Advanced Accelerator Concepts – AAC2026
Luskin Conference Center, UCLA

Experimental Demonstration of Beam-Driven Wakefield Acceleration in Laser-Plasma Filament

Mario Galletti (LNF, INFN)

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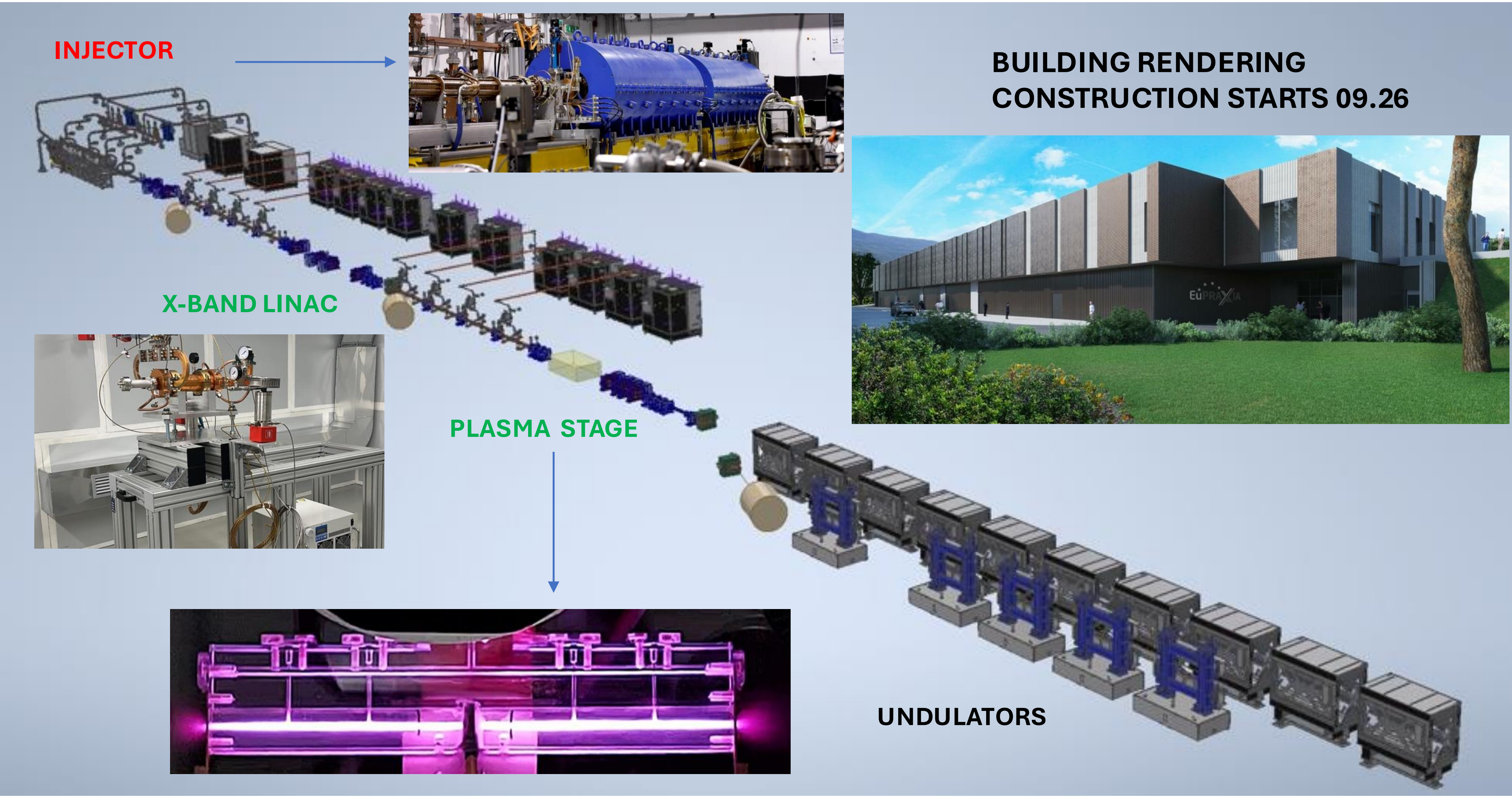
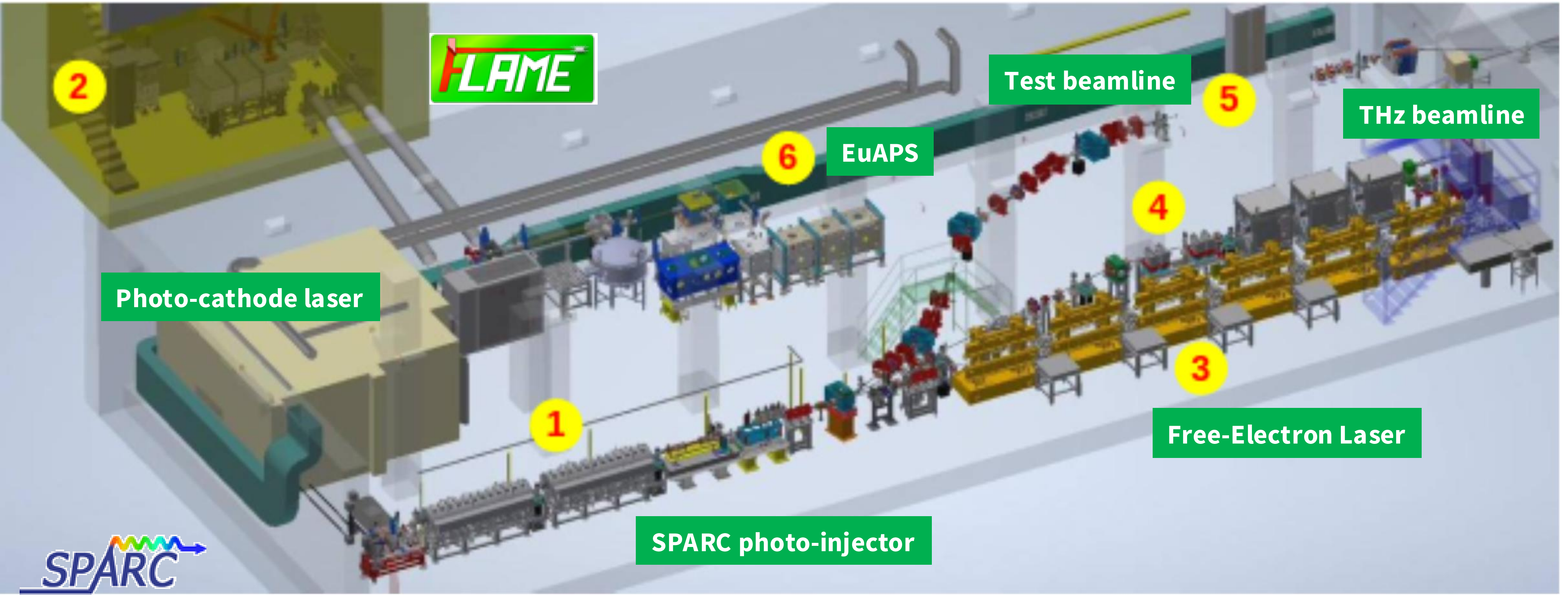
On behalf of the SPARC_LAB collaboration

LNF future facility

Europe’s most compact FEL and the world’s most compact GeV class RF accelerator



SPARC_LAB facility

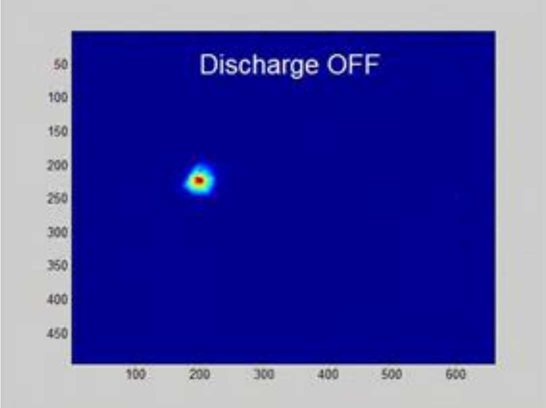


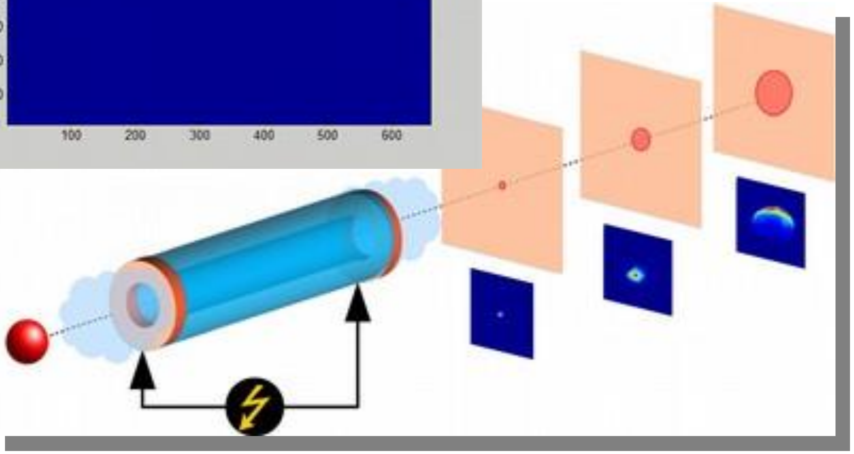
Layout of the SPARC_LAB facility. The bunker hosts the SPARC photo-injector (1), its photo-cathode laser and the three experimental beamlines: the FEL (3), the SABINA THz radiation source (4) and, finally, a test beamline (5) available for user experiments. The FLAME bunker (2) is connected to the SPARC one by means of an in-vacuum laser transport line and drives the EuAPS X-rays betatron source (6).

Pompili, R.; et al. The SPARC LAB facility for advanced acceleration and radiation experiments. **Phys. Rev. Accel. Beams 29, 051602 (2026), https://doi.org/10.1103/rnz7-3qyj**

Experience with plasma @SPARC _LAB

Activities with the high-brightness SPARC photo-injector

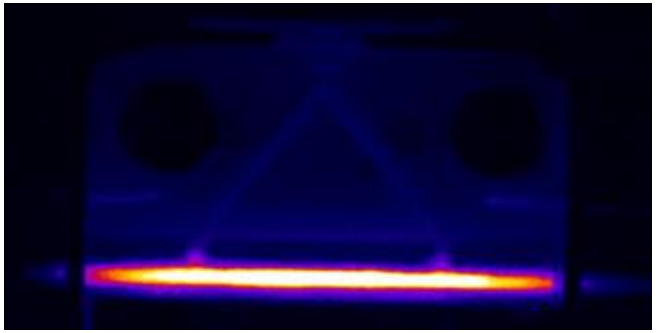




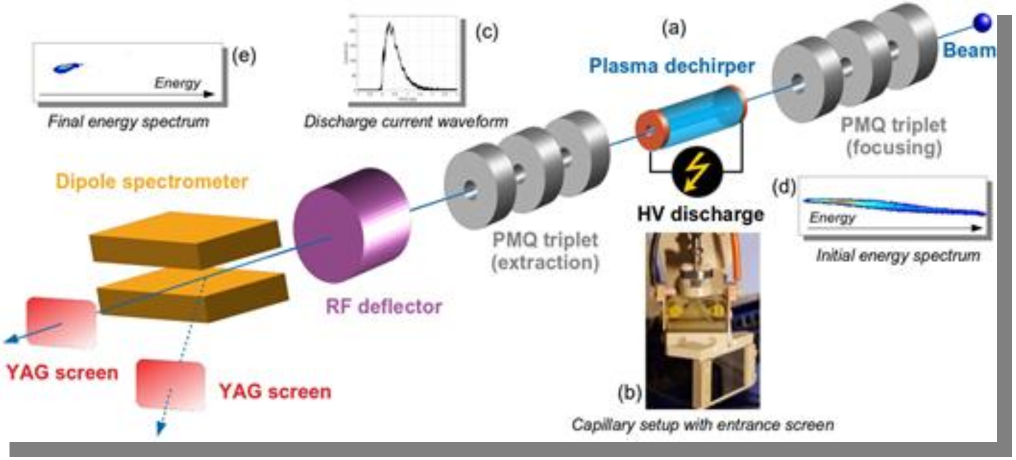
Focusing with active-plasma lenses

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

Plasma characterization



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



Longitudinal phase-space manipulation

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

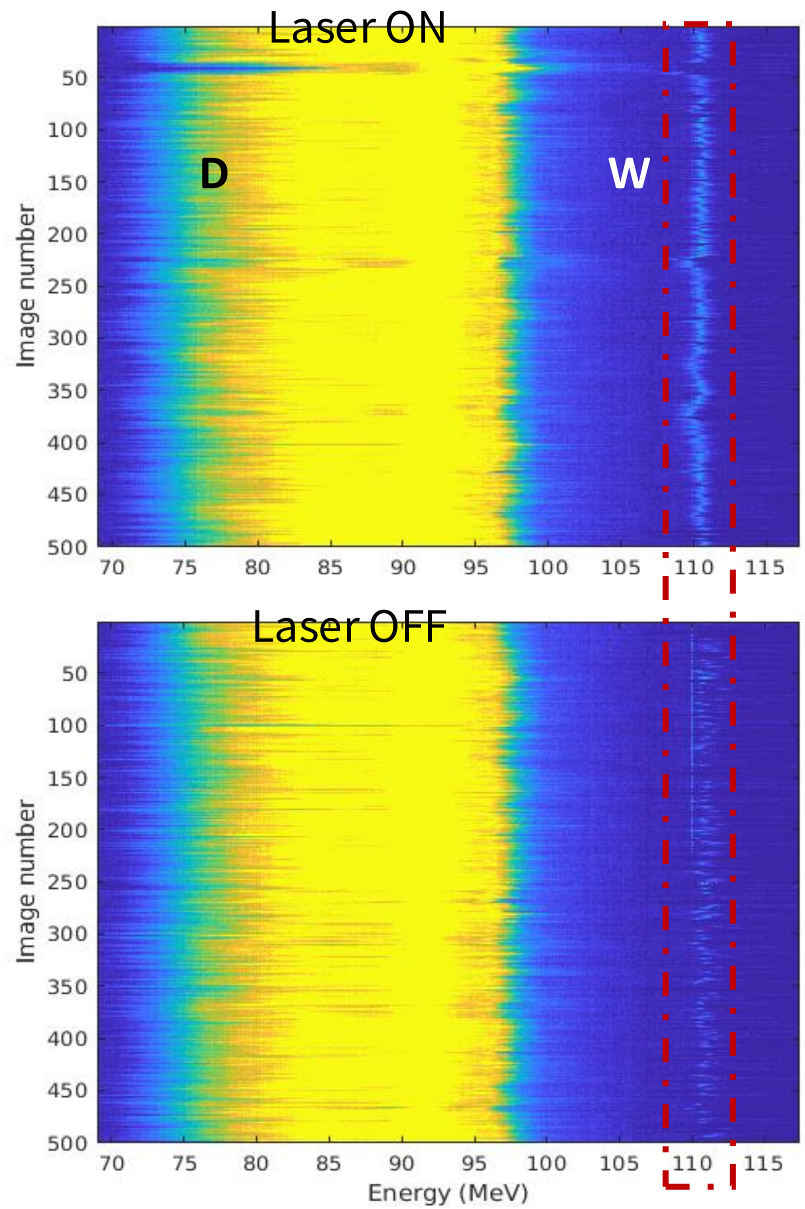
Plasma stabilization

There are two main sources of jitter

- Driver-witness separation jitter in a beam-driven plasma is limited by RF sync
- Plasma density fluctuations

To reduce the 2nd source, we pre-ionize the gas with an external laser

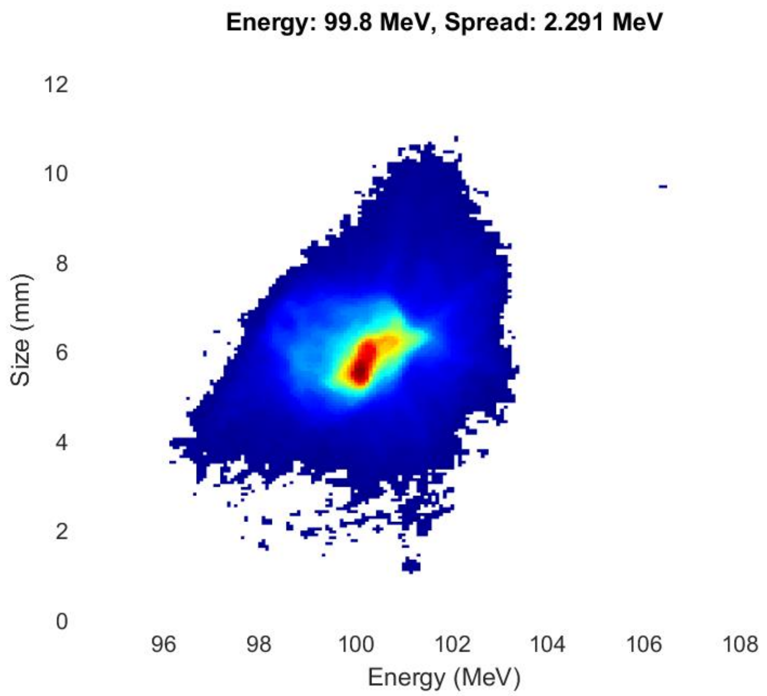
The laser (~100 uJ, 2mm diameter) reaches the negative electrode hole ~200ns before the discharge trigger.

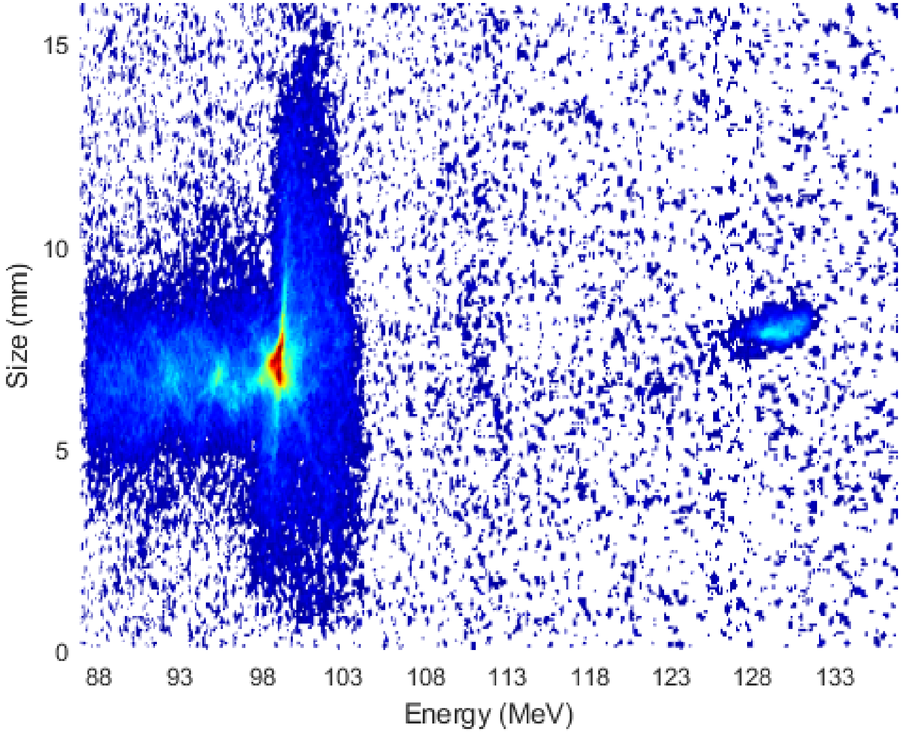


Biagioni A., et al. *"Gas-filled capillary-discharge stabilization for plasma-based accelerators by means of a laser pulse."*, **Plasma Physics and Controlled Fusion.**
M. Galletti, et al. "Advanced Stabilization Methods of Plasma Devices for Plasma-Based Acceleration", **Symmetry 2022, 14(3), 450.**

Preliminary results: GV/m gradients

Around 1 GV/m accelerating gradient was achieved by using a 500-pC driver followed by a 50-pC witness. Results obtained at plasma density ~$2 * 10^{15} cm^{-3}$





- ✓ Results confirmed that larger charge on the driver bunch was needed to get larger accelerations at the same plasma density used so far
- ✓ Average energy of the D+W configuration is 100+-0.15 MeV with no plasma; while, with the plasma on, the D loses ~15 MeV and the W gains ~30 MeV.

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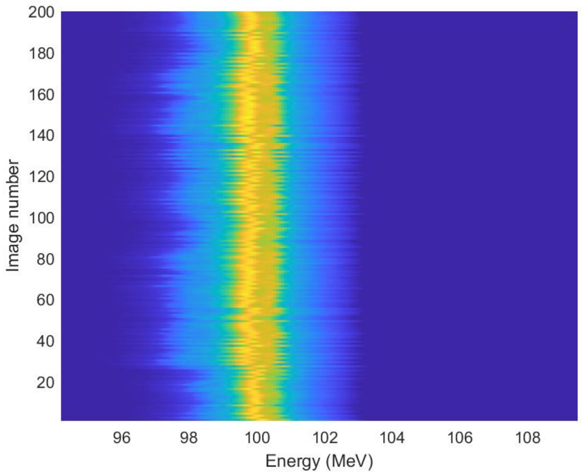
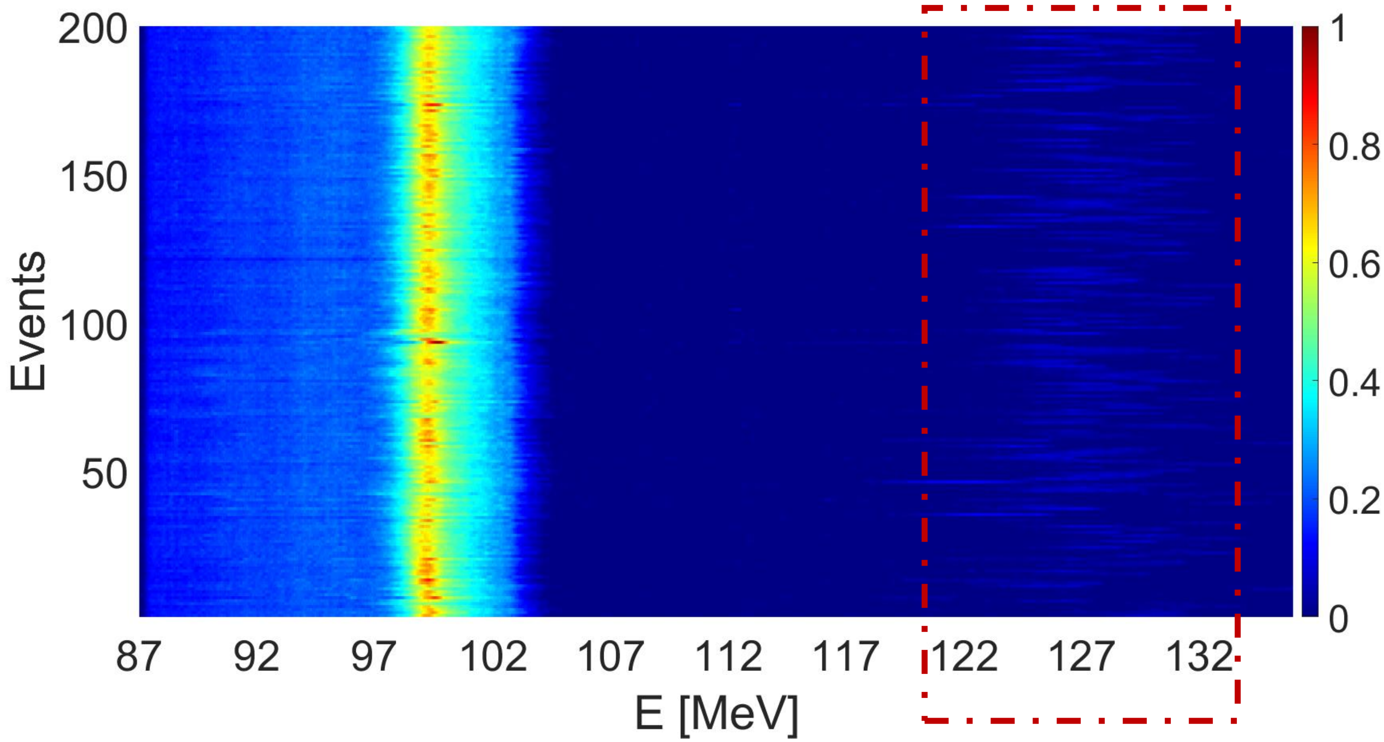




- ✓ The final W energy is 128+-3 MeV meaning an energy jitter around 2.5% considering 200 events.

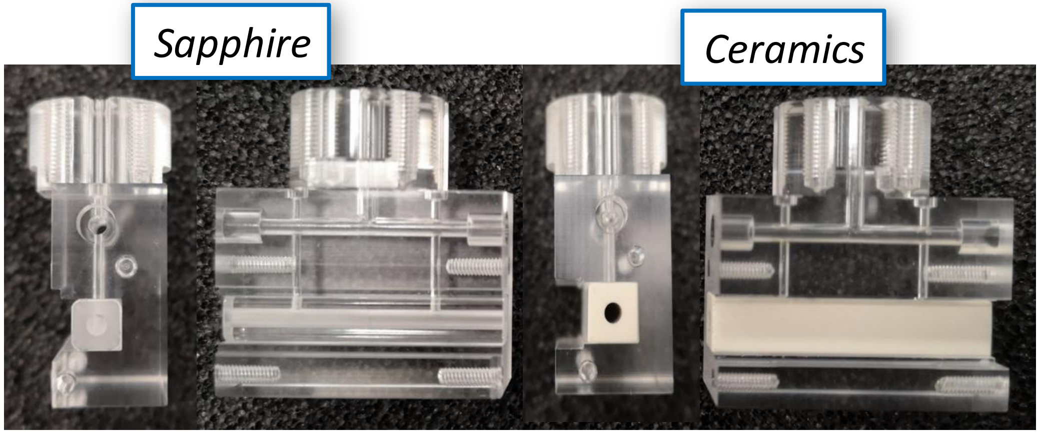
Pompili, R.; et al. Multi-dimensional snapshots for a stable plasma-wakefield accelerator. **Sub Nat. Comm. (2026)**

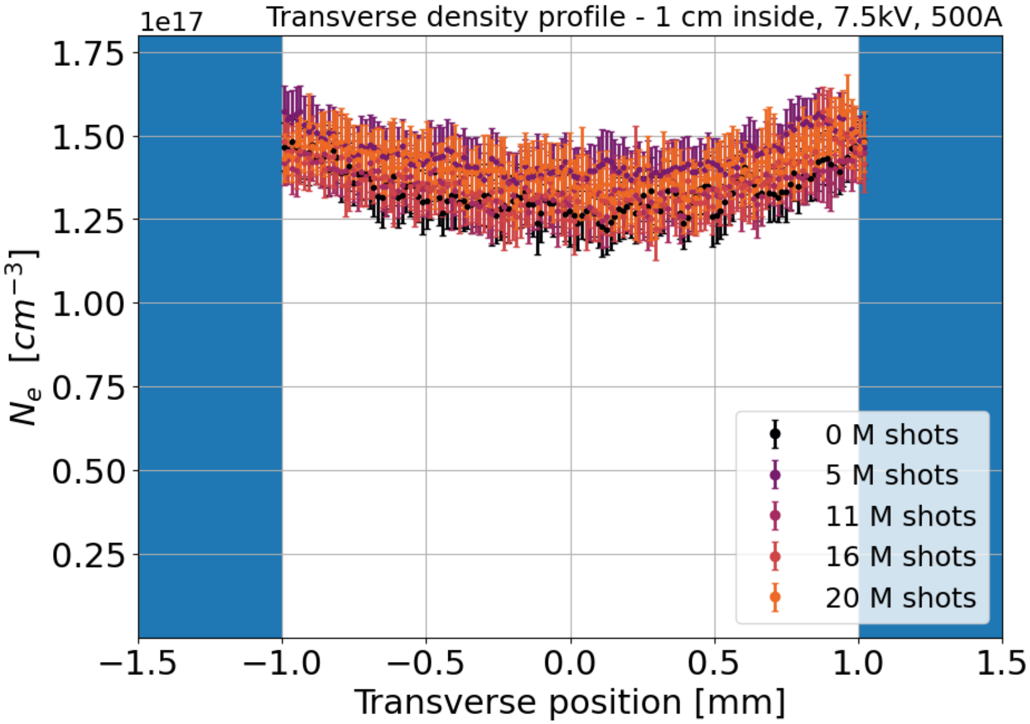
Plasma Module R&D

Plasma module operation at high repetition rate

1. Solid-state high repetition-rate discharge system
2. High temperature-resistant materials capable of withstanding the plasma thermal load
3. Vacuum systems suitable for continuous flow gas injection (turbo and primary pumps cooling system)

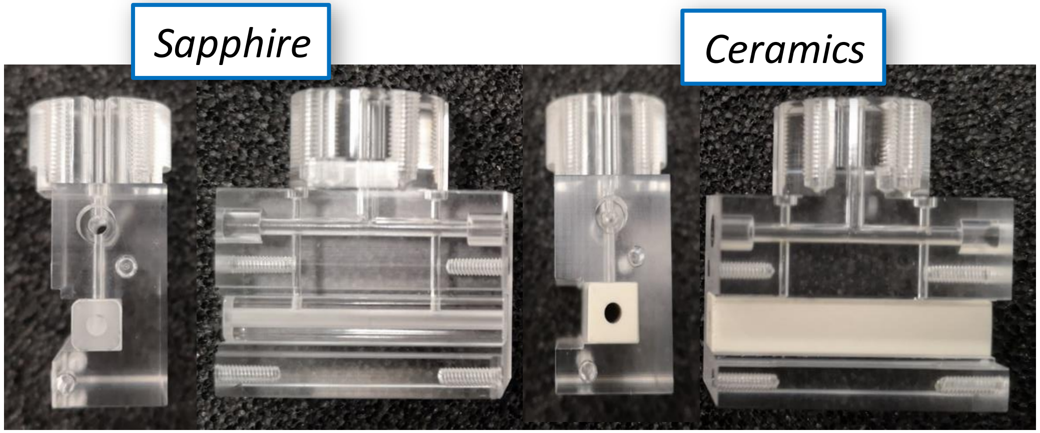
100 Hz repetition rate discharges





L. Crincoli et al. Advanced ceramic plasma discharge capillaries for high repetition rate operation. **Scientific Reports 15(1) (2025) https://doi.org/10.1038/s41598-025-96882-y**

Plasma Module R&D



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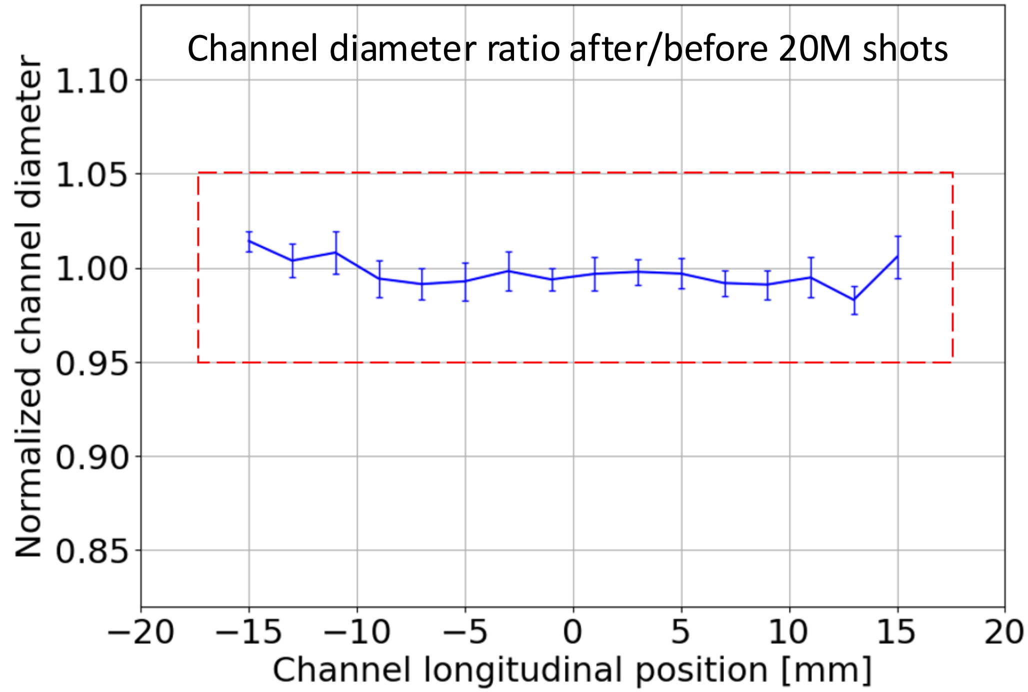
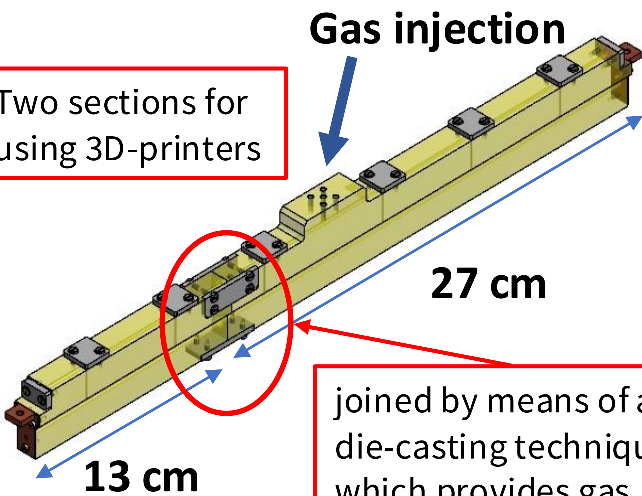


L. Crincoli et al. Advanced ceramic plasma discharge capillaries for high repetition rate operation. **Scientific Reports 15(1) (2025) https://doi.org/10.1038/s41598-025-96882-y**

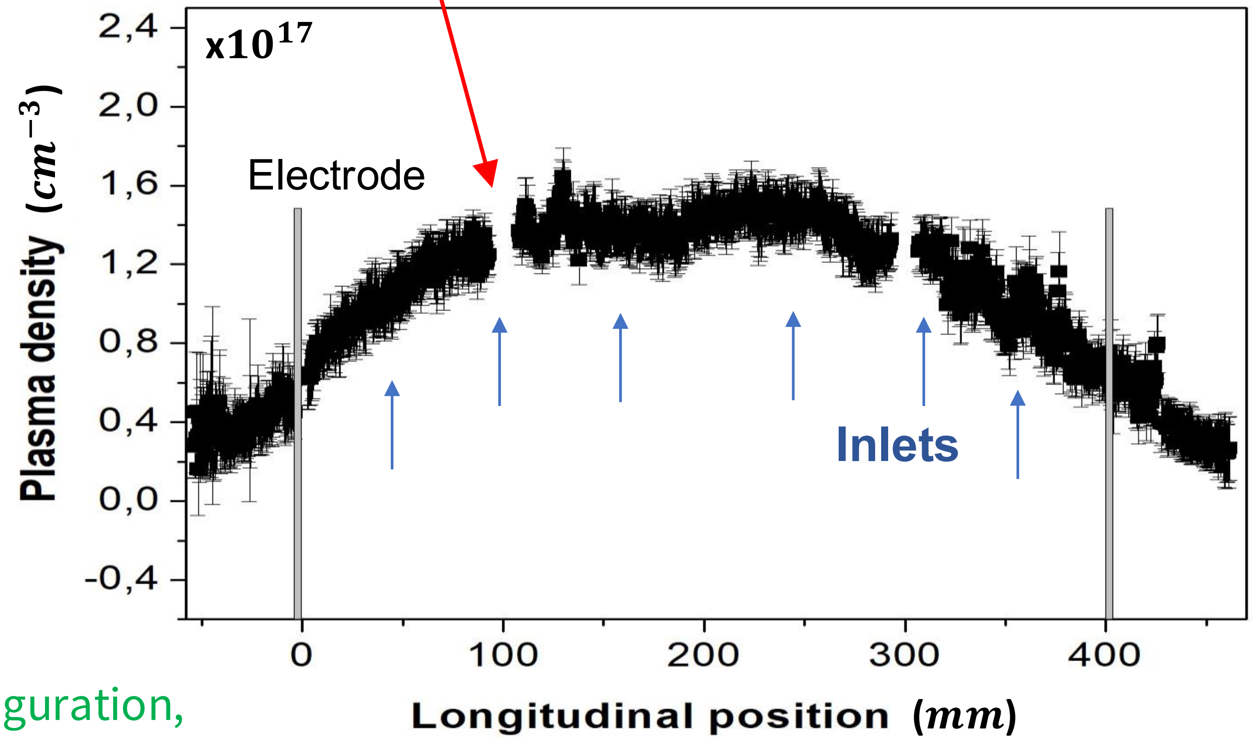
Preliminary results: longer plasma stage

Operating conditions:
- **Nitrogen gas**
- **Rep rate at 1 Hz**
- **10 kV – 380 A**
- **6 inlets of 1 mm diameter**



Two sections for using 3D-printers

joined by means of a die-casting technique, which provides gas losses of the order of 10^{-10} mbar

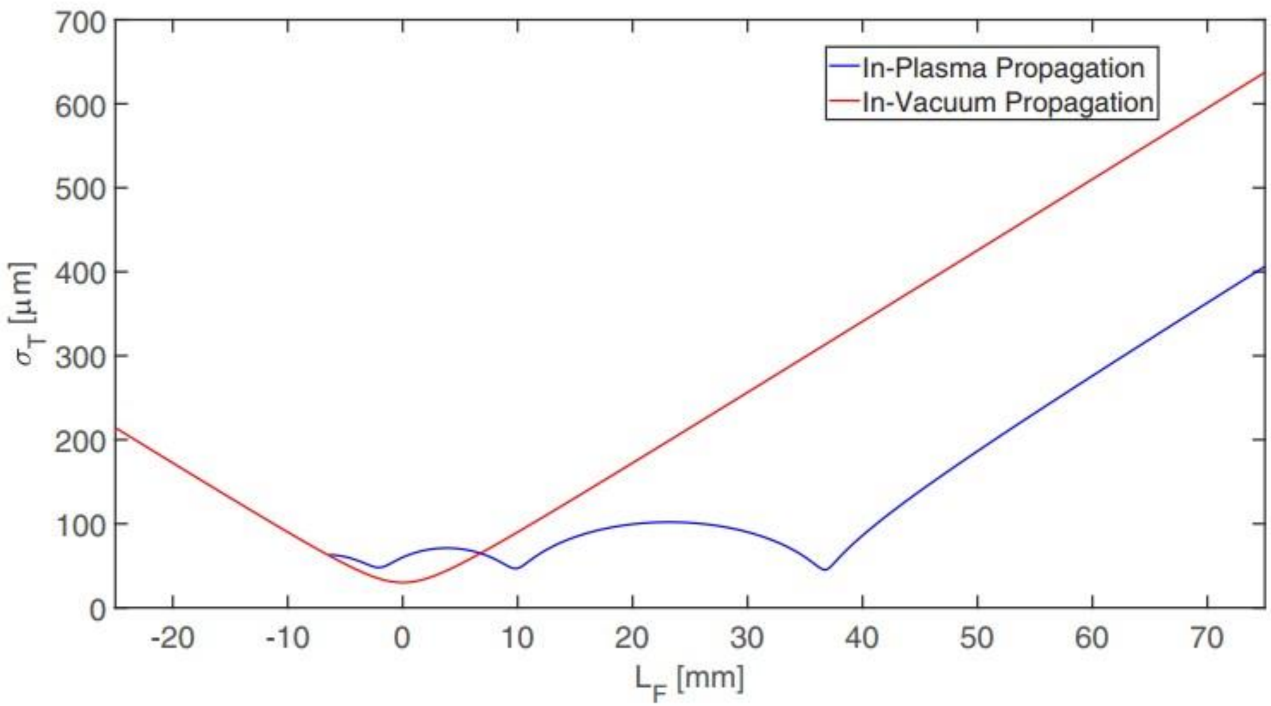


✓ With longer capillary configuration, nitrogen gas allow us to have 10 Hz RR.

A. Biagioni, et al. Plasma density manipulation in long staged gas-filled discharge capillaries for plasma-based accelerators. **sub PRE (2026)**

Laser-induced plasma filaments

We generate plasma filaments using a fs laser in low-pressure nitrogen.
The filament acts as the medium for beam-driven wakefield acceleration.



The **achievable plasma length** is not set by the incident beam's diffraction-limited Rayleigh range, but by the **dynamic balance between Kerr self-focusing and plasma defocusing** that sustains self-guided propagation.

Laser-induced plasma filaments

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The filament acts as the medium for beam-driven wakefield acceleration.

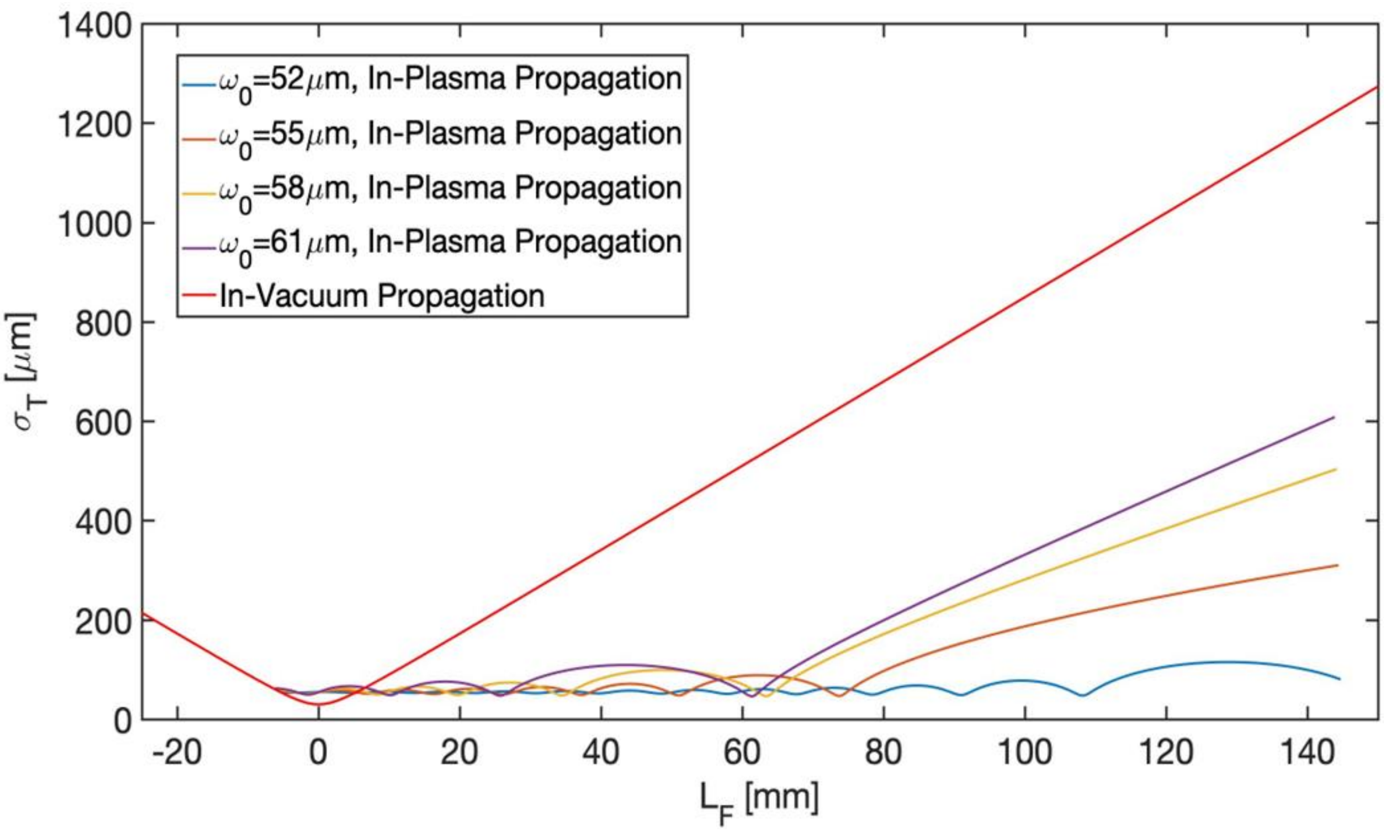
Filament operation

- **Low energy operation.** Tens of mJ vs Joule-range respect discharge systems and high-power laser.
- **No need of high-voltage discharge systems**.
- **Low energy deposition.** No need of high temperature-resistant materials capable of withstanding the thermal load.
- **Low gas injection**. Vacuum systems suitable for continuous flow gas injection.
- **High repetition rate operations** up to multi-kHz.
- **No time-jitter** because the same laser generates the electron beam and the plasma stage.
- **Easily tunable** dimension varying laser and gas parameters.

Laser-induced plasma filaments: simulation

The filament properties as dimensions and density can be easily tunable scanning gas pressure, laser energy and transverse dimensions. Allows matching to beam parameters and experimental needs

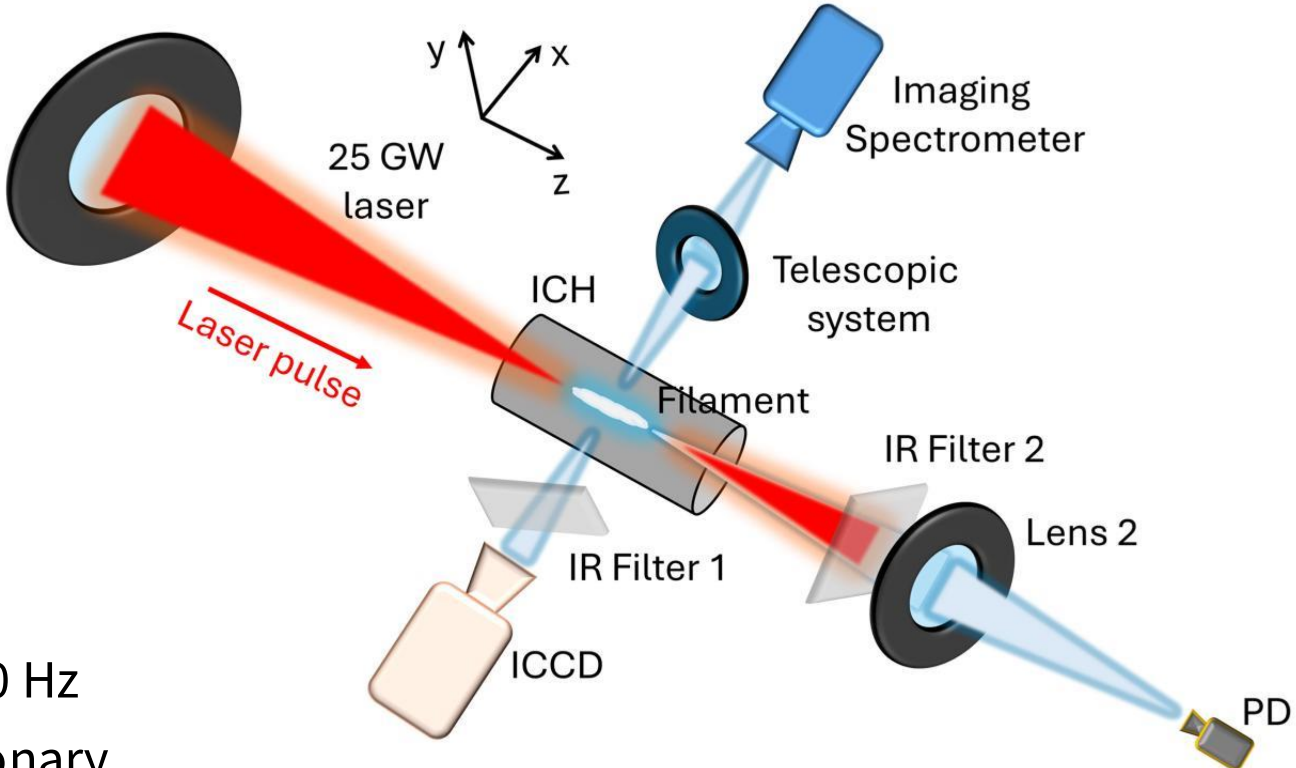
$$\frac{\partial A}{\partial z} = \frac{i}{2k}\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}\right)A - \frac{ik''}{2}\frac{\partial^2}{\partial t^2}A + ik_0 n_2\left((1-f)I + f\int_{-\inf}^{t} R(t-t')I(t')dt'\right)A - \frac{\sigma}{2}(1+i\omega_0\tau_c)n_e A - \frac{\beta_K}{2}I^{K-1}A$$



Envelope equation: *diffraction, self-focusing, group-velocity dispersion as well as plasma generation and energy losses due to multiphoton/tunnel ionization.*

Laser-induced plasma filaments

Off-line experimental setup to produce stable, reproducible plasma channels allowing high rep rate (multi-kHz potential).



Experimental setup

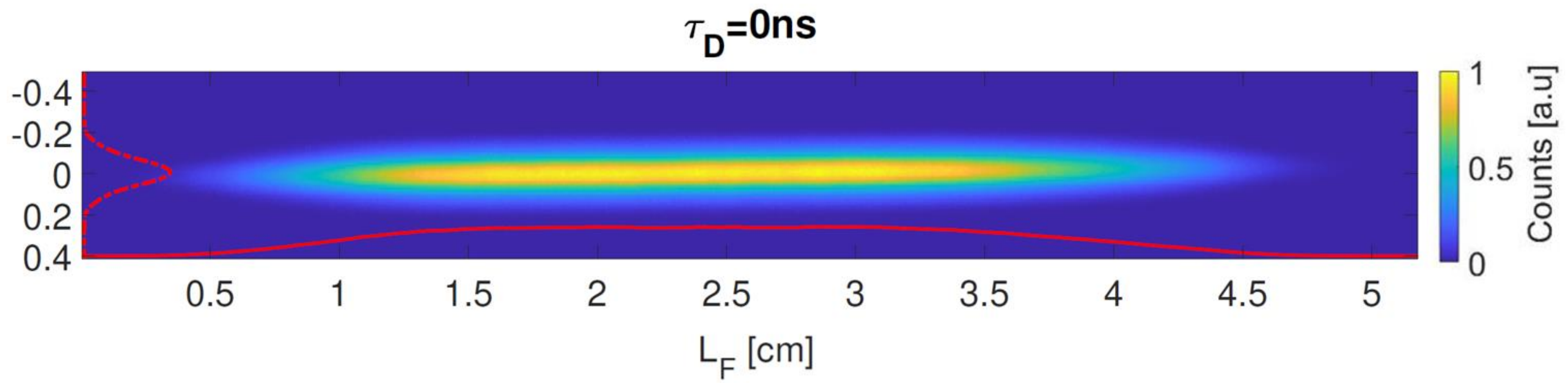
- Ti:Sapphire laser system:
  - 10 mJ, 350 fs FWHM, 10 Hz
- 10 cm X 1 m gas cell (stationary condition)
- 1 mbar N_2 95% - H_2 5%

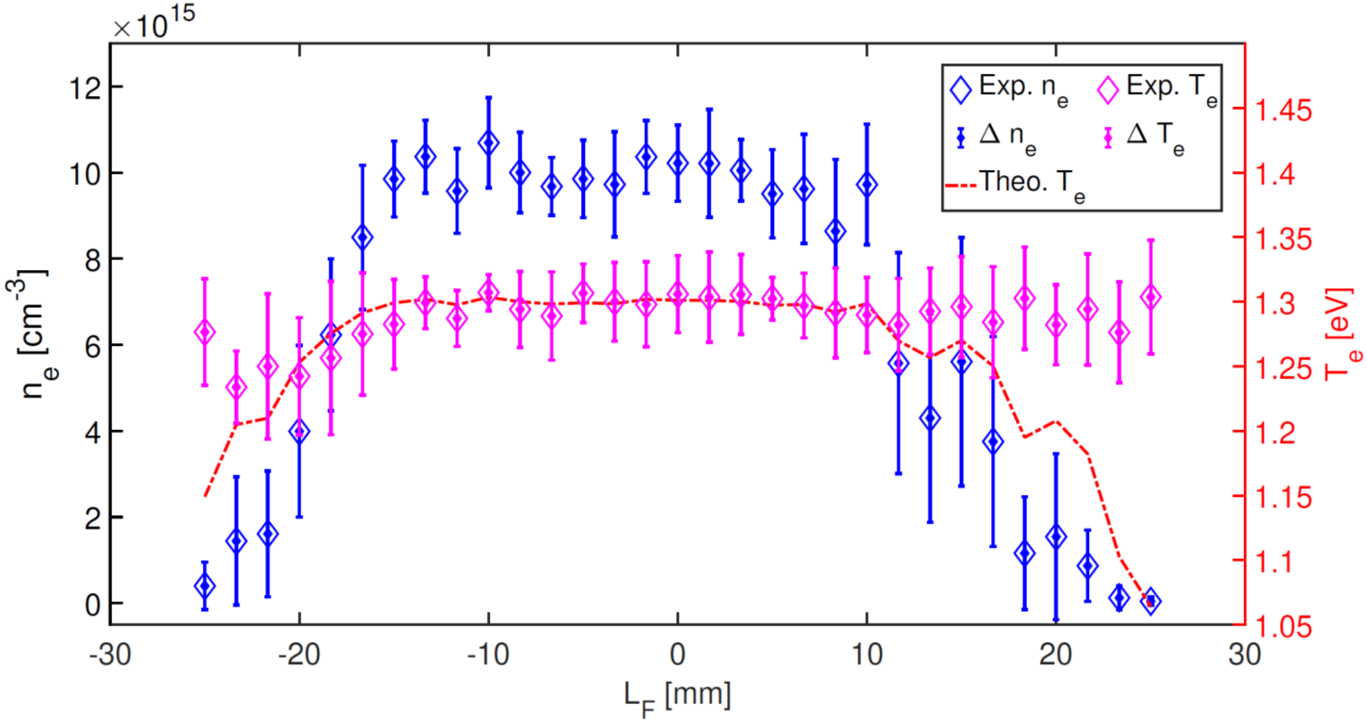
M. Galletti, et al., *"Femtosecond laser-induced plasma filaments for beam-driven plasma wakefield acceleration",* **Phys. Rev. E 111, 025202 (2025)**

Experimental characterization

- Side imaging fluorescence technique
  - Filament size and decay time
- Spectral analysis
  - Plasma density and temperature distribution
- Photodiode
  - Decay time

Laser-induced plasma filaments





Plasma density:

$n_e \approx 10^{16}\ cm^{-3}$

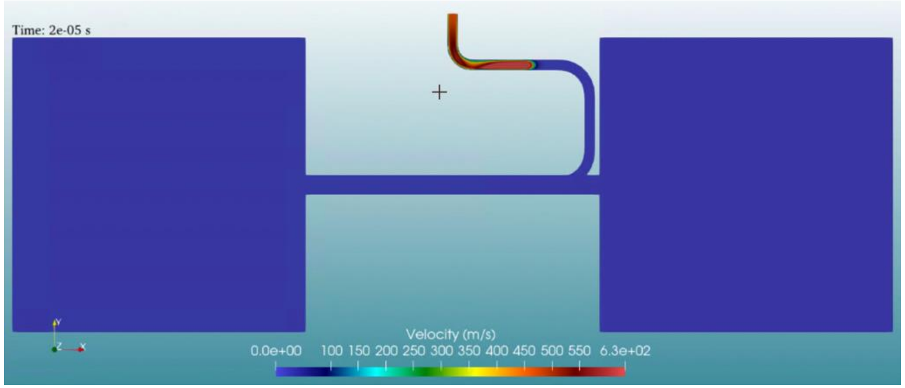
Electron temperature:

$T_e \approx 1.3\ eV$

Derived from Stark broadening analysis of emission spectra

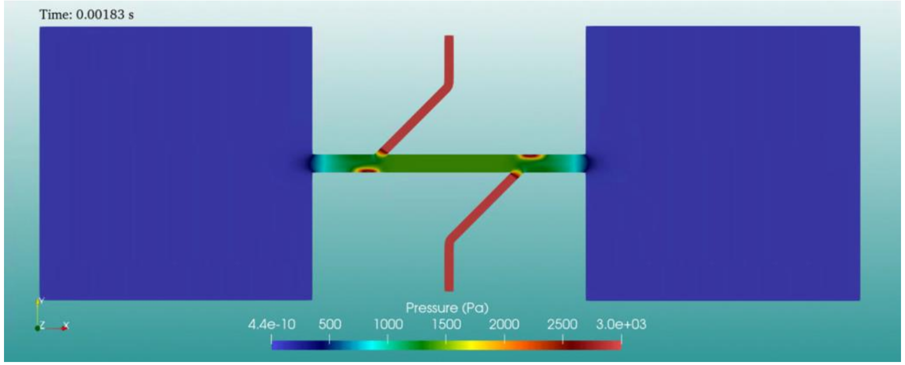
Laser-induced plasma filaments cell: design

3cm capillary with 45° injection inlet



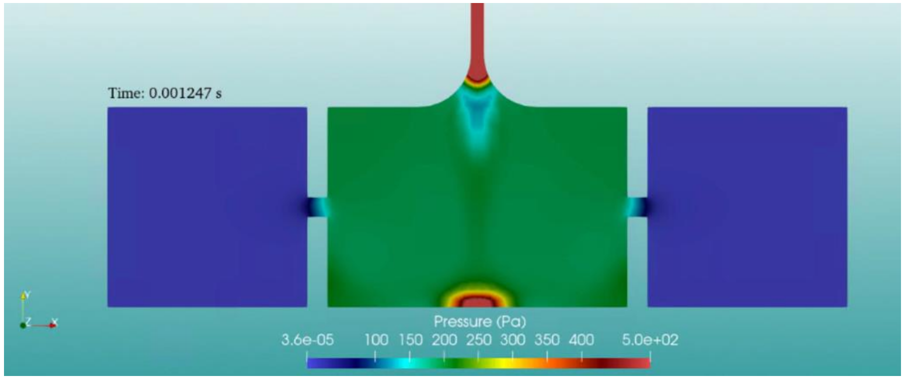
- ✓ Smooth pressure ramped profile along the channel
- ✓ Turbulences localized at the exit

3cm capillary with 45° injection inlets



- ❖ Minimized turbulences respect to the 90° inlets configuration towards the inlets
- ✓ Smoother pressure distribution with tilted inlets

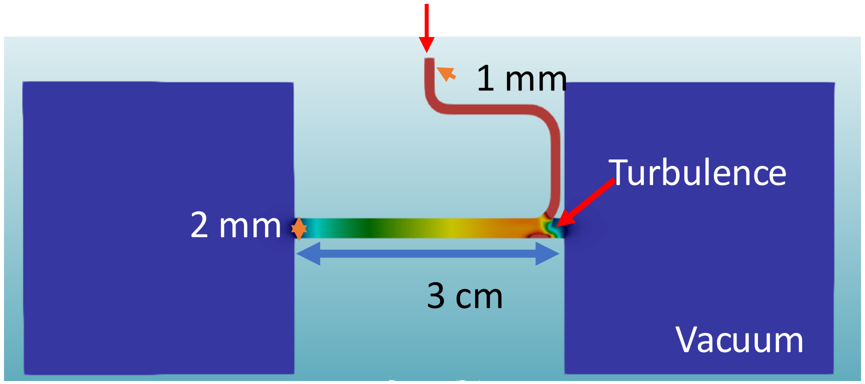
3cm gas cell with 2mm inlet

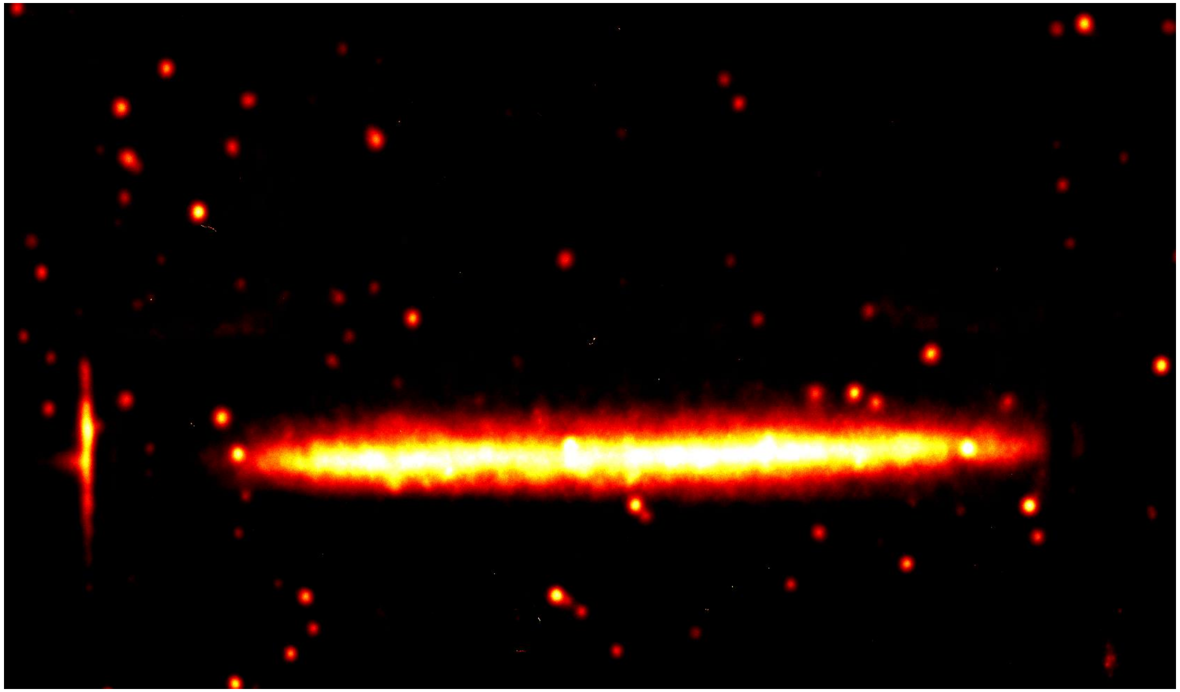


- ❖ Slow filling
- ✓ Flat-top pressure (and density) profile, mbar range on-axis when 100mbar injected

3cmx2mm with 1mm diameter single inlet @45deg injection

- Localized and minimized turbulence at the inlet position
- Smooth pressure ramp from the entrance



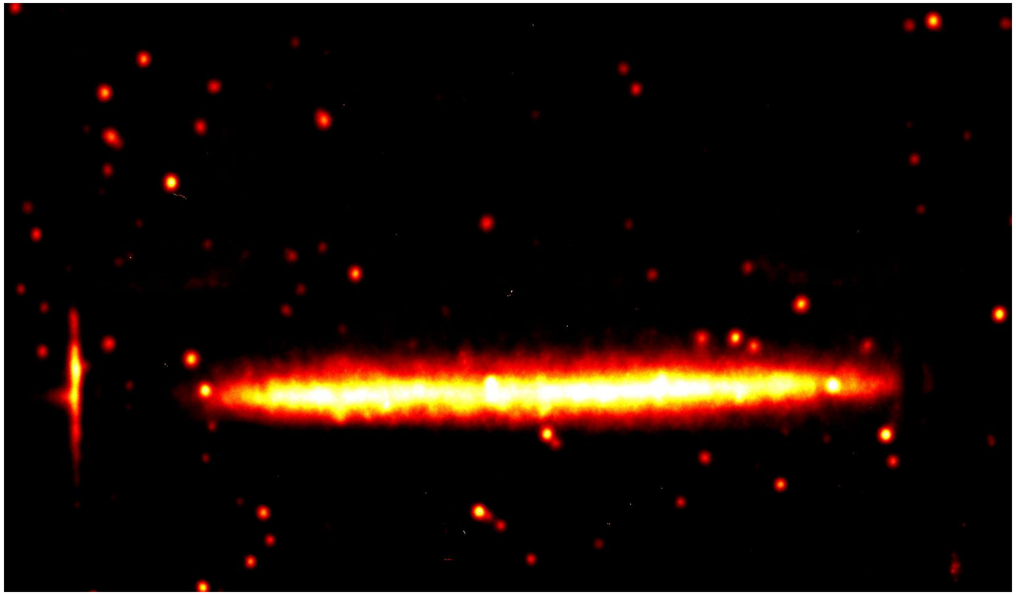


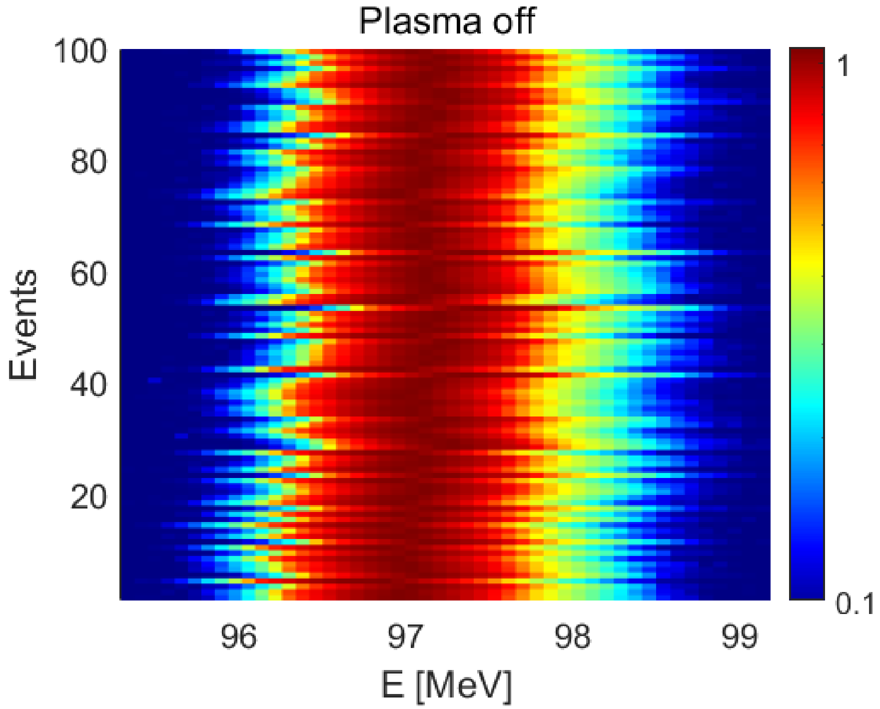
Proof of electron beam deceleration

3cmx2mm with 1mm diameter single inlet @45deg injection was installed in the COMB interaction chamber (LINAC beamline).

Fluorescence Interaction Length ≈ 30 mm

Driver e-beam ≈ 500 pC



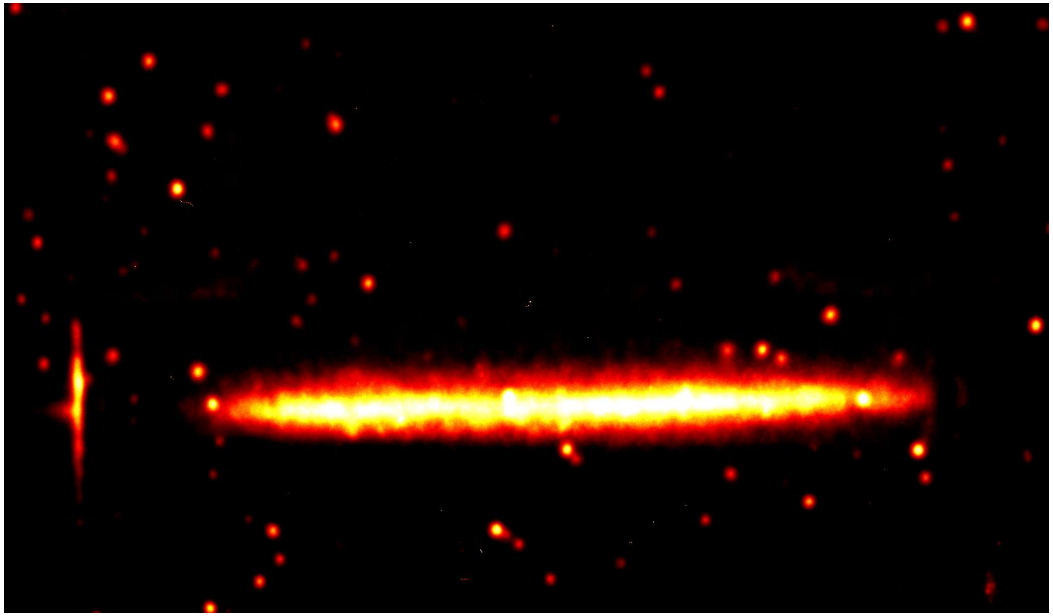


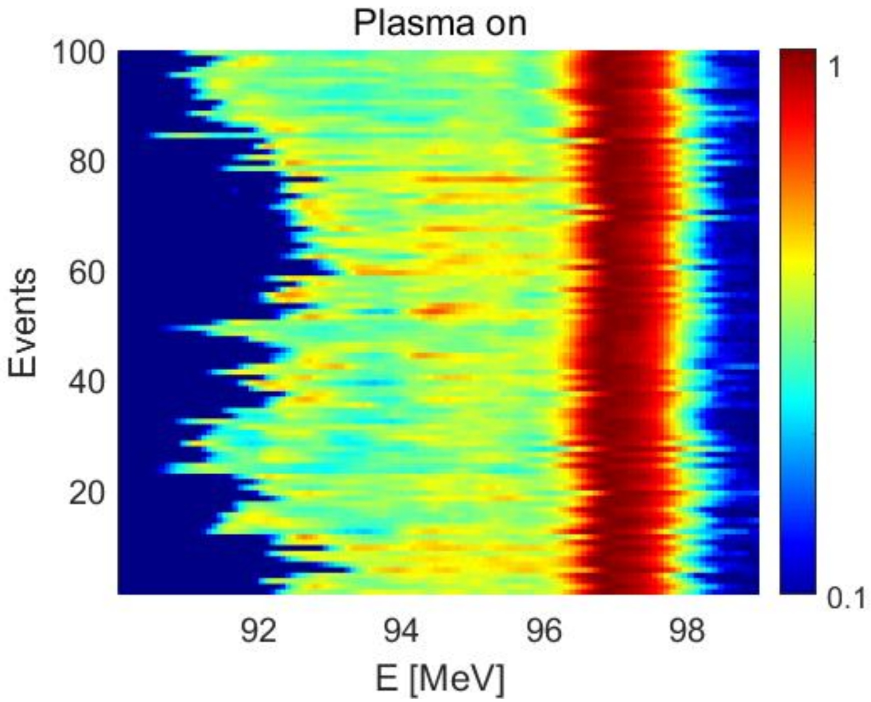
Proof of electron beam deceleration

3cmx2mm with 1mm diameter single inlet
@45deg injection was installed in the COMB interaction chamber (LINAC beamline)..

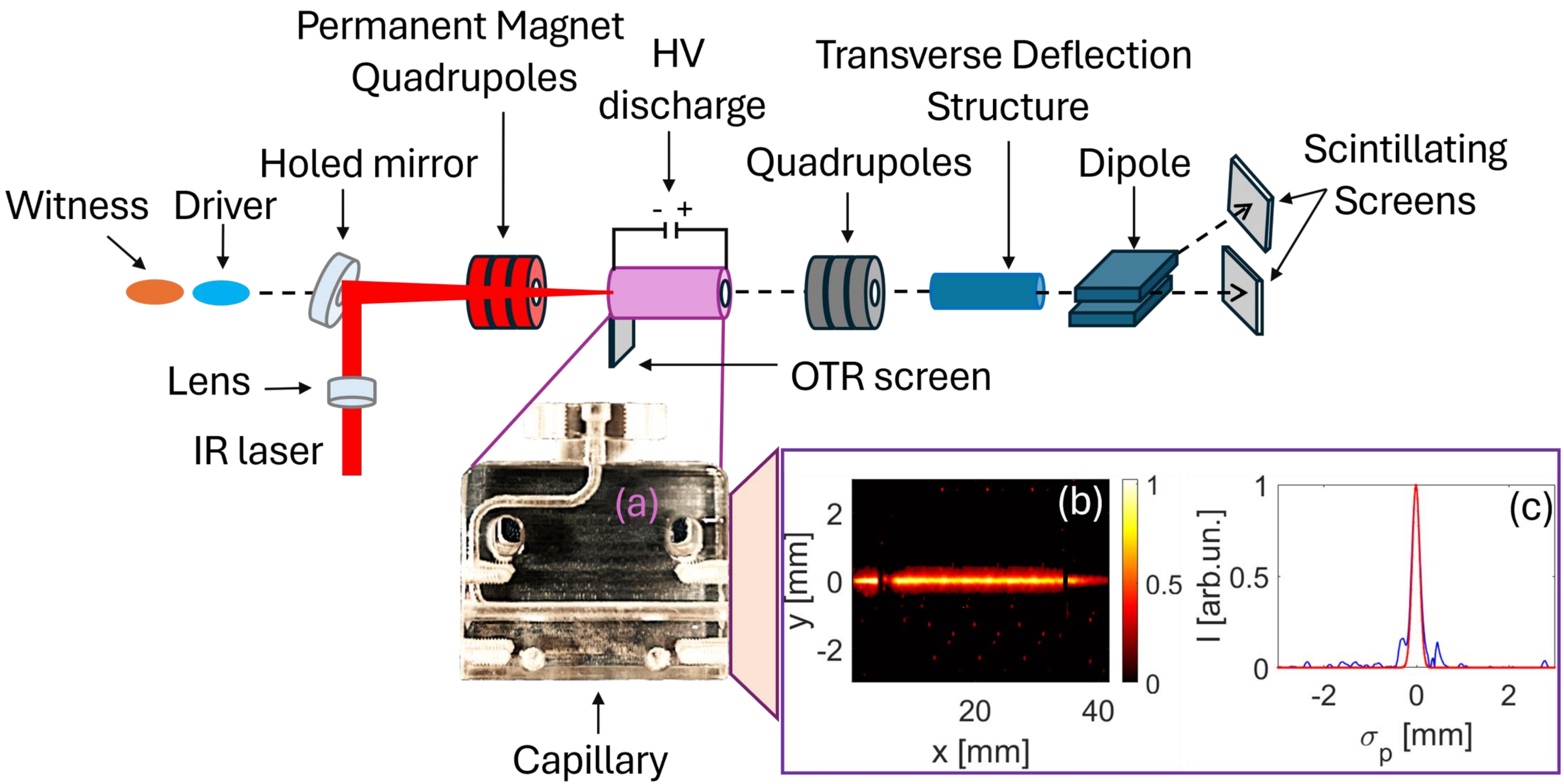
Fluorescence Interaction Length ≈ 30 mm

E-beam deceleration ≈ 5 MeV



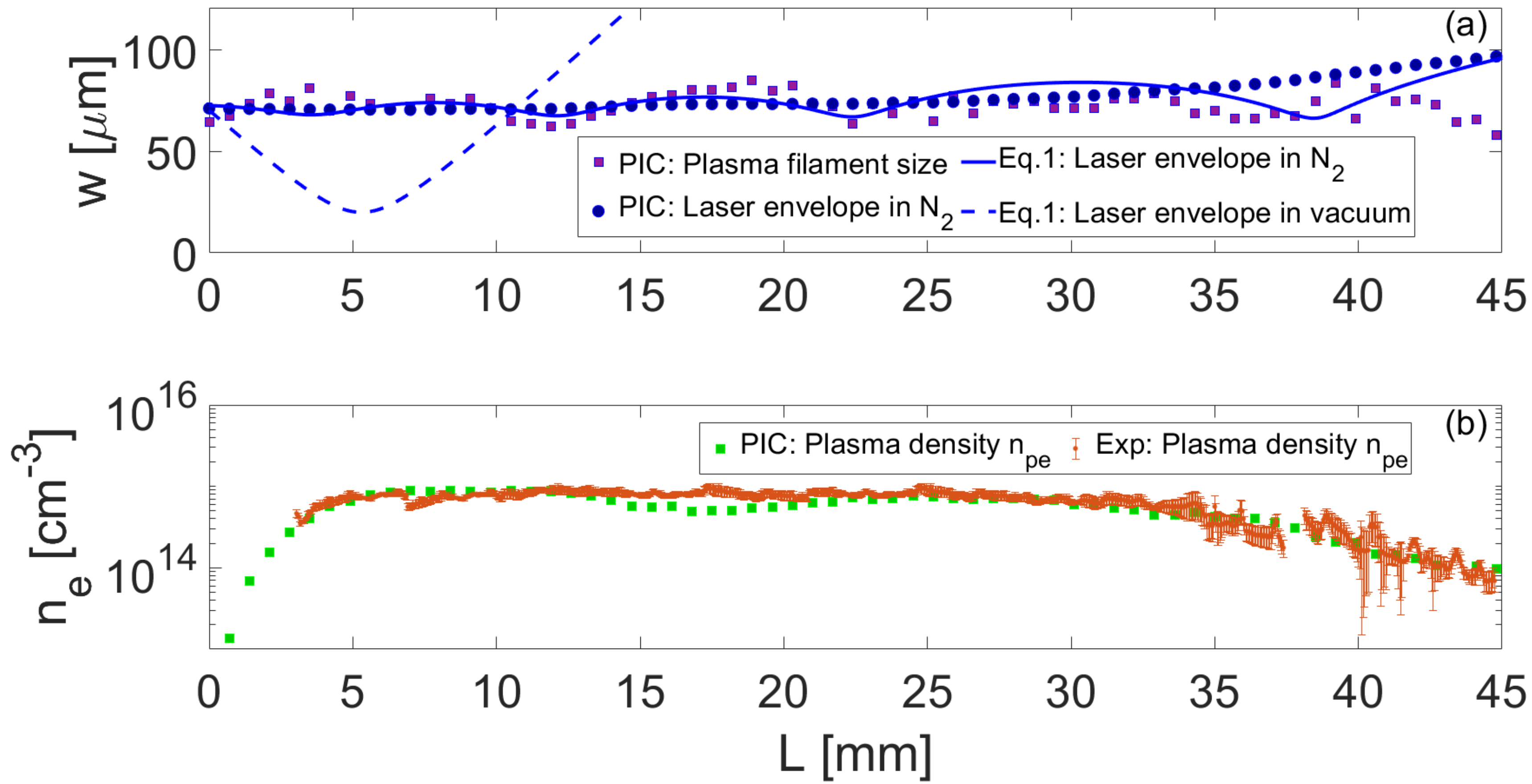


Experimental setup



Schematic layout of the SPARC LAB linac. The interaction chamber arranged for the plasma filament-based acceleration experimental campaign. (a) 45◦, single-inlet capillary design. (b) Typical filament snapshots taken via the side imaging technique.

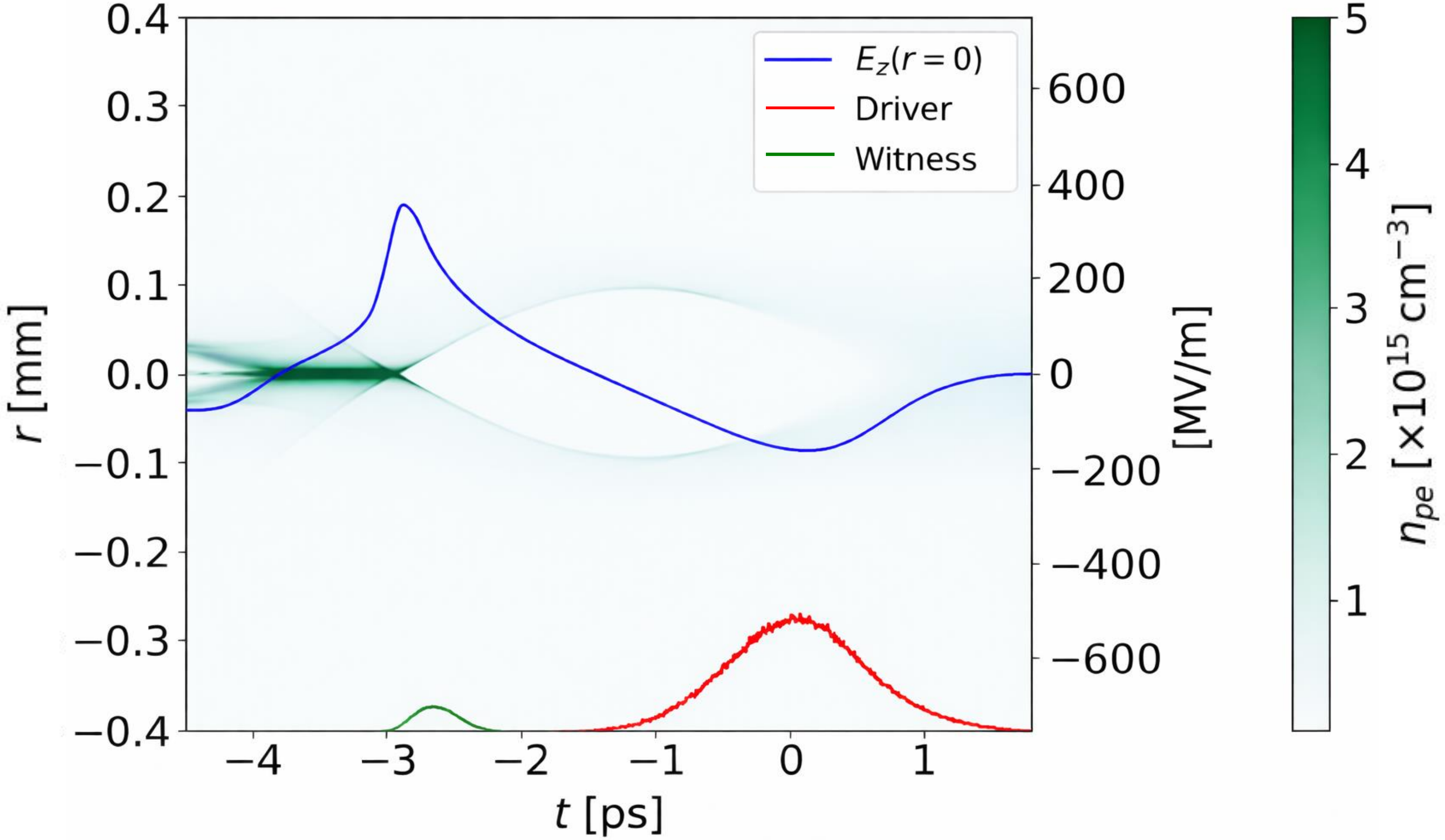
Filament generation



(a) **Theoretical calculations** both regarding the laser nonlinear propagation, the plasma filament generation and (b) the density of the filament. The latter compared to the density retrieved from the side imaging technique.

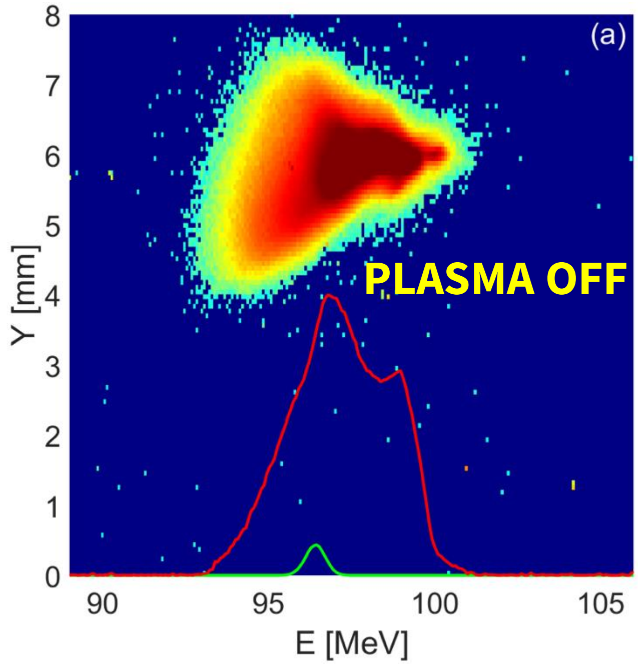
M. Galletti, et al. Experimental Demonstration of Beam-Driven Wakefield Acceleration in Laser-Plasma Filament. **sub PRE (2026) http://arxiv.org/abs/2602.22841**

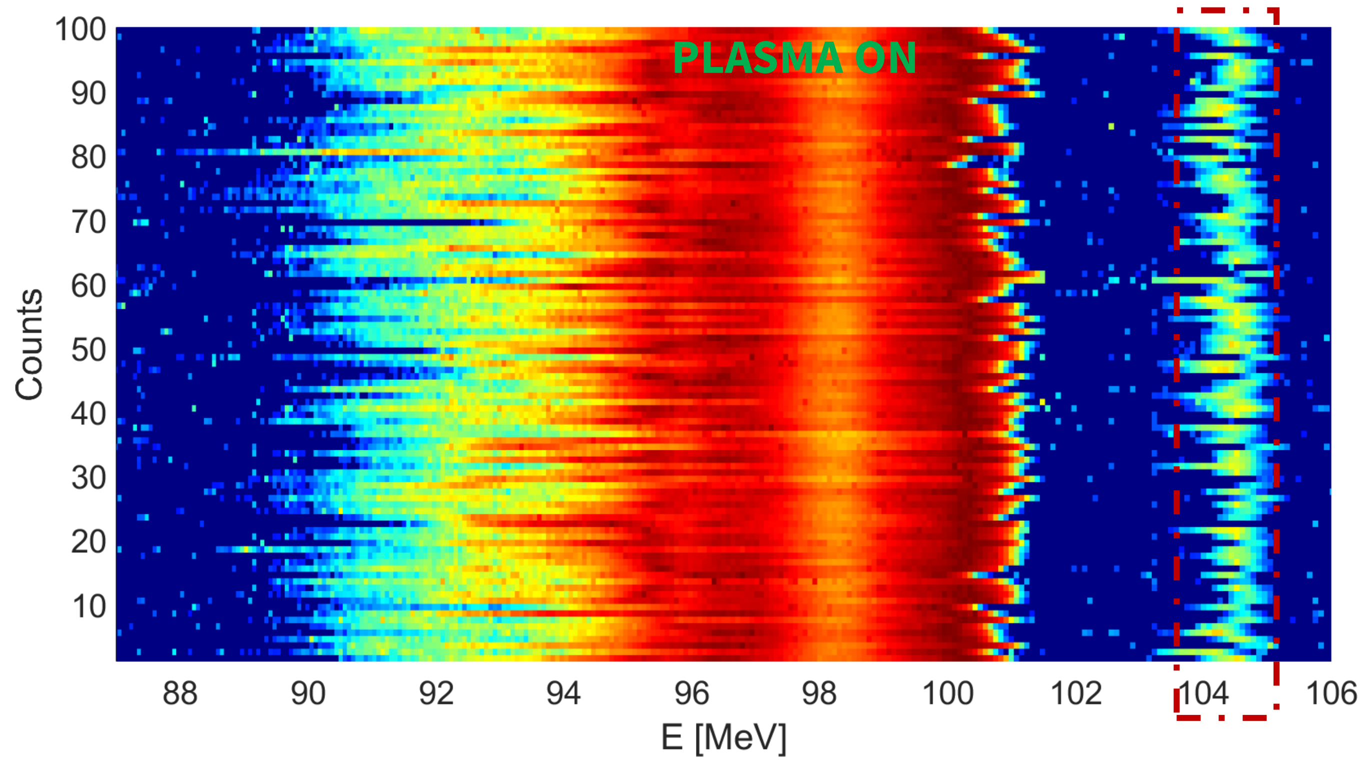
PWFA stage simulation



- ❖ Adopting a **filament size 70 μm waist** with a **electron plasma density 8e^{14} cm^{-3}** and experimental input for the driver (**500 pC, 0.6 ps, 27 µm waist**) and witness (**50 pC, 0.2 ps, 20 µm waist, delay ~2.7 ps**).
- ✓ **An accelerating gradient of ~250 MeV/m and a decelerating gradient of ~150 MeV/m** are retrieved.

PWFA stage acceleration and stability



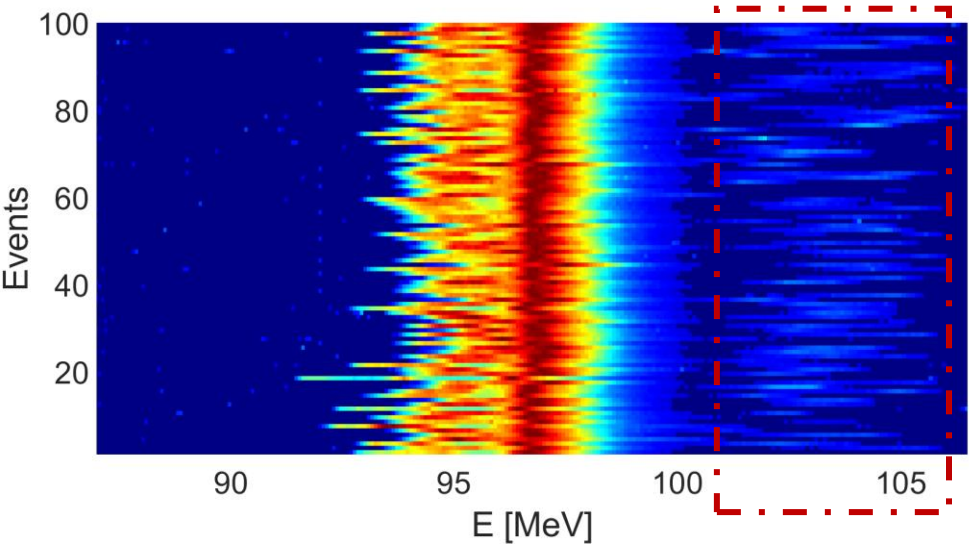


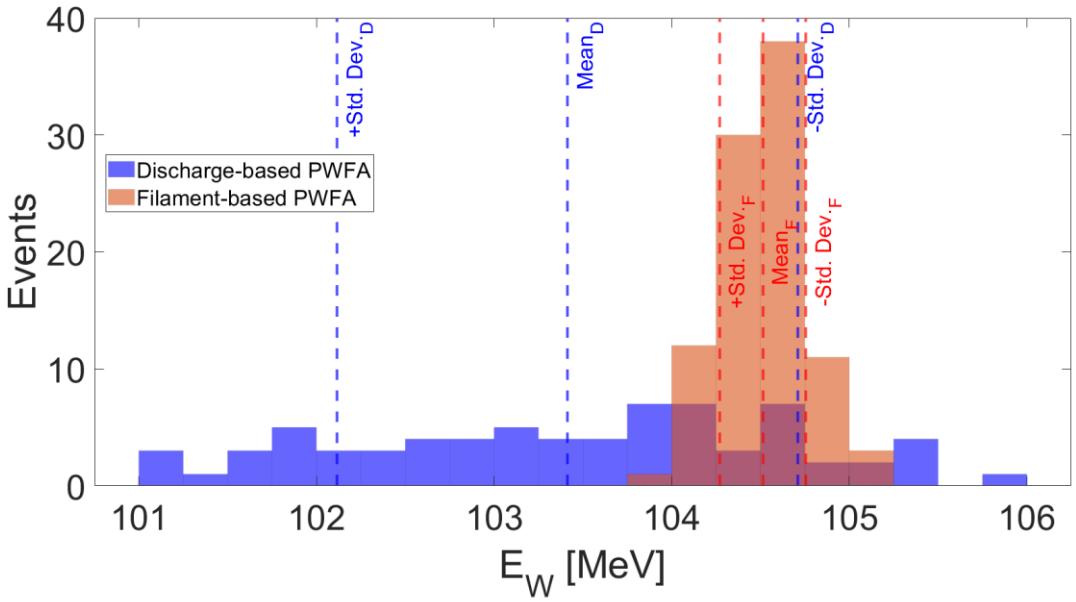
- An **energy gain of ~8 MeV in 30mm** acceleration length means an acceleration gradient of ~250 MeV/m (~4 MeV driver deceleration → 150 MeV/m).
- **The relative energy spread σ_E and the charge Q are preserved** through the acceleration length. **The energy jitter** is less than 0.5%.

The filament is a highly-stable acceleration stage (95% success-rate), showing to be a high-quality plasma booster stage.

M. Galletti, et al. Experimental Demonstration of Beam-Driven Wakefield Acceleration in Laser-Plasma Filament. **sub PRE (2026) http://arxiv.org/abs/2602.22841**

PWFA stage acceleration and stability





The equivalent measurement with a discharge-based plasma (same parameters) but without additional stabilization methods is performed.

- An **energy gain of ~8 MeV in 30mm** acceleration length.
- **The charge Q are preserved** through the acceleration length.

- **The energy jitter** is about 1.3%. The **relative energy spread** σ_E is about 4%.
- The witness is accelerated in only 75% of events.

Conclusions and outlook on the future

Development of plasma-based accelerators is still ongoing; many exciting results obtained in the last few years. **To deliver a plasma-based user-oriented facilities a high-quality, tunable plasma stage is needed.**

Preliminary Results obtained @SPARC_LAB both theoretically and experimentally show that stable femtosecond laser filament is a viable solution for PWFAs

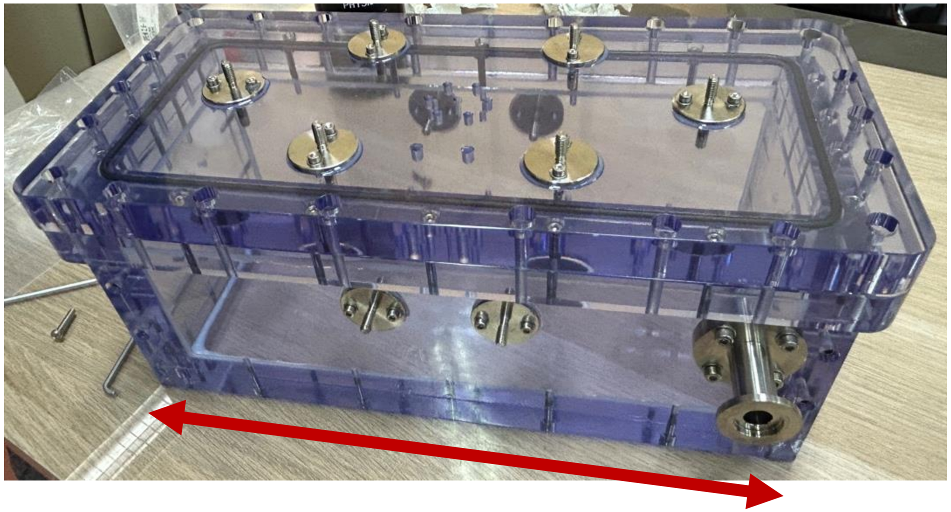
- ✓ Complete characterization of the plasma stage has been performed in a pulsed operation regime
- ✓ Experimentally demonstrated plasma-based acceleration via plasma filaments retrieving an energy gain of approximately **8 MeV in a 3-cm stage**, together with a significant **stability and quality of the acceleration process**.

Next steps:

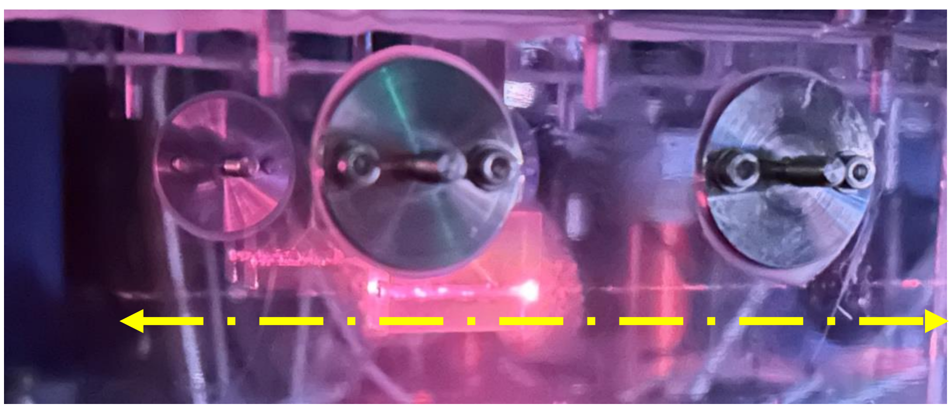
- ❑ **Run-3** Demonstration of 13cm plasma filaments for PWFA
- ❑ **Run-4** Demonstration of 13cm plasma filaments @ KHz rep rate for PWFA

Fundamental steps toward the EuPRAXIA facility for user-oriented applications

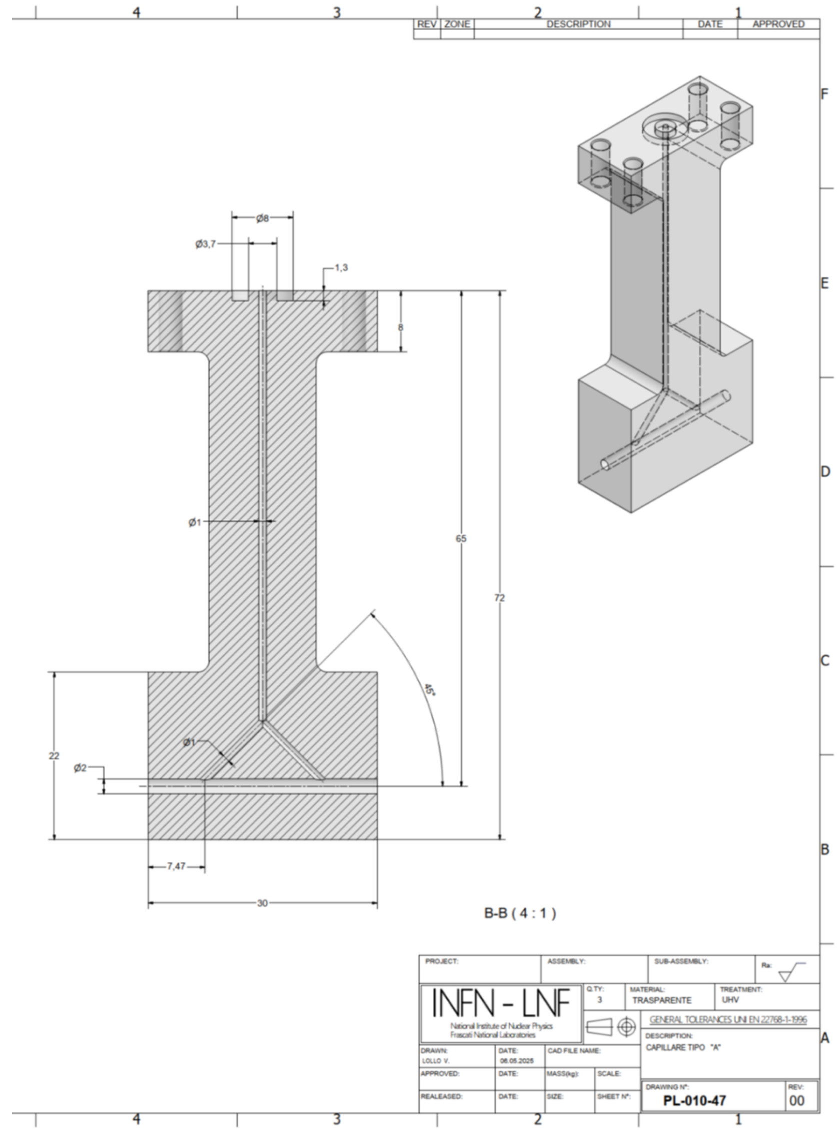
Conclusions – Preliminary results R-3, R-4



50 cm length interaction chamber



Around 20 cm length filament @ ~10s of mbar



Courtesy of V. Lollo

Thank you for your kind attention!

Mario Galletti (LNF, INFN)

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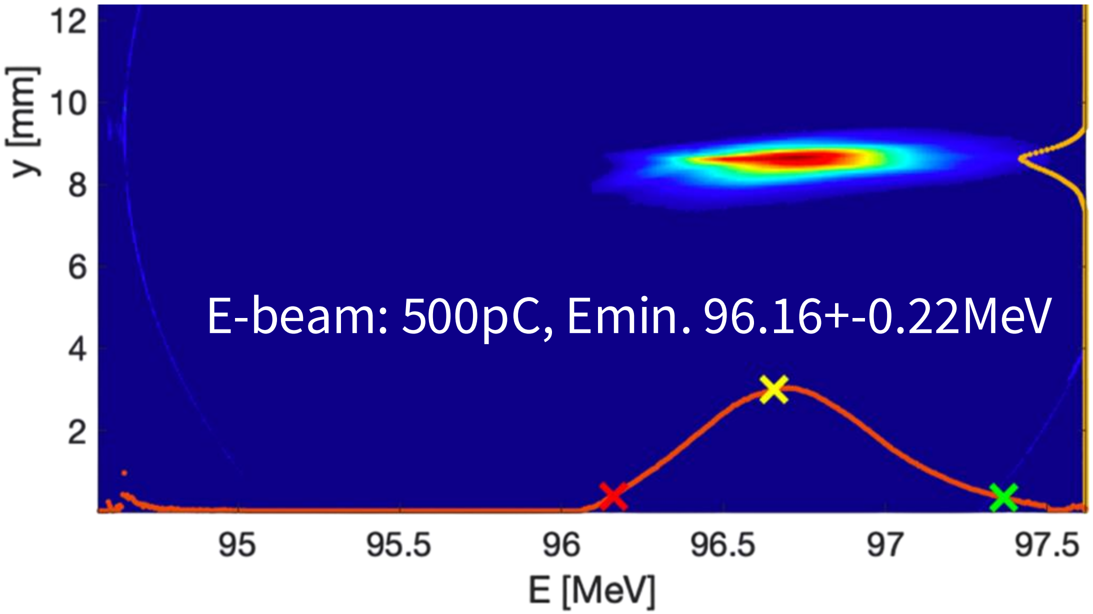
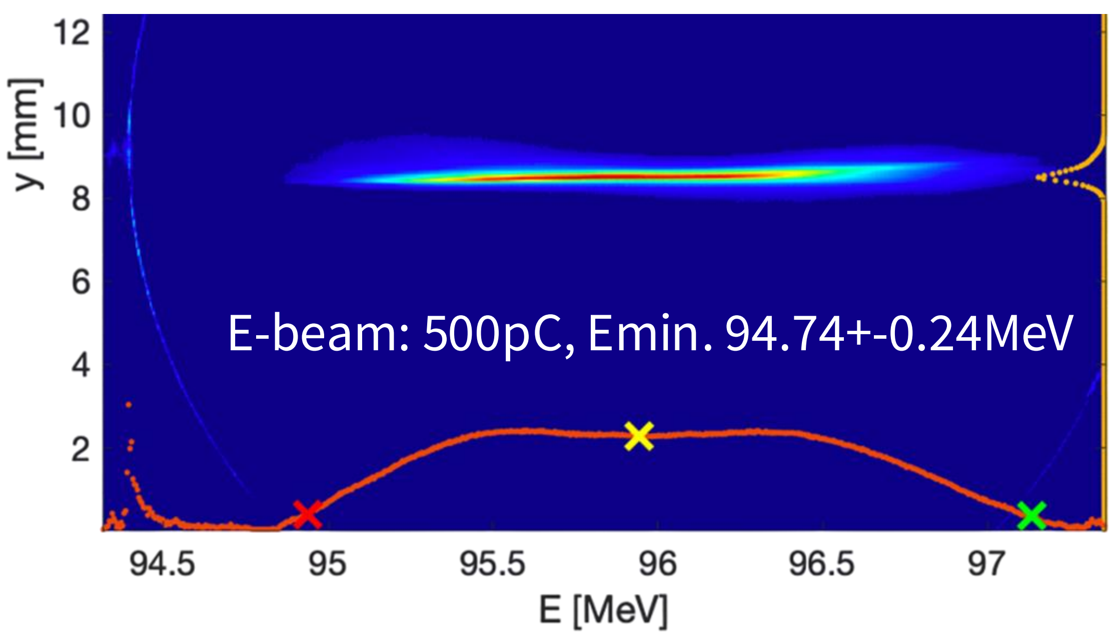
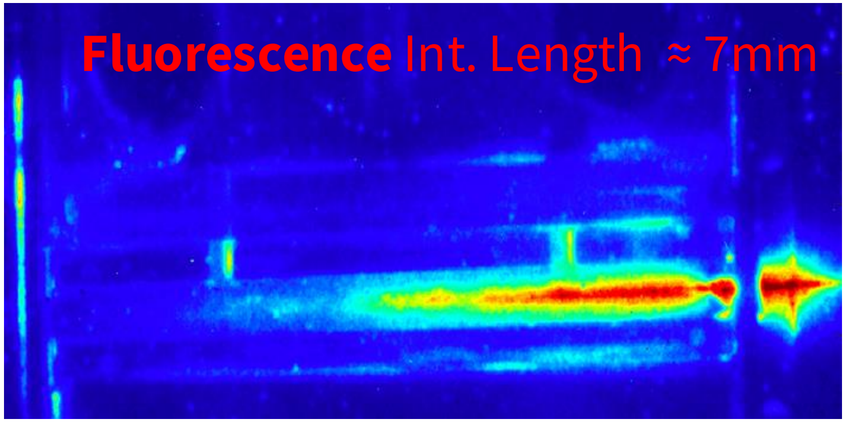
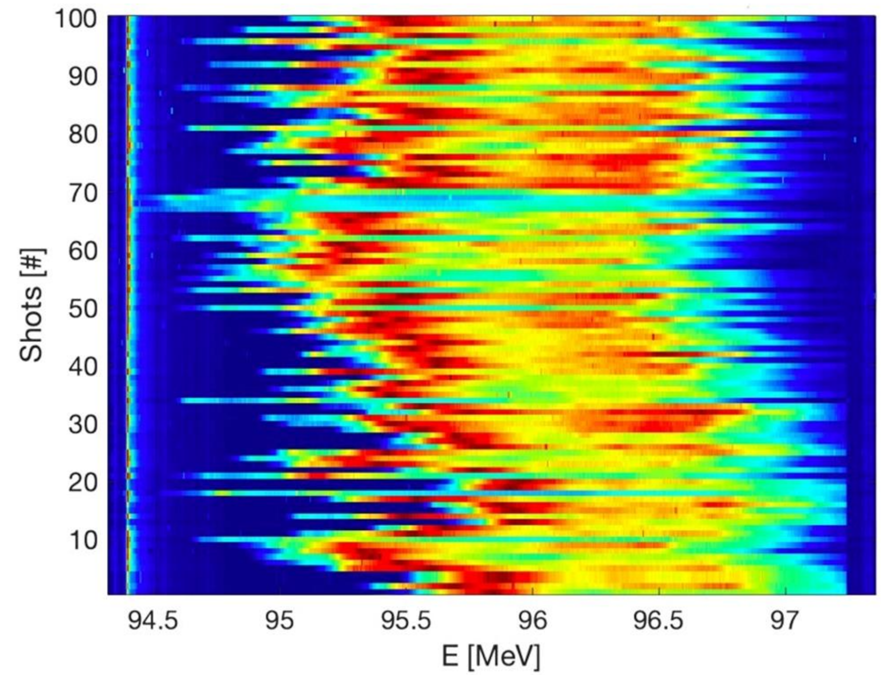
On behalf of the SPARC_LAB collaboration

Proof of electron beam deceleration



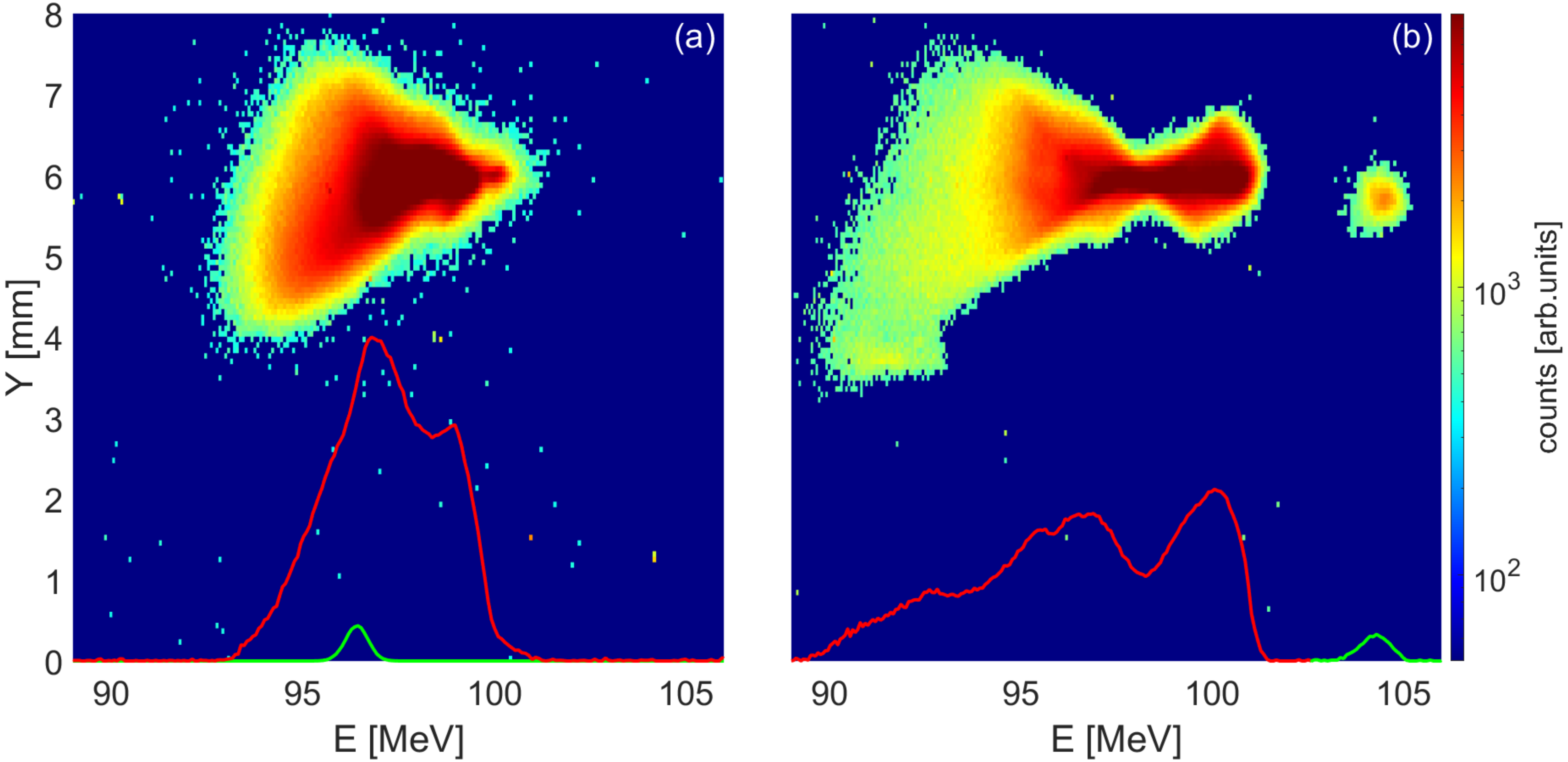






Averaged e-beam deceleration ≈ 1.3MeV

PWFA stage experiment



Spectra of the driver and witness configuration with (a) no plasma and (b) with plasma, showing a 4 MeV driver deceleration and a 8 MeV witness acceleration. The results are in agreement with the previously mentioned simulations.

M. Galletti, et al. Experimental Demonstration of Beam-Driven Wakefield Acceleration in Laser-Plasma Filament. sub PRE (2026) http://arxiv.org/abs/2602.22841