ALIC Plans at SPARC_LAB

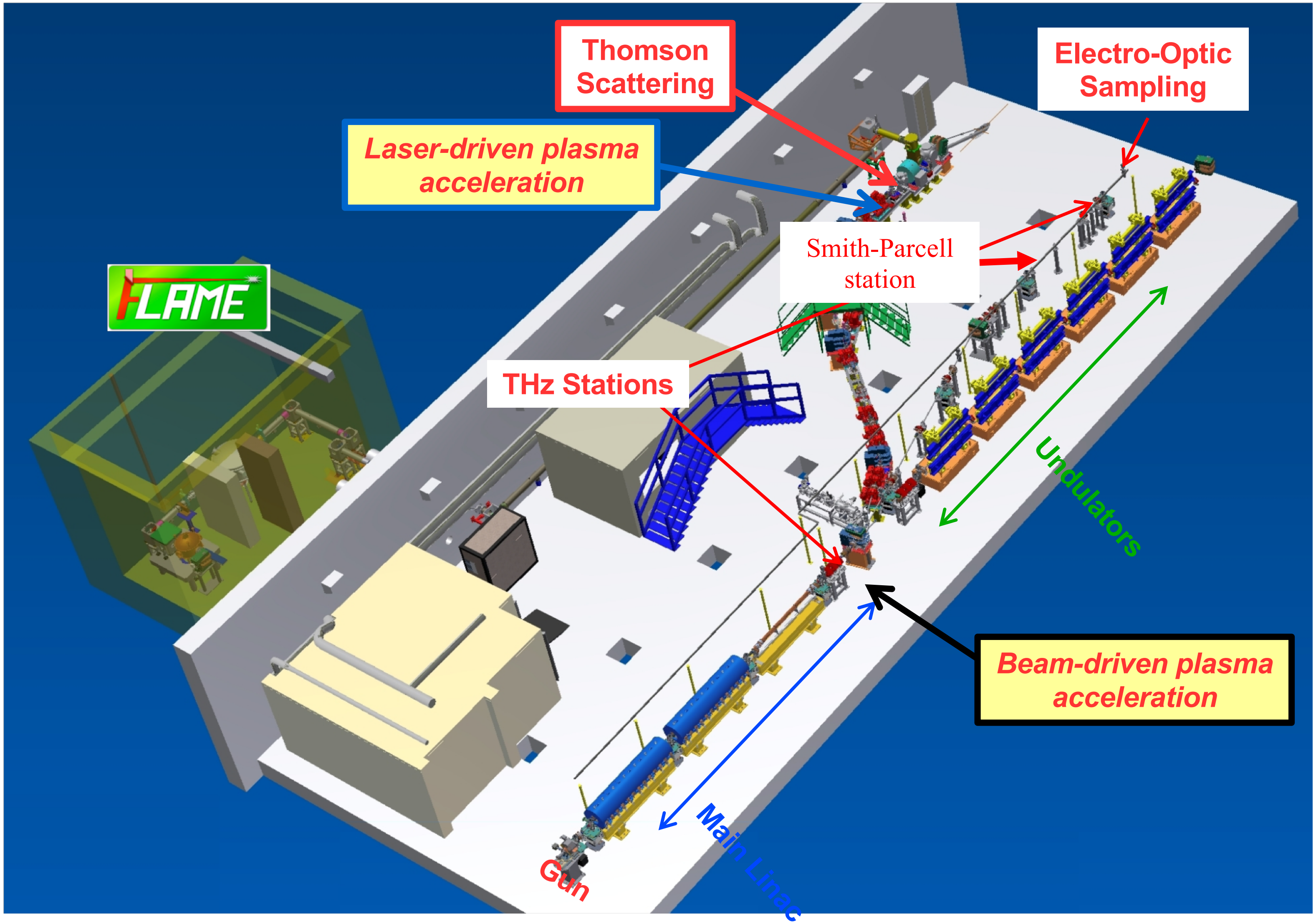
Cristina Vaccarezza

On behalf of SPARC_LAB collaboration

Outline

- The SPARC_LAB facility
- SPARC_LAB for EuPRAXIA
  - Design principles
  - S2E simulations
- Experimental Activities update:
  - Plasma lens experiment
  - Longitudinal Phase-Space Manipulation with BD Plasma Wakefields
  - Plasma density measurements and tapered capillaries
  - Plasma ramps
  - Laser Guiding setup and first results

SPARC_LAB Facility

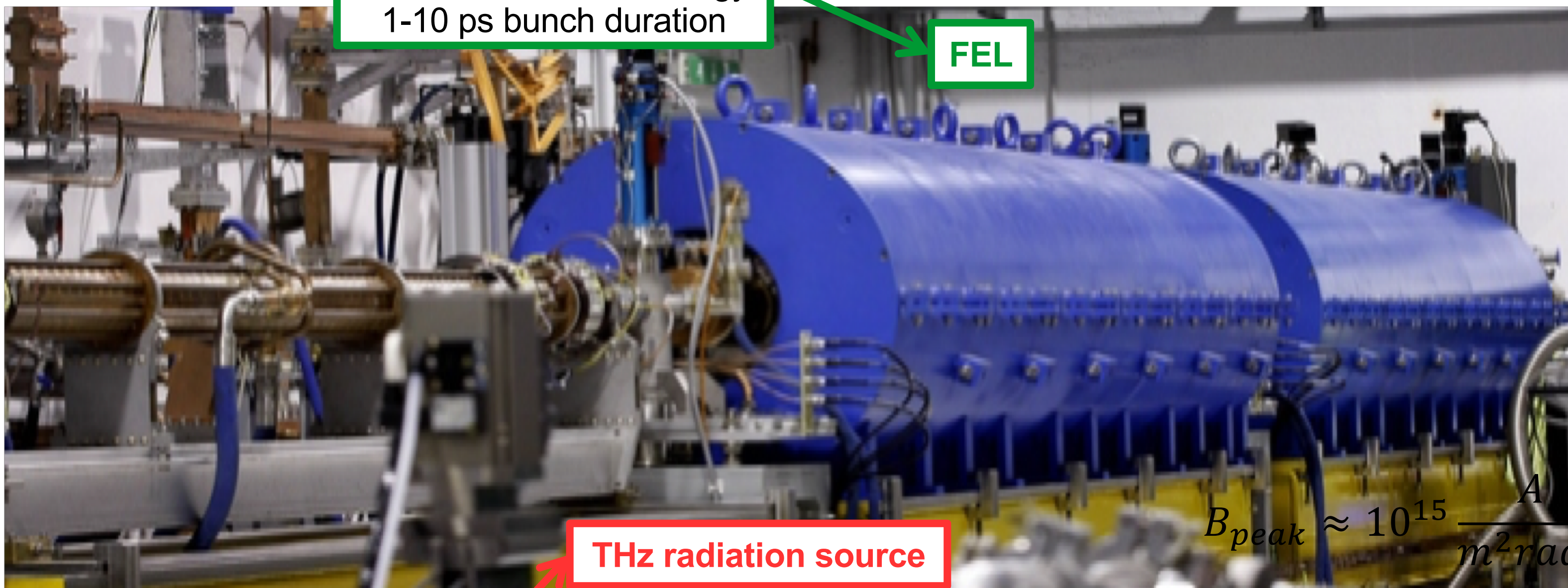


Ferrario, M., et al. "SPARC_LAB present and future." NIMB 309 (2013): 183-188.

High Brightness PhotoInjector

Low-current operation
30-170 MeV beam energy
1-10 ps bunch duration

→ **Thomson source**
→ **FEL**



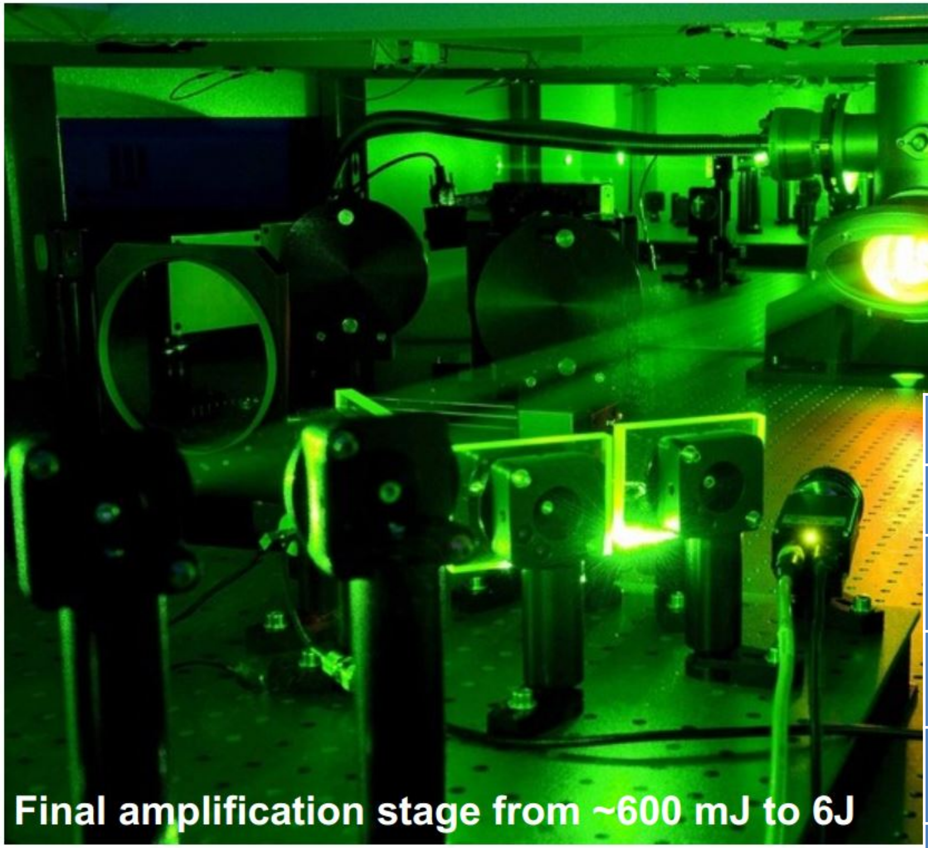
$$B_{peak} \approx 10^{15} \frac{A}{m^2 rad^2}$$

High-current operation (VB)
80-120 MeV beam energy
20 fs - 1 ps bunch duration

→ **THz radiation source**
→ **FEL (single spike + seeding)**
→ **Multi-bunch trains**
  → **Narrowband THz**
  → **FEL (2 colors)**
  → **PWFA (w/ resonant scheme)**
→ **LWFA (external injection)**

Serafini L., Ferrario M. "Velocity bunching in photo-injectors." AIP conference proceedings. 2001.
Anderson, S. G., et al. "Velocity bunching of high-brightness electron beams." PRSTAB 8.1 (2005): 014401.

The FLAME laser: parameters on target

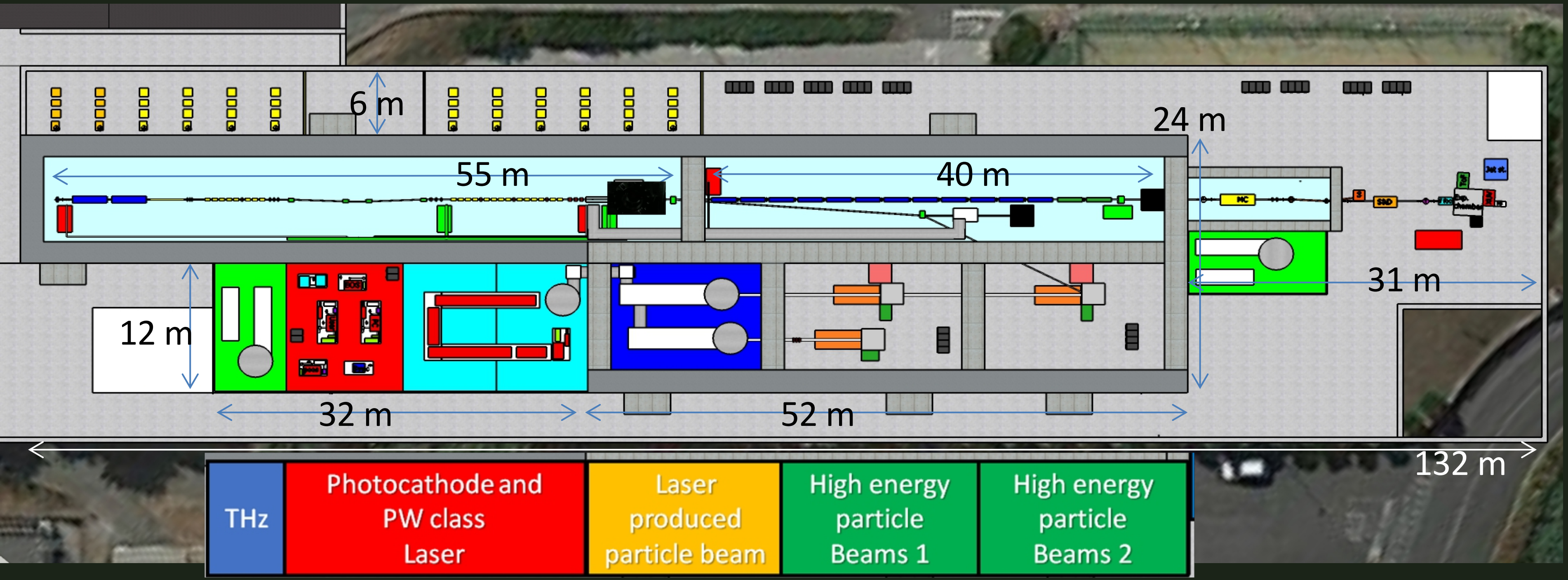


FLAME laser final amplifier.

Energy on target	4 J
Central wavelength	800 nm
Spectral bandwidth (FWHM)	70 nm
Spot size at focus (1/e^2 radius)	15 um
Temporal duration (FWHM)	25 fs
Peak Power	> 150 TW
Intensity	$5 * 10^{19}\ W/cm^2$
Contrast Ratio (@ 100 ps)	10^9

EuPRAXIA@SPARC_LAB

- Candidate LNF to host EuPRAXIA (1-5 GeV)
- FEL user facility (1 GeV – 3nm)
- Advanced Accelerator Test facility (LC) + CERN



- 500 MeV by RF Linac + 500 MeV by Plasma (LWFA or PWFA)
- 1 GeV by X-band RF Linac only
- Final goal compact 5 GeV accelerator

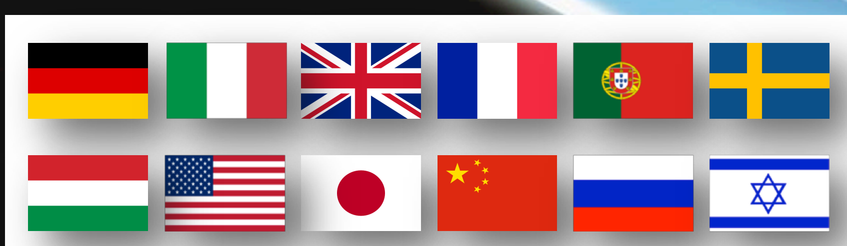
EUROPEAN
PLASMA RESEARCH
ACCELERATOR WITH
EXCELLENCE IN
APPLICATIONS

EuPRAXIA

EuPRAXIA Design Study started on November 2015

Approved as HORIZON 2020 INFRADEV, 4 years, 3 M€

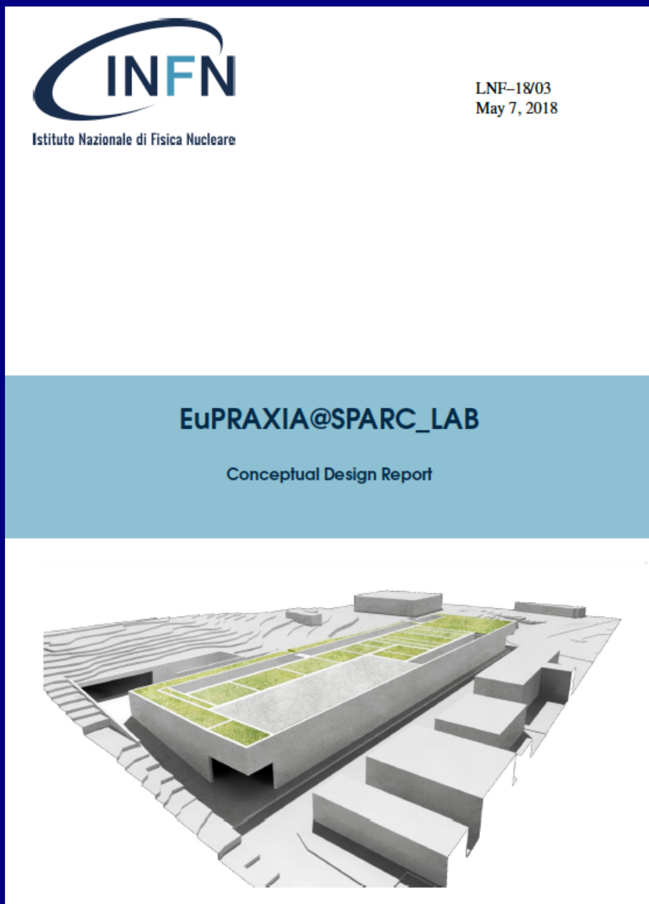
Coordinator: Ralph Assmann (DESY)



http://eupraxia-project.eu

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 653782.

Conceptual Design Report Ready for the LNF site


INFN
Istituto Nazionale di Fisica Nucleare

LNF–18/03
May 7, 2018

EuPRAXIA@SPARC_LAB

Conceptual Design Report

- D. Alesini, M. P. Anania, R. Bedogni, M. Bellaveglia, A. Biagioni, F. Bisesto, E. Brentegani, B. Buonomo, P.L. Campana, G. Campogiani, S. Cantarella, F. Cardelli, M. Castellano, E. Chiadroni, R. Cimino, R. Clementi, M. Croia, A. Curcio, G. Costa, S. Dabagov, M. Diomede, A. Drago, D. Di Giovenale, G. Di Pirro, A. Esposito, M. Ferrario, F. Filippi, O. Frasciello, A. Gallo, A. Ghigo, A. Giribono, S. Guiducci, S. Incremona, F. Iungo, V. Lollo, A. Marcelli, A. Marocchino, V. Martinelli, A. Michelotti, C. Milardi, L. Pellegrino, L. Piersanti, S. Pioli, R. Pompili, R. Ricci, S. Romeo, U. Rotundo, L. Sabbatini, O. Sans Plannell, J. Scifo, B. Spataro, A. Stecchi, A. Stella, V. Shpakov, C. Vaccarezza, A. Vannozzi, A. Variola, F. Villa, M. Zobov.
- **INFN - Laboratori Nazionali di Frascati**
- A. Bacci, F. Broggi, C. Curatolo, I. Debrot, A. R. Rossi, L. Serafini. **INFN - Sezione di Milano**
- D. Cirrincione, A.Vacchi. **INFN - Sezione di Trieste**
- G. A. P. Cirrone, G. Cuttone, V. Scudieri. **INFN - Laboratori Nazionali del Sud**
- M. Artioli, M.Carpanese, F.Ciocci, D.Dattoli, S.Licciardi, F.Nguyen, S. Pagnutti, A.Petralia, E. Sabia. **ENEA – Frascati and Bologna**
- L. Gizzi, L. Labate. **CNR - INO, Pisa**
- R. Corsini, A. Grudiev, N. Catalan Lasheras, A. Latina, D. Schulte, W. Wuensch. **CERN, Geneva**
- C. Andreani, A. Cianchi, G. Festa,V. Minicozzi, S. Morante, R. Senesi, F. Stellato. **Universita' degli Studi di Roma Tor Vergata and Sezione INFN**
- V. Petrillo, M. Rossetti. **Universita' degli Studi di Milano and Sezione INFN**
- G. Castorina, L. Ficcadenti, S. Lupi, M. Marongiu, F. Mira, A. Mostacci. **Universita' degli Studi di Roma Sapienza and Sezione INFN**
- S. Bartocci, C. Cannaos, M. Faiferri, R. Manca, M. Marini, C. Mastino, D. Polese, F. Pusceddu, E. Turco. **Università degli Studi di Sassari, Dip. di Architettura, Design e Urbanistica ad Alghero**
- M. Coreno, G. D'Auria, S. Di Mitri, L. Giannessi, C. Masciovecchio. **ELETTRA Sincrotrone Trieste**
- A. Ricci. **RICMASS, Rome International Center for Materials Science Superstripes**
- A. Zigler. **Hebrew University of Jerusalem** J. B. Rosenzweig. **University of California Los Angeles**

http://www.lnf.infn.it/sis/preprint/pdf/getfile.php?filename=INFN-18-03-LNF.pdf

Free Electron Laser design principles

	Units	Full RF case	Plasma case
Electron Energy	GeV	1	1
Bunch Charge	pC	200	30
Peak Current	kA	2	3
RMS Energy Spread	%	0.1	1
RMS Bunch Length	fs	40	4
RMS matched Bunch Spot	µm	34	34
RMS norm. Emittance	µm	1	1
Slice length	µm	0.5	0.45
Slice Energy Spread	%	0.01	0.1
Slice norm. Emittance	µm	0.5	0.5
Undulator Period	mm	15	15
Undulator Strength K		1.03	1.03
Undulator Length	m	12	14
Gain Length	m	0.46	0.5
Pierce Parameter ρ	x 10^{-3}	1.5	1.4
Radiation Wavelength	nm	3	3
Undulator matching β_u	m	4.5	4.5
Saturation Active Length	m	10	11
Saturation Power	GW	4	5.89
Energy per pulse	µJ	83.8	11.7
Photons per pulse	x 10^{11}	11	1.5

Table 2.1: Beam parameters for the EuPRAXIA@SPARC_LAB FEL driven by X-band linac or Plasma acceleration

Driver S2E

Bunch parameters				
bunch	Q [pC]	σ_x [μm]	σ_z [μm]	ϵ_x [mm mrad]
Driver	200	4	75	3
Witness	25–30	1.5	6	1

Plasma parameters		
n_0 [cm^{-3}]	λ_p [μm]	k_p [μm^{-1}]
10^{16}	334	0.02

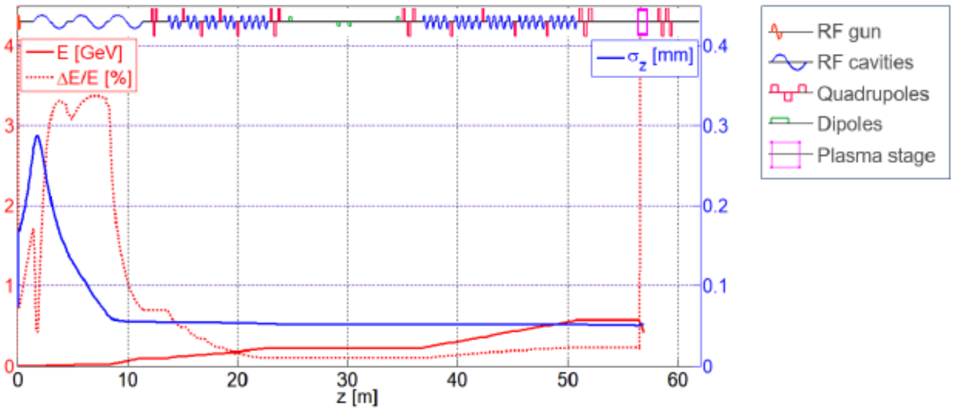
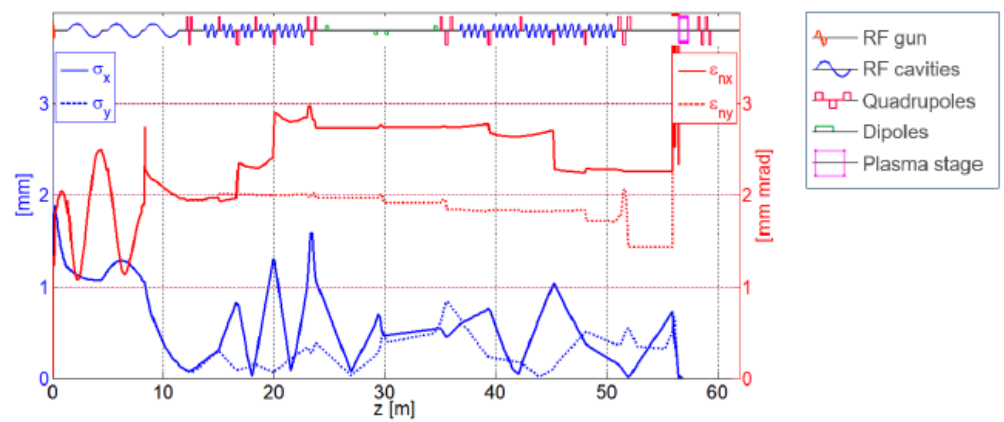


Figure 4.7: Start to end simulation results for the driver bunch for the PWFA case: evolution along the injector of the energy (E red line) and energy spread ($\Delta E/E$ red dotted-line) and longitudinal bunch length (σ_z blue line).



