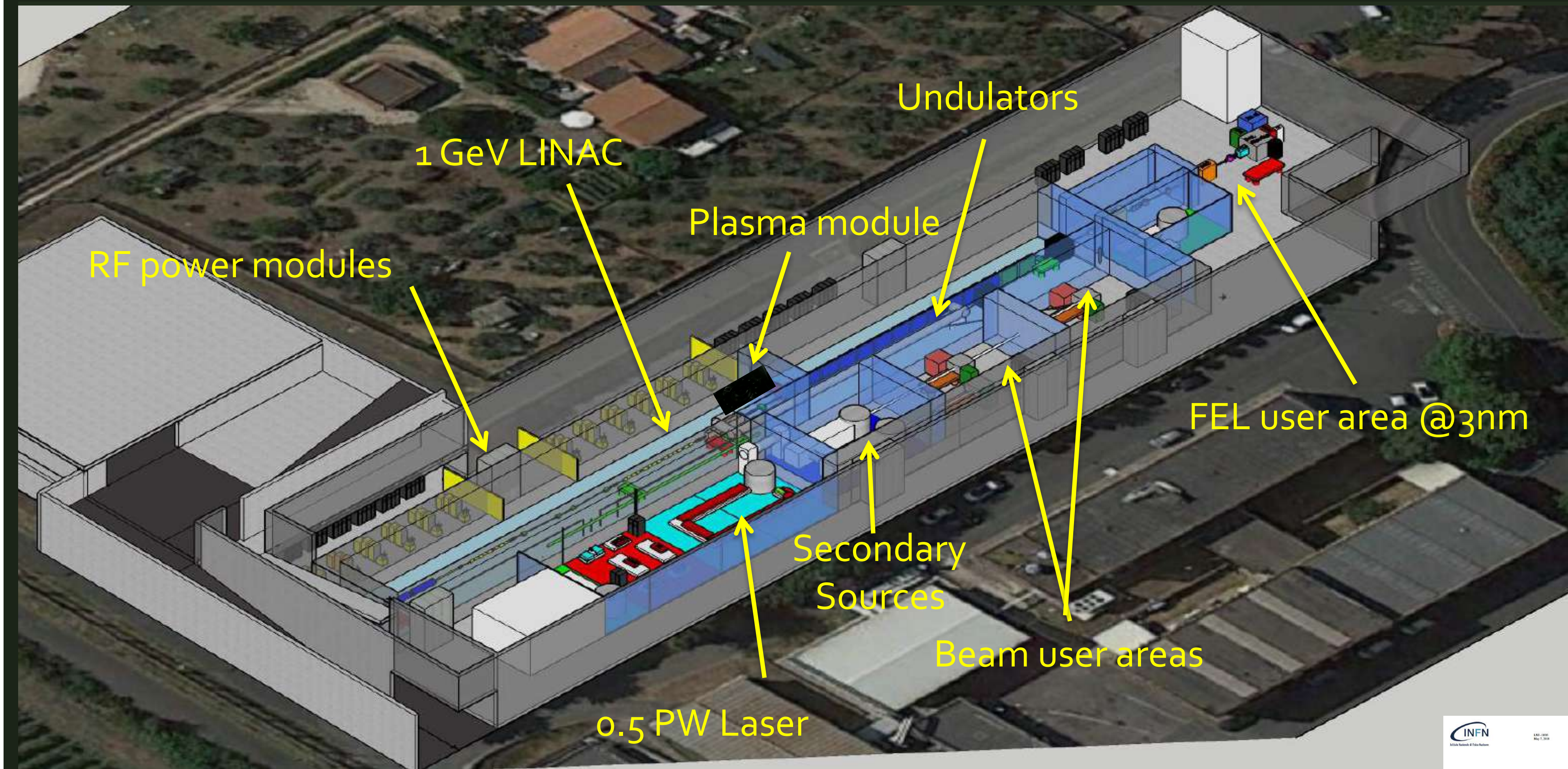
EuPRAXIA@SPARC_LAB

Massimo.Ferrario@LNF.INFN.IT

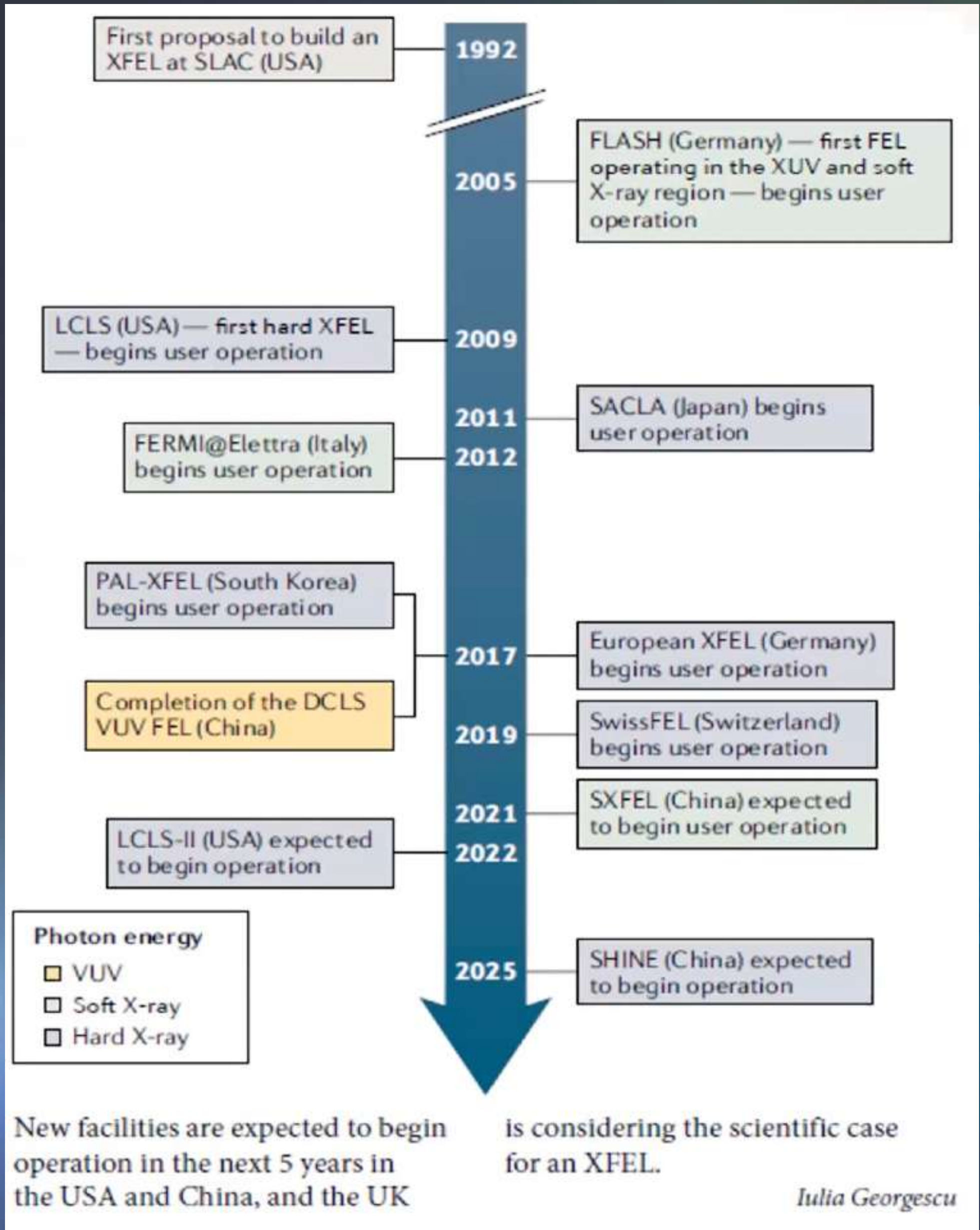
EuPRAXIA@SPARC_LAB

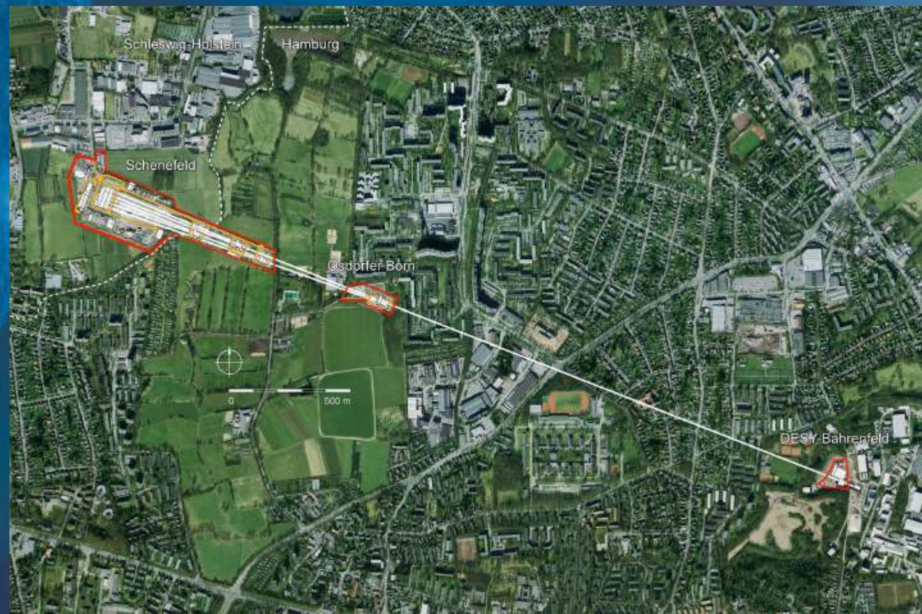


http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

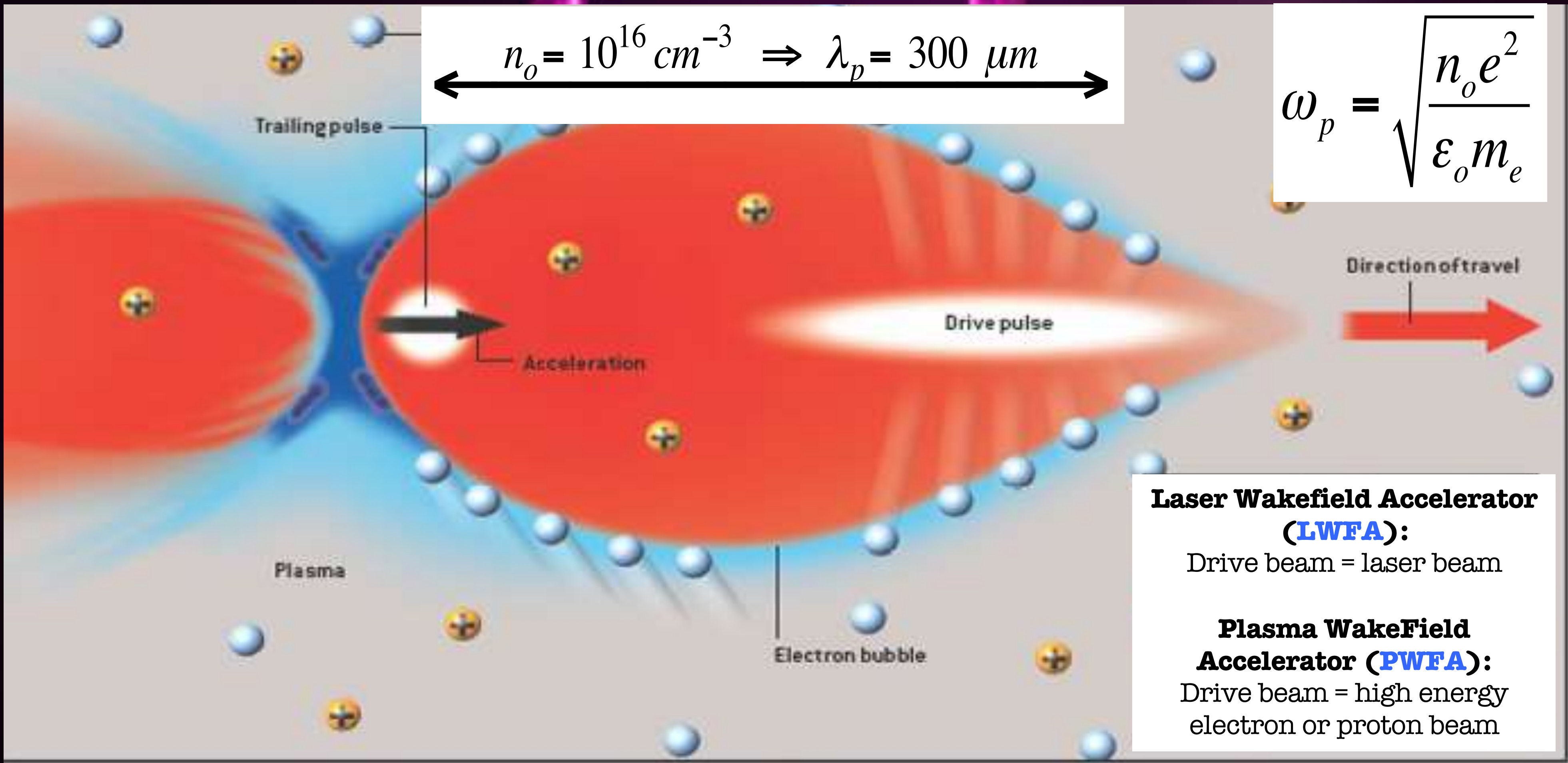
FEL is a well established technology

(But a widespread use of FEL is partially limited by size and costs)





