EuroNNAc Special Topics Workshop
Isola d'Elba, Italy

First SASE and Seeded FEL Lasing based on a beam-driven wakefield accelerator

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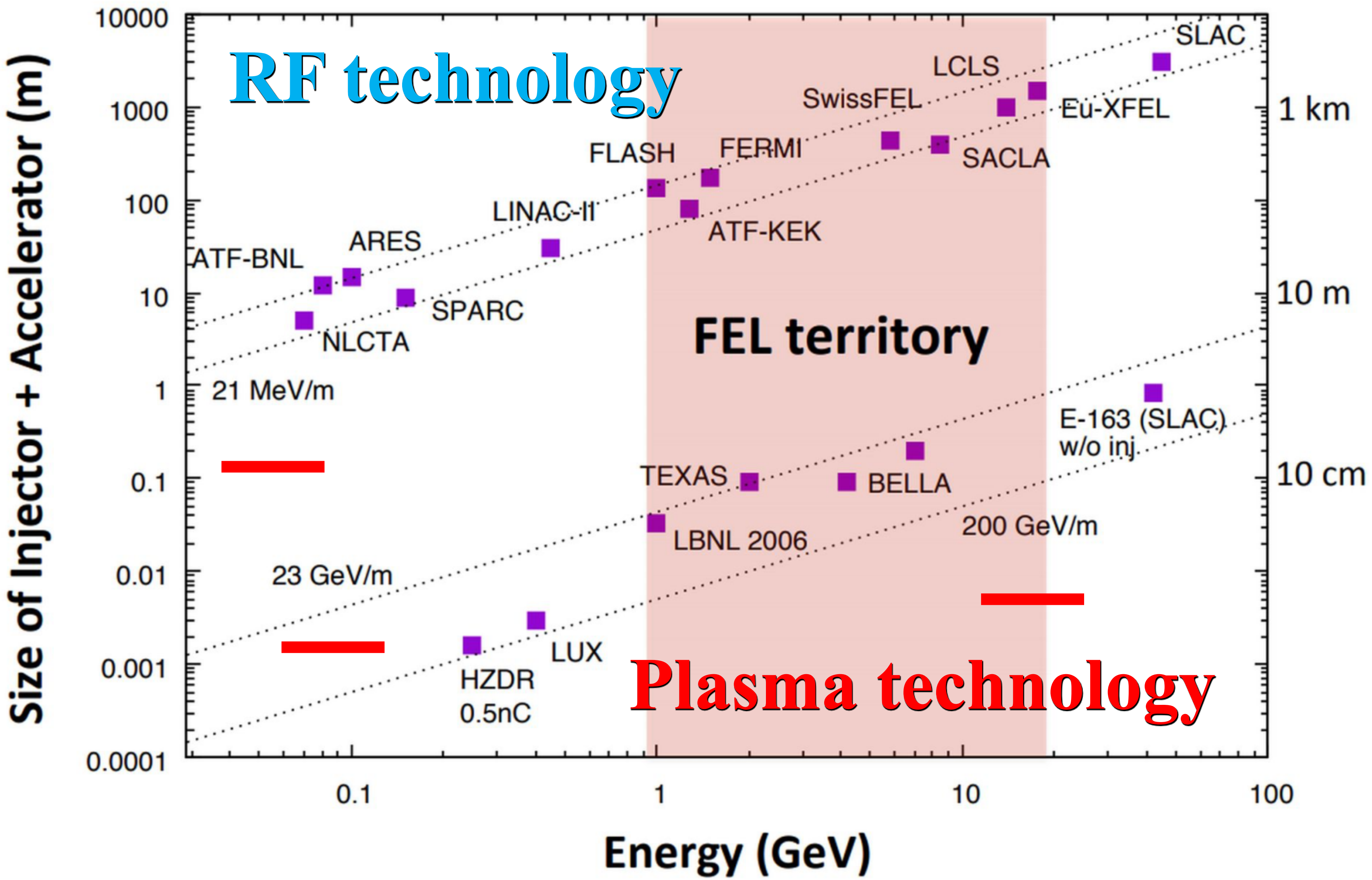
On behalf of the SPARC_LAB collaboration

INFN

SPARC LAB

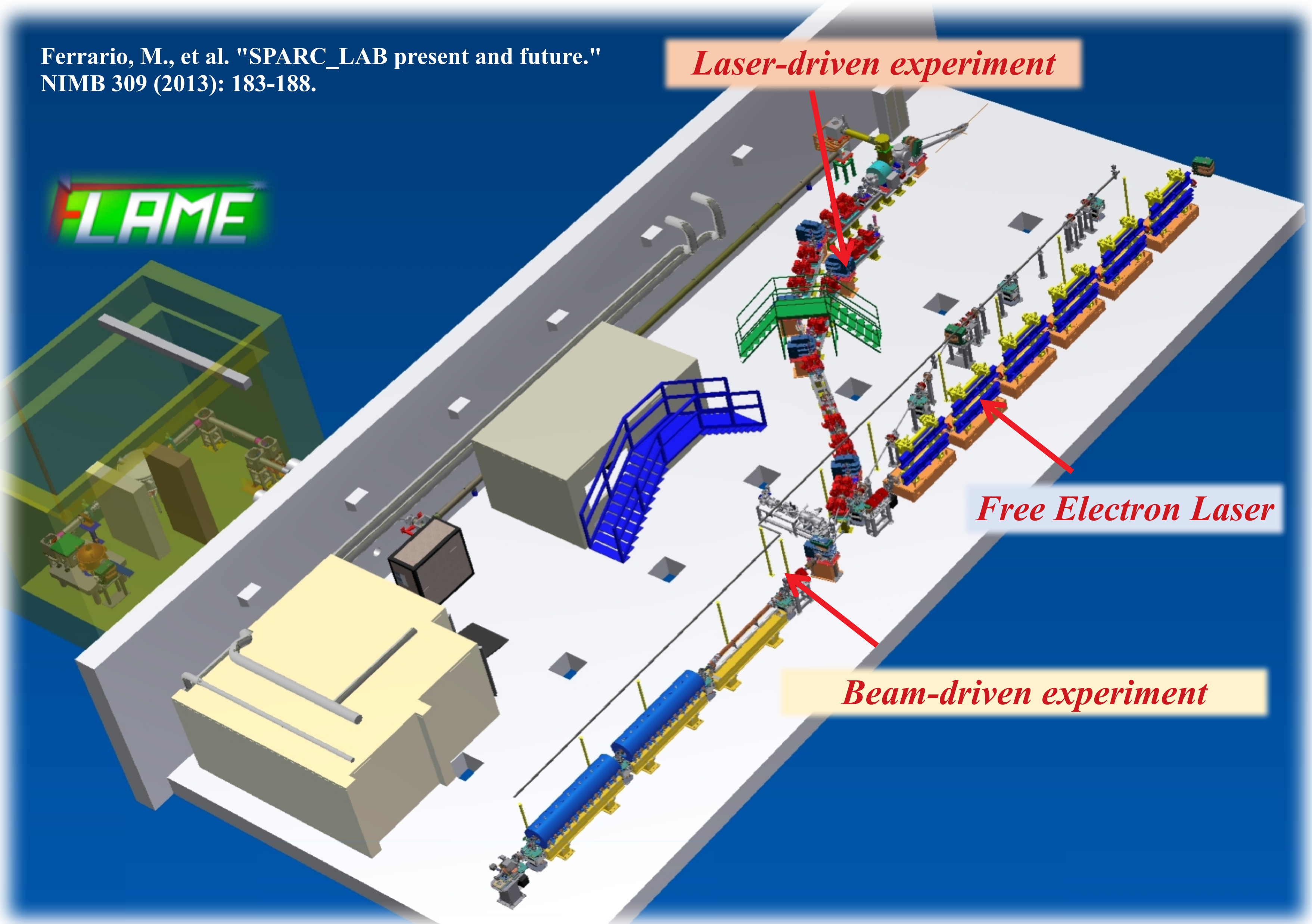
Standard vs Plasma accelerators



From R. Assmann (3rd EAAC Workshop, 2017)

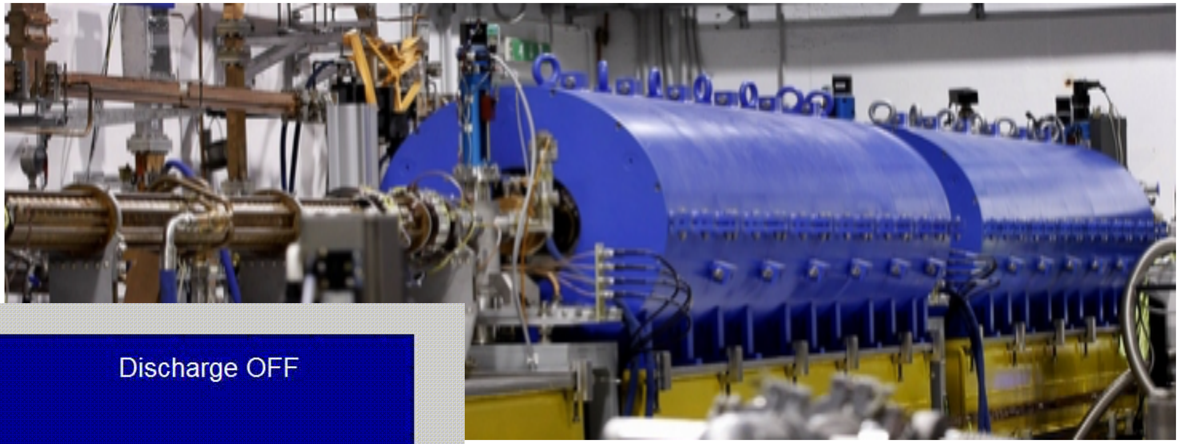
SPARC_LAB facility

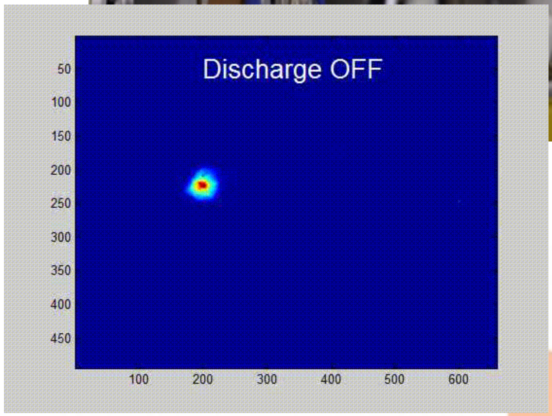
Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

