7th European Advanced Accelerator Conference – EAAC2025
Isola D'Elba, Italy

# *Femtosecond laser-induced plasma filaments for beam-driven plasma wakefield acceleration*

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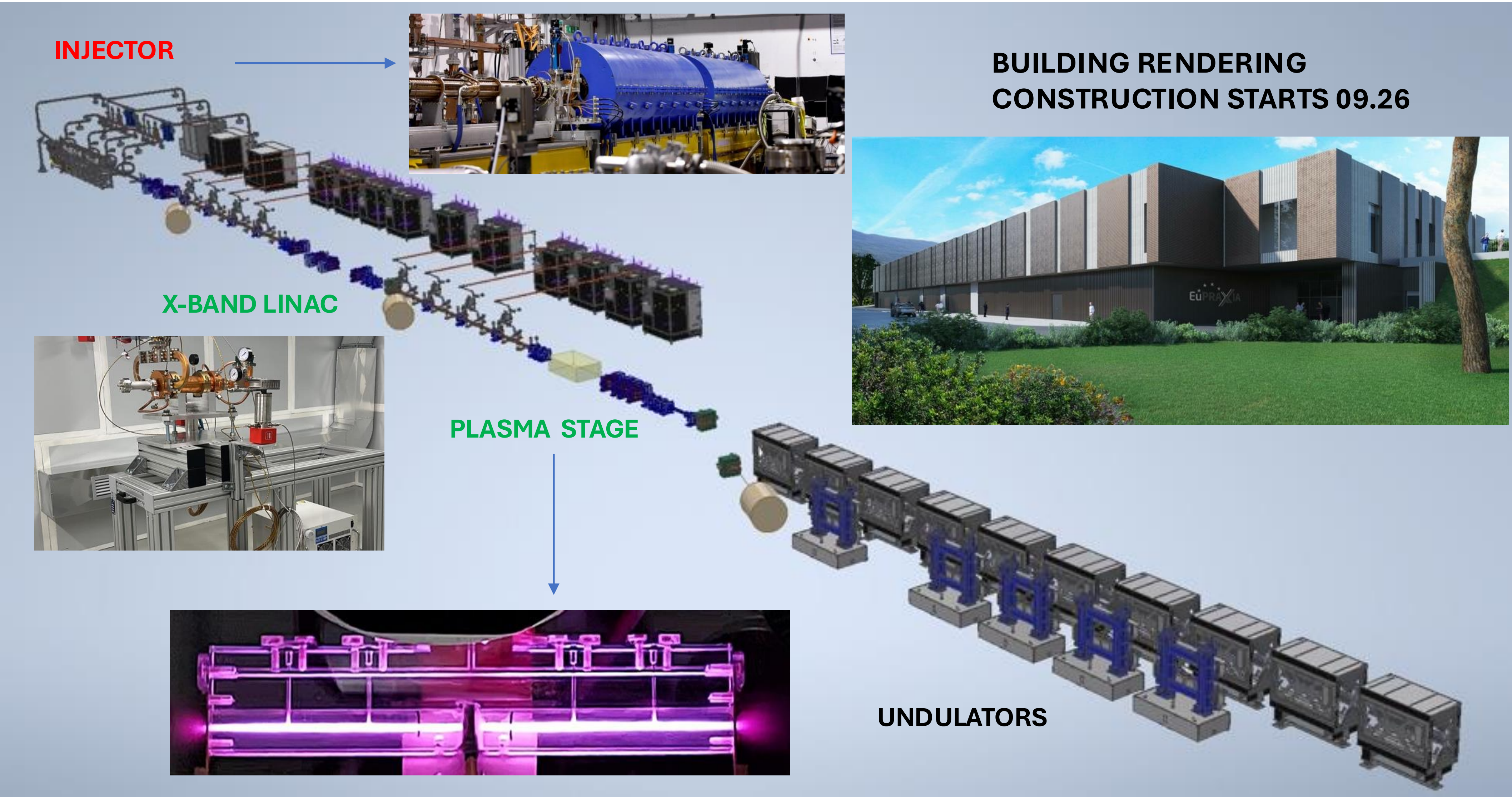
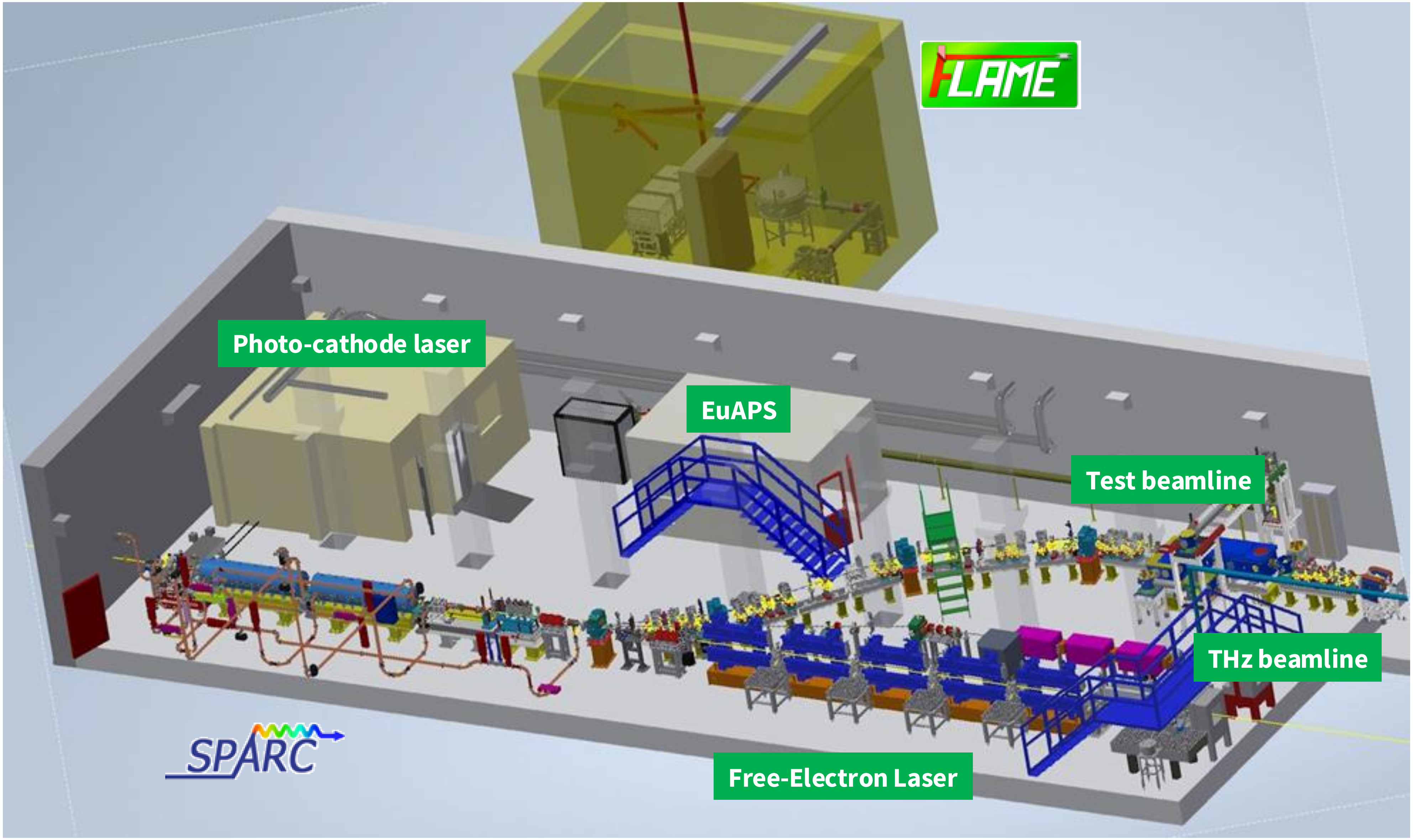
*On behalf of the SPARC_LAB collaboration*

# *LNF future facility*

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



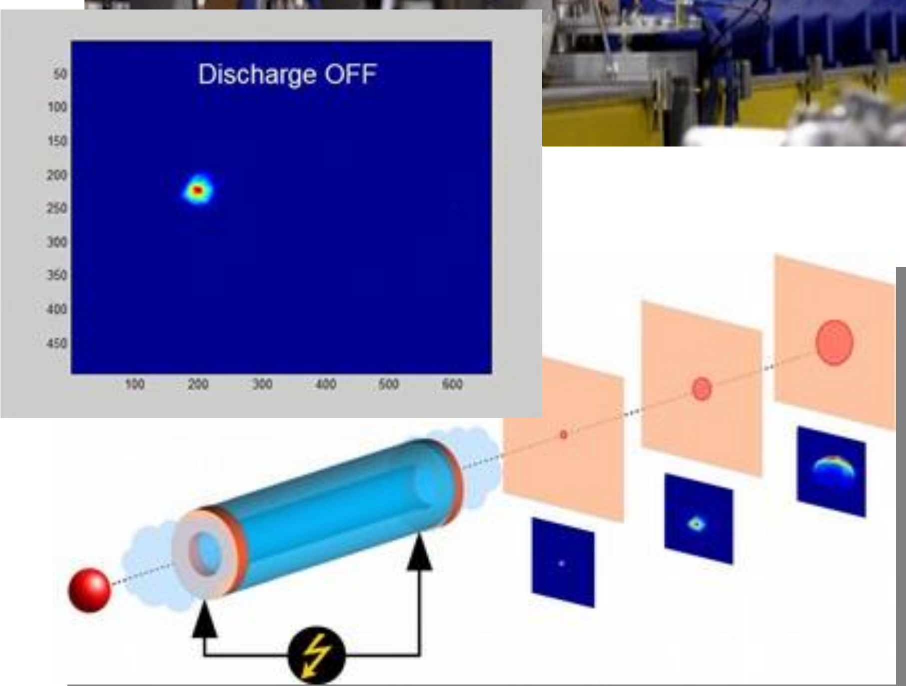
# SPARC_LAB facility




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

# Experience with plasma @SPARC_LAB

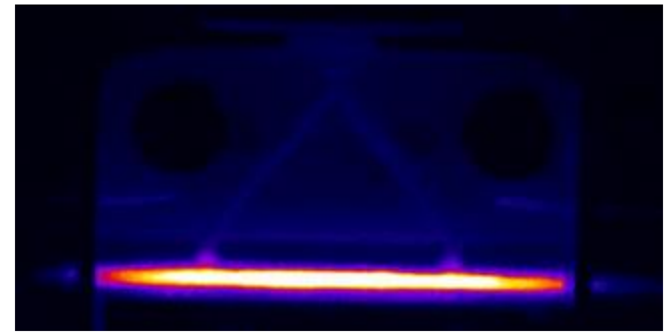
### *Activities with the high-brightness SPARC photo-injector*



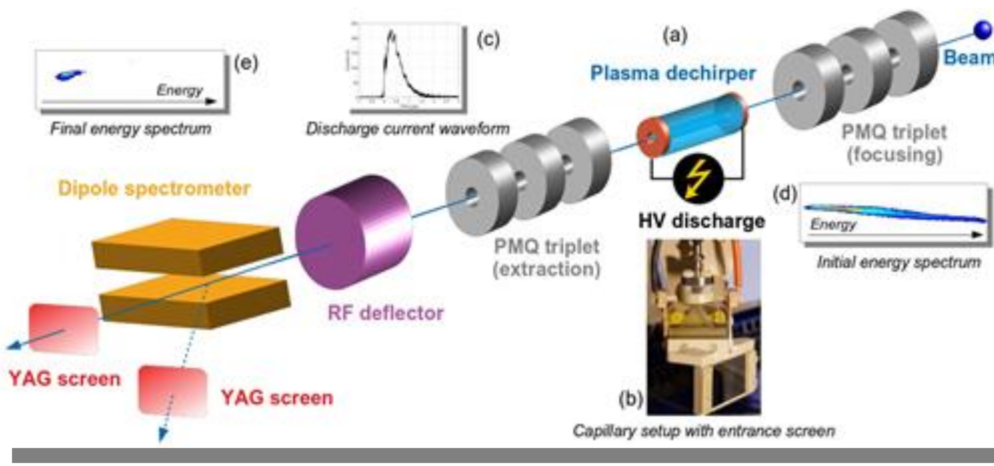

### *Focusing with active-plasma lenses*

**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)**

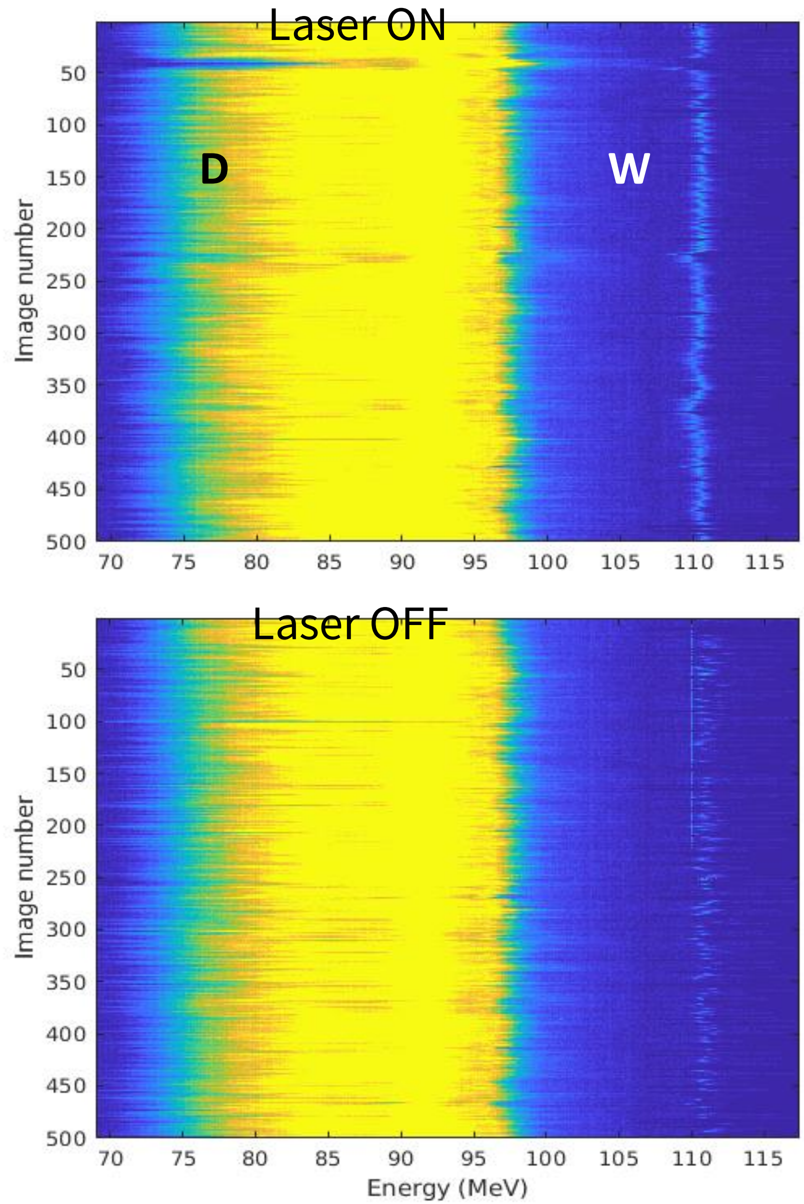
# Plasma stabilization

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.

