SPARC_LAB – CLARA meeting

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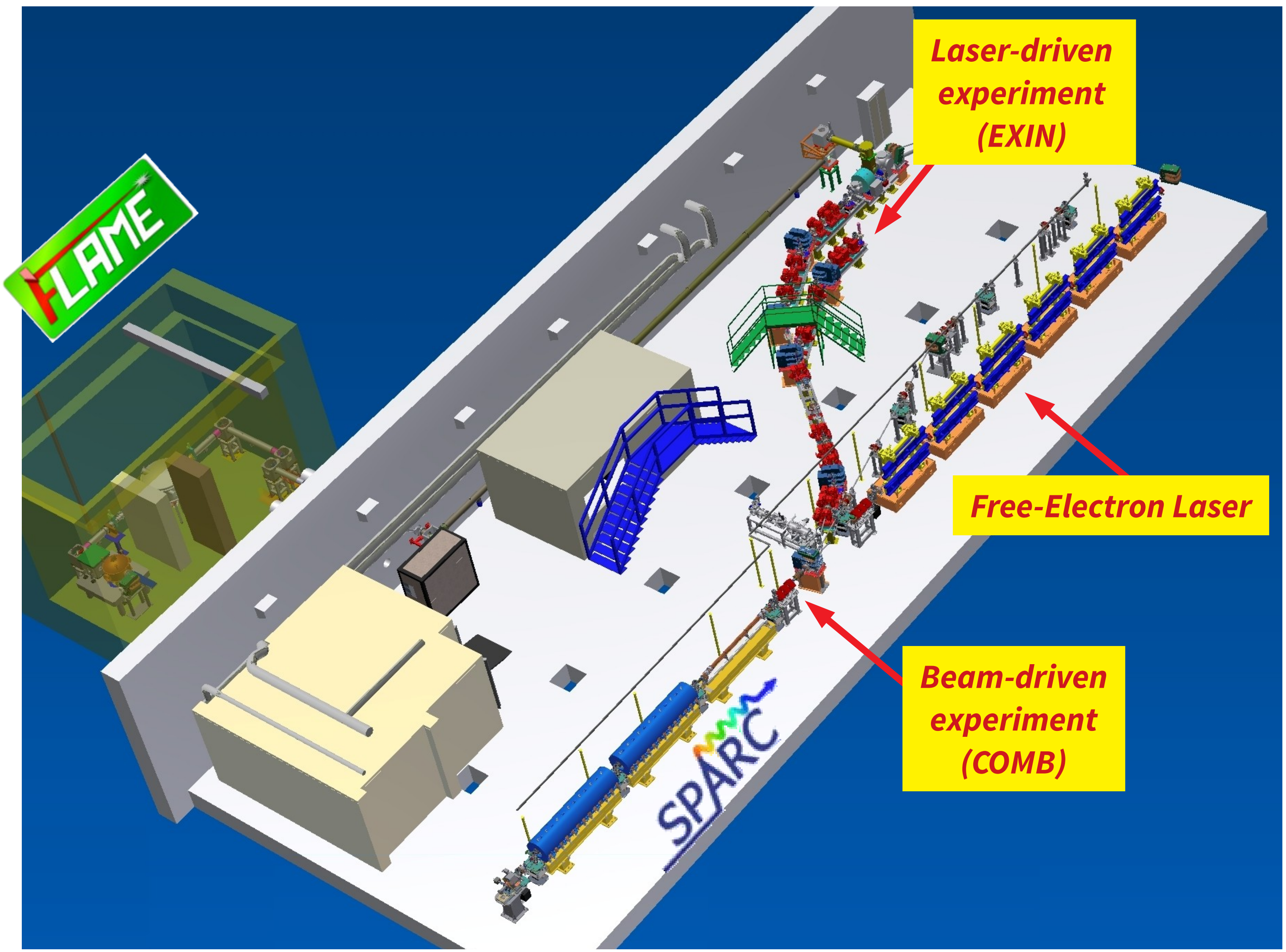
On behalf of the SPARC_LAB collaboration

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

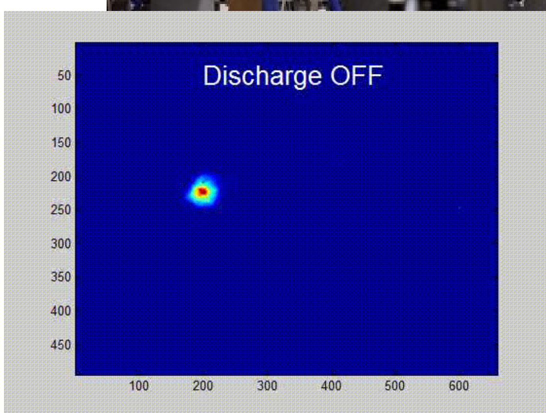
SPARC_LAB facility



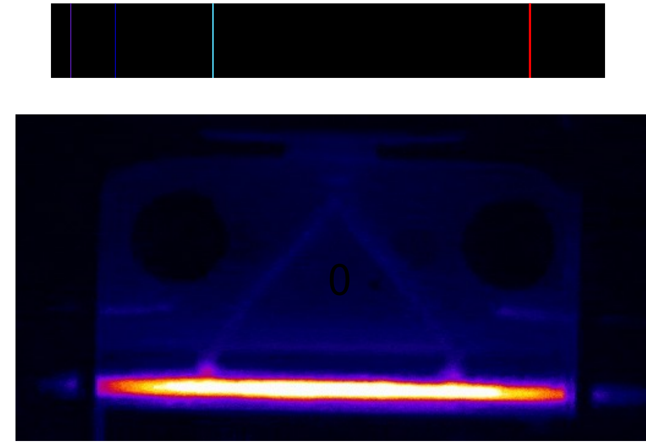
Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

Experience with plasma @ SPARC

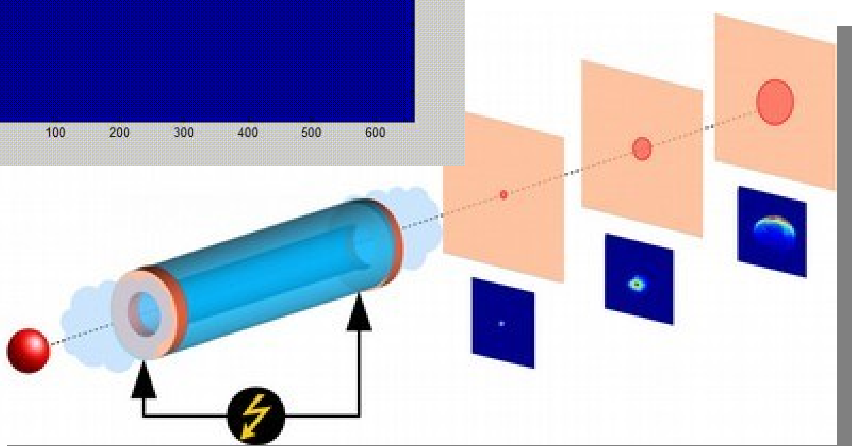
Activities with the high-brightness SPARC photo-injector



Plasma characterization

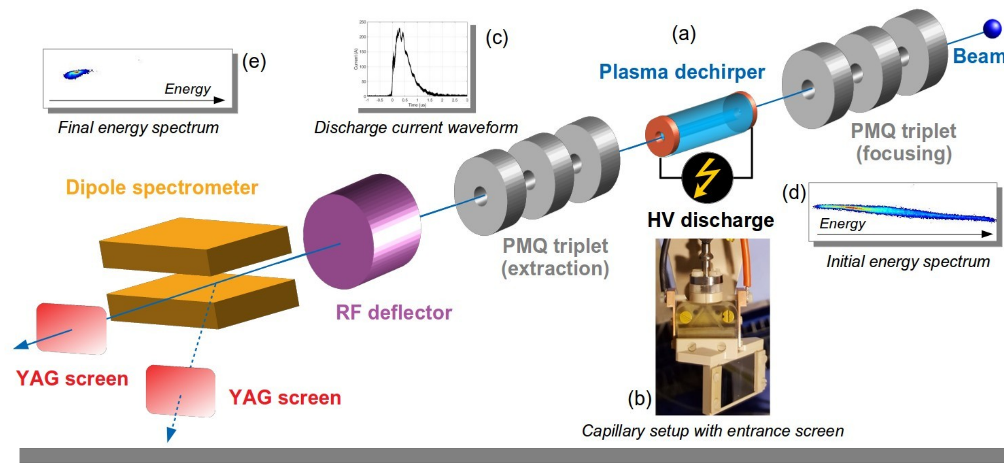


Biagioni, A., et al., Journal of Instrumentation 11.08 (2016): C08003.



