Plasma source characterization for plasma-based acceleration experiment

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OUTLINE

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

- Plasma sources: gas filled and laser trigger ablative capillary
  - Stark broadening caused by the emitter interaction with the electric field produced by nearby particles
  - Spectral lines ratio the different intensities of the spectral lines depends on the free electron temperature in LTE.

- Plasma sources: gas jet
  - Interferometry that uses the dephasing of a probe laser caused by the variation of refractive index of plasma
  - Shadowgraphy the light of a probe laser deviates from its initial direction due to strong variation of refractive index.

Importance of plasma properties

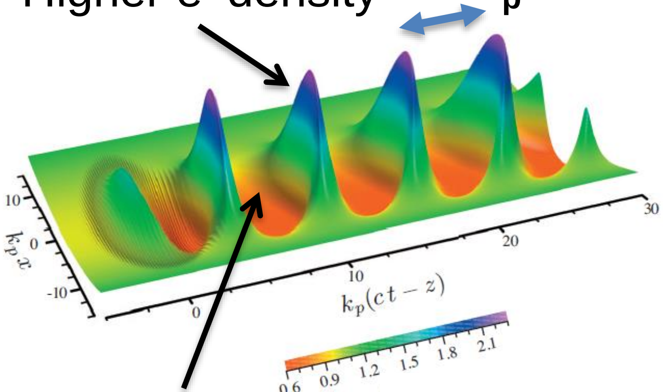
Depending on the electron density :

- The accelerating electric field $E[V/m] \approx 96\, n_0[cm^{-3}]^{1/2}$

- Dimensions of accelerating structures (depending on λ_p) $\lambda_p\, [\mu m] \approx 3.3\; 10^{10}\, n_0[cm^{-3}]^{-1/2}$

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!

Density
Spatial and temporal evolution

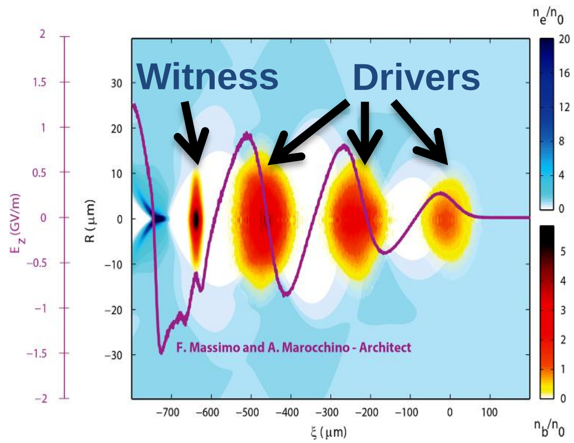
- Stark broadening
- Interferometry (Shadowgraphy)

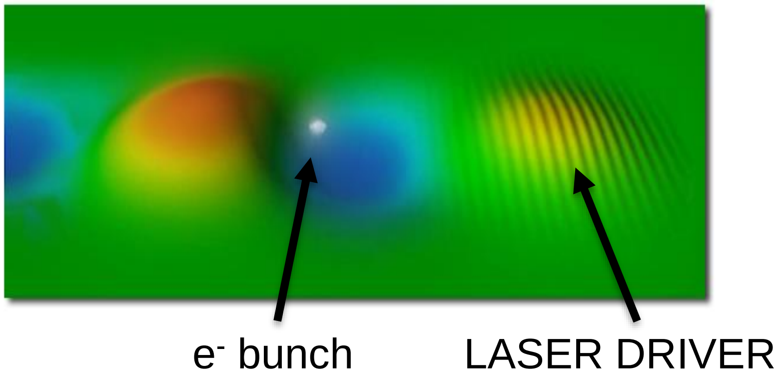
Temperature
Needed to set density distribution

- Line ratio analysis

There are different schemes. The most investigated are:

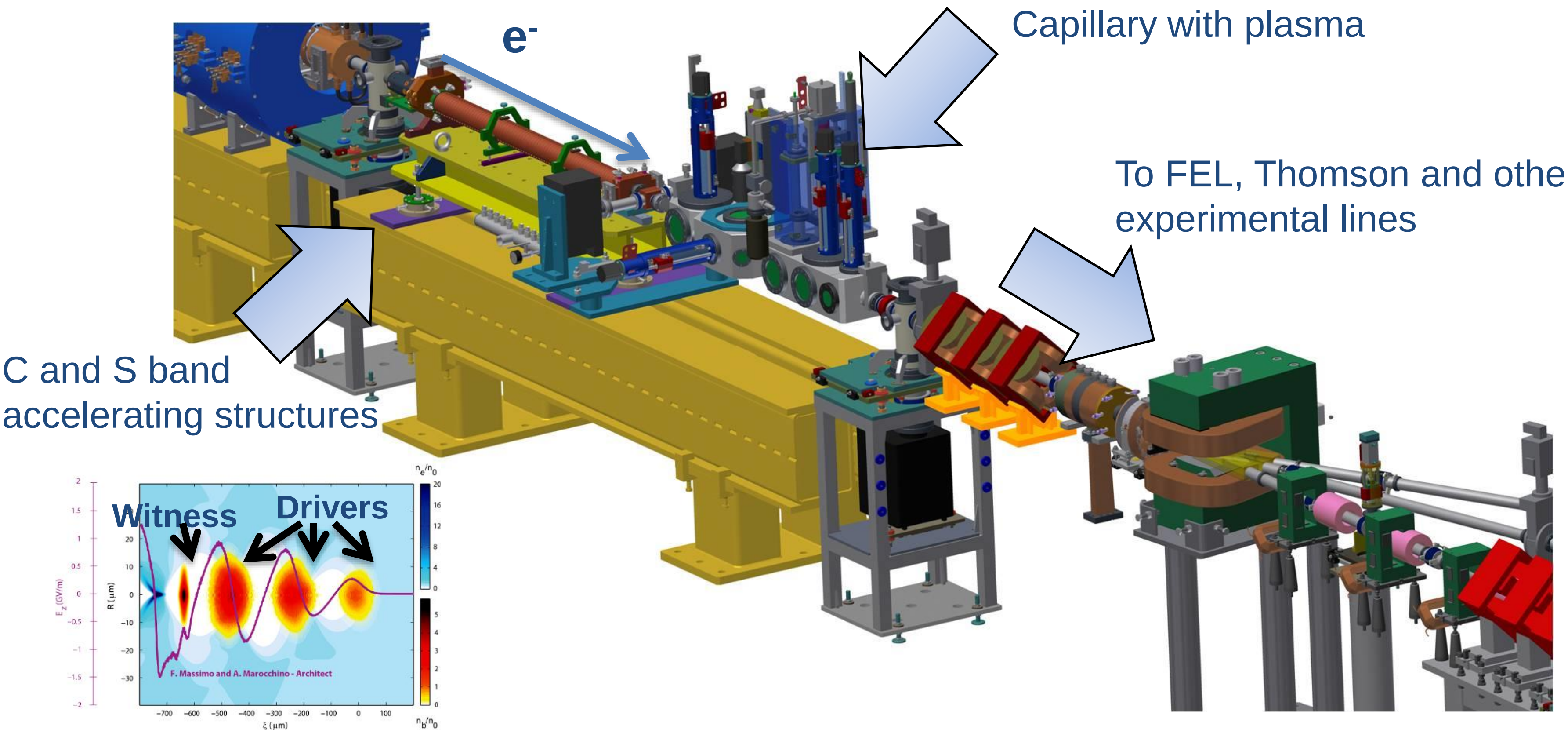
	PWFA	**LWFA**
driver(s)	Particles, space charge forces	Laser, ponderomotive forces





Resonant PWFA experiment

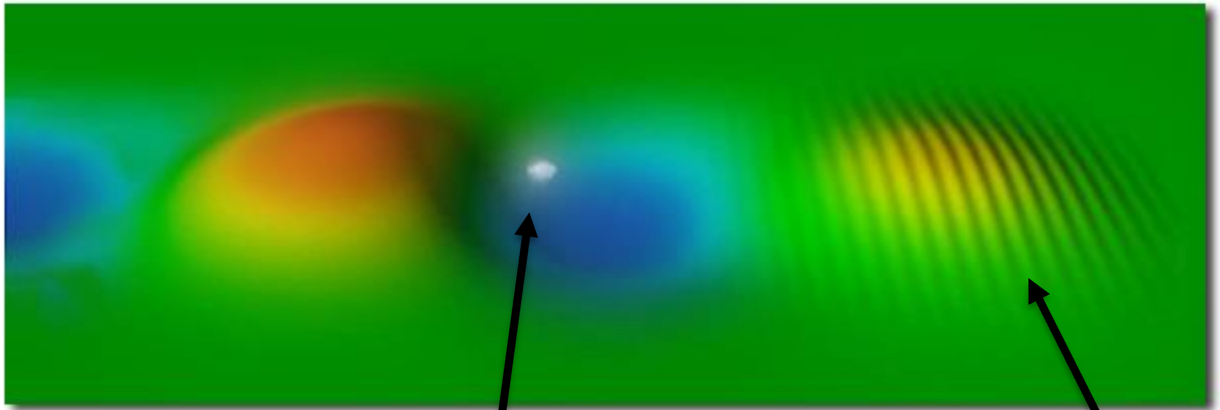
A train of three electron bunches is sent through a preformed plasma inside a capillary discharge to excite a resonant plasma wave that a fourth high brightness electron beam use to be accelerated.



