Web Seminar at IJCLab Orsay - June 25th, 2021

From SPARC_LAB to EuPRAXIA@SPARC_LAB: recent results and project status

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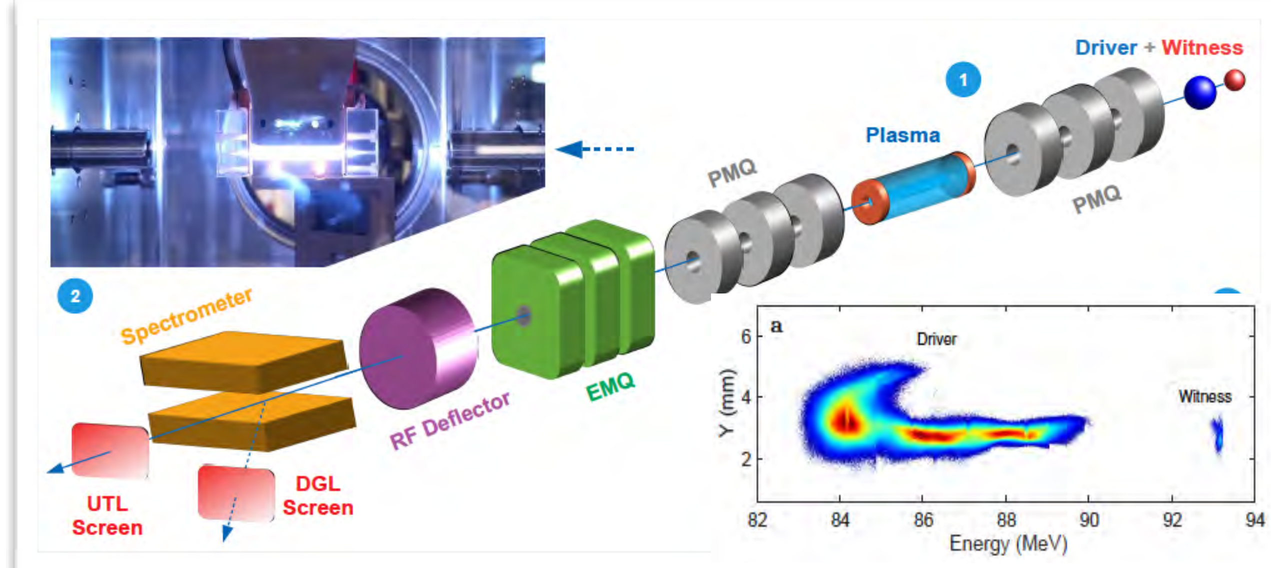
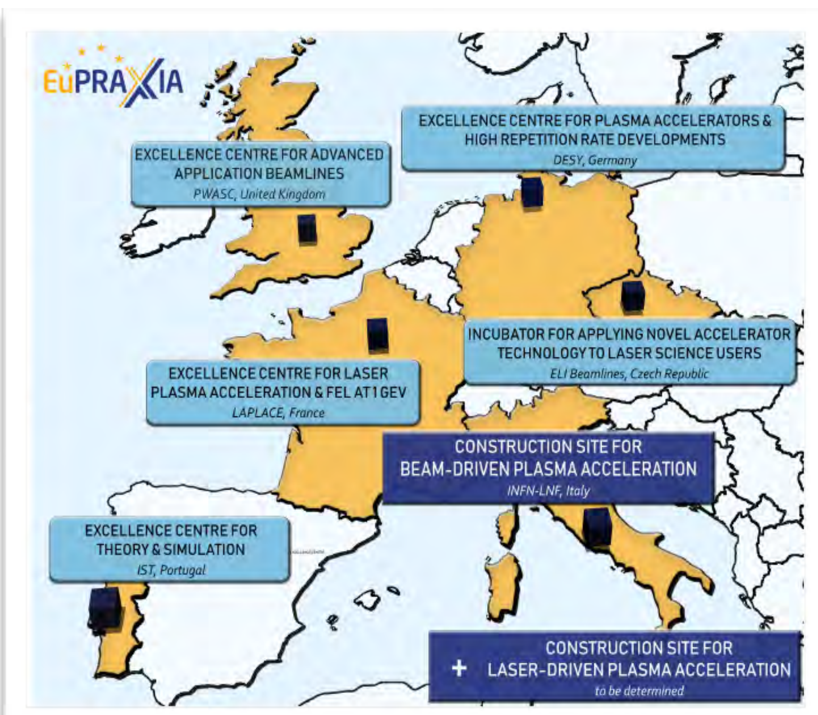
LABORATORI NAZIONALI DI FRASCATI

Outline

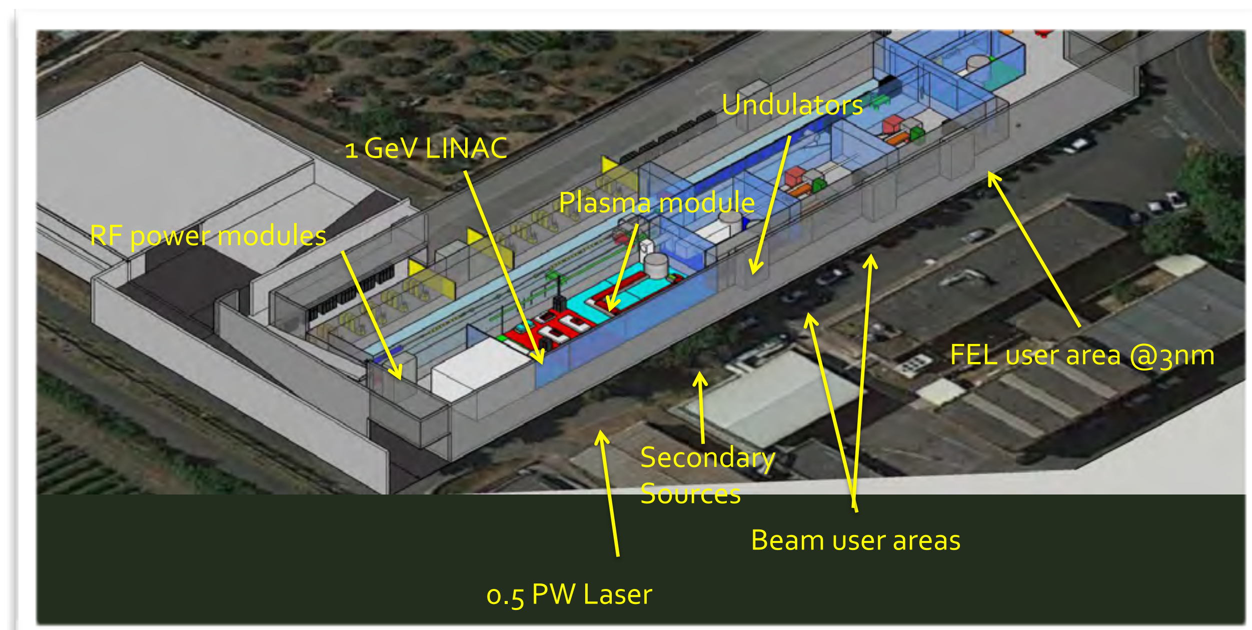
- Plasma-based R&D activities at SPARC_LAB





- EuPRAXIA concept distributed research infrastructure

- EuPRAXIA@SPARC_LAB test user facility
  - Performances and time schedule



Motivation

✓ **Plasma-based acceleration has already proved the ability to reach ultra-high, ~GV/m, accelerating gradients**

- J. Rosenzweig et al., Phys. Rev. Lett. **61**, 98 (1988): *First experimental demonstration of PWFA*
- Mangles, Geddes, Faure et al., Nature **431**, (2004): *The dream beam*
- W. P. Leemans, Nature Physics vol. **2**, p.696-699 (2006): *GeV electron beams from a centimetre-scale accelerator*
- I. Blumenfeld et al., Nature **445**, p. 741 (2007): *Doubling energy in a plasma wake*
- P. Muggli et al, in Proc. of PAC 2011, TUOBN3: *Driving wakefields with multiple bunches*

➡ The **next step** is the acceleration, extraction and transport of **stable and reliable high brightness electron beams** to **drive a plasma-based user facility** (the EUPRAXIA Design Study has been funded from EU)

- M. Litos et al., Nature **515**, 92 (2014): *High efficiency acceleration in the driver-trailing bunches*
- S. Steinke et al., Nature **000** (2016) doi:10.1038/nature16525: *Multi-stage coupling*

➡ **Plasma-based user facility**

- EuPRAXIA@SPARC_LAB Test User Facility

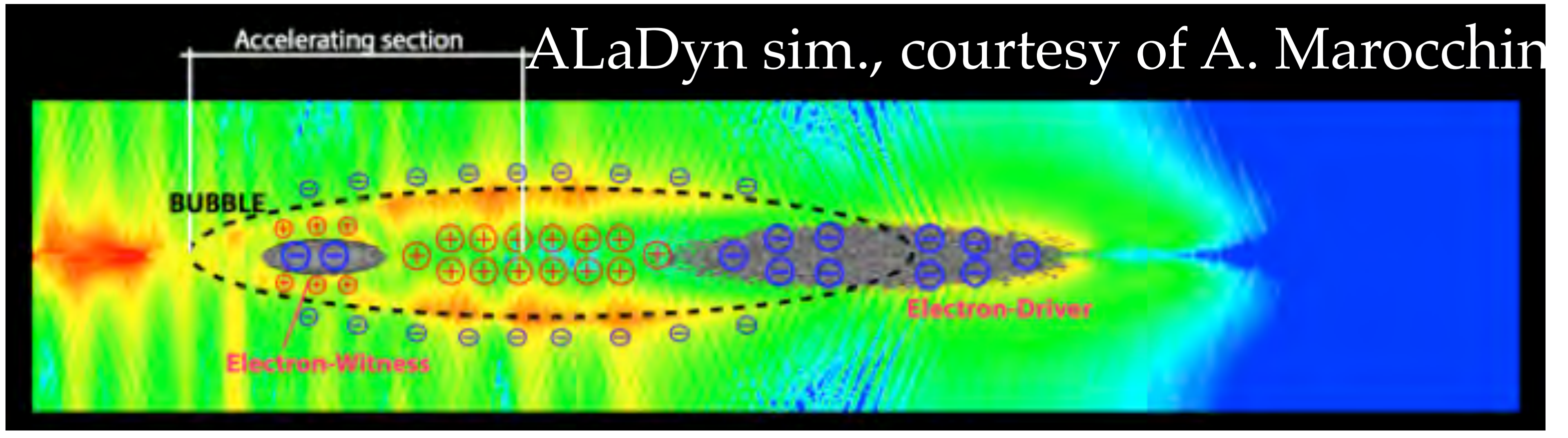
Advanced Accelerators Concepts

- **Conventional RF structures** reached a **practical limit**: they cannot sustain accelerating gradients larger than ~100 MV/m (X-band structures) due to **breakdown** on the wall surfaces
- **Ultra-high gradients** require structures to sustain high fields
  - **Plasma-filled structures**
    - Maximum accelerating field a plasma can sustain: **Wave breaking field**

$$E_{Max}[V/m] = \frac{m_e c \omega_p}{e} \approx 100\sqrt{n_0[cm^{-3}]} \qquad n_0 = 10^{16} \div 10^{18} cm^{-3}$$

$$\lambda_p[\mu m] \approx \frac{3.3 \cdot 10^{10}}{\sqrt{n_0[cm^{-3}]}}$$ Scale length of the plasma wake

Two-bunch Train PWFA



- An **intense, high-energy charged particle beam** (**driver**) drives a **high-gradient wakefield** as it passes through the plasma

- The **space-charge** of the electron bunch **blows out plasma electrons**

- **Plasma electrons rush back in and overshoot** setting up a plasma density oscillation

$$\omega_p = \sqrt{\frac{n_0 e^2}{m_e \varepsilon_0}}$$

- A second beam (**witness**), injected at the accelerating phase, is then accelerated by the wake