Focusing with active-plasma lenses

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

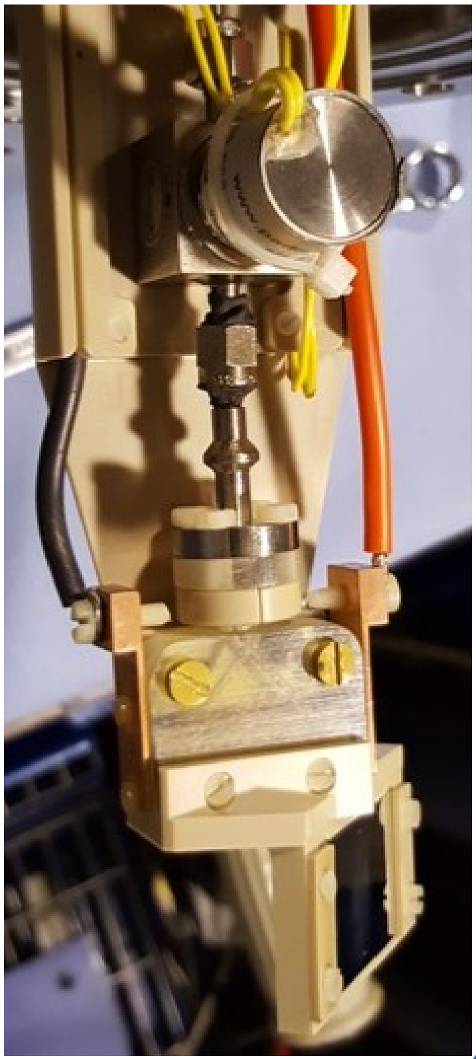


Longitudinal phase-space manipulation

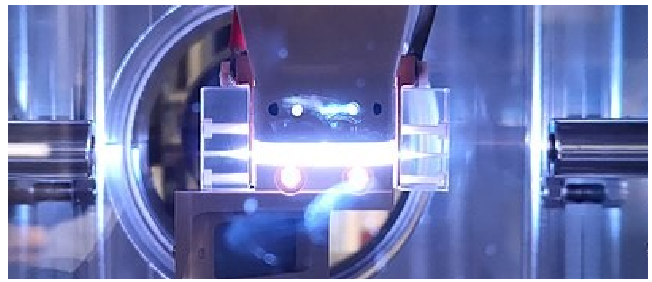
V. Shpakov et al. Phys. Rev. Lett. 122, 114801 (2019)

Plasma stabilization: valve insulation

Original setup



Use of outer elongations



Additional insulation

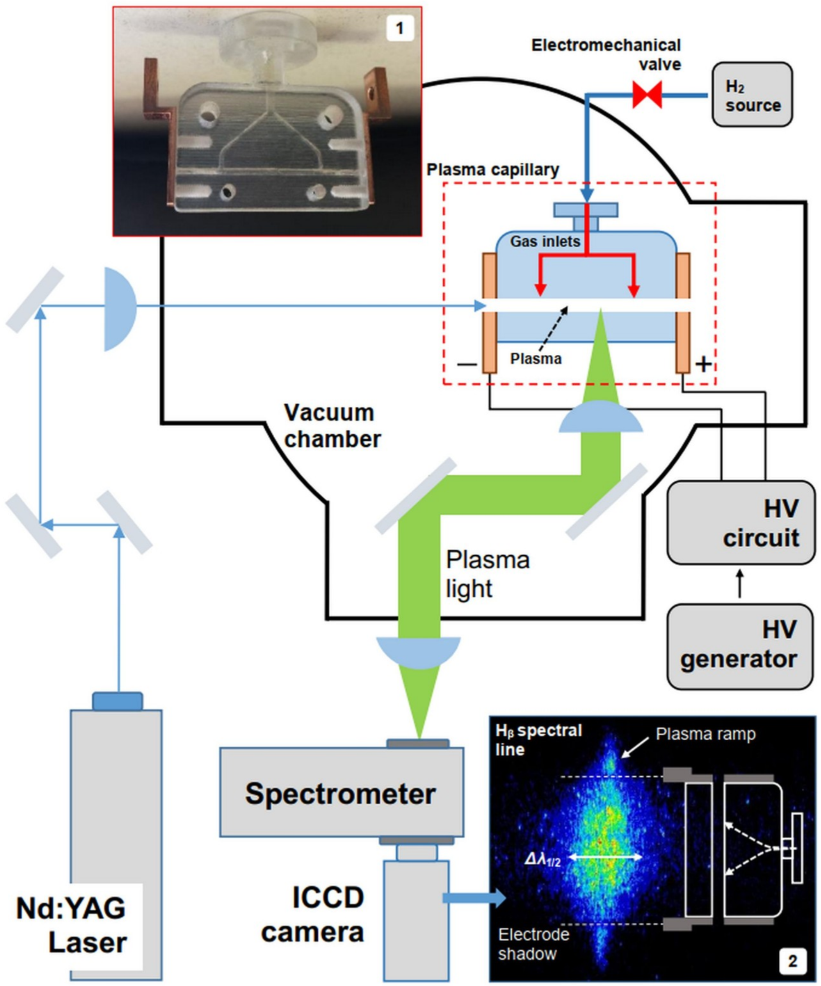
Plasma stabilization

We found that in PWFA with the driver and witness bunches externally injected from the linac, there are two main sources of jitter

- *Plasma density fluctuations*
- *Driver-witness separation jitter (limited by RF sync)*

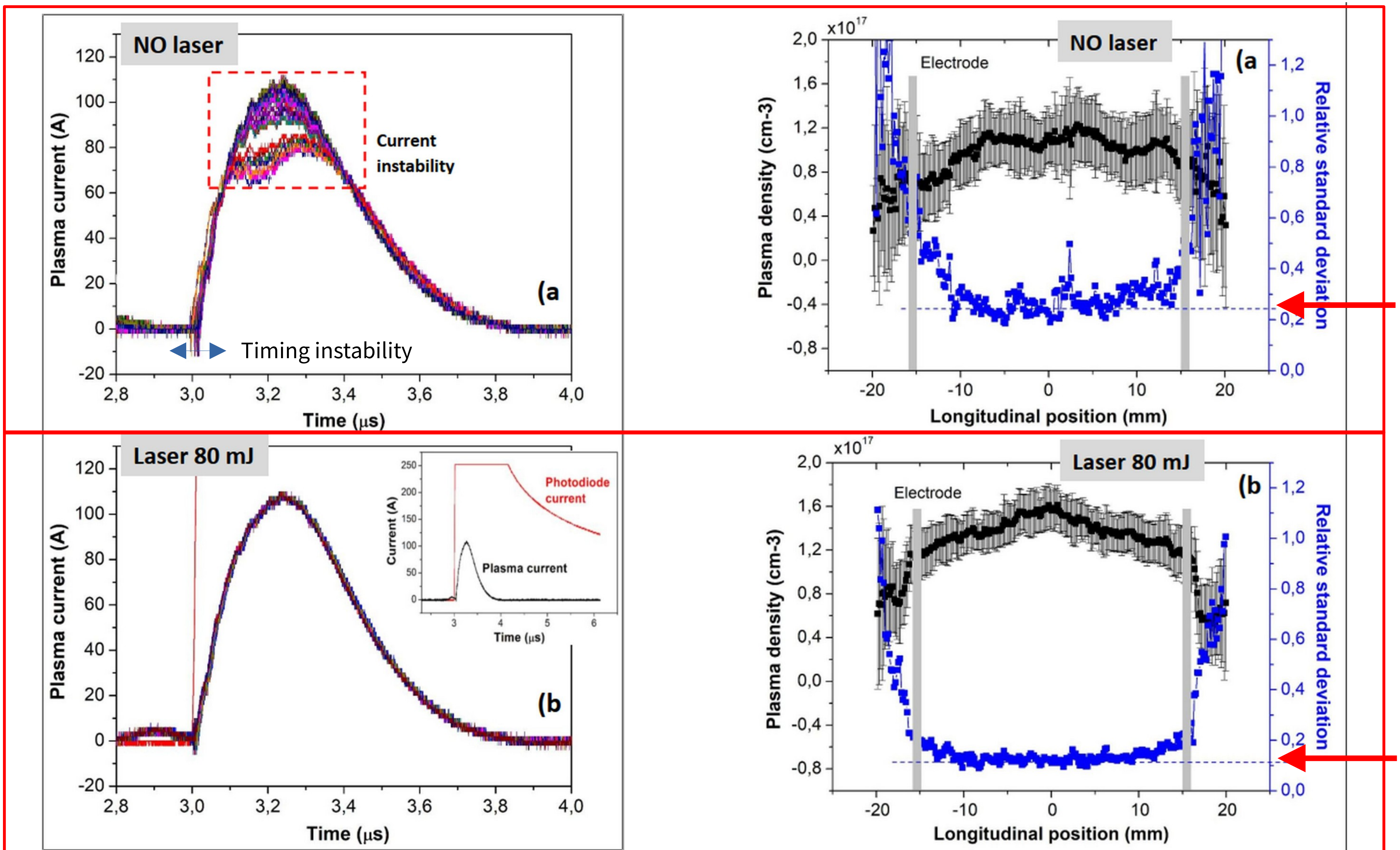
To reduce the 1st source, we pre-ionize the Hydrogen gas with an external laser

- *The laser reaches the negative electrode hole ~100ns before the discharge trigger*
- *Low laser energy is enough (~100 uJ, 2mm diameter)*
- *Plasma density measured with Stark-broadening*

