

# *First lasing of a free-electron laser with a compact beam-driven plasma accelerator*

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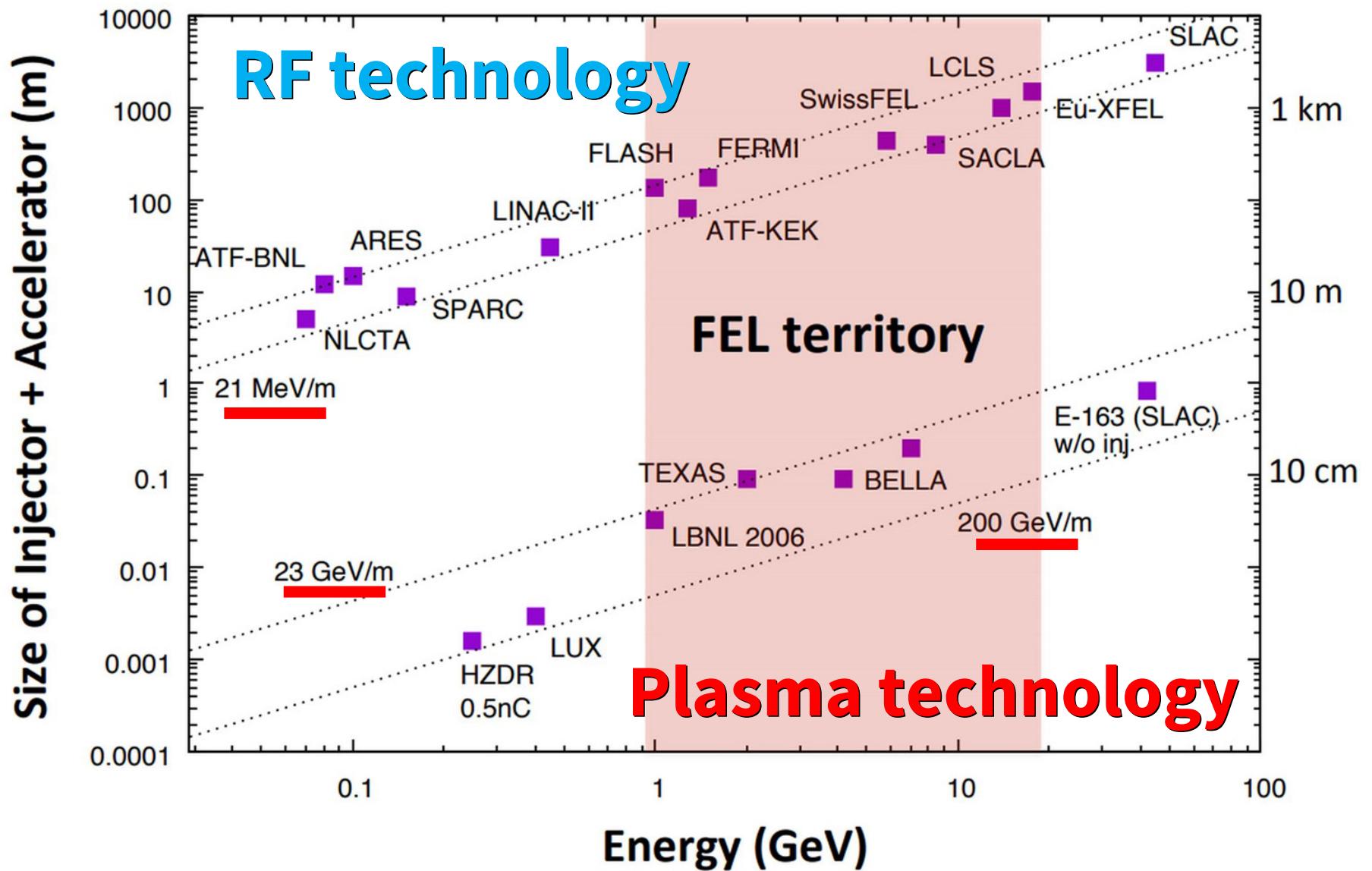
*On behalf of the SPARC\_LAB collaboration*

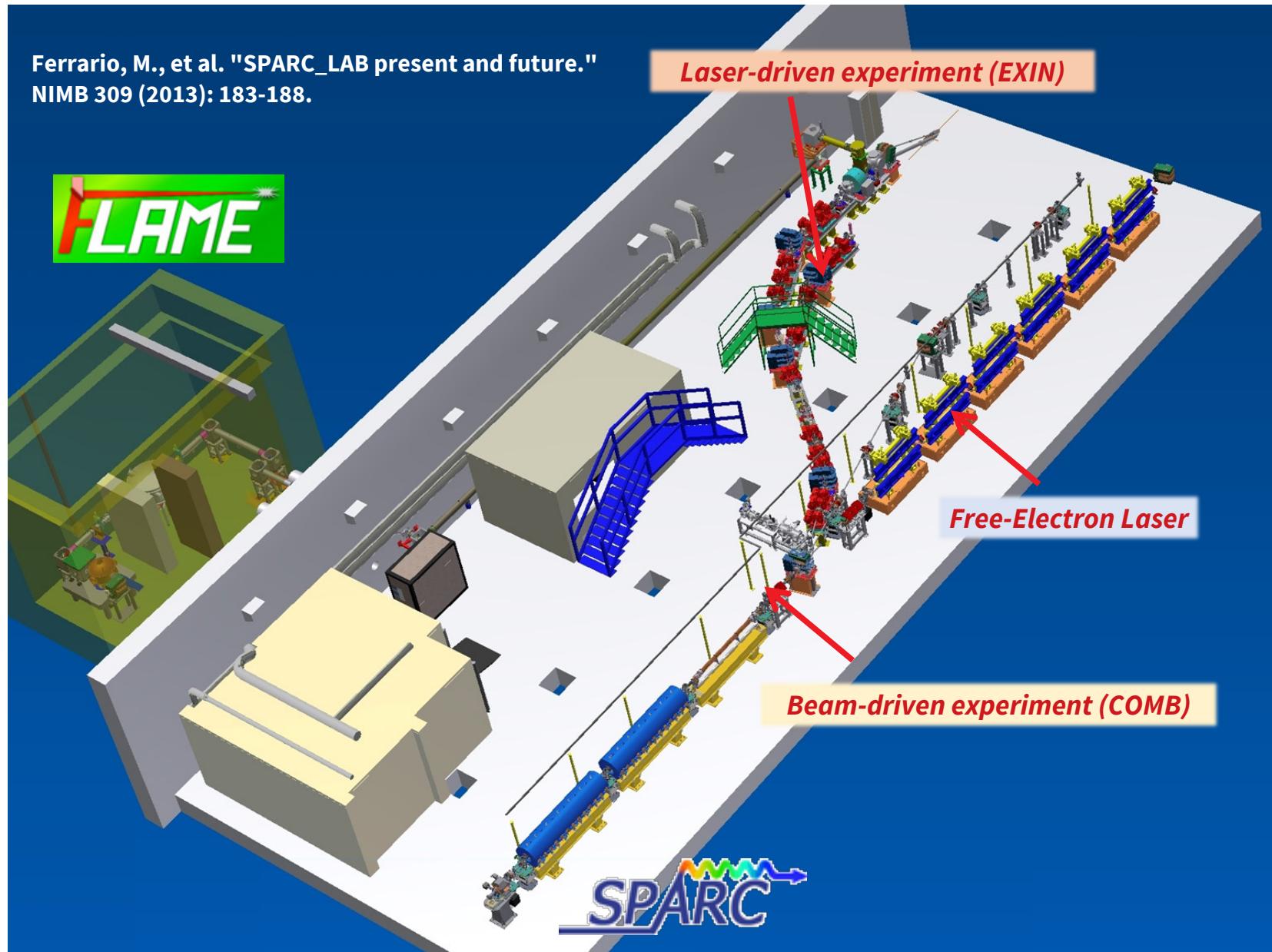


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Laboratori Nazionali di Frascati

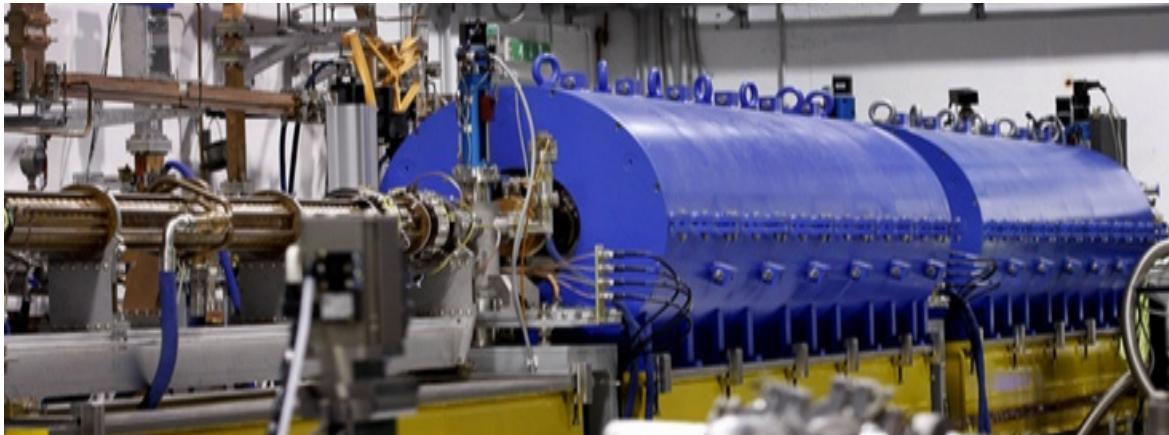


From R. Assmann (3<sup>rd</sup> EAAC Workshop, 2017)



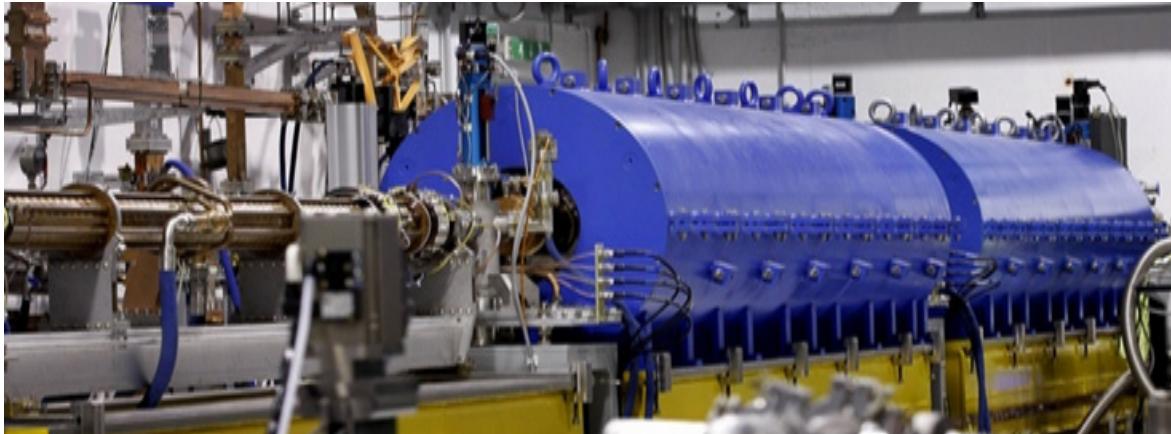


## *Activities with the high-brightness SPARC photo-injector*

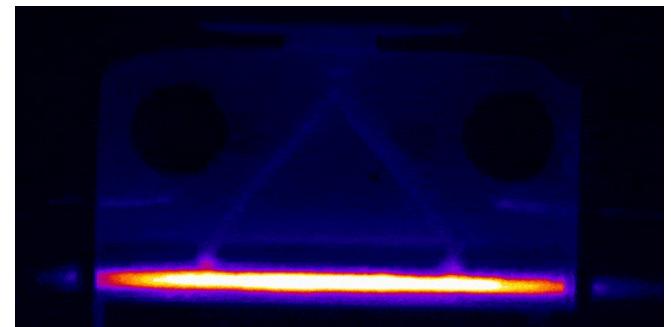


# Experience with plasma @ SPARC

## Activities with the high-brightness SPARC photo-injector

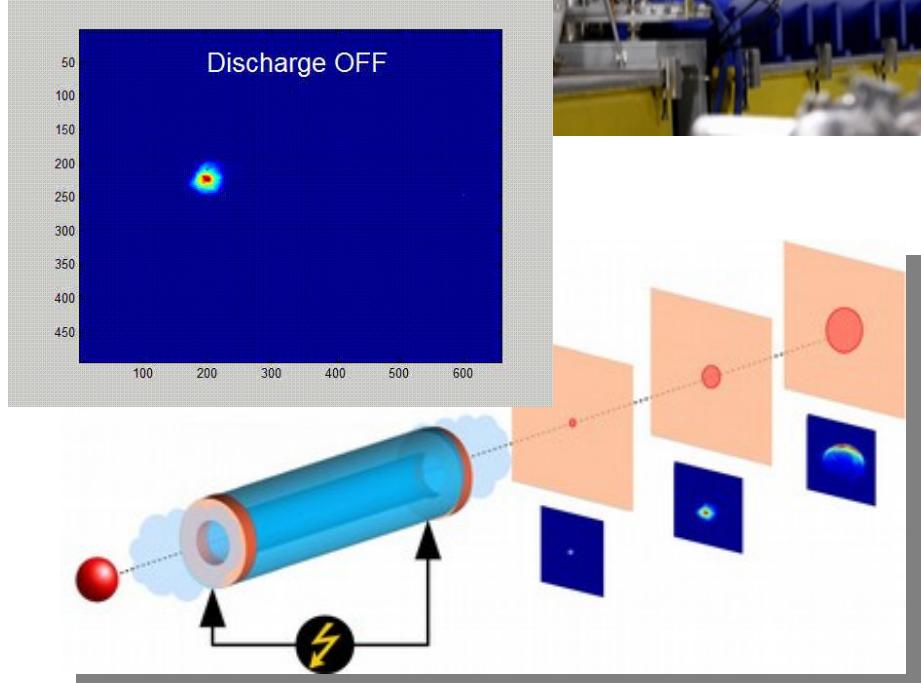


## Plasma characterization



Biagioni A., et al., JINST 11.08 (2016): C08003.

## Activities with the high-brightness SPARC photo-injector

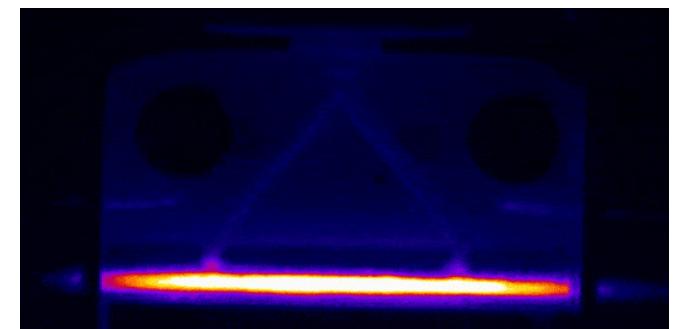


### Focusing with active-plasma lenses

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

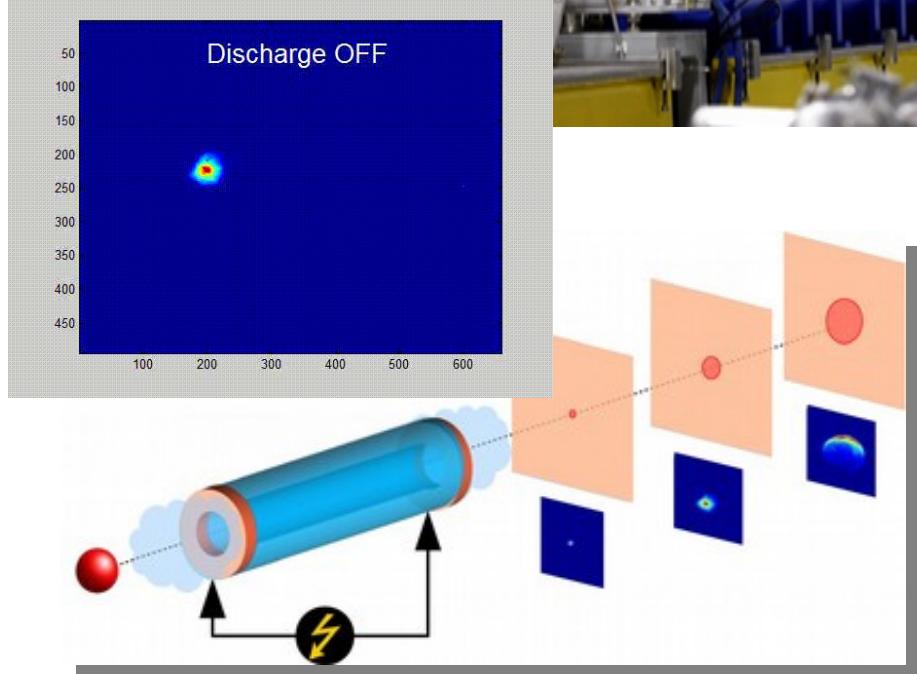
Pompili, R., et al., Applied Physics Letters 110.10 (2017): 104101.

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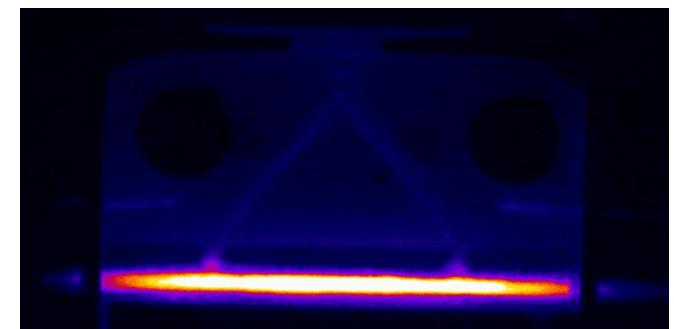


### Focusing with active-plasma lenses

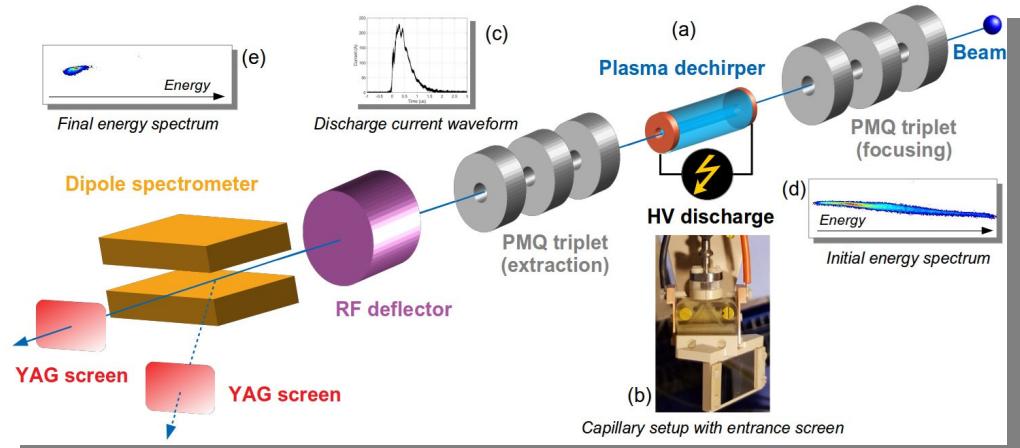
Pompili, R., et al., Physical review letters 121.17 (2018): 174801.

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

### Plasma characterization



Biagioni A., et al., JINST 11.08 (2016): C08003.



### Longitudinal phase-space manipulation

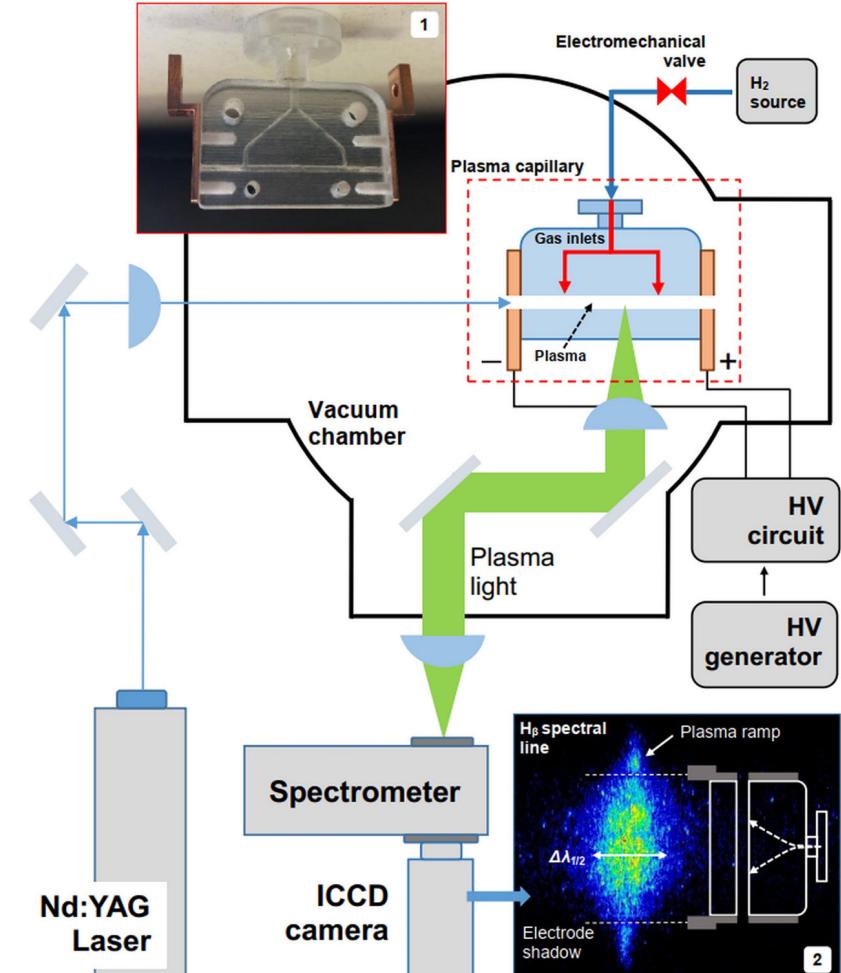
V. Shpakov et al. Phys. Rev. Lett. 122, 114801 (2019)

There are two main sources of jitter

- ❖ Plasma density fluctuations
- ❖ Driver-witness separation jitter (limited by RF sync)

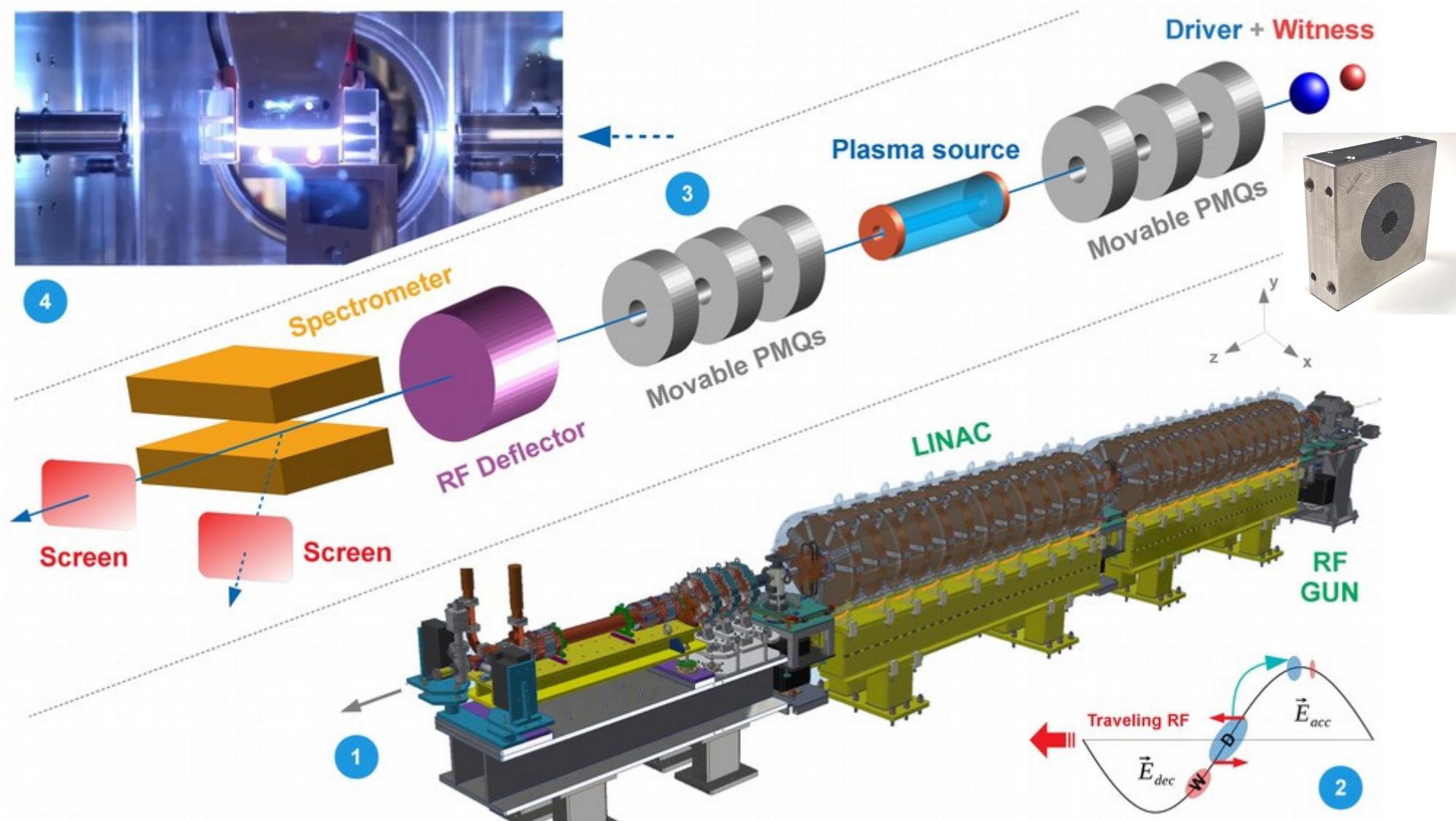
To reduce the 1<sup>st</sup> source, we pre-ionize the Hydrogen gas with an external laser

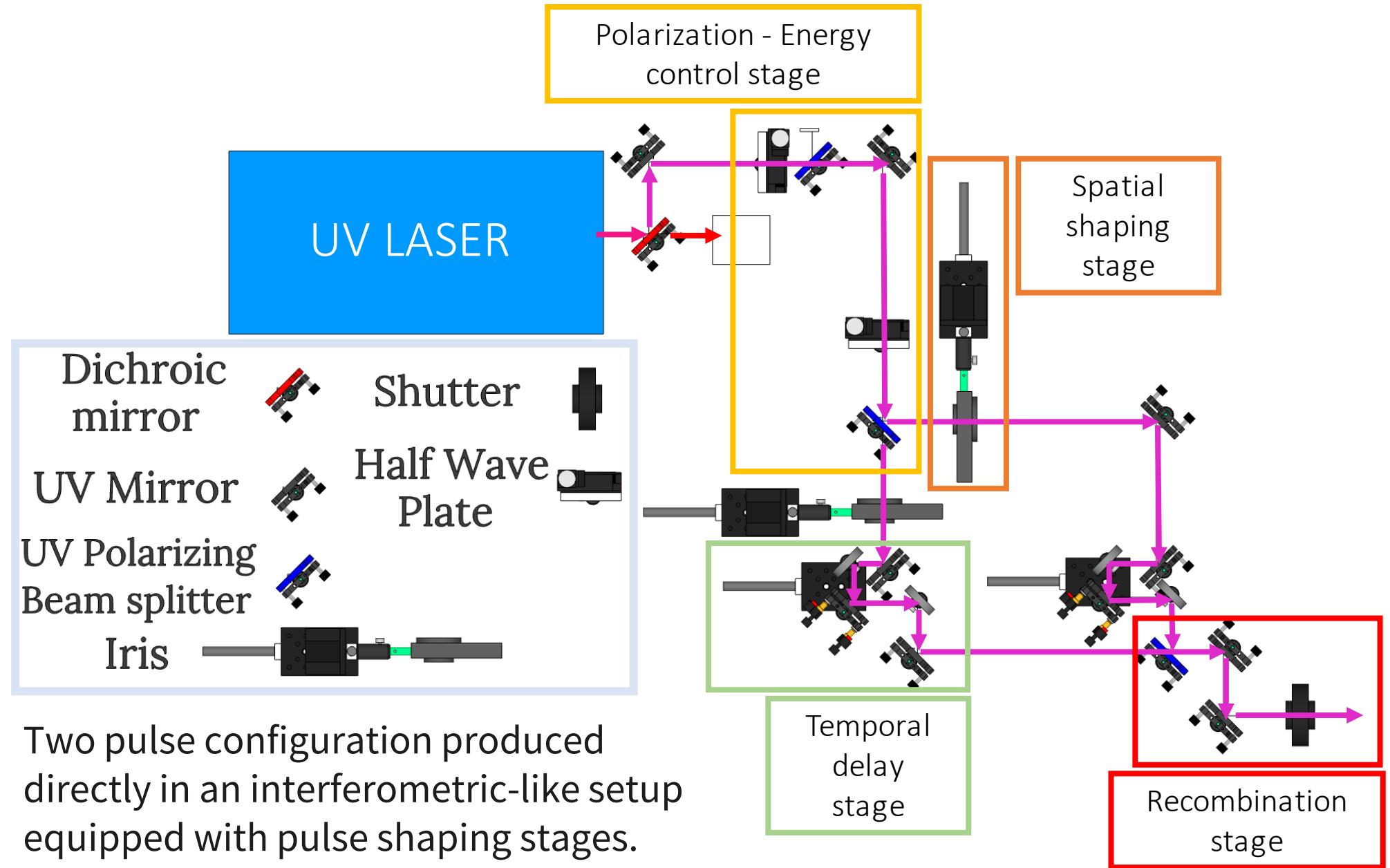
The laser (~100 uJ, 2mm diameter) reaches the negative electrode hole ~100ns before the discharge trigger.



Biagioni A., et al. "Gas-filled capillary-discharge stabilization for plasma-based accelerators by means of a laser pulse." *Plasma Physics and Controlled Fusion* (2021).

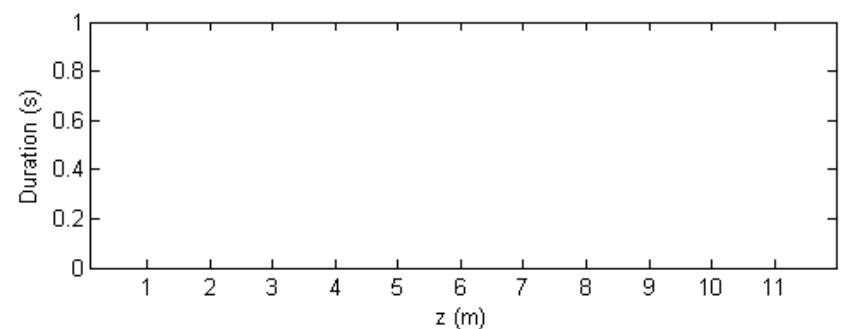
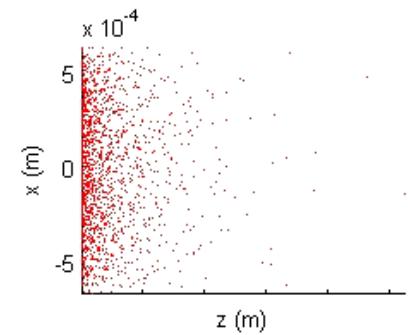
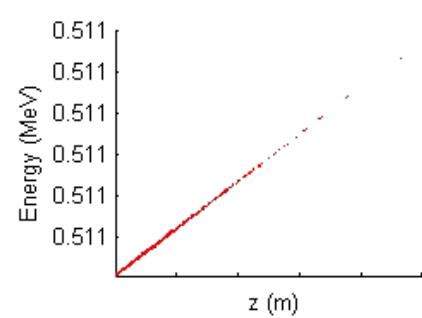
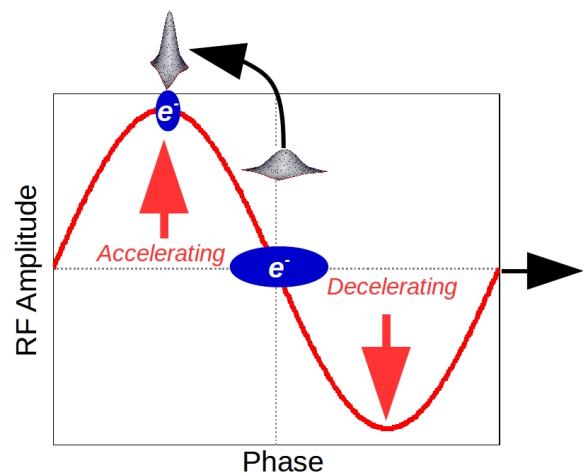
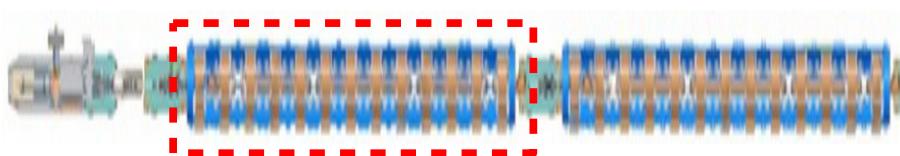
M. Galletti, et al.: "Advanced Stabilization Methods of Plasma Devices for Plasma-Based Acceleration." *Symmetry* 2022, 14(3), 450. <https://doi.org/10.3390/sym14030450>



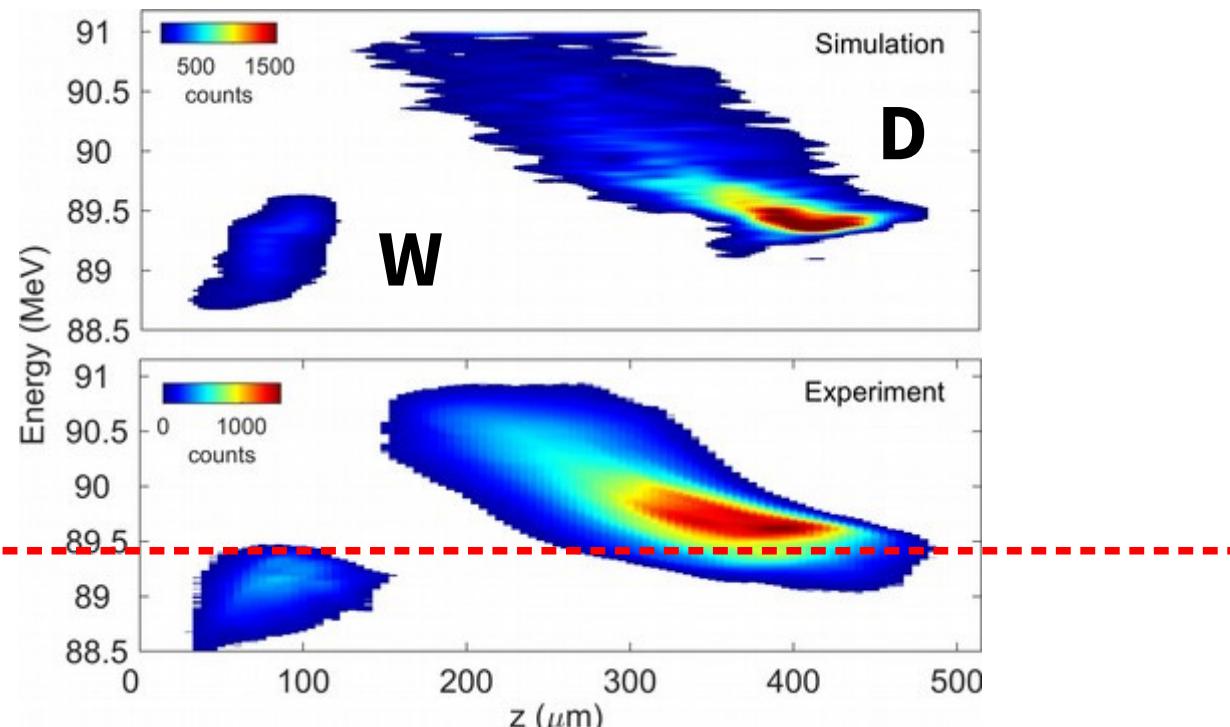


It simultaneously accelerate and compress the electron bunches, making the photo-injector very compact.

## Velocity bunching compression    200+20pC COMB GPT simulation



It requires injection in the 1<sup>st</sup> travelling-wave section at the zero crossing of the RF wave. The longitudinal compression is achieved by accelerating the tail of the beam while decelerating its head. This rotates the beam LPS and, as a consequence, it is simultaneously chirped and compressed.

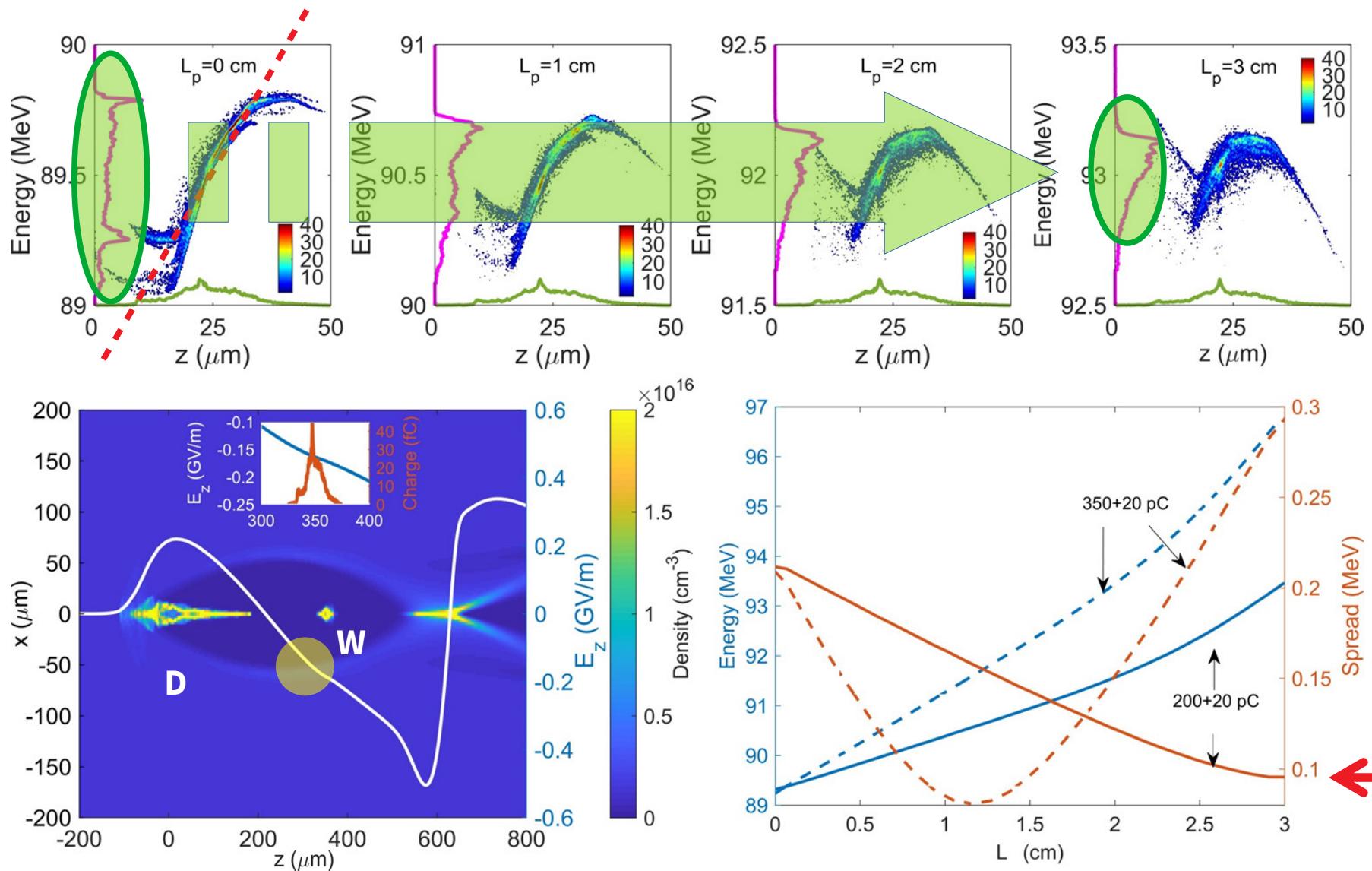


Two-bunches configuration produced directly at the cathode with **laser-comb technique**

Separation approximately equal to  $\frac{3}{4}$  of the plasma wavelength ( $\sim 1$  ps)

COMB	Driver	Witness
$Q$ (pC)	200 up to 350	20
$\tau$ (fs)	200	30

## Pre-chirp to compensate wakefield slope

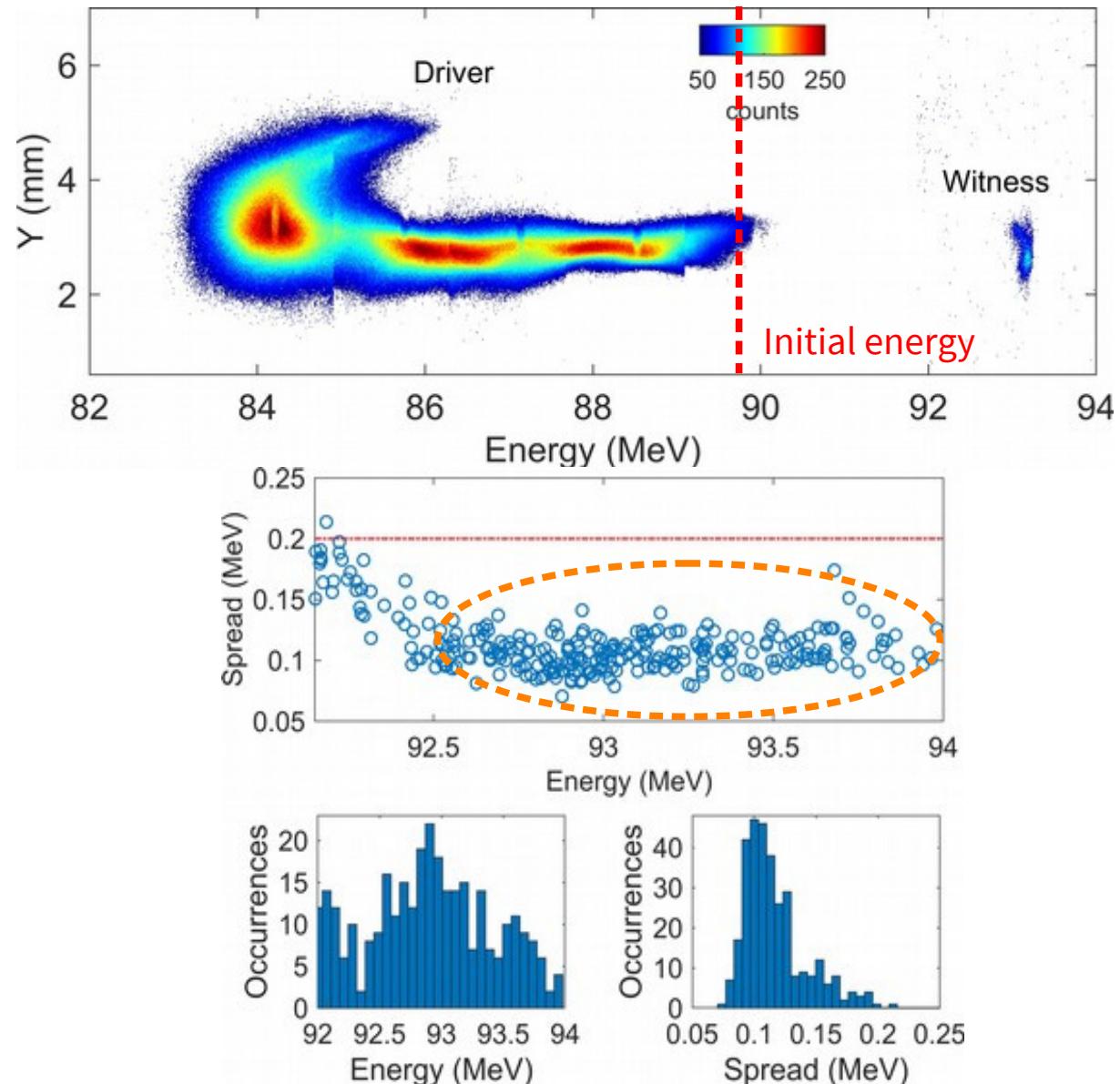


4 MeV acceleration in 3 cm plasma with 200 pC driver

- $2 \times 10^{15} \text{ cm}^{-3}$  plasma density
- $\sim 133 \text{ MV/m}$  accelerating gradient

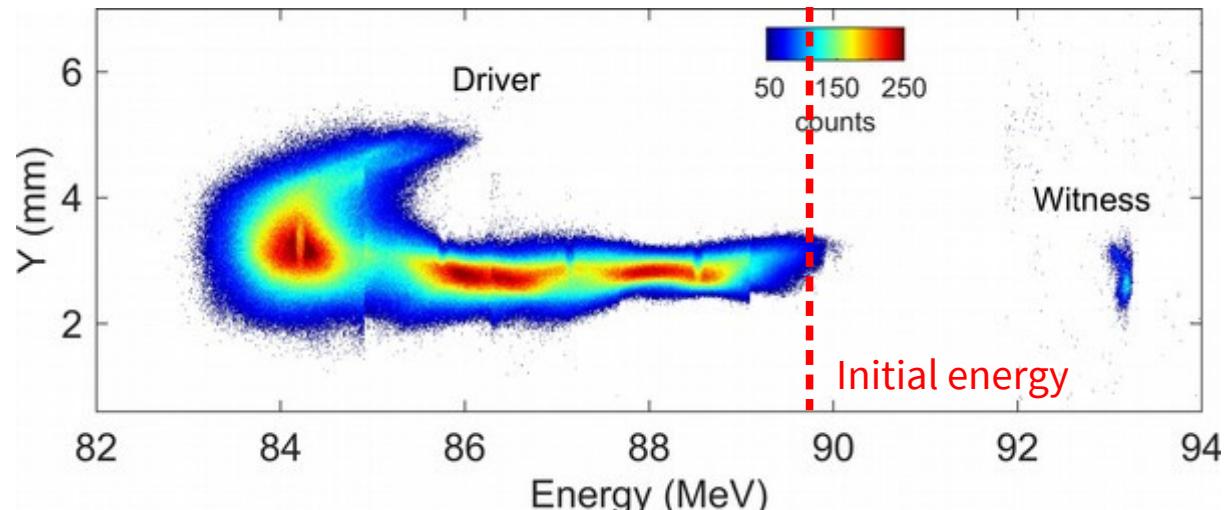
### Demonstration of projected energy spread compensation

*Spread from 0.2% to 0.12%*



4 MeV acceleration in 3 cm plasma with 200 pC driver

- $2 \times 10^{15} \text{ cm}^{-3}$  plasma density
- $\sim 133 \text{ MV/m}$  accelerating gradient



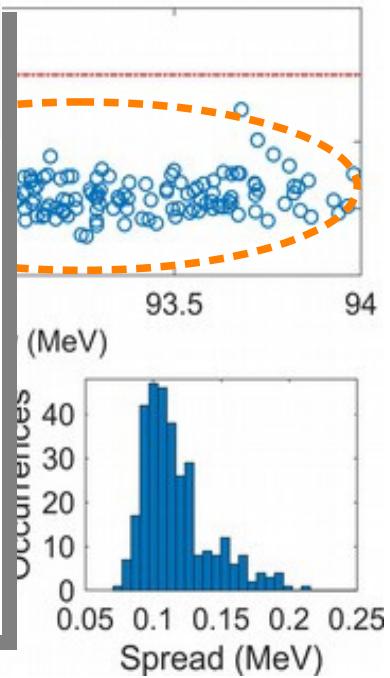
## LETTERS

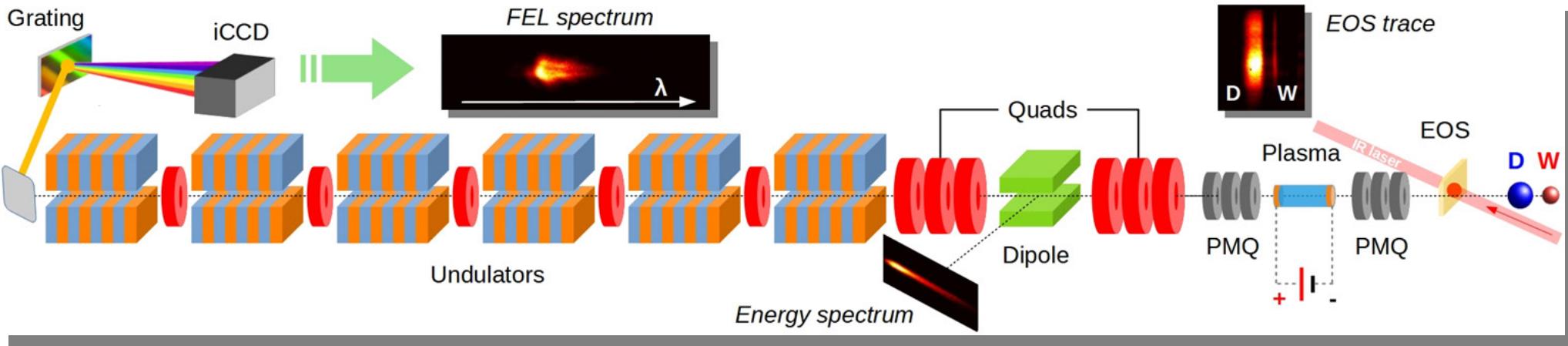
<https://doi.org/10.1038/s41567-020-01116-9>

Check for updates

# Energy spread minimization in a beam-driven plasma wakefield accelerator

R. Pompili<sup>1</sup>✉, D. Alesini<sup>1</sup>, M. P. Anania<sup>1</sup>, M. Behtouei<sup>1</sup>, M. Bellaveglia<sup>1</sup>, A. Biagioni<sup>1</sup>, F. G. Bisesto<sup>1</sup>, M. Cesarini<sup>1,2</sup>, E. Chiadroni<sup>1</sup>, A. Cianchi<sup>3</sup>, G. Costa<sup>1</sup>, M. Croia<sup>1</sup>, A. Del Dotto<sup>1</sup>, D. Di Giovenale<sup>1</sup>, M. Diomede<sup>1</sup>, F. Dipace<sup>1</sup>, M. Ferrario<sup>1</sup>, A. Giribono<sup>1</sup>, V. Lollo<sup>1</sup>, L. Magnisi<sup>1</sup>, M. Marongiu<sup>1</sup>, A. Mostacci<sup>1</sup>, L. Piersanti<sup>1</sup>, G. Di Pirro<sup>1</sup>, S. Romeo<sup>1</sup>, A. R. Rossi<sup>4</sup>, J. Scifo<sup>1</sup>, V. Shpakov<sup>1</sup>, C. Vaccarezza<sup>1</sup>, F. Villa<sup>1</sup> and A. Zigler<sup>1,5</sup>



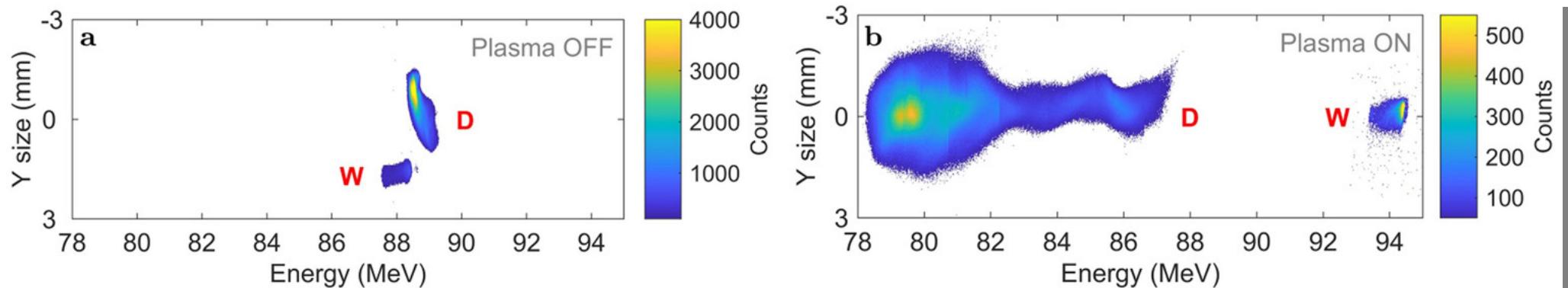


## Demonstration of high-quality PWFA acceleration able to drive a FEL

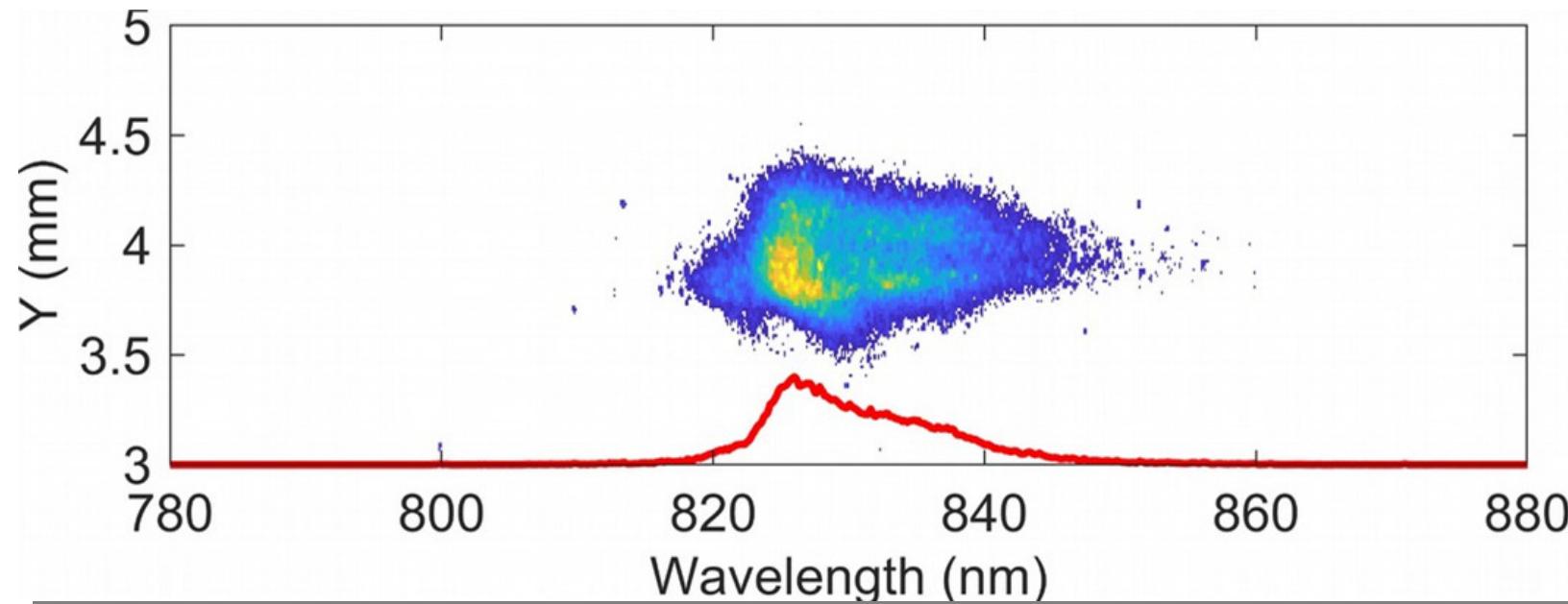
- ❖ Witness is completely characterized (energy, spread, X/Y emittance)
- ❖ Jitter is online monitored with Electro-Optical Sampling (EOS) diagnostics
- ❖ Imaging spectrometer with iCCD used to detect FEL radiation

*In collaboration with*





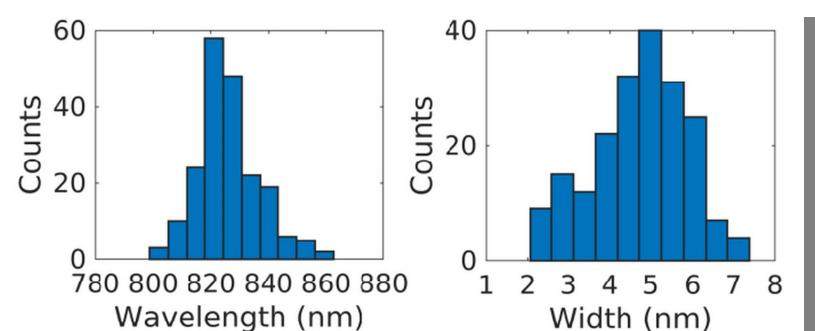
- Plasma density set to  $1.6 \times 10^{15} \text{ cm}^{-3}$
- Accelerated witness
  - Energy: 94 MeV, 0.3 MeV spread ( $\sim 200 \text{ MV/m}$  acceleration)*
  - Emittance: 2.7(X)  $\mu\text{m}$ , 1.3(Y)  $\mu\text{m}$*
- Driver decelerated by almost 10 MeV

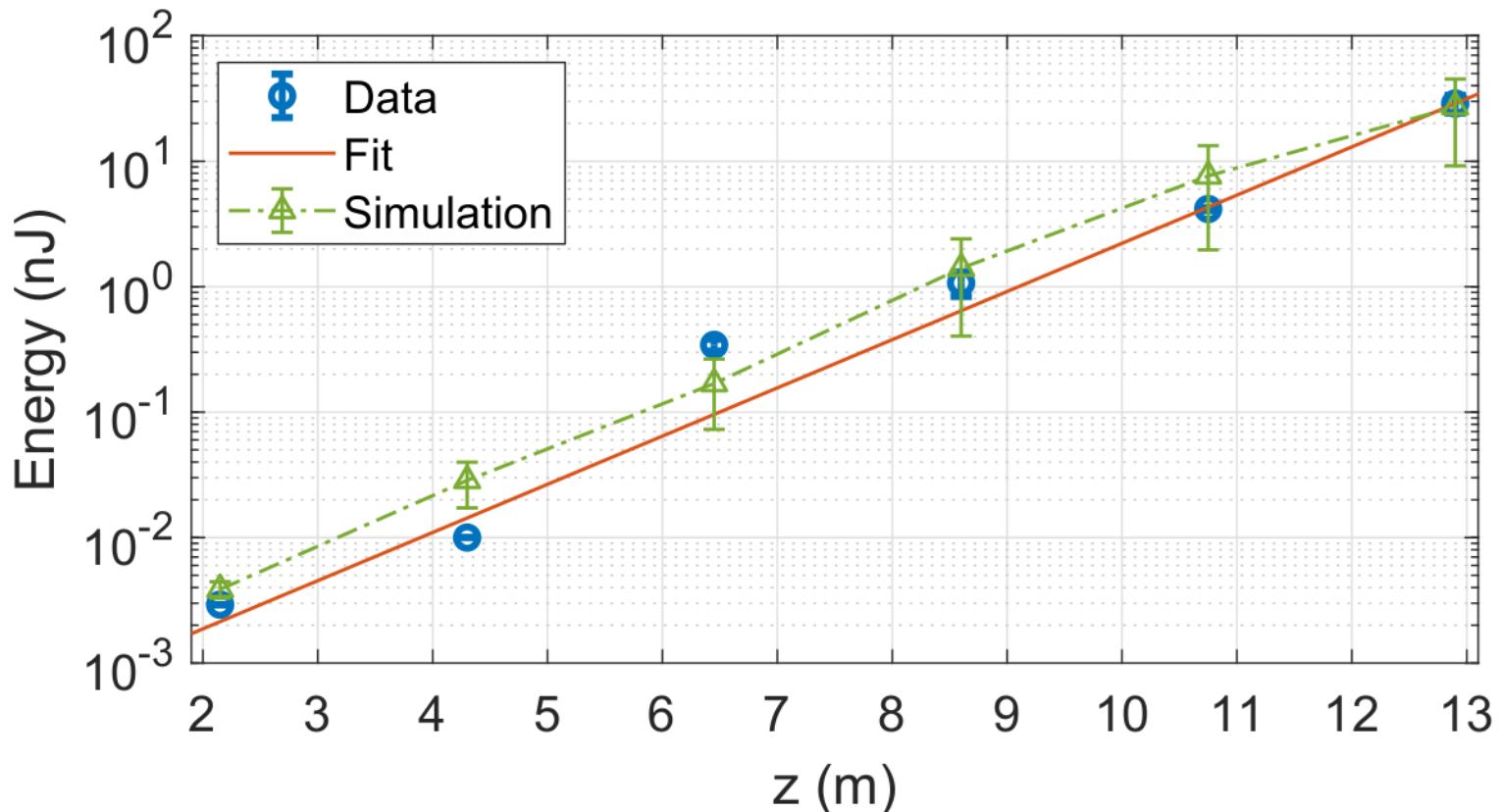


## Single-shot spectrum of the SASE FEL at 830 nm

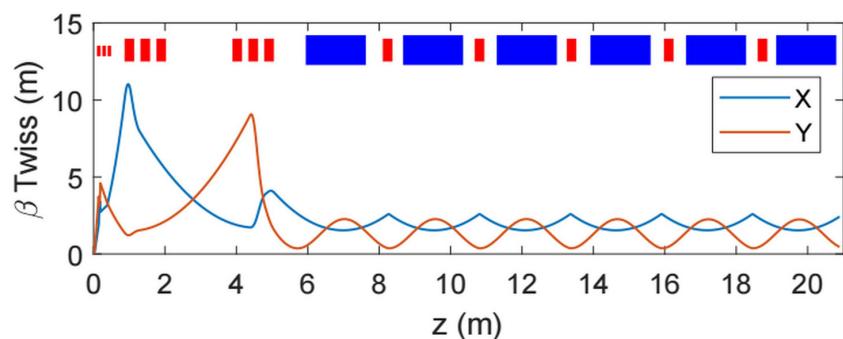
Clear signals, reproducible day by day

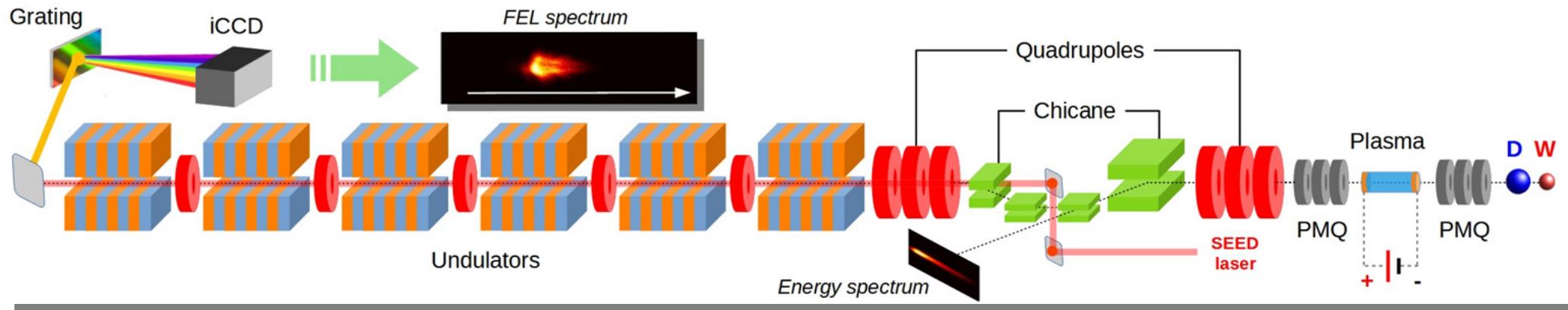
- ✓ 30% shot-to-shot reproducibility
- ✓ Centered @827 nm with 5 nm BW





R. Pompili, et al.  
“Free-electron lasing  
with compact beam-  
driven plasma  
wakefield accelerator.”  
Nature 605, 659–662  
(2022).





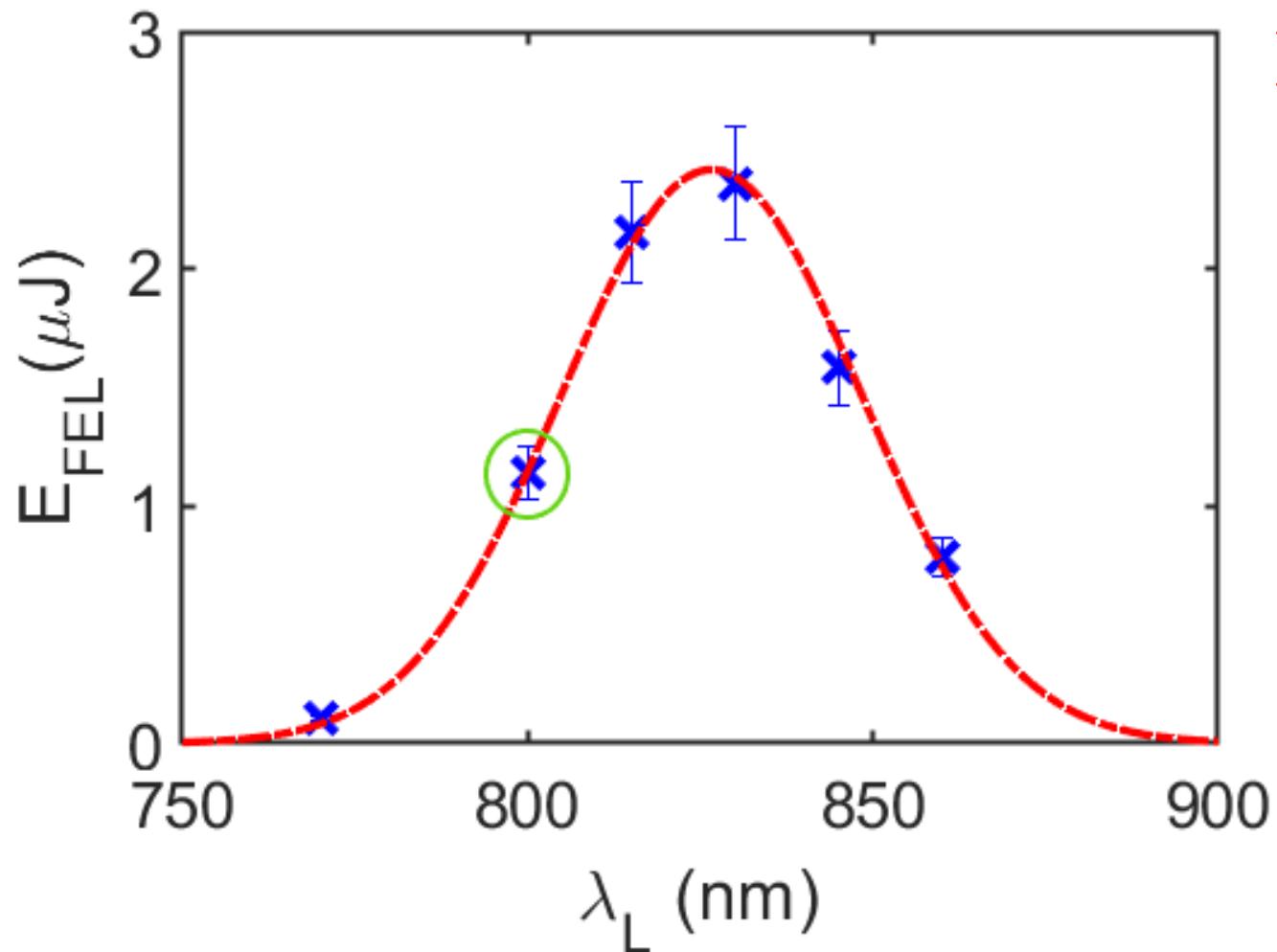
## The FEL setup is extended, and part of the EOS (IR) laser is used as seed laser

- ✓ Naturally synchronized with the beam, tunable energy (~10 nJ used in the experiment).
- ✓ Duration increased from ~100 fs to 600 fs (fwhm). Focused at the entrance of 1<sup>st</sup> undulator

Beam is partially displaced by using a magnetic chicane (~few mm offset) to allow laser injection into the beamline

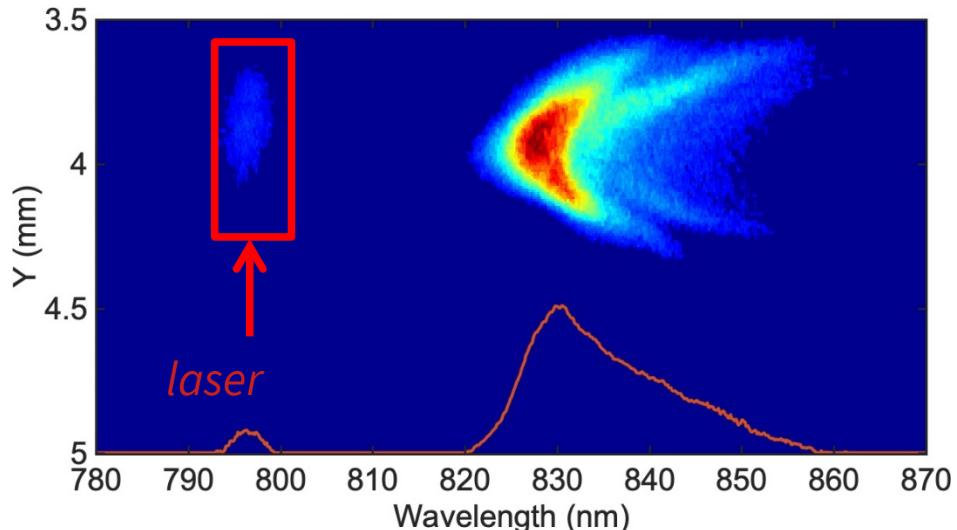
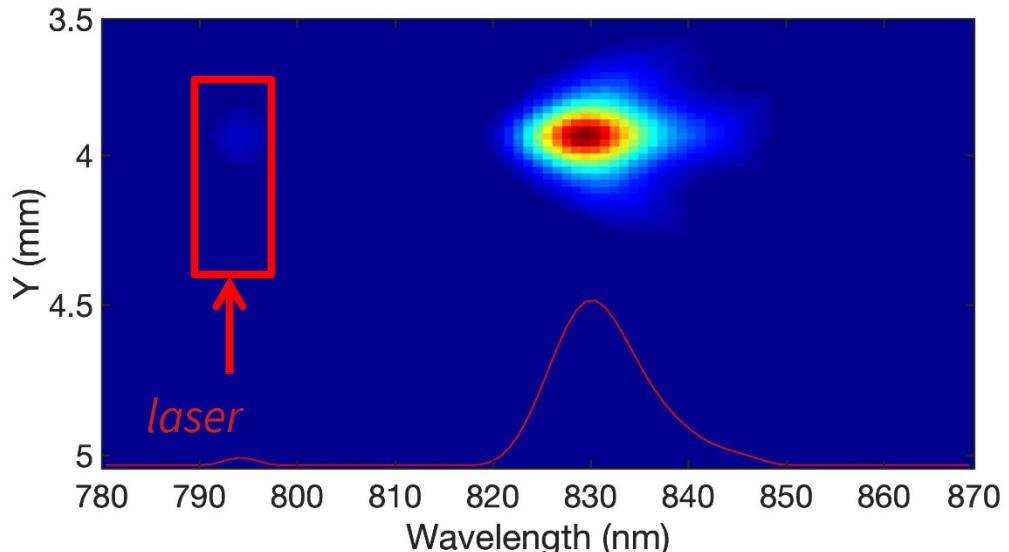
Same detection setup used (ND filter changed for larger intensity signals)

Seed Laser is transported up to the imaging spectrometer



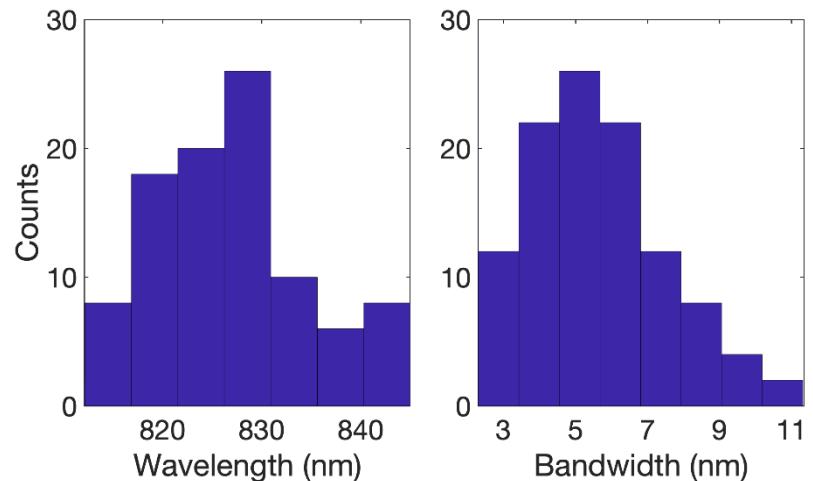
**Seeded FEL radiation energy gain obtained with a varying seeded laser wavelength (blue crosses)**

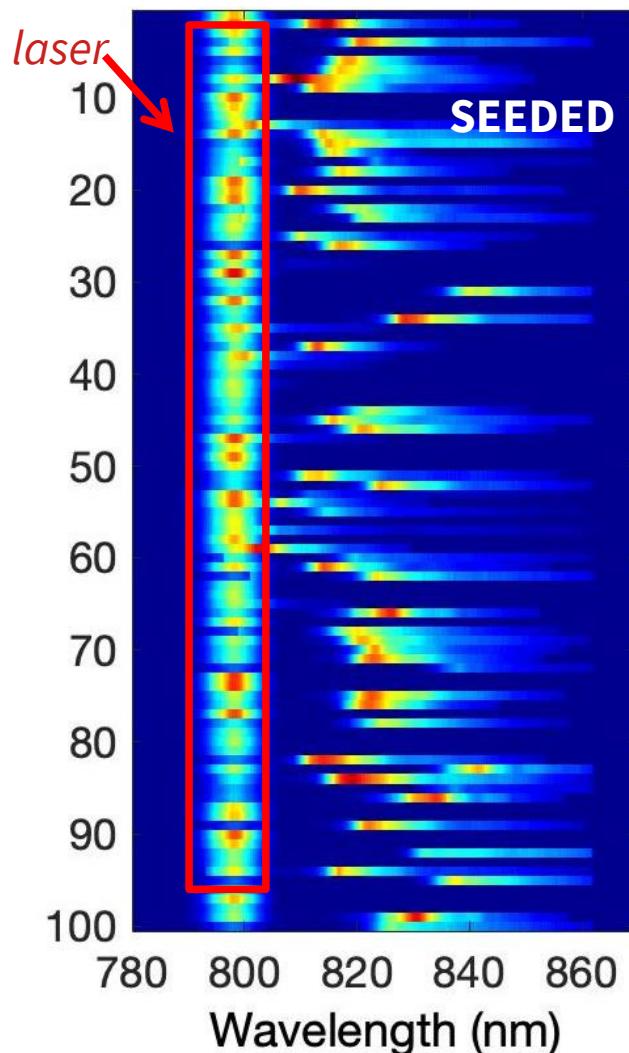
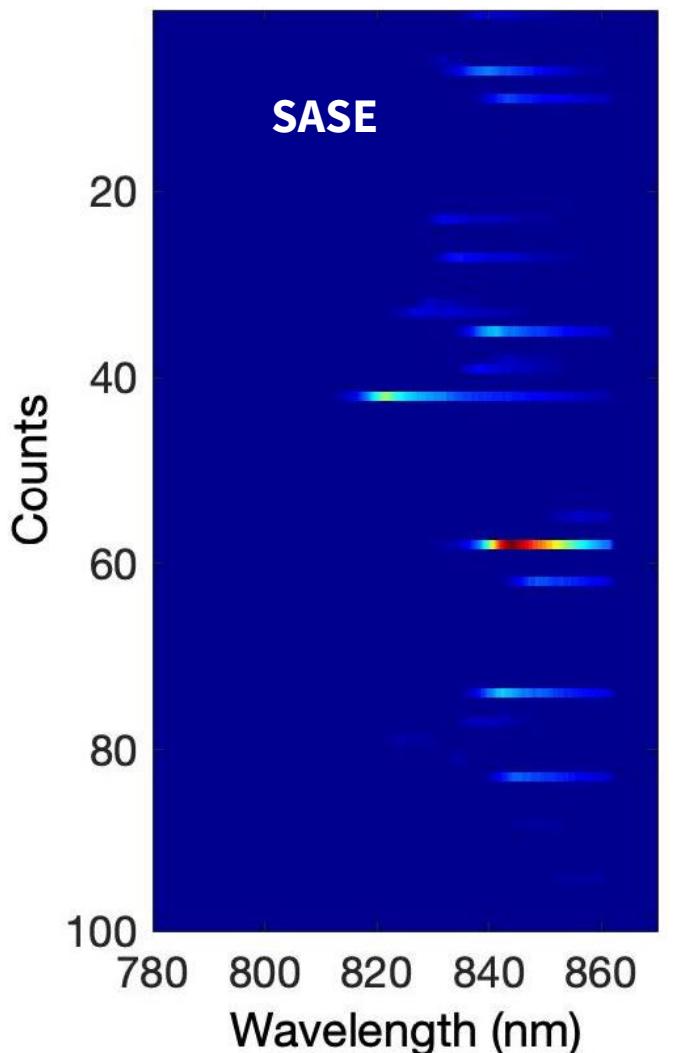
- ✓ Theoretically pulse energy increased 2 order of magnitude respect to SASE radiation
- ✓ The red dashed line shows the Gaussian fit of the theoretical data centered at 826.6 nm, meaning maximum extraction when FEL radiation and seed laser have the same wavelengths.
- ✓ The green circle shows the prediction of the energy gain of the FEL seeded with our experimental parameters.

Experimental spectrumTheoretical spectrumSingle-shot spectrum of the SASE FEL at 830 nm

Clear signals, reproducible day by day

- ✓ 90% shot-to-shot reproducibility
- ✓ Centered @827 nm with 5 nm BW

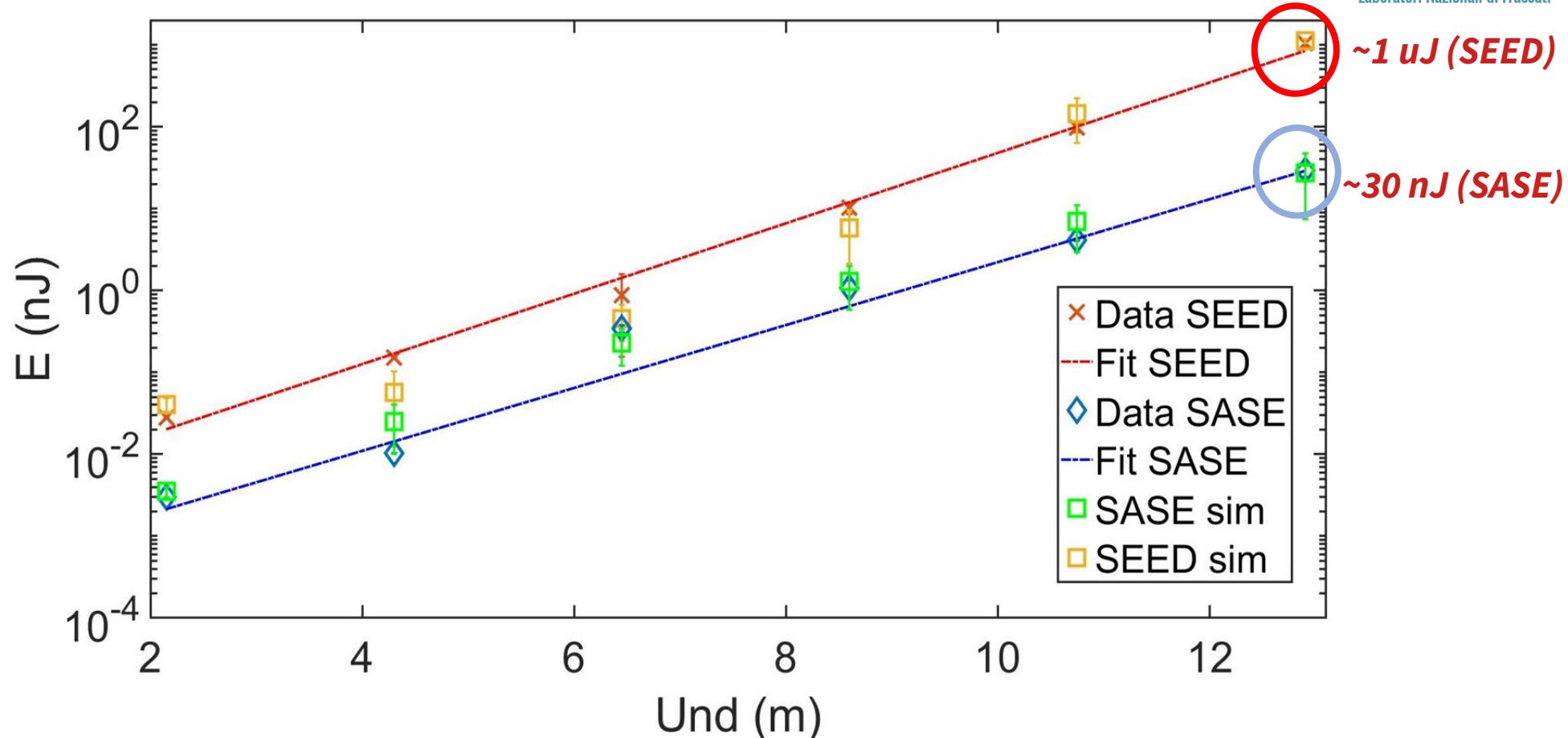




M. Galletti, et al.  
*Submitted*

FEL radiation output is largely stabilized by the seed laser, larger output energy

Undulators tuned for FEL radiation at ~830 nm → separated from the laser (~800 nm)



### Seeded FEL radiation at 830 nm

- ✓ Pulse energy increased 2 order of magnitude respect to SASE radiation
- ✓ 6% pulse energy RMS fluctuations over 90% of successful shot respect to 17% over 30% of shot for SASE

**Development of plasma-based accelerators is still ongoing, many exciting results obtained in the last few years**

- ❖ Operation over long distances and/or multiple stages
- ❖ Control of the accelerated beam parameters over many hours of operation
- ❖ Preservation of the beam quality in terms of energy spread (next step: emittance)

**We have now evidence of first FEL lasing from plasma boosted beams**

Proof-of-principle experiments using both LWFA and PWFA

**Results obtained at SPARC LAB show that PWFA is a viable solution for FELs**

Complete characterization of the witness bunch allowed proper matching into the undulators

Measurements of the emitted radiation confirm the typical FEL amplification signatures

**Fundamental steps toward the future EuPRAXIA plasma-based facility for user-oriented applications**

***Thank you for your attention!***

Stefano Romeo (Frascati National Laboratories, INFN)

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