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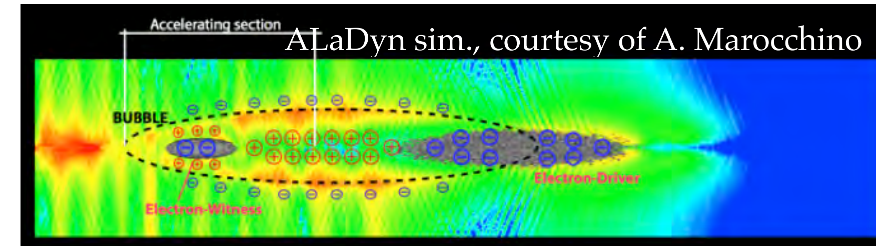
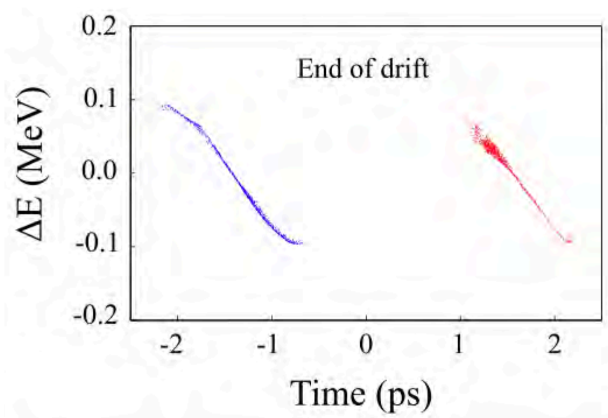
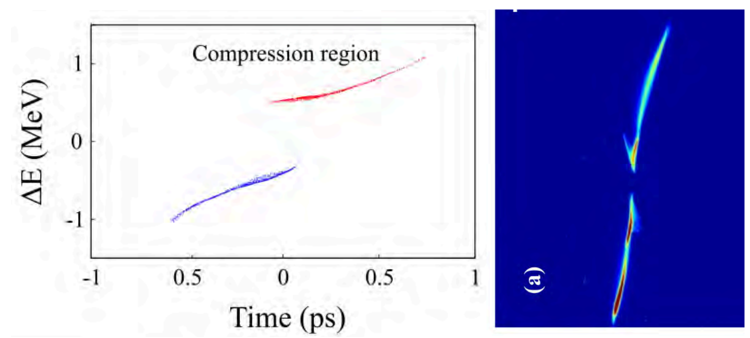
PWFA at SPARC_LAB

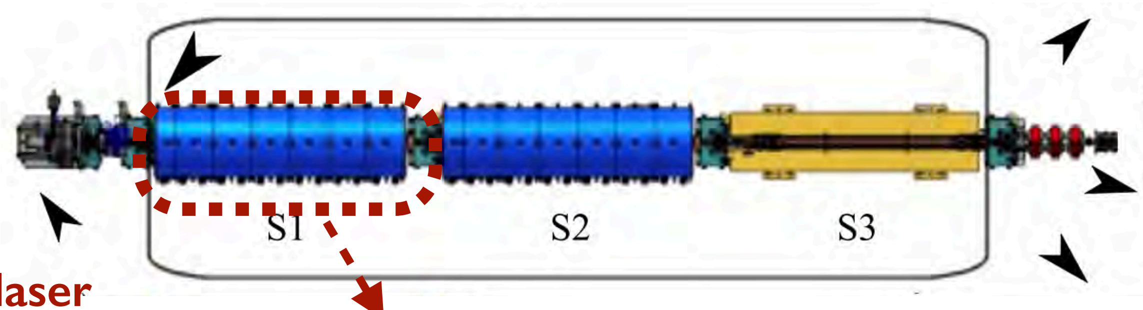
- **High quality** $\varepsilon_n \ll 1 mm\ mrad, I_{peak} \sim kA, \frac{\Delta\gamma}{\gamma} \ll 1\%$
  - External injection of high brightness electron beams

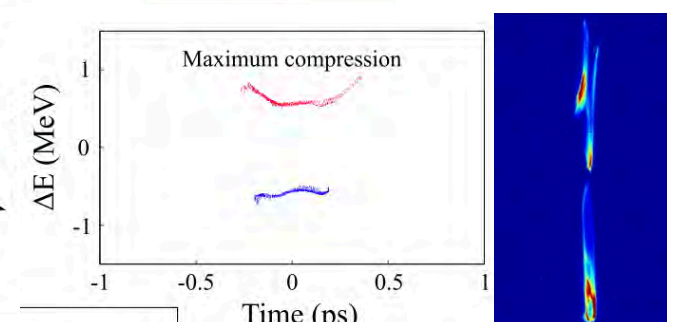


$\lambda_p \approx 330\mu m\ @\ n_p = 10^{16} cm^{-3}$

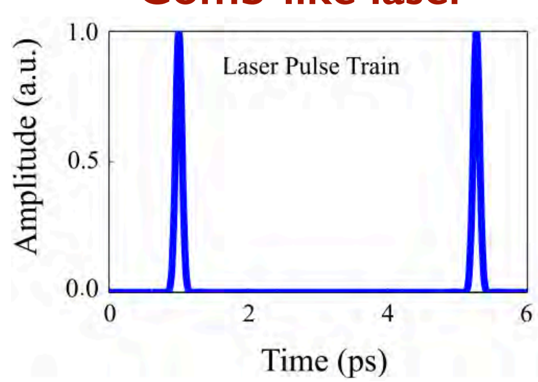




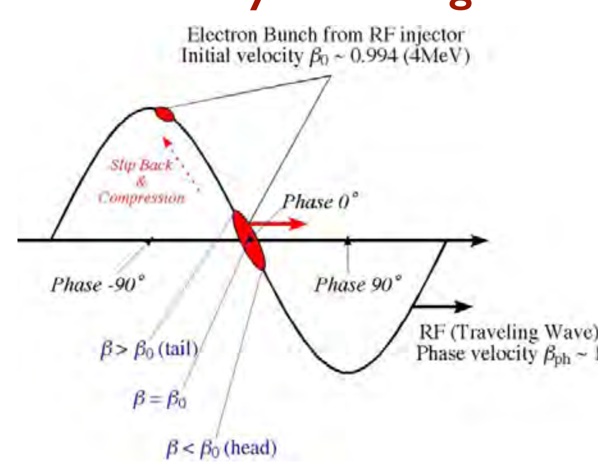


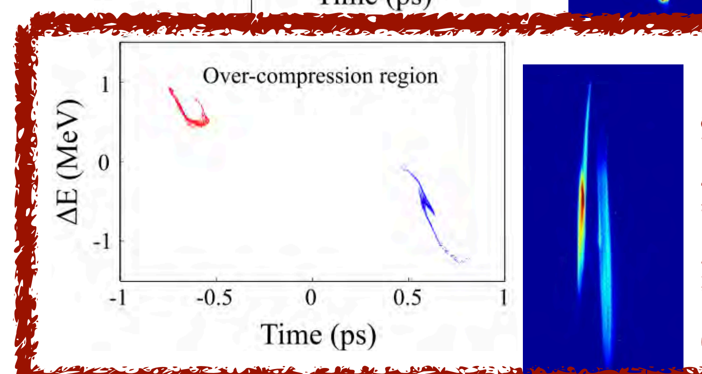


Comb-like laser



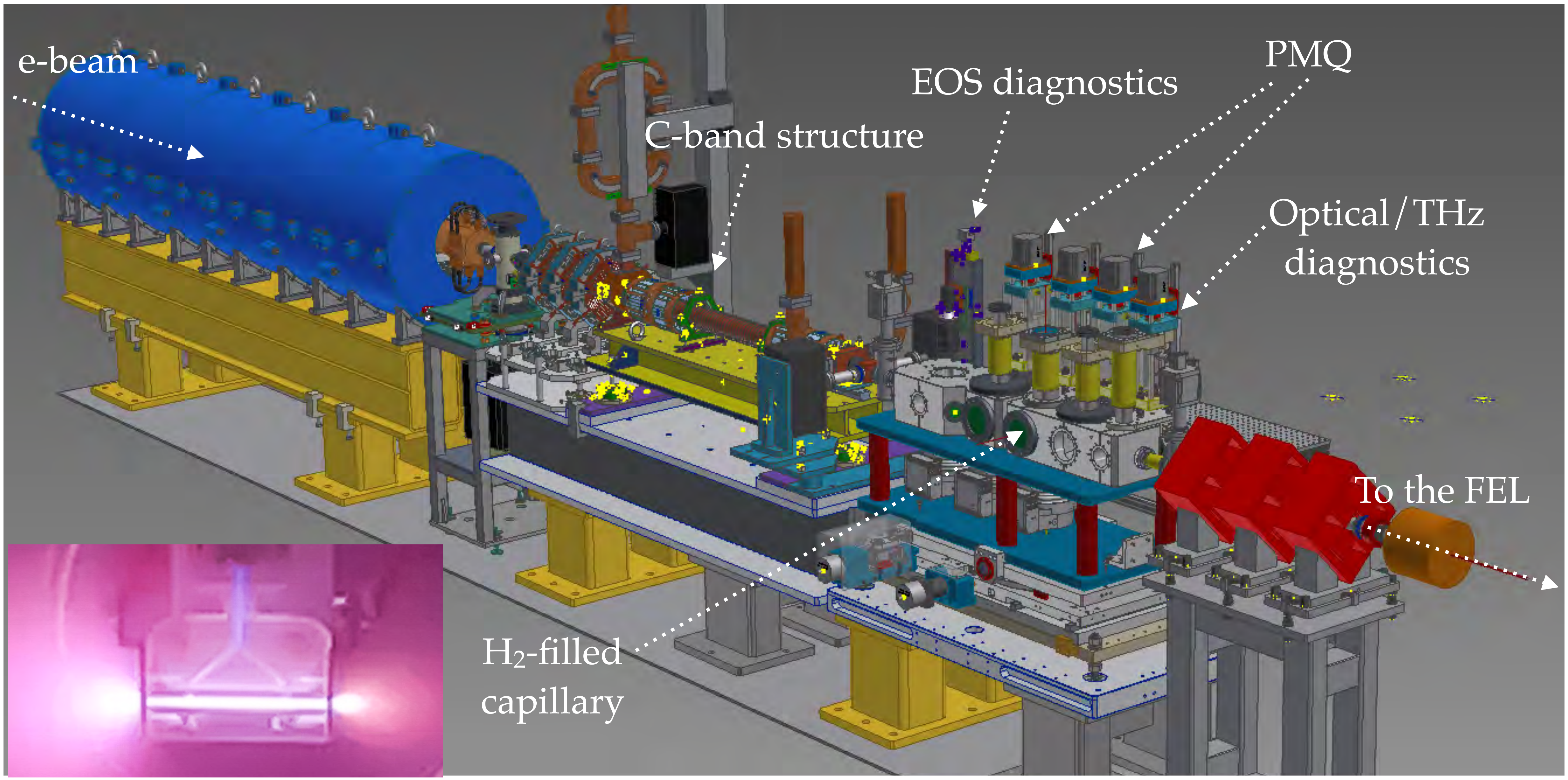
Velocity bunching





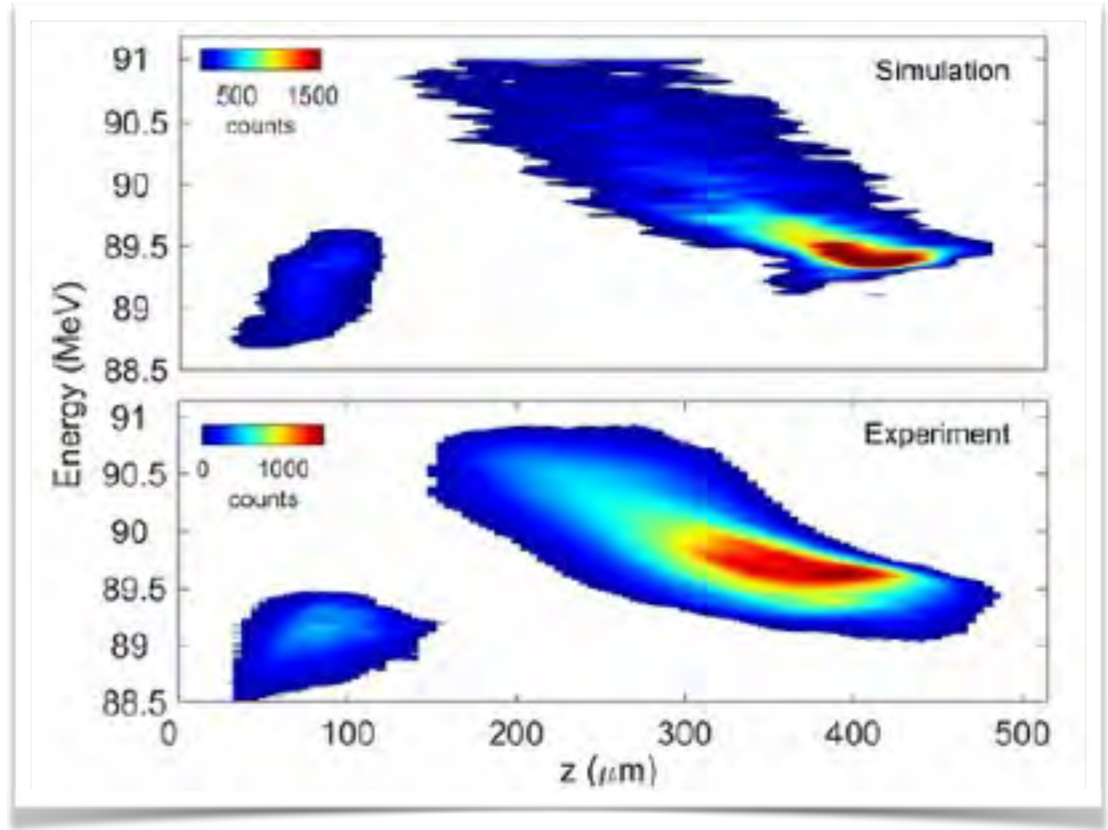
- **P. O. Shea et al.**, Proc. of 2001 IEEE PAC, Chicago, USA (2001) p.704.
- **M. Ferrario et al.**, Int. J. of Mod. Phys. B, 2006

