



# Measuring the temporal evolution of a laser induced plasma

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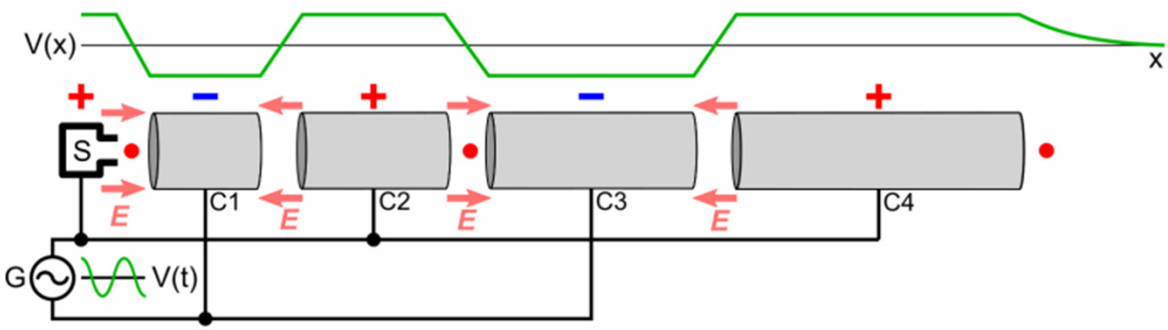
IPEN-CNEN/SP



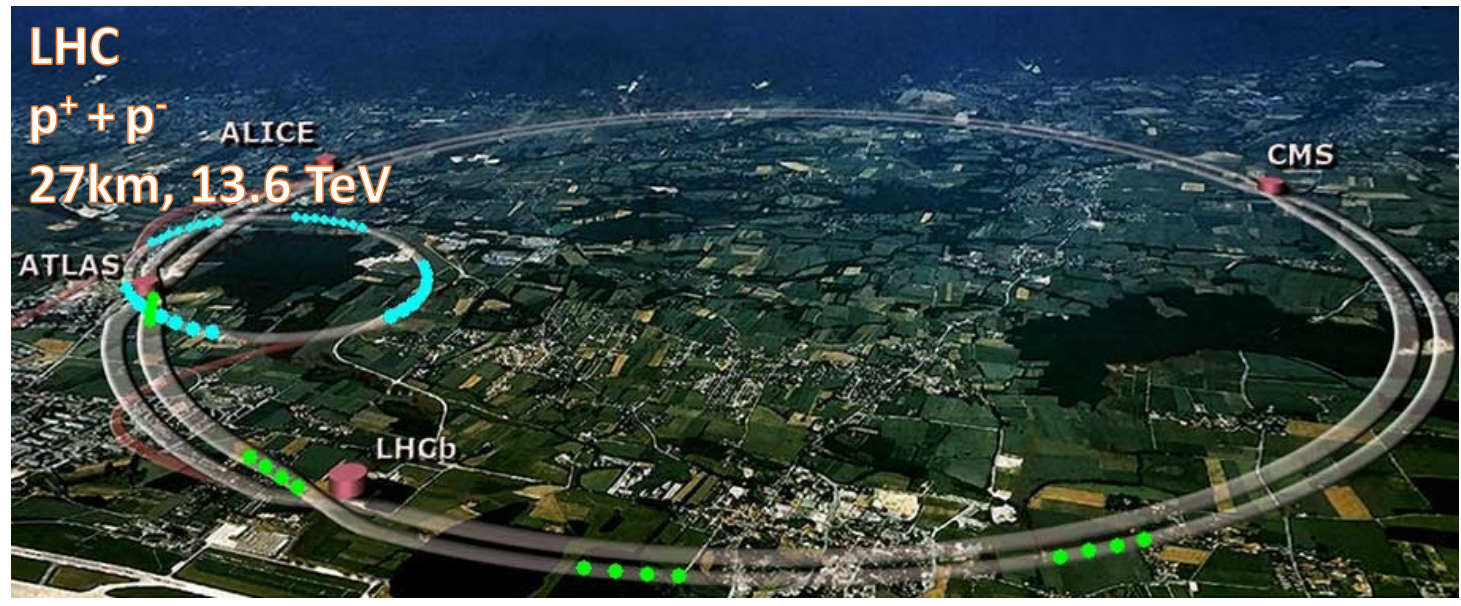
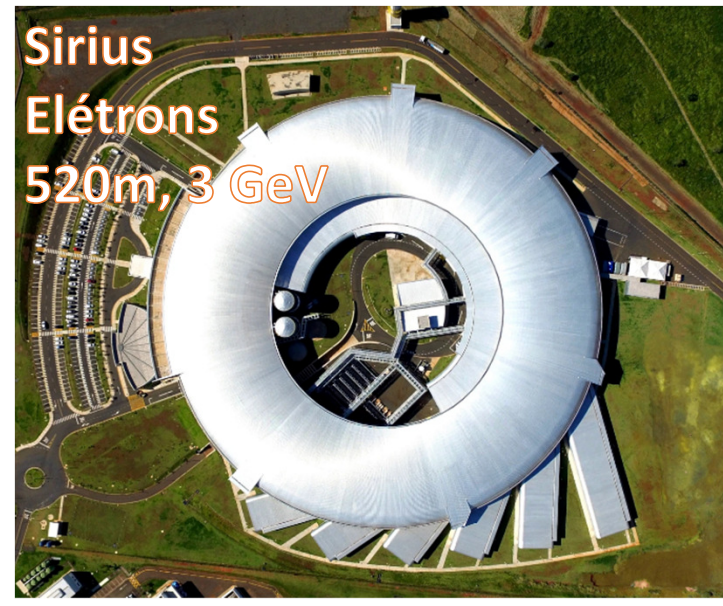
# Why laser induced plasmas??

# Motivation: Particle accelerators

~30.000 worldwide

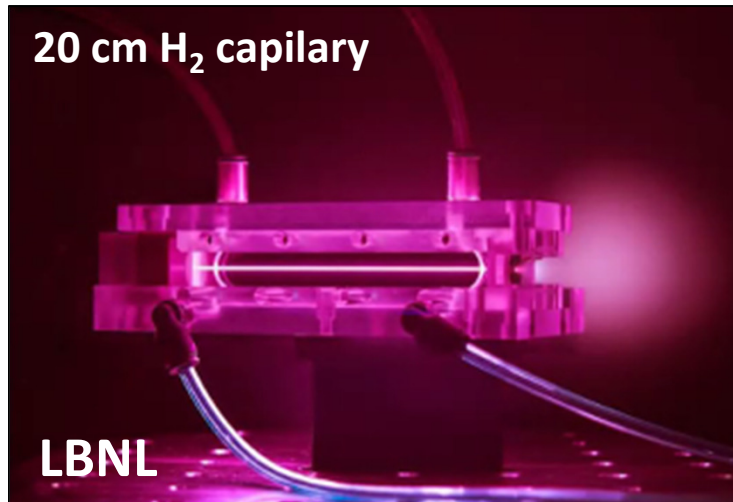


<30 MV/m acceleration fields  
(materials breakdown)

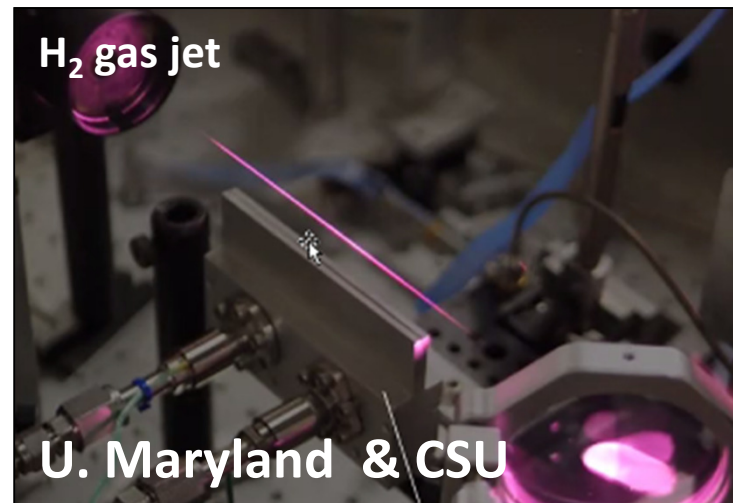


# Motivation: Laser Particle Accelerators

35fs, 850TW  
8GeV, 5pC, 0.2mrad  
*A.J. Gonsalves,  
Phys. Rev. Lett. (2019)*



45fs, 300TW  
5GeV, 10pC, 1mrad  
*B. Miao,  
Phys. Rev. X (2022)*

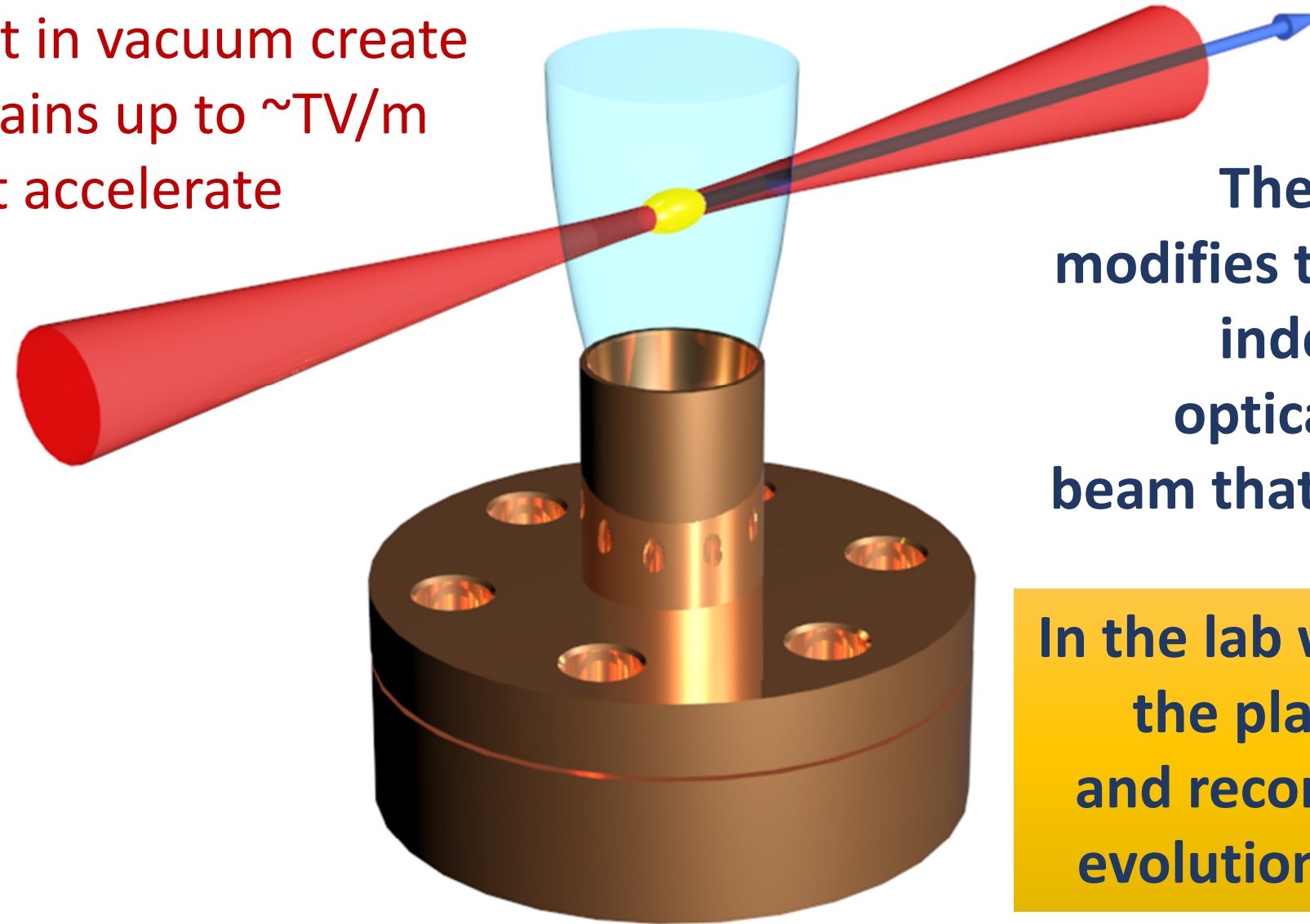


- New technology
- Low repetition rates
- Irregular beams
- Shot-to-shot variation
- Small dimensions
- Less complexity
- Moderate costs
- Small shielding
- Potential to increase beam energy



# Laser Driven Particle Acceleration

**Ultrashort** (5-100 fs) Laser pulses focused in a gas jet in vacuum create a plasma that sustains up to  $\sim$ TV/m electric fields that accelerate electrons



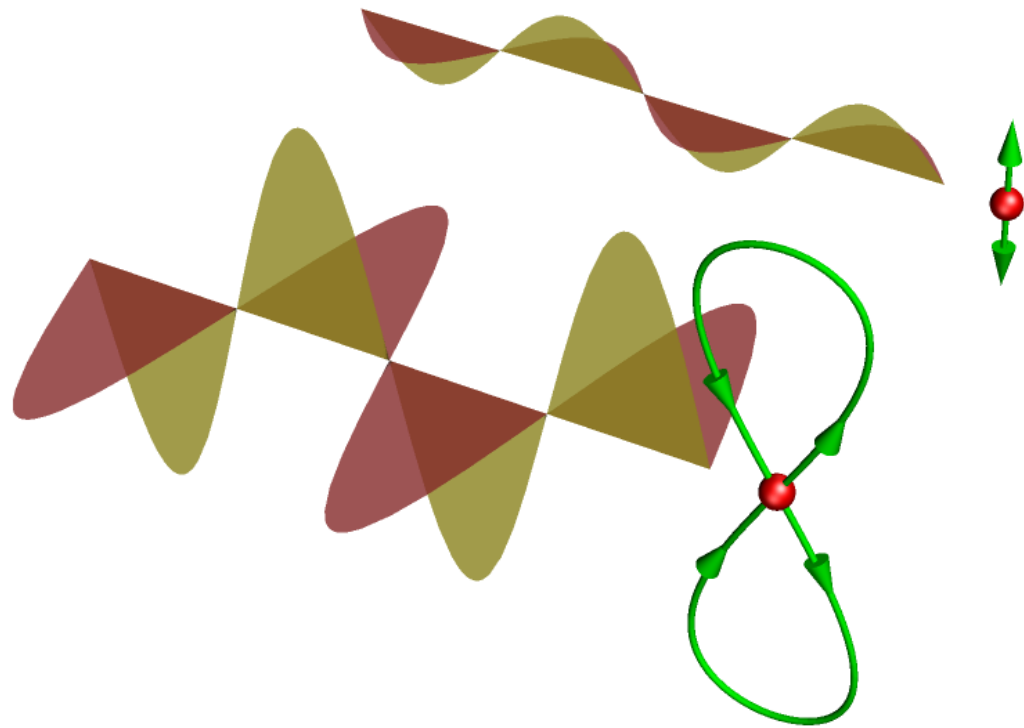
The plasma volume modifies the air refractive index, changing the optical path of a light beam that goes through it

In the lab we will measure the plasma density and record its temporal evolution, from fs to ns

# Forces acting on electrons

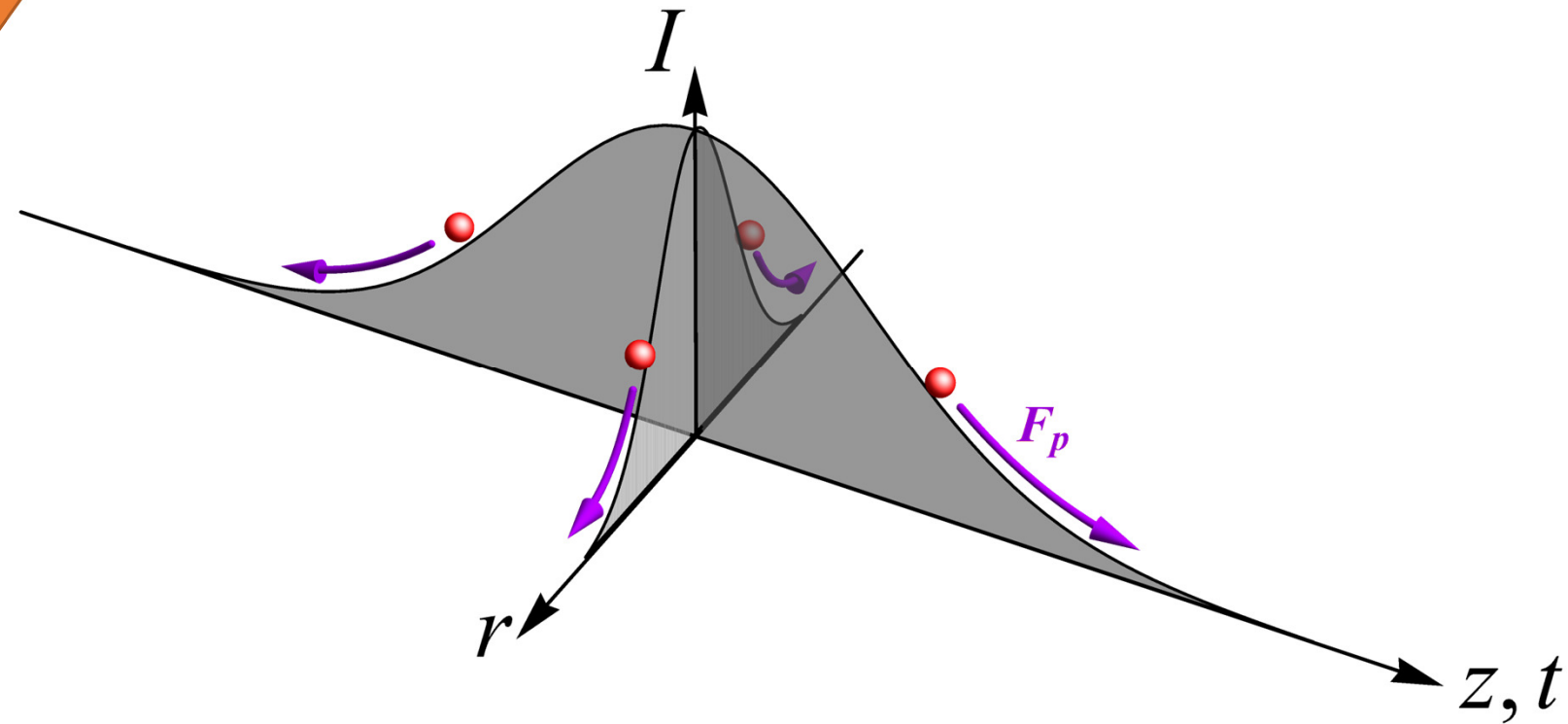
## LORENTZ FORCE

$$\vec{F} = q(\vec{E} + \vec{v} \times \vec{B})$$

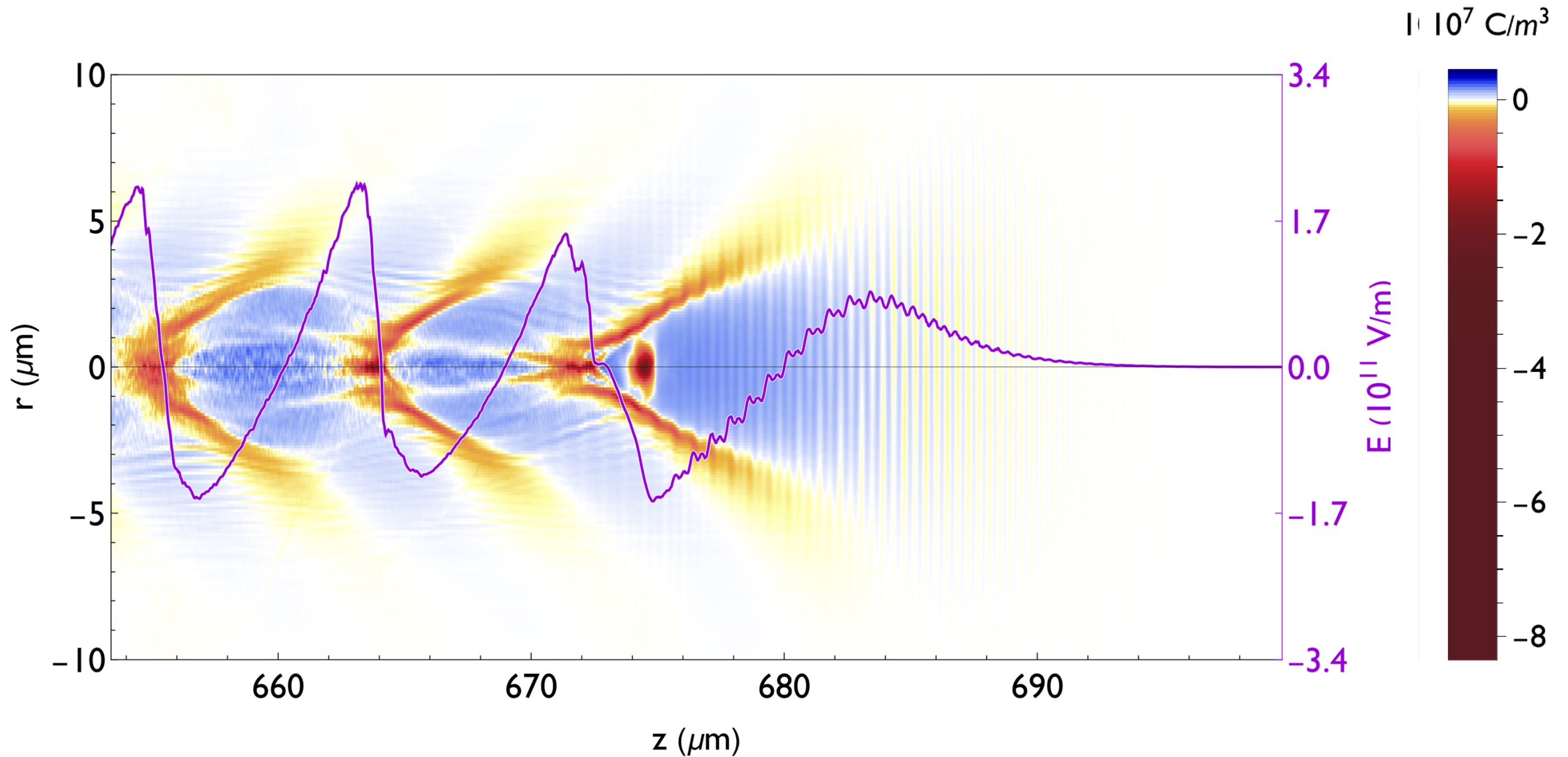


## PONDEROMOTIVE FORCE (AT HIGH INTENSITIES)

$$F_p = -\frac{e^2}{4m_e\omega^2} \nabla E^2$$



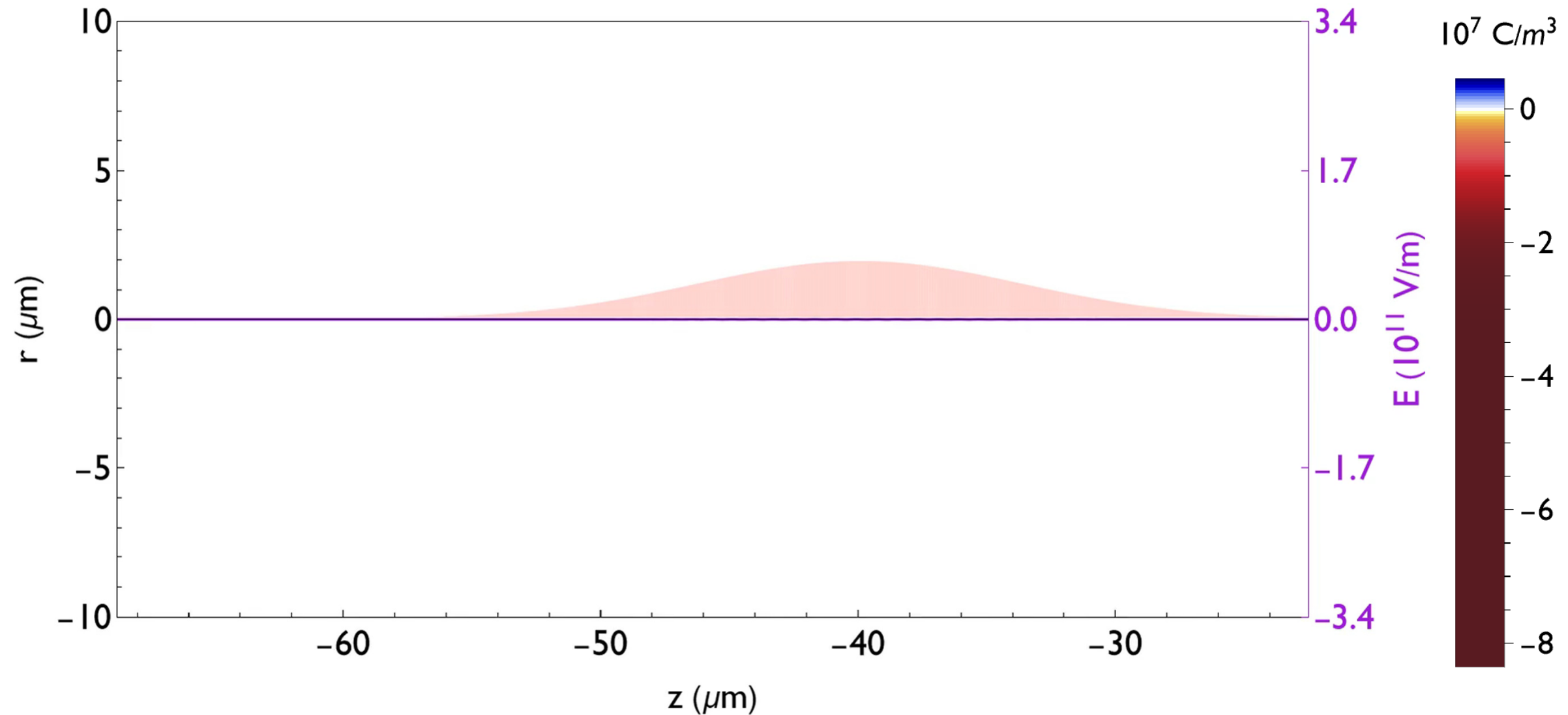
# Longitudinal Electric Field (Wakefield)



# 2TW pulse on He+N2 target

PIC simulation results

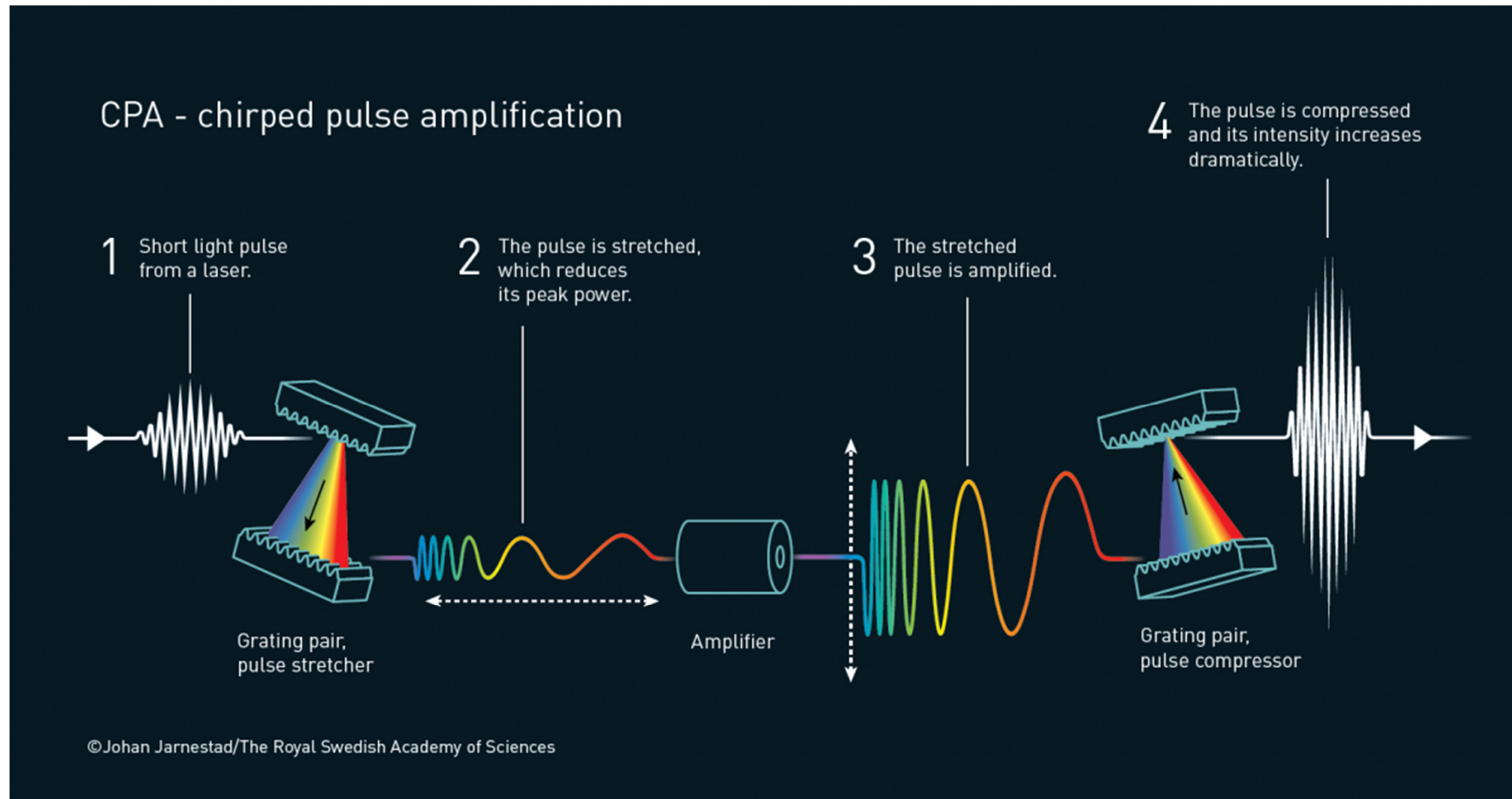
Charge density and Wakefield (longitudinal electric field)



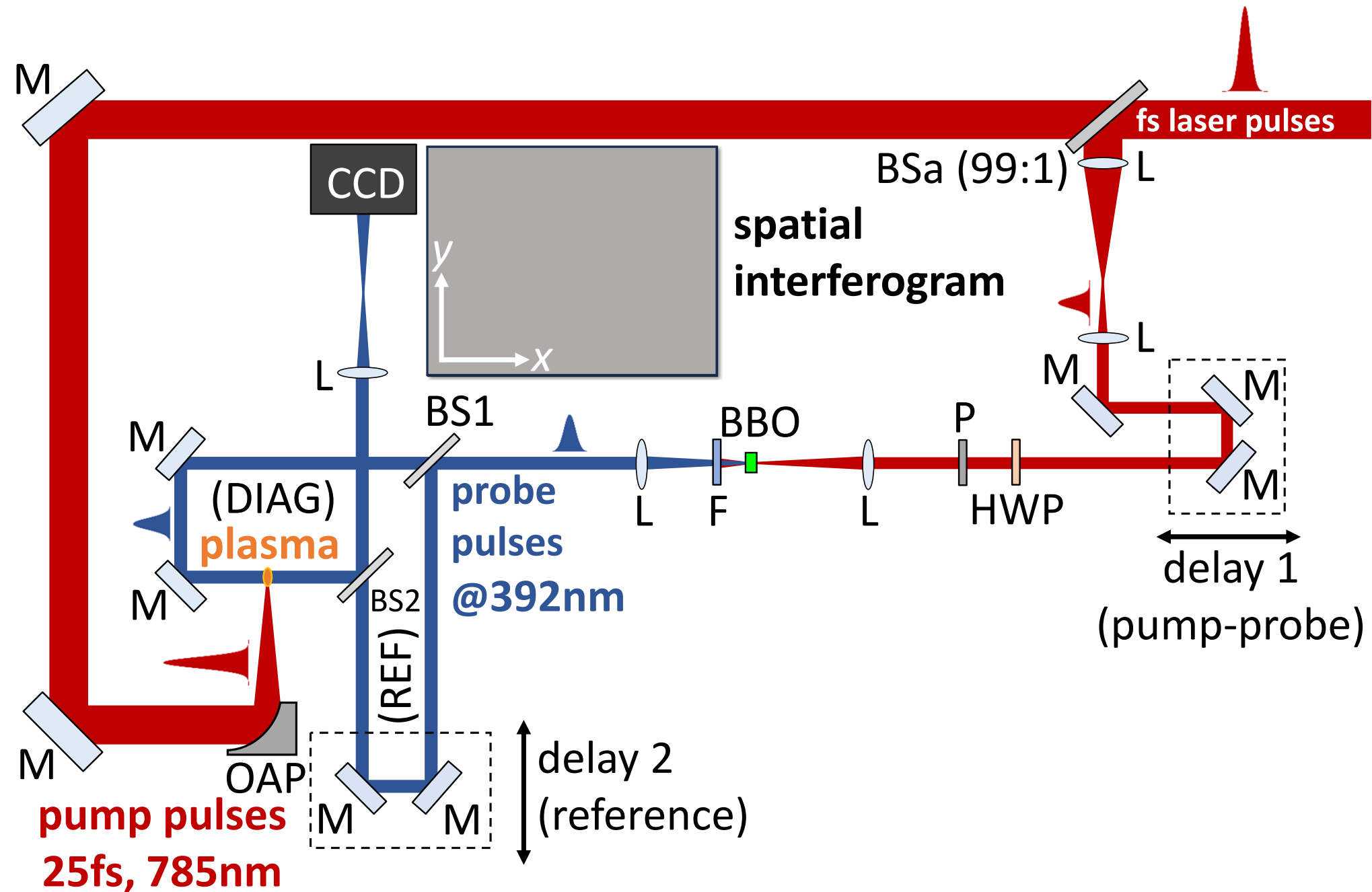


# CPA Lasers required to accelerate electrons

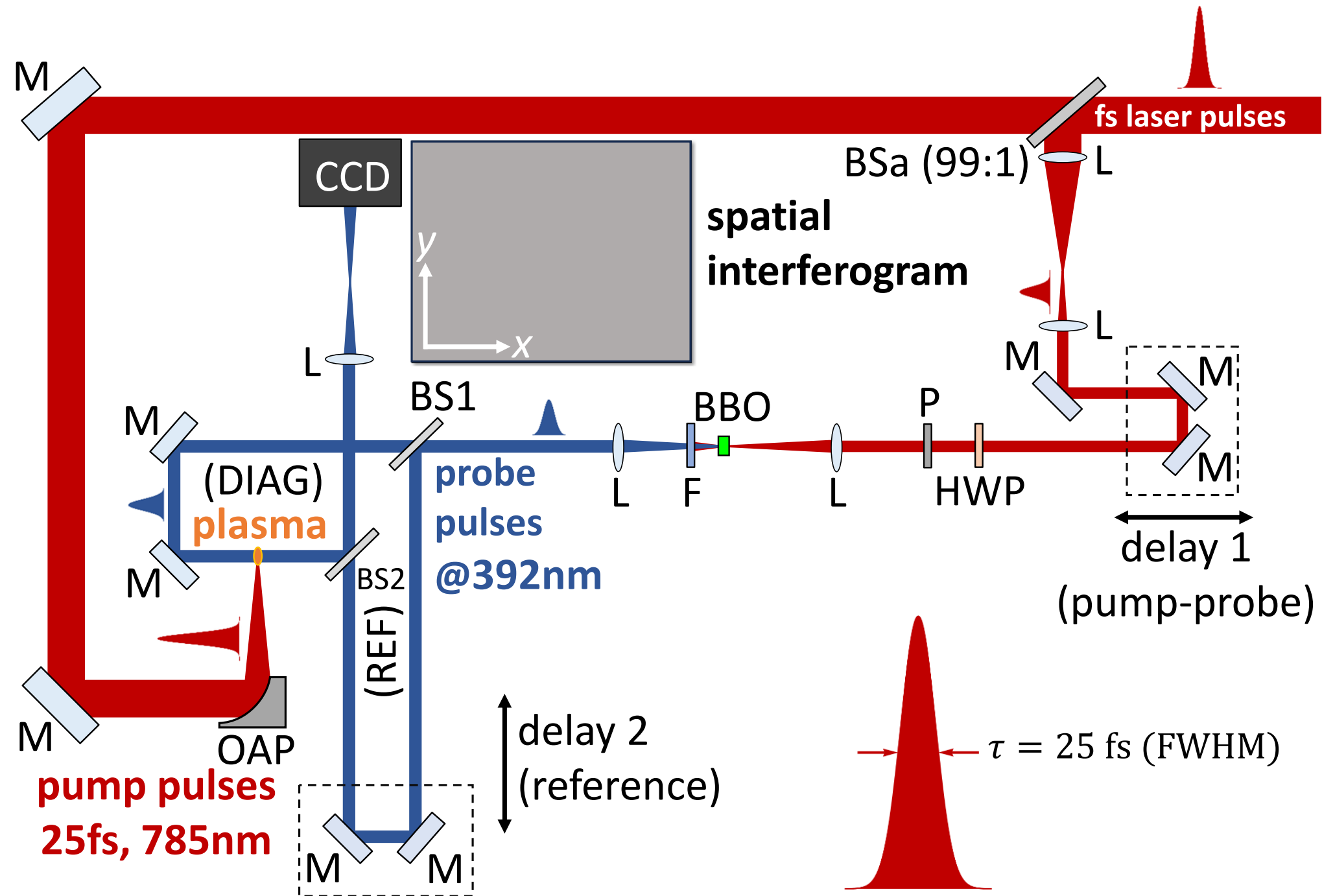
- Chirped Pulse Amplification generates pulses with up to a few PW of peak power



# Time-Resolved Mach-Zehnder Like Interferometer

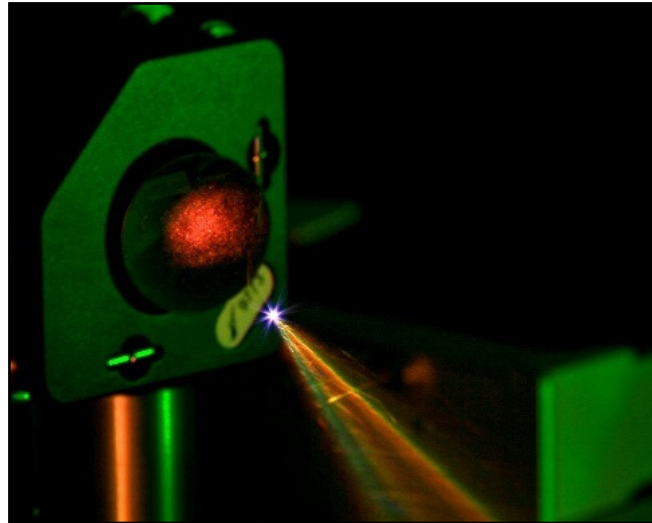


# Time-Resolved Mach-Zehnder Like Interferometer

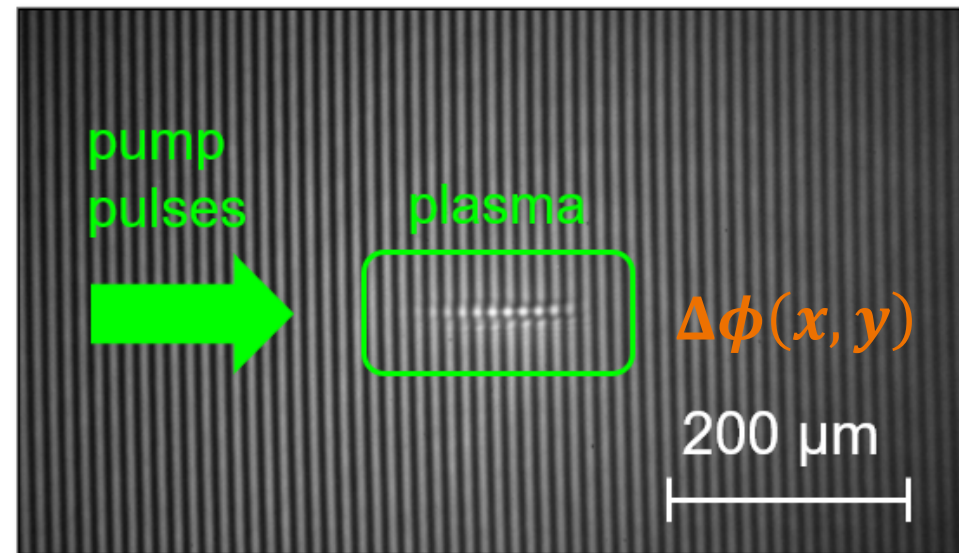


# Laser-induced Plasma Characterization

25fs laser pulses,  $\sim 100\mu\text{J}$ ,  
focused in air by a parabolic  
mirror to  $10^{16} \text{ W/cm}^2$

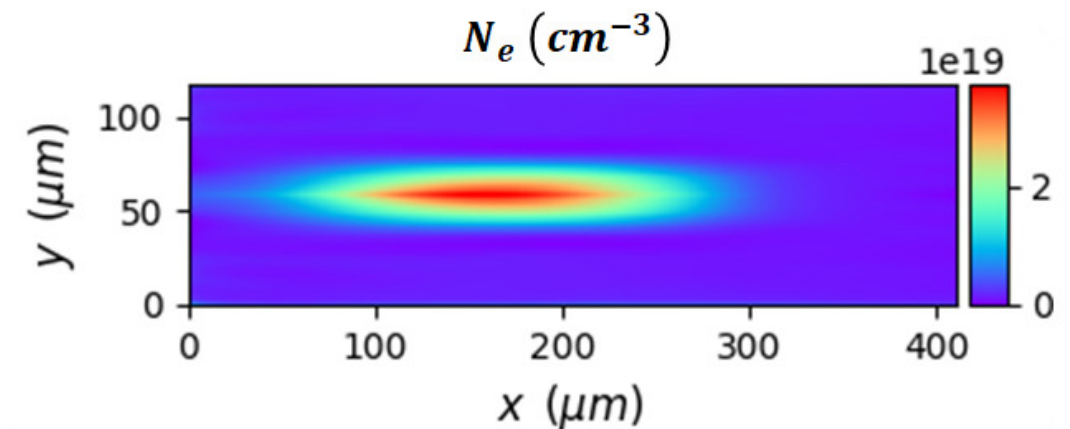


Laser-induced plasma interferogram



*Fourier Transform + Frequency filtering +  
Inverse FT + phase difference +  
phase unwrap + Abel inversion*

Laser-induced plasma density map

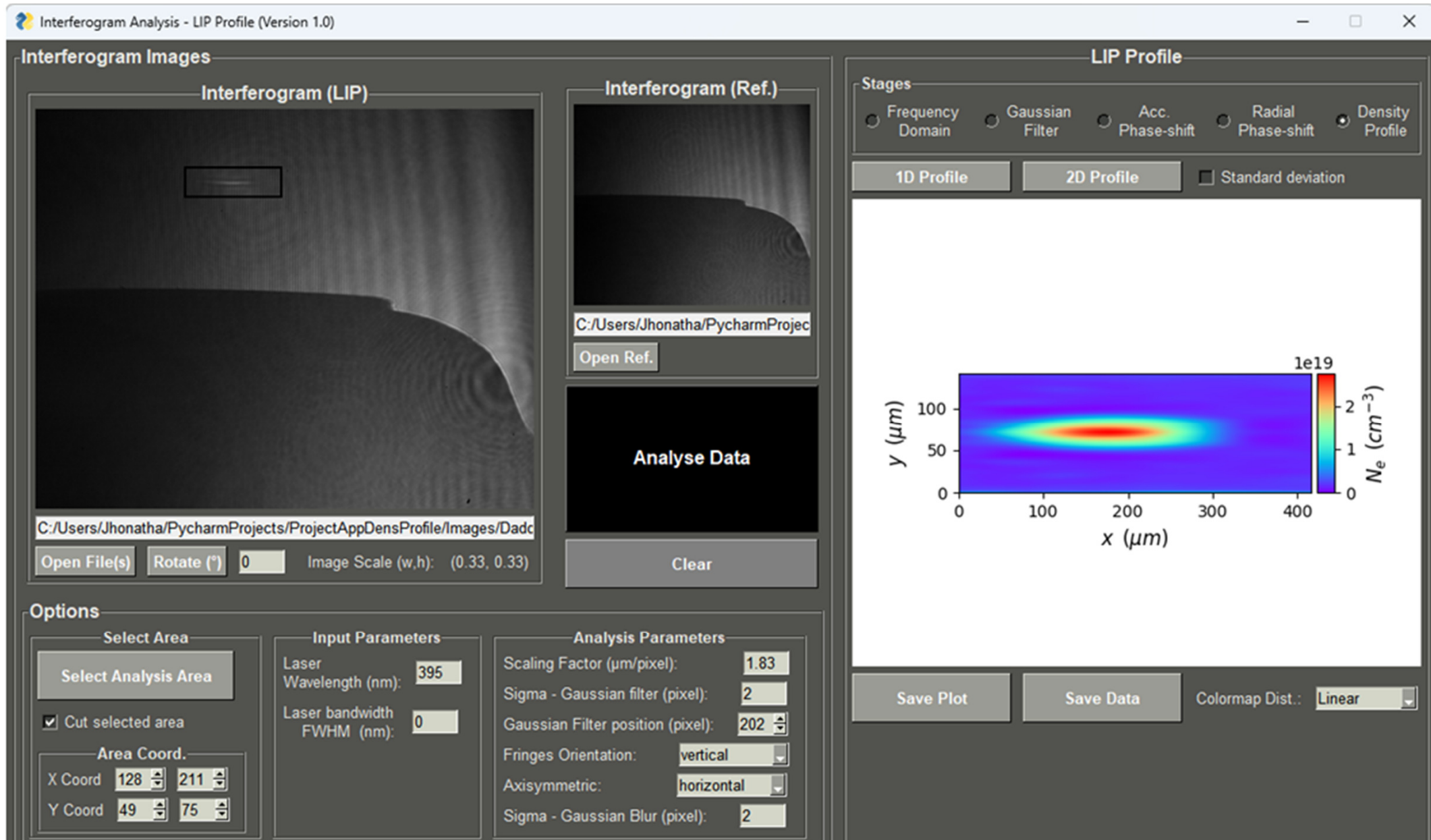


Plasma (electronic) density

$$n_e(x, y) = \frac{4\pi^2 c^2 \epsilon_0 m_e}{e^2 \lambda^2} \left\{ 1 - \left[ 1 + \frac{\Delta\phi(x, y) \lambda}{2\pi l} \right]^2 \right\}$$

# Plasma Density Retrieval

- Interferograms analysis by Fourier Transforms and Abel Transforms

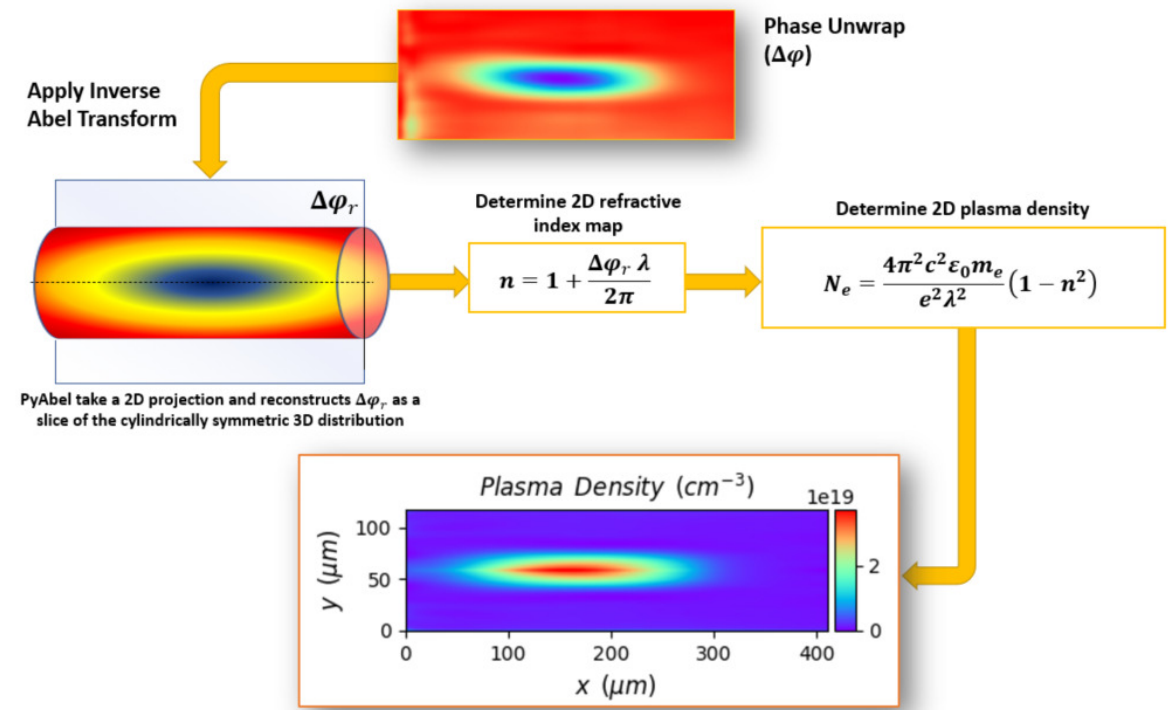
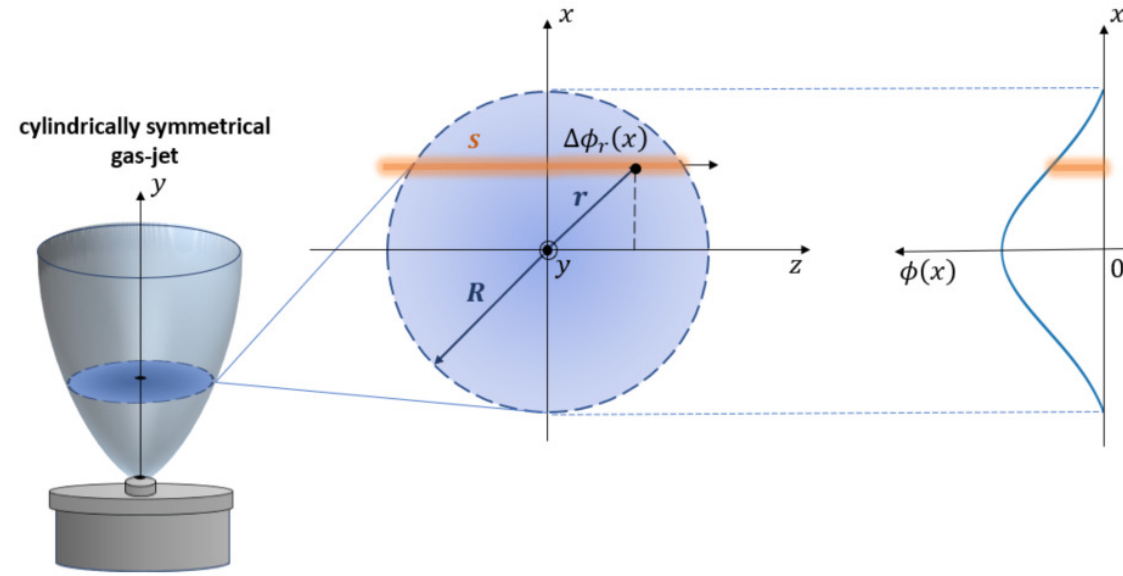


The screenshot displays the 'Interferogram Analysis - LIP Profile (Version 1.0)' software interface. It is divided into several sections:

- Interferogram Images:** Contains two image viewers. The left one shows the 'Interferogram (LIP)' with a file path: `C:/Users/Jhonatha/PycharmProjects/ProjectAppDensProfile/Images/Dadc`. The right one shows the 'Interferogram (Ref.)' with a file path: `C:/Users/Jhonatha/PycharmProjec`. Below these are buttons for 'Open File(s)', 'Rotate (\*)', 'Image Scale (w,h): (0.33, 0.33)', and 'Open Ref.'.
- Options:**
  - Select Area:** Includes a 'Select Analysis Area' button, a checked 'Cut selected area' checkbox, and 'Area Coord.' fields for X (128, 211) and Y (49, 75).
  - Input Parameters:** 'Laser Wavelength (nm): 395' and 'Laser bandwidth FWHM (nm): 0'.
  - Analysis Parameters:** 'Scaling Factor (μm/pixel): 1.83', 'Sigma - Gaussian filter (pixel): 2', 'Gaussian Filter position (pixel): 202', 'Fringes Orientation: vertical', 'Axisymmetric: horizontal', and 'Sigma - Gaussian Blur (pixel): 2'.
- LIP Profile:**
  - Stages:** Radio buttons for 'Frequency Domain', 'Gaussian Filter', 'Acc. Phase-shift', 'Radial Phase-shift', and 'Density Profile' (selected).
  - Profile Type:** '1D Profile' and '2D Profile' buttons, with a 'Standard deviation' checkbox.
  - Plot:** A 2D heatmap showing the density profile  $N_e$  ( $\text{cm}^{-3}$ ) as a function of  $x$  ( $\mu\text{m}$ ) and  $y$  ( $\mu\text{m}$ ). The color scale ranges from 0 to  $2 \times 10^{19}$ .
  - Actions:** 'Save Plot', 'Save Data', and 'Colormap Dist.: Linear' dropdown.

# Inverse Abel Transform

When a target is observed in the side-on direction (z - direction) by interferometry, the recovered phase-shift  $\Delta\phi$  is the accumulated phase-shift along the laser beam propagation direction.



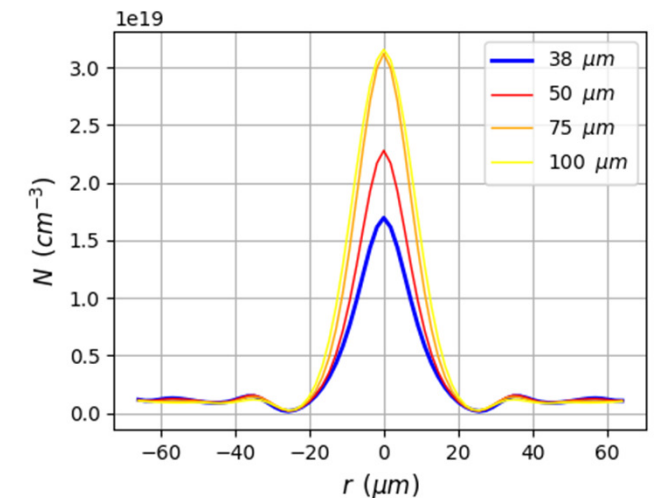
inverse Abel transform takes a 2D projection and reconstructs cylindrically symmetric 3D distribution

Assuming a cylindrically symmetrical target, the integrated information along z is enough to reconstruct the radial information. The relationship between radial phase-shift,  $\Delta\phi_r$ , and accumulated phase-shift,  $\Delta\phi$ , is given by Abel-inversion:

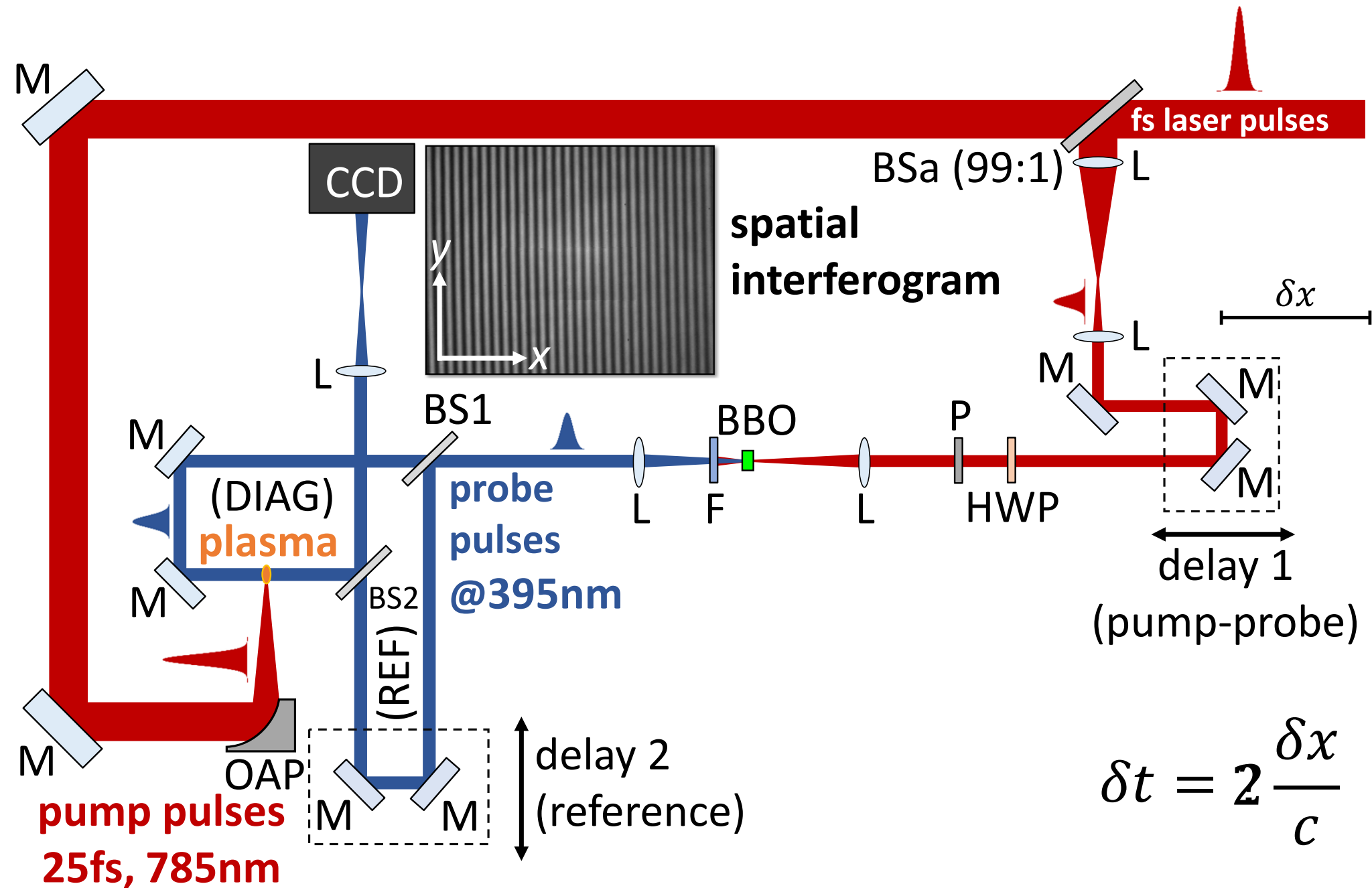
$$\Delta\phi_r = -\frac{1}{\pi} \int_r^\infty \frac{d[\Delta\phi]}{dx} \frac{dx}{\sqrt{r^2 - x^2}}$$

$$N_e = \frac{4\pi^2 c^2 \epsilon_0 m_e}{e^2 \lambda^2} (1 - n^2)$$

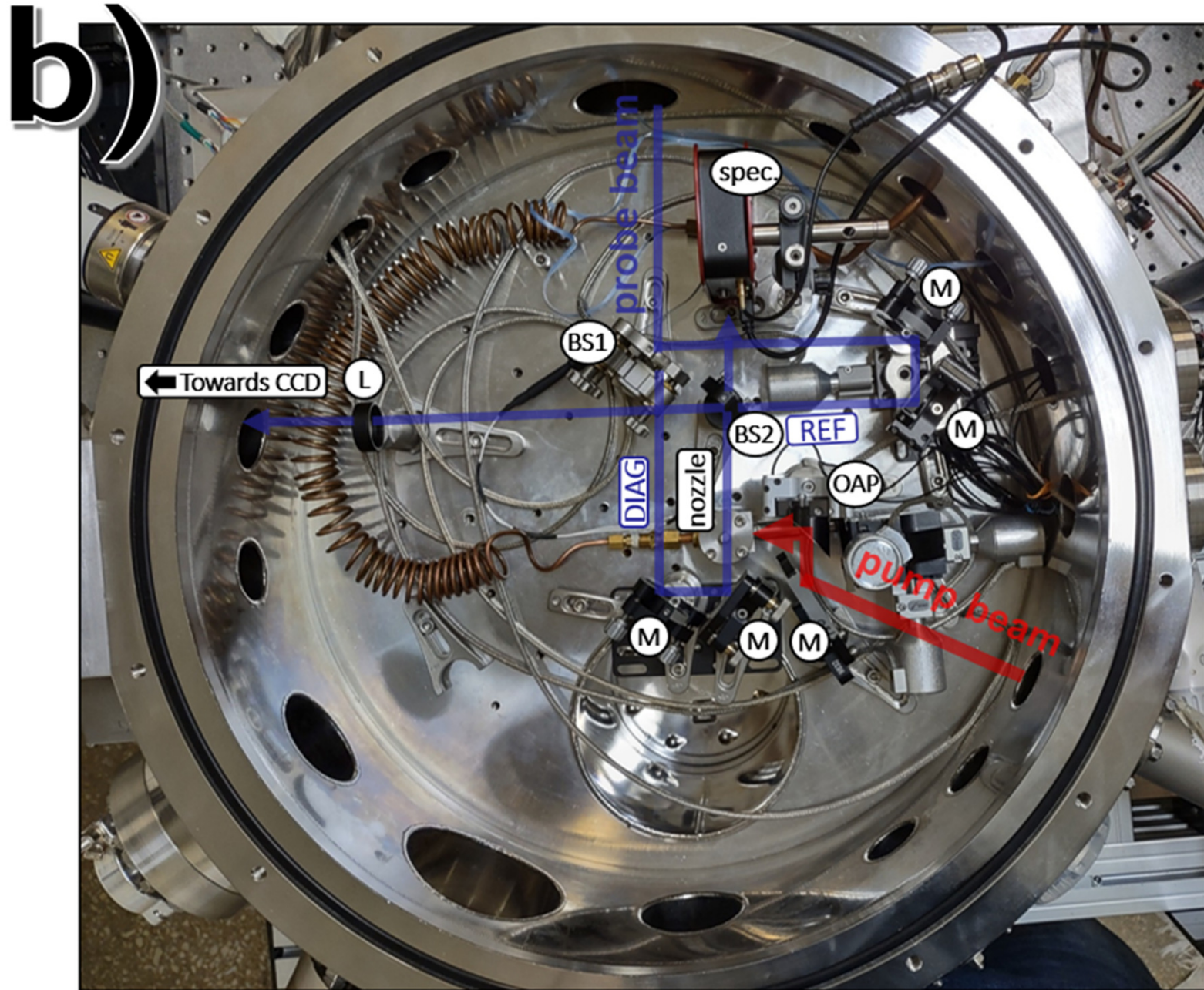
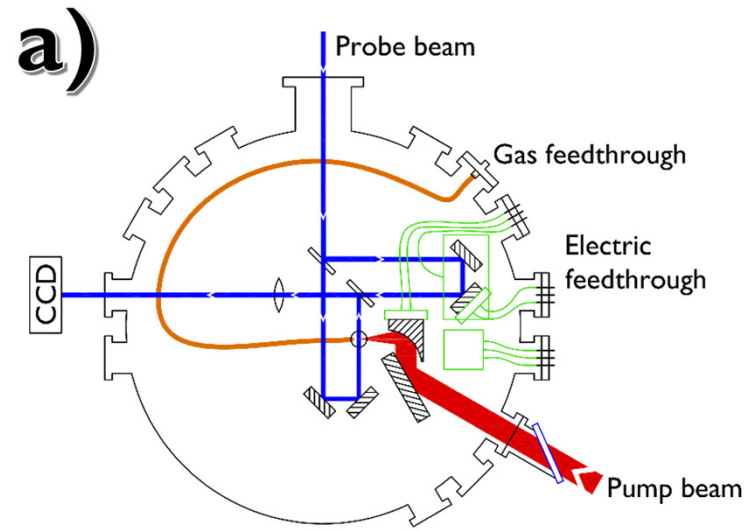
In our code, the radial phase-shift map is constructed from the application of a PyAbel algorithm on the accumulated phase-shift map  $\Delta\phi$ . PyAbel is a Python package that provides efficient implementations of several forward and inverse Abel transform algorithms.



# Time-Resolved Mach-Zehnder Like Interferometer

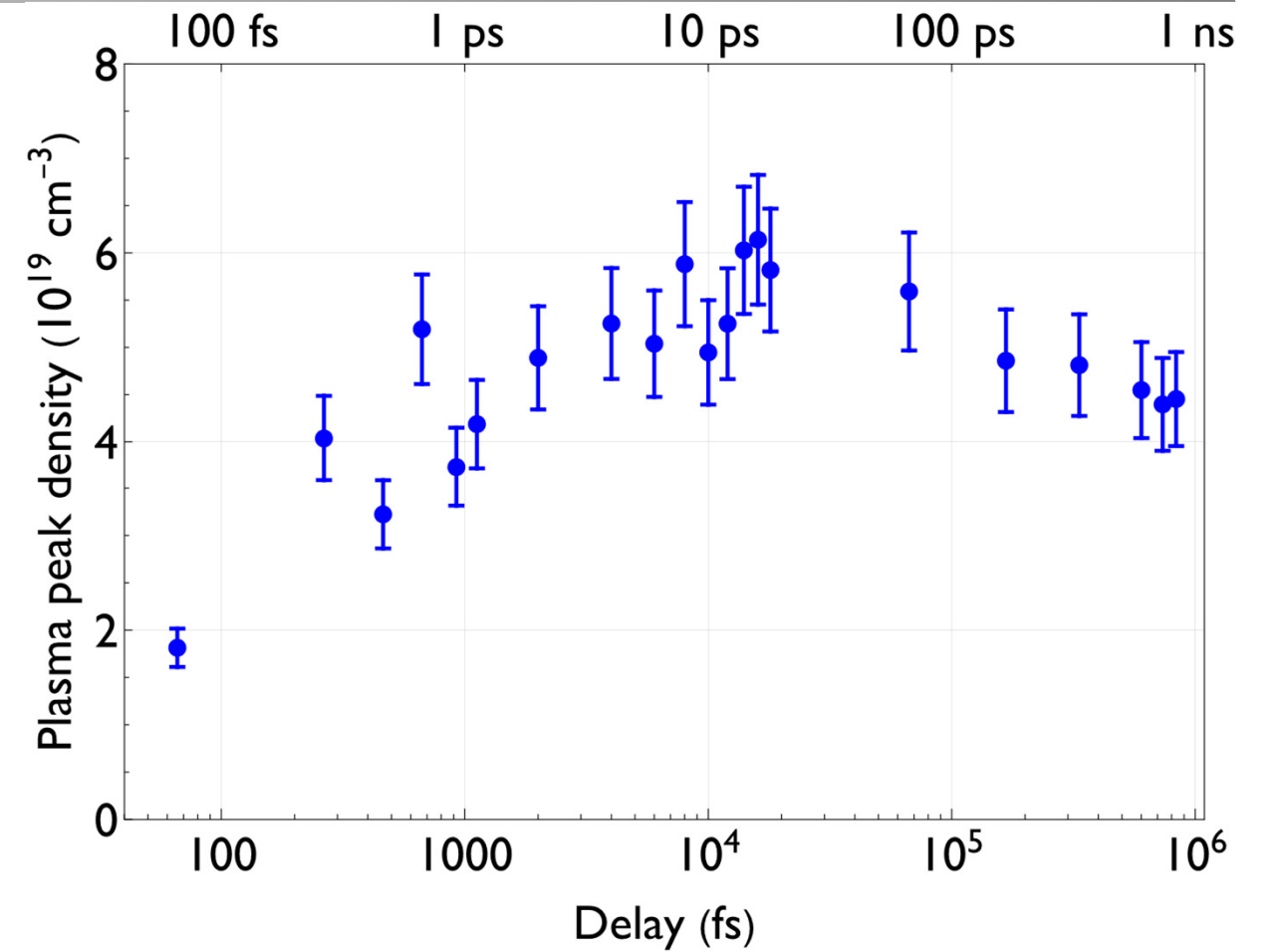
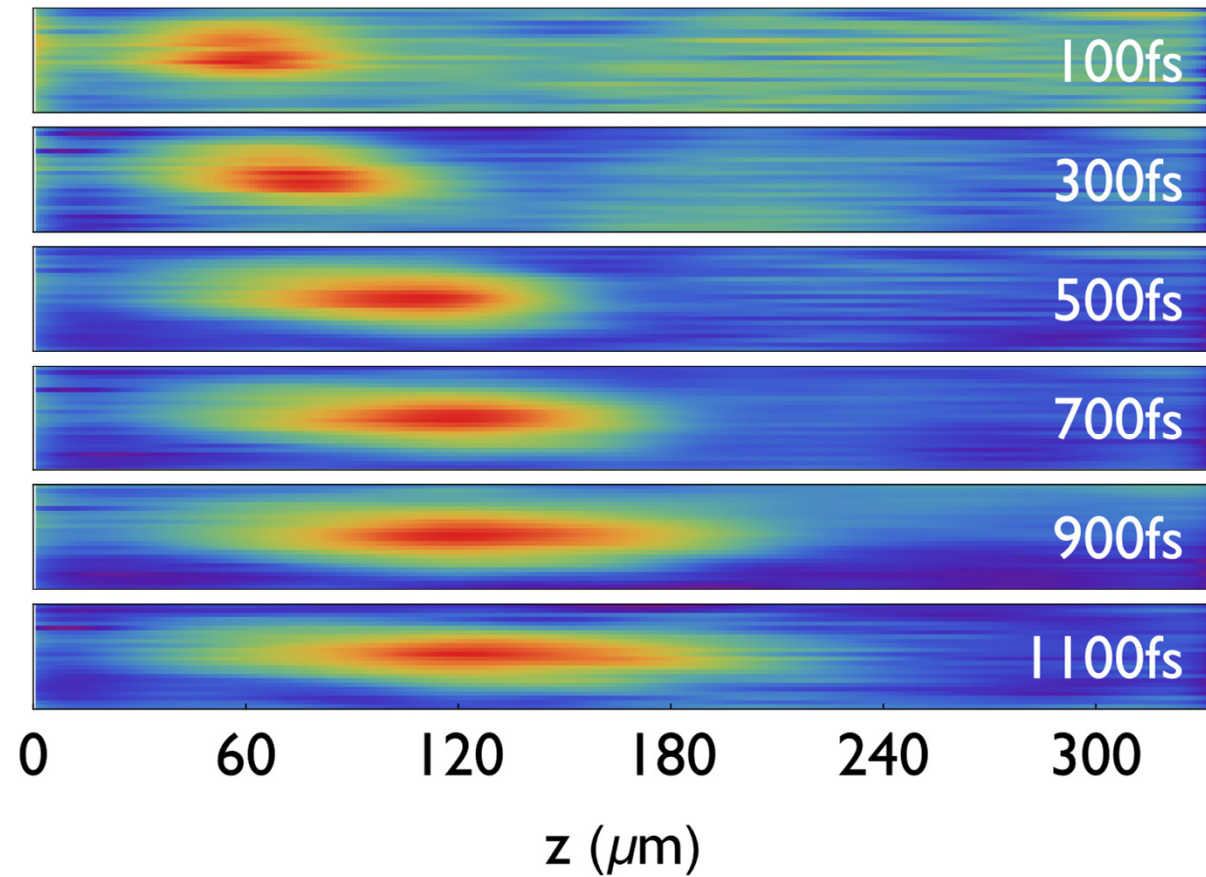


# Experimental Setup





# Plasma Temporal Evolution



## Possible Measurements:

- Laser Intensity
- Plasma spatial profile
- Plasma spatial Density distribution
- Plasma refractive index
- Plasma maximum density

- Plasma density temporal evolution
- Plasma lifetime
- Estimate plasma temperature
- Estimate plasma temperature temporal evolution

