Laser-plasma accelerator at kHz repetition rate using a gas jet operating in continuous flow

B. Beaurepaire, A.Vernier, D. Guénot A. Lifschitz, J. Faure
M. Bocoum, F. Böhle, A. Jullien, R. Lopez Martens
Laboratoire d'Optique Appliquée
Ecole Polytechnique
Palaiseau, France

FemtoElec

UMR 7639

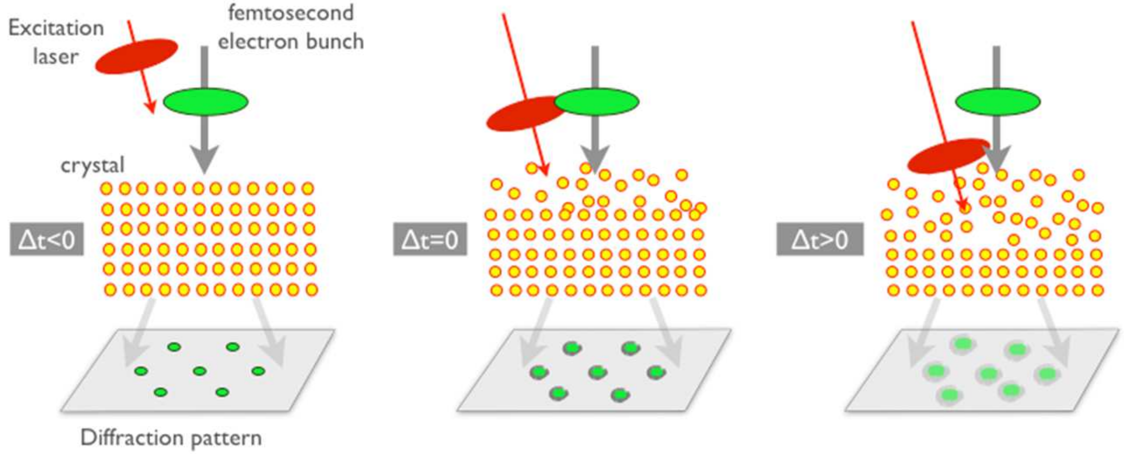
http://loa.ensta.fr/

Motivations

- Source of electrons at high repetition rate to study ultrafast dynamics in condensed matter.

Experimental technique for a microscopic understanding

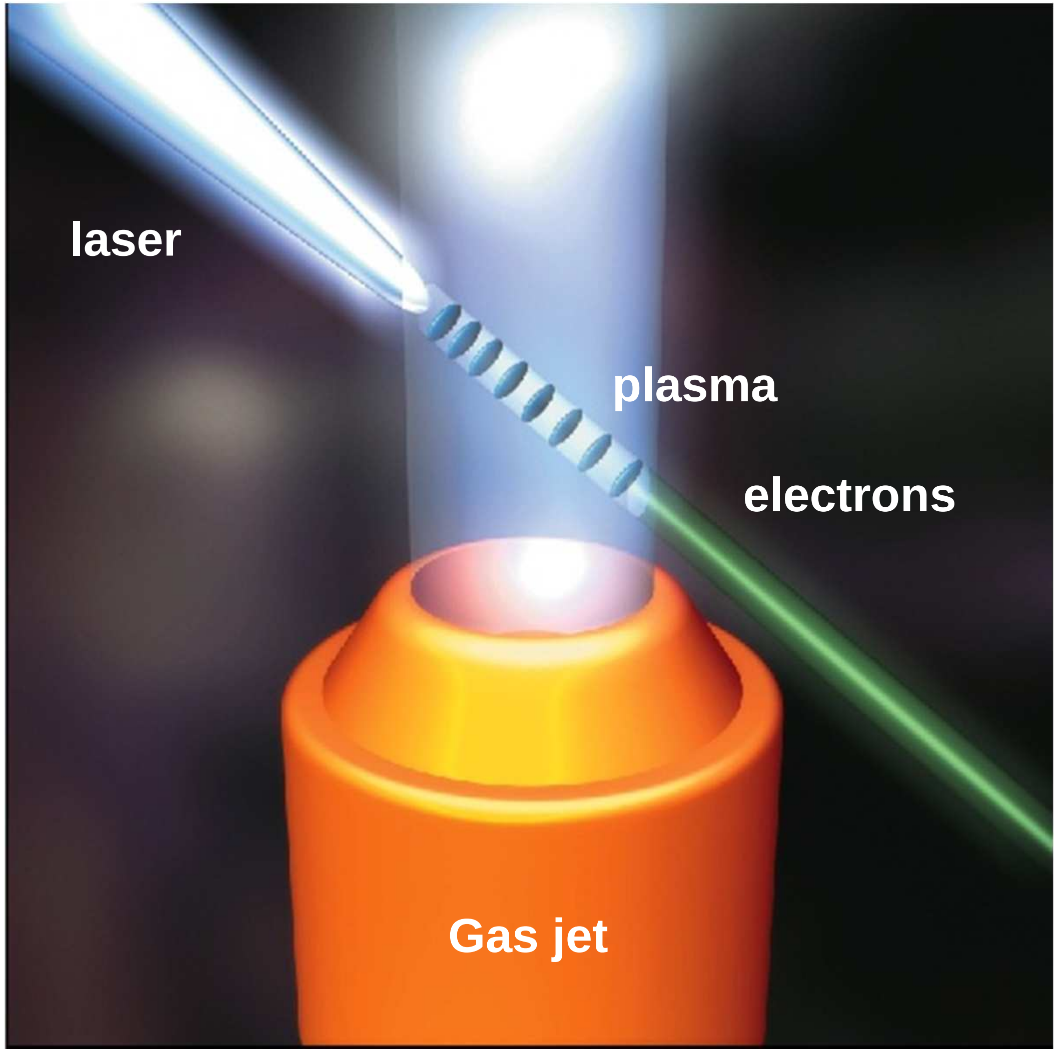
- Monitoring lattice dynamics through the Bragg peaks



- **Required parameters of the source** : designing a new source of electrons.

- time resolution< 10 fs
- energy 50 keV – 5 MeV
-rep. rate > 100 Hz
- stability < few %