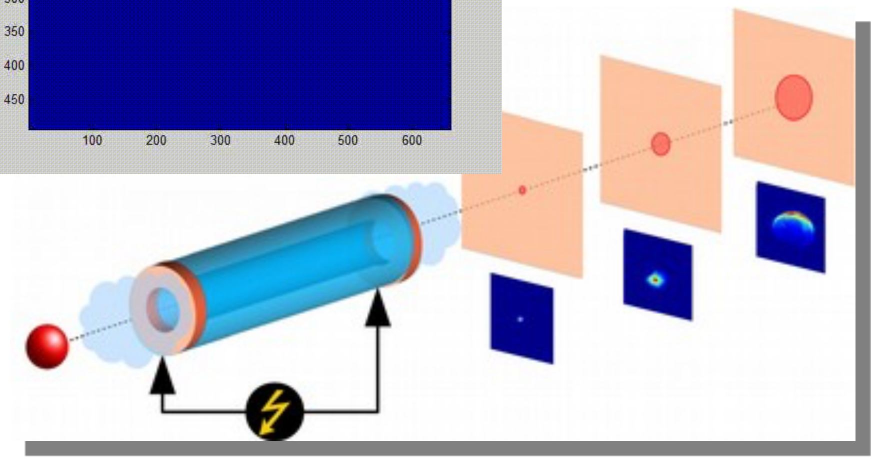


Experience with plasma @ SPARC

Activities with the high-brightness SPARC photo-injector



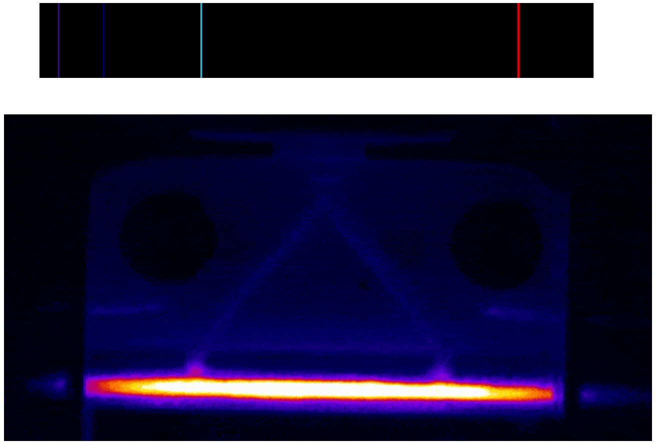




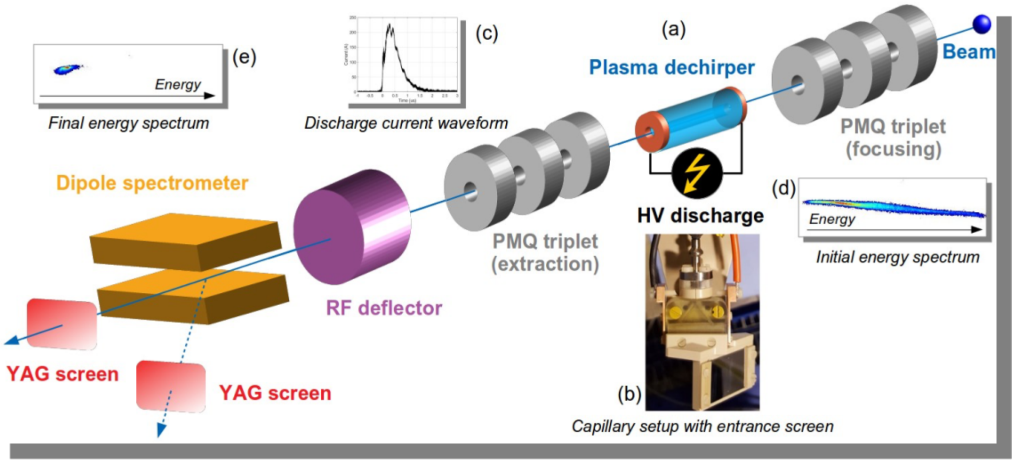
Focusing with active-plasma lenses

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

Plasma characterization



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



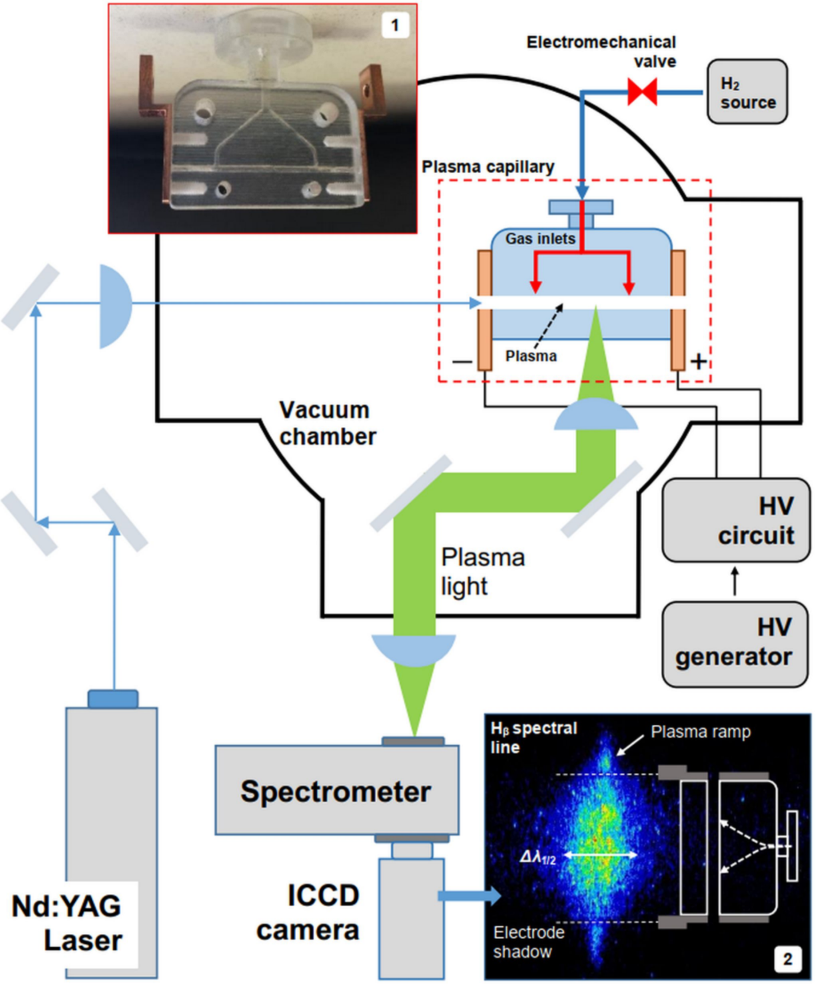
Longitudinal phase-space manipulation

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

Plasma stabilization

There are two main sources of jitter

- Plasma density fluctuations
- Driver-witness separation jitter in a beam-driven plasma is limited by RF sync

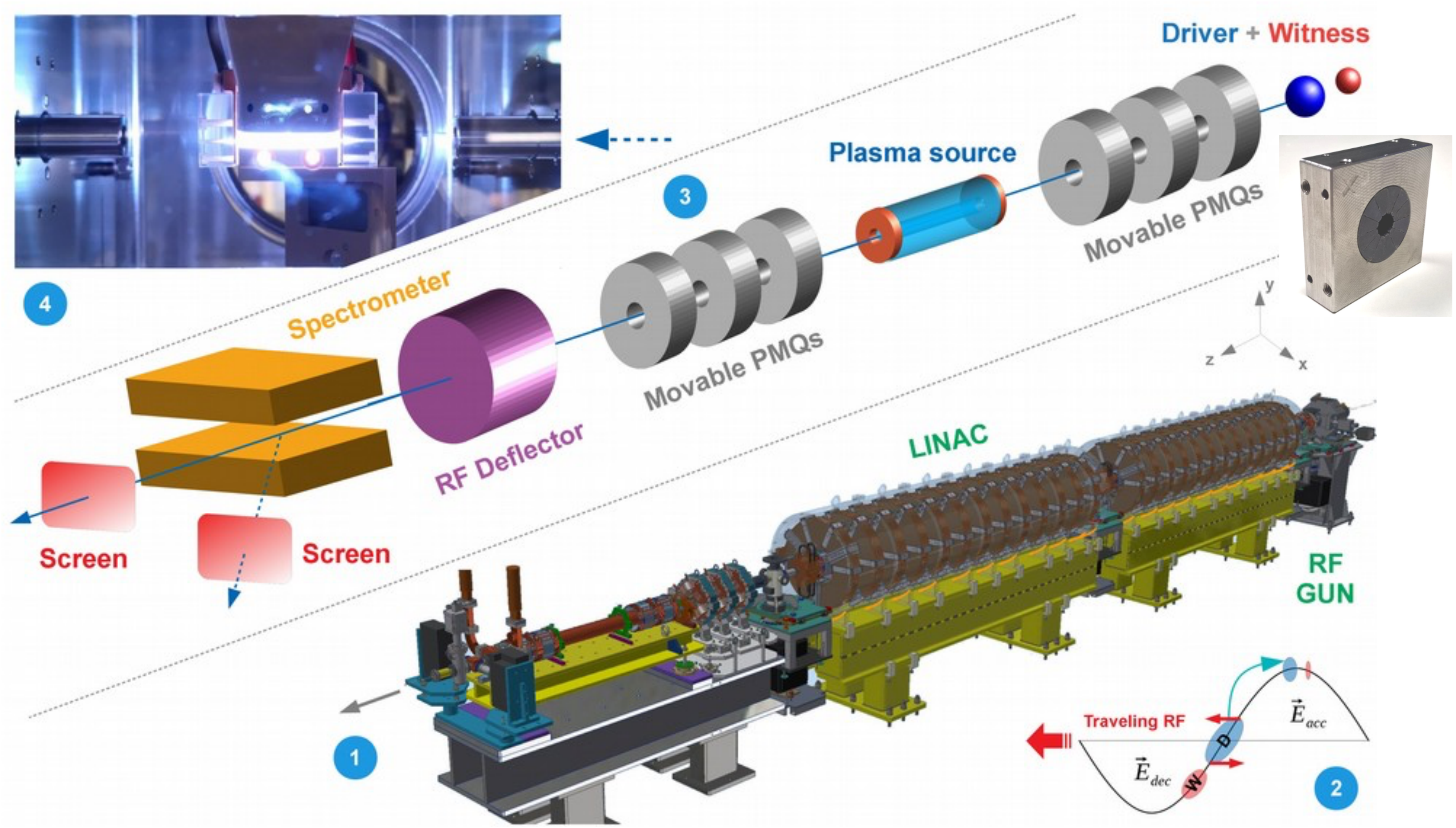


To reduce the 1st source, we pre-ionize the Hydrogen gas with an external laser

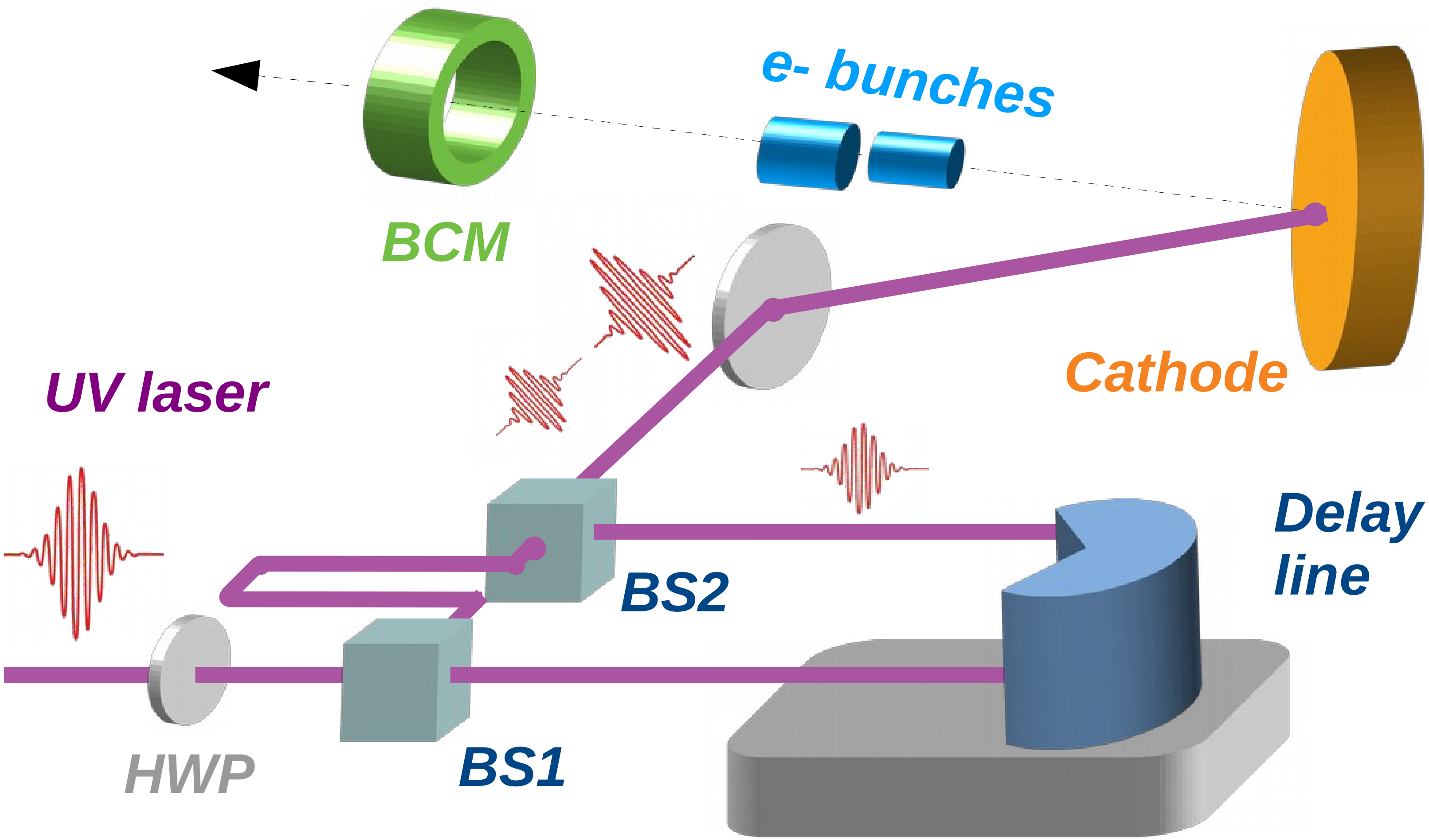
The laser (~100 uJ, 2mm diameter) reaches the negative electrode hole ~100ns before the discharge trigger.

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

Plasma acceleration experiment



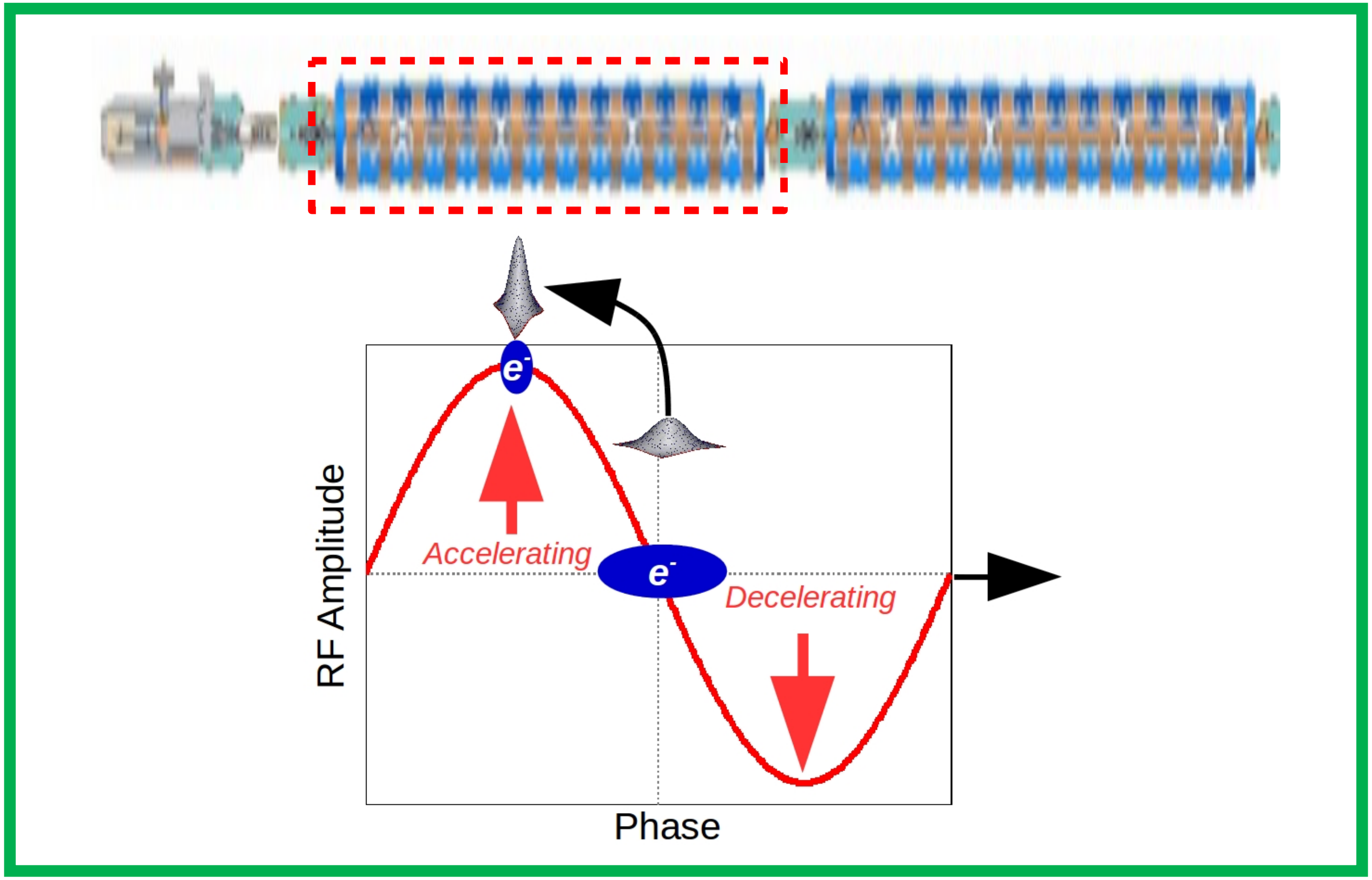
Driver-witness generation



Two pulse configuration produced directly in an interferometric-like setup equipped with pulse shaping stages.

Velocity bunching configuration

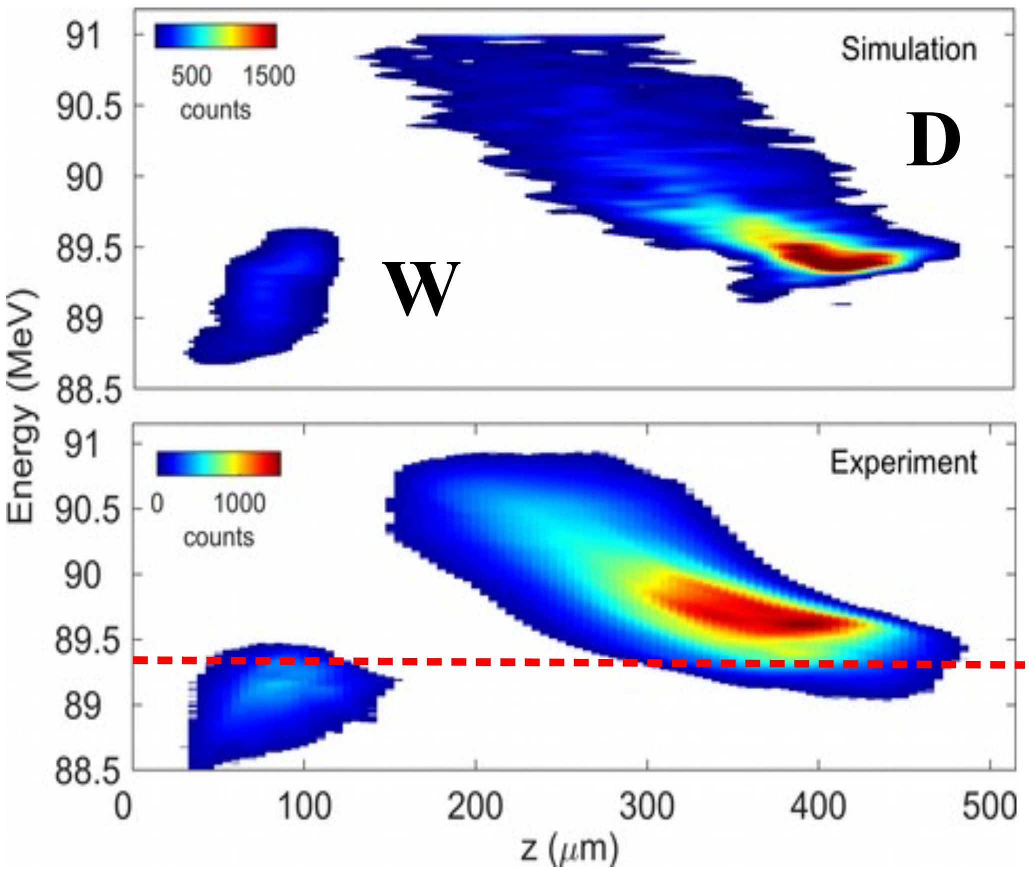
Alternative technique to magnetic compression in chicanes / doglegs.



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

Beam configuration @ the plasma entrance

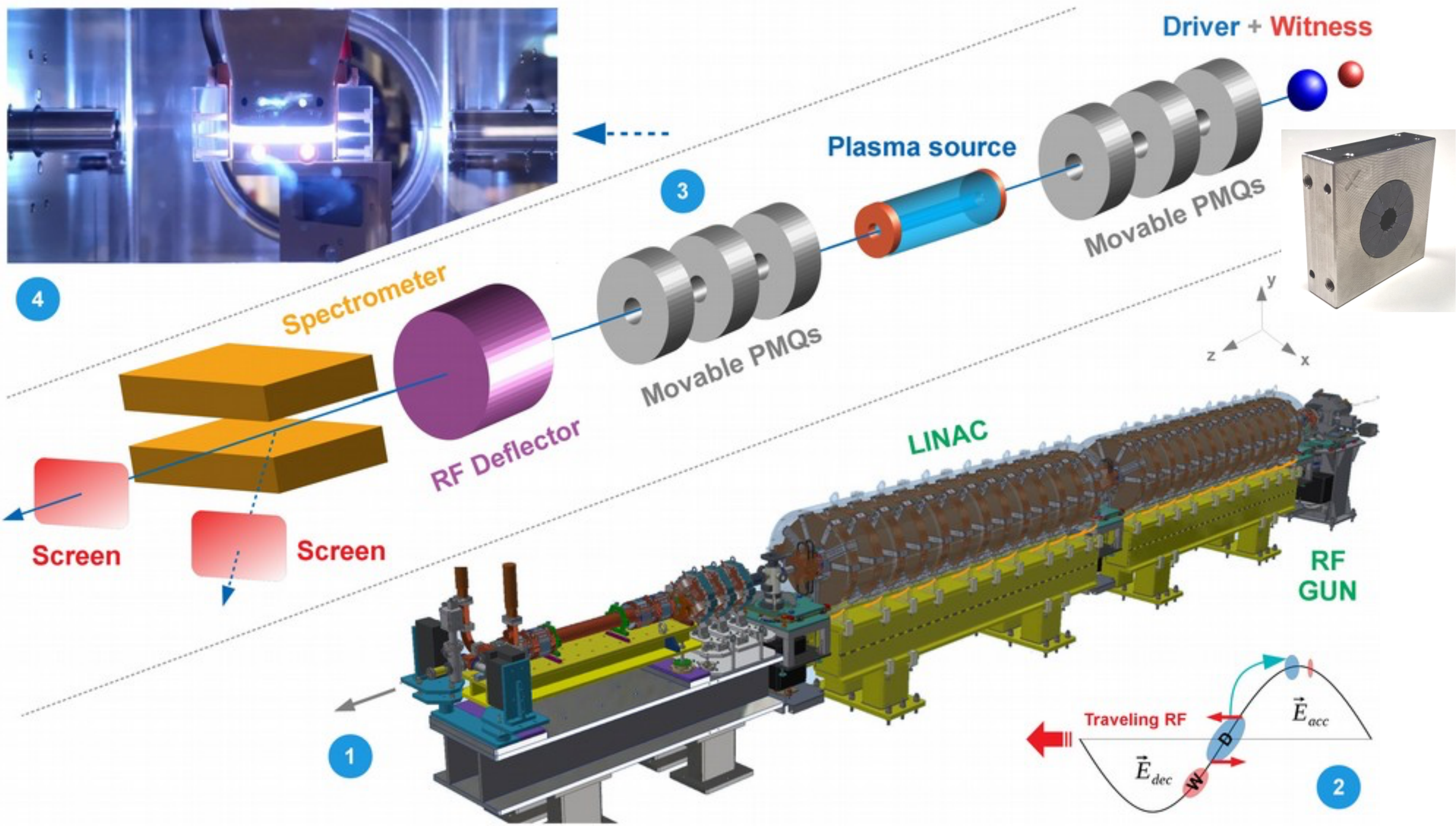
Two-bunches configuration produced directly at the cathode with **laser-comb technique** with a time-separation of approximately ~1 ps



COMB	Driver	Witness
Q (pC)	200	20
τ (fs)	200	30
σ (µm)	20	14
E (MeV)	89.5	89.1
σ_E (MeV)	0.2	0.2
ϵ_x (µm)	2.5	1.4
ϵ_y (µm)	1.7	1.2

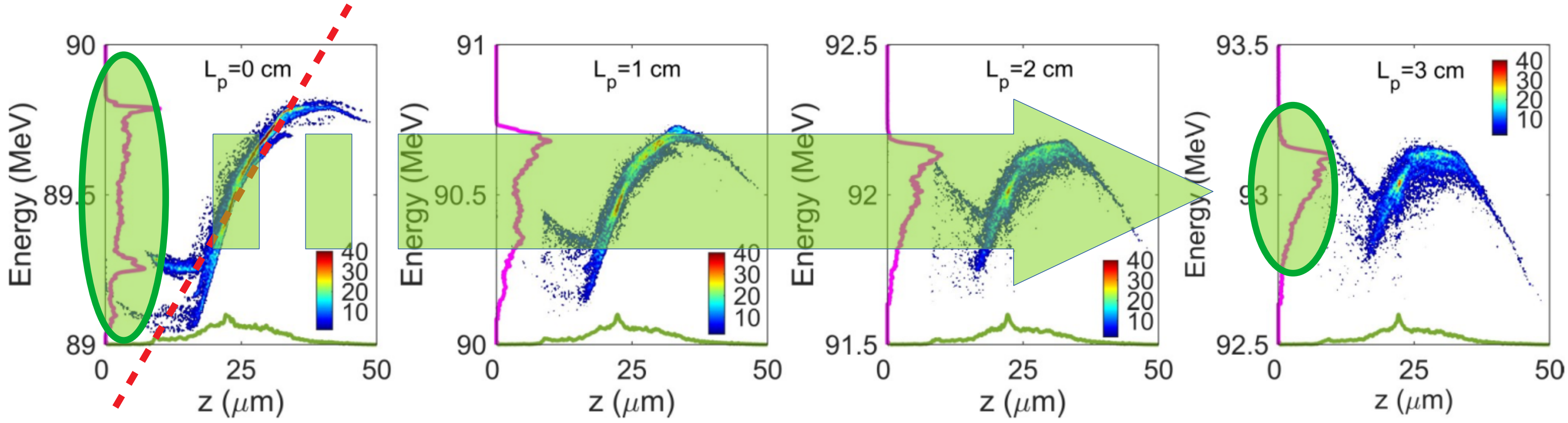
Nearly the same energy with plasma OFF

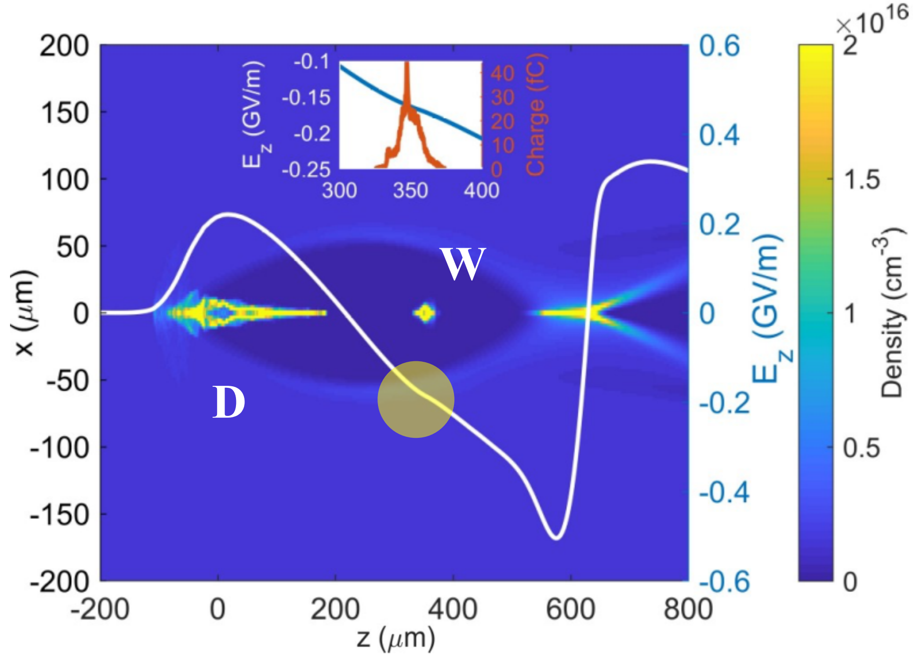
Plasma acceleration experiment

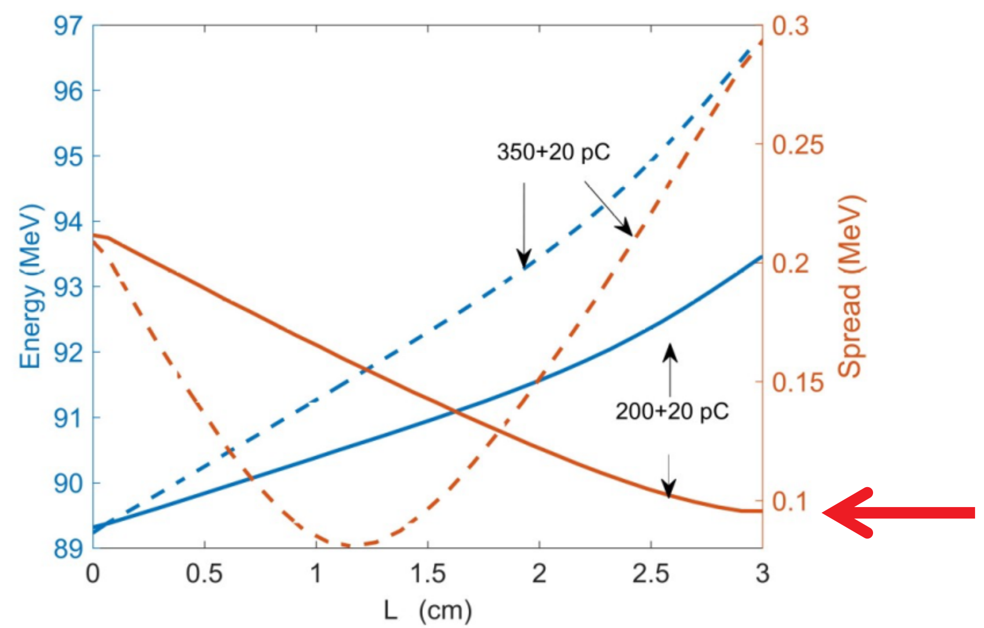


Assisted beam-loading technique

Pre-chirp to compensate wakefield slope



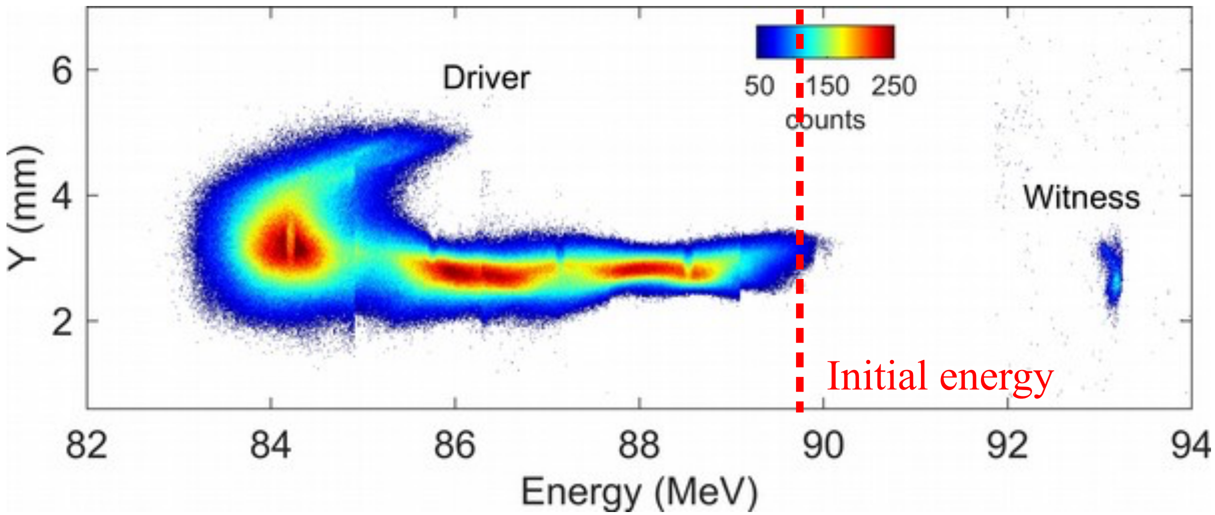




First Plasma acceleration results

4 MeV acceleration in 3 cm plasma with 200 pC driver

- $2\mathrm{x}10^{15}\ \mathrm{cm}^{-3}$ plasma density
- ~133 MV/m accelerating gradient

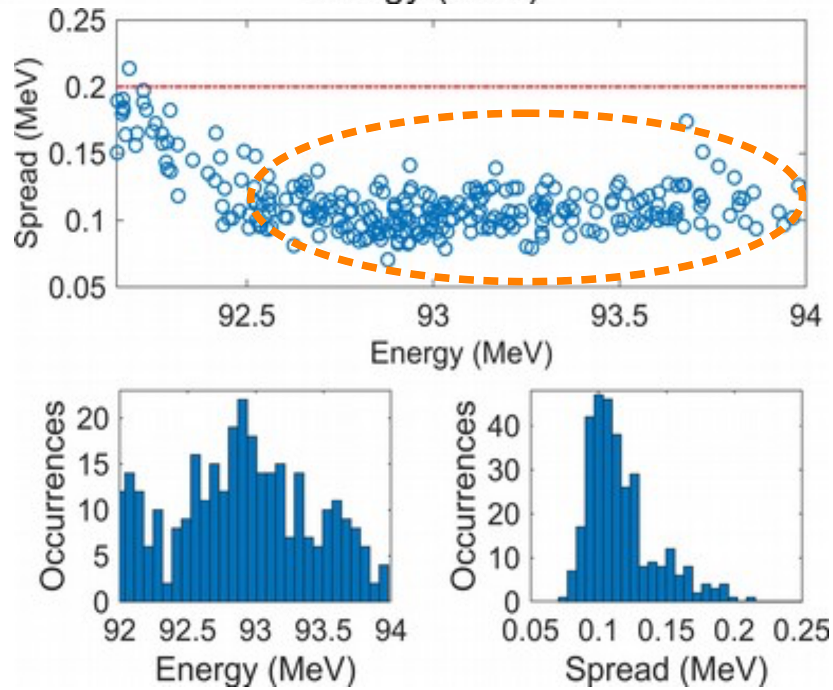


Demonstration of energy spread compensation

Total projected spread

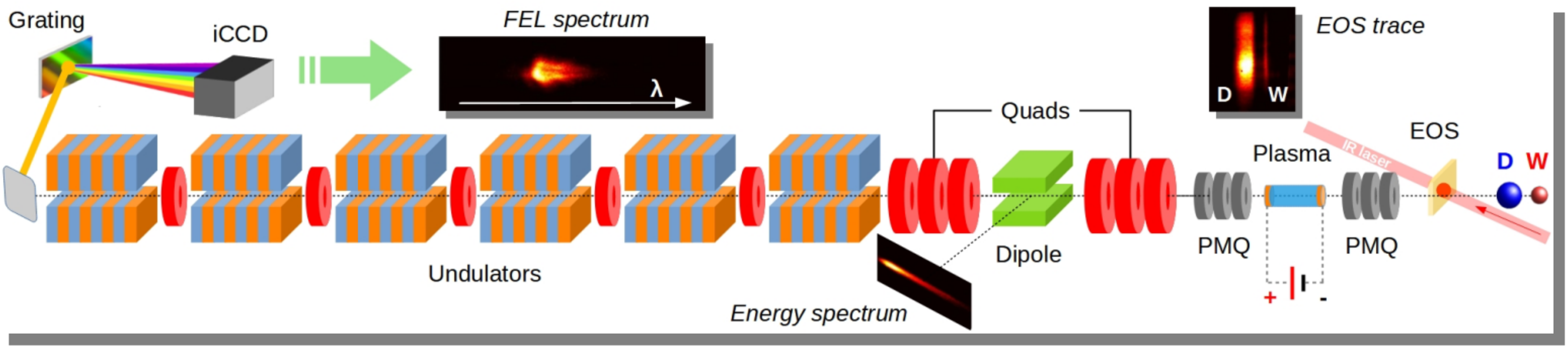
from 0.2 MeV

to 0.12 MeV



Pompili, R., et al. "Energy spread minimization in a beam-driven plasma wakefield accelerator." Nature Physics 17.4 (2021): 499-503.

Proof of SASE FEL driven by PWFA



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

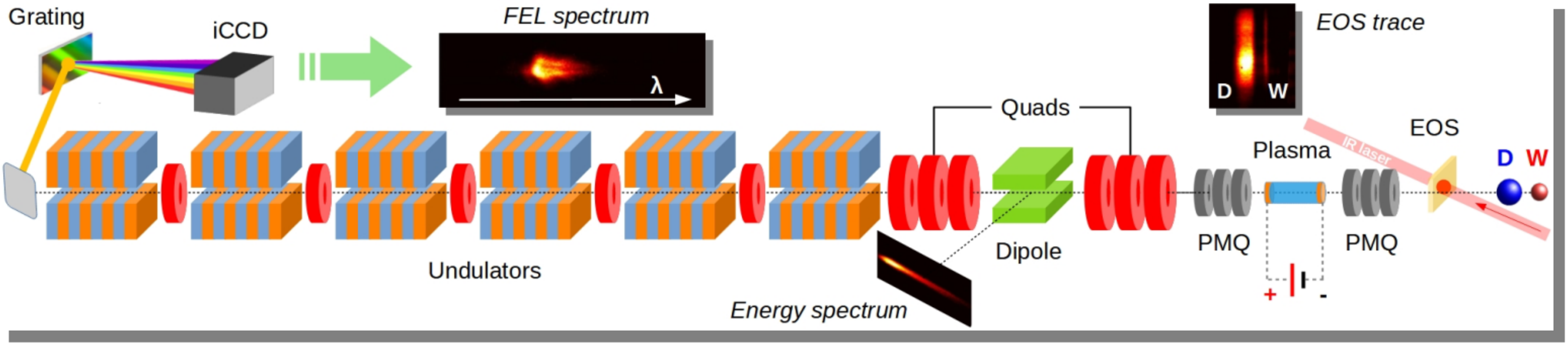
- Witness is completely characterized
- Jitter is online monitored with Electro-Optical Sampling (EOS) diagnostics
- Imaging spectrometer with iCCD used to detect FEL radiation

15 m FEL beamline

- L_u= 2.5 m
- *77 periods*
- λ_u= 2.8 cm
- K = 1.4
- L_g= 1.1 m

In collaboration with

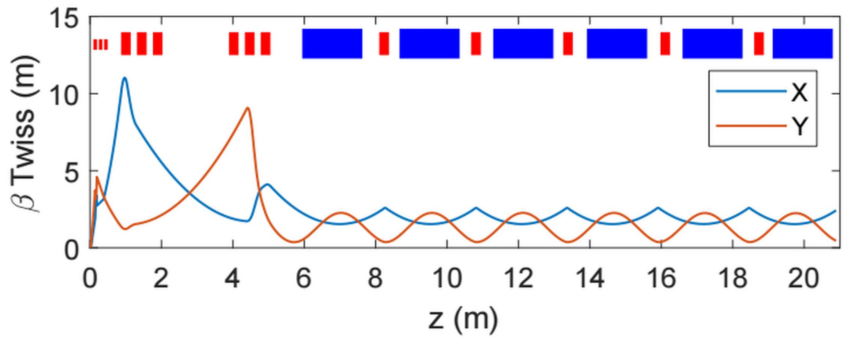
Beam transport - SASE FEL experiment



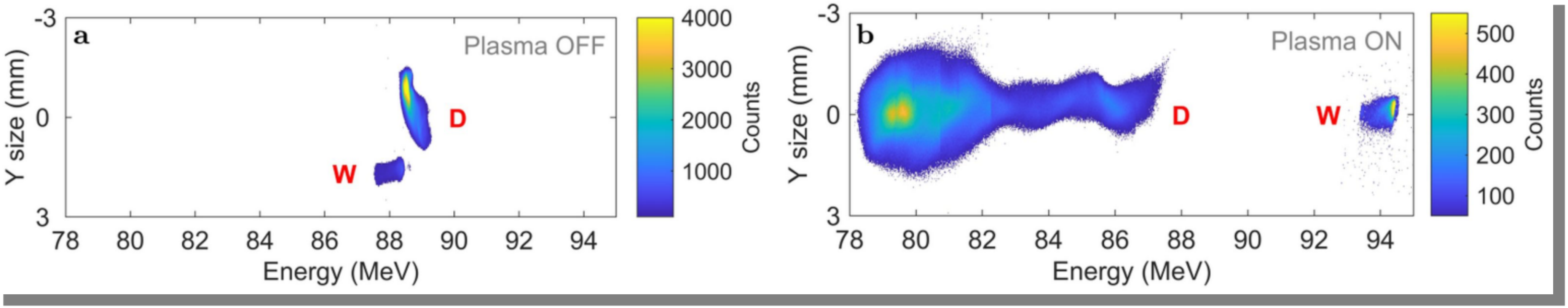
1. PMQs triplet catches the beam and removes the high divergence.
2. The 6 m FODO (6 e.m. quads) stage sets the required Twiss parameters to optimize the FEL performance.

$$\beta_T \cong mm \text{ @ } plasma\ exit \overset{to}{\Rightarrow} \beta_T \cong m \text{ @ } FEL\ entrance$$

3. Low energy beams so UNDs are transport elements (vertical focusing).
4. Optimal transport is ensured by 5 short e.m. quads allowing horizontal matching.



Beam configuration @ the FEL entrance



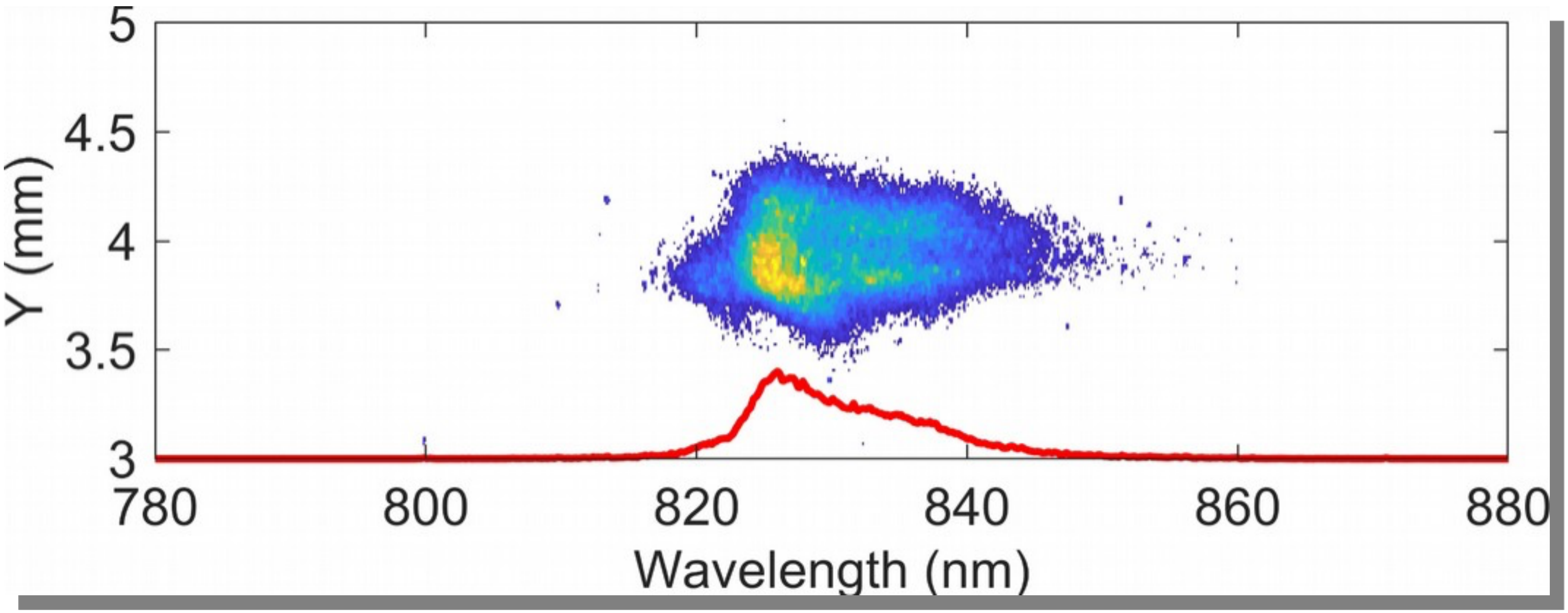
- Plasma density set to 1.6×10^{15} cm^{-3}
- Accelerated witness *(~200 MV/m acceleration gradient)*
- Driver decelerated by almost 10 MeV

Witness		E (MeV)	94
Q (pC)	20	σ_E (MeV)	0.3
τ (fs)	30	ϵ_x (µm)	2.7
$\sigma_{x,y}$ (µm)	200	ϵ_y (µm)	1.3

Increase of 30% due to the transverse mismatch.

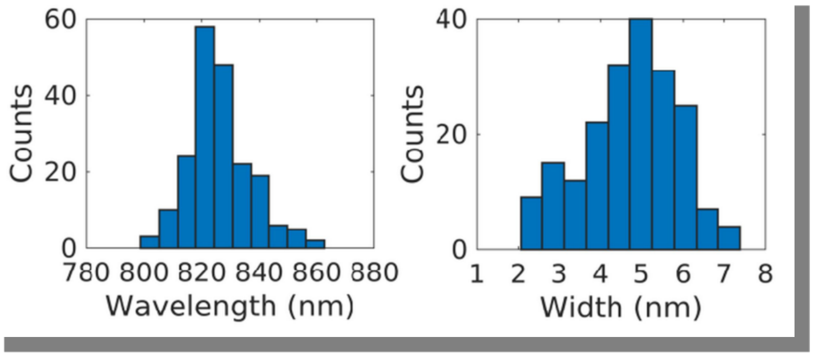
$$\sigma_{eq} = \left(\frac{\beta_{eq}\,\epsilon}{\gamma}\right)^{0.5} \cong 5\ \mu m$$

that is 3x the ideal one

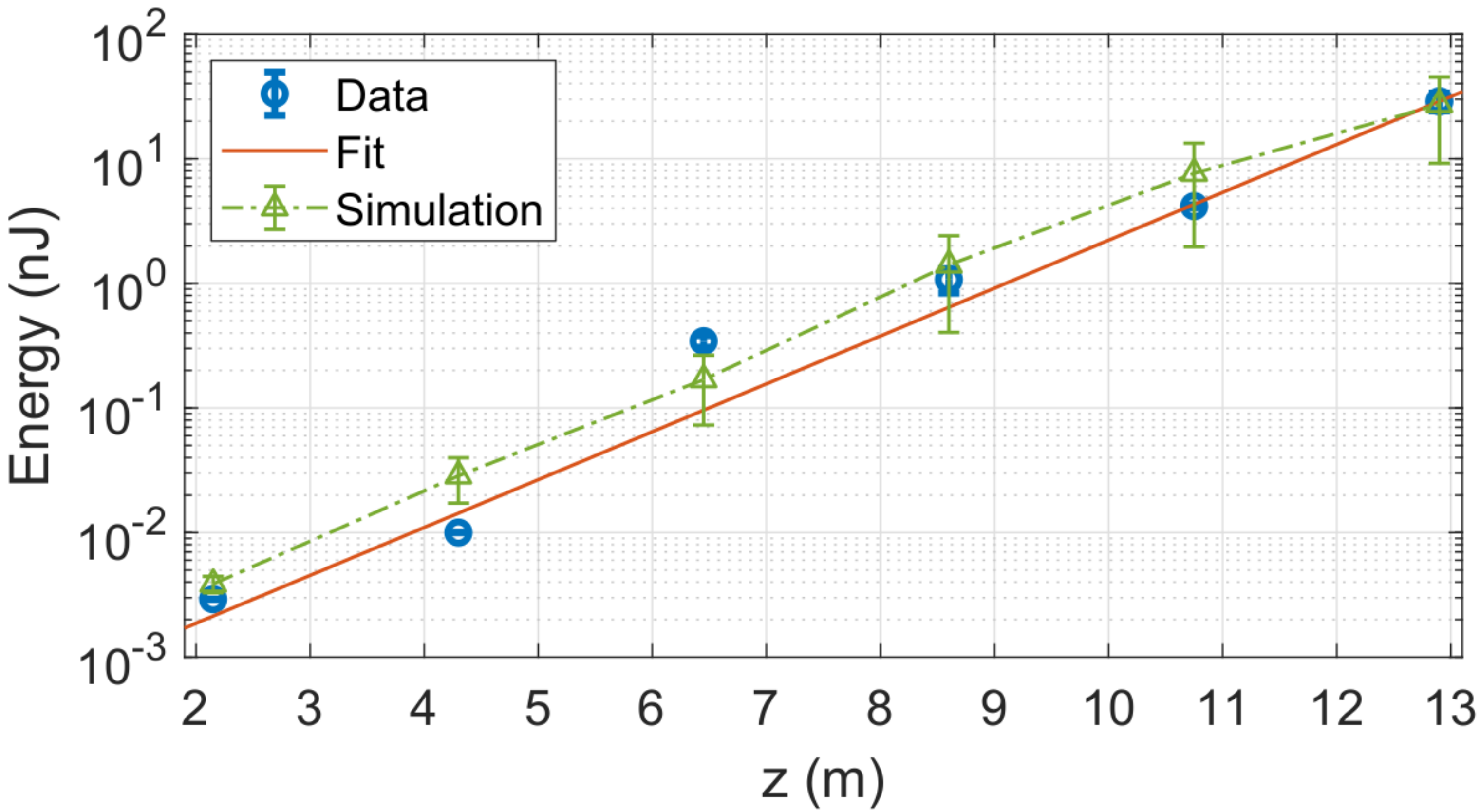


SASE FEL single-shot spectrum

- ✓ 30% shot-to-shot reproducibility
- ✓ Centered @827 nm with 5 nm BW
- ✓ Pulse energy up to 30 nJ



FEL driven by PWFA: exponential gain

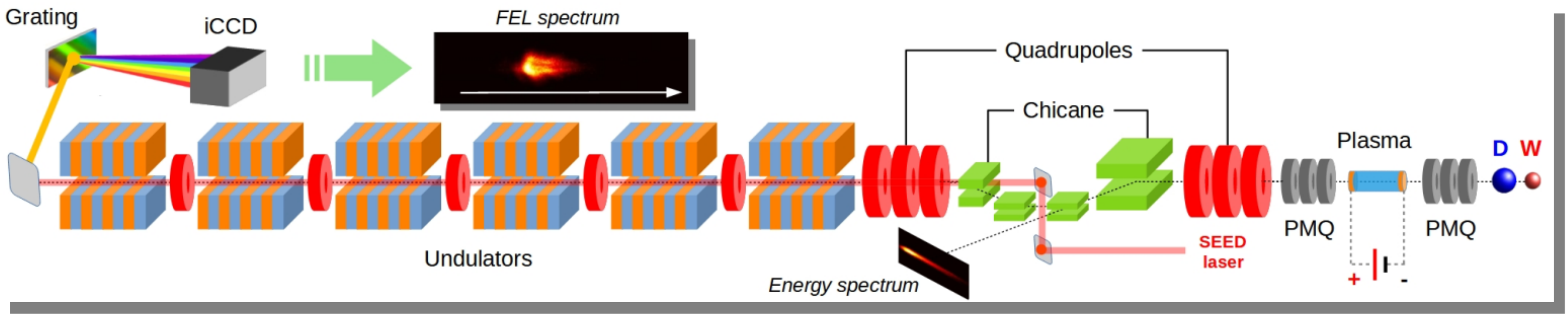


R. Pompili, et al. "Free-electron lasing with compact beam-driven plasma wakefield accelerator." Nature 605, 659–662 (2022).

SASE FEL radiation @827 nm

- ✓ Pulse energy increased 4 order of magnitude throughout the UNDs stage.
- ✓ 17% pulse energy RMS fluctuations over 30% of successful shot

Proof of Seeded FEL from PWFA



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

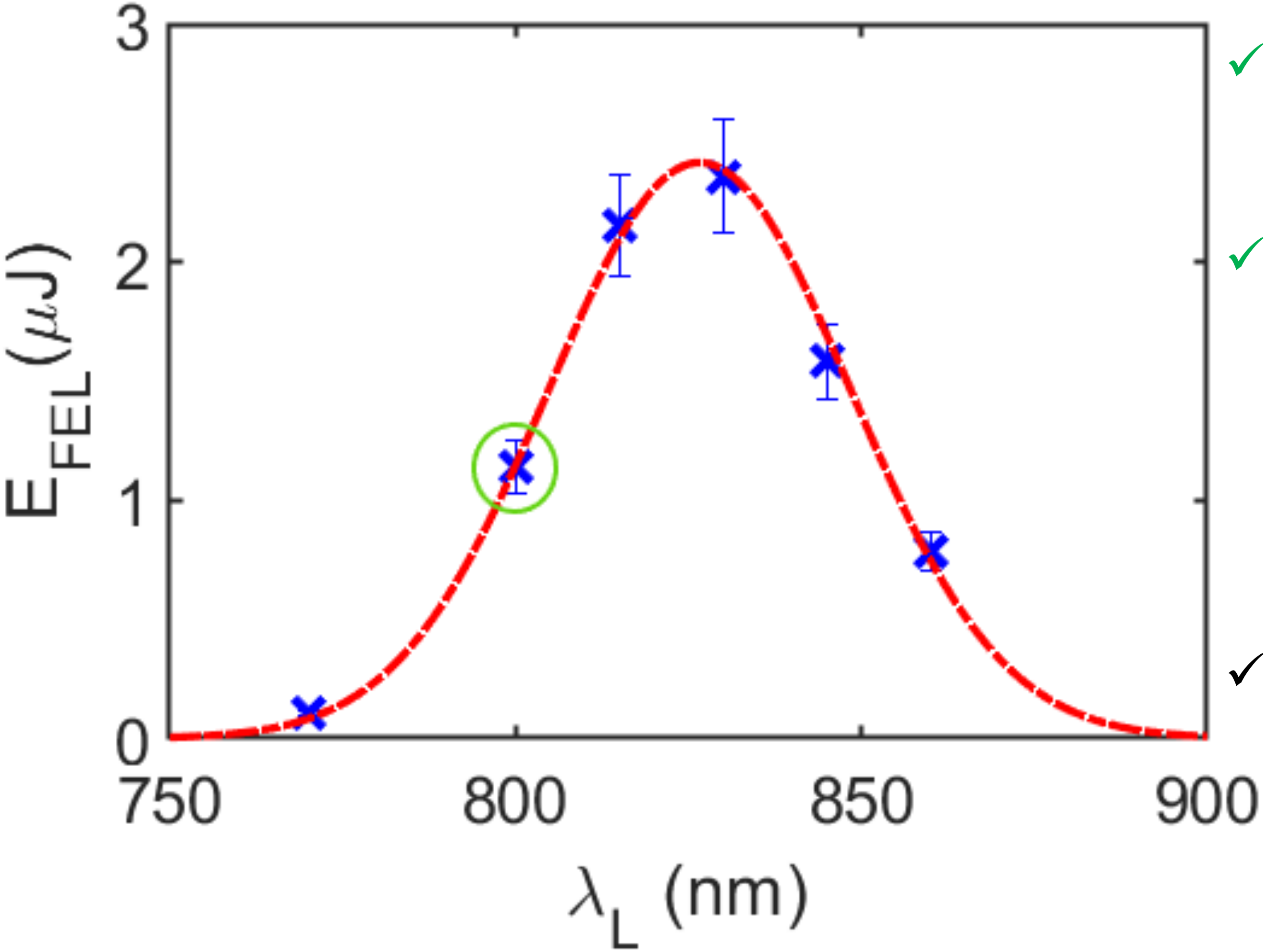
- ✓ Naturally synchronized with the beam, tunable energy (~10 nJ used in the experiment).
- ✓ Duration increased from ~100 fs to 600 fs (fwhm). Focused at the entrance of 1st undulator

Beam is partially displaced by using a magnetic chicane (4 dipoles in 5.75 m) to allow laser injection into the beamline (~2 mm offset , R56 ~ -10 µm)

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

Seed Laser is transported up to the imaging spectrometer

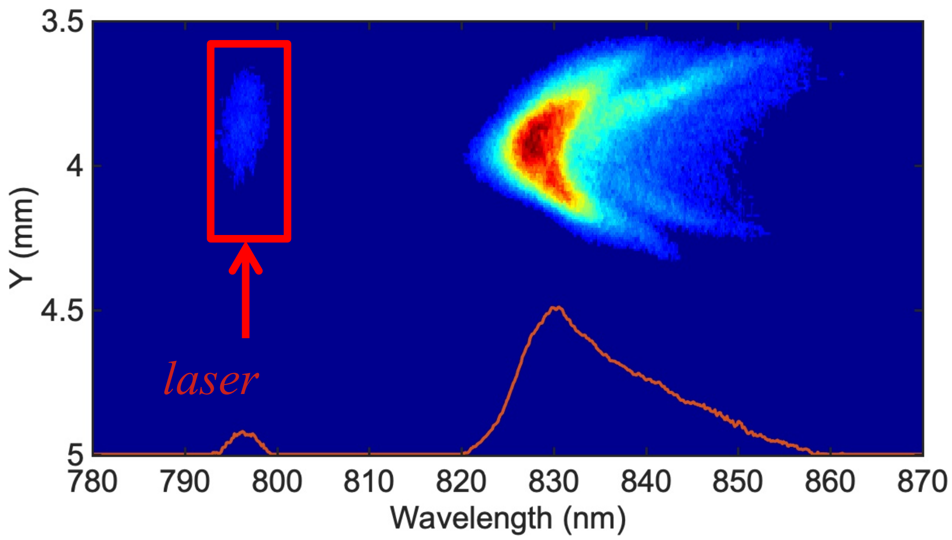
Seeded FEL radiation @827 nm energy gain obtained with a varying seeded laser wavelength (blue crosses)



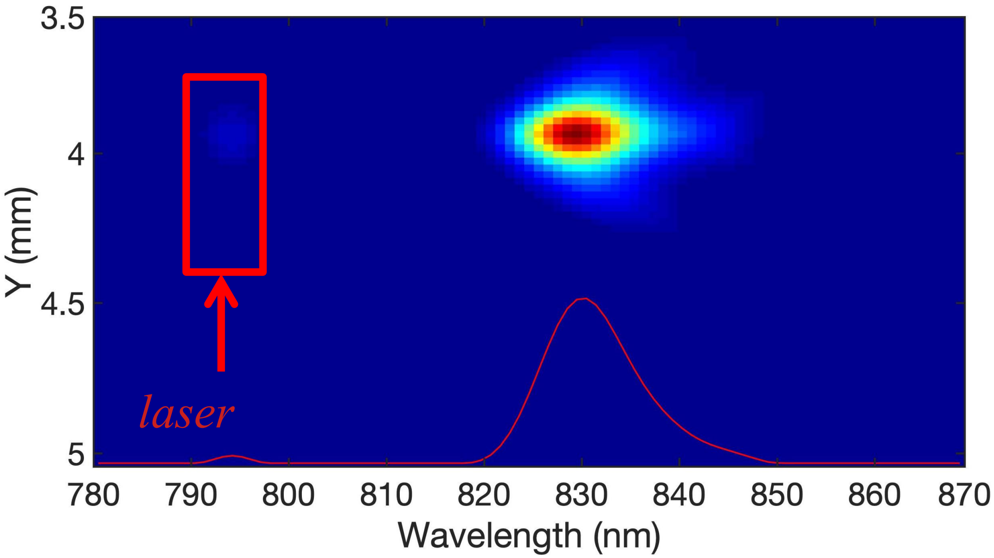
- ✓ Theoretically pulse energy increased 2 order of magnitude respect to SASE radiation
- ✓ The red dashed line shows the Gaussian fit of the theoretical data centered @826.6 nm, meaning maximum extraction when FEL radiation and seed laser have the same wavelengths.
- ✓ The green circle shows the prediction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

Radiation spectrum

Experimental spectrum



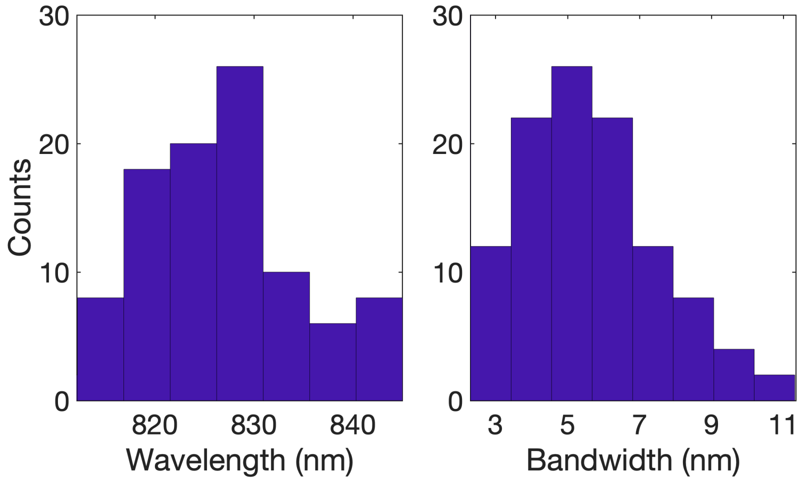
Theoretical spectrum



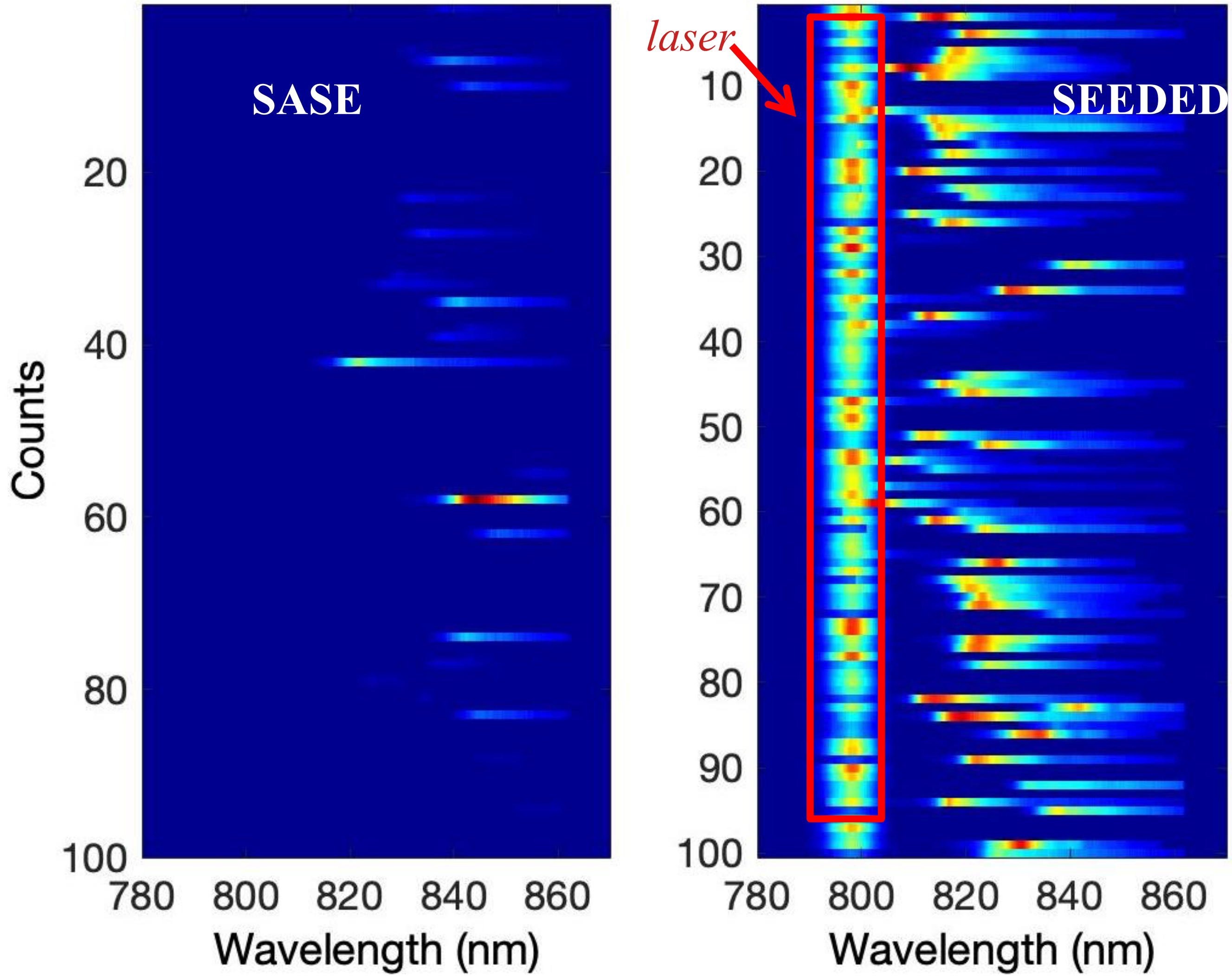
Seeded FEL single-shot spectrum

Clear signals, reproducible day by day

- ✓ 90% shot-to-shot reproducibility
- ✓ Centered @827 nm with 5 nm BW
- ✓ Pulse energy up to 1 μJ



Seeded FEL Performances

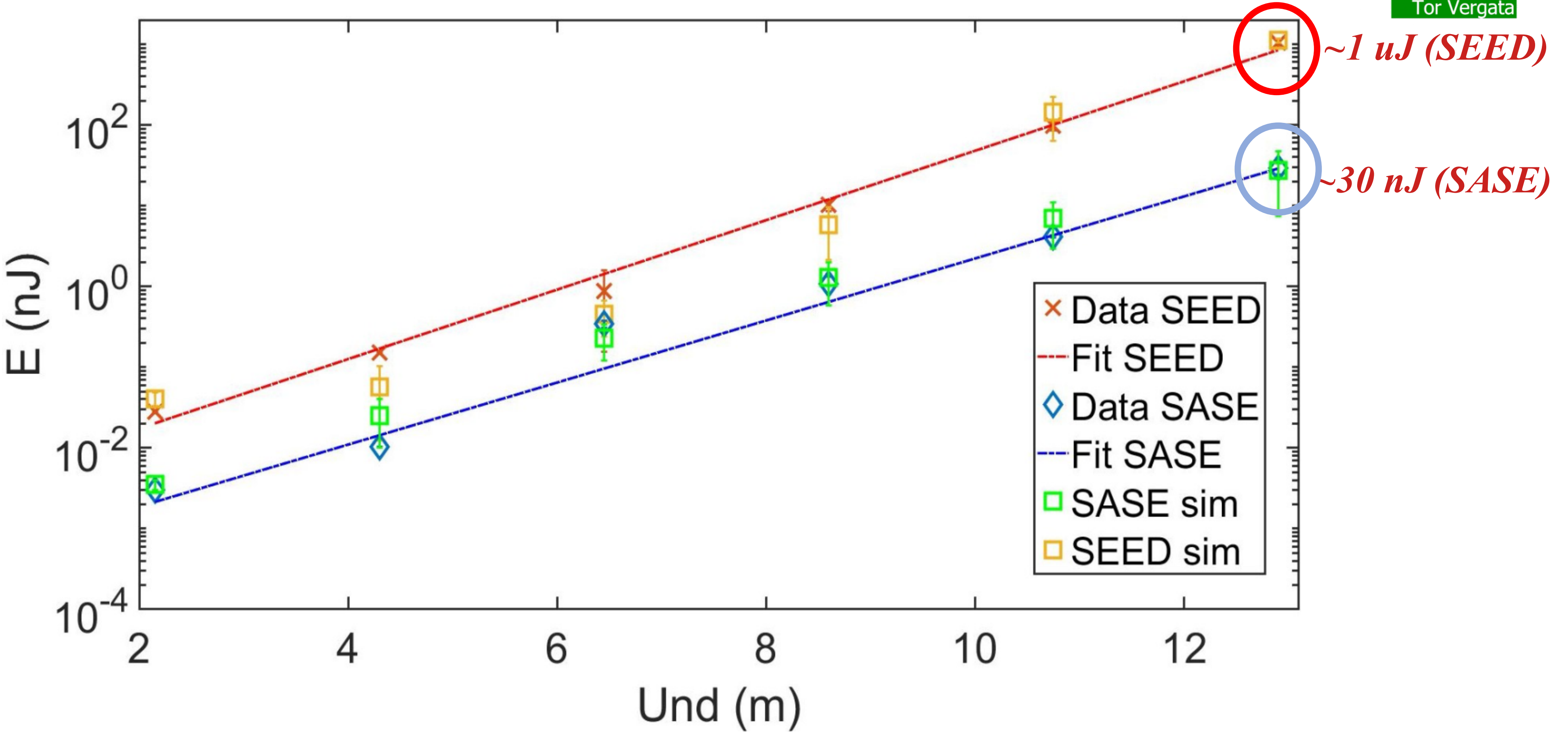


M. Galletti, et al.
Submitted

10^3 ND filter used
@ 6^{th} photodiode

- FEL radiation output is largely stabilized by the seed laser, larger output energy
- UNDs tuned for FEL radiation @827 nm → separated from the laser (@800 nm)

FEL driven by PWFA: exponential gain



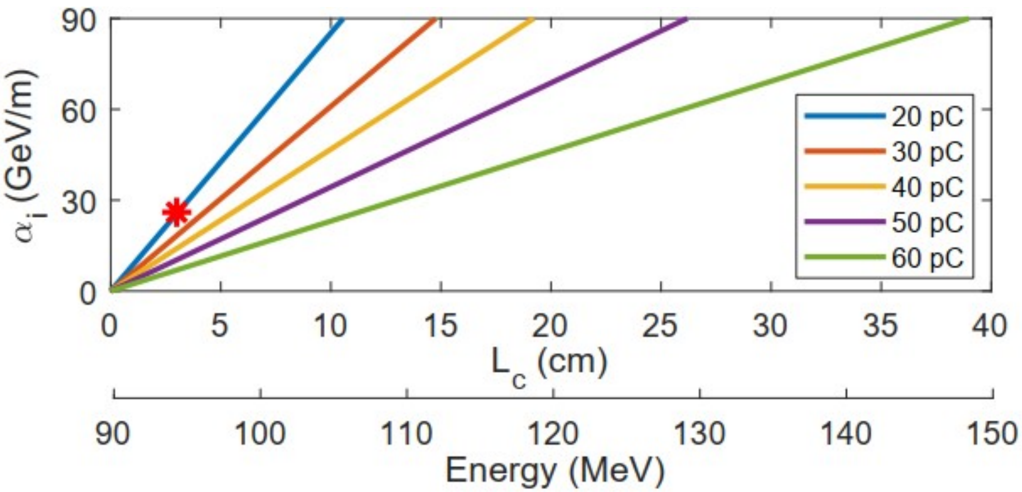
Seeded FEL radiation

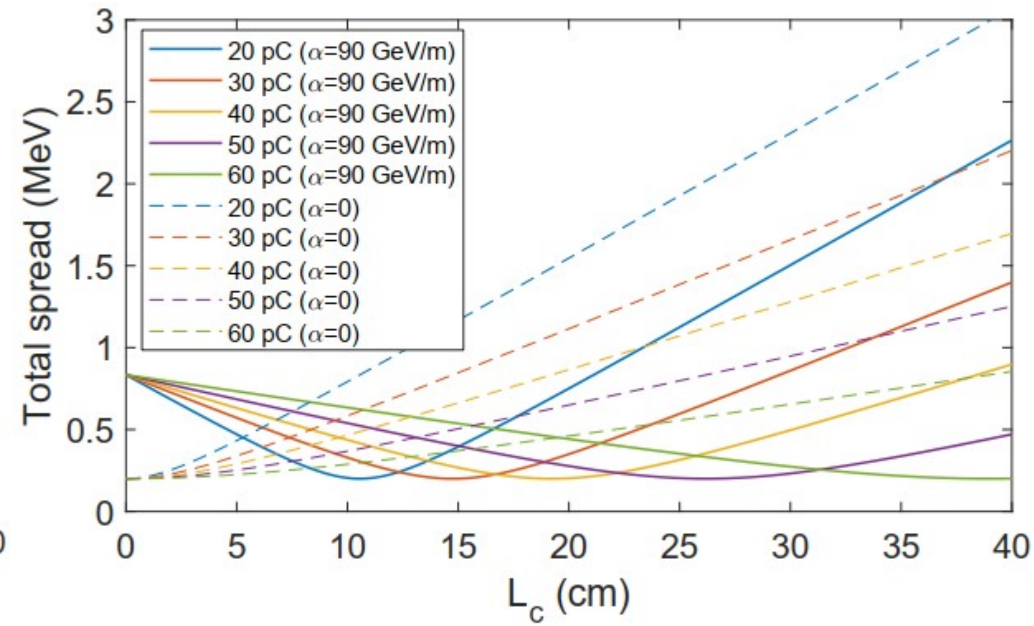
- ✓ Pulse energy increased 2 order of magnitude respect to SASE radiation
- ✓ 6% pulse energy RMS fluctuations over 90% of successful shot respect to 17% over 30% of shot for SASE

Scaling of the assisted beam-loading technique

Energy-chirp required as a function of L_c and for several witness charges to achieve the minimum energy spread at the exit of the PWFA.

$$\alpha_i = -eL_c \cdot \frac{d}{dz}\left[E_d(z) - \frac{1}{2}E_w(z)\right]$$



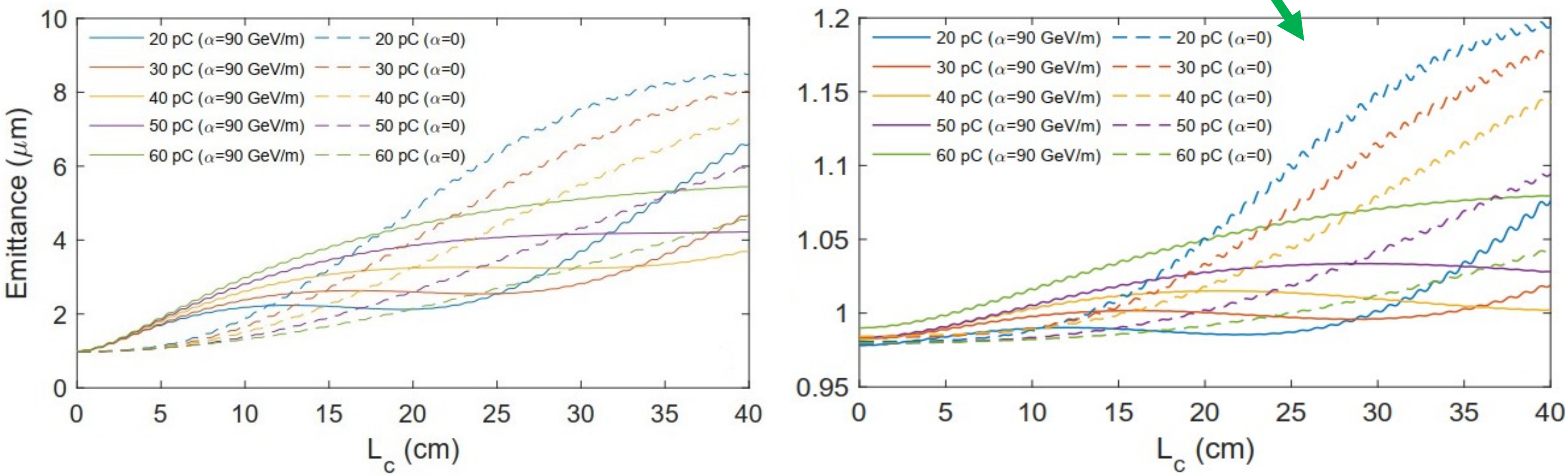


- ✓ By setting 200 MeV/m, we can achieve 150 MeV with 60 pC witness beam and 40 cm long capillary.
- ✓ Larger energy chirp allow to minimize the energy spread over longer capillary length like higher charges enhancing the beam loading.

Scaling of the assisted beam-loading technique

Optimal acceleration with no detrimental effects on the emittance requires the beam transversely matched to the plasma.

$$\beta_{eq} = \left(\frac{\gamma}{2\pi\, r_e\, n_e}\right)^{0.5} \cong 2.6\ mm \overset{to}{\Rightarrow} \sigma_{eq} = \left(\frac{\beta_{eq}\,\epsilon}{\gamma}\right)^{0.5} \cong 5\ \mu m$$



✓ When the energy spread is minimized, an emittance growth of 7% (unavoidable chromatic effects) is retrieved.

Conclusions

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

- ❖ 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 @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 kind attention!

Mario Galletti (University of Rome Tor Vergata and INFN)

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On behalf of the SPARC_LAB collaboration

Università di Roma

Tor Vergata

INFN

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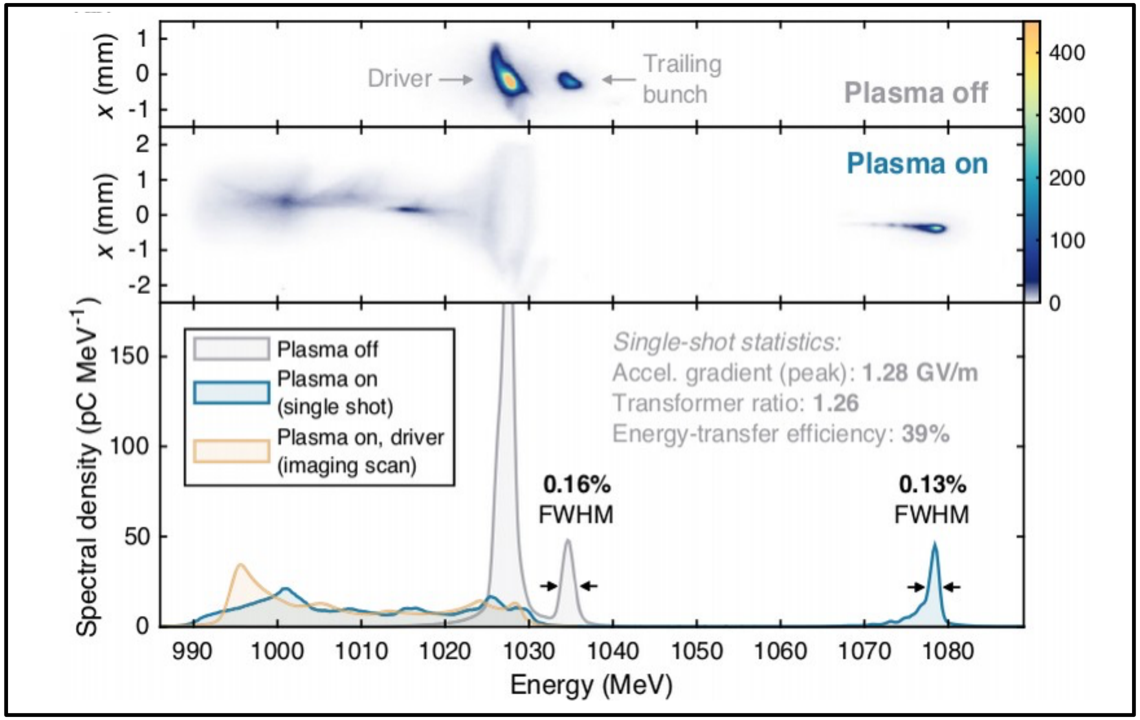
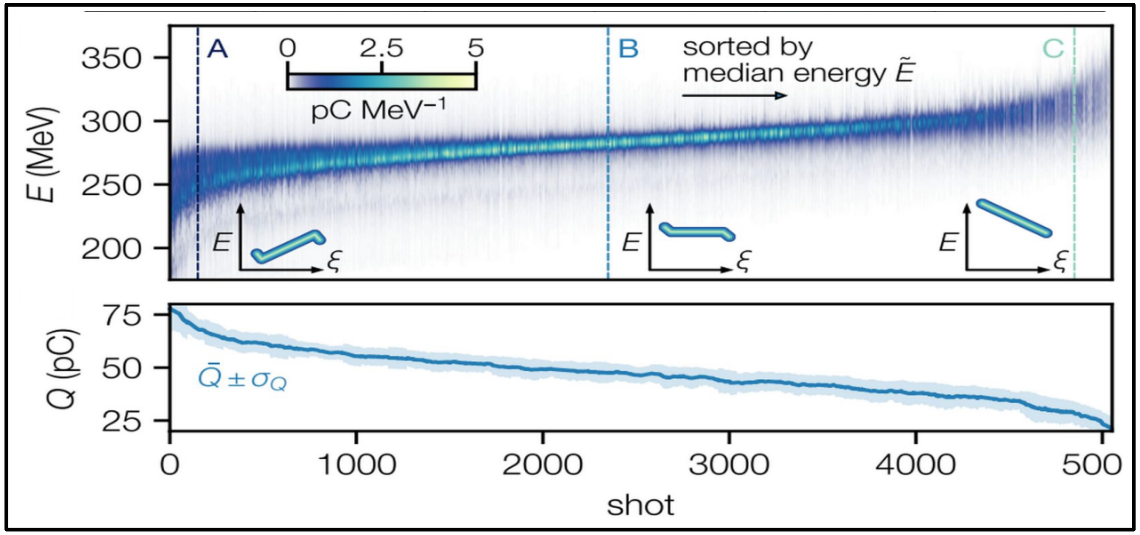
Recent advances toward high-quality

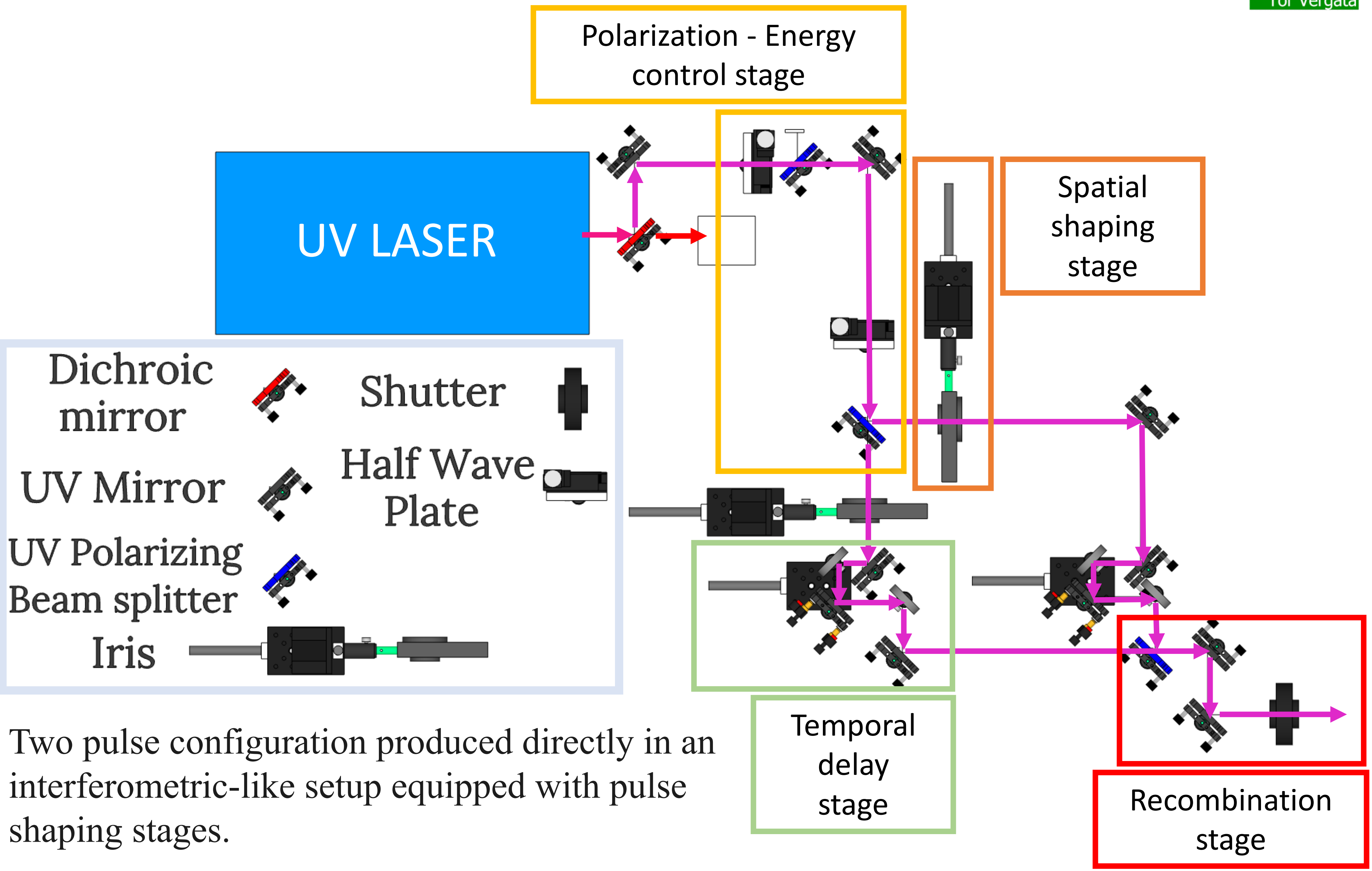


Lindstrøm C.A., et al. "Energy-spread preservation and high efficiency in a plasma-wakefield accelerator." Physical Review Letters 126.1 (2021): 014801.



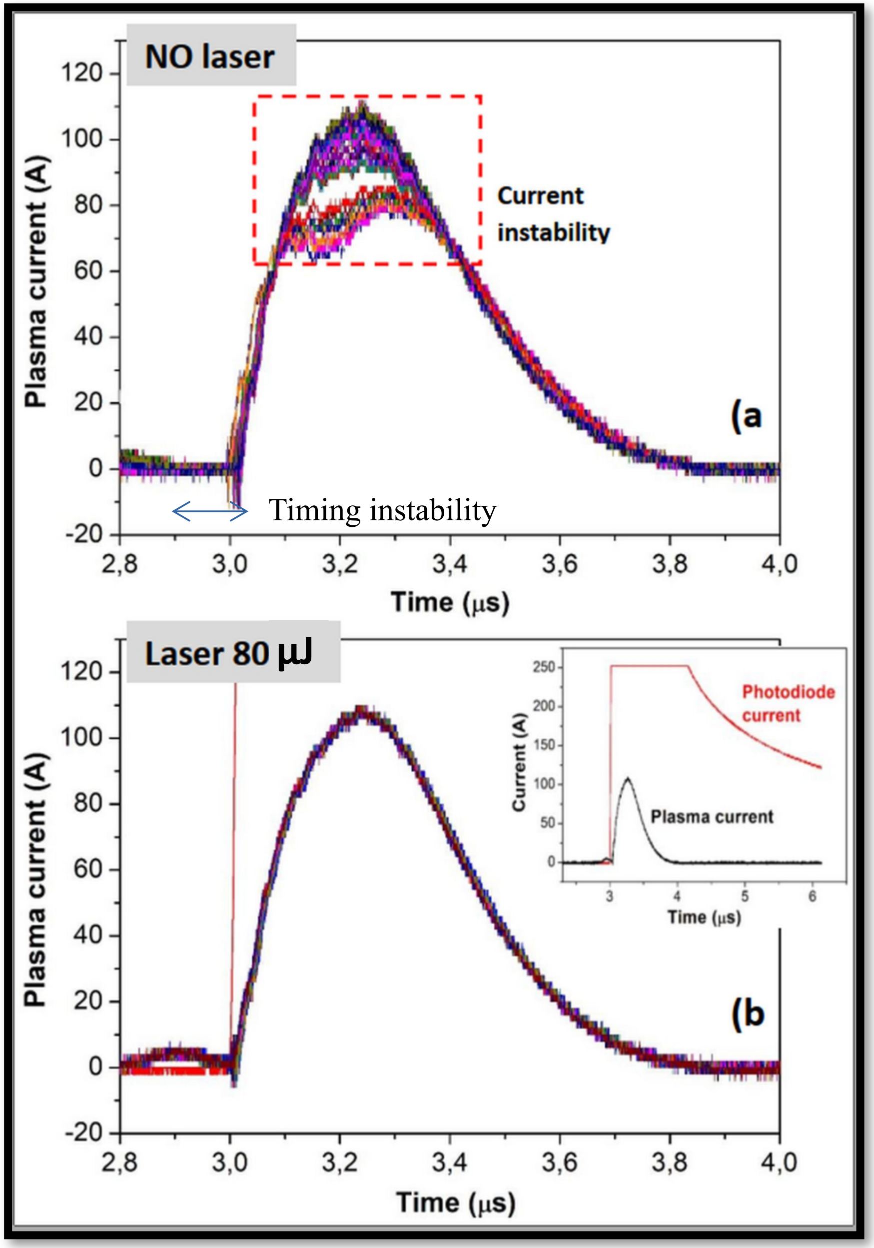
Kirchen, M., et al. "Optimal Beam Loading in a Laser-Plasma Accelerator." Physical Review Letters 126.17 (2021): 174801.

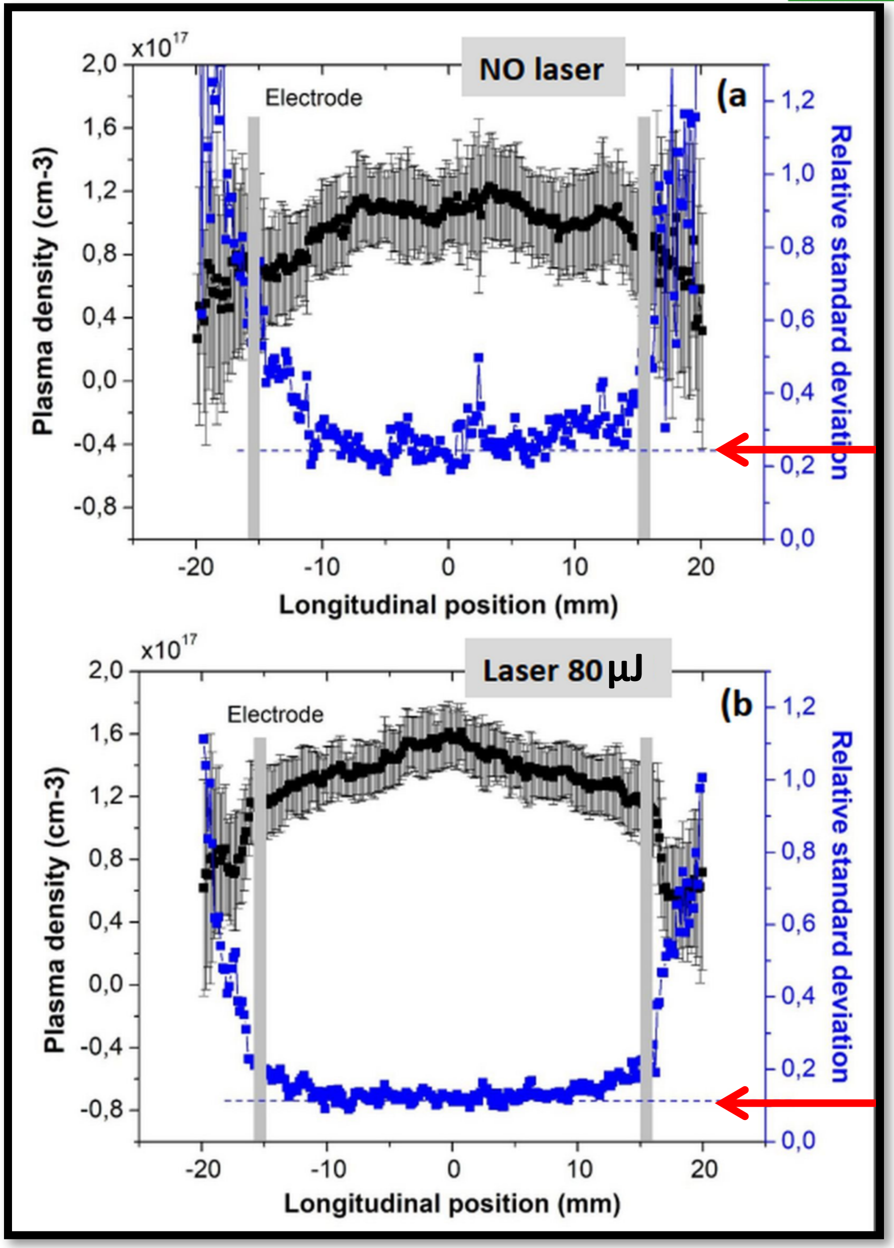
Laser-comb technique



Two pulse configuration produced directly in an interferometric-like setup equipped with pulse shaping stages.

Plasma stabilization

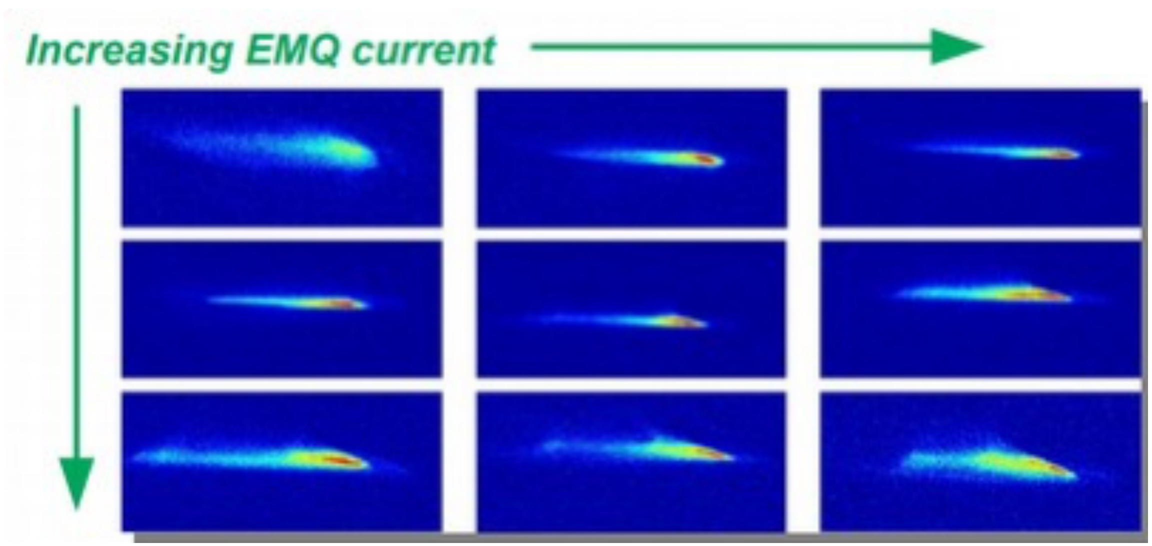


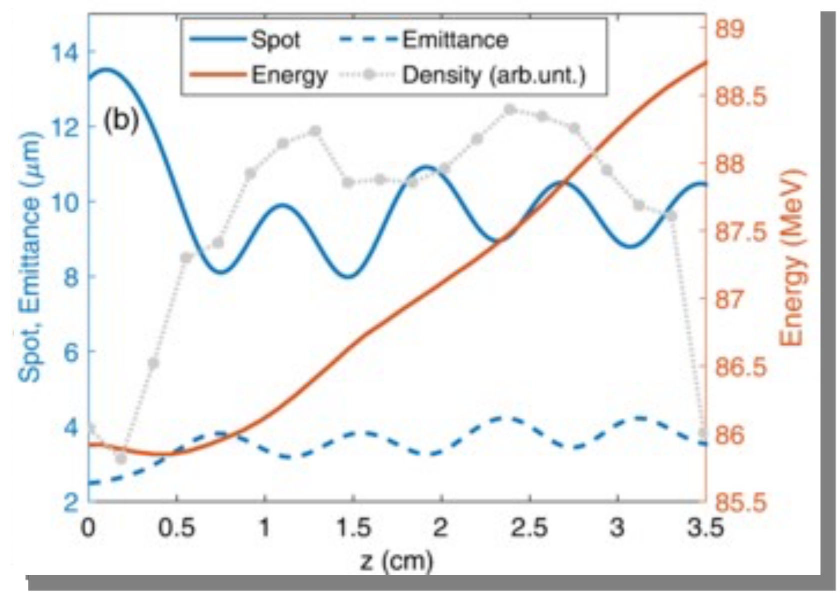


PWFA characterization completed by measuring the witness emittance

Measurement of its normalized emittance through quadrupole scan technique

We found emittance increase from 2.7 um to 3.7 um (rms) during acceleration





Shpakov, V., et al. "First emittance measurement of the beam-driven plasma wakefield accelerated electron beam." Physical Review Accelerators and Beams 24.5 (2021): 051301.

Analytical model developed for the quasi-nonlinear regime

By describing the blowout region as an ellipsoid with normalized radial and longitudinal semi-axes

$$R_b = 2\sqrt{\alpha}k_p\sigma_r \qquad L_b = k_p\lambda_p/2 = \pi \qquad \alpha = n_b/n_p$$

The axial electric field can be written as

$$E_b(z) = -f_b\frac{en_p}{\epsilon_0}\cdot z \qquad f_b = R_b/3L_b$$

Considering thus the field produced by the driver (E_d) and witness self-field (E_w), the overall electric field acting on the latter is given by

$$E_z(z) = E_d(z) - \frac{1}{2}E_w(z) = -\frac{en_p}{\epsilon_0}\left(f_d - \frac{1}{2}f_w\right)\cdot z$$

and consequently

$$\alpha_i = -eL_c\cdot\frac{d}{dz}\left[E_d(z) - \frac{1}{2}E_w(z)\right] = \frac{e^2n_p}{\epsilon_0}\left[f_d - \frac{1}{2}f_w\right]\cdot L_c$$

1D Model for FELs

e-beam peak current

Undulator parameter

$[JJ] = J_0(\xi) - J_1(\xi)$ with $\xi = \frac{K^2}{2(2+K^2)}$, J_0, J_1 =Bessel Functions

$$\boxed{\rho = \left[\frac{I}{\gamma^3 I_A} \frac{\lambda_u^2}{2\pi\sigma_x\sigma_y} \frac{(K \times [JJ])^2}{32\pi} \right]^{1/3}}$$

Alfven current $I_A \simeq 17kA$

Transverse rms beam size (gauss distribution) *

Notice 1/3 exponent

- **Pierce parameter ρ.** The jack of all trades of 1D FEL theory. Typical values $\rho \lesssim 10^{-3}$

- Two important beam requirements
  - *beyond cold-beam 1D theory*

$$\boxed{\sigma_\delta < \rho}$$

- <u>E-beam relative energy spread</u> σ_δ should be smaller (in fact a bit smaller) than ρ, say < 0.5ρ . Electrons with energy too different from nominal slip off the FEL resonance and do not contribute to lasing

$$\boxed{\varepsilon_\perp \lesssim \frac{\lambda}{4\pi}}$$

- <u>E-beam transverse geometric rms emittance</u> $\varepsilon_\perp$ should be on the order of, or smaller than, the radiation emittance $\varepsilon_r = \frac{\lambda}{4\pi}$.

Beam-jitters FEL acceptance study

FEL radiation was mimicked by GENESIS 1.3 with maximum precision available (mesh resolution λ_r and temporal step λ_u/c).

Electron beam microcopy is randomly changed. 10% jitters on bunch charge, length, energy, energy spread and emittance were considered.

SASE configuration

- 100% final energy fluctuation
  - beam parameters jitters
  - microscopic shot-noise starting the process.

Seeded configuration

- 3x less final energy fluctuation
  - beam parameters jitters
  - 1% laser energy jitter

SEEDED configuration strongly suppressed the fluctuations observed in previous experiments operating in the SASE regime.

EuPRAXIA design study

EuPRAXIA collaboration foresees the realization of two plasma-based FEL facilities in the **X-rays range driven by GeV energy beams accelerated by a PWFA stage**.

COMB	Driver	Witness
Q (pC)	200	30
τ (fs)	200	10
E (MeV)	500	500

$n_e = 10^{16}\ cm^{-3}$
$E_{acc} = 1.2\ GV/m$

PLASMA stage	Witness
E(GeV)	1
I_p(kA)	2.6
σ_E (MeV)	0.7
$\epsilon_{x,y}$ (μm)	0.4

30 m FEL beamline

- λ_u= 1.5 cm
- K = 1.1
- L_g= 0.4 m
- L_s= 20 m

FEL stage	Radiation
$\lambda_r\ (nm)$	3
E_r (μJ)	7
Phot/shot	10^{11}