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Progress Towards Demonstration of a Plasma-based FEL

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Outline

- Motivation
- Methods and Acceleration Mechanism
    - Laser-based plasma accelerators and beam-based plasma wakefield
- International Scenario
    - Breakthrough results
- Towards a Plasma-based FEL User Facility

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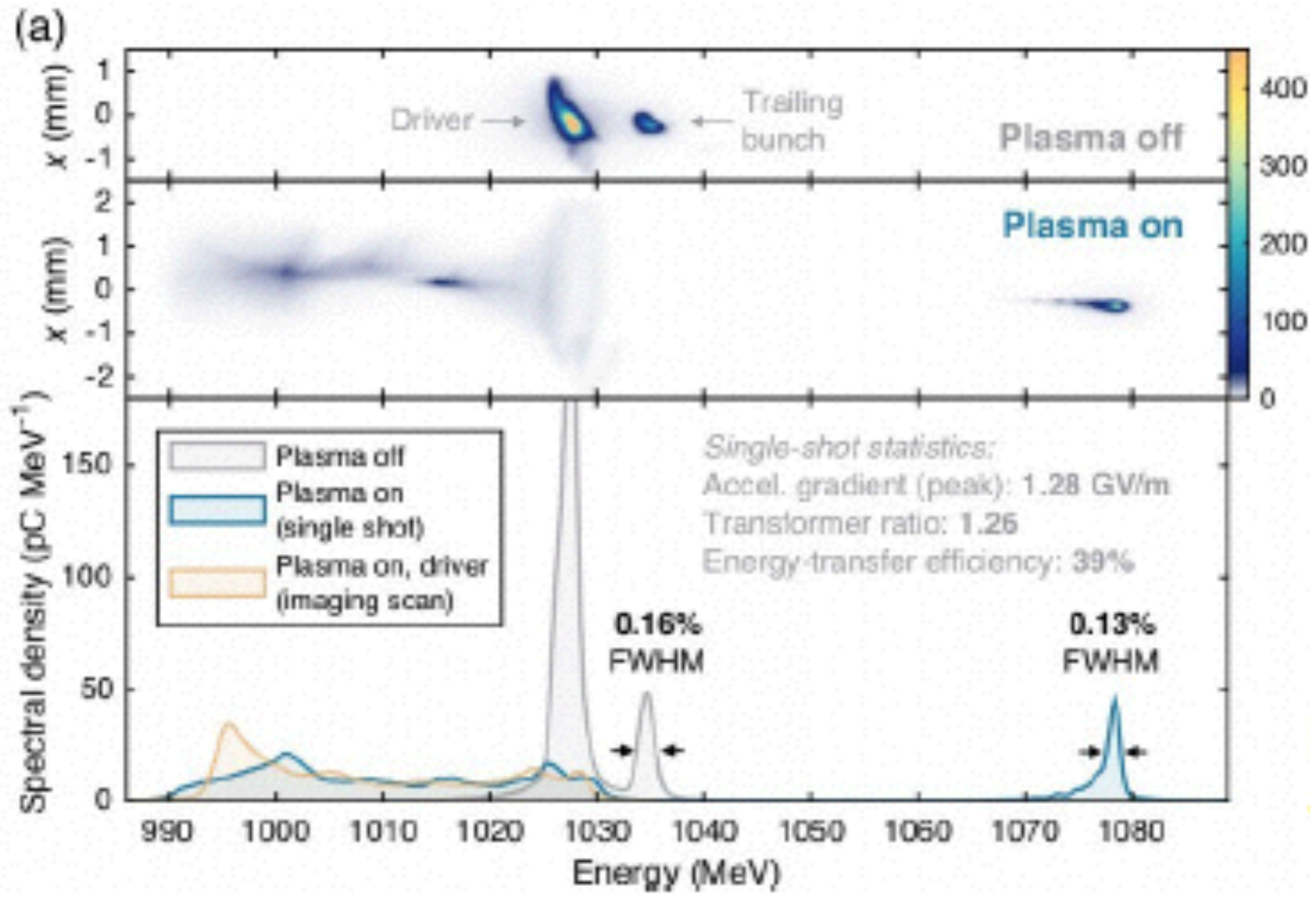
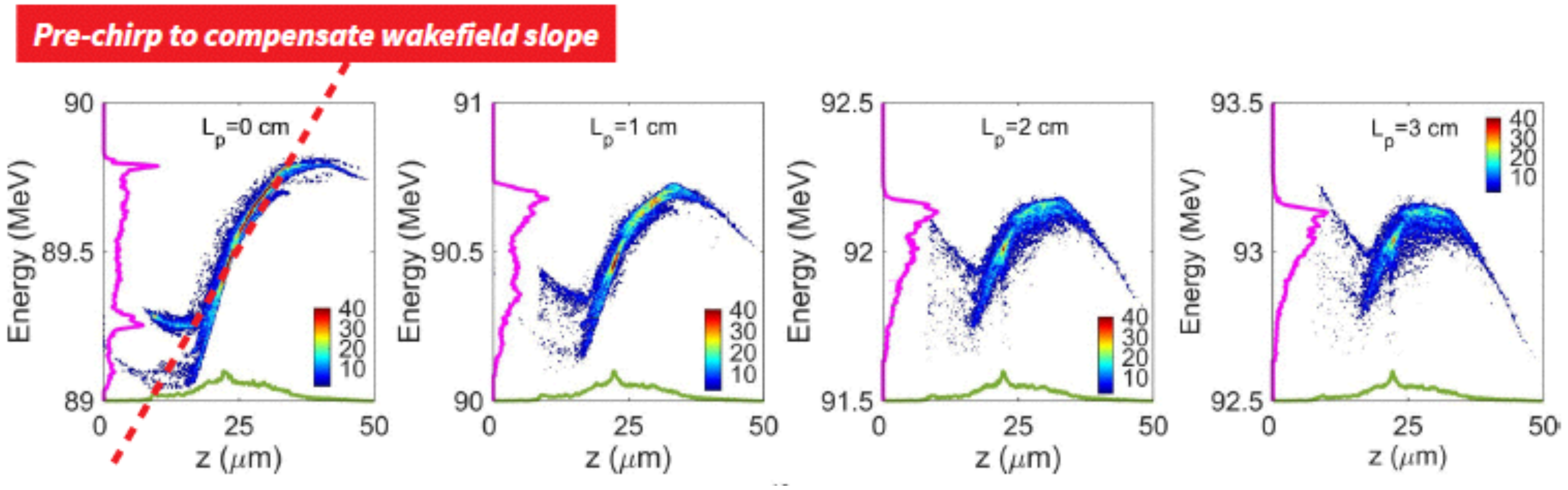
Motivation

- **Plasma-based accelerators** hold **great potential to drive** new generation of compact Free-Electron Lasers (**FELs**) based facilities
- Several advances toward **high quality plasma-accelerated beams**
  - In particular, energy spread optimization

C. A. Lindstroem et al., *Energy-spread preservation and high efficiency in a plasma-wakefield accelerator,* PRL **126,** 014801 (2021)



FLASHForward (DESY)



SPARC_LAB (INFN)

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

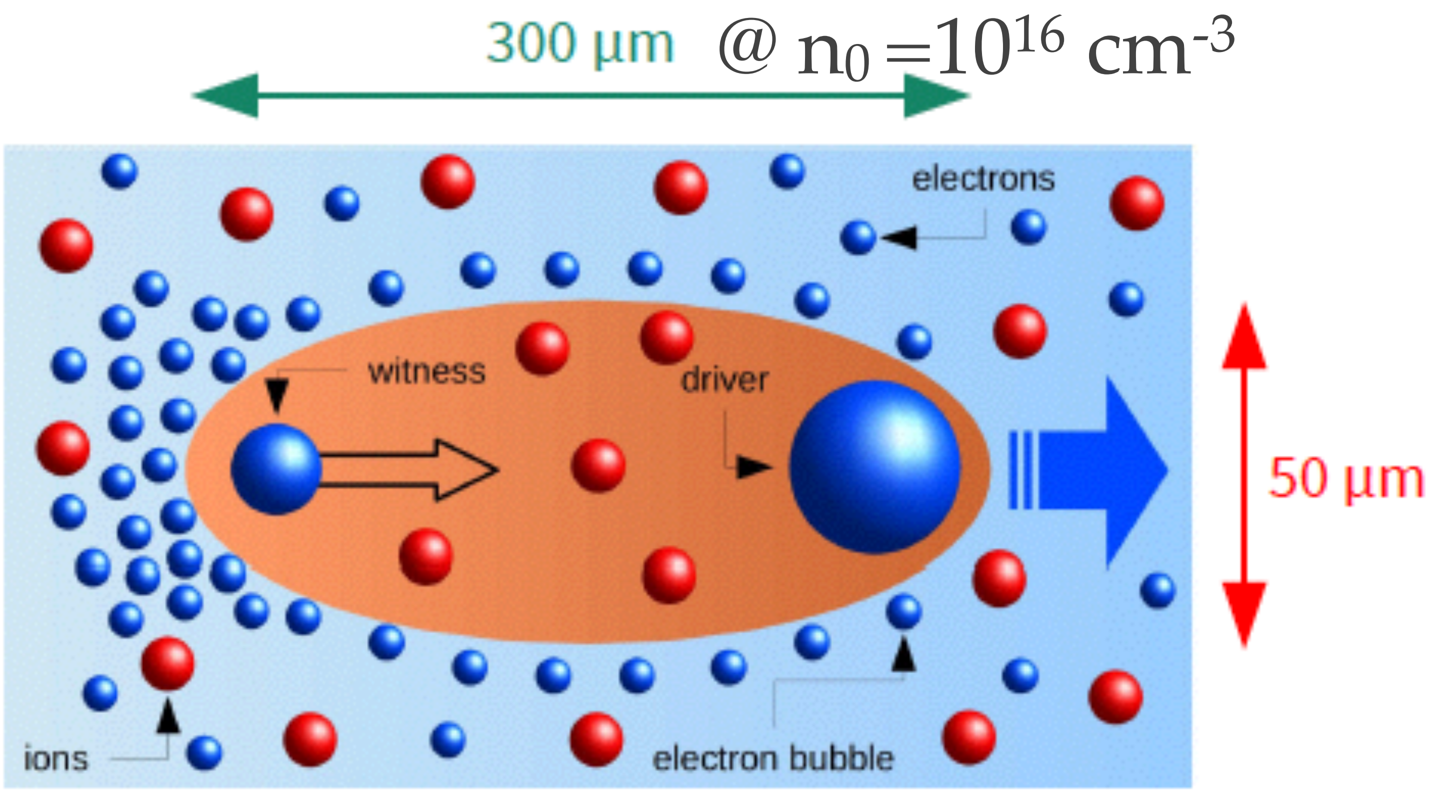
Methods

- The **ionized plasma** in a gas-filled discharge capillary, a gas cell or a gas jet **can sustain** accelerating gradient 2-3 orders of magnitude larger than in conventional RF-based accelerators
    - Maximum accelerating field a plasma can sustain: **Wave breaking field**