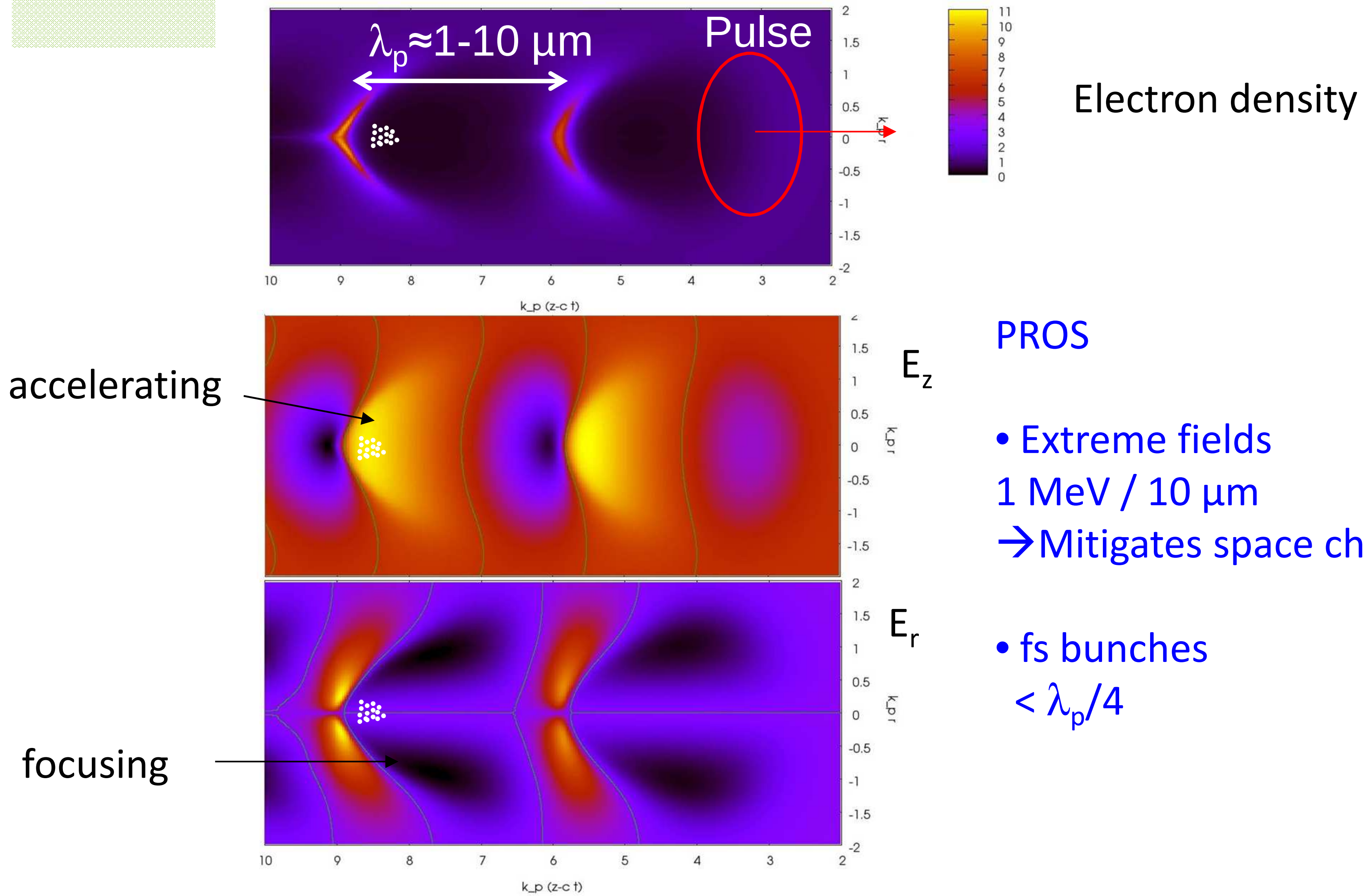
Laser wakefield acceleration



Relativistic intensity:
10^{18} W/cm^2

Short pulse:
$c\tau \approx \lambda_p/2$

Accelerating electrons in wakefields

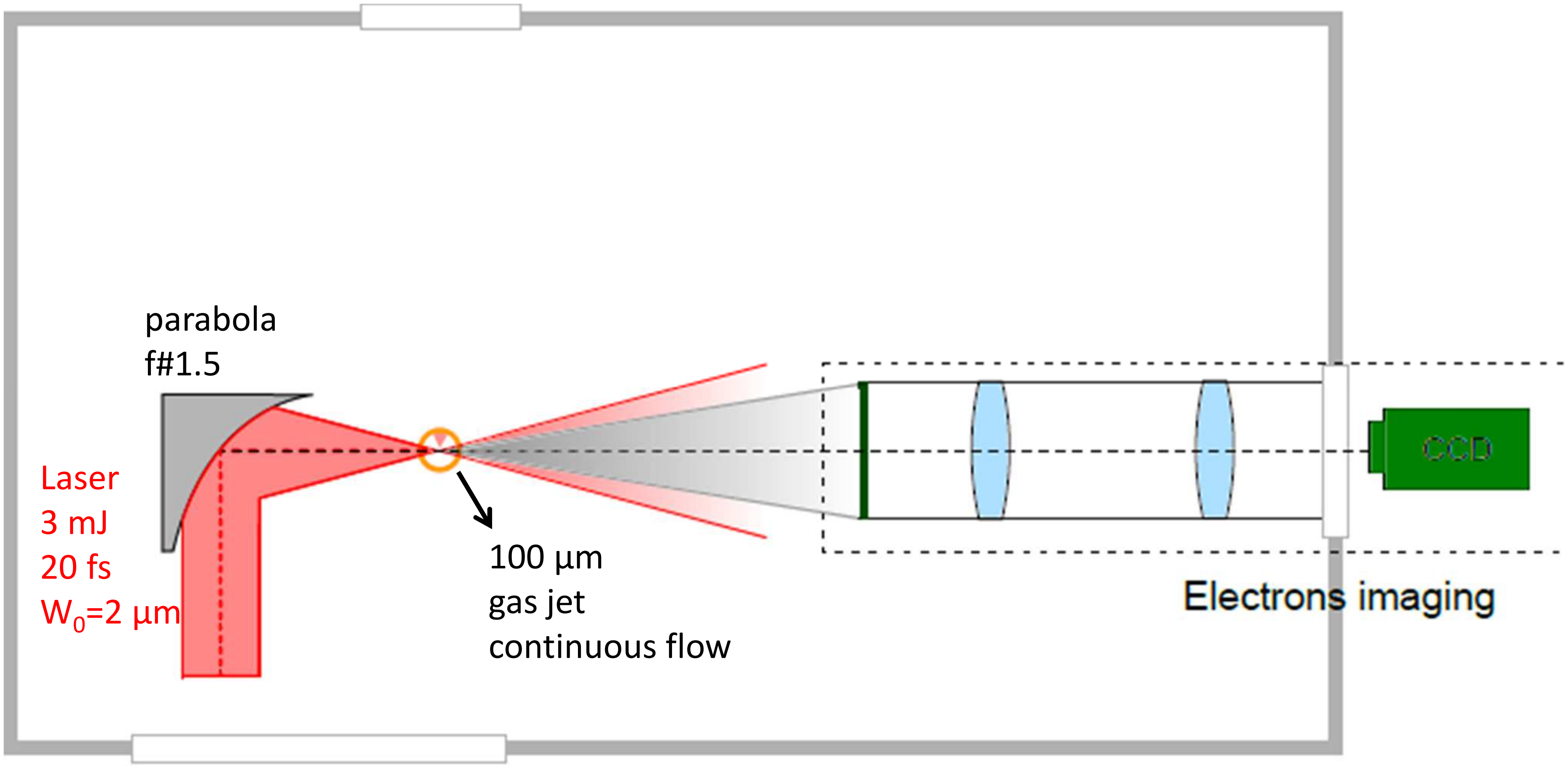


PROS

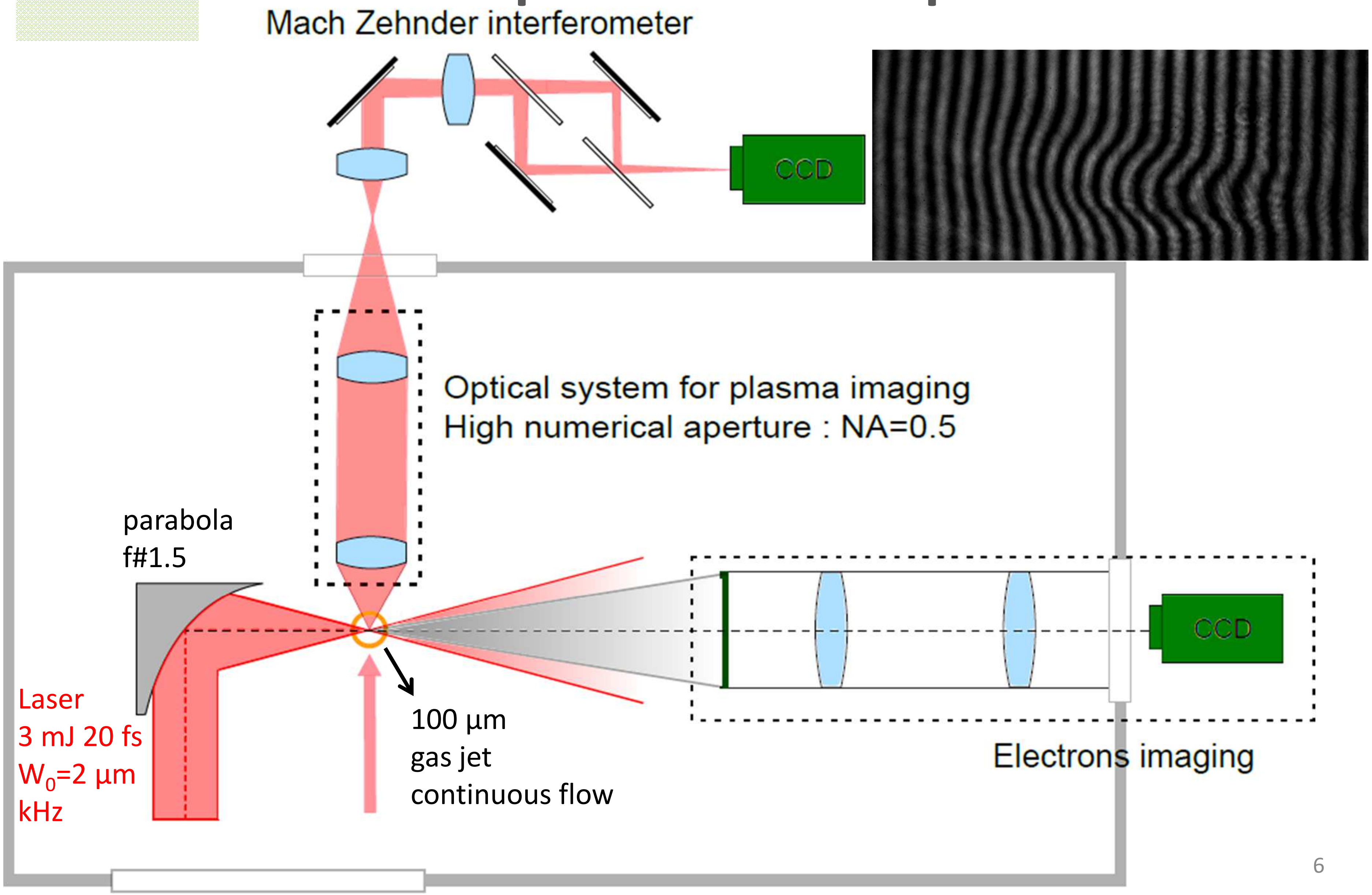
• Extreme fields
1 MeV / 10 µm
→Mitigates space charge