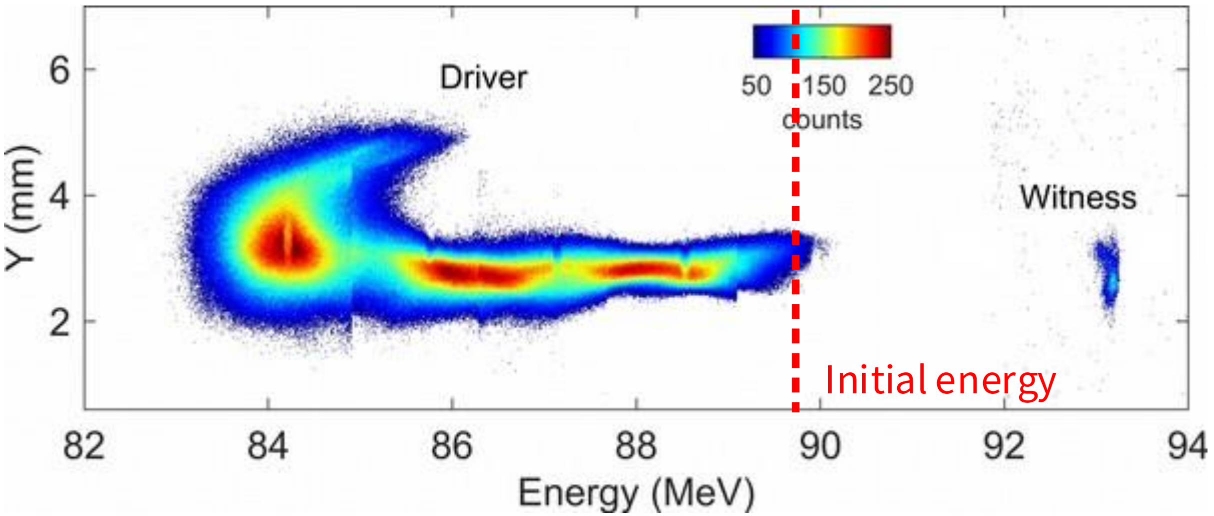



**Biagioni A., et al.** *"Gas-filled capillary-discharge stabilization for plasma-based accelerators by means of a laser pulse.“,* **Plasma Physics and Controlled Fusion.**
**M. Galletti, et al.** "Advanced Stabilization Methods of Plasma Devices for Plasma-Based Acceleration“, **Symmetry 2022, 14(3),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

# *First plasma acceleration results*

4 MeV acceleration in 3 cm plasma with 200 pC driver

- ➢ 2x$10^{15}$ $cm^{-3}$ plasma density
- ➢ ~133 MV/m accelerating gradient

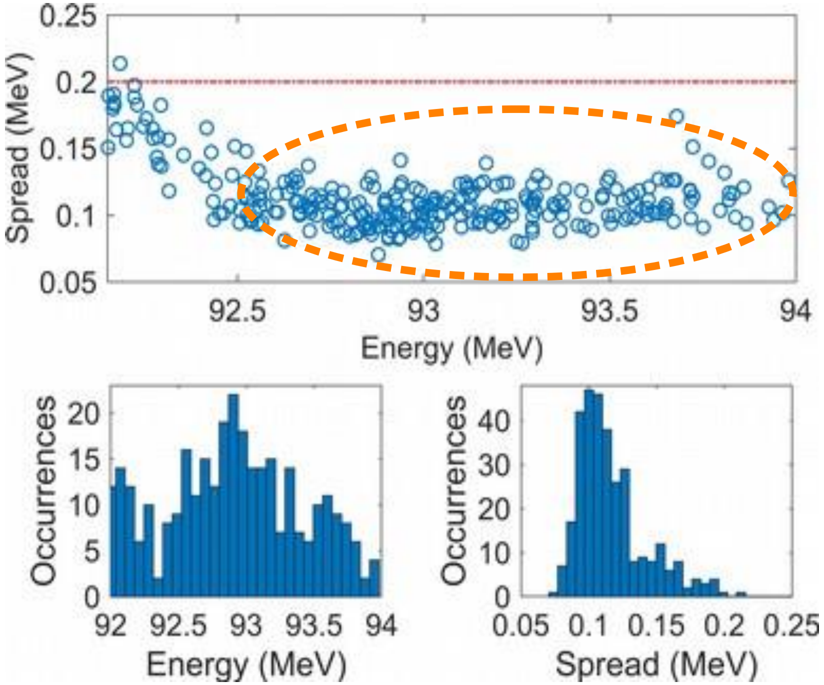



## <u>Energy spread</u>

*from 0.2 MeV*

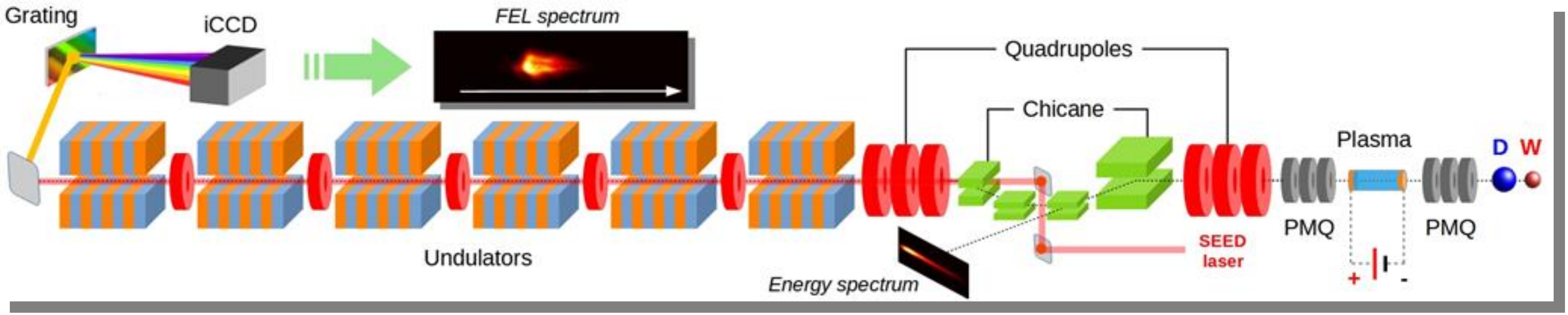
*to 0.12 MeV*

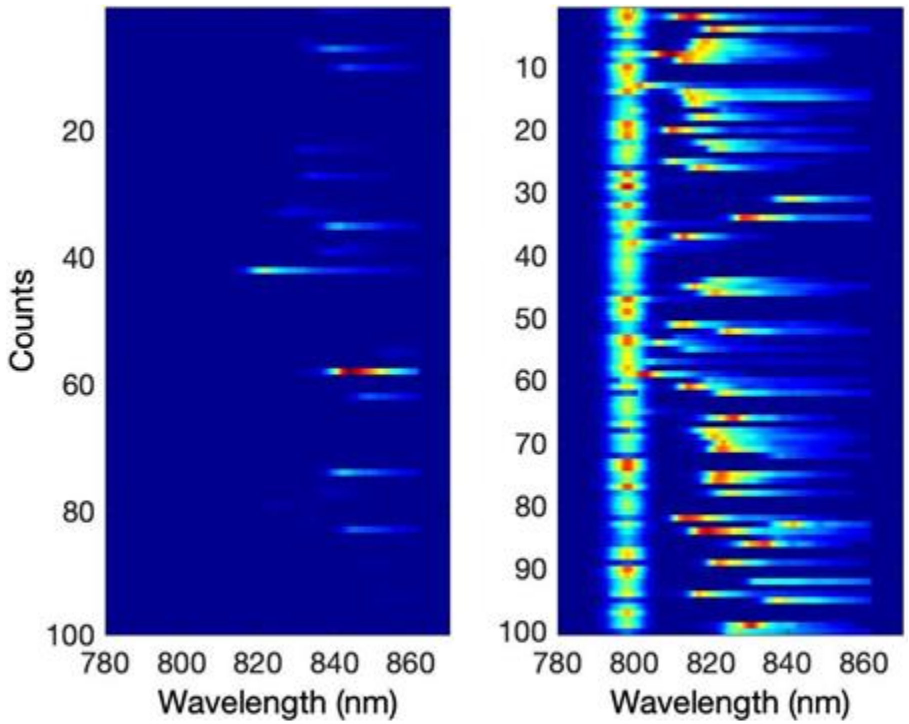
*adopting the assisted beam-loading technique*




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

# Proof of SASE and seeded PWFA-based FEL



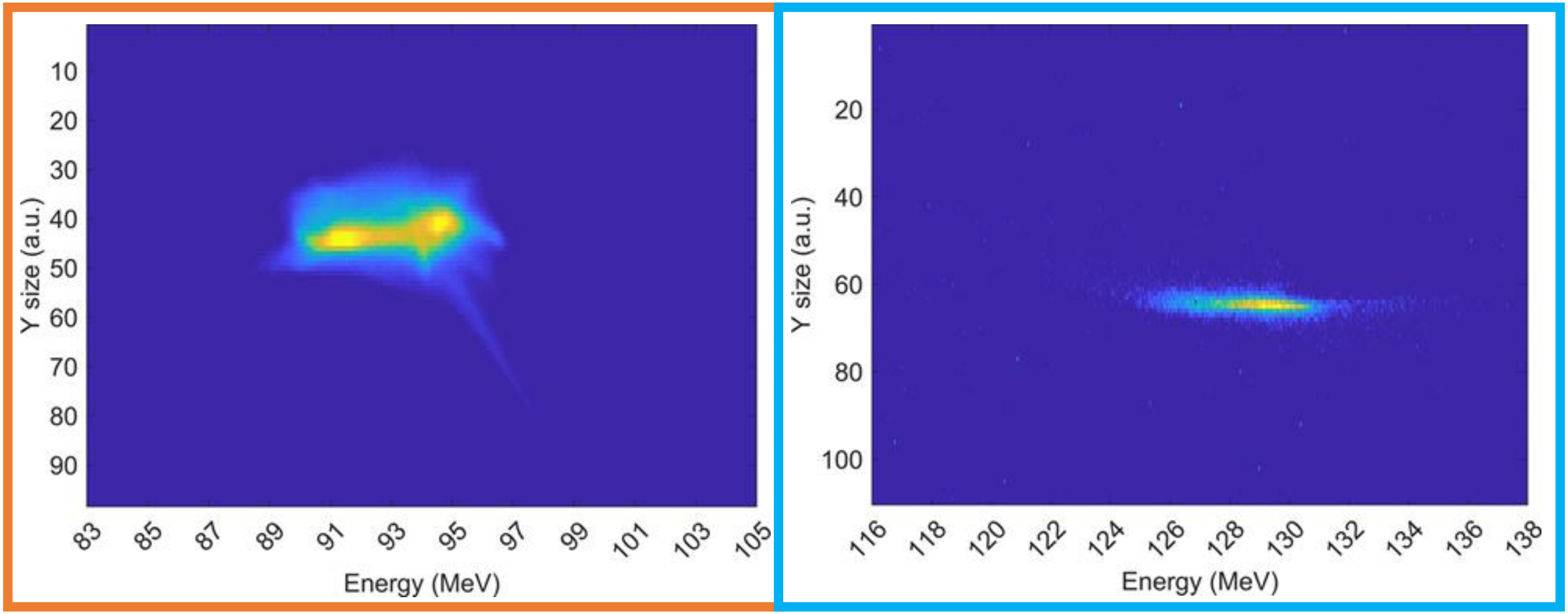

## Seeded FEL radiation

- ✓ 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


**R. Pompili, et al.** *"Free-electron lasing with compact beam-driven plasma wakefield accelerator"*, **Nature 605, 659–662 (2022).**
**M. Galletti, et al**. *"Stable Operation of a Free-Electron Laser Driven by a Plasma Accelerator"*, **Physical Review Letters 129 (23) , 234801 (2022).**
**M. Galletti, et al.** *" Prospects for free-electron lasers powered by plasma-wakefield-accelerated beams "*, **Nature Photonics 18(8) (2024)**

# Preliminary results: GV/m gradients

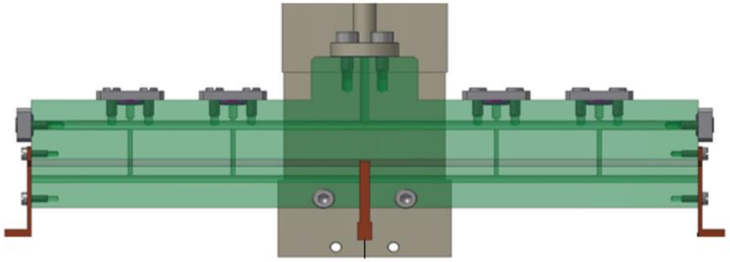
Around 1.2 GV/m accelerating gradient was achieved by using a 500 pC driver followed by a 50 pC witness. Results obtained at plasma density ~$2* 10^{15}\ cm^{-3}$

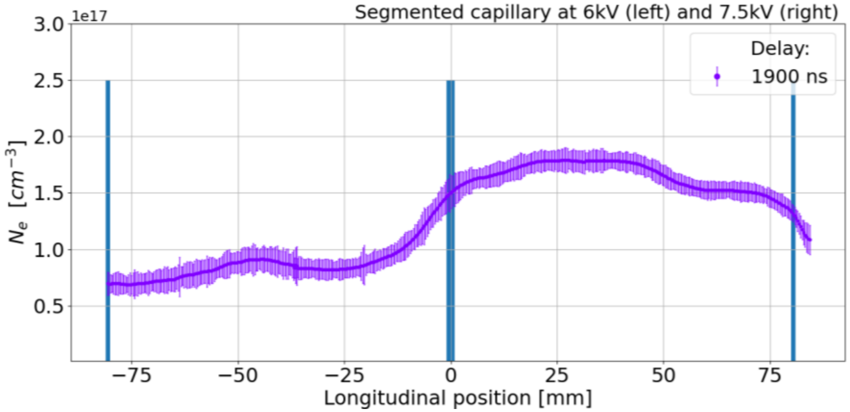


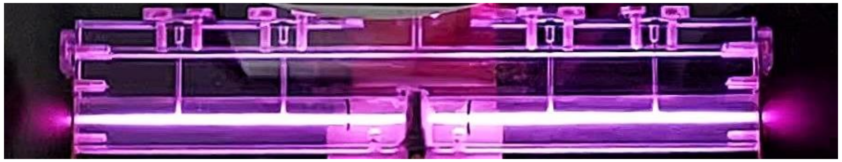

- ✓ Results confirmed that larger charge on the driver bunch was needed to get larger accelerations at the same plasma density used so far
- ✓ Large energy instability observed on the witness. In this configuration, timing-jitters and plasma density fluctuations become more evident on the resulting witness energy

# Plasma Module R&D

Segmented capillary

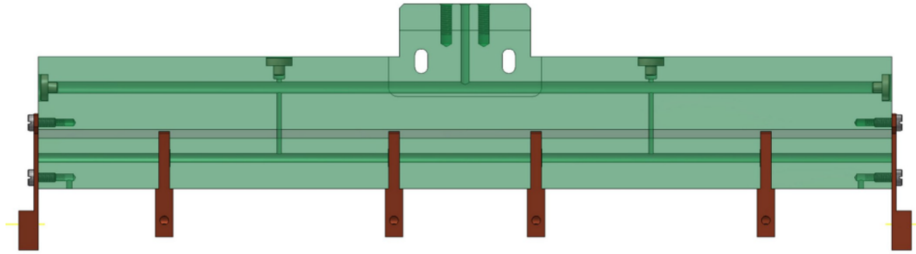


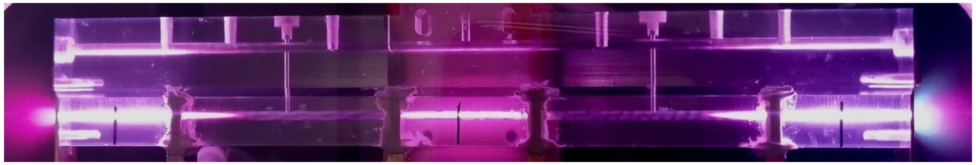


**A. Biagioni, et al.** 'Plasma density manipulation in long staged gas-filled discharge capillaries for plasma-based accelerators', in preparation (2025)

Integrated plasma module





- **Independent** sections powered in parallel
- **60 cm** (m-scale) plasma discharge capillaries with **~10 kV** HV pulses
- Longitudinal **density modulation**
- **Compact plasma module** for acceleration – focusing

**R. Pompili, et al.** *"Acceleration and focusing of relativistic electron beams in a compact plasma device"*, **PHYSICAL REVIEW E 109(5) (2024)**

Courtesy of A. Biagioni, L. Crincoli, V. Lollo

# Plasma Module R&D

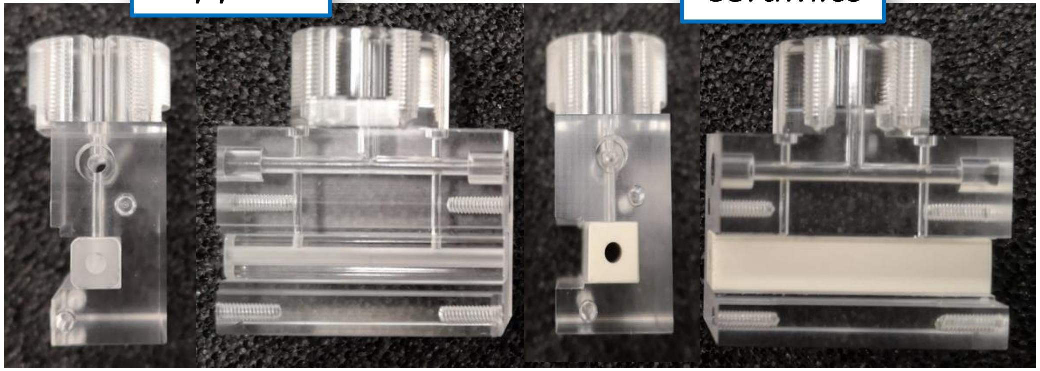
**Plasma module operation at high repetition rate**

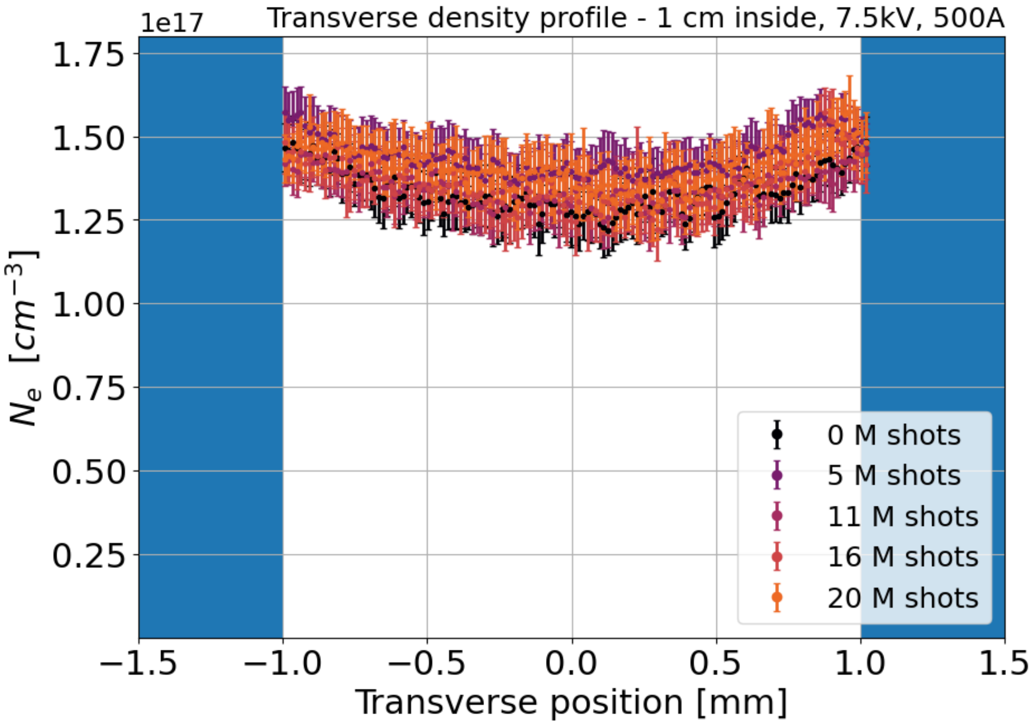
1. Solid-state high repetition-rate discharge system
2. High temperature-resistant materials capable of withstanding the plasma thermal load
3. Vacuum systems suitable for continuous flow gas injection (turbo and primary pumps cooling system)

100 Hz repetition rate discharges

Sapphire

Ceramics






Courtesy of A. Biagioni, L. Crincoli, R. Demitra

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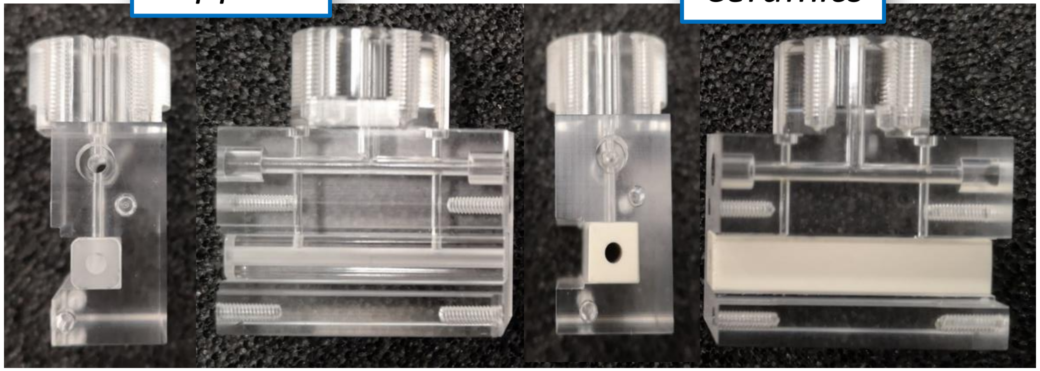
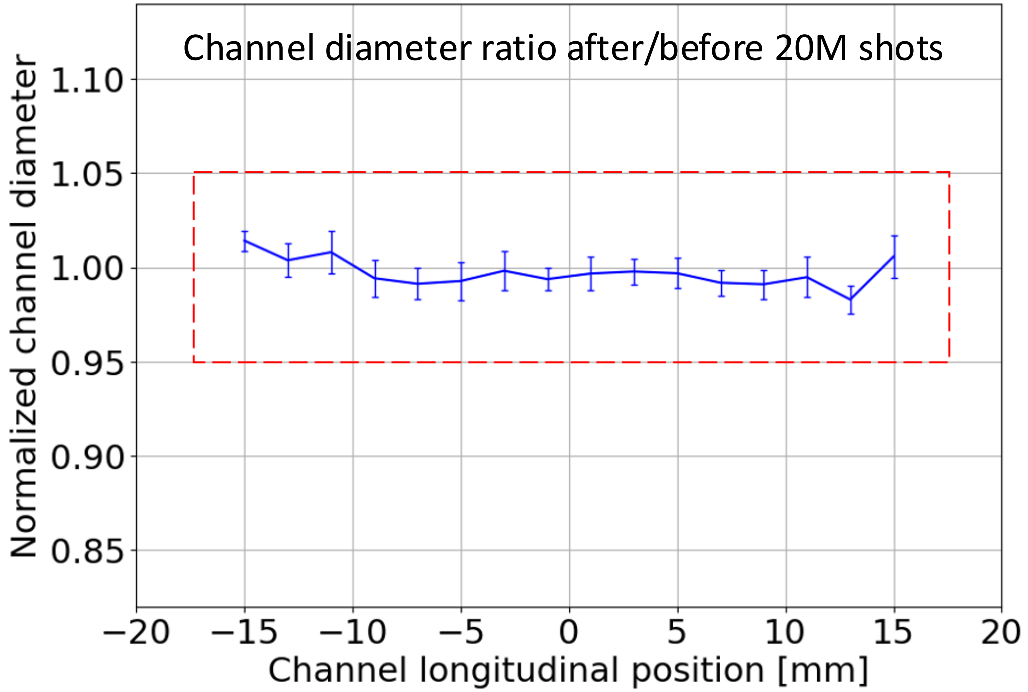



**L. Crincoli et al.** "*Advanced ceramic plasma discharge capillaries for high repetition rate operation*", **Scientific Reports 15(1) (2025)**

# Laser-induced plasma filaments

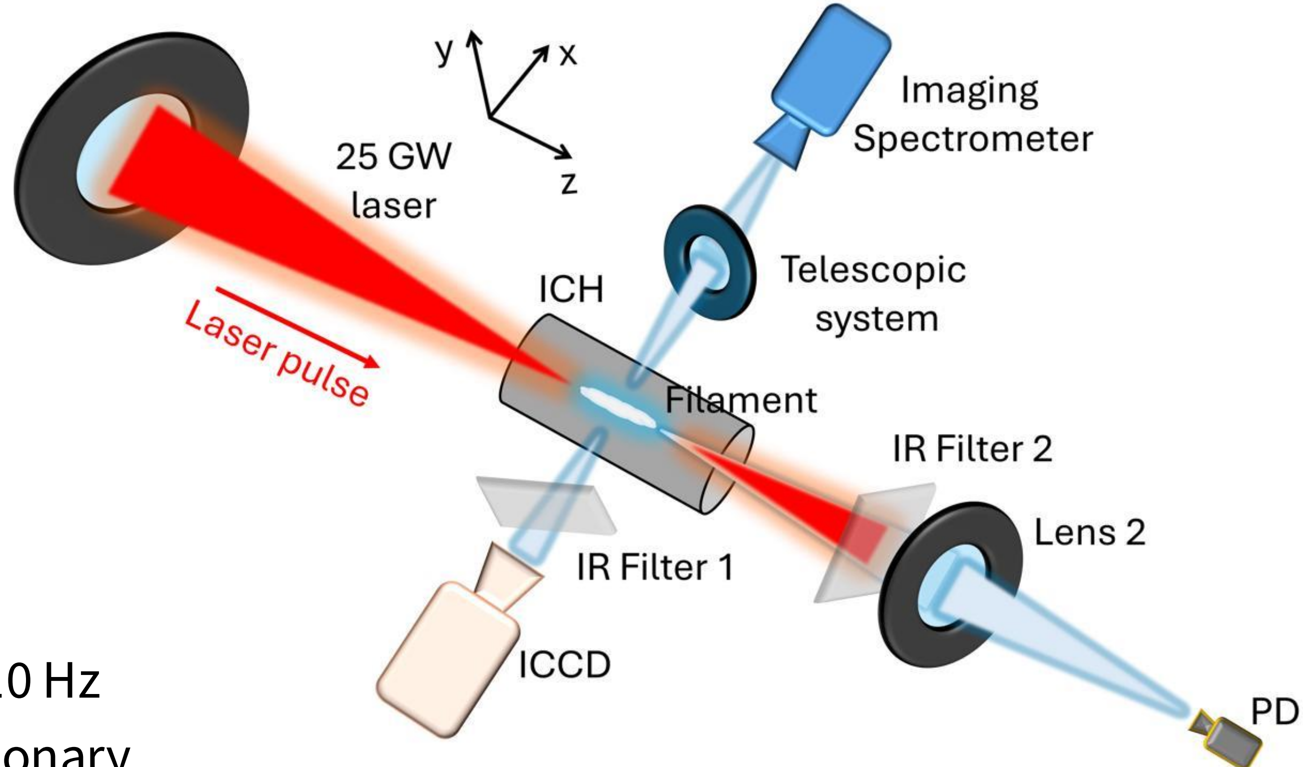
We generate plasma filaments using a low-energy femtosecond laser in low-pressure nitrogen gas environment.
The filament acts as the medium for beam-driven wakefield acceleration.

## *Filament operation*

- **Low energy operation.** Tens of mJ vs tens of Joule 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** dimensions varying laser and/or gas parameters.

# Laser-induced plasma filaments

Off-line experimental setup to produce stable, reproducible plasma channels allowing high rep rate.




## Experimental setup

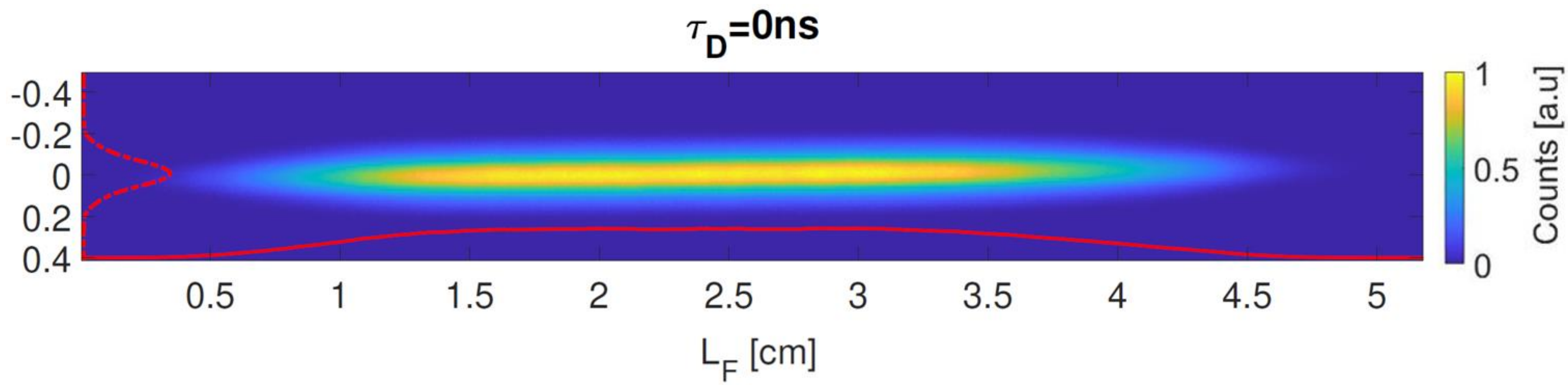
- ❖ Ti:Sapphire laser system
  - ➢ 10 mJ, 350 fs FWHM, 10 Hz
- ❖ 10 cm X 1 m gas cell (stationary condition)
- ❖ 1 mbar $N_2$ 95% - $H_2$ 5%

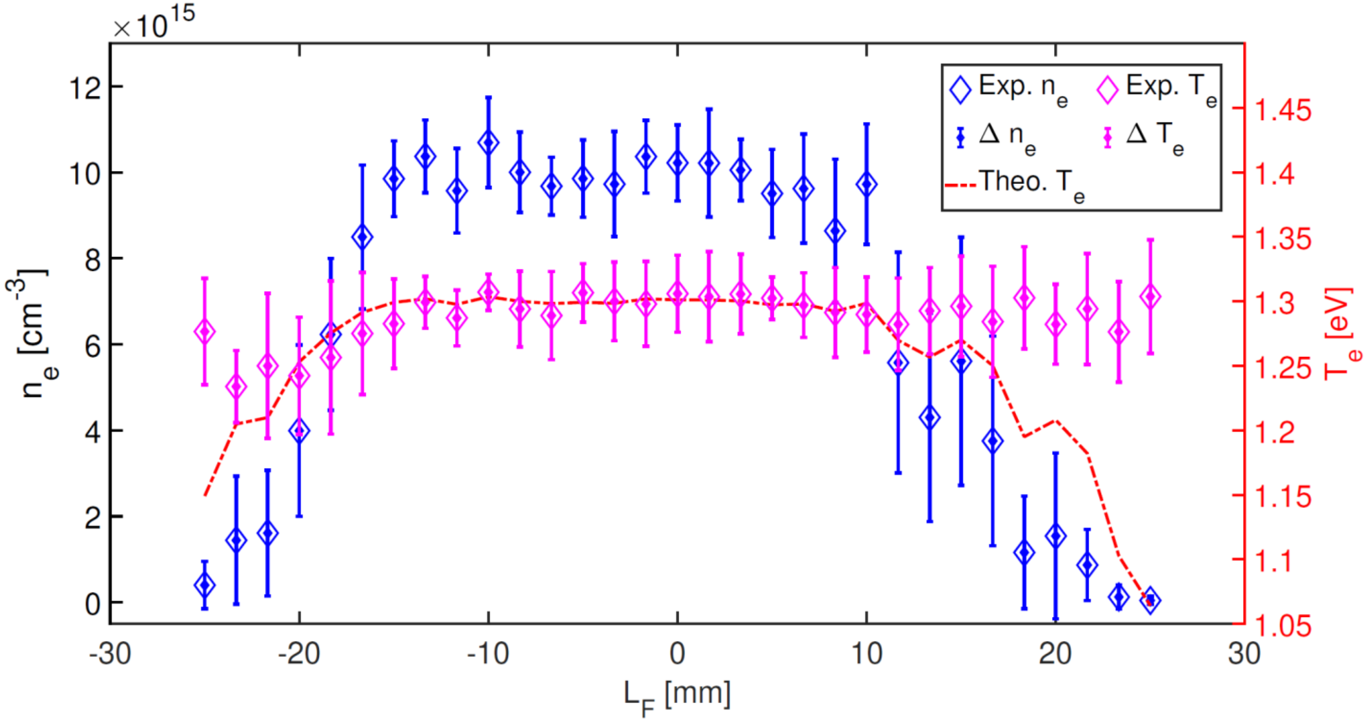
**M. Galletti, et al.,** *"Femtosecond laser-induced plasma filaments for beam-driven plasma wakefield acceleration",* **Phys. Rev. E 111, 025202 (2025)**

## Experimental characterization

- ❖ Side imaging fluorescence technique
  - ➢ Filament dimensions and density evolution
- ❖ Spectral analysis
  - ➢ Plasma density and temperature distribution
- ❖ Photodiode
  - ➢ Decay time

# Laser-induced plasma filaments




***Plasma density:***

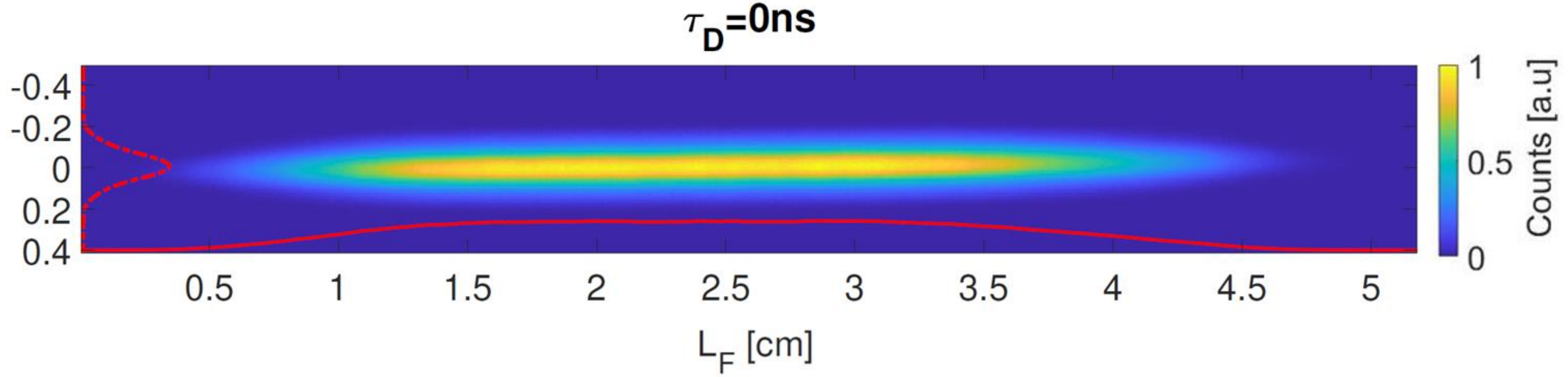
$n_e \approx 10^{16}\ cm^{-3}$

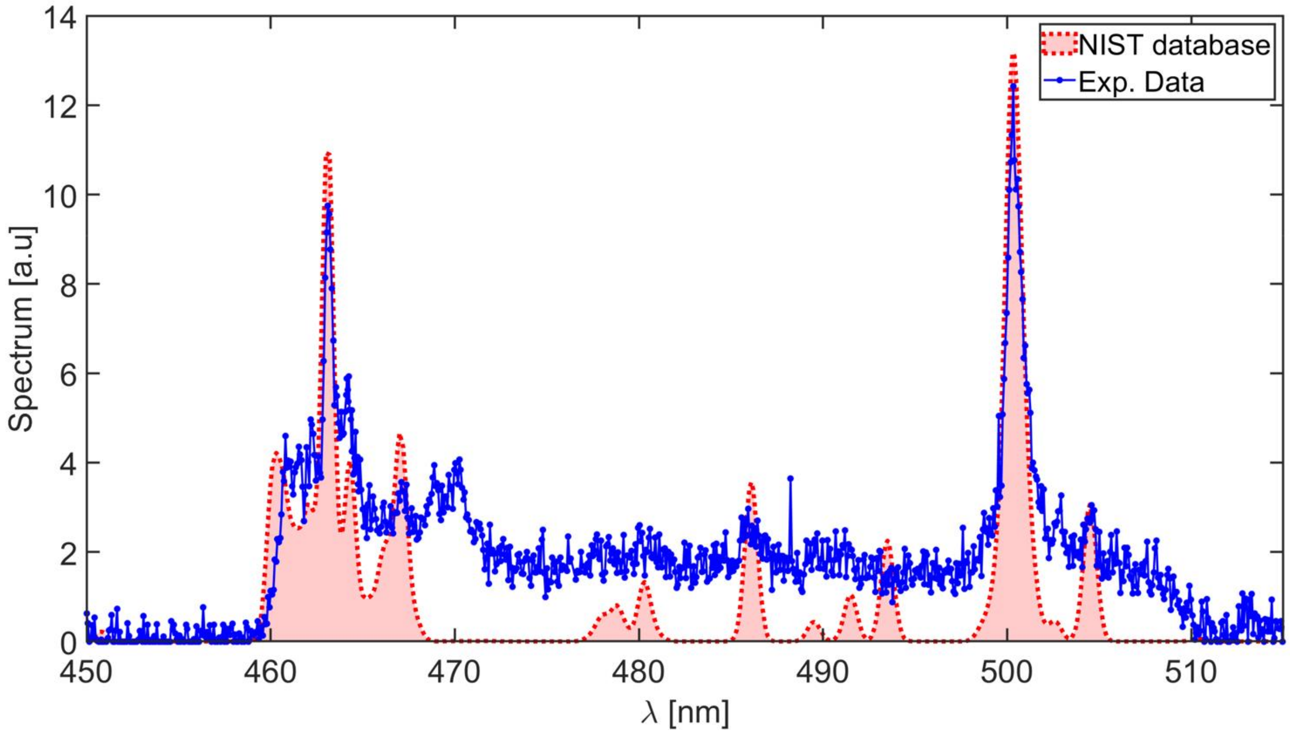
***Electron temperature:***

$T_e \approx 1.3\ eV$

Retrieved from Stark broadening analysis of $H_2$ emission spectra

# Laser-induced plasma filaments

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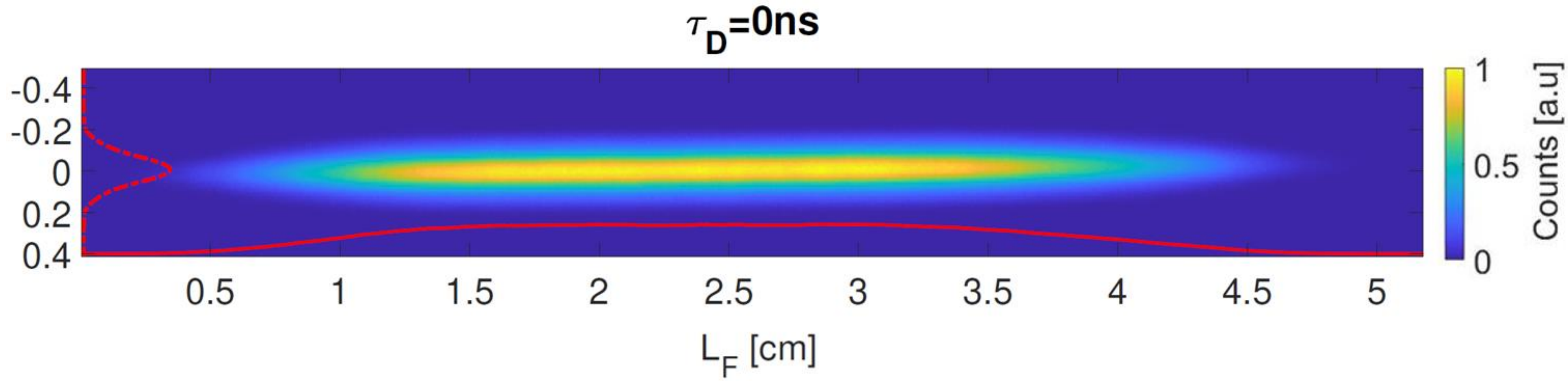
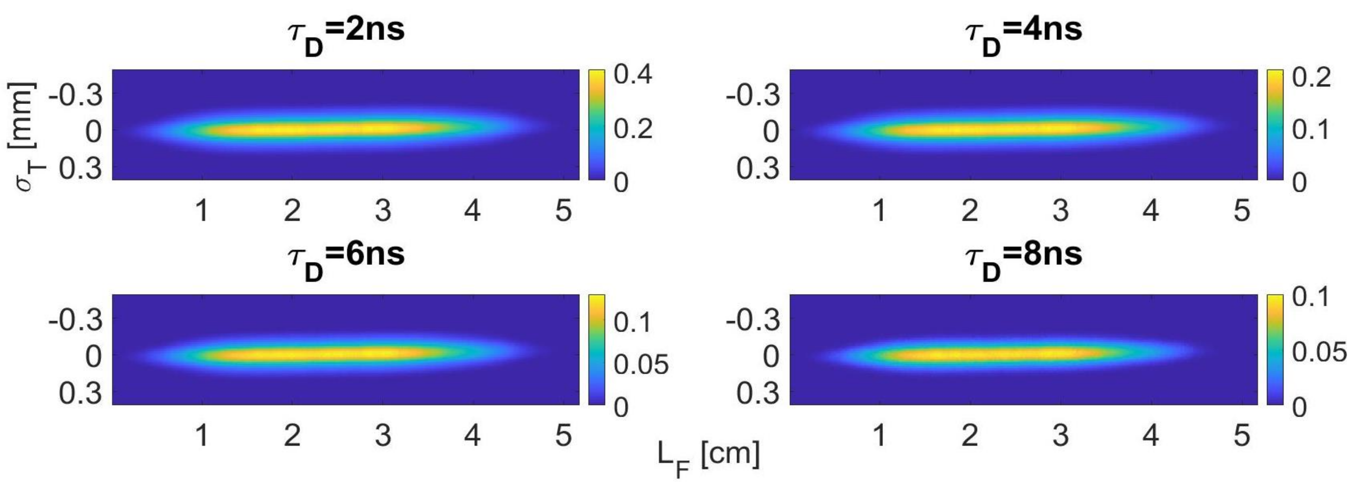


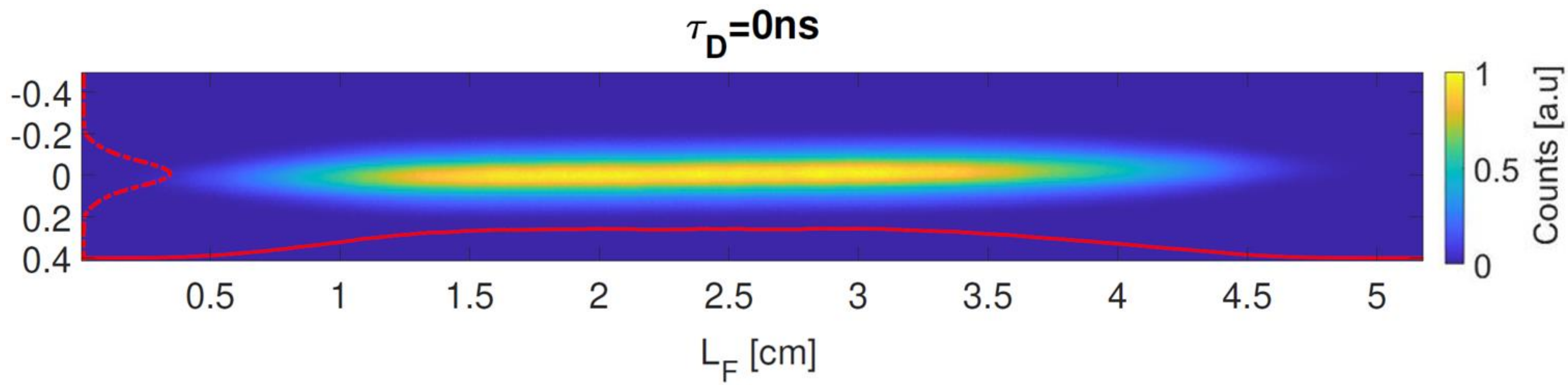

***Filament dimensions and density time-evolution***

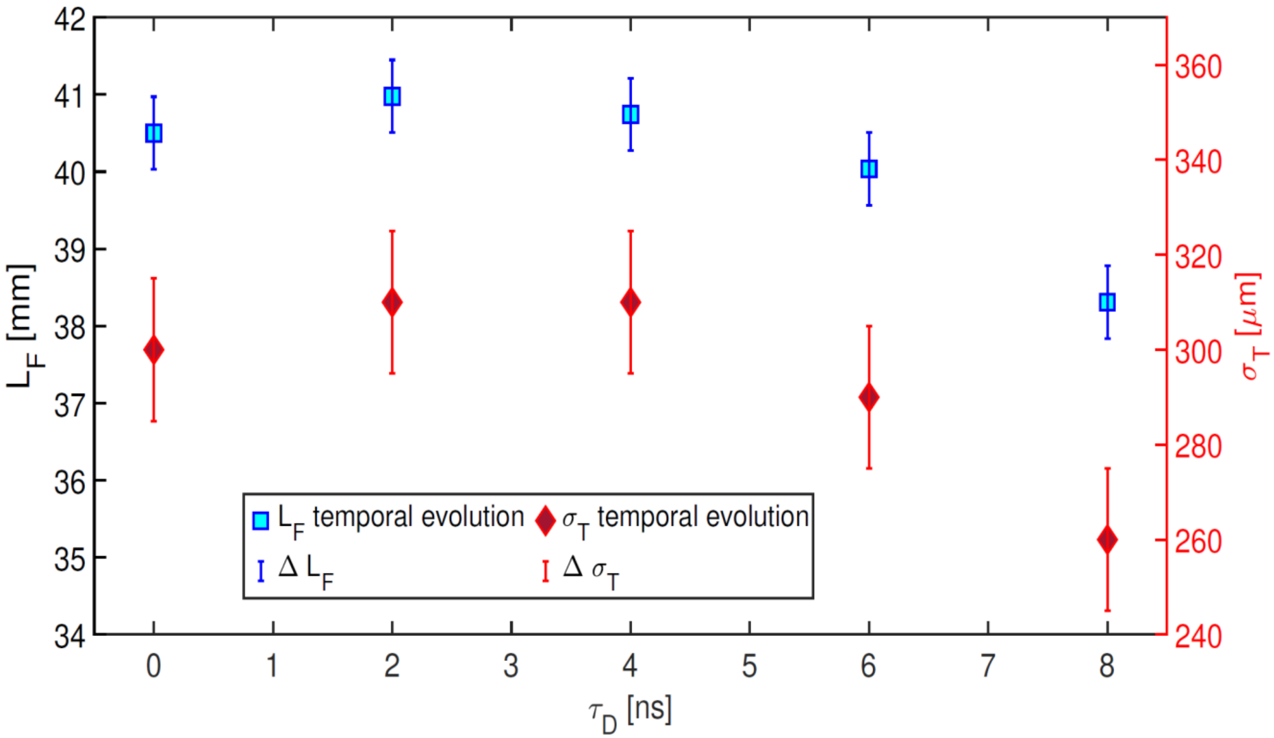



Evolution retrieved with ICCD camera coupled with Stark broadening technique

Varying the e-beam arrival time, a different effective acceleration configuration can be set.

## Laser-induced plasma filaments



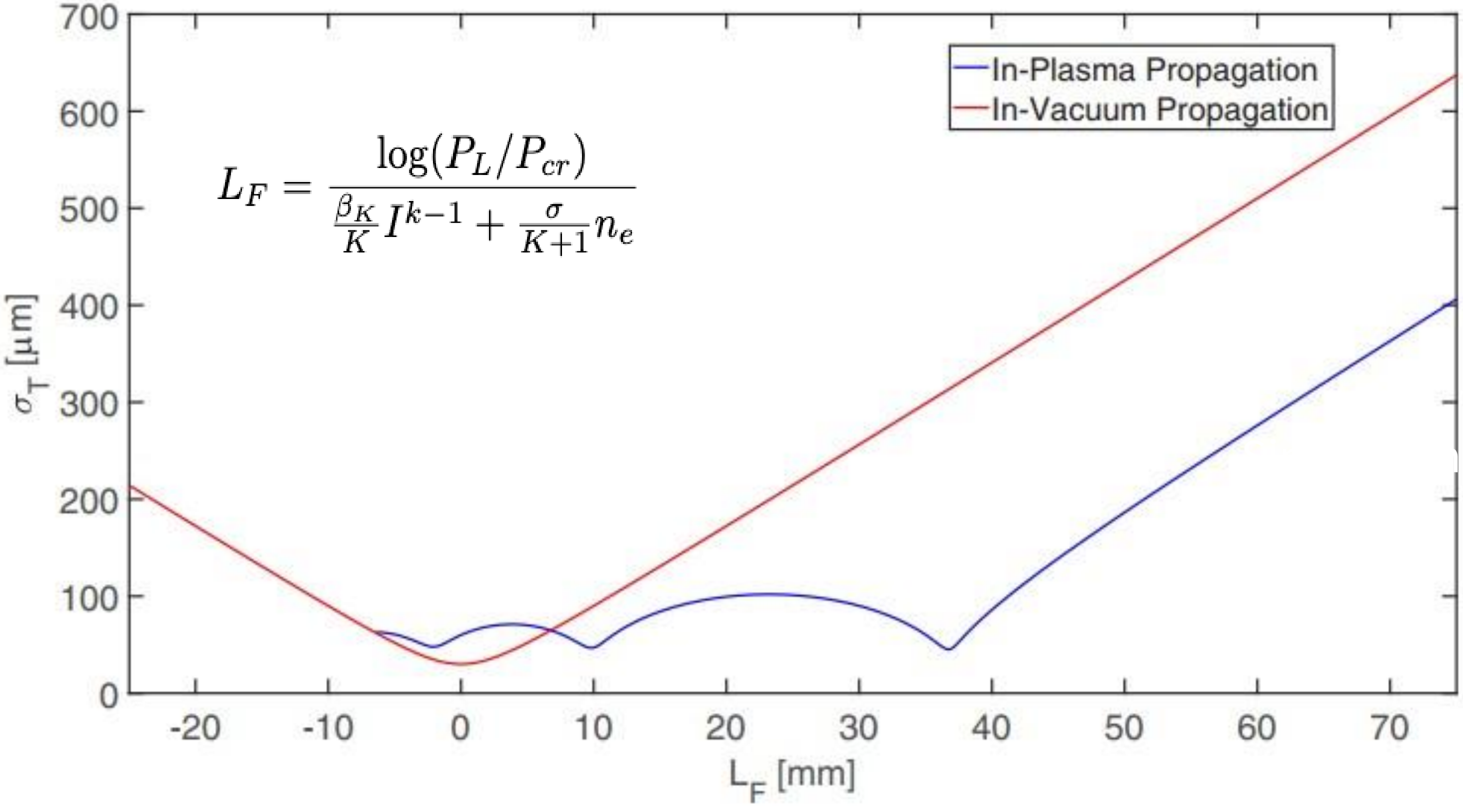

***Length***: ~4 cm
***Diameter***: ~300 µm

Long enough to serve as an effective acceleration channel for the SPARC_LAB interaction chamber configuration

# 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, group-velocity dispersion self-focusing, as well as plasma absorption/defocusing and energy losses due to multiphoton/tunnel ionization.*

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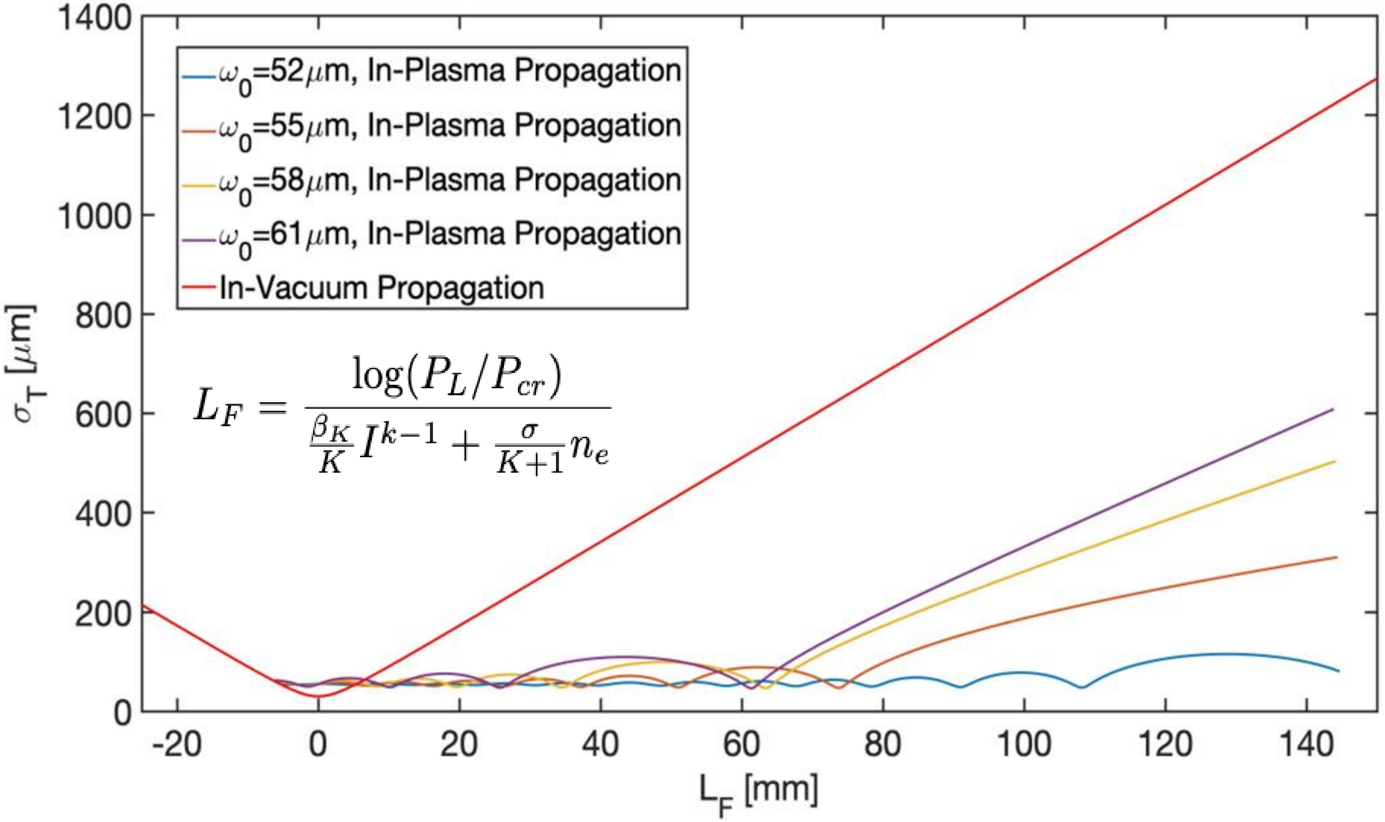


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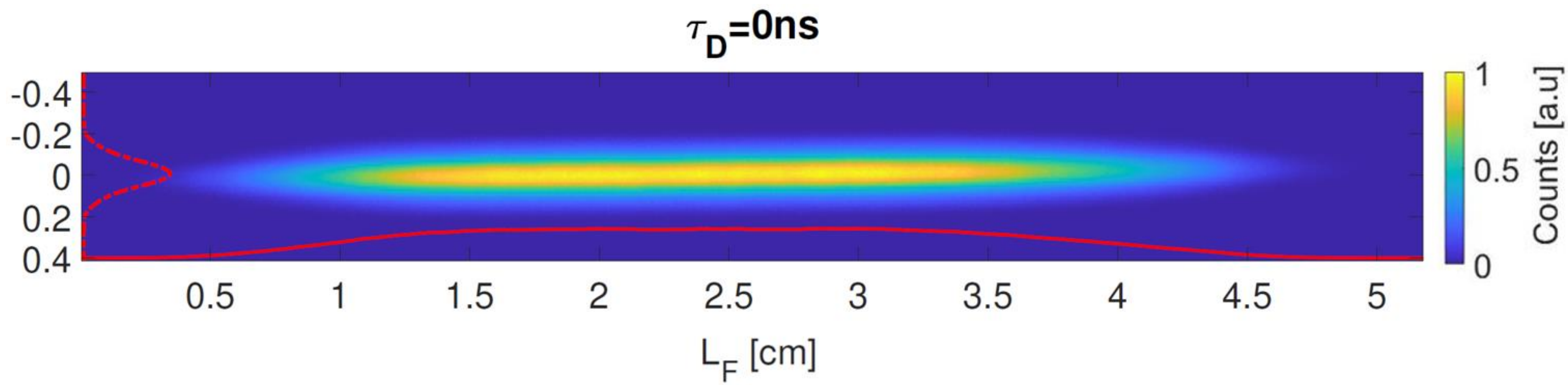
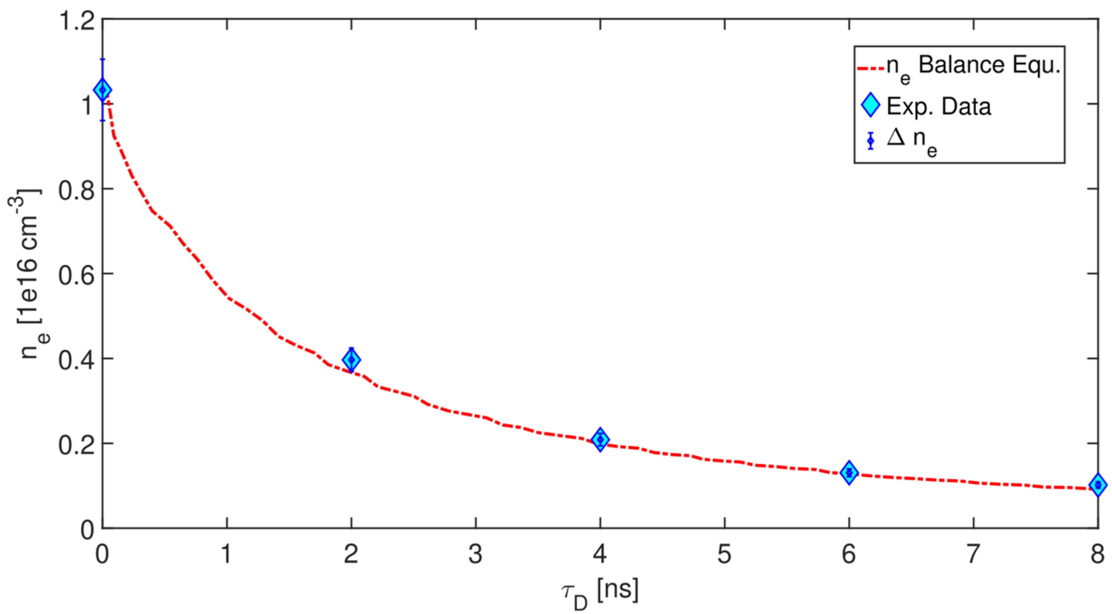



***Filament density decays*** of 1 order of magnitude over ≈ 8 ns



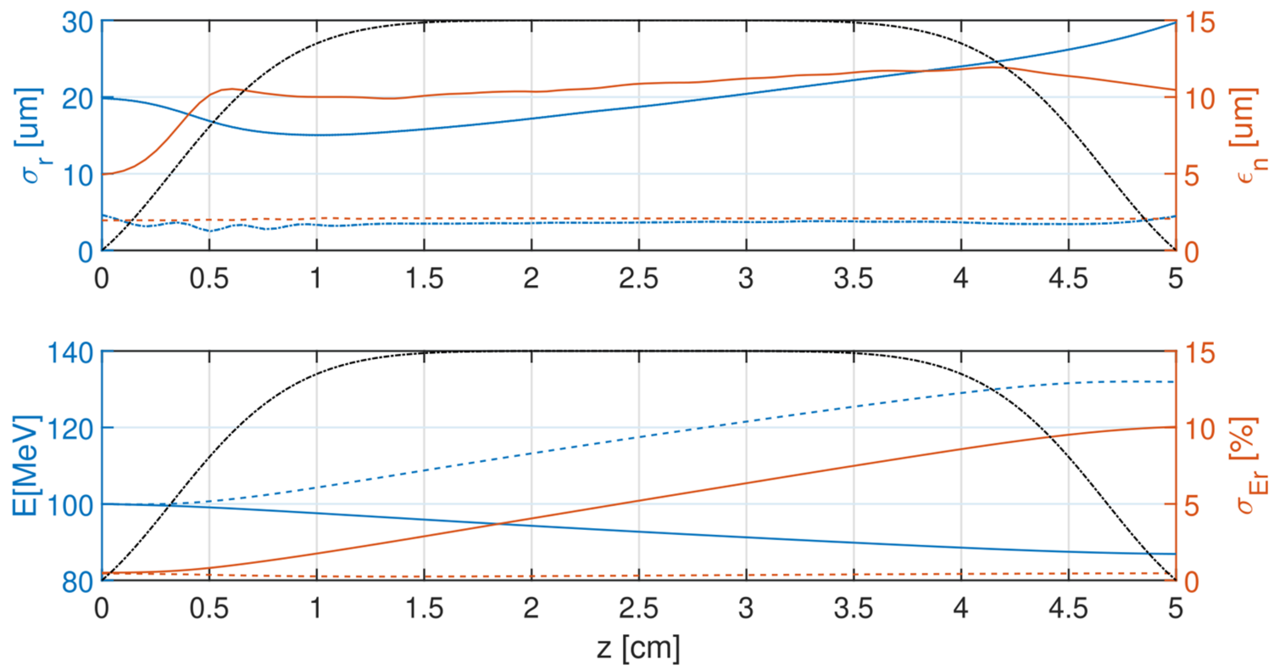

$$
\begin{cases}
\frac{\partial n_e}{\partial t} = -n_e \sum_j (n_e k_{3j}(T_e) + k_{2j}(T_e)) n_{pj} + \frac{\partial n_e}{\partial t}|_{EX} \\
\frac{\partial n_p j}{\partial t} = Q_{pj} - R_{pj} + \frac{\partial n_{pj}}{\partial t}|_{EX} \\
\frac{\partial N_j}{\partial t} = Q_{pj} - R_{pj} + \frac{\partial N_j}{\partial t}|_{EX}
\end{cases}
$$

$$
\begin{cases}
\frac{\partial T_e}{\partial t} = -(T_e - T)\nu_\epsilon(T_e) - \frac{2}{3} T_e^2 \sum_j (n_e \frac{\partial k_{3j}}{\partial T_e} + \frac{\partial k_{2j}}{\partial T_e}) n_{pj} \\
\frac{3N}{2} \frac{\partial T}{\partial t} = n_e \sum_j \Delta_{3j} k_{3j}(T_e) n_{pj} + \sum_j \Delta_{2j} k_{2j}(T_e) n_{pj}
\end{cases}
$$

# Laser-induced plasma filaments as a PWFA stage

| Parameters | SPARC_LAB |
|---|---|
| $L_F$ (cm) | 4 |
| $n_e$ ($10^{15}$ cm$^{-3}$) | 2 |
| E (MeV) | 100(D,W) |
| $\sigma_t$ (fs) | 200(D),20(W) |
| $\Delta t$ (ps) | 1.2 |
| Q (pC) | 500(D),50(W) |
| $\varepsilon_n$ ($\mu$m) | 5(D), 2(W) |
| $\sigma_E$ (%) | 0.5(D),0.4(W) |

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



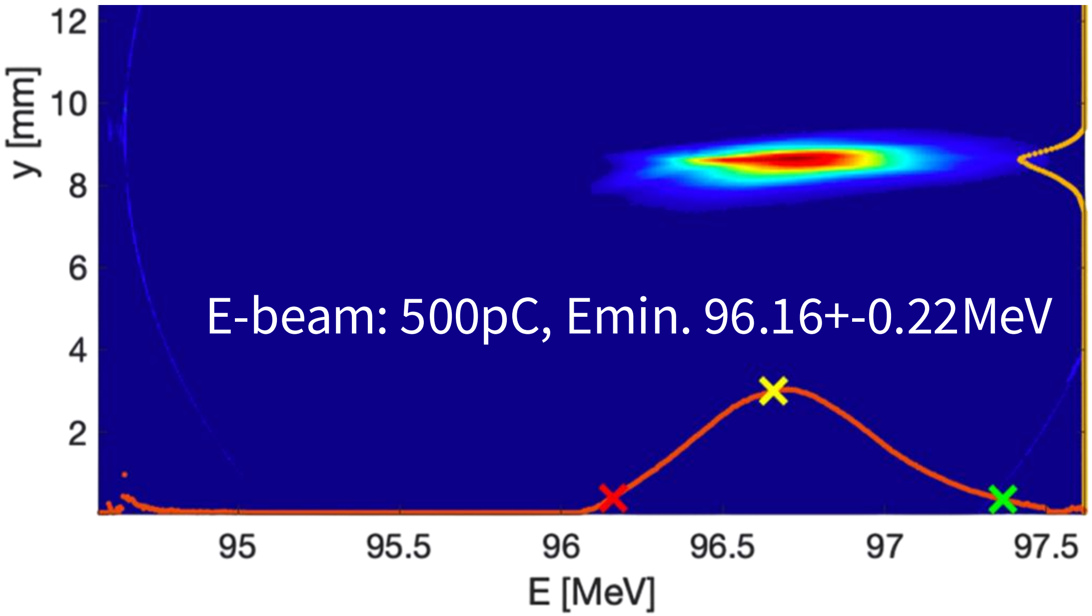

It shows theoretically the full characterization of the witness beam @SPARC_LAB.

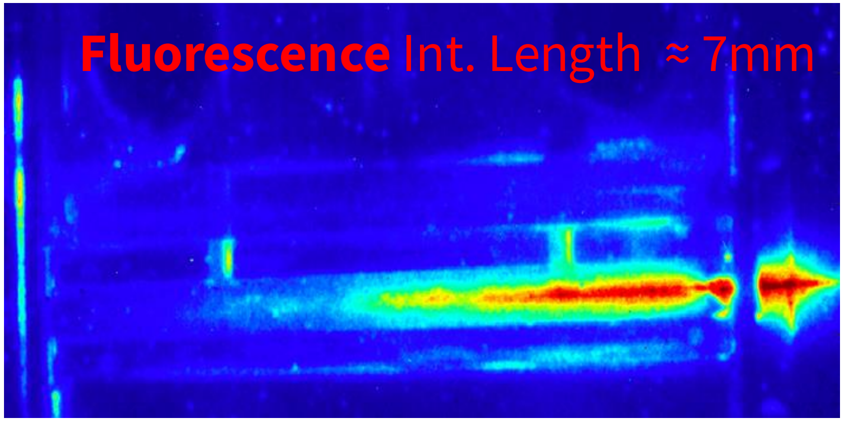
- An **energy gain of about 37MeV in 37mm** acceleration length means an acceleration gradient of ~1GeV/m.
- Moreover, **the size $\sigma_r$, the emittance $\epsilon_n$ and the relative energy spread $\sigma_E$ are preserved** through the acceleration length.

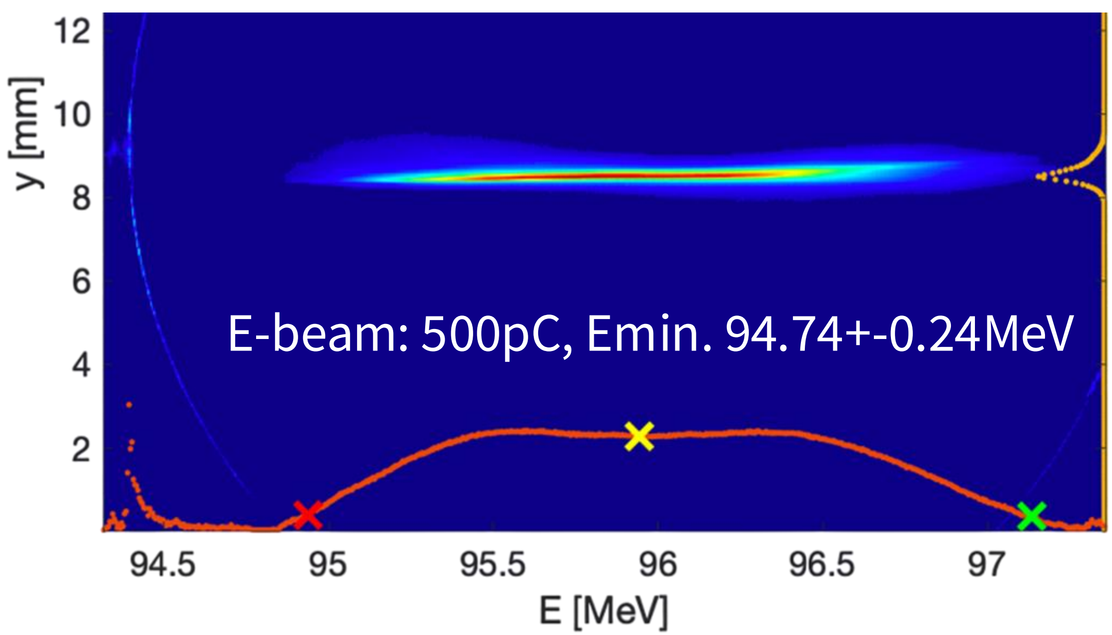
The filament is a high-quality acceleration stage, with comparable performances respect to the plasma discharge capillary sources.

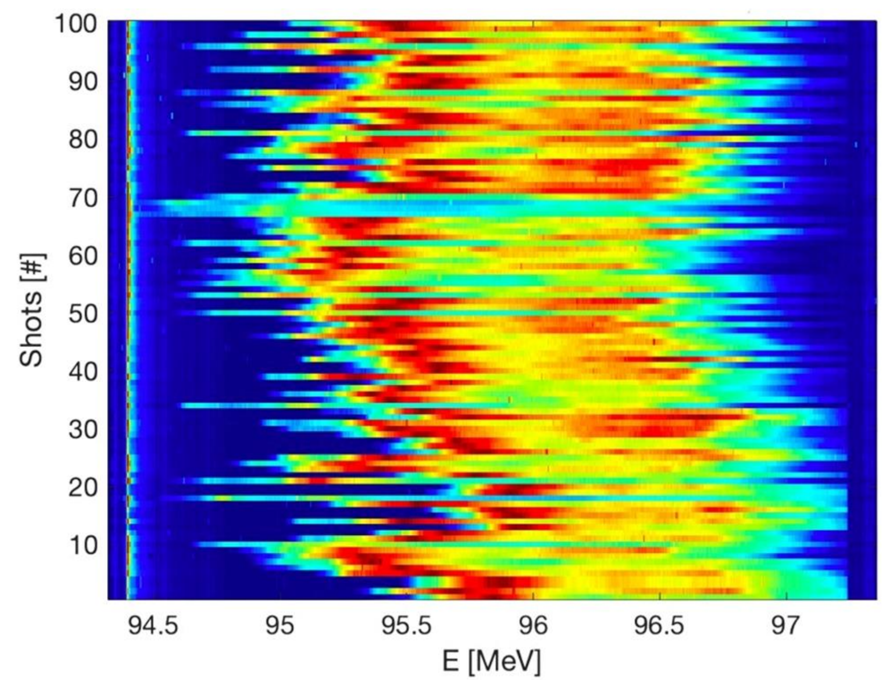
**Y. Fang, et al.,** *"The effect of plasma radius and profile on the development of self-modulation instability of electron bunches",* **Phys. Plasmas 21, 056703 (2014)**

# Proof of electron beam deceleration



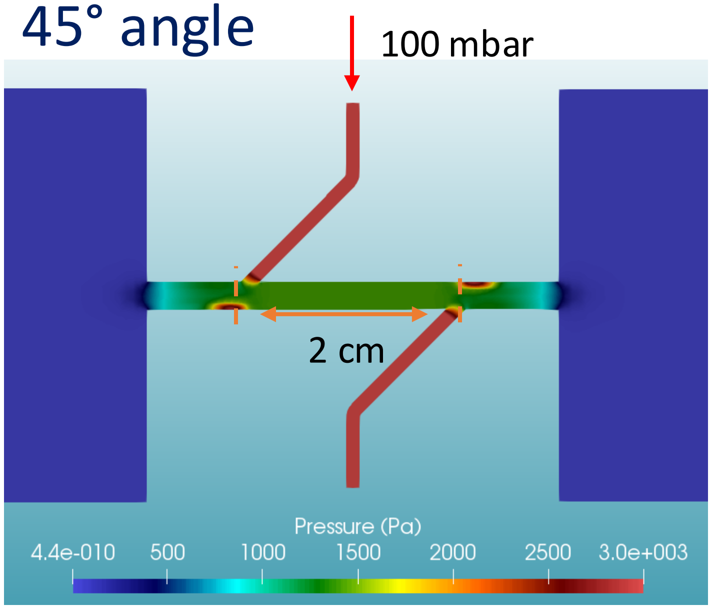



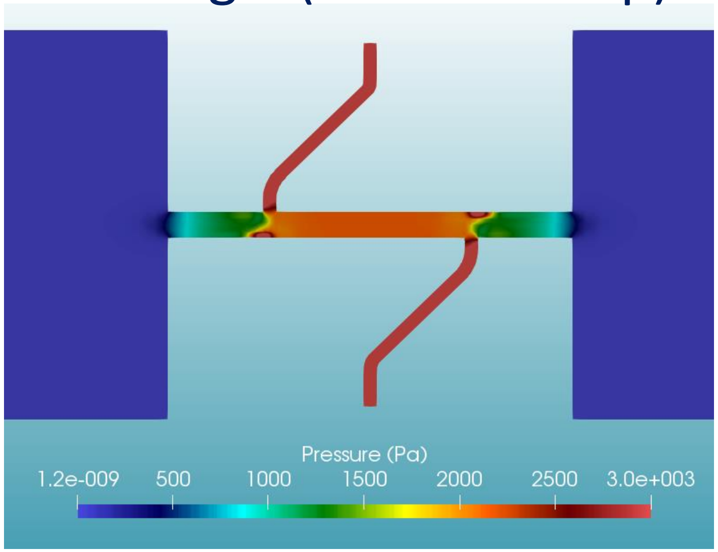

**Averaged e-beam deceleration ≈ 1.3MeV**

# Laser-induced plasma filaments cell: design

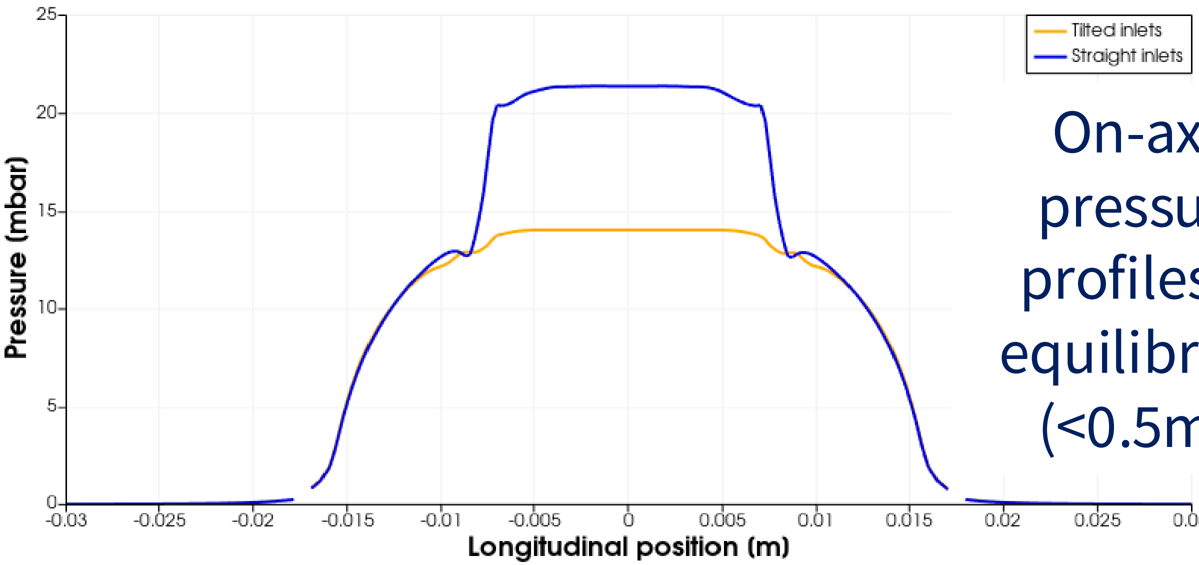
45° angle




90° angle (current setup)




- 3cm length, 2mm diameter capillary with two inlets of 1mm diameter
- Minimized turbulences in the velocity map
- Sharp pressure ramps with straight 90° inlets




On-axis pressure profiles at equilibrium (<0.5ms)

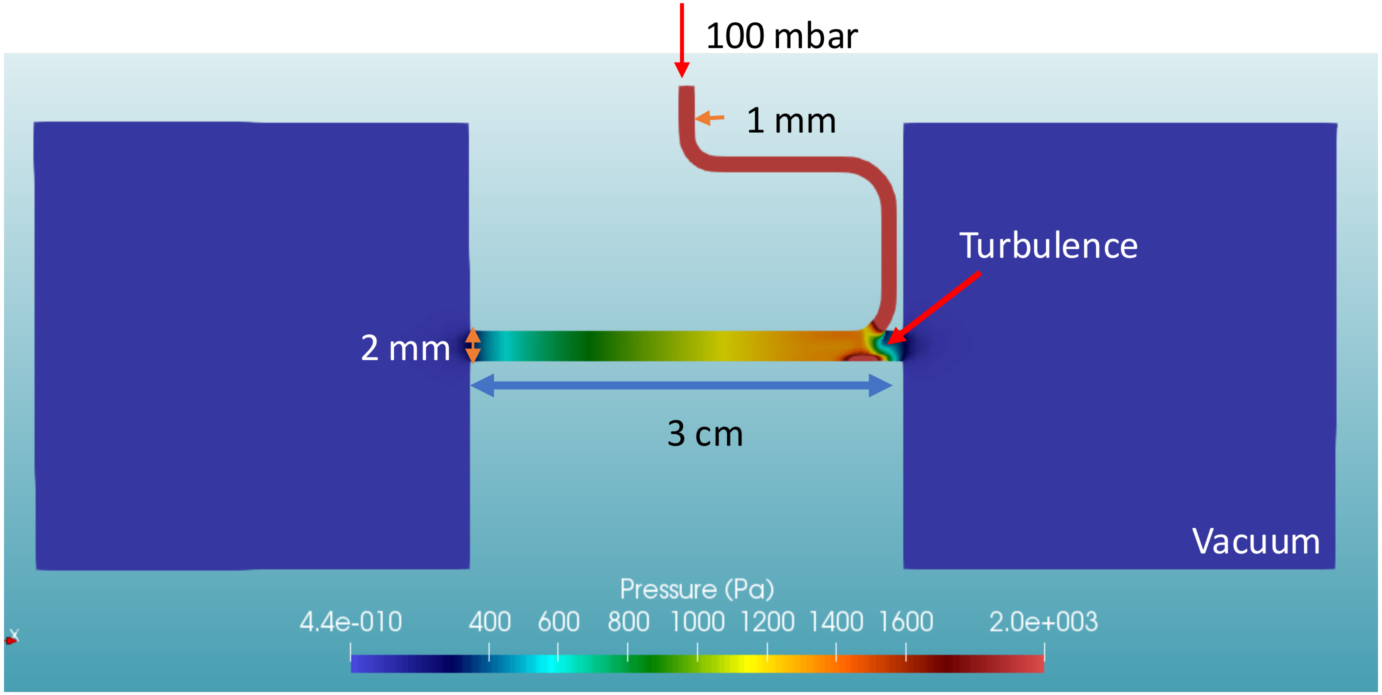
Courtesy of L. Crincoli

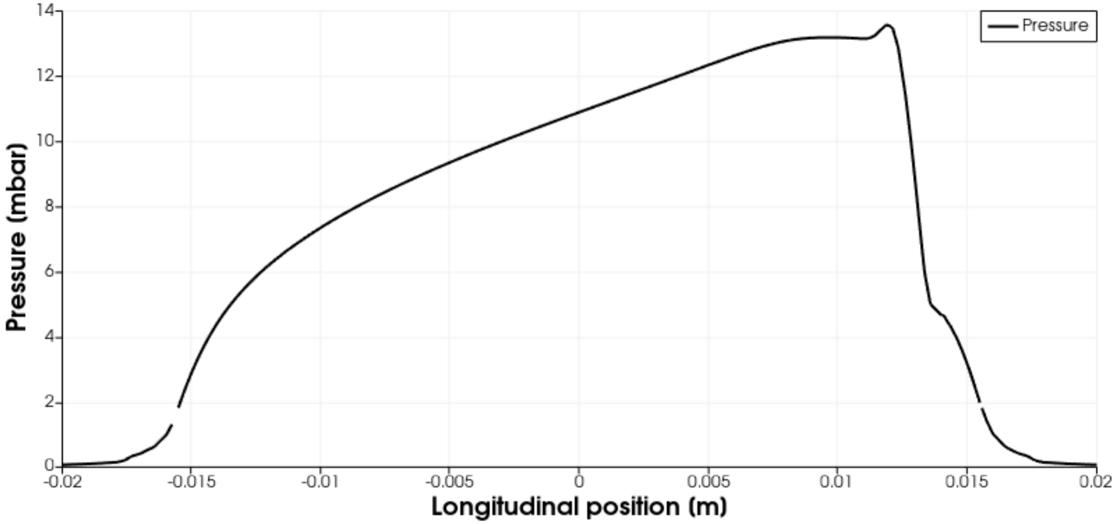
# Laser-induced plasma filaments cell: design

***2D pressure distribution at equilibrium (<0.5ms)***

- Localized turbulence at channel exit
- Smooth pressure ramp from the entrance (considering laser traveling from left to right)
- 100 mbar from the valve -> 3-13 mbar along the gas column

Courtesy of L. Crincoli

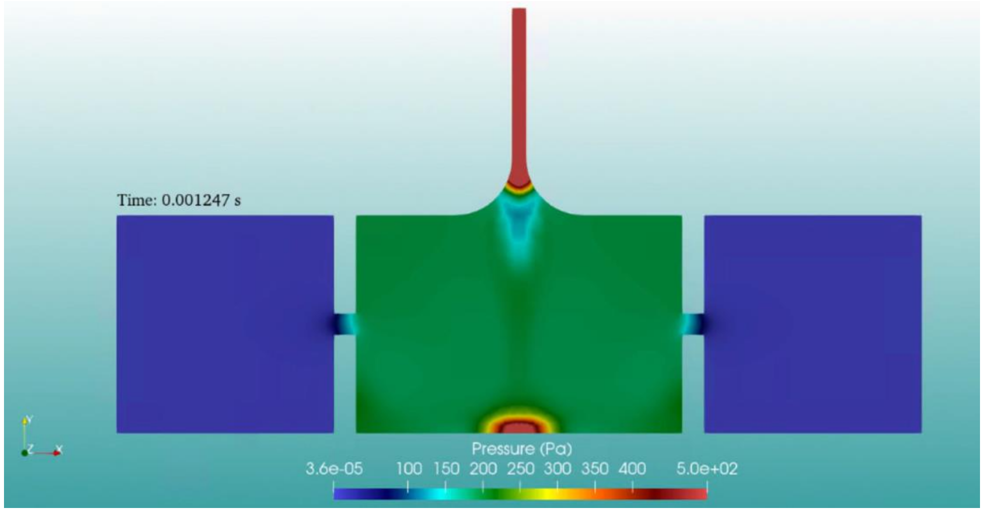


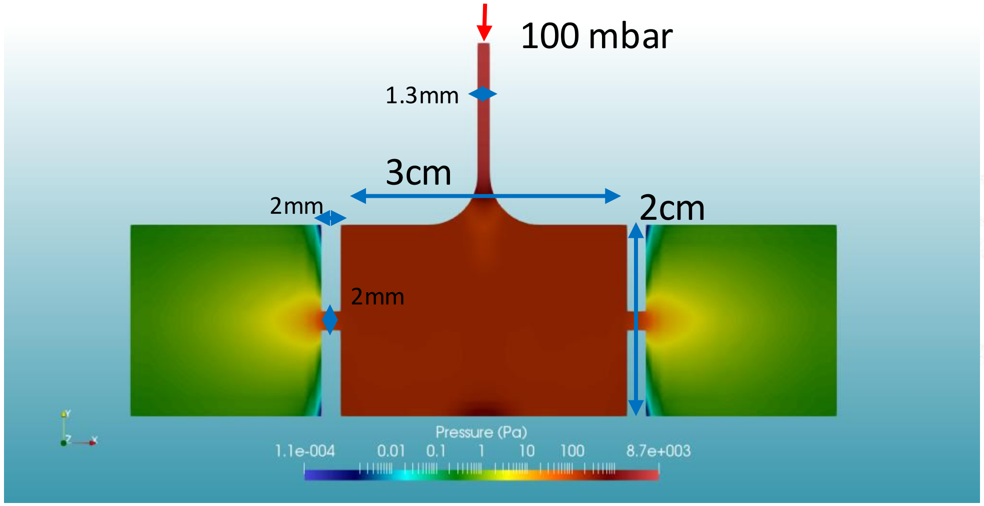



# Laser-induced plasma filaments cell: design

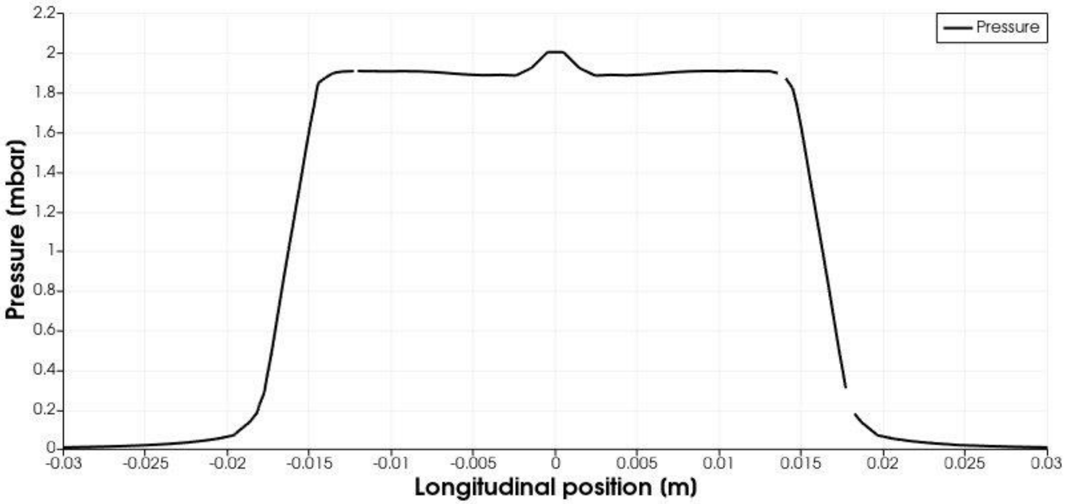
## 3cm by 2cm gas cell

- Slow filling of the gas cell
- Around 1 ms there are 1-2 mbar inside the cell with 100 mbar injected from the valve
- Supersonic vertical flux
- Flat-top on-axis profile




On-axis pressure profile at equilibrium

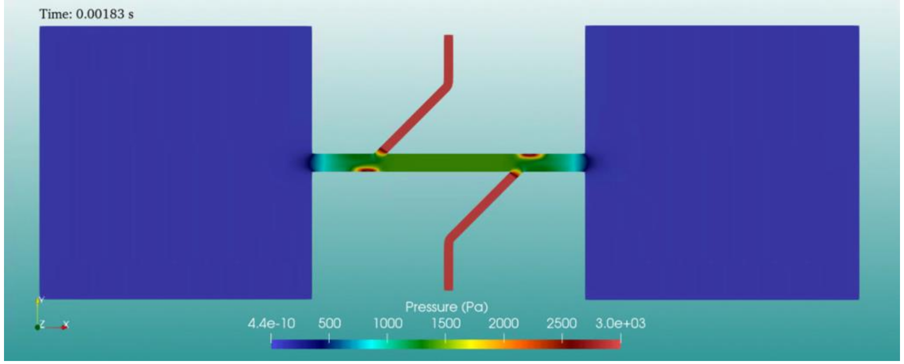



Courtesy of L. Crincoli

# Laser-induced plasma filaments cell: design

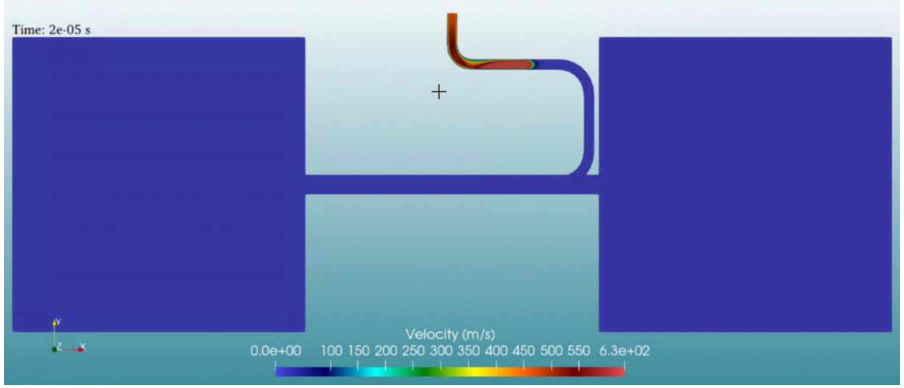
## 3cm capillary with 45° injection inlets

- ✓ Minimized turbulences vs 90° inlets
- ✓ Smoother pressure distribution



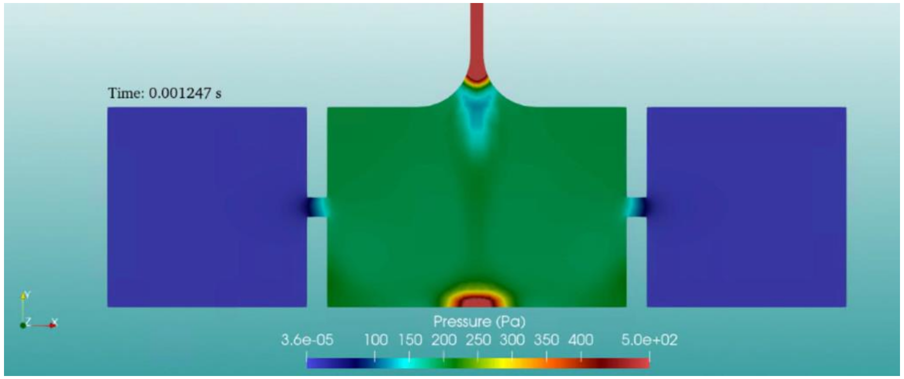

## 3cm capillary with 45° injection inlet

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

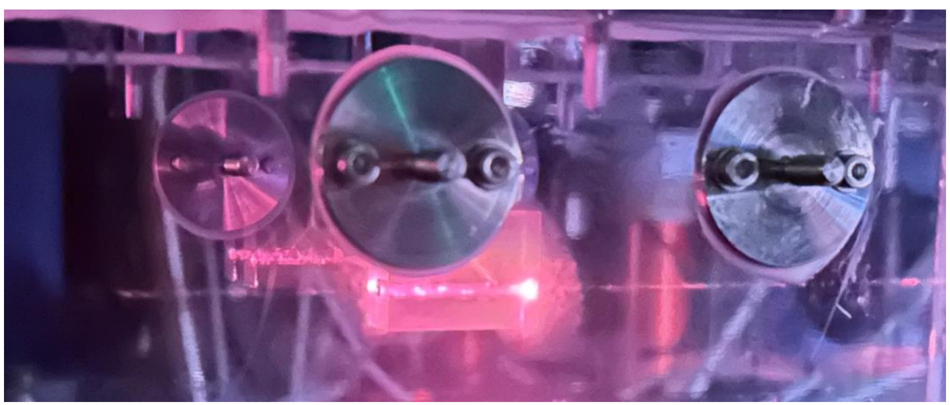


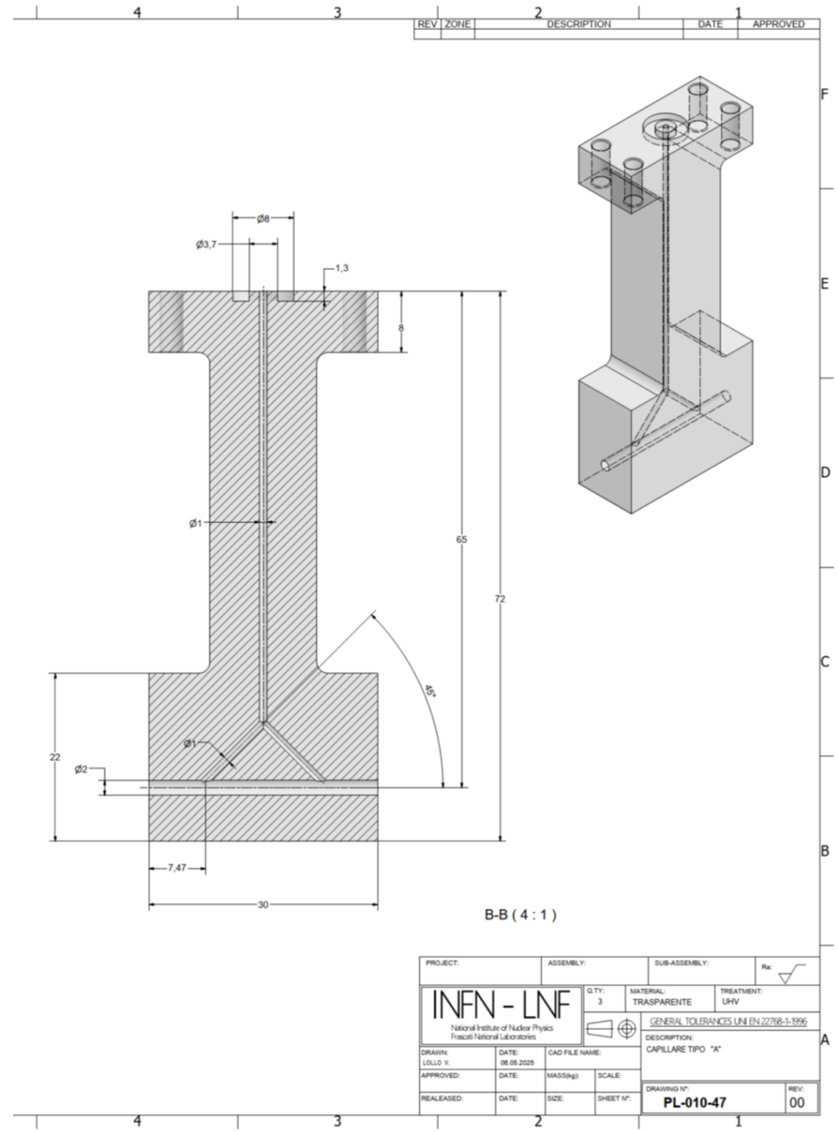

## 3cm gas cell with 2mm inlet

- ✓ Slow filling
- ✓ Flat-top pressure (and density) profile



# Conclusions






Courtesy of V. Lollo

# Conclusions

Development of plasma-based accelerators is still ongoing; many exciting results obtained in the last few years. **To deliver a plasma-based user-oriented facility 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 (HRR, tunable, energy-efficient) of the plasma stage has been performed in a stationary condition
- ✓ Preliminary measurements of a decelerated e-beam show the problem of replicate a high-quality filament plasma stage in a pulsed gas-injection regime with the current capillary configuration.
- ✓ Turbulence-free, stable pressure capillary design for filament operation
- ✓ *Next steps: New design integration into full accelerator systems, longer interaction length, operation at kHz rates.*

**Fundamental steps toward the future EuPRAXIA plasma-based facility for user-oriented applications**

## *Thank you for your kind attention!*

Mario Galletti (LNF, INFN)

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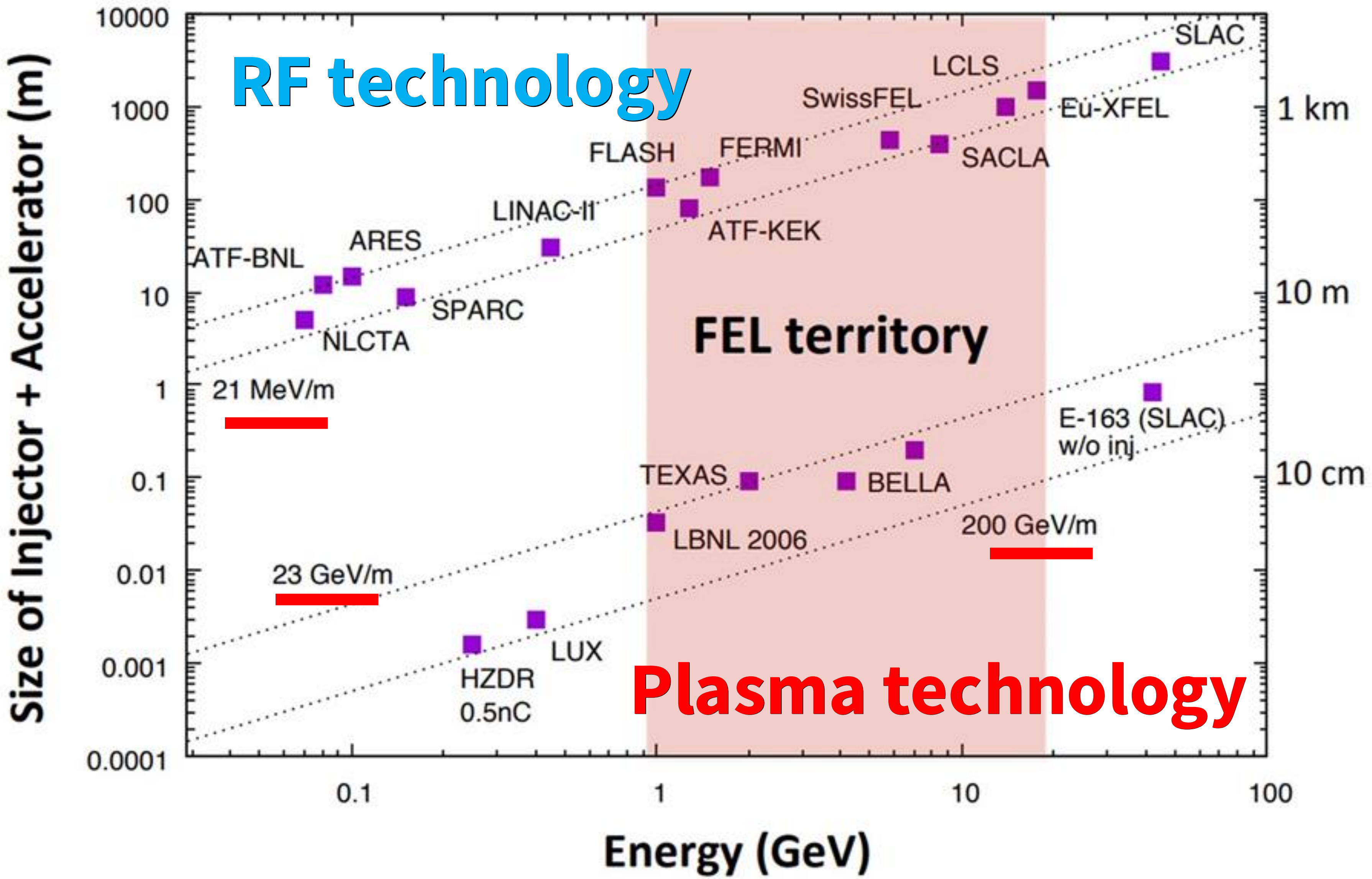
*On behalf of the SPARC_LAB collaboration*

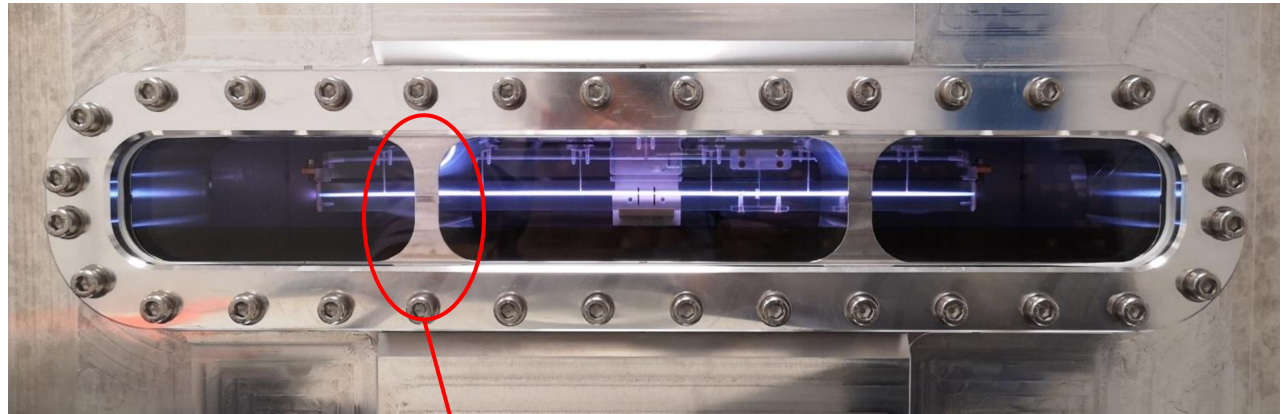
# Standard vs Plasma accelerators

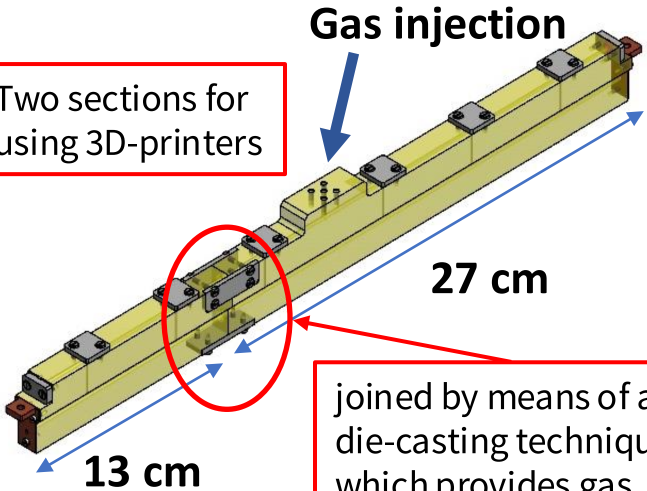



*From R. Assmann (3rd EAAC Workshop, 2017)*

# Preliminary results: longer plasma stage

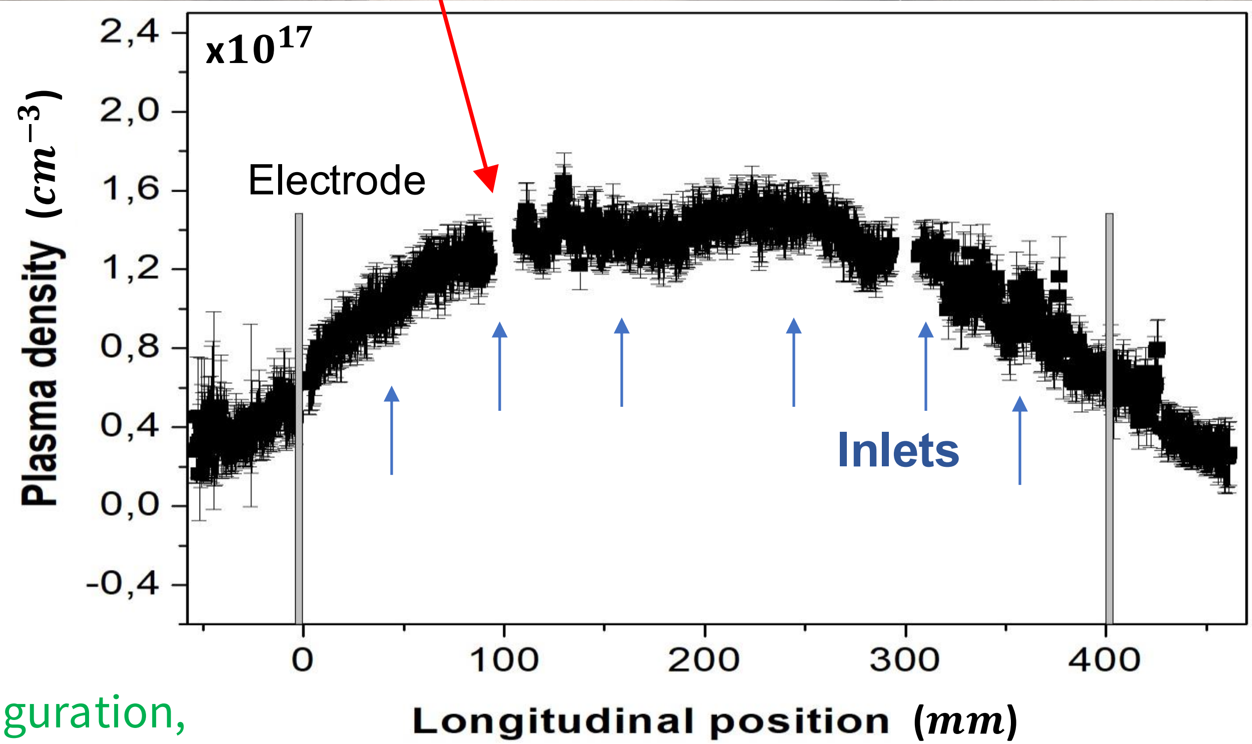
**Operating conditions:**
- Nitrogen gas
- Rep rate at 1 Hz
- 10 kV – 380 A
- 6 inlets of 1 mm diameter






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', in preparation (2025)