70th LNF Scientific Committee

Frascati, Italy

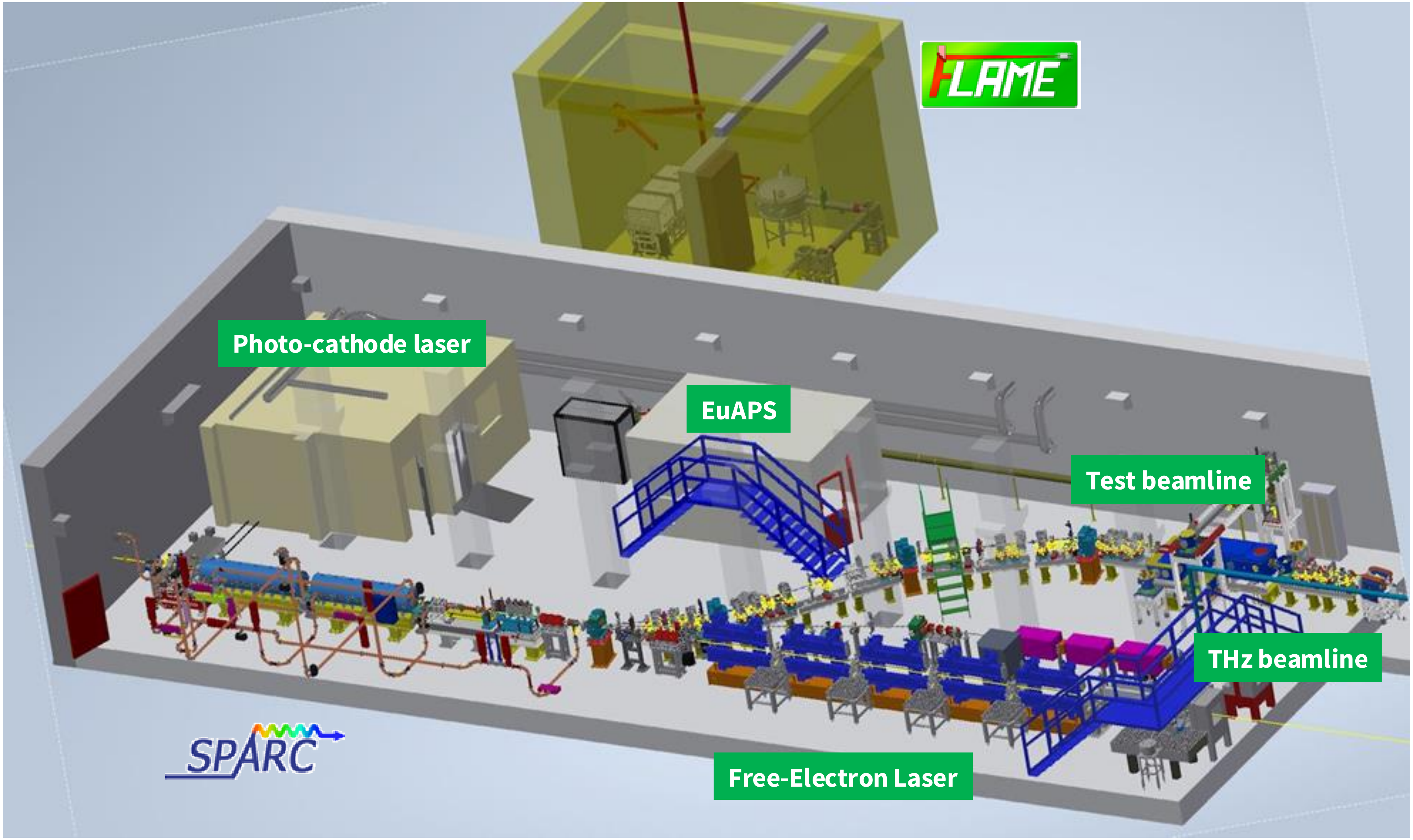
SPARC_LAB activity report

Mario Galletti (LNF, INFN)

mario.galletti@lnf.infn.it

On behalf of the SPARC_LAB collaboration

SPARC_LAB facility



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

SPARC_LAB – Main considerations

After the last SciCom (May 2025), SPARC has not been in operation but September 2025 and it is on operation till the end of November 2025. Several 'off-line' activities have been performed:

- **Gun conditioning** because of substitution of the cathode.
- Resonant plasma acceleration scheme. Test the plasma response using N drivers followed by a witness bunch. **Interesting results obtained, paper published on PRE and proposal on preparation @SLAC user call.**
- **Plasma acceleration using a laser-generated filament. The Run-1 highlighted several issues that have being fixed for the Run-2 scheduled for the last two weeks of November 2025.**

SPARC will be shutdown to allow the EuAPS-SABINA installations in the bunker; the exact timeline of the next-year experiments will be defined soon.

SPARC_LAB – from previous SciCom

- For the SC it was not clear if the resonant plasma excitation can in practice increase the total plasma acceleration voltage of a probe bunch compared with past experiments with a more standard drive-probe bunch scheme. The measurements shown do not imply this. Furthermore, it is not clear if the requirements on timing jitters for this scheme are not even more severe than for the standard scheme.

- As experimentally demonstrated, using a **train of properly adjusted driver bunches** so that the perturbation induced by each bunch is in resonance with the plasma density oscillation, it is possible to either:
  - ✓ **Maximize the amplitude of the accelerating field**: advantageous with respect to the usual case of confining the entire charge in one single driver, because of the difficulties in manipulating a high-charge driver rather than a train of low-charge ones in the preceding linac
  - ✓ **Enhance the energy-transfer efficiency**: Adjusting each driver density (same decelerating fields), a train of N ramped bunches can enhance the transformer ratio by a factor N (usually <2!)
- **The requirements of time jitter are not more severe, just N more to deal with!** An experimental campaign to evaluate them is scheduled.

SPARC_LAB – from previous SciCom

- The measurement of beam size with the new PMQ needs a careful analysis since this is also a critical quantity for the performance of EuPRAXIA@SPARC_LAB. The SPARC_LAB team needs to understand why these measurements are not consistent with the simulated beamsize, and if this is a beam dynamics issue or an issue of beam size monitor resolution.

- Unfortunately, the new set of PMQs have not been further investigated because of the GUN-EuAPS-SABINA installation.
- The new set of PMQs have been employed for two experimental campaigns. The resulting focusing of the PMQs allowed to reach ~10 um spot sizes, that is still 2-3 times larger than expectations.
- **Additional studies will be done during the setting up of the Run-2 filament experiment and additional comparison with the plasma focusing technique are planned.** A new experiment involving two active-plasma lenses (APL) has been theoretically studied and a GRUPPO 5 proposal has been submitted. This will be an occasion to better quantify the focusing ability of the APL compared with PMQs.

SPARC_LAB – from previous SciCom

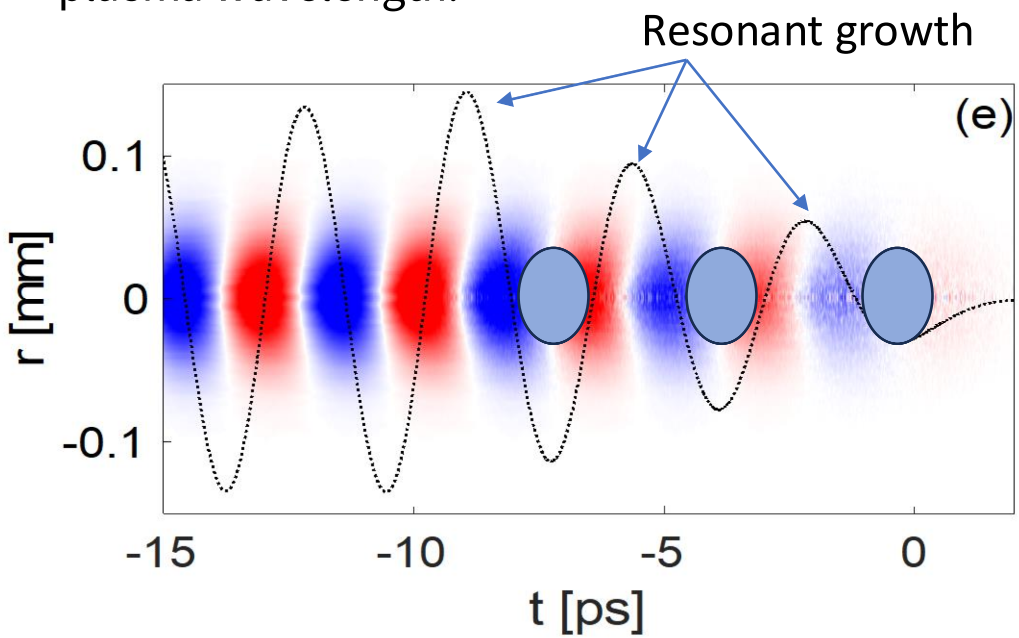
- The developments towards increased robustness of the plasma capillaries, both laser filament and improved SHAPAL, have the full support of the SC, since this robustness is a key feature to be demonstrated before plasma acceleration can be applied to a user facility. Related beam tests should have a high priority for the next beam periods.

- **The SHAPAL activity has been carried out at PLASMA_LAB that demonstrated the feasibility of working at large repetition rates (100-150 Hz) using a SHAPAL capillary.** The tests included the evaluation of the thermal load on the plasma discharge pulser. Everything has been reported in the EuPRAXIA TDR.
- **The 60 cm prototype will be delivered @PLASMA_LAB within January 2026** and full characterized at the beginning of next year.
- **The filament stage issue has been solved** (non optimal gas injection was not allowing to create a proper filament of few cm lengths). The Run-2 is scheduled at the end November 2025.

SPARC linac plasma beamline

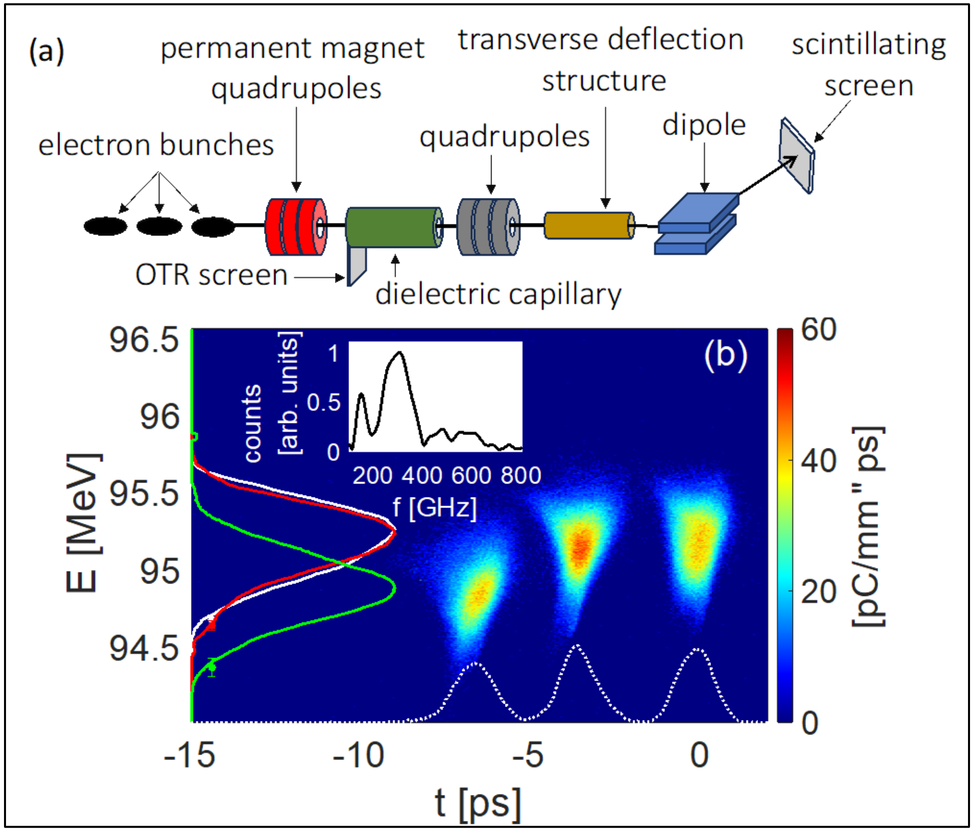
Resonant Excitation of Plasma Wakefields with Train of Charged Particle Bunches

Train of equally spaced bunches drive wakefields resonantly when spacing equal to plasma wavelength.



- In linear regime, wakefields superpose linearly
- Configuration with $\Delta t = N \cdot T_{pe}$
  → Amplitude growth along the train
- Configuration with $\Delta t = \frac{N}{2} \cdot T_{pe}$ and ramped charge
  → Transformer ratio enhancement

Train of electron bunches generated with replicas of the UV pulse.



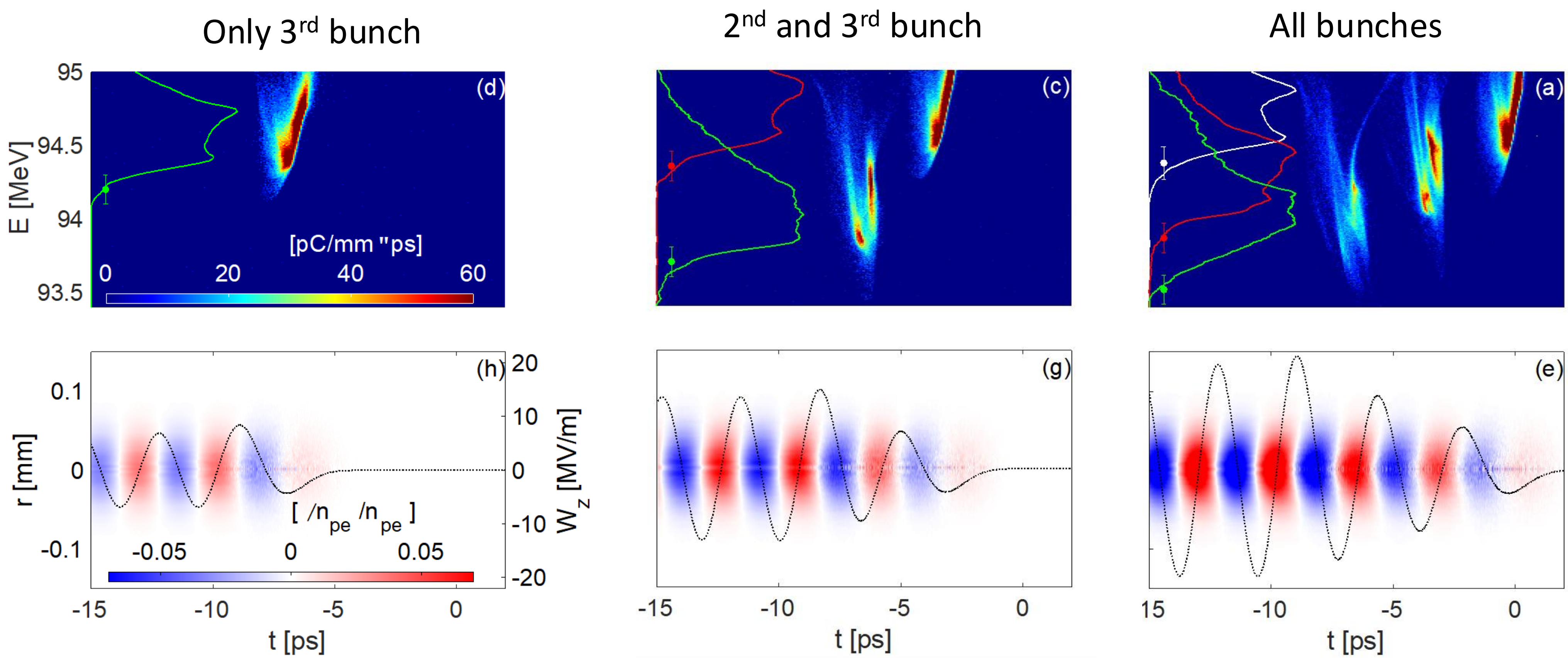
PHYSICAL REVIEW E **112**, 045205 (2025)

Resonant excitation of plasma wakefields with a train of relativistic particle bunches

L. Verra,[1,*] M. Galletti,[1] M. P. Anania,[1] A. Biagioni,[1] M. Carillo,[1] E. Chiadroni,[2] A. Cianchi,[3,4,5] G. Costa,[1] L. Crincoli,[1] A. Del Dotto,[1] M. Del Giorno,[1] R. Demitra,[1] G. Di Pirro,[1] A. Giribono,[1] V. Lollo,[1] M. Opromolla,[1] G. Parise,[1] D. Pellegrini,[1] R. Pompili,[1] S. Romeo,[1] G. Silvi,[1] F. Stocchi,[1,3] F. Villa,[1] and M. Ferrario[1]

Courtesy of L. Verra

Resonant Excitation of PWFA - Results

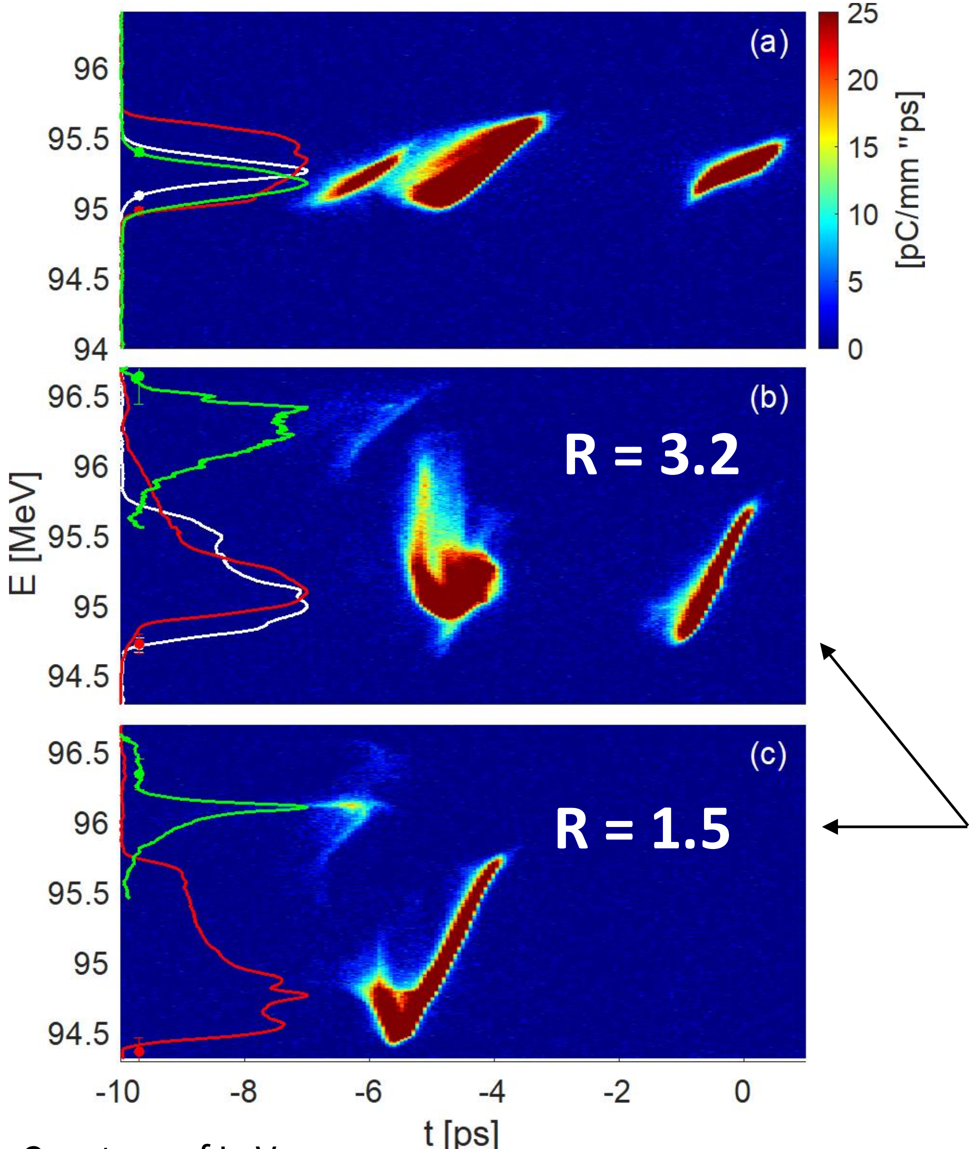


Linear regime → wakefields driven by each bunch sum up linearly

❖ Losses of third bunch increase when **more bunches ahead are present**
→ **Larger amplitude of the wakefields**
→ **Resonant excitation**

Courtesy of L. Verra

Resonant Excitation of PWFA - Results



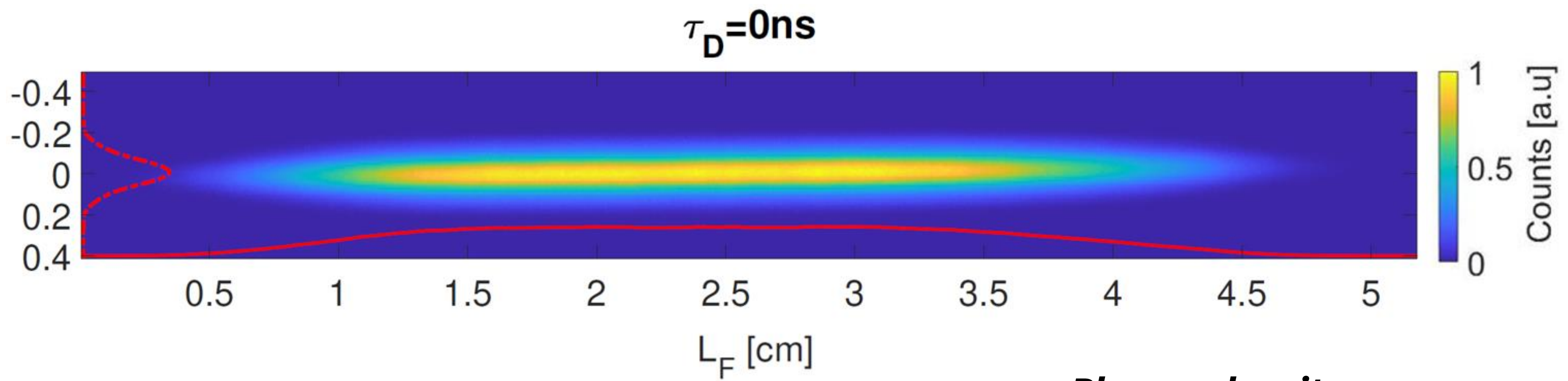
Courtesy of L. Verra

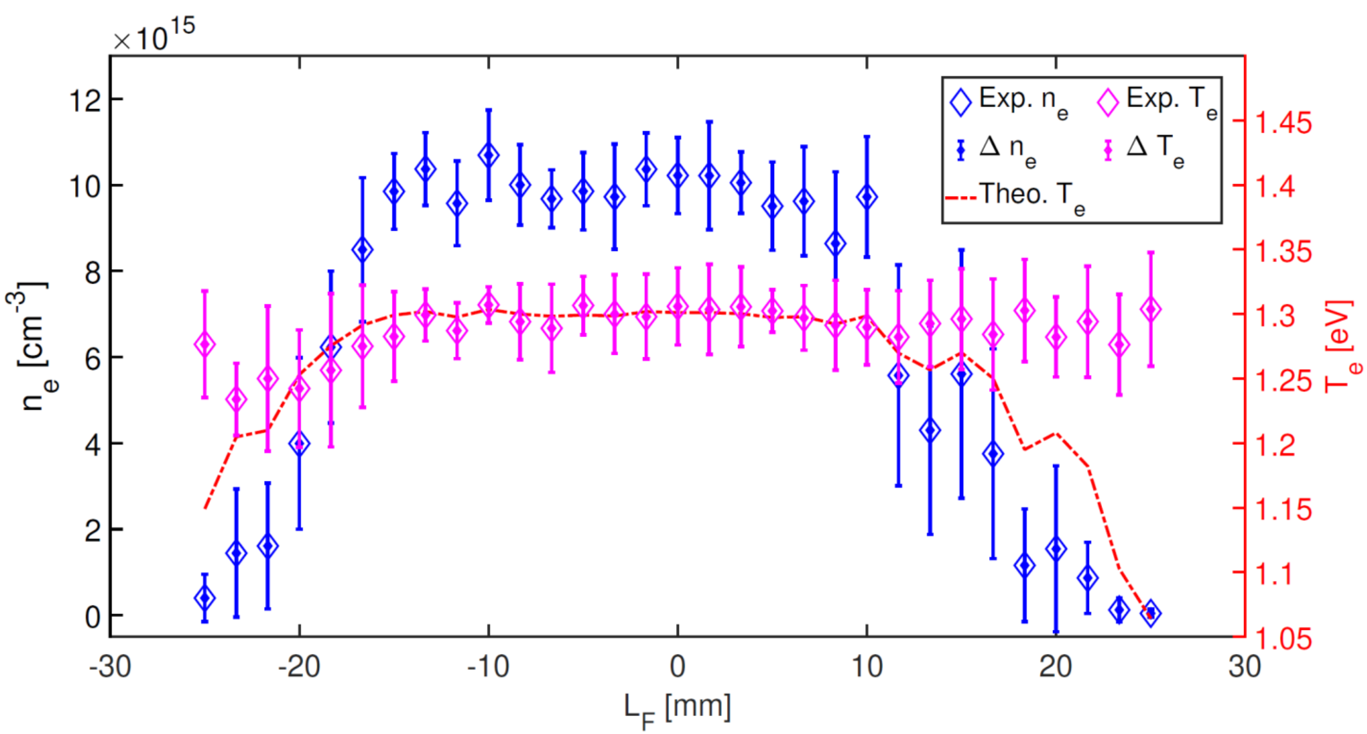
- Important to maximize the energy transfer efficiency, the interaction length, and the final energy reach of a PWFA stage.
- Resonant configuration allows for maximizing energy transfer
  → maximization of transformer ratio R

$$R = \frac{maximum\ energy\ gain}{maximum\ energy\ loss} = \frac{\Delta E^+}{\max(\Delta E^-)}$$

- Second driver in the accelerating phase of the wakefields driven by first bunch
- Increased charge → still decelerating (beam loading)
- Enhanced transformer ratio respect single bunch configuration
- **Run-2 will repeat with compressed bunches to show high-gradient, high-transformer ratio acceleration**

Laser-induced plasma filaments





Plasma density:

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

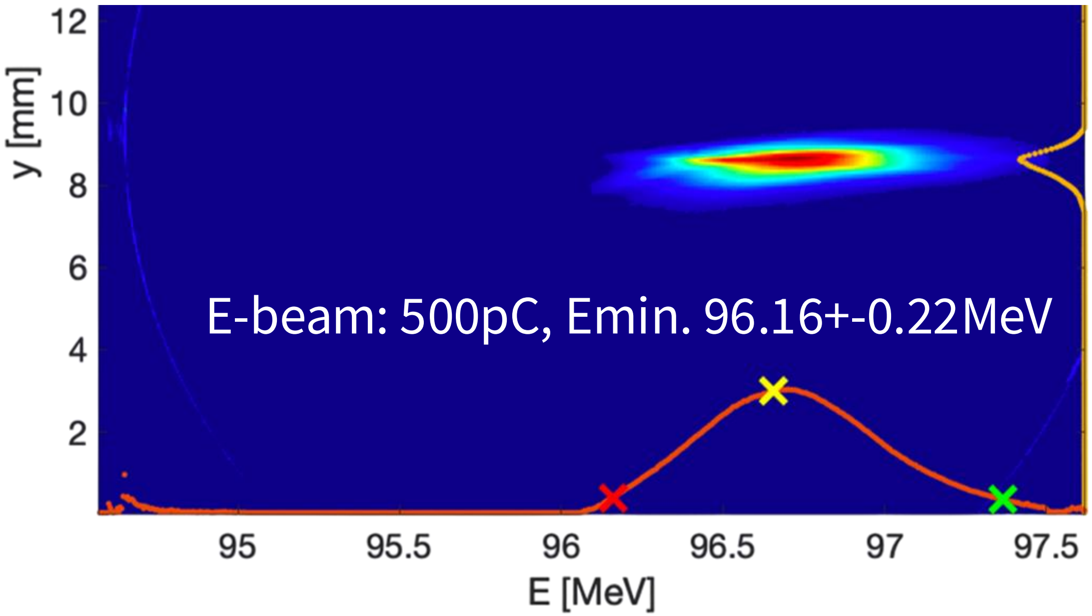
Electron temperature:

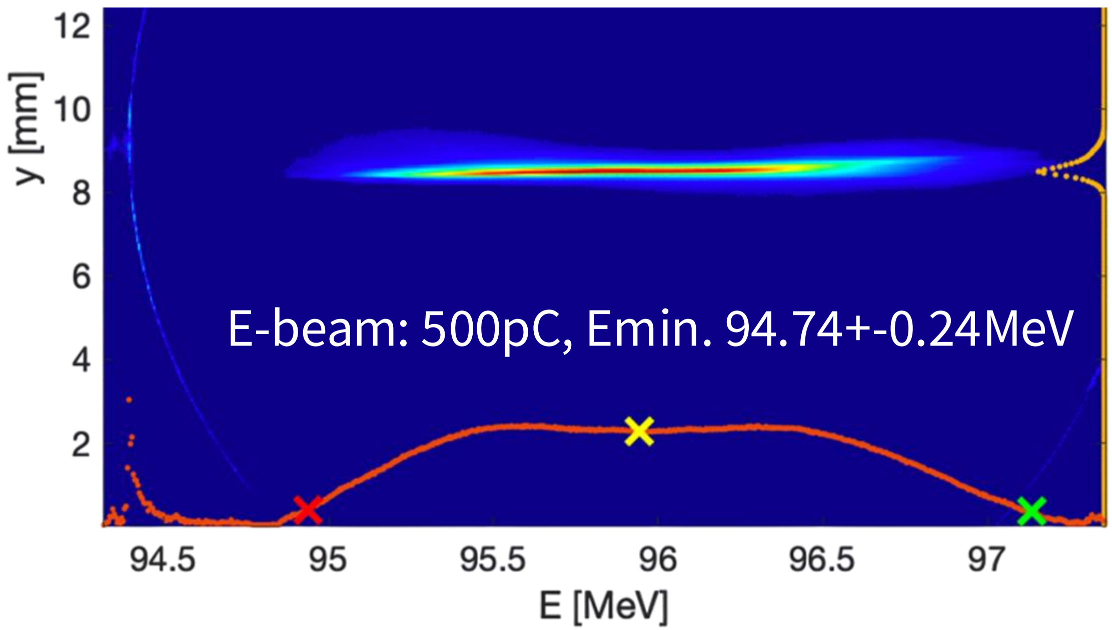
$T_e \approx 1.3$ eV

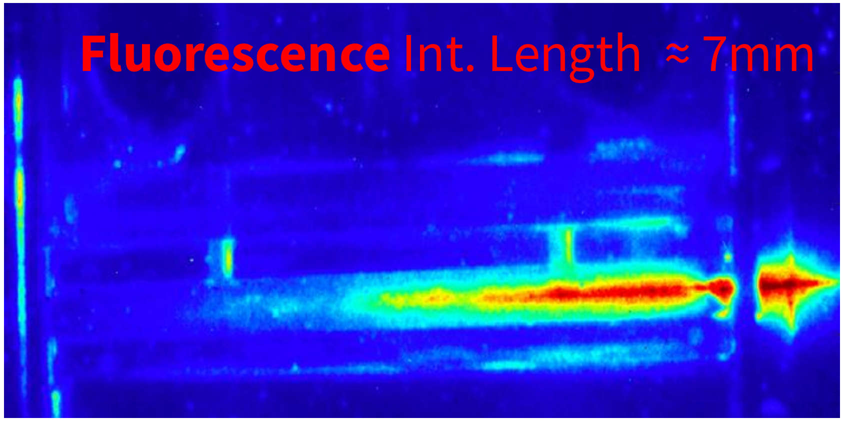
Retrieved from Stark broadening analysis of H_2 emission spectra

