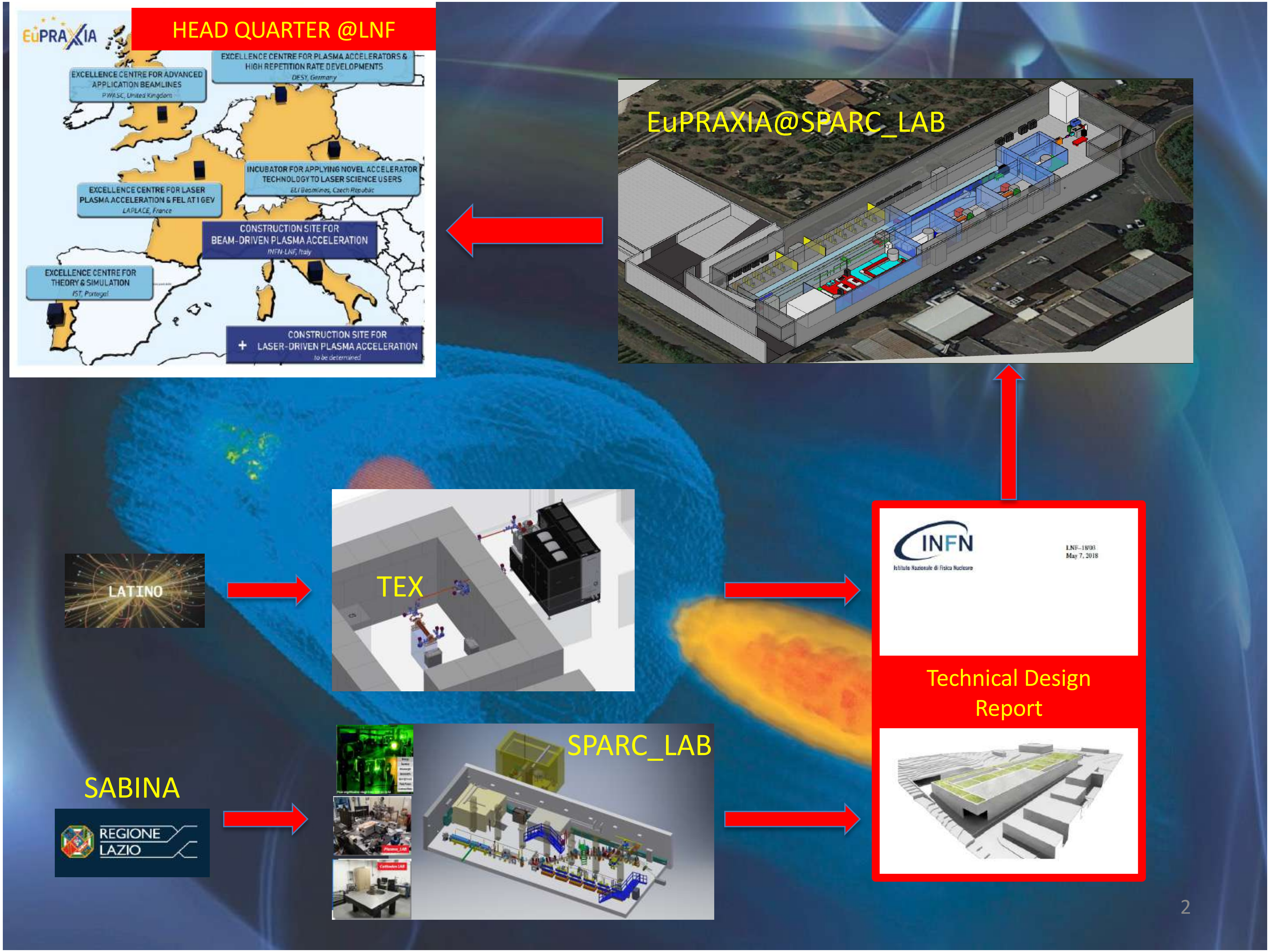
EuPRAXIA SPARC LAB

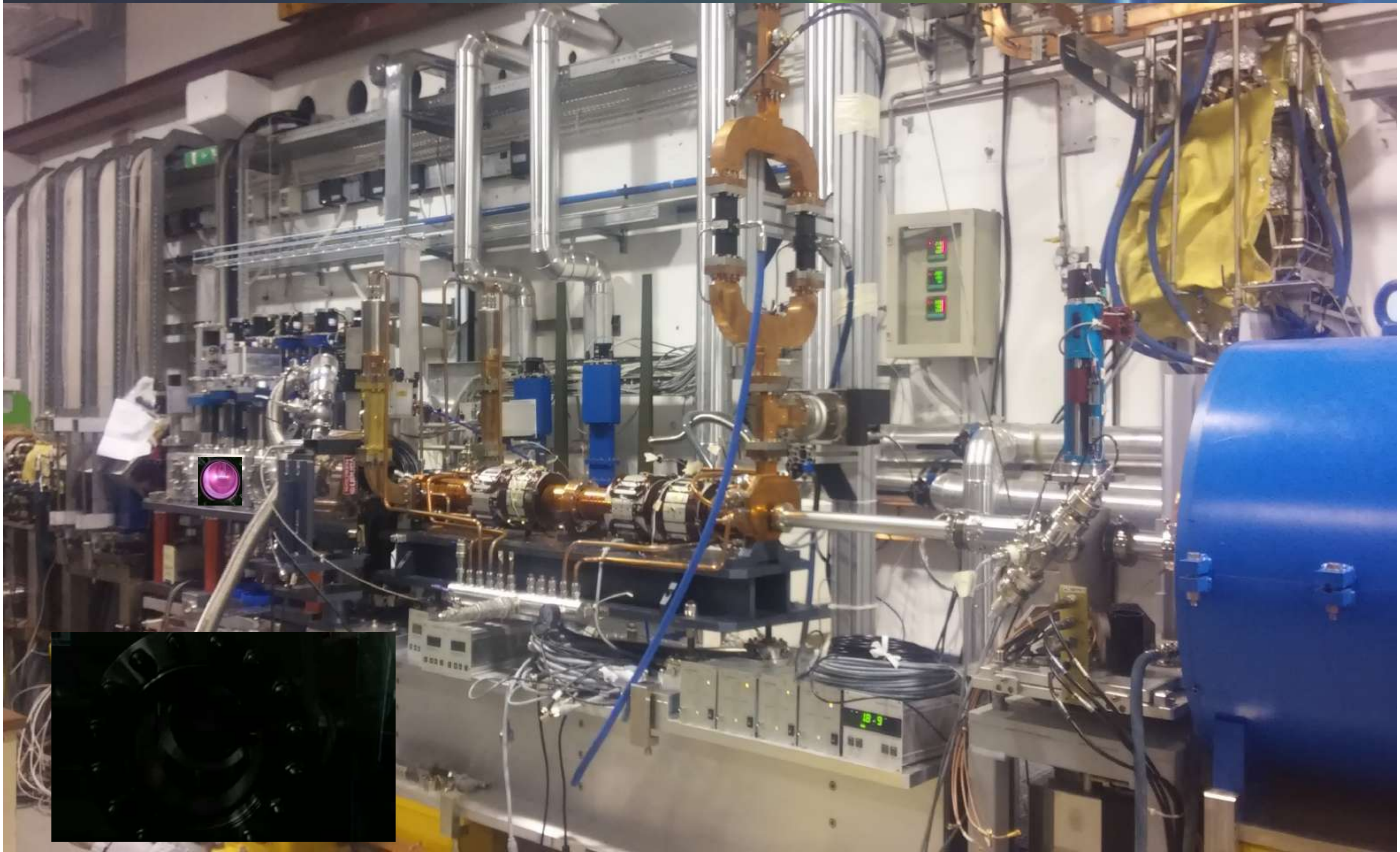
Snowmass “2021 AF1 community meeting”, November 23, 2021

INFN
Istituto Nazionale di Fisica Nucleare



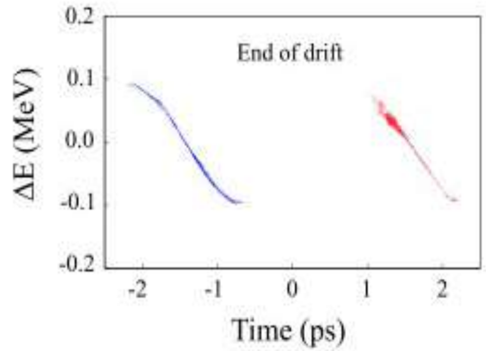
HEAD QUARTER @LNF
EuPRAXIA
EXCELLENCE CENTRE FOR PLASMA ACCELERATORS & HIGH REPETITION RATE DEVELOPMENTS
DESY, Germany
EXCELLENCE CENTRE FOR ADVANCED APPLICATION BEAMLINES
PWASC, United Kingdom
INCUBATOR FOR APPLYING NOVEL ACCELERATOR TECHNOLOGY TO LASER SCIENCE USERS
ELI Beamlines, Czech Republic
EXCELLENCE CENTRE FOR LASER PLASMA ACCELERATION & FEL AT 1 GEV
LAPLACE, France
CONSTRUCTION SITE FOR BEAM-DRIVEN PLASMA ACCELERATION
INFN-LNF, Italy
EXCELLENCE CENTRE FOR THEORY & SIMULATION
IST, Portugal
CONSTRUCTION SITE FOR LASER-DRIVEN PLASMA ACCELERATION
to be determined
EuPRAXIA@SPARC_LAB
LATINO
TEX
INFN
Istituto Nazionale di Fisica Nucleare
LNF–18/03
May 7, 2018
Technical Design Report
SABINA
REGIONE LAZIO
SPARC_LAB

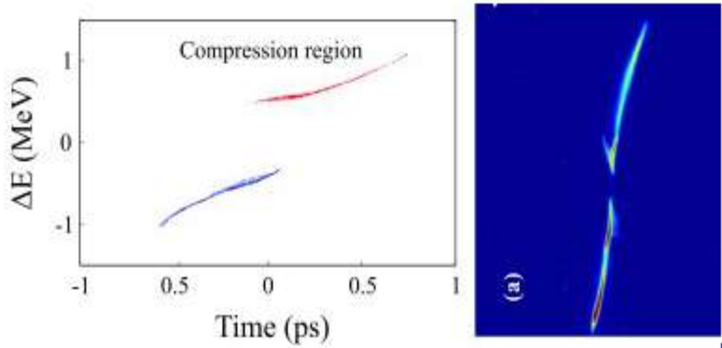
PWFA vacuum chamber at SPARC_LAB

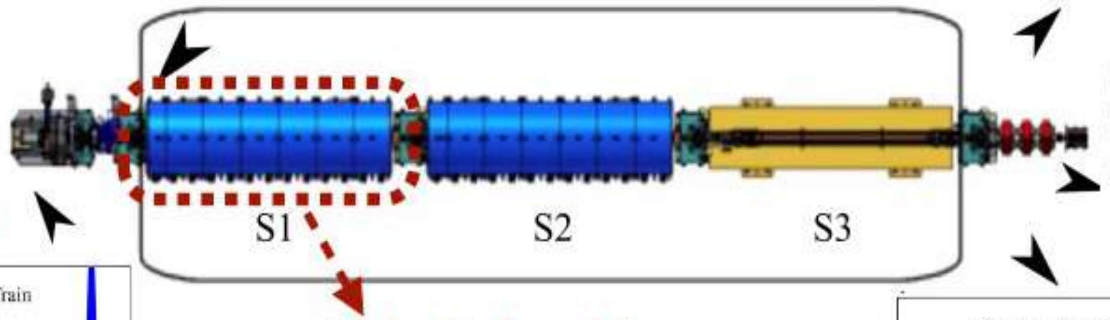


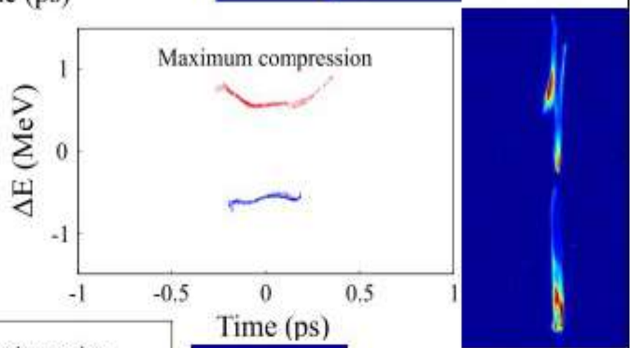
Generation of multi-bunch trains

Sub-relativistic electrons ($\beta_c < 1$) injected into a traveling wave cavity at zero crossing move more slowly than the RF wave ($\beta_{RF} \sim 1$). The electron bunch slips back to an accelerating phase and becomes simultaneously accelerated and compressed.

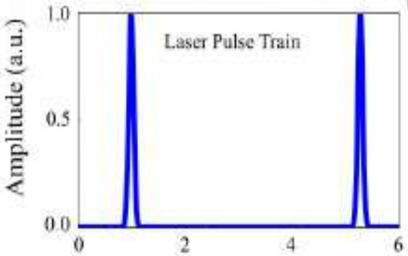






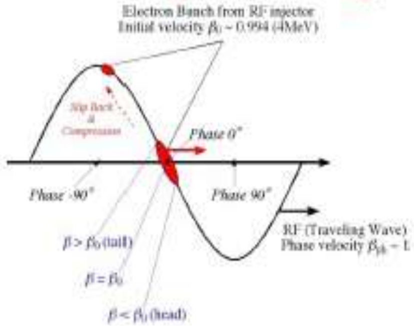


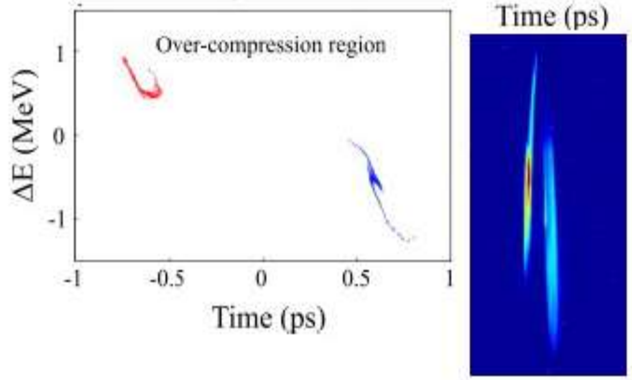
Comb-like laser



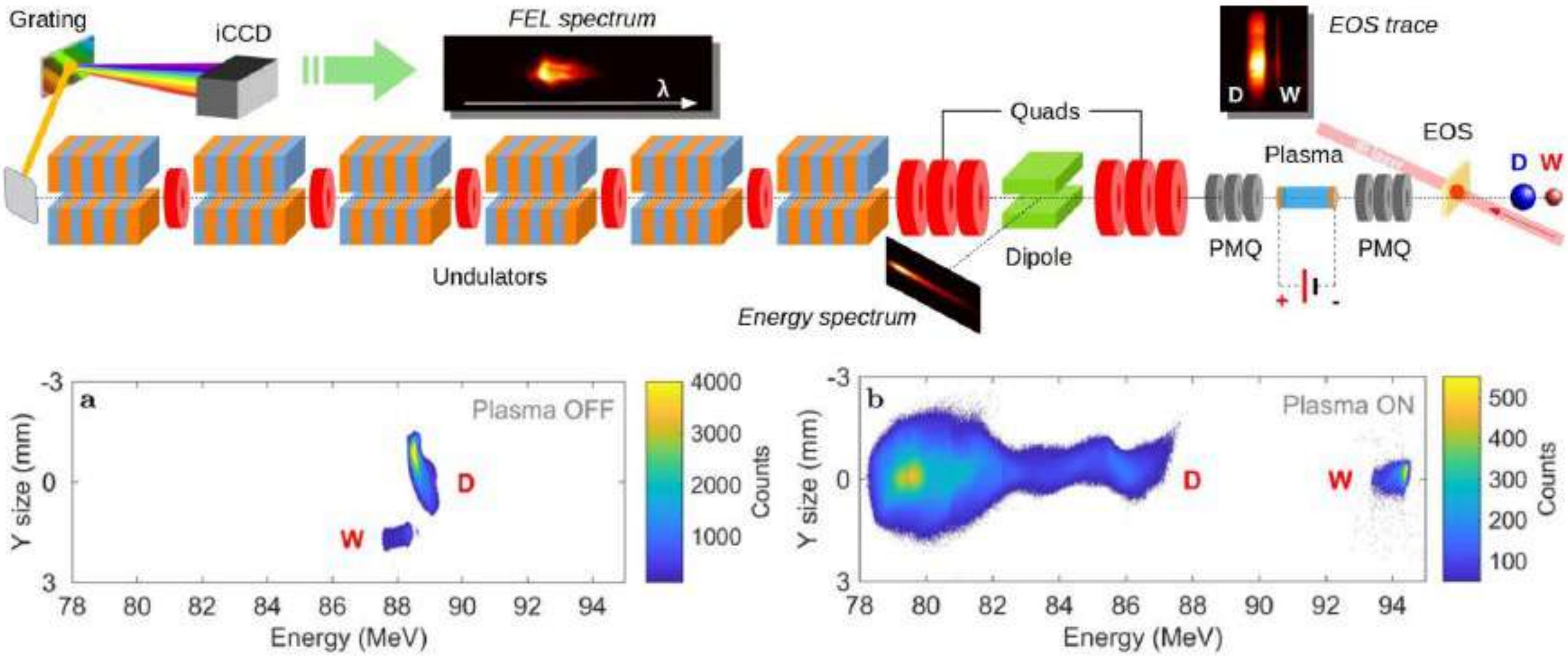
$$\Delta\phi_\infty = \frac{\sin\phi_0}{\sin\phi_\infty}\Delta\phi_0 + \frac{1}{2\alpha\gamma_0^2\sin\phi_\infty}\Delta\gamma_0 + \frac{1}{2}\left[\frac{\cos\phi_0}{\sin\phi_\infty} - \frac{\cos\phi_\infty\sin^2\phi_0}{\sin^3\phi_\infty}\right](\Delta\phi_0)^2.$$

Velocity bunching





Energy Spread Compensation at SPARC_LAB



Plasma density set to 1.6x10^{15} cm^{-3}

Train configuration:

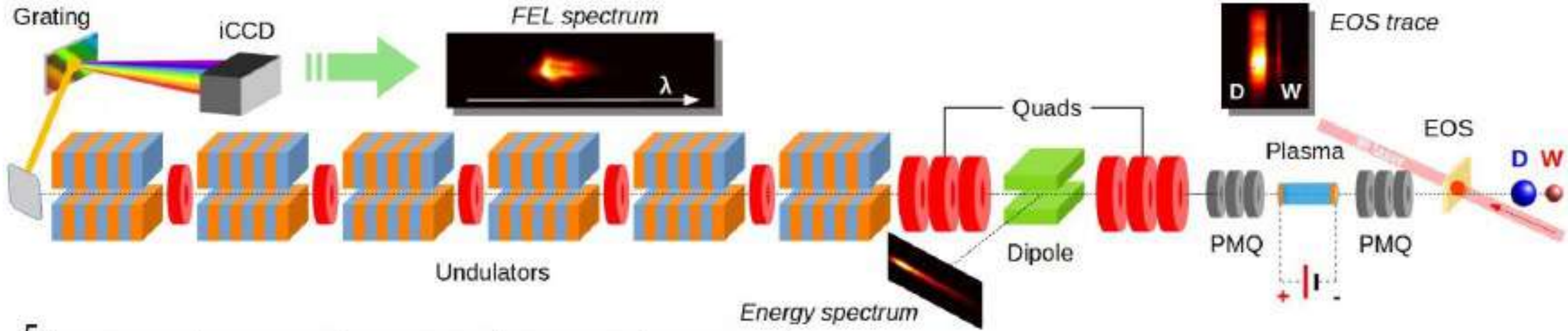
- 200 pC driver + 20 pC witness
- Separation between bunches ~1 ps
- Driver duration ~230 fs, witness ~30 fs

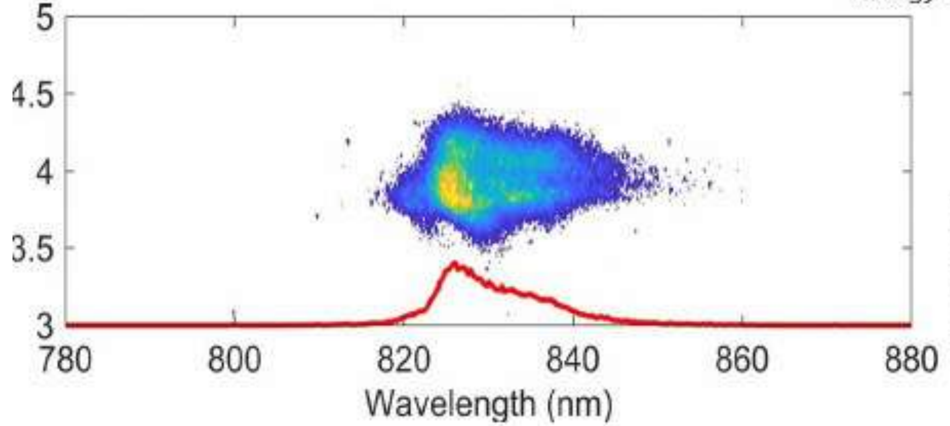
Witness after the plasma:

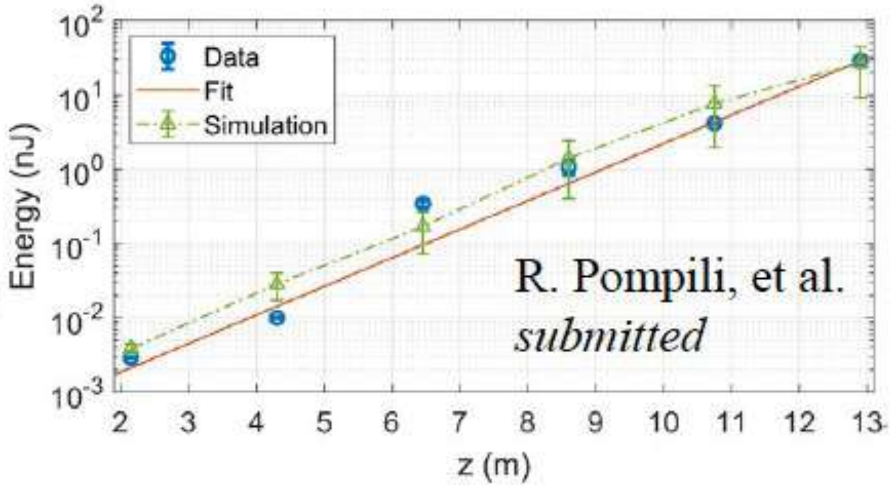
- Energy: 94 MeV (~200 MV/m gradient)
- Energy spread 0.3 MeV
- Emittance: 2.7(X) um, 1.3(Y) um

Energy spread minimization in a beam-driven plasma wakefield accelerator R Pompili et al., **Nature Physics** 17 (4), 499-503 (2021)

First Beam Driven SASE-FEL Lasing at SPARC_LAB (May 2021)





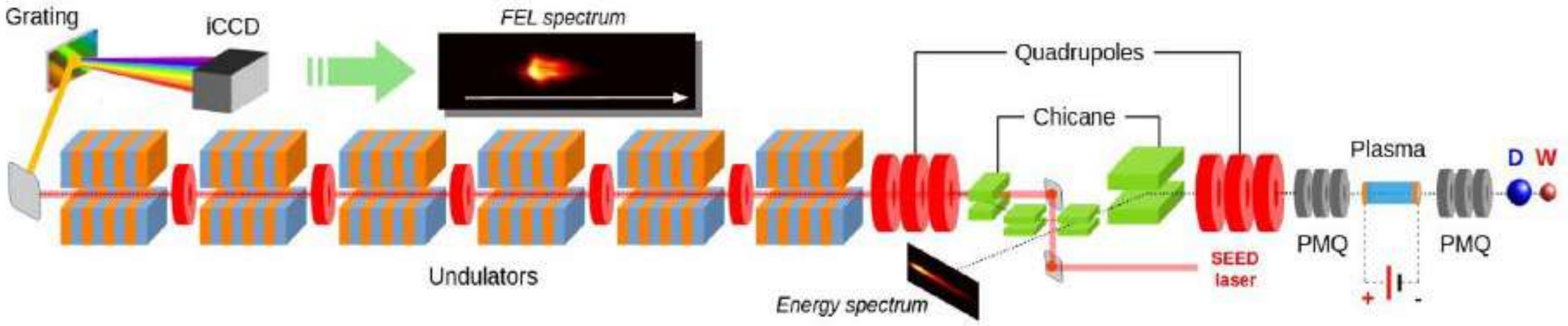


SASE FEL radiation:

- peak at 830 nm;
- 6 undulators, ~ 15 m;
- data taken with 6 (Si) photo-diodes, after each undulator.

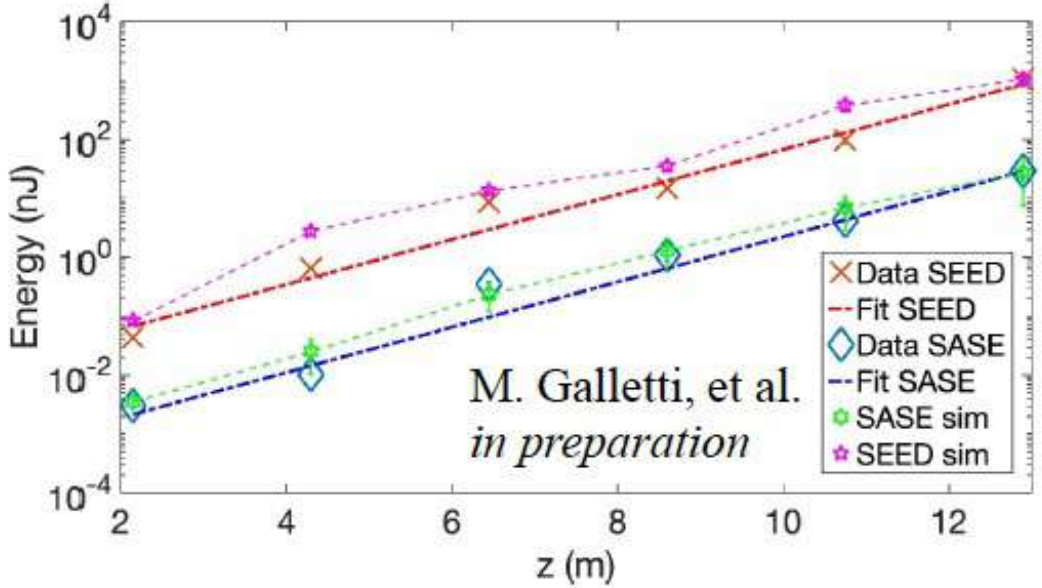
Exponential gain of FEL radiation energy

First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)

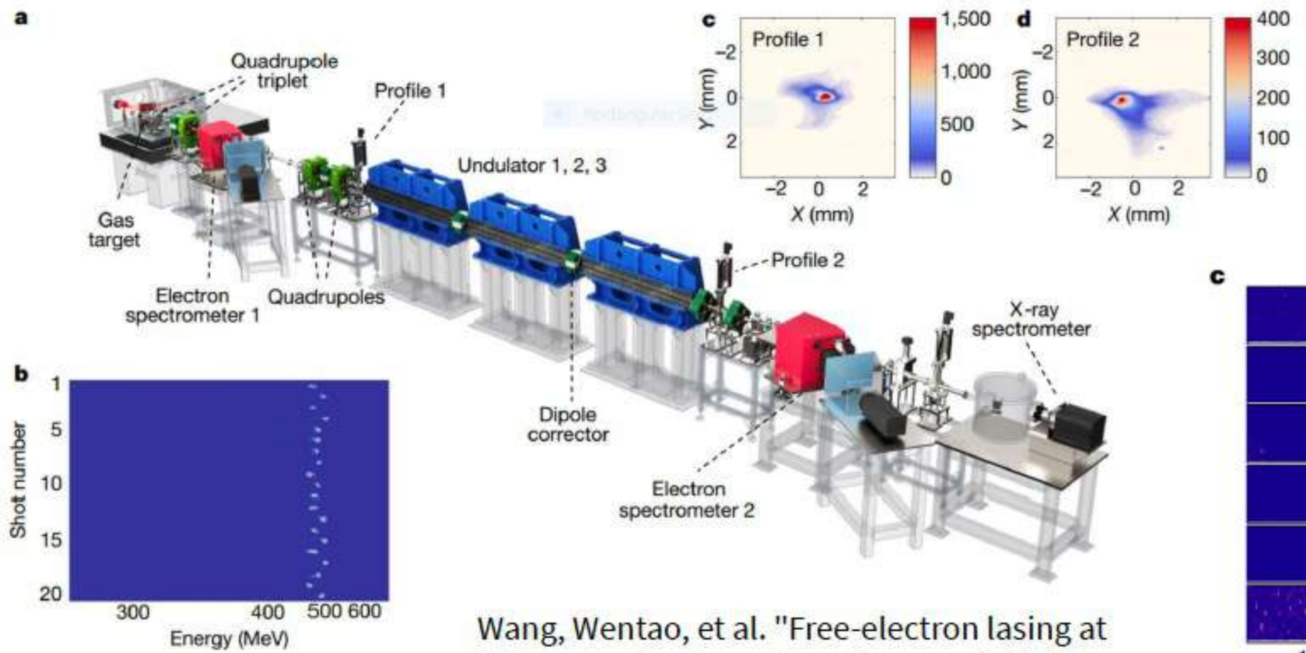


Seeded FEL radiation:

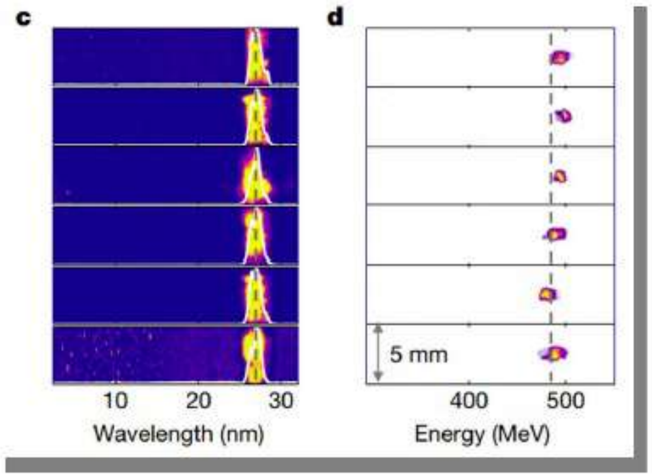
- part of the EOS laser was used as a seed;
- seed laser 795 nm, FEL peak still at 827 nm;
- pulse energy increase from ~30 nJ up to ~ 1 μJ;
- increased stability of radiation.



First Lasing with LWFA at SIOM



Wang, Wentao, et al. "Free-electron lasing at 27 nanometres based on a laser wakefield accelerator." Nature 595.7868 (2021): 516-520.



Observation of FEL radiation @ 27 nm using LWFA

Electron beam generated from a 200 TW (I~4x10^{18} W/cm^2) laser focused on a gas-jet

Peak energy ~ 490 MeV, 0.5% spread (measured), emittance 0.5 um (estimated)

Radiation energy from 0.5 to 150 nJ

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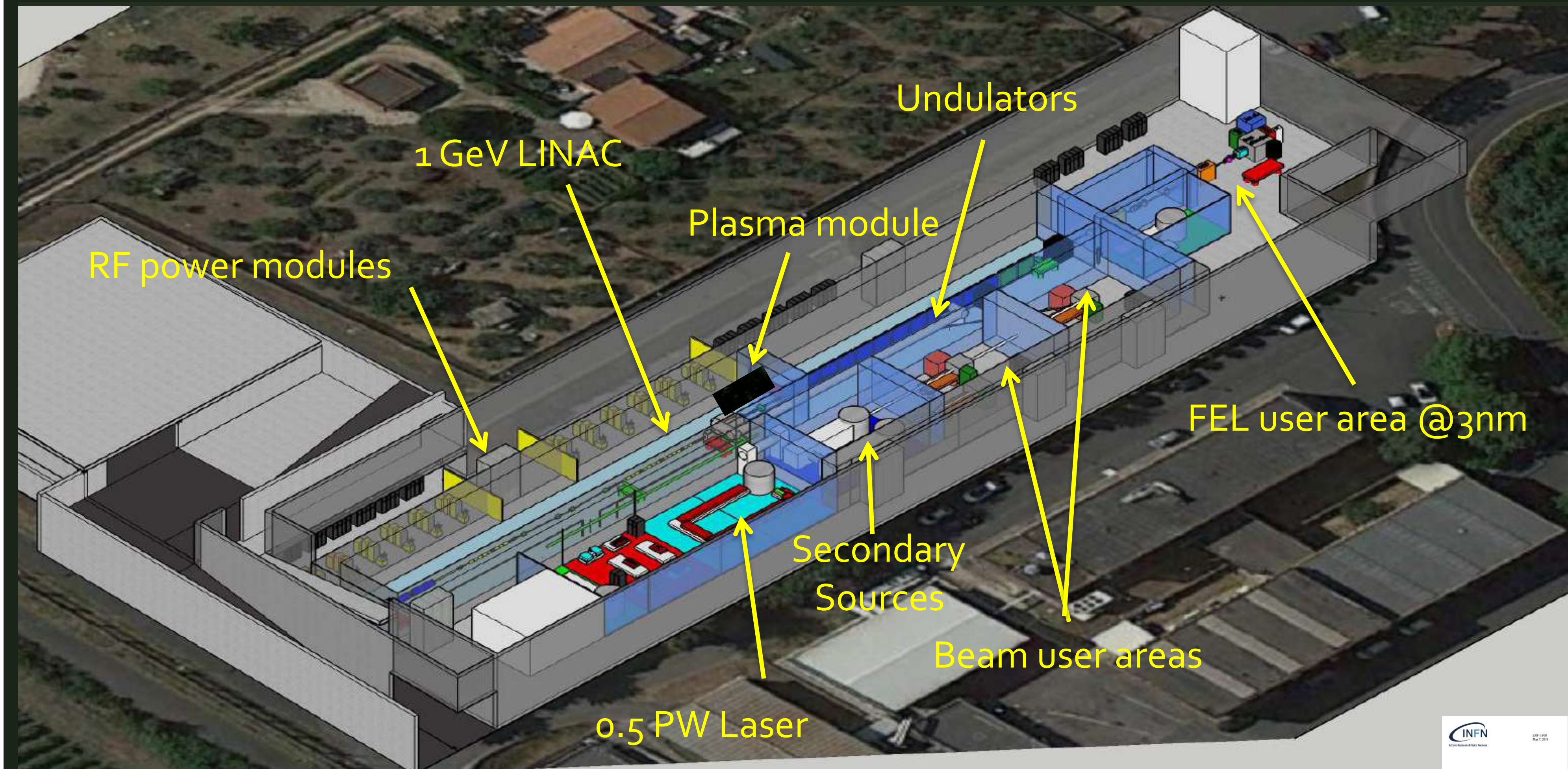
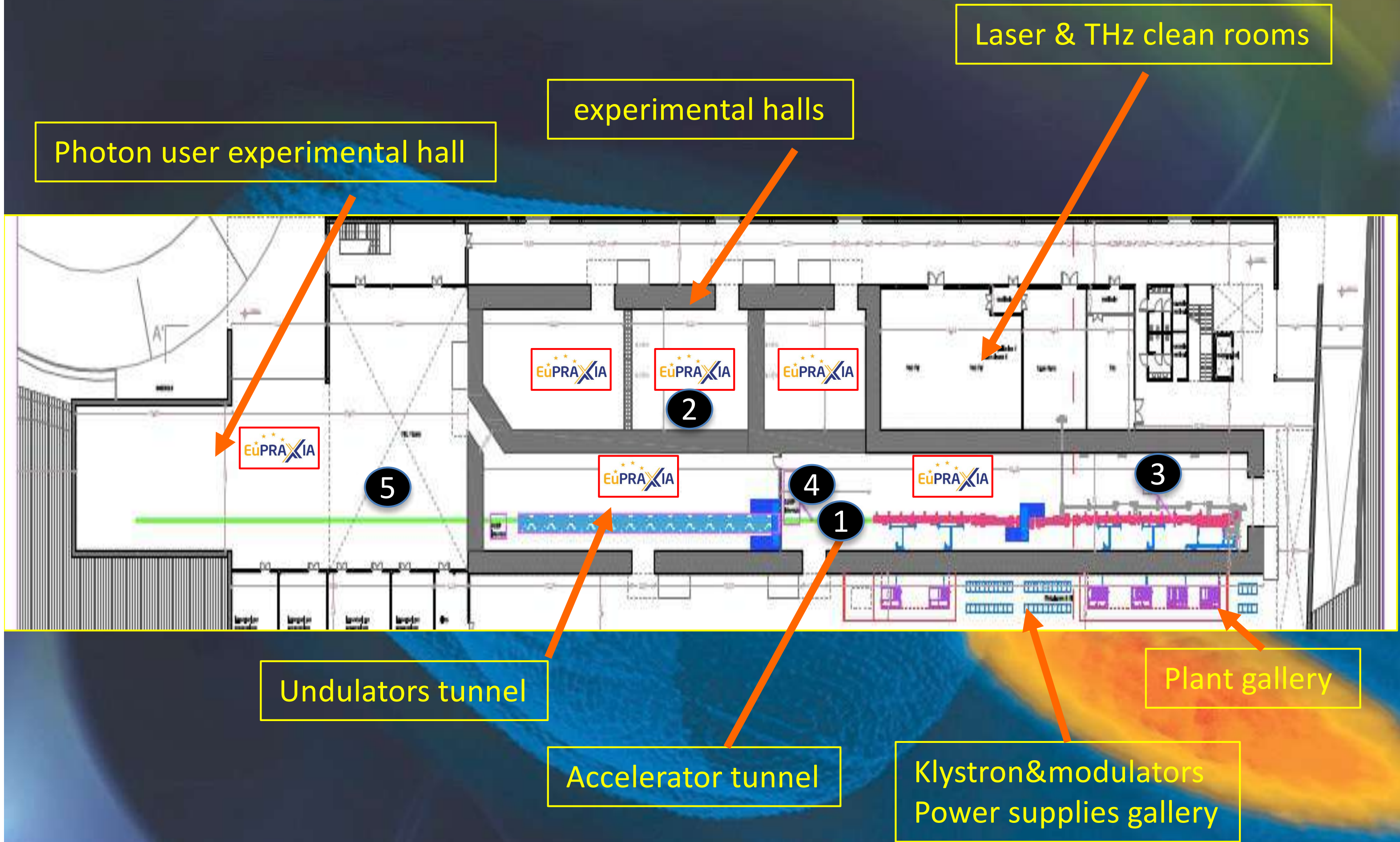


http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

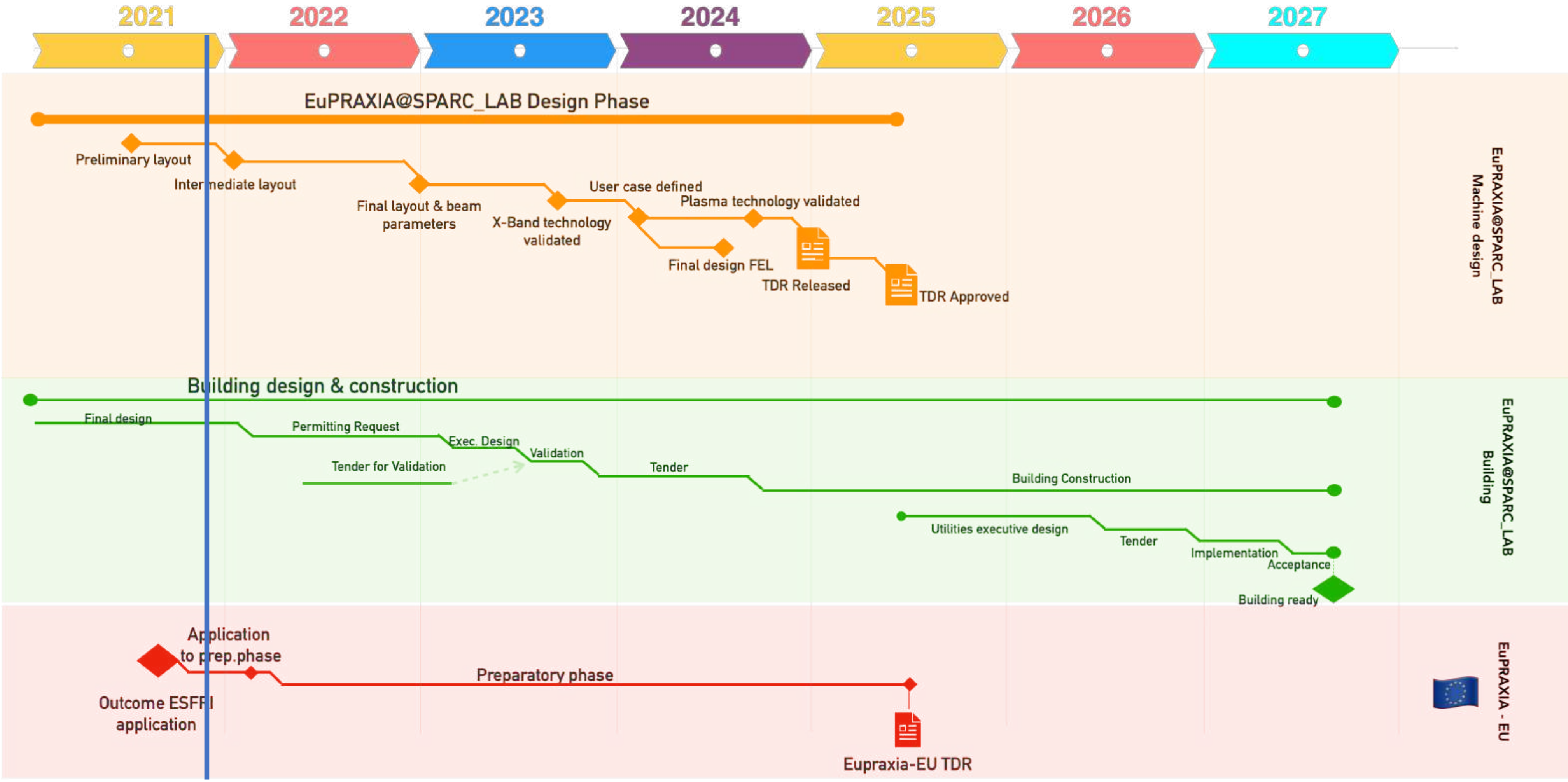
Opportunities for Collaborations at EuPRAXIA@SPARC_LAB



European interests & possible contributions to Frascati site:

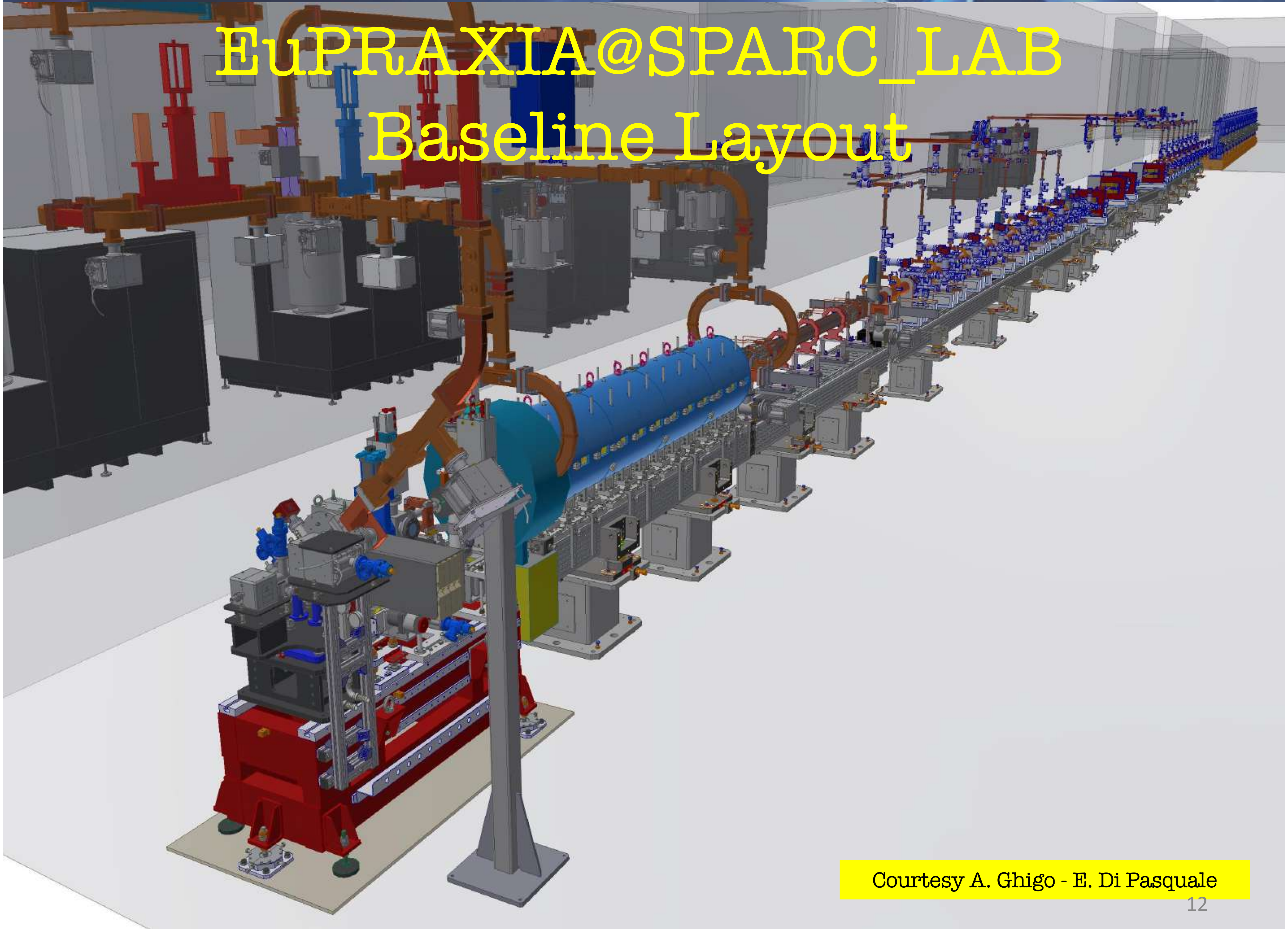
1. Plasma structure designs, devices
2. Compact positron source
3. HQ 150 MeV laser plasma injector
4. HQ laser driver
- Hybrid concepts
- Simulations
5. User experiments and lines

To be detailed in TDR phase.



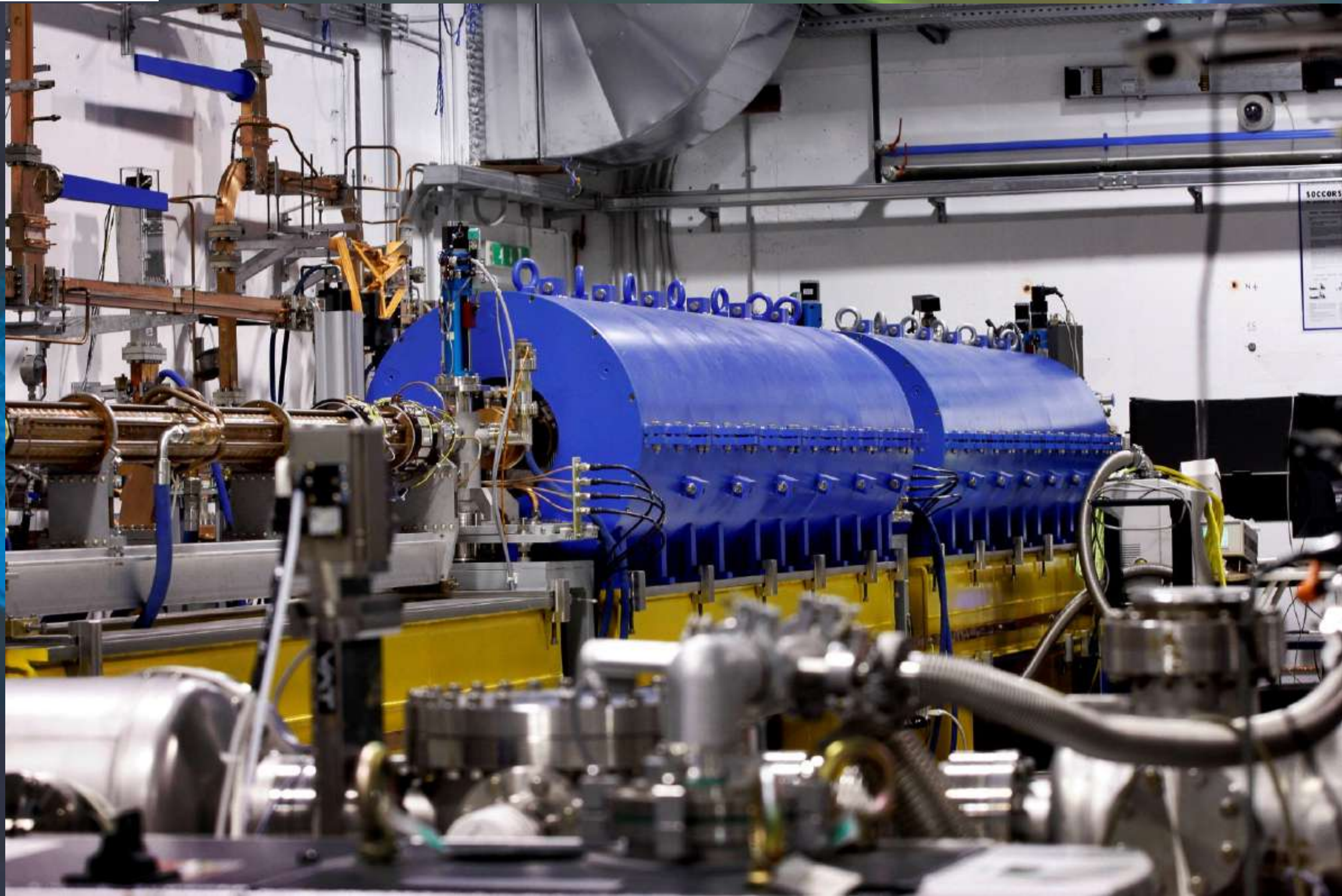
Courtesy A. Falone

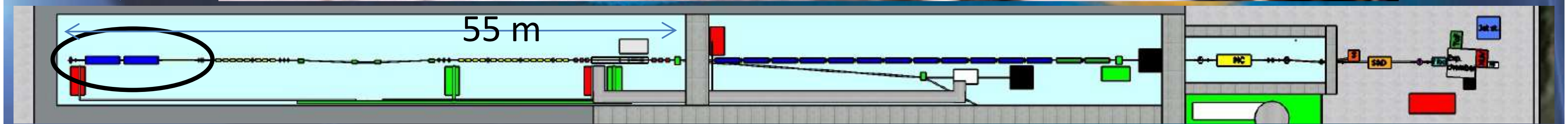
EuPRAXIA@SPARC_LAB Baseline Layout

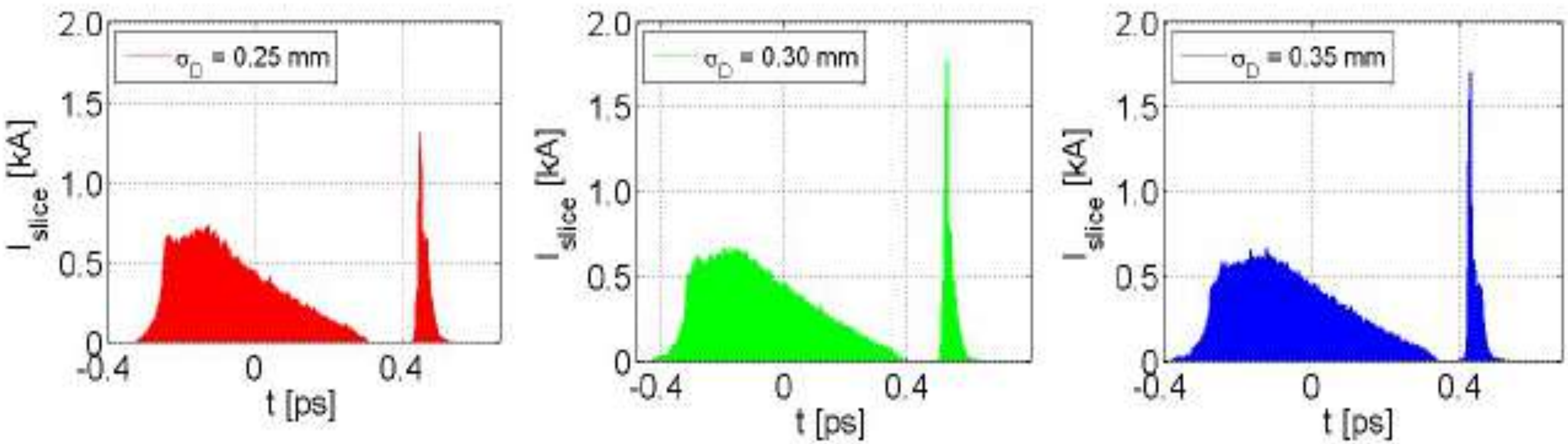


Courtesy A. Ghigo - E. Di Pasquale

SPARC_LAB HB photo- injector



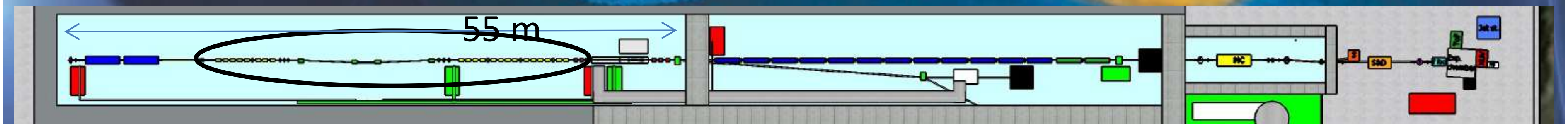




Parameter	Unit	Witness	Driver
Charge	pC	30	200
Energy	MeV	101.5	103.2
RMS energy spread	%	0.15	0.67
RMS bunch length	fs	12	20
RMS norm. emittance	mm mrad	0.69	1.95
Rep. rate	Hz	10	10

Table 7.2: Driver and witness beam parameters at the end of photo-injector.

X-band Linac

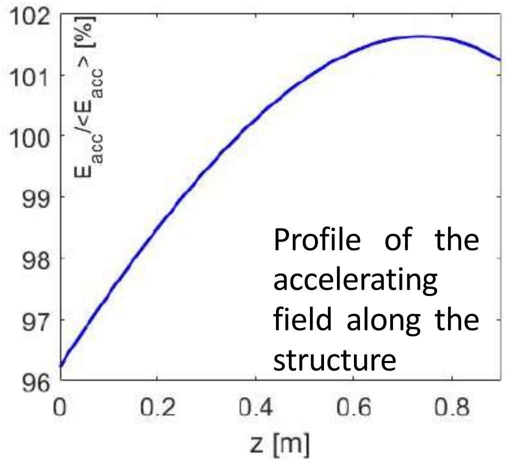


X BAND STRUCTURES: PARAMETERS

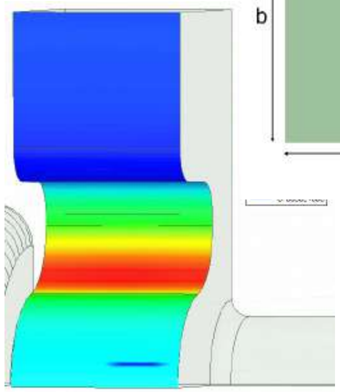
1. **e.m. design**: **linear tapering of the irises**, race track coupler to cancel the quadrupole field components (*PhD M. Diomede*);

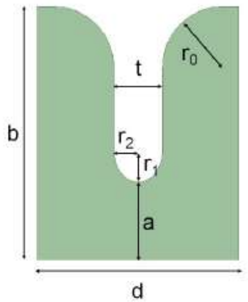
2. **0.9 m long** structures with 3.5 mm average iris radius

3. **60 MV/m** average accelerating field

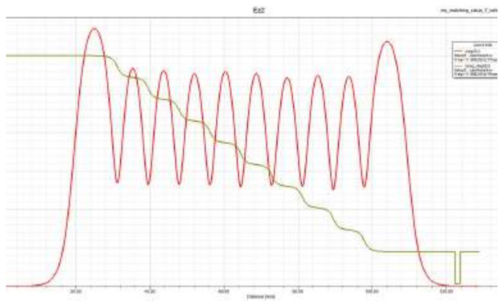


Profile of the accelerating field along the structure





Courtesy M. Diomede



Parameter	Value
Frequency [GHz]	11.9942
Average acc. gradient [MV/m]	**60**
Structures per module	4
Iris radius a (linear tapering) [mm] <a>=3.5	3.8-3.2
Tapering angle [deg]	0.04
Structure length L_s [m]	**0.9**
No. of cells	109
Shunt impedance R [MΩ/m]	94-107
Peak input power per structure [MW]	65
Input power averaged over the pulse [MW]	45
Average dissipated power [kW]	1
Filling time [ns]	126
Effective shunt Imp. R_s [MΩ/m]	350
Peak Modified Poynting Vector [W/μm^2]	3.5
Unloaded SLED/BOC Q-factor Q_0	150000
External SLED/BOC Q-factor Q_E	21000
Required Kly power per module [MW]	**37/19**
RF pulse [μs]	**1.5**
Klystron power (available) [MW]	**50/25**
Rep. Rate [Hz]	**100**

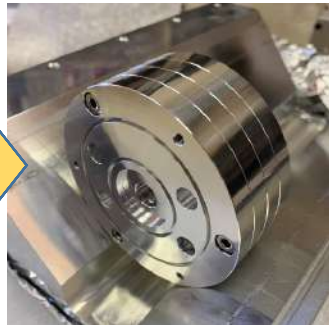
$$R_s = \frac{G^2 L}{P_{kly}}$$

G=average accelerating gradient
L=structure length
P_{kly}=klystron power (pre-sled pulse)

X-BAND STRUCTURE PROTOTYPING ACTIVITIES: REALIZATIONS

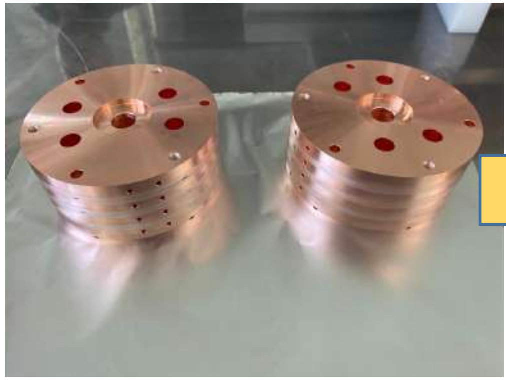
Realization

Assembly



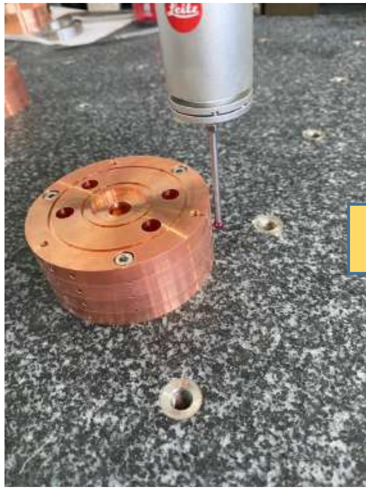
Characterization CMC

Brazing



Vacuum test

Characterization CMC



<+/-5 μm alignment (before/after brazing)

Realizations in parallel to all LNF activities…

TEX facility – TEst stand for X-band at Frascati

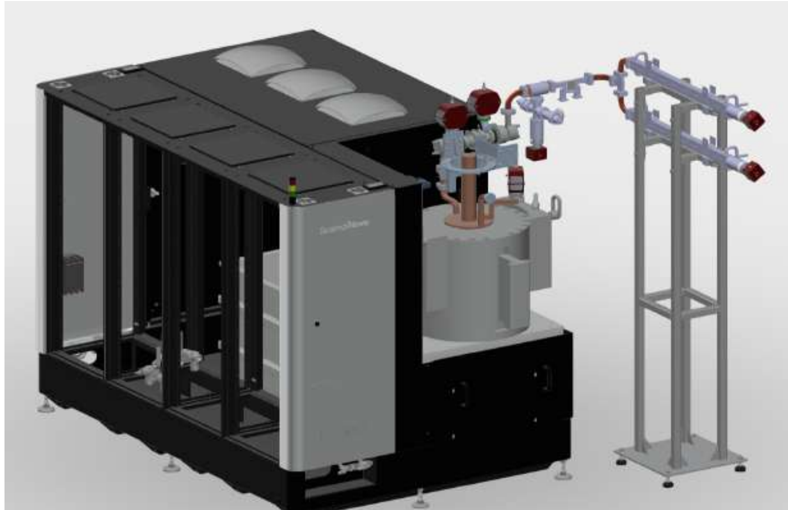
- The *TEst-stand for X-band* (**TEX**) is a facility conceived for R&D on high gradient X-band accelerating structures and waveguide components in view of Eupraxia@SPARC_LAB project.
- It has been co-funded by Lazio regional government in the framework of **the LATINO project** (*Laboratory in Advanced Technologies for INnOvation*). The setup has been done in **collaboration with CERN** and it will be also used to test CLIC structures.
- TEX is located in bld. 7 of LNF, which is being fully refurbished and upgraded to host the high gradient facility and other labs.

Concrete shielded Bunker and Modulator Cage

Control room and Rack room

Courtesy S. Pioli

TEX - TEst-stand for X-band



RF Source SAT setup

VKX-8311A CPI Klystron

- Cathode Voltage 428 kV
- Cathode Current 328 A
- Operating Frequency 11.994 GHz
- RF Drive power 865 W
- RF Output Power 51 MW

RF Source Site Acceptance on-going status:

- Setup with RF-Load (able to handle up to 25MW) installed.
- Baking at 150 °C performed for 5 days. Vacuum in 10^-11 mbar.
- LLRF, Controls, Timing, Safety and plants installed.
- Klystron conditioned in diode mode at 50Hz full-power.
- ScandiNova K400 Modulator SAT will finish this week.
- **WG and RF-Load currently conditioned at nominal power 25 MW (50 Hz, 200ns pulse length).**

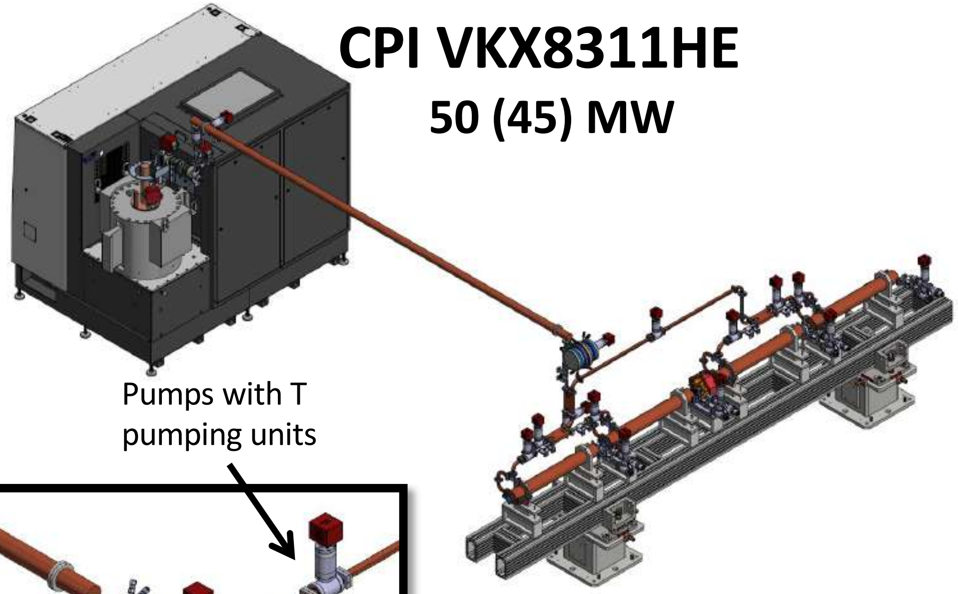
What next:

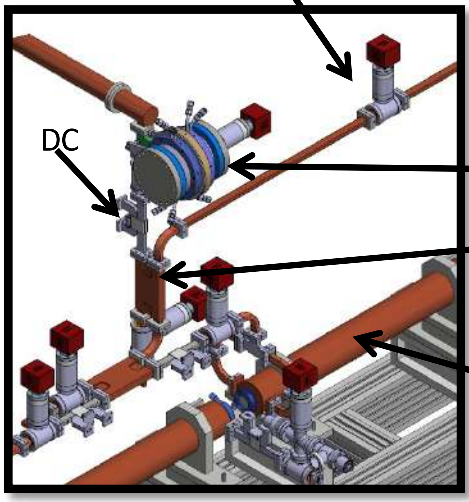
- Within end of 2021, final WG setup will be installed.
- Ready to start accelerating structures conditioning in early 2022.

Courtesy S. Pioli

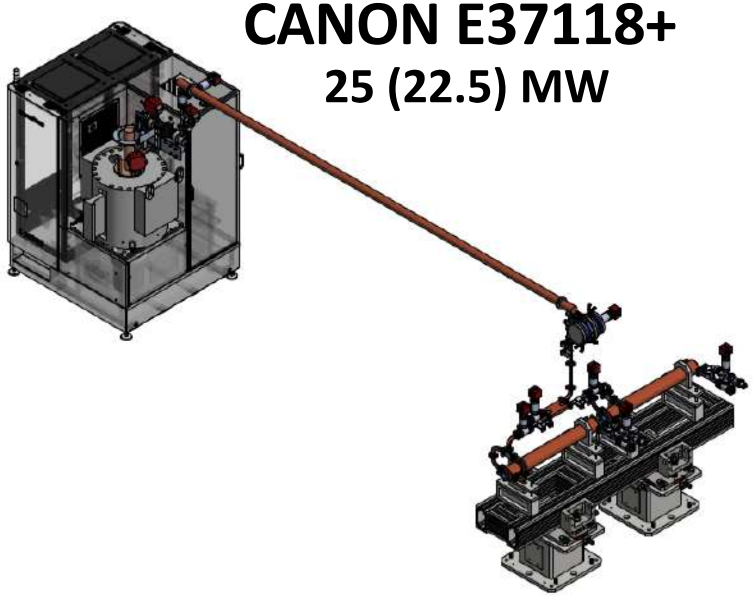
RF MODULE LAYOUT

CPI VKX8311HE
50 (45) MW





CANON E37118+
25 (22.5) MW



Courtesy G. Di Raddo,
E. Di Pasquale, F. Cardelli

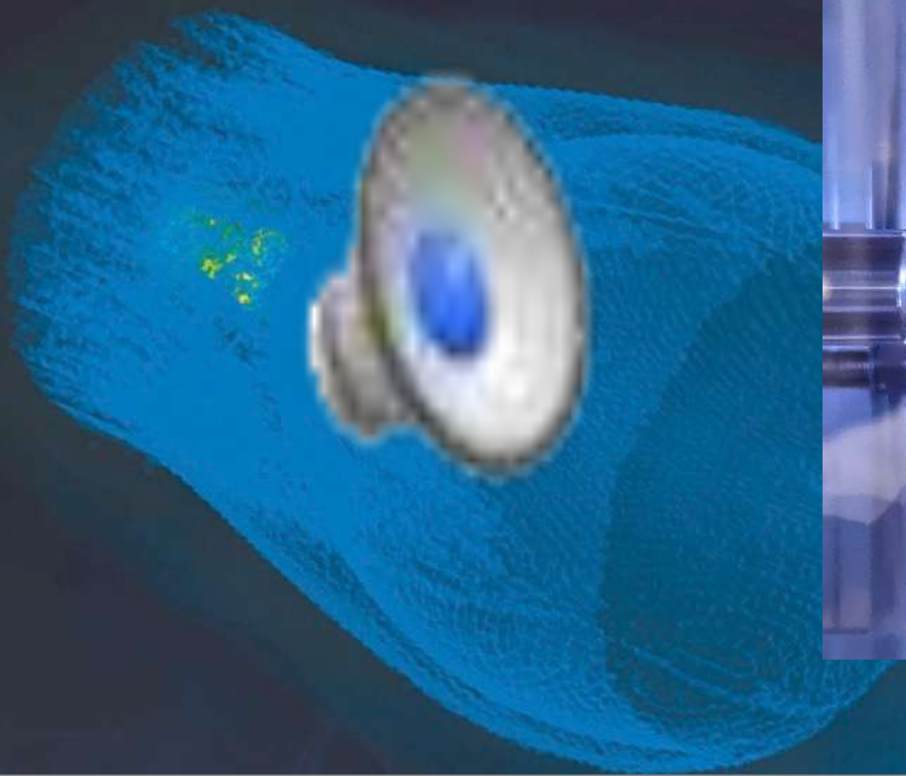
⇒ **Waveguide components** (DC, T pumping, hybrids,…) **CERN design** but there are some components for which we have to fix the design (circular-rectangular waveguide mode converter, pumping unit on circular waveguide)

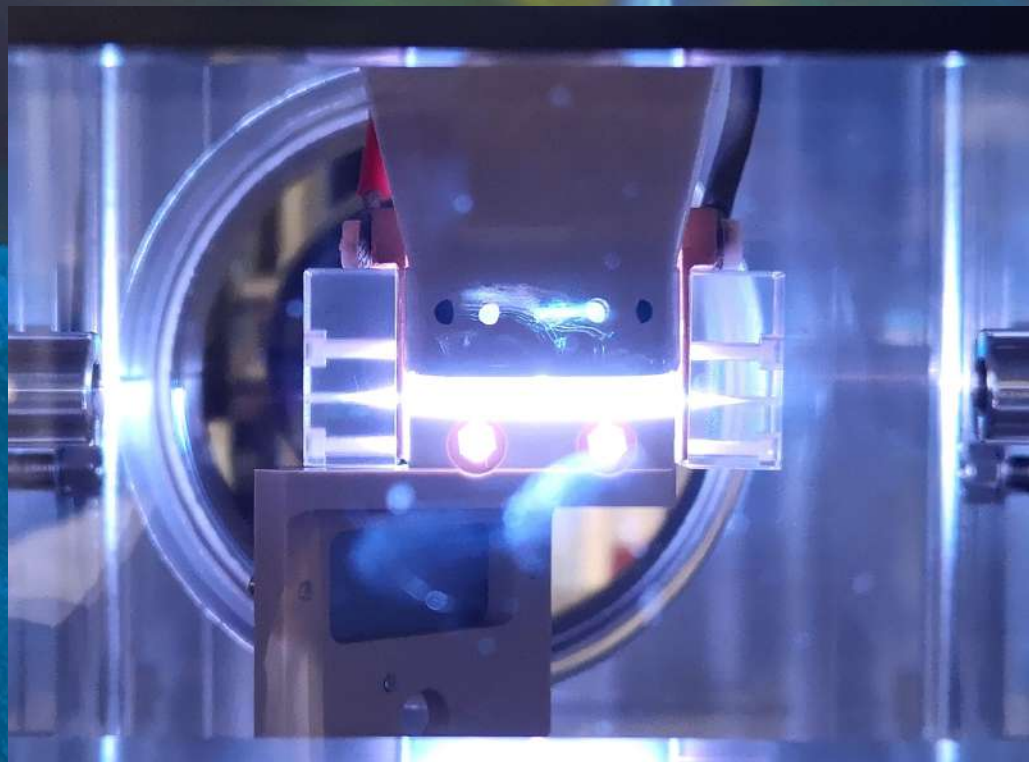
⇒ **Pulse compressor: BOC (PSI) or INFN Design**

⇒ **Asymmetric waveguide distribution system to take into account the RF propagation time**

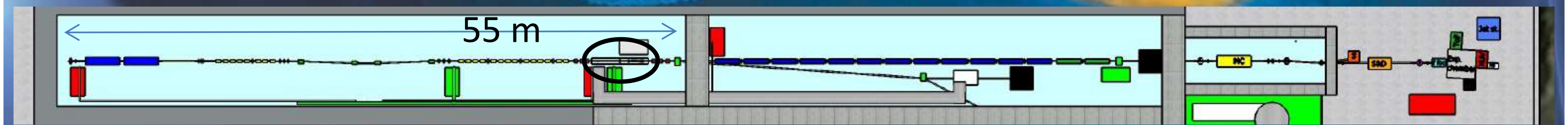
⇒ **400 Hz repetition rate possible**

Plasma WakeField Acceleration

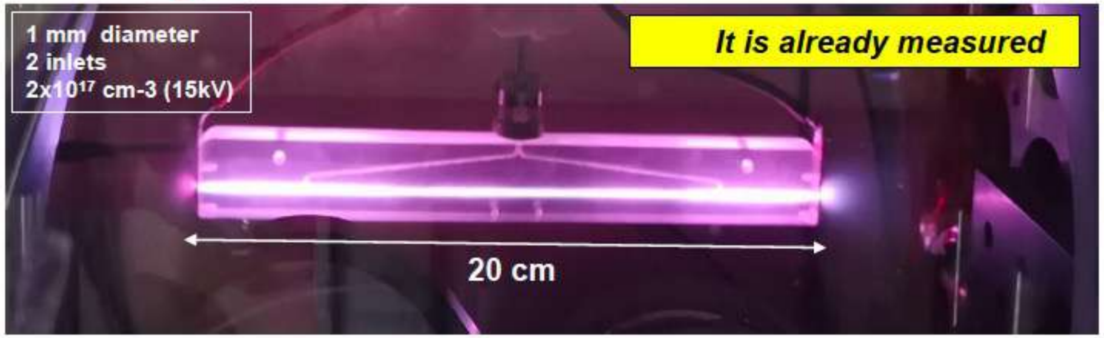




Capillary discharge at SPARC_LAB

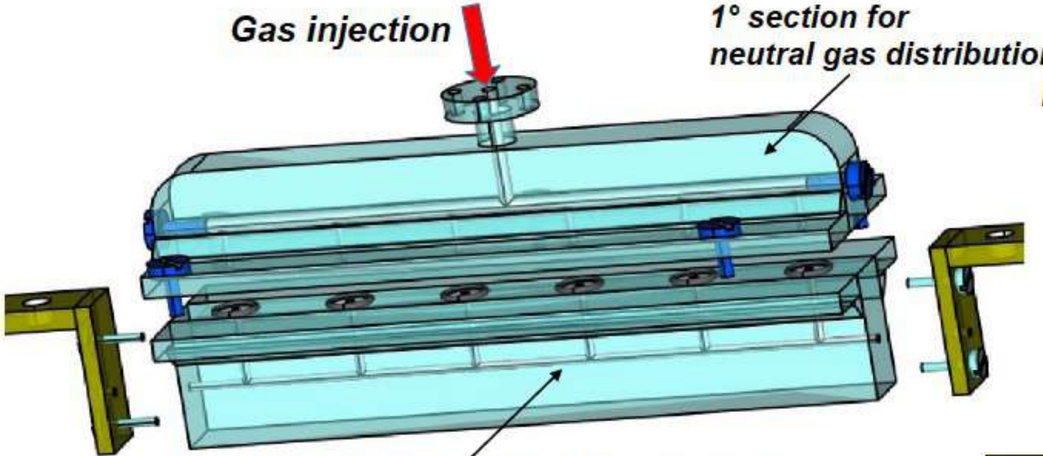


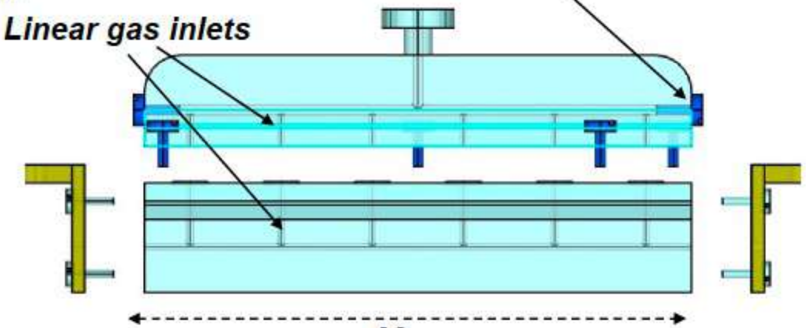
40 cm-long Gas-filled discharge-capillary



Paschen curves (50 mbar)

Length	Density	Vb
3 cm	$4x10^{16}$ cm-3	3 kV
10 cm	$4x10^{16}$ cm-3	8 kV
20 cm	$4x10^{16}$ cm-3	14 kV
40 cm	$4x10^{16}$ cm-3	23 kV



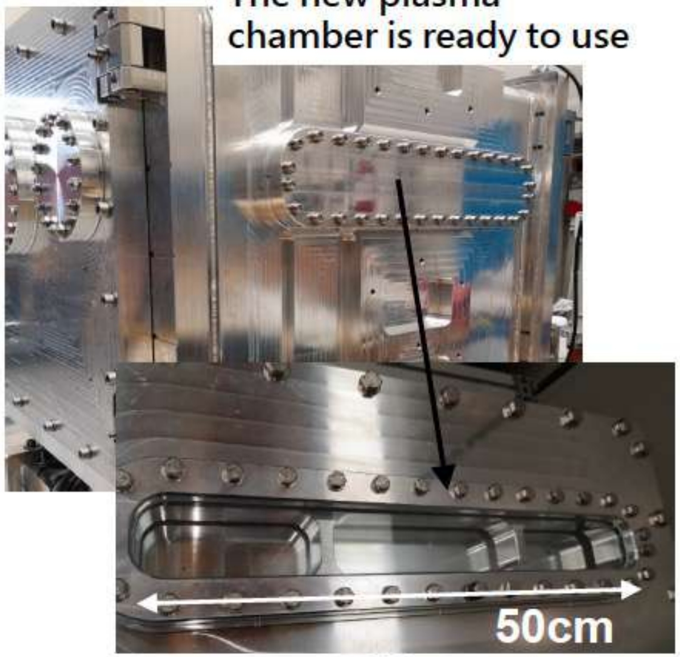


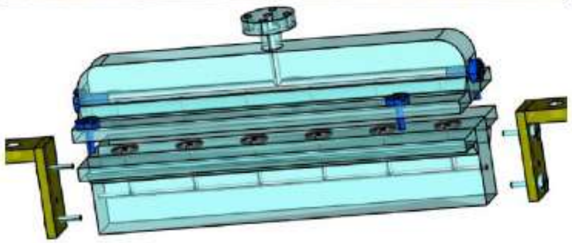
Linear channel/inlets allow us to clean them from printing residuals

40cm-long Gas-filled discharge-capillary

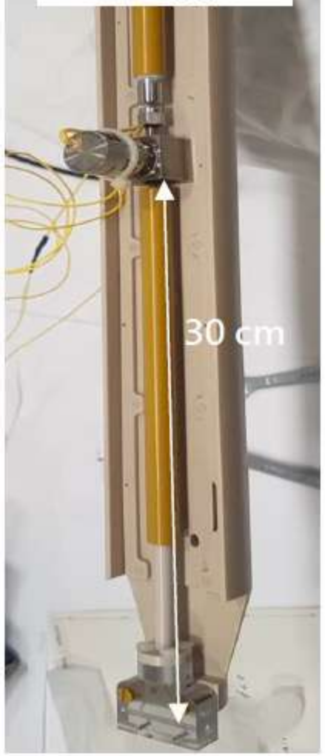
A crucial point to produce a gas discharge is the insulation of others components of the plasma module with respect to the HV pulse

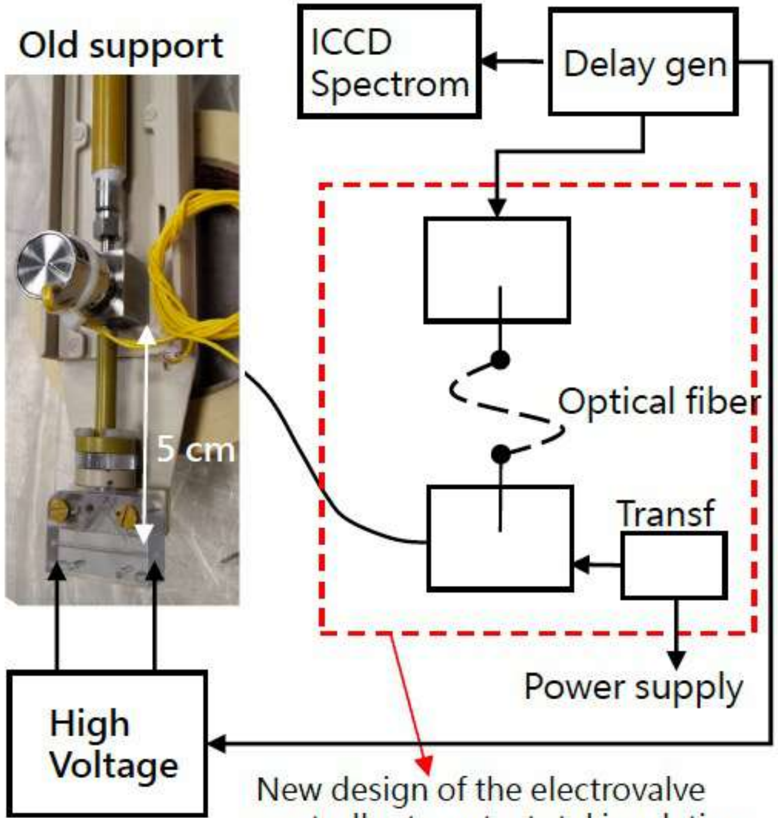
The new plasma chamber is ready to use





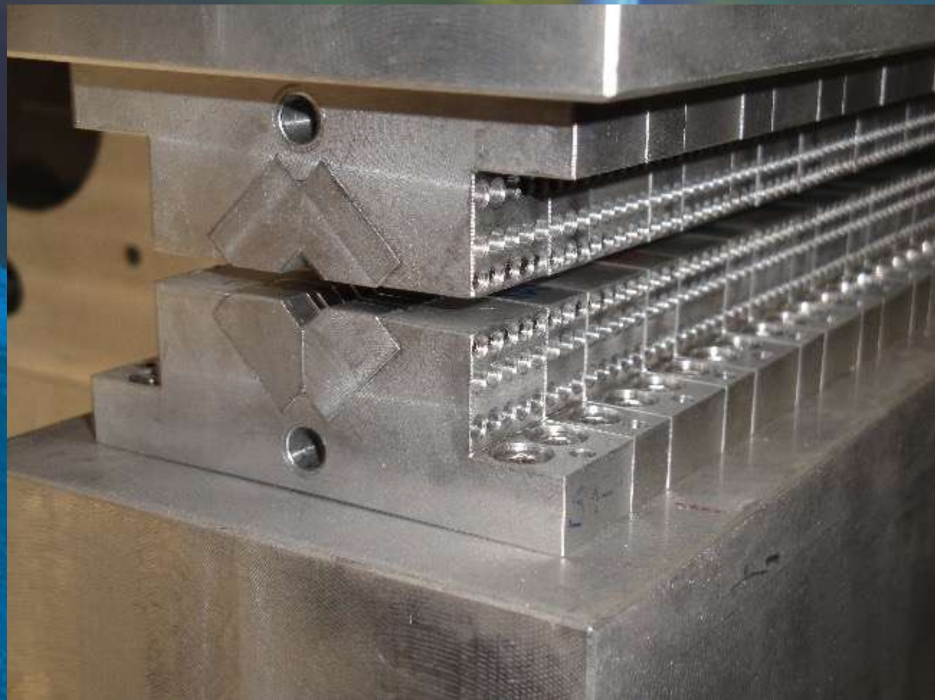
New support



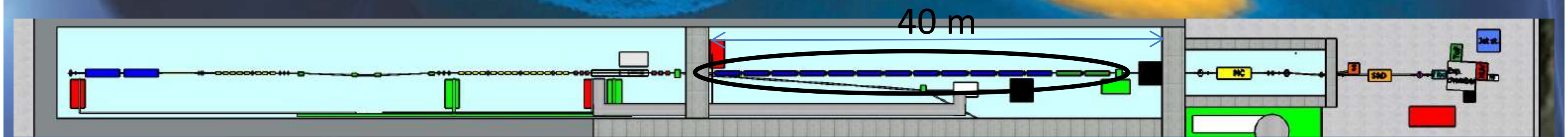


New design of the electrovalve controller to get a total insulation of the electro valve

Undulators



KYMA Δ udulator at SPARC_LAB: λ=1.4 cm, K1



Undulator technology

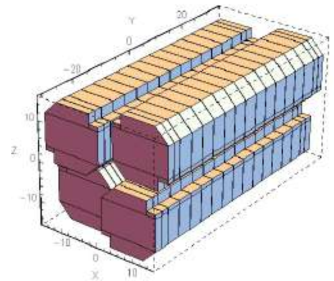
Superconducting Undulator

Responsible C. Boffo (FNAL)

Agreement with FNAL signed 1y ago
Development plan 4 ys – 2024
prototype in Frascati

Costs for the entire undulator in excess of the baseline for the project

Permanent Magnet Undulator



Respons. A. Petralia (ENEA)

Apple X - Variable gap, variable polarization
New poles design, scaled from SABINA (LNF- THz FEL) undulator

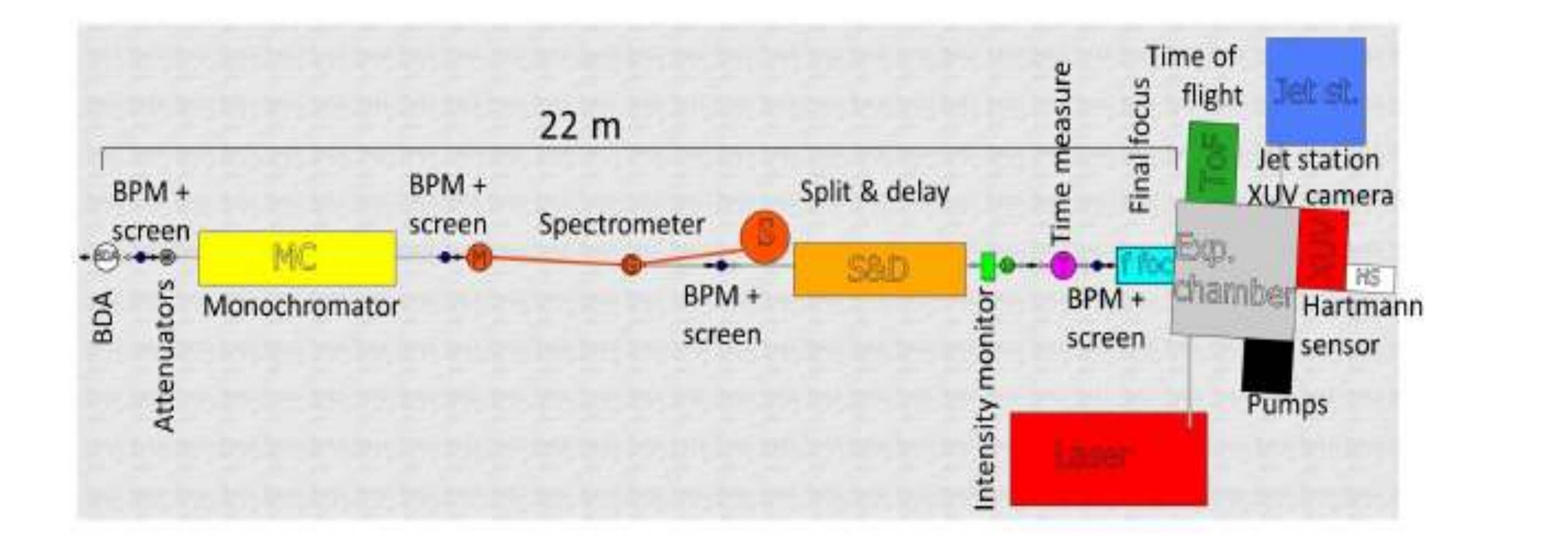
Period increased to 18 mm to increase tuning range.

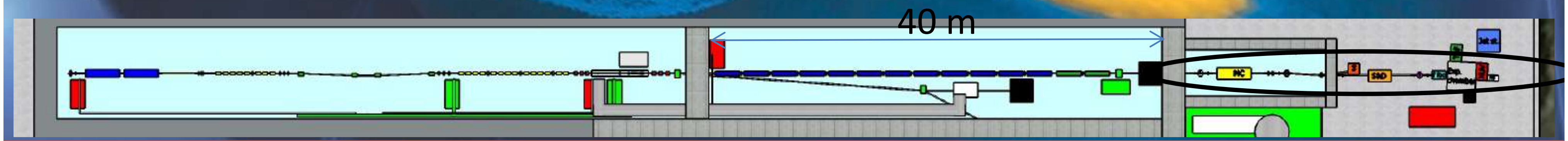
Unconventional undulator design: prototyping required

Observers in the LEAPS – INNOV: several labs investing in this kind of devices.

Alternative: sacrifice the tuning range - fixed gap PMU – less expensive, but poor flexibility

Photon beam line





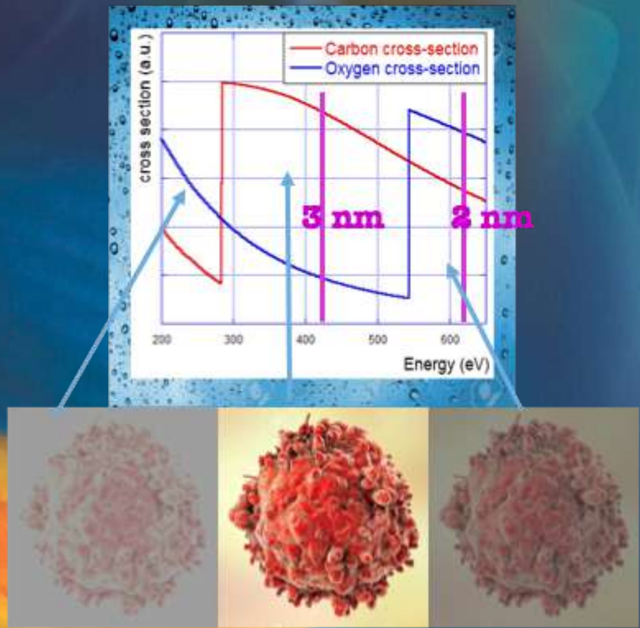
Expected SASE FEL performances

54 Chapter 2. Free Electron Laser design principles

	Units	Full RF case	Plasma case
Electron Energy	GeV	1	1
Bunch Charge	pC	200	30
Peak Current	kA	2	3
RMS Energy Spread	%	0.1	1
RMS Bunch Length	fs	40	4
RMS matched Bunch Spot	µm	34	34
RMS norm. Emittance	µm	1	1
Slice length	µm	0.5	0.45
Slice Energy Spread	%	0.01	0.1
Slice norm. Emittance	µm	0.5	0.5
Undulator Period	mm	15	15
Undulator Strength K		1.03	1.03
Undulator Length	m	12	14
Gain Length	m	0.46	0.5
Pierce Parameter ρ	x 10^{-3}	1.5	1.4
Radiation Wavelength	nm	3	3
Undulator matching β_u	m	4.5	4.5
Saturation Active Length	m	10	11
Saturation Power	GW	4	5.89
Energy per pulse	µJ	83.8	11.7
Photons per pulse	x 10^{11}	11	1.5

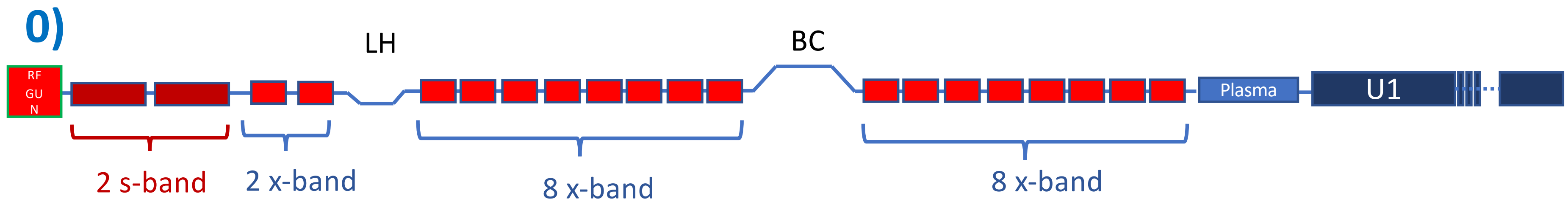
Table 2.1: Beam parameters for the EuPRAXIA@SPARC_LAB FEL driven by X-band linac or Plasma acceleration

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)

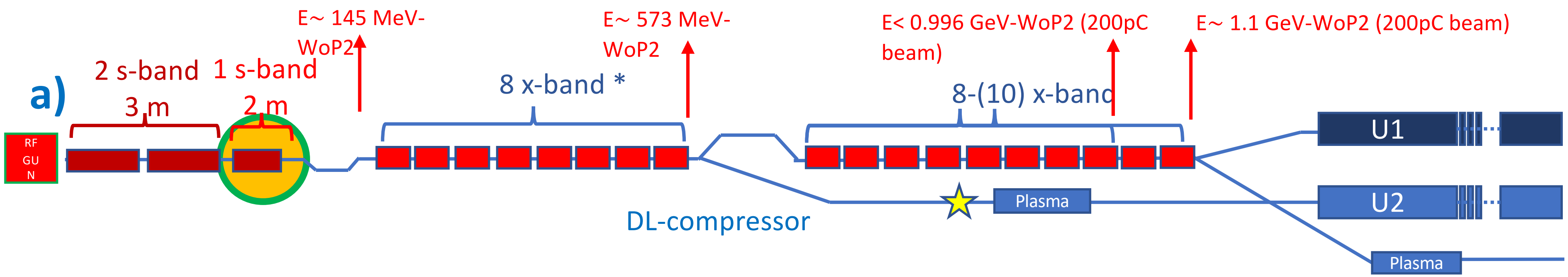


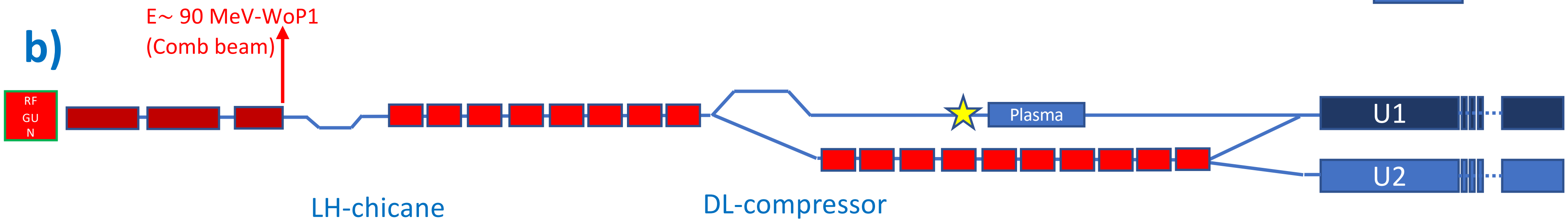
Coherent Imaging of biological samples protein clusters, VIRUSES and cells living in their native state
Possibility to study dynamics
~10^{11} photons/pulse needed

Courtesy F. Stellato, UniToV



From Baseline Single Beamline Design to the Double Beamline

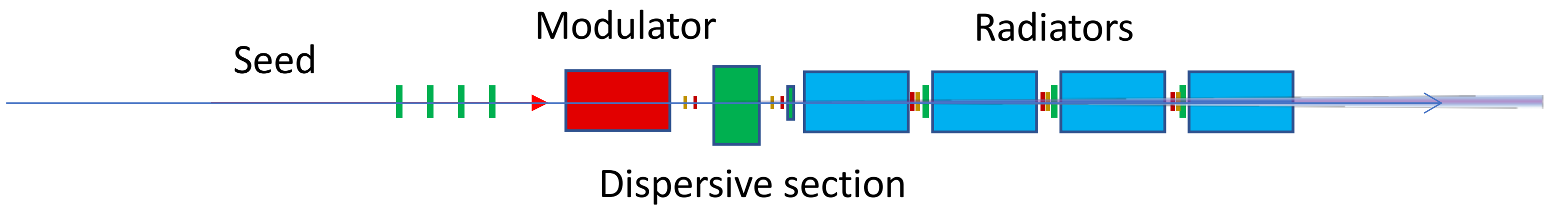




Operation at 400 Hz is under investigation

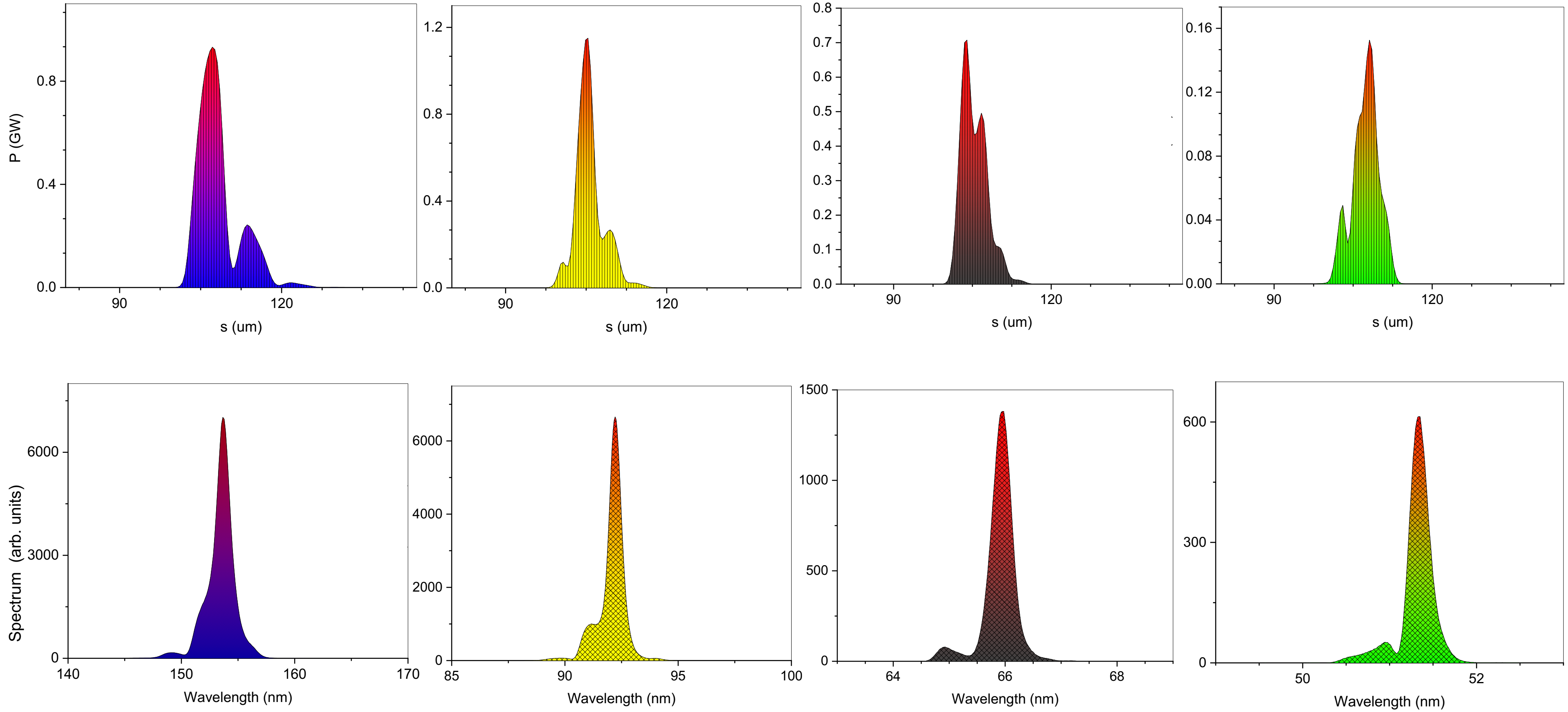
ARIA

SEEDED FEL line – Full coherence – Short/Long pulses – Close to FT Limit



- High-Gain Harmonic Generation seeded FEL: modulator – dispersive section – 4 radiators
- Wavelength range 50 nm (then 30 nm) – 180 nm – continuously tunable – 10-100 uJ pulse energy
- Apple II Undulators: variable polarization (circular left/right, horizontal and vertical), undulator periods: 10 cm (modulator) and 5.5cm (radiators), K = 3.
- Ready for users since the first commissioning phase. Would contribute to establish a user community for the EupraXia at SparcLab user facility

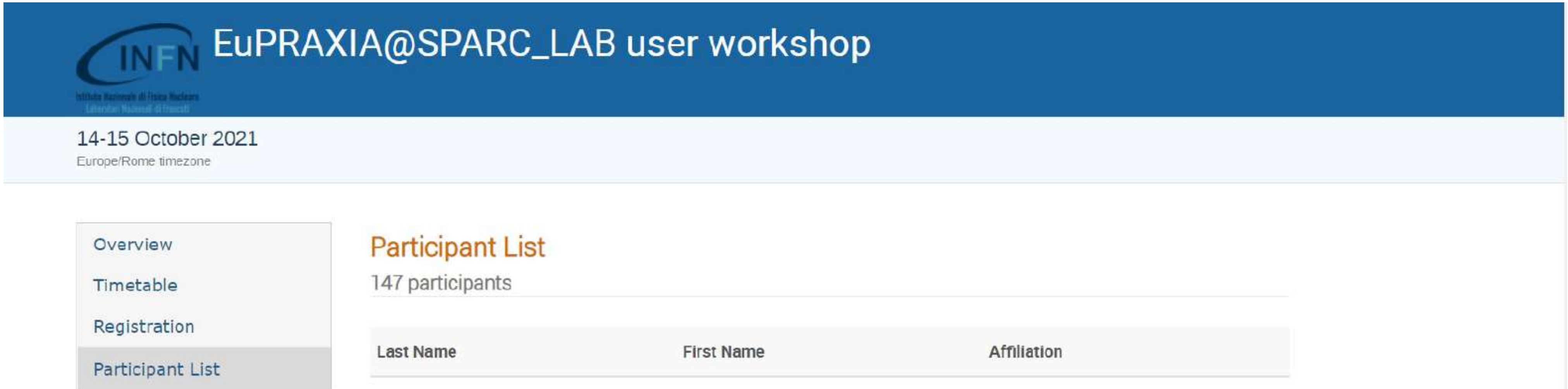
GENESIS 1.3 simulations (courtesy of M. Opromolla/V. Petrillo ~beam D parameters)



153nm (nh=3)   92nm (nh=5)   66nm (nh=7)   51nm (nh=9)

26/10/2021 – L. Giannessi

AQUA/ARIA - A growing community



The first EuPRAXIA@○SPARC_LAB user workshop

More than 140 registrants from 9 countries and ~30 institutions

https://agenda.infn.it/event/27926/overview

AQUA - Techniques & Samples @ 3 nm

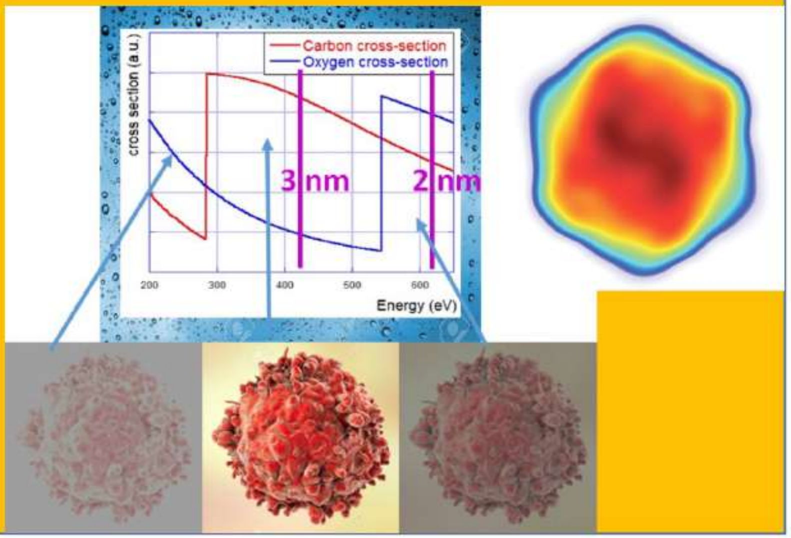
Scientific case assembled and published.
Contributions from >15 different institutions

Balerna *et al.* Condensed Matter 4, 30 (2019)

Bio & Inorganic Samples

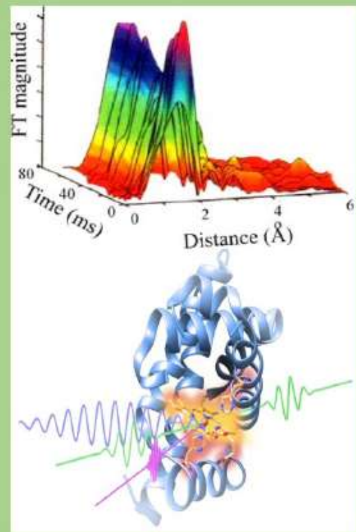
Proteins - Viruses
Bacteria- Cells
Metals – Magnetic materials
Superconductors -Semiconductors

Coherent imaging



X-ray absorption spectroscopy

Raman spectroscopy



ARIA - Techniques & Samples @ 50-180 nm

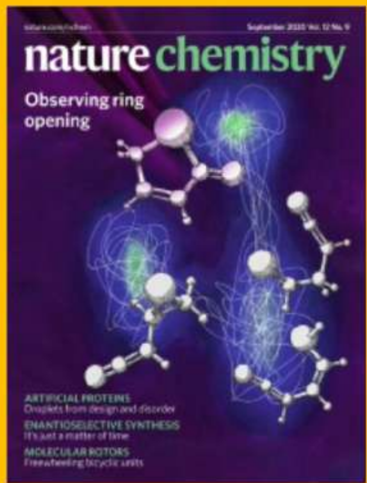
Scientific case in the DUV (DeepUV) and VUV (VacuumUV) is being assembled
Wavelength interval **complementary** with FEL1 @ Fermi

Samples & (techniques)

Gas phase & Atmosphere (Earth & Planets)
Aerosols (Pollution, nanoparticles)
Molecules & gases (spectroscopies, time-of-flight)
Proteins (spectroscopies)
Surfaces (ablation e deposition)

Photoemission Spectroscopy

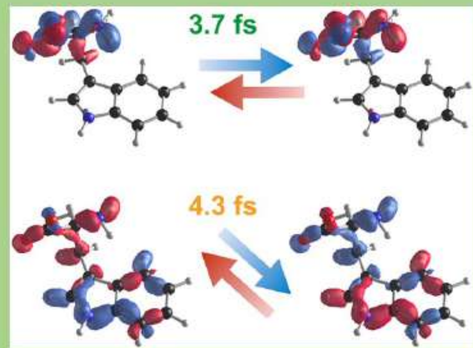
Ring opening in organic molecules
Pathak *et al. Nature Chemistry* 2020



Raman spectroscopy

Photo-fragmentation of molecules

Ultrafast Quantum Interference in the Charge Migration of Tryptophan.
J Phys Chem Lett 2020



Time of Flight Spectroscopy


Thank for your attention