I.FAST 1st Annual Meeting
CERN, Geneva, Switzerland

First lasing of a FEL in SASE and seeded regimes with a compact beam-driven plasma accelerator

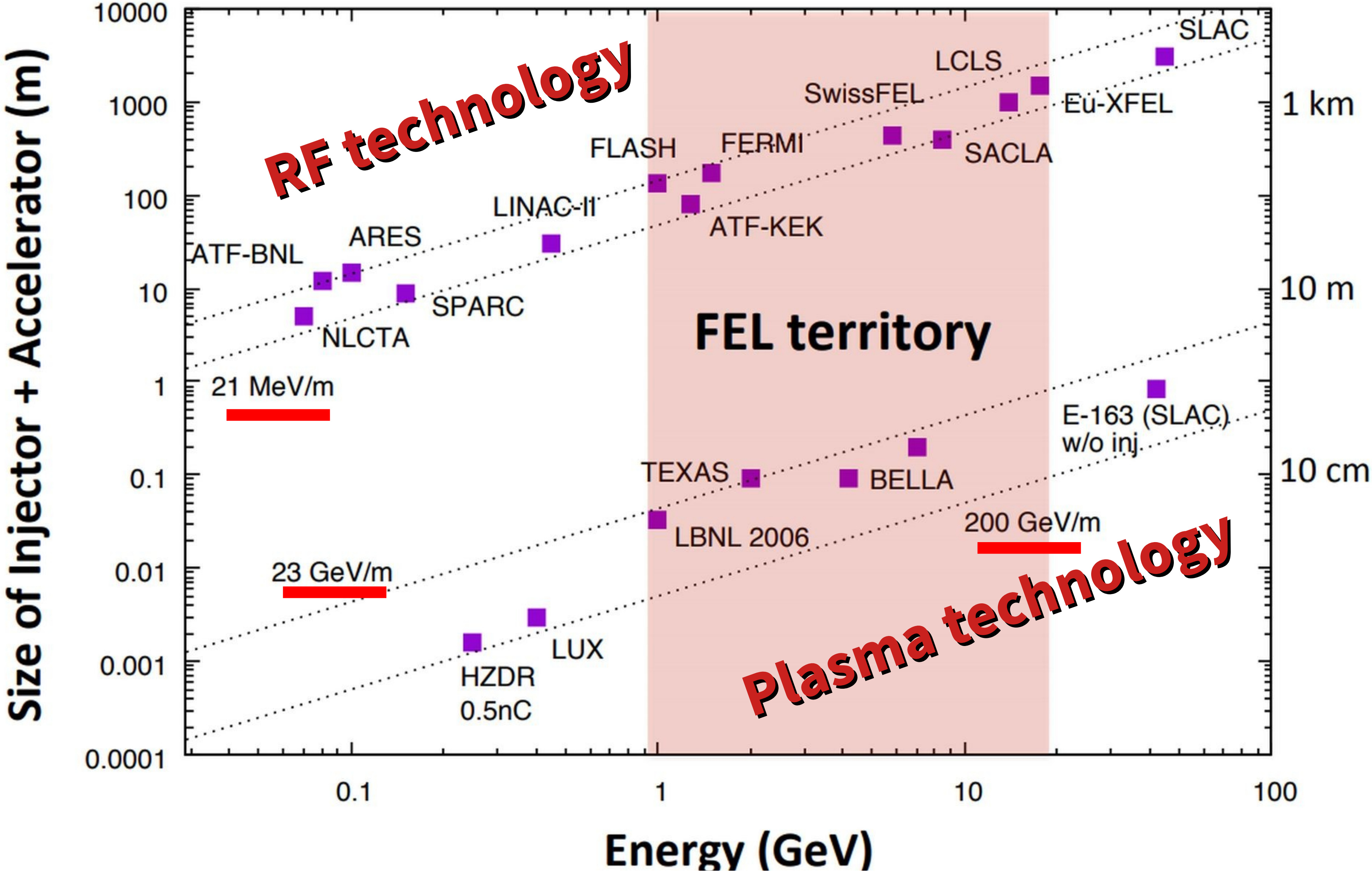
R. Pompili (LNF-INFN)
riccardo.pompili@lnf.infn.it

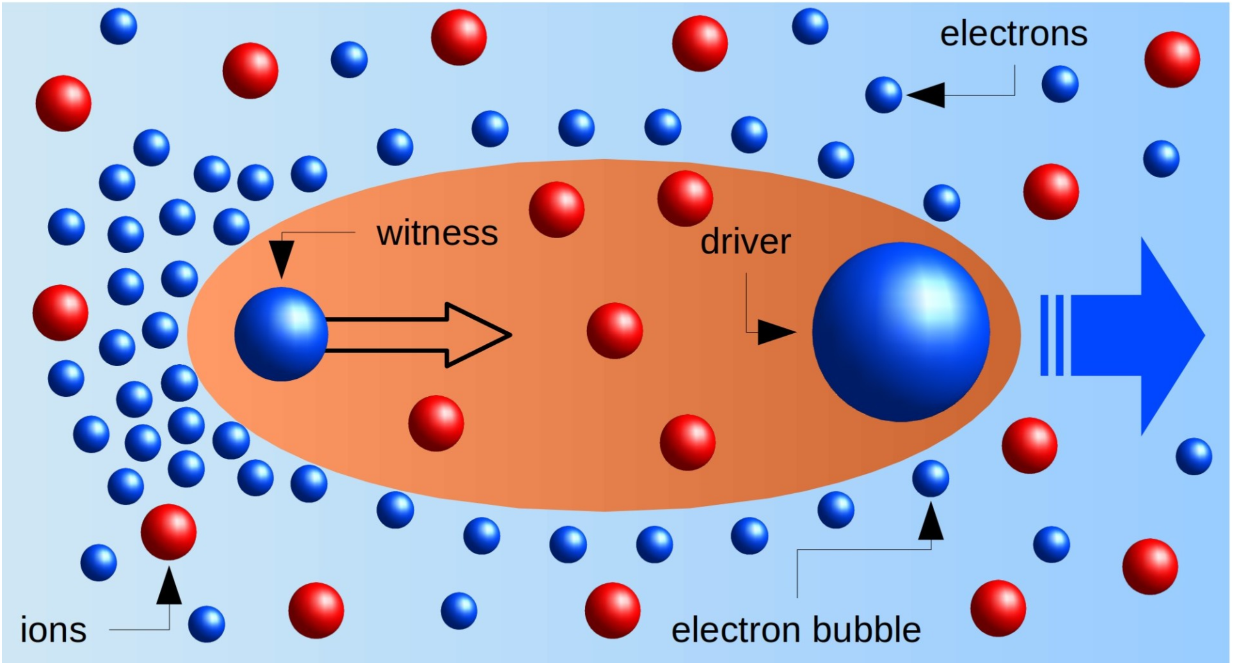
On behalf of the SPARC_LAB collaboration

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Standard vs plasma accelerators

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

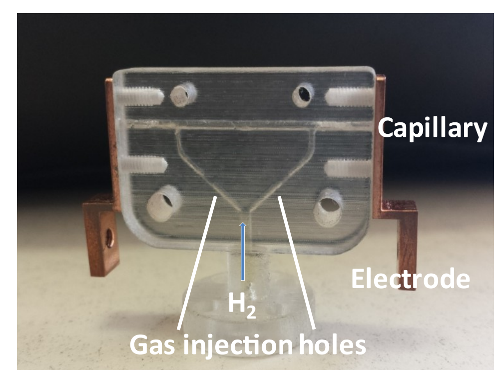




The **driver** creates the positive sphere (or ***bubble***). It can be a
- *particle bunch (PWFA)*
- *laser pulse (LWFA)*

The **witness** can be
- *Self-injected*
- *Externally injected*

$$E_0 = \frac{m_e c \omega_p}{e} \simeq 96\sqrt{n_0(cm^{-3})} \rightarrow E_0 \approx 10\frac{GV}{m} @ n_0 = 10^{16}\,cm^{-3}$$

