12th International Particle Accelerator Conference

Recent results and future perspectives for high-quality electron beams from plasma accelerators

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On behalf of the SPARC_LAB collaboration

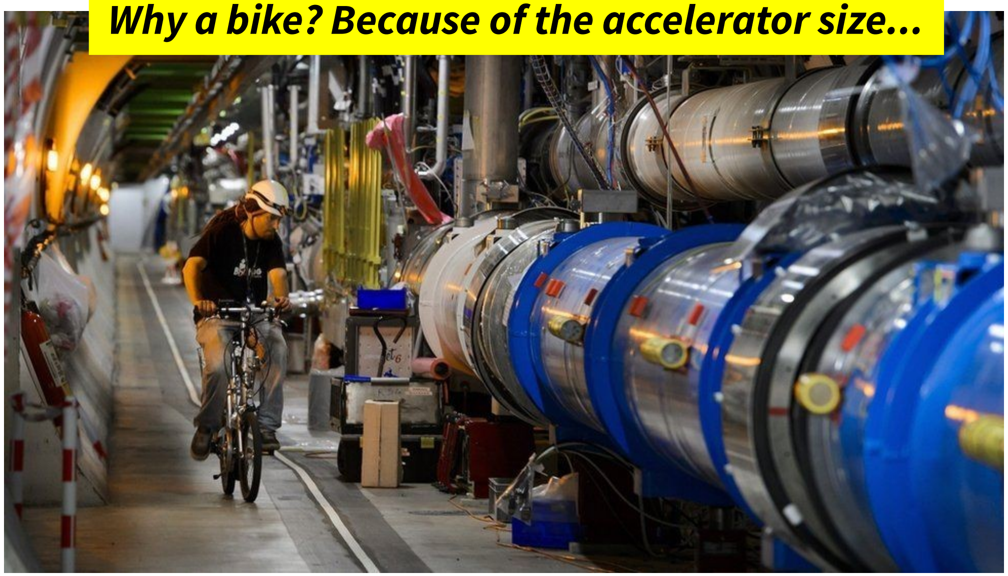
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Particle accelerators

A particle accelerator is a machine that uses electromagnetic fields to propel charged particles to very high speeds and energies, and to contain them in well-defined beams

Wikipedia

Why a bike? Because of the accelerator size...



According to the De Broglie hypothesis, larger is the particle **energy** better is the **spatial resolution** at which matter can be investigated

Today use of particle accelerators

- *High-energy and nuclear physics*
- *Sources of synchrotron and FEL radiation*
- *Medical/industrial applications*

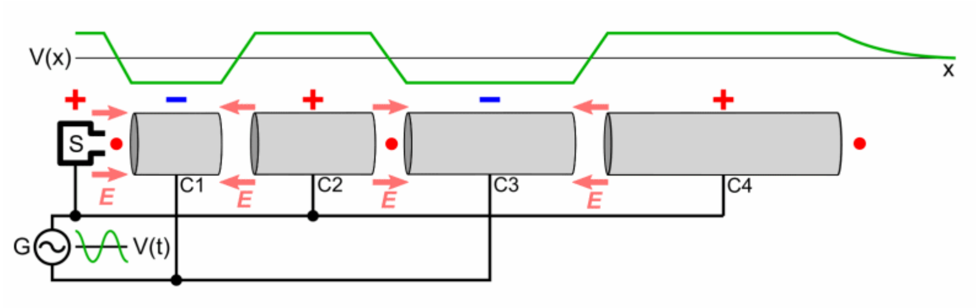
$$\lambda = \frac{h}{p}$$

Planck constant

Microscope resolution

Particle momentum (~energy)

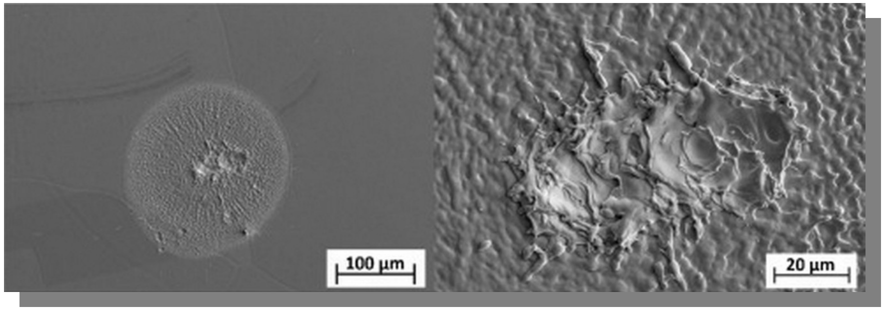
Conventional RF technology



RF technology uses high power microwaves in resonant cavities with metallic walls.

Typical RF frequencies are in GHz range.

The cavities dimensions are of the order of the microwaves wavelength (1-60 cm)



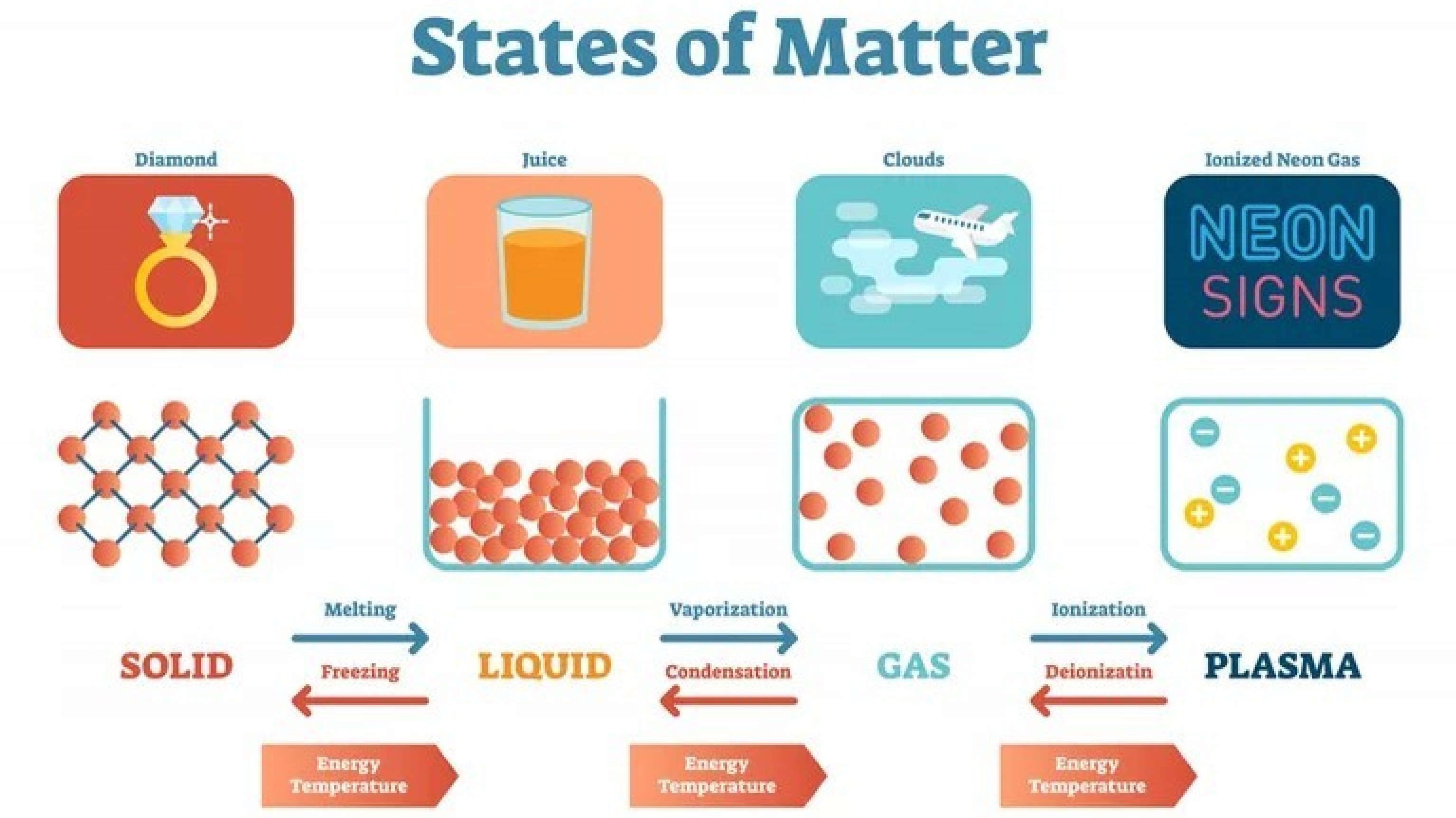
The power stored in the cavity cannot grow to infinite

***RF breakdown**: imperfections on the cavities can trigger sparks and damage the structure*

There exists a maximum tolerable accelerating field

$$E_{max} \approx 150 \frac{MV}{m}$$

Use of plasma to exceed RF limits



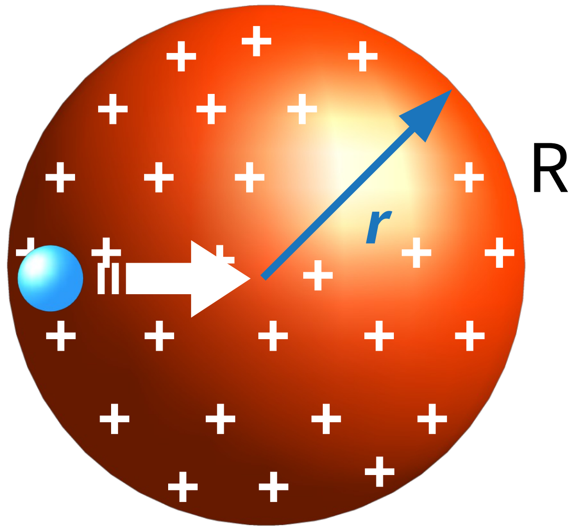
Plasma is the 4th state of matter and is made of free electrons and positively charged ions

It is typically made by heating a gas until its electrons have sufficient energy to escape from the (positive) nuclei

Being already ionized, the plasma cannot be "damaged" by any spark and can thus sustain huge fields

From Maxwell's equations, the electric field in a (positively) charged sphere with uniform density n_i at location **r** is

$$\boxed{\vec{E}(r) = \frac{q_i n_i}{3\epsilon_0} r}$$

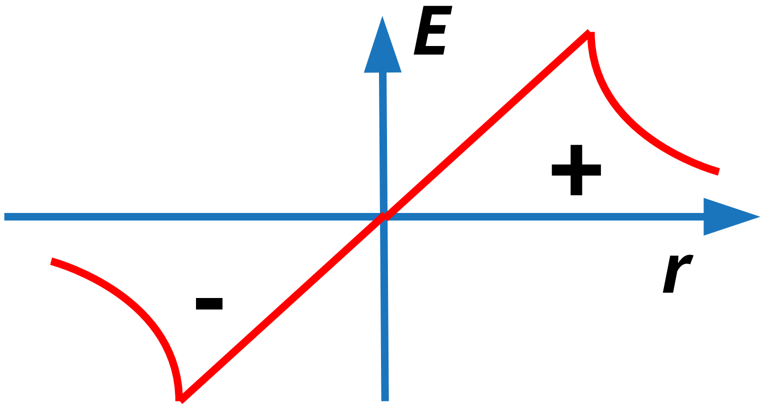


The field is **increasing** inside the sphere

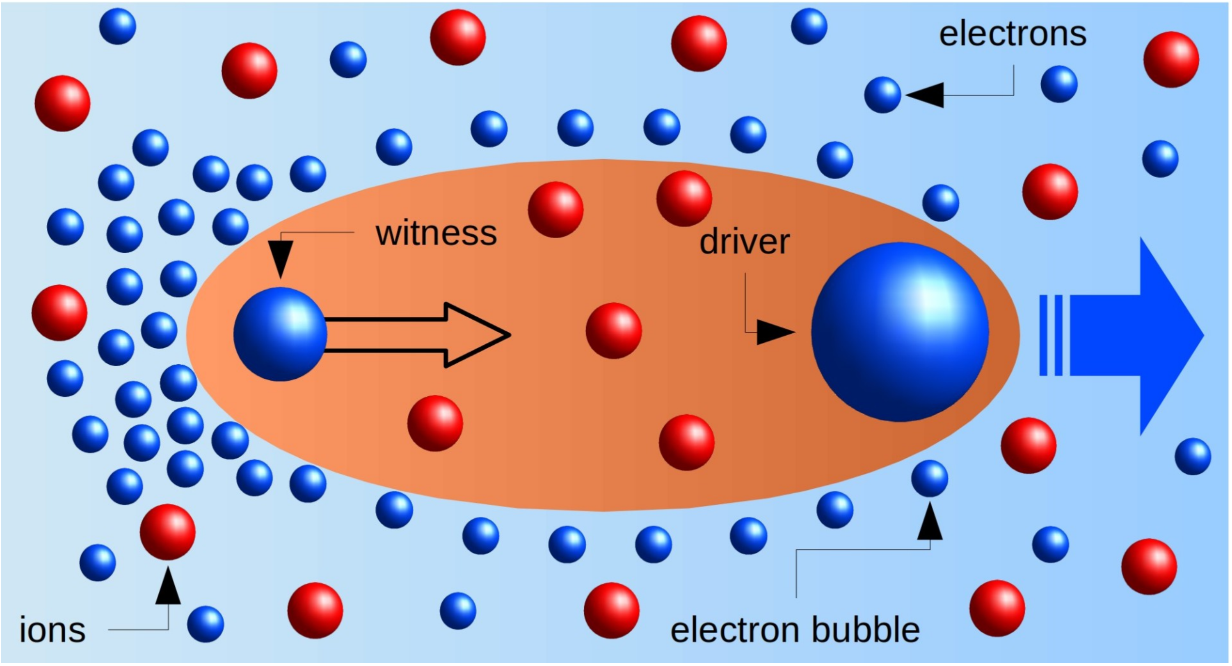
Let's put some numbers

$n_i = 10^{16}\ cm^{-3}$

$R = 0.5\ \lambda_p = 150\ \mu m$ $\Rightarrow$ $E \approx 10 \frac{GV}{m}$



Generation of the ionic bubble



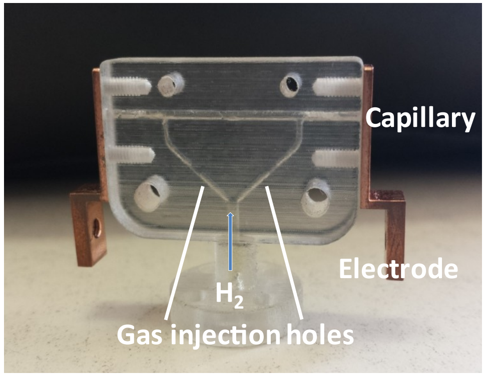
The **driver** creates the positive sphere (or ***bubble***). It can be a

- *particle bunch (PWFA)*
- *laser pulse (LWFA)*

The **witness** can be

- *Self-injected*
- *Externally injected*

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



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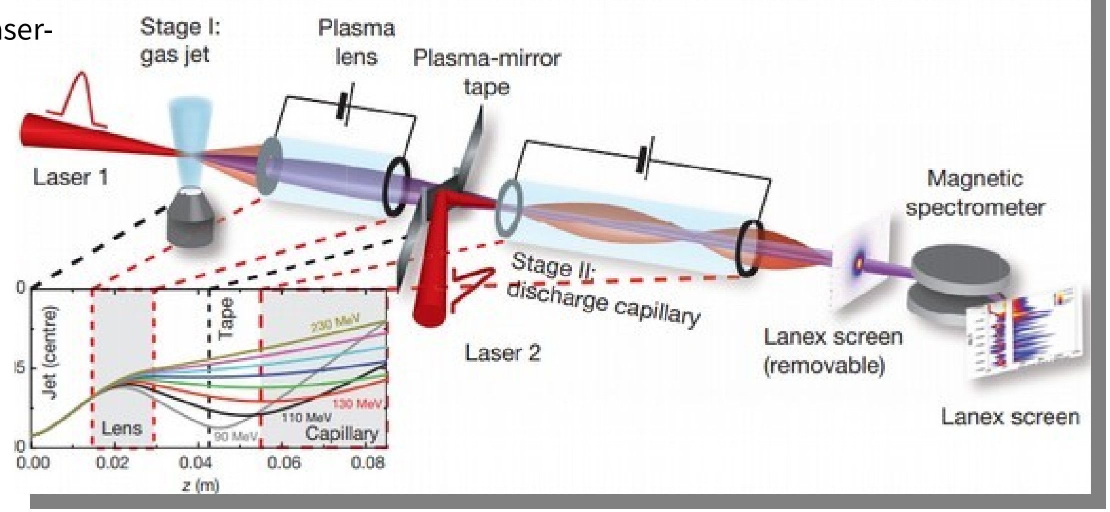
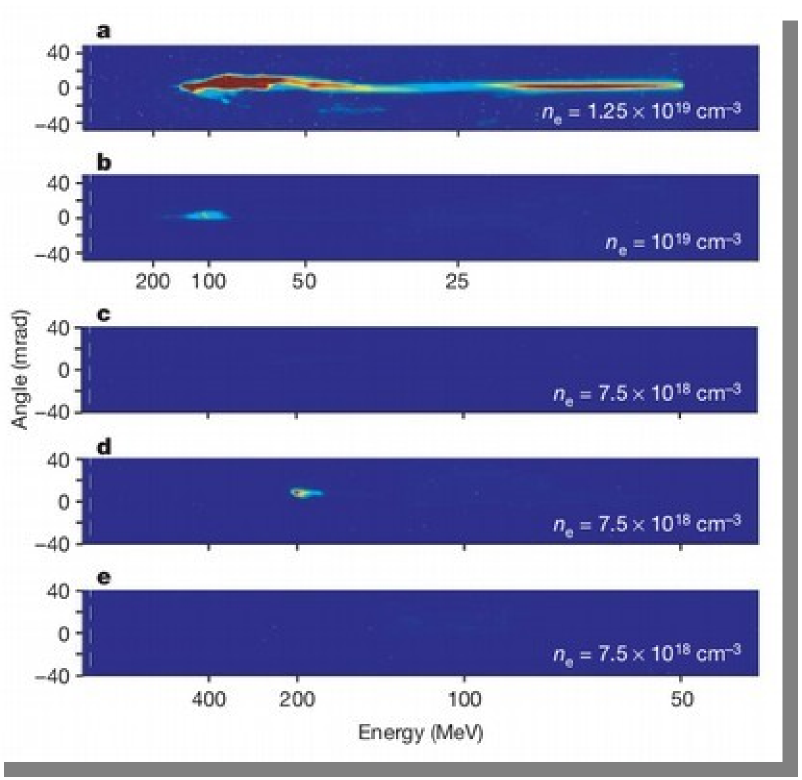
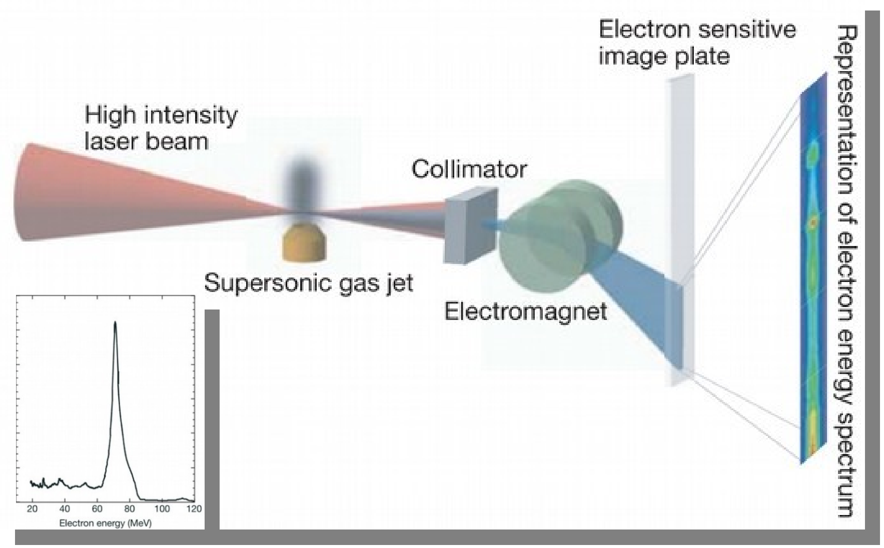


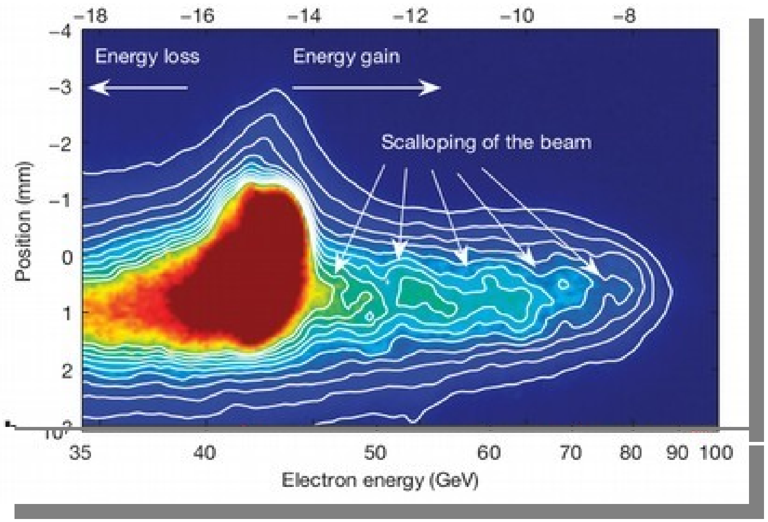


Faure, Jérôme, et al. "Controlled injection and acceleration of electrons in plasma wakefields by colliding laser pulses." Nature 444.7120 (2006): 737-739.

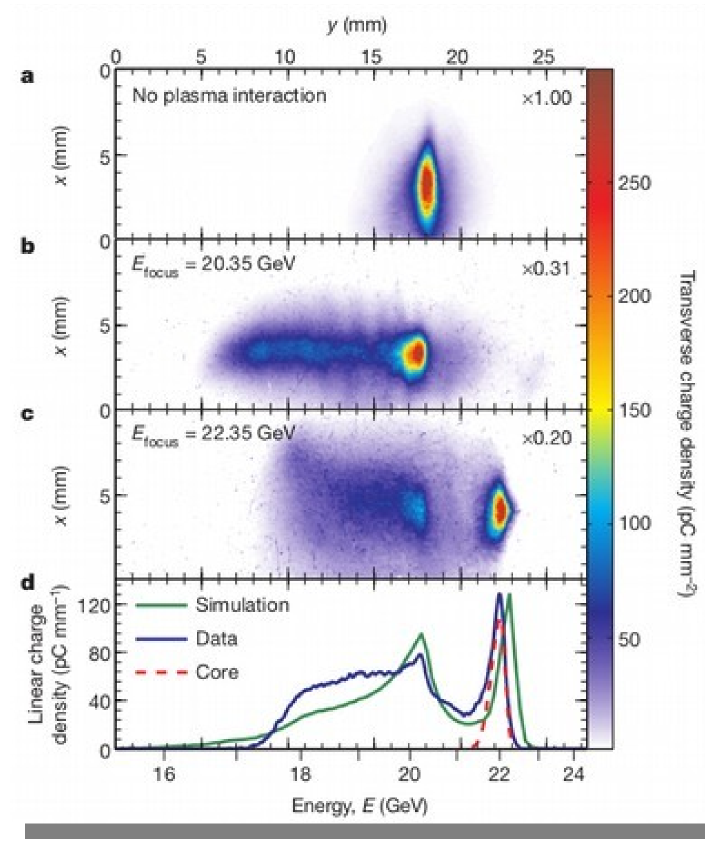


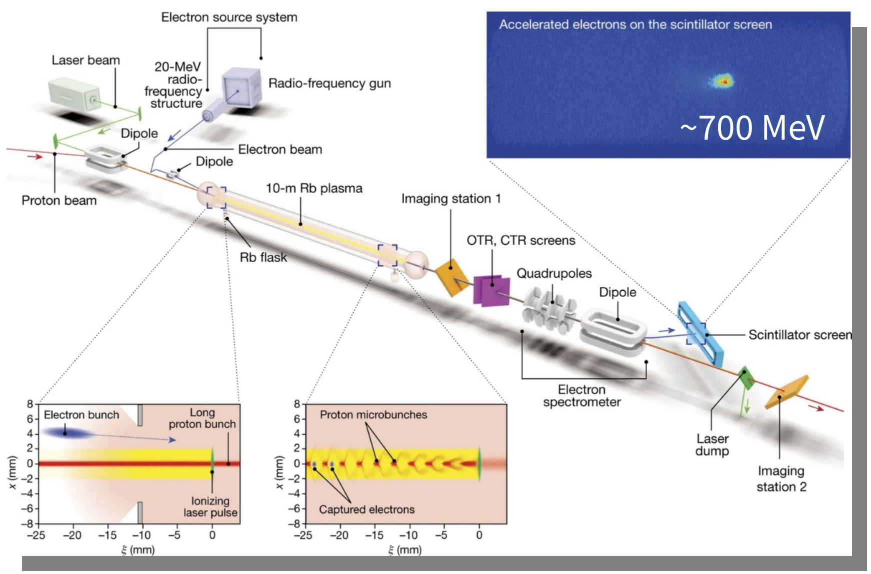
Mangles, Stuart PD, et al. "Monoenergetic beams of relativistic electrons from intense laser–plasma interactions." Nature 431.7008 (2004): 535-538.

Milestones in PWFA



Blumenfeld, Ian, et al. "Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator." Nature 445.7129 (2007): 741-744.



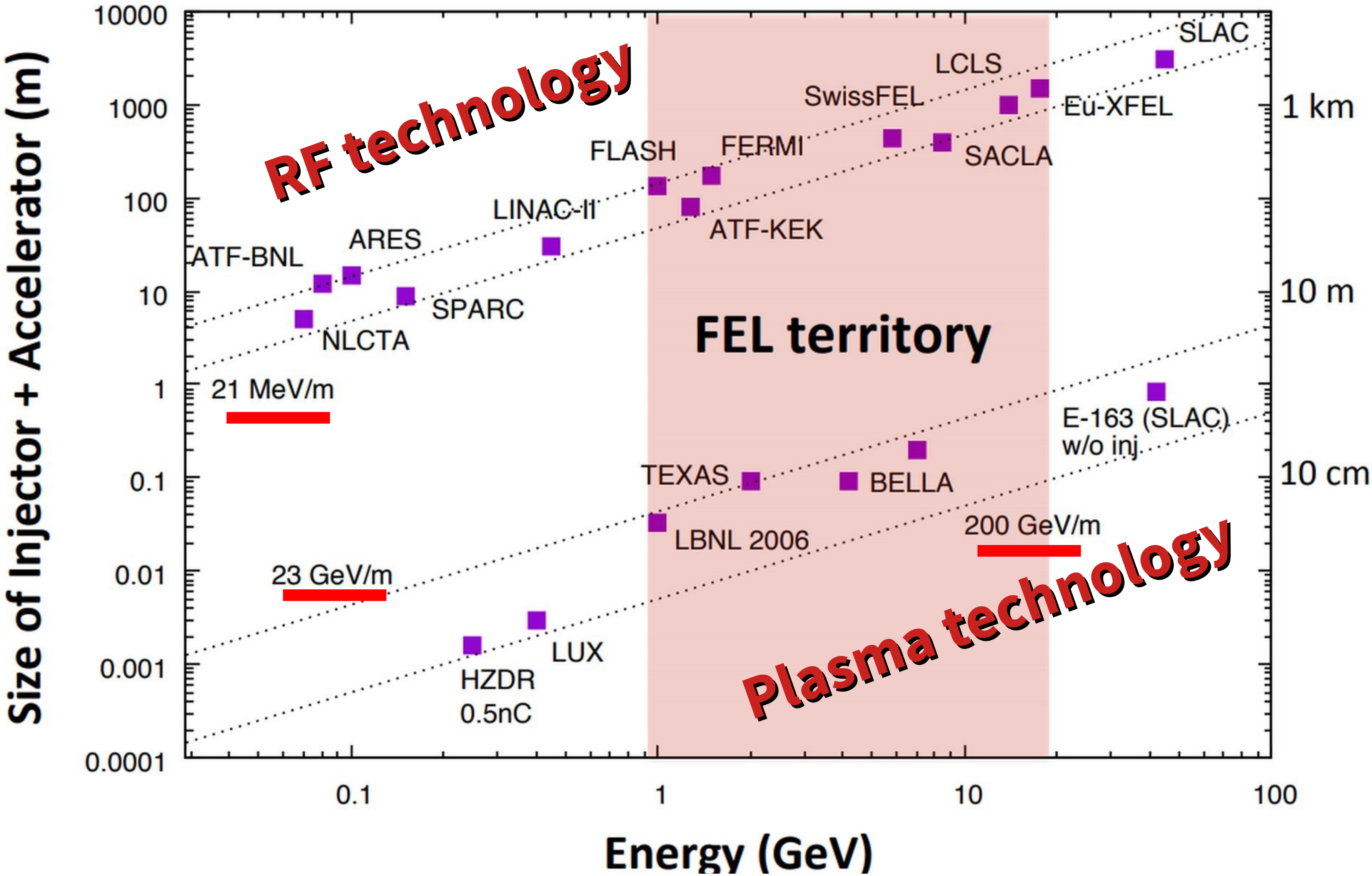


Adli, Erik, et al. "Acceleration of electrons in the plasma wakefield of a proton bunch." Nature 561.7723 (2018): 363-367.

Litos, M., et al. "High-efficiency acceleration of an electron beam in a plasma wakefield accelerator." Nature 515.7525 (2014): 92-95.