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

- Characteristic scale length of the accelerating field, i.e. the plasma wake, is the plasma wavelength, $\boldsymbol{\lambda_p}$

$$\lambda_p[\mu m] \approx \frac{3.3 \cdot 10^{10}}{\sqrt{n_0[cm^{-3}]}}$$



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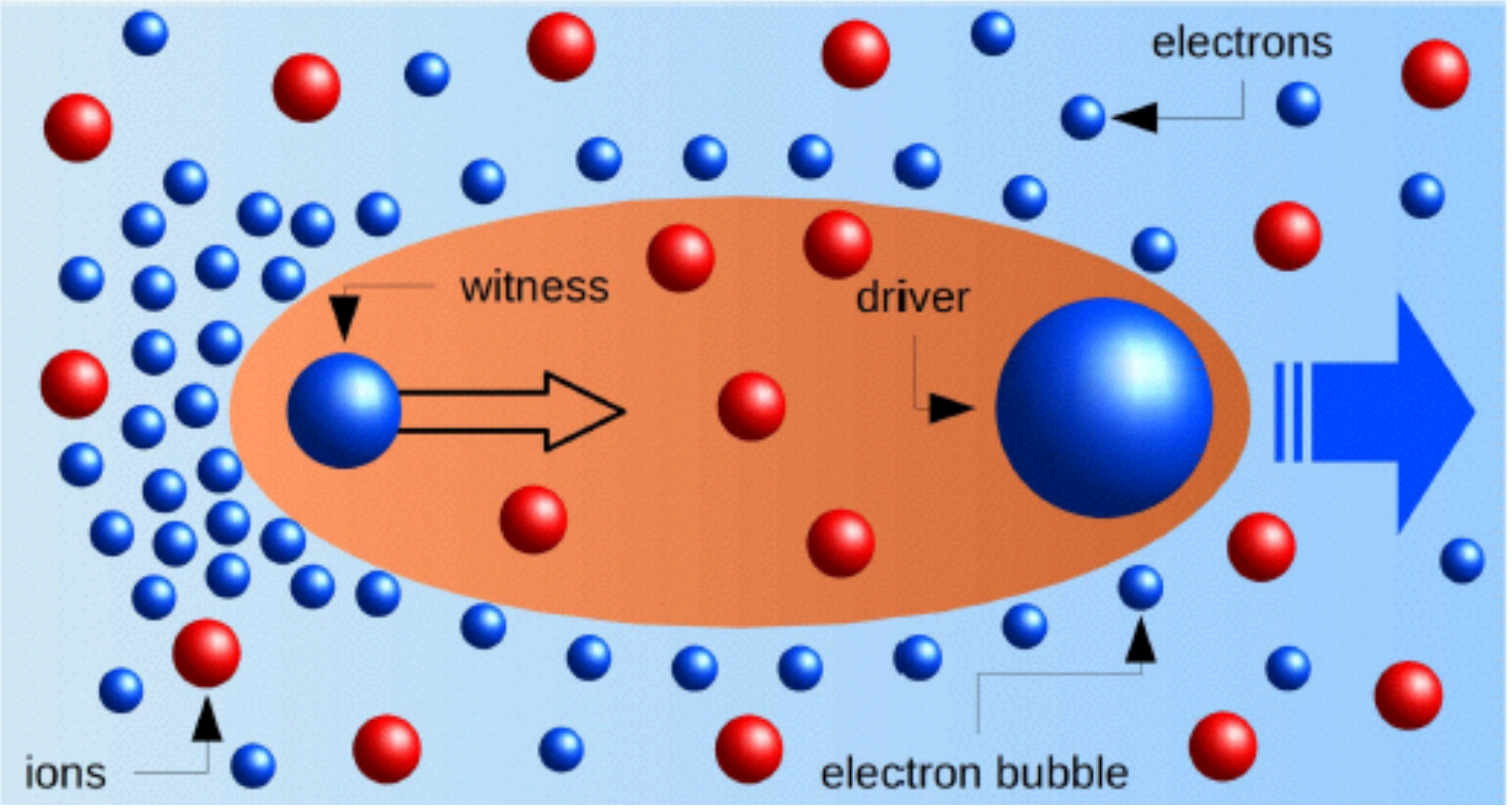
Acceleration Mechanism



- The **driver**, creating the bubble, can be either a
  - **dense relativistic particle beam** (**PWFA**) of sub-ps duration and kA level peak current
  - **ultra-intense laser pulse** (**LWFA**), ~10^{18} W/cm^2, of few 10s fs duration
- The **witness** can be either **self-injected** or **externally injected**

- Rapid acceleration of injected electrons to ultra-relativistic energies, inside the micrometer-sized structured plasma environment
  - the trapped electron beam remains short, dense, and free of significant space-charge driven emittance degradation

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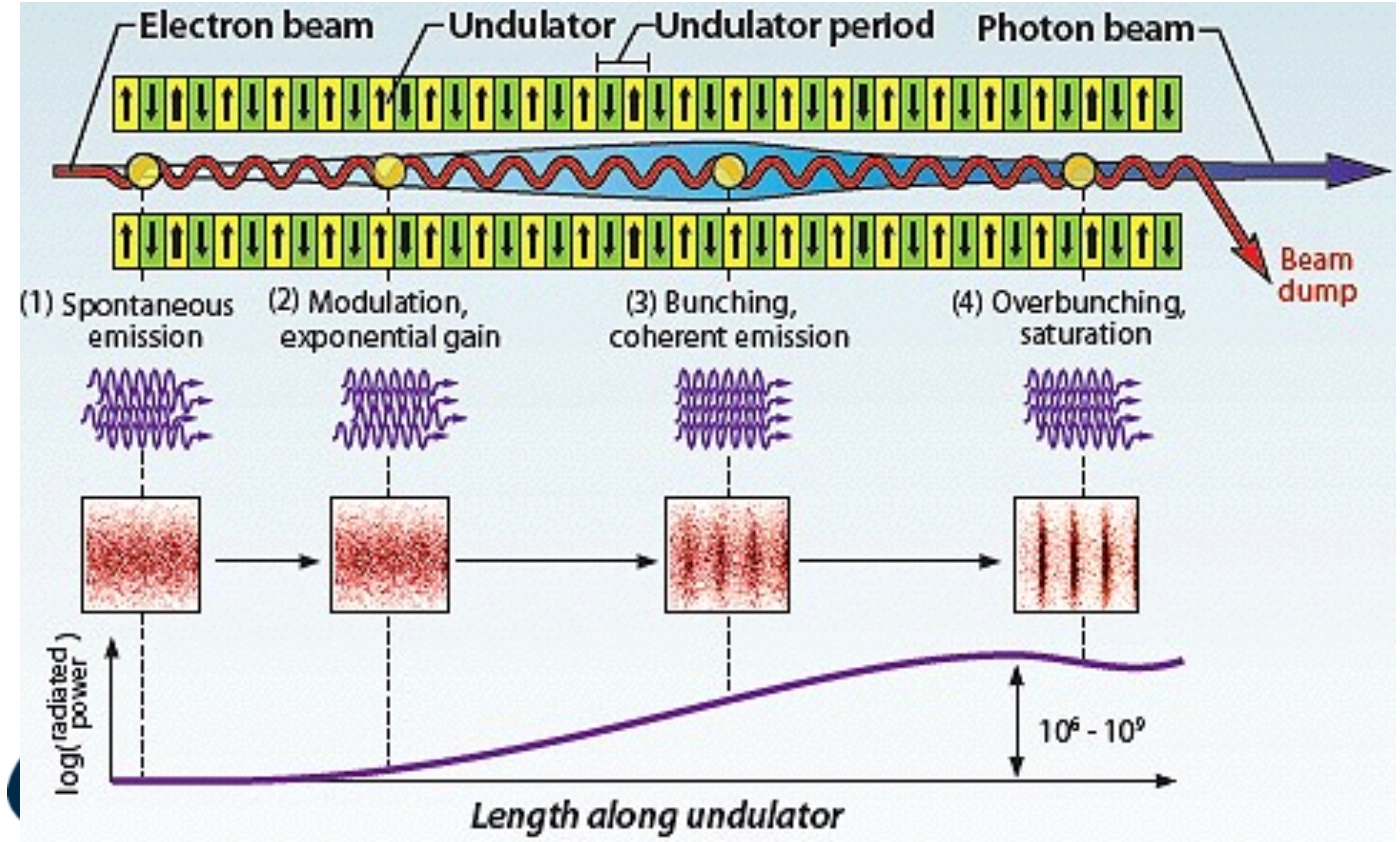
Towards a Plasma-based FEL Facility

- **High quality beam** $\varepsilon_n \ll 1 mm\ mrad, I_{peak} \sim kA, \frac{\Delta\gamma}{\gamma} \ll 1\%$
- 1D model of FEL interaction => Pierce Parameter $\rho = \frac{1}{2\gamma}\left[\frac{I}{I_A}\left(\frac{\lambda_u K[JJ]}{\sqrt{8\pi}\sigma_x}\right)^2\right]^{1/3}$
- 1D gain length $L_g = \frac{\lambda_u}{4\sqrt{3}\pi\rho}$ => Saturation Power $P = P_{in}e^{\frac{z}{L_g}}$



https://www.lanl.gov/science/1663/june2010/story4b.shtml

- **Long term and shot-to-shot stability and reproducibility**
- **High repetition rate: from 10s Hz to 100s Hz and ~kHz**
  - Preferable for maximizing average power

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International Scenario for LWFA

	COXINEL	DESY-LUX	SIOM	LBNL-BELLA
Charge density [pC/MeV]	0.5	4	1–5	2
Repetition rate [Hz]	1–10	1	1–5	5
Mean energy [GeV]	0.18–0.4	0.3	0.84	0.1–0.3
Slice energy spread RMS [%]	NA	0.5	0.24–0.4	0.2–1
Charge [pC]	NA	50	8–25	25
Emittance [mm-mrad]	1	1.5 (horz.), 0.3 (vert.)	0.4	0.3–1
FEL wavelength [nm]	UV-VUV	100	6–10	80
Undulator technology	Cryo-PMU	Cryo-PMU	Planar and TGU	Planar + strong focusing
FEL operation modes	Decompression + seeding	Decompression + SASE	SASE, transverse decompression	Decompression + seeding
Key challenge pursued	Demonstrate FEL gain	Demonstrate FEL gain	Demonstrate FEL gain	Demonstrate FEL gain

FEL, free-electron laser; PMU, permanent magnet undulator; RMS, root mean square; SASE, self-amplification of spontaneous radiation; TGU, transverse gradient undulator.

Credits by C. Emma et al., High Power Laser Science and Engineering, (2021), Vol. 9, e57, 15 pages.

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First LWFA-driven SASE FEL

@ SIOM, Shangai

Article

Free-electron lasing at 27 nanometres based on a laser wakefield accelerator

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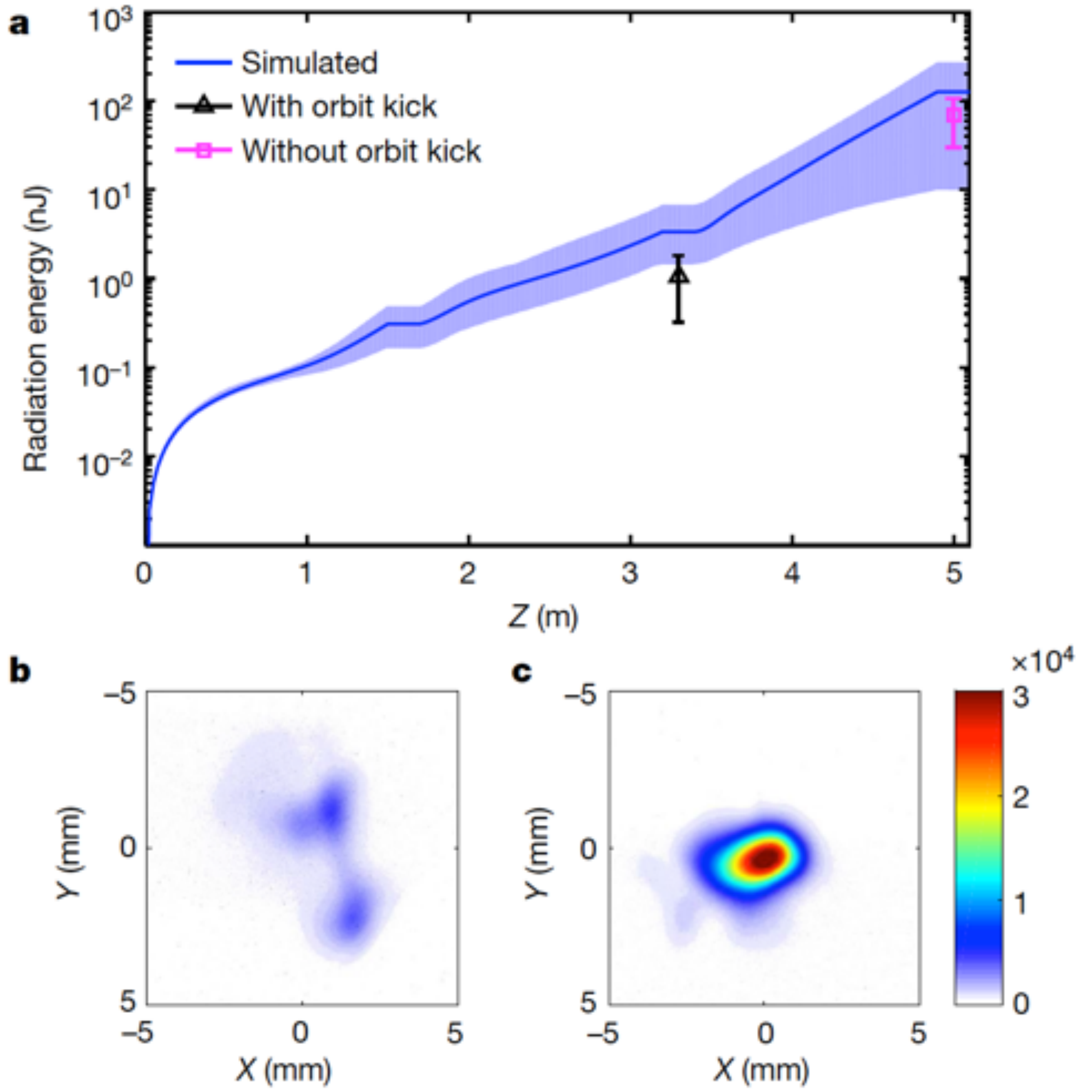

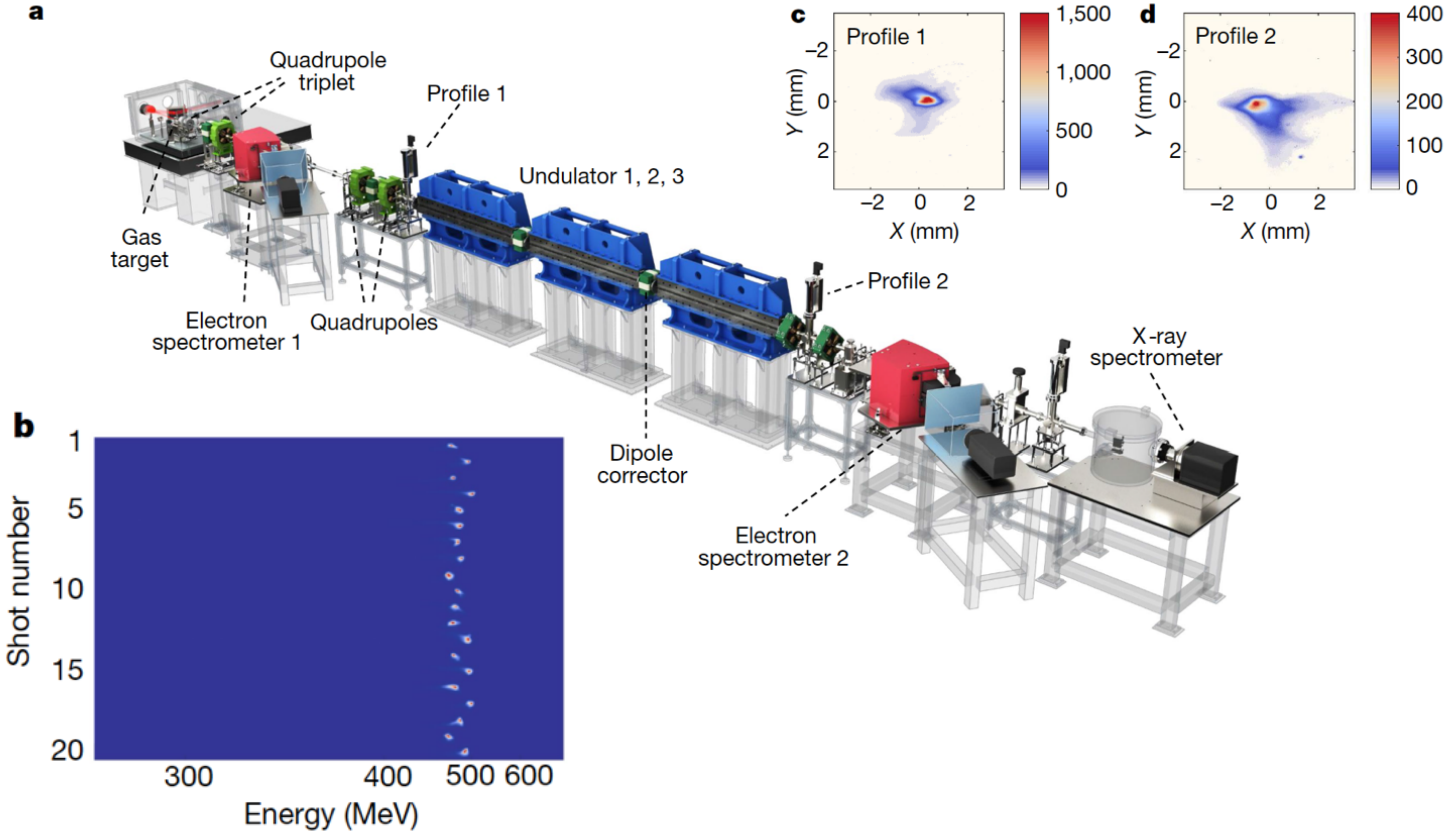

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International Scenario for PWFA

	SLAC FACET-II*	DESY - FLASHForward	Strathclyde*	SPARC LAB
Peak current [kA]	10–500	1	1–100	2.6
Repetition rate [Hz]	1	10 (10^4 after future upgrades)	Variable	1
Mean energy [GeV]	5–10	1	1–5	0.094
Slice energy spread RMS [%]	0.1–1	0.15	0.01–2	0.3
Charge [pC]	10–100	100	0.1–500	20
Emittance [mm-mrad]	1–10	1–20	0.01–1	~2
FEL wavelength [nm]	10–50	Soft X-rays	Hard X-rays	~800
FEL operation modes	Compression + pre-bunching	SASE	Multiple	SASE and Seeded
Key challenge pursued	Attosecond FEL pulses	High average power FEL	Hard X-ray FEL gain	Demonstration of the gain growth in different FEL operation modes

FEL, free-electron laser; RMS, root mean square; SASE, self-amplification of spontaneous radiation.

Credits by C. Emma et al., High Power Laser Science and Engineering, (2021), Vol. 9, e57, 15 pages.

First PWFA-driven SASE FEL

@ SPARC_LAB, INFN Frascati

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

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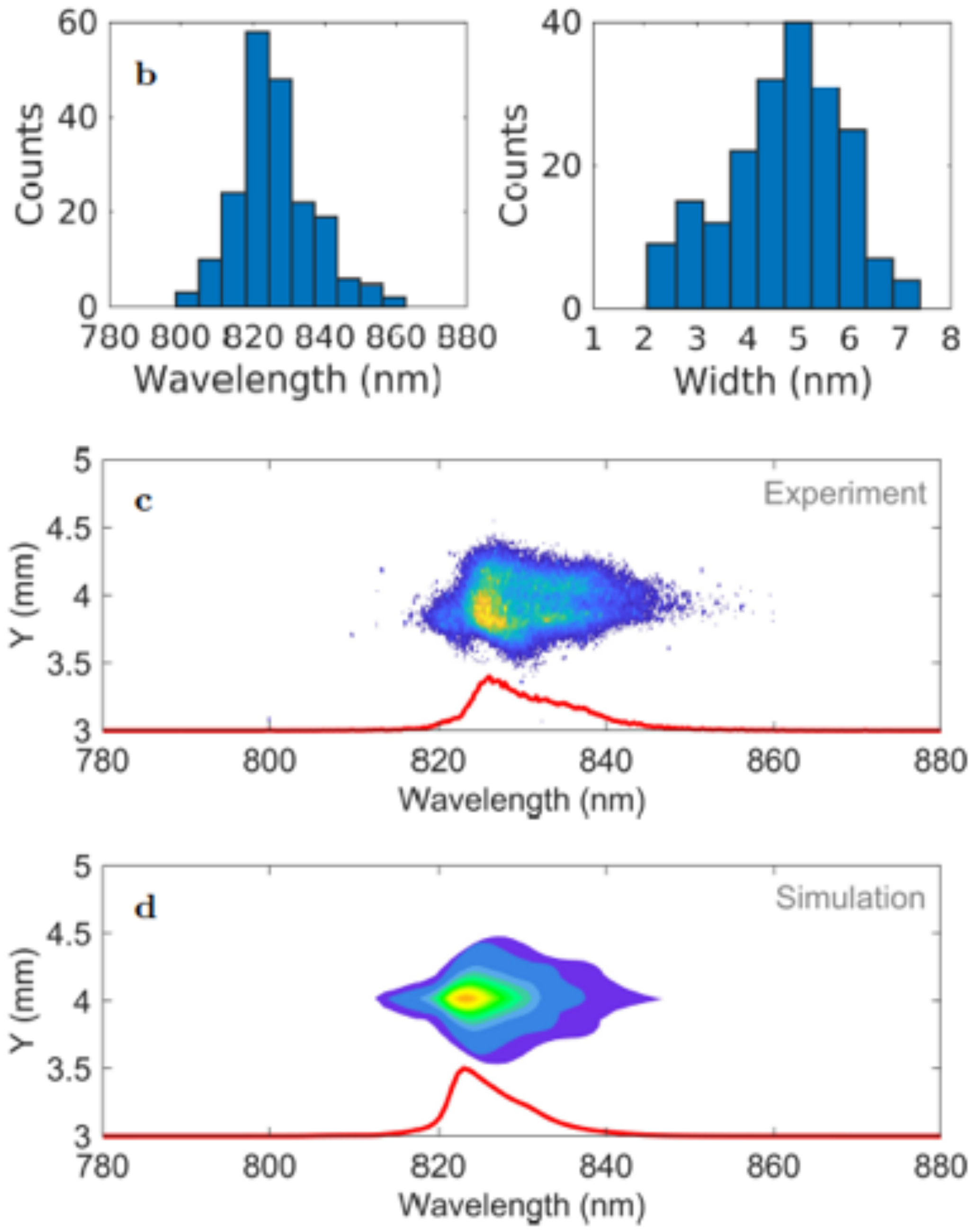