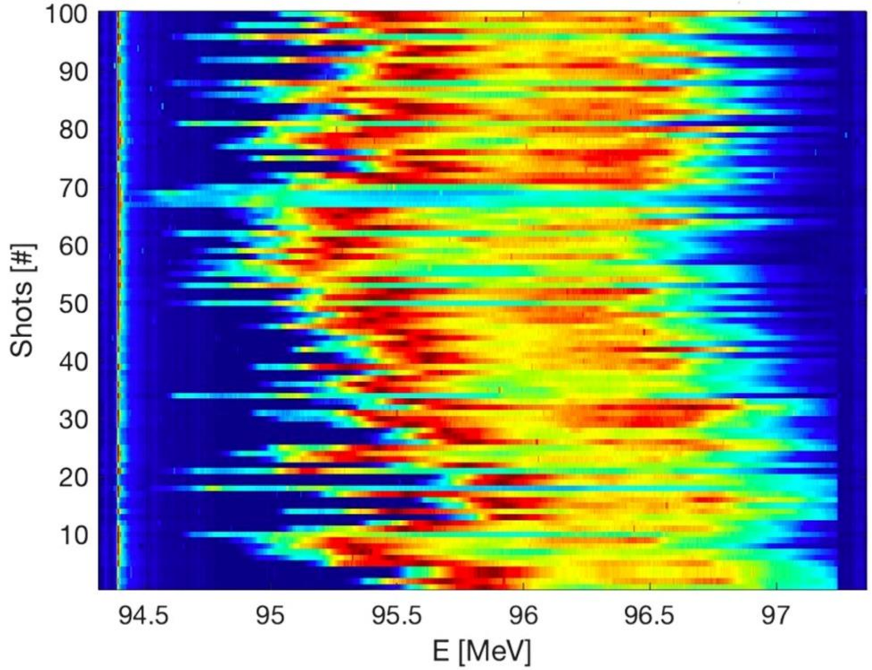
M. Galletti, et al., *"Femtosecond laser-induced plasma filaments for beam-driven plasma wakefield acceleration"*, **Phys. Rev. E 111, 025202 (2025)**

Proof of electron beam deceleration







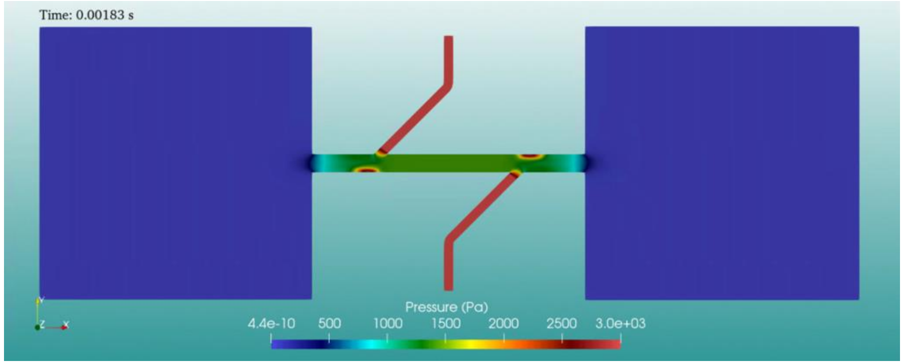


Averaged e-beam deceleration ≈ 1.3MeV

Laser-induced plasma filaments cell: new design

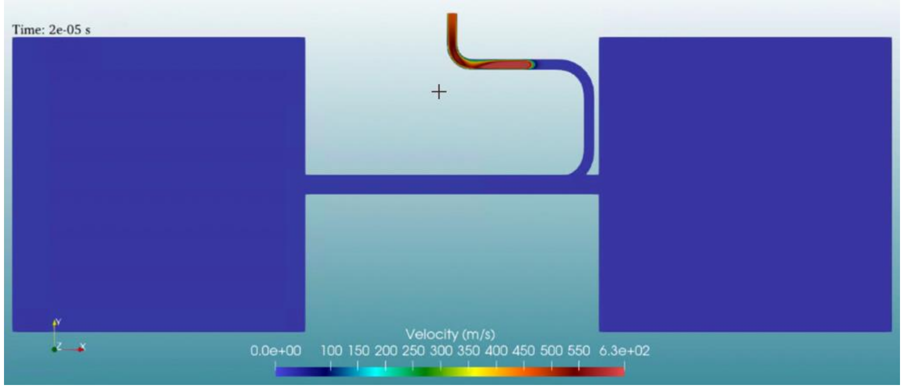
3cm capillary with 45° injection inlets

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



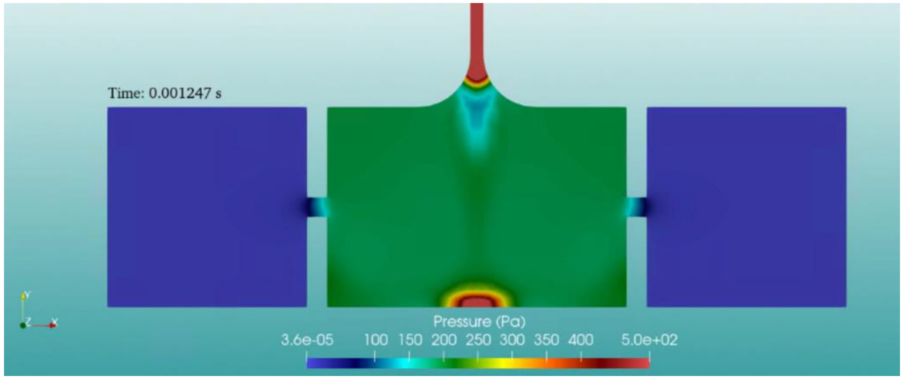
3cm capillary with 45° injection inlet

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

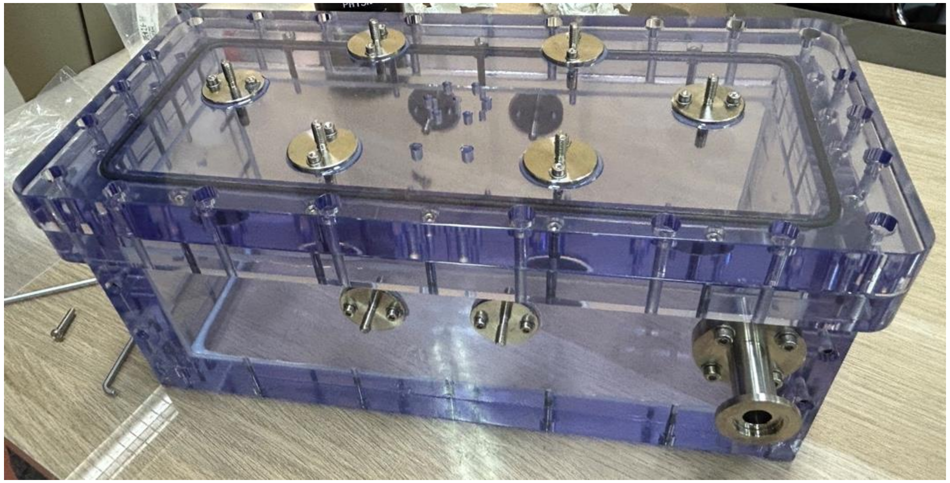


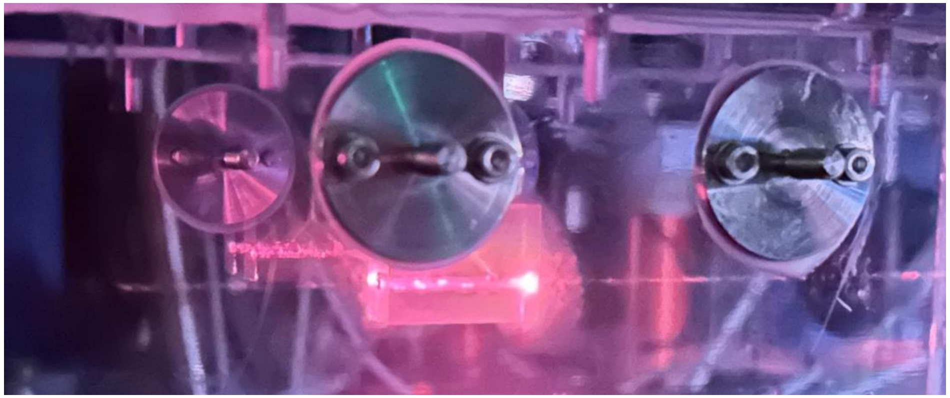
3cm gas cell with 2mm inlet

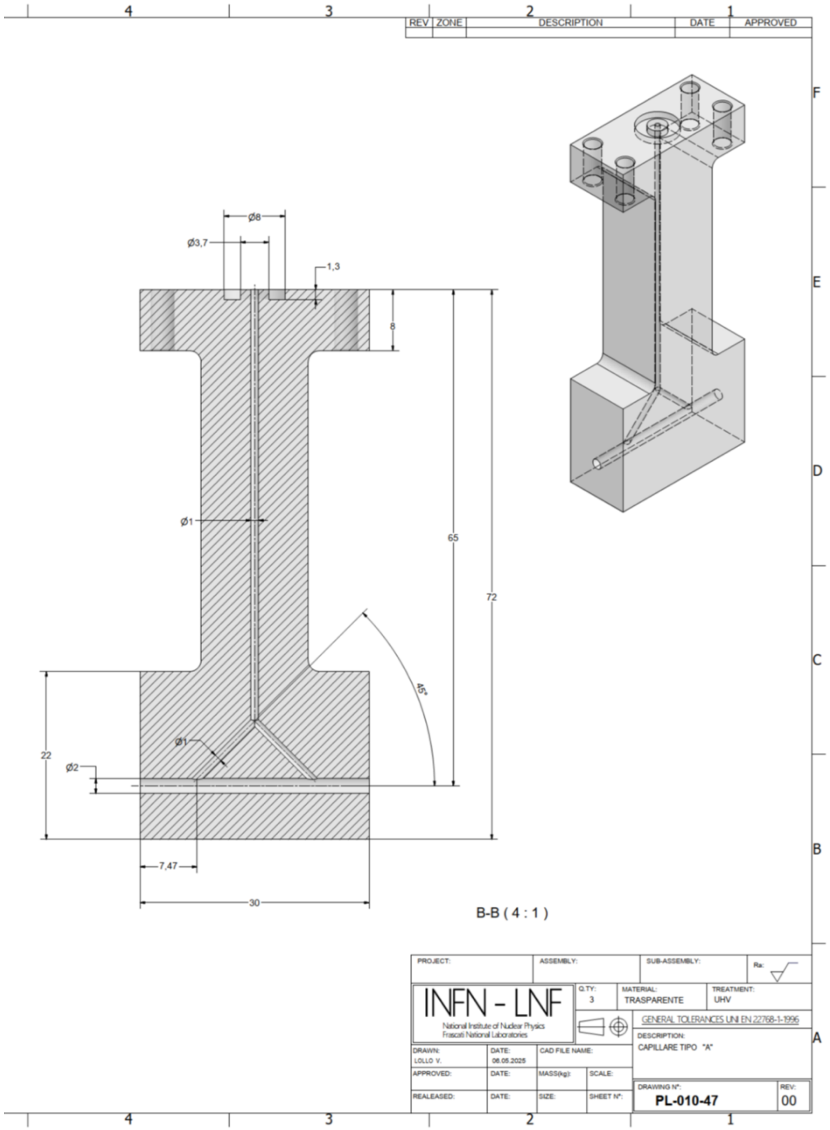
- ✓ Slow filling
- ✓ Flat-top pressure (and density) profile



Laser-induced plasma filaments cell: new design







Courtesy of V. Lollo

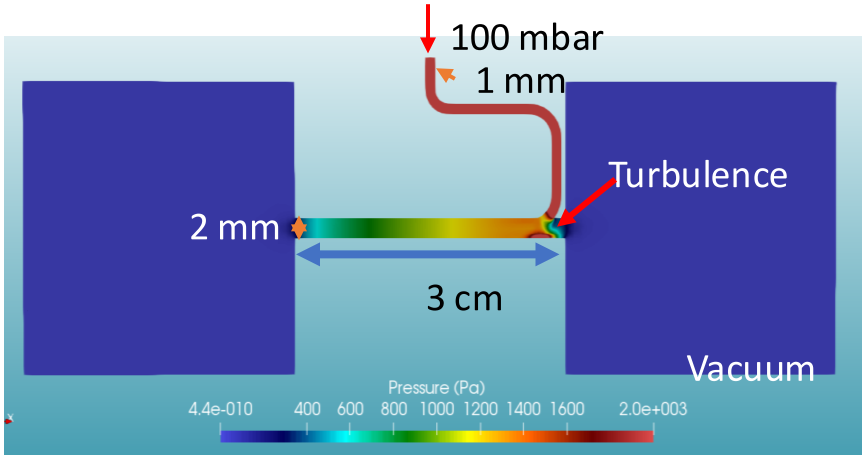
Laser-induced plasma filaments cell: Laser and filament parameters

- Wavelength = 800 nm
- Energy = 16 mJ (@clean room, around 10 mJ @COMB)
- Length = 250 fs (FWHM)
- Lens focal length = 1m
- Laser spot around 50 um (rms)

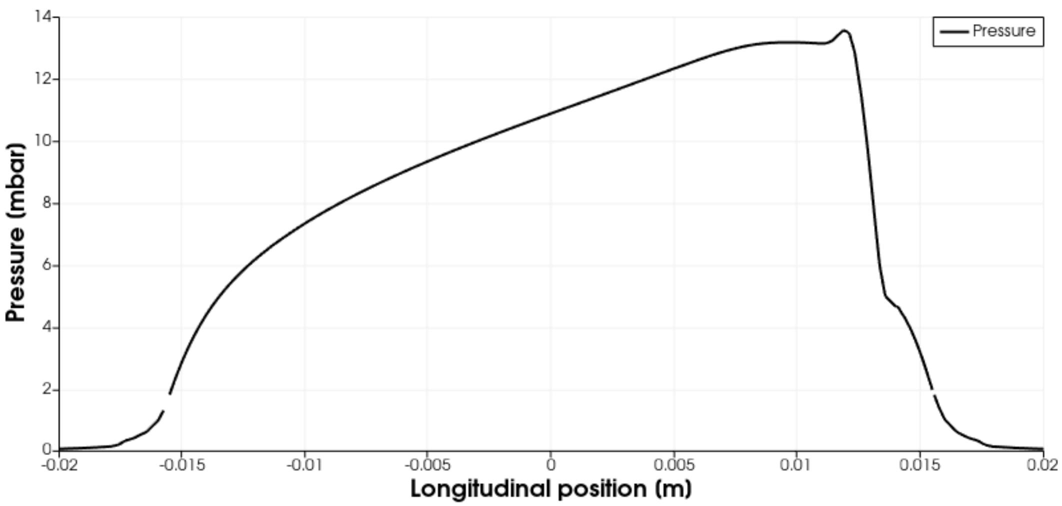
- Filament length more than 5 cm @1 bar (stationary regime)
- Filament length more than 3 cm @10ish mbar (pulsed regime)

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

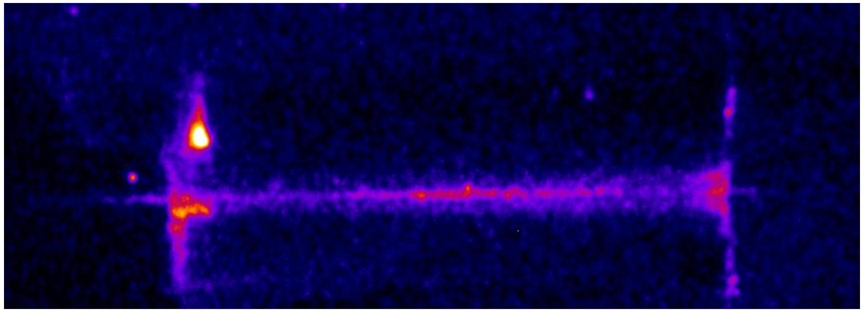
- Localized turbulence at channel exit
- Smooth pressure ramp from the entrance
- 100 mbar from the valve -> 3-13 mbar along the gas column
- $N=1.5\text{-}3\times10^{17}$ cm^{-3}



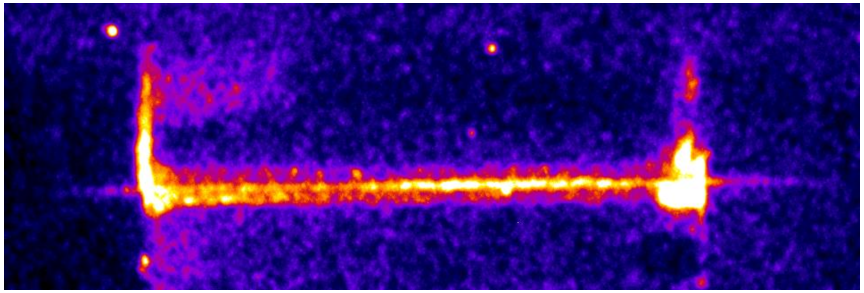
On-axis pressure profiles at equilibrium (<0.5ms)



Inlet @exit @10Hz rep rate



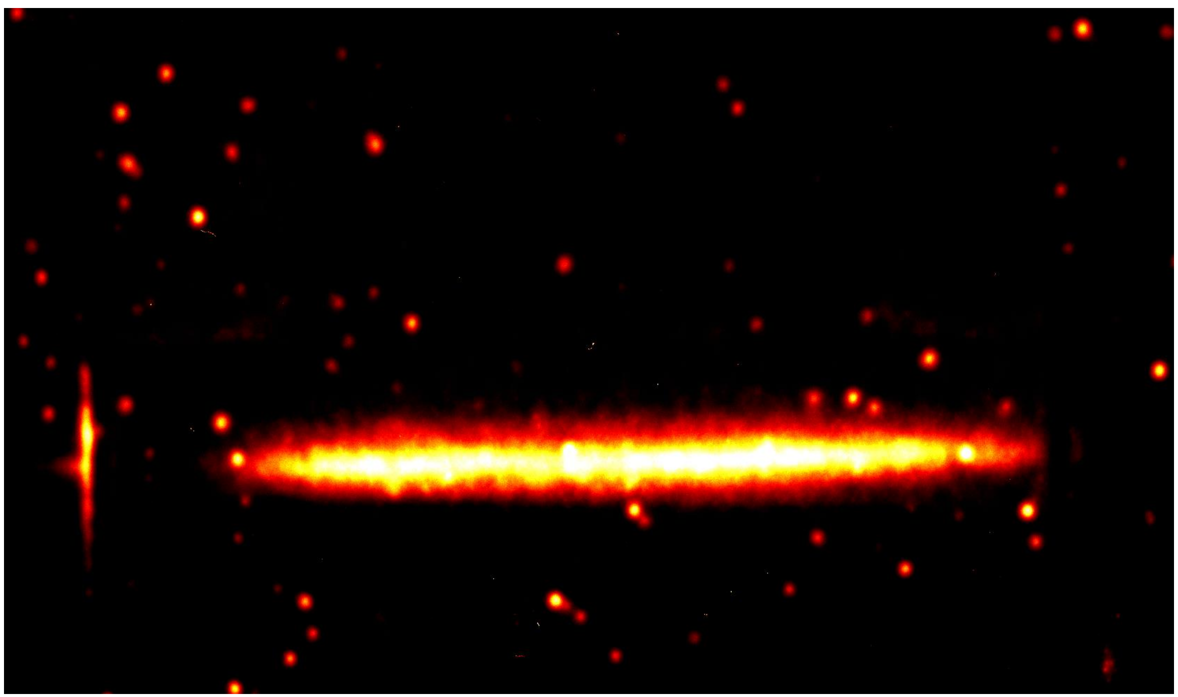
Inlet @input @10Hz rep rate

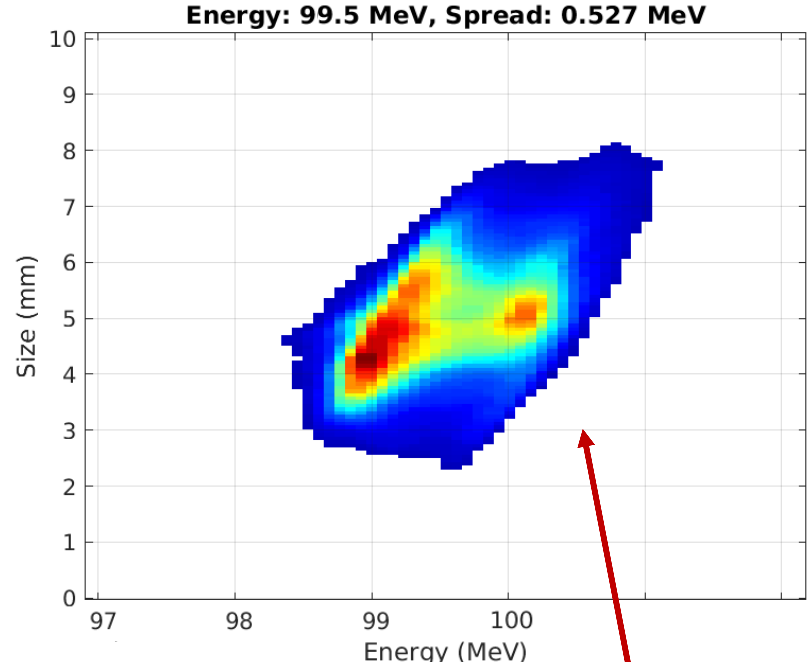


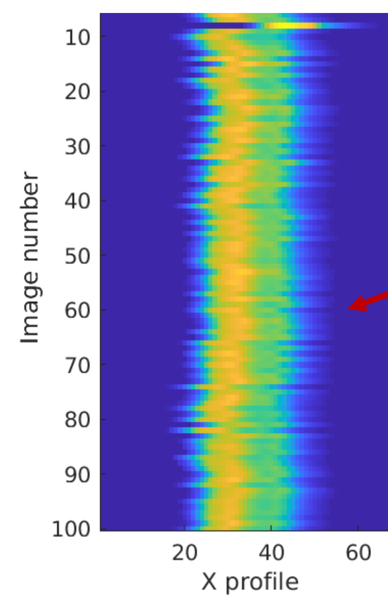
R2 - Proof of electron beam deceleration Preliminary results

3cmx2mm with 1mm diameter single inlet @45deg injection was installed in the COMB.

Fluorescence Interaction Length ≈ 30 mm







Averaged e-beam ≈ 500 pC, 500 fs

R2 - Proof of electron beam deceleration
Preliminary results

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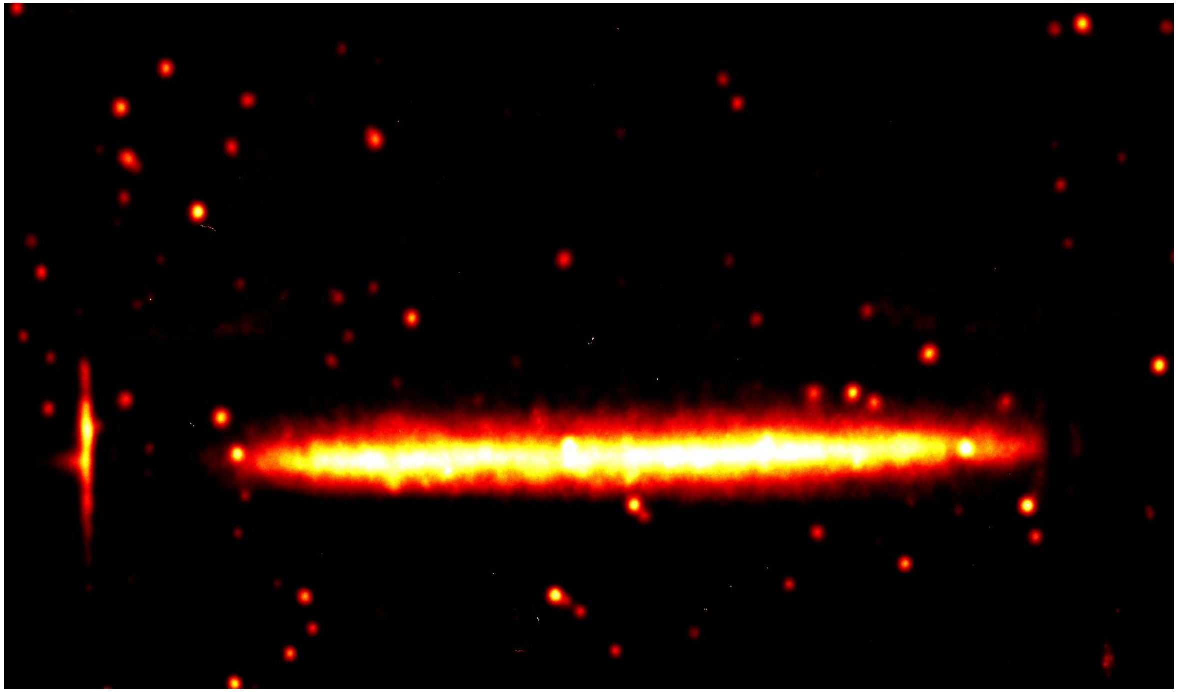
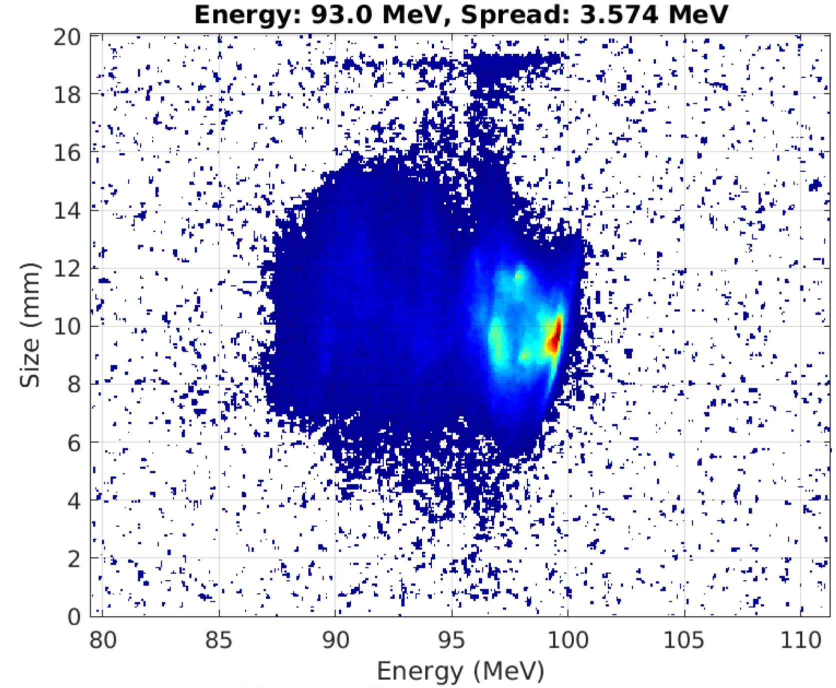
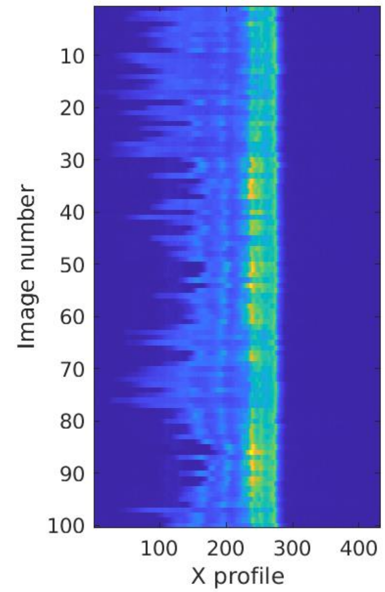


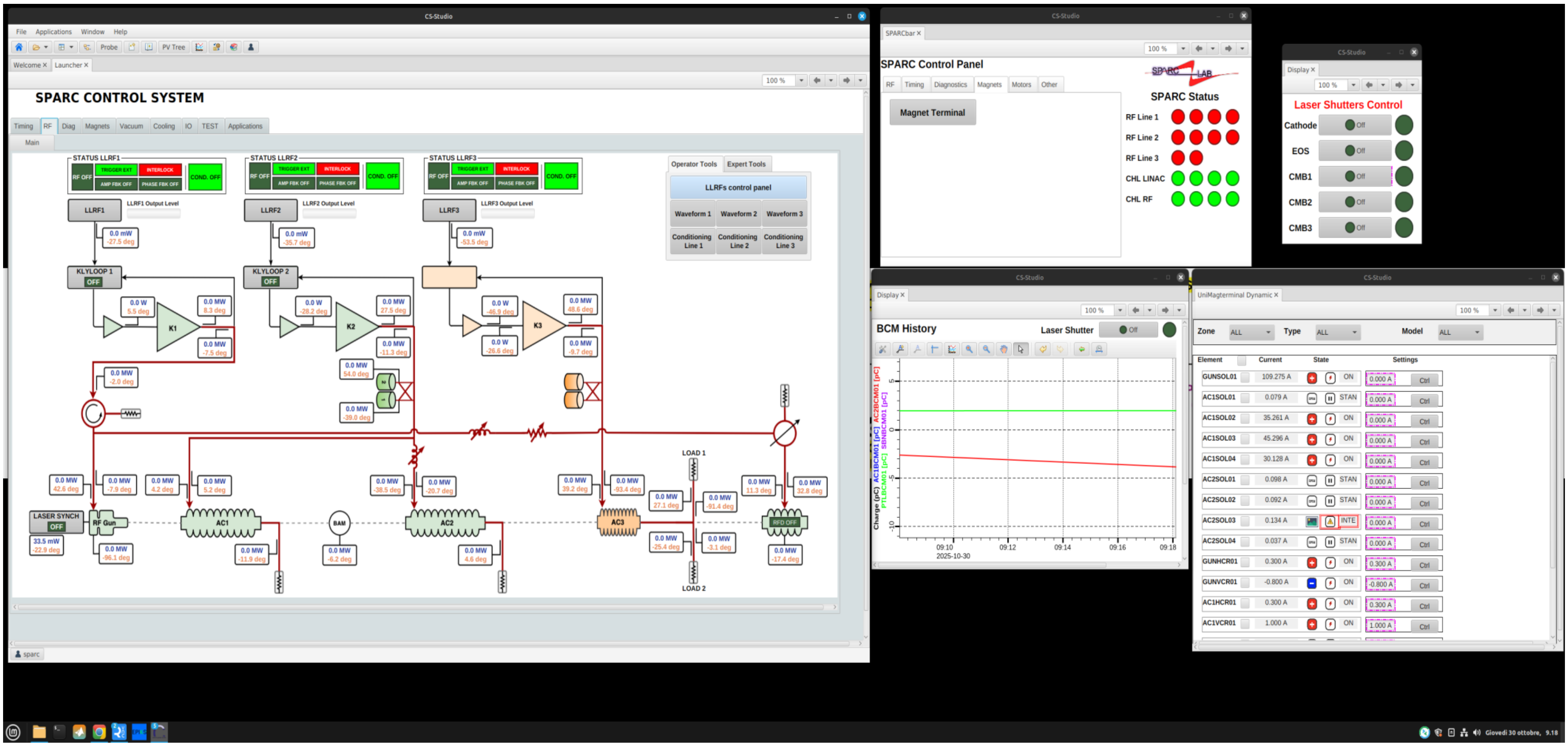




E-beam deceleration ≈ 6-10 MeV

EPICS control system

- Debug of the EPICS control system almost complete.



Possible next activities (tbd)

- ❑ **Run-2 Filament experiment (Nov 2025)**
  - Demonstration of high-rep rates plasma columns for PWFA
- ❑ **Driver-Witness separation with APLs (Feb 2026)**
  - Compact plasma-based system with witness focusing/extraction and driver separation features
- ❑ **High-gradient, high-quality PWFA beams (Mar 2026)**
  - Acceleration of a low energy spread/emittance witness with acceleration >1GV/m
- ❑ **PWFA vs EOS (RF timing)-Plasma (density)-Laser (charge) jitter study (Mar 2026)**
  - Evaluation of the jitter sources (laser vs RF vs plasma) of the plasma-accelerated beam
- ❑ **Run-2 Resonant Excitation of plasma wakefields (Apr 2026)**
  - Compressed bunches for high-gradient, high-transformer ratio acceleration
- ❑ **Test of the EuPRAXIA working point @ SPARC_LAB (May 2026)**
  - Demonstration of high-current low-emittance beam from an EuPRAXIA-like injector

- ❑ **Commissioning of the SABINA beamline (Jan-Dec 2026 in parallel)**
  - Commissioning of the electron beamline, THz undulators and THz beamline
- ❑ **Commissioning of the EuAPS facility (Jan-Dec 2026 in parallel)**
  - Commissioning of the electron beamline and X-ray beamline

PLASMA_LAB off-line measurements

Plasma Module R&D

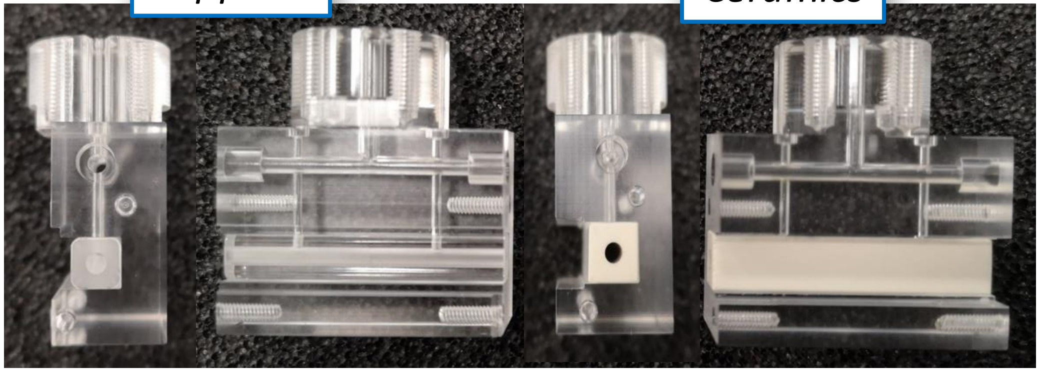
Plasma module operation at high repetition rate

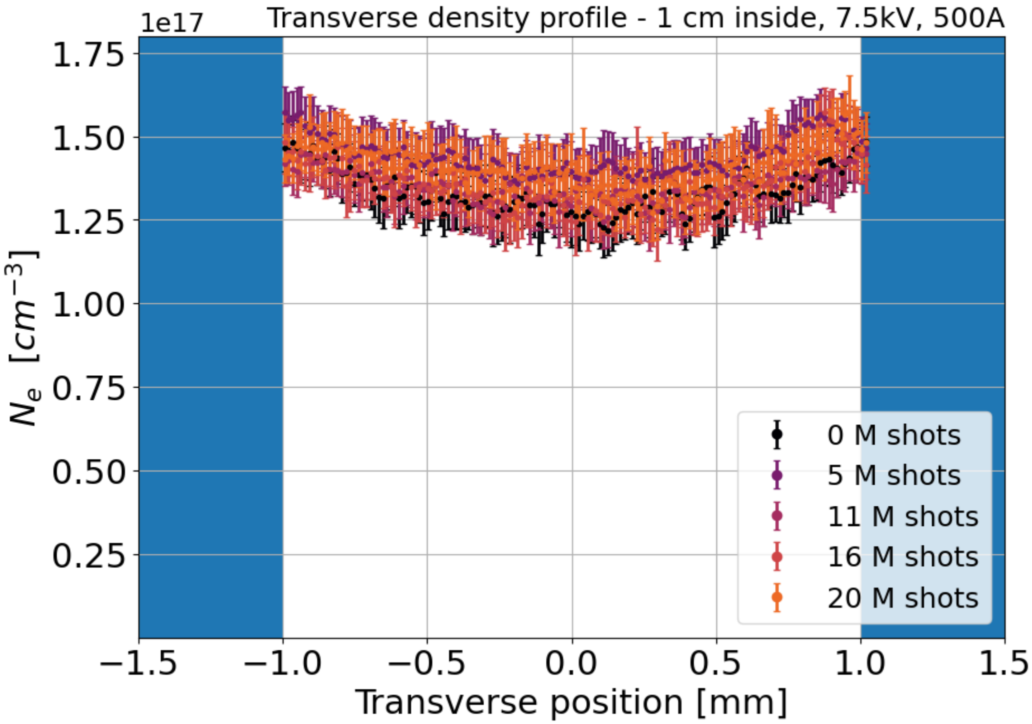
1. Solid-state high repetition-rate discharge system
2. High temperature-resistant materials capable of withstanding the plasma thermal load
3. Vacuum systems suitable for continuous flow gas injection (turbo and primary pumps cooling system)

100 Hz repetition rate discharges

Sapphire

Ceramics





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

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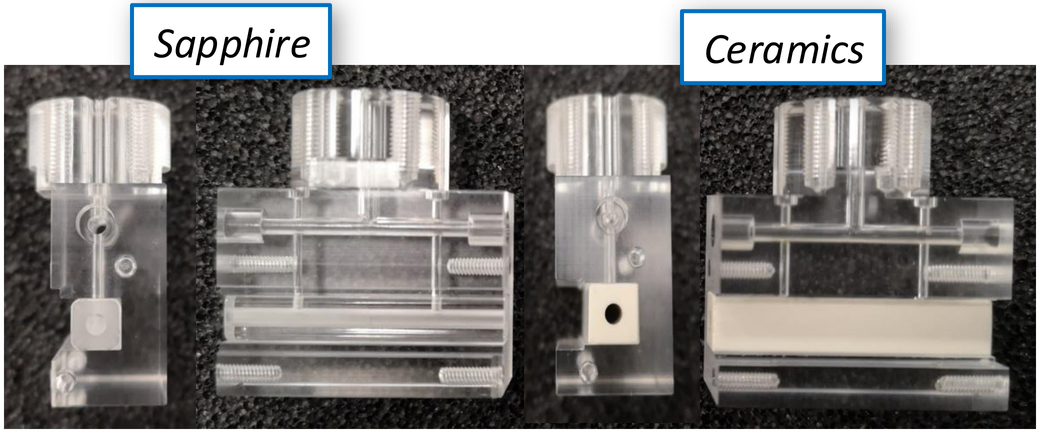
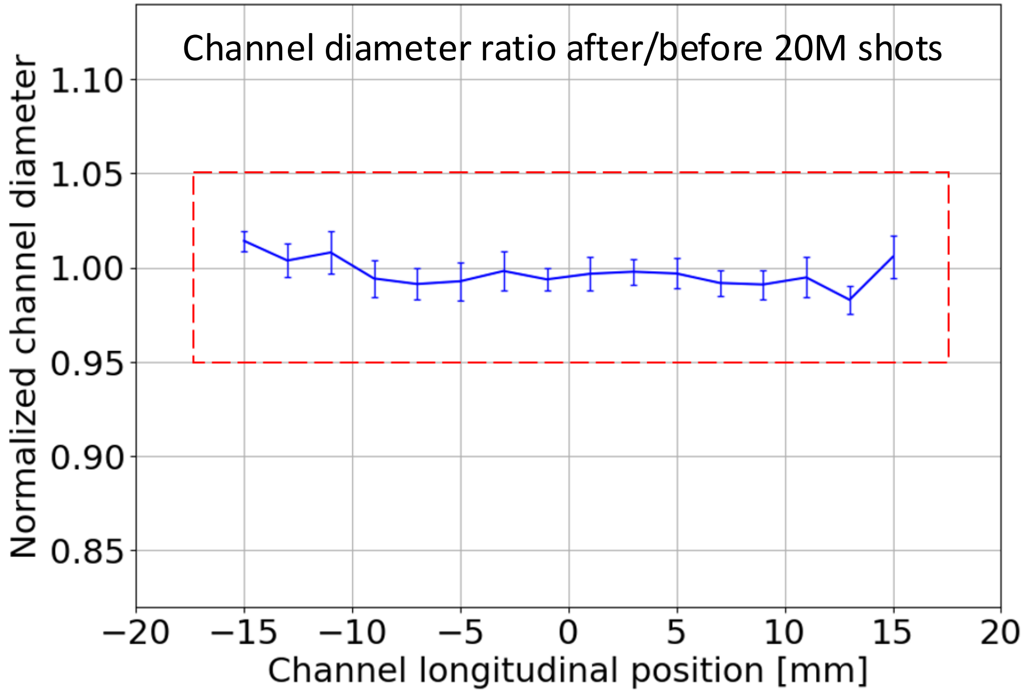


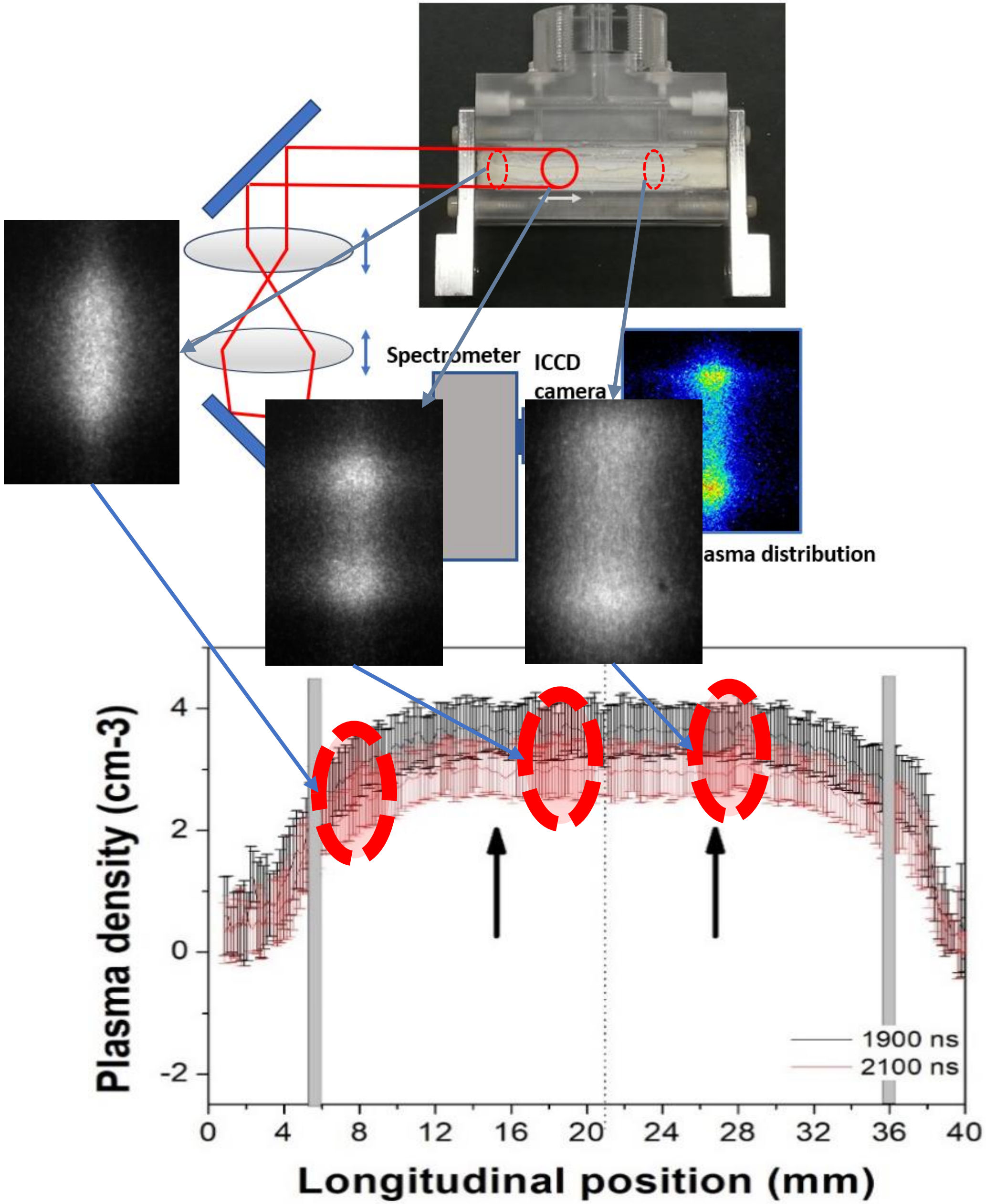


L. Crincoli et al. "*Advanced ceramic plasma discharge capillaries for high repetition rate operation*", **Scientific Reports 15(1) (2025)**

Plasma Module R&D

Transverse measurements

- Use transverse spectroscopic diagnostic line
- **Take different image of a plasma "slice" inside the capillary**
- Repeat this measurements at different positions inside
- Take the mean plasma transverse density profile for each position and reconstruct the longitudinal profile
- **Allow us to make a 3D plasma profile (radial profile + longitudinal)**

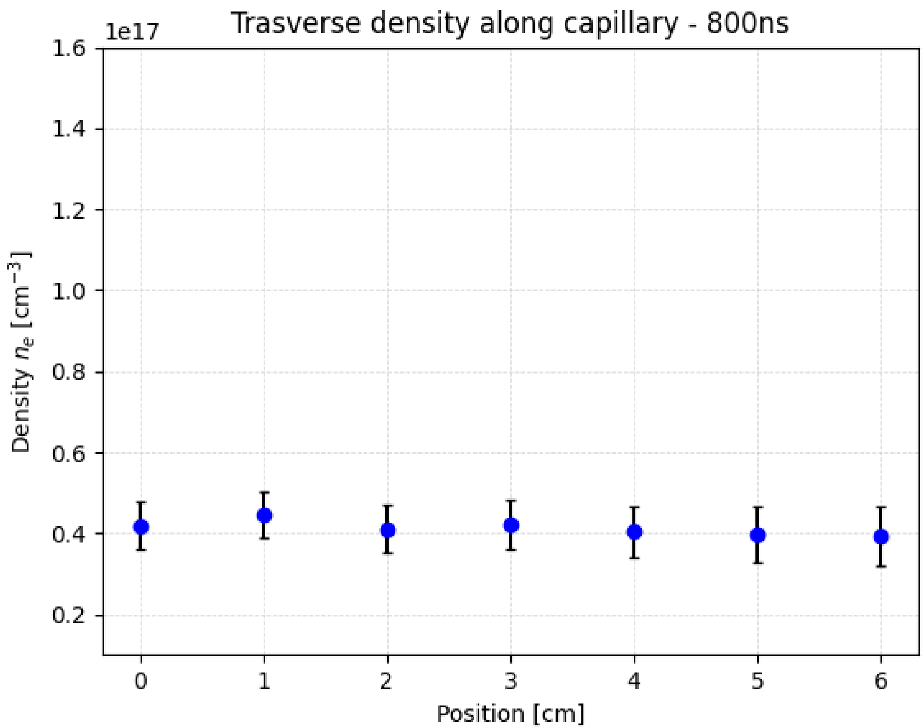


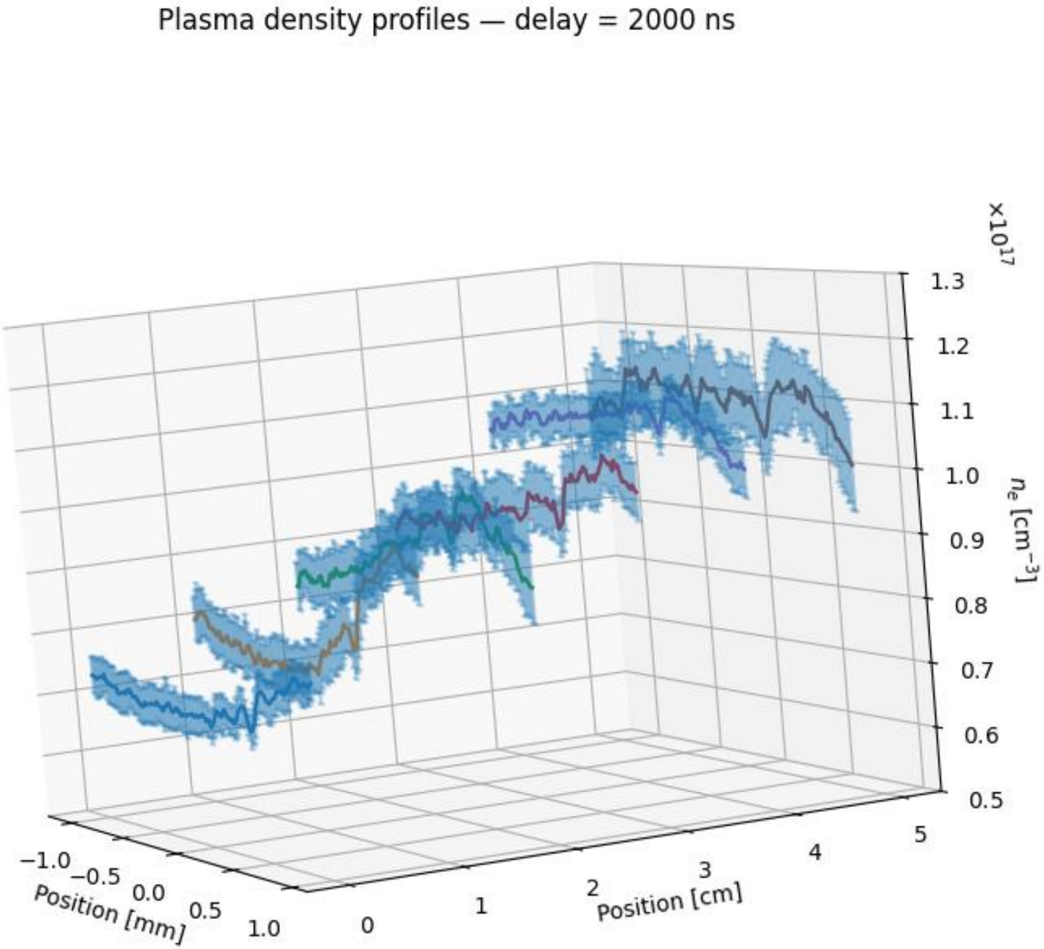
Courtesy of R. Demitra, A. Biagioni

Plasma Module R&D

Transverse measurements

- Data shown here correspond to 10 kV discharge voltage and 620 A peak current

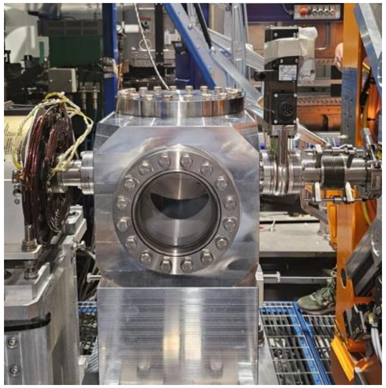


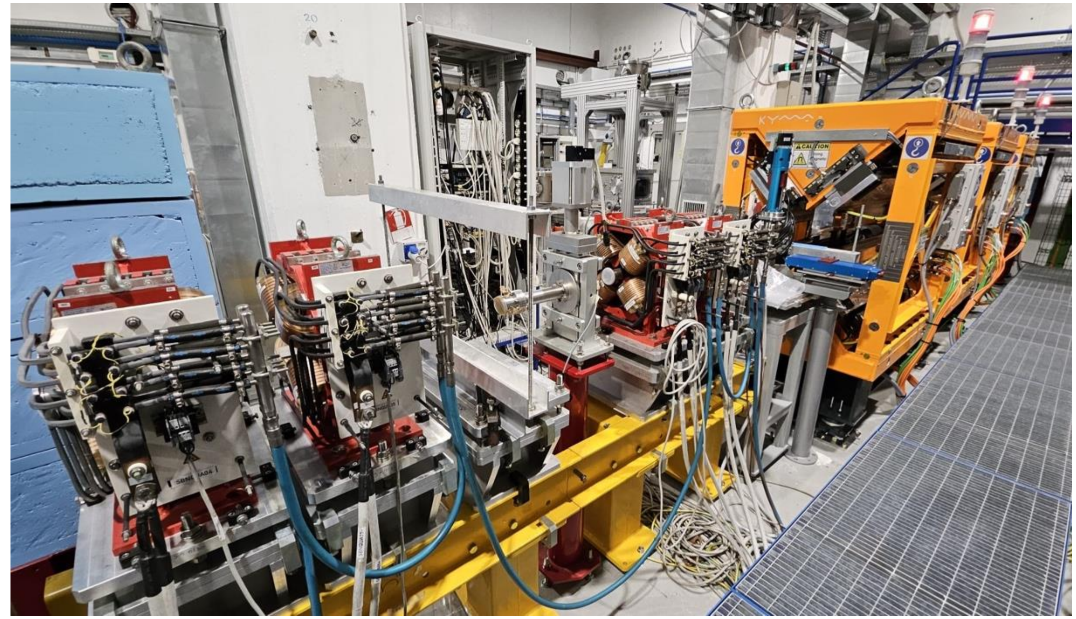


Courtesy of R. Demitra, A. Biagioni

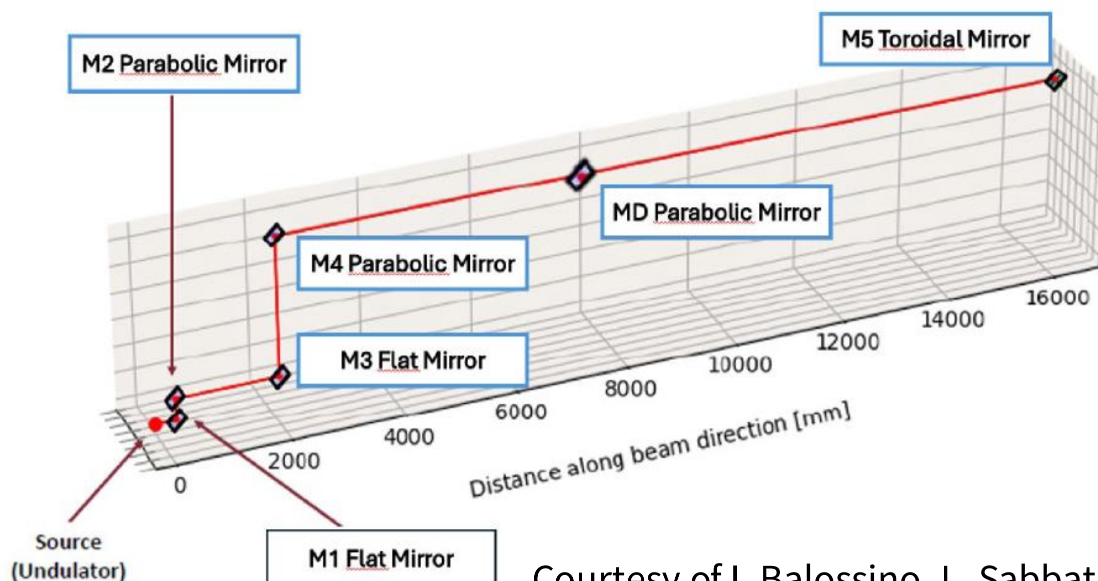
SABINA beamline

THz user beamline





SABINA project aim to develop a THz radiation production line at SPARC_LAB by means of a system of undulators, chosen to be **APPLE-X profiting of their key properties** (symmetric focusing properties, tunable polarization, etc).
The facility will therefore enable the generation and control of **intense pulses in a large spectral extension from 3 to 30 THz** for advanced scientific applications.

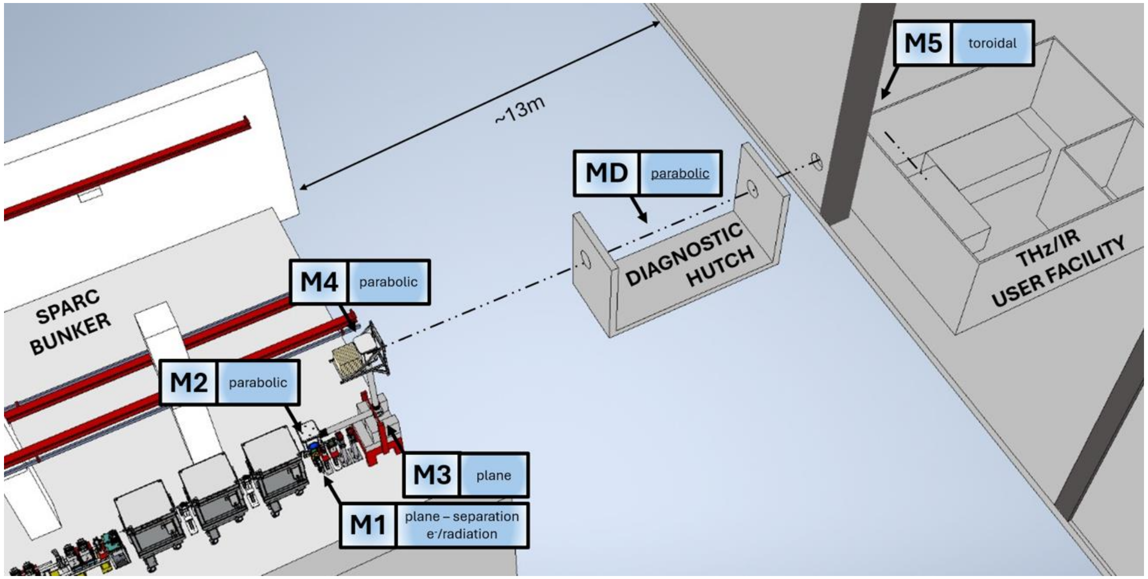


Courtesy of I. Balossino, L. Sabbatini

SABINA status

✔ **Electron beamline**

- Almost all electron-beamline elements in position
- M1 vacuum chamber installed on the line and its assembly is ongoing
- Diagnostic installation finalization ongoing
- Full power test to be performed within few weeks
- Ready by the end of 2025



Our goals: - TESTING **E-BEAMLINE BY EARLY 2026**
- TESTING **THz BEAMLINE BY 2° HALF OF 2026**

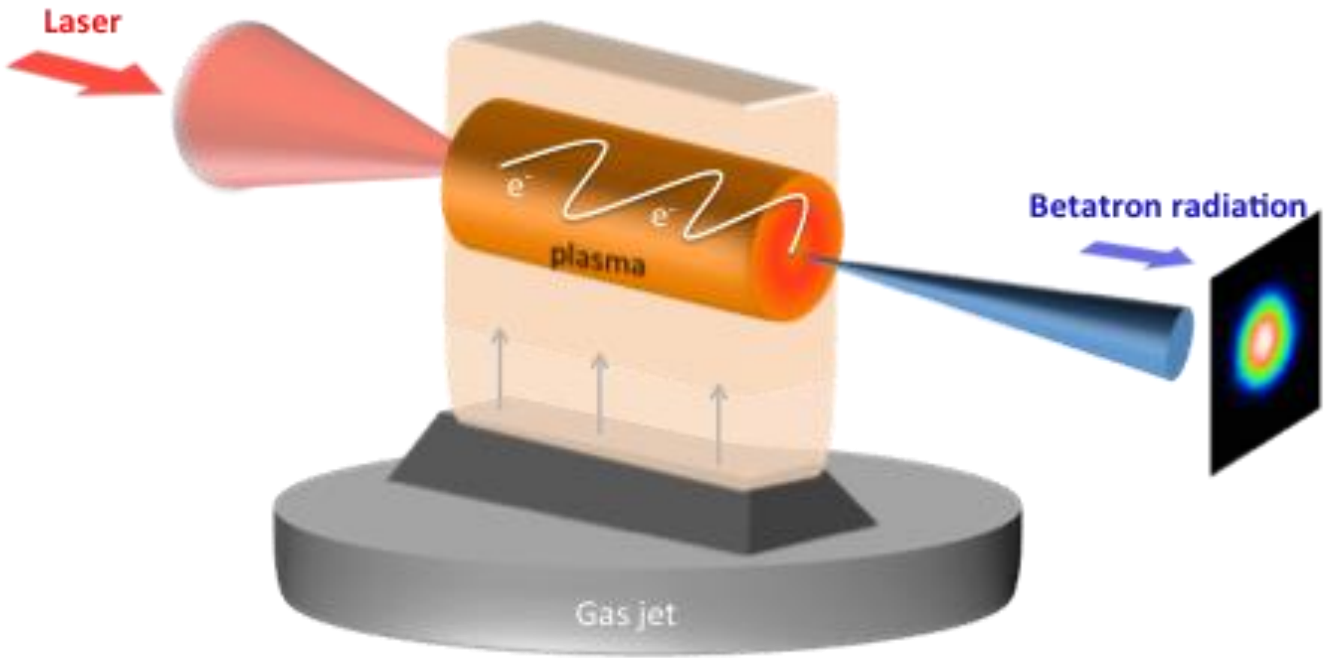
THz beamline

- <u>Vacuum Chambers</u>: M2 delivered and tested, M3 and M4 ready for order, MD and M5 design ongoing
- <u>Motions motors</u>: for M2 and M3 under purchase, funds are needed for the others
- Safety measures in preparation
- User facility and diagnostic hutch: final design ongoing
- Mirrors' alignment procedure defined

Delays: - workforce and coordination with other experiments and installations
- hardware replacement and delivery

FLAME - EuAPS beamline

X-ray photon source



Source Parameter	Value	unit
Electron beam Energy	100-500	MeV
Plasma Density	10^{17}-10^{19}	cm-3
Photon Critical Energy	1 -10	keV
Photons per pulse	10^{6}-10^{9}	
Repetition rate	1-5	Hz
Beam divergence	3-13	mrad

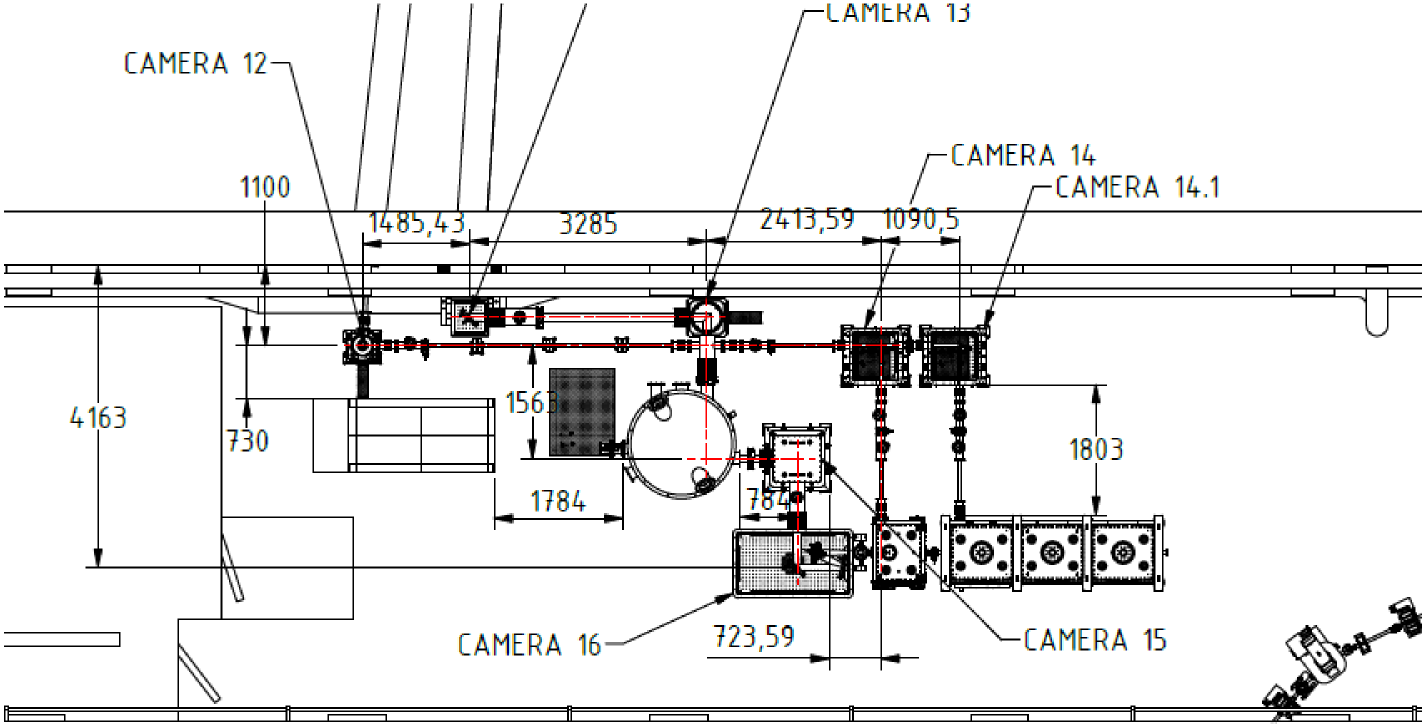
Laser Parameter (Site Acceptance Test)	Value	unit
Energy (pre compression)	7	J
Temporal length	<25	fs
Rep. Rate	5	Hz
Wavelength	800	nm
Contrast	10^{-9}	
Bandwidth	90	nm

EuAPS status

- Flame Laser upgrade and refurbishment are ongoing-> end in November
  - **Problems with thermal effect on the last amplifier**
- Installation of transport lines in Flame bunker ongoing -> end 2025
- Installation in SPARC bunker started -> end in March 2026

- **Source optimization and characterization -> April 2026**
- **Pilot experiment -> May 2026**

EuAPS status



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Thank you for your kind attention!

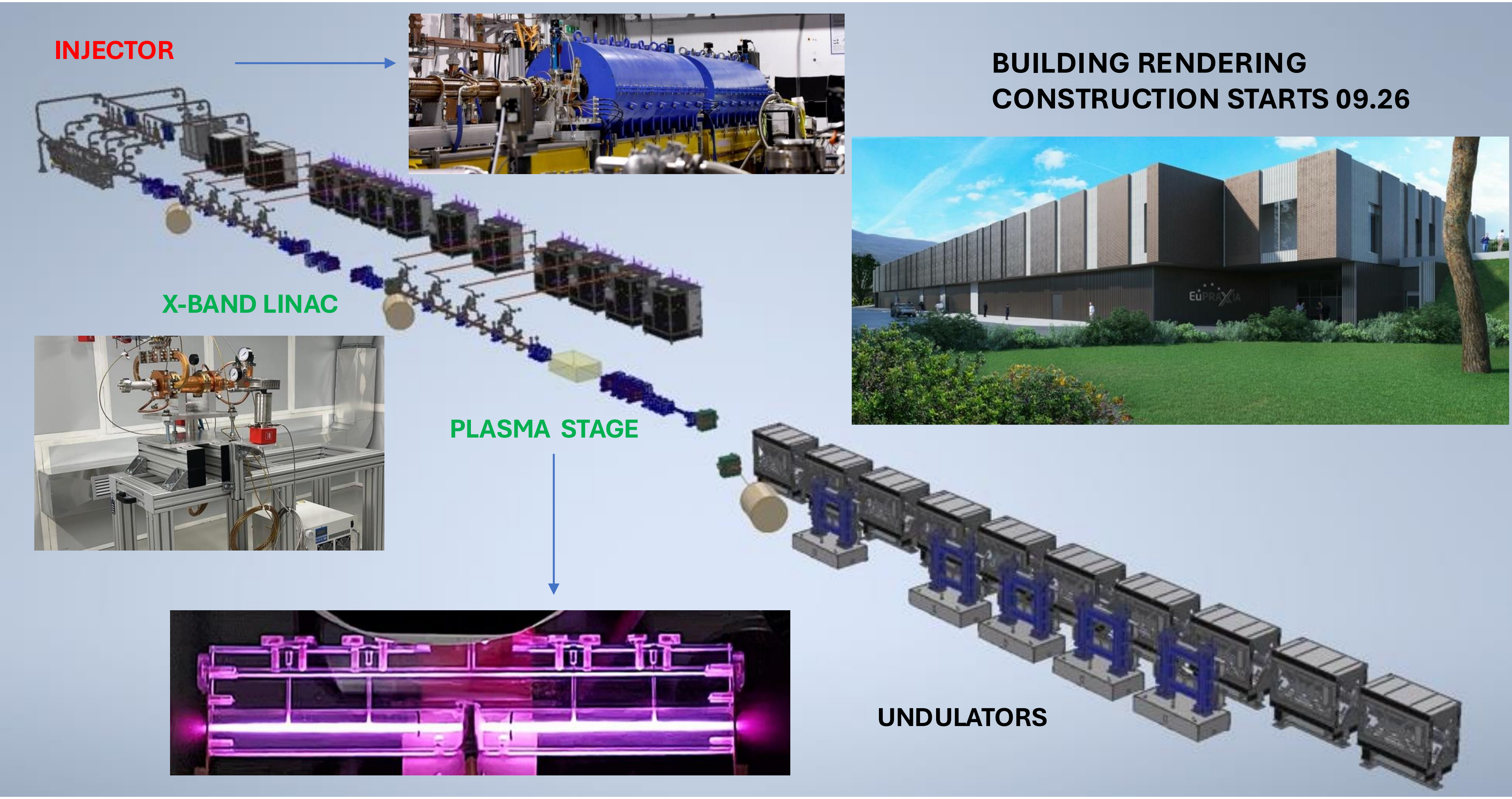
Mario Galletti (LNF, INFN)

mario.galletti@lnf.infn.it

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

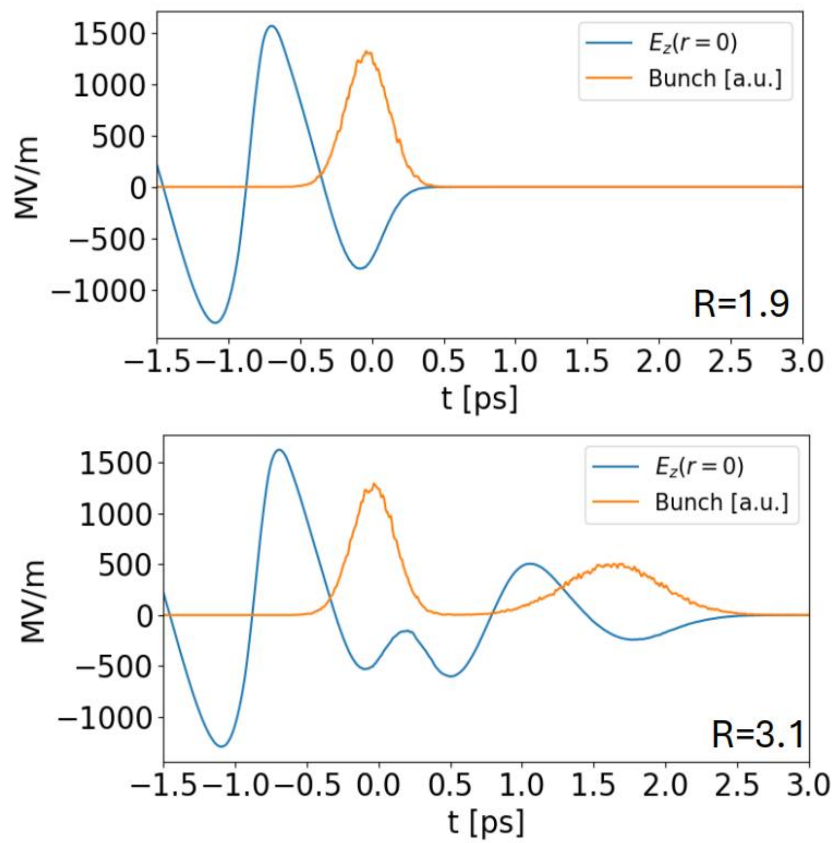


Resonant Excitation of PWFA - Results

- The non-linear, high-transformer-ratio configuration could be used at EuPRAXIA@SPARC_LAB to maximize the final energy reach of the witness bunch towards 5 GeV
- Low-charge driver bunch ahead of the main driver "jump-starts" the wakefields, reducing E^{-} within drivers
  → R enhancement

➔ Higher final energy with the same main driver bunch

➔ Lasing at shorter wavelength



EuPRAXIA@SPARC_LAB

Courtesy of L. Verra

Laser-induced plasma filaments

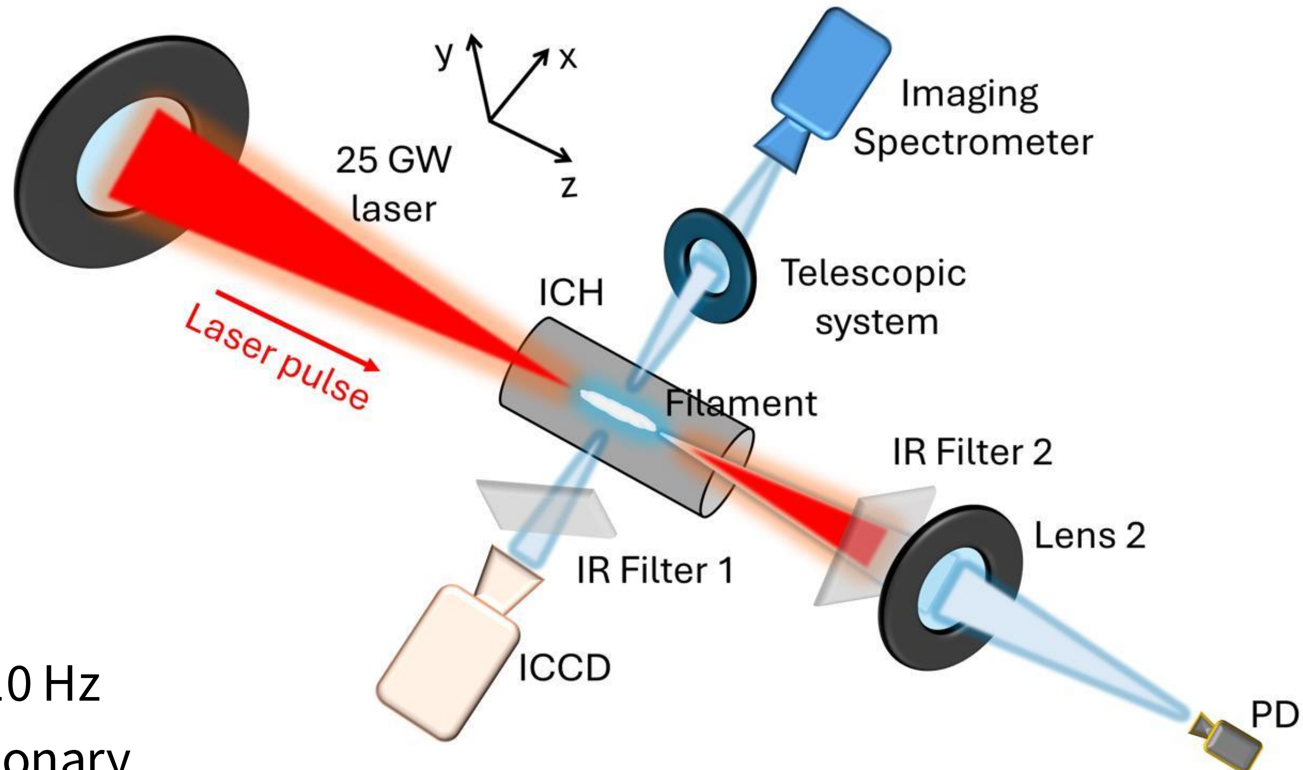
We generate plasma filaments using a low-energy femtosecond laser in low-pressure nitrogen gas environment.
The filament acts as the medium for beam-driven wakefield acceleration.

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)**

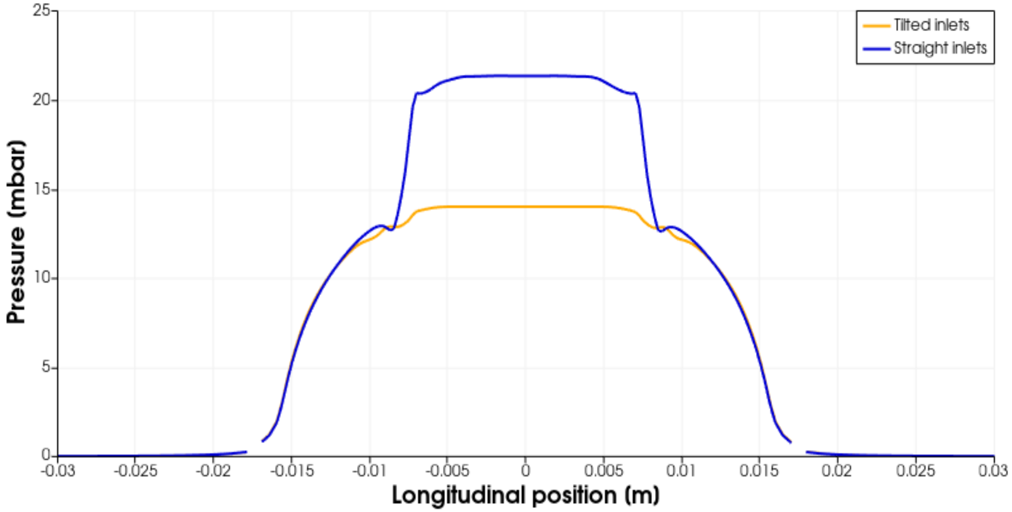
Experimental characterization

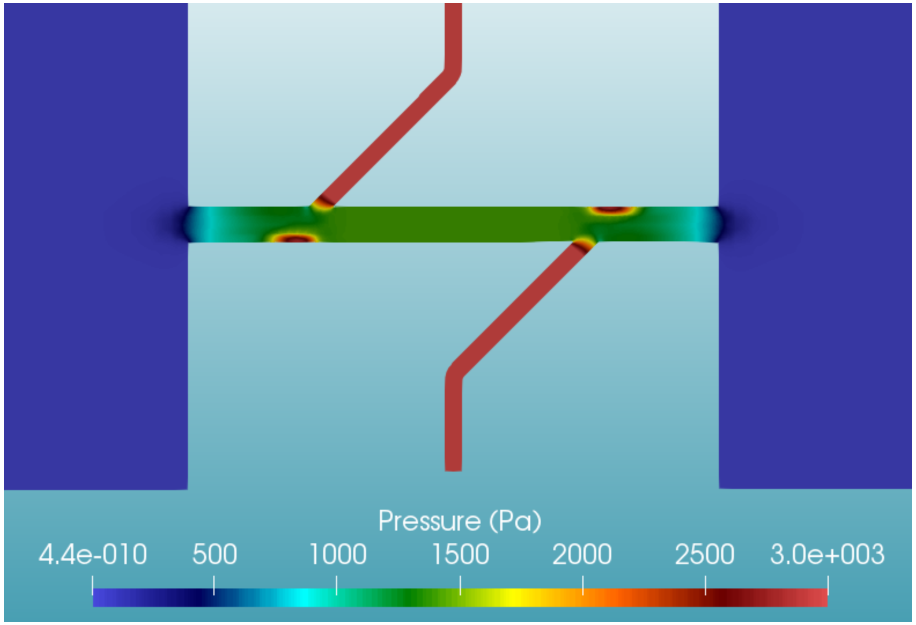
- Side imaging fluorescence technique
  - Filament dimensions and density evolution
- Spectral analysis
  - Plasma density and temperature distribution
- Photodiode
  - Decay time

3cmx2mm channel with 1mm diameter double inlets @45deg injection

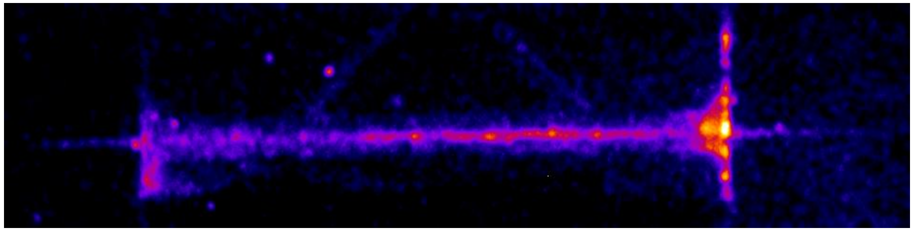
- Minimized turbulences in the velocity map
- Sharp pressure ramps with straight 90° inlets
- N_n=1-3x10^{17} cm^{-3}

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



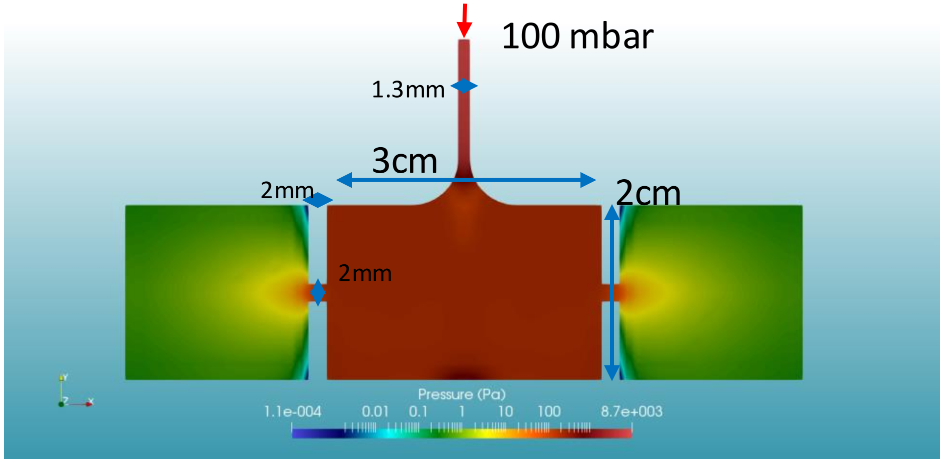


@10Hz rep rate

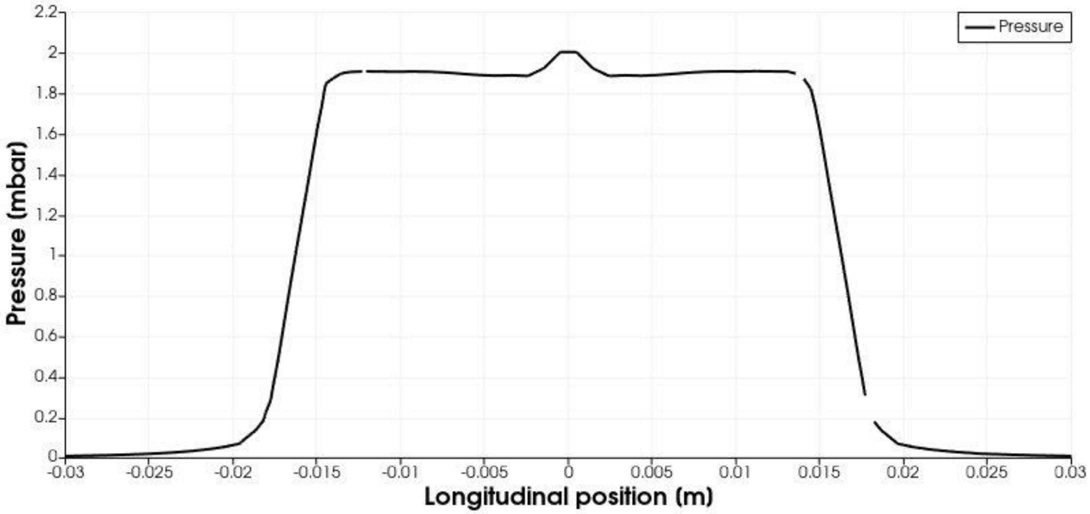


3cmx2cm Gas-cell with single inlet @90 deg injection

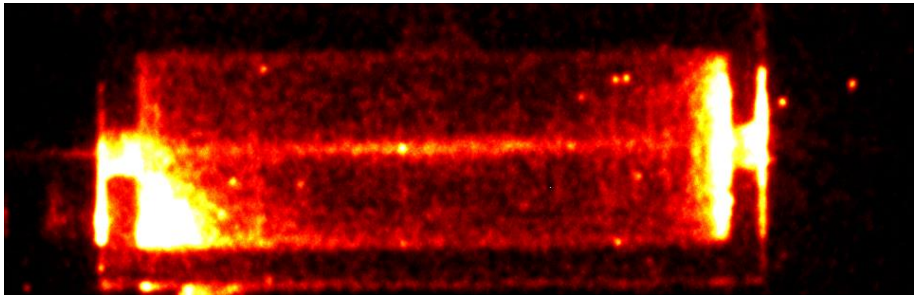
- Slow filling of the gas cell
- 1-2 mbar inside the cell with 100 mbar
- N= 4×10^{16} cm^{-3}



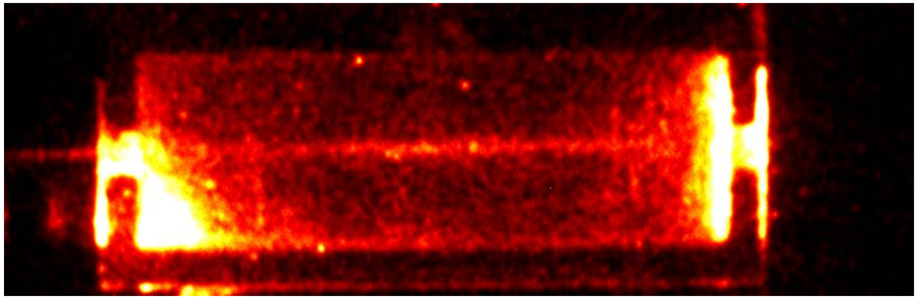
On-axis pressure profile at equilibrium



@1Hz rep rate

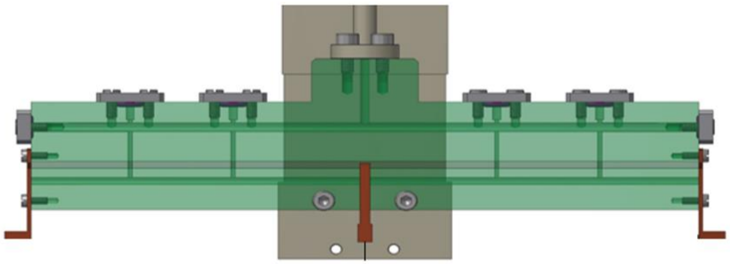


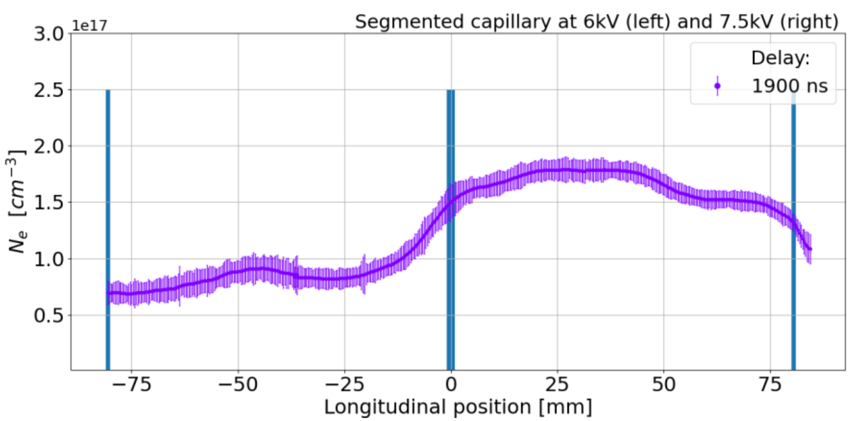
@10Hz rep rate

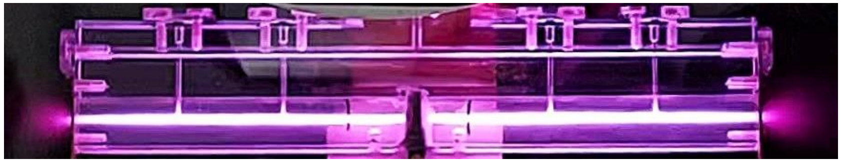


Plasma Module R&D

Segmented capillary

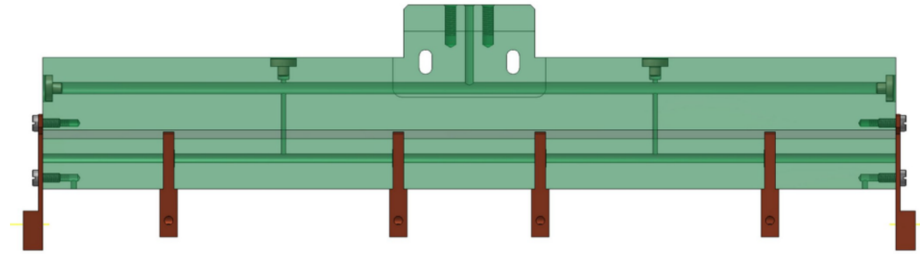


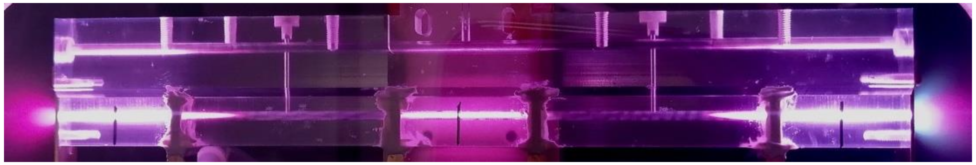




A. Biagioni, et al. 'Plasma density manipulation in long staged gas-filled discharge capillaries for plasma-based accelerators', in preparation (2025)

Integrated plasma module





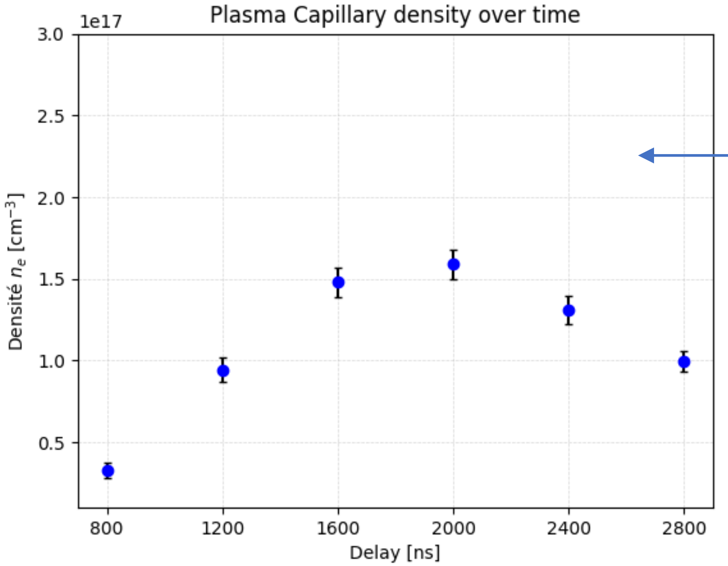
- **Independent** sections powered in parallel
- **60 cm** (m-scale) plasma discharge capillaries with **~10 kV** HV pulses
- Longitudinal **density modulation**
- **Compact plasma module** for acceleration – focusing

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

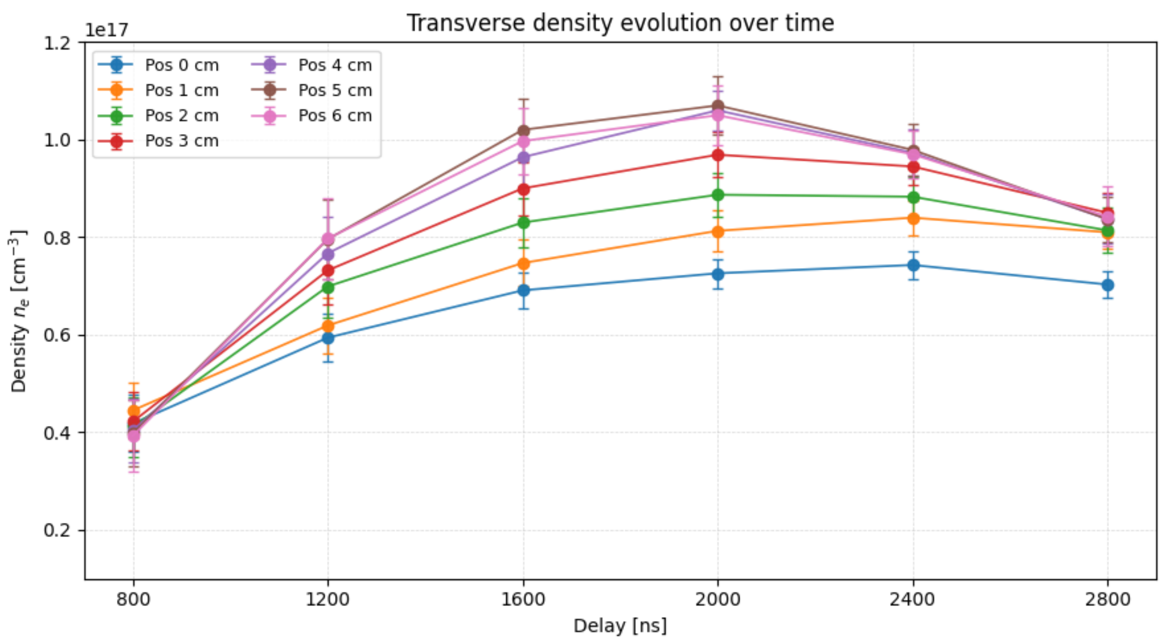
Courtesy of A. Biagioni, L. Crincoli, V. Lollo

Transverse measurements

- Data shown here correspond to 10 kV discharge voltage and 620 A peak current



Time profile of plasma density from longitudinal measurement



Courtesy of R. Demitra, A. Biagioni