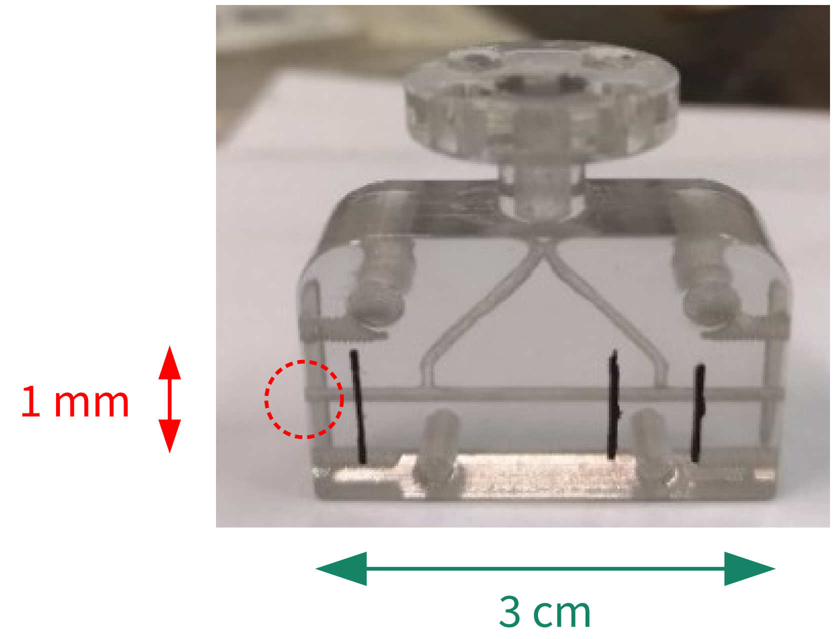


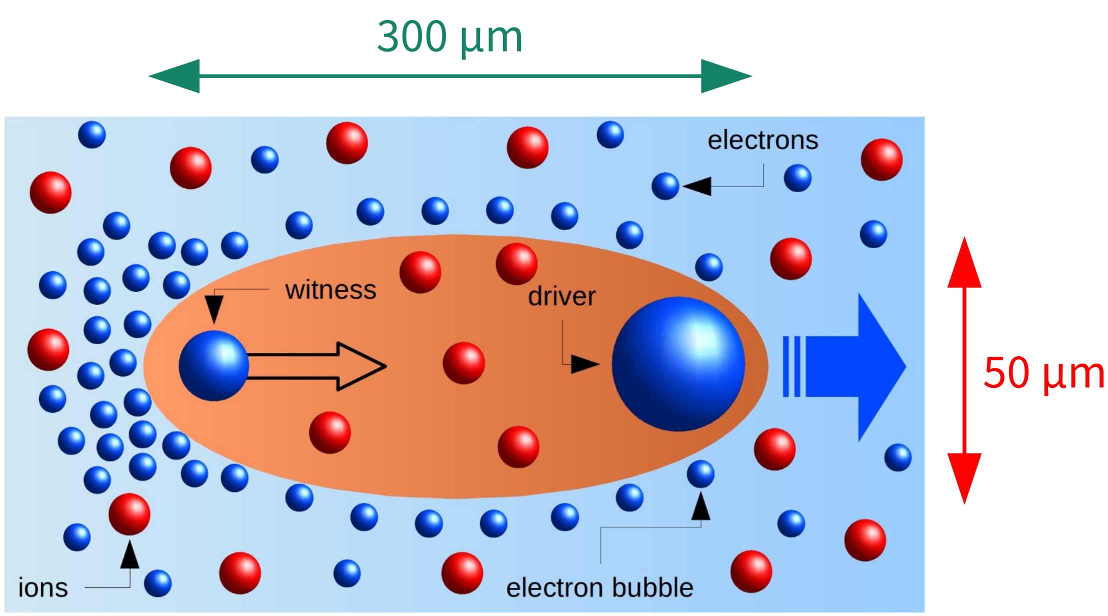
Typical sizes

The most critical part of a plasma-based accelerator is given by its typical size

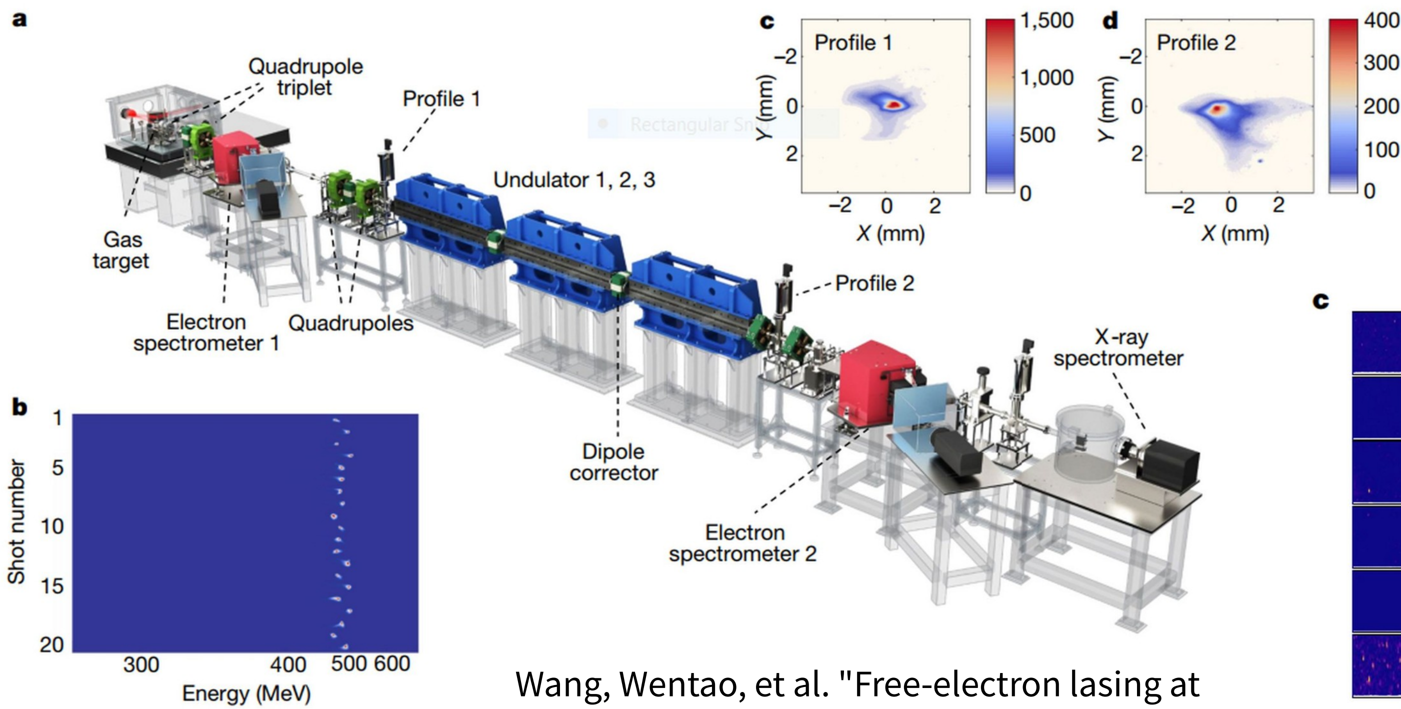
The bubble is tiny (tens/hundreds of micron scale)

The witness beam must be even smaller!!!

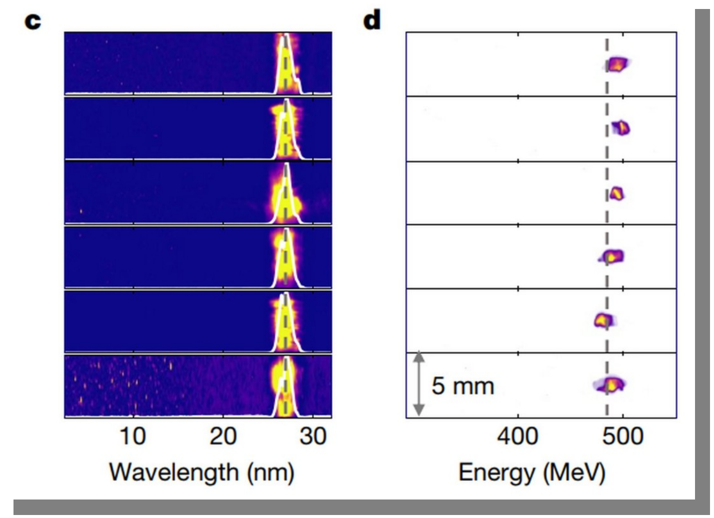




First results of FEL lasing from LWFA



Wang, Wentao, et al. "Free-electron lasing at 27 nanometres based on a laser wakefield accelerator." Nature 595.7868 (2021): 516-520.



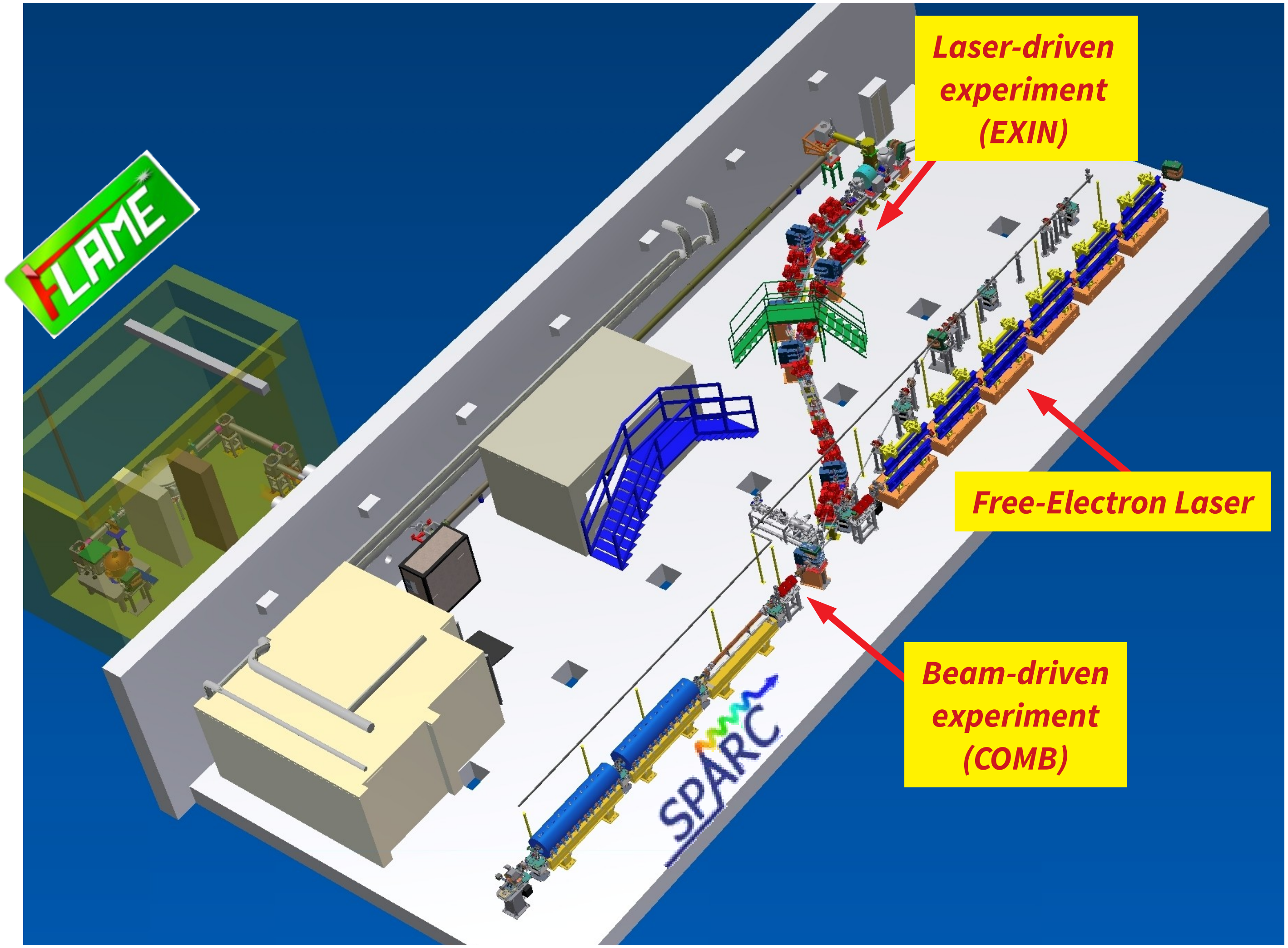
Observation of FEL radiation @ 27 nm using LWFA

Electron beam generated from a 200 TW (I~4x10^{18} W/cm^2) laser focused on a gas-jet

Peak energy ~ 490 MeV, 0.5% spread (measured), emittance 0.5 um (estimated)

Radiation energy from 0.5 to 150 nJ

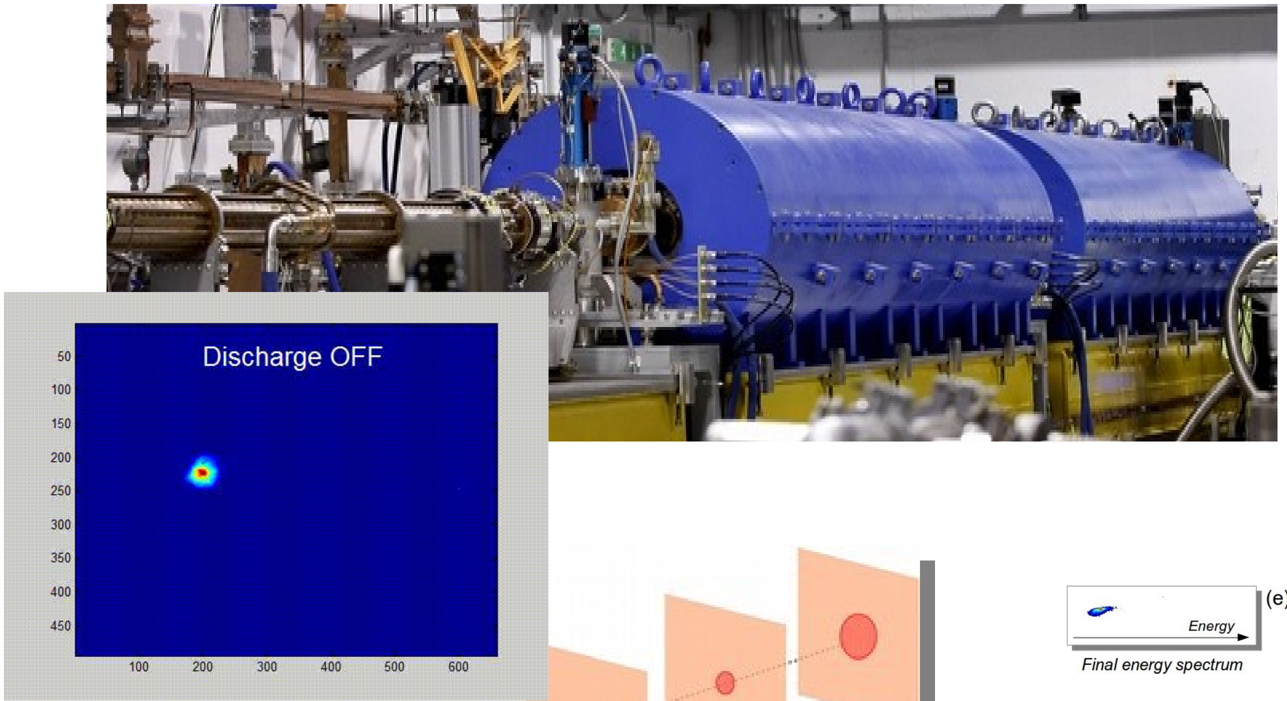
SPARC_LAB facility

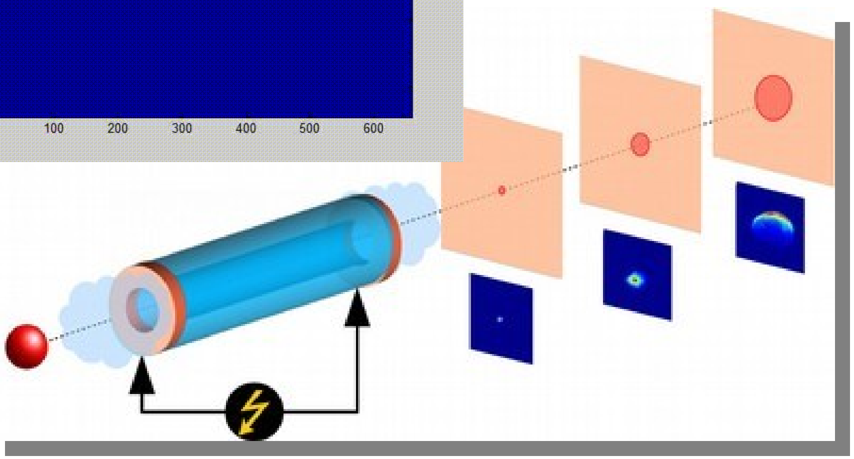


Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

Experience with plasma @ SPARC

Activities with the high-brightness SPARC photo-injector

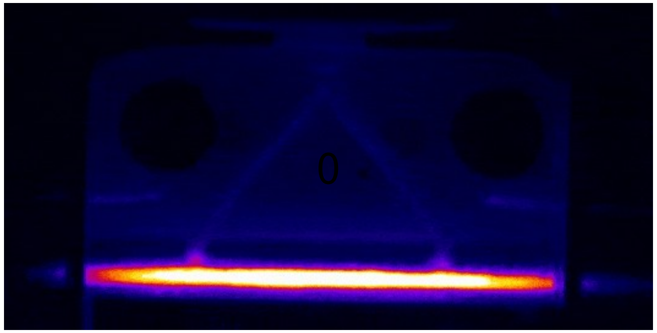




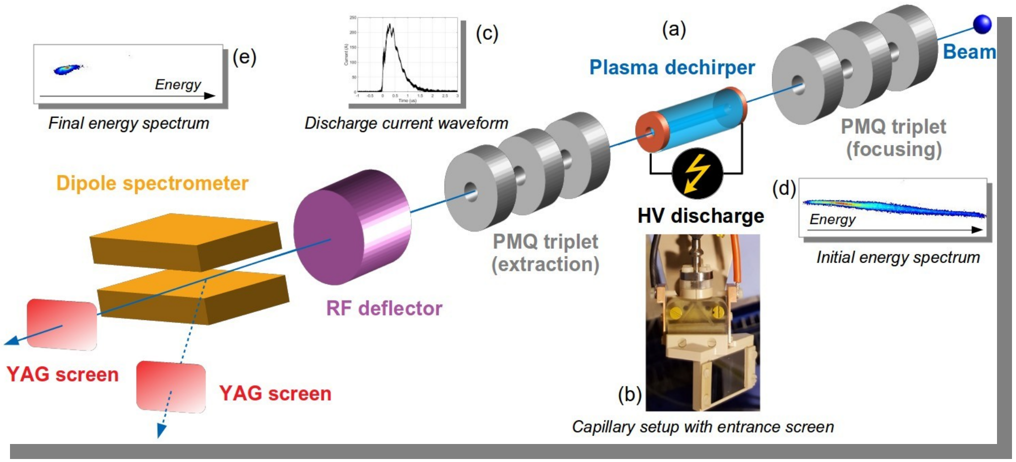
Focusing with active-plasma lenses

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

Plasma characterization



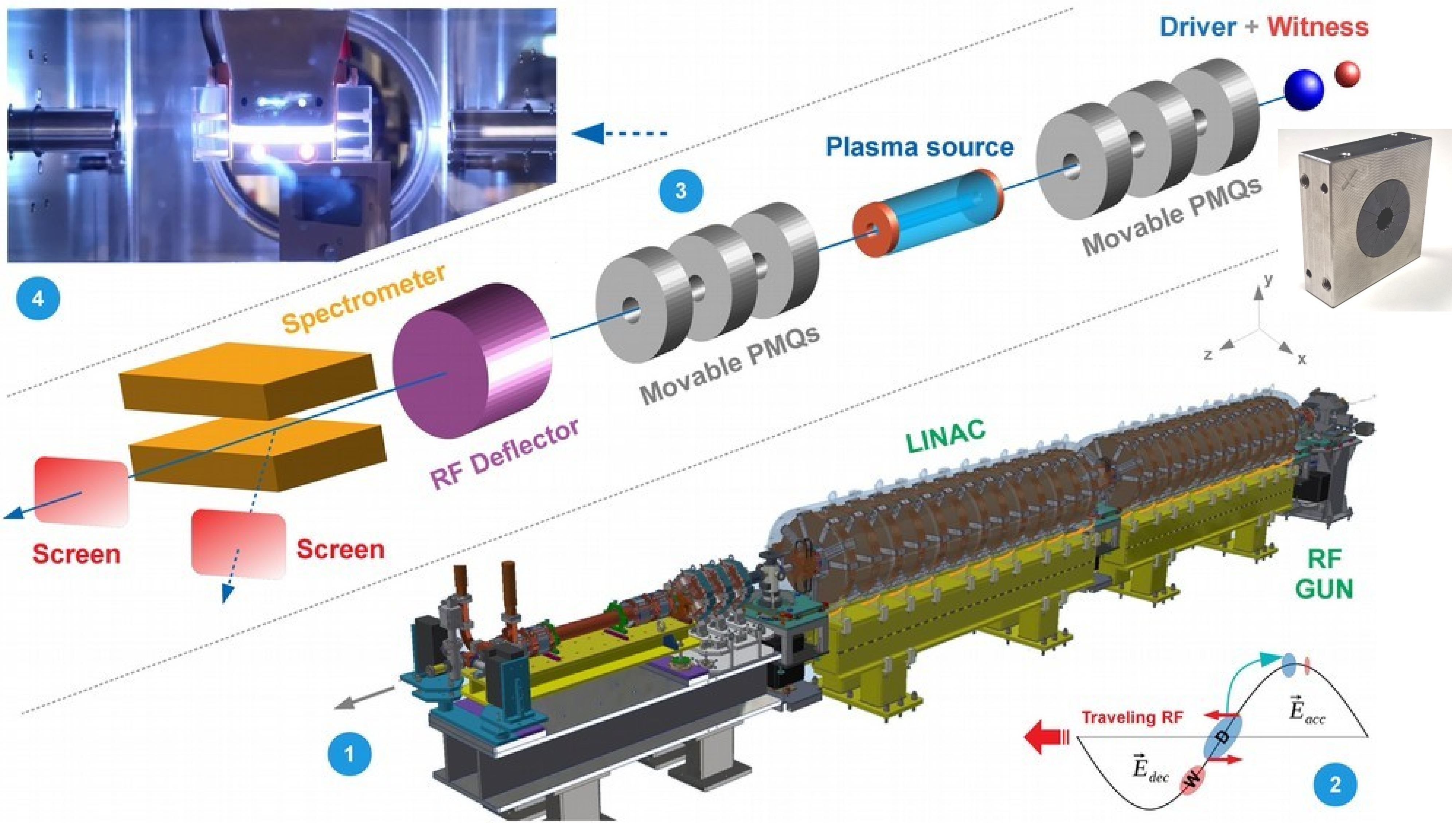
Biagioni, A., et al., Journal of Instrumentation 11.08 (2016): C08003.



Longitudinal phase-space manipulation

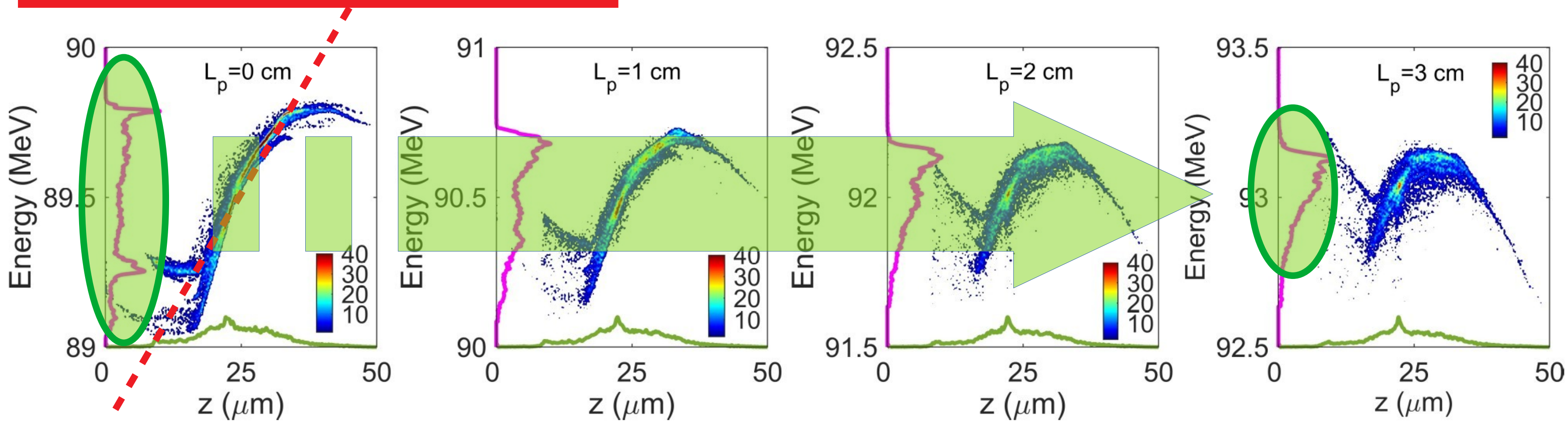
V. Shpakov et al. Phys. Rev. Lett. 122, 114801 (2019)

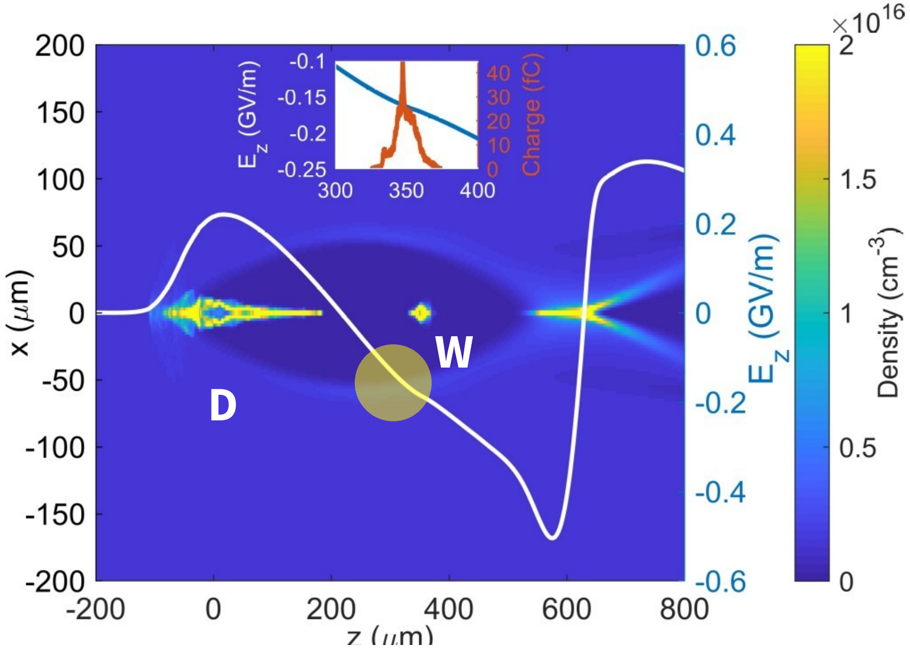
Plasma acceleration experiment

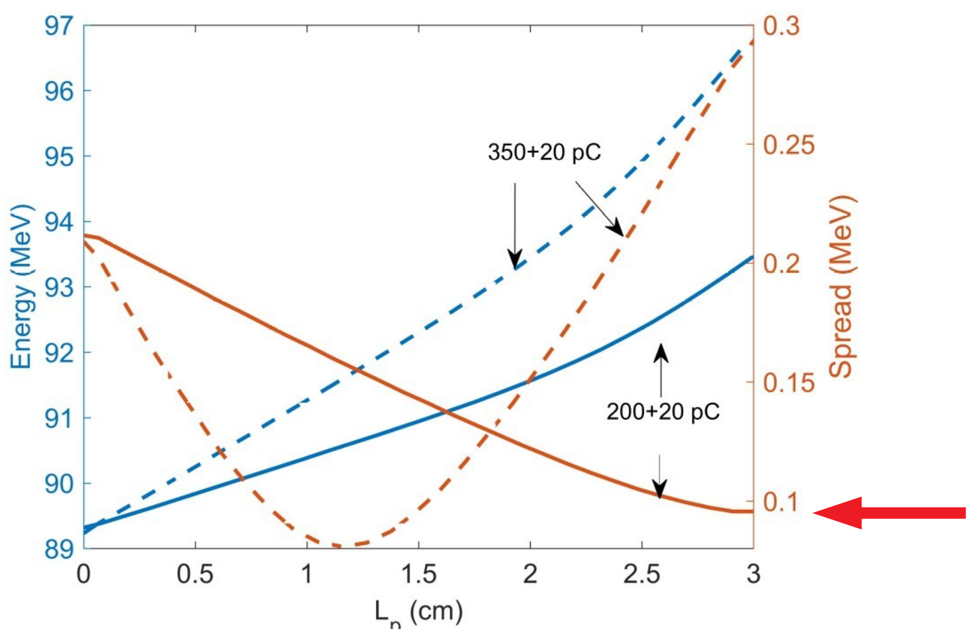


Assisted beam-loading technique

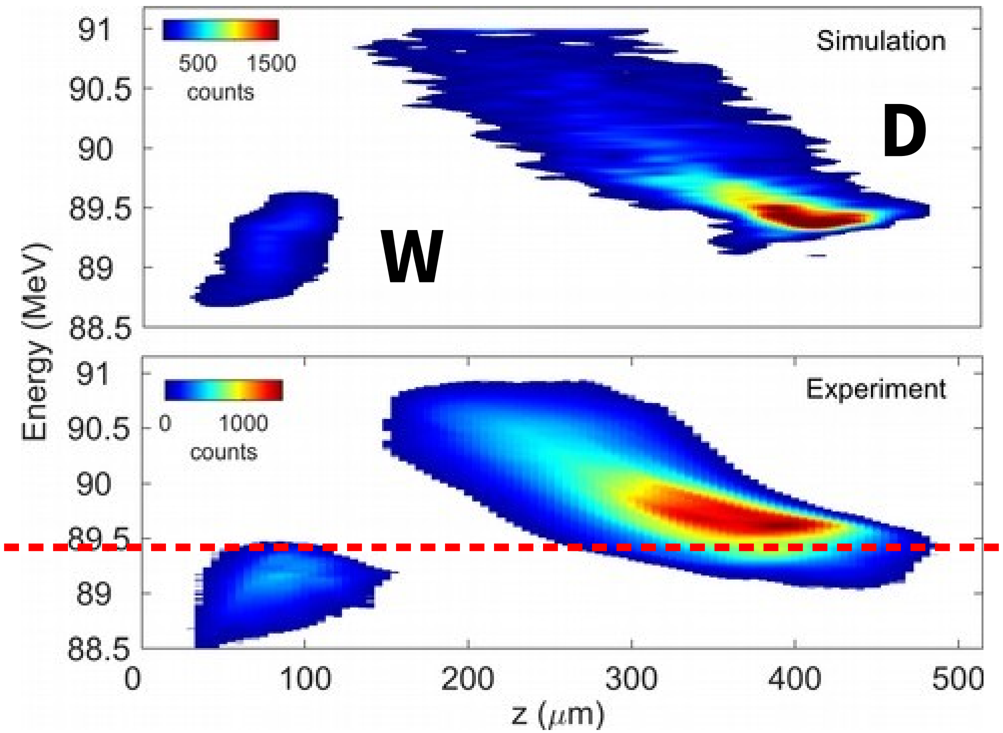
Pre-chirp to compensate wakefield slope







Beam configuration



Nearly the same energy with plasma OFF

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

200 pC driver (charge increased up to 350 pC) followed by witness bunch (20 pC)

Ultra-short durations (200 fs + 30 fs)

Separation approximately equal to ¾ of the plasma wavelength (~1 ps)

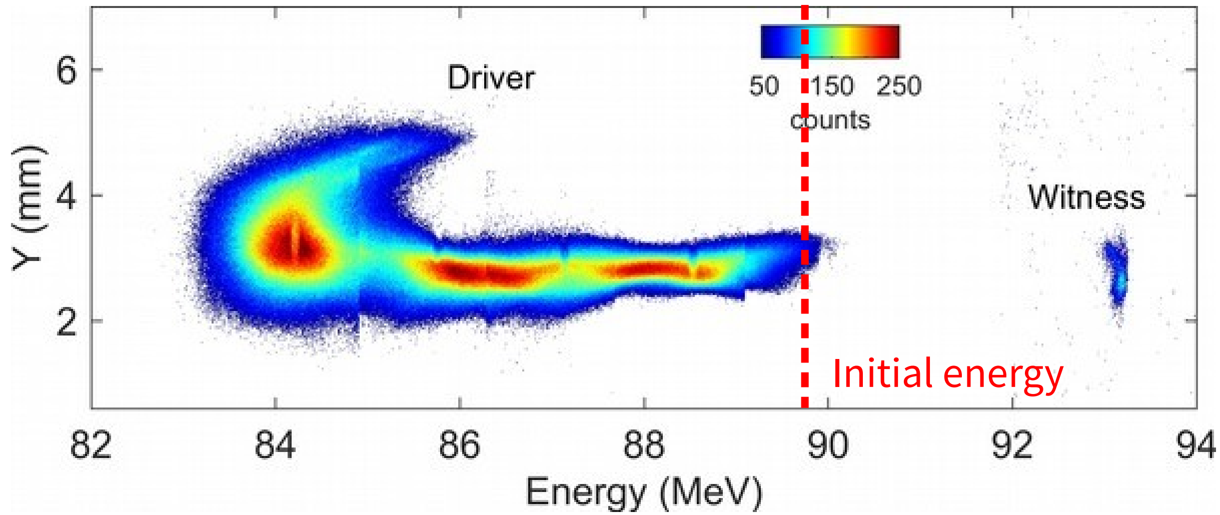
4 MeV acceleration in 3 cm plasma with 200 pC driver

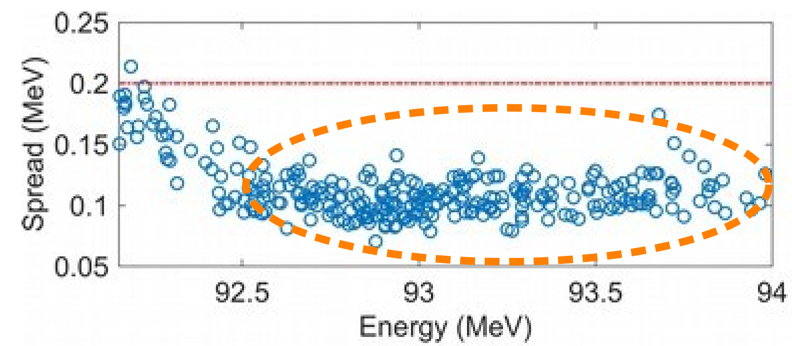
~133 MV/m accelerating gradient

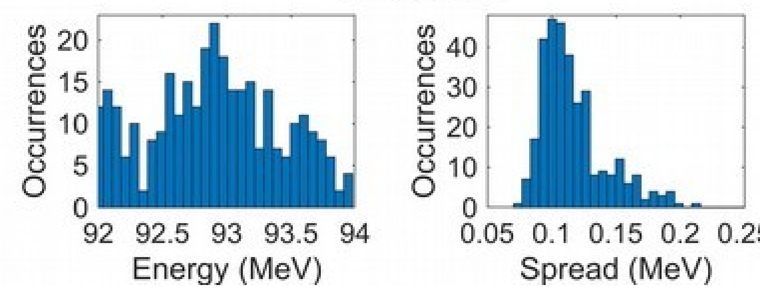
2x10^{15} cm^{-3} plasma density

<u>Demonstration of projected energy spread compensation</u>

Spread from 0.2% to 0.12%







nature physics

LETTERS

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

Check for updates

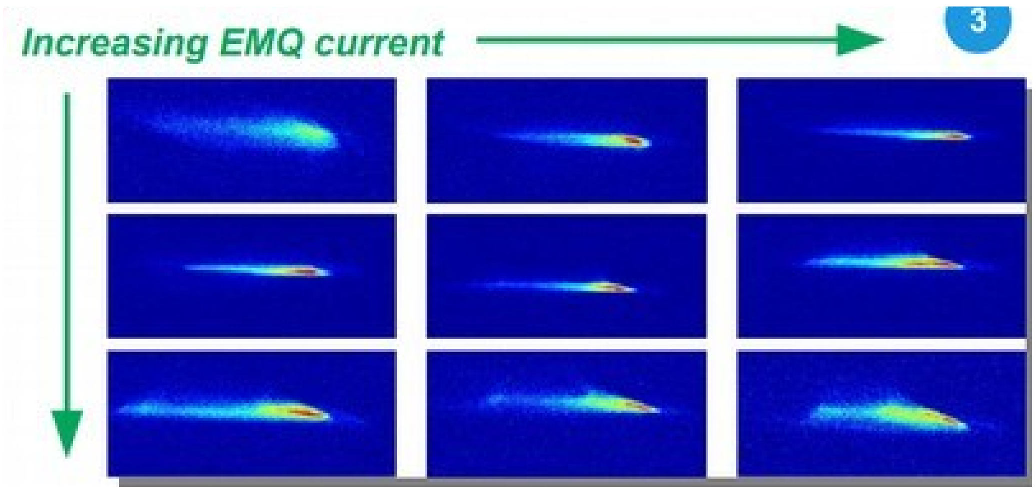
Energy spread minimization in a beam-driven plasma wakefield accelerator