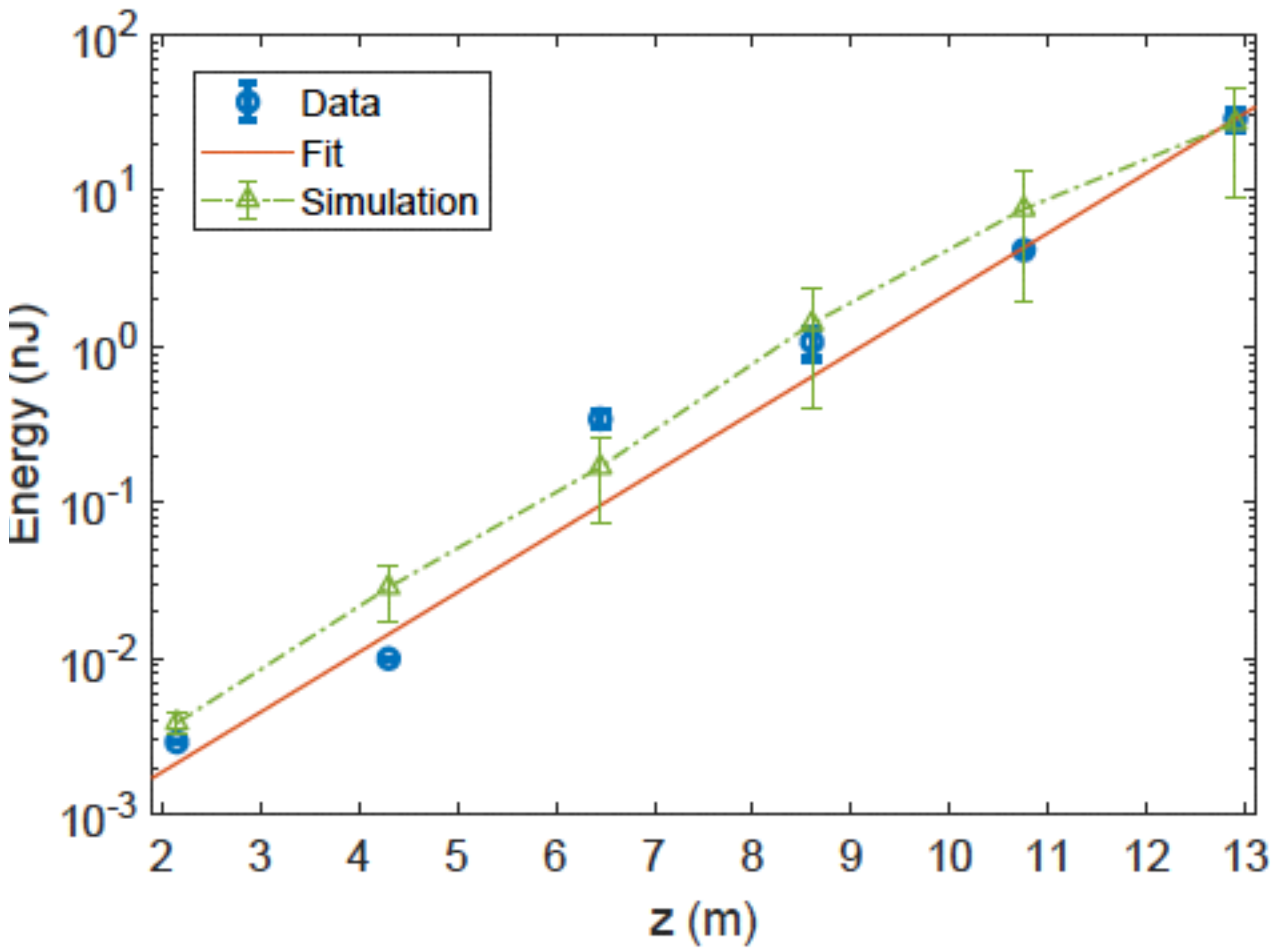

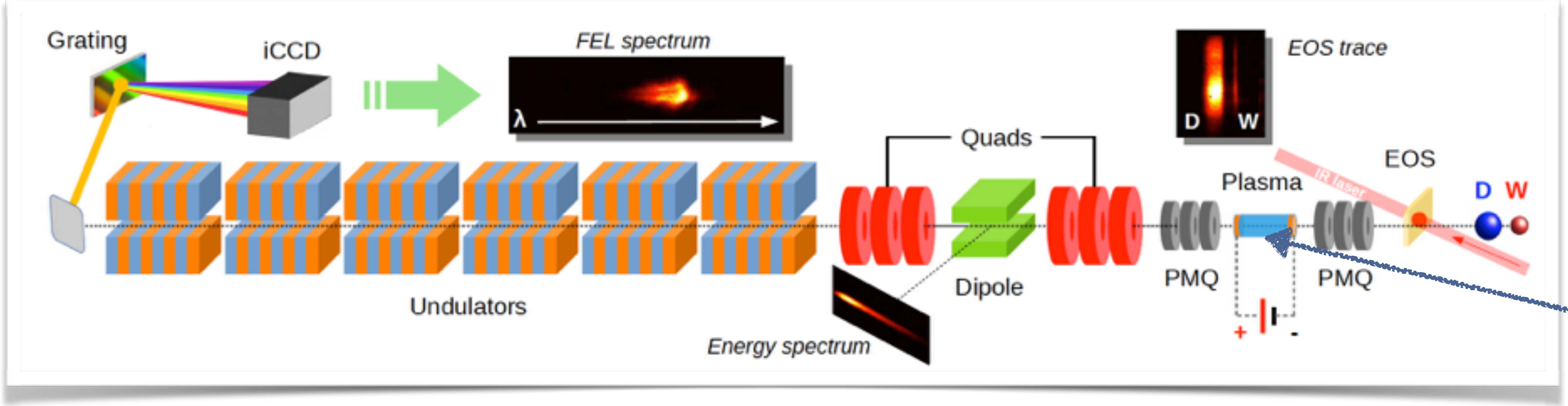

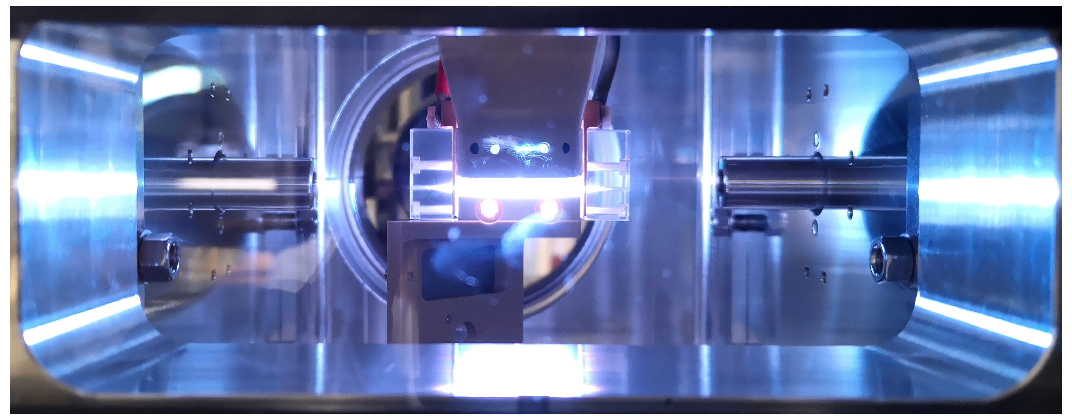

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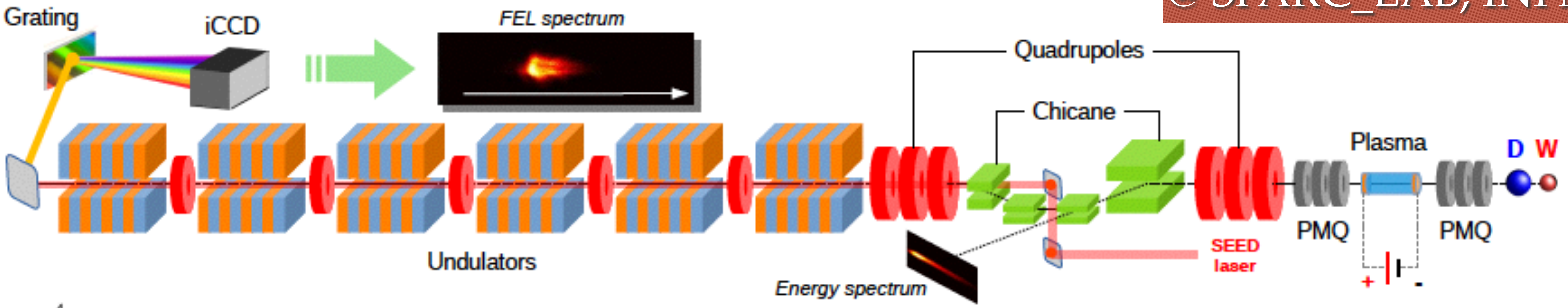
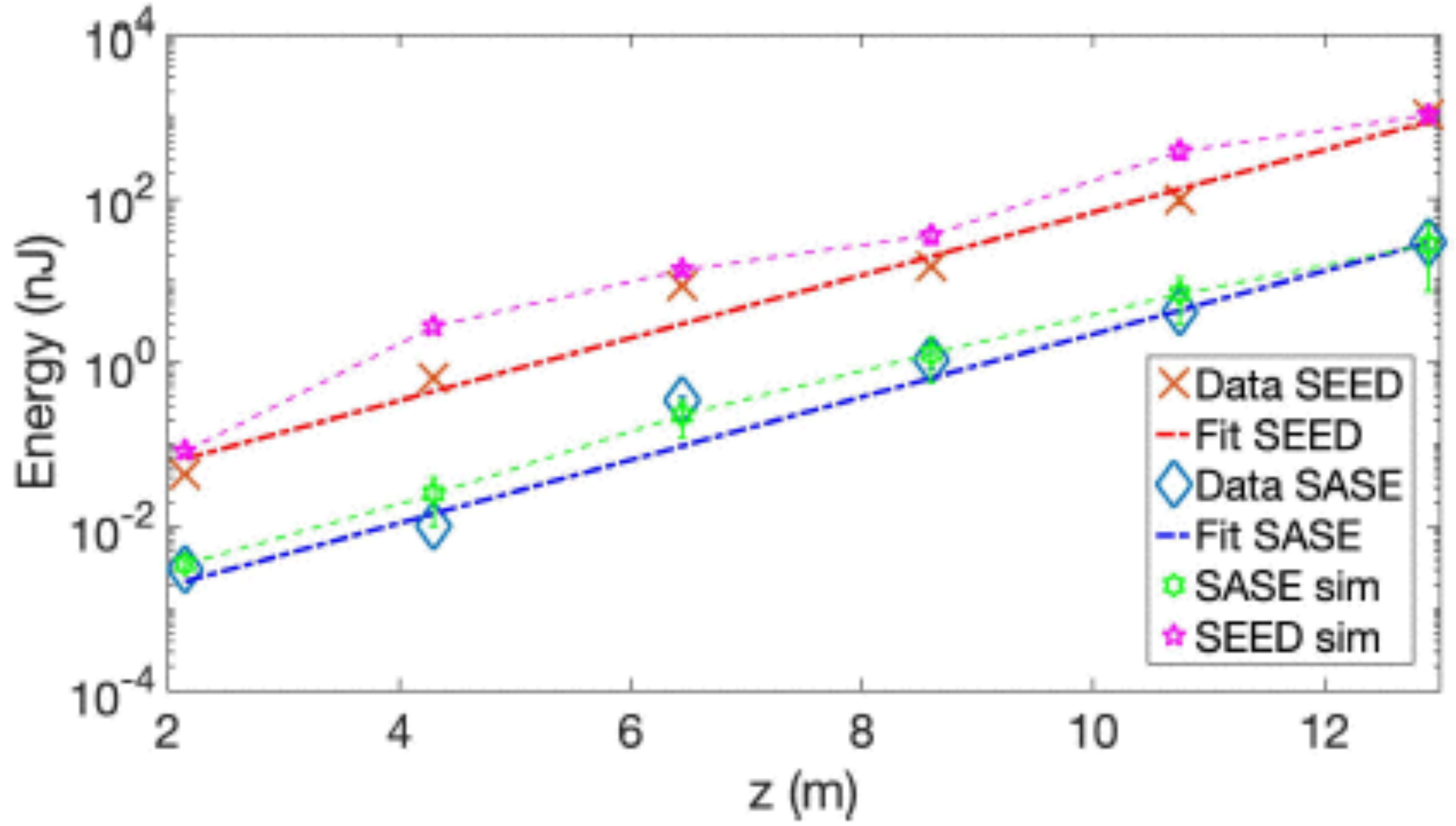
First PWFA-driven Seeded FEL

@ SPARC_LAB, INFN Frascati





Seeded FEL Radiation

- Part of the EOS laser used as seed
- Seed laser ~ 795 nm, FEL peak 827 nm
- Pulse energy increase from 30 nJ up to 1 μm
- Increased stability of emitted radiation

M. Galletti et al., submitted to NaturePhotonics

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First PWFA-driven Seeded FEL

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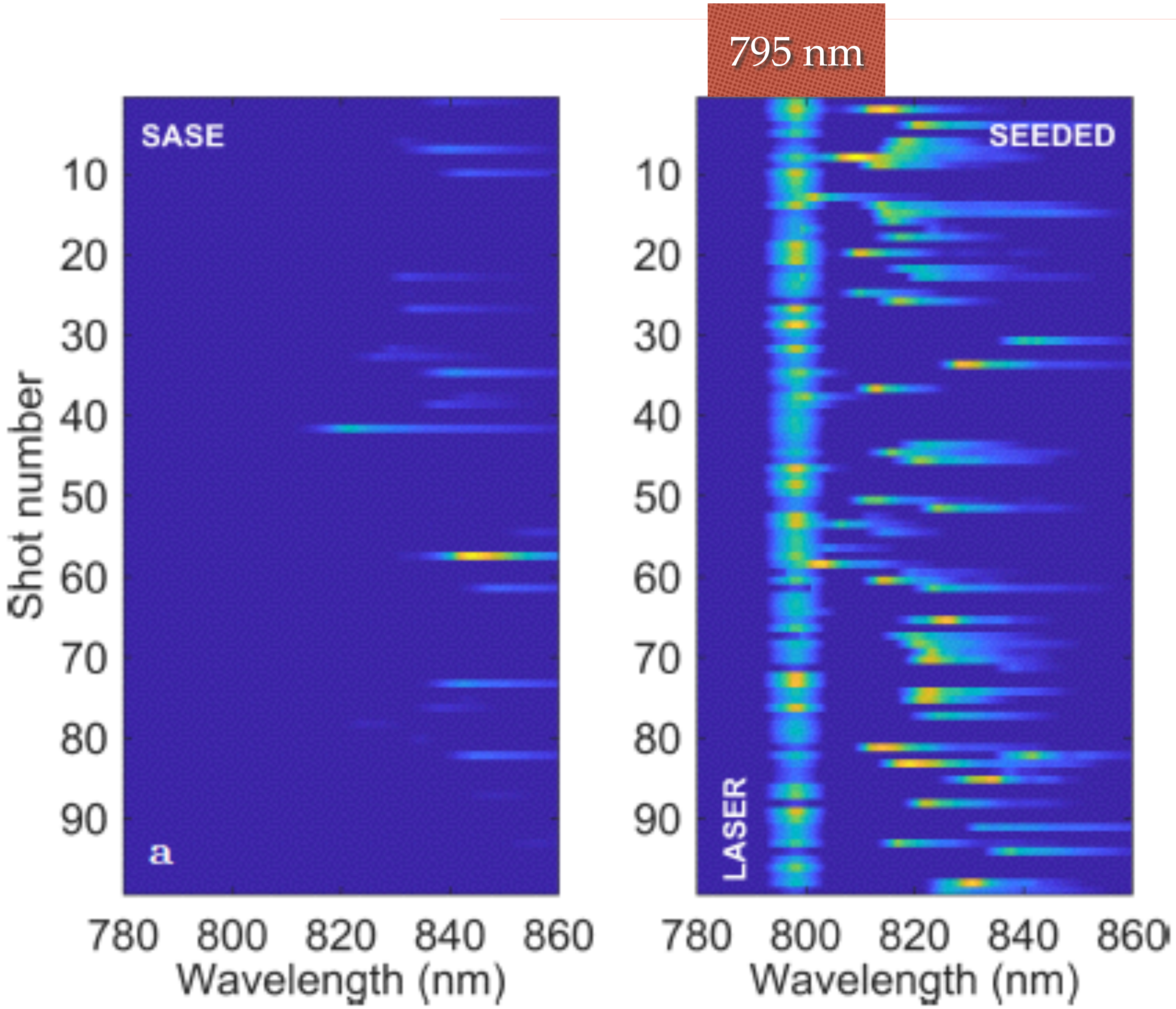
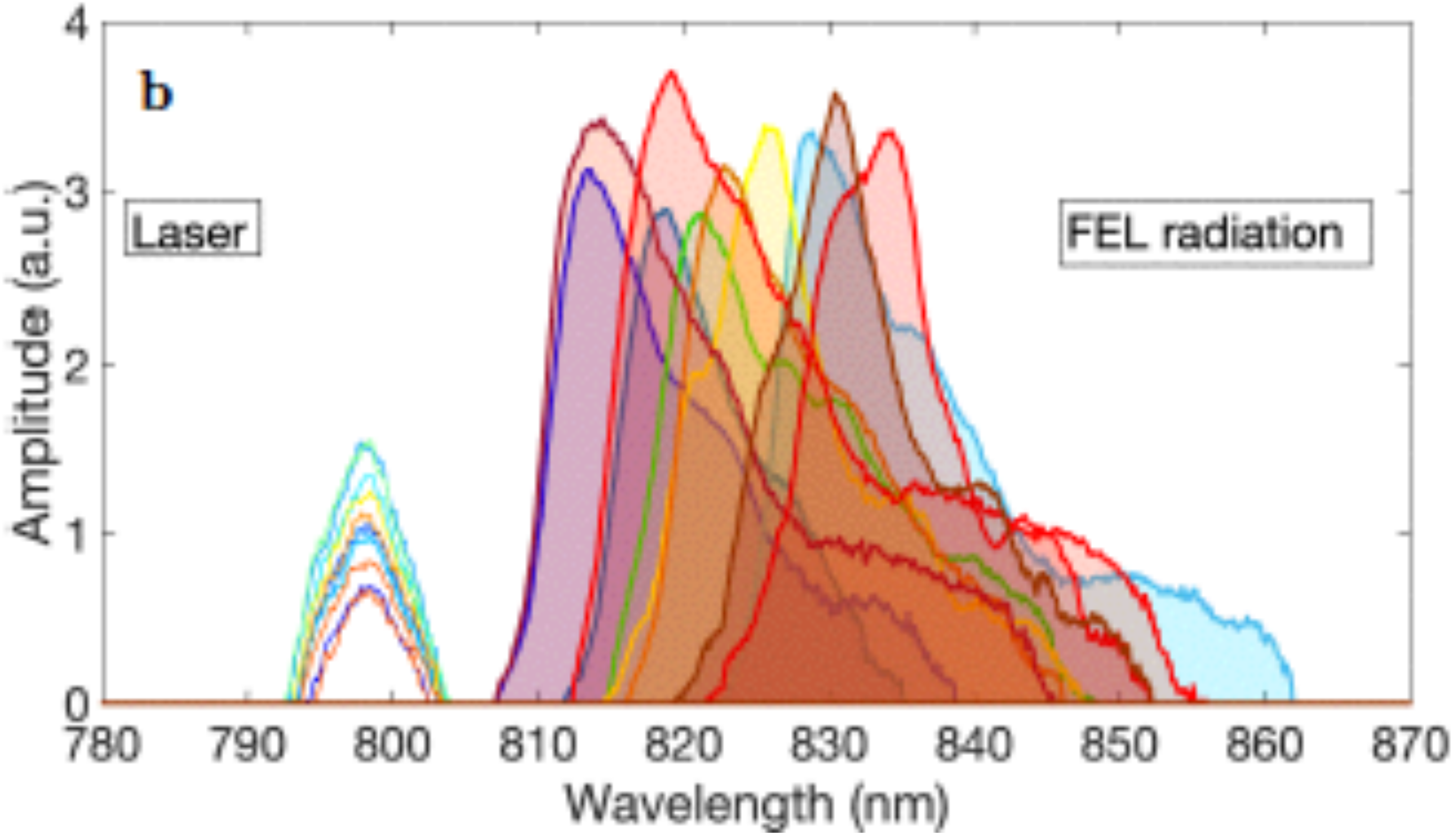


27% stability

90% stability



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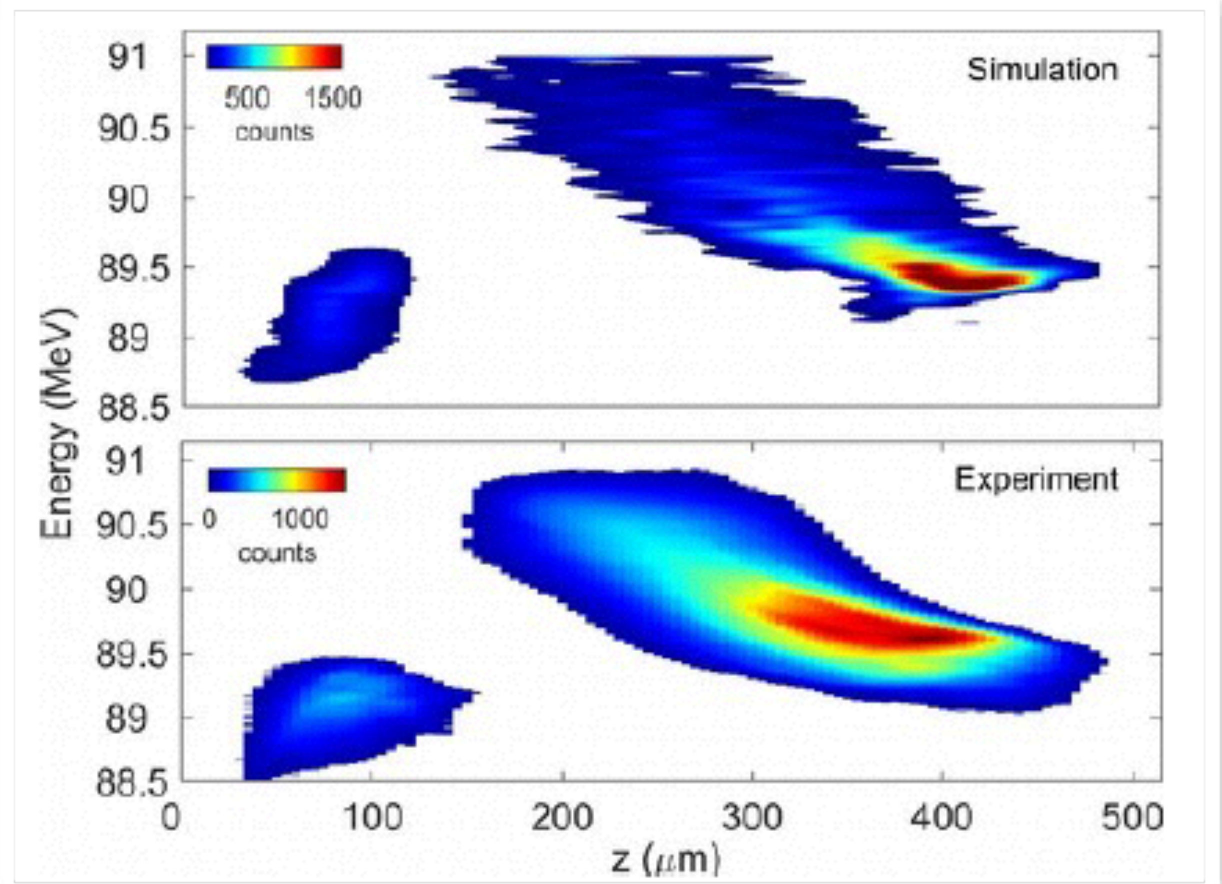
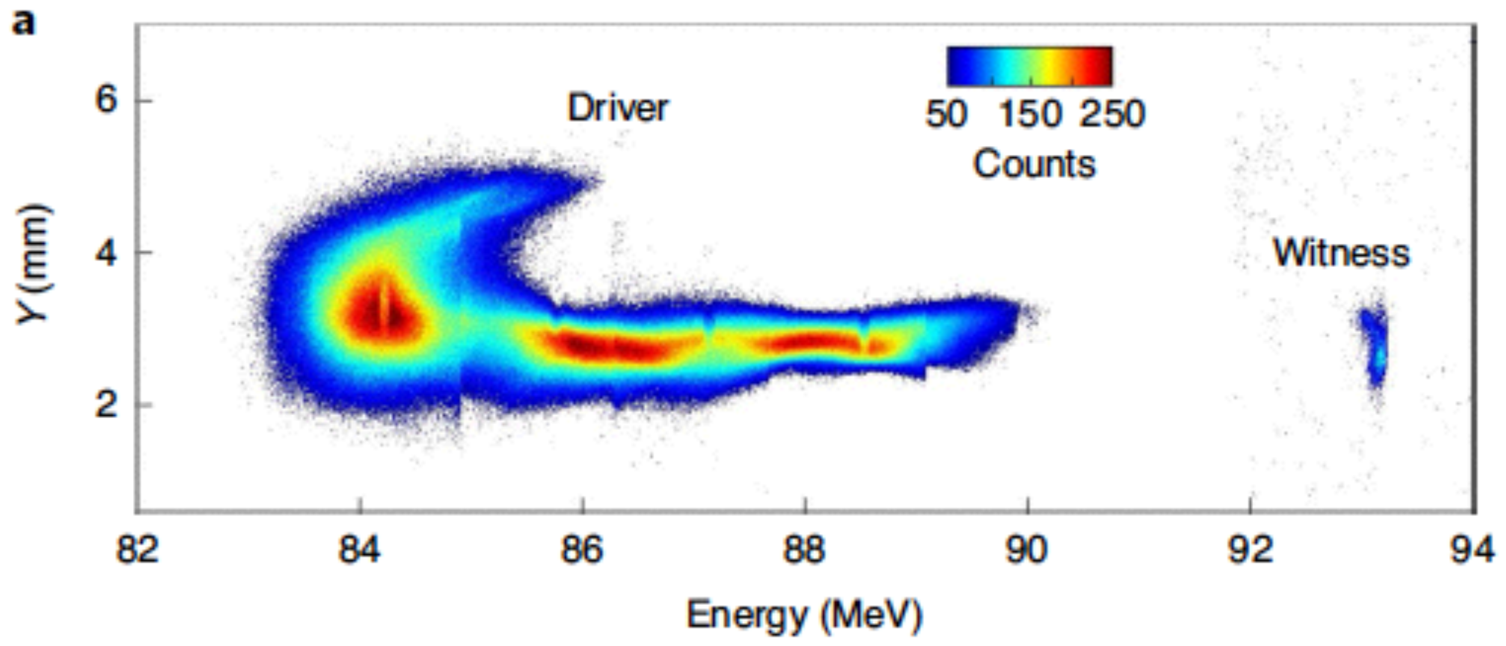
Two-Bunches in the Driver-Witness Configuration

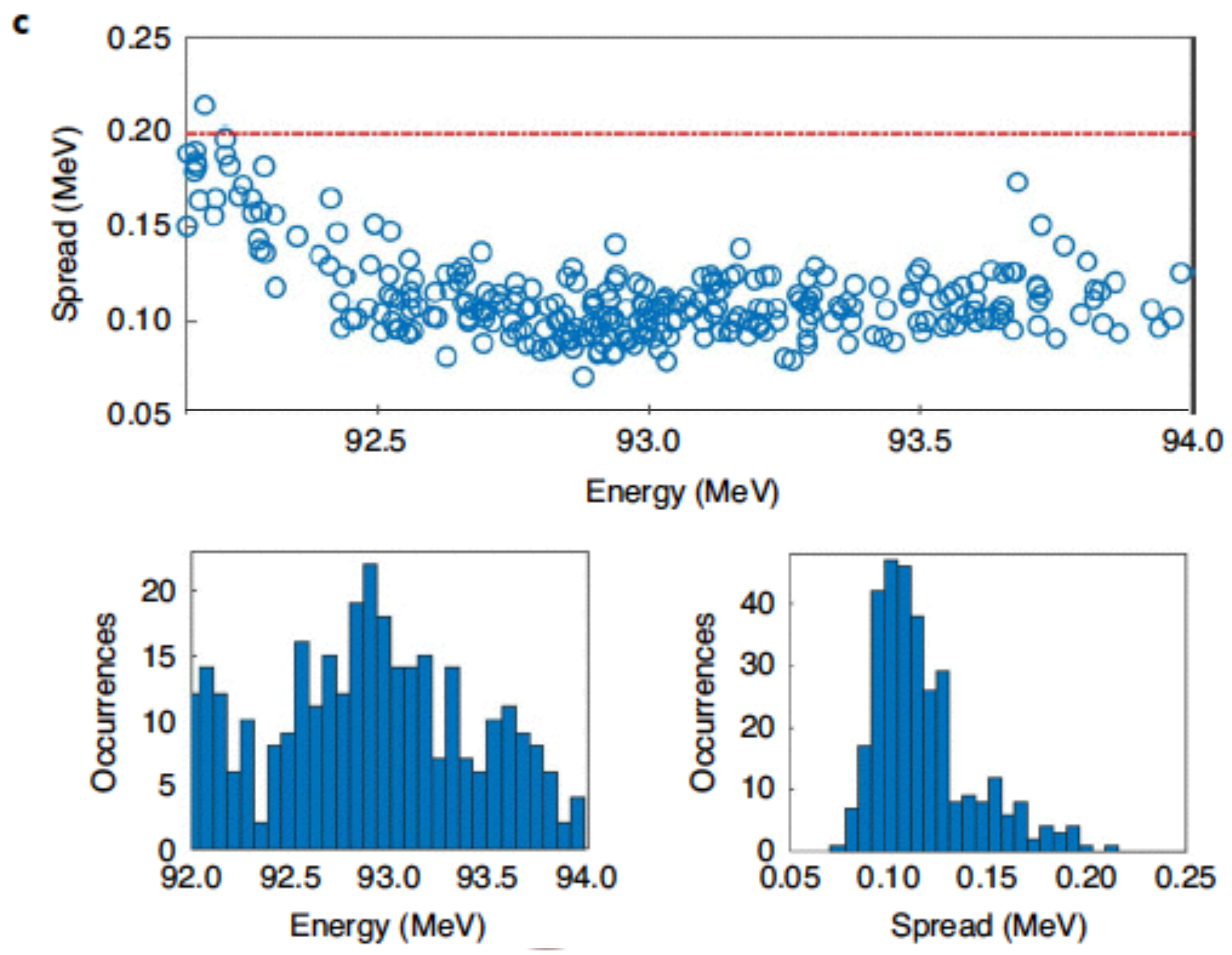


- Two-bunches configuration produced directly at the cathode with laser-comb technique
  - 200 pC driver followed by witness bunch (20 pC)
- Ultra-short durations (200 fs + 30 fs)
- Separation approximately equal to half plasma wavelength (~1.2 ps)

- **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%





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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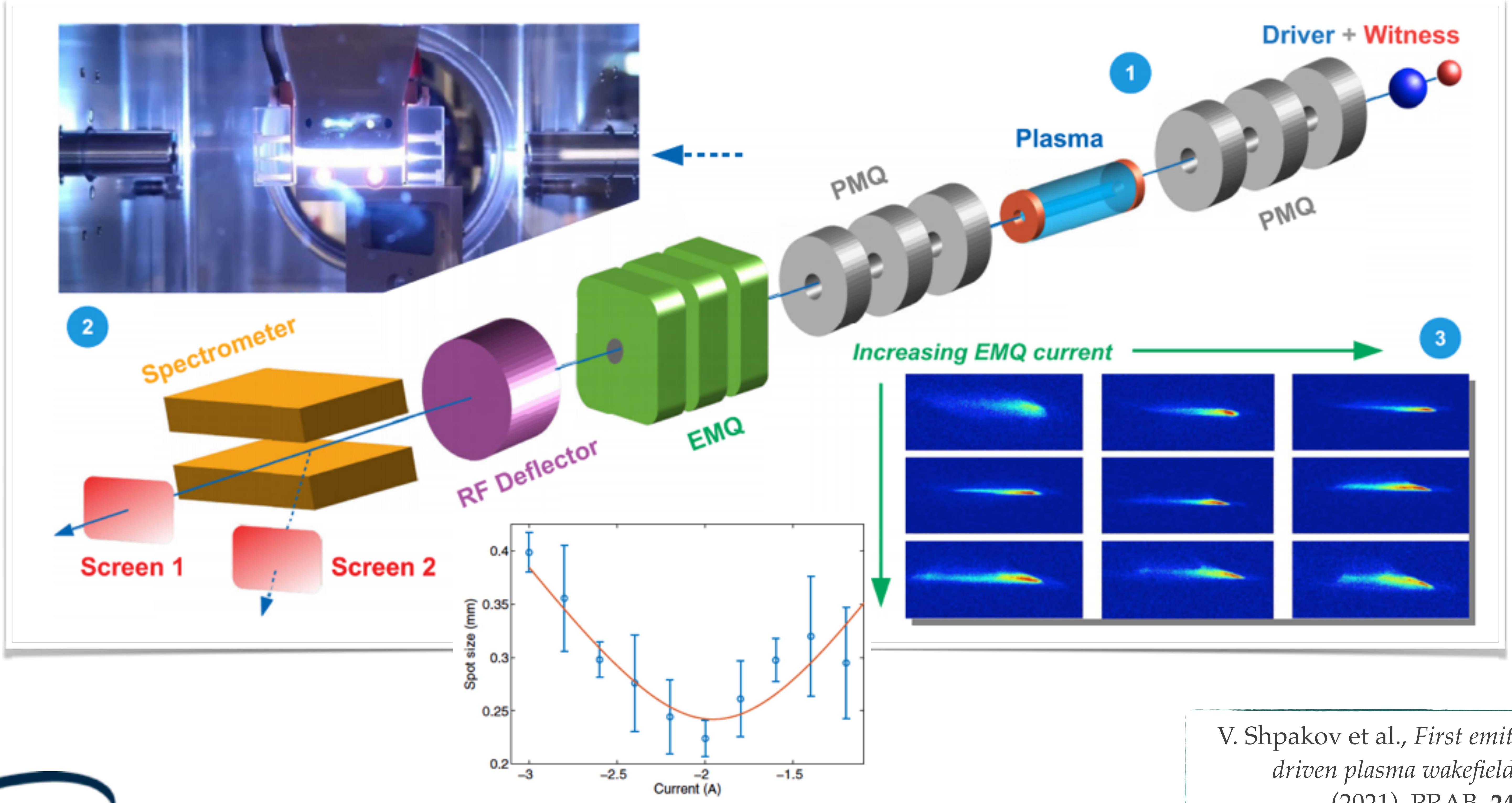
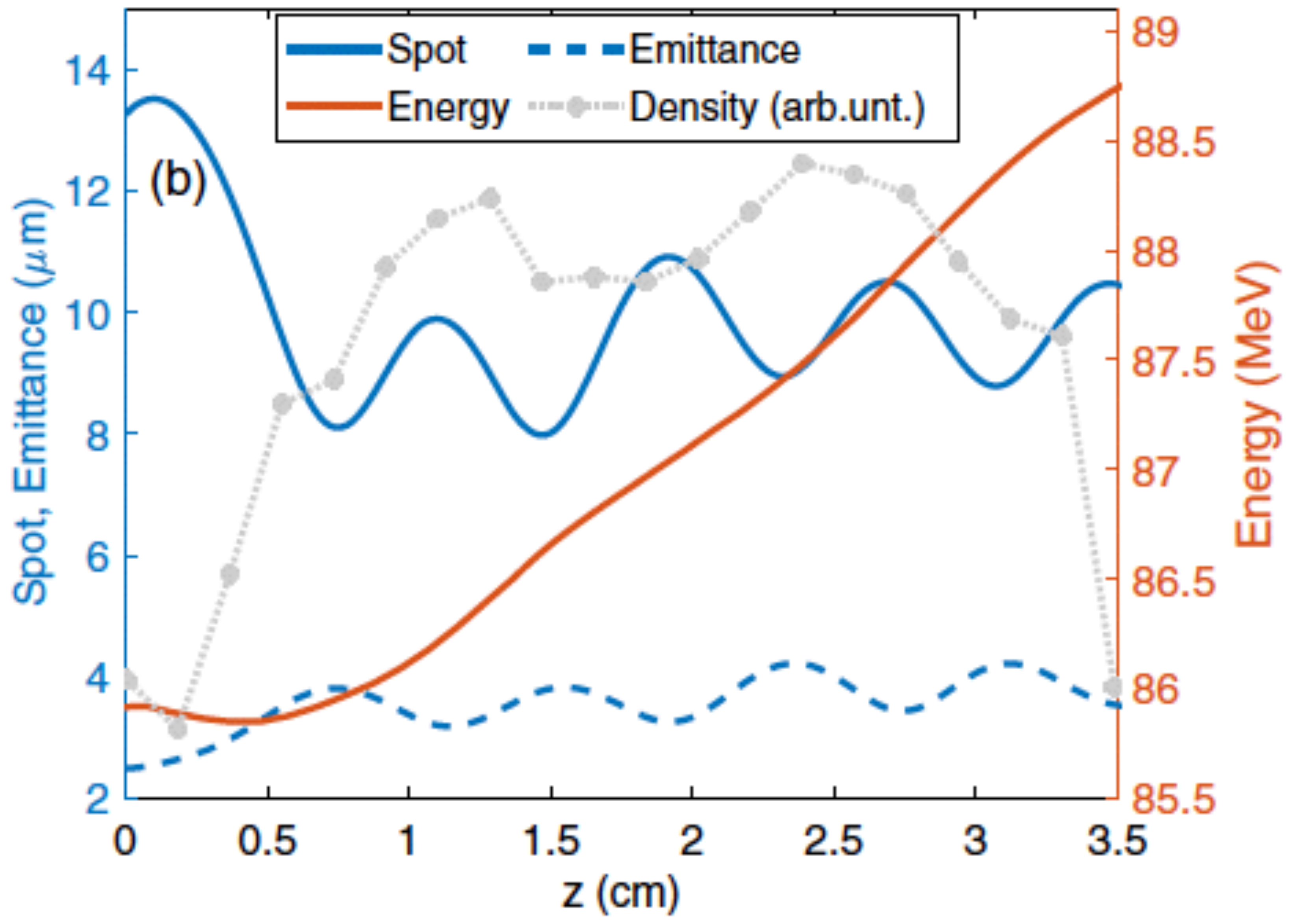
First normalized emittance measurement

- **First PWFA 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 because of non optimized matching



Simulation



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

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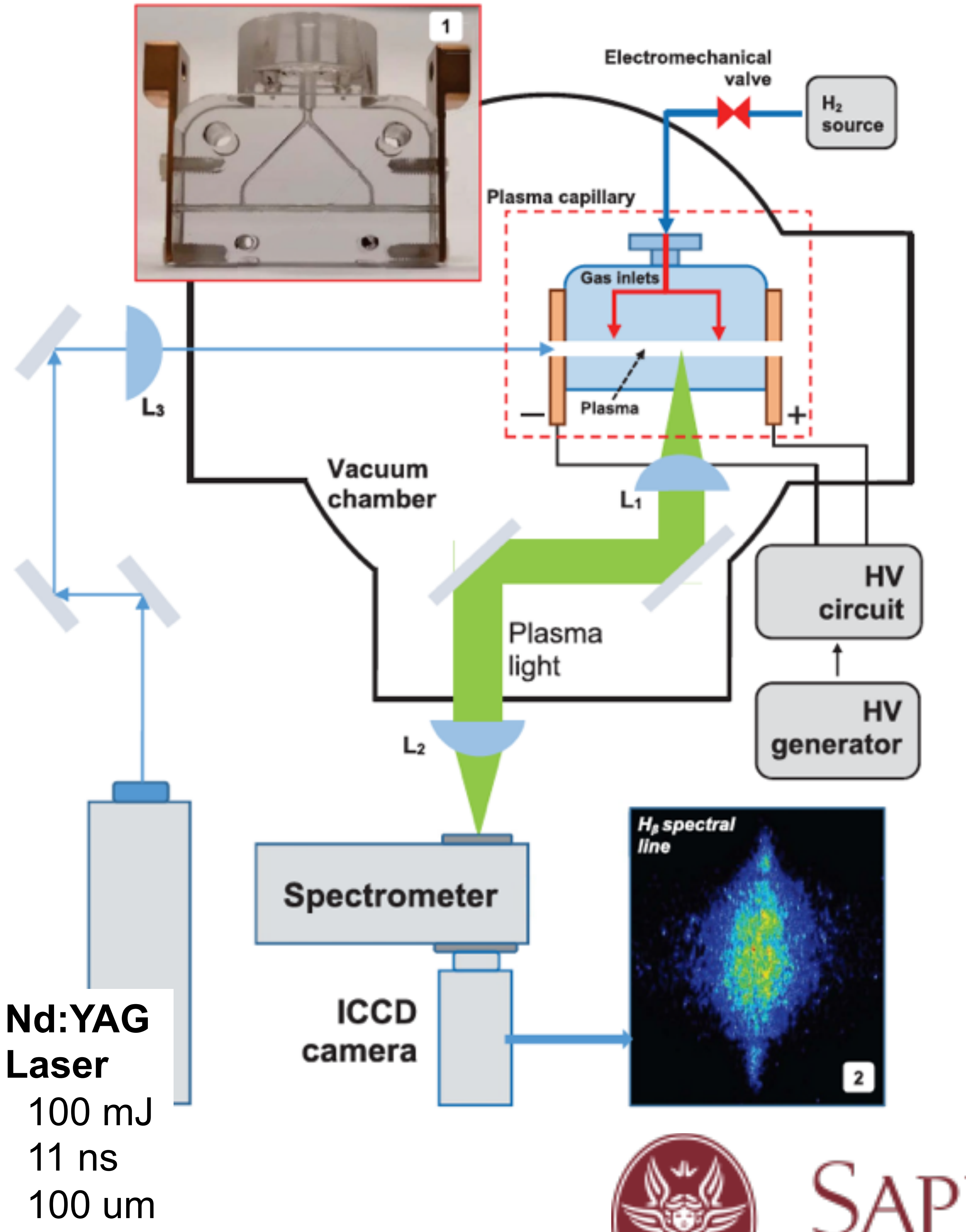
Gas-filled Capillary-Discharge Stabilization

Courtesy of A. Biagioni (INFN-LNF)

- **Discharge ignition depends on the operating conditions**, since the breakdown voltage depends on the molecules distribution inside the capillary (pressure and length)
- Discharge timing jitter is affected by the **voltage** and the **gas pressure** in the capillary
- To **decrease the time jitter** (and so the shot-to-shot instability) **a laser pulse** can be used **to ignite the discharge**



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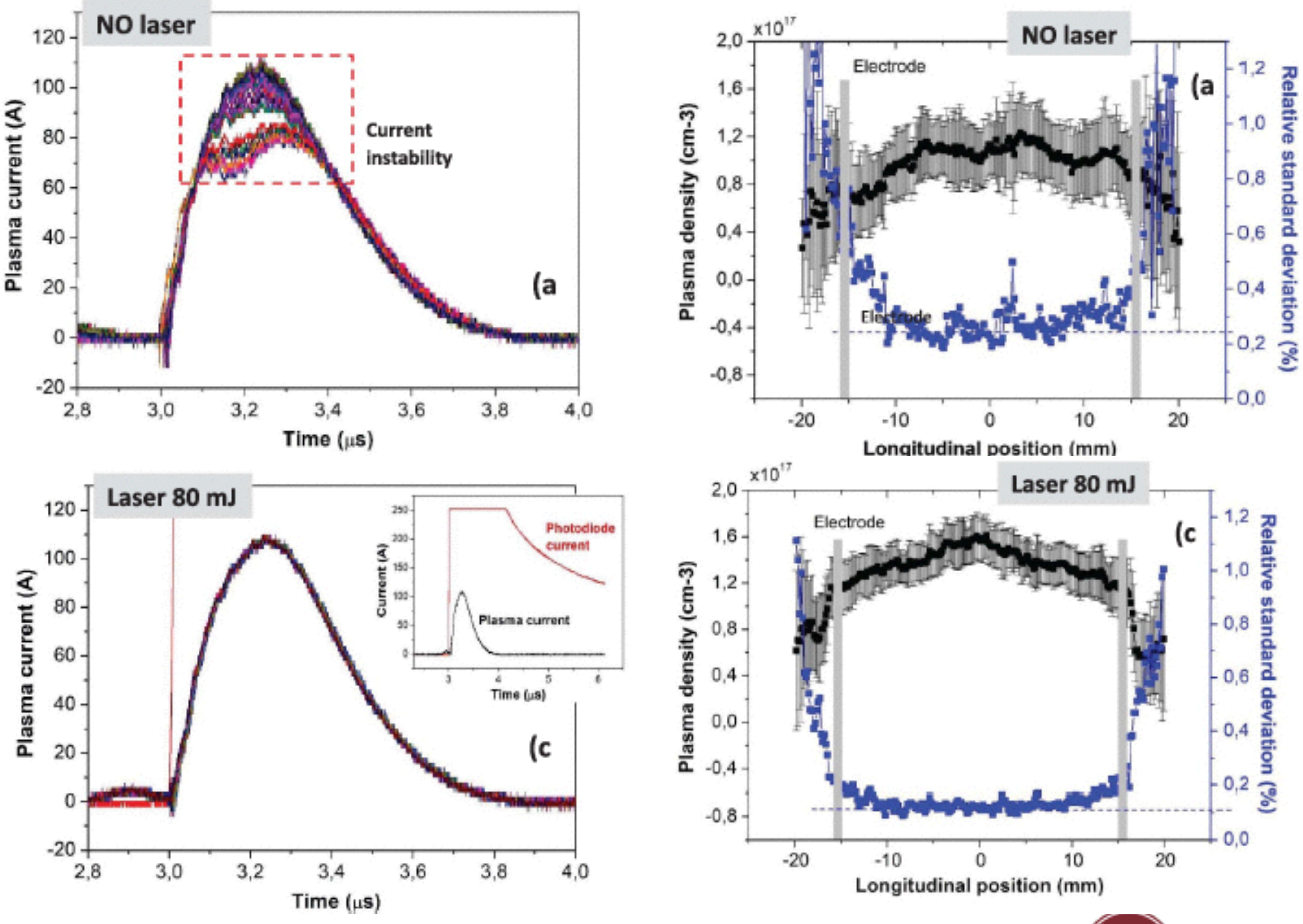
Gas-filled Capillary-Discharge Stabilization

Courtesy of A. Biagioni (INFN-LNF)

- Plasma density instability reduced **from 25% to 11%** at 5kV
- Instability of **5%** when operating **at 8 kV** (evaluated from Stark measurement)



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EuPRAXIA@SPARC_LAB

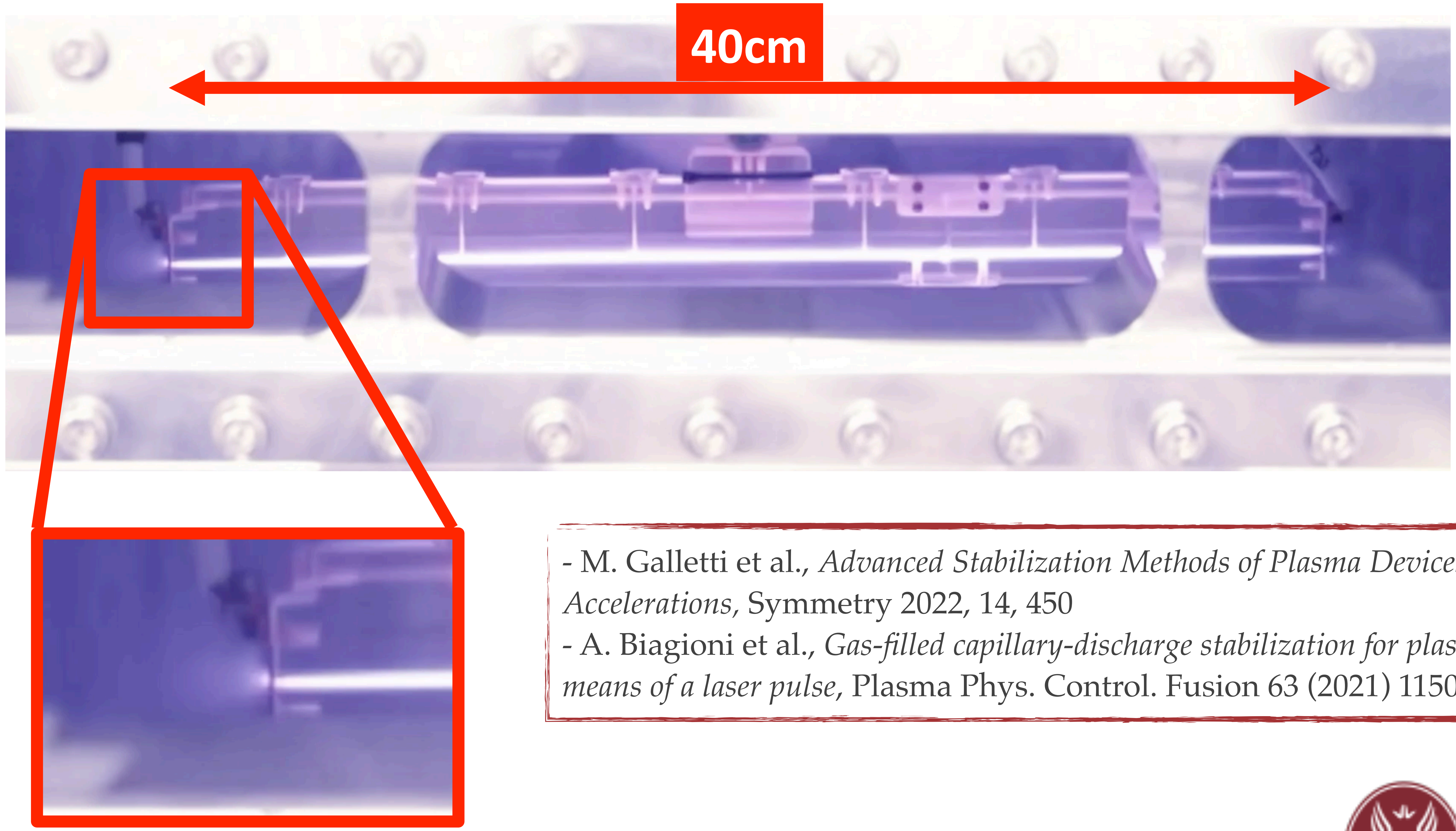
The first 40 cm Long Gas-filled Capillary Discharge

Courtesy of A. Biagioni (INFN-LNF)

Recent result in the Plasma Lab at SPARC_LAB: First EuPRAXIA plasma source enabling 1.1 GeV (1.5 GV/m)

Image captured during the formation of plasma in the **capillary 40 cm long** and **2 mm** in **diameter**.

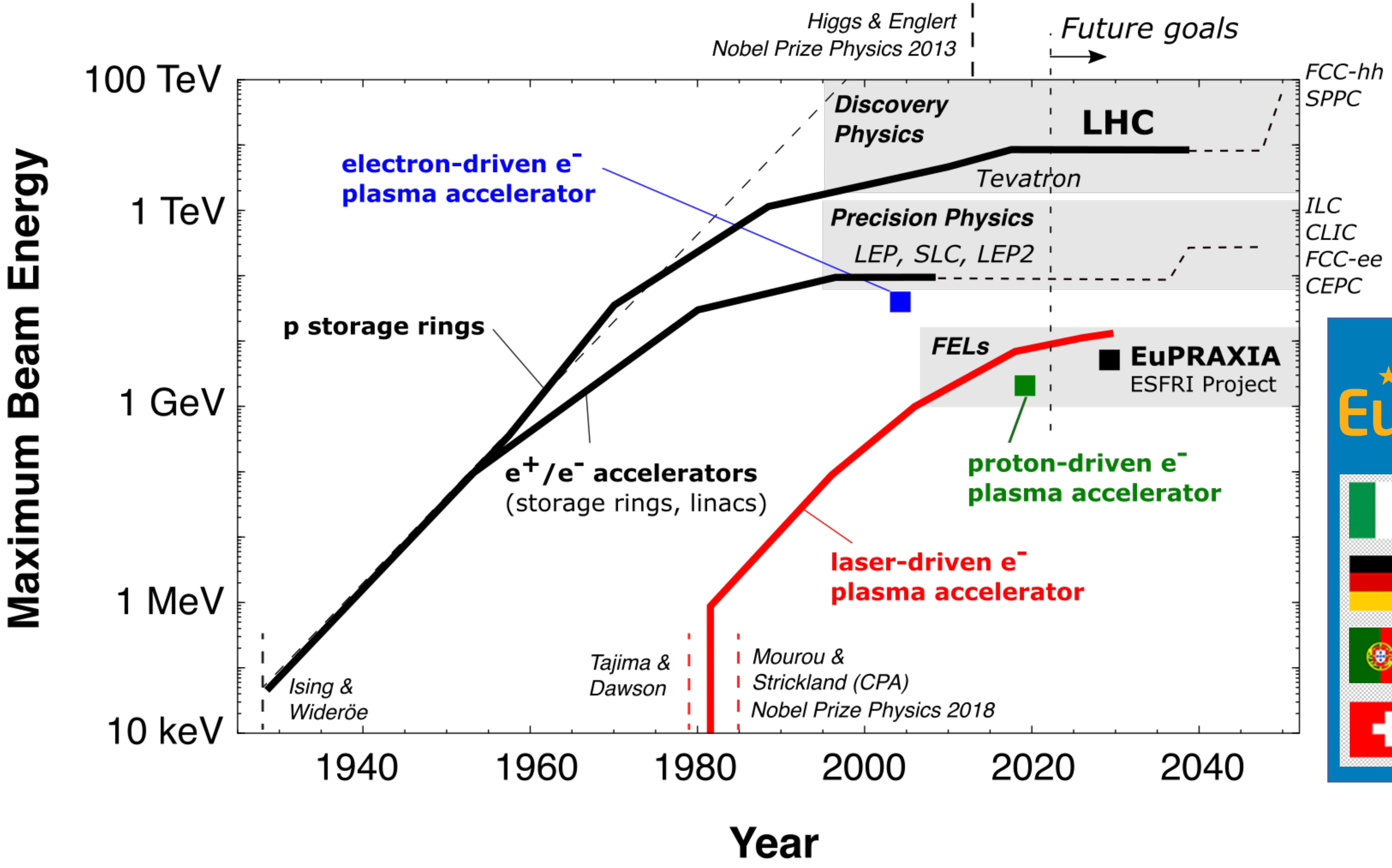
The **applied voltage** pulse is **9 kV** and the **peak current** reaches about **500 A**.



- M. Galletti et al., *Advanced Stabilization Methods of Plasma Devices for Plasma-Based Accelerations*, Symmetry 2022, 14, 450
- A. Biagioni et al., *Gas-filled capillary-discharge stabilization for plasma-based accelerators by means of a laser pulse*, Plasma Phys. Control. Fusion 63 (2021) 115013

EuPRAXIA: Build a Compact & New Facility

Courtesy R. Assmann



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Courtesy R. Assmann

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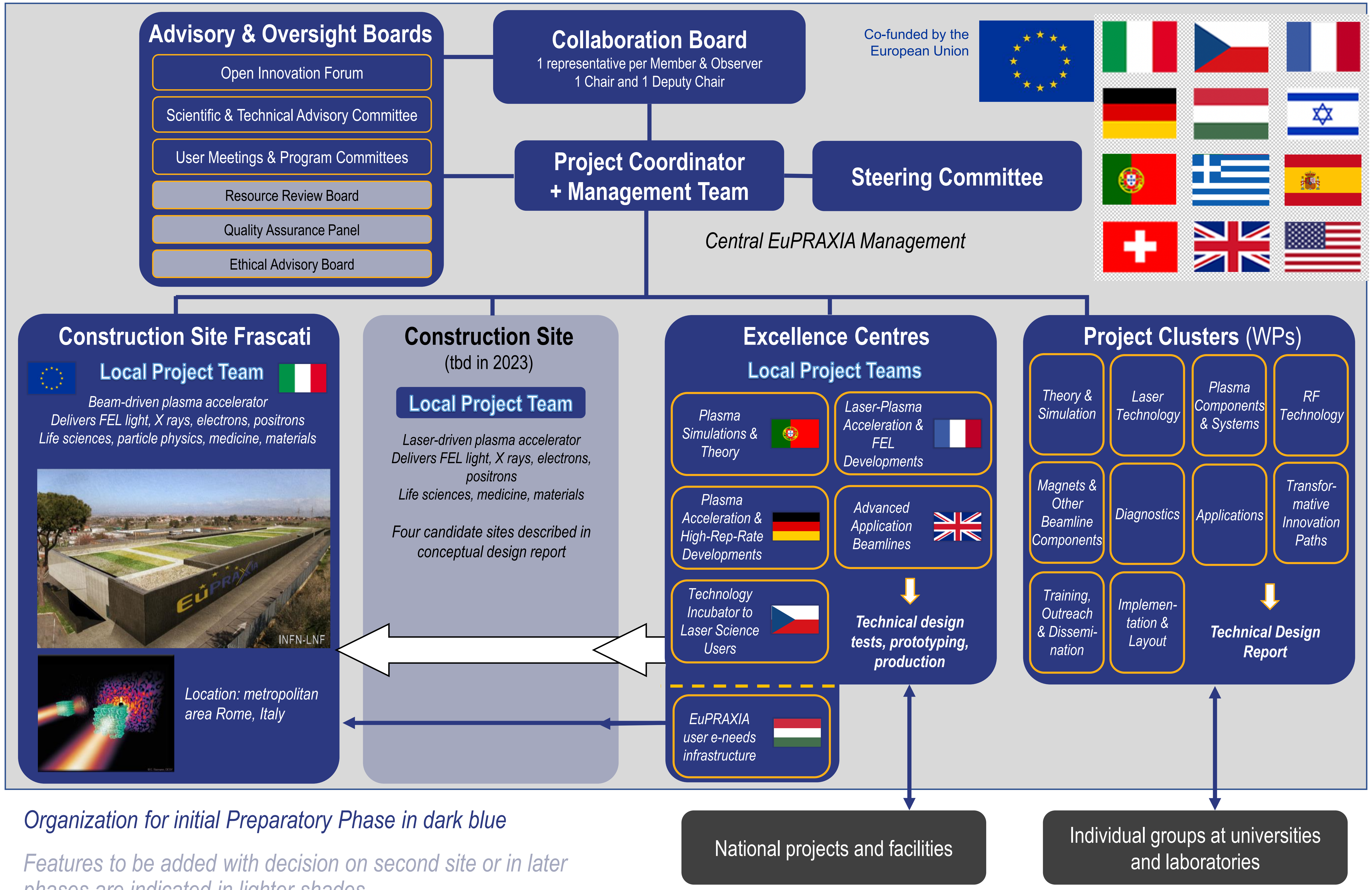
Distributed RI Concept

Courtesy R. Assmann



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

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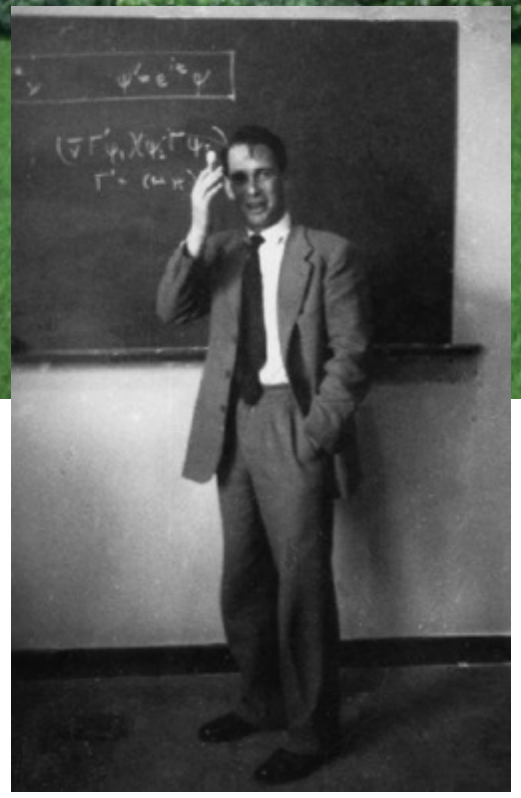
Headquarter and Site #1: EuPRAXIA@SPARC_LAB

- Frascati`s future facility > 108 M€ invest funding
- Beam-driven plasma accelerator
- Europe`s most compact and most southern FEL
- The world`s most compact RF accelerator (X band with CERN)

Courtesy R. Assmann



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Expected SASE FEL Performances

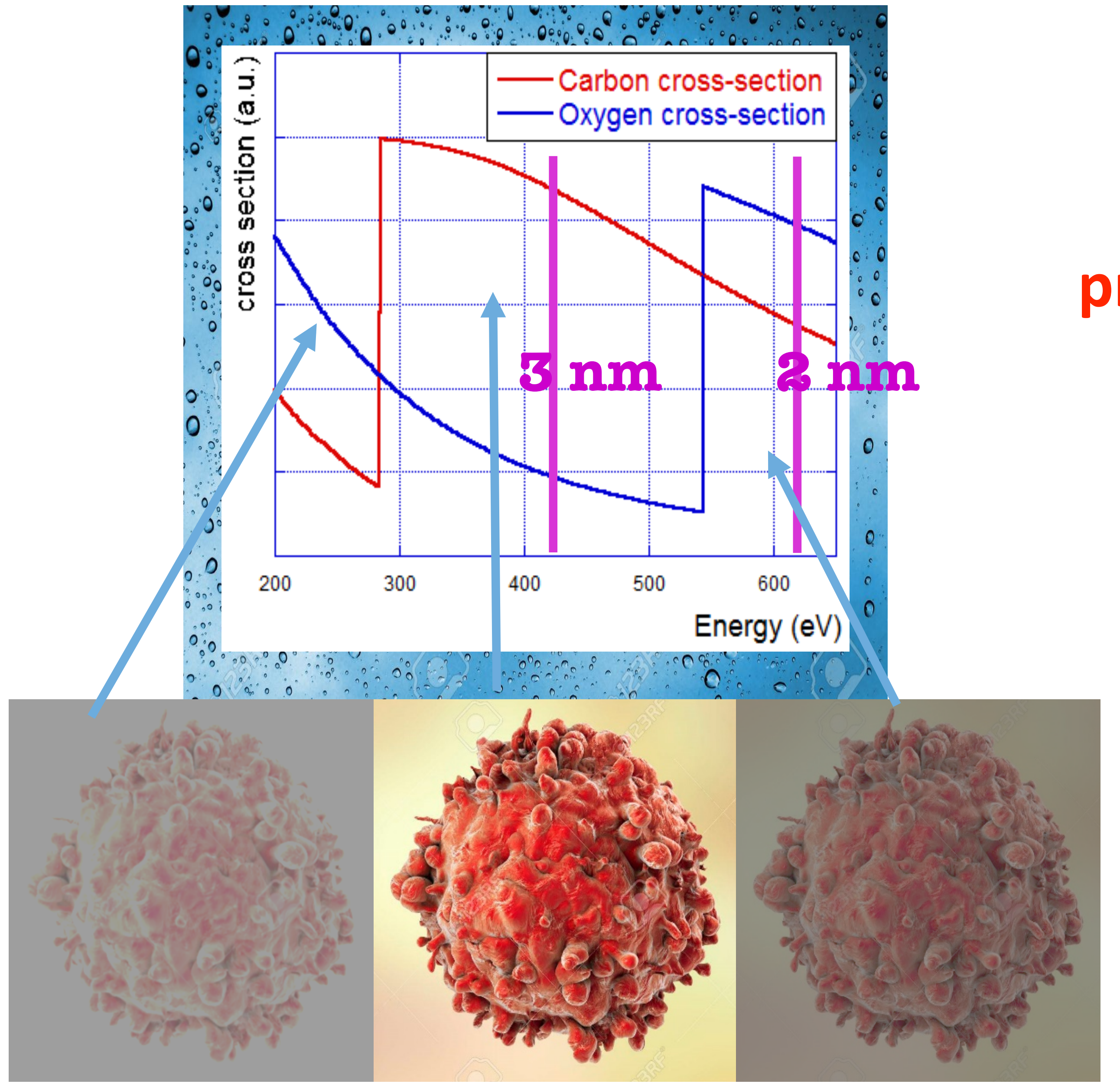
	Units	Full RF case	Plasma case
Electron Energy	GeV	1	1
Bunch Charge	pC	200	30
Peak Current	kA	2	3
RMS Energy Spread	%	0.1	1
RMS Bunch Length	fs	40	4
RMS matched Bunch Spot	μm	34	34
RMS norm. Emittance	μm	1	1
Slice length	μm	0.5	0.45
Slice Energy Spread	%	0.01	0.1
Slice norm. Emittance	μm	0.5	0.5
Undulator 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)

Courtesy F. Stellato, UniToV



Coherent Imaging of biological samples

protein clusters, VIRUSES and cells living in their native state

Possibility to study dynamics

~10 ^{11} photons/pulse needed

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Conclusions

- **Impressive progress** has been done **toward the operation of a FEL user facility**
  - **Recent demonstration of SASE FEL driven by both PWFA** (SPARC_LAB, INFN -Frascati) **and LWFA** (SIOM, Shangai)
    - Success driven by the **ability of the community to overcome** several **key challenges** facing plasma-FEL operation
      - **stabilization** and **control** of the acceleration process, which turns into **energy spread mitigation**, normalized **emittance preservation**, overall stability gain
- However, **improvements** are **still needed** in terms of
  - electron beam quality
    - **sub-percent to sub-per-mille energy spread** and **mm mrad to sub-mm mrad emittances**
  - **increase** of the **repetition rate** from a few hertz to kilohertz
  - **improvement of shot-to-shot stability**
- An entire community is working hard to achieve this result and the selection of **EuPRAXIA**, as **first ever plasma accelerator project**, **in the ESFRI Roadmap** is the validation of the quality and readiness of the work done and the technology
    - **The realization of a plasma-based user facility seems more and more a reality!**

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IPAC22

Thank you all for the kind attention