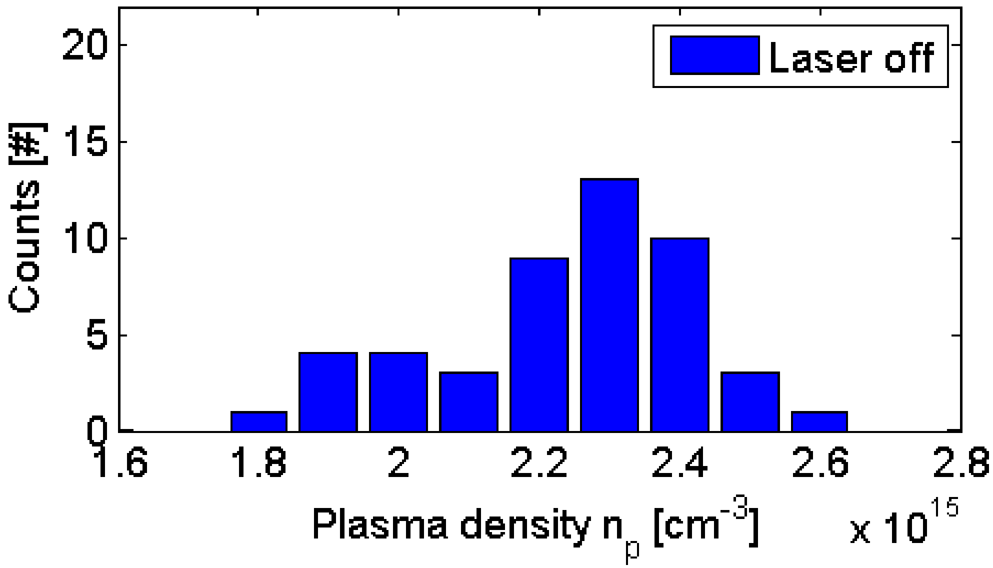


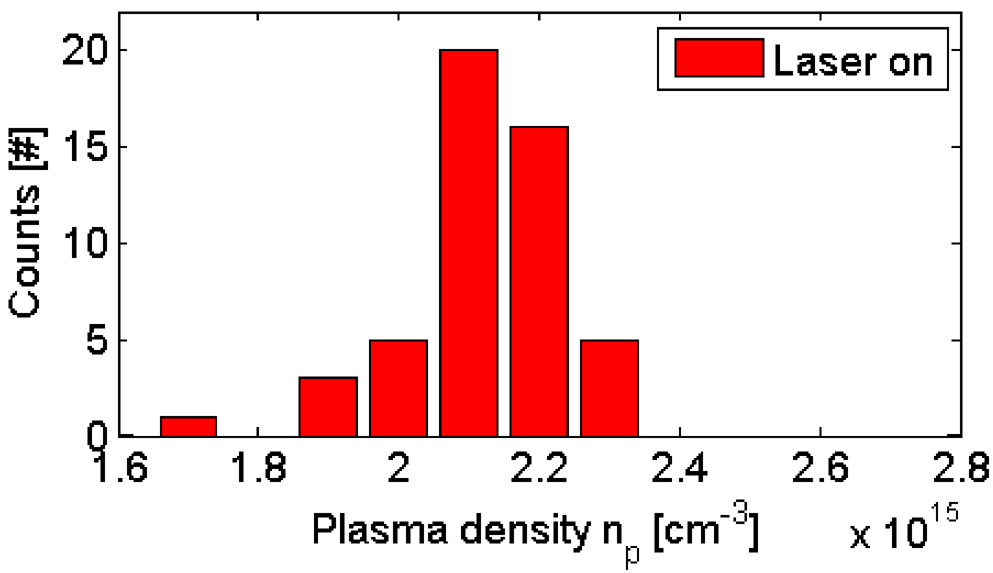
Biagioni, A., et al. "Gas-filled capillary-discharge stabilization for plasma-based accelerators by means of a laser pulse." Plasma Physics and Controlled Fusion (2021).

Plasma stabilization



Beam-based measurements





Plasma density was measured via LPS (50 images) in the new capillary at the delay -2600 ns with trigger laser on and off (11 kV HV)

Laser OFF results

$$n_p = 2.2 \cdot 10^{15} \pm 18\%$$

Laser ON results

$$n_p = 2.1 \cdot 10^{15} \pm 6\%$$

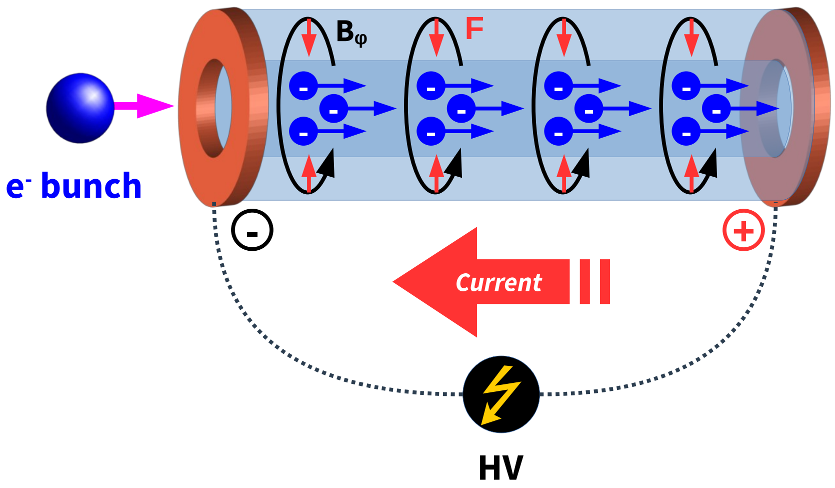
Romeo, S., et al. "Beam-based characterization of plasma density in a capillary-discharge waveguide." AIP Advances 11.6 (2021): 065217.

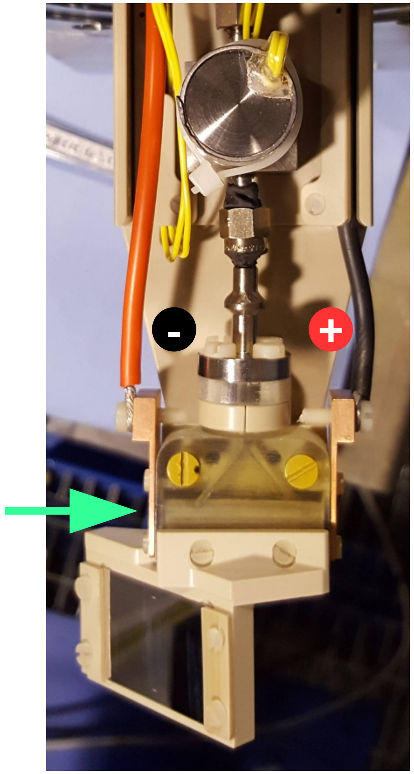
Active-plasma lens

Focusing produced by electric discharge in plasma-filled capillary

Magnetic field follows Ampere Law

$$B_\phi(r) = \frac{\mu_0}{r}\int_0^r J(r')\,r'\,dr'$$





Weak chromaticity

Like in quadrupoles → K~1/γ

Radially symmetric

Like in solenoids

Compactness

kT/m magnetic field → much larger than strongest quadrupoles available (PMQ)

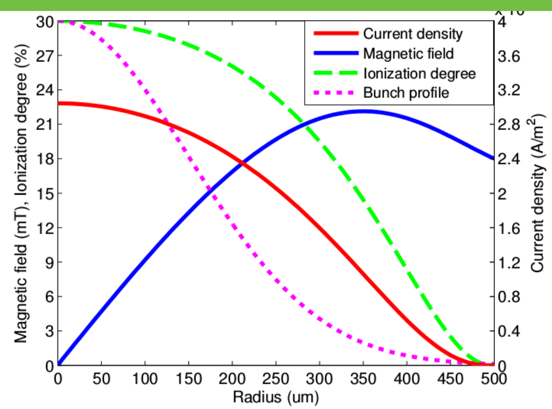
Not sensitive to beam distribution

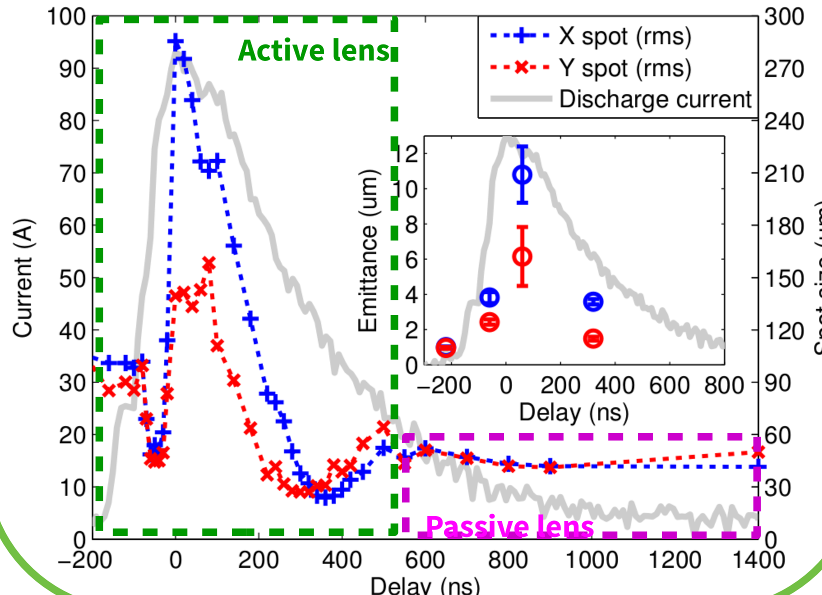
As in passive-plasma lenses

Panofsky, Wolfgang Kurt Hermann, and W. R. Baker.
Review of Scientific Instruments 21.5 (1950): 445-447.