Standard vs plasma accelerators

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

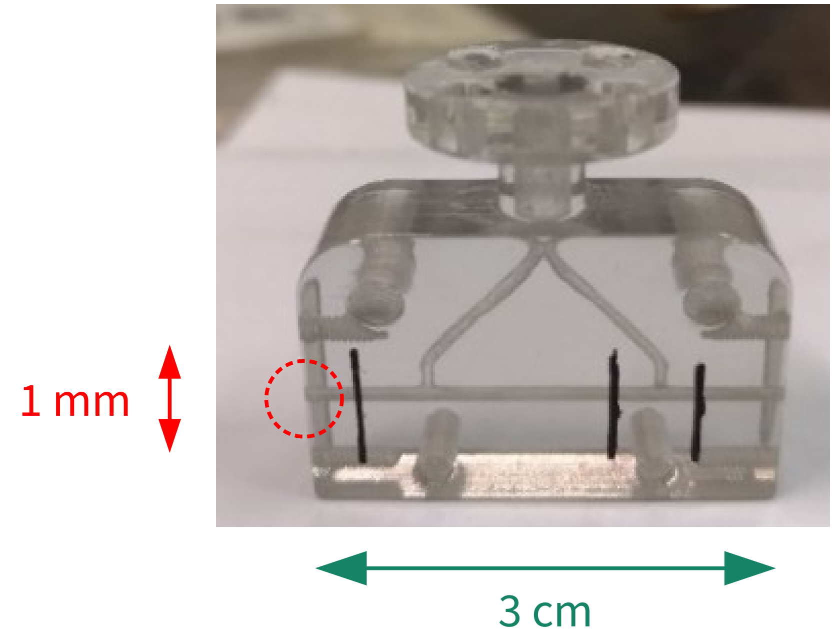


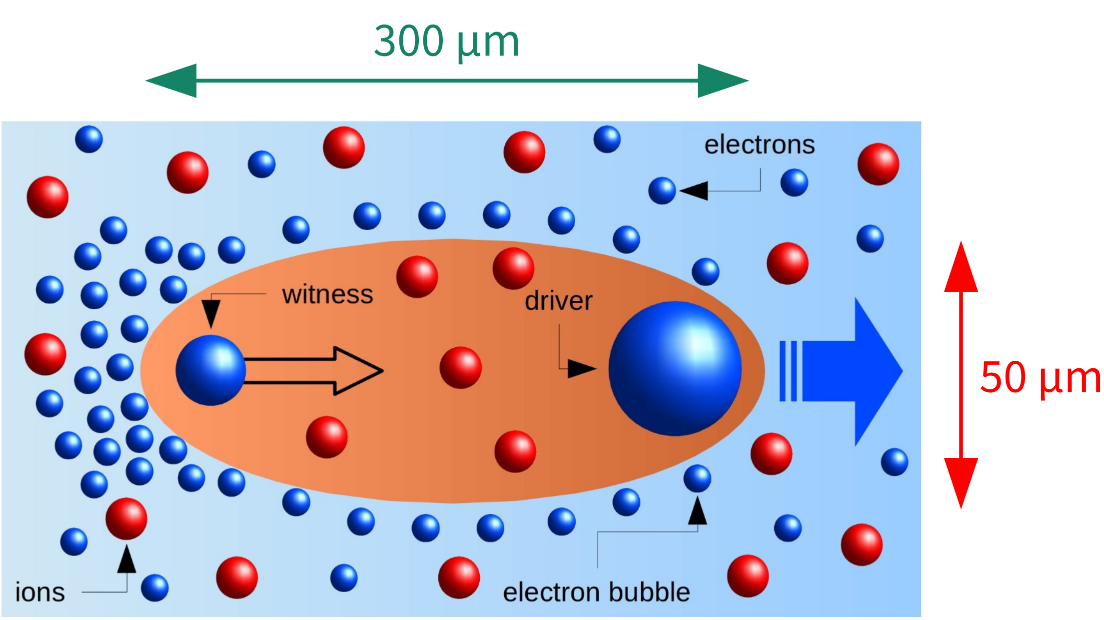
Typical sizes

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

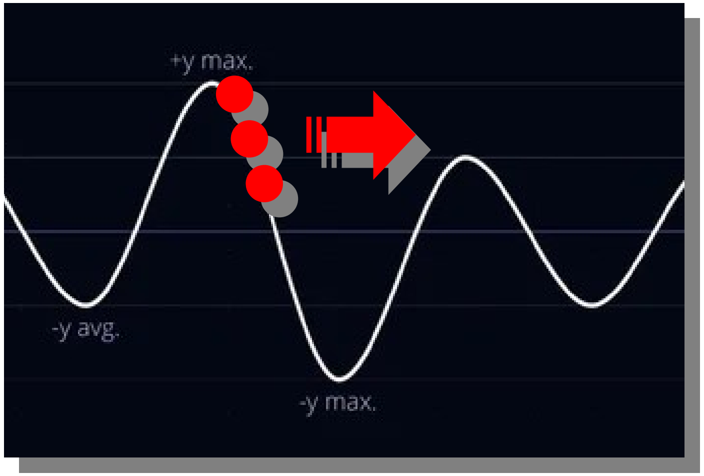
The bubble is tiny (tens/hundreds of micron scale)

The witness beam must be even smaller!!!

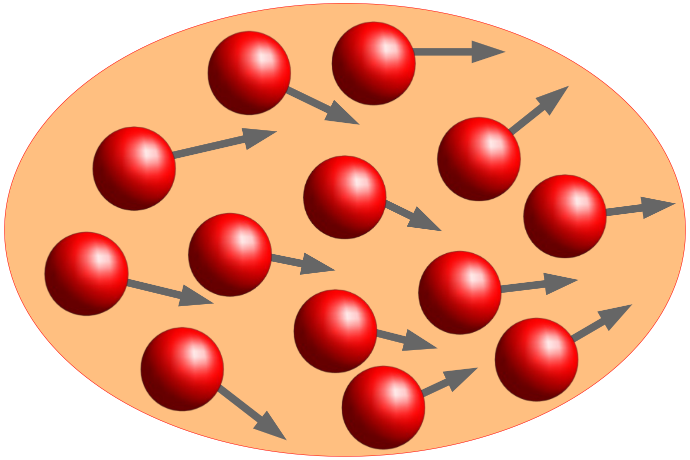




Beam quality

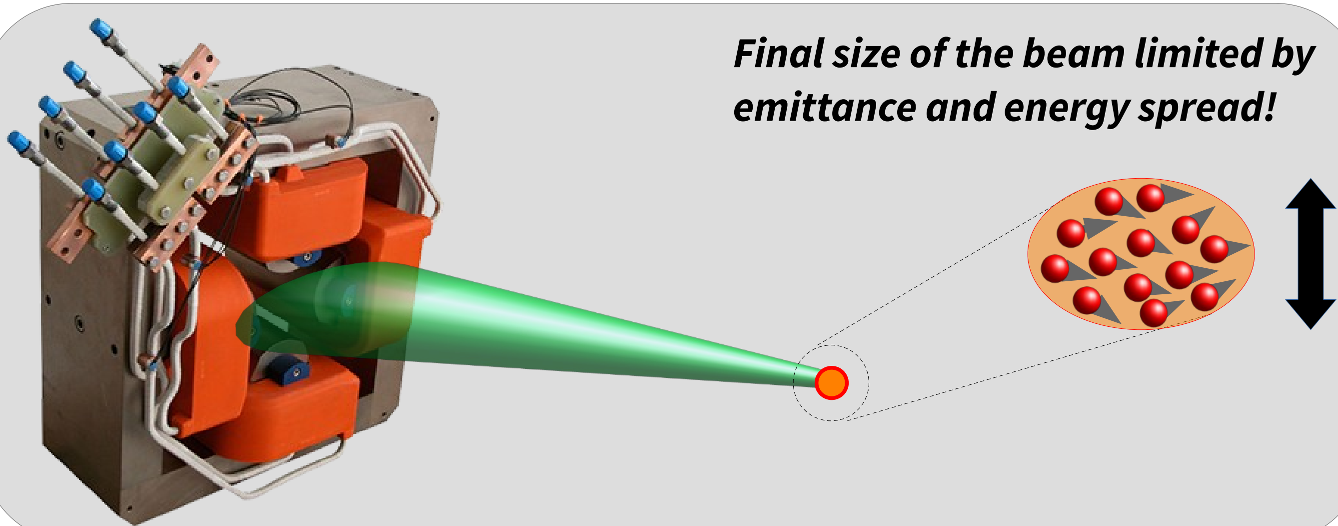


Energy spread

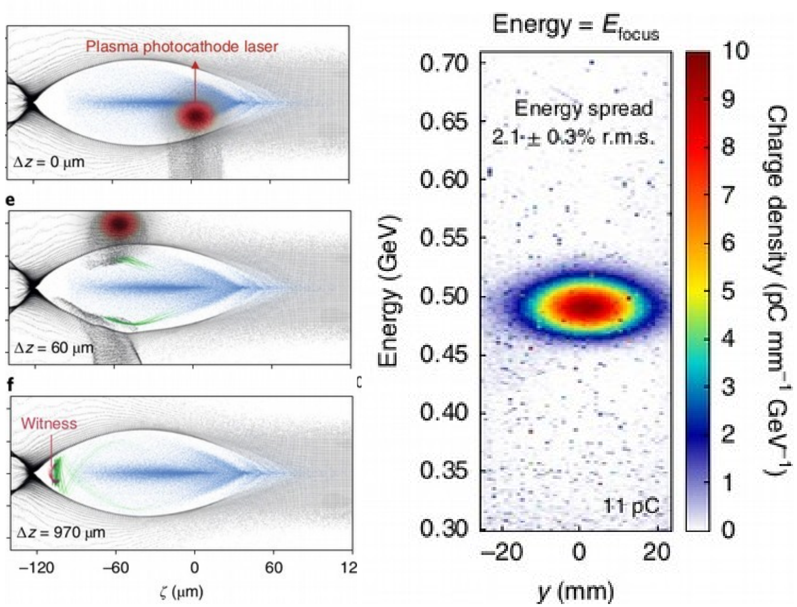


Emittance

Final size of the beam limited by emittance and energy spread!



Recent advances toward high-quality



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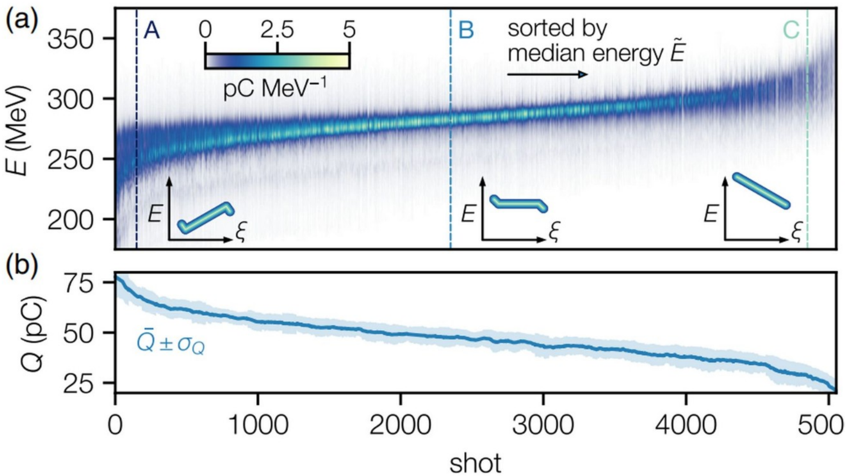
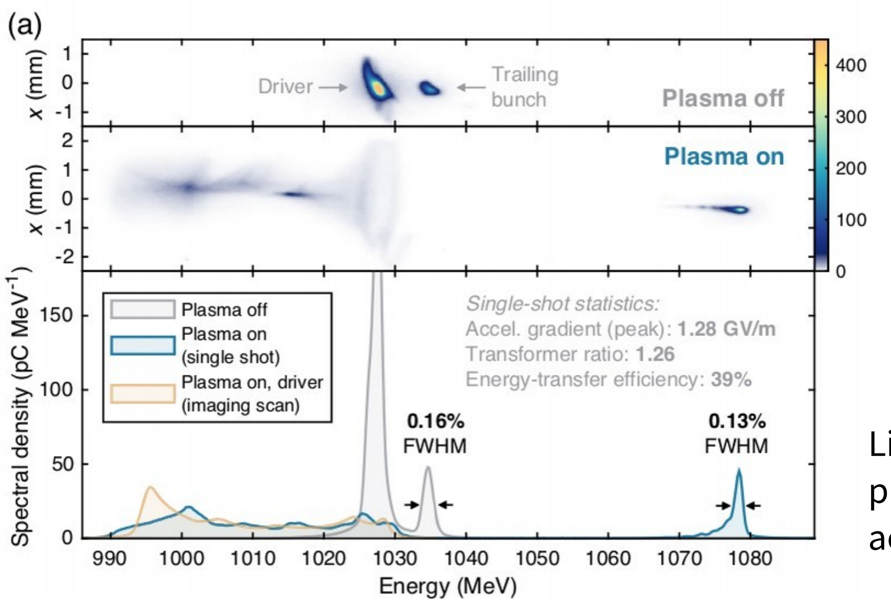
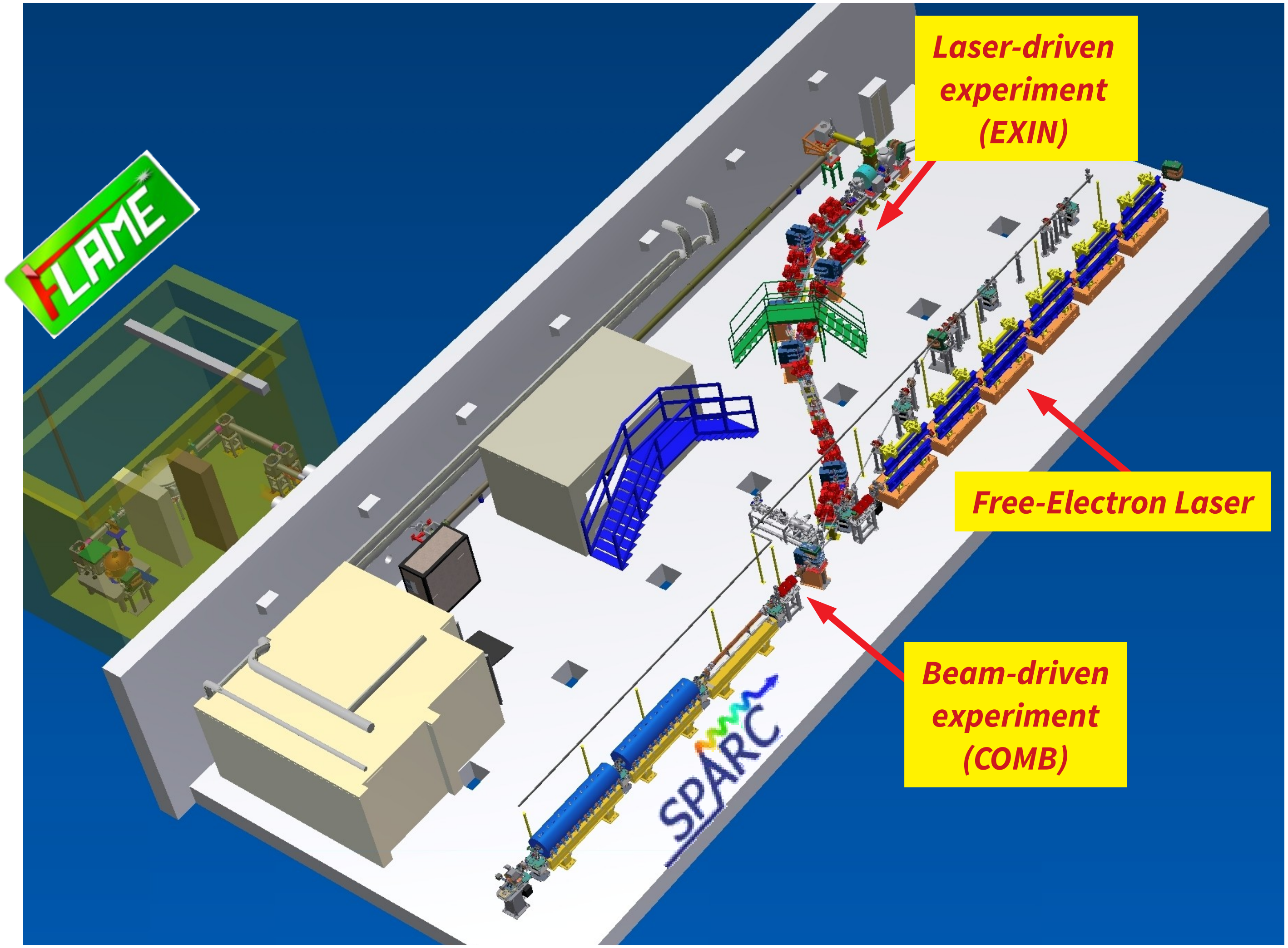


Kirchen, Manuel, et al. "Optimal Beam Loading in a Laser-Plasma Accelerator." Physical Review Letters 126.17 (2021): 174801.



Lindstrøm, Carl Andreas, et al. "Energy-spread preservation and high efficiency in a plasma-wakefield accelerator." Physical review letters 126.1 (2021): 014801.

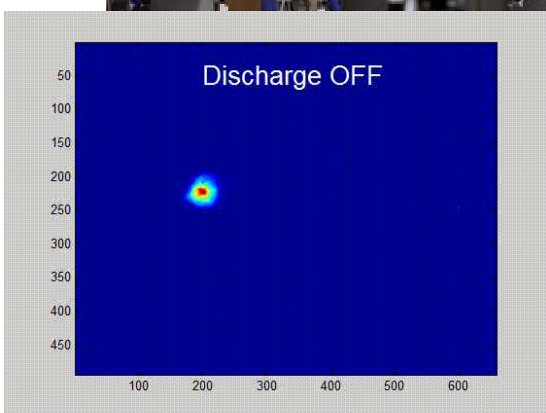
SPARC_LAB facility



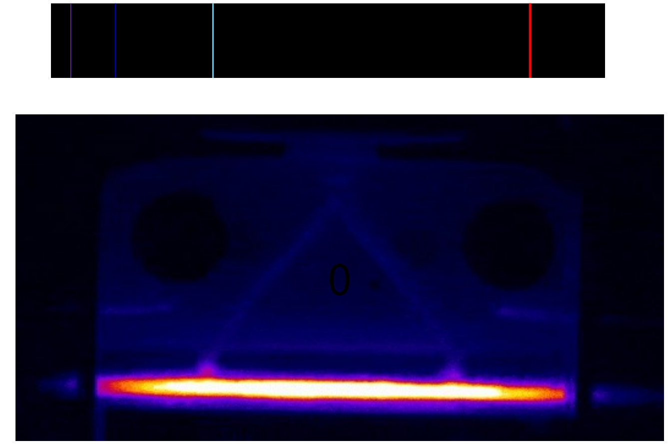
Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

Experience with plasma @ SPARC

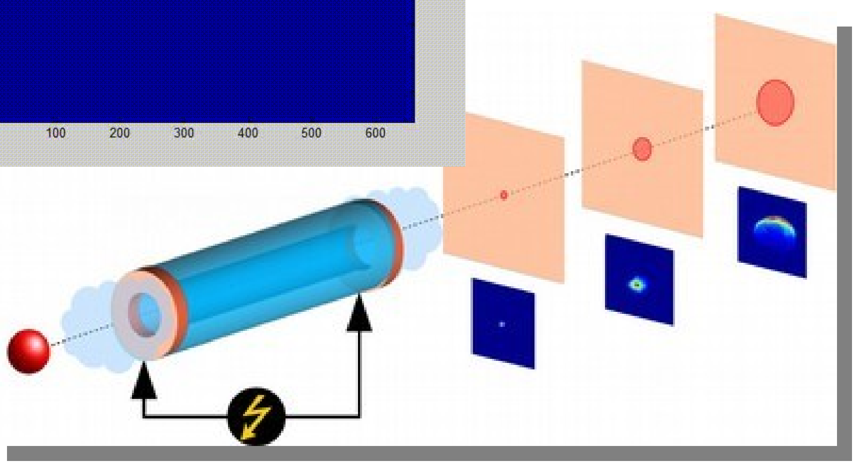
Activities with the high-brightness SPARC photo-injector



Plasma characterization



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



Focusing with active-plasma lenses

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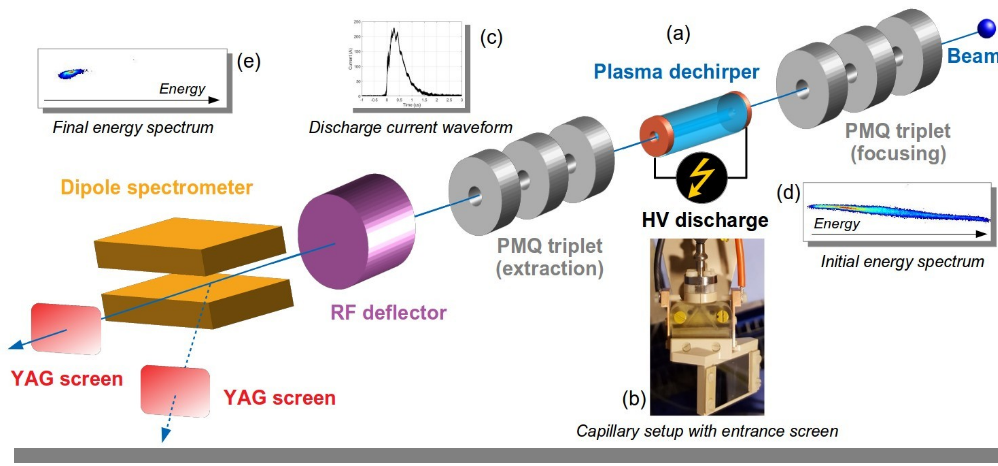
Pompili, R., et al., Applied Physics Letters 110.10 (2017): 104101.



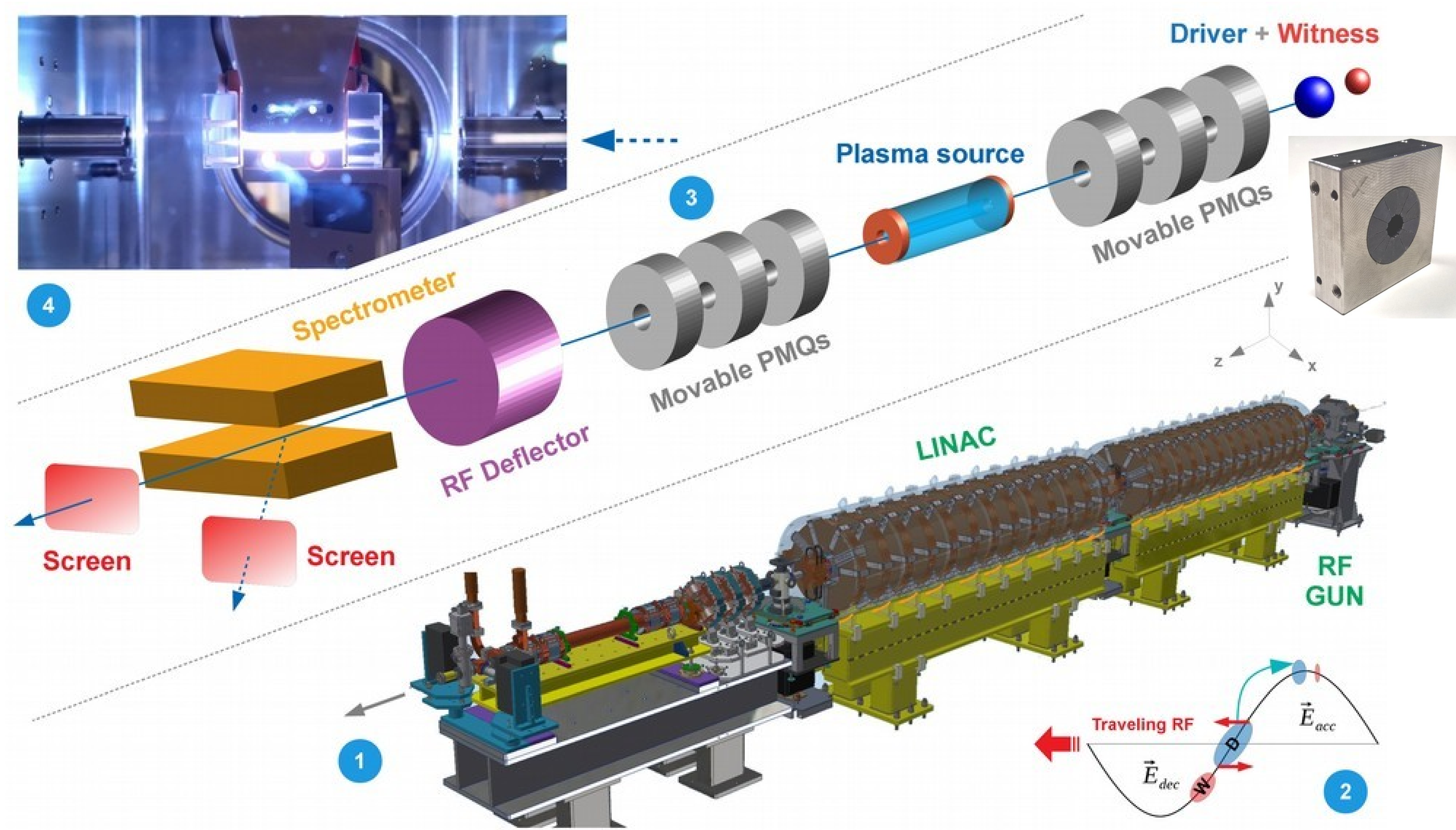
Plasma-dechirper

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

References on these topics

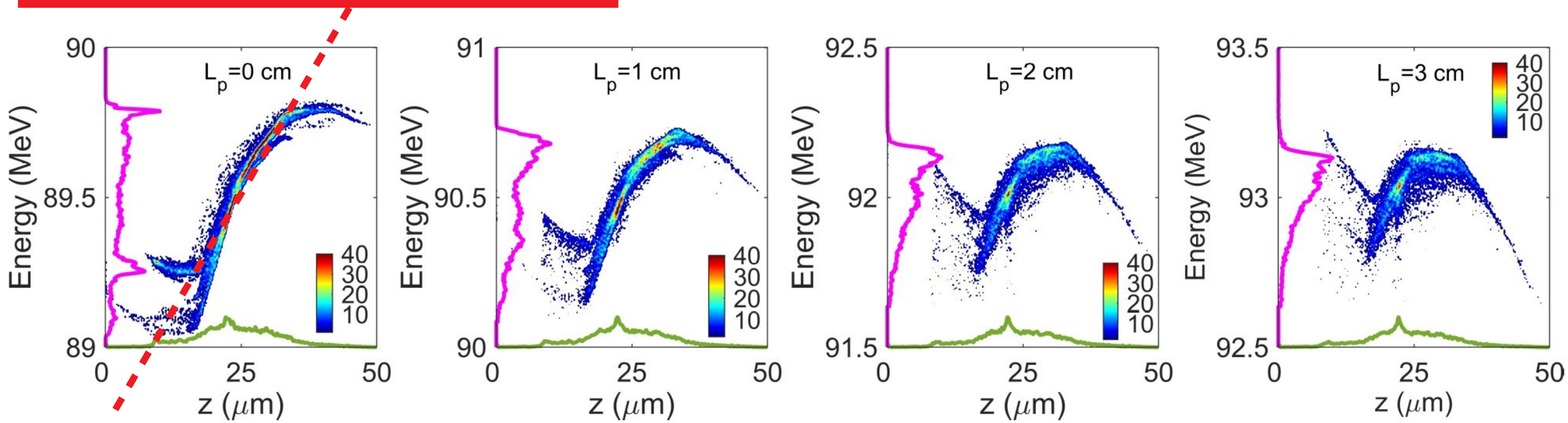
- Active-Plasma lenses
  - *Van Tilborg, J., et al. "Active plasma lensing for relativistic laser-plasma-accelerated electron beams." Physical review letters 115.18 (2015): 184802.*
  - *Van Tilborg, J., et al. "Nonuniform discharge currents in active plasma lenses." Physical Review Accelerators and Beams 20.3 (2017): 032803.*
  - *Lindstrøm, C.A., et al. "Emittance preservation in an aberration-free active plasma lens." Physical review letters 121.19 (2018): 194801.*
- Plasma “dechirper”
  - *Wu, Y. P., et al. "Phase space dynamics of a plasma wakefield dechirper for energy spread reduction." Physical review letters 122.20 (2019): 204804.*
  - *D’Arcy, R., et al. "Tunable plasma-based energy dechirper." Physical review letters 122.3 (2019): 034801.*

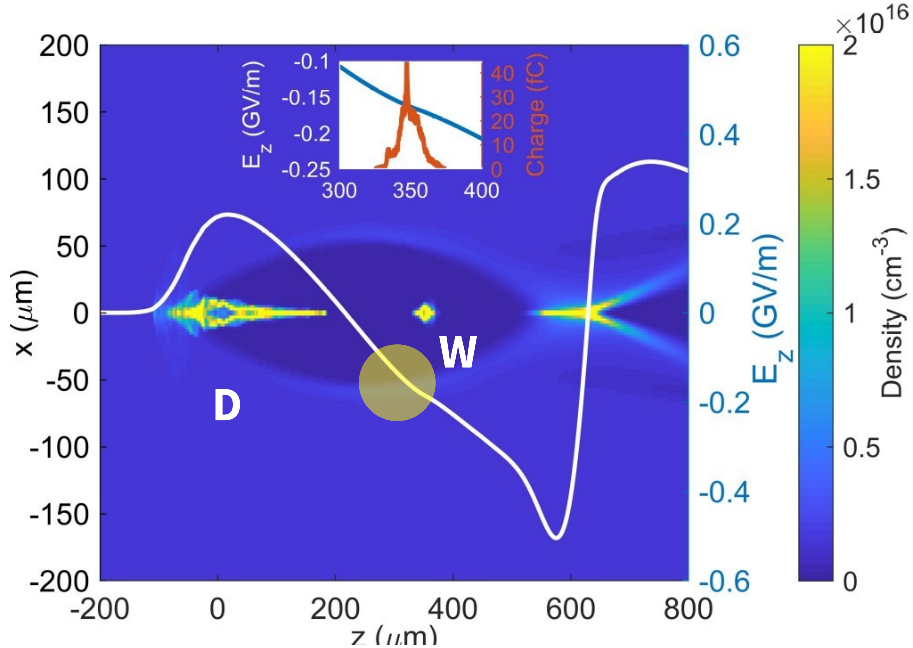
Plasma acceleration experiment

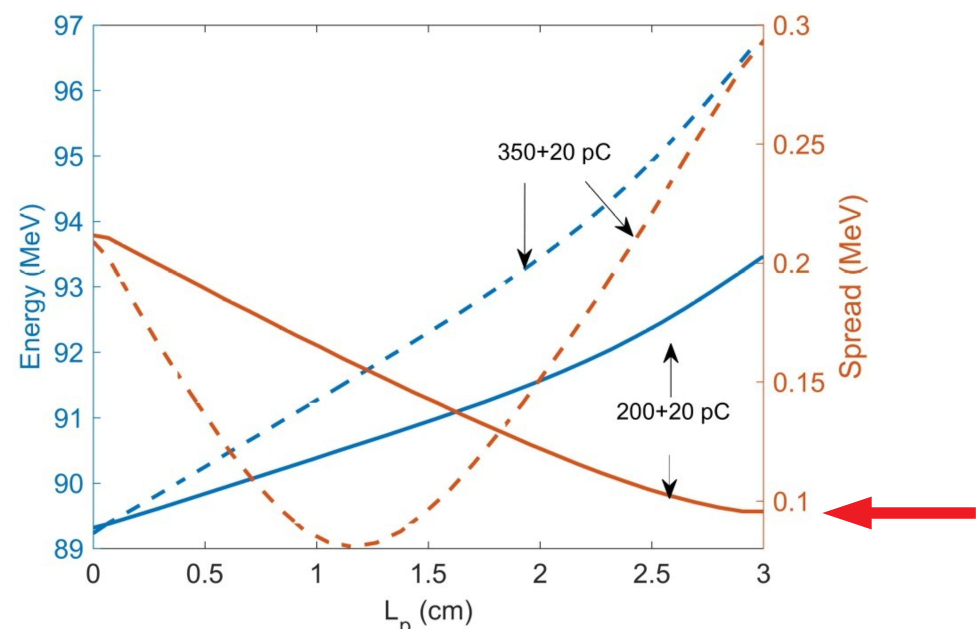


Assisted beam-loading technique

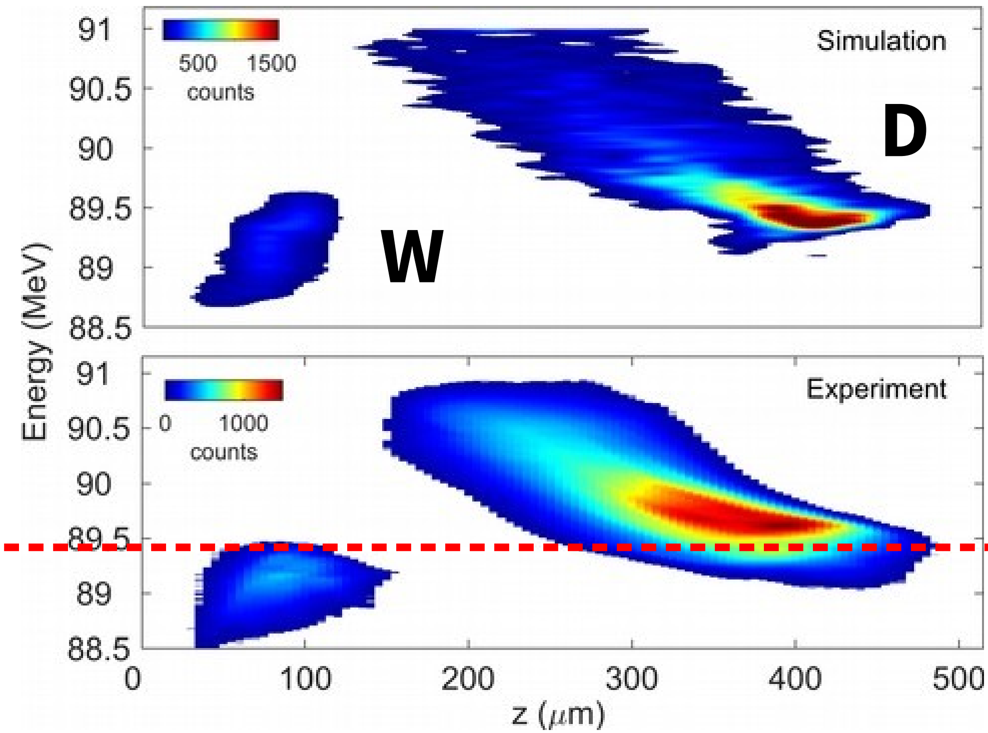
Pre-chirp to compensate wakefield slope







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)

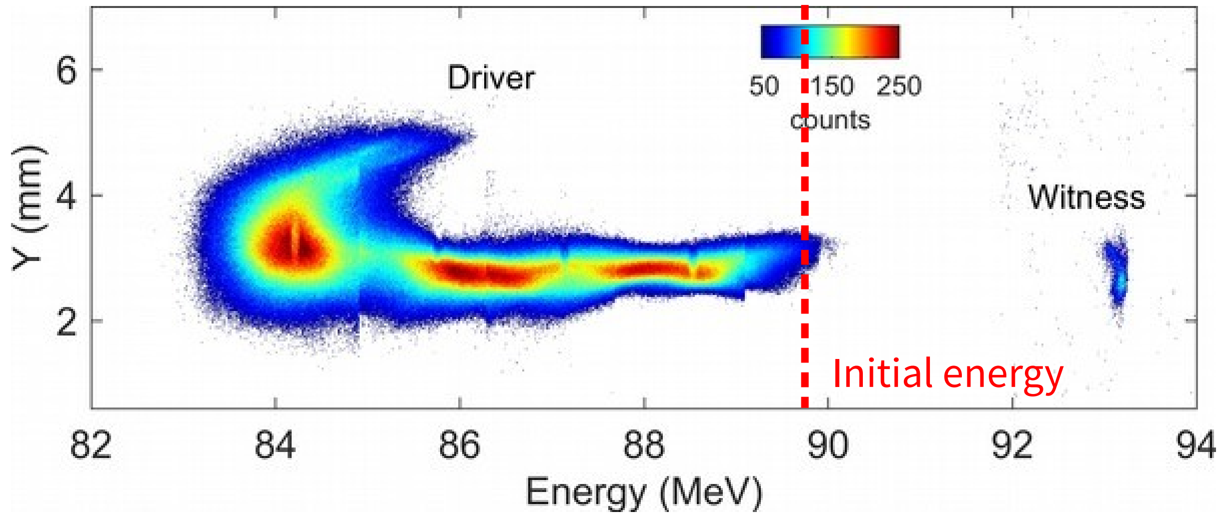
Plasma acceleration results (1)

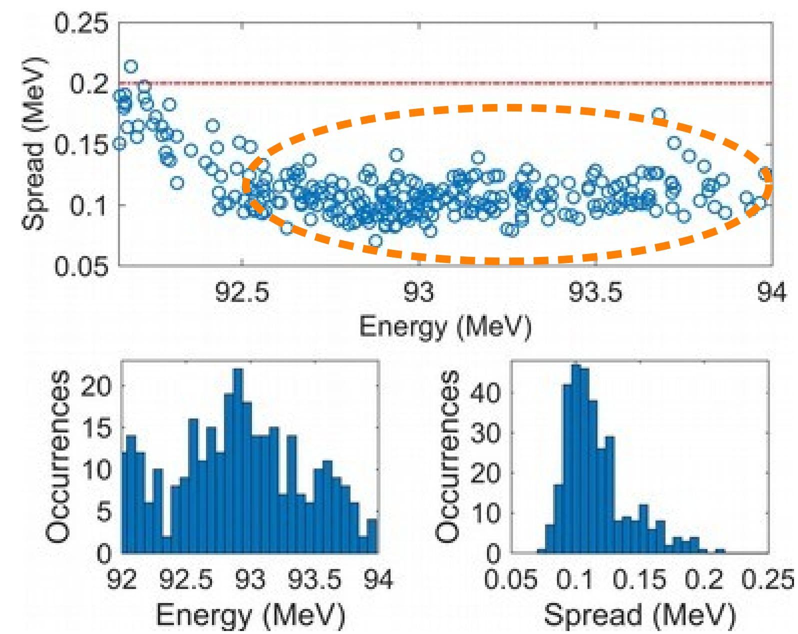
4 MeV acceleration in 3 cm plasma with 200 pC driver

- *~133 MV/m accelerating gradient*
- *2×10^{15} cm^{-3} plasma density*

First ever demonstration of energy spread reduction

- ***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]

Plasma acceleration results (2)

By increasing the driver charge a **larger ion bubble is produced**

Achieved 7 MeV acceleration in 3 cm plasma with 350 pC driver

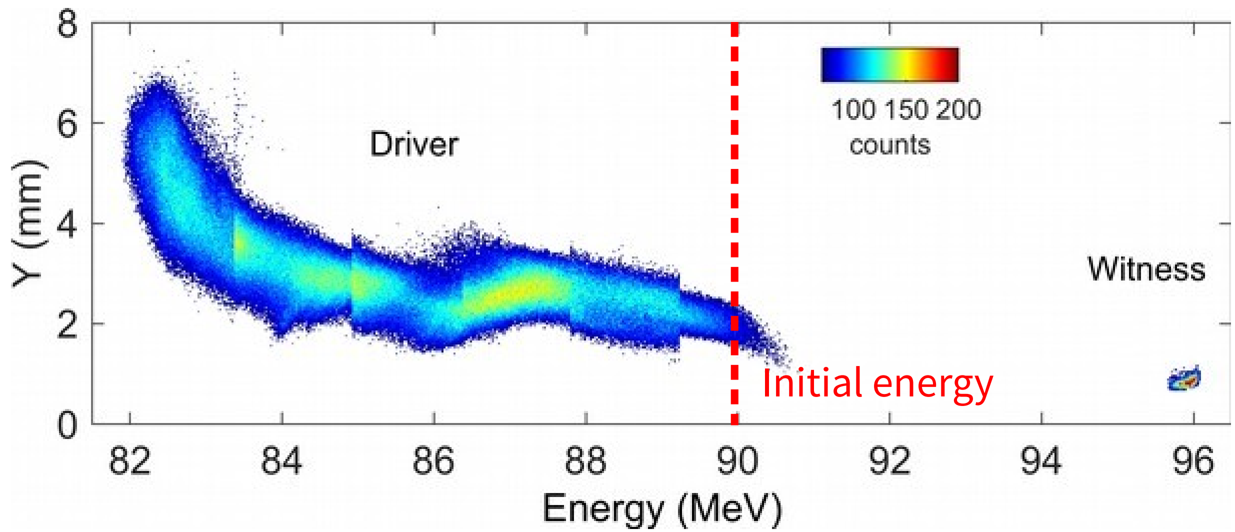
~233 MV/m accelerating gradient

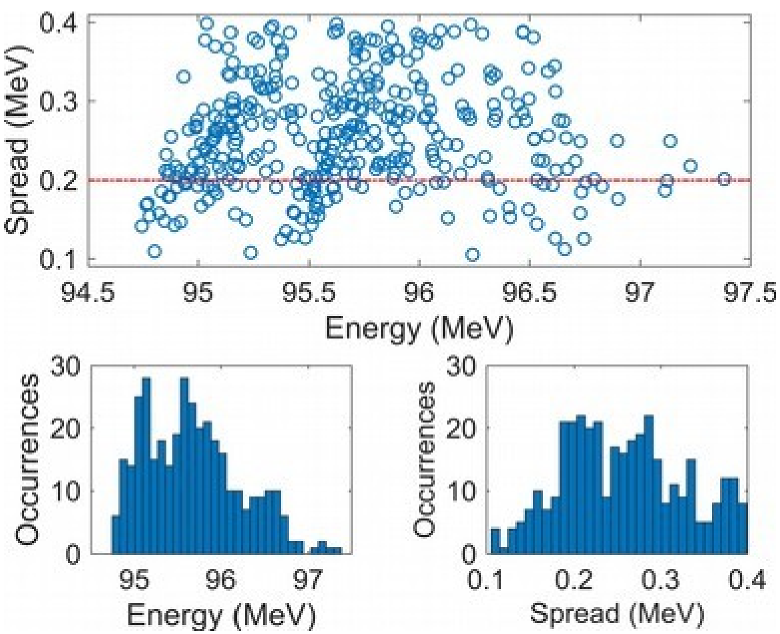
2x10^{15} cm^{-3} plasma density

Energy spread of the accelerated beam slightly increased

Energy spread from 0.2% to 0.26%

Still order of magnitudes lower spread with respect to previous experiments

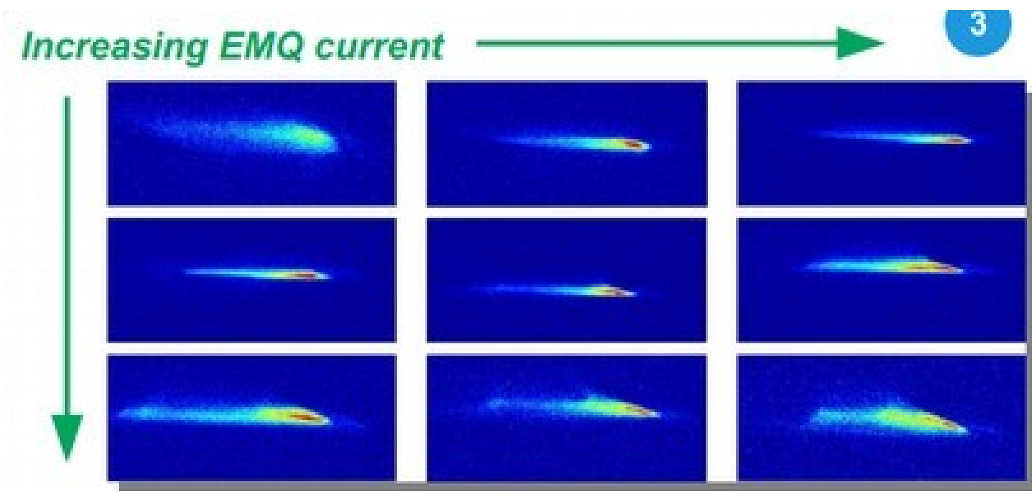




PWFA characterization completed by measuring the witness emittance

Measurement of its normalized emittance through quadrupole scan technique

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



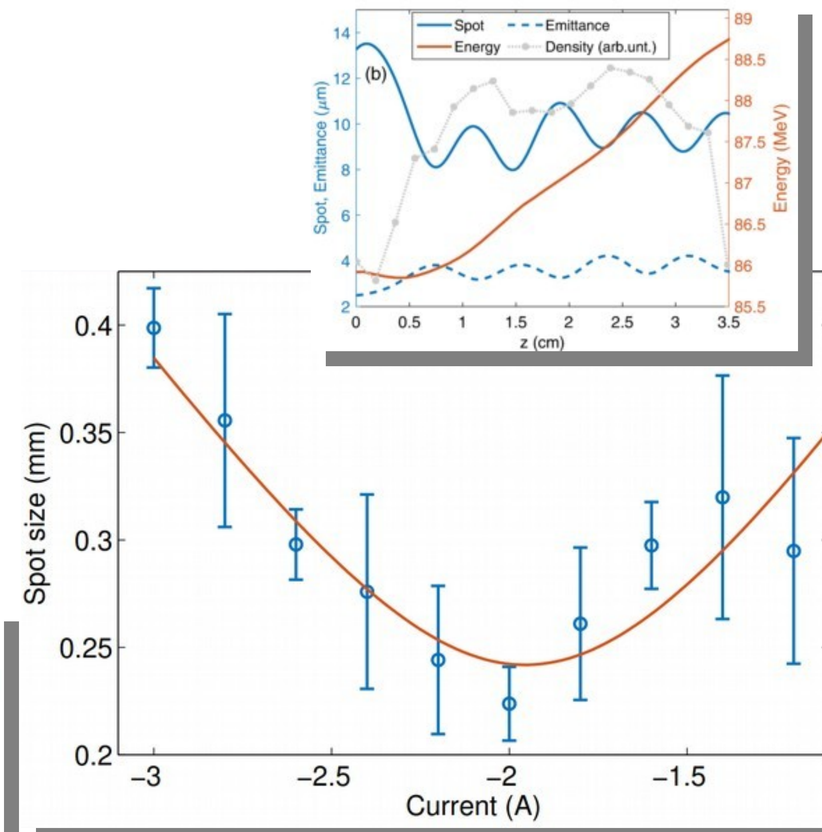
Accepted Paper

First emittance measurement of the beam-driven plasma wakefield accelerated electron beam