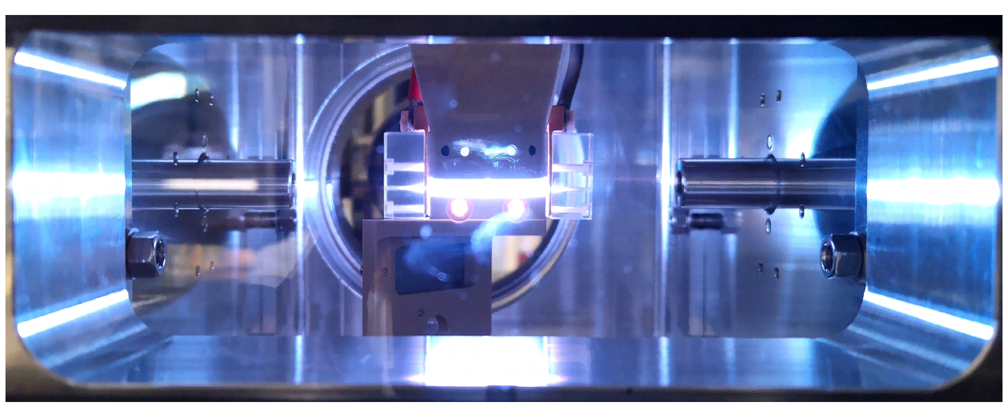
Experimental Layout



Two-beams configuration

- Two-bunches configuration produced directly at the cathode with laser-comb technique
  - 200 pC driver followed by witness bunch (20 pC)
- Ultra-short durations (200 fs + 30 fs)
- Separation approximately equal to half plasma wavelength (~1.2 ps)





- 3 cm long 3D-printed plastic capillary, 1 mm diameter aperture
- plasma is produced by ionizing hydrogen gas, injected through two inlets, by means of a high-voltage discharge (12 kV, 300 A) at 1 Hz repetition rate

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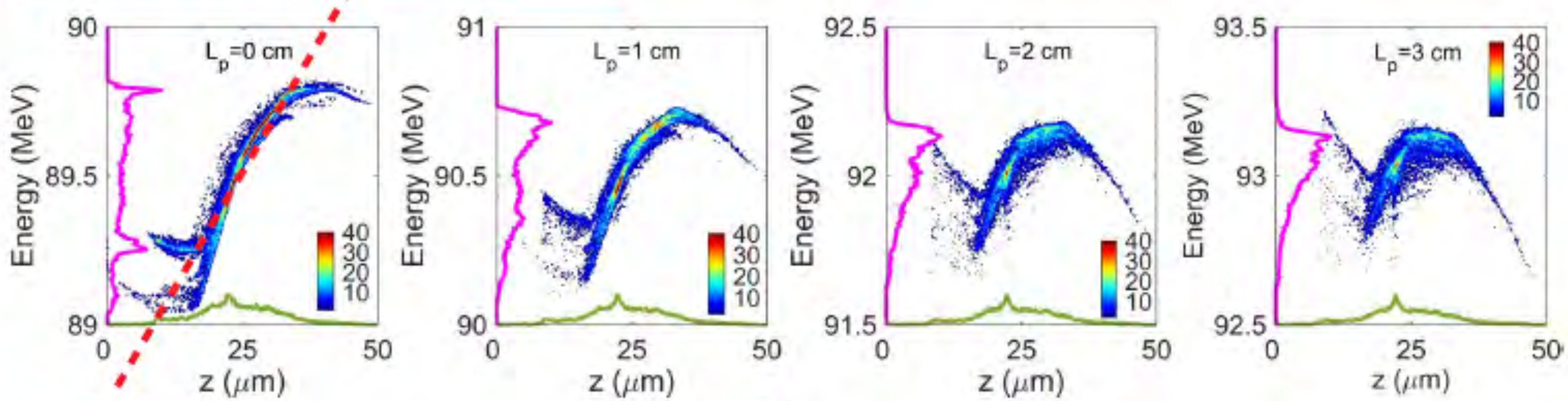
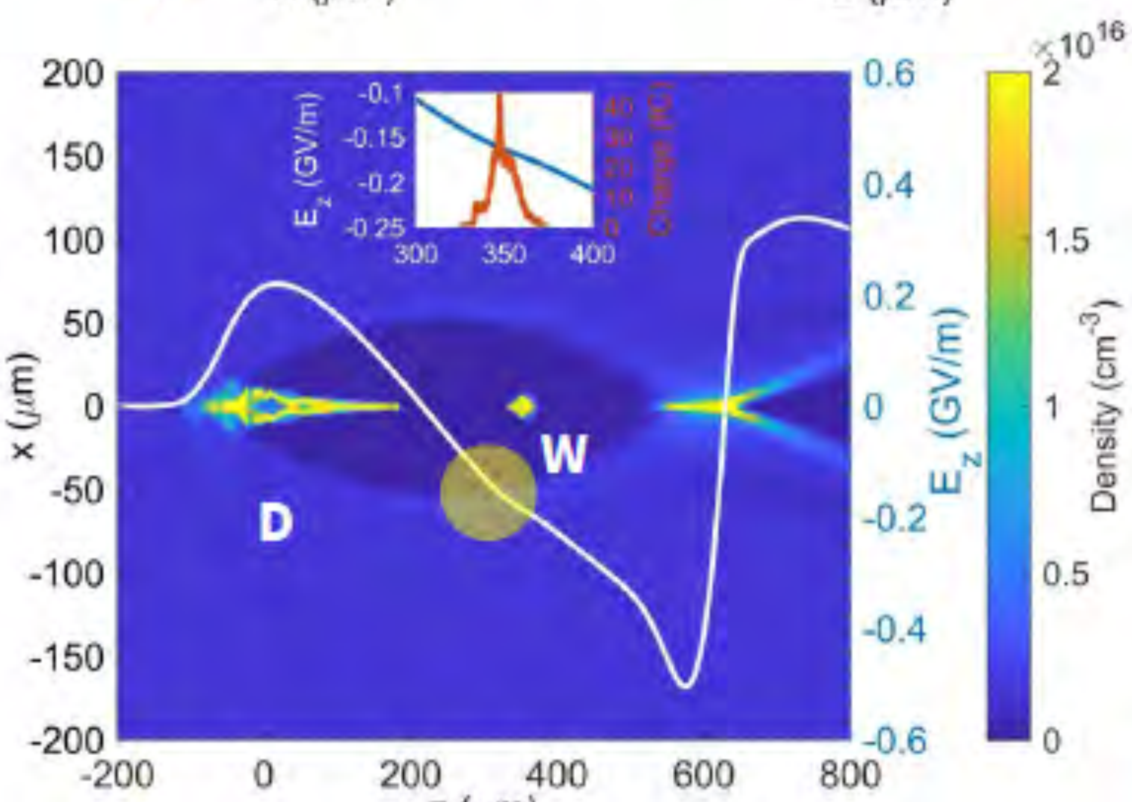
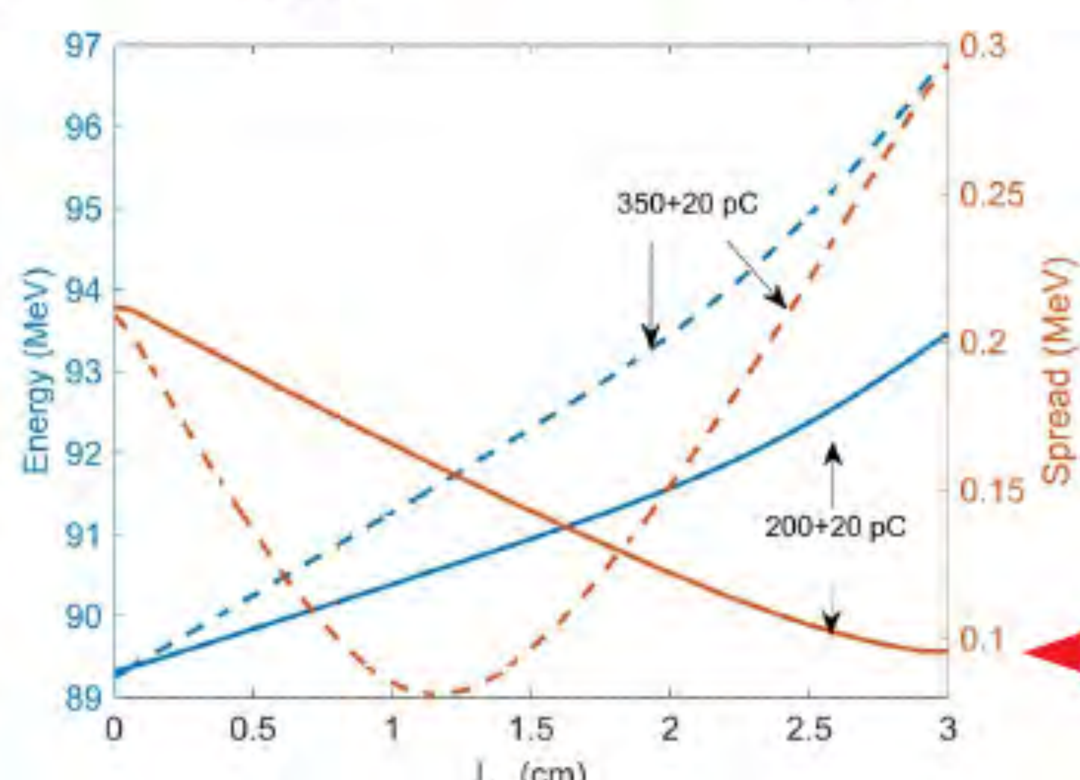
Assisted beam-loading technique