Density must match the distance between the different bunches of the bunch train.

$n_e \approx 2\text{x}10^{16}$ cm^{-3}
Cylindrical Capillary

Self and external injection LWFA



Self-injection LWFA

Electrons are generated inside the plasma due to wave breaking.
Needs for higher densities.

$n_e \approx 2x10^{19}$ cm^{-3}
Gas-jet

External-injection LWFA

Electrons are generated externally and injected in a preformed plasma wave excited by a short high power laser.
Plasma density must be not too high to avoid wave breaking

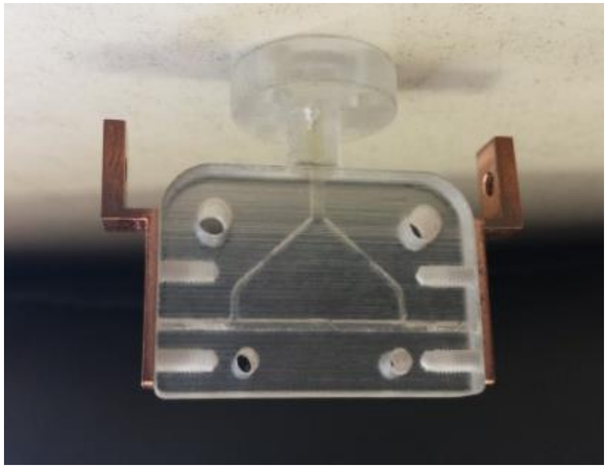
$n_e \approx 2x10^{17}$ cm^{-3}
Cylindrical Capillary

Plasma Capillaries

Allows longer plasma channel, easier to control.
Used for PWFA and external injection LWFA.

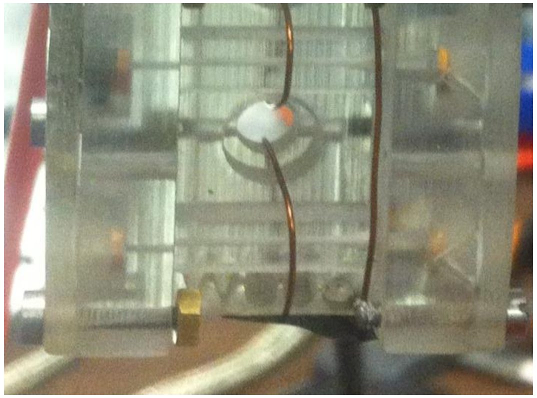
GAS FILLED CAPILLARIES

20kV is applied between the two ends of the capillary to completely ionize the gas inside the capillary. No laser is used.



LASER-TRIGGER ABLATIVE CAPILLARIES

6.3kV between the two ends of the plastic capillary is applied. A short laser pulse is focused at the entrance from the cathode triggering the discharge.

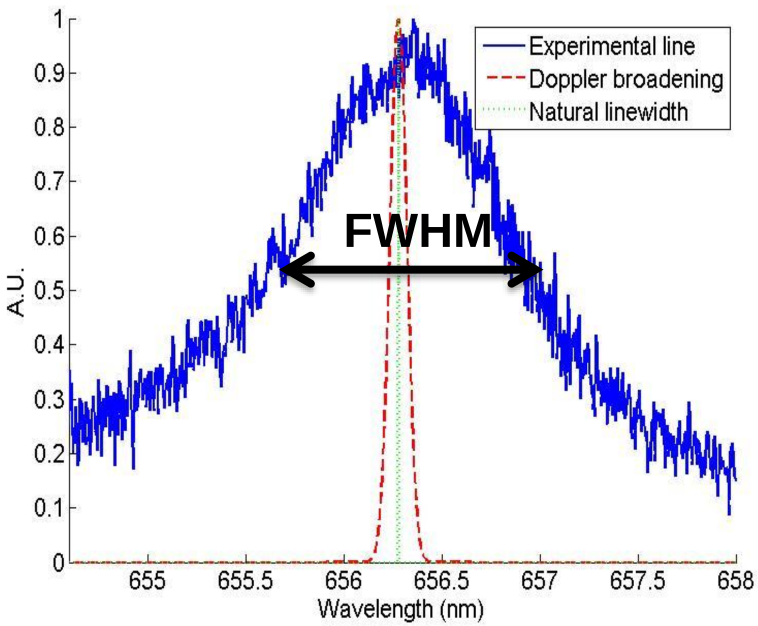


Transverse probing is not possible due to: diffraction of cylindrical capillary AND low density!

Spectroscopic measurements are most suitable!!!

Stark broadening

Hα, λ=656.3 nm



@T=4 eV

Ionized Hydrogen emits in visible range four lines of the Balmer series. The broaden of these lines depends on many mechanisms:

- Doppler broadening caused by thermal particle motion, depends on plasma temperature

  $$\Delta\lambda[nm]=7{,}13 \cdot 10^{-7} \cdot T[K]^{3/2}\,\lambda$$

- Stark broadening caused by the emitter interaction with the electric field produced by nearby charges.

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

- Other broadenings that for visible light, at temperatures of the order of 1-3eV **can be neglected**.

Stark broadening

Suitable for densities between **10^{14} cm^{-3}-10^{18} cm^{-3}** due to fine structure effects and plasma self absorption.

Hα, λ=656,3nm

n_e (cm^{-3})	Expected Stark broadening Δλ FWHM (nm)
$1*10^{16}$	0,250
$5*10^{16}$	0,733
$1*10^{17}$	1,163
$5*10^{17}$	3,402

Doppler broadening 4eV 0,1008nm

Hβ, λ=486,1nm

n_e (cm^{-3})	Expected Stark broadening Δλ FWHM (nm)
$1*10^{16}$	1,000
$5*10^{16}$	2,994
$1*10^{17}$	4,800
$5*10^{17}$	14,367

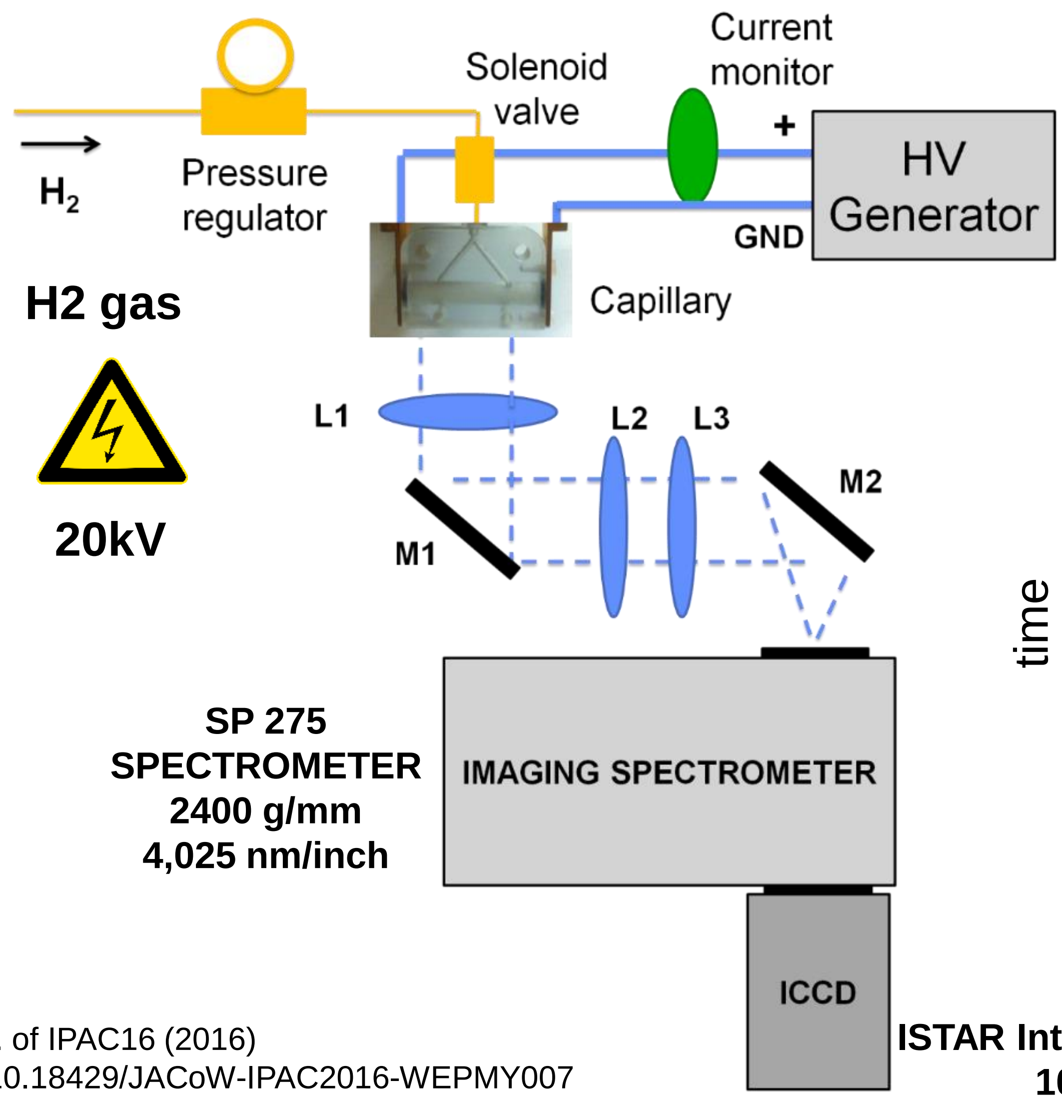
Doppler broadening 4eV 0,0745nm

Hα stronger, but more sensitive to temperature

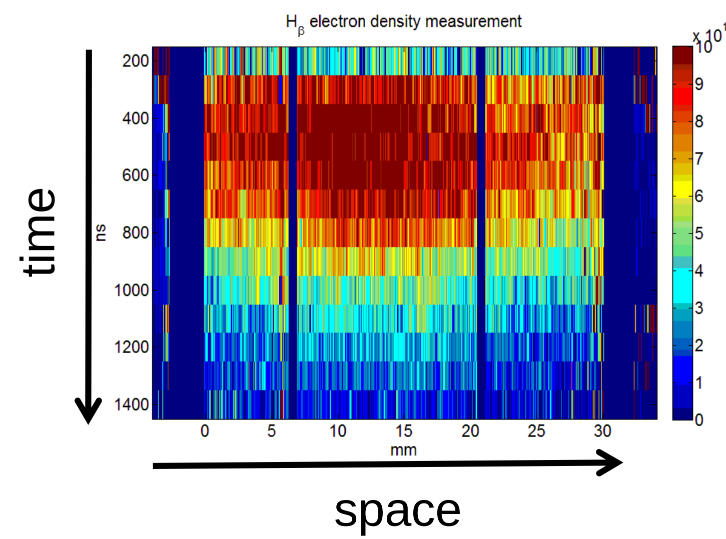
Hβ weaker signal, but more insensitive to temperature

Gigosos et al., Spectrochimica Acta part B, 58 (2003)

Stark broadening



Single-shot measurement
Allows to detect spatial variations

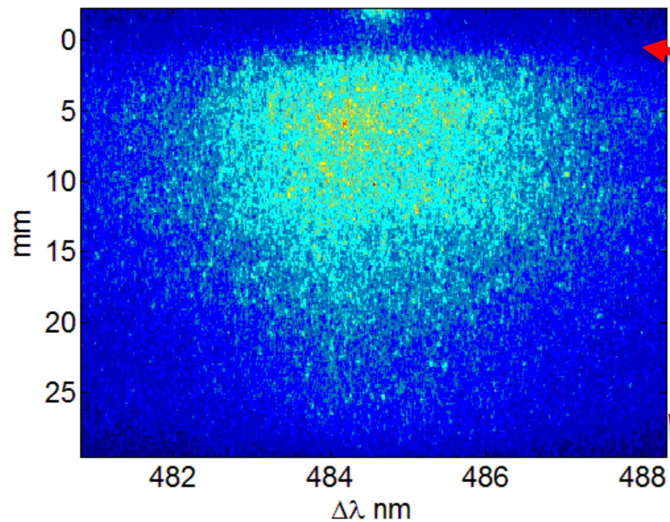


ISTAR Intensified gated camera
100ns gate time

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

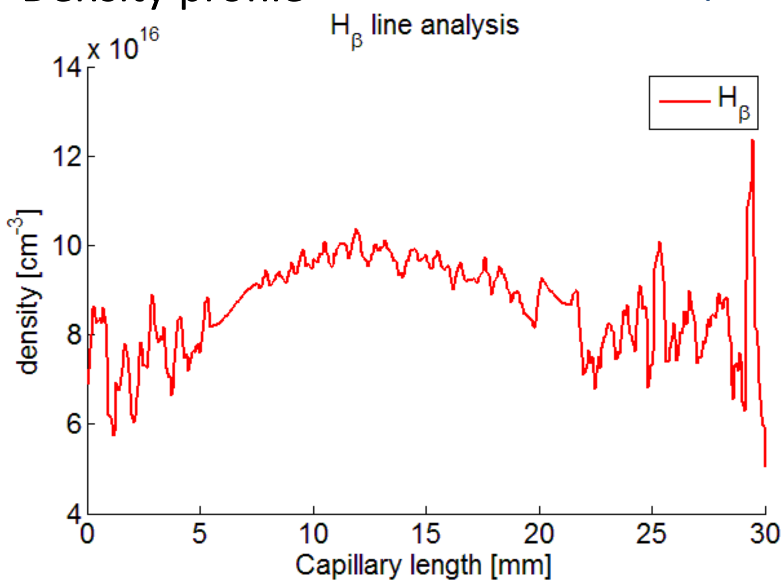
Stark broadening

Spectrogram

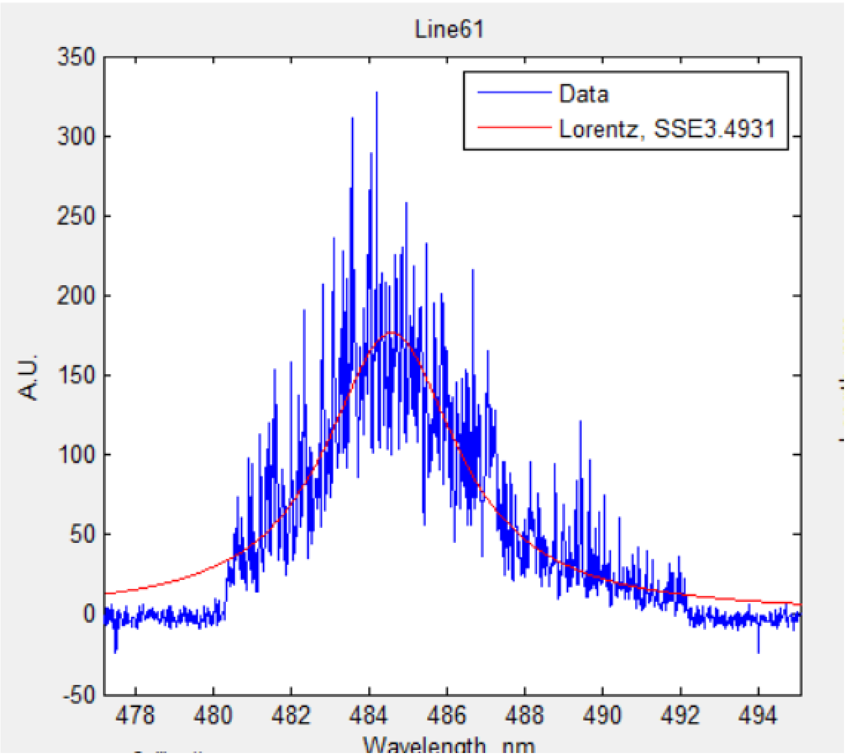


Electrode shadows

Density profile



Single lineout



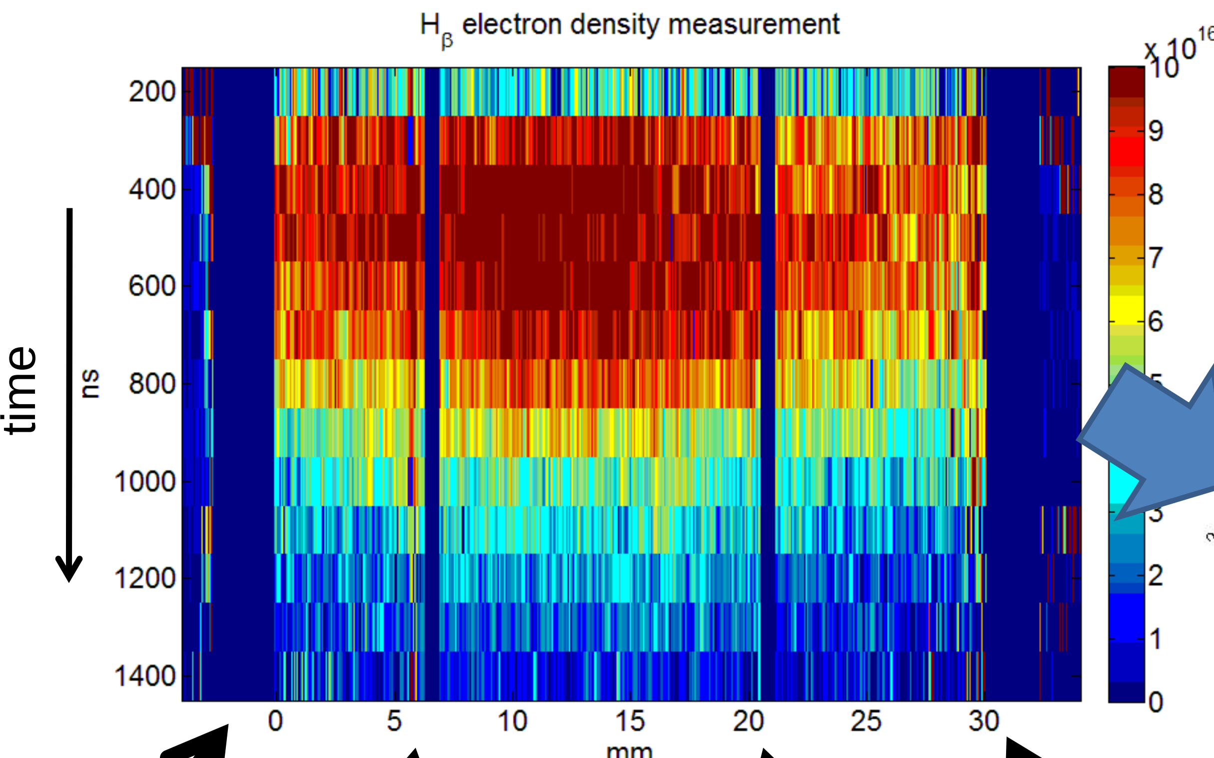
0.017 dispersion [nm/px]

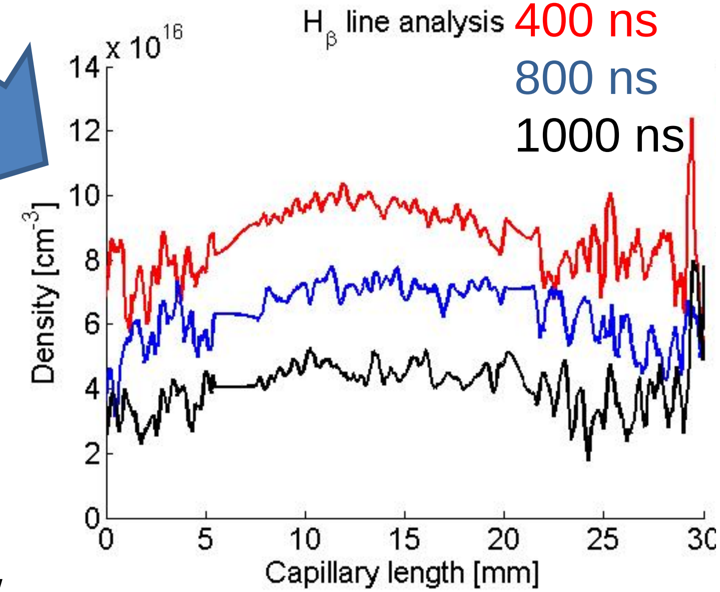
0.125 spatial res. [mm]

100ns temporal res.

Stark broadening

Temporal and spatial characterization of the plasma





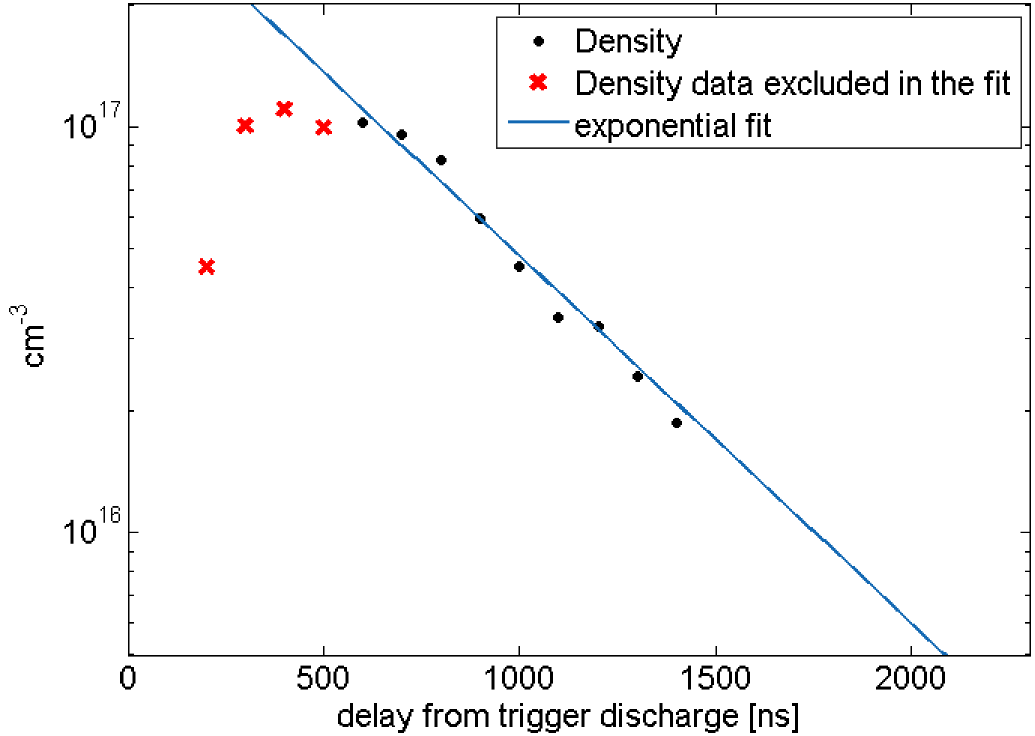
Shadows of wires put on the capillary as reference

Shadow of the positive electrode

Shadow of the negative electrode

Stark broadening

Temporal and spatial characterization of the plasma



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

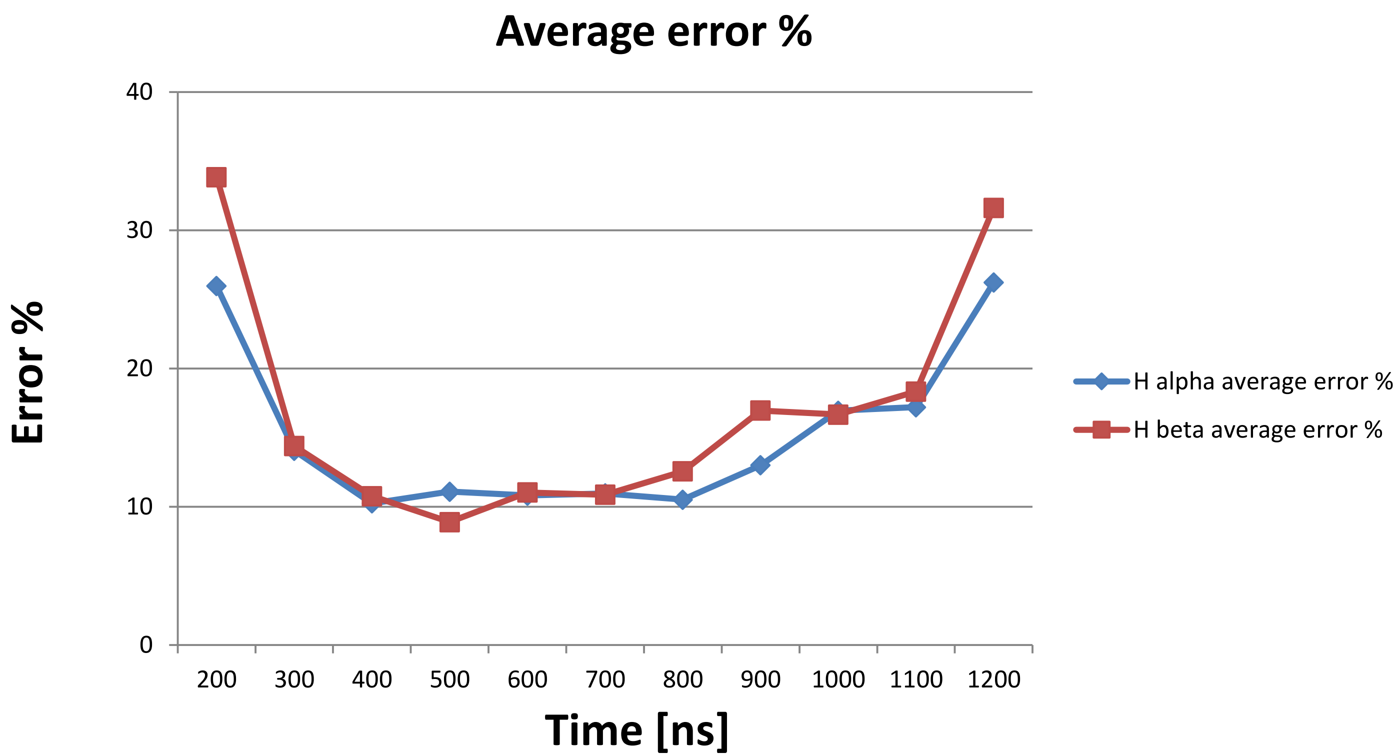
τ= 479 ns

To reach the correct density need to know the decay of the plasma density

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

Shot to shot variation

Error values averaged over 14 mm in the middle of the capillary for different time delay with respect to the discharge trigger.

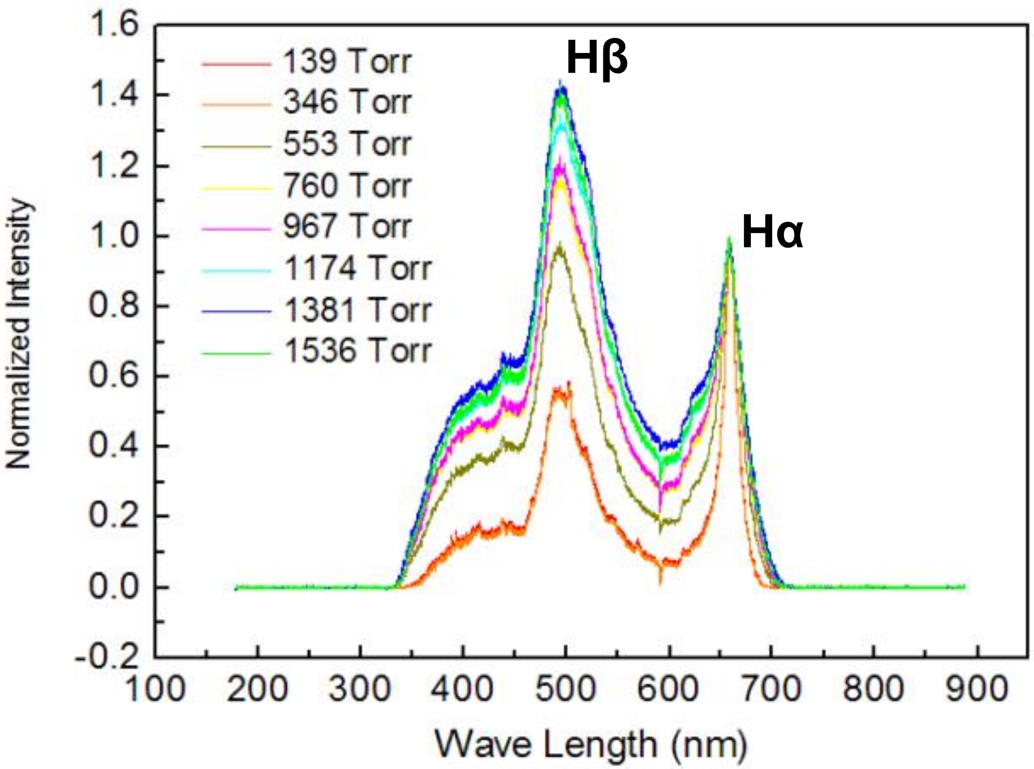


JINST 11 C09015 (2016)
dx.doi.org/10.1088/1748-0221/11/09/C09015

Balmer lines ratio

The ratio between the emitted lines gives the free electron temperature.

The acquiring system must be absolutely calibrated!



Balmer lines ratio

Assuming the LTE it is possible to measure the plasma **temperature** from the ratio of the intensities of the spectral lines emitted by an element with same degree of ionization.

Emission factor

$$\epsilon_{nk} = \frac{h\nu_{nk}}{4\pi}\frac{A_{nk}g_n}{S}N\exp\left(-E/kT\right)$$

Parameters depending on emitter atom and the excited states

Emitter density

Energy

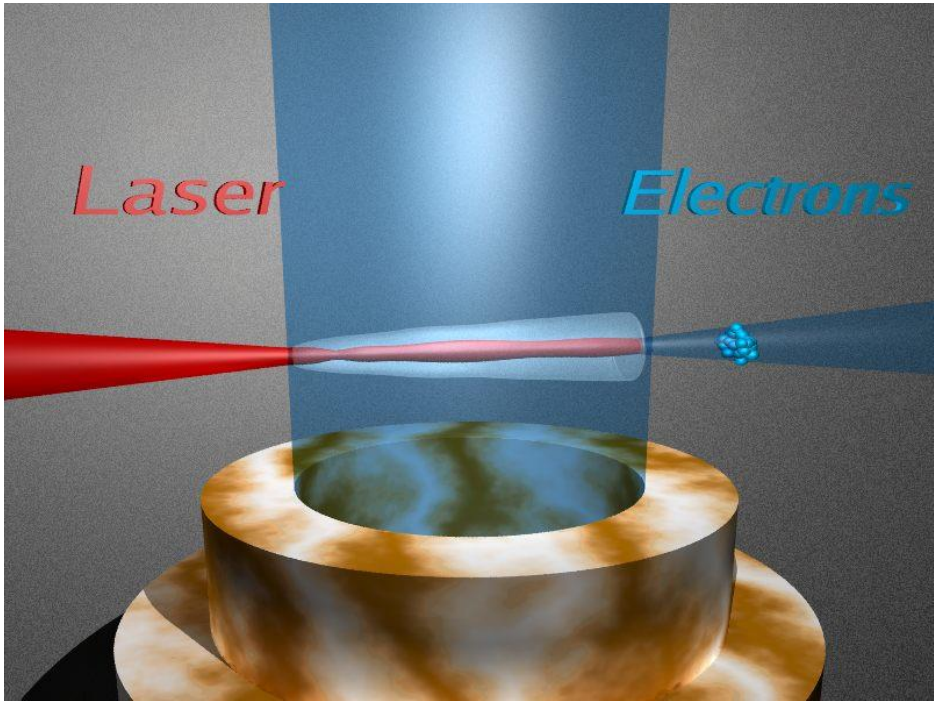
Temperature

$$T\,[eV] = \frac{E_{nk} - E_{hk}}{\ln\frac{\nu_{nk}A_{nk}g_n}{\nu_{hk}A_{hk}g_h} - \ln\frac{\epsilon_{nk}}{\epsilon_{hk}}}$$

Gas jets

It allows to control gas flux in order to obtain densities of the order of $n_e \approx 2 \times 10^{19}$ cm^{-3}. Mainly used for self injection LWFA.

Transverse direction is accessible!



Transverse probe diagnostics are commonly used

Interferometry

The refractive index of the plasma at a given λ depends on its electron density.

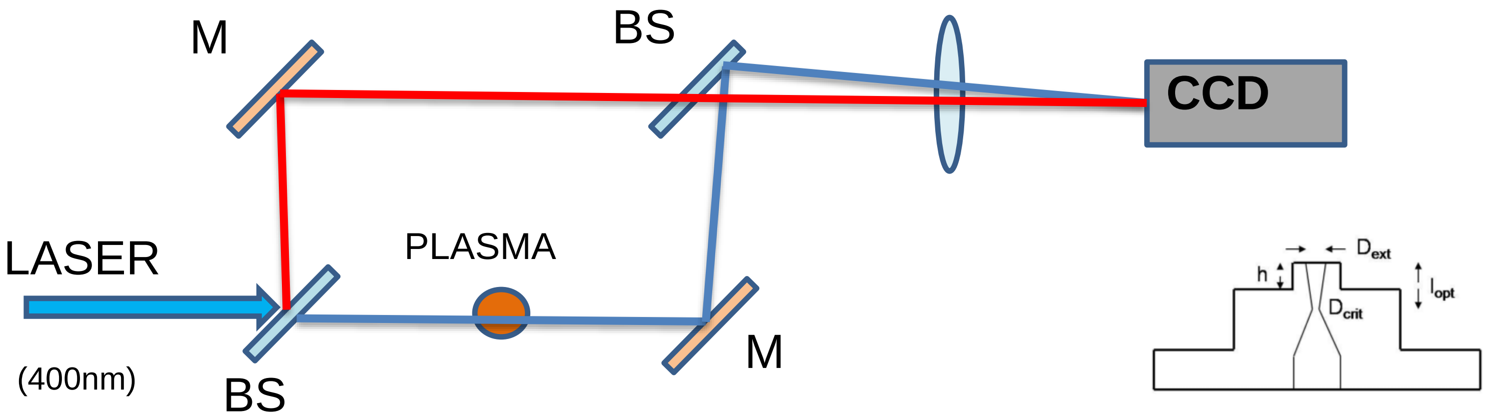
PLASMA REFRACTIVE INDEX

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

Free e⁻ density → n_e

Critical density → n_c

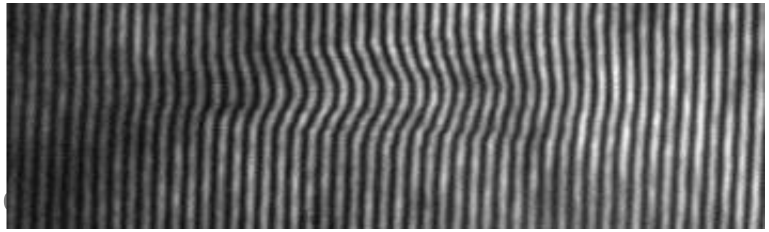
Mach-Zehnder interferometer



Supersonic gas-jet

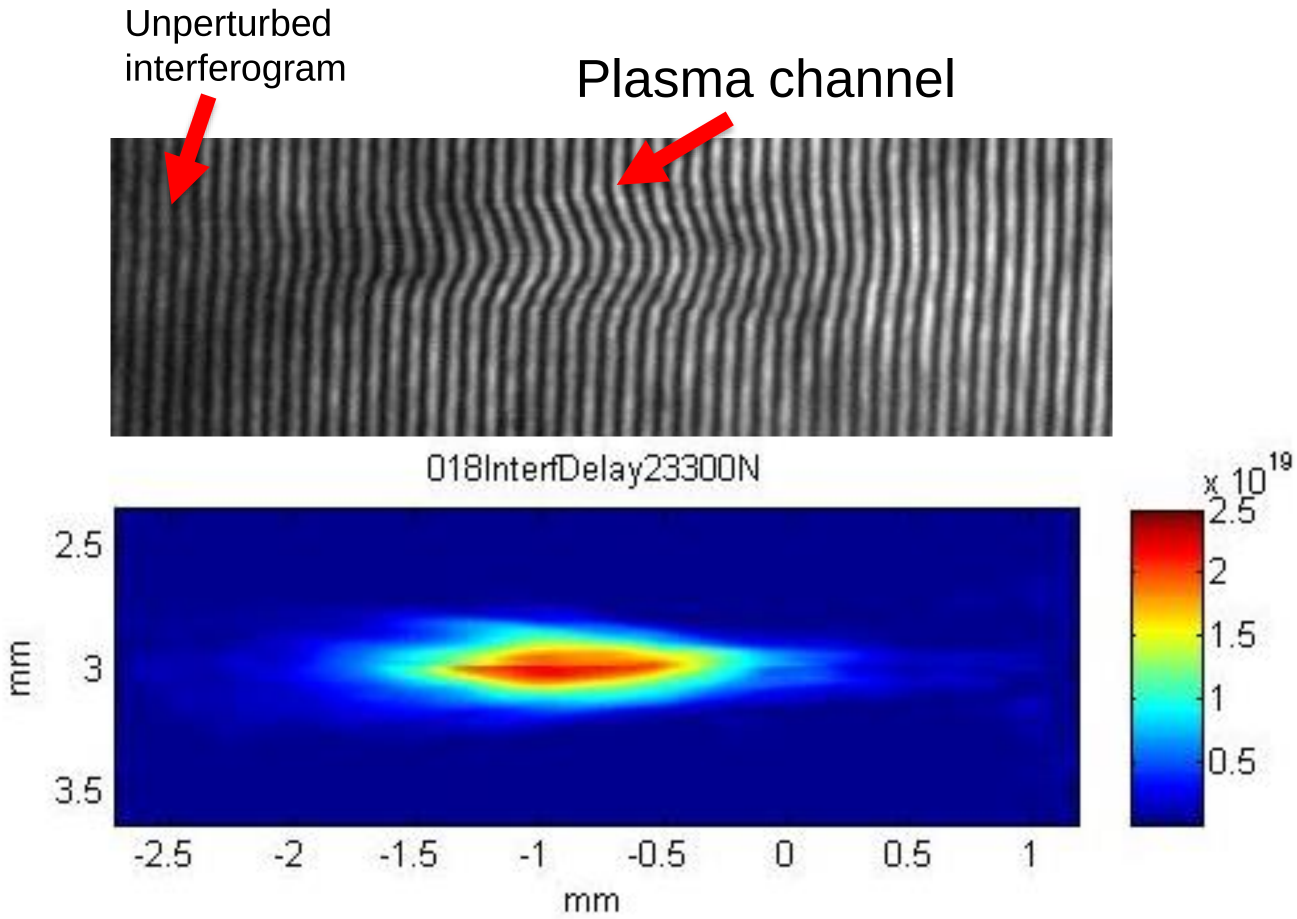
The refractive index variation causes a dephasing that is directly related to the electron density

$$\Delta\phi = \frac{2\pi}{\lambda}\int_{z_1}^{z_2}\frac{n_e(z)}{n_c}dz$$



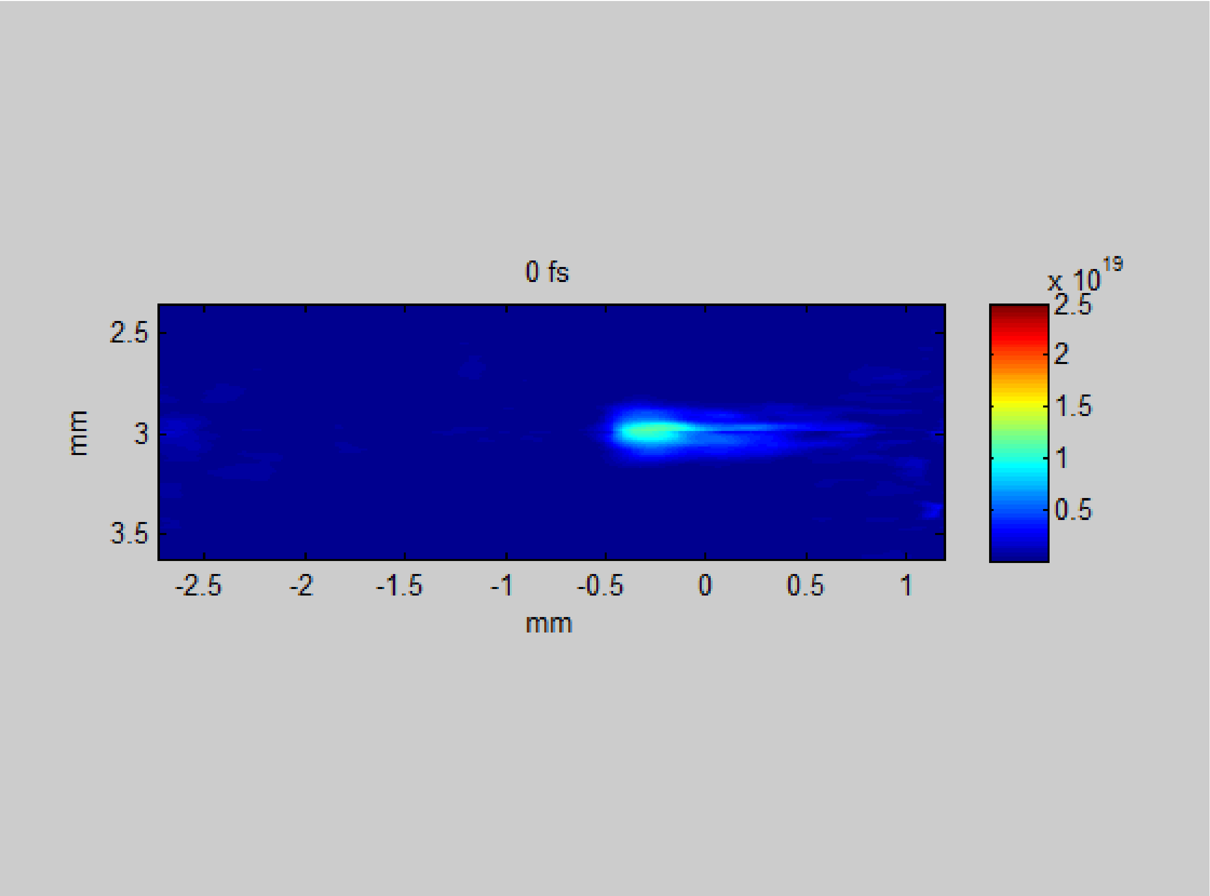
Interferometry

Abel inversion allow to reconstruct the plasma density assuming cylindrical symmetry



Interferometry

Snapshot of the laser evolution inside the gas is possible with multishot acquisition.

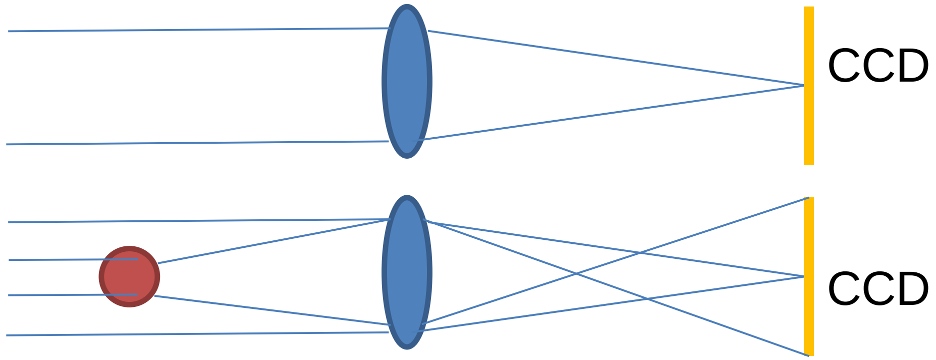


Spatial resolution is given by the imaging system

Temporal resolution is given by the probe duration

Shadowgraphy

Refractive index is determined from the angle of deviation of the light from its initial direction.



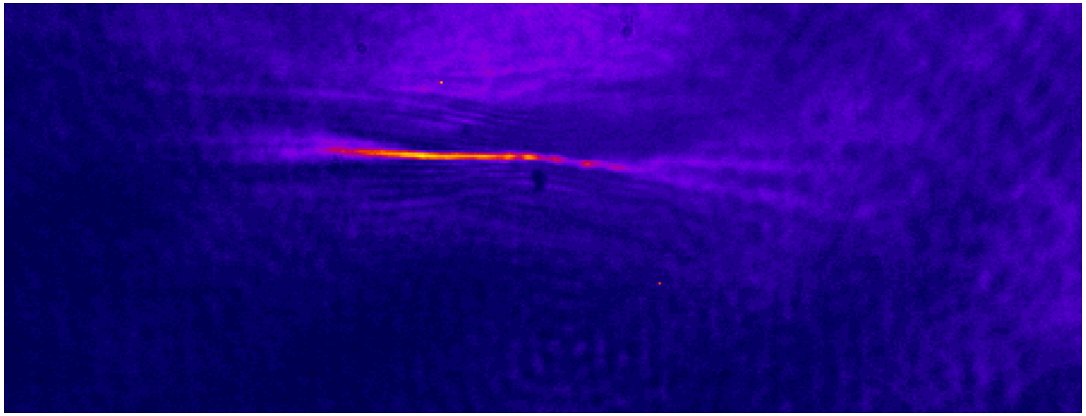
Refraction angle $$\alpha = \int_0^L \frac{1}{n_e} \frac{dn}{dx} dz$$

Intensity var. $$\frac{\Delta I}{I} = L \cdot \int_0^L \frac{1}{n_e} \left[\frac{d^2 n}{dx^2} + \frac{d^2 n}{dy^2} \right] dz$$

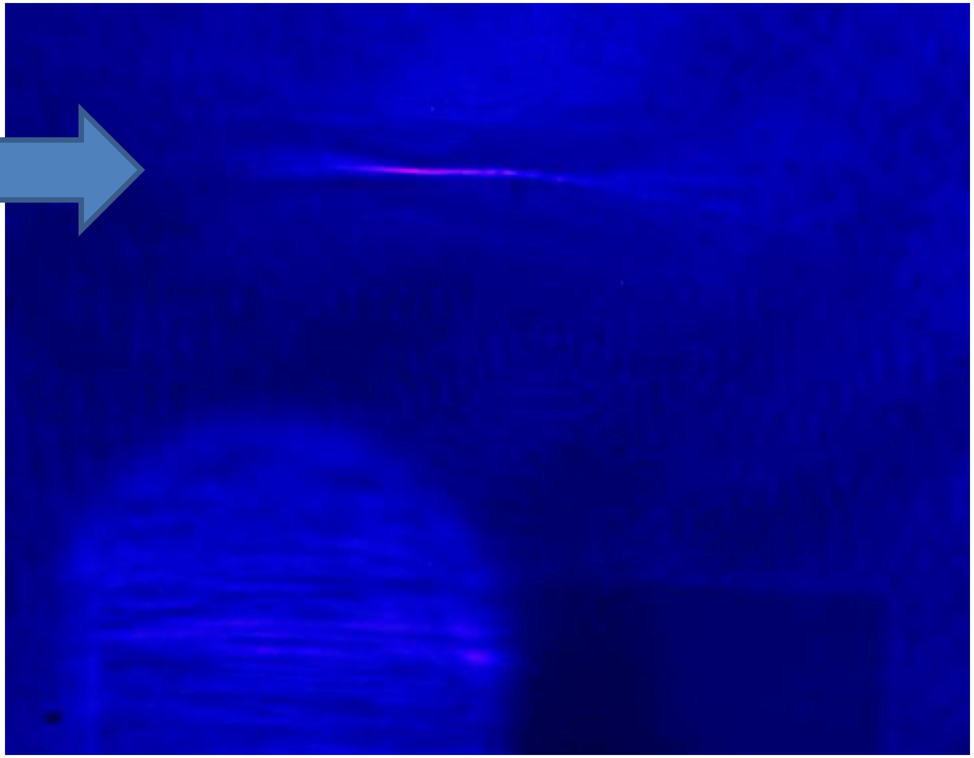
The defocusing effect of the plasma produces a shadow on the CCD.
It allows only for qualitative analysis! (not reliable for quantitative)

Shadowgraphy

The self emitted light of the plasma channel is well visible on the image.



Plasma channel



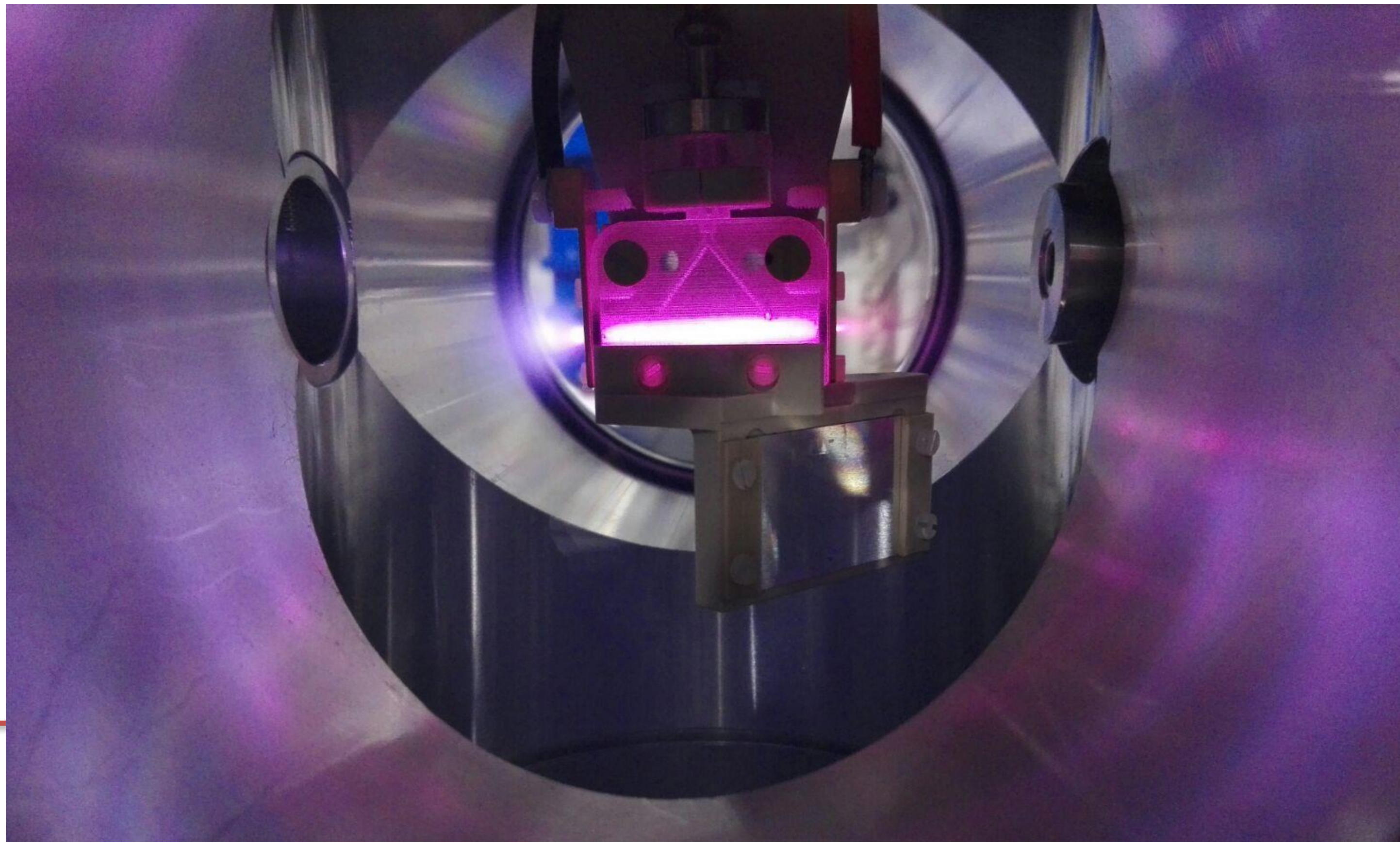
gasjet

A bit of laser impinge on it

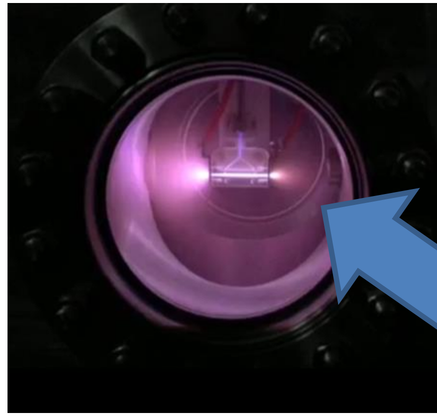
CONCLUSIONS

- Diagnostic setups for different plasma sources have been implemeted.
- The temporal and spatial evolution of plasma density in gas-filled capillaries has been studied.
- Plasma temperature in hydrogen plasma is going to be examinated.
- Plasma density in gas-jets has been measured and characterized with interferometric and shadowgraphyc technique.

THANKS FOR YOUR ATTENTION!

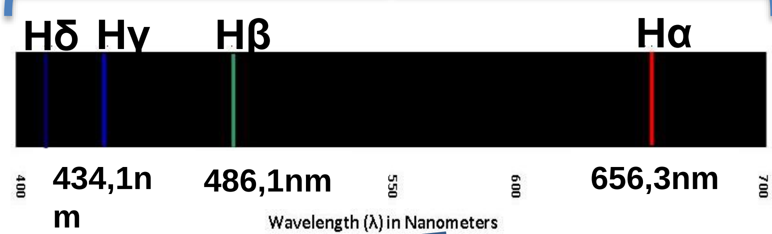


Stark broadening

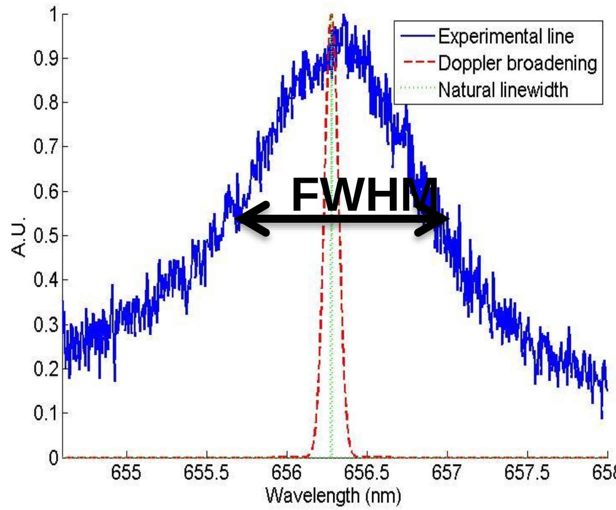


H2 gas

20kV



Suitable for densities between **10^{14} cm^{-3}-10^{18} cm^{-3}** due to fine structure effects and plasma self absorption. Suitable for PWFA and ext.inj. LWFA!



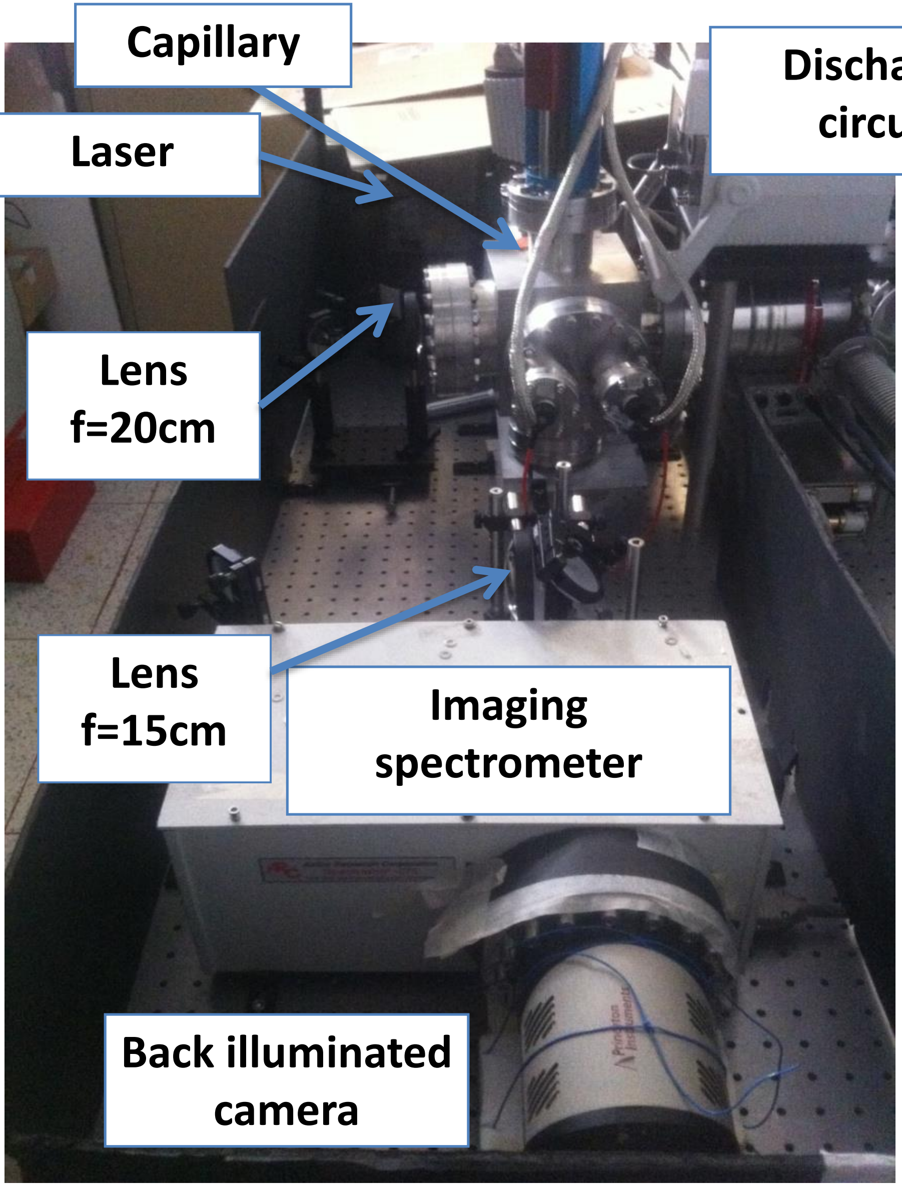
@T=4 eV

Hα stronger, but more sensitive to temperature

Hβ weaker signal, but more insensitive to temperature

Density measurement setup

Nd:Yag laser
10ns pulse
30mJ
1064nm



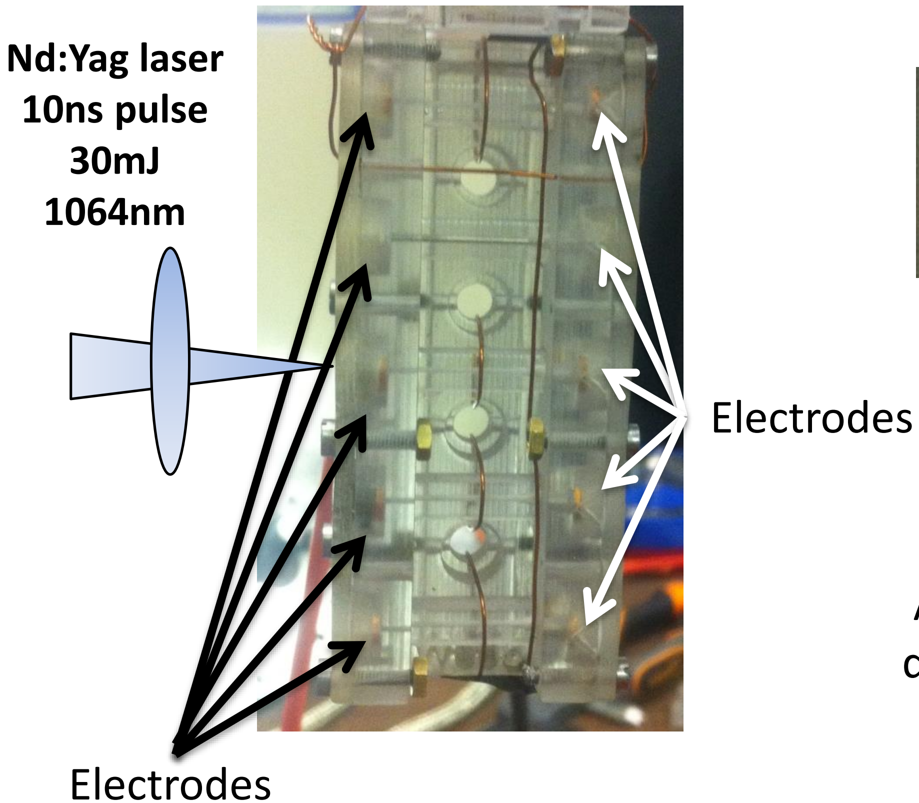
A test chamber is used

SP 275
SPECTROMETER
2400 g/mm
4,025 nm/inch

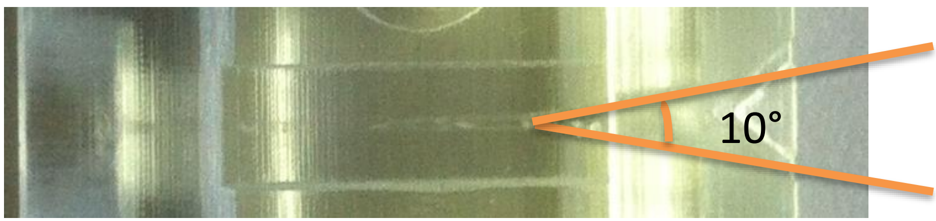
PIXIS 1300
Back Illuminated
Camera

Ablative capillaries

Set of 5 capillaries with 500um diameter.



Tapered capillary

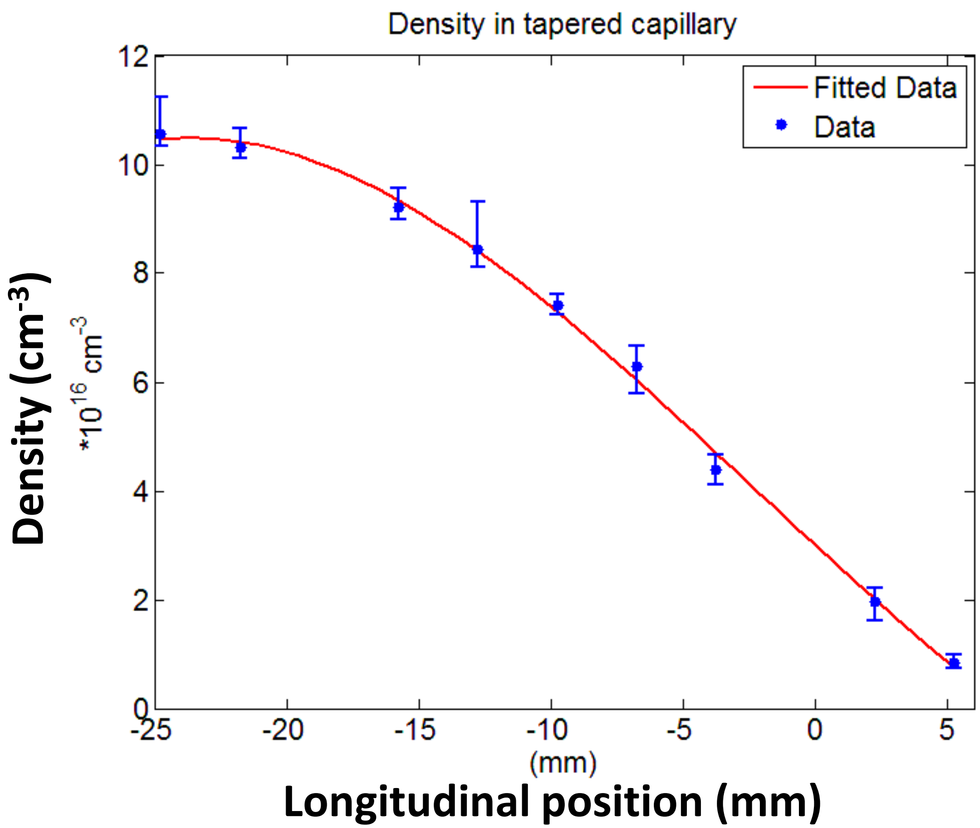


The tapering of the capillary allows to change the electron density along the capillary!

All capillaries are connected in parallel to the discharge circuit but only the one triggered by the laser produces plasma.

Analysis: results

The density variation caused by the tapering was detected.
Data were averaged over 9 shots



The results are fitted with a polynomial function of the third order

First measurements

The image acquired from the exit of the spectrometer is binned and the background (previously acquired) is subtracted.
Spatial references allow to determine the longitudinal dimension.