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

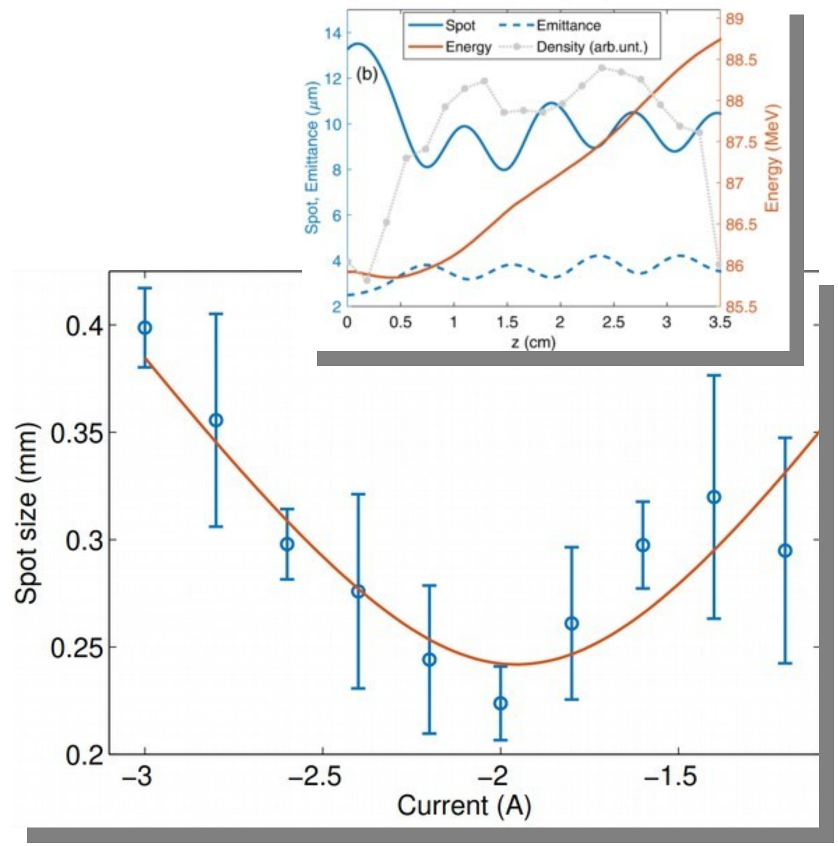
PWFA characterization completed by measuring the witness emittance

Measurement of its normalized emittance through quadrupole scan technique

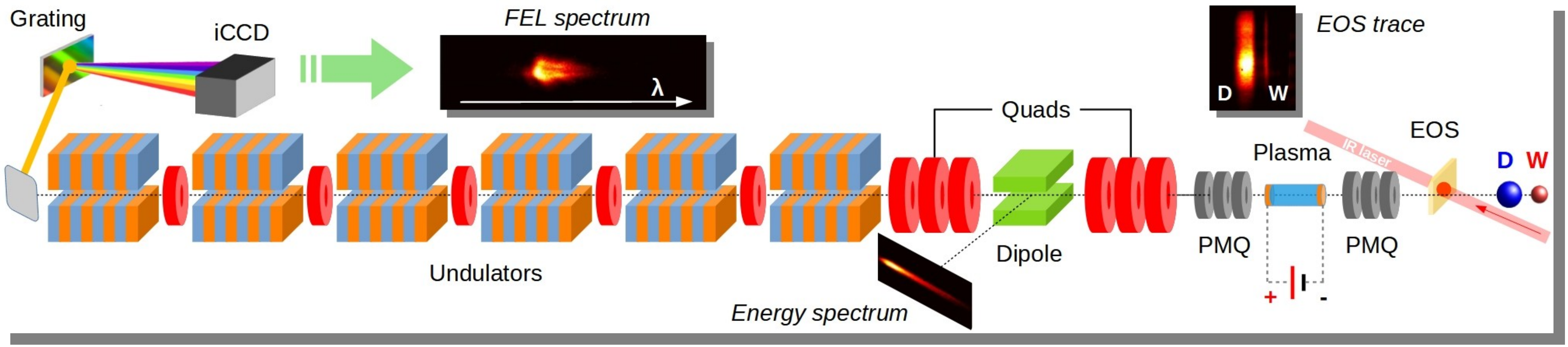
We found emittance increase from 2.7 um to 3.7 um (rms) during acceleration



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.



Proof of SASE FEL driven by PWFA



Proof-of-principle experiment to demonstrate high-quality PWFA acceleration able to drive a Free-Electron Laser

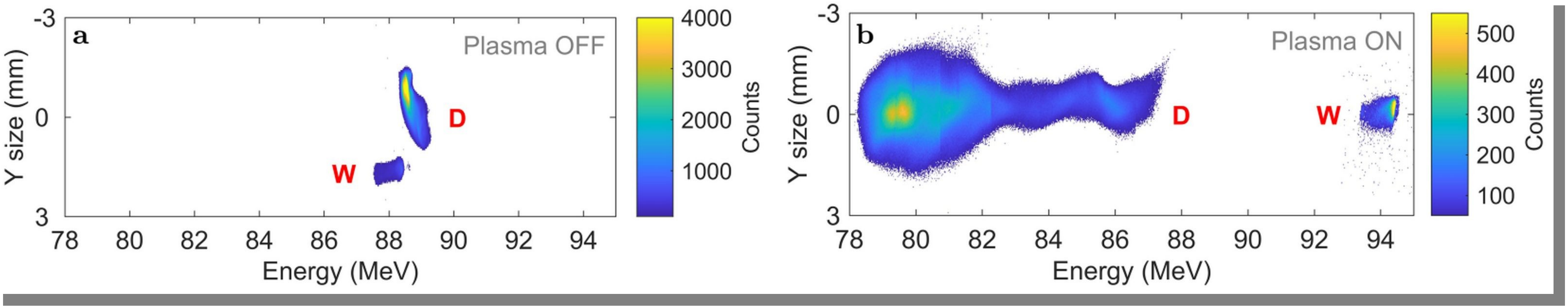
Witness is completely characterized (energy, spread, X/Y emittance) allowing to match it into the undulators beamline

Jitter is online monitored with Electro-Optical Sampling (EOS) diagnostics

Imaging spectrometer with iCCD used to detect FEL radiation

In collaboration with

Beam configuration at the FEL entrance



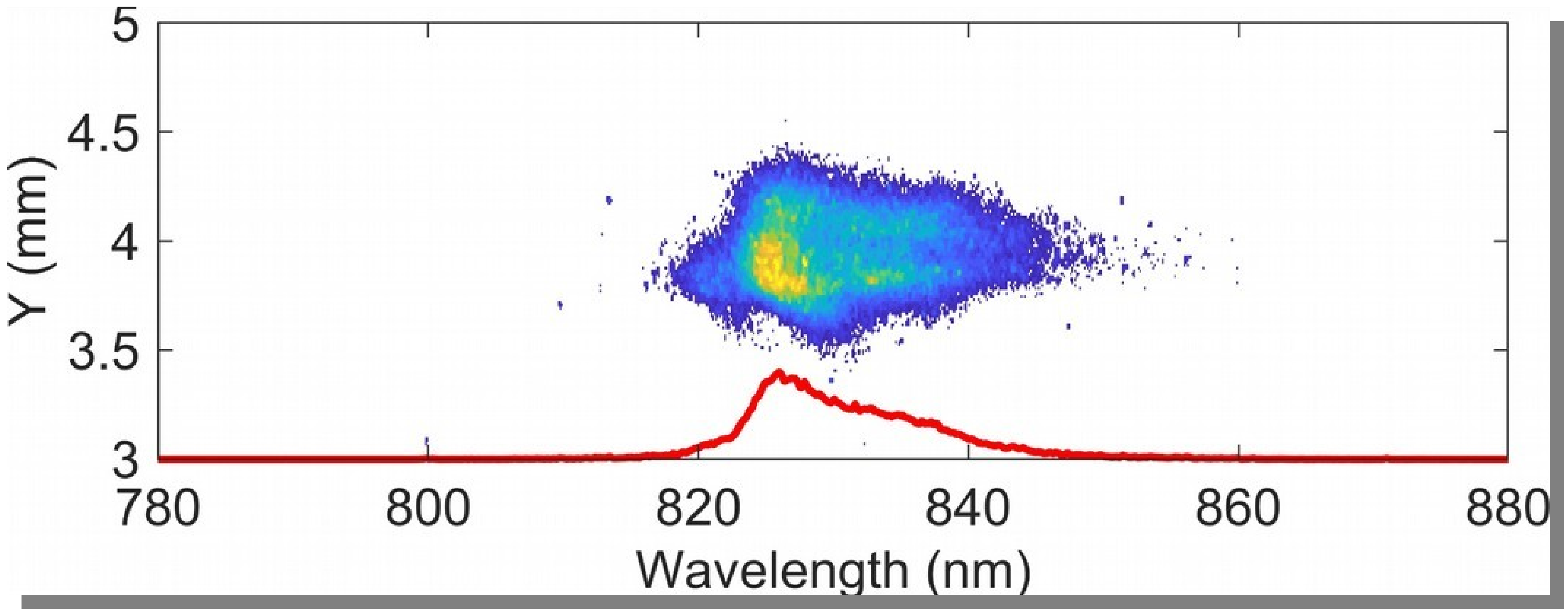
Plasma density set to 1.6×10^{15} cm^{-3}