Pre-chirp to compensate wakefield slope



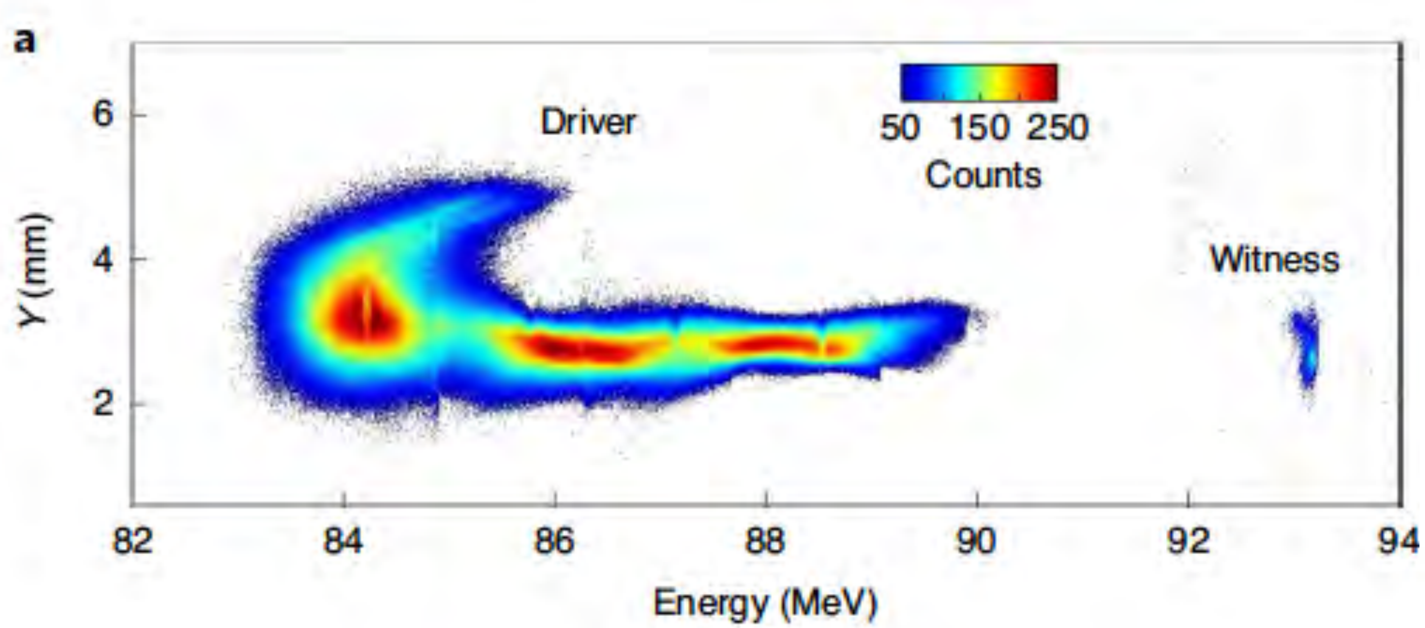


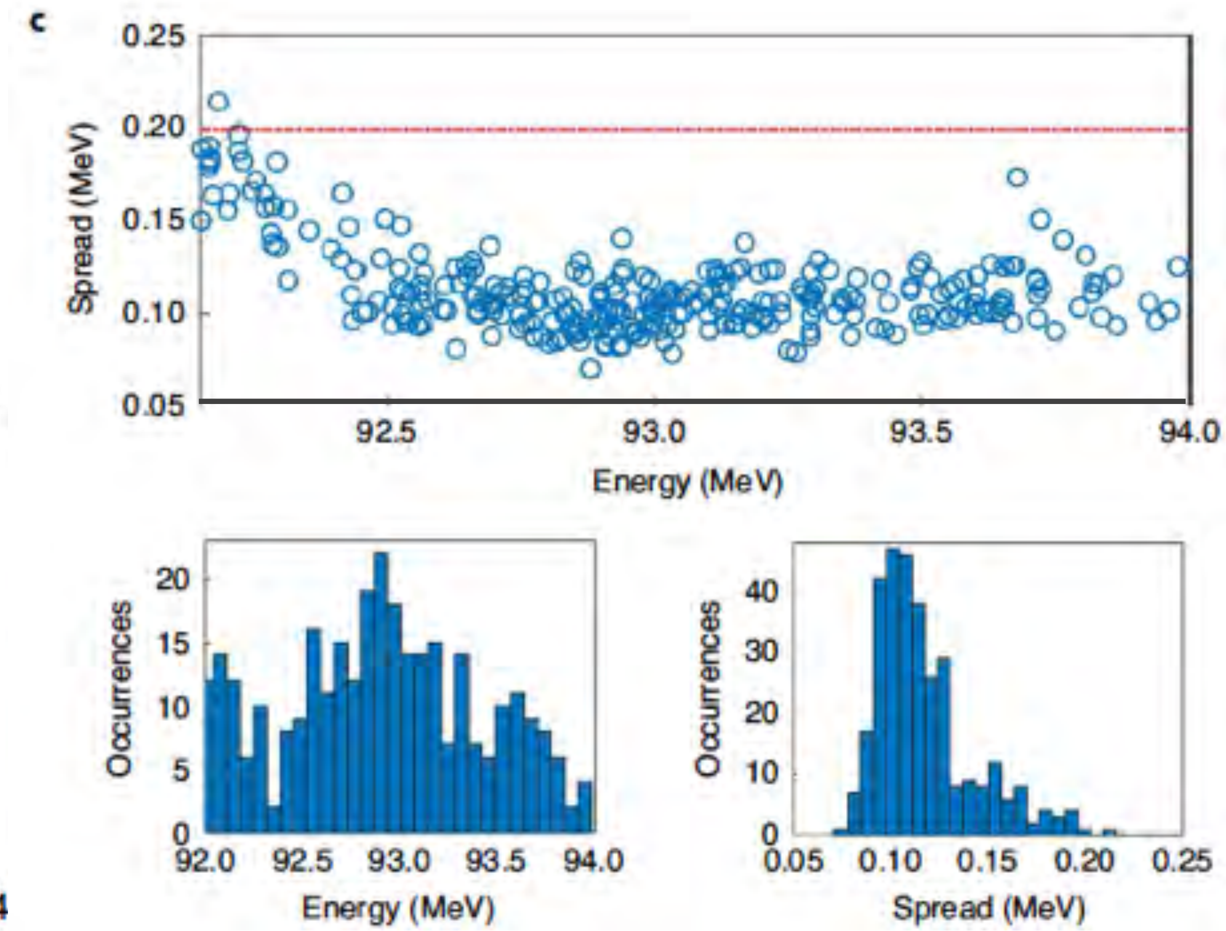


Energy Spread Minimization

- **Energy spread reduction in the beam driven PWFA experiment**

- 4 MeV acceleration in 3 cm plasma with 200 pC driver
  - ~133 MV/m accelerating gradient
  - 2×10^{15} cm^{-3} plasma density
  - Energy spread from 0.2% to 0.12%





Energy jitter of the witness energy is 0.5 MeV

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

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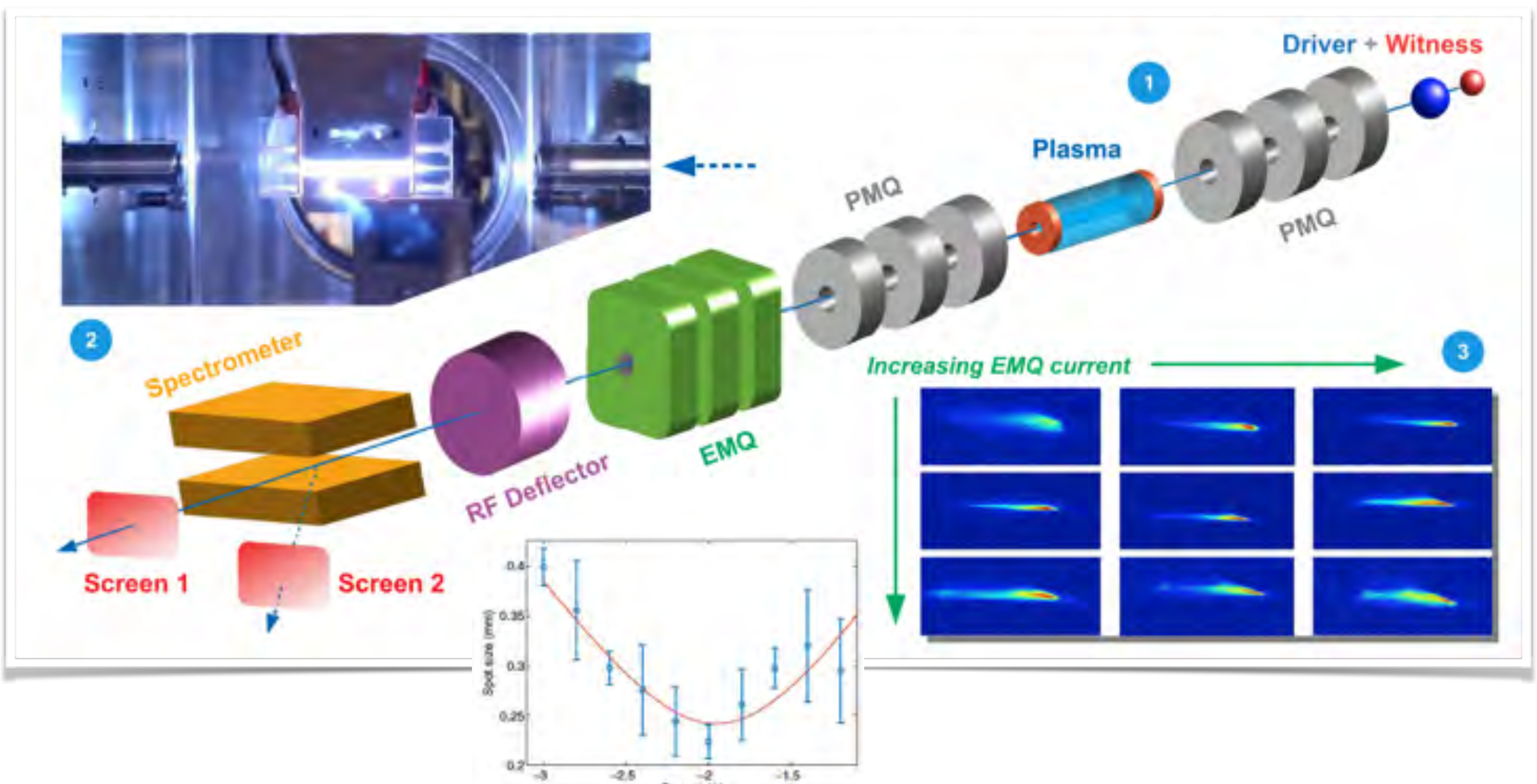
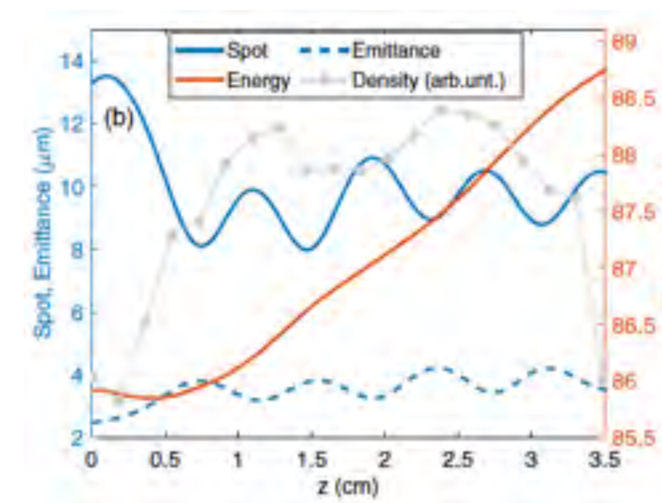
Emittance Characterization

- **First transverse normalized emittance characterization**
  - Multi-shot quadrupole scan technique to measure the plasma-accelerated witness normalized emittance
    - emittance increase from 2.7 um to 3.7 um (rms) during acceleration





V. Shpakov et al., *First emittance measurement of the beam-driven plasma wakefield accelerated electron beam*, (2021), Physical Review Accelerators and Beams, **24** (5), art. no. 051301

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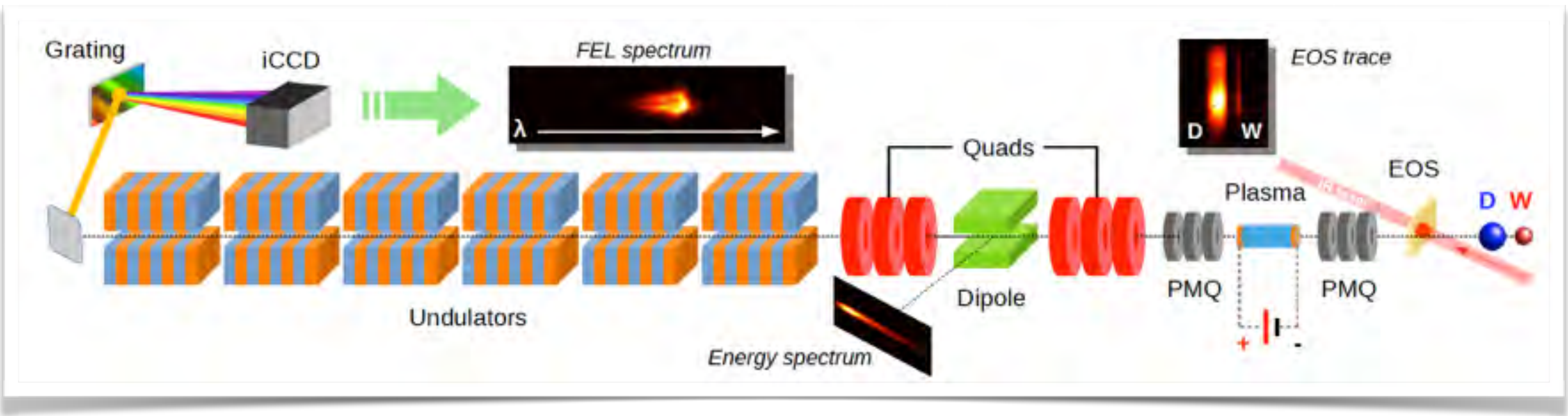
PWFA-driven FEL Studies

- **First experimental observation of the gain growth** of a plasma-driven SASE FEL



- **Witness** is completely **characterized** (energy, spread, X/Y emittance) allowing to match it into the undulator beamline
- **Jitter** is online **monitored** with Electro-Optical Sampling (EOS) diagnostics
- Imaging spectrometer with **iCCD** used **to detect FEL radiation**

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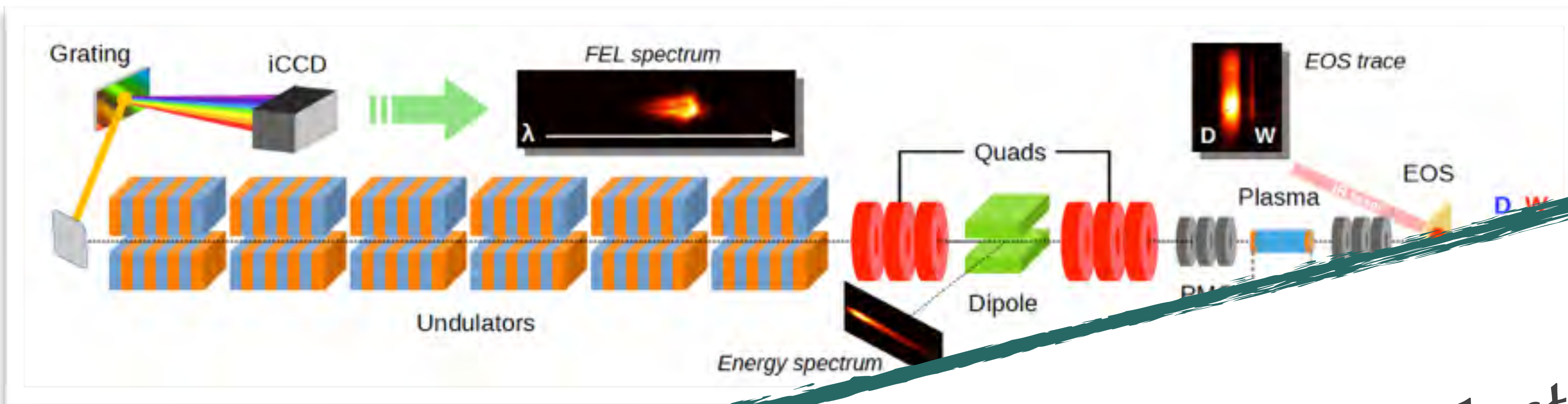

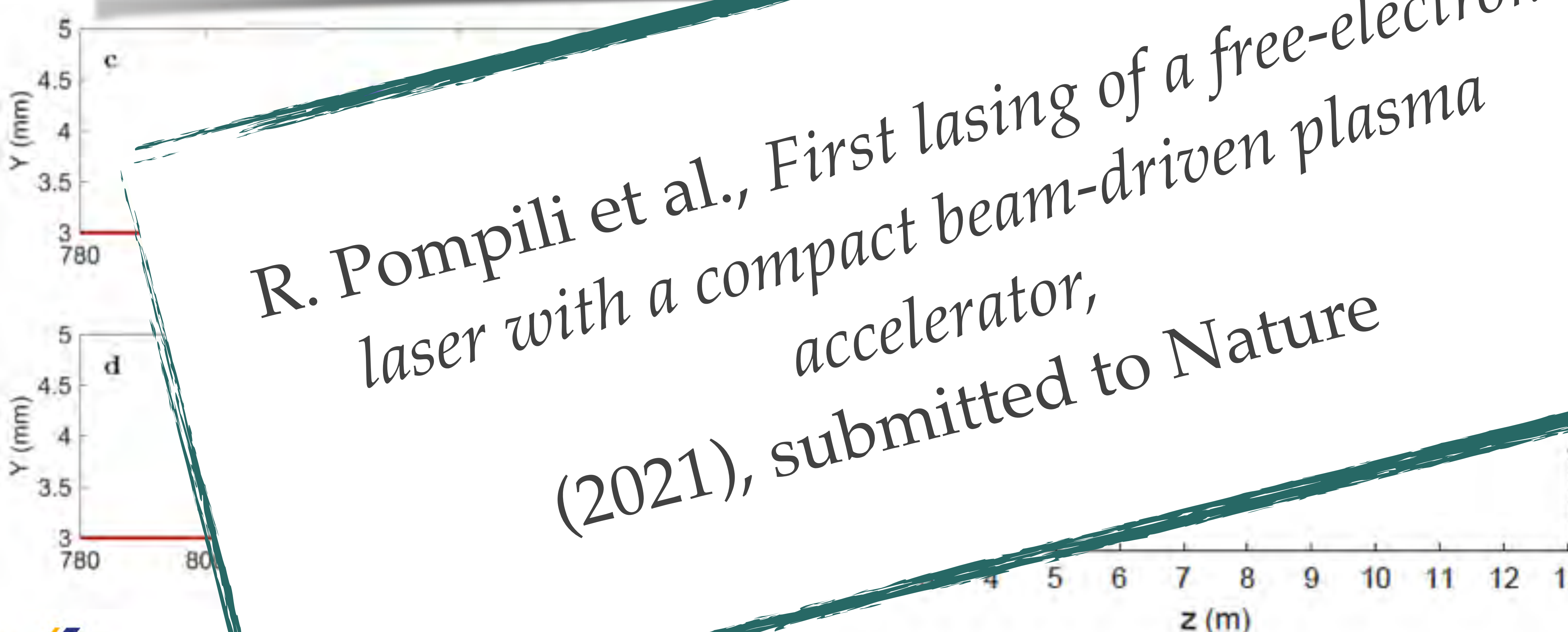

R. Pompili et al., First lasing of a free-electron laser with a compact beam-driven plasma accelerator, (2021), submitted to Nature

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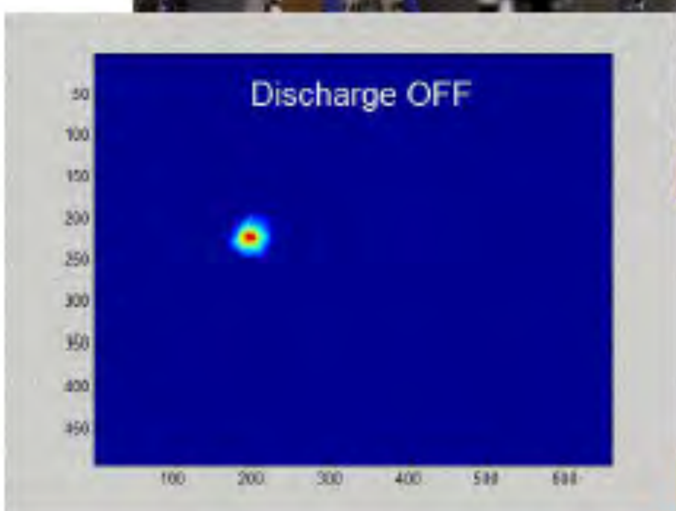
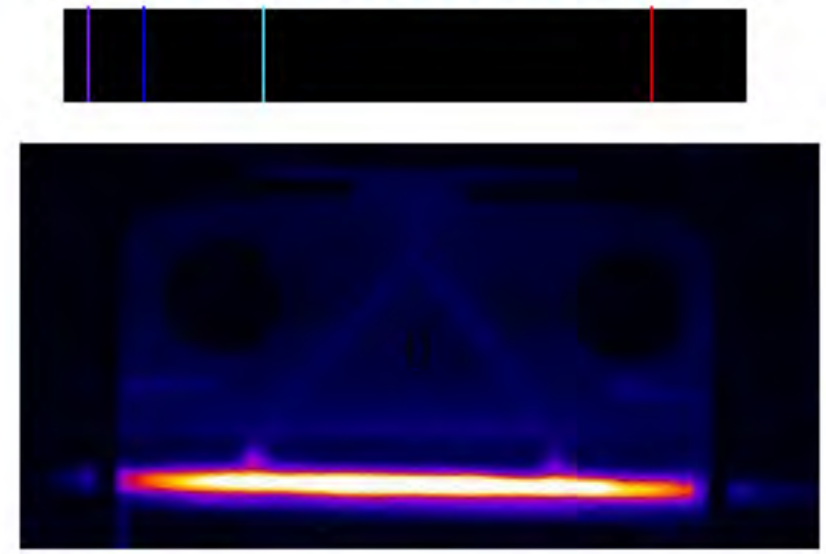
Experience with plasma at SPARC_LAB

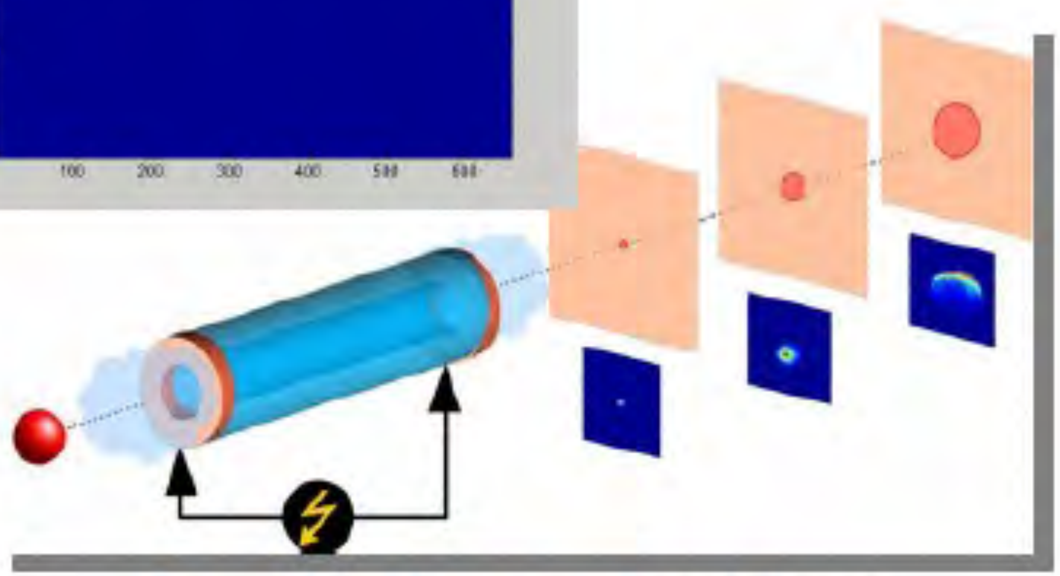
Activities with the high-brightness SPARC photo-injector



Plasma characterization

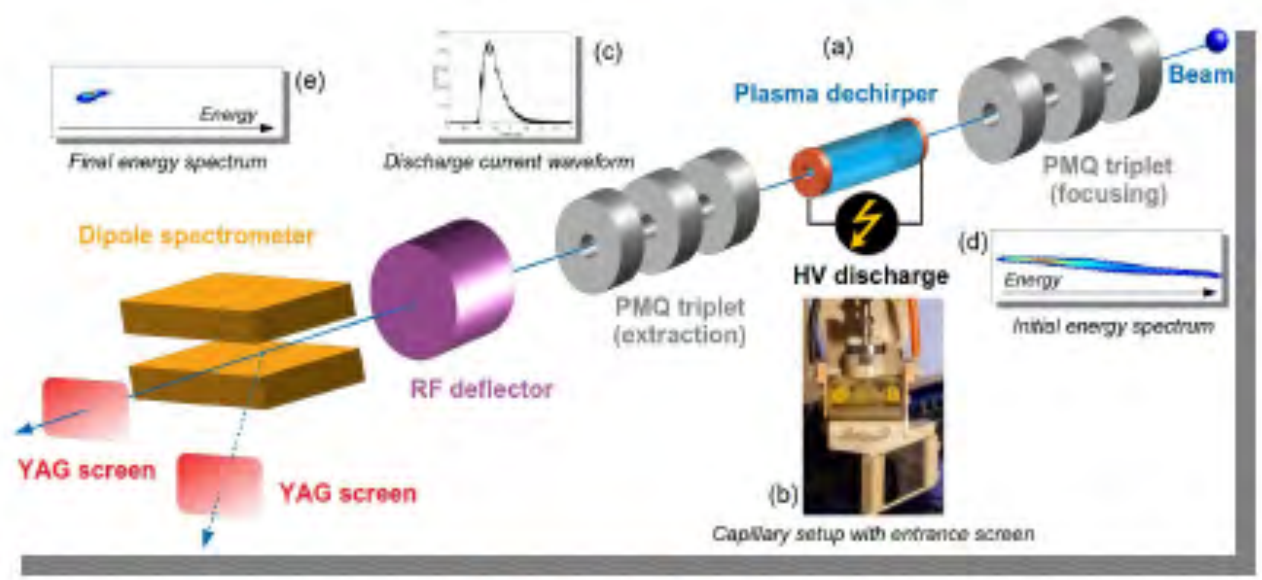


Biagioni, A., et al., Journal of Instrumentation 11.08 (2016): C08003.



Focusing with active-plasma lenses

Pompili, R., et al., Physical review letters 121.17 (2018): 174801.
Pompili, R., et al., Applied Physics Letters 110.10 (2017): 104101.



Plasma-dechirper

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

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The path towards EuPRAXIA@SPARC_LAB

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Conceptual Design Report

Courtesy R. Assmann

- **First ever international design of a plasma accelerator facility**
- Funded 2015-2019 by European Union (Horizon2020) with 3 Million Euro
- Coordinating lab: DESY (R. Assmann)
- Growing **consortium**: 32 → 41 labs, ELI, CERN, LBNL, Osaka, Shanghai, Russian labs
- **Industry**: Thales (France), Amplitude (France), Trumpf Scientific (Germany)

Conceptual Design Report submitted to EU on November 1st, 2019

653 page CDR, 240 scientists contributed

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

Assmann, R.W., Weikum, M.K., Akhter, T. et al. *EuPRAXIA Conceptual Design Report*. Eur. Phys. J. Spec. Top. **229**, 3675–4284 (2020)

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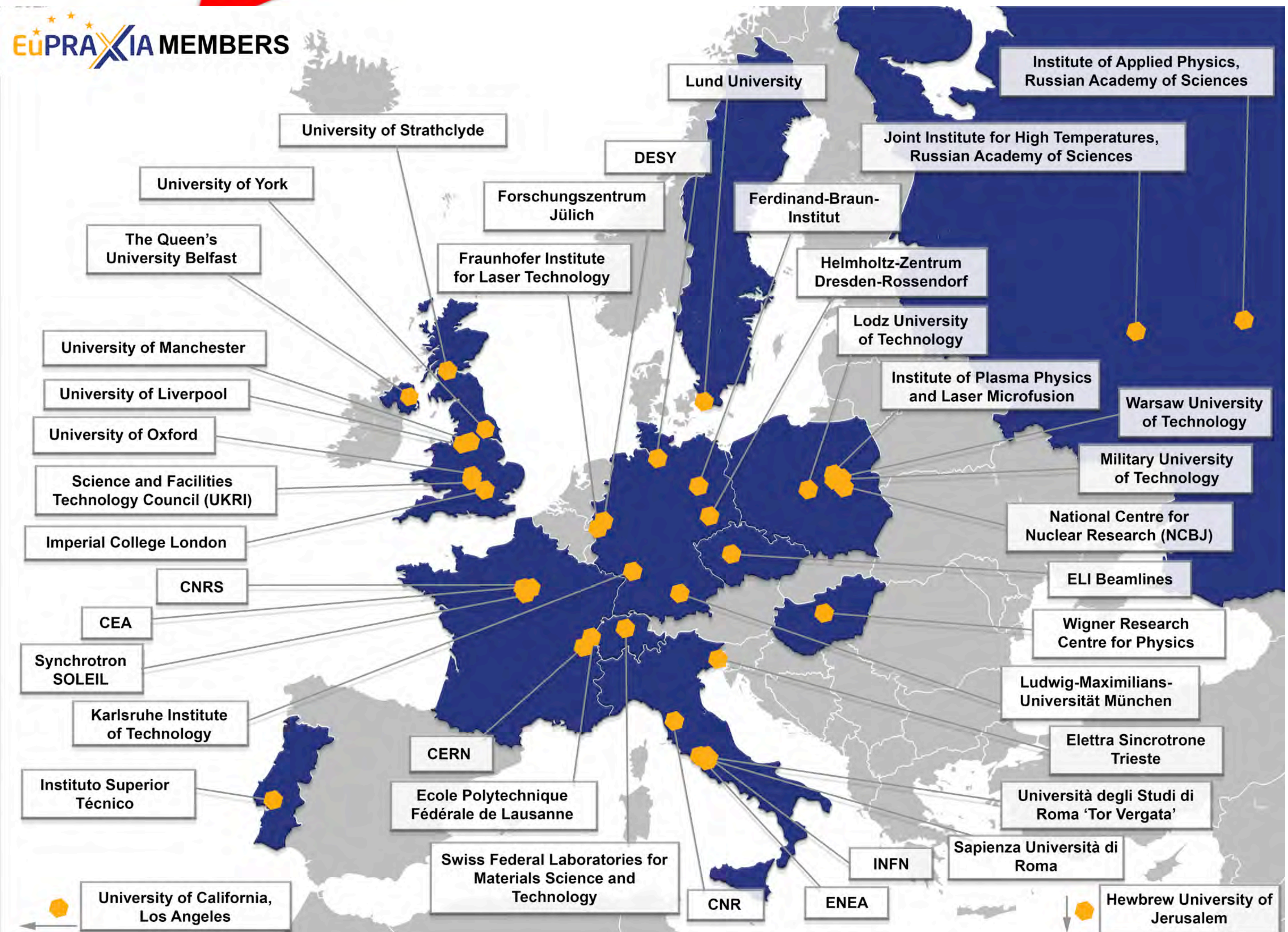
The Consortium Members for the Next Phase (from 16 to 40 Consortium Agreement signed*)



Courtesy R. Assmann

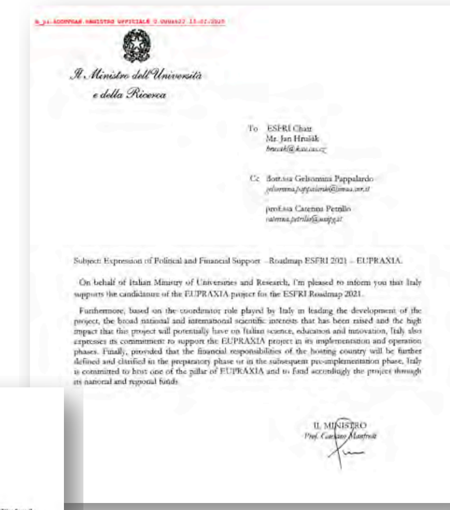
40 Member institutions in:

- **Italy** (INFN, CNR, Elettra, ENEA, Sapienza Università di Roma, Università degli Studi di Roma "Tor Vergata")
- **France** (CEA, SOLEIL, *CNRS *pending*)
- **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) *pending
- **CERN**
- **ELI Beamlines**

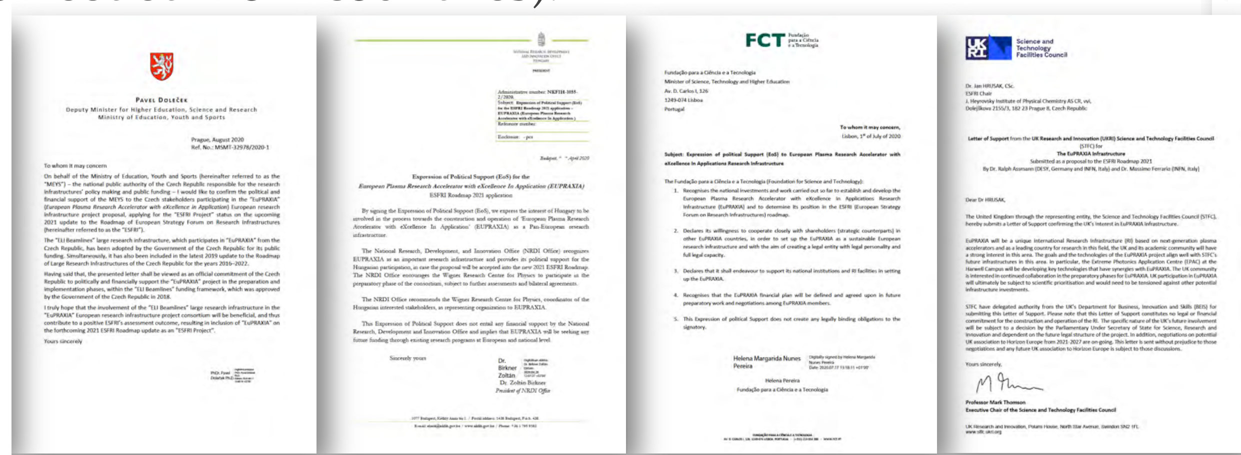
ESFRI Proposal: Financial and Political Support (European Strategy Forum on Research Infrastructure)

Courtesy R. Assmann

To become official European Research Infra-structure (RI) the EuPRAXIA project applied to **2021 update of the European Roadmap** for RI's. Process managed by **ESFRI**.



- Formal process with clear requirements.
- **Lead Country**: Italy (LNF/INFN)
  Political and financial support letter sent to ESFRI by Italian Ministry
- **Political support letters** (at least two needed from countries):
  - Hungary
  - Portugal
  - Czech Republic (ELI beamlines)
  - UK



- Note: All operational costs covered by host countries.

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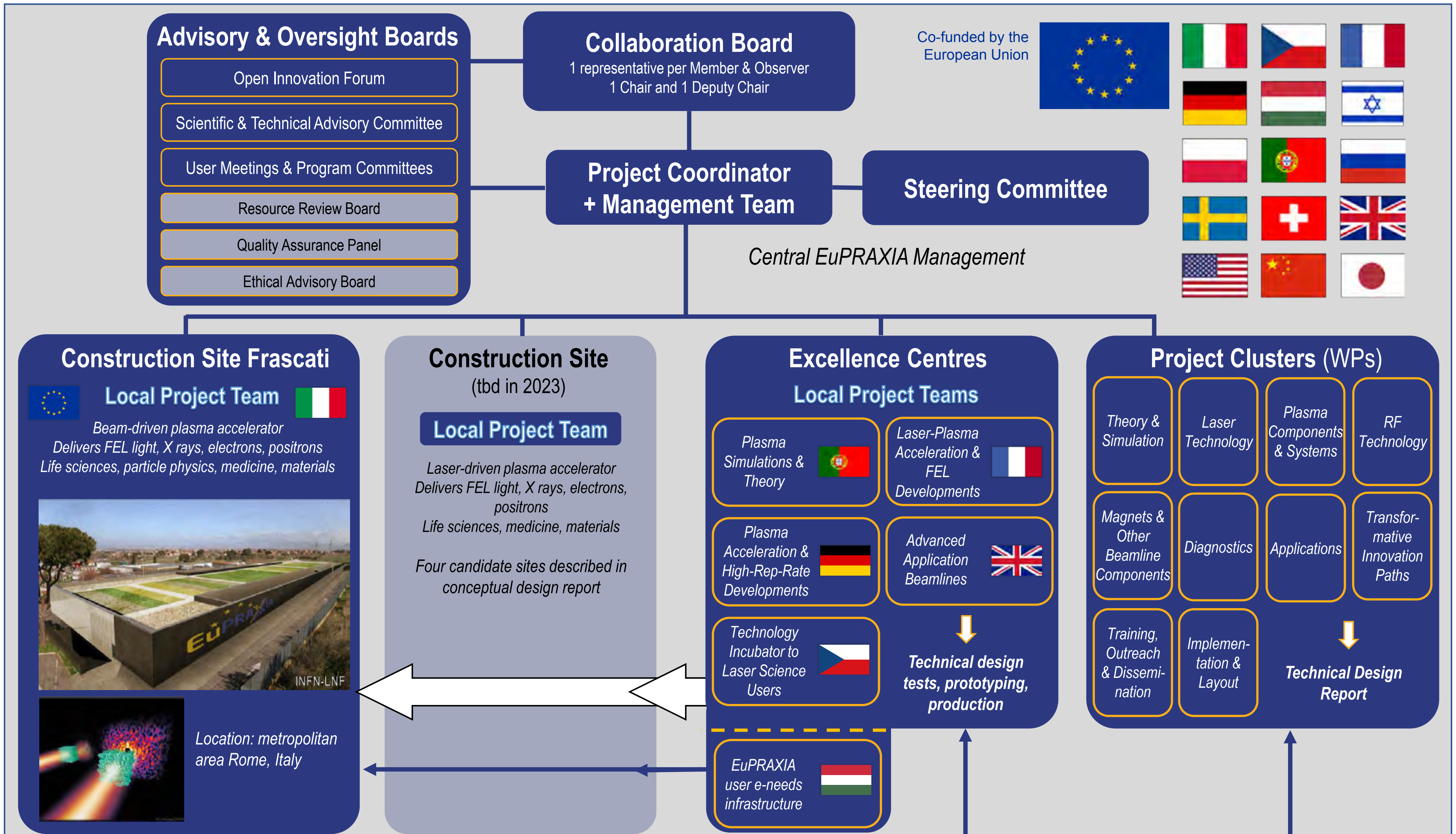
First Feedback from EU

We are glad to inform you that, following ESFRI internal procedures, **the proposal "European Plasma Research Accelerator with Excellence in Applications - EuPRAXIA" has been considered eligible** and can now be assessed for entering the ESFRI Roadmap 2021.
The evaluation exercise has just started and below you can find the next steps with an indicative timeframe:

- invitation for the hearing with list of critical questions: February - March 2021
- Hearing: April - May 2021

Organization

Courtesy R. Assmann



National projects and facilities

Individual groups at universities and laboratories

Organization for initial Preparatory Phase in dark blue

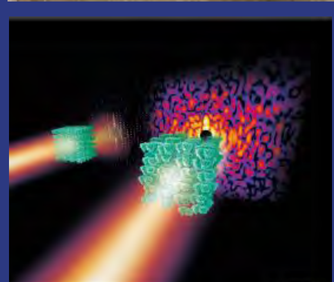
Features to be added with decision on second site or in later phases are indicated in lighter shades

Concept Distributed Research Infrastructure

Construction Site Frascati

Local Project Team

Beam-driven plasma accelerator
Delivers FEL light, X rays, electrons, positrons
Life sciences, particle physics, medicine, materials



Location: metropolitan area Rome, Italy

Construction Site

(tbd in 2023)

Local Project Team

Laser-driven plasma accelerator
Delivers FEL light, X rays, electrons, positrons
Life sciences, medicine, materials

Four candidate sites described in conceptual design report

Excellence Centres

Local Project Teams

- *Plasma Simulations & Theory* (Portugal)
- *Laser-Plasma Acceleration & FEL Developments* (France)
- *Plasma Acceleration & High-Rep-Rate Developments* (Germany)
- *Advanced Application Beamlines* (UK)
- *Technology Incubator to Laser Science Users* (Czech Republic)

Technical design tests, prototyping, production

- *EuPRAXIA user e-needs infrastructure* (Hungary)

Courtesy R. Assmann

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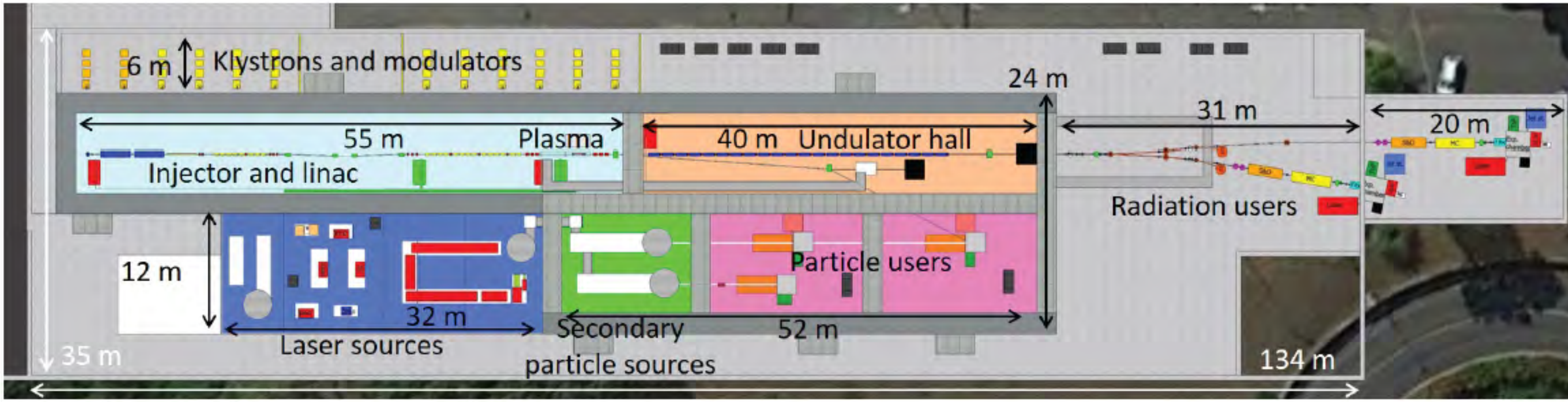
EuPRAXIA@SPARC_LAB Test User Facility



EuPRAXIA@SPARC_LAB will combine **compact X band RF technology** from CLIC and the plasma accelerator **at its Frascati construction site.**

Multiple users from different fields (A. Balerna et al., Condens. Matter 2019, 4(1), 30):

- studying and understanding **bacteria**, **viruses**, **materials**, ...
- using intense bursts of photons, electrons, positrons resolving time-dependent processes in **ultra-fast science**
- co-developing **novel technologies** for accelerators, users, ...

EuPRAXIA@SPARC_LAB Conceptual Design Report is publicly available and can be downloaded from http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

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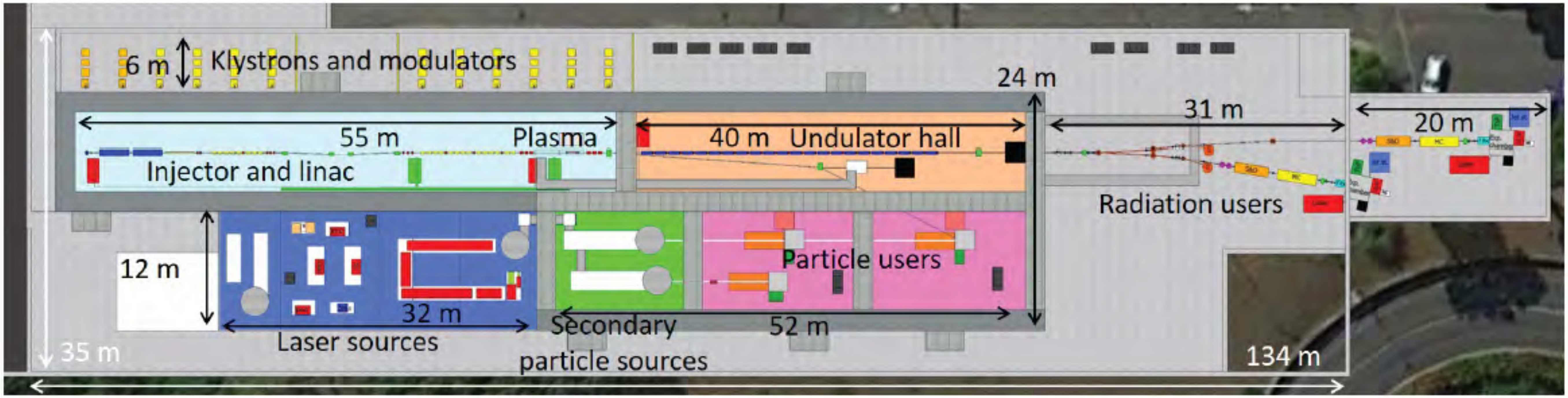
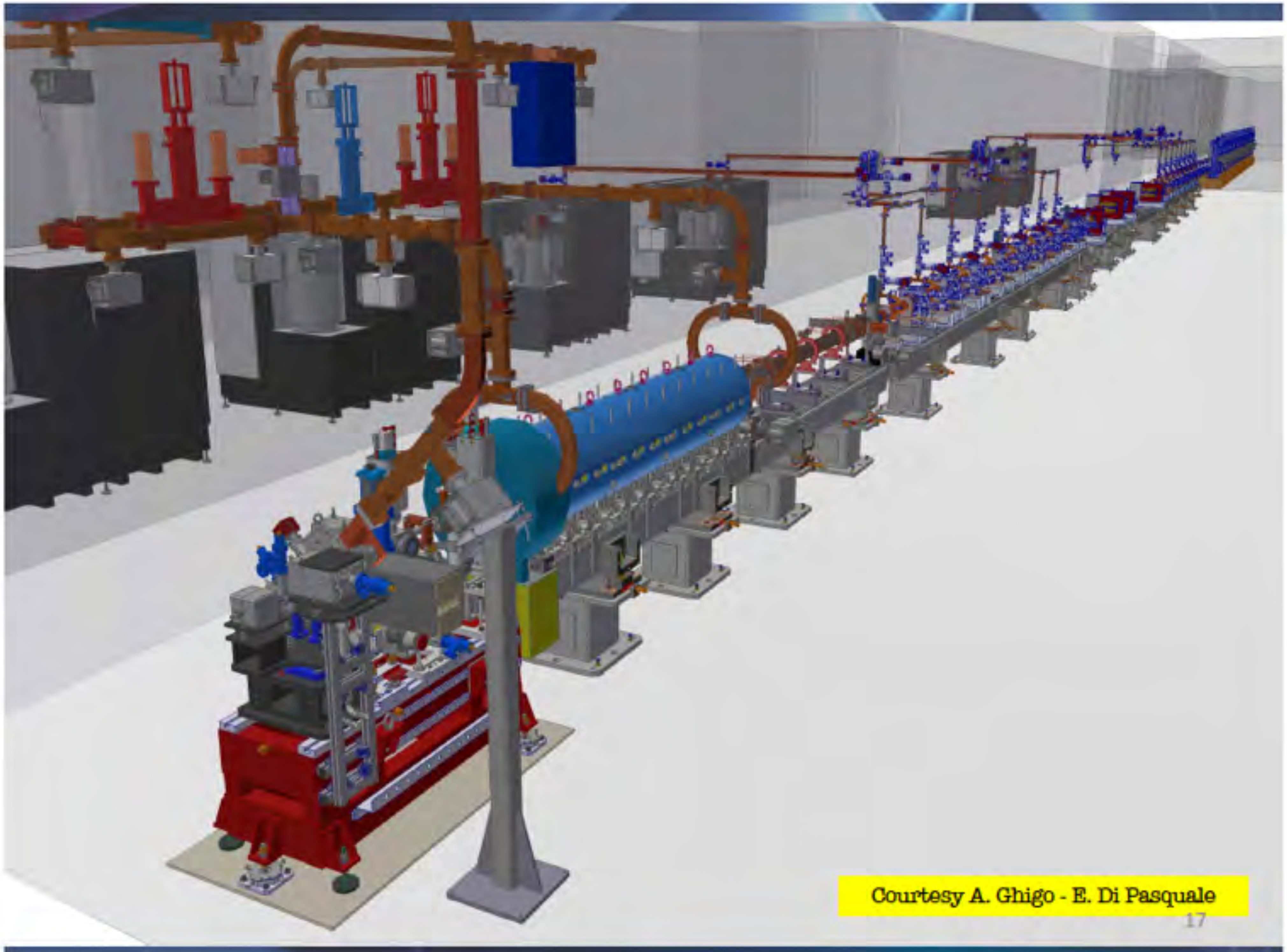
EuPRAXIA@SPARC_LAB Test User Facility



Executive design of the building officially started: delivery of the design expected by the end of 2021.

Preliminary Layout



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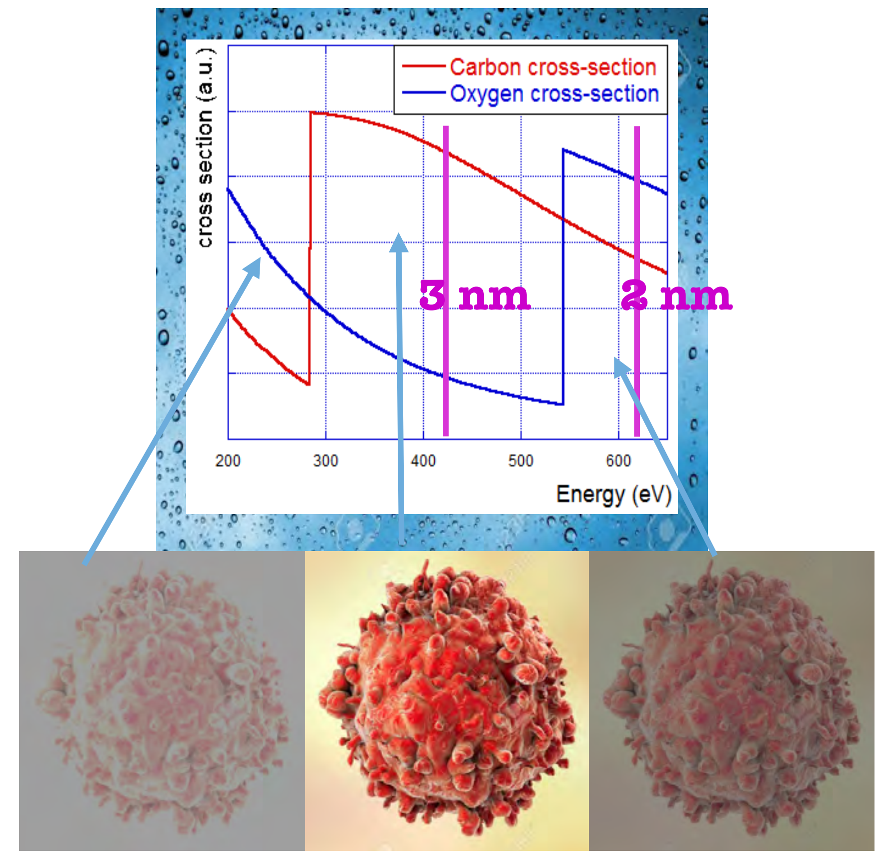
Expected SASE FEL Performances

	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

Energy region between Oxygen and Carbon K-edge 2.34 nm – 4.4 nm (530 eV -280 eV)

Water is almost transparent to radiation in this range 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

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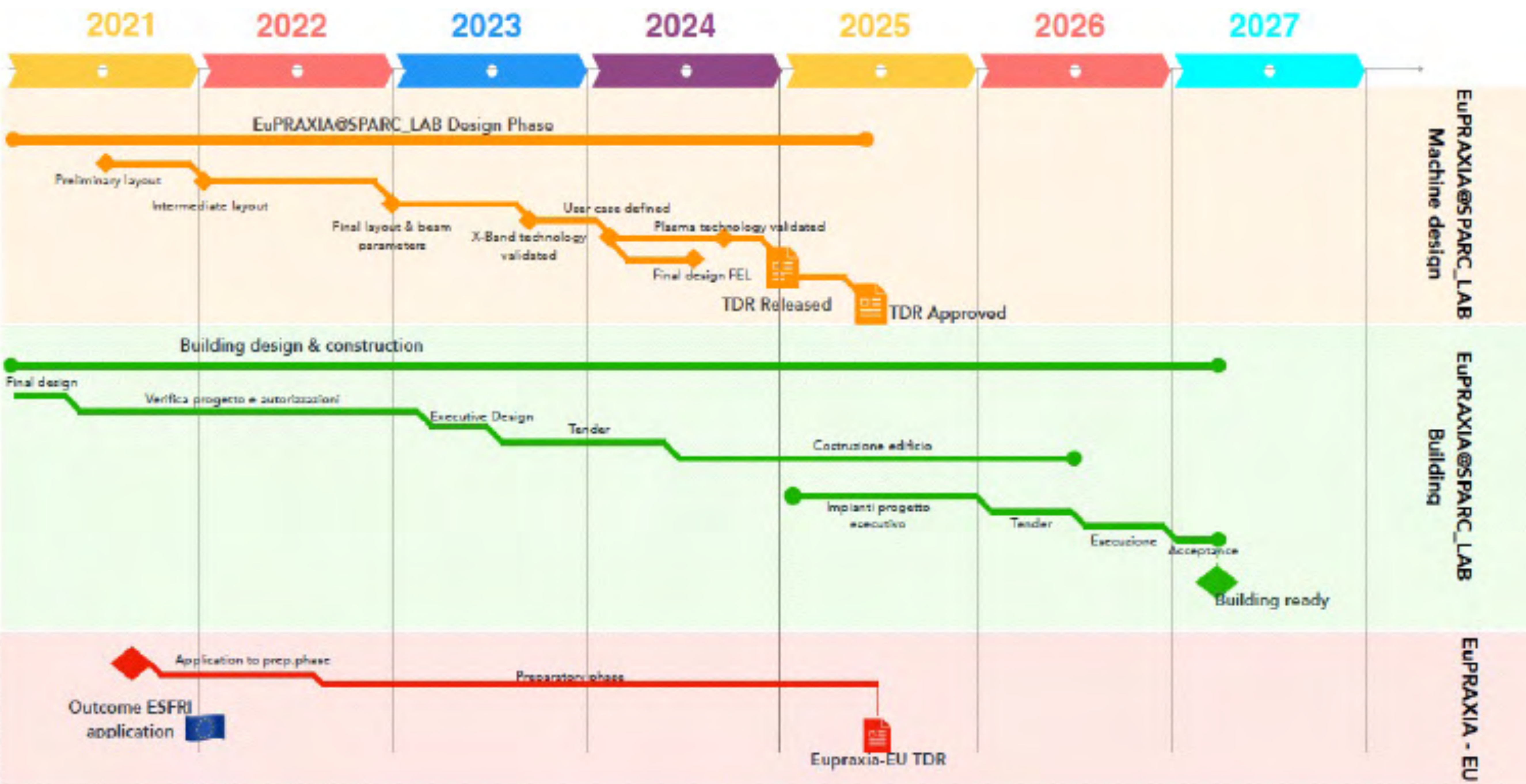
Road Map



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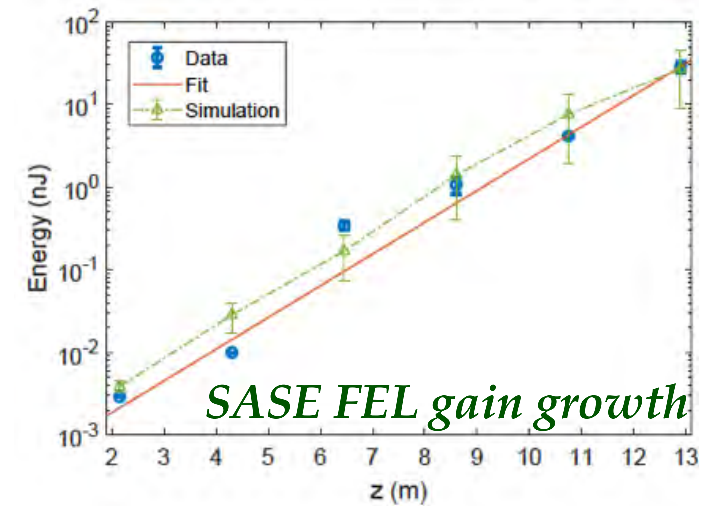
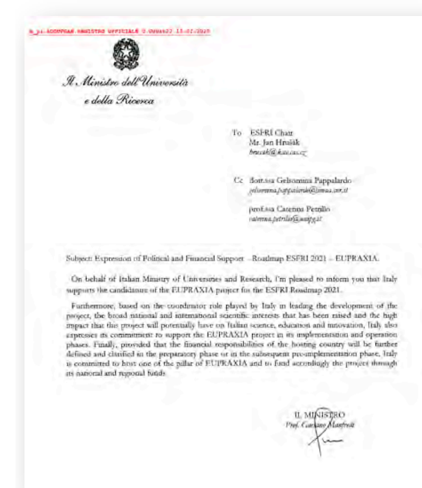
Conclusions

- R&D activities on PWFA at SPARC_LAB show promising results concerning stability and beam quality needed to pilot a FEL
  - First observation of SASE FEL gain growth



- The EuPRAXIA project is ongoing
  - ESFRI roadmap submitted



Il Ministro dell'Università e della Ricerca

To ESFRI Chair
Mr. Jan Hrušák

Cc dott.ssa Gelsomina Pappalardo

prof.ssa Caterina Petrillo

Subject: Expression of Political and Financial Support – Roadmap ESFRI 2021 – EUPRAXIA.

On behalf of Italian Ministry of Universities and Research, I'm pleased to inform you that Italy supports the candidature of the EUPRAXIA project for the ESFRI Roadmap 2021.

Furthermore, based on the coordinator role played by Italy in leading the development of the project, the broad national and international scientific interests that has been raised and the high impact that this project will potentially have on Italian science, education and innovation, Italy also expresses its commitment to support the EUPRAXIA project in its implementation and operation phases. Finally, provided that the financial responsibilities of the hosting country will be further defined and clarified in the preparatory phase or in the subsequent pre-implementation phase, Italy is committed to host one of the pillar of EUPRAXIA and to fund accordingly the project through its national and regional funds.

IL MINISTRO
Prof. Gaetano Manfredi

- The Italian EuPRAXIA, i.e. EuPRAXIA@SPARC_LAB, has received binding commitments for more than 100 M€

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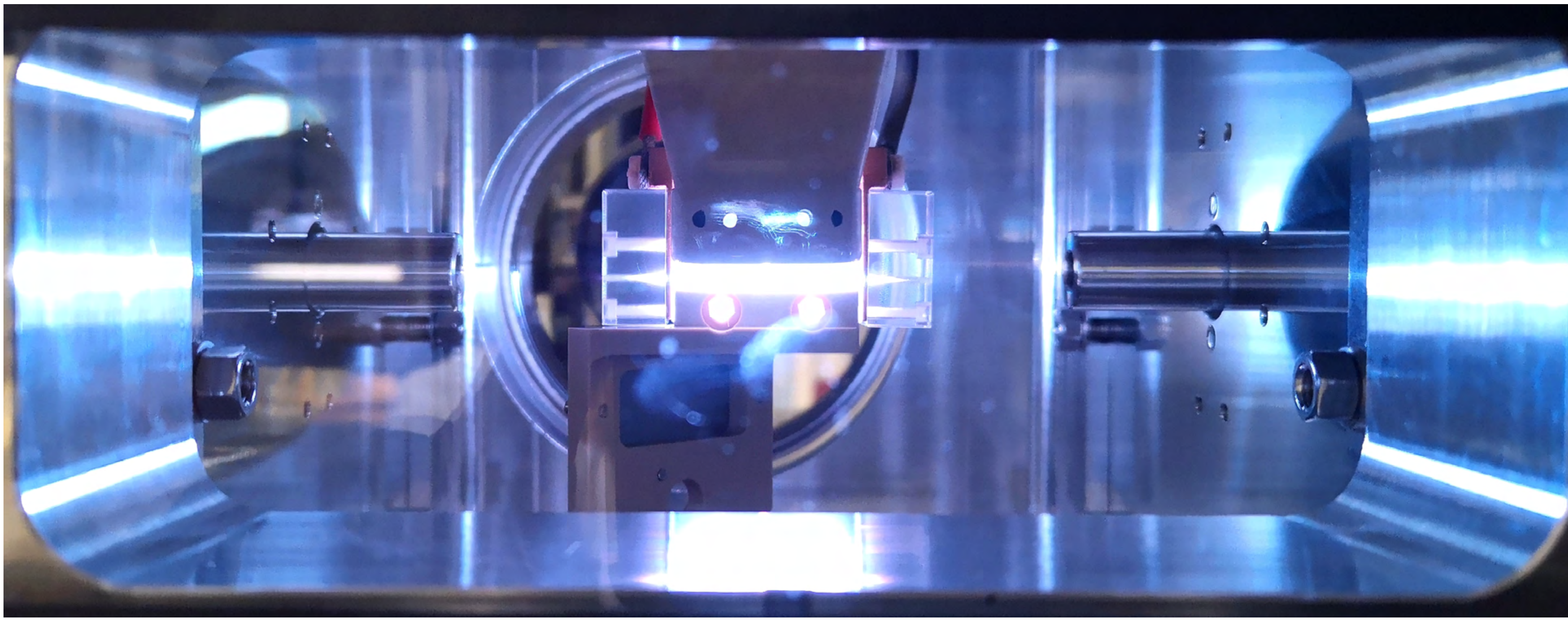

THANK YOU FOR THE KIND ATTENTION

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