• fs bunches
< $\lambda_p/4$

Experimental setup



Experimental setup



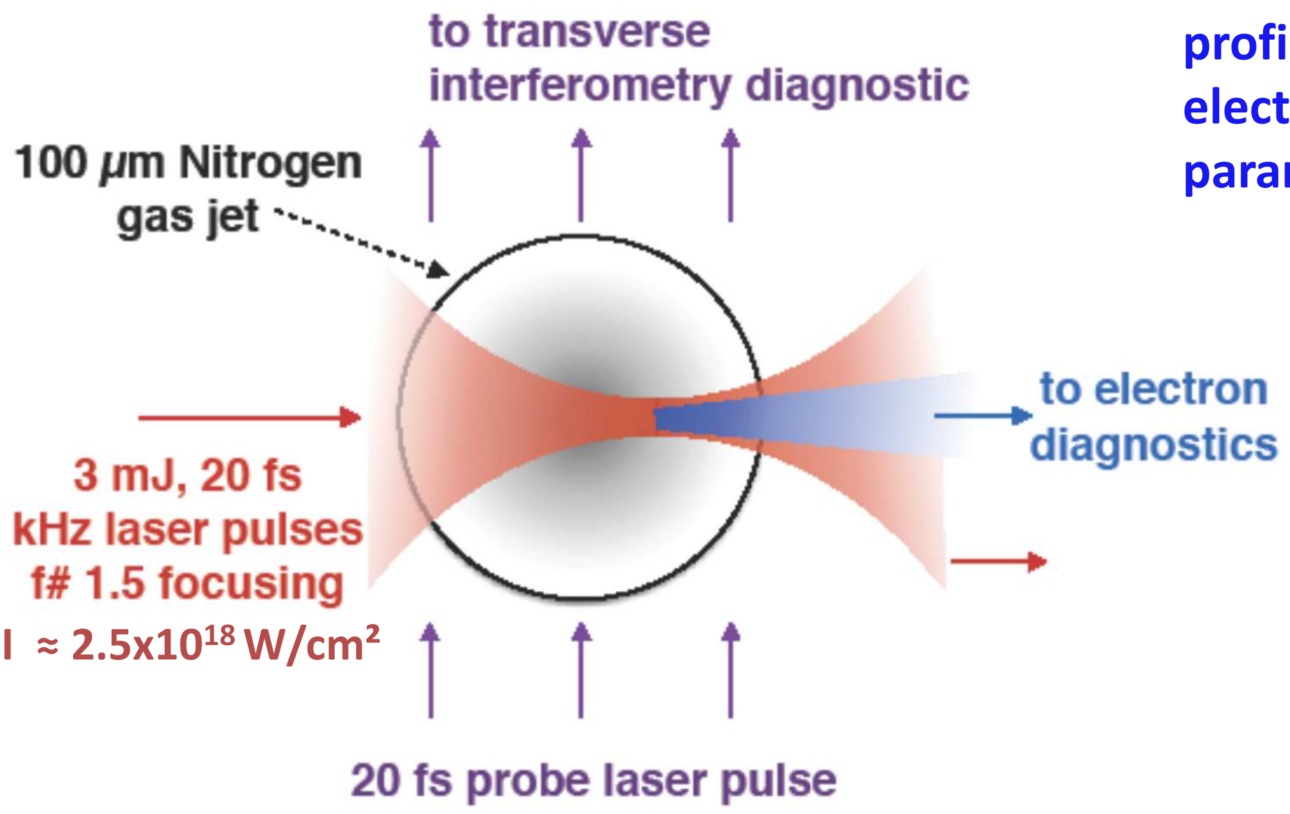
Experimental parameters

f# 1.5 parabola:

W_0 = 2 µm ➡ z_R = 16µm ➡ **Thin gas jet**

- No self focusing
- Interaction over many rayleigh ranges

What ideal density profile to accelerate electrons with these parameters ?



I ≈ 2.5x10^{18} W/cm²

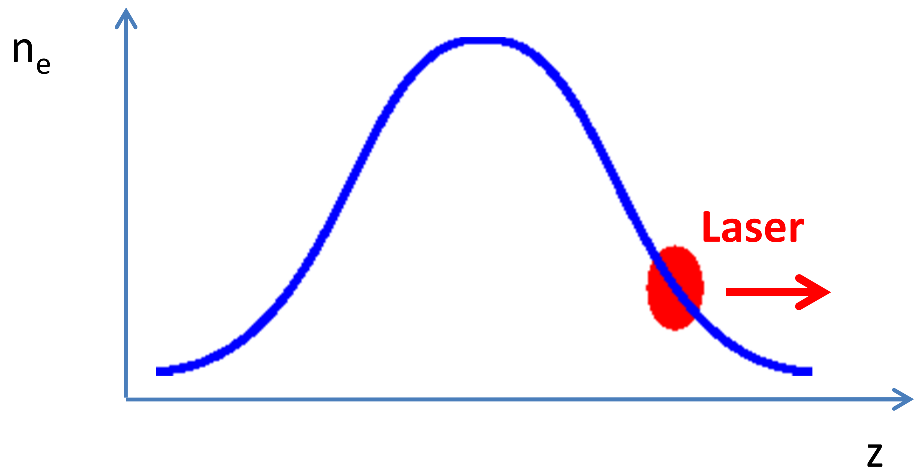
Ideal density profile

Requirements:

- A density downramp for electron injection.

No self focusing = no self-injection of electrons:

➡ We need to trigger the injection of electrons in the wakefield: by focusing the laser in the density downramp



Z. He et al., NJP **15** 05316 (2013)

Ideal density profile

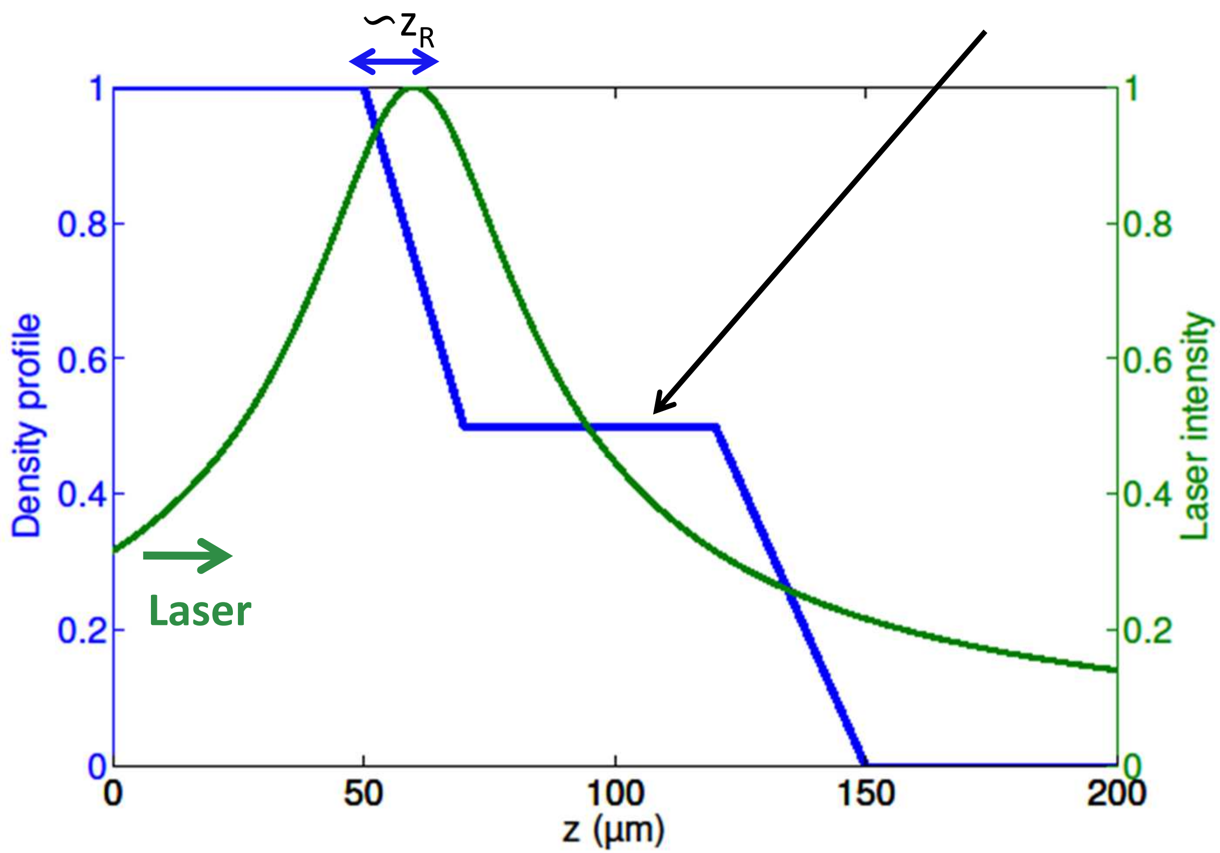
Requirements:

- A density downramp for electron injection.
- A plateau for the acceleration.

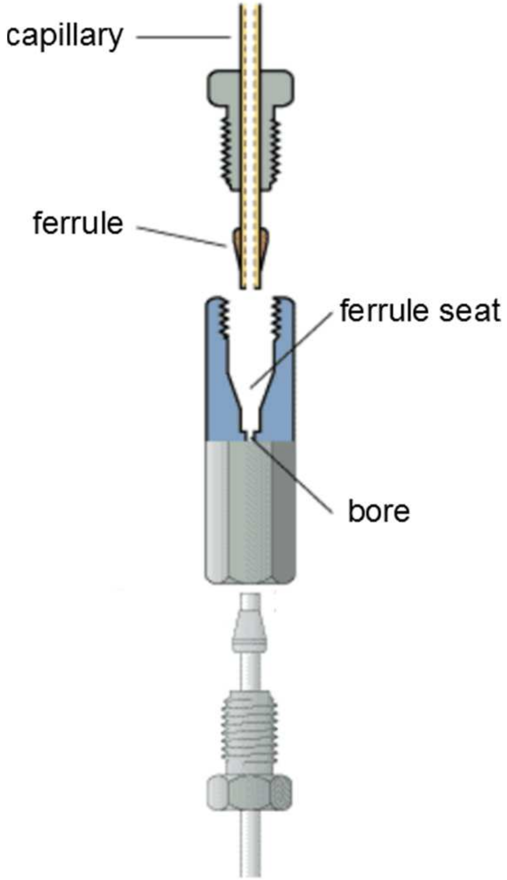
@ kHz rep. rate

Short injection zone:

Acceleration zone: L_{deph}
at resonant density ($\lambda_p/2 \sim \tau c$)

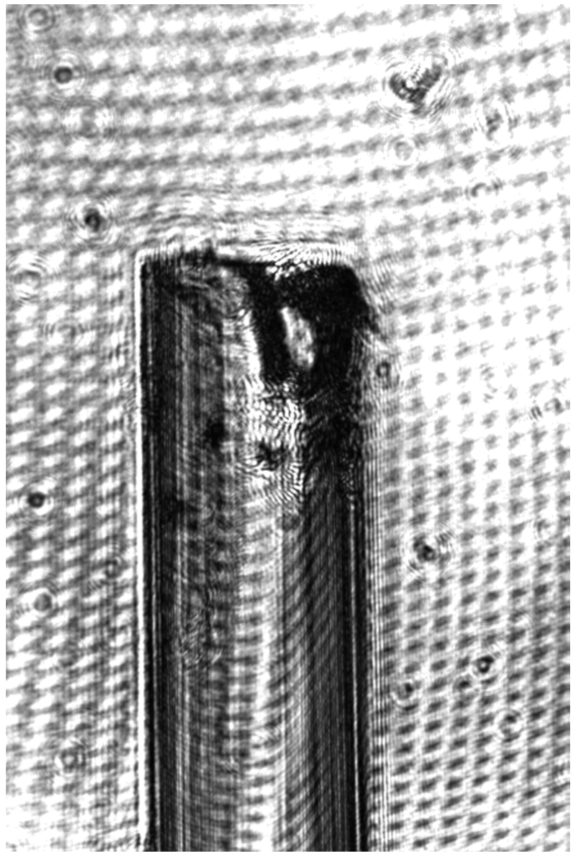


As electrons gain speed, they start dephasing with the plasma waves.
Dephasing length:
$L_{deph} \approx$ 50-100µm



Gas jet

Jet operating in **continuous flow** → kHz operation



ϕ_{ext} = 140µm

Commercial fused silica capillaries,
ϕ_{int} = 2 – 700 µm

We characterized a capillary ϕ_{int} = 100 µm

Pumping issues

Limitation on the backing pressure:

Leakeage rate through a ϕ=100µm capillary to reach a density $n_e \geq 10^{20} cm^{-3}$:

Gas	Leakeage rate (mbar.L/s)
He	22.5
N_2	1.5

Ionisation for $I_{laser} > 10^{16}$ W/cm²:
He : 2 electrons
N_2 : 10 electrons

Pumping issues

Limitation on the backing pressure:

Leakeage rate through a ϕ=100μm capillary to reach a density $n_e \geq 10^{20} cm^{-3}$:

Gas	Leakeage rate (mbar.L/s)
He	22.5
N_2	1.5

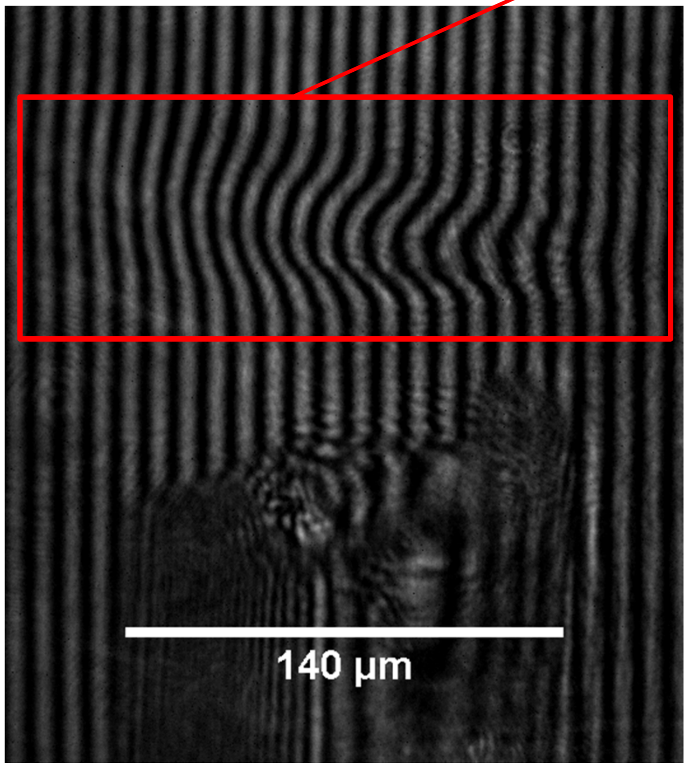
Maximal pumping speed for turbomolecular pump ∽2000 L/s

