European Advanced Accelerator Workshop 2023
Isola d’Elba, Italy

Enhanced stability of a Free-Electron Laser driven by a plasma beam-driven accelerator and seeded by an external laser beam

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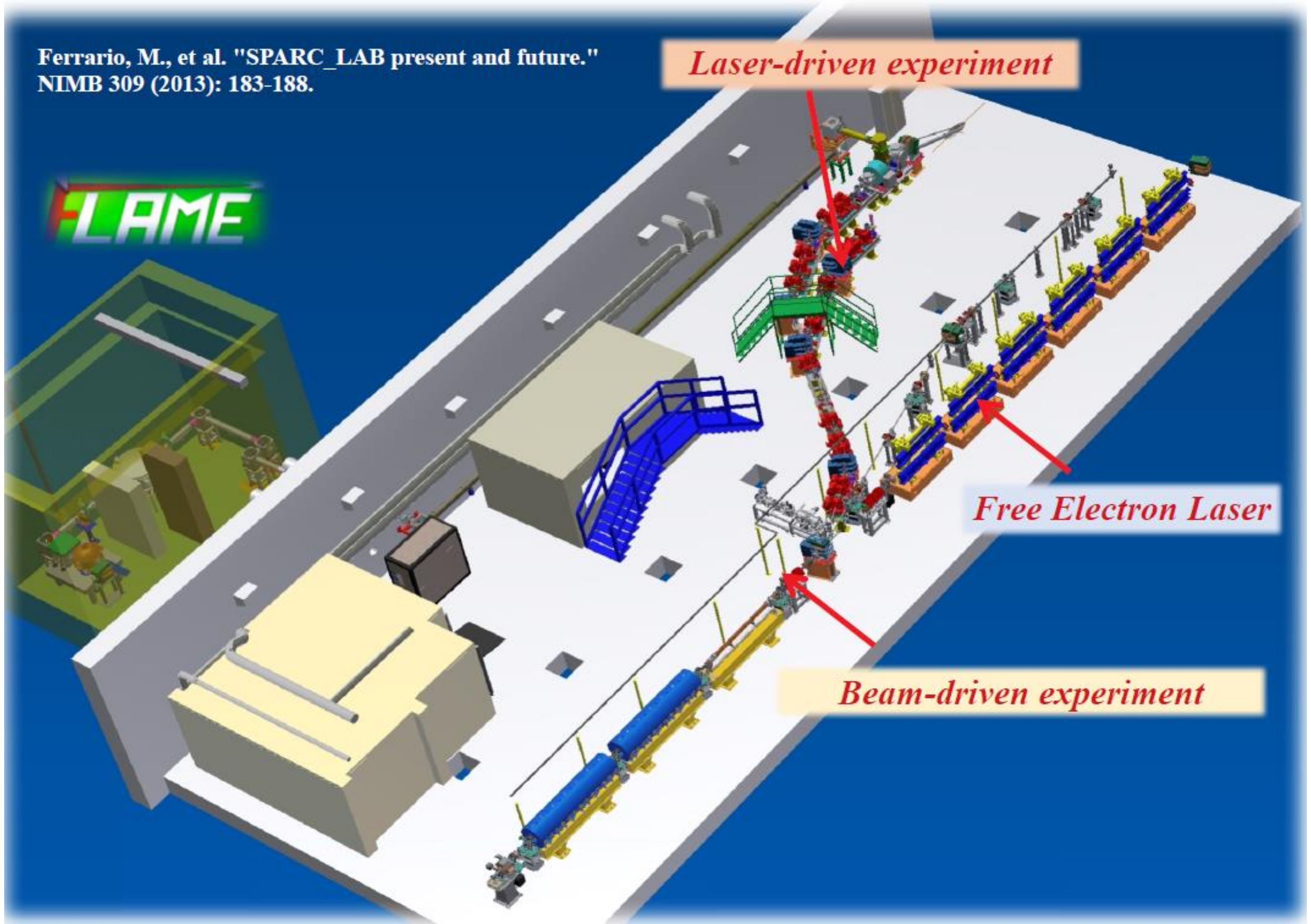
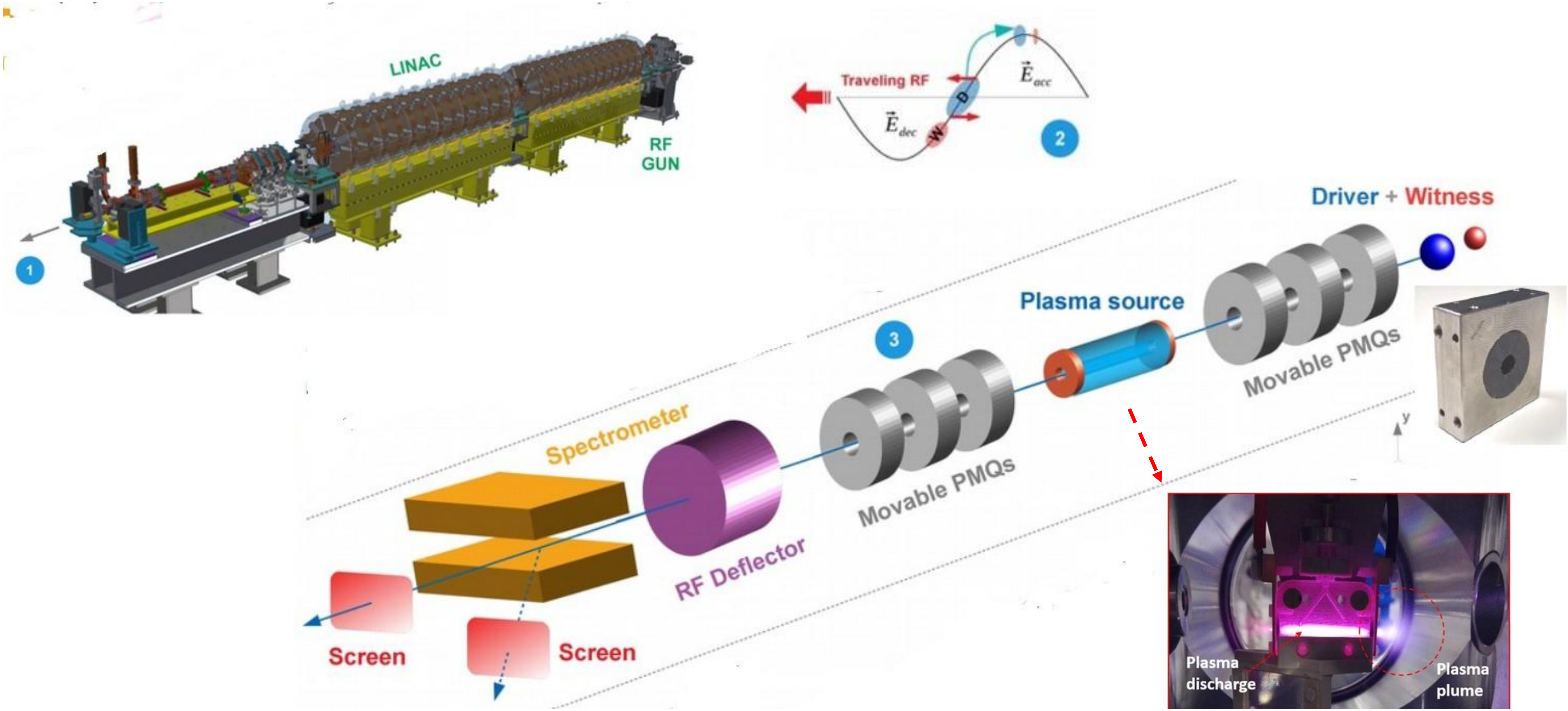
On behalf of the SPARC_LAB collaboration

SPARC_LAB facility



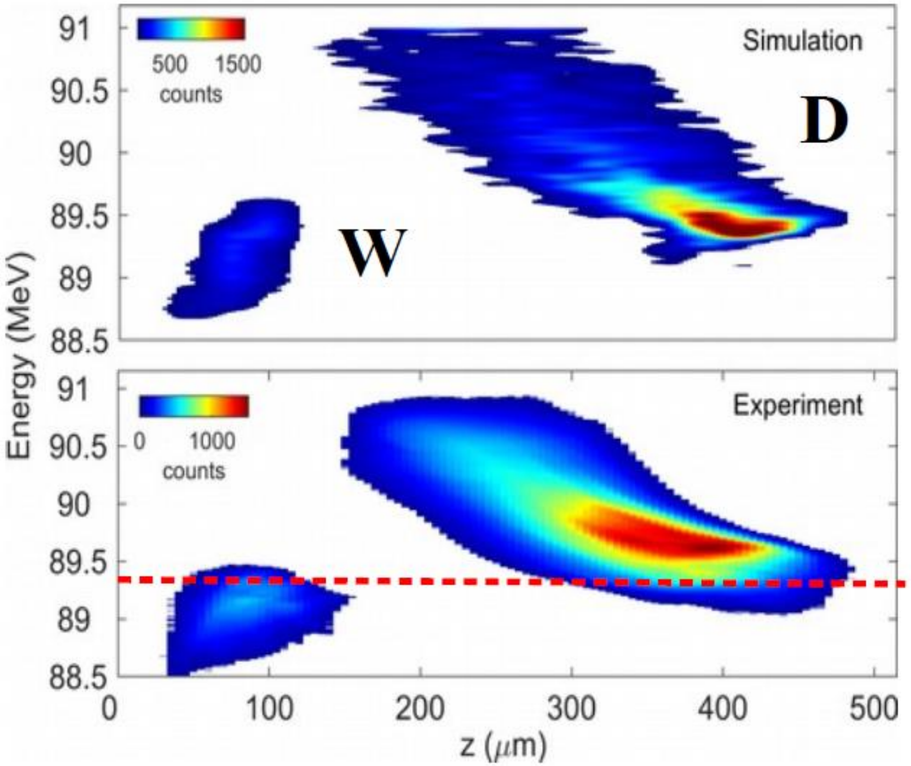
Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

Plasma acceleration experiments



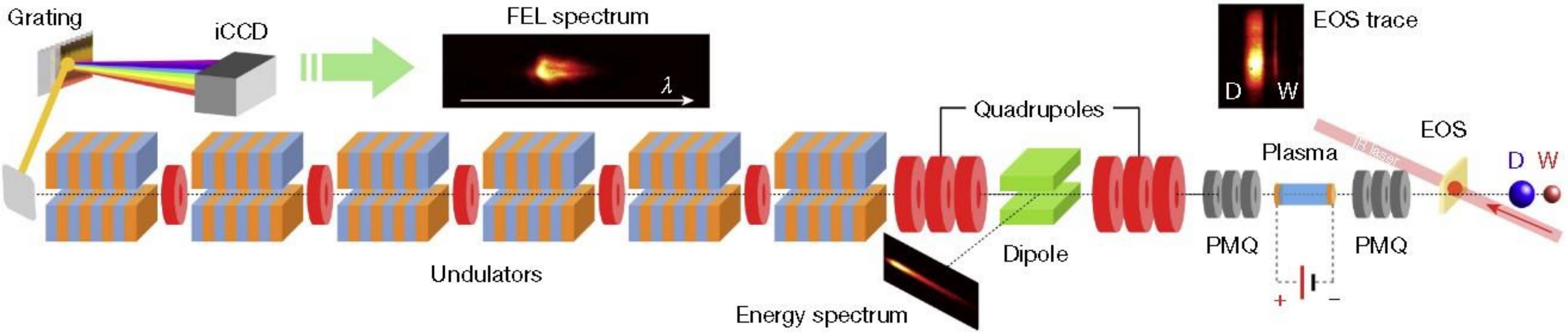
Beam configuration @ plasma entrance

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
t (fs)	200	30
E (MeV)	89.5	89.1
σ_E **(MeV)**	0.2	0.2
σ (μm)	20	14
$\varepsilon_{x,y}$ **(μm)**	2.5, 1.7	1.4, 1.2

FEL experiments



UNDs + 5 short EM quads:
Vertical focusing
Horizontal matching

Quads triplet:
6 m matching stage
$\beta_T \cong mm$->m

PMQs triplet:
Catches the beam
Removes high divergence

<u>FEL simulations</u> (3D time-dependent)

Set of 100 independent runs with GENESIS 1.3

- beam microscopic distribution randomly changed shot-to-shot
- jitters of beam macroscopic parameters included (10% on bunch charge, length, energy, energy spread and emittance)

FEL driven by PWFA

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

- ❖ Witness is completely characterized
- ❖ Jitter online monitored with Electro-Optical Sampling (EOS) diagnostics
- ❖ Imaging spectrometer with iCCD used for detection

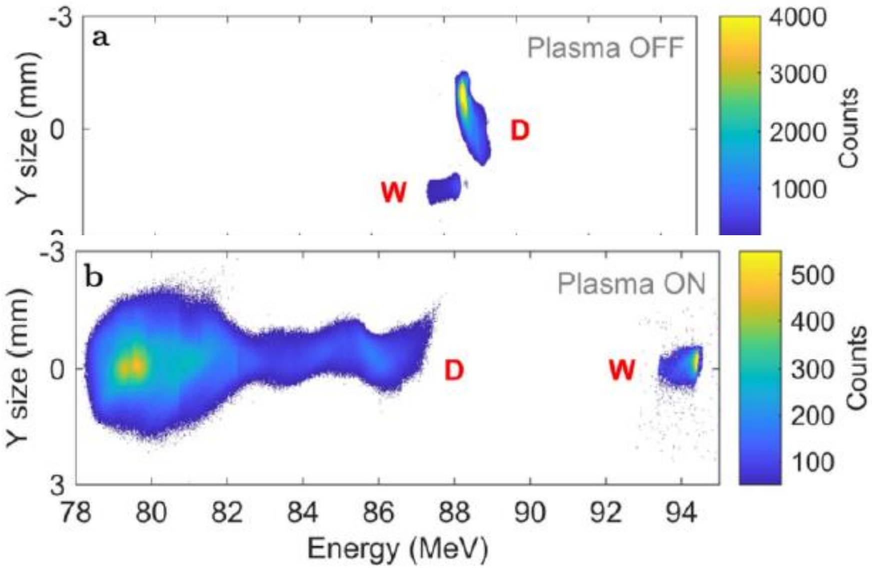
15 m FEL beamline

- L_u = 2.5 m (77 periods)
- λ_u = 2.8 cm
- K = 1.4

~200 MV/m @ $1.6 \times 10^{15} cm^{-3}$ plasma density

Witness @ FEL entrance

E (MeV)	94	**Q (pC)**	20
σ_E (MeV)	0.3	**t (fs)**	30
$\varepsilon_{x,y}$ (µm)	2.7,1.3	**$\sigma_{x,y}$ (µm)**	200



Seeded FEL driven by PWFA - seed laser

Photocathode Laser → Ti:Sa delivering ≈100 fs long pulses @10 Hz

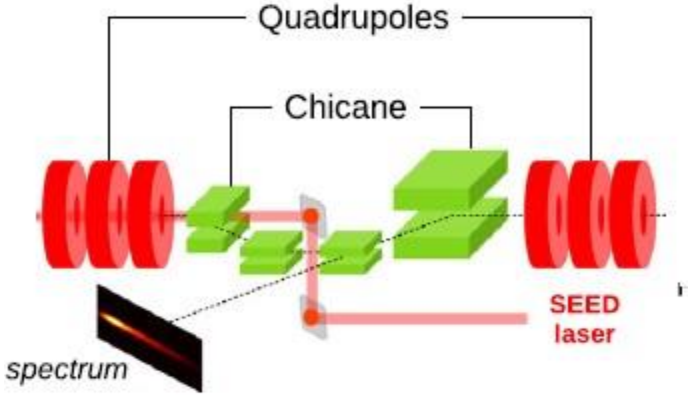
- tens of mJ converted to UV and sent on the photo-cathode to generate the driver and witness bunches;
- low energy (hundreds of nJ) line used both to drive the EOS diagnostics and as **seed laser**.
  - ✓ Naturally synchronized
  - ✓ Tunable energy (~10 nJ used)

Laser propagation and 1% laser energy jitters included in the simulations

Seed pulse	
λ (nm)	797 ± 3
BW σ_λ (nm)	7 ± 1
E_L (nJ)	24.2 ± 0.2
τ_L (fs, rms)	≈ 250
σ_L(μm)	> 500

Seeded FEL driven by PWFA - seeding stage

- A small magnetic chicane (4 dipoles in 5.75 m, R_{56}~-10 µm) displaces the beam (~2 mm kick)
- A 15 cm glass material stretches the pulse inducing a group-delay-dispersion of about 187 fs^2/mm
- Two motorized in-vacuum high-reflective mirrors for laser injection
- A motorized delay-line tunes the laser-electron delay.



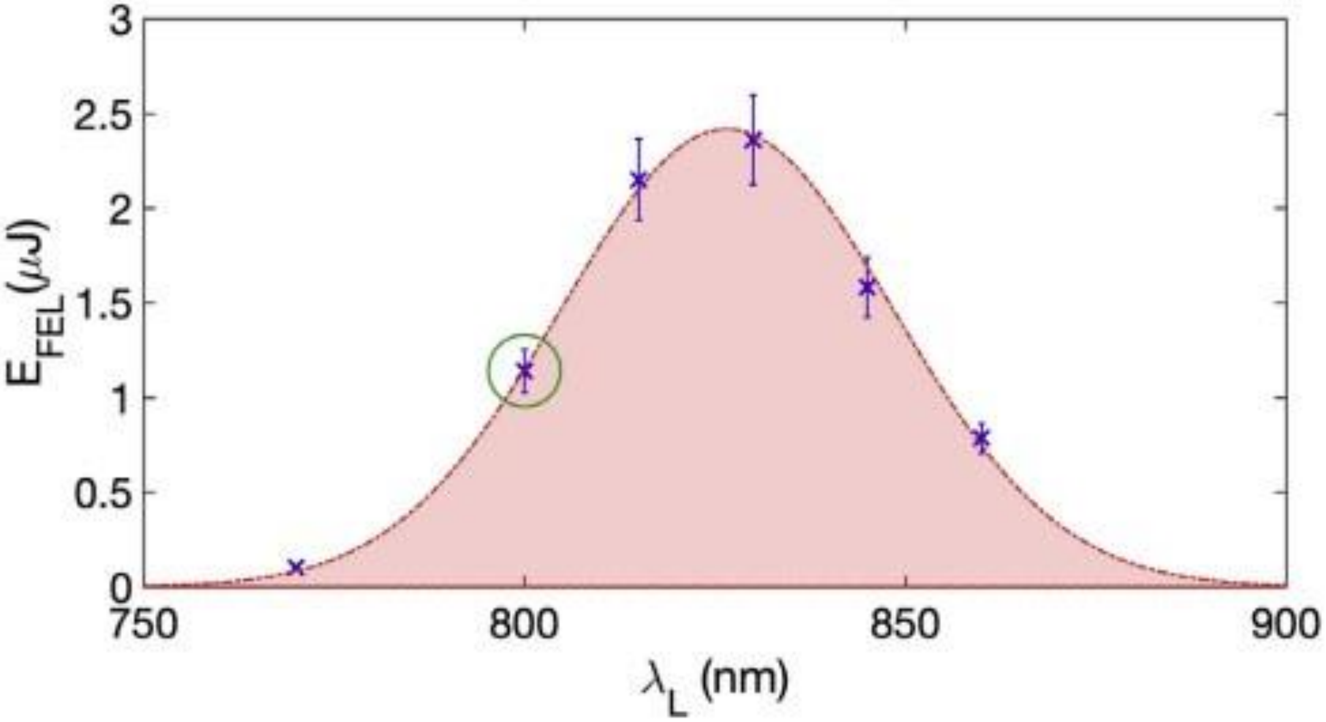
✓ Duration increased from ~100 fs to 600 fs (fwhm)
✓ Focused at the entrance of 1st undulator

Same detection setup used
ND filter @ 6th photodiode was changed for larger intensity signals

Seeded FEL driven by PWFA - lasing condition

UNDs tuned for FEL radiation @827 nm
→ wavelength shift

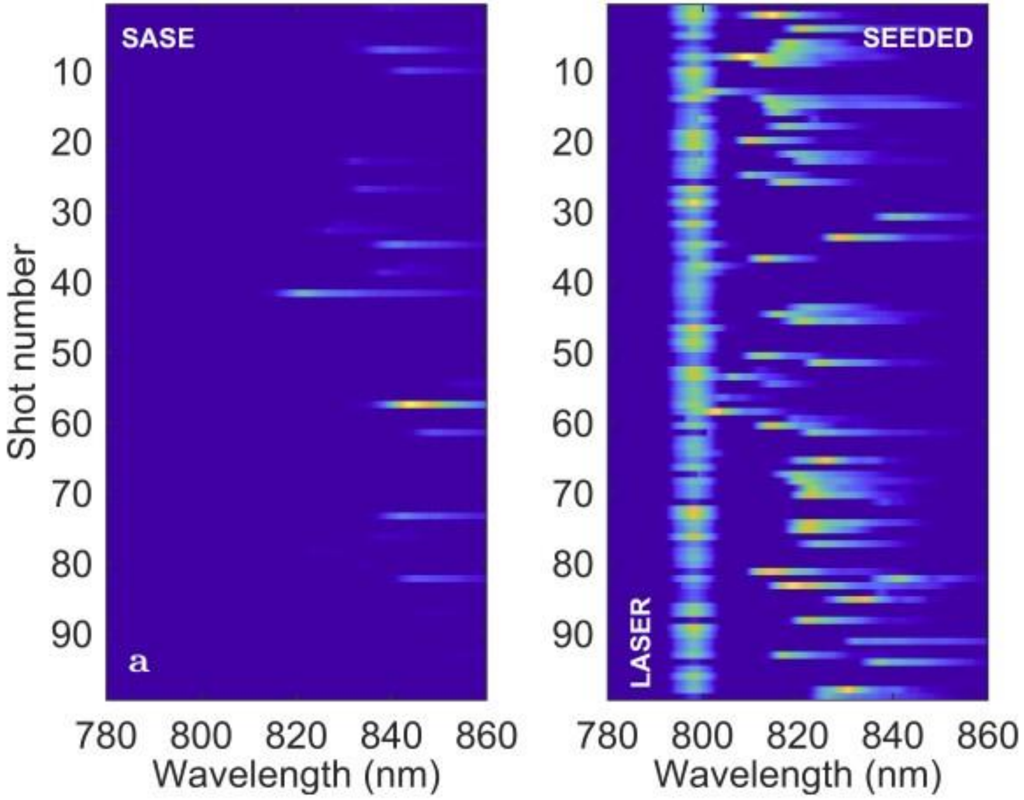
FEL energy gain with varying seed laser wavelength

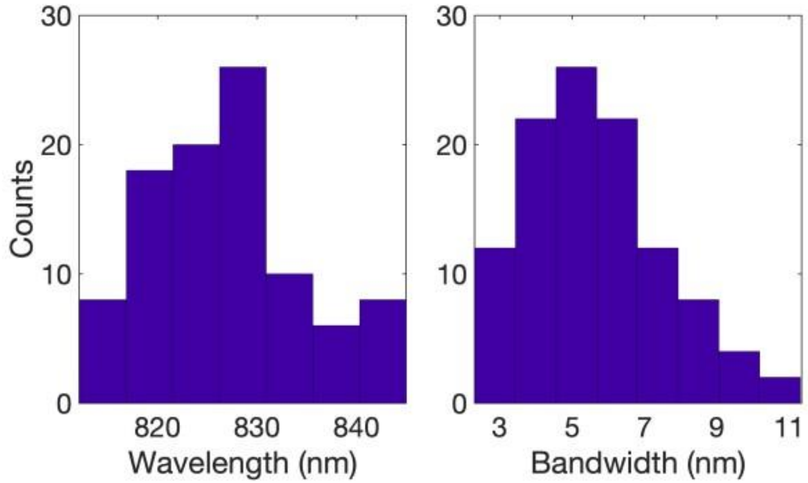


- The red dashed line shows the Gaussian fit of the theoretical data centered @826.6 nm;
- The green circle shows the prediction of the energy gain of the FEL seeded with our experimental parameters.

Seeded FEL driven by PWFA - performances

- FEL radiation output largely stabilized by the seed laser

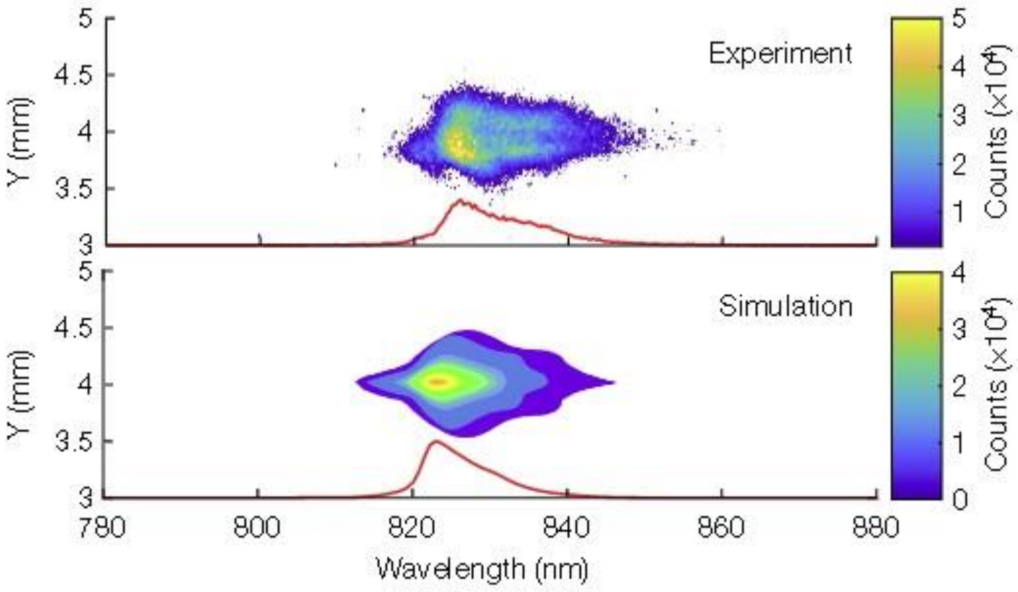




✓ Centered @827±7 nm with 4.5±1.2 nm BW

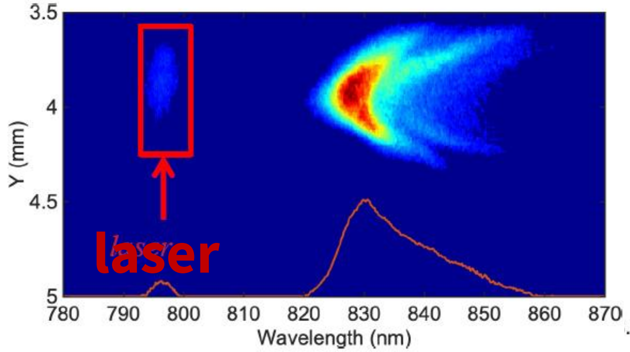
Seeded vs SASE FEL driven by PWFA

SASE



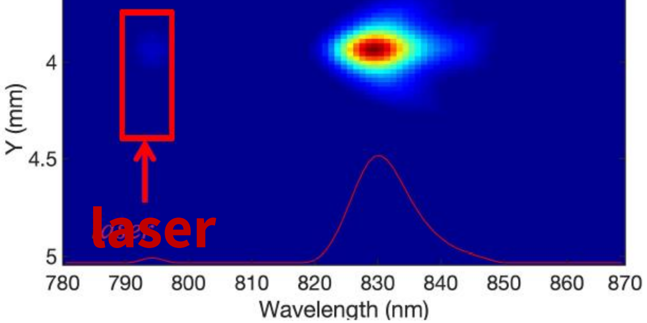
- ✓ $\lambda_r \approx 826 \pm 9$ nm, 4.7 ± 1.1 nm BW
- ✓ 27 ± 5 % shot-to-shot reproducibility

Seeded



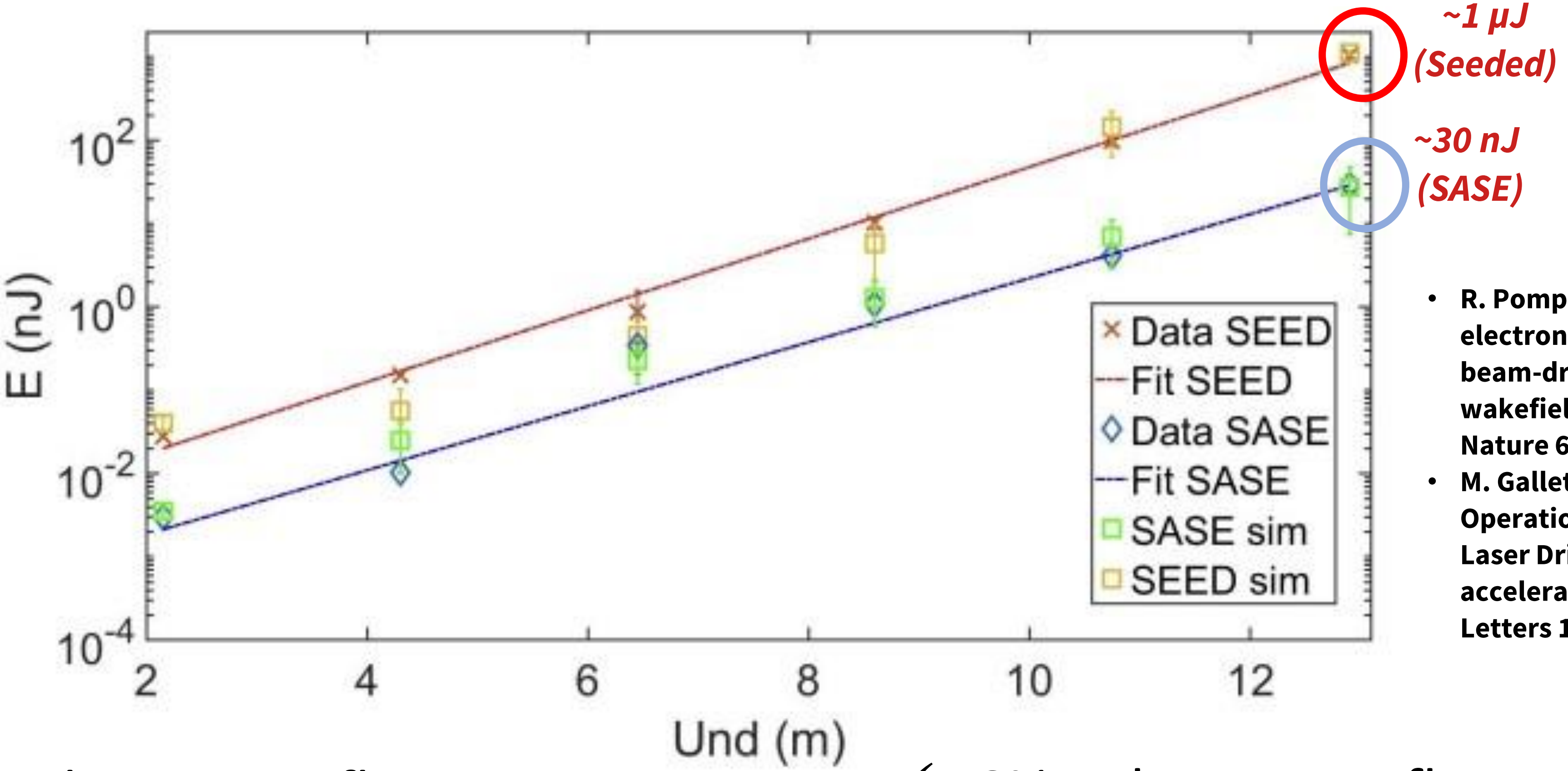
Experimental single-shot spectrum

Theoretical single-shot spectrum



- ✓ $\lambda_r \approx 827 \pm 7$ nm, 4.5 ± 1.2 nm BW
- ✓ 89 ± 3 % shot-to-shot reproducibility

Seeded vs SASE FEL driven by PWFA - exp. gain



~1 μJ (Seeded)

~30 nJ (SASE)

- **R. Pompili, et al., "Free-electron lasing with compact beam-driven plasma wakefield accelerator" Nature 605, 659–662 (2022).**
- **M. Galletti et al., "Stable Operation of a Free-Electron Laser Driven by a plasma accelerator" Physical Review Letters 129, 234801 (2022).**

✓ 17% pulse energy fluctuations (RMS) over the successful shots

✓ Gain length L_g = 1.1 ± 0.1 m

✓ 6% pulse energy fluctuations (RMS) over the successful shots

✓ Gain length L_g = 1.03 ± 0.1 m

Conclusions

- **<u>The two proof-of-principle FEL experiments done @SPARC_LAB show that PWFA is a viable solution for FELs</u>**

✓ Theoretical analysis and experimental results indicate that an off-resonant laser beam with respect to the FEL resonance can seed the FEL process

✓ The amplified and stabilized FEL radiation is centered at the undulator resonance due to the ultra-short bunch length

✓ The FEL pulses’ stability could only be further improved by reducing electron beam fluctuations related to the plasma formation and acceleration process

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

Thank you for your kind attention!

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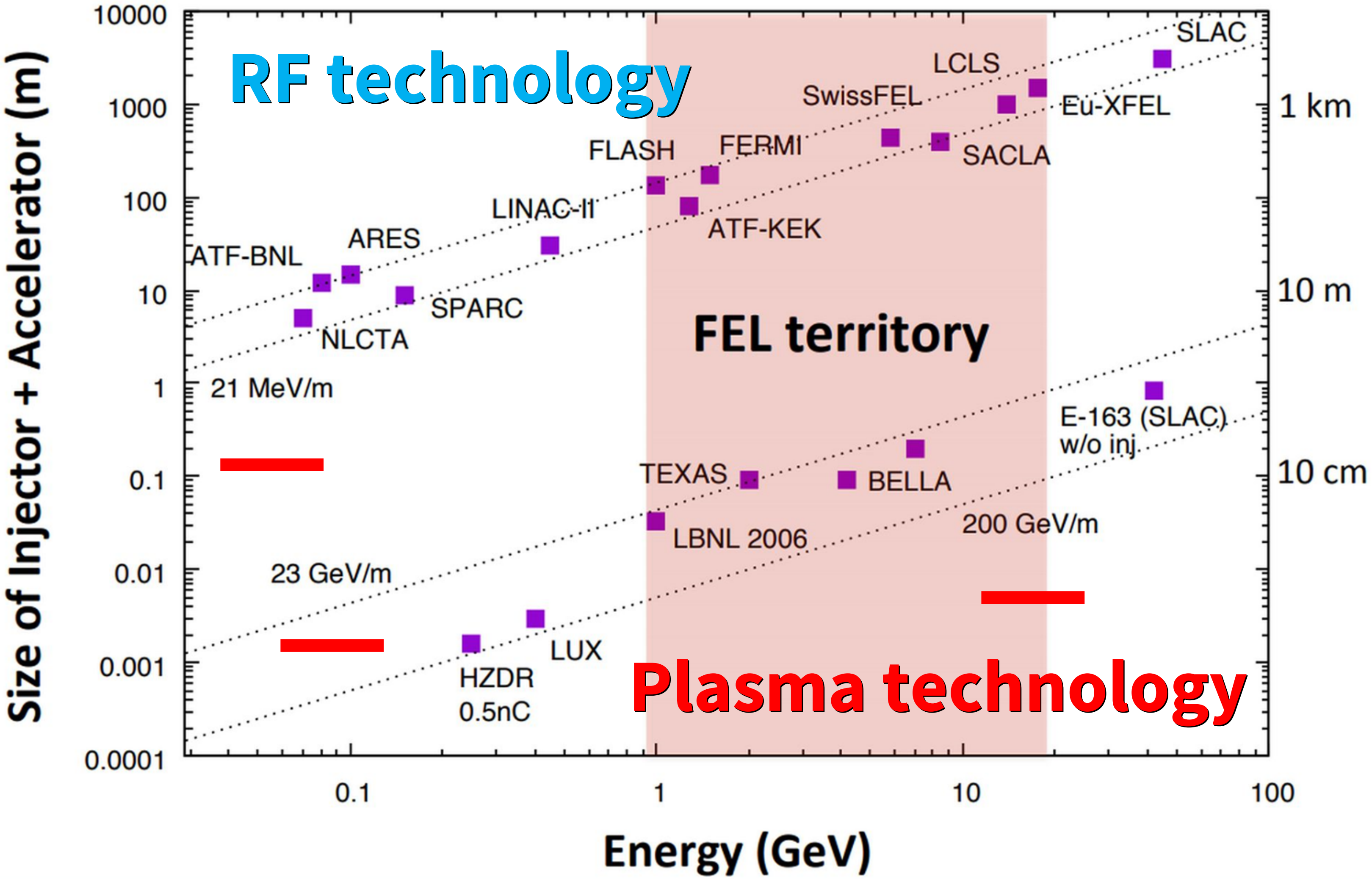
Standard vs Plasma accelerators

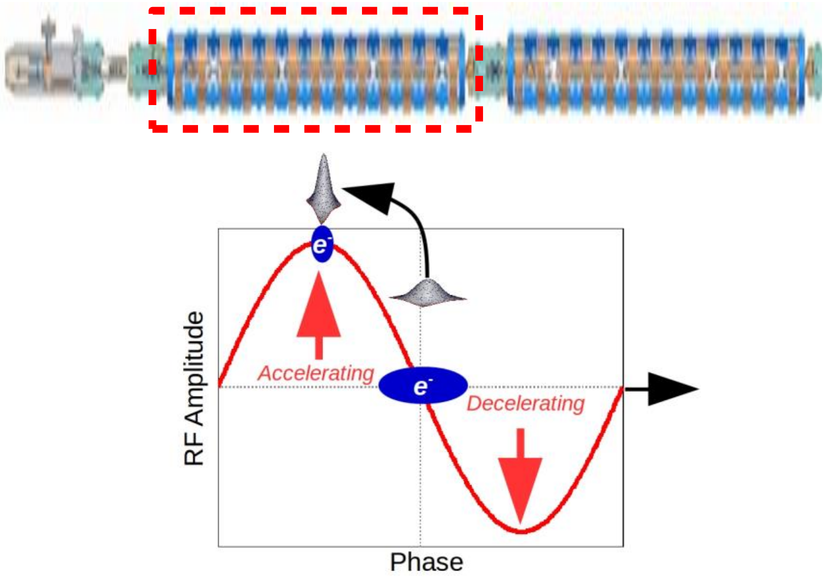


From R. Assmann (3rd EAAC Workshop, 2017)

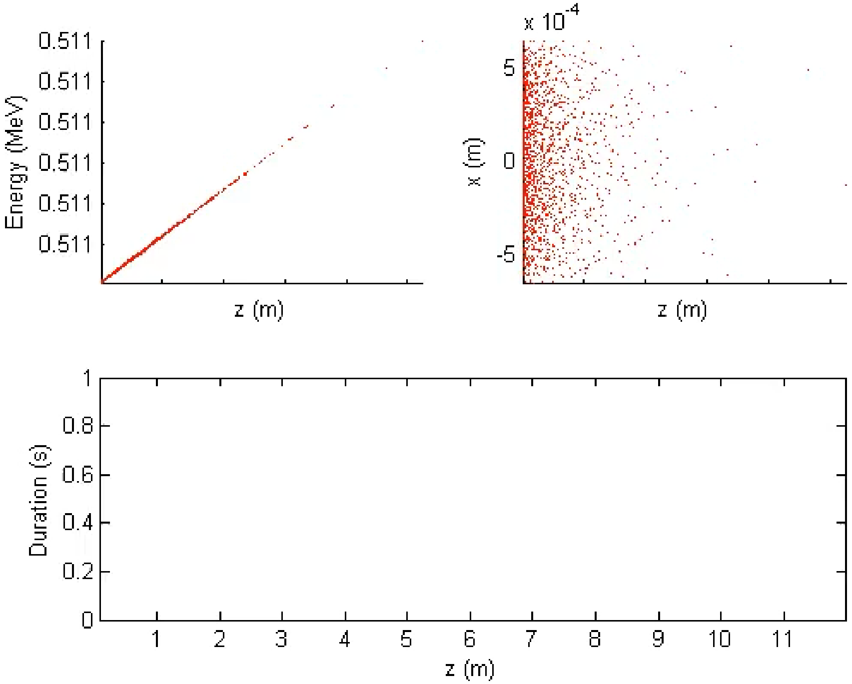
Velocity bunchng

Alternative technique to magnetic compression in chicanes / doglegs.

Velocity bunching compression

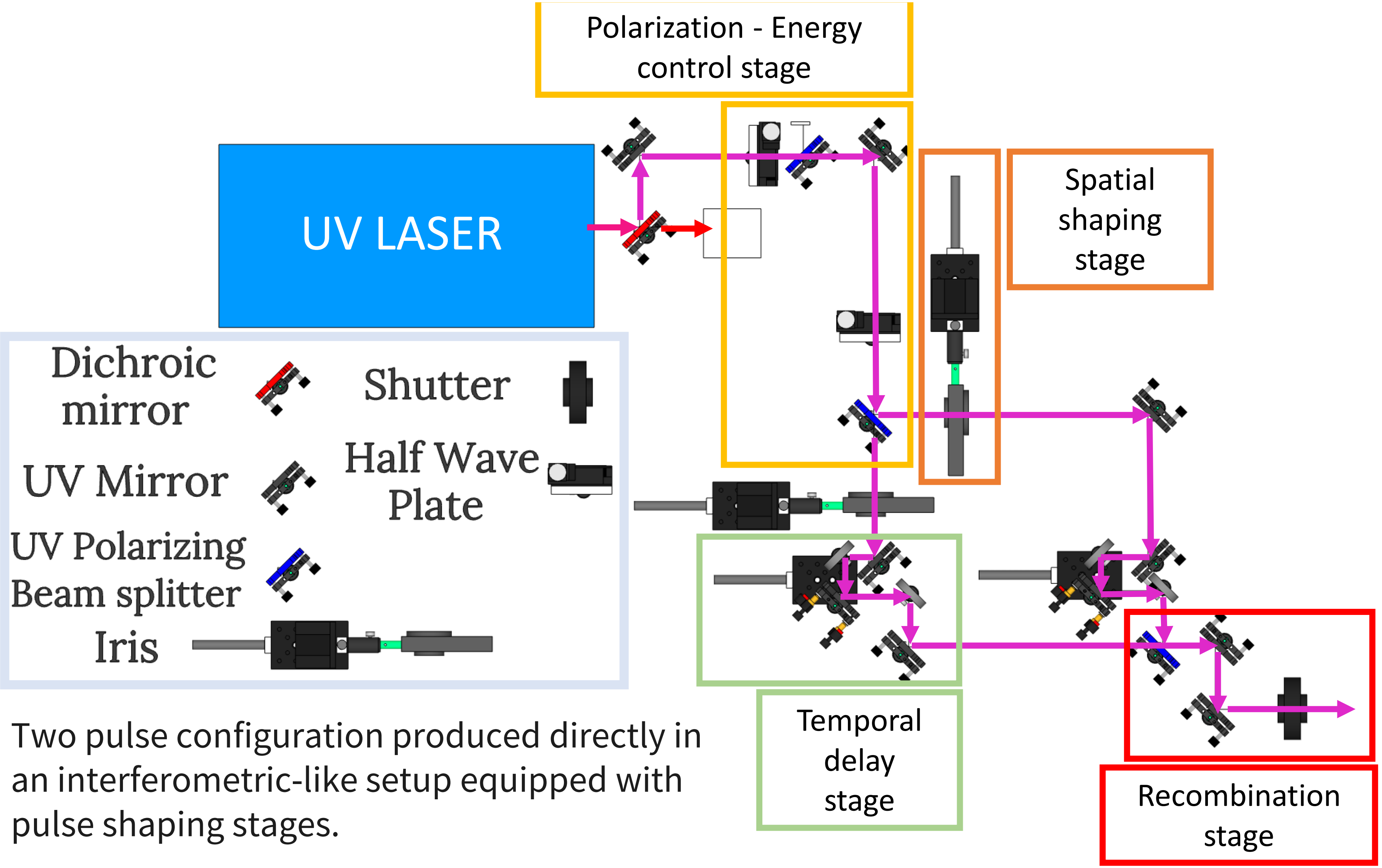


200+20 pC GPT simulation



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

Laser-comb technique

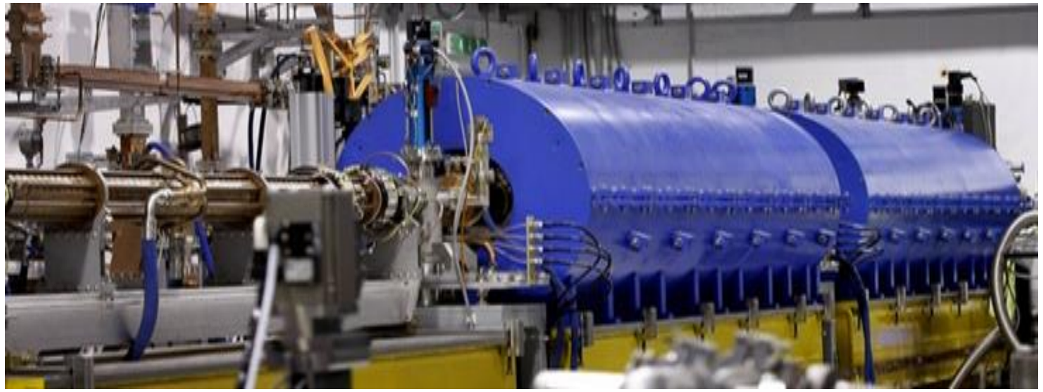


Two pulse configuration produced directly in an interferometric-like setup equipped with pulse shaping stages.

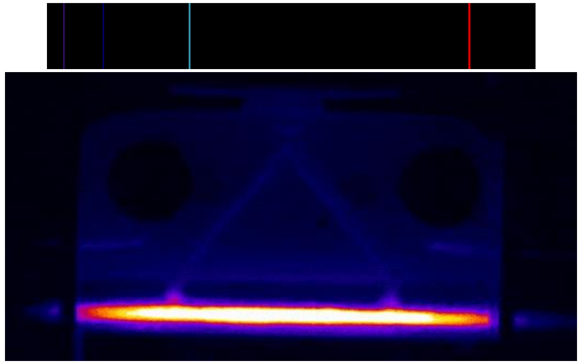
Plasma experience @SPARC

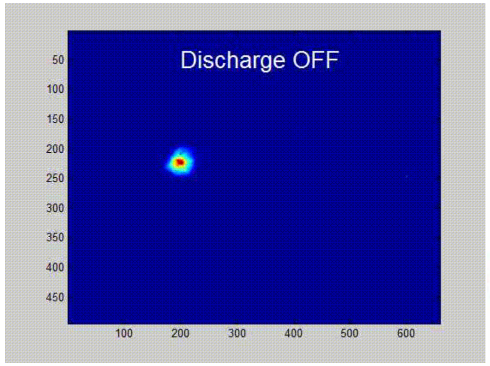
Activities with the high-brightness photo-injector

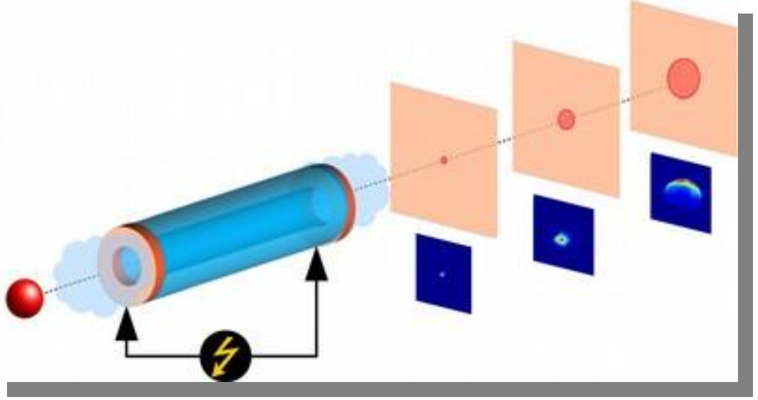
Plasma characterization

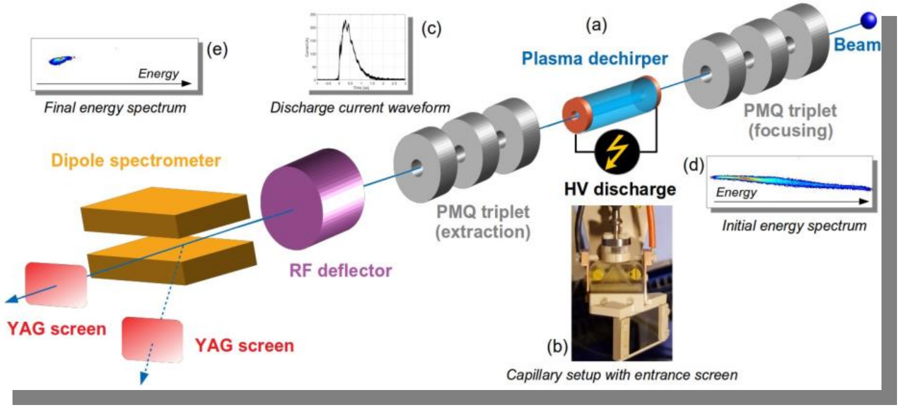


Biagioni A., et al., JINST 11.08 (2016): C08003.









Focusing with active-plasma lenses

Longitudinal phase-space manipulation

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

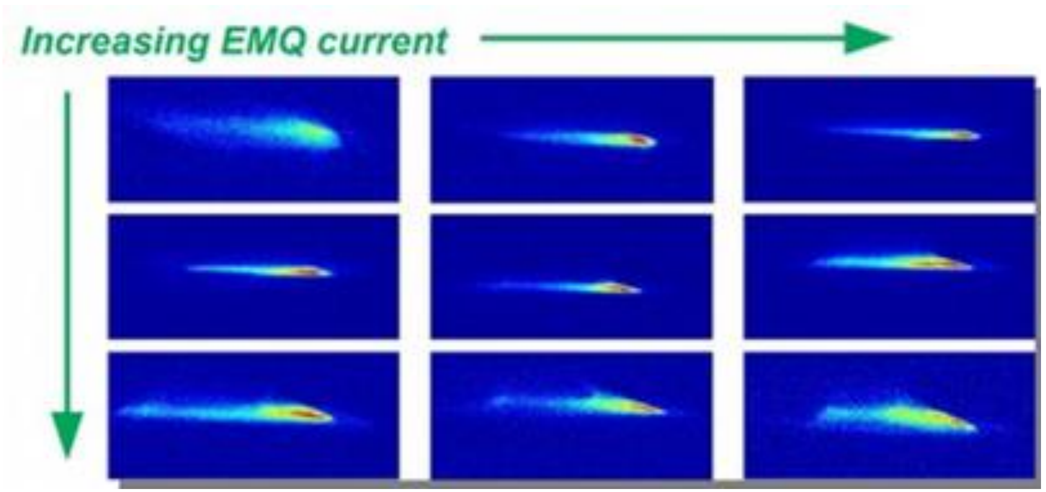
Pompili, R., et al., Phys. Rev. Lett. 121.17 (2018): 174801.
Pompili, R., et al., Applied Physics Letters 110.10 (2017): 104101.

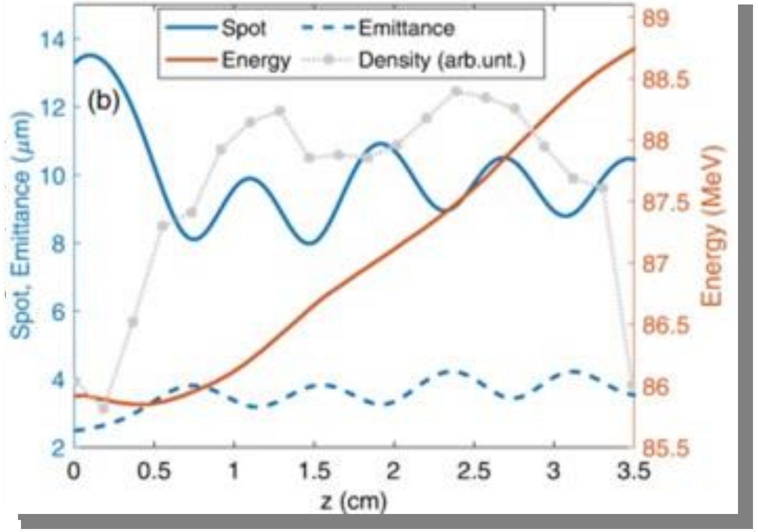
First emittance measurements in PWFA

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.

Jitters and stabilization

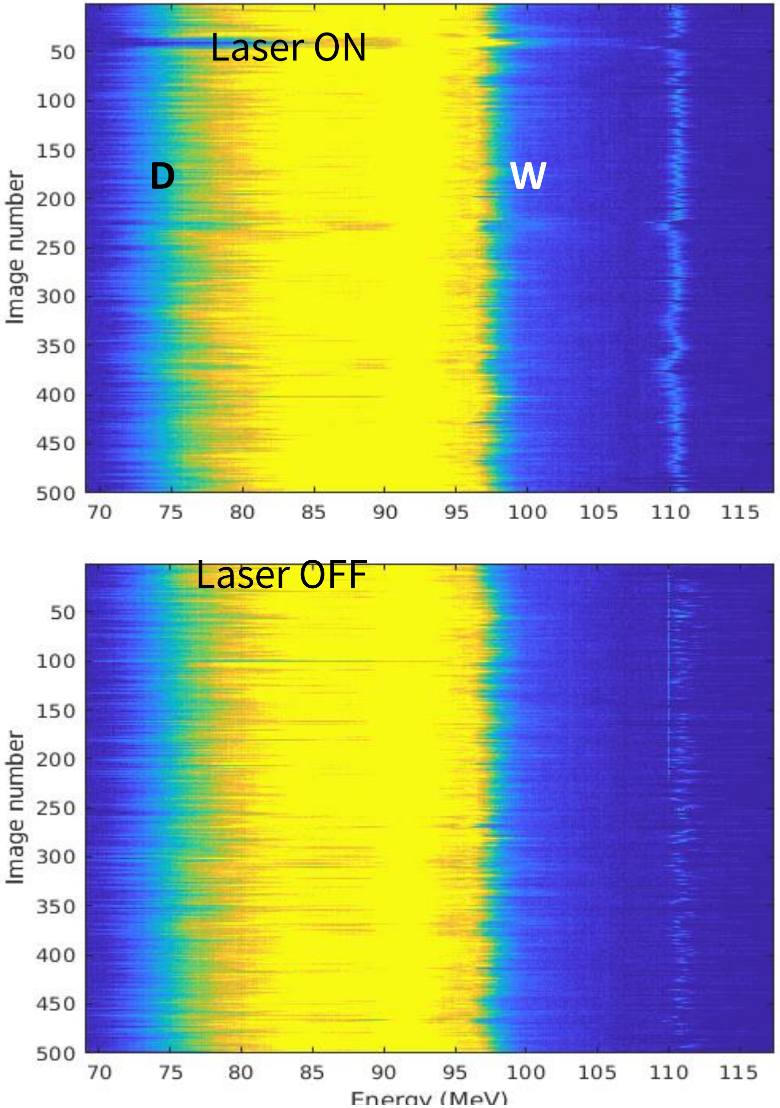
Two main sources of jitters

- Driver - witness separation:

- Plasma density fluctuations

  limited by RF sync. in a beam-driven plasma

To reduce the 2nd source, we pre-ionize the Hydrogen gas with an external laser (~100 μJ, 2mm diameter)



Beam transport @ the FEL entrance

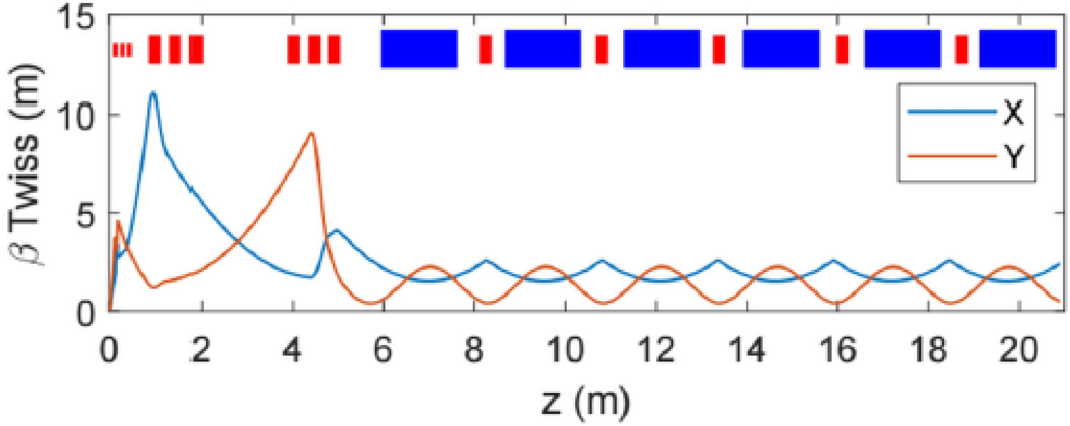
1. PMQs triplet catches the beam and removes the high divergence

2. The 6 m FODO (6 e.m. quads) stage sets the required Twiss parameters to optimize the FEL performance

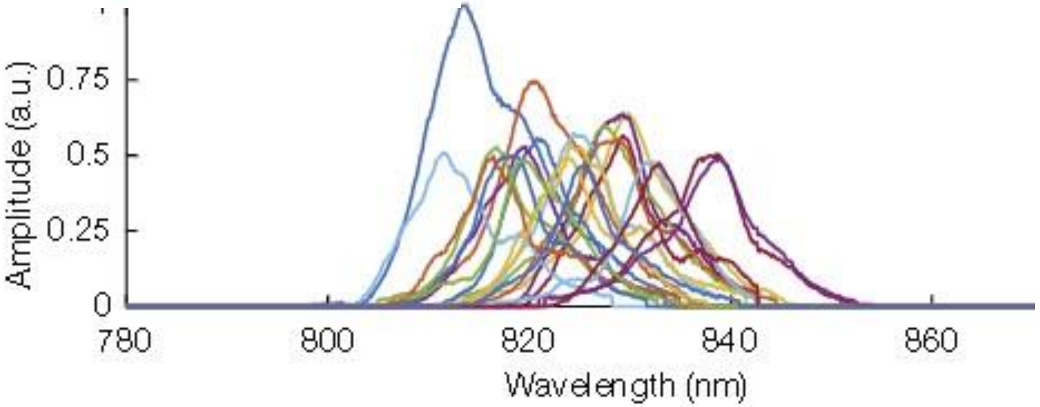
$$\beta_T \cong mm \ @ \ plasma\ exit \Rightarrow \beta_T \cong m \ @ \ FEL\ entrance$$

3. Low energy beams → UNDs are transport elements (vertical focusing)

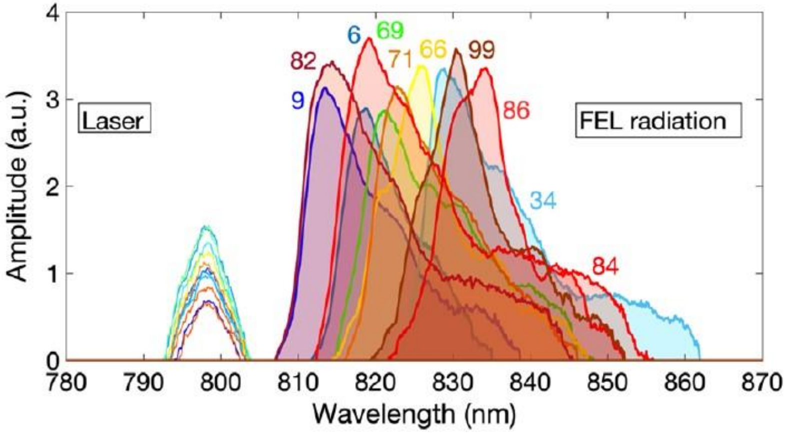
4. 5 short e.m. quads allow horizontal matching, ensuring optimal transort



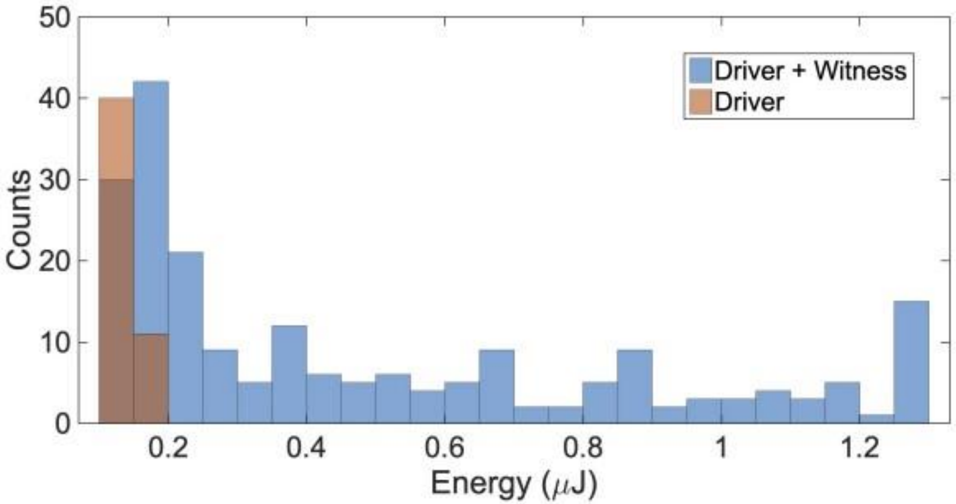
SASE vs Seeded FEL driven by PWFA



	SASE	Seeded
Shot-to-shot reproducibility	30%	90%
Pulse energy fluctuations	17%	6%
Pulse energy	30 nJ	1.1 µJ
Final energy fluctuations	100%	3x less
Gain length (±0.1 m)	1.1	1.03



Clear signals, reproducible day by day



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

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

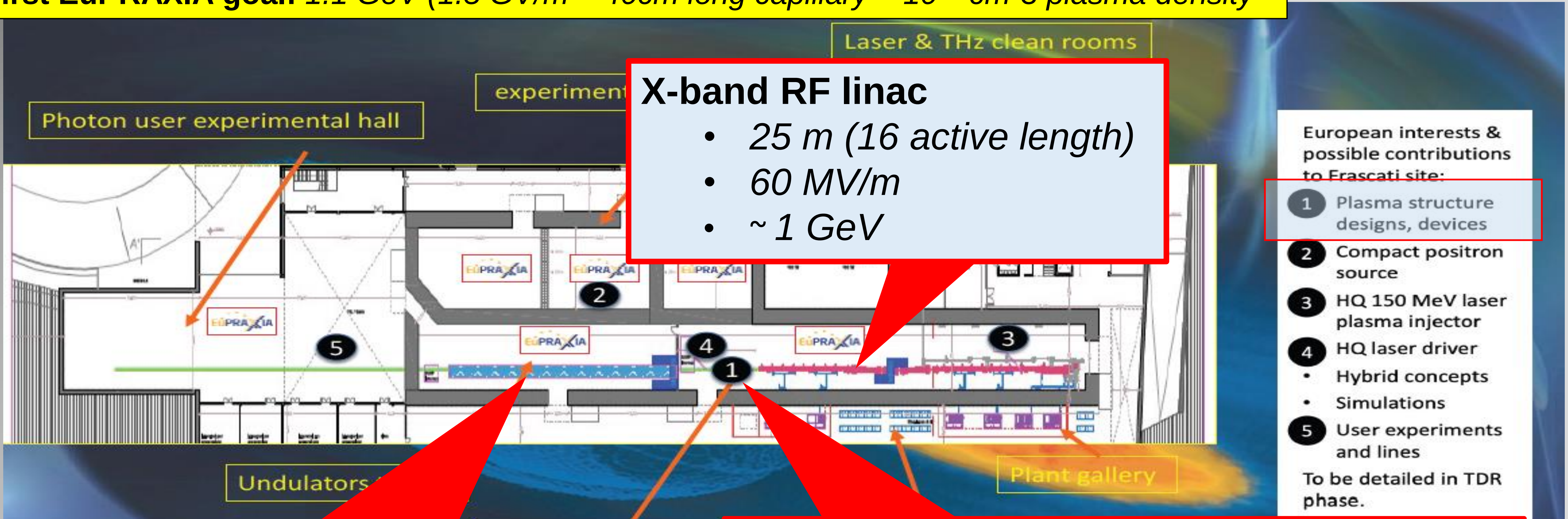
PLASMA stage	Witness
E(GeV)	1
I_p(kA)	2.6
σ_E (MeV)	0.7
$\epsilon_{x,y}$ (µm)	0.4

30 m FEL beamline

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

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

First EuPRAXIA goal: *1.1 GeV (1.5 GV/m – 40cm long capillary – 10^{16} cm-3 plasma density*



European interests & possible contributions to Frascati site:

1. Plasma structure designs, devices
2. Compact positron source
3. HQ 150 MeV laser plasma injector
4. HQ laser driver
   - Hybrid concepts
   - Simulations
5. User experiments and lines

To be detailed in TDR phase.

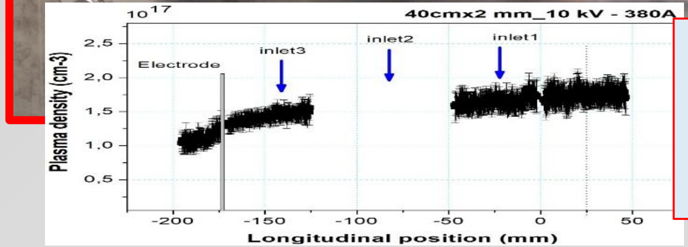
X-band RF linac

- *25 m (16 active length)*
- *60 MV/m*
- *~ 1 GeV*

30 m FEL beamline

- $\lambda_u = 1.5$ cm
- $K = 1.1$
- $L_g = 0.4$ m
- $L_s = 20$ m

100 Hz repetition rate



- **40cm x 2mm long capillary**
- **Rep rate at 10 Hz**
- **10 kV – 380 A (10^{17} cm^{-3})**
- **6 inlets of 1 mm in diameter**