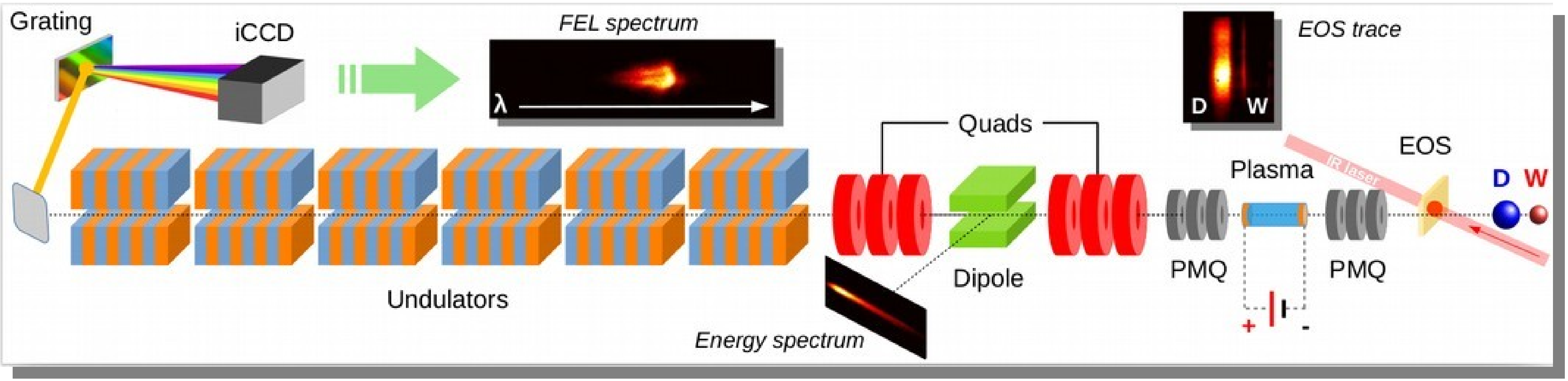
Phys. Rev. Accel. Beams

V. Shpakov et al.

Accepted 13 April 2021



Demonstration of FEL driven by PWFA



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

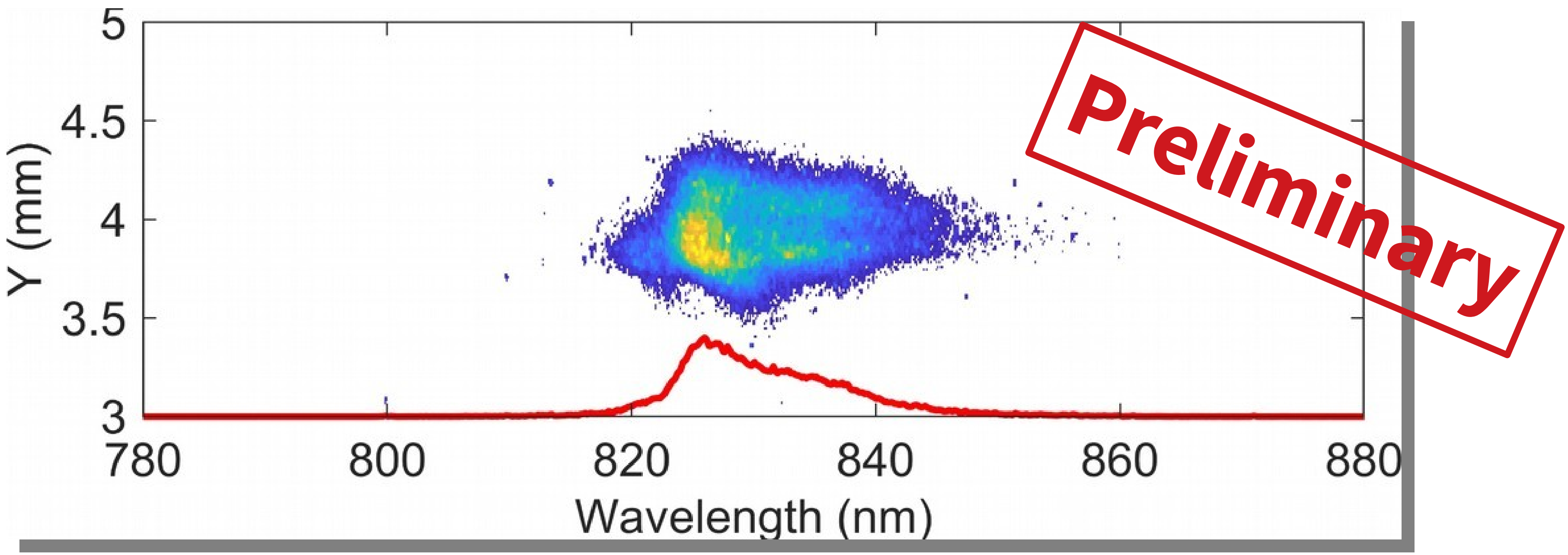
Witness is completely characterized (energy, spread, X/Y emittance) allowing to match it into the undulators beamline

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

Imaging spectrometer with iCCD used to detect FEL radiation

In collaboration with

FEL driven by PWFA: first spectrum

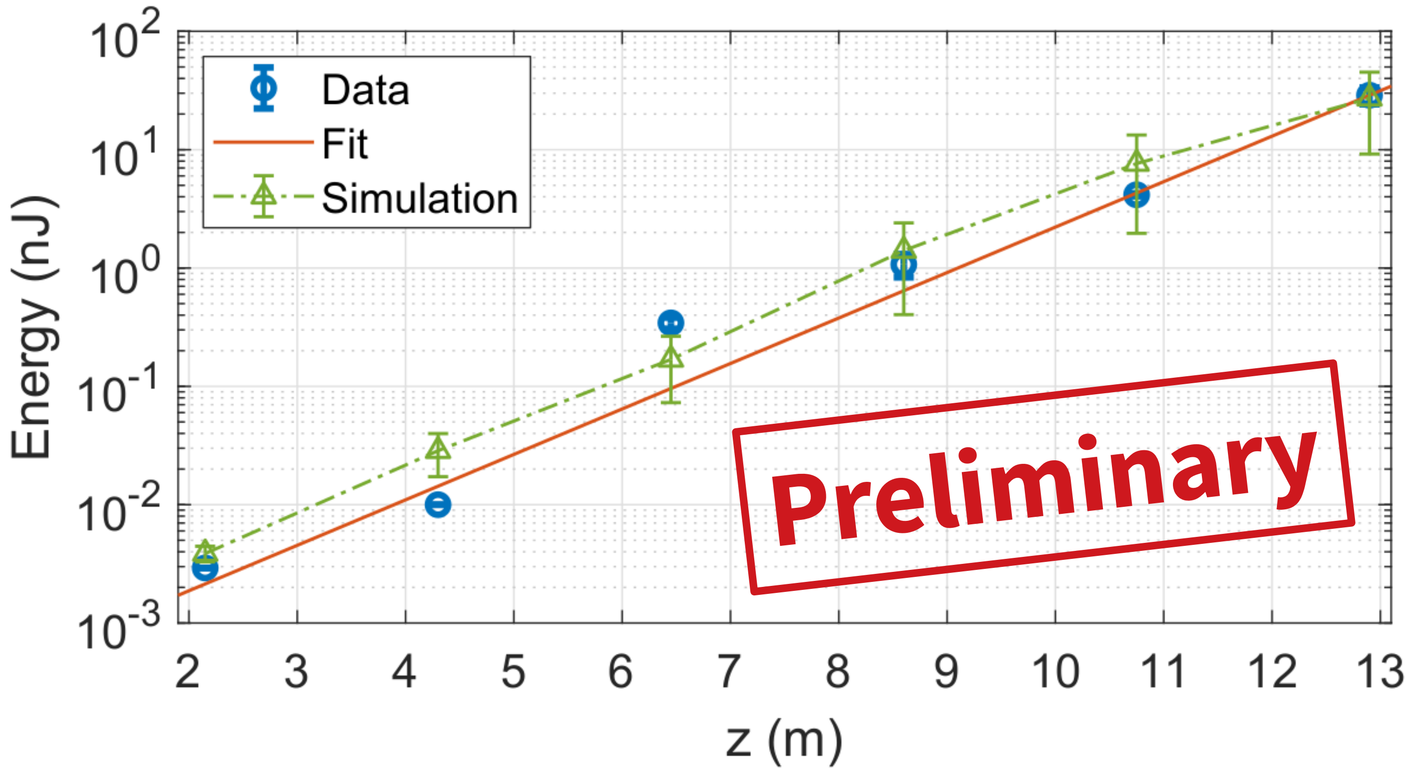


Single-shot spectrum of SASE FEL radiation emitted at 830 nm

6 undulators matched on the plasma accelerated witness bunch

Clear signals, reproducible and stable (<10% disregarded shots)

FEL driven by PWFA: exponential gain



Exponential gain of FEL radiation energy

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

EuPRAXIA@SPARC_LAB

Pictorial view of the new infrastructure @ LNF


EuPRAXIA

INFN
Istituto Nazionale di Fisica Nucleare

LNF–18/03
May 7, 2018

Coordinated by **M. Ferrario**

EuPRAXIA@SPARC_LAB

Conceptual Design Report

Thanks!

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On behalf of the SPARC_LAB collaboration

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati