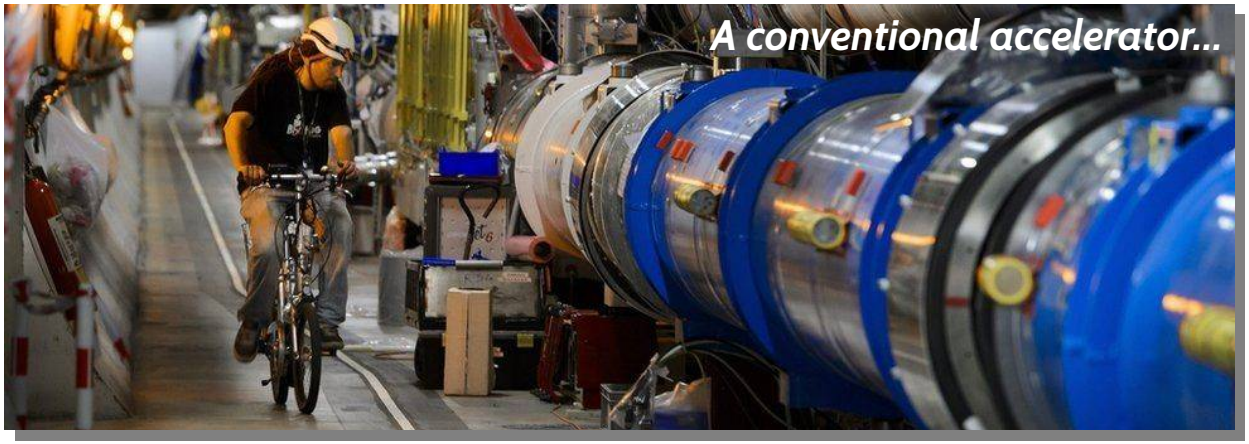
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Novel particle accelerators - progress in the last 4 years

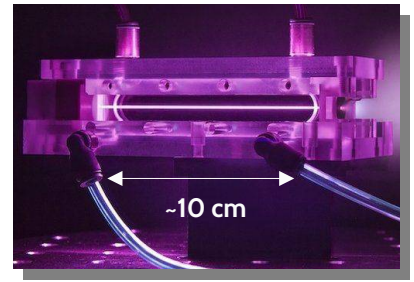
R. Pompili (LNF-INFN)
riccardo.pompili@lnf.infn.it

On behalf of the SPARC_LAB collaboration

Plasma acceleration



...a plasma accelerator



Conventional accelerators use RF waves propagating in metallic cavities

*Limited by **electric breakdown**: largest electric fields are ≈ **10-100 MV/m***

For this reason the accelerator size can reach many km

Plasma accelerators can go beyond such limits

*Plasma not affected by electric breakdown → electric fields reach **100s GV/m***

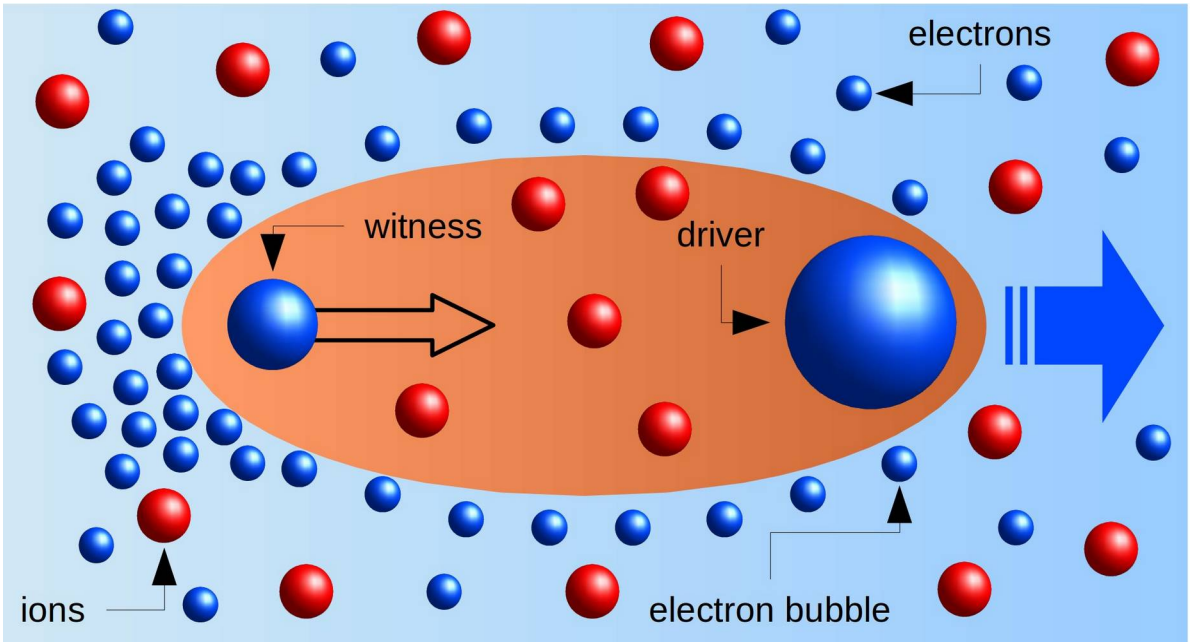
*Sizes reduce from **km to cm → next-generation compact accelerators***

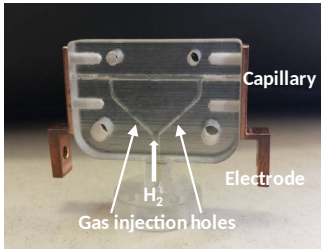
EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

EuPRAXIA

This project has received funding from the European Union´s Horizon Europe research and innovation programme under grant agreement No. 101079773

Working principle





$$E_0 = \frac{m_e c \omega_p}{e} \simeq 96 \sqrt{n_0 (cm^{-3})}$$

$$\rightarrow E_0 \approx 10 \frac{GV}{m} @ n_0 = 10^{16} cm^{-3}$$

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*

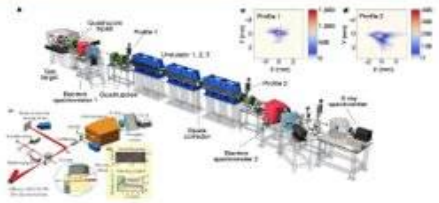
Free-Electron Laser driven by plasma accelerators (1)

Laser-driven plasma accelerators

Beam-driven plasma accelerators

2021 Plasma FEL Feasibility Proven: Laser-driven

W. T. Wang, K. Feng, *et al.*, *Nature*, **595**, 561 (2021).



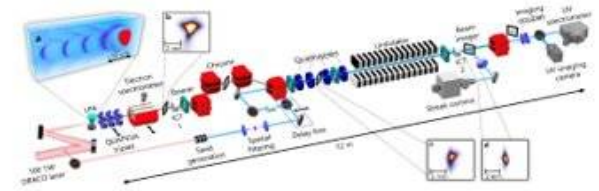
Recent ground-breaking result in China

500 MeV electron beam from a laser wakefield accelerator

FEL lasing **amplification of 100** reached at 27 nm wavelength (average radiation energy 70 nJ, peak up to 150 nJ)

Seeded UV free-electron laser driven by LWFA

Collaboration Soleil/HZ Dresden, published on
Nat. Photon. (2022). https://doi.org/10.1038/s41566-022-01104-w



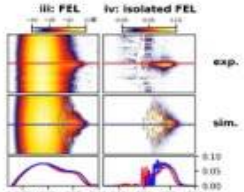


FIG. 1. **Experimental layout.** The electron beam generated in the LPA is first characterized using a removable electron spectrometer and then sent through a triplet of quadrupoles (QUAPEVAs) for beam transport to the undulator and FEL radiation generation. ICTic Integrated Current Transformers. Non-labelled elements: dipoles (red blocks), optical lenses (blue), mirrors (grey *overlaid black disks*). Inset a: Particle-in-Cell simulation renders of the accelerating structure driven by the laser pulse (red), the electron cavity sheet formed from the plasma medium (light blue) is visible in purple and the accelerated electron bunch visible in green. Insets b,c,d: Electron beam transverse distribution measured at LPA exit (b), at undulator entrance (c) and at undulator exit (d).

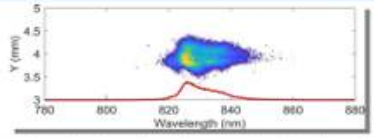
2021 Plasma FEL Feasibility Proven: Electron-driven

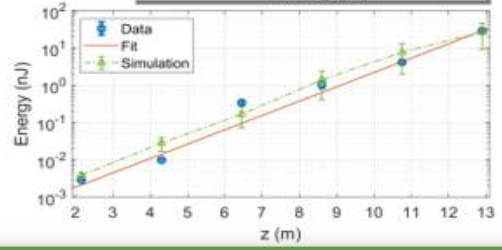
Recent ground-breaking results in Frascati:

First FEL lasing from a beam-driven plasma accelerator

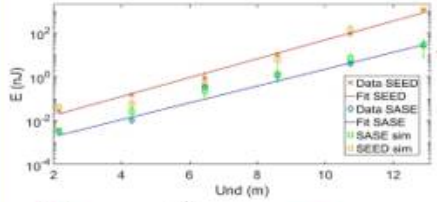
Pompili et al., Nature **605**, 659–662 (2022)

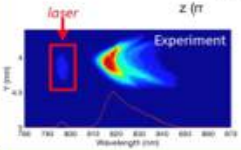
Single Spike SASE spectrum

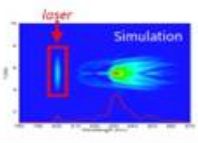




First Beam Driven SEEDED - FEL Lasing at SPARC_LAB (June 2021)



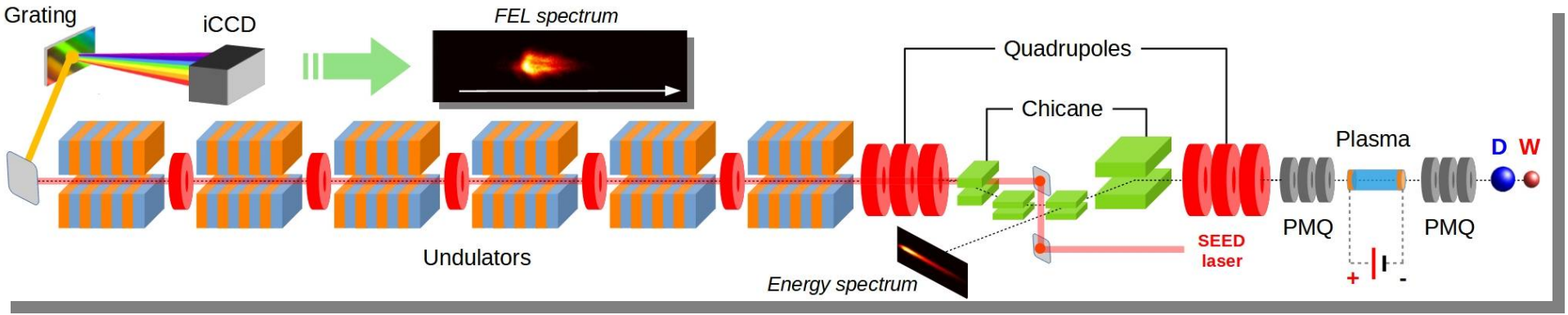




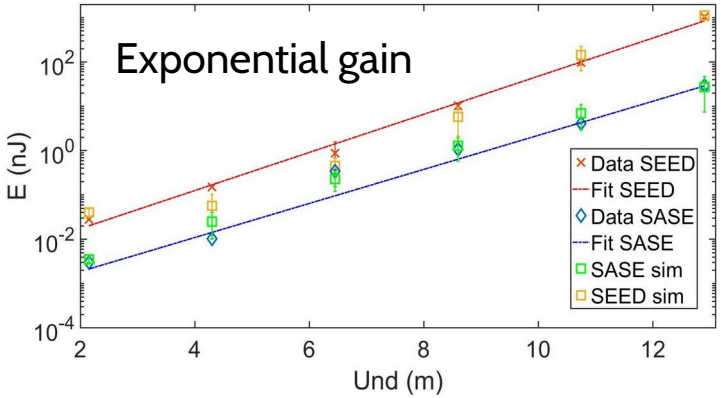
Seeded FEL radiation

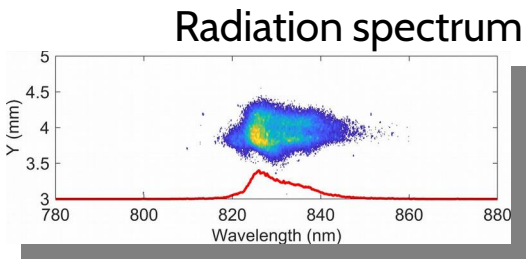
- ✓ Pulse energy increased 2 order of magnitude respect to SASE radiation
- ✓ 6% pulse energy RMS fluctuations over 90% of successful shot respect to 17% over 30% of shot for SASE

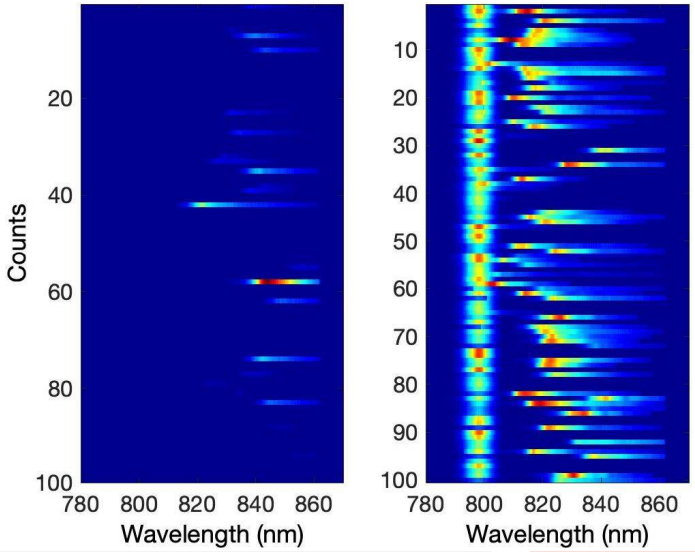
Free-Electron Laser driven by plasma accelerators (2)



Pompili, R., et al., Nature 605.7911 (2022): 659-662.



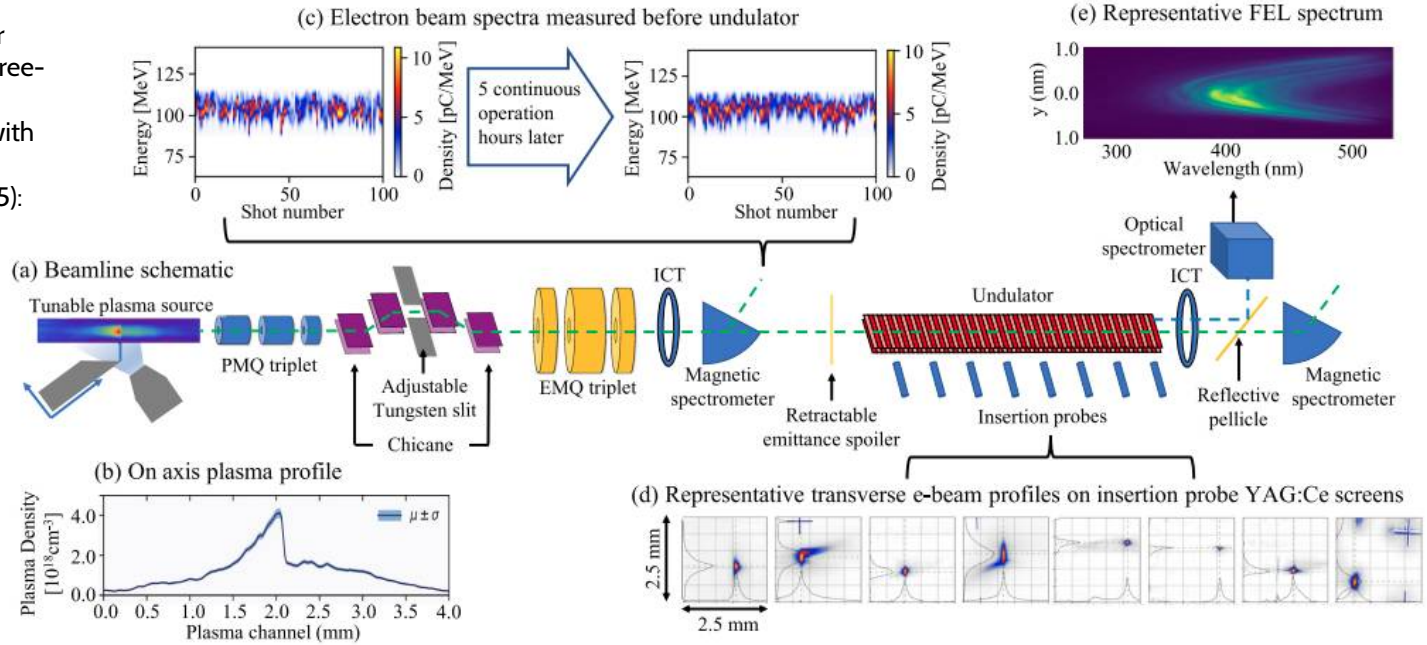




Galletti, M., et al. Physical review letters 129.23 (2022): 234801.
Galletti, M., et al., Nature Photonics 18.8 (2024): 780-791.

Free-Electron Laser driven by plasma accelerators (3)

Barber, S. K., et al. "Greater than 1000-fold gain in a free-electron laser driven by a laser-plasma accelerator with high reliability." Physical Review Letters 135.5 (2025): 055001.



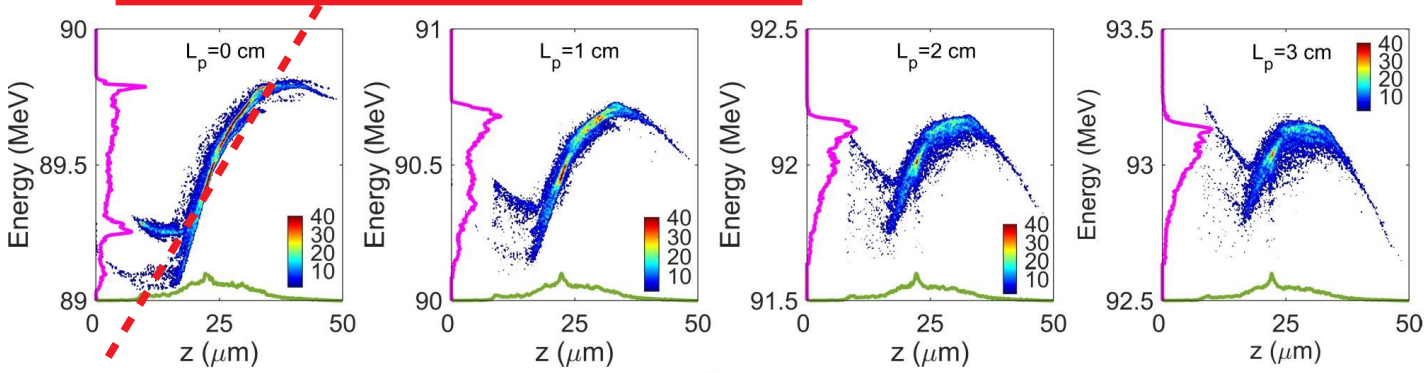
Latest results (2025) obtained by the LBNL group demonstrating improved gain and reliability

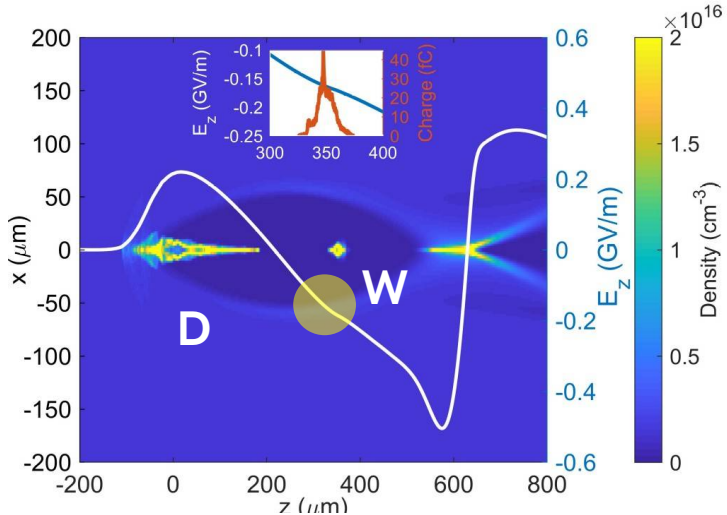
Exponential gain @ 420 nm obtained in SASE along 4 undulators (1 m long each one)

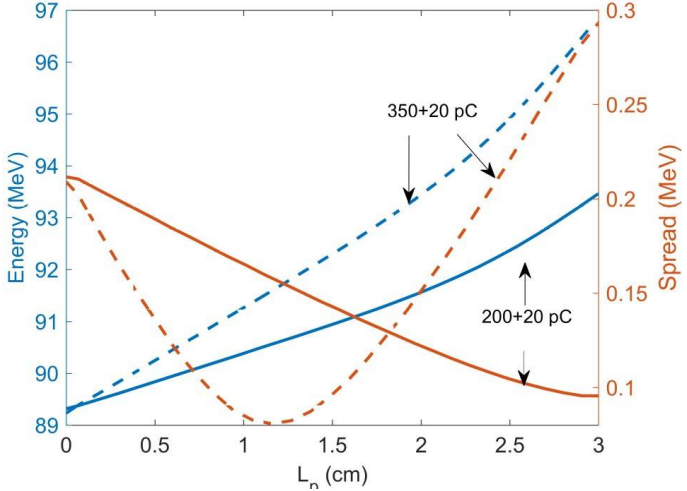
>90% shots obtained with FEL radiation

Taking energy spread under control

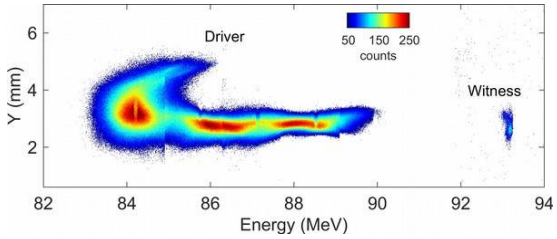
Pre-chirp to compensate wakefield slope







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



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>

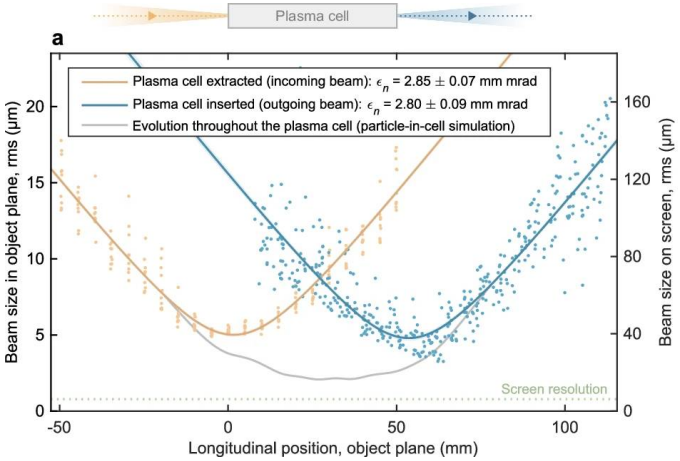
- ***Spread from 0.2% to 0.12%***

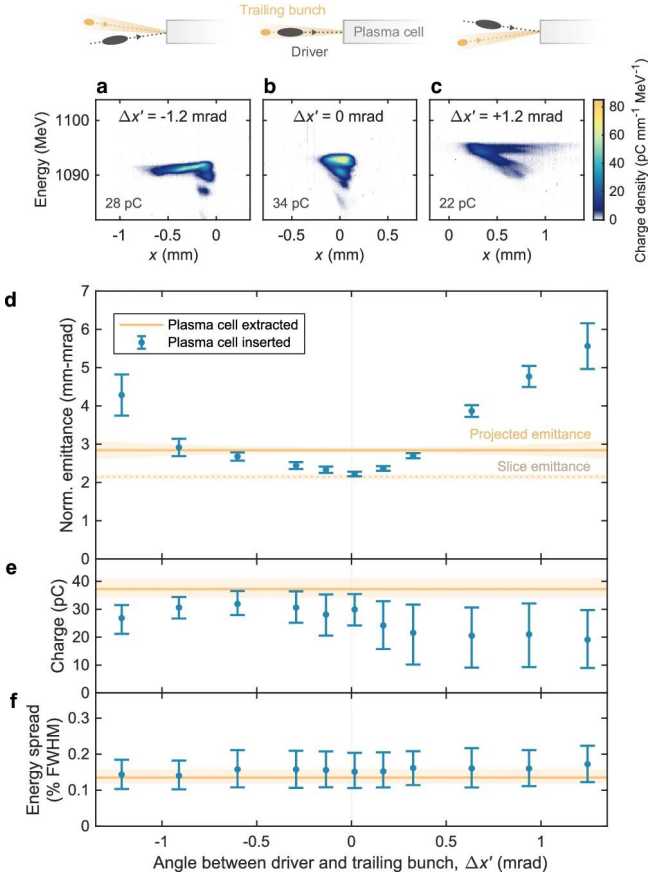
Taking emittance under control

Demonstration of emittance preservation in a beam-driven plasma accelerator

Preservation obtained thanks to a proper transverse matching of the beam into the plasma channel

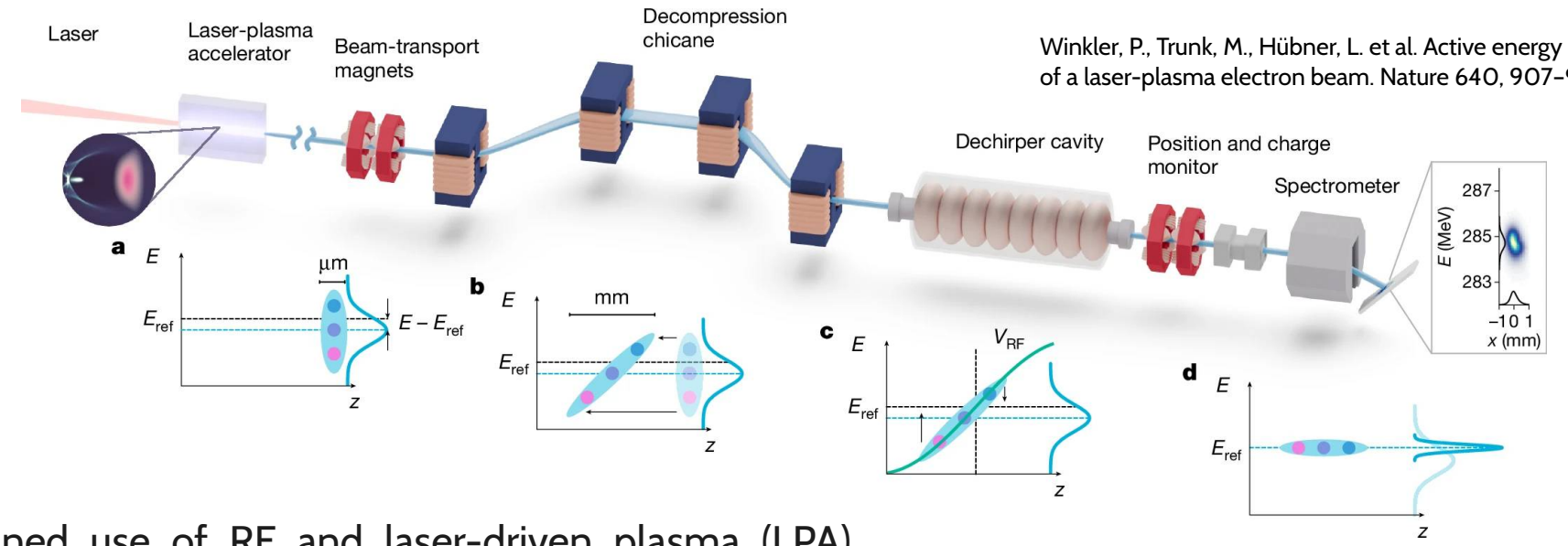
Effects of driver-witness angular misalignment studied





Lindstrøm, Carl Andreas, et al. "Emittance preservation in a plasma-wakefield accelerator." Nature Communications 15.1 (2024): 6097.

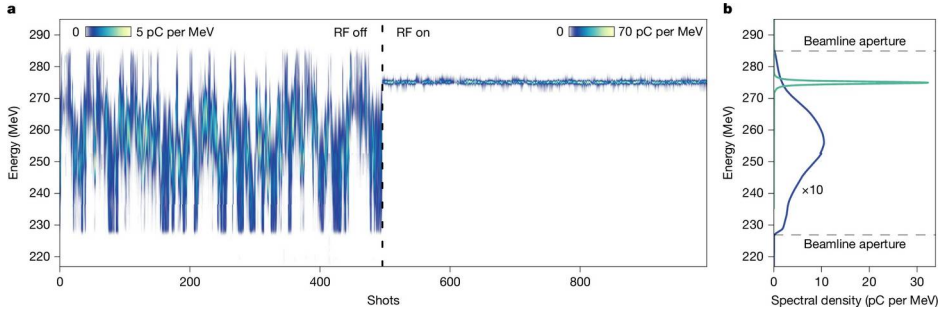
Taking energy-jitter under control



Winkler, P., Trunk, M., Hübner, L. et al. Active energy compression of a laser-plasma electron beam. Nature 640, 907–910 (2025)

Combined use of RF and laser-driven plasma (LPA) accelerators

- *Magnetic chicane in between used to convert the LPA energy-jitter into a timing (phase)-jitter*
- *A 5 m long S-band RF cavity used as "dechirper" → RF phase counteracts the incoming beam timing-jitter*
- ***Energy jitter from 3.5%→0.05%, spread from 1.8%→ 0.1%***



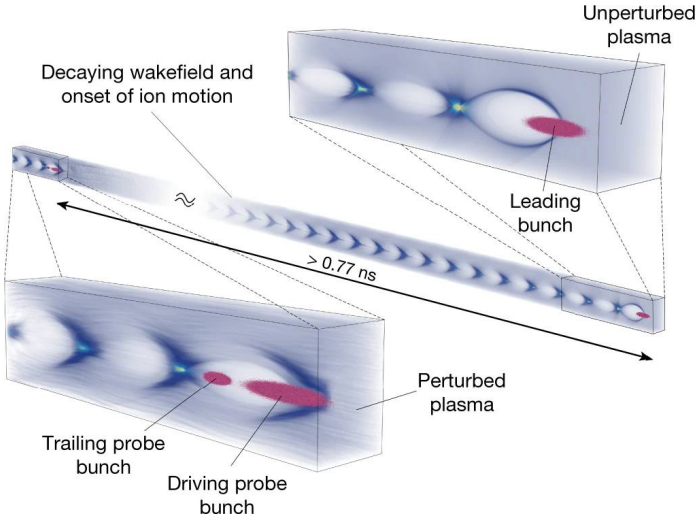
Recovery time of a plasma accelerator (1)

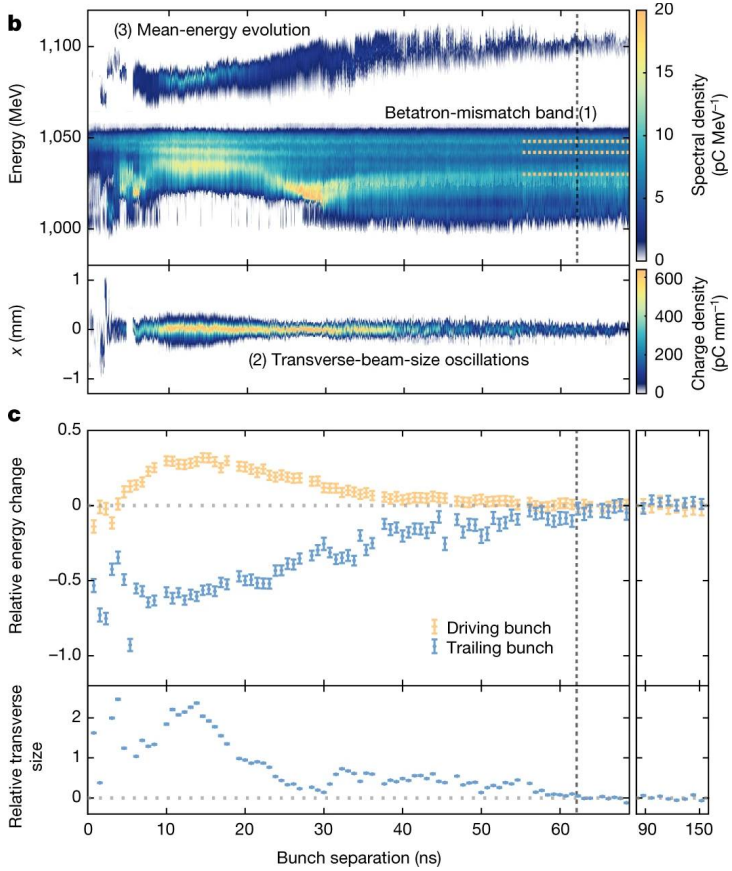
Goal: define the upper limit on repetition rates of beam-driven plasma accelerators

Measurement of the time it takes for the plasma to recover to its initial state after the perturbation induced by a driver bunch

Finding: **~63 ns wait time for an Argon plasma source**

*Equivalent to **~15 MHz max repetition rates***

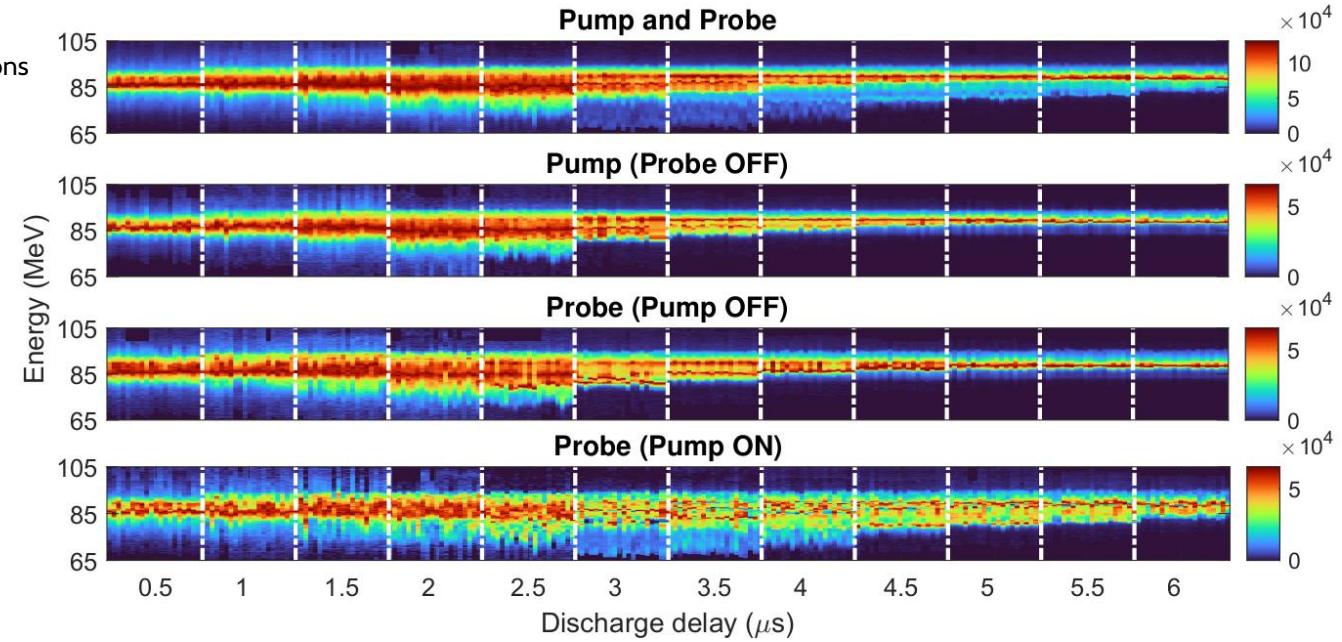




D'Arcy, R., et al. Recovery time of a plasma-wakefield accelerator. Nature 603, 58–62 (2022)

Recovery time of a plasma accelerator (2)

Pompili, R., et al., Communications Physics 7.1 (2024): 241.

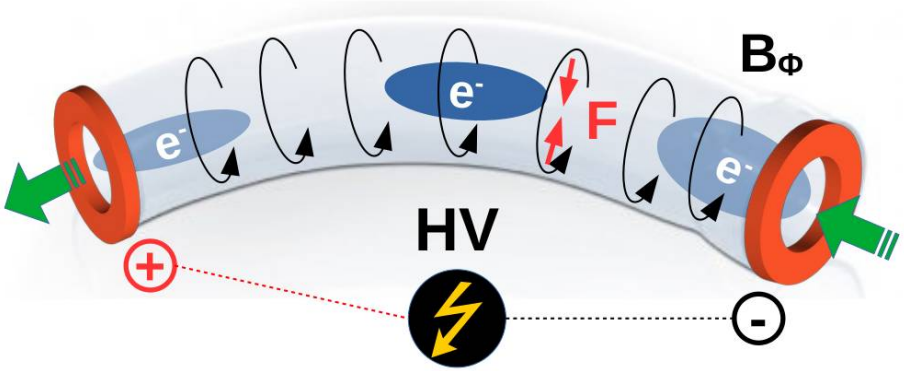


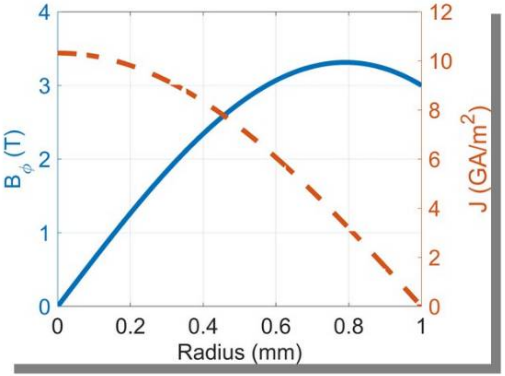
Following DESY results with Argon, we repeated the experiment with a Hydrogen plasma source

Expected to observe faster recovery time due to the smaller ion masses. The experiment revealed signatures of "ion motion" that were completely removed in **less than a nanosecond (~0.7 ns)**

GHz repetition rates are in principle feasible for Hydrogen plasma-based accelerators!

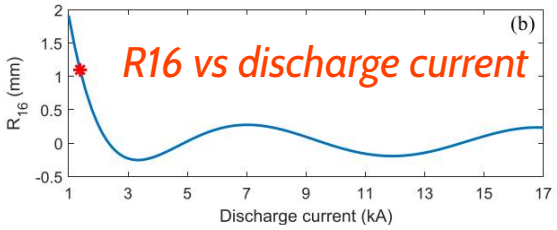
Other uses of plasmas: beam bending





Active-Plasma Bending device: a plasma-discharge propagates in a curved capillary

- ✔ ***Compact*** → *bending and focusing in one device!*
- ✔ ***Achromatic*** → *propagation of ultra-short particle beams*



Example:
15 kA pulses
→ 4 T fields!

Pompili, R., et al. "Guiding of charged particle beams in curved plasma-discharge capillaries." Physical Review Letters 132.21 (2024): 215001.

Proof-of-principle experiment at SPARC_LAB

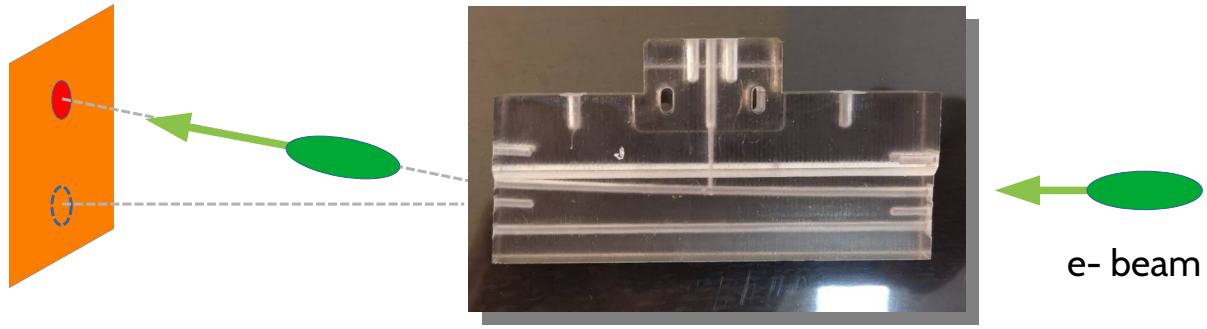
Conventional bending magnet ~ 50 cm

In 2023 we conducted a proof-of-principle experiment at SPARC_LAB (**LNF-INFN**)

- *60 MeV electron beam from the **SPARC_LAB** linac*
- *2.2 kA peak discharge-current with 1 us pulse duration*

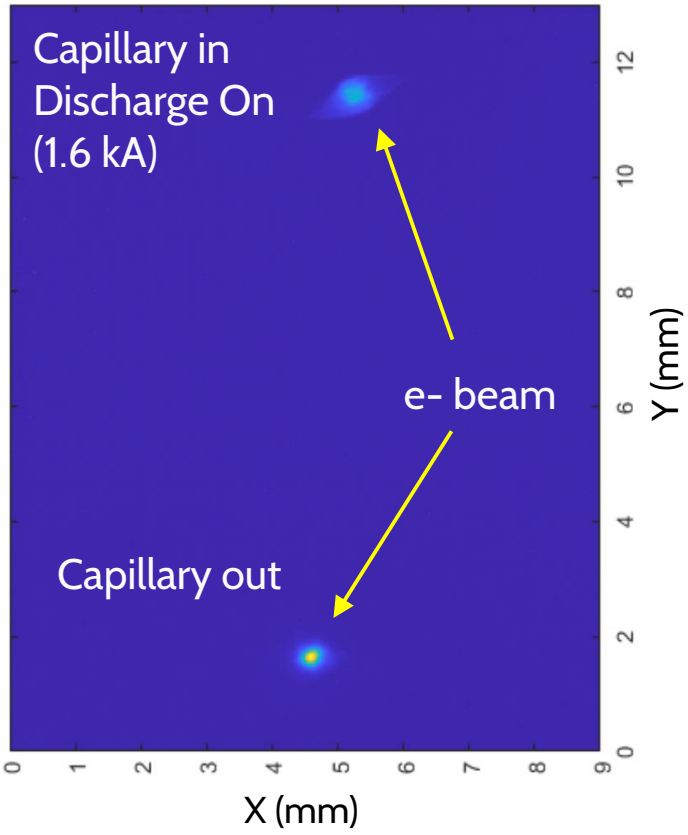
Goal: demonstrate achromatic bending

APPLE prototype: 10 cm

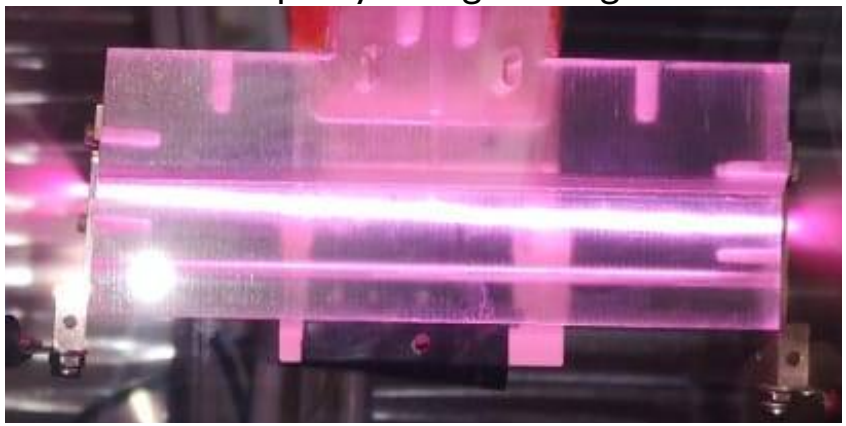


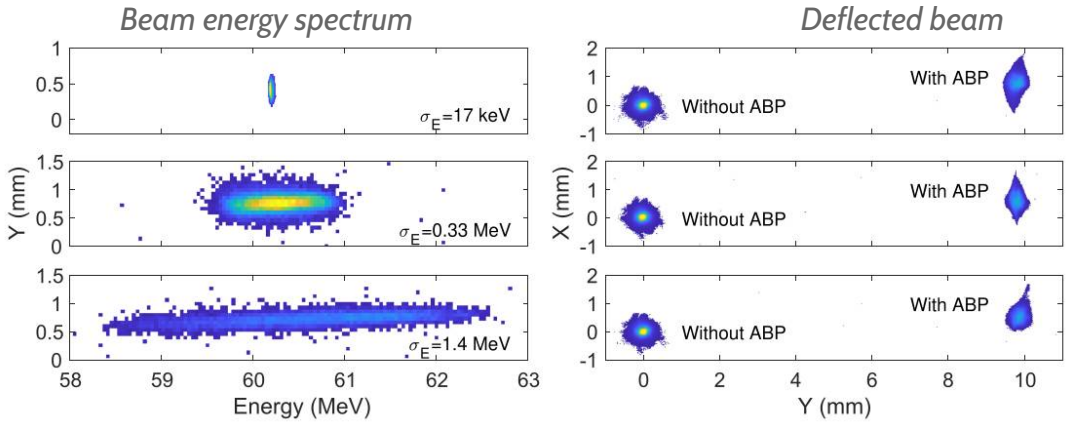
It worked!

Electron beam measured on a screen



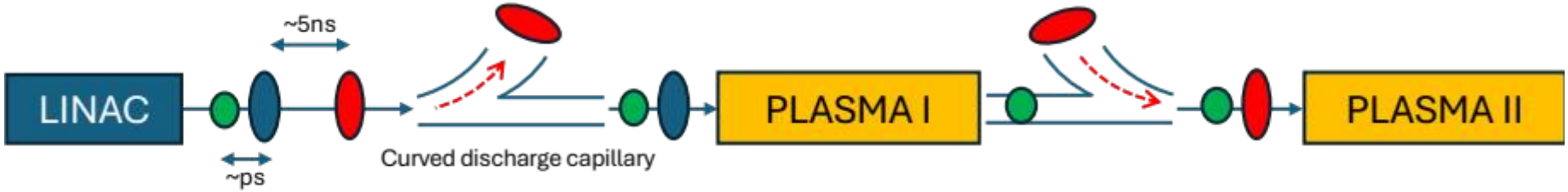
Capillary during discharge





Task included in the EPITA proposal

Thanks to L. Verra



Active-plasma bending can be exploited to demonstrate the staging of multiple plasma modules.

Staging of multiple PWFAs requires capturing the witness bunch after each stage and re-injecting it into the following one, while independent driver bunches generate high-amplitude wakefields in each stage.

One of the key aspects is the delivery of the driver bunches, that, due to power-consumption considerations, need to be generated by a single main accelerator.

Each driver must be injected into each stage with the appropriate timing synchronization (at the picosecond level), while bypassing the preceding ones.

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Thanks!

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

On behalf of the SPARC_LAB collaboration

Further analysis

Parametric scan obtained by varying the discharge-current for each energy spread conf.

Each point is the average of 100 consecutive shots

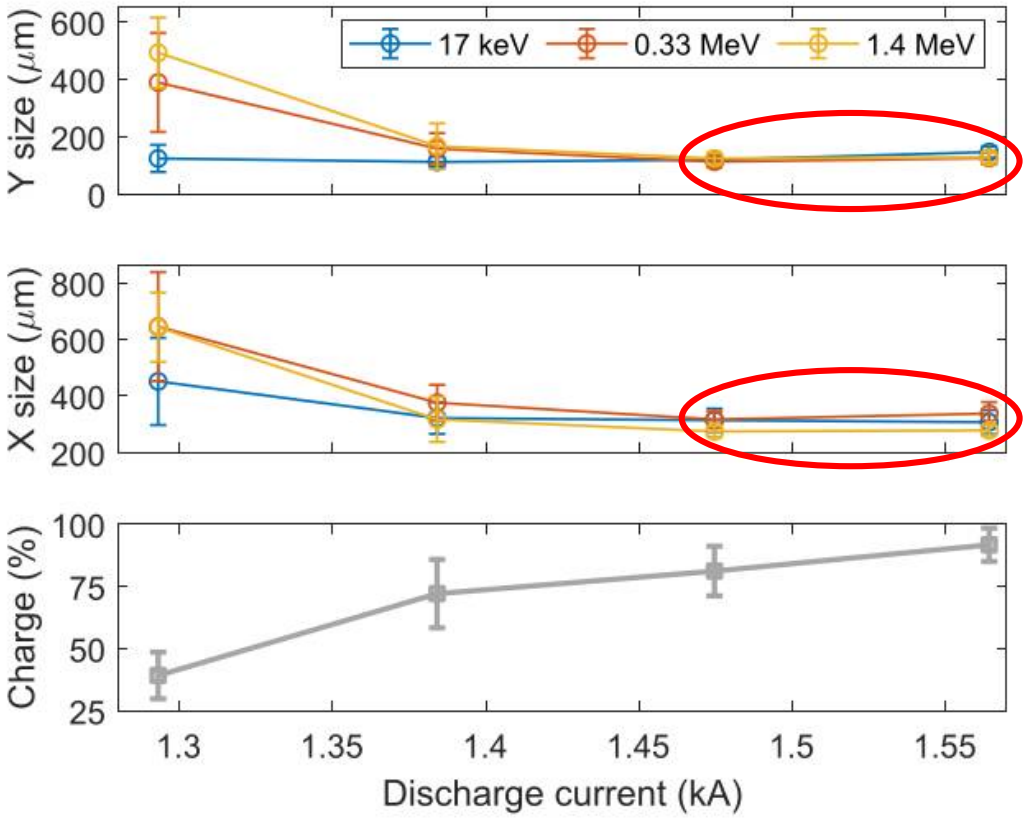
Last plot shows the transmitted charge

Guiding efficiency proportional to the discharge current. No transmitted charge when it is turned off (charge absorbed by the capillary walls)

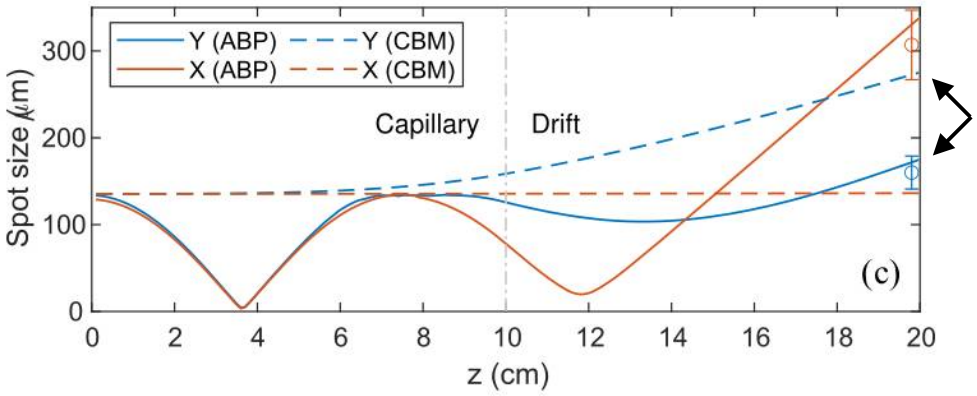
Negligible dependence of the X/Y transverse beam sizes on the energy spread

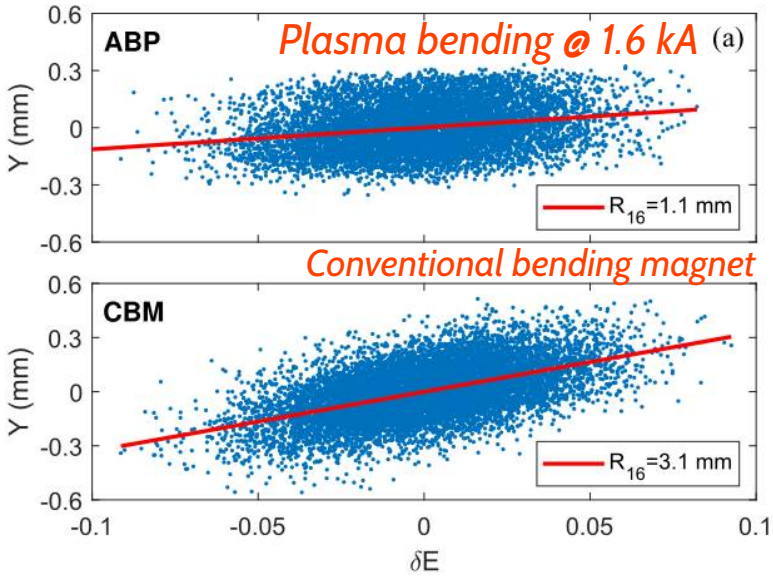
Beam deflection is obtained achromatically

$$\sigma^2 = R_{11}^2 \beta \epsilon - 2 R_{11} R_{12} \alpha \epsilon + R_{22}^2 \gamma \epsilon + R_{16}^2 \sigma_E^2$$



Tunability of the R16 matrix term

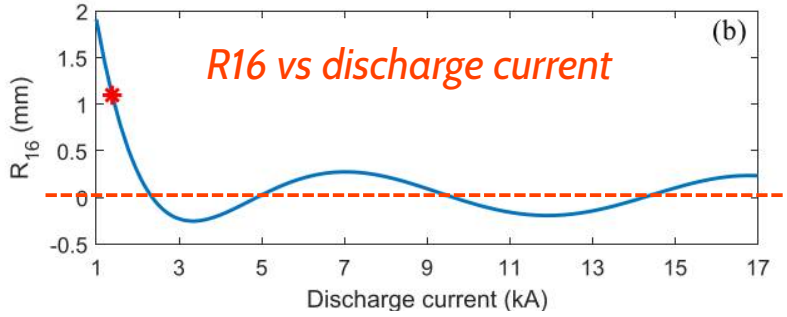




Achromatic bending is achieved because particles at different energies have traveled along a similar path

Larger discharge-currents reduce particles trajectories differences

$$R_{16} = \frac{1}{\rho_0 k_x^2}\left(1-\cos k_x s\right) \qquad k_x = \sqrt{\frac{I}{\tilde{I}_0 \gamma r_c^2} + \frac{1}{\rho_0^2}}$$



Frazzitta, A., at al., Physical Review Accelerators and Beams 27.9 (2024): 091301.