Active-plasma lens results

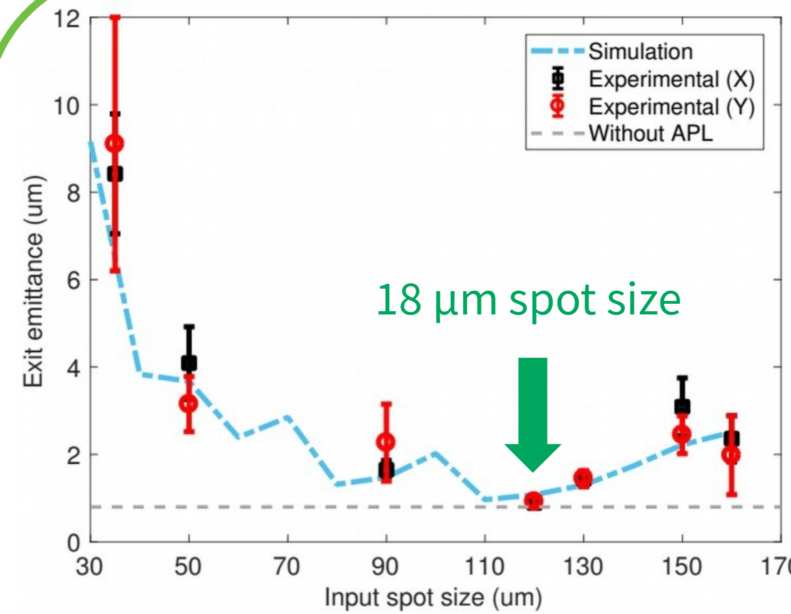
Demonstration of emittance growth

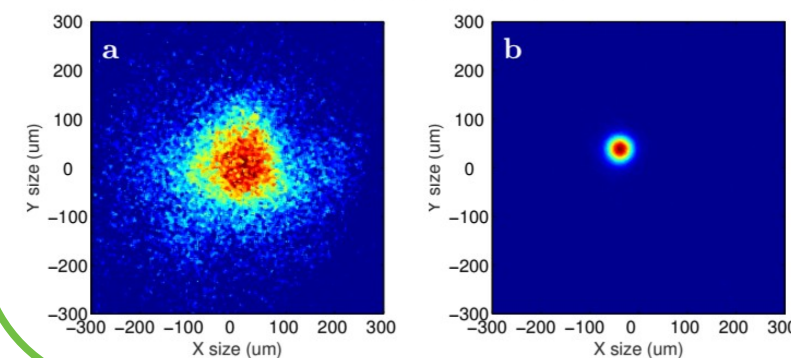




Pompili, R., et al. Applied Physics Letters 110.10 (2017): 104101.
Marocchino, A., et al. Applied Physics Letters 111.18 (2017): 184101.

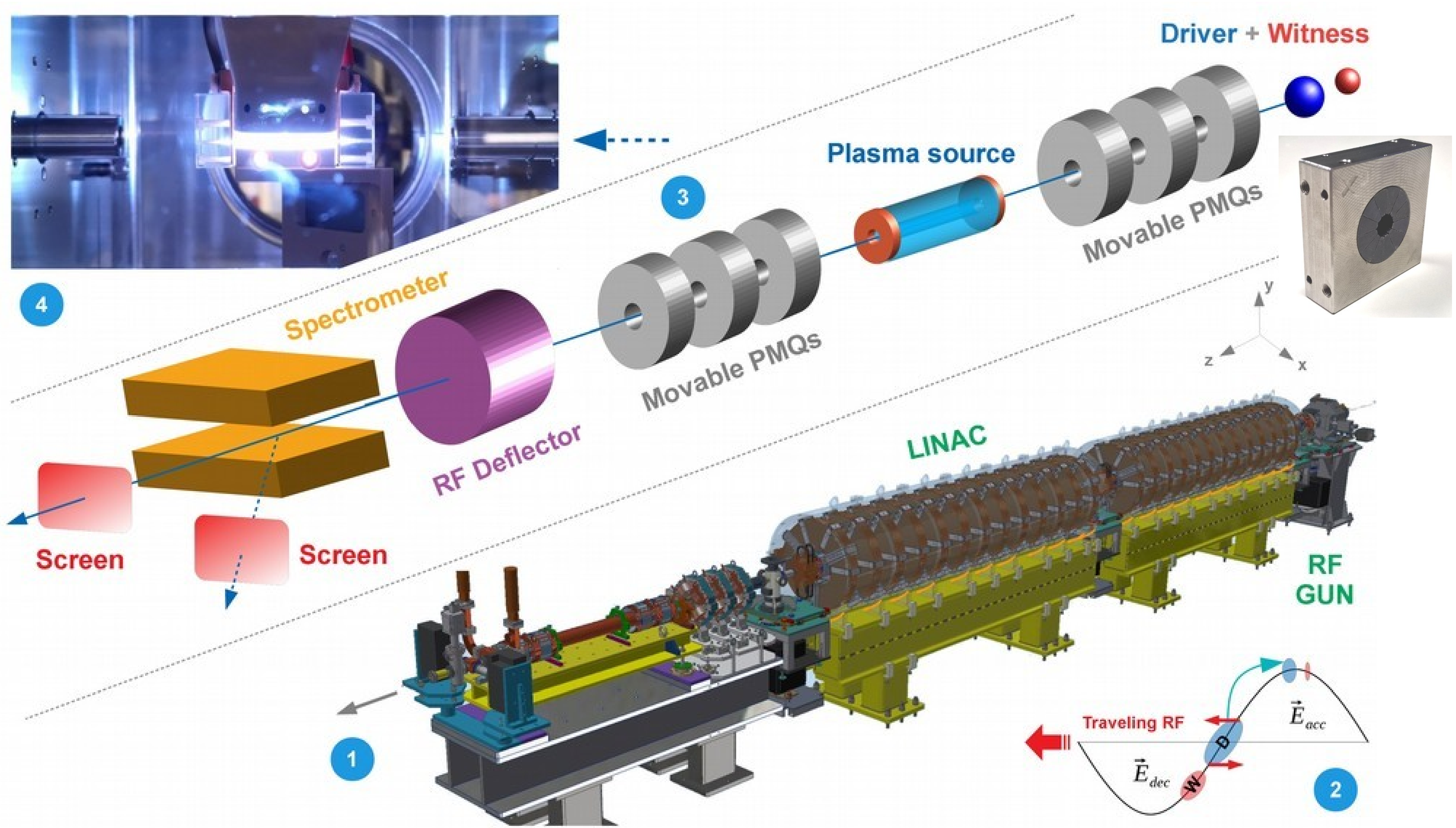
Demonstration of emittance preservation



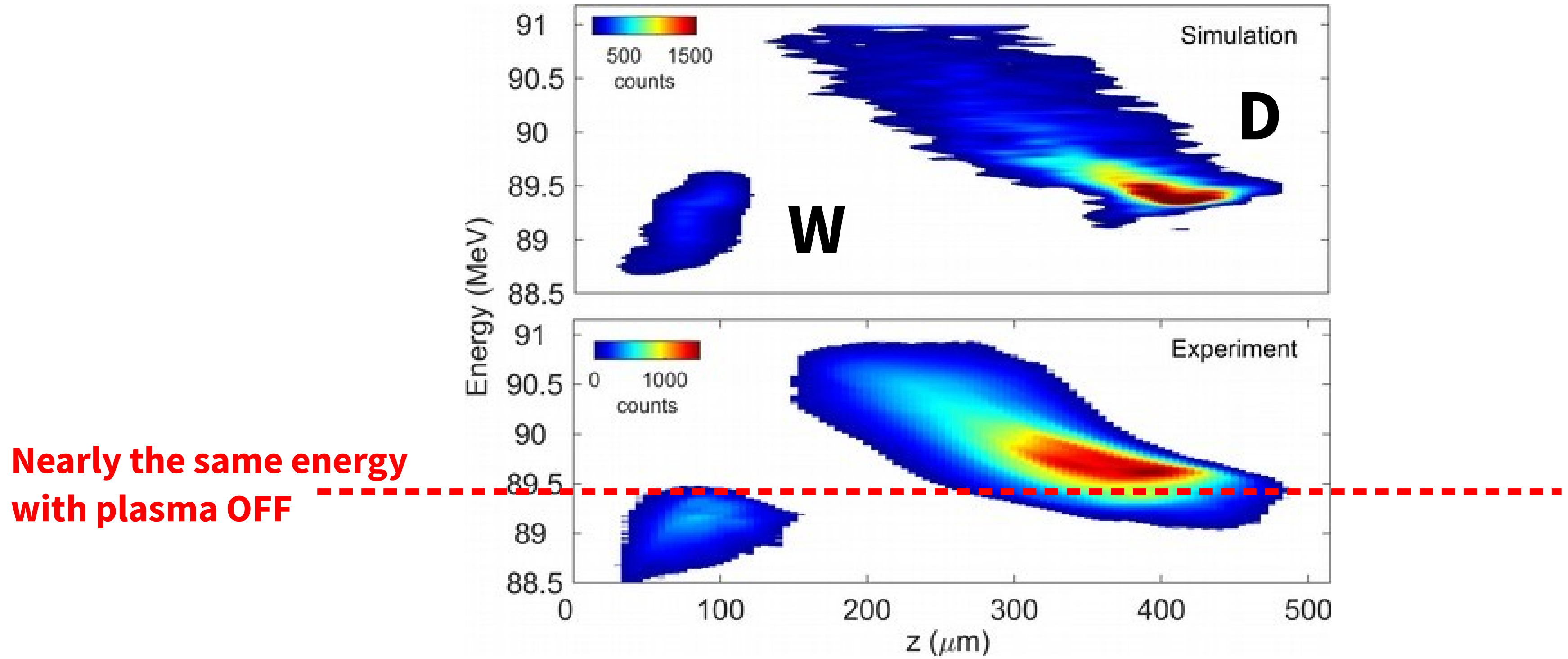


Pompili, R., et al. Physical Review Letters 121.17 (2018): 174801.

Plasma acceleration experiment



Beam configuration



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) obtained with **velocity-bunching technique**

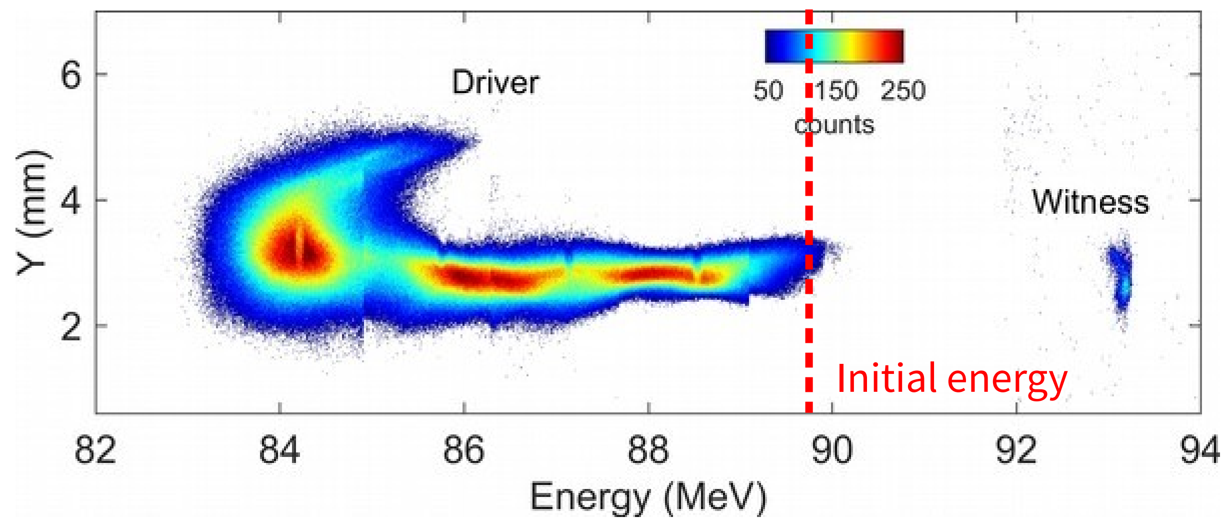
Separation approximately equal to ¾ of the plasma wavelength (~1 ps)

Plasma acceleration results

4 MeV acceleration in 3 cm plasma with 200 pC driver

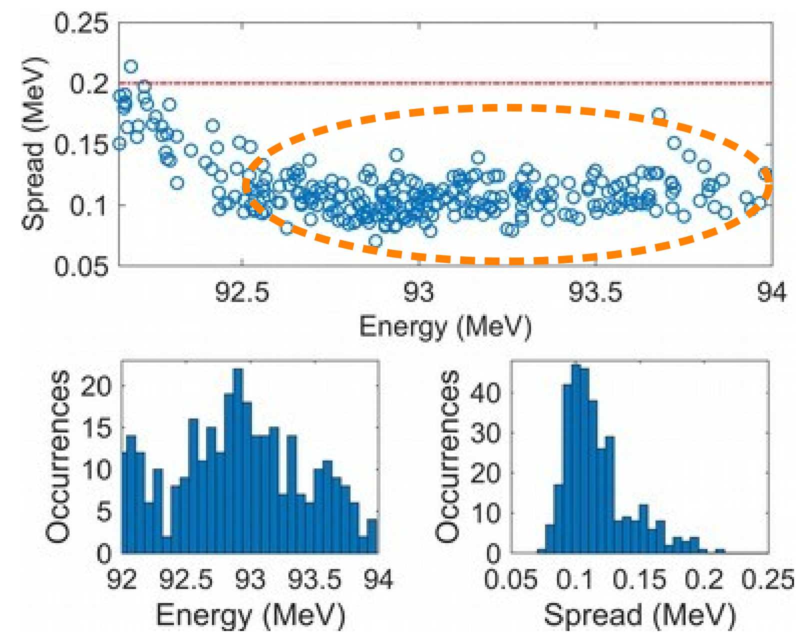
~133 MV/m accelerating gradient

2×10^{15} cm^{-3} plasma density



Demonstration of projected energy spread compensation

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

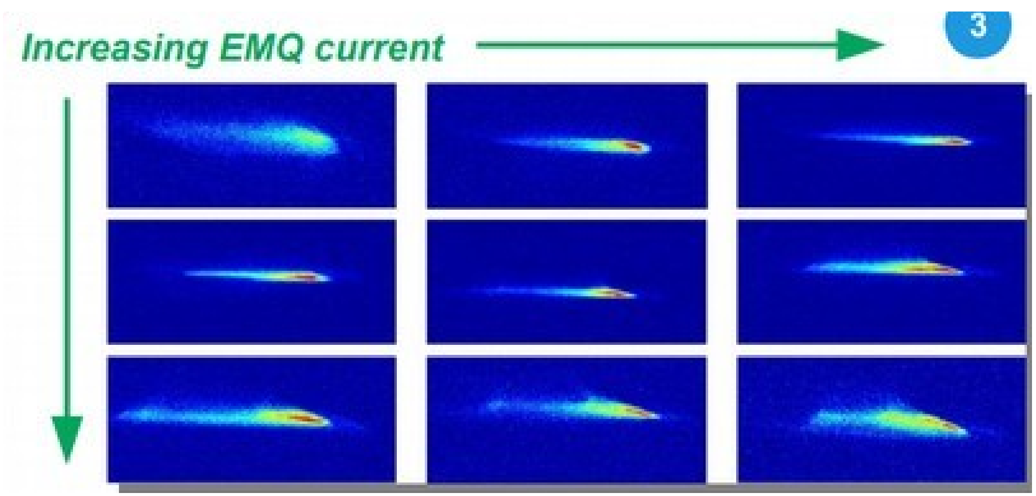
R. Pompili[1✉], D. Alesini[1], M. P. Anania[1], M. Behtouei[1], M. Bellaveglia[1], A. Biagioni[1], F. G. Bisesto[1], M. Cesarini[1,2], E. Chiadroni[1], A. Cianchi[3], G. Costa[1], M. Croia[1], A. Del Dotto[1], D. Di Giovenale[1], M. Diomede[1], F. Dipace[1], M. Ferrario[1], A. Giribono[1], V. Lollo[1], 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]

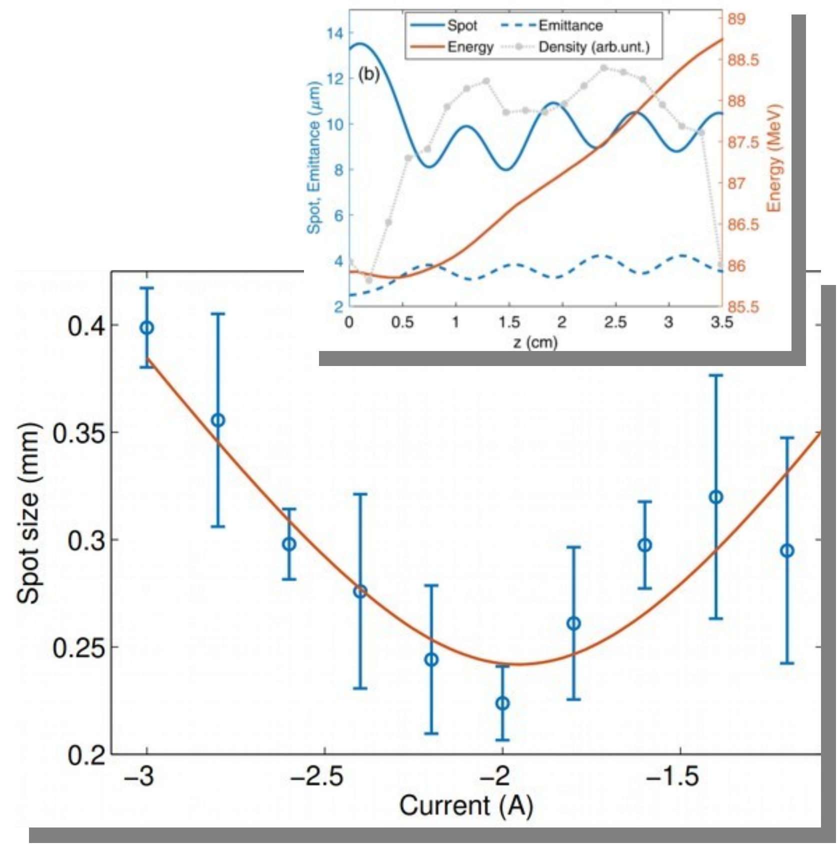
First emittance measurement in PWFA

PWFA characterization completed by measuring the witness emittance

Measurement of its normalized emittance through quadrupole scan technique

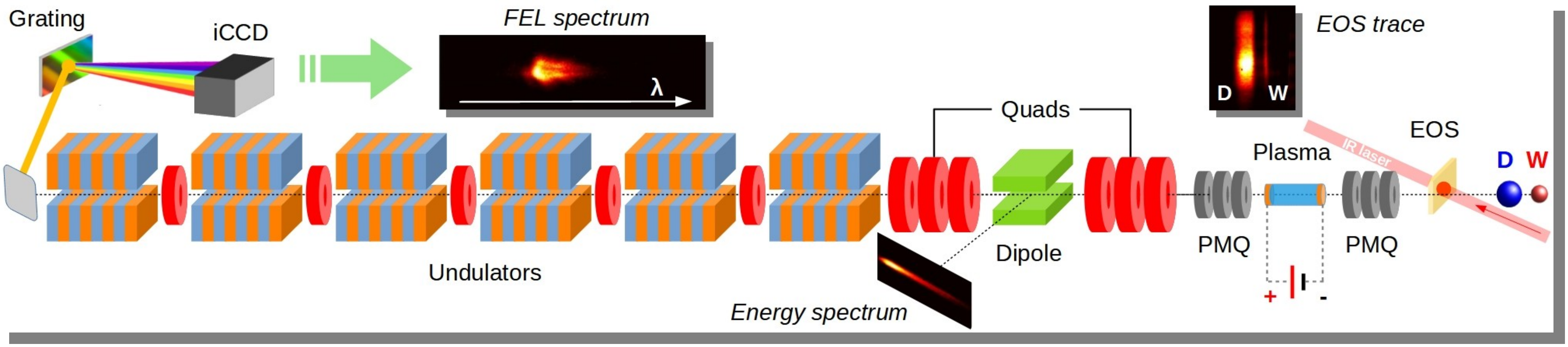
We found emittance increase from 2.7 um to 3.7 um (rms) during acceleration, we need to improve transverse matching into the plasma





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.

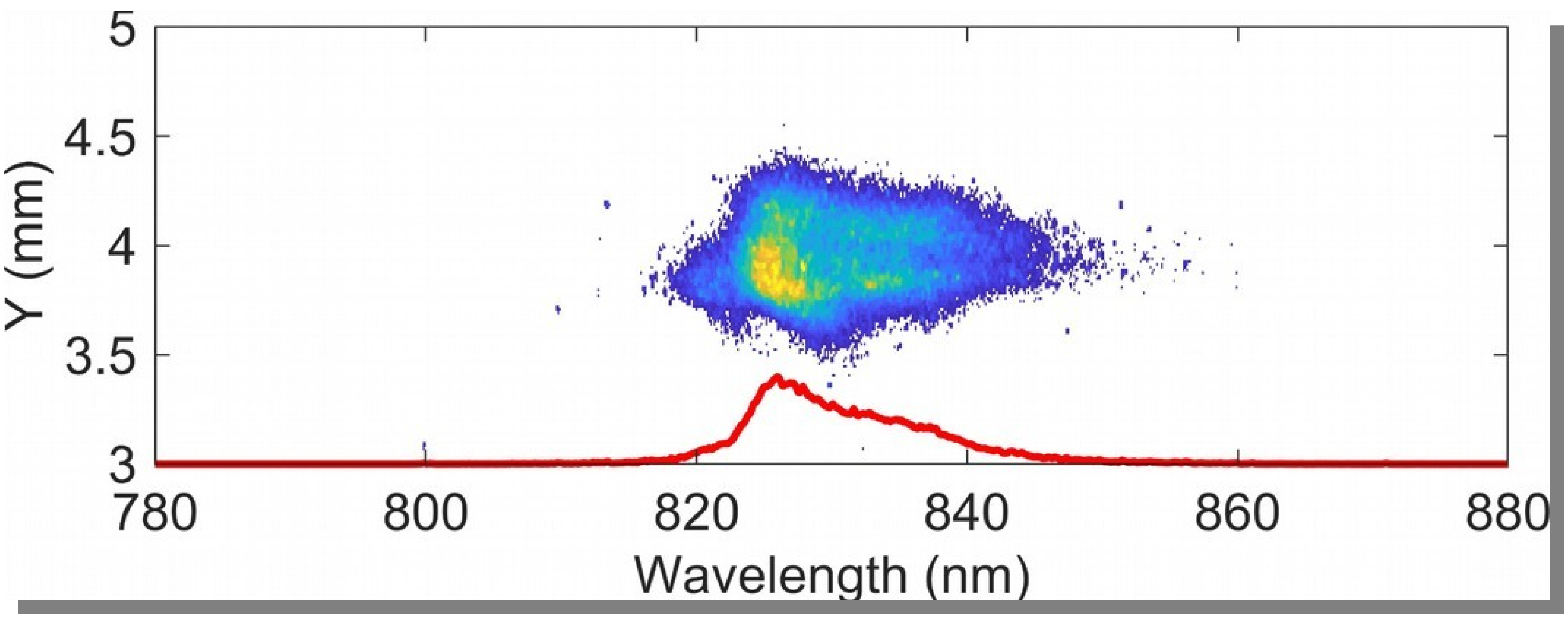
Proof of SASE FEL driven by PWFA



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*

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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Article | Published: 25 May 2022

Free-electron lasing with compact beam-driven plasma wakefield accelerator

R. Pompili, D. Alesini, ... M. Ferrario + Show authors

Nature **605**, 659–662 (2022) | Cite this article

Electro-Optical Sampling diagnostics

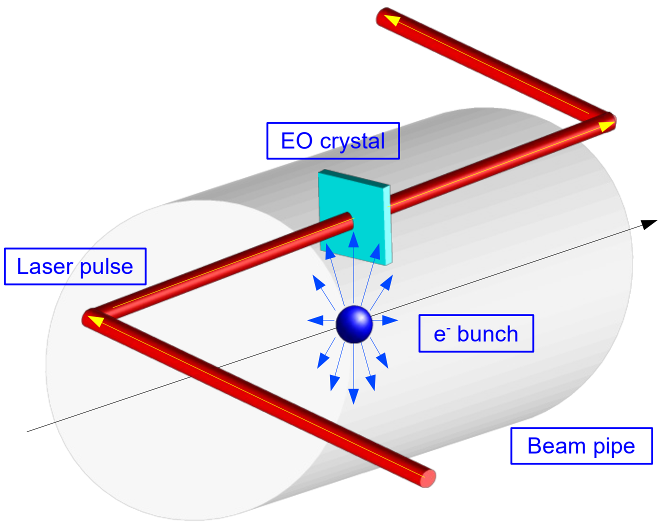
30° angle of the IR laser when impinges on the crystal (ZnTe, GaP)

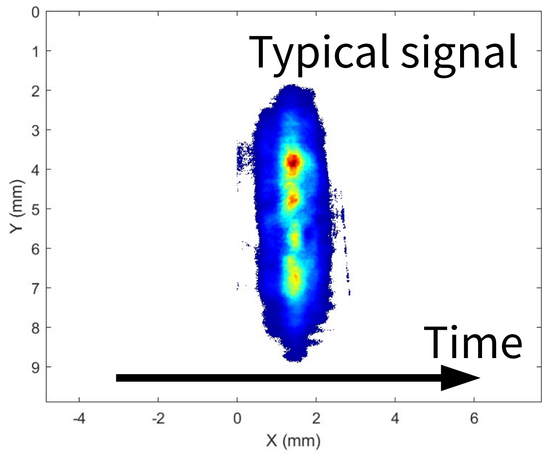
The signal is read by a CCD

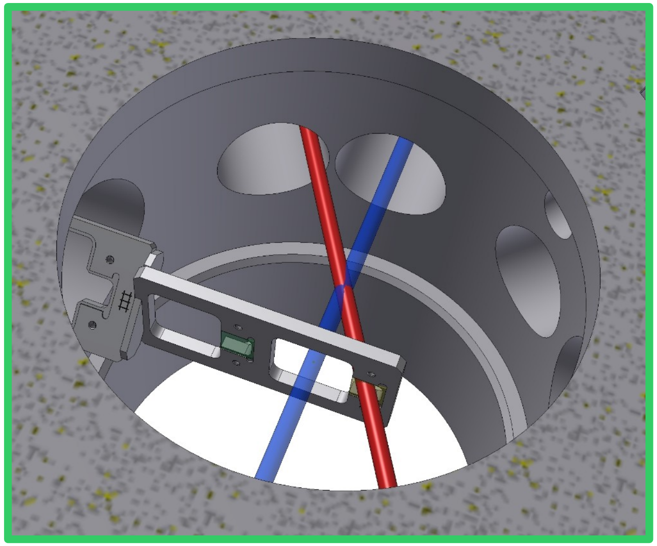
The spatial resolution is 19 fs/pixel

IR laser monitored with a fast Hamamatsu photo-diode

A 300 mm delay line is used to sync the IR laser and the electron bunch







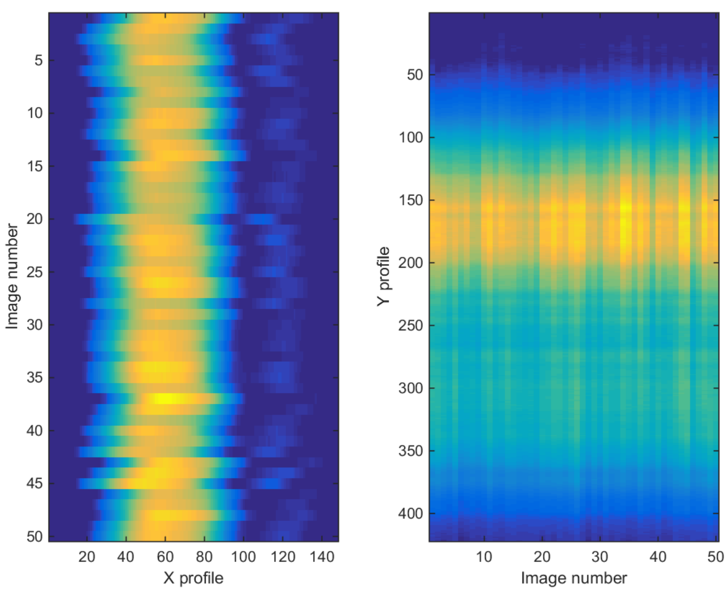
Measurements with two bunches

ID	Pos(ps)	RMS(ps)	Err(ps)	Q(%)	Err(%)	**Jitter(ps)**	RFD OFF(m)
1	5.291	0.279	0.007	94.458	7.030	0.051	0.000
2	6.334	0.133	0.024	5.542	12.246	0.046	0.000
All	5.294	0.296	0.010	100.000	7.231	0.049	0.000

Laser vs bunch

Bunch 1 vs bunch 2

Dist(ps)	Err(ps)
1.043	**0.016 (up to 40 fs)**



Time

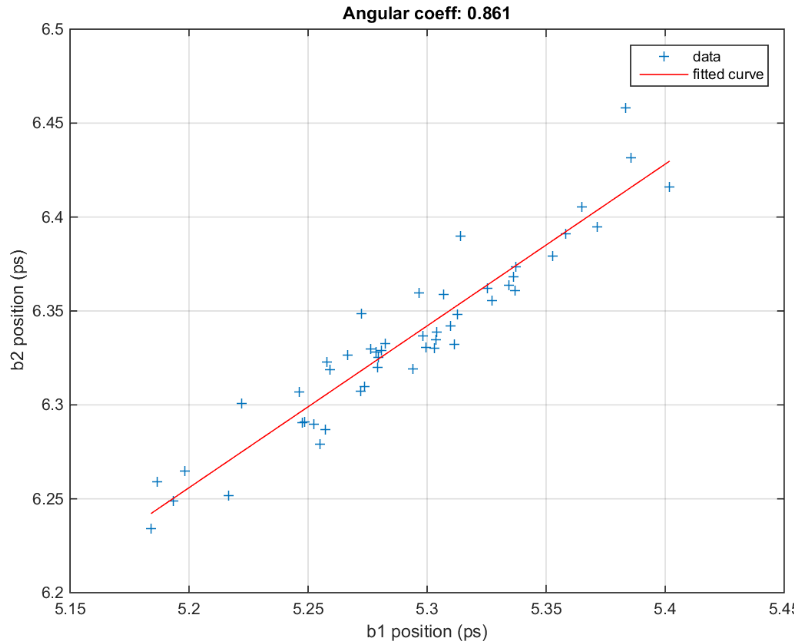


Photo-cathode studies – UV vs BLUE

From the generalized Fowler-DuBridge theory the expression of the total current emitted by a metal during laser irradiation is

$$J = \sum_{n=0}^{\infty} J_n \quad \Rightarrow \quad J_n = a_n \left(\frac{q_e}{h\nu} (1-R) I_L \right)^n A_0 T^2 F(X_n)$$

← **Absorbed photons**

$$X_n = \frac{n h\nu - \phi_0 + E_{Sch} - E_{img}}{k_B T}$$

n=0 → thermionic emission (Richardson law)

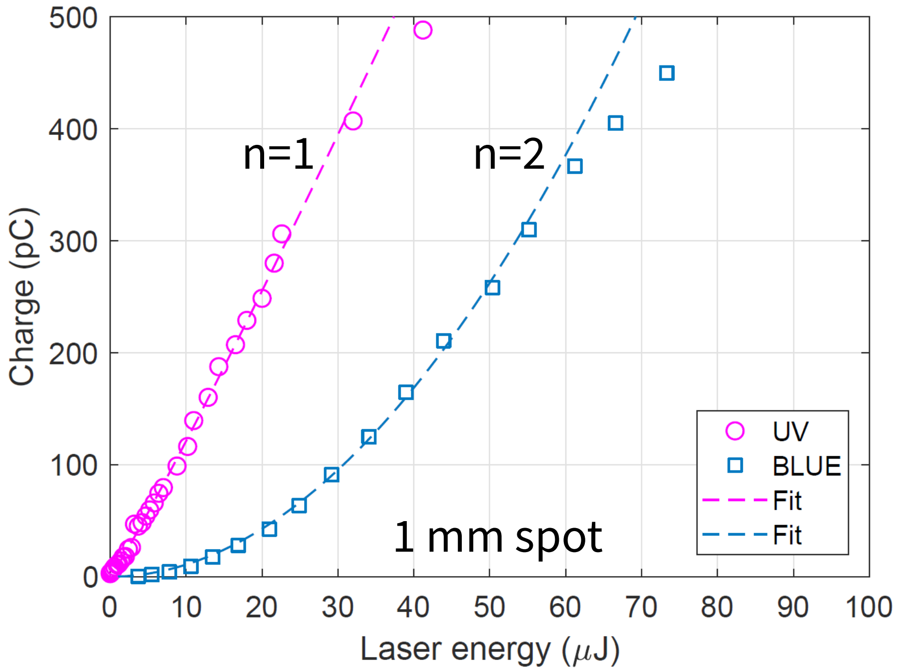
Several factors affect the overall photo-emitted electrons

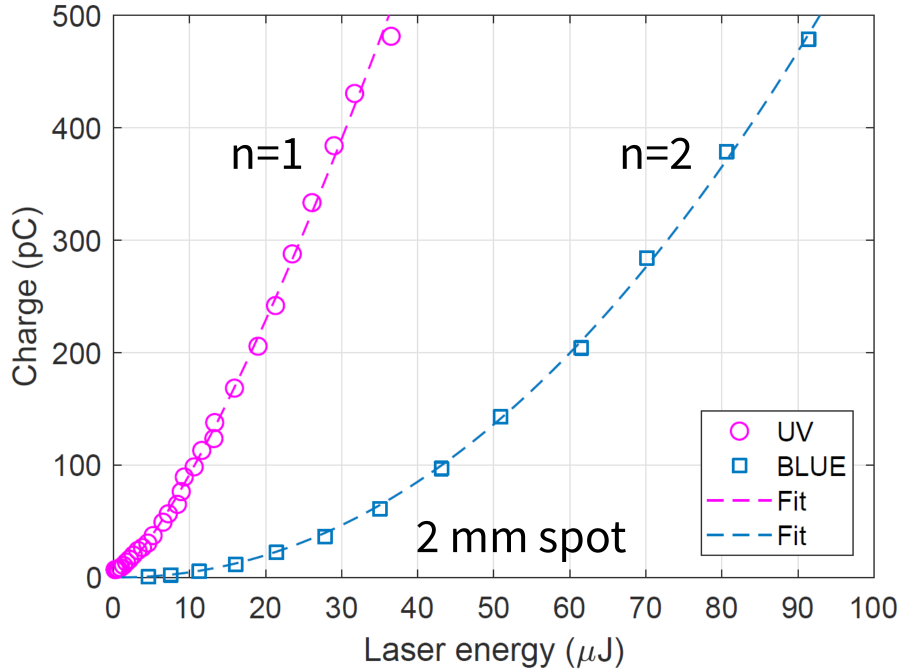
Multi-photon absorption, Schottky effect, image-charge, temperature

Optics Letters

Time-resolved study of nonlinear photoemission in radio-frequency photoinjectors

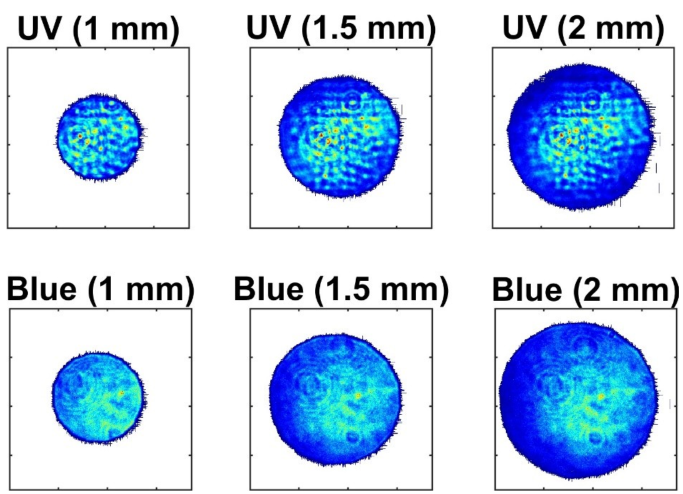
Measurements



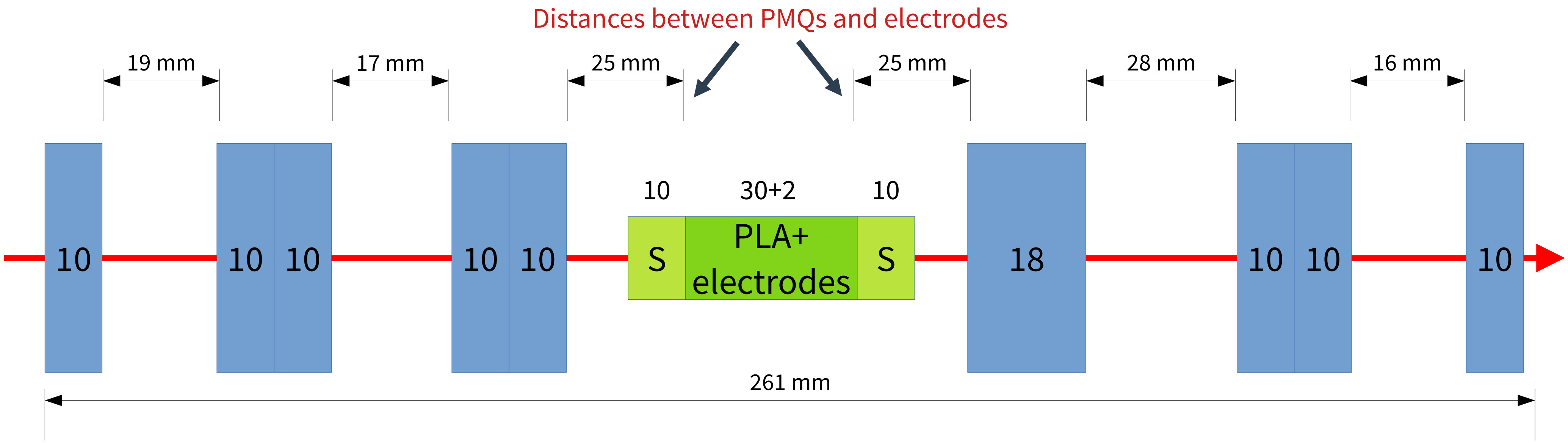


Operation with blue enabled only at ultra-short laser durations (~100 fs)

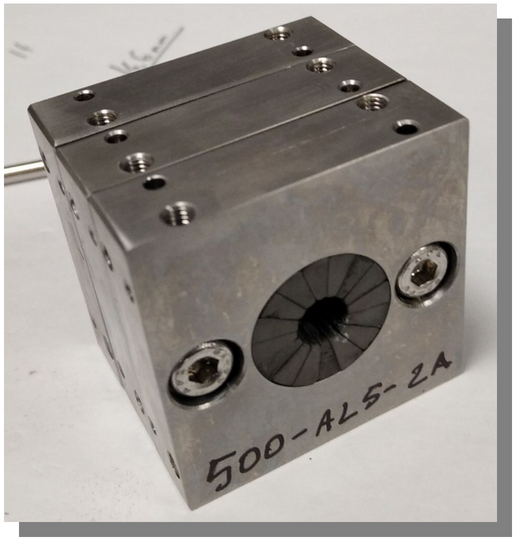
QE is comparable with UV one (2-3 times lower, order 10^{-5} e/ph)



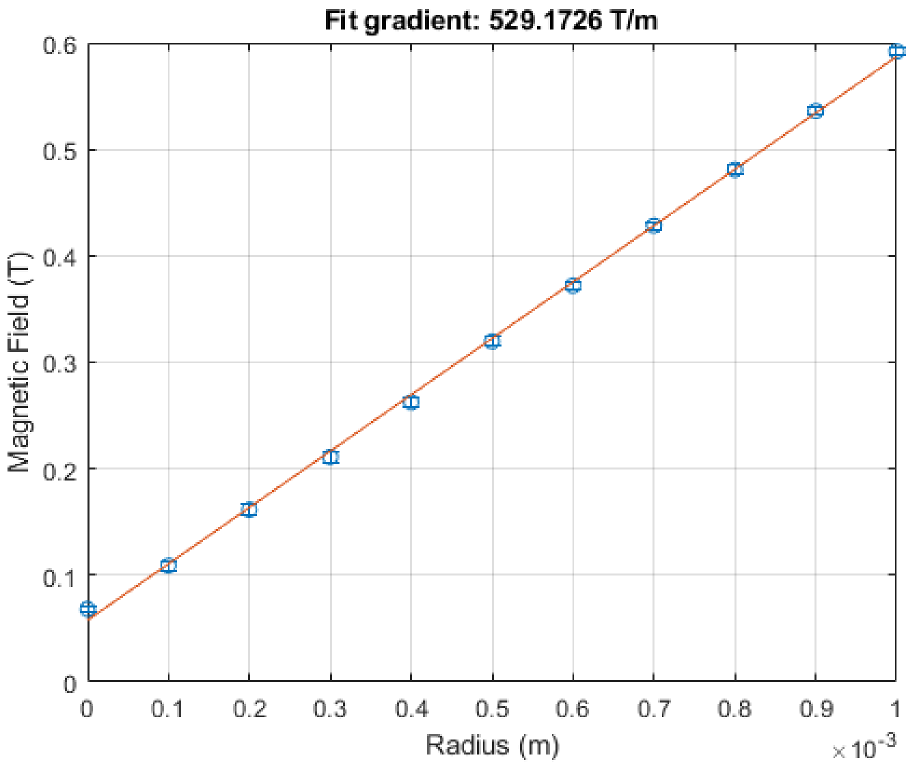
Ongoing activities – tests with new PMQs



- PMQs should move by ±7 mm between them
- 500 T/m, r=3 mm, L=10,18,20 mm
- Obtained by merging single 10 mm pieces
- Currently available @ SPARC_LAB
  - *1xAL6+1xAL4 = 4x18 mm*
  - *2xAL5+2*AL3 = 8*10 mm*



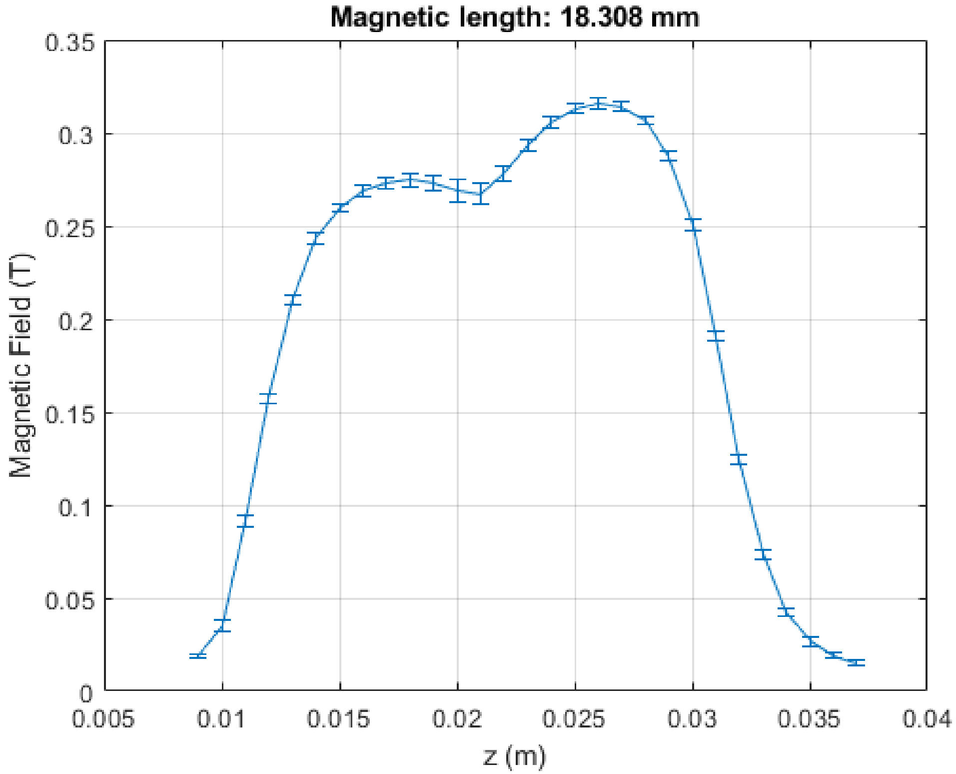
Example of characterized PMQ



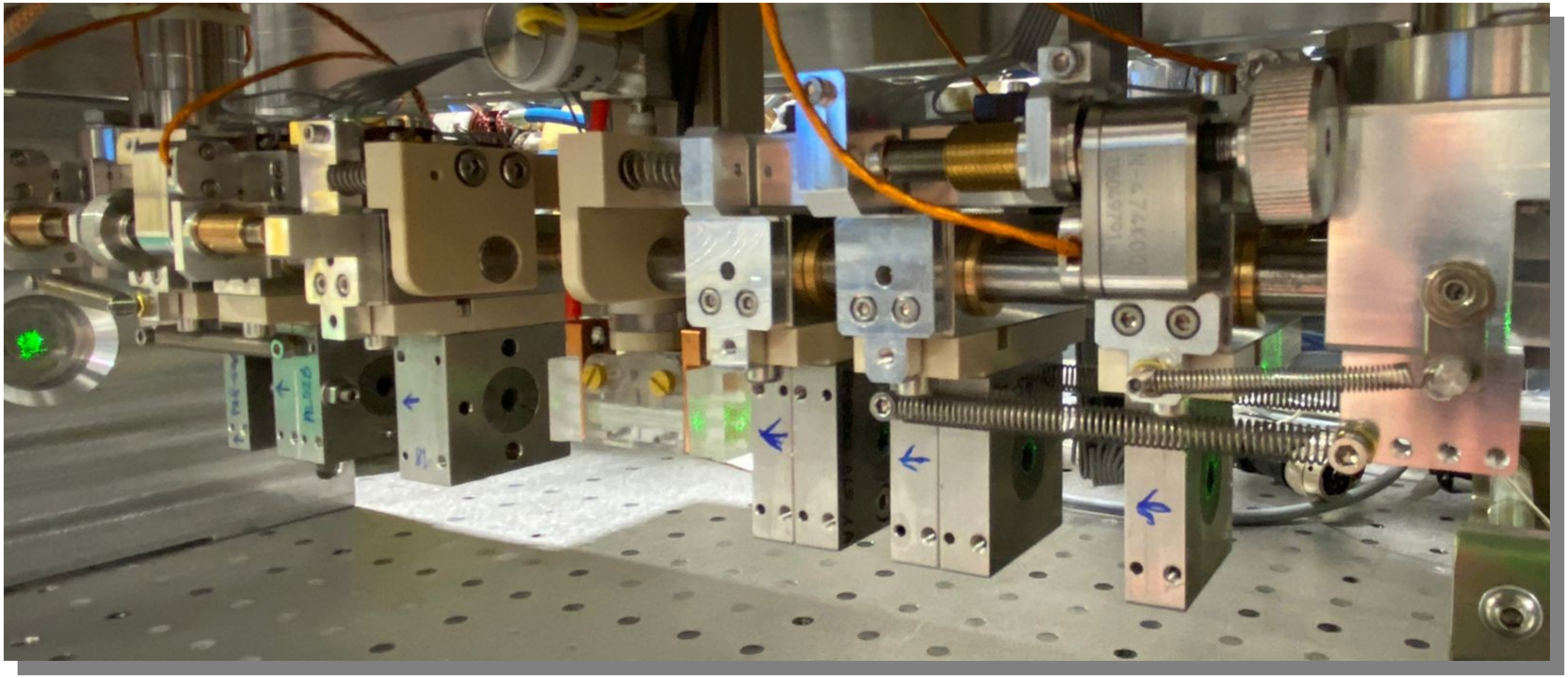
From KYMA

- 500 T/m
- 10+10 mm

Integrated field @ 0.5 mm
B*z=5.78 T*mm



Current setup



Simulations foresee beam waist of approx 4 um. Actually we measured 30-40 um minimum spots…

Even by introducing large misalignments (1-2 mm) between PMQs, the waist is below 10 um…

We think to dismount the entire system and check again in August/September

Open issues

High gradient PWFA

Demonstrate GV/m accelerations. Currently on hold due to problems with current PMQ setup

Driver-Witness timing-jitter

Laser vs beam jitter is 50-100 fs. This translates in approx 20-40 fs jitter between the two bunches and ultimately will limit acceleration at large plasma densities

Conclusions

Possible topics to include in the collaboration

- *Plasma acceleration*
- *FEL studies (SASE, seeded)*
- *Betatron radiation from plasma*
- *THz radiation use/generation*
- *Beam diagnostics*
- *Beam dynamics (ultra-short, high peak current beams)*
- *Photo-emission studies (cathode materials, laser pulse shaping, etc.)*
- *Strong focusing (permanent quadrupoles, plasma lenses, etc.)*

Thanks!

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On behalf of the SPARC_LAB collaboration

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati