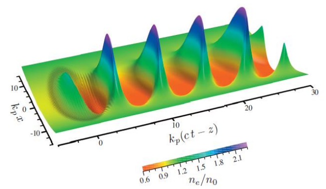
Plasma sources
for plasma-based acceleration experiments

Francesco Filippi

On behalf of SPARC_LAB collaboration

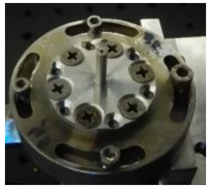
OUTLINE

➢ Plasma Acceleration Schemes: resonant PWFA, external and self-injection LWFA

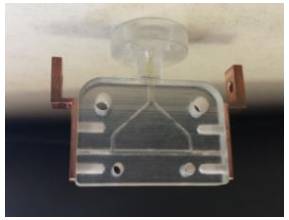


➢ Plasma sources:

- Gas jet
  - Density profile
  - Laser propagation in gas jet



- Gas filled capillaries
  - Density profile and its temporal evolution
  - Plasma ramps
  - 3D printed capillaries
  - Tapering capillaries
  - Curved capillaries



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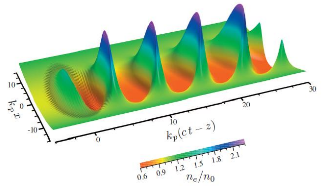

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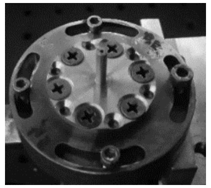

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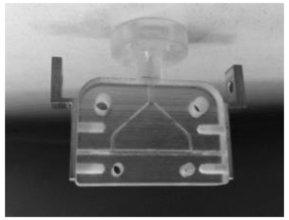


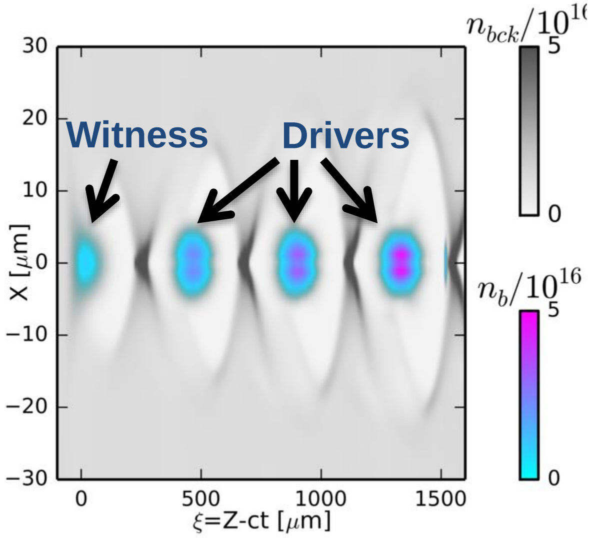
Plasma acceleration schemes

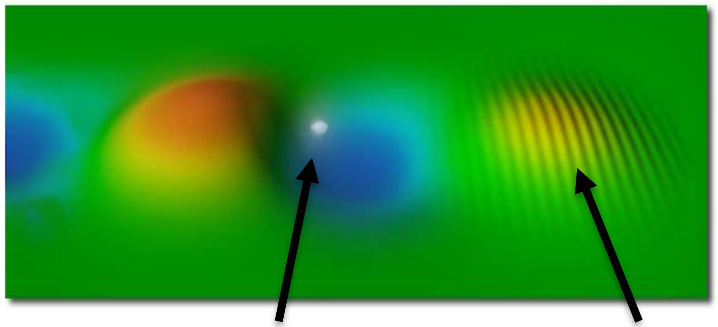
Plasma-based acceleration techniques are of great interest for future, compact accelerators due to their high accelerating gradient (~GV/m).

By exciting large amplitude plasma waves (**wakefields**) it is possible to transfer energy from a **driver** source to a particle beam (**witness**).

There are different schemes:

	PWFA Plasma wakefields acceleration	**LWFA** Laser wakefields acceleration
driver(s)	Particles, space charge forces	Laser, ponderomotive forces





 Courtesy of F. Massimo, A. Marocchino

Plasma acceleration schemes: plasma requirements

Depending on the plasma electron density :

- The accelerating electric field

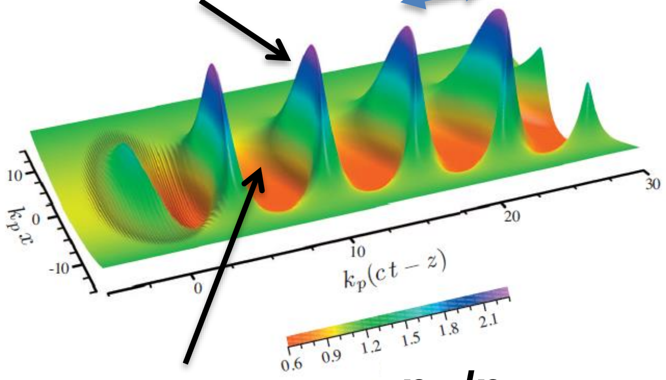
  $E[V/m] \approx 96 \boxed{n_0[cm^{-3}]^{1/2}}$

- Dimensions of accelerating structures (depending on λ_p)

  $\lambda_p\ [\mu m] \approx 3.3\ 10^{10} \boxed{n_0[cm^{-3}]^{-1/2}}$

Higher e^- density

λ_p



Lower e^- density

n_e / n_0

The efficiency of the acceleration and the quality of the accelerated beams depend on **plasma density**!

We need to control:

- Spatial n_e distribution
- Temporal n_e evolution

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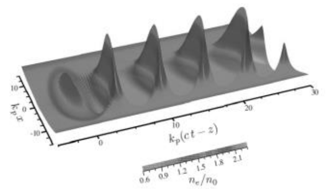
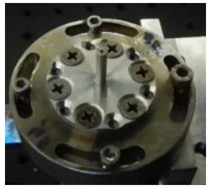


- Plasma Acceleration Schemes: resonant PWFA, external and self-injection LWFA



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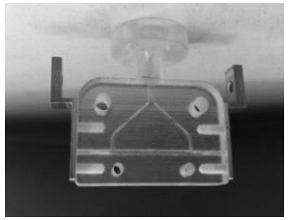

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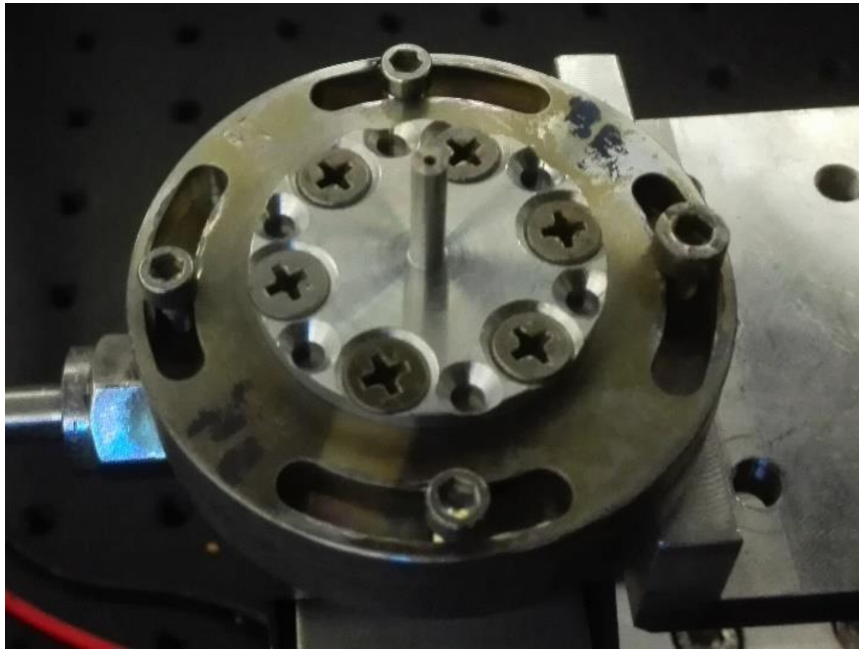
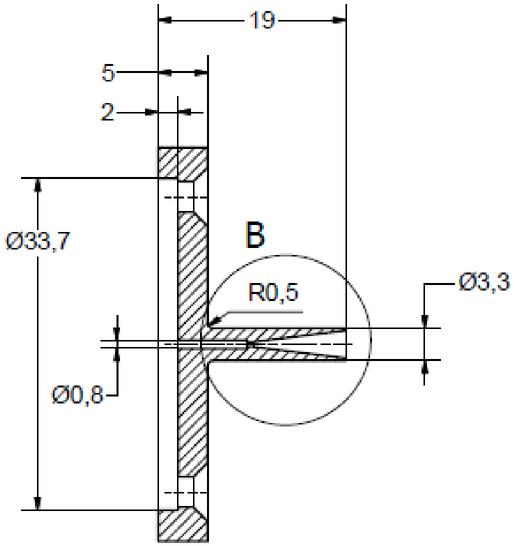
Gas-jets

The shape of the nozzle allows to control the flux of a gas and its velocity, then varying the density of the neutral gas.
Plasma is produced by focusing a laser pulse onto the edge of a gas jet, ionizing the gas.





Courtesy of V. Lollo

- Allows to reach densities of the order of $n_e \approx 10^{19}$ cm^{-3}.
- Have relatively constant density along the interaction path with the laser (~ mm)
- Sharp density edge

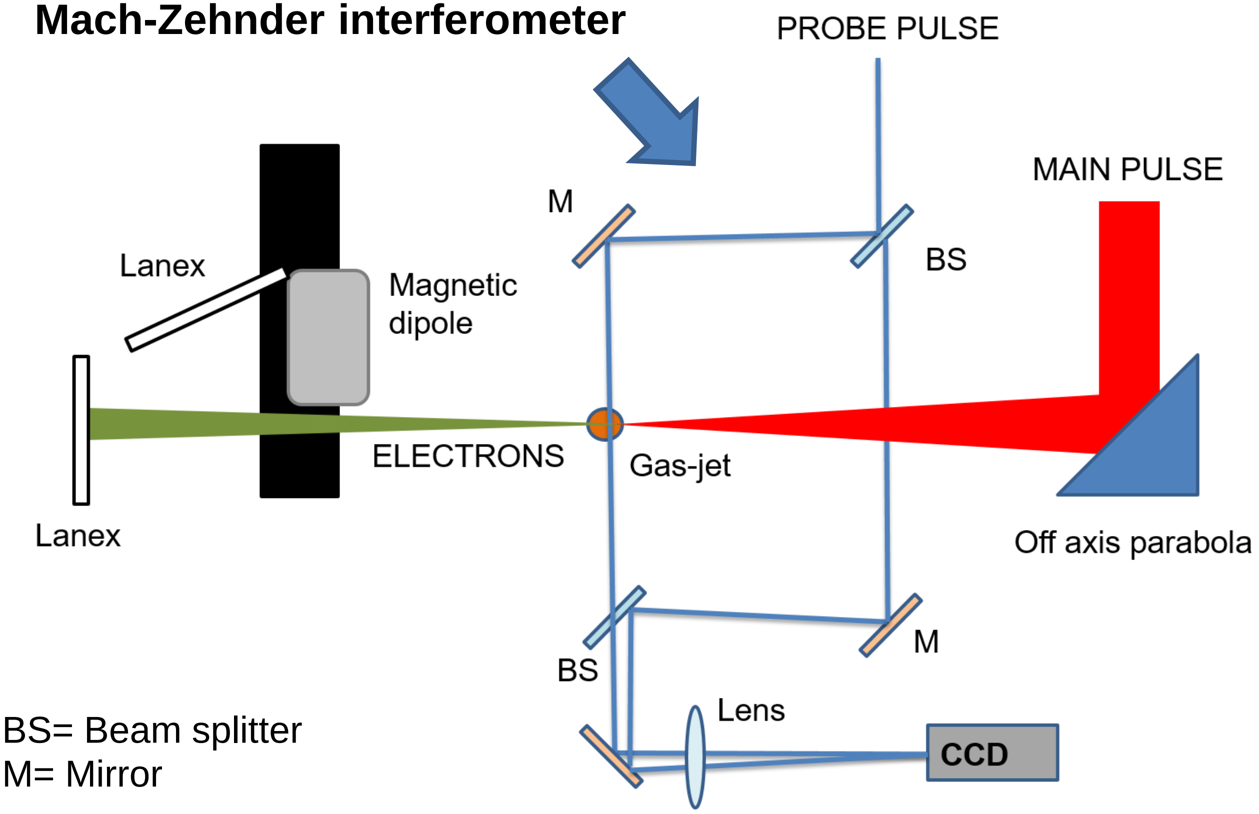
Used in LWFA experiment

C. Aniculaesei, Ph.D. dissertation, Strathclyde University (2015).

Gas-jets: density measurements

Interferometry lead to measure the refractive index variation caused by the plasma which is related to electron plasma density.

Mach-Zehnder interferometer



BS= Beam splitter
M= Mirror

PLASMA REFRACTIVE INDEX

$$\eta = \sqrt{1 - \frac{n_e}{n_c}}$$

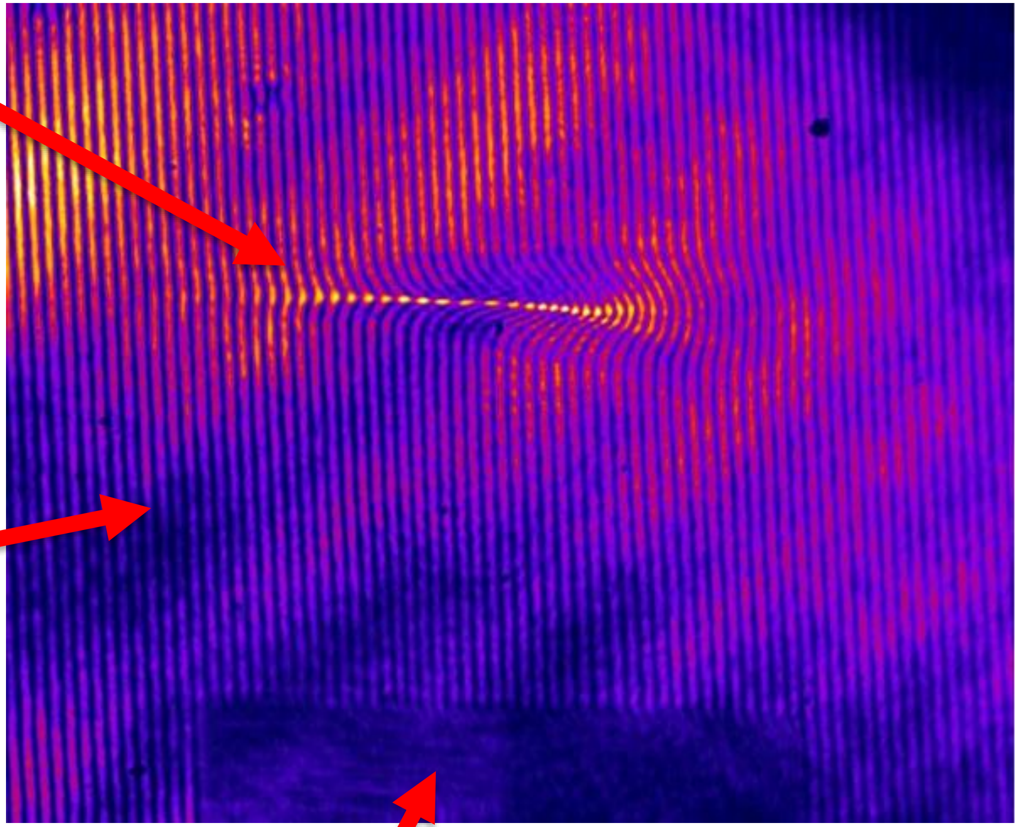
Free e$^-$ density

Critical density

Gas-jets: density measurements

Example of interferogram

Plasma channel



Unperturbed interferogram

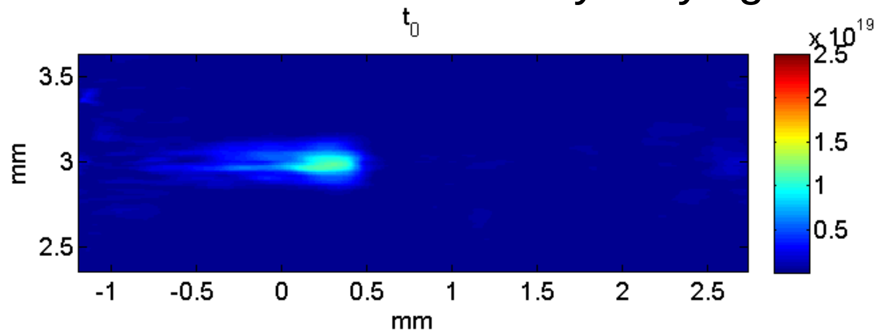
Shadow of the gas-jet

Spatial resolution is given by the imaging system (0,007 mm/pixel)

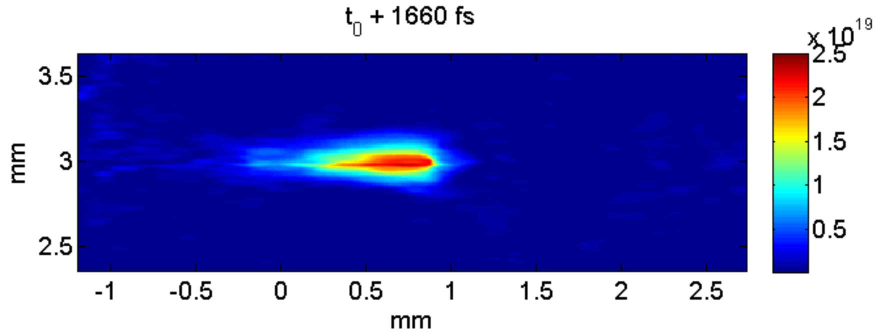
Temporal resolution is given by the probe duration (~50 fs)

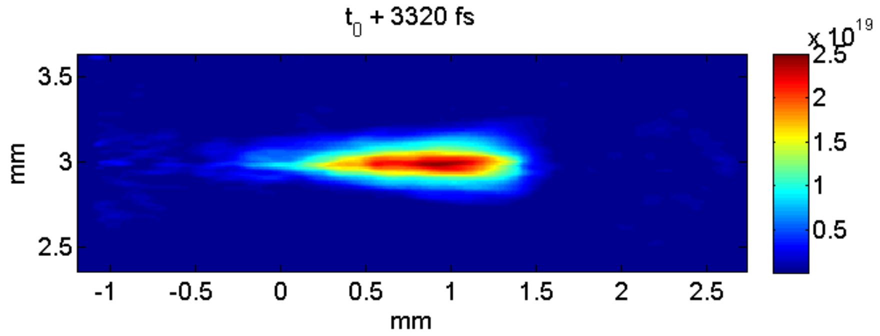
Gas jet: laser propagation

Snapshot of the laser evolution inside the gas is possible with multishot acquisition by varying the delay between probe and main pulse.



Laser propagation in He gas with 20 bar of backing pressure.

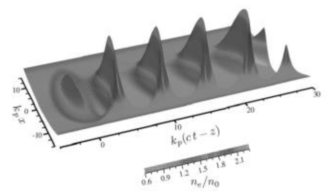




The ionization front follows the laser propagation velocity inside the capillary.

Measured speed of laser: $2.8301 \pm 0.15822\ 10^{8}$ m/s

OUTLINE



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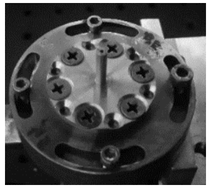

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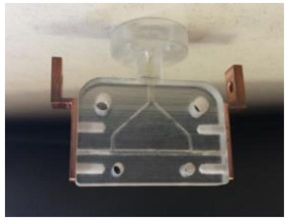

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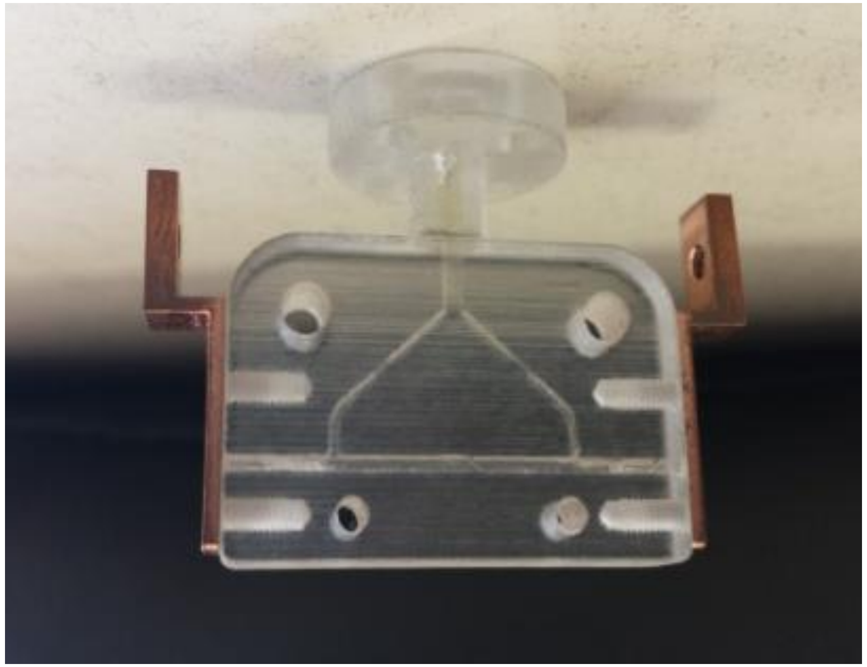
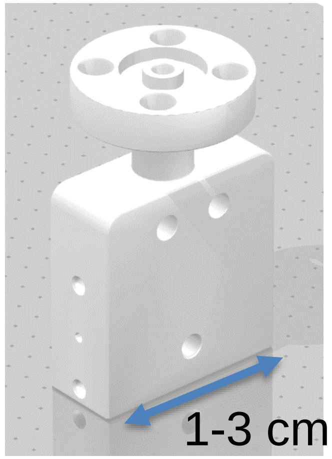
Gas filled capillaries

20kV is applied between the two ends of the capillary already filled with hydrogen. A **current discharge** of hundreds of amperes ionizes the gas, H_2 based plasma is formed before the beam interaction.





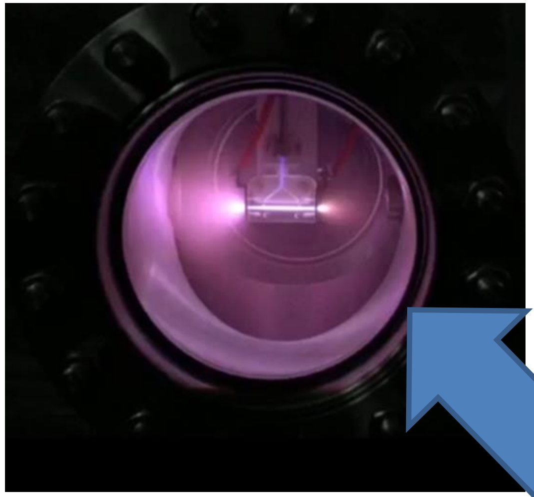
Courtesy of V. Lollo

- Allow for longer and almost constant density profile up to centimeter scale.
- High ionization level can be reached by the discharge (reducing the ionization losses acting on the driver(s))
- Suitable for low energy particle bunches which are not intense enough to ionize the gas

Studied for PWFA and external injection LWFA experiments!

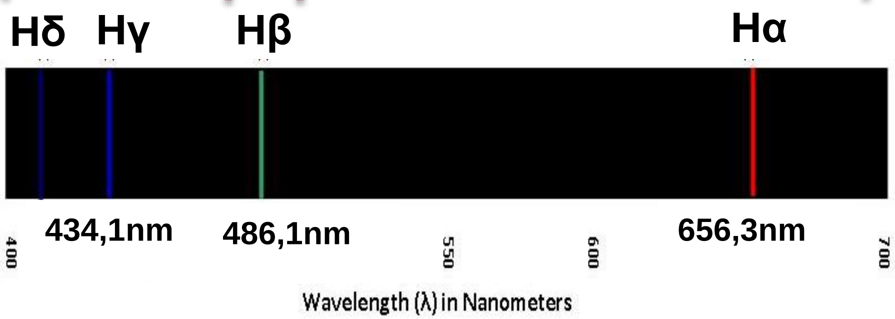
Gas filled capillaries: plasma density measurements

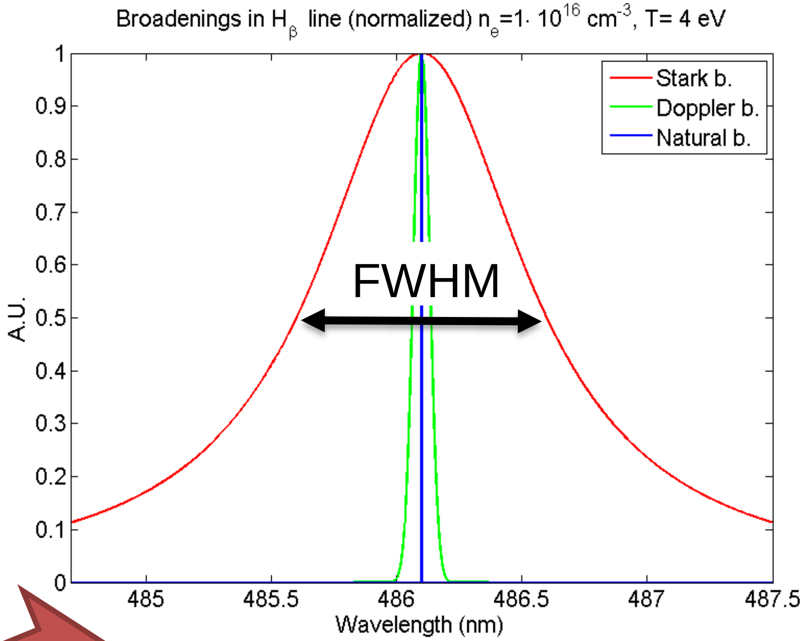
Light self-emitted by plasma allows to reconstruct the electron density from spectroscopy.



Ionized hydrogen emits in visible range four lines of the Balmer series.
The broaden of these lines depends on many mechanisms, but the most important one is the **Stark broadening**

$$\Delta\lambda[nm]=\alpha(T)*n[10^{18}cm^{-3}]^{2/3}$$





@T=4 eV, $n_e = 1 \cdot 10^{16}$

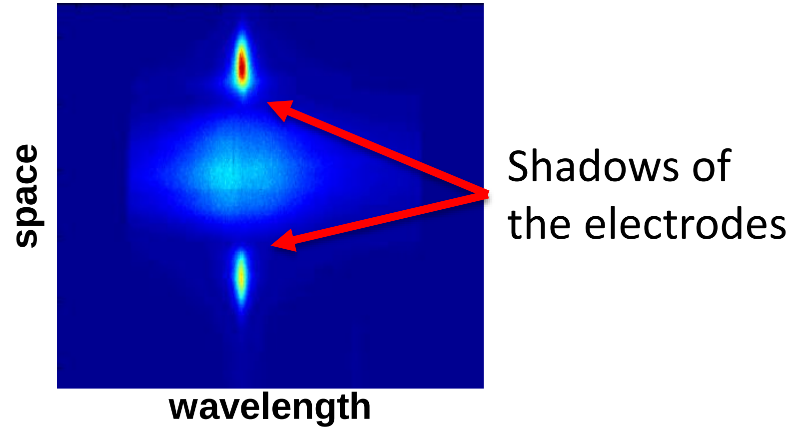
Hα stronger, but more sensitive to temperature
Hβ weaker signal, but more insensitive to temperature

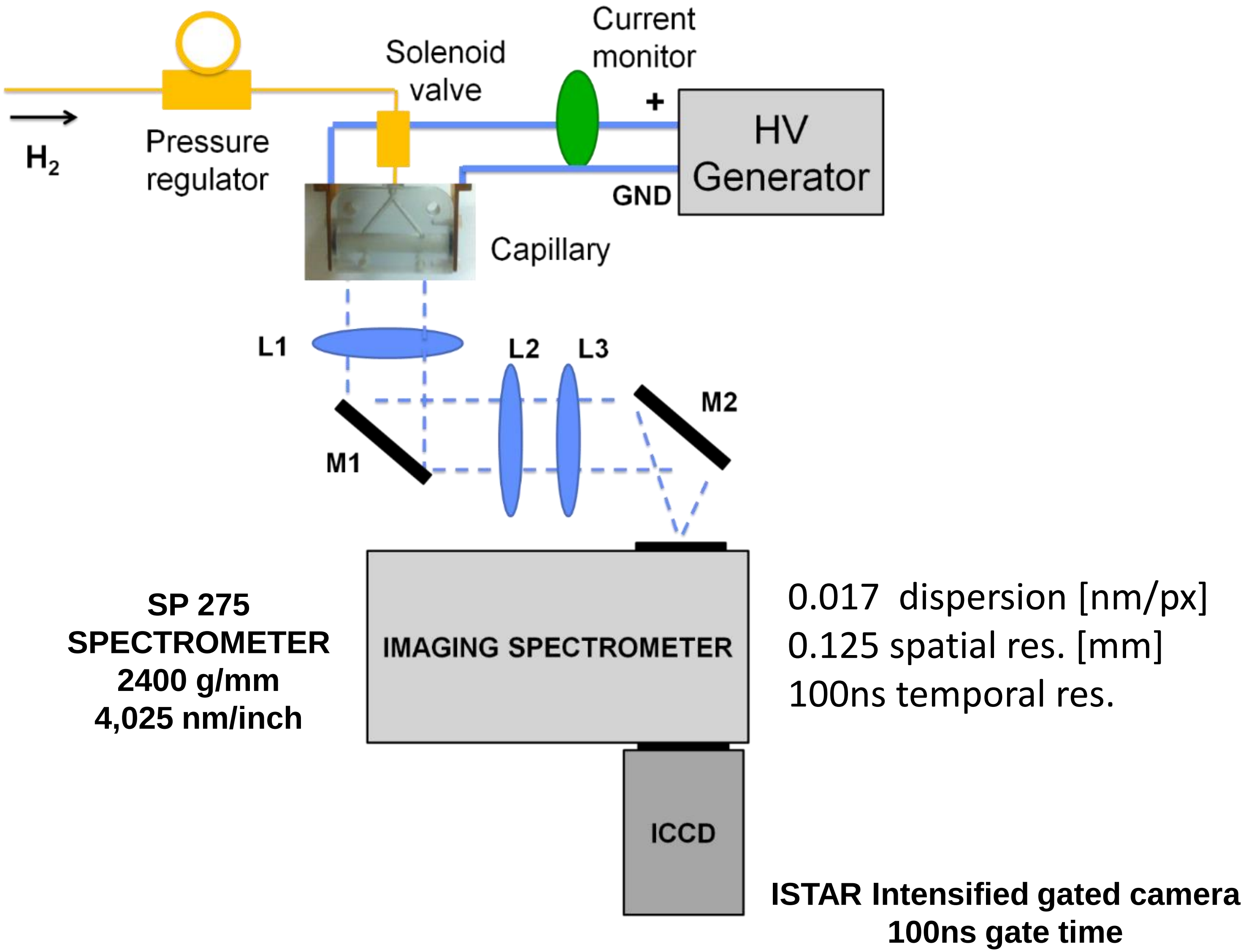
Gigosos et al., Spectrochimica Acta part B, 58 (2003)
Griem, *Spectral line broadening by plasmas*, (1974)

Gas filled capillaries: plasma density measurements

A system of lenses collects the self-emitted light of the capillary and image it onto the spectrometer slit.

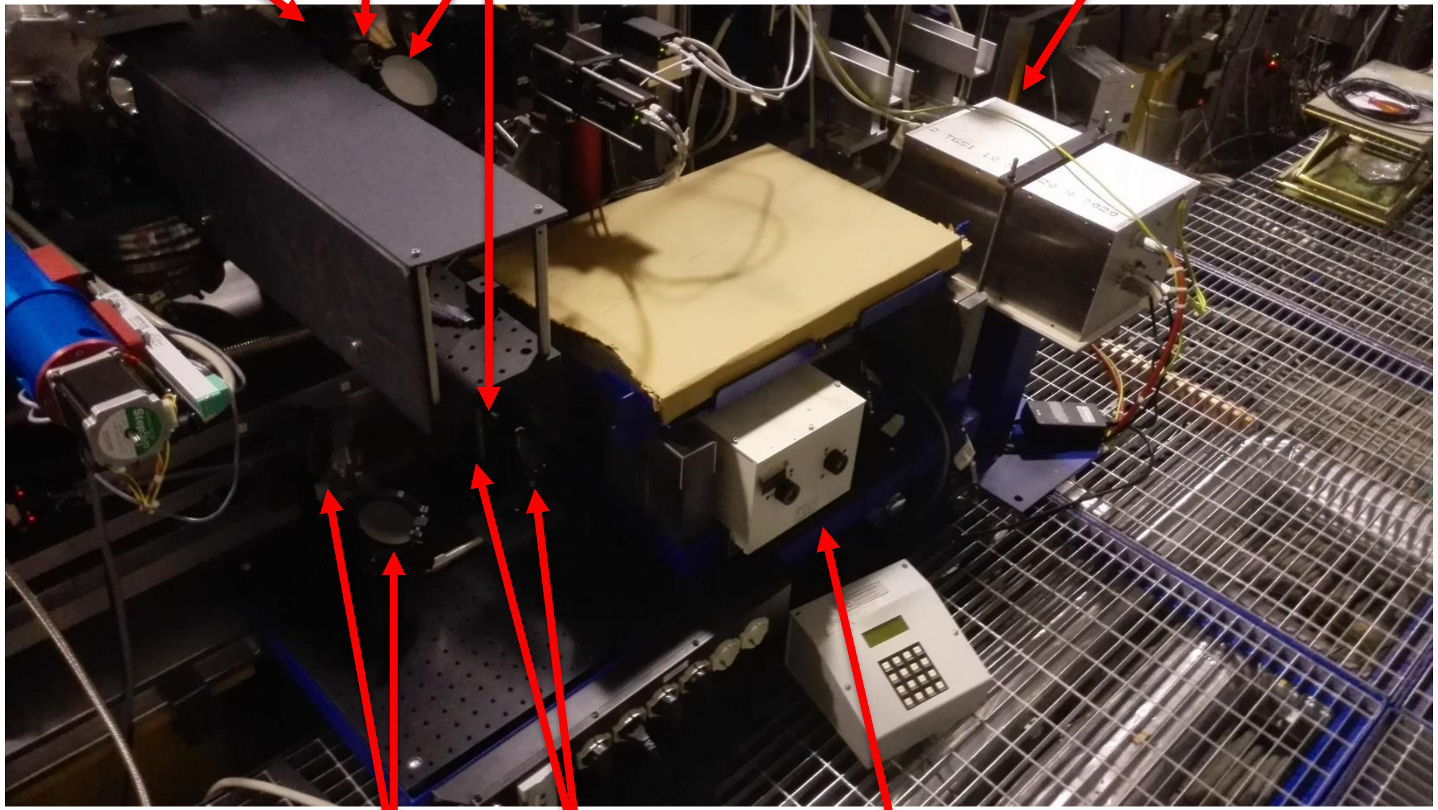
Example of spectrometer output





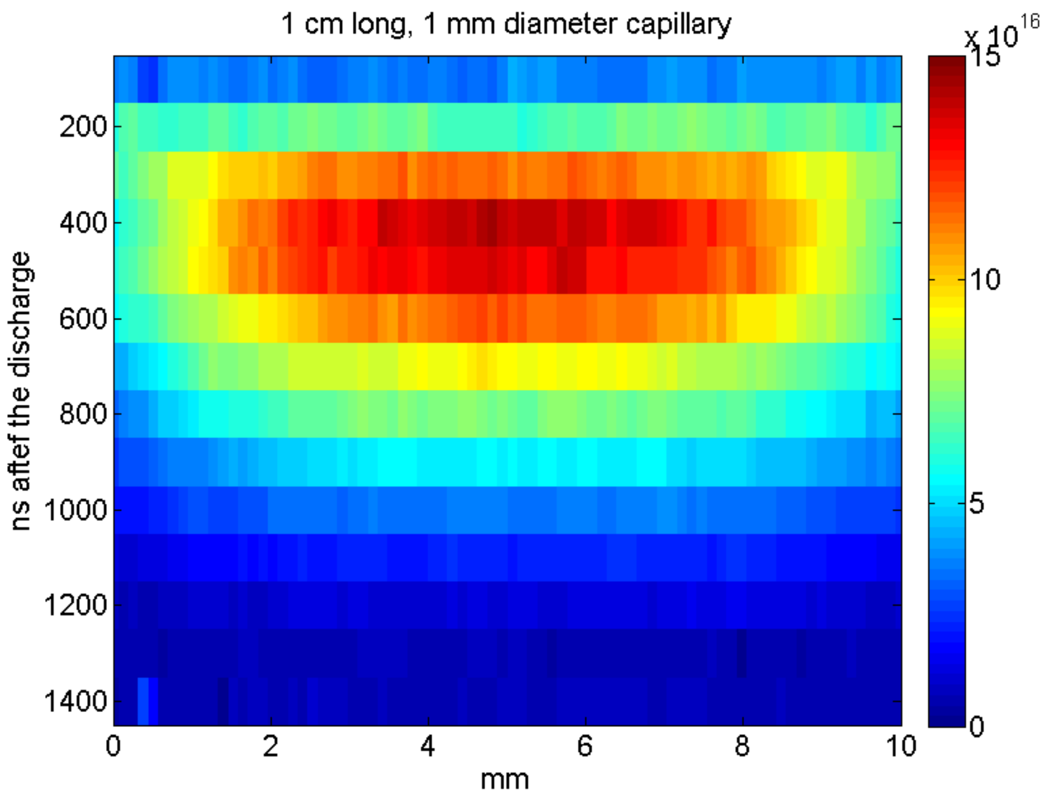
Filippi et al.
Proc. of IPAC16 (2016)
doi:10.18429/JACoW-IPAC2016-WEPMY007

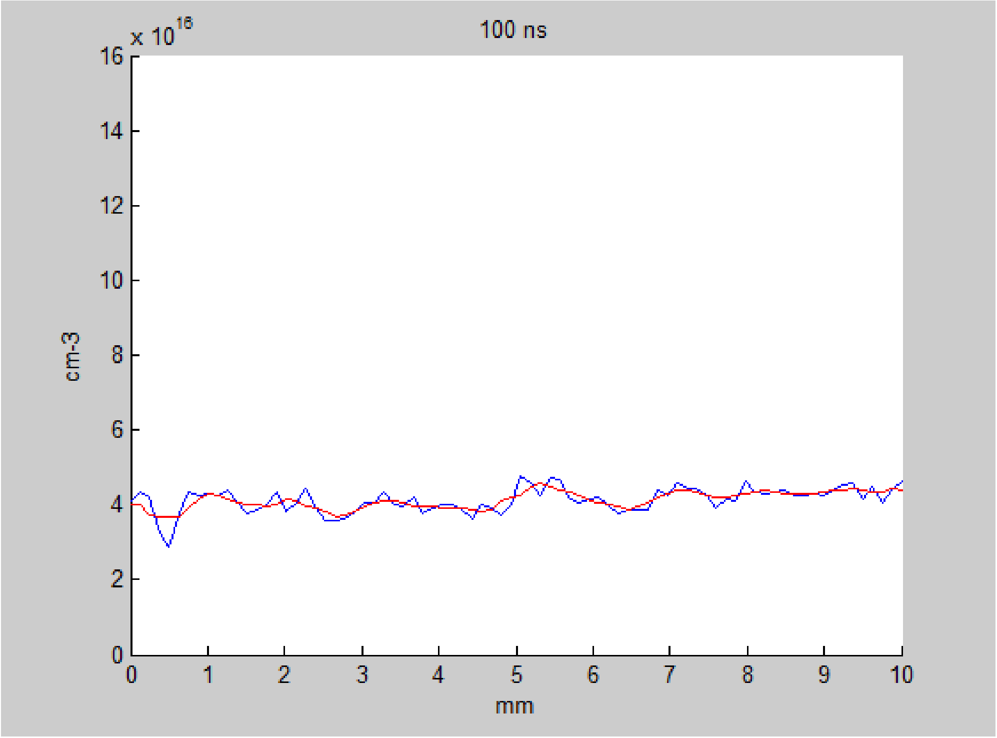
Gas filled capillaries: plasma density measurements



Gas filled capillaries: longitudinal profile

The implemented technique let the temporal and spatial characterization of the longitudinal plasma density is mandatory for a correct knowledge of the beam propagation through the plasma.



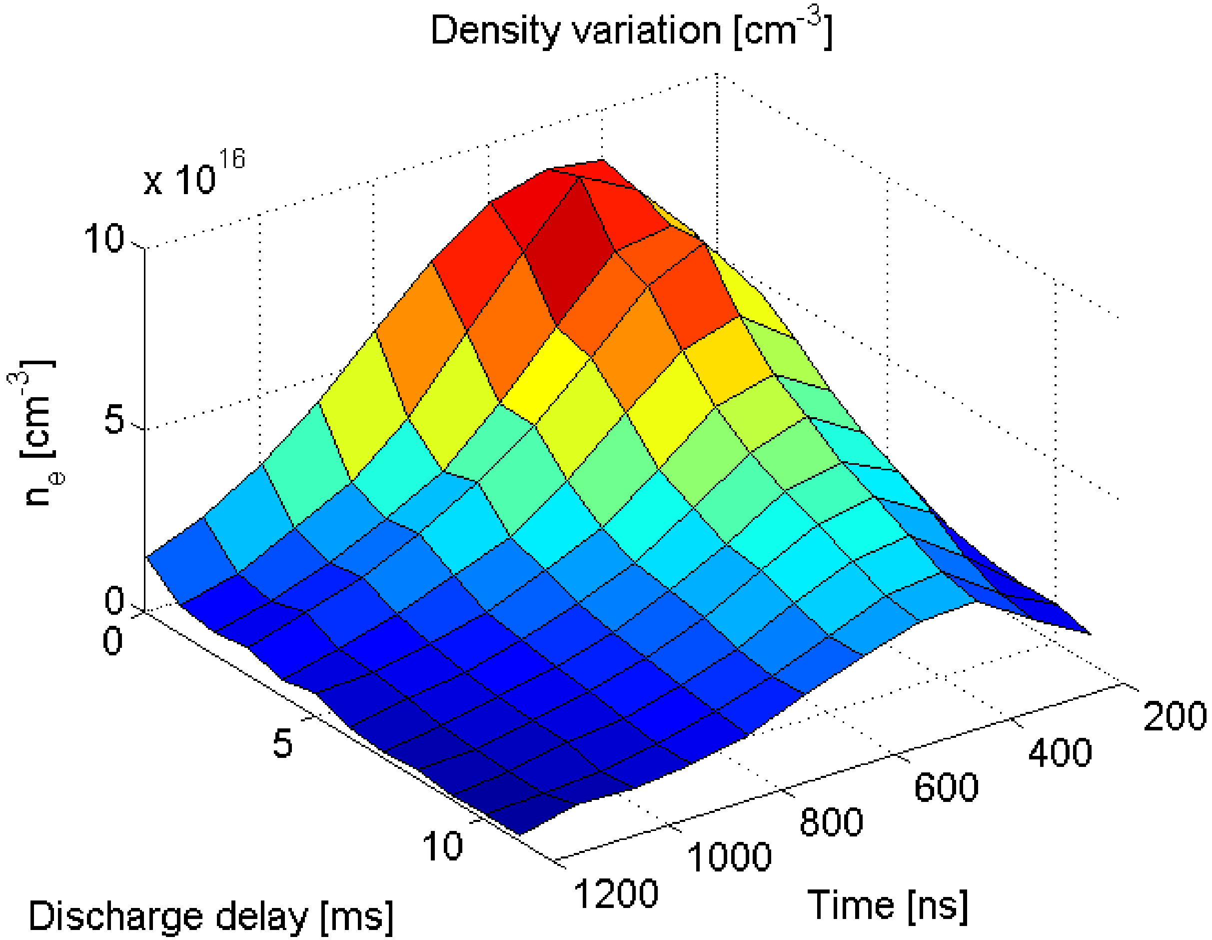


20 kV
250 A peak current

Filippi et al.
JINST, 11, 9 (2016)
doi:10.1088/1748-0221/11/09/C09015

Gas filled capillaries: plasma density control

To online vary the mean plasma density it is required to:



Discharge delay [ms] from the closure of the electrovalve

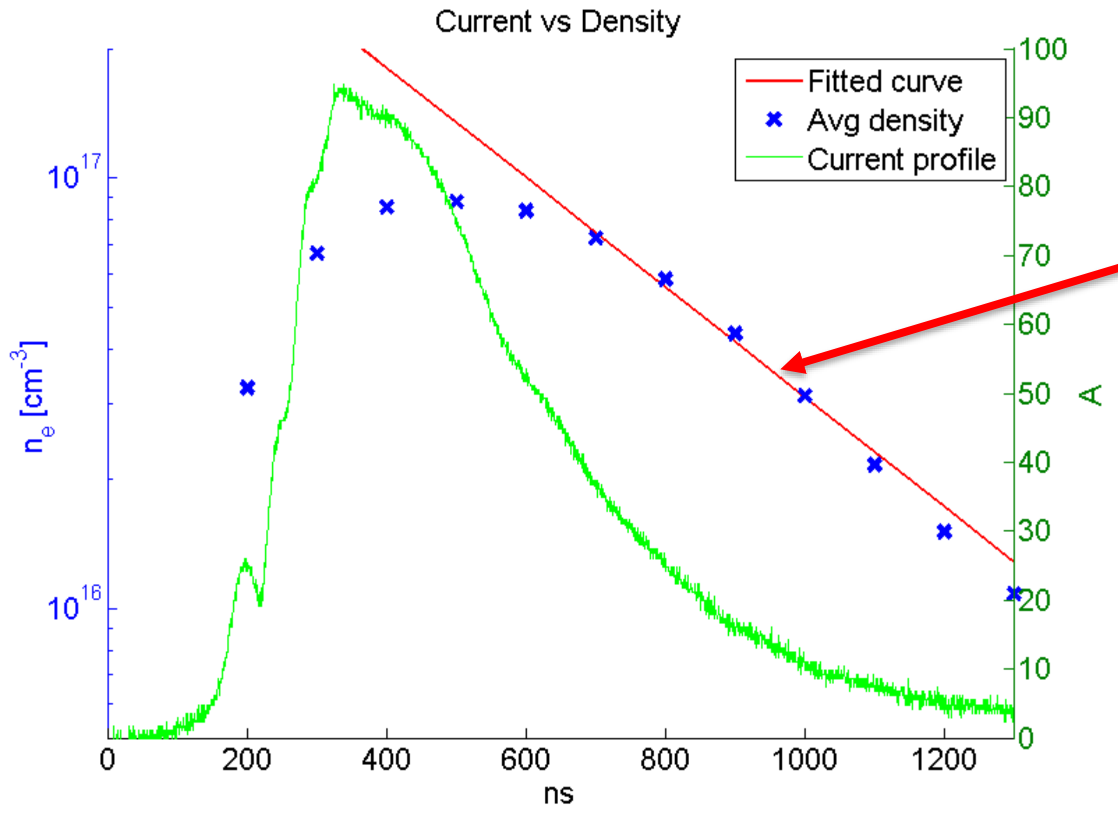
Time [ns] from the beginning of the discharge

- Change the discharge trigger time respect to closure of the electrovalve (which let the gas flow in)
- Wait until recombination/outflow of the plasma

Filippi PhD thesis

Gas filled capillaries: plasma ramps

The density is averaged over the entire length of the capillary every 100 ns from the discharge trigger.
The density shows an exponential decay from its maximum to the complete recombination.



$$n_e \propto e^{-\frac{t\,[ns]}{\tau}}$$

Decay constant

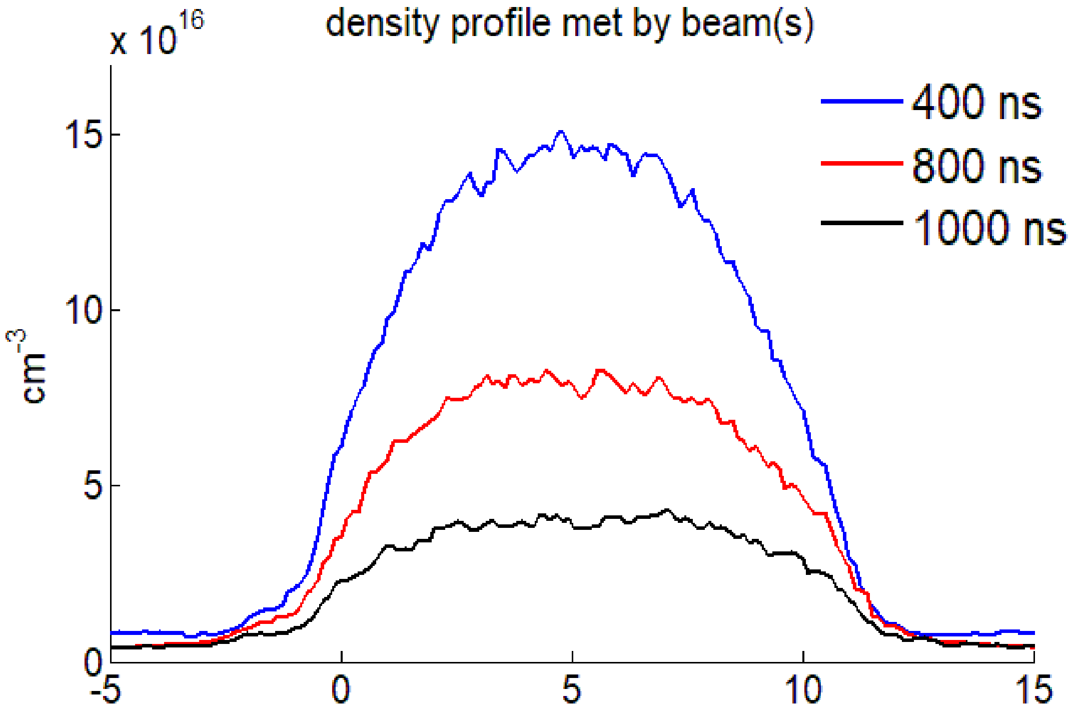
τ~=340 ns

Outflow
+
recombination

Bobrova et al.
Physical Review E, (2001)

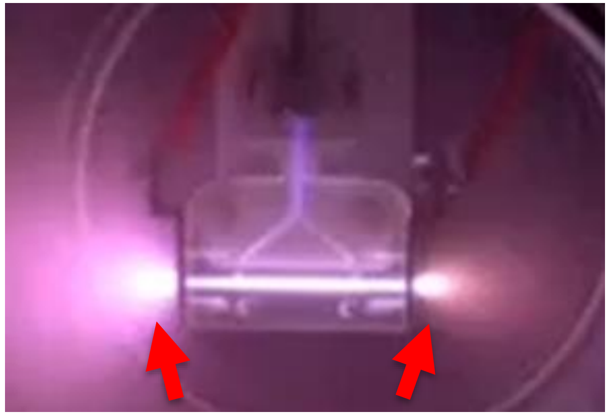
Gas filled capillaries: plasma ramps

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



capillary

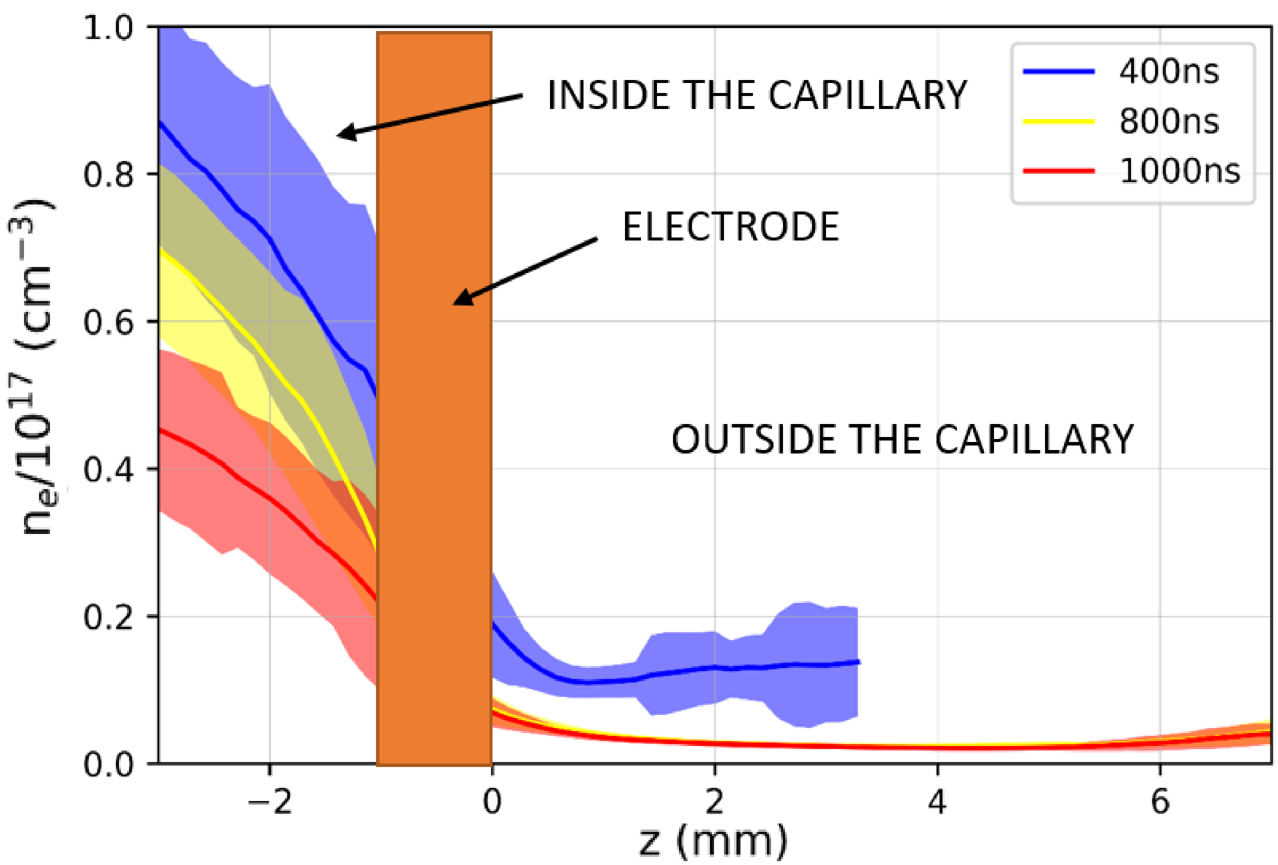
Longer interaction path



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

Gas filled capillaries: plasma ramps

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



Filippi et al. NIMA(2018), DOI: 10.1016/j.nima.2018.02.102

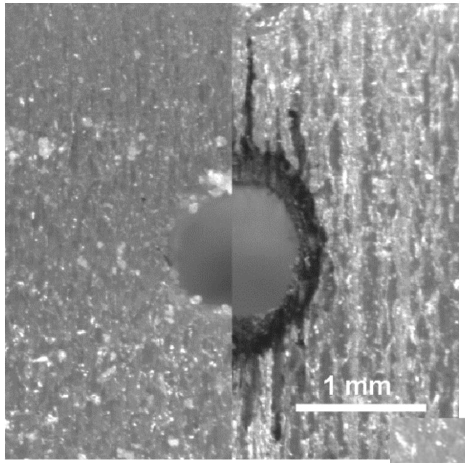
Marocchino et al. Applied Physics Letters (2017), 111(18):184101

3D printed capillaries: design and characterisation

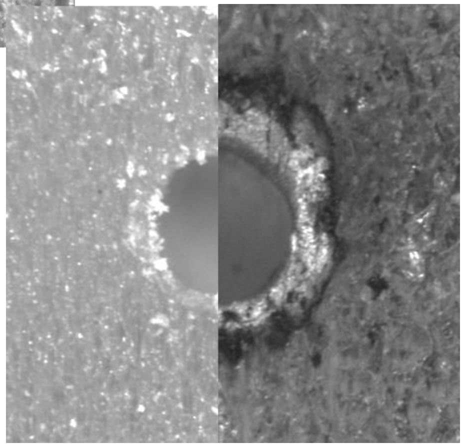
We studied the duration of the **3D printed capillaries**, fundamental for plasma based experiments.

They allows for:

- capillary shape with high spatial resolution (not easy to obtain with other technique)
- they are particularly suitable for plasma diagnostics like spectroscopic or interferometric analysis

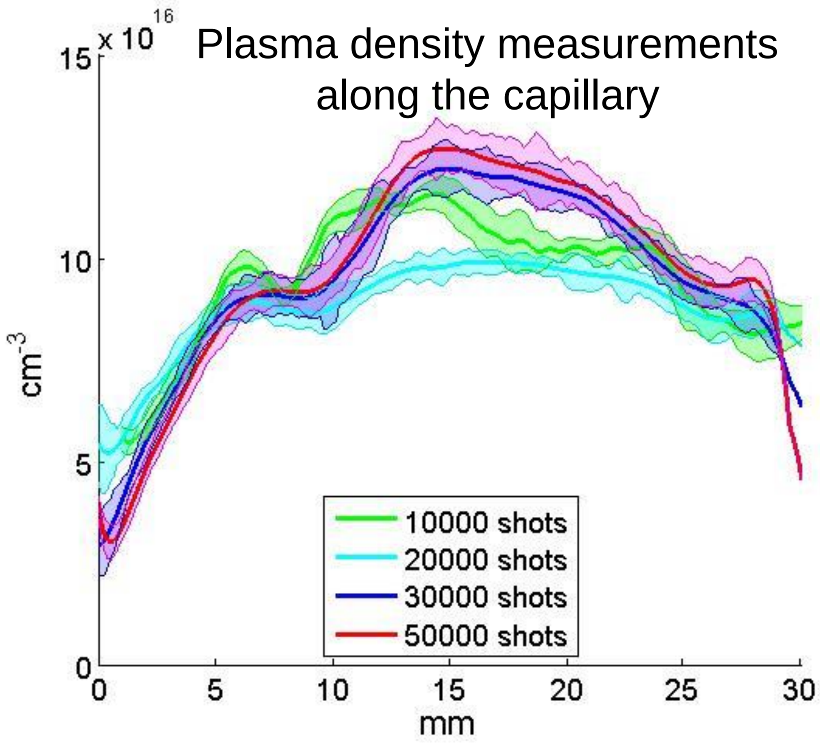


After 55000 shots
(16 h of working time)
capillary radius is larger
by 79 um



After 200000 shots
(55 h of working time)
radius was larger by 102
um

Plasma density measurements
along the capillary



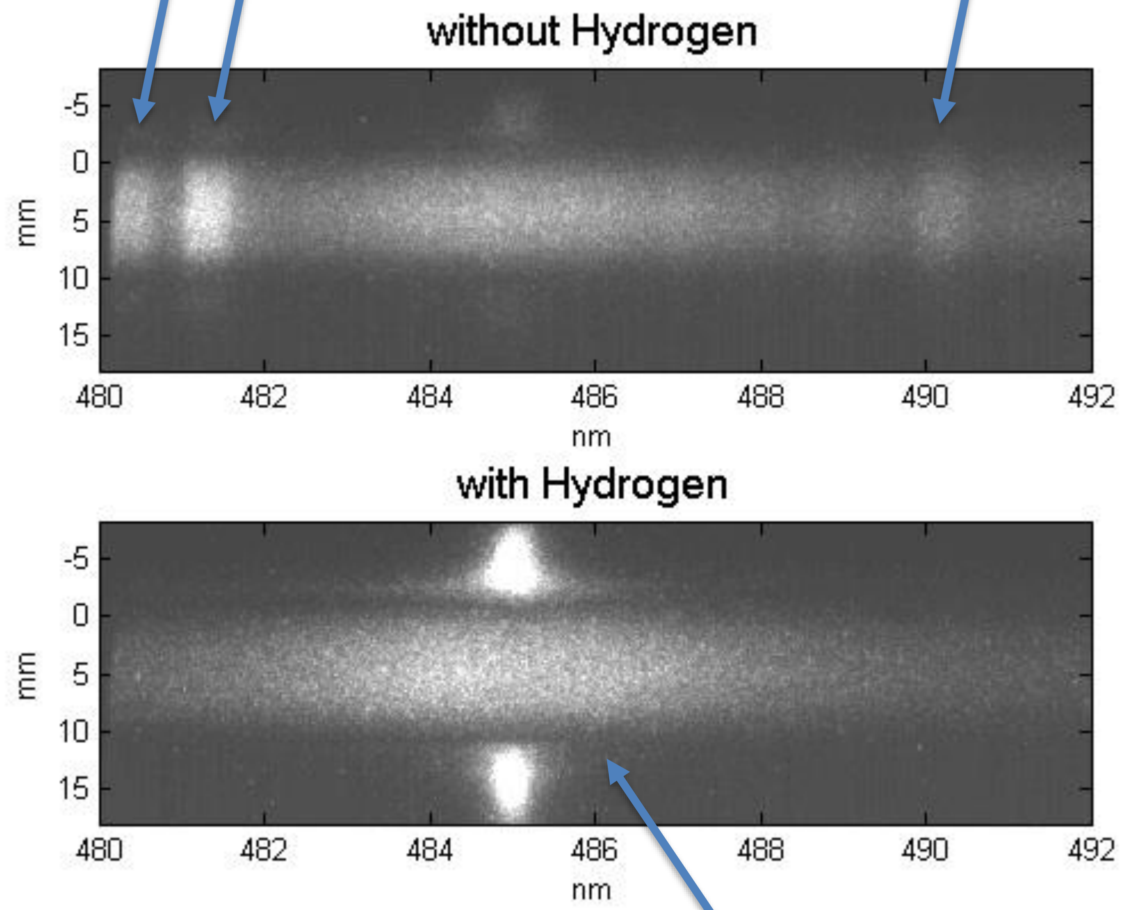
Uniform plasma density for long plasma acceleration experiments can be obtained.

Filippi et al., "3D-printed capillary for hydrogen filled discharge for plasma based experiments in RF-based electron linac accelerator"

3D printed capillaries: ablation marks

Ablation can be observed spectrally.

Many spectral lines are present



Only hydrogen Balmer line can be observed

Spectra acquired on a 3D printed capillary:

- during the breakdown of the capillary surface (with no hydrogen gas into the capillary)
- during the normal operation of the capillary (the capillary is filled with hydrogen).

Tapering capillaries: Adiabatic Plasma Lens

One of the key elements of the PWFA blowout regime is the strong, linear focusing provided by the ion density.
The extreme strength of the focusing gradient is simply proportional to n_0, which may be easily changed experimentally.

Conditions for the adiabatic plasma lens

- $k_p\sigma_z \gg 1$ little longitudinal wake compared to transverse
- $n_b > n_0$ beam denser than plasma
- $n_0(z)/n'_0(z) \gg \beta_{qeq}(z)$ background plasma must increase with a scale length much longer than the quasi-equilibrium β-function

Focusing strength

$$\kappa_\beta^2(z) = \frac{2\pi r_e n_0(z)}{\gamma}$$

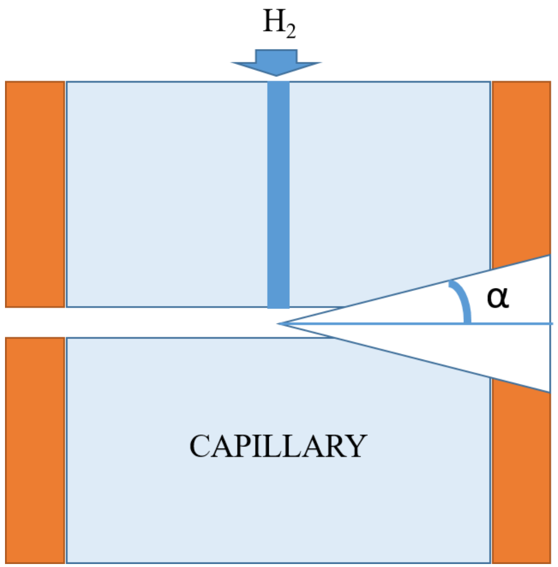
The plasma density increase serves to increase the beam density as well.

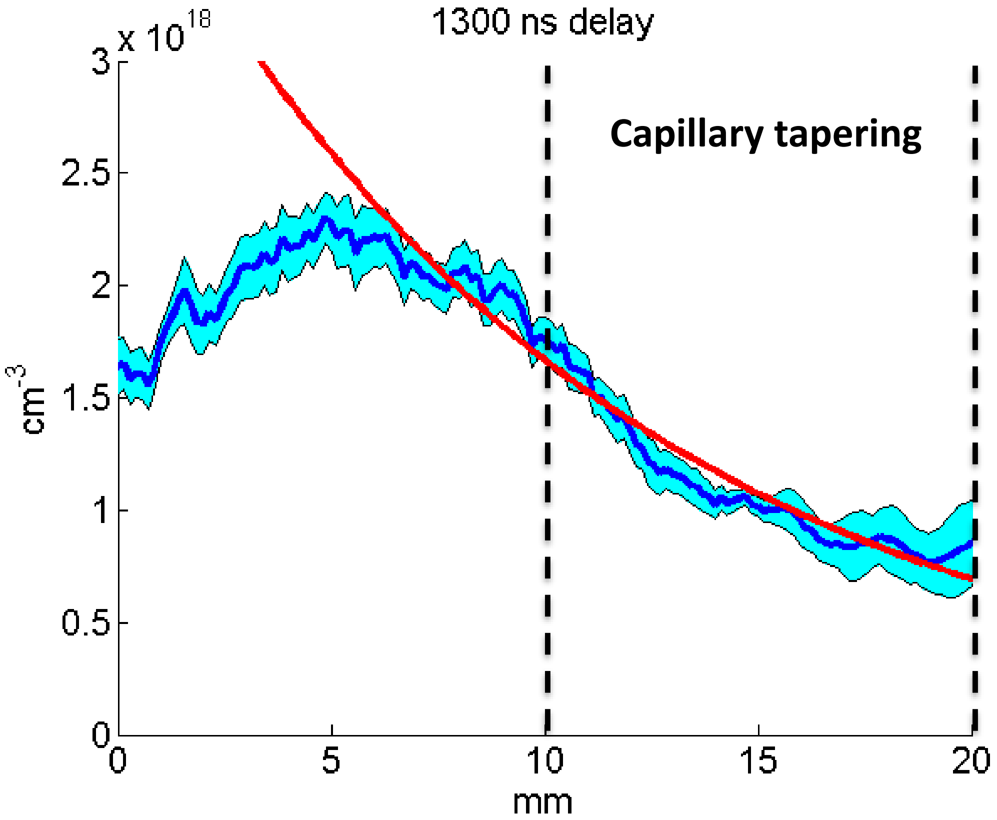
P. Chen, S. Rajagopalan, and J. Rosenzweig. *Physical Review D* 40.3 (1989): 923.

Tapering capillaries: experiments

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





Measures on tapered capillary

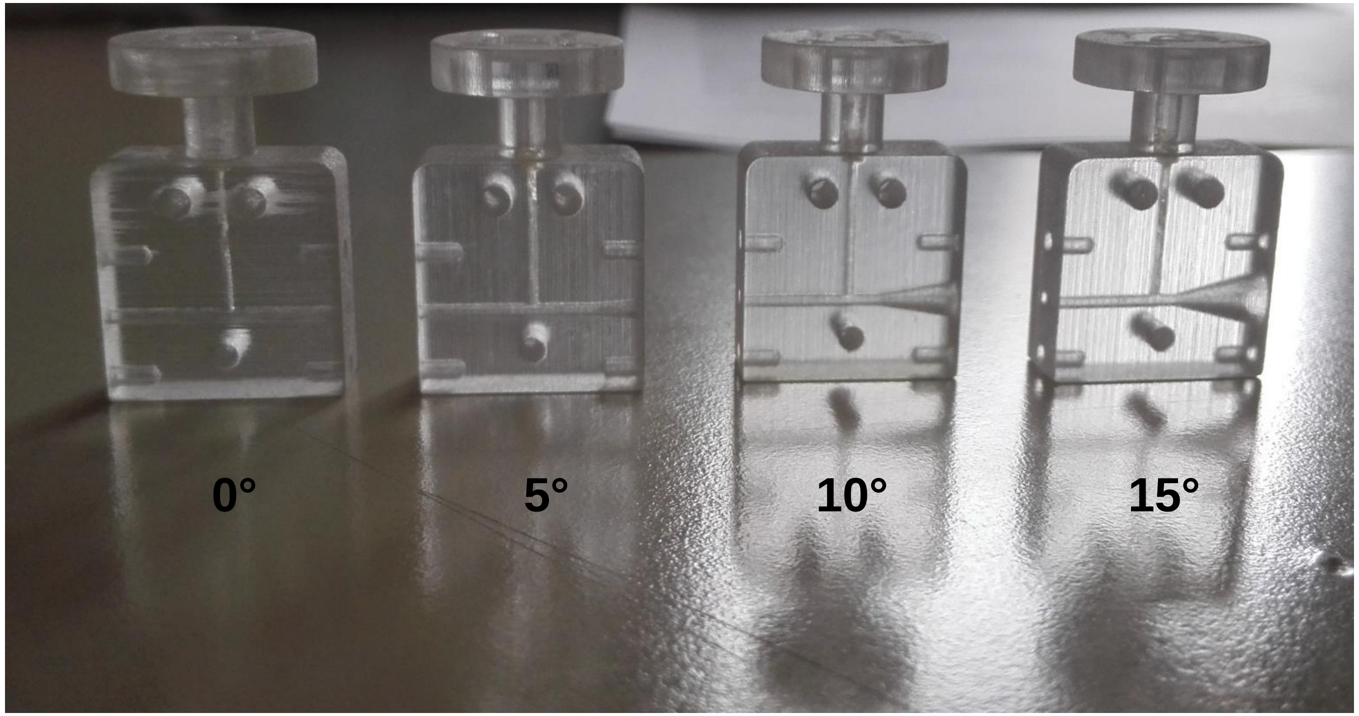
Kaganovich et al., Appl. Phys. Lett. 75, 772–774 (1999).

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

Tapering capillaries: experiments

3D printing process allow to produce prototypes for those studies quite easily.

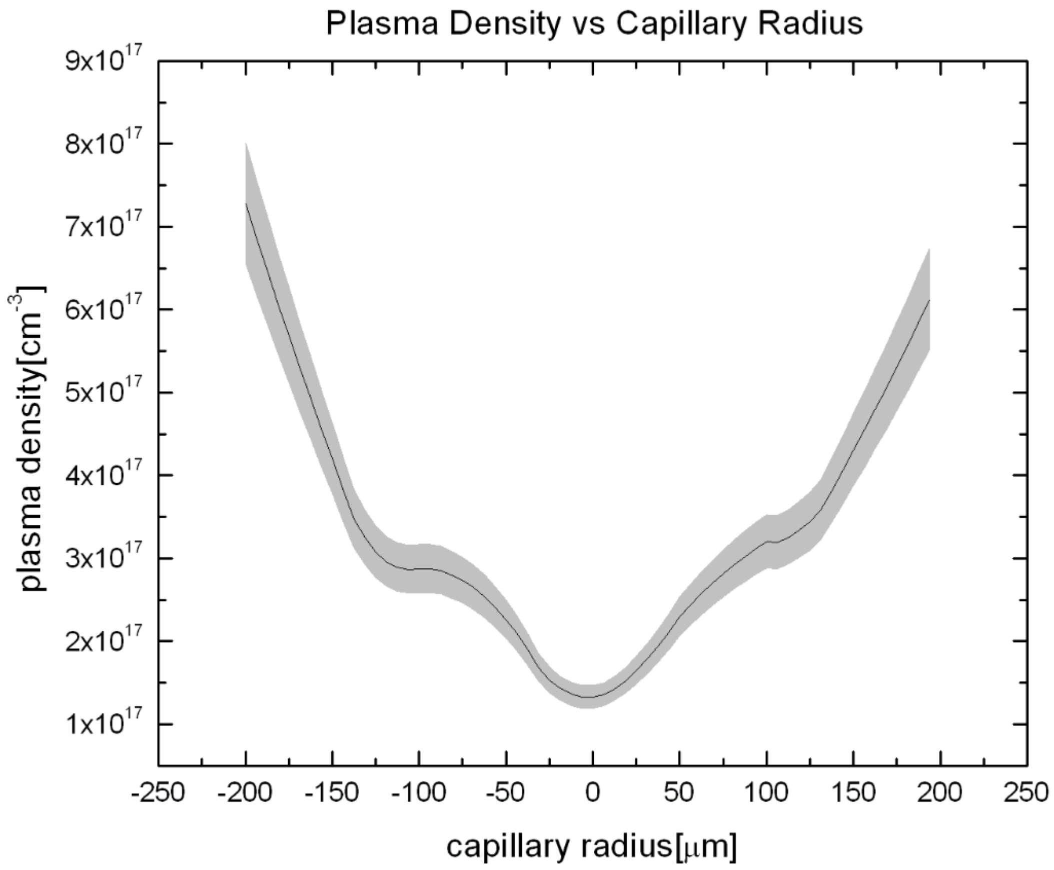
TAPERING OF:



Measurements are ongoing.

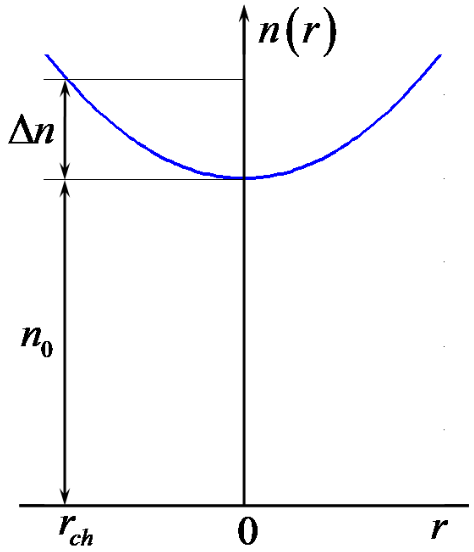
Curved capillaries: laser guiding

Pre-formed plasma hollow profile let to guide the laser through a preferred path enabling to extend the length along which the beam remains sufficiently focused.



Parabolic density profile is formed after few tens of nanoseconds because of the lower temperature of the walls

$$n(r) = n_0 + \Delta n \frac{r^2}{r_{ch}^2}$$



Laser spot must be matched with the hollow profile to be guided along the capillary

$$w_m = \left(r_{ch}^2 / \pi r_e \Delta n\right)^{1/4}$$

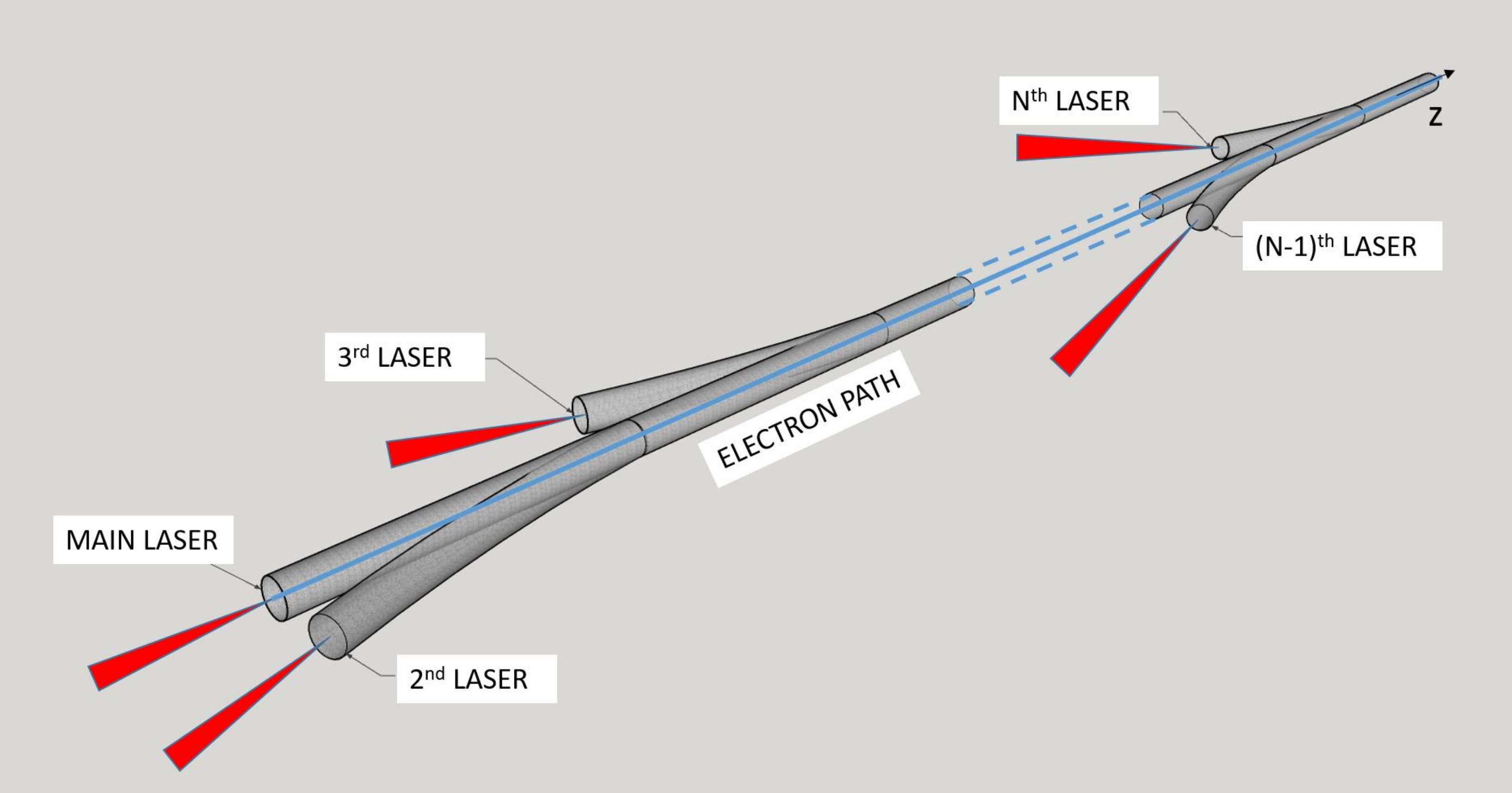
Beam waist

Classical electron radius

$r_e = e^2/mc^2$

Curved capillaries: Multistaging

Guiding can be used to guide laser through curved capillaries into the straight acceleration path to renew the laser energy reducing driver depletion




THANKS FOR YOUR ATTENTION!