Gas	Pressure in the vacuum chamber (mbar)
He	10^{-2}
N_2	$7.5x10^{-4}$

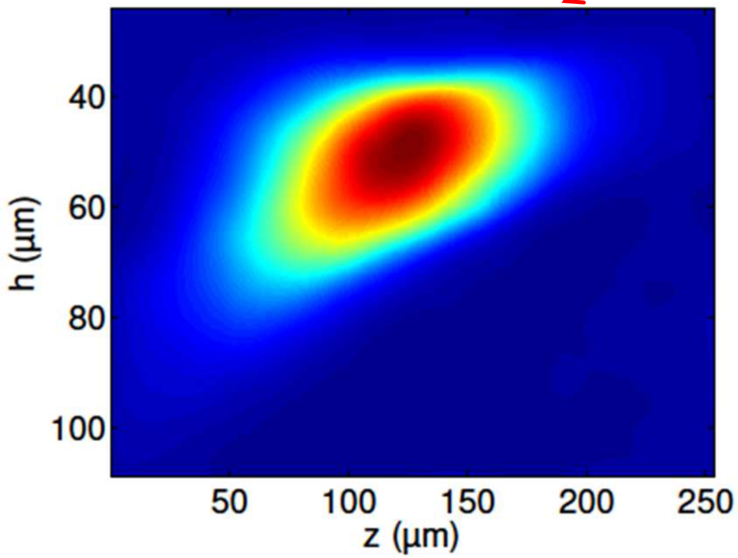
➡ **Experiments with Nitrogen**

Phase measurement

$$g(x,y) = a(x,y) + b(x,y)\cos[2\pi f_0 x + \phi(x,y)]$$



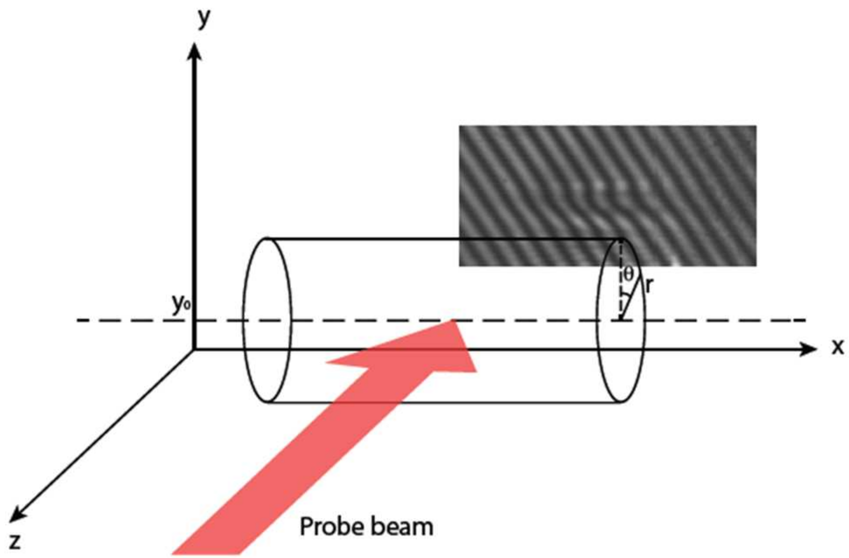
Fourier transform



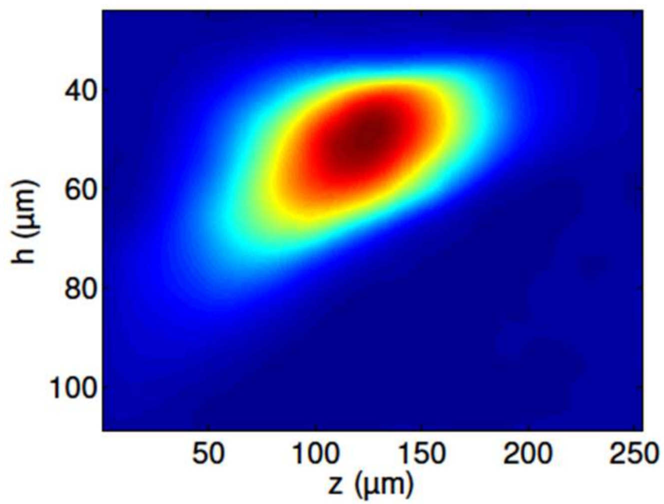
Dephasing map

Plasma density measurement

Assuming a circular symmetry of the plasma, the electronic density can be retrieved using the Abel inversion.

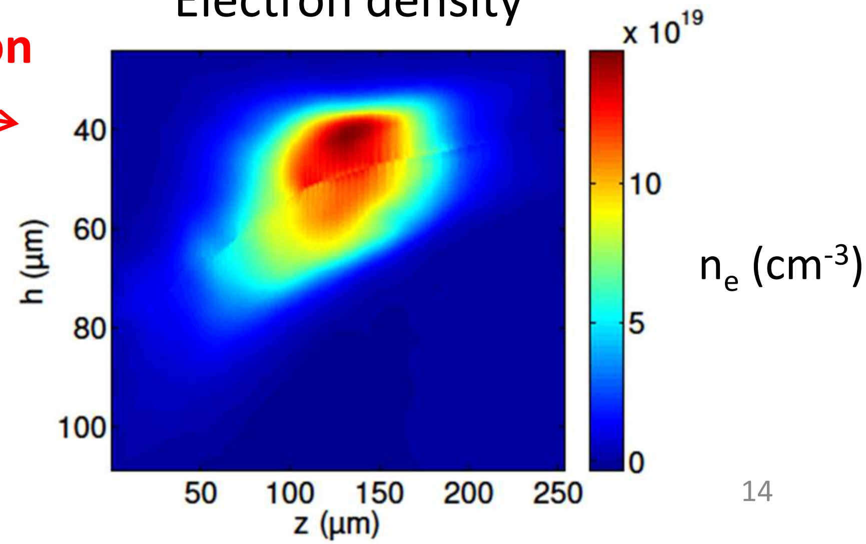


Dephasing map

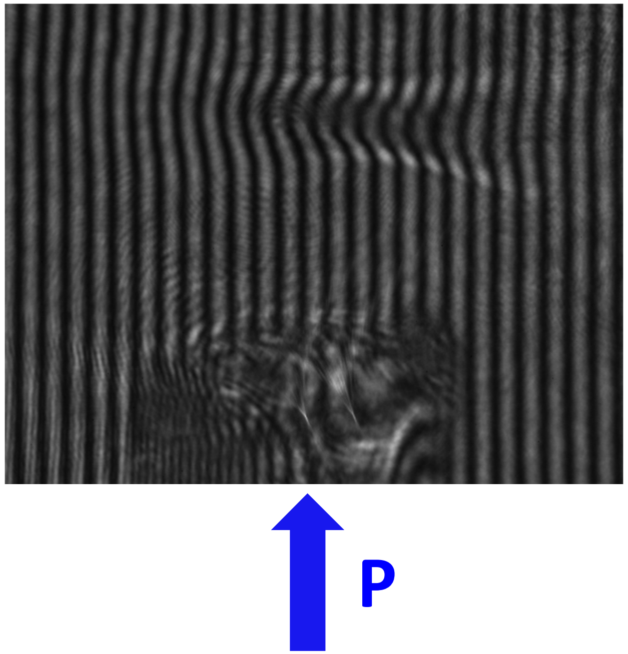


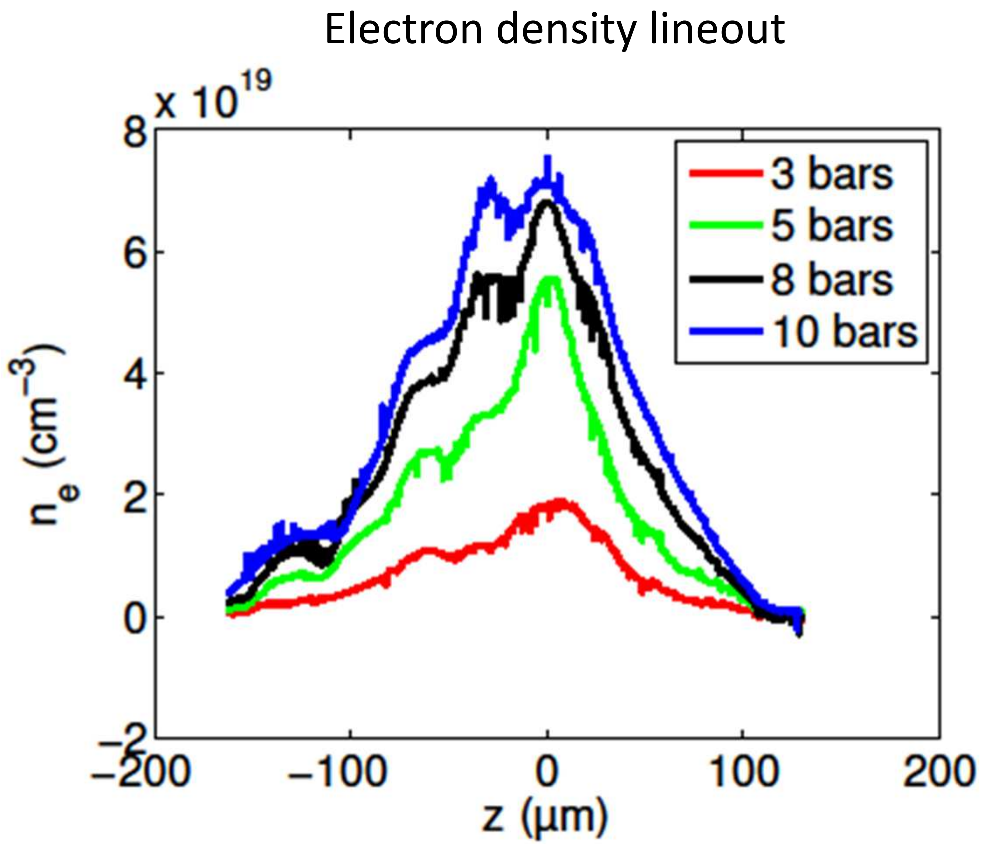
Abel inversion

Electron density



Controlling the density profile

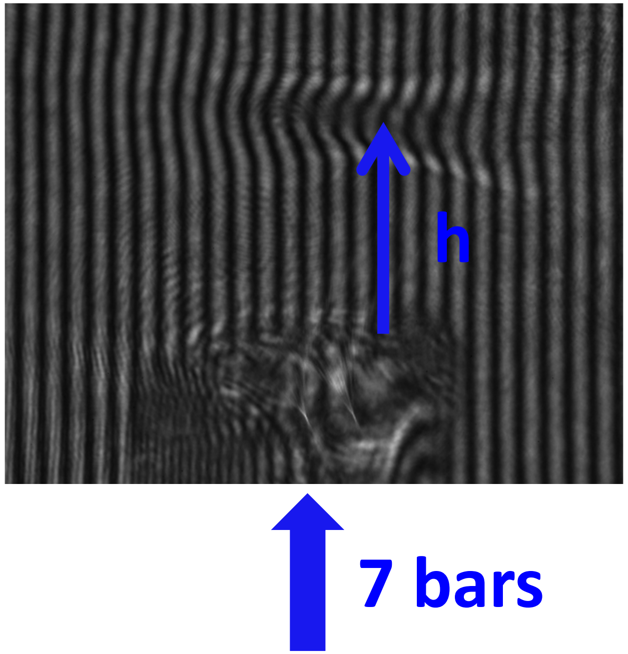




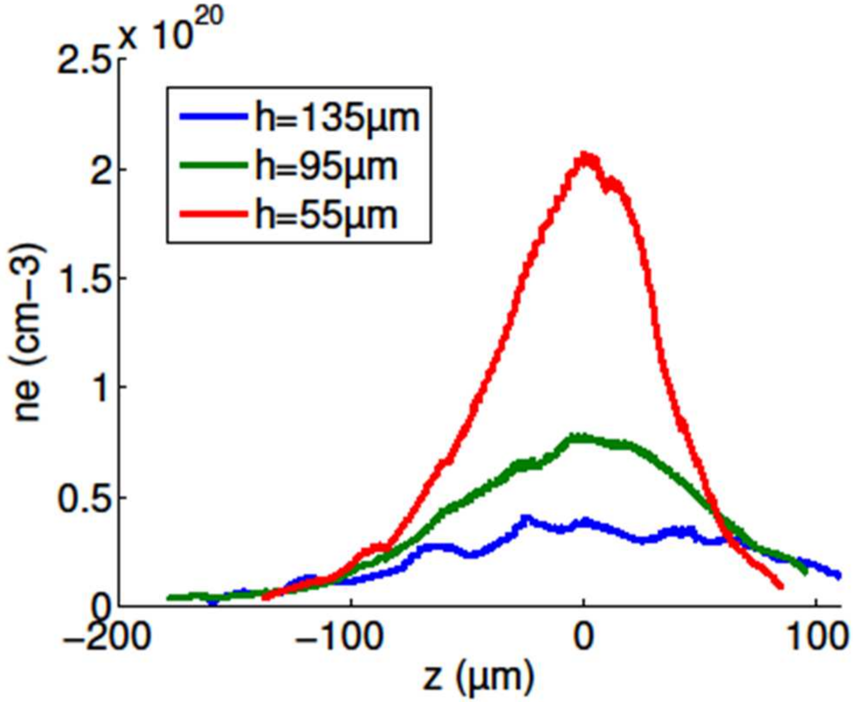
Changing the backing pressure does not increase the plasma width

Knob to adjust the gradient

Controlling the density profile



Electron density lineout



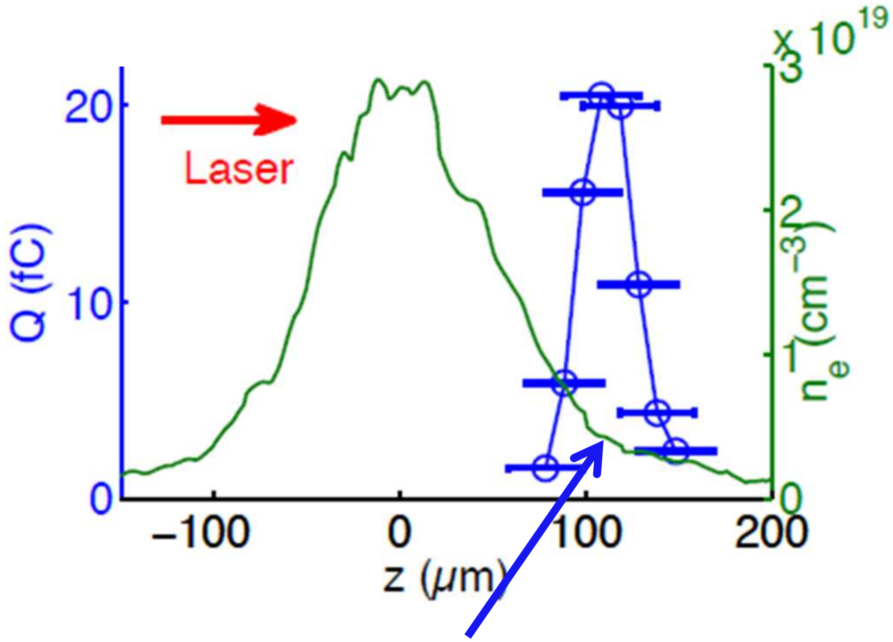
☺ High electronic density: up to 10^{20} cm^{-3} @ kHz

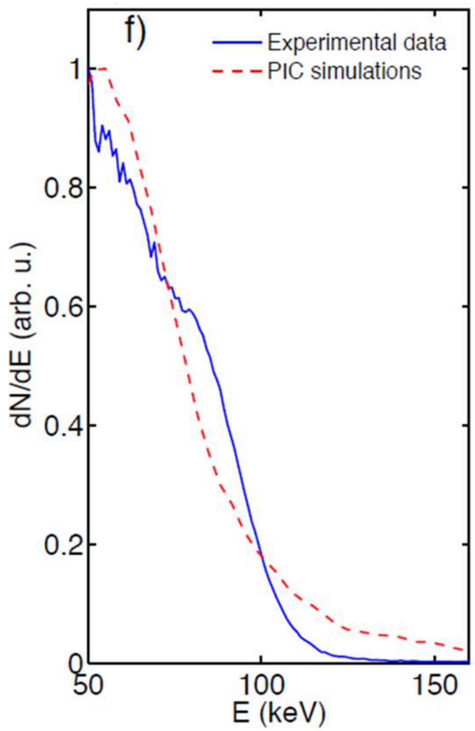
☹ The gas jet is not supersonic → no sharp gradient

Experimental results

Precise characterization of the interaction using interferograms (density profile, laser focal position).

➡ Electron injection in the density downramp.

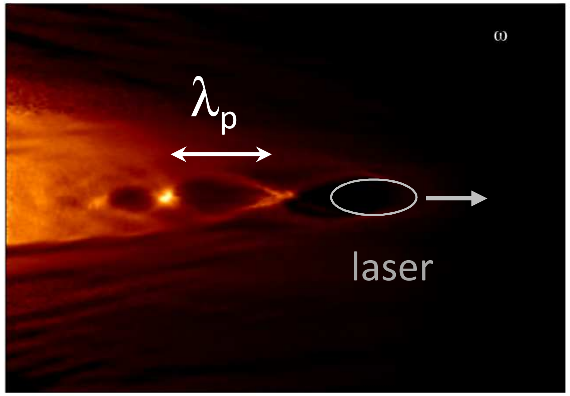




Focal plane: density for which the laser pulse is resonant with the plasma waves

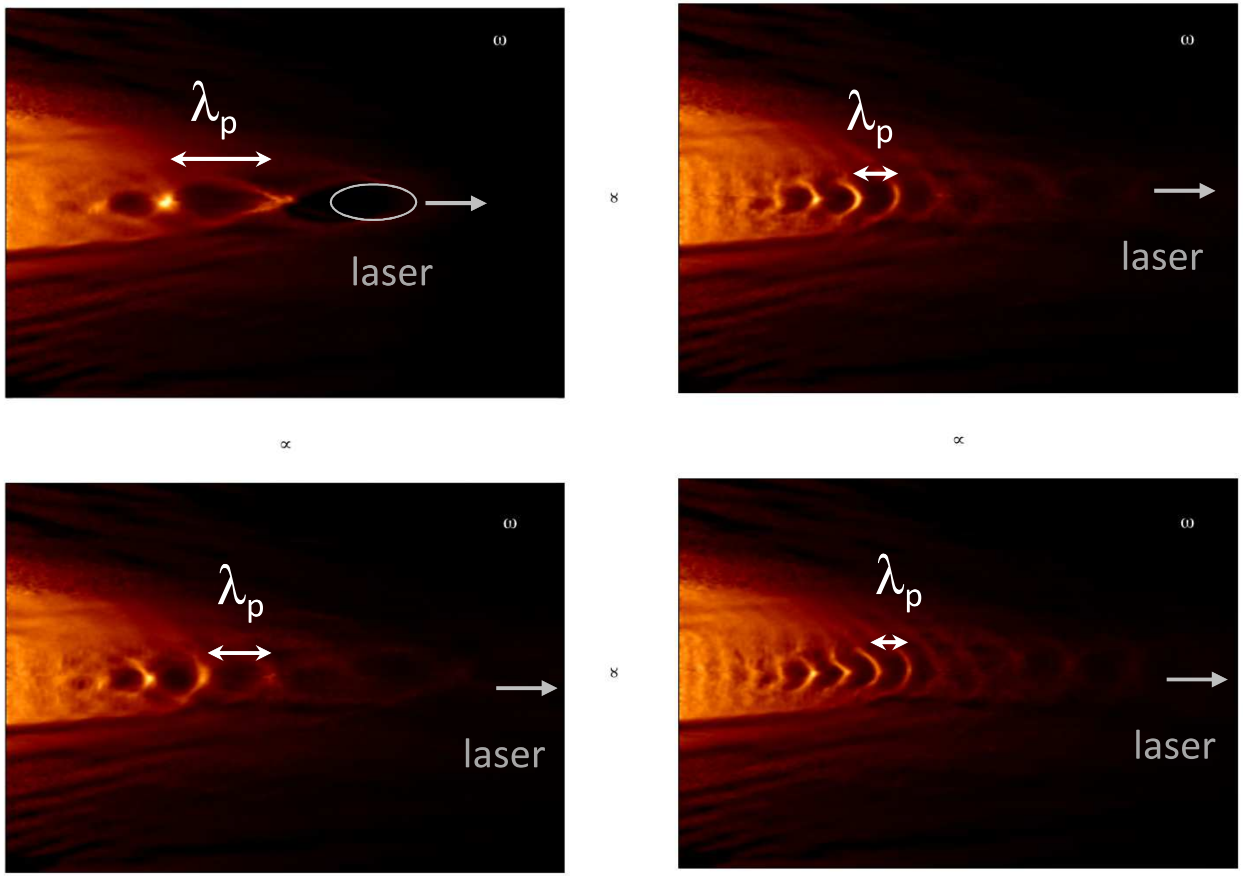
PIC simulation: Trapping in density gradient

Electron density (2D maps from PIC simulations)



PIC simulation: Trapping in density gradient

Electron density (2D maps from PIC simulations)



We see that:
$\lambda_p(t)$ decreases

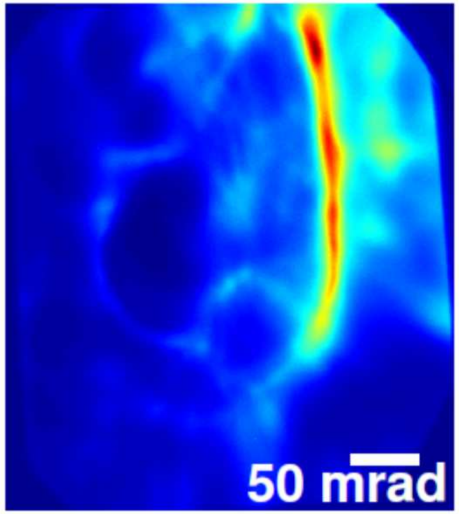
$$v_p(t) = 2\pi\omega_p\lambda_p(t)$$

Wakefield phase
phase velocity:
$v_p(t)$ decreases

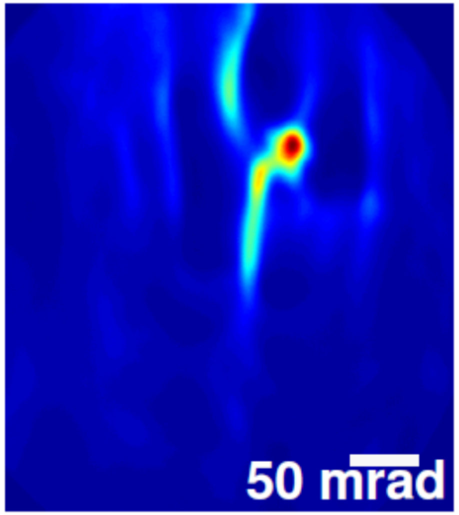
→ Trapping occurs when the wakefield slows down

Typical electron beams

50 fC, large divergence



50 fC, 10 mrad divergence

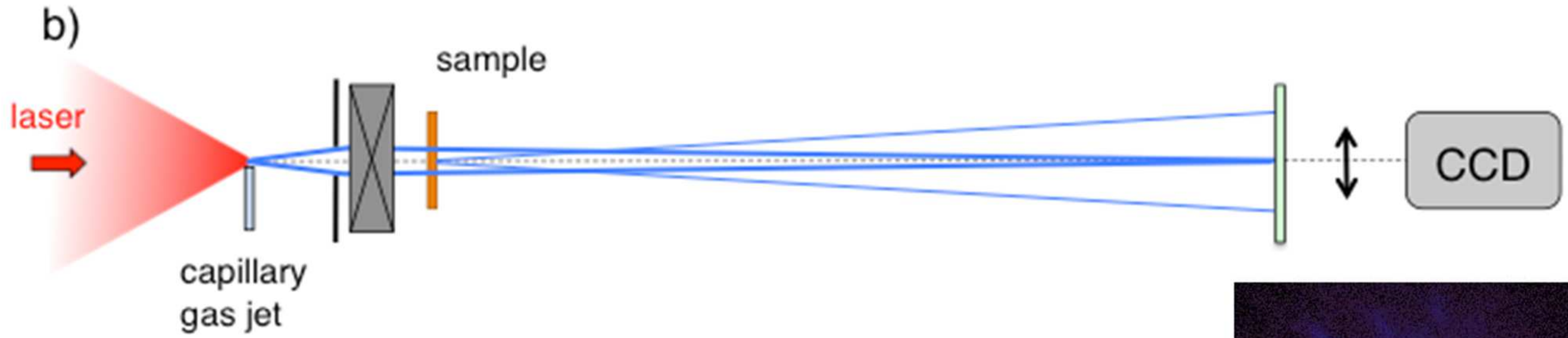


- Complex structures: holes and hot spots in distribution
- Stable ! (charge fluctuates by less than 5 %)
- Slight difference in the laser wavefront: large impact on electron beam ?

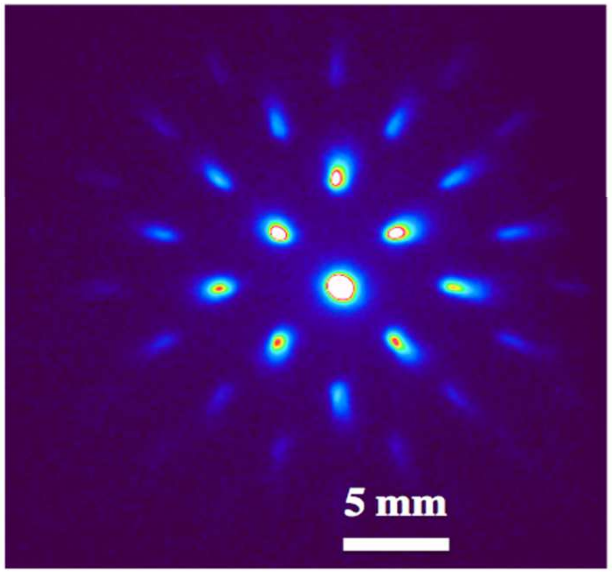
Application to electron diffraction

CUOS of University of Michigan:
Z. He, A. Thomas, J. Nees, B. Xou, K. Krushelnick

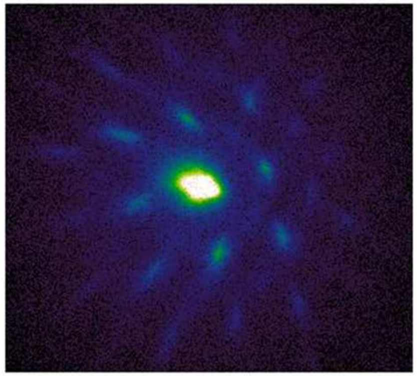
MichiganEngineering



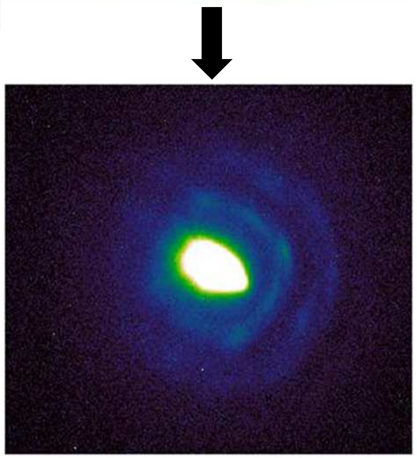
Plasma source at 100 keV, diffraction on single crystal Au sample



Z. He et al., Appl. Phys. Lett. 102, 064104 (2013)



Laser induced melting



2 gas jets experiment: preliminary results

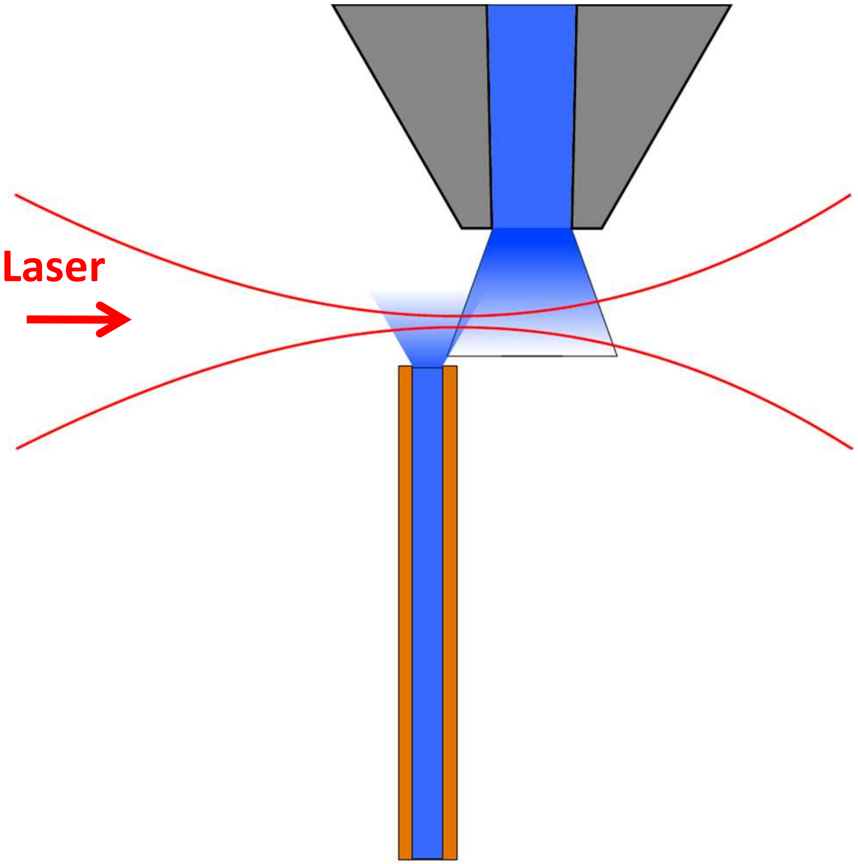
Challenge :

- **Inject electrons** in the first gas jet

  ➡ ϕ=100 µm capillary

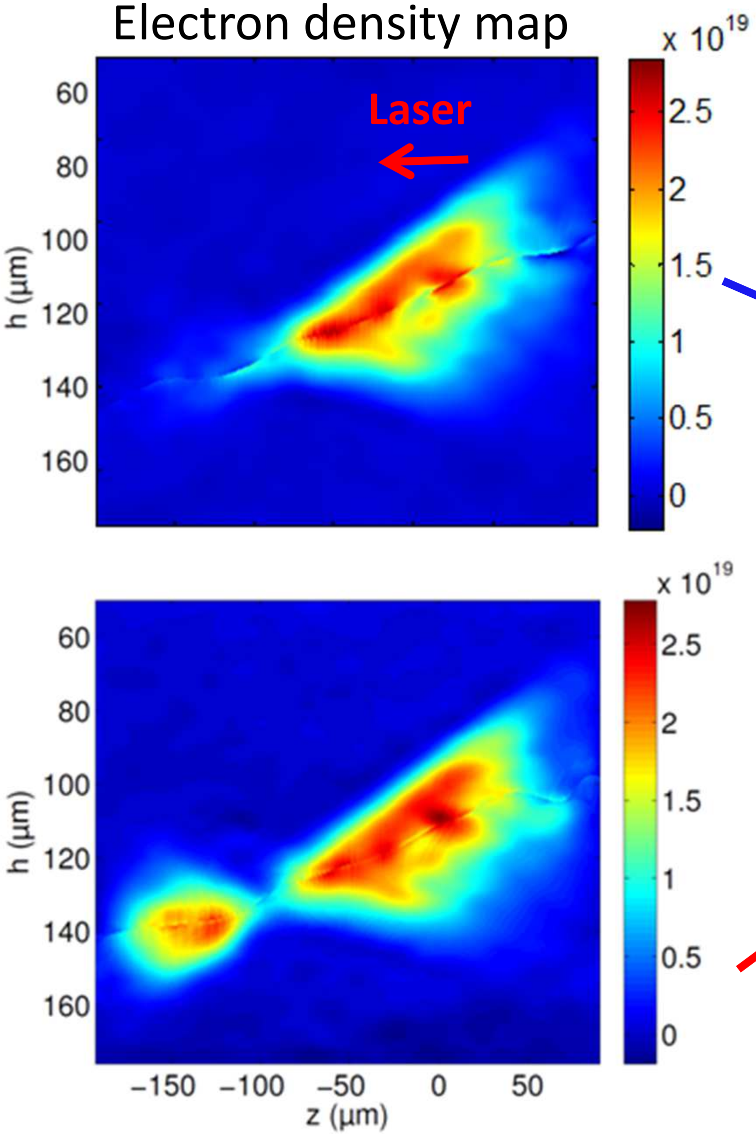
- **further accelerate the electrons** in a second gas jet

  ➡ ϕ=200 µm nozzle

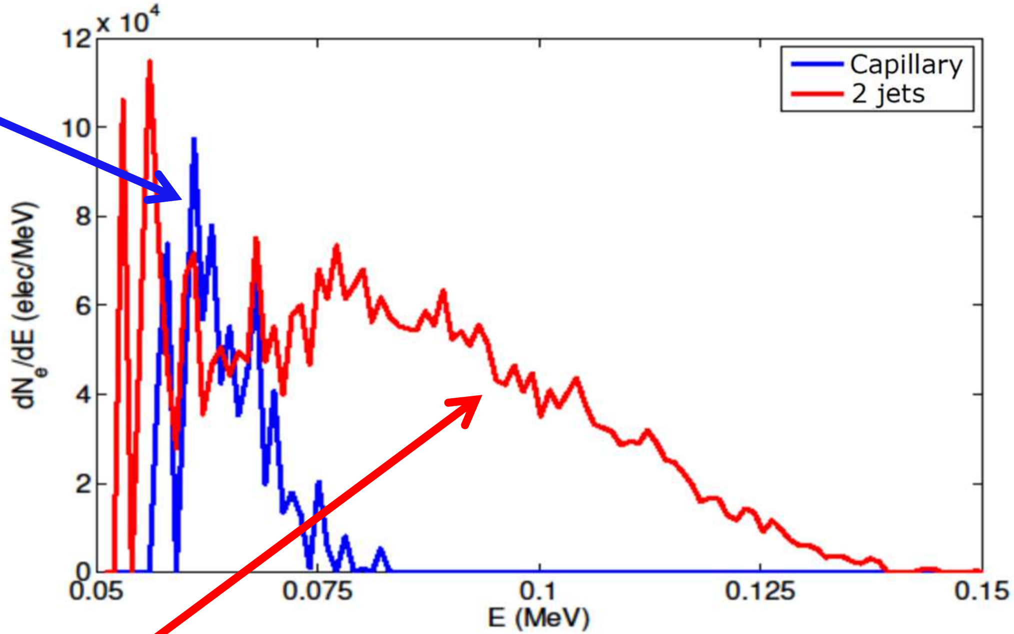


2 gas jets experiment: preliminary results

Electron density map



Electron energy distribution



Conclusions / perspectives

- ***Characterization of the gas jet:***
  - Φ100 µm gas jet: adjustable density (up to 10^{20} cm^{-3}) at kHz.
  - kHz source of electrons at 100 keV.

- ***Futur work:***
  - Characterize the acceleration with 2 gas jets.
  - Going to MeV electrons: laser upgrade to 5 mJ, 5 fs pulses.