Principle of plasma acceleration



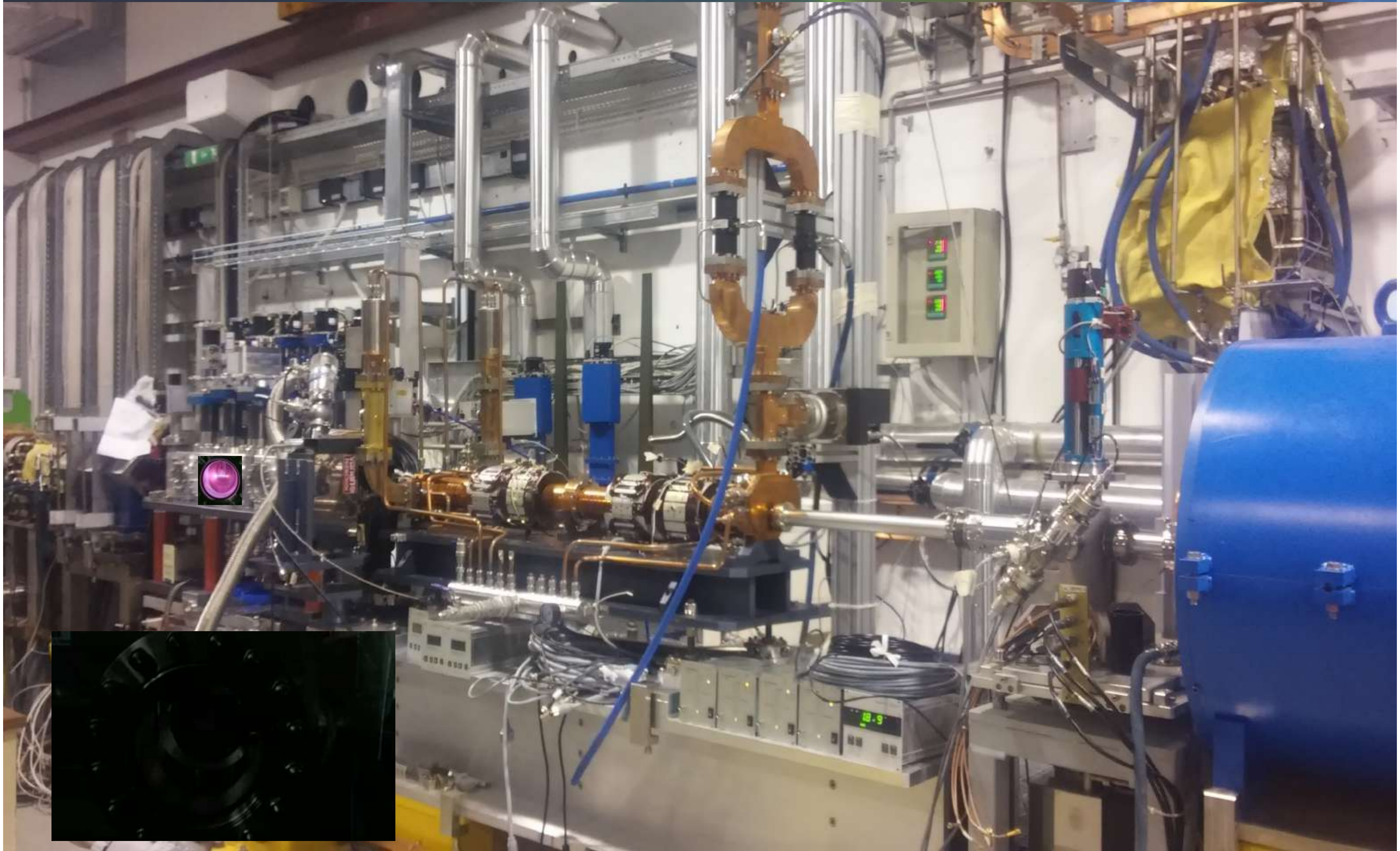
$$n_o = 10^{16}\ cm^{-3} \Rightarrow \lambda_p = 300\ \mu m$$

$$\omega_p = \sqrt{\frac{n_o e^2}{\varepsilon_o m_e}}$$

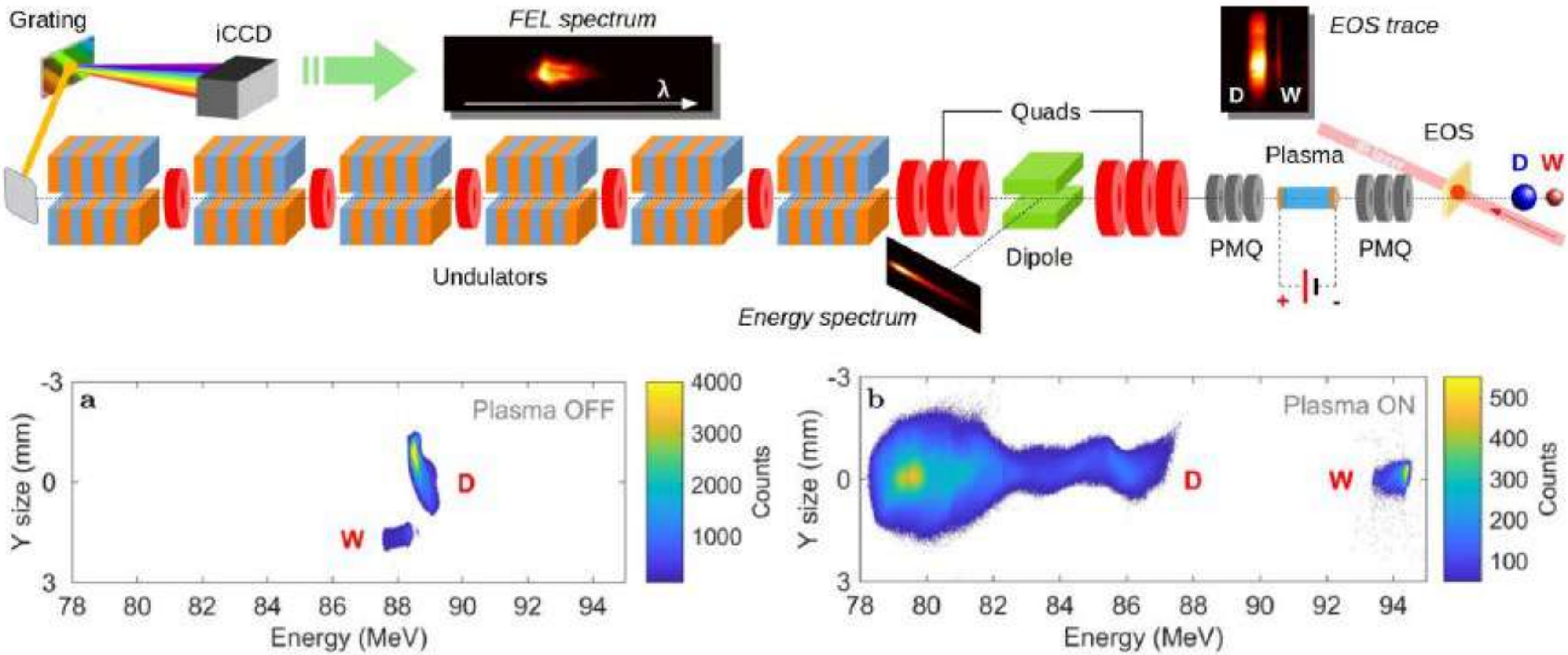
Laser Wakefield Accelerator (LWFA):
Drive beam = laser beam

Plasma WakeField Accelerator (PWFA):
Drive beam = high energy electron or proton beam

PWFA vacuum chamber at SPARC_LAB



Energy Spread Compensation at SPARC_LAB



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

Train configuration:

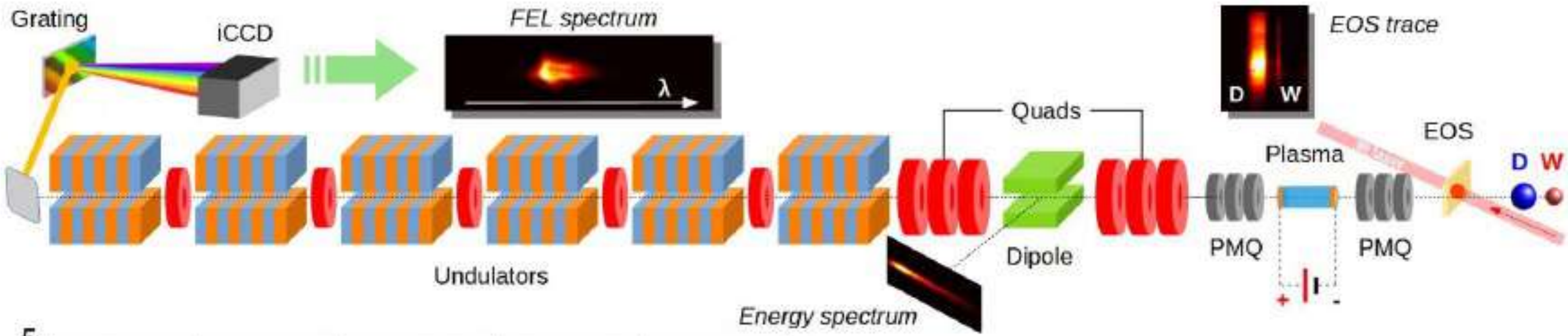
- 200 pC driver + 20 pC witness
- Separation between bunches ~1 ps
- Driver duration ~230 fs, witness ~30 fs

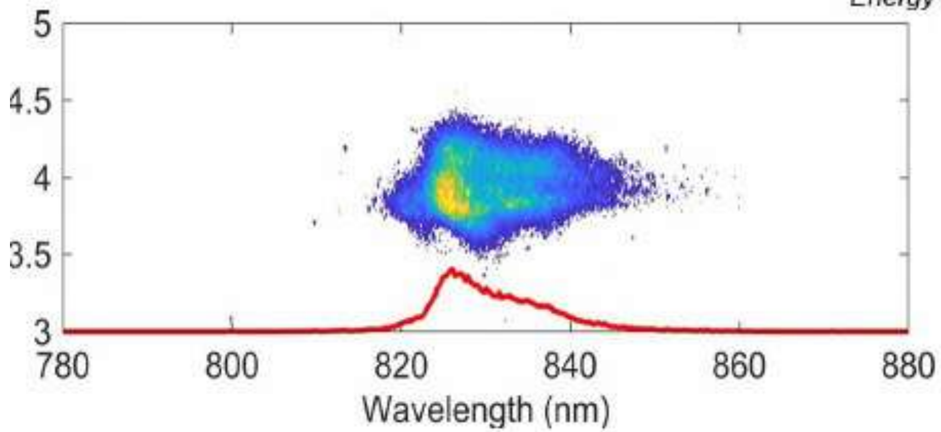
Witness after the plasma:

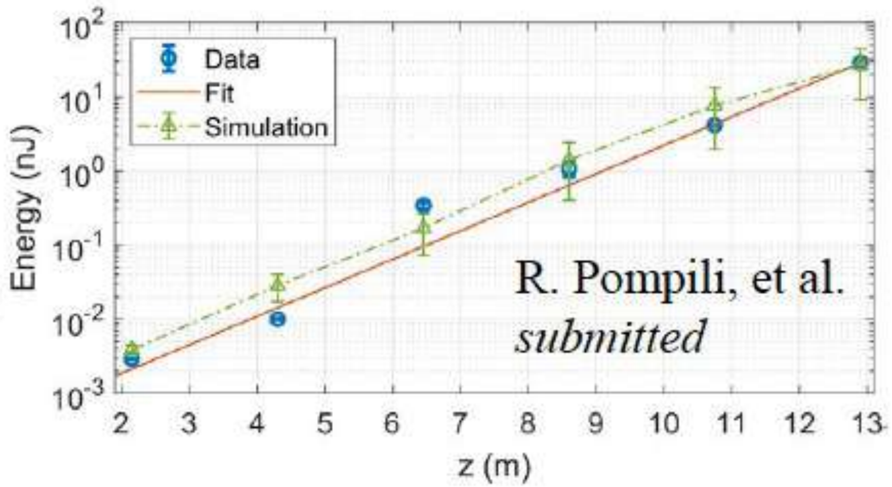
- Energy: 94 MeV (~200 MV/m gradient)
- Energy spread 0.3 MeV
- Emittance: 2.7(X) um, 1.3(Y) um

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)







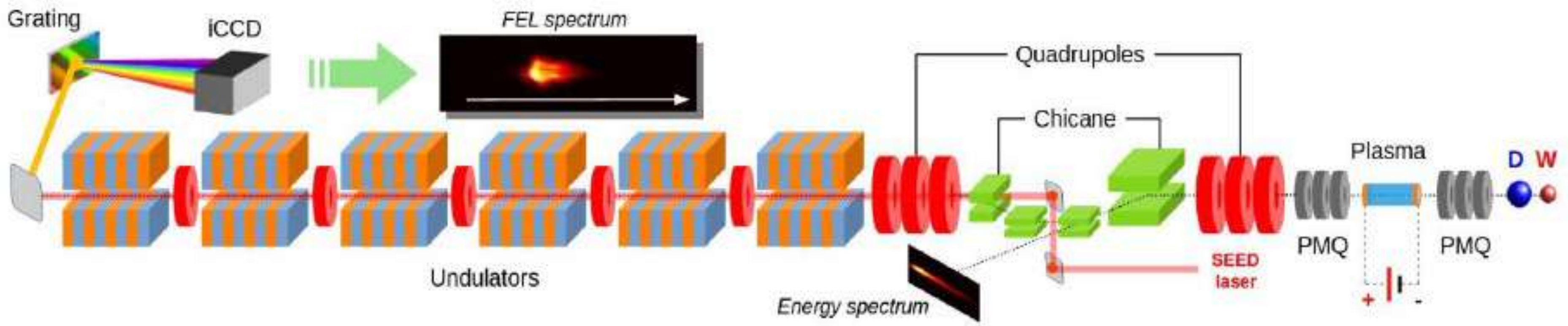
R. Pompili, et al. *submitted*

SASE FEL radiation:

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

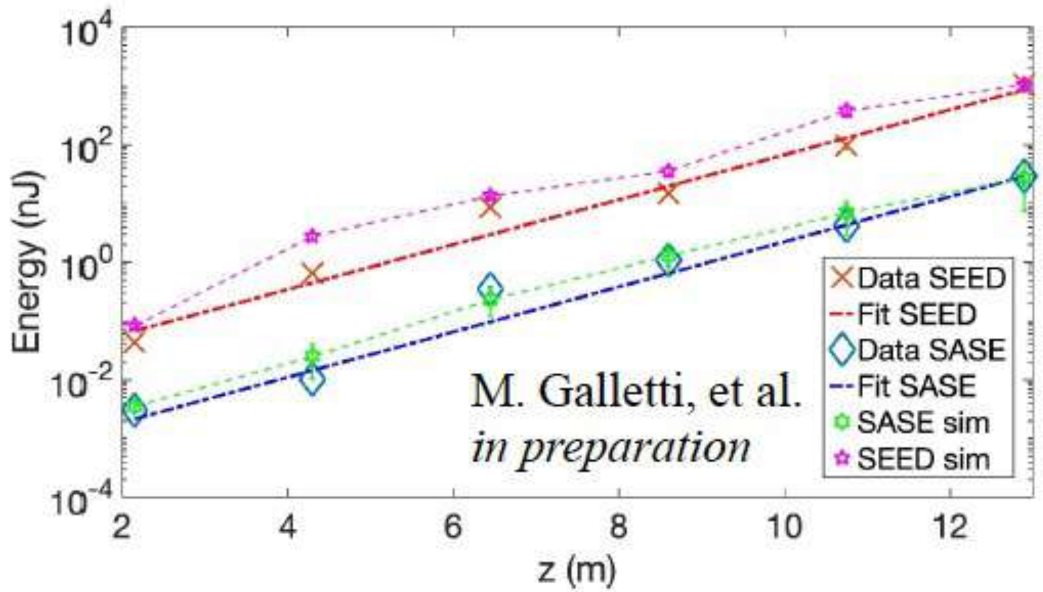
Exponential gain of FEL radiation energy

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

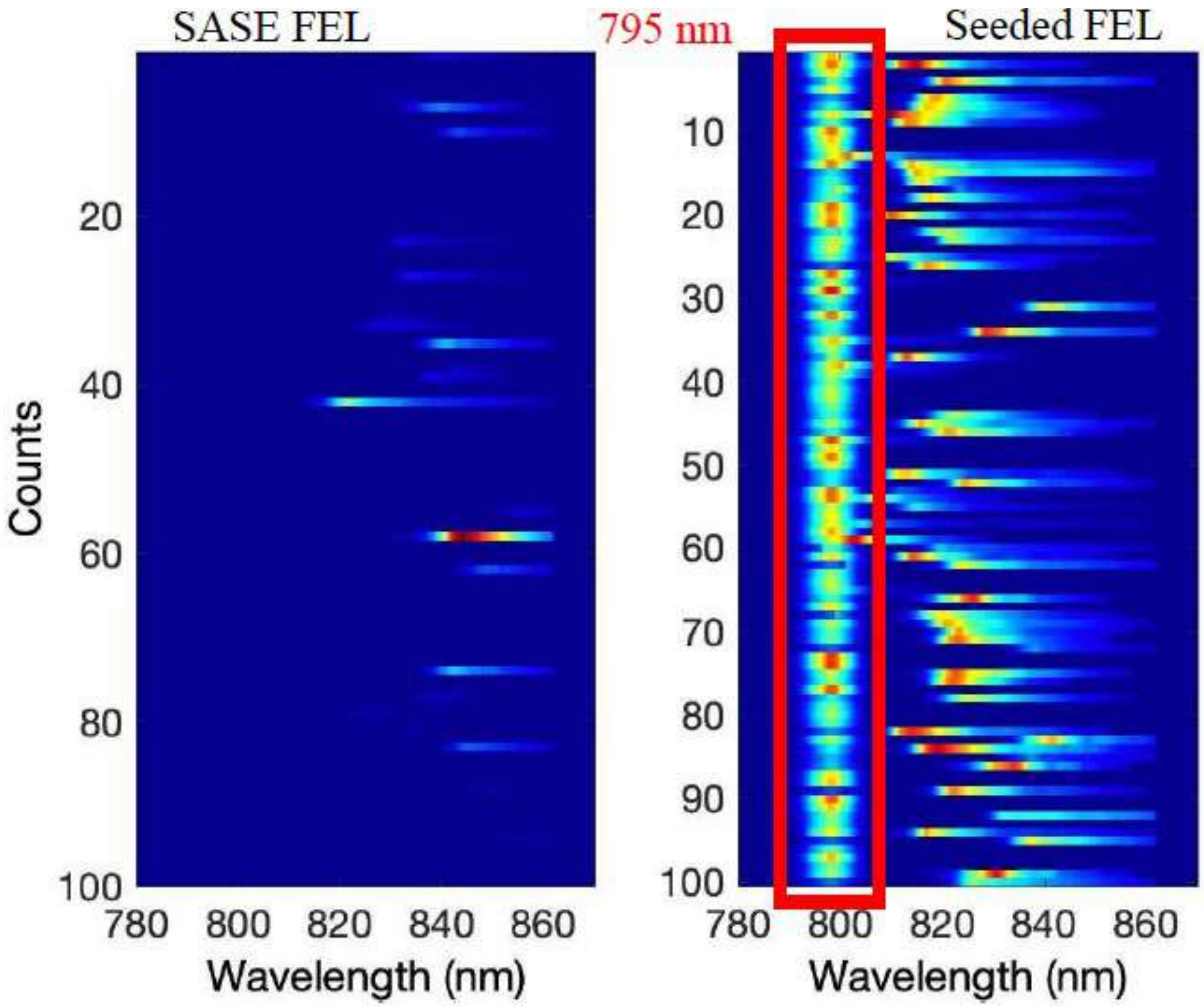


Seeded FEL radiation:

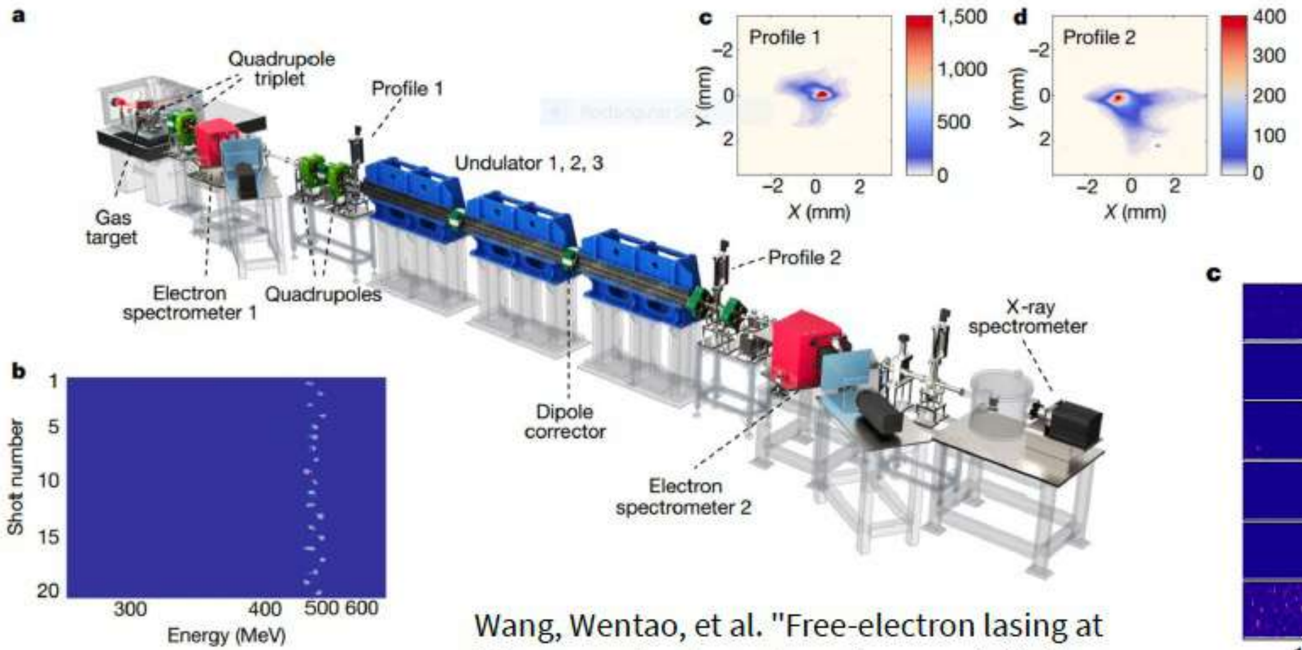
- part of the EOS laser was used as a seed;
- seed laser 795 nm, FEL peak still at 827 nm;
- pulse energy increase from ~30 nJ up to ~ 1 μJ;
- increased stability of radiation.



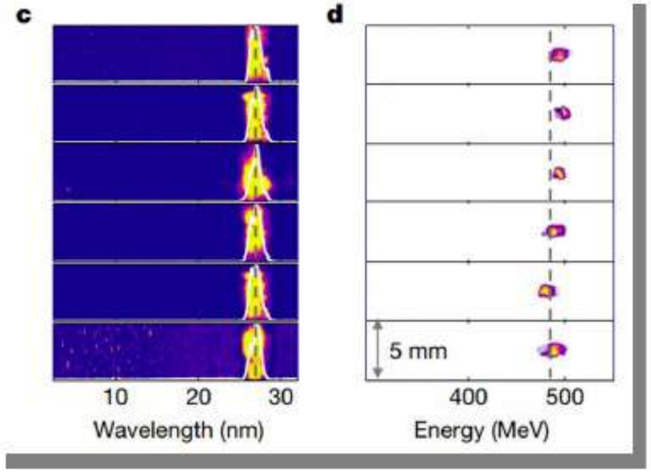
First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)



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*

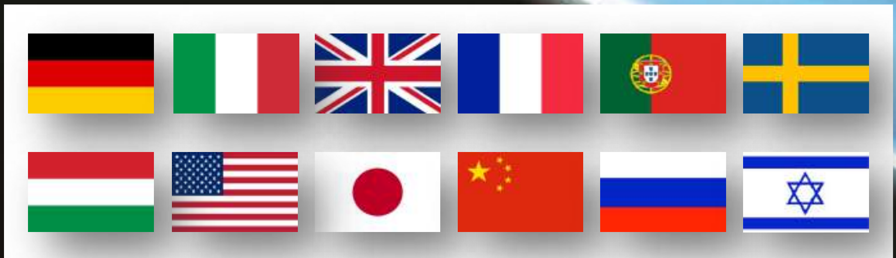
Peak energy ~ 490 MeV, 0.5% spread (measured), emittance 0.5 um (estimated)

Radiation energy from 0.5 to 150 nJ

EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

EuPRAXIA Design Study started on Novemebr 2015
Approved as HORIZON 2020 INFRADEV, 4 years, 3 M€
Coordinator: Ralph Assmann (DESY)



This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

http://eupraxia-project.eu

The EuPRAXIA Project

http://www.eupraxia-project.eu/

Horizon 2020

- First ever international design of a **plasma accelerator facility.**
- Challenges addressed by EuPRAXIA since 2015:
  - How **can plasma accelerators produce usable electron beams**?
  - **For what can we use those beams** while we increase the beam energy towards HEP and collider usages?
- **CDR for a distributed research infrastructure** funded by EU Horizon2020 program. Completed by 16+25 institutes.
- **Next phase consortium** with 40 partners, 10 observers.
- **Applied to ESFRI roadmap update 2021** with government support in Sep 2020.
- **Successful** and and placed on ESFRI roadma.

653 page CDR, 240 scientists contributed

Great News 30.6.2021

Building the first plasma accelerator facility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HOME > NEWS > LATEST ESFRI NEWS

ESFRI announces new RIs for Roadmap 2021

New RIs for Roadmap 2021 announced

Strategy Report on Research Infrastructures

ROADMAP **2021**

30.06.2021

PRESS RELEASE

ESFRI announces the 11 new Research Infrastructures to be included in its Roadmap 2021

€4.1 billion investment in excellent science contributing to address European challenges

After two years of hard work, following a thorough evaluation and selection procedure, ESFRI proudly announces the **11 proposals** that have been scored high for their science case and maturity for implementation and will be included as new Projects in the **ESFRI 2021 Roadmap Update**.

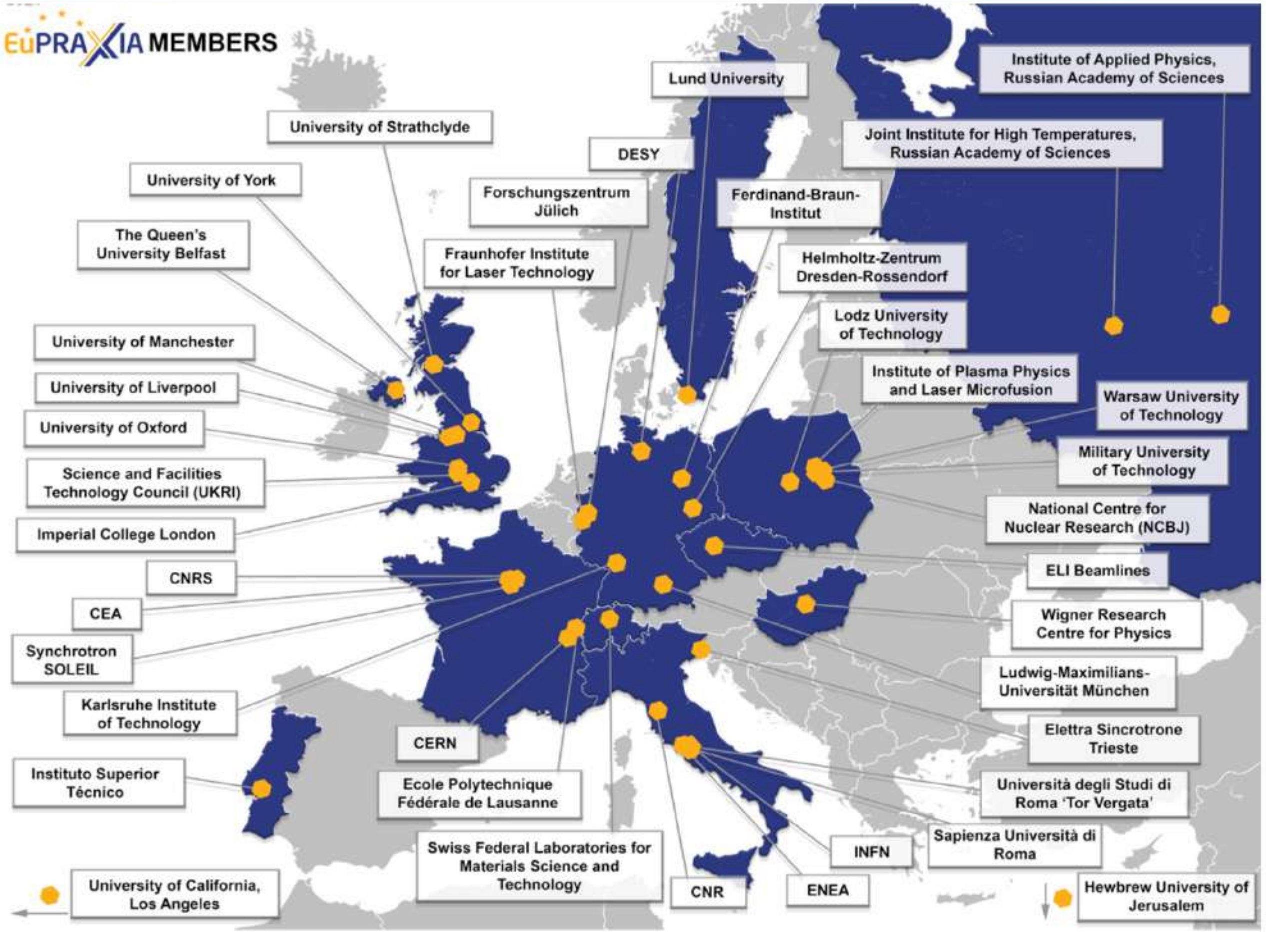
About the ESFRI Roadmap

ESFRI has established a European Roadmap for Research Infrastructures (new and major upgrades, pan-European interest) for the next 10-20 years, stimulates the implementation of these facilities, and updates the roadmap as needed. The ESFRI Roadmap arguably contains the best European science facilities based on a thorough evaluation and selection procedure. It combines ESFRI Projects, which are new Research Infrastructures in progress towards implementation, and ESFRI Landmarks successfully implemented Research Infrastructures enabling excellent science.

The Consortium Members for the Next Phase

(from 16 to 40)

Horizon 2020



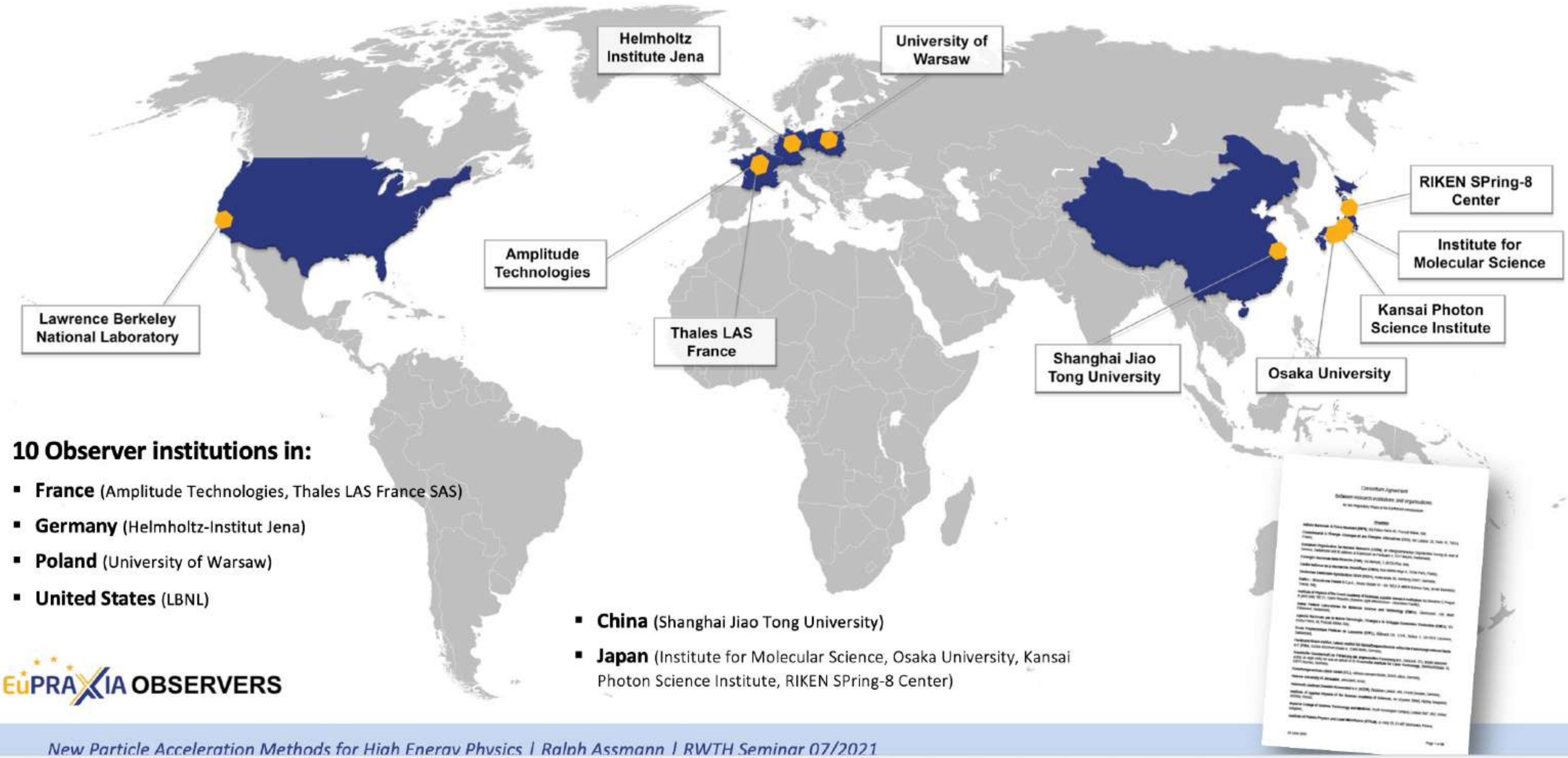
40 Member institutions in:

- **Italy** (INFN, CNR, Elettra, ENEA, Sapienza Università di Roma, Università degli Studi di Roma "Tor Vergata")
- **France** (CEA, SOLEIL, CNRS)
- **Switzerland** (EMPA, Ecole Polytechnique Fédérale de Lausanne)
- **Germany** (DESY, Ferdinand-Braun-Institut, Fraunhofer Institute for Laser Technology, Forschungszentrum Jülich, HZDR, KIT, LMU München)
- **United Kingdom** (Imperial College London, Queen's University of Belfast, STFC, University of Liverpool, University of Manchester, University of Oxford, University of Strathclyde, University of York)
- **Poland** (Institute of Plasma Physics and Laser Microfusion, Lodz University of Technology, Military University of Technology, NCBJ, Warsaw University of Technology)
- **Portugal** (IST)
- **Hungary** (Wigner Research Centre for Physics)
- **Sweden** (Lund University)
- **Israel** (Hebrew University of Jerusalem)
- **Russia** (Institute of Applied Physics, Joint Institute for High Temperatures)
- ***United States*** (UCLA)
- **CERN**
- **ELI Beamlines**

The Consortium Observers for the Next Phase

(from 25 to 10, Consortium Agreement signed)

Horizon 2020



10 Observer institutions in:

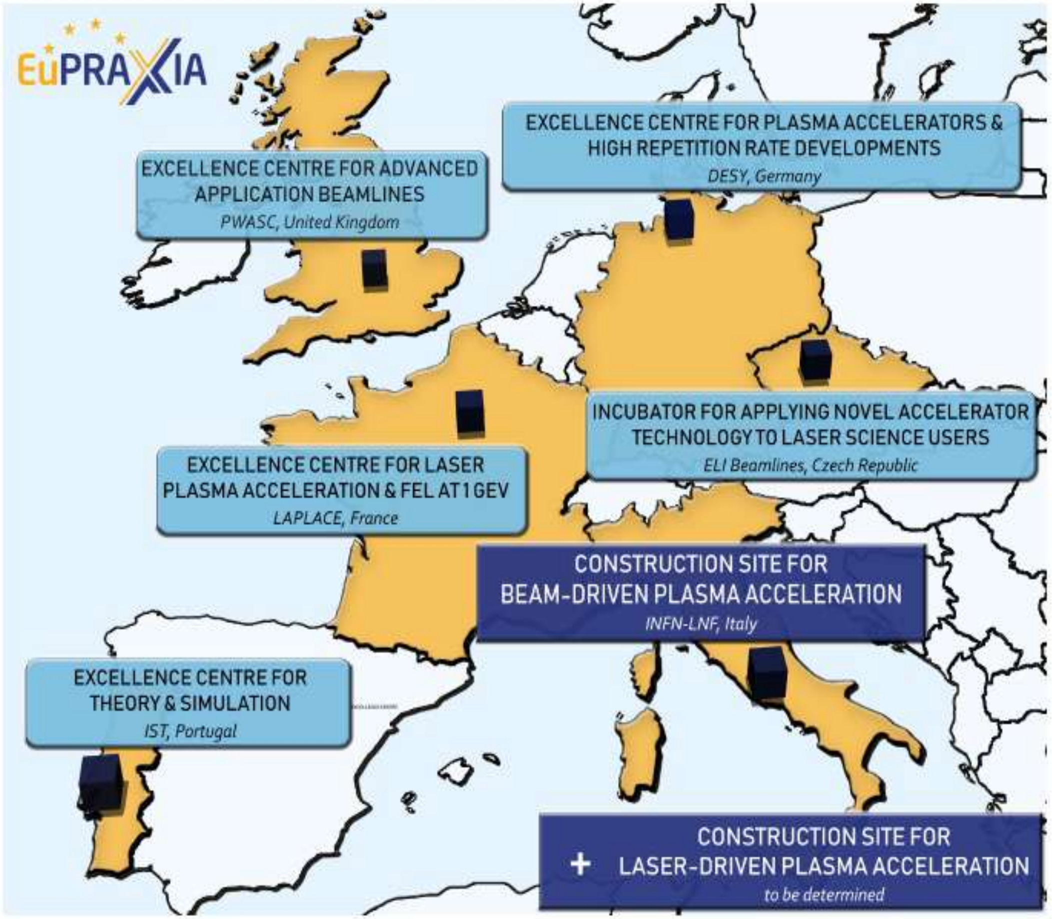
- **France** (Amplitude Technologies, Thales LAS France SAS)
- **Germany** (Helmholtz-Institut Jena)
- **Poland** (University of Warsaw)
- **United States** (LBNL)
- **China** (Shanghai Jiao Tong University)
- **Japan** (Institute for Molecular Science, Osaka University, Kansai Photon Science Institute, RIKEN SPring-8 Center)

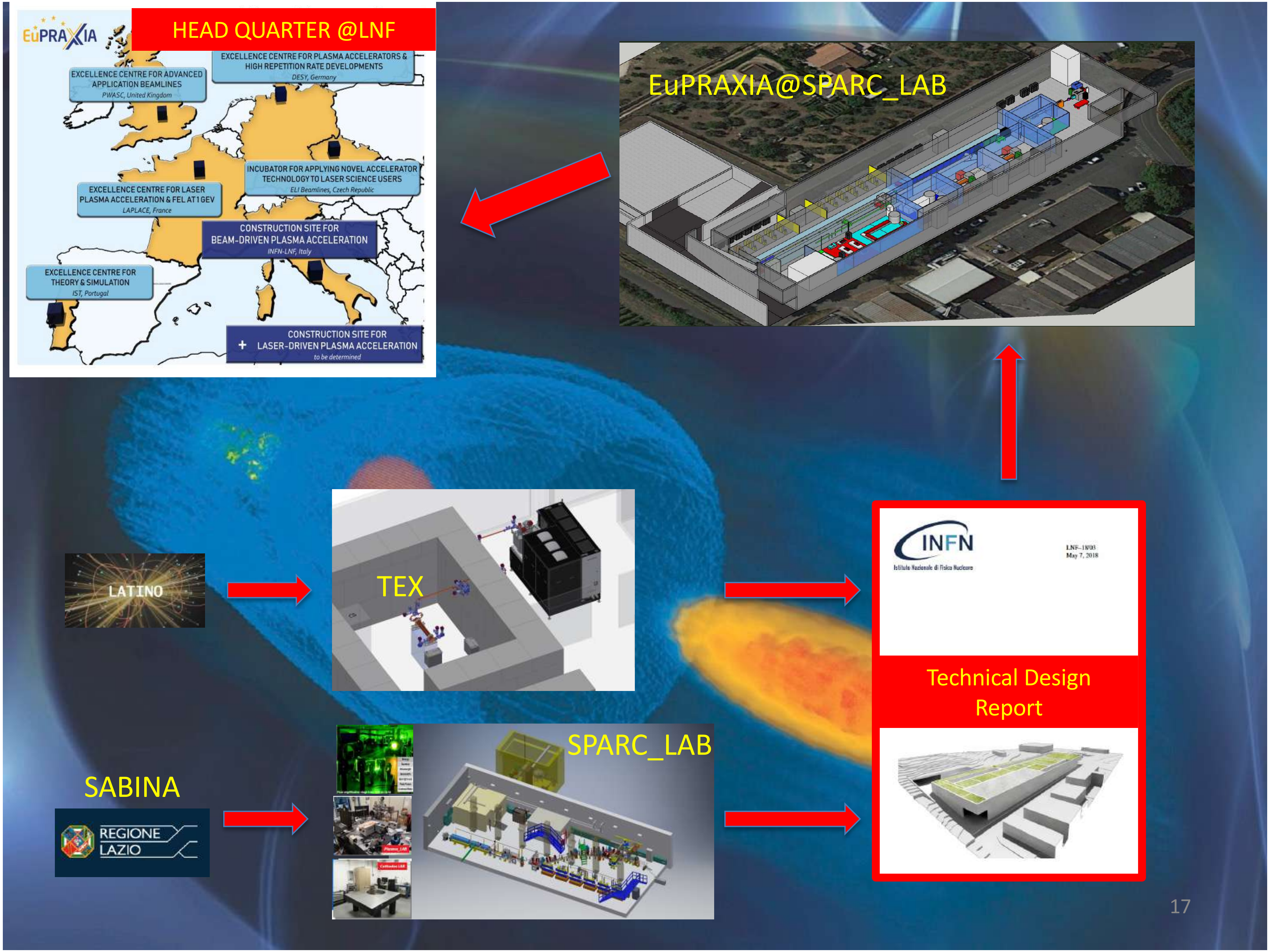
EuPRAXIA OBSERVERS

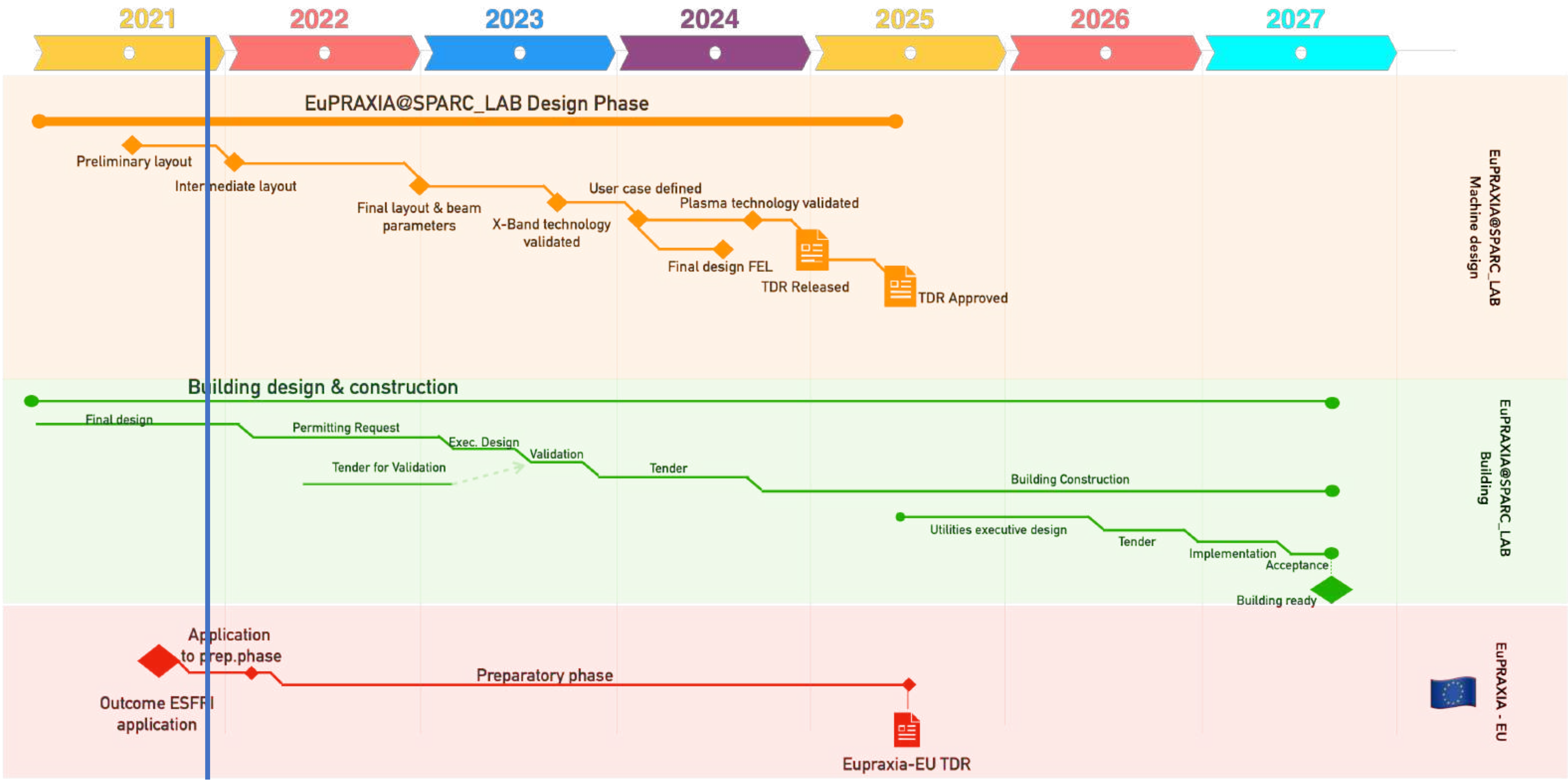
… and Builds a European Distributed Facility

Position Europe as a Leader in the Global Context

1. Lean overall **EuPRAXIA management**
2. **Ten clusters:** Collaborations of institutes on specific problems, developing solutions, technical designs, driving developments with EuPRAXIA generated funding → **expertise of Helmholtz centers required - opportunities**
3. **Five excellence centers** at existing facilities: Using pre-investment, support tests, prototyping, production with EuPRAXIA generated funding → **DESY excellence center**
4. **One or two construction sites** at existing facilities with EuPRAXIA generated funding:
   - **Beam-driven** at Frascati (Italy).
   - **Laser-driven** at CLF/STFC (UK), CNR/ INFN (Italy) or ELI-Beamlines.

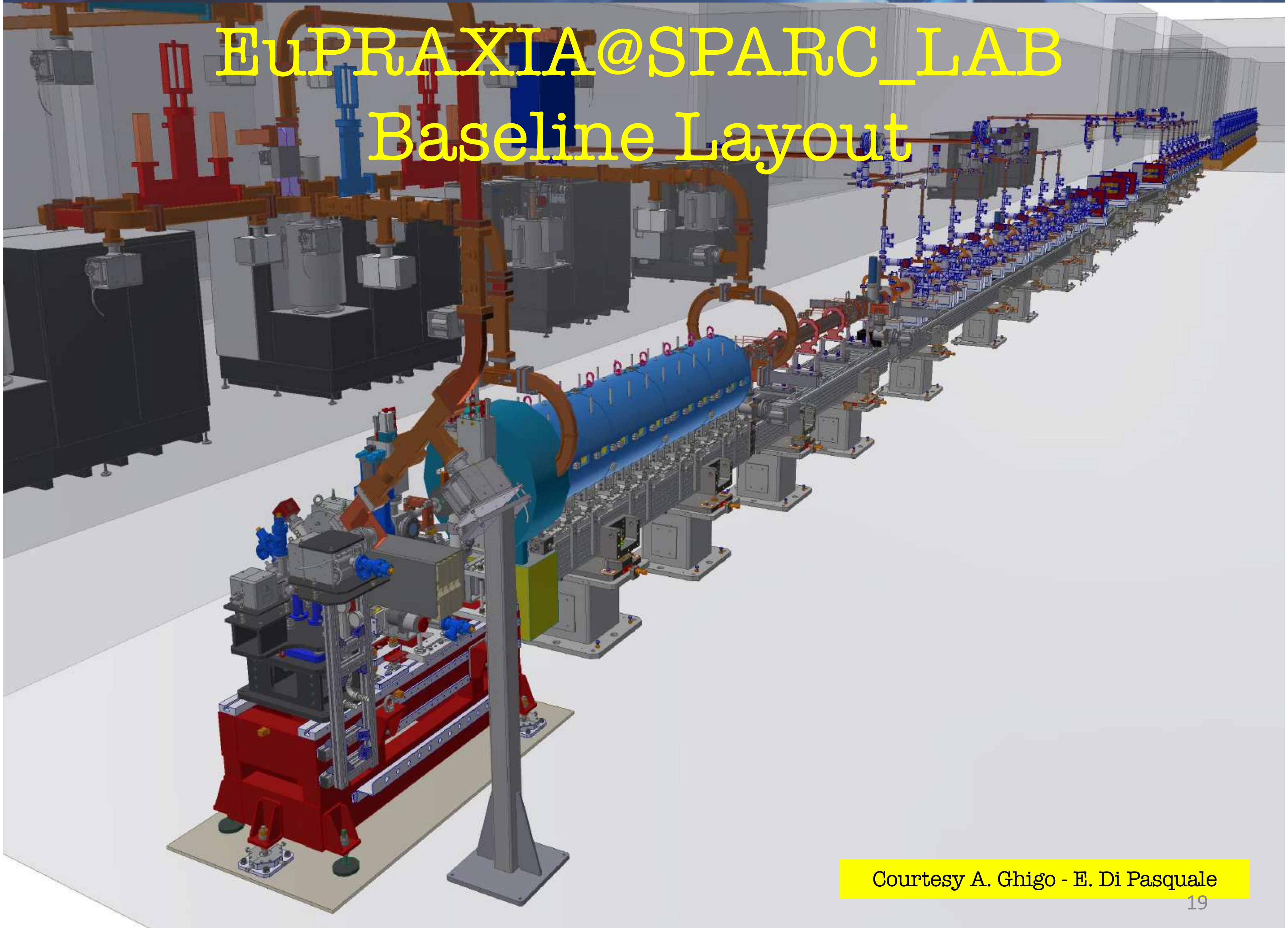



HEAD QUARTER @LNF
EuPRAXIA
EXCELLENCE CENTRE FOR PLASMA ACCELERATORS & HIGH REPETITION RATE DEVELOPMENTS
DESY, Germany
EXCELLENCE CENTRE FOR ADVANCED APPLICATION BEAMLINES
PWASC, United Kingdom
INCUBATOR FOR APPLYING NOVEL ACCELERATOR TECHNOLOGY TO LASER SCIENCE USERS
ELI Beamlines, Czech Republic
EXCELLENCE 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
17



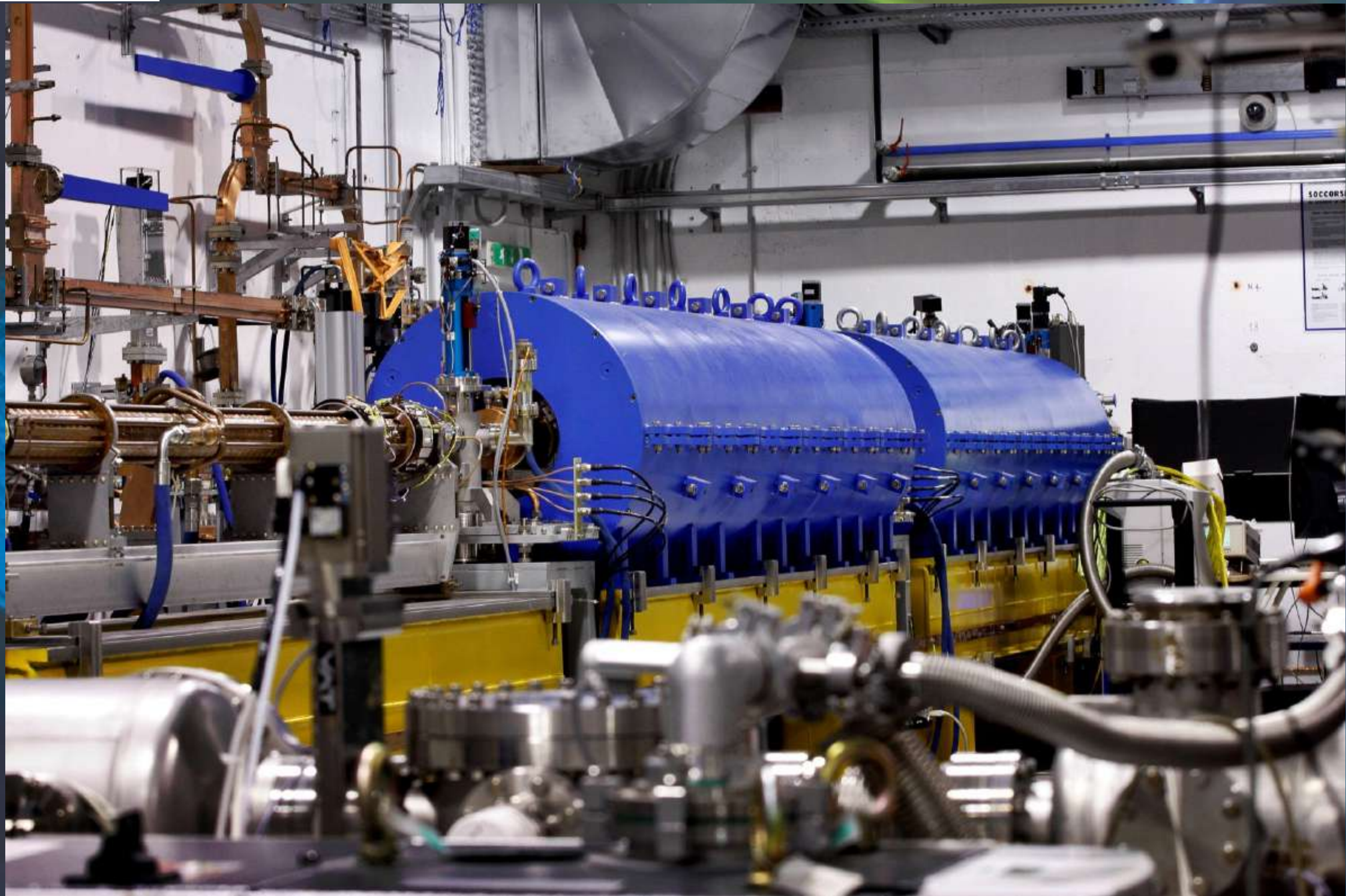
Courtesy A. Falone

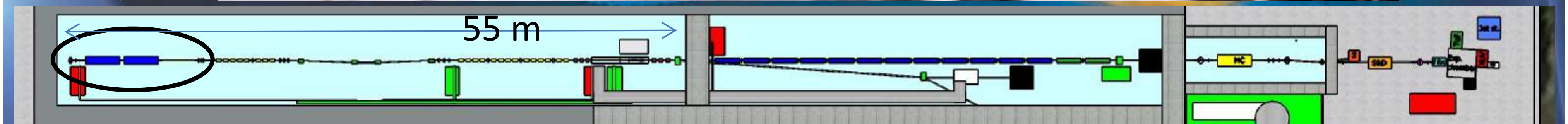
EuPRAXIA@SPARC_LAB Baseline Layout



Courtesy A. Ghigo - E. Di Pasquale

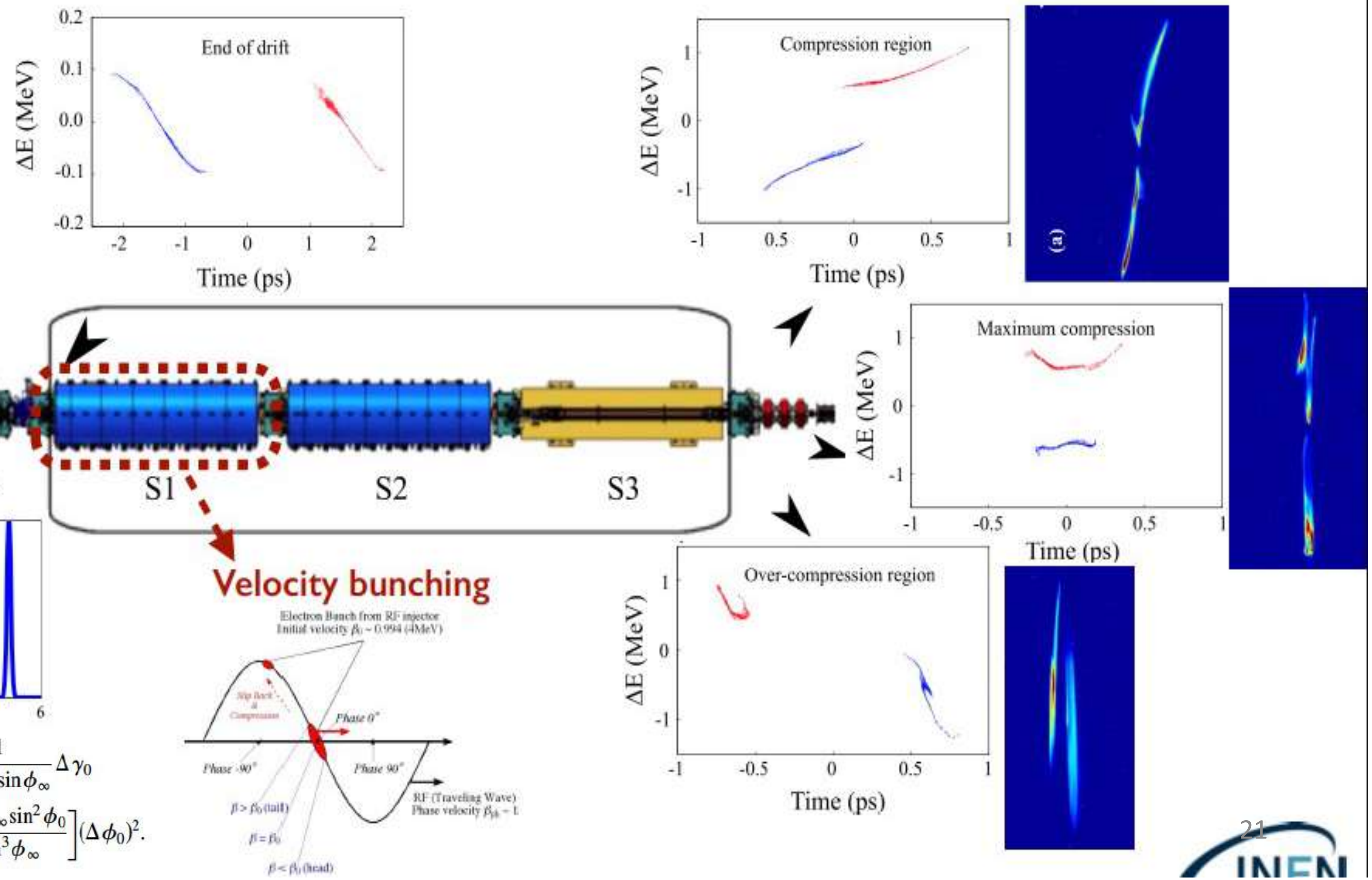
SPARC_LAB HB photo- injector



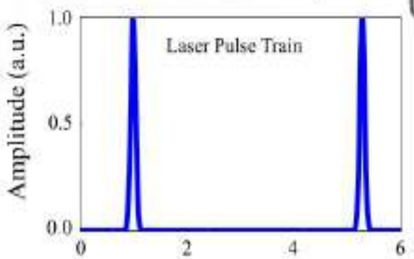


Generation of multi-bunch trains

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



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

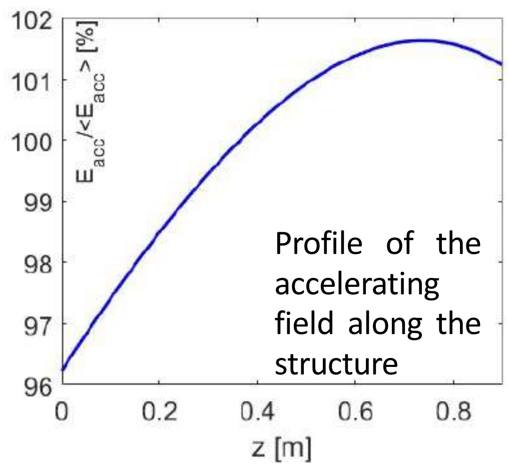
X-band Linac

X BAND STRUCTURES: PARAMETERS

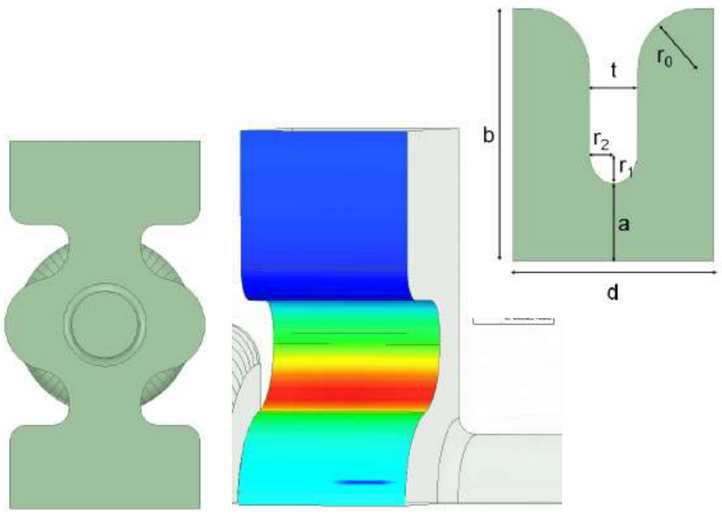
1. **e.m. design**: **linear tapering of the irises**, race track coupler to cancel the quadrupole field components (*PhD M. Diomede*);

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

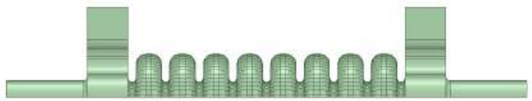
3. **60 MV/m** average accelerating field

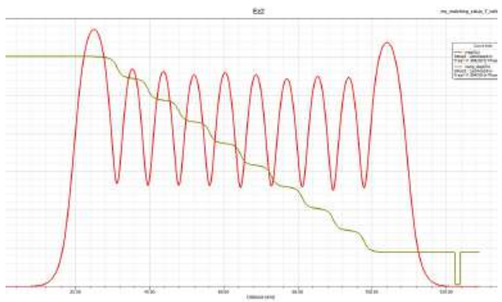


Profile of the accelerating field along the structure



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**

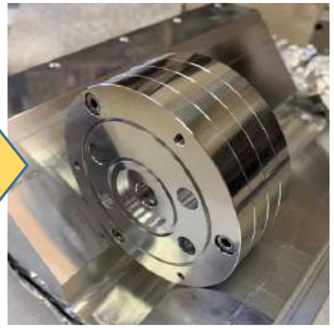
$$R_s = \frac{G^2 L}{P_{kly}}$$

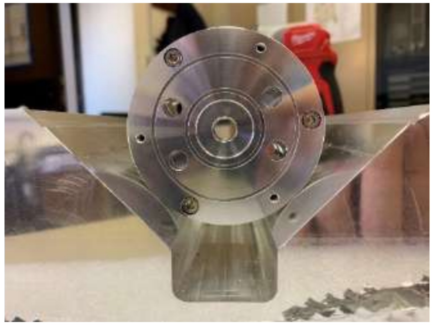
G=average accelerating gradient
L=structure length
P_{kly}=klystron power (pre-sled pulse)

X-BAND STRUCTURE PROTOTYPING ACTIVITIES: REALIZATIONS

Realization

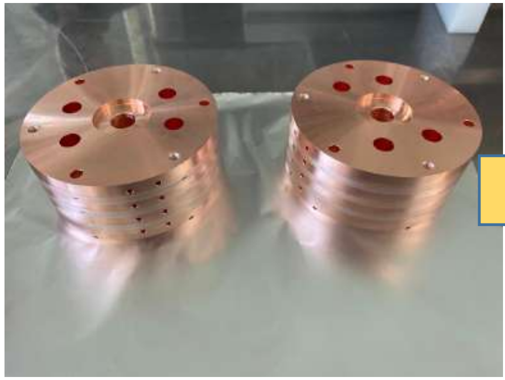
Assembly





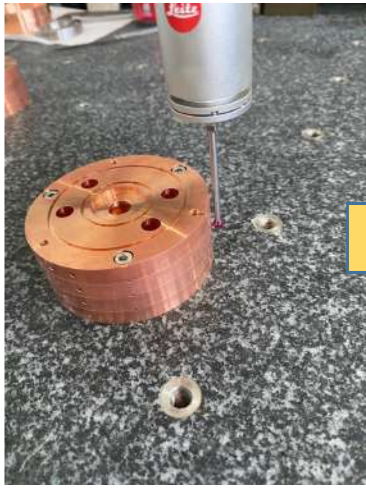
Characterization CMC

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

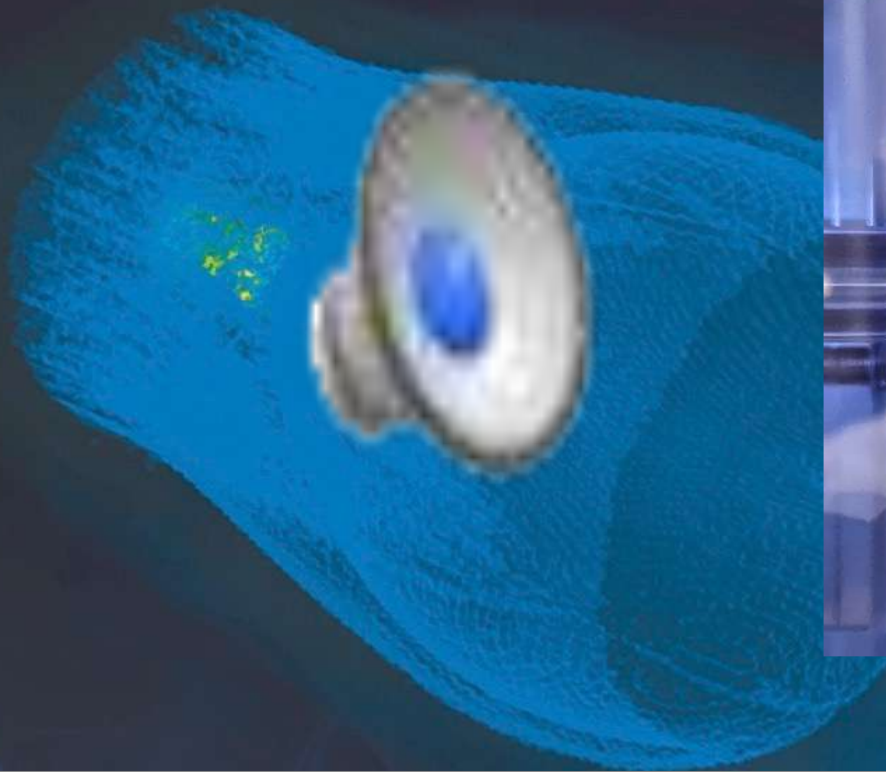
- The *TEst-stand for X-band* (**TEX**) is a facility conceived for R&D on high gradient X-band accelerating structures and waveguide components in view of Eupraxia@SPARC_LAB project.
- It has been co-funded by Lazio regional government in the framework of **the LATINO project** (*Laboratory in Advanced 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.

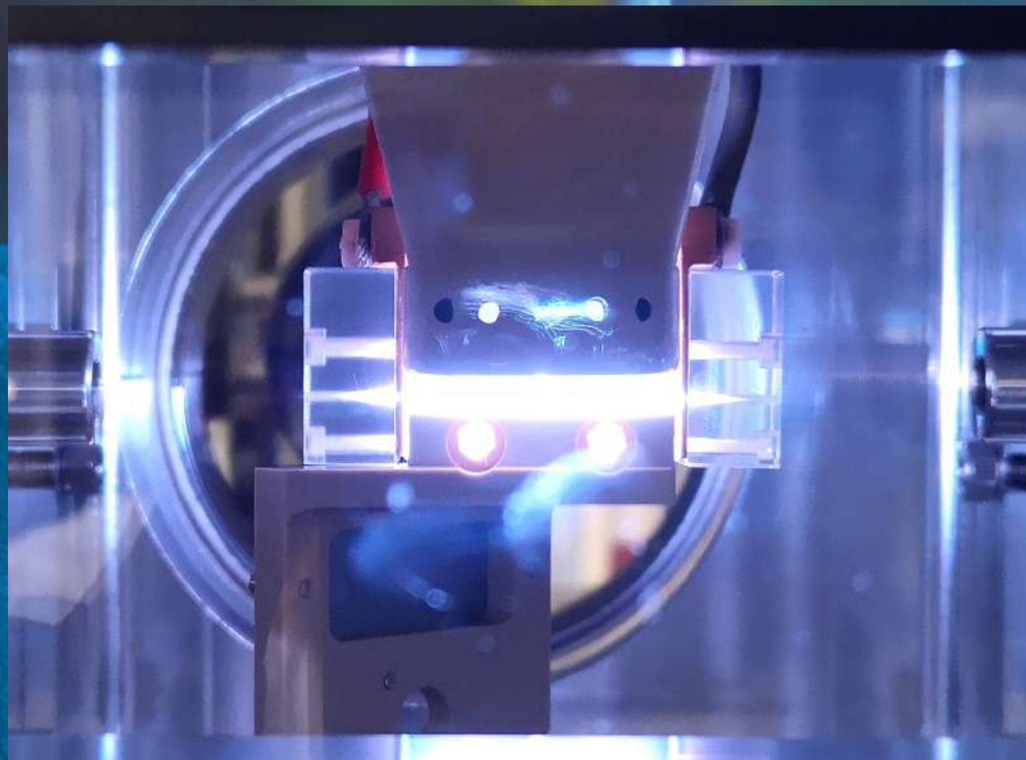
Concrete shielded Bunker and Modulator Cage

Control room and Rack room

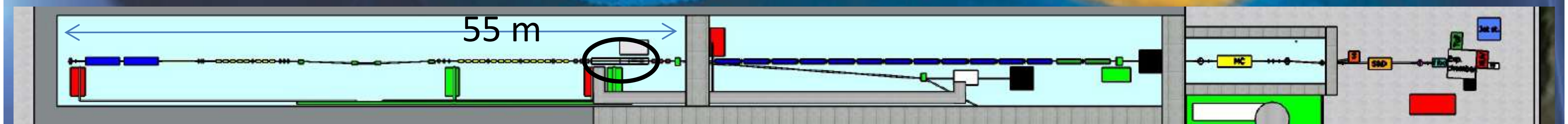
Courtesy S. Pioli

Plasma WakeField Acceleration

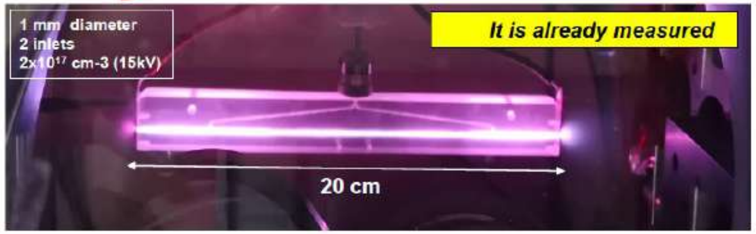




Capillary discharge at SPARC_LAB

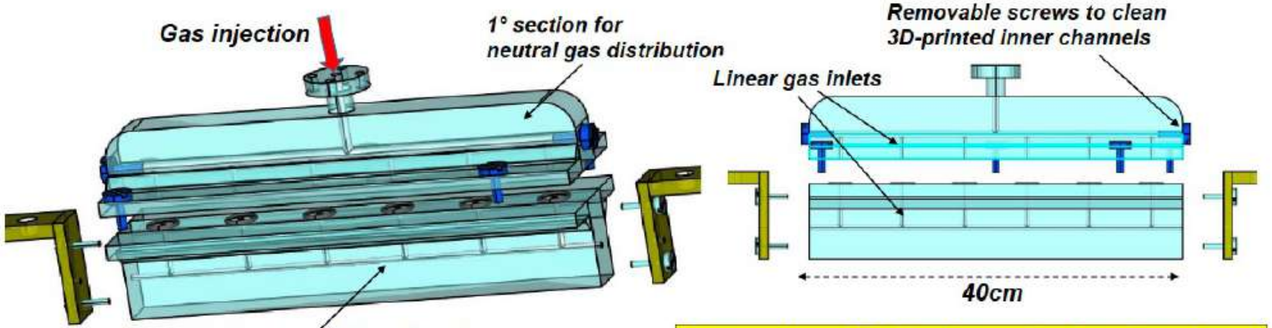


40 cm-long Gas-filled discharge-capillary



Paschen curves (50 mbar)

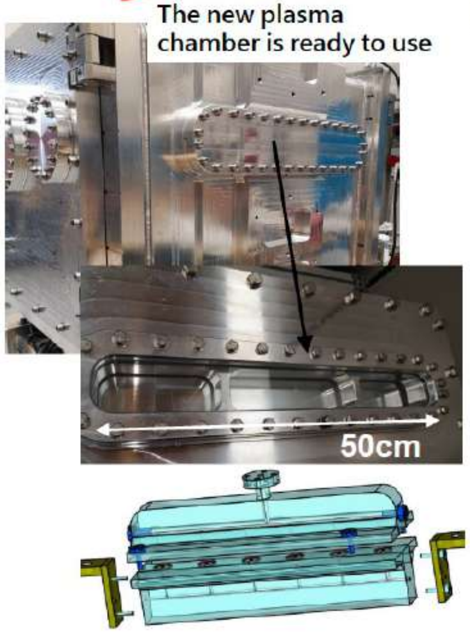
Length	Density	Vb
3 cm	$4x10^{16}$ cm-3	3 kV
10 cm	$4x10^{16}$ cm-3	8 kV
20 cm	$4x10^{16}$ cm-3	14 kV
40 cm	$4x10^{16}$ cm-3	23 kV



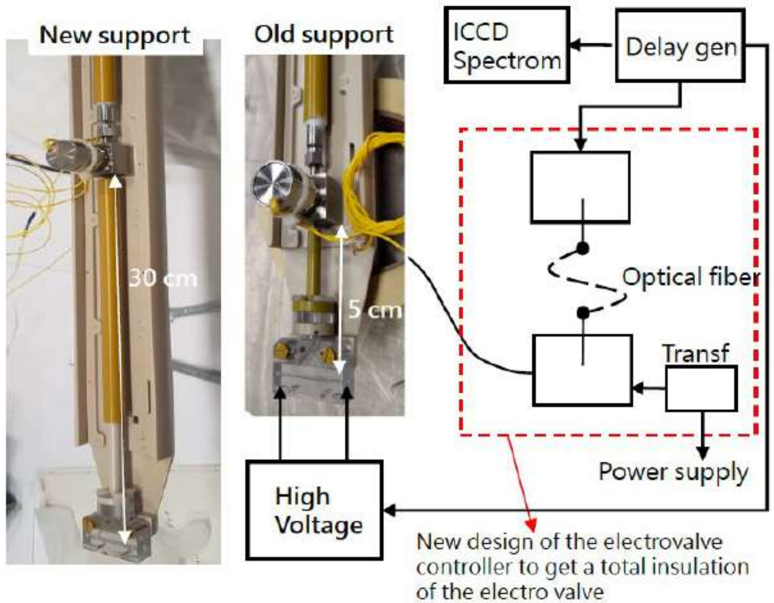
Linear channel/inlets allow us to clean them from printing residuals

40cm-long Gas-filled discharge-capillary

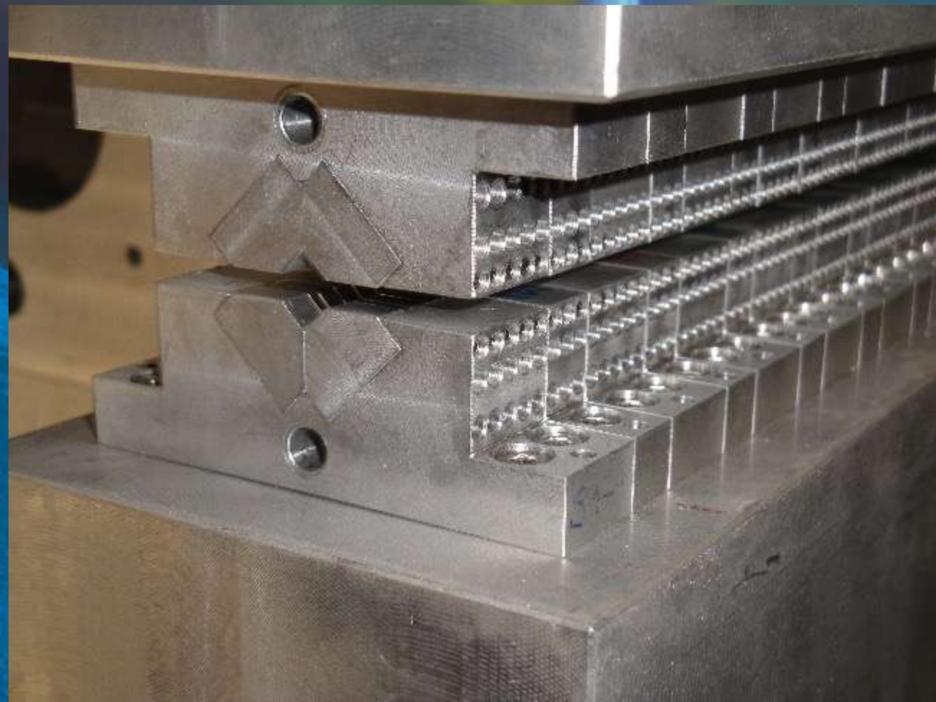
The new plasma chamber is ready to use



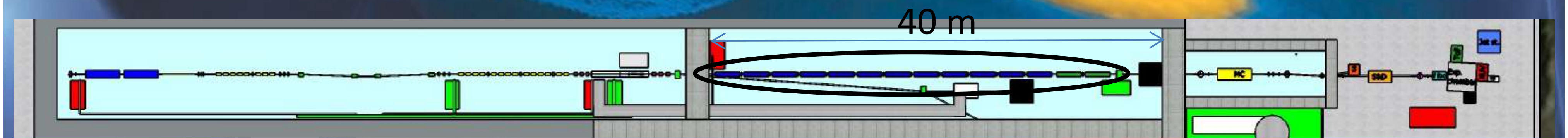
A crucial point to produce a gas discharge is the insulation of others components of the plasma module with respect to the HV pulse



Undulators



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



Undulator technology

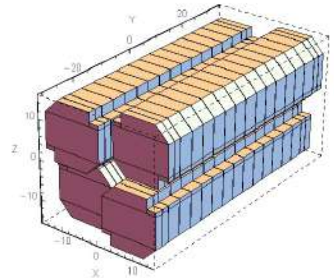
Superconducting Undulator

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

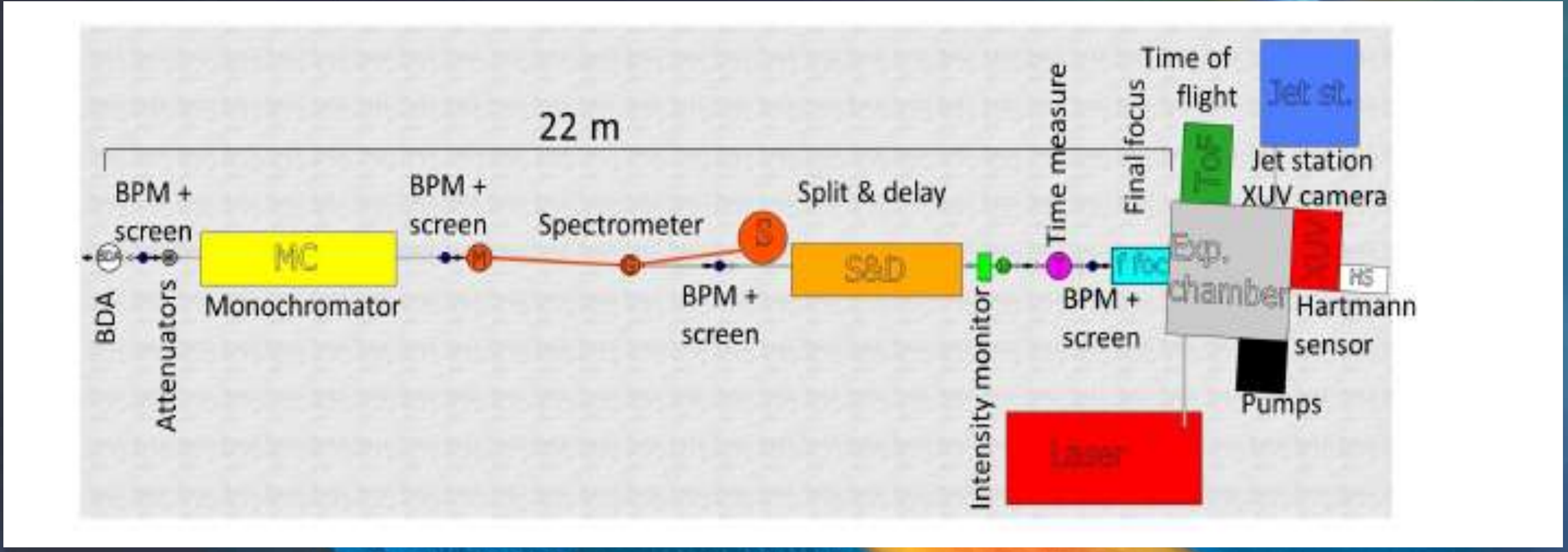
Period increased to 18 mm to increase tuning range.

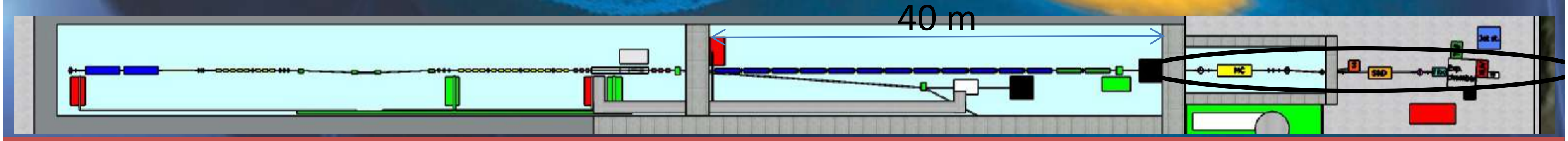
Unconventional undulator design: prototyping required

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





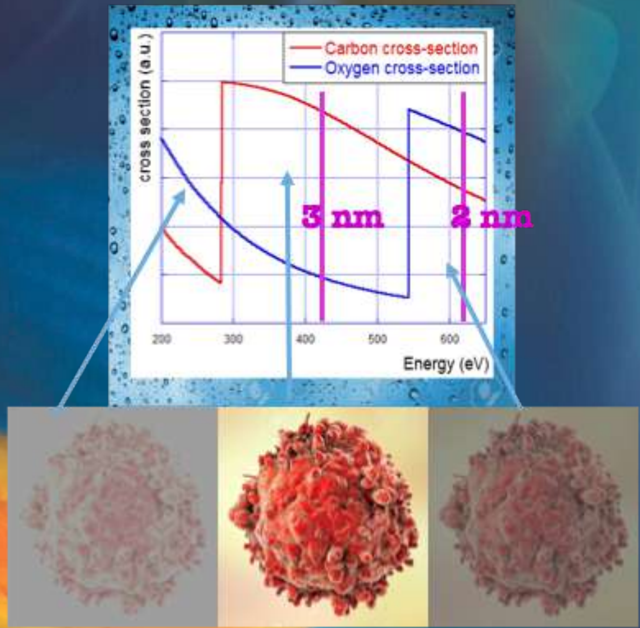
Expected SASE FEL performances

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

AQUA - Techniques & Samples @ 3 nm

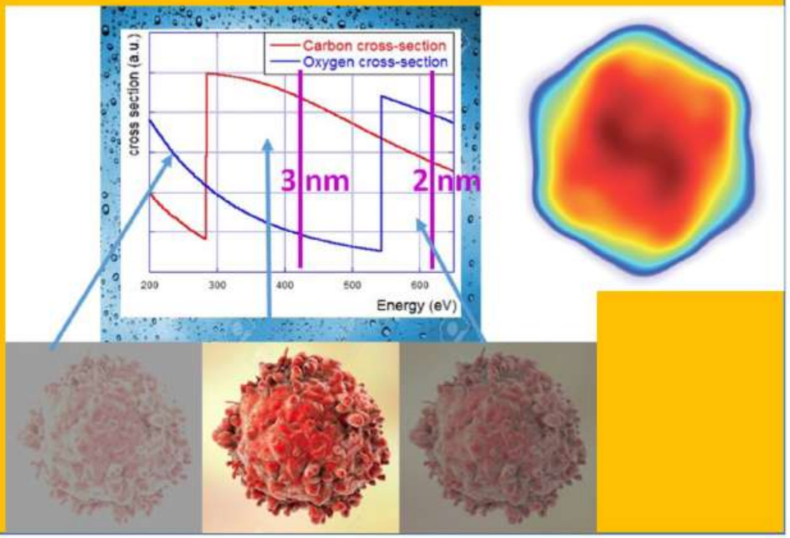
Scientific case assembled and published.
Contributions from >15 different institutions

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

Bio & Inorganic Samples

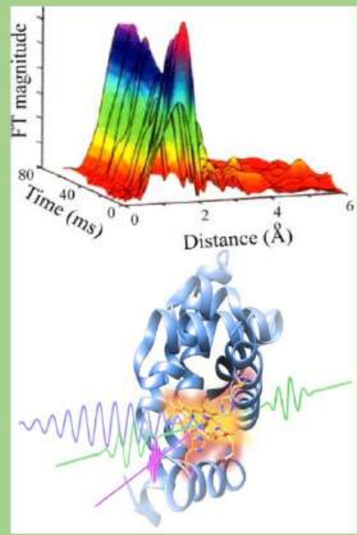
Proteins - Viruses
Bacteria- Cells
Metals – Magnetic materials
Superconductors -Semiconductors

Coherent imaging



X-ray absorption spectroscopy

Raman spectroscopy



ARIA - Techniques & Samples @ 50-180 nm

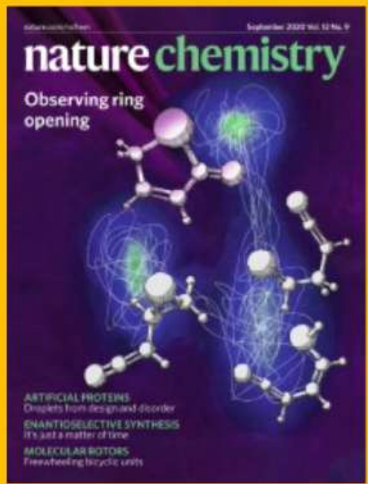
Scientific case in the DUV (DeepUV) and VUV (VacuumUV) is being assembled
Wavelength interval **complementary** with FEL1 @ Fermi

Samples & (techniques)

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

Photoemission Spectroscopy

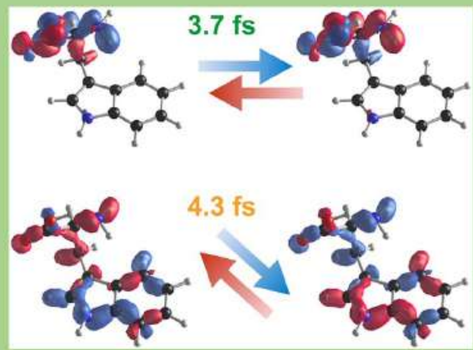
Ring opening in organic molecules
Pathak *et al. Nature Chemistry* 2020



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