Sim. chain: Tstep => Elegant=> Architect => Elegant=> Genesis

Witness S2E

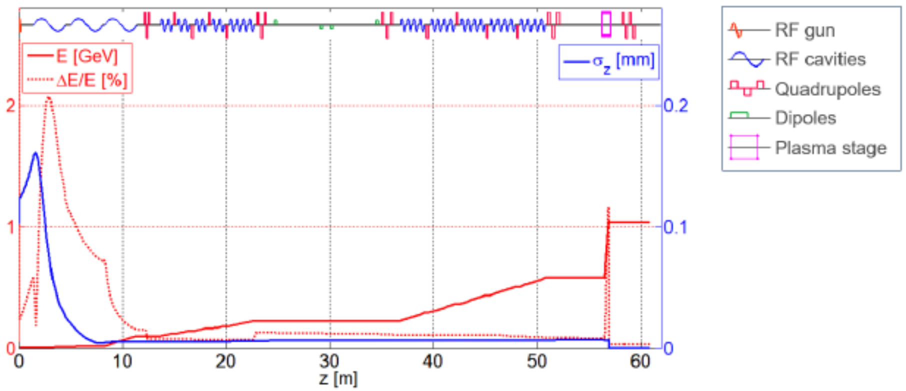
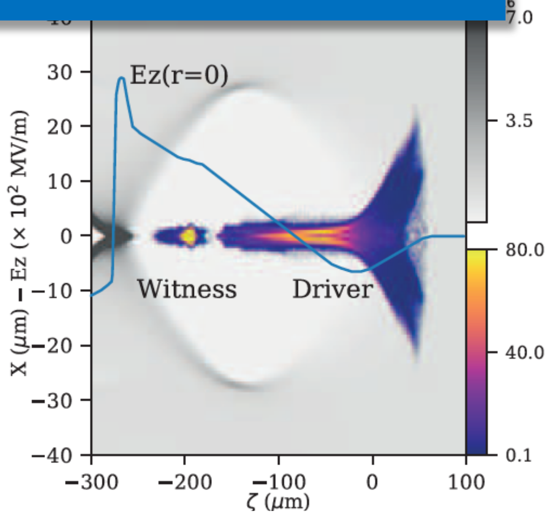
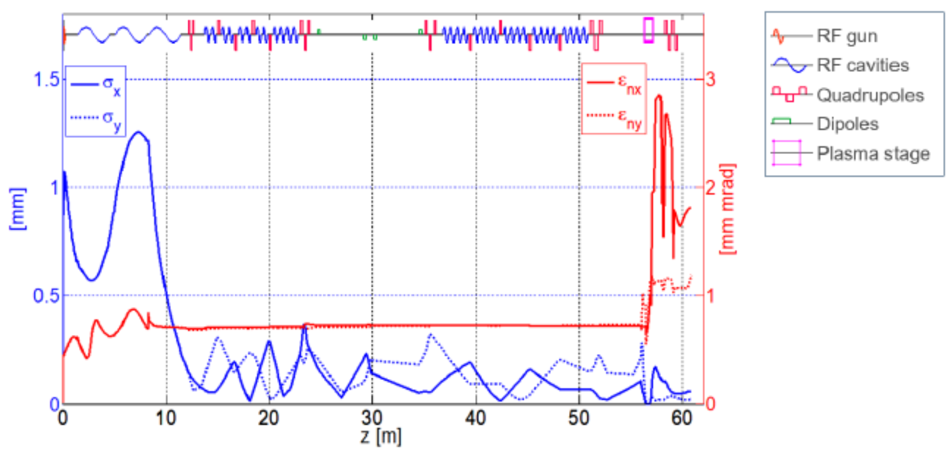
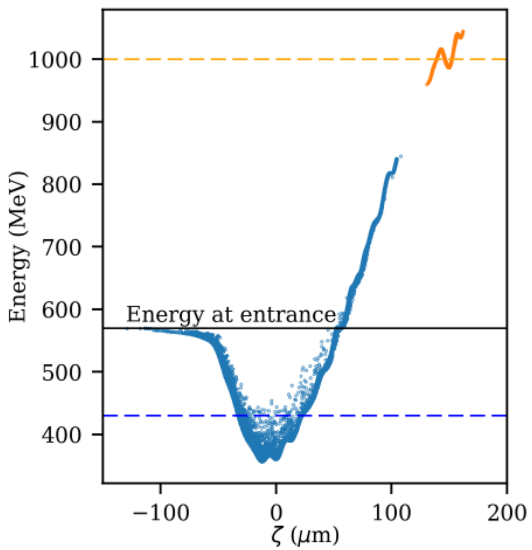


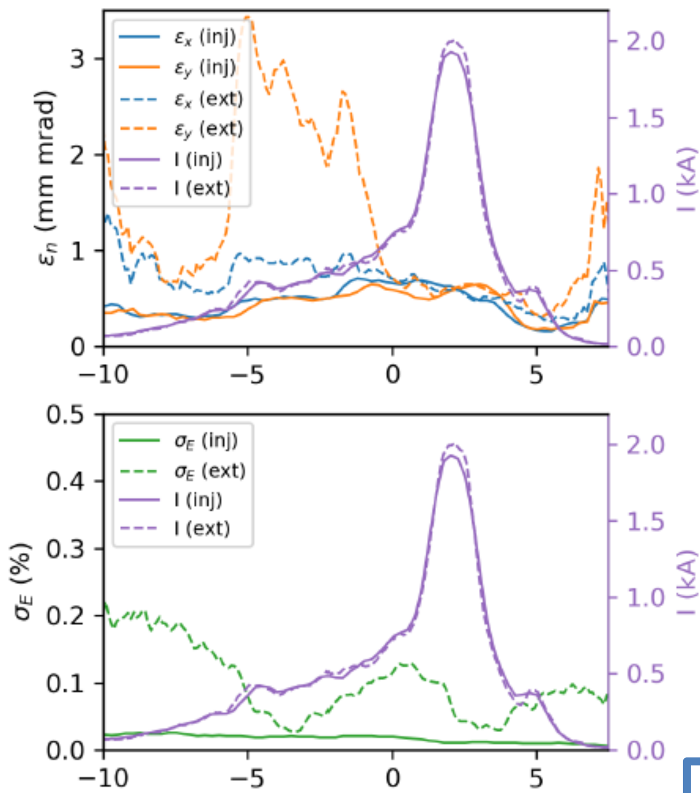
Figure 4.5: Start to end simulation results for the trailing bunch for the PWFA case: evolution along the injector of the energy (E red line) and energy spread ($\Delta E/E$ red dotted-line) and longitudinal bunch length (σ_z blue line).







Plasma Exit: Rolling Slice analysis



$$L_s = \frac{\lambda_r}{2\sqrt{3}\rho} \approx 1\ \mu m$$

Figure 7.12: Rolling slice analysis for the witness bunch at plasma input, dashed line, and at plasma exits, solid line. The top panel report the emittance in both transverse plane and the current. The bottom panel plots the energy spread together with the current. The corresponding current axis is the left y axis.

FEL Simulations (Genesis)

Beam	units	Driver-IN	Driver-OUT	Witness-IN	Witness-OUT
Charge	pC	200	200	30	30
σ_x	µm	8	6.4	1.47	1.42
					1.4
					3.8
					0.96
					1.2
					1.1
					1030

	Best Slic
2.0	current
0.57	ε_x
0.62	ε_y
0.034	σ_E

'he best slice value is

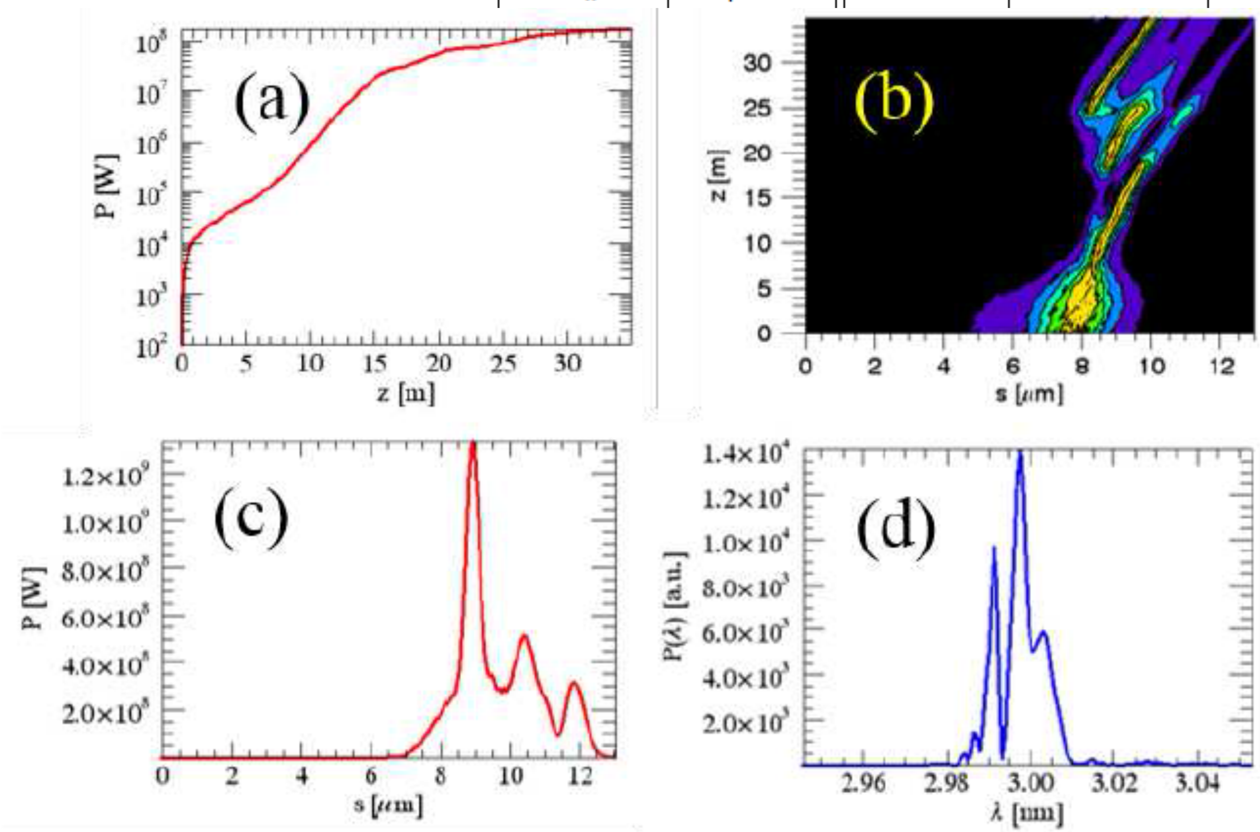


Figure 7.18: Particle driven acceleration: (a) Radiation growth along the undulator coordinate z(m). (b): Contour plot of the power P in the plane (s,z). (c) Power and (d) spectrum of the radiation at 30 m.

EuPraxia@SPARC_LAB summary table

	Units	Full RF case	LWFA case	PWFA case
Electron Energy	GeV	1	1	1
RMS Energy Spread	%	0.05	2.3	1.1
Peak Current	kA	1.79	2.26	2.0
Bunch Charge	pC	200	30	30
RMS Bunch Length	µm (fs)	16.7 (55.6)	2.14 (7.1)	3.82 (12.7)
RMS normalized Emittance	mm mrad	0.5	0.47	1.1
Slice Length	µm	1.66	0.5	1.2
Slice Charge	pC	6.67	18.7	8
Slice Energy Spread	%	0.02	0.03	0.034
Slice normalized Emittance (x/y)	mm mrad	0.35/0.24	0.45/0.465	0.57/0.615
Undulator Period	mm	15	15	15
Undulator Strength $K(a_w)$		0.978 (0.7)	1.13 (0.8)	1.13 (0.8)
Undulator Length	m	30	30	30
Pierce parameter ρ (1D/3D)	$\times 10^{-3}$	1.55/1.38	2/1.68	2.5/1.8
Radiation Wavelength	nm (keV)	2.87 (0.43)	2.8 (0.44)	2.98 (0.42)
Photon Energy	µJ	177	40	6.5
Photon per pulse	$\times 10^{10}$	255	43	10
Photon Bandwidth	%	0.46	0.4	0.9
Photon RMS Transverse Size	µm	200	145	10
Photon Brilliance per shot	(s mm^2 mrad^2 bw(0.1%))$^{-1}$	1.4×10^{27}	1.7×10^{27}	0.8×10^{27}

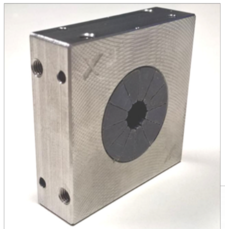
Table 4.1: Beam parameters from start-to-end simulations for full RF and for plasma wakefield acceleration cases with electron (PWFA) or laser (LWFA) driver beam

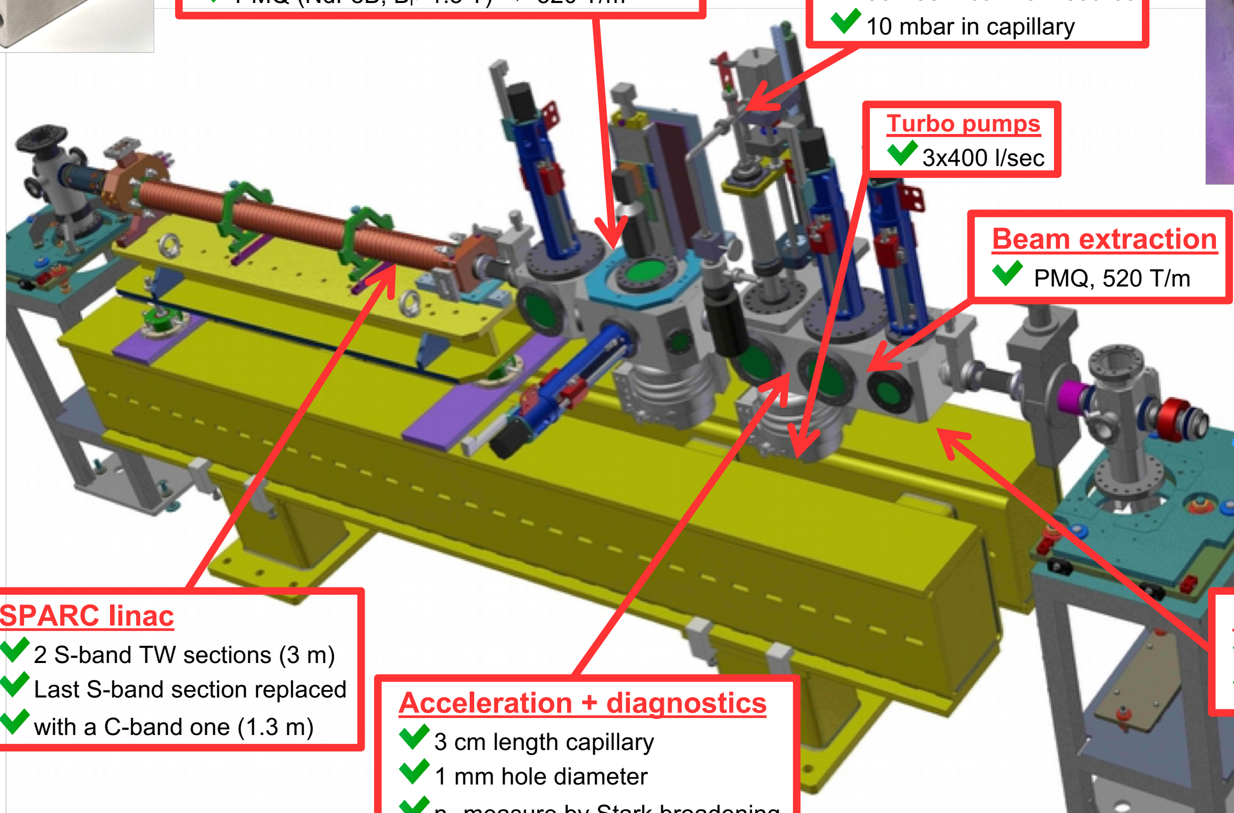
SPARC_LAB activity

SPARC LAB

INFN
Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

PFWA Experimental setup





Beam injection
- ✔ Longitudinal diagnostics (EOS)
- ✔ Transverse diagnostics (Ce:YAG screen)
- ✔ PMQ (NdFeB, B_r>1.3 T) → 520 T/m

Hydrogen inlet
- ✔ 50-100 mbar from source
- ✔ 10 mbar in capillary

Turbo pumps
- ✔ 3x400 l/sec

Beam extraction
- ✔ PMQ, 520 T/m

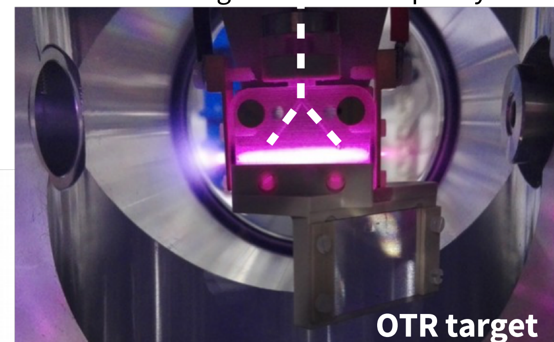
SPARC linac
- ✔ 2 S-band TW sections (3 m)
- ✔ Last S-band section replaced with a C-band one (1.3 m)

Acceleration + diagnostics
- ✔ 3 cm length capillary
- ✔ 1 mm hole diameter
- ✔ n_0 measure by Stark broadening

Beam diagnostics
- ✔ Transverse diagnostics (Ce:YAG screen)
- ✔ THz station (CTR/CDR)

to FEL

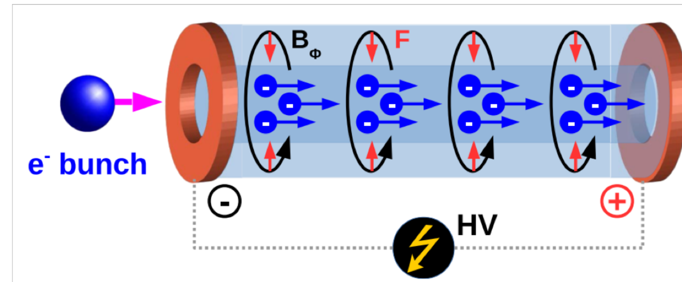
Plasma generation in capillary



Active Plasma lens: how it works

R. Pompili

- Discharge-current flowing in a gas-filled capillary
  - The gas acts like a conductor between the two electrodes
  - By the Ampere law, an azimuthal magnetic field is induced
    - It radially grows across the current and decreases outside of it
  - The capillary radially confine the gas and, thus, the current



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

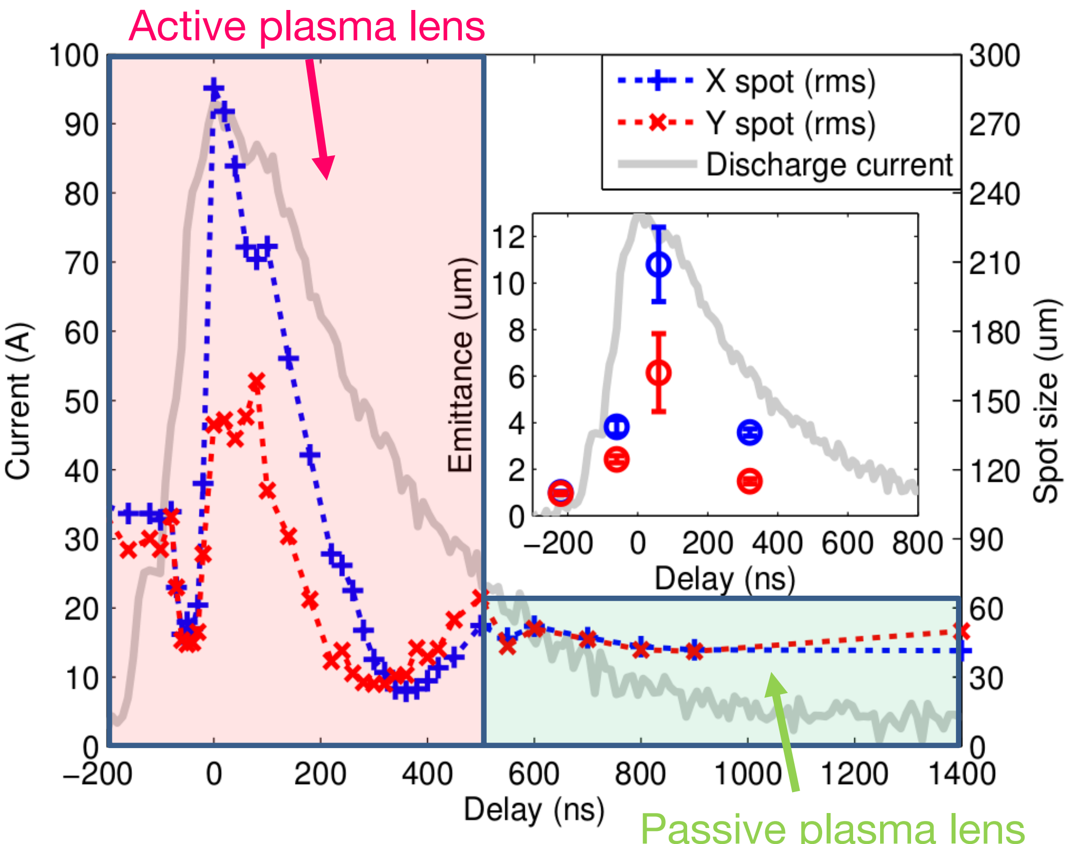
- Benefits
  - Cylindrical symmetry in focusing (like solenoids)
  - Favorable focusing strength K~1/γ (like quadrupoles)
  - Large focusing gradients (~ kT/m) → short focal length
  - Tunability by adjusting the current amplitude

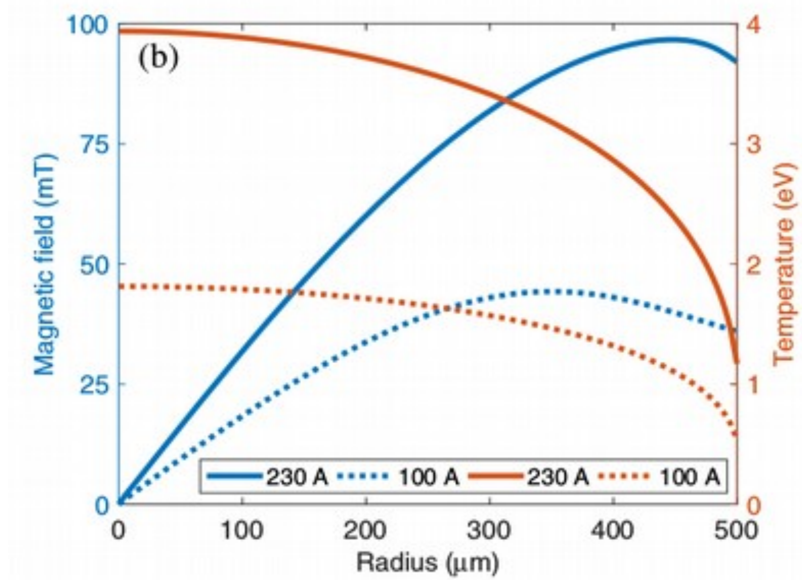
Similar to "passive" lenses

This is the real added value!

Panofsky, Wolfgang Kurt Hermann, and W. R. Baker.
"A Focusing Device for the External 350-Mev Proton Beam of the 184-Inch Cyclotron at Berkeley."
Review of Scientific Instruments 21.5 (1950): 445-447.

ActivePlasma Lens: Results at SPARC_LAB



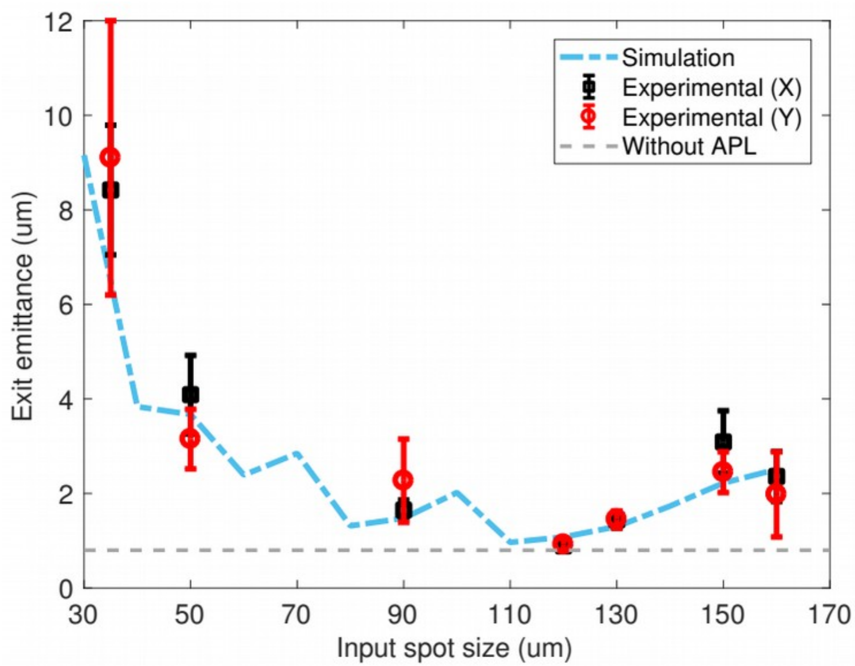


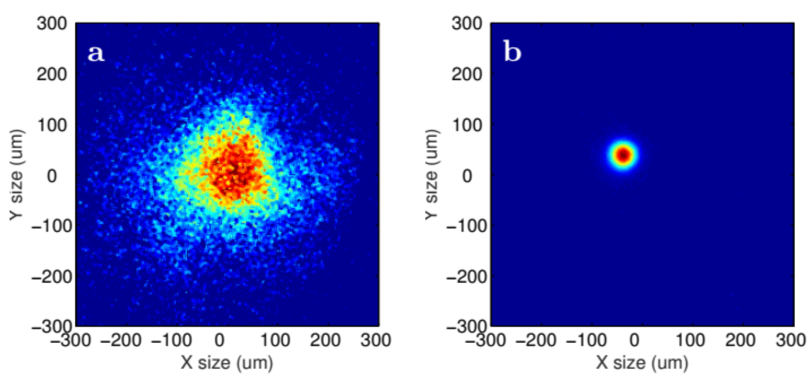
Beam quality dependencies:

- ✓ *current distribution → non-linear focusing (aberrations at the edges)*
- ✓ *passive plasma lens effects*
- ✓ *size of the beam at the injection into the lens*

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

ActivePlasma Lens: more on beam quality preservation





Demonstration of the beam emittance preservation

- ✓ *amplitude of the current was increased from 100 A to 250 A*
- ✓ *the optimal beam size at the injection to the capillary was $\sigma_{x,y} \approx 110\ \mu m$*
- ✓ *minimum spot size achieved at the screen located 20 cm downstream the lens was $\sigma_{x,y} \approx 17.5 \pm 0.3\ \mu m$ ($\sigma_{x,y} \approx 24 \pm 3\ \mu m$ for 100A discharge)*
- ✓ *the emittance of the beam prior the active plasma lens $\varepsilon_{x,y} \approx 0.8(0.5)\ \mu m$, after the lens $\varepsilon_{x,y} \approx 0.9\ \mu m$*

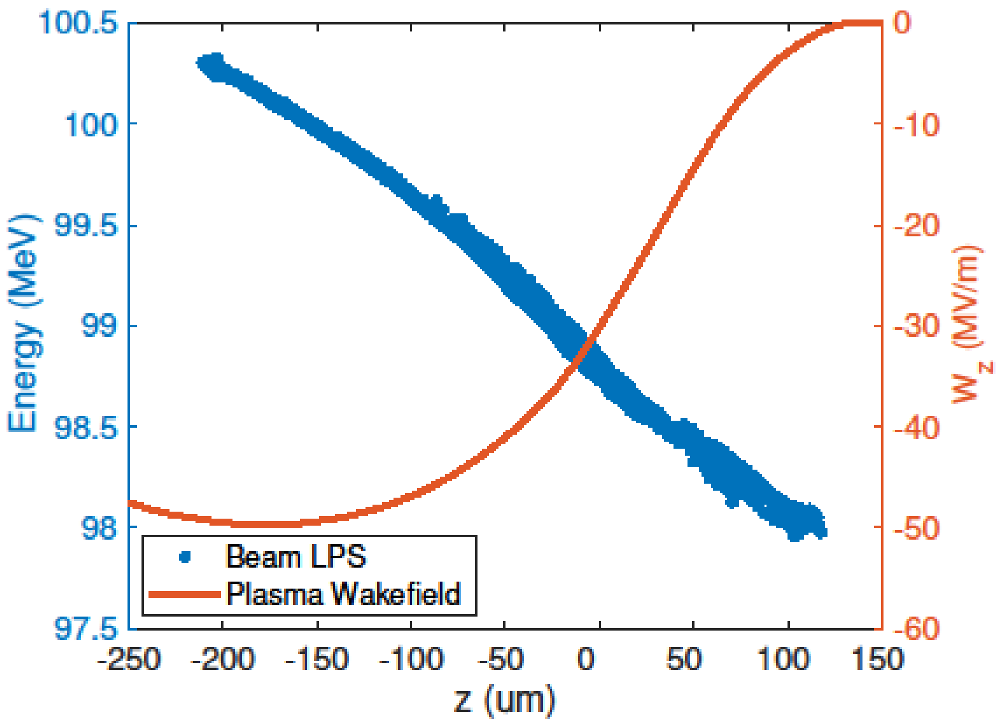
Conclusions on APL:

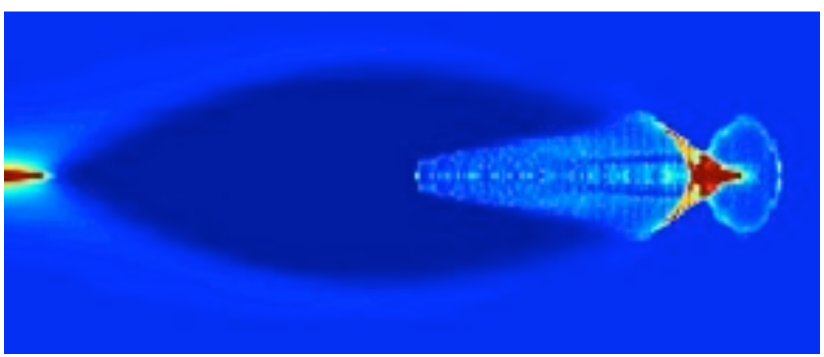
- ✓ *Active plasma lens favors higher peak current, due to the better linearity of the resulting magnetic field*
- ✓ *Low bunch densities ($n_b << n_p$) are preferable for preventing passive plasma lens effects*

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

Plasma dechirper: basic idea

V. Shpakov





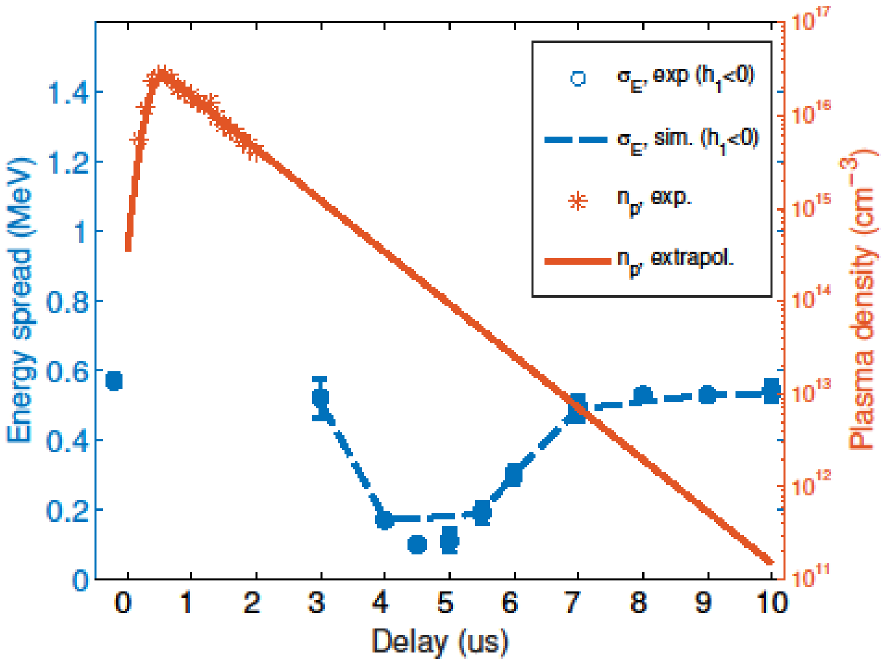
- **Longitudinal phase-space manipulation with the wakefield induced in plasma by the beam itself.**
  - ✓ *the large gradient that plasma can sustain (~ GV/m) allows to imprint or remove large energy correlation (chirp) from the beam by means of relatively short structures (~ cm).*
- **Large flexibility of the method, by varying parameters of the system:**
  - ✓ *plasma density (large density → large wake amplitude)*
  - ✓ *beam density (large density → large wake amplitude)*
  - ✓ *length of the plasma channel (cumulative effect)*
- **Applications:**
  - ✓ *energy-chirp removal (“dechirper”) for PWFA, LWFA*
  - ✓ *bunch compressors (dogleg/chicane beamlines)*

Shpakov V. *et al.* Physical Review Letters 122, 114801 (2019)

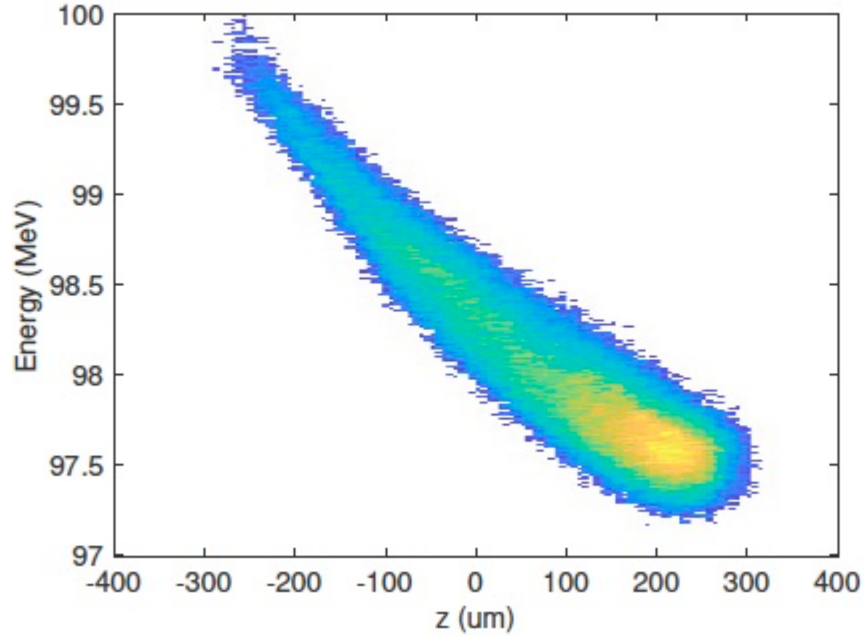
Editors' Suggestion

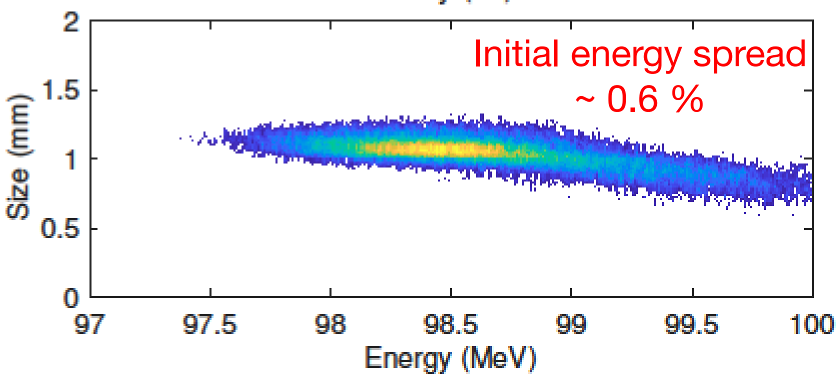
Plasma dechirper: experimental results

Energy spread (plasma density)



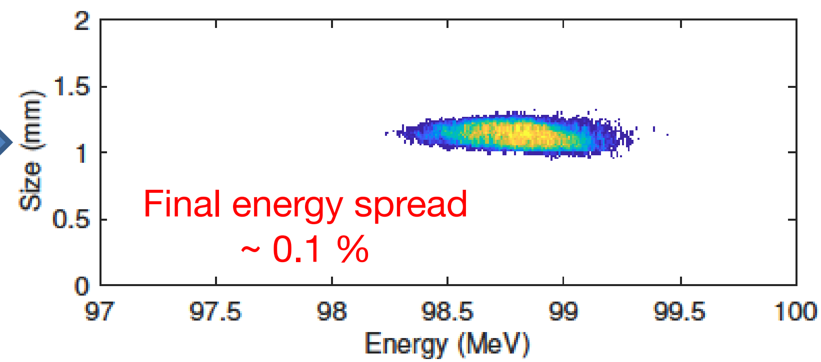
Beam LPS at the injection





Initial energy spread ~ 0.6 %

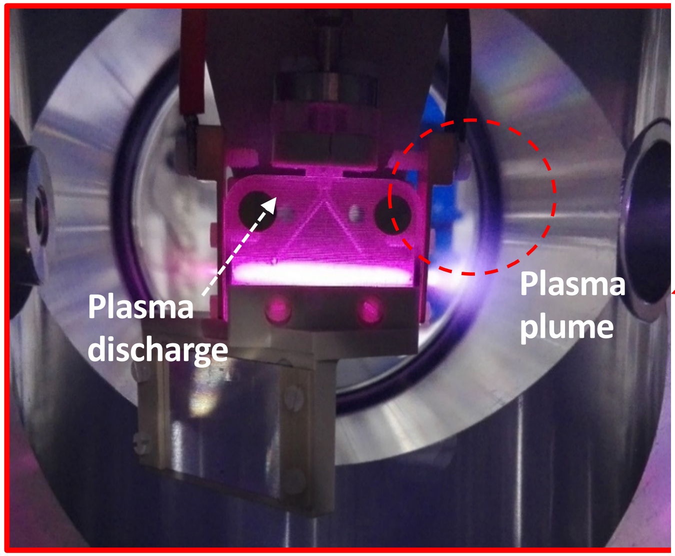
Dechirper

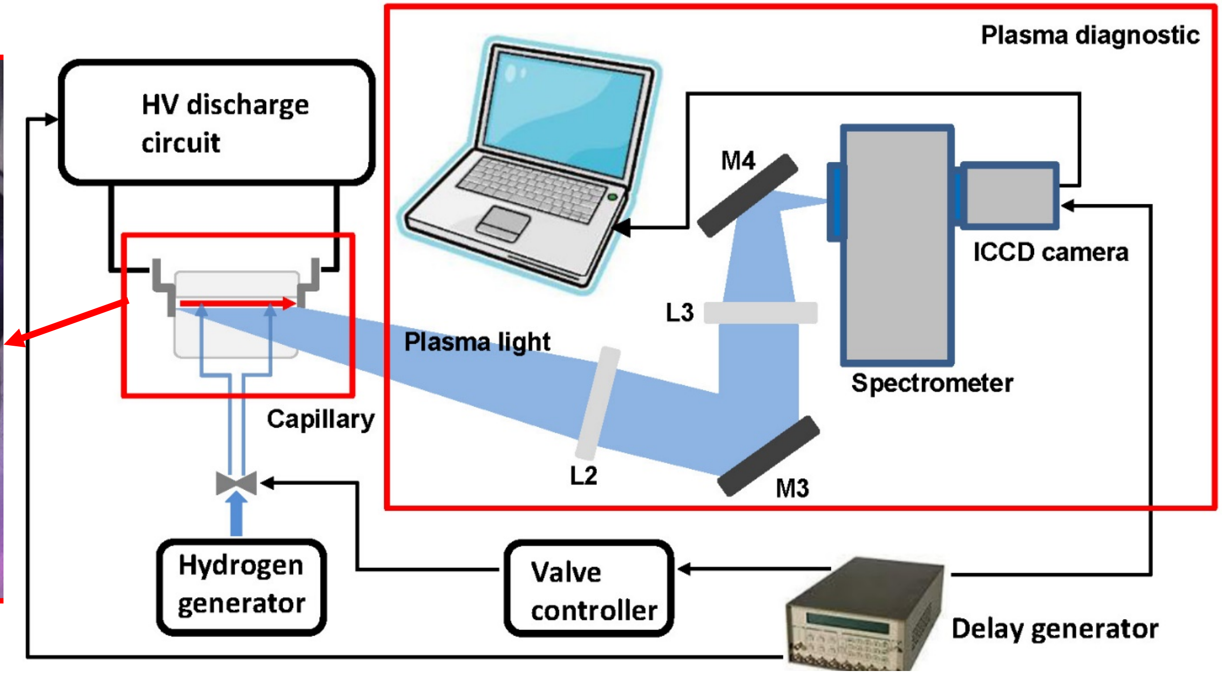


Final energy spread ~ 0.1 %

Experimental activity upon plasma capillaries

A. Biagioni

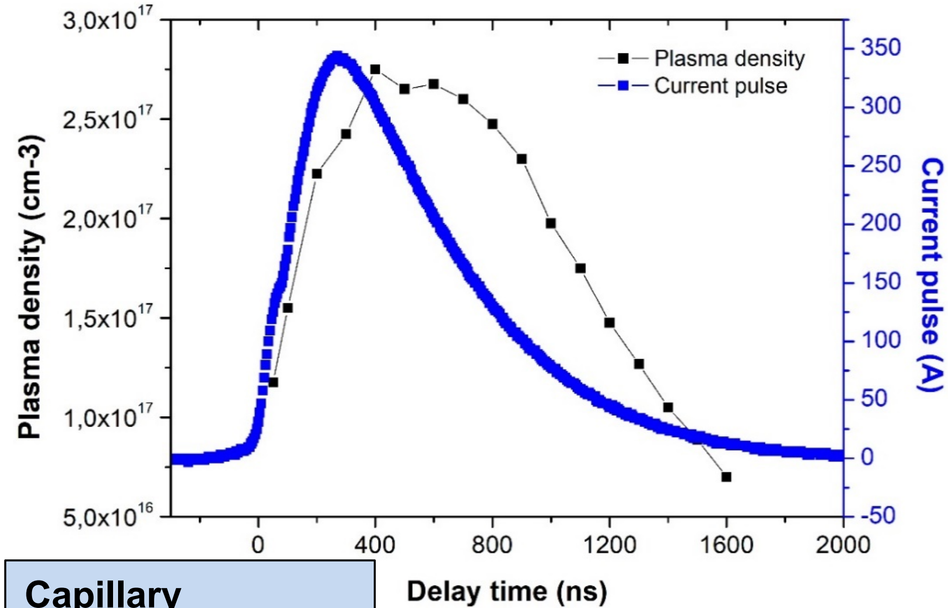




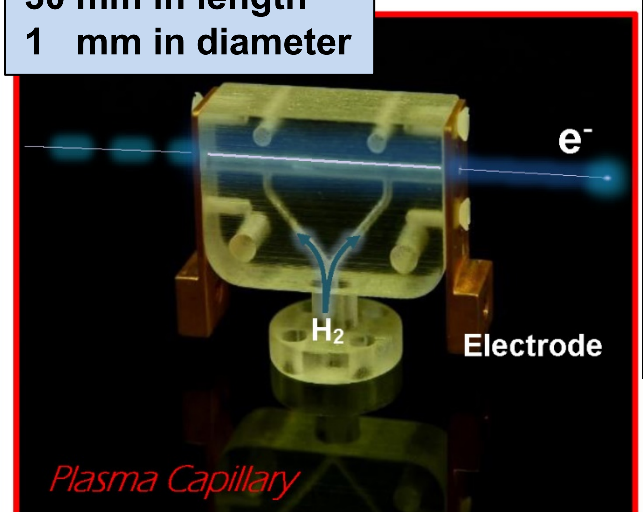
- Plasma capillary characterization (plasma density measurements both inside and outside capillary by using Stark broadening technique)
- Plasma capillary development for beam acceleration (tapered capillaries ecc)
- HV-circuit improvement to optimize plasma formation for beam acceleration and beam focusing

Plasma density measurements

Time-resolved measures



Capillary
30 mm in length
1 mm in diameter

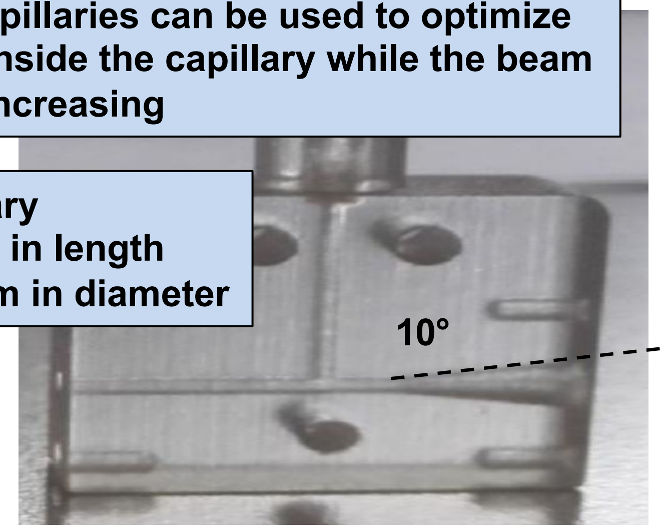


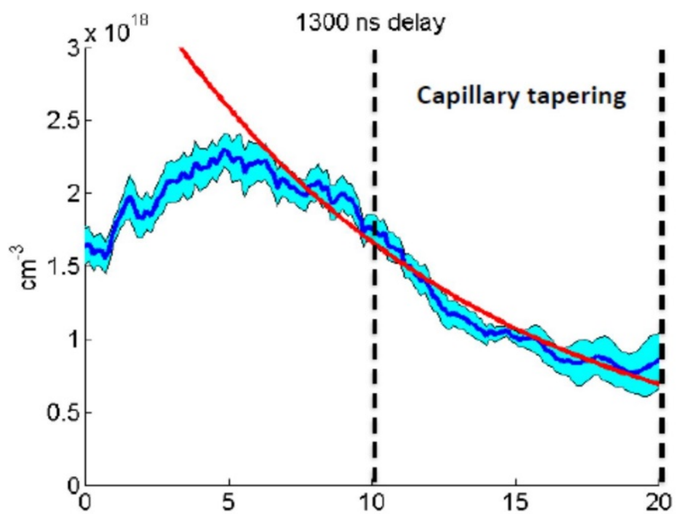
By using the Stark broadening method we measure plasma densities as a function of the delay time from the zero-time of the current pulse and for each one we obtain a longitudinal profile of the density itself

Space-resolved measures

Tapered capillaries can be used to optimize matching inside the capillary while the beam energy is increasing

Capillary
30 mm in length
0.5 mm in diameter



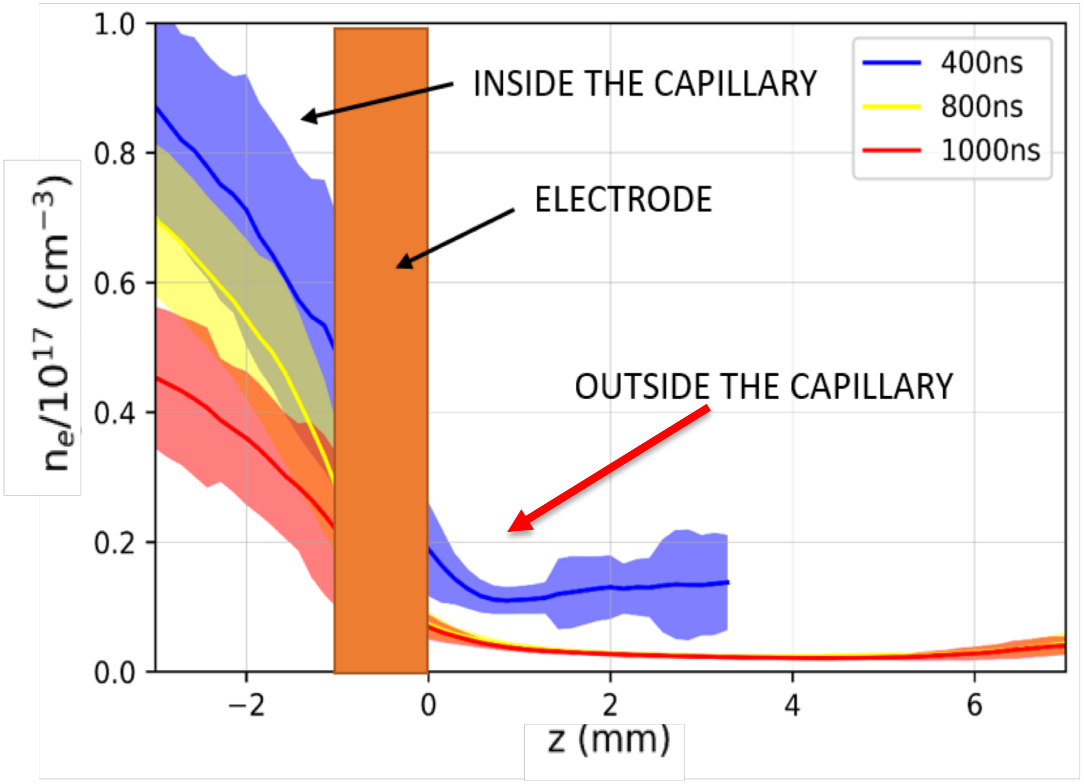


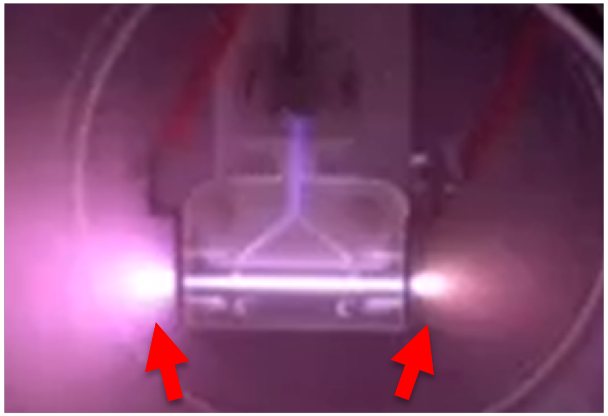
Filippi et al. NIMA(2018), DOI: 10.1016/j.nima.2018.04.037

Plasma Modules: plasma ramps

F. Filippi

Due to the outflow, the laser/particle beam(s) interact with a different plasma profile, undergoing to unwanted (if uncontrolled) effects on the beam dynamics.





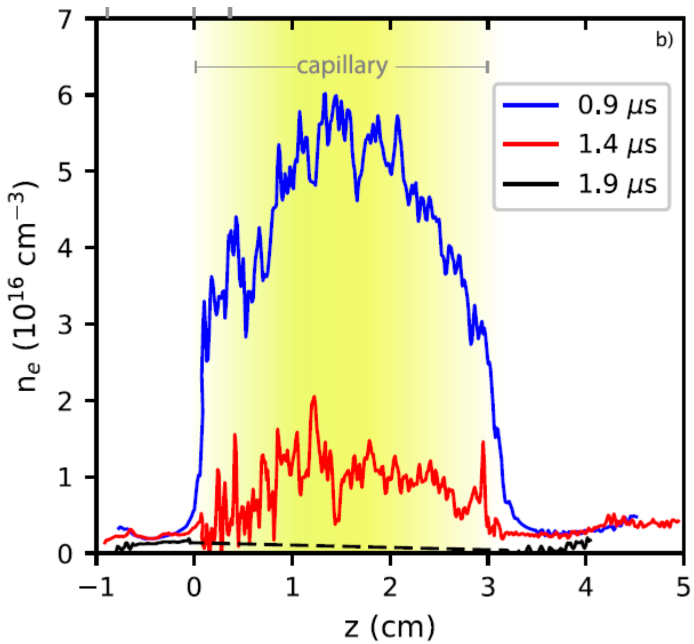
Almost constant plasma density outside the capillary of the order of 10^{15} cm^{-3}

Studies to mitigate the effects of the plasma ramps are on going.

F. Filippi et al. Nuclear Inst. and Methods in Physics Research, A 909 (2018) 346–34

Plasma ramps: emittance degradation

Experimental studies demonstrated that uncontrolled plasma ramps with wavenumber plasma density $k_p\ \sigma_z \approx 1$ causes emittance degradation.



It is possible to control the density ramp in order to mitigate negative effects.

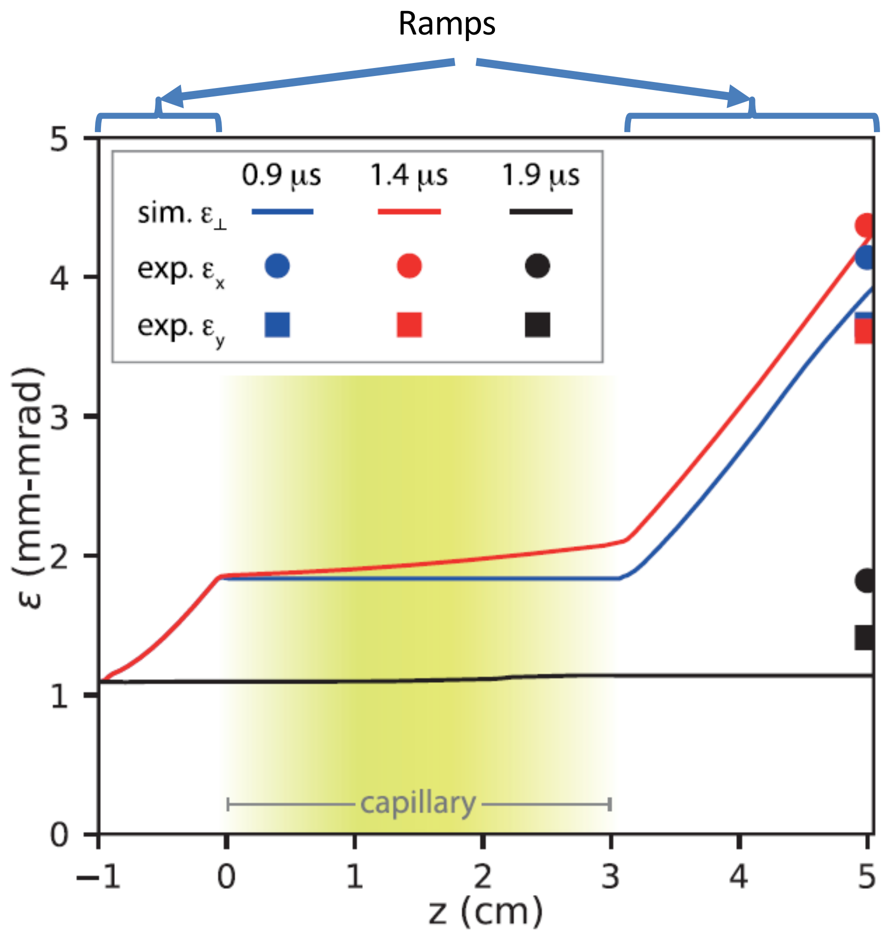


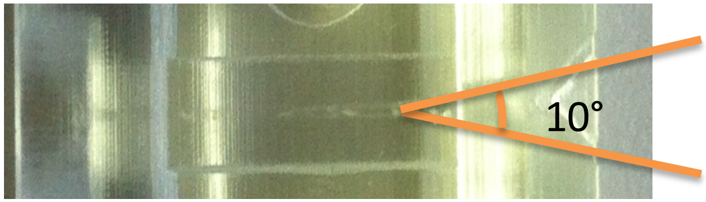
FIG. 5. Plot of the normalized transverse rms-emittance as a function of z. The numerically computed emittance is plotted with a solid line, and the experimental values are reported on the right edge. The ε_x experimentally measured quantities are reported with a circle and ε_y with a square.

Filippi et al. Nuclear Inst. and Methods in Physics Research, A 909 (2018) 346–34
Marocchino et al. Applied Physics Letters (2017), 111(18):184101

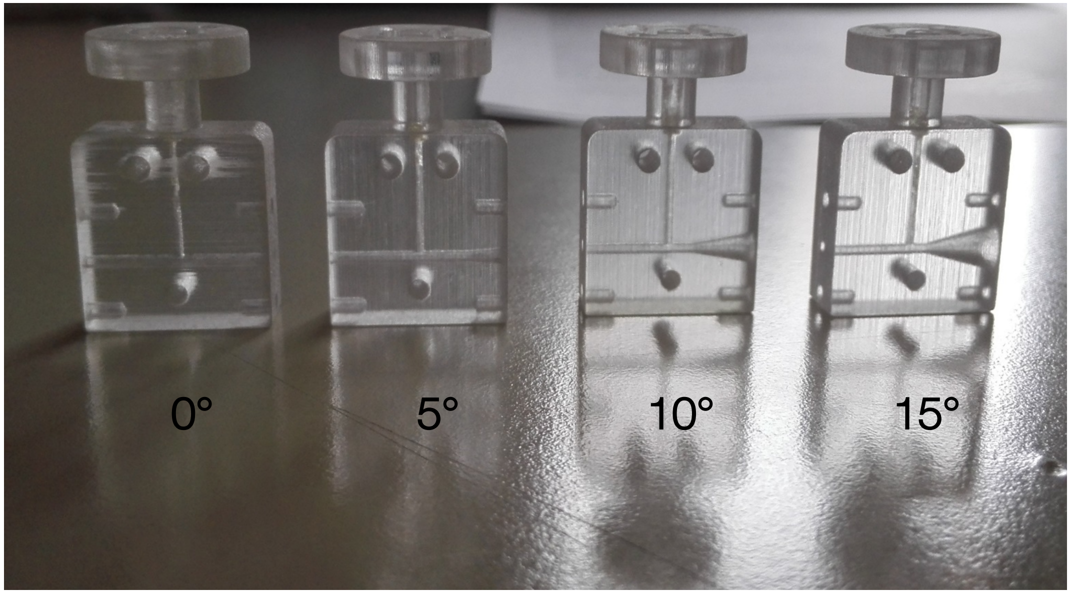
Tapered capillaries

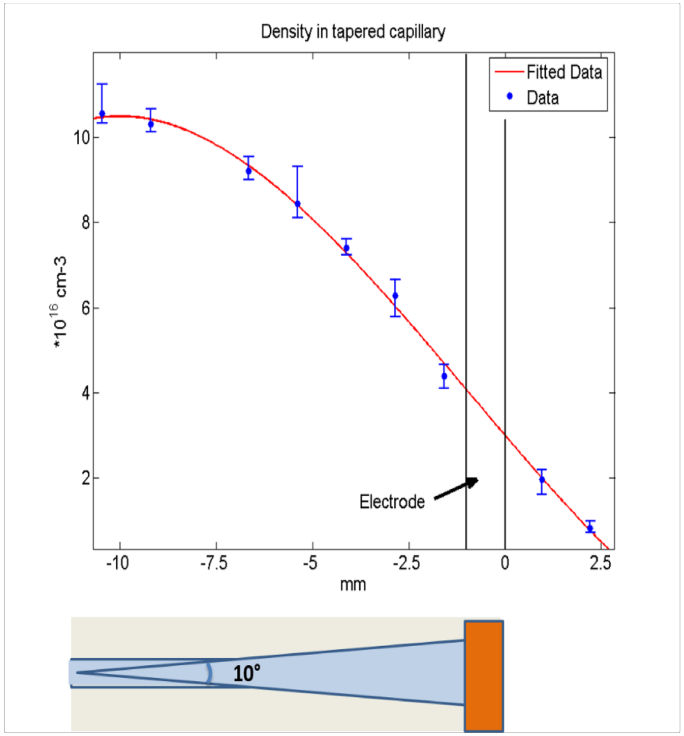
The local control of the plasma density helps to match the laser/electron beam into the plasma. Tapering the capillary diameter is the easiest way to change locally the density.

By monotonically varying the radius of the capillary it is possible to change the density.



Kaganovich et al., Appl. Phys. Lett. 75, 772–774 (1999).

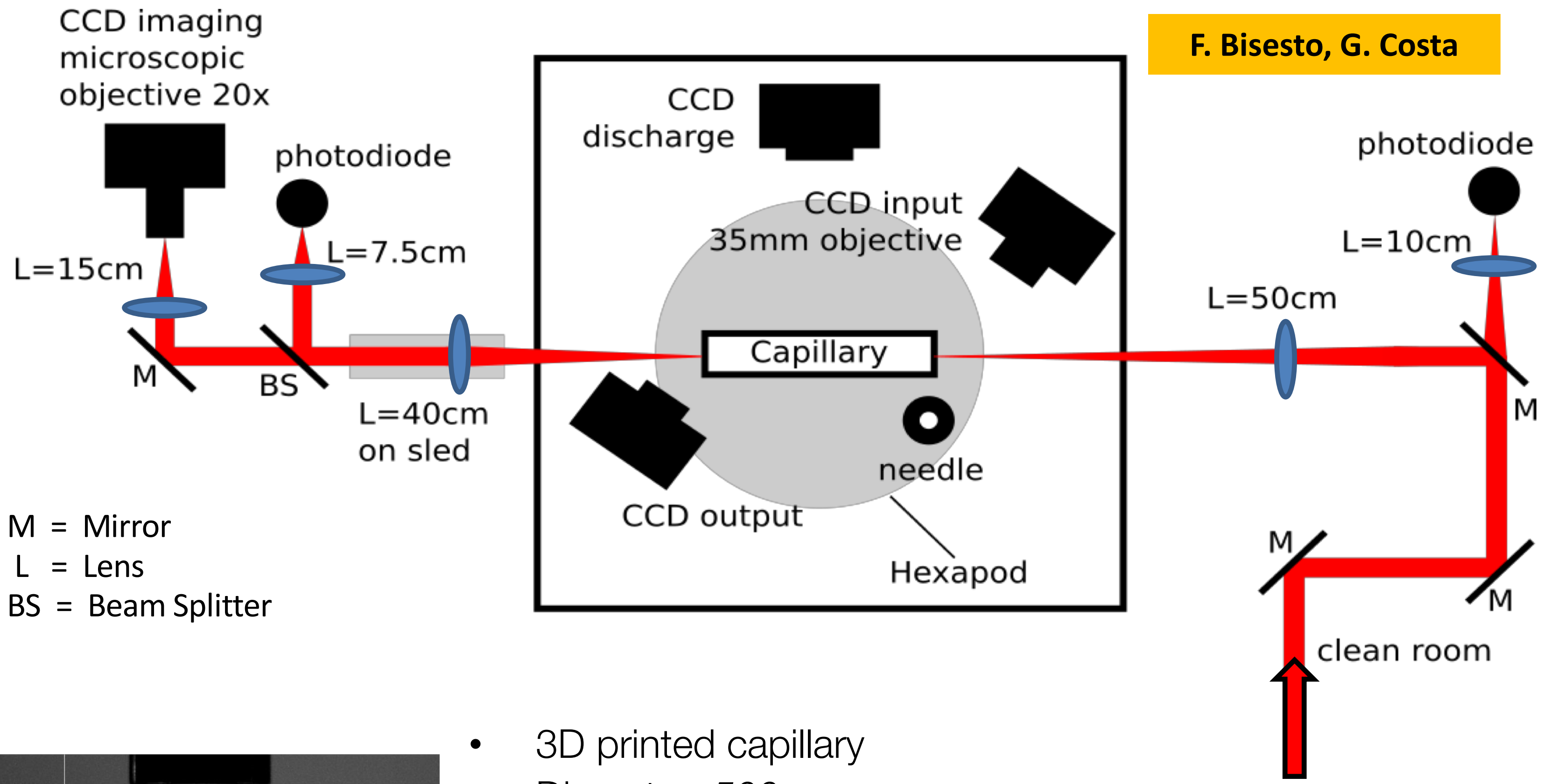




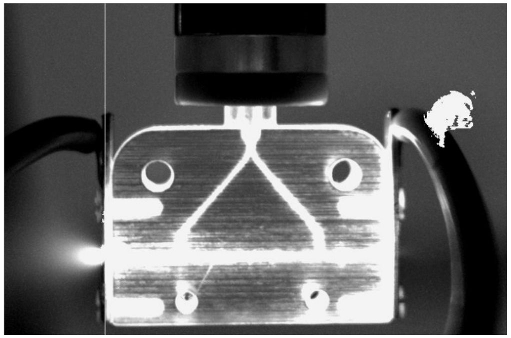
Studies on plasma tapering are currently in progress in the SPARC_LAB Plasma lab.

Optical setup for laser guiding activity

F. Bisesto, G. Costa

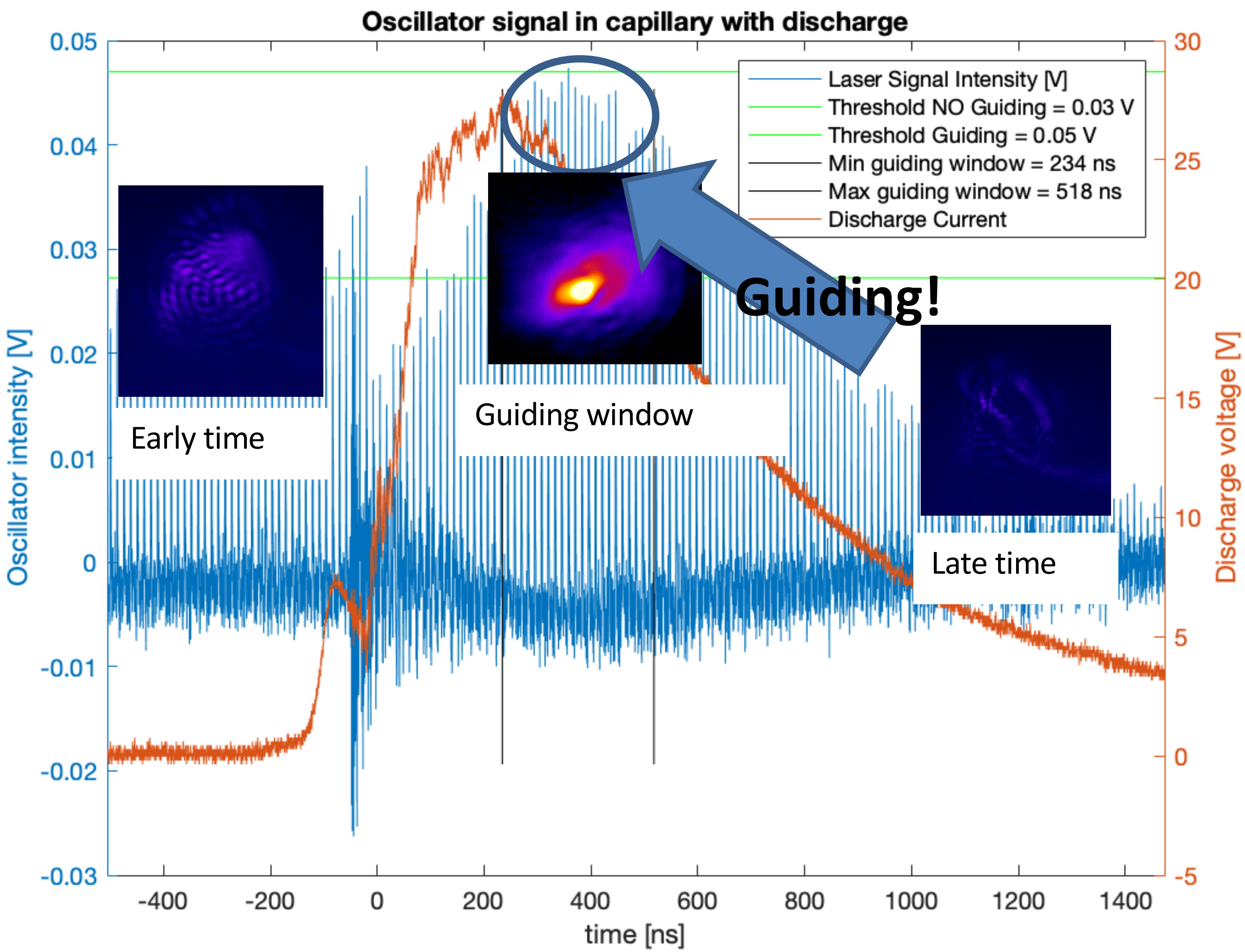


M = Mirror
L = Lens
BS = Beam Splitter



- 3D printed capillary
- Diameter: *500 μm*
- Length: *3 cm*
- Discharge voltage: *20 kV*
- Discharge peak current: 270A
- Gas: Hydrogen
- Max density: 1×10^{18} cm^{-3}

Laser mode output



- Low intensity (<10^{12} W/cm^2) single pulse laser has been detected at capillary exit with relay imaging system.
- A temporal scan has been performed to investigate laser output mode by delaying discharge.

FLAME oscillator has been sent into the plasma to easily find the temporal window for guiding thanks to the high rep.rate (79.667 MHz)

Transmission efficiency:
- no plasma 40%
- with guiding 70%

THANK YOU!