Accelerated witness

- *Energy: 94 MeV, 0.3 MeV spread (~200 MV/m acceleration)*
- *Emittance: 2.7(X) um, 1.3(Y) um*

Driver decelerated by almost 10 MeV

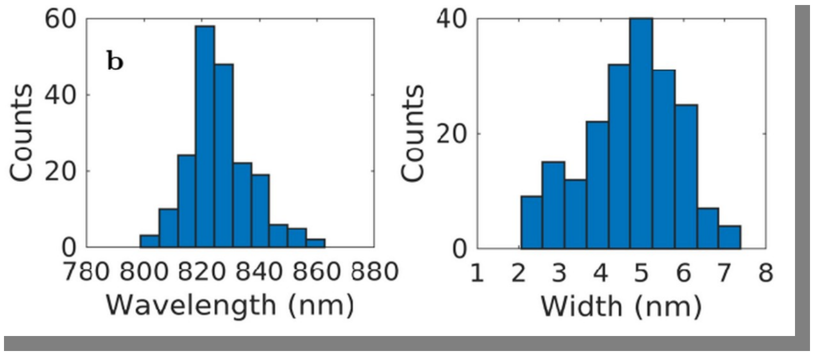
Radiation spectrum



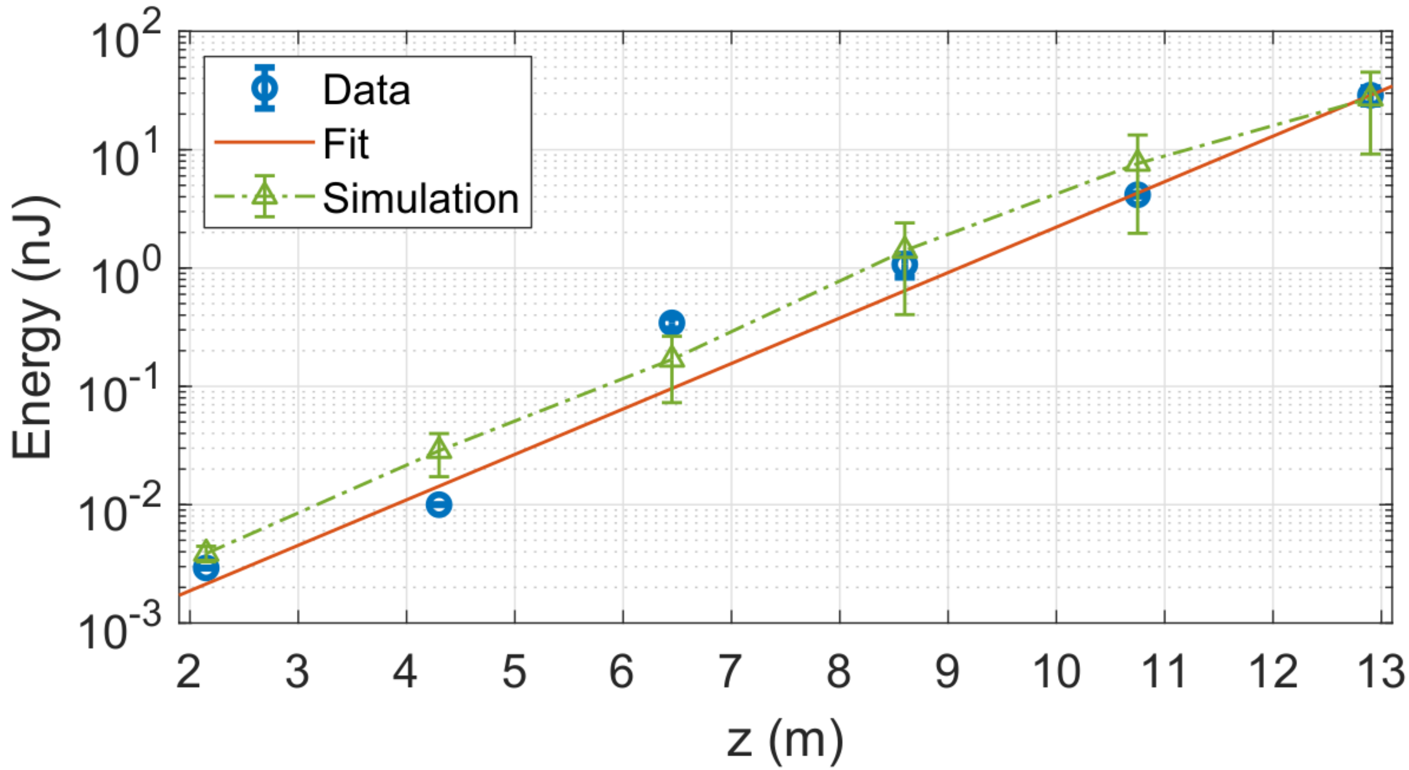
Single-shot spectrum of the SASE FEL radiation emitted at 830 nm

6 undulators matched on the parameters of the plasma accelerated witness

Clear signals, reproducible day by day



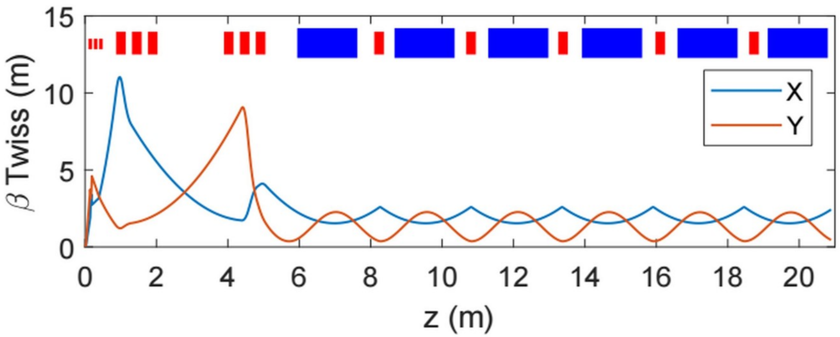
FEL driven by PWFA: exponential gain



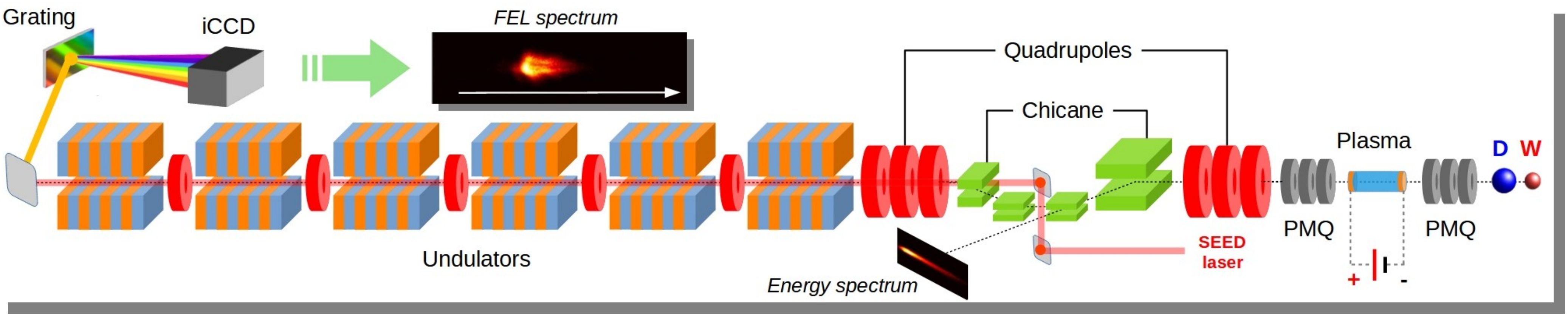
R. Pompili, et al.
Accepted by Nature

Exponential gain of FEL radiation energy

Data taken with 6 (Si) photo-diodes downstream the undulators



Next step: Seeded FEL from PWFA



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

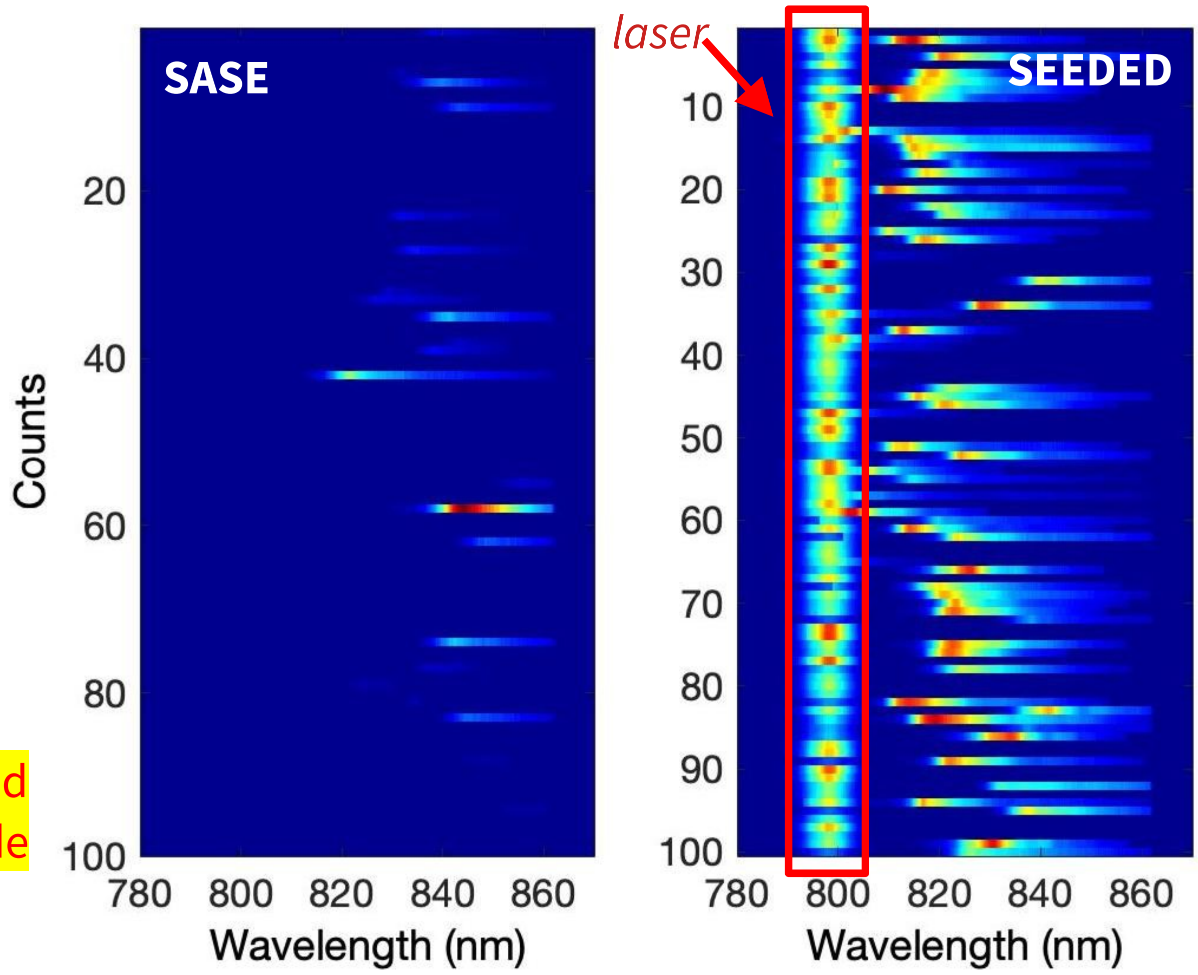
- *Naturally synchronized with the beam, tunable energy (~10 nJ used in the experiment).*
- *Duration increased from ~100 fs to 600 fs (fwhm). Focused at the entrance of 1st undulator*

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)

Laser seed is transported up to the imaging spectrometer

Seeded FEL Performances



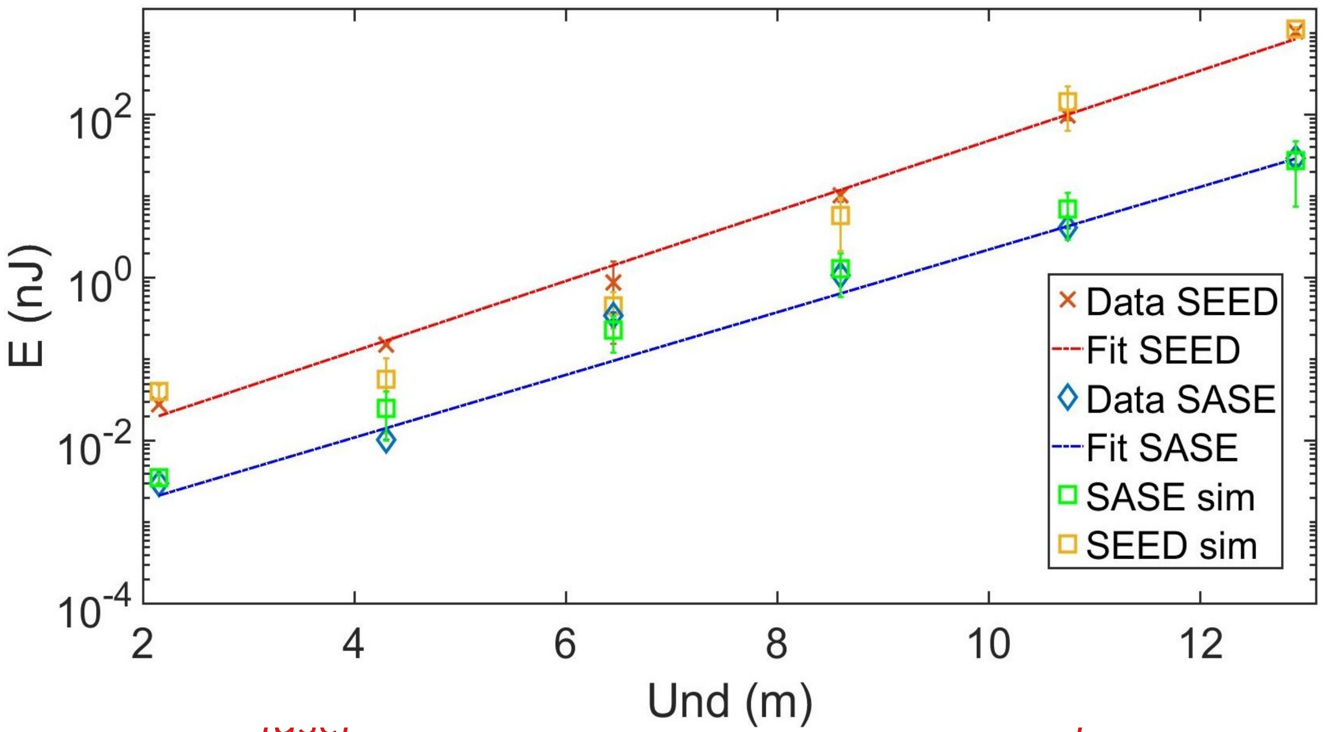
M. Galletti, et al. *submitted*

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

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

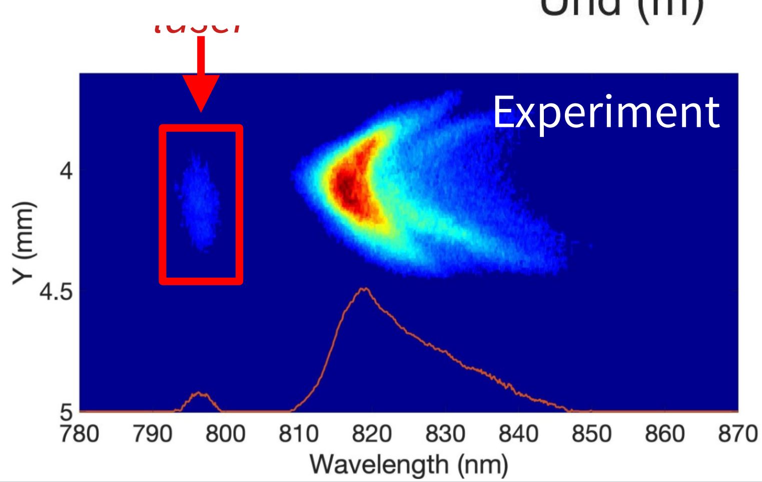
Undulators tuned for FEL radiation at ~830 nm → separated from the laser (793 nm)

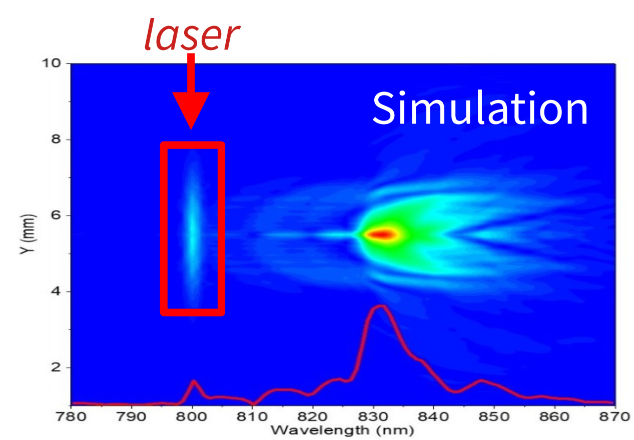
Exponential growth



~1 uJ (SEEDED)

~30 nJ (SASE)





Conclusions

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

Thanks!

R. Pompili (LNF-INFN)
riccardo.pompili@lnf.infn.it

On behalf of the SPARC_LAB collaboration

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati