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Measuring the temporal evolution of a laser induced plasma

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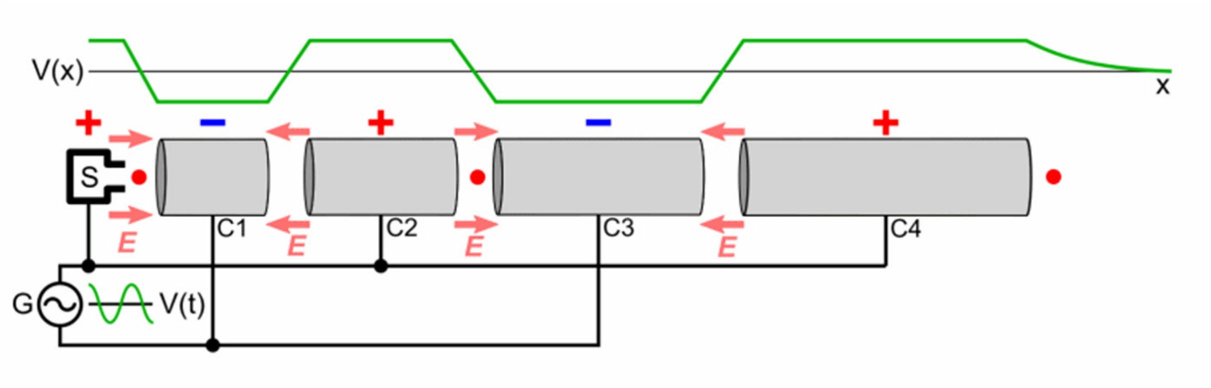
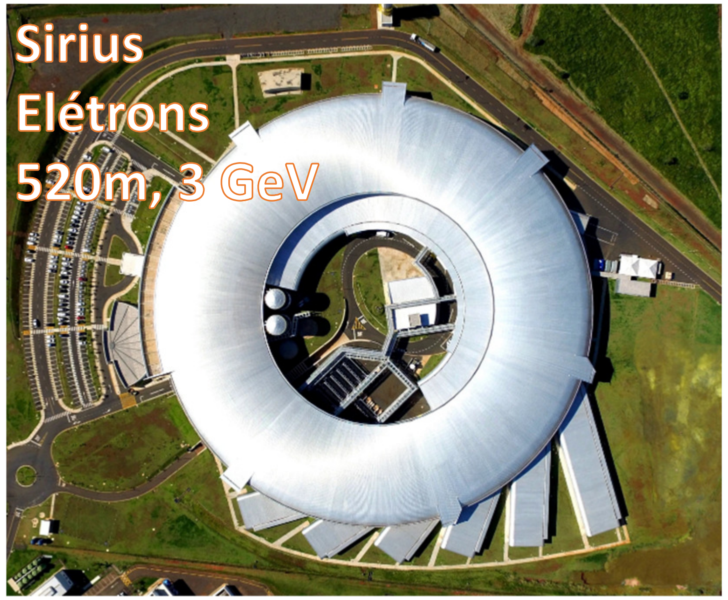
Why laser induced plasmas??

Motivation: Particle acclerators

~30.000 worldwide

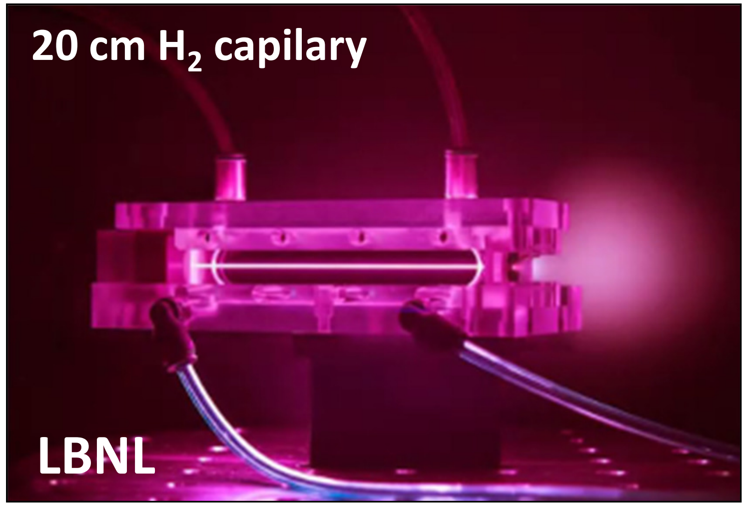


<30 MV/m acceleration fields (materials breakdown)

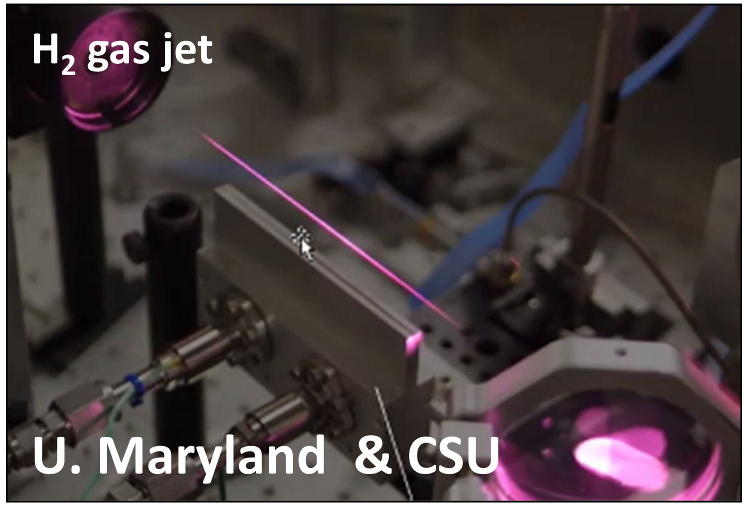


Motivation: Laser Particle Accelerators

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



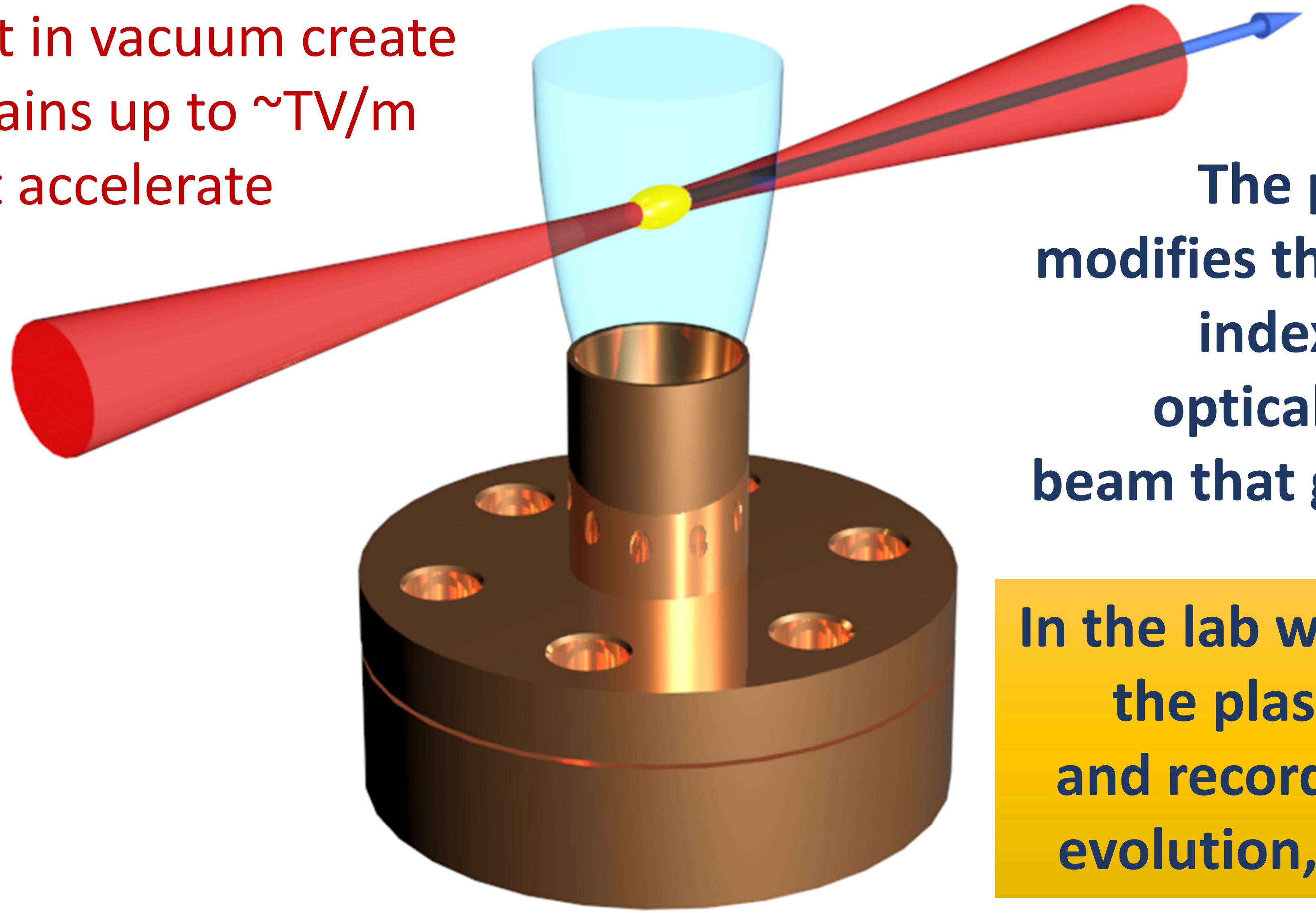
45fs, 300TW
5GeV, 10pC, 1mrad
B. Miao, Phys. Rev. X (2022)



- 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 ~TV/m electric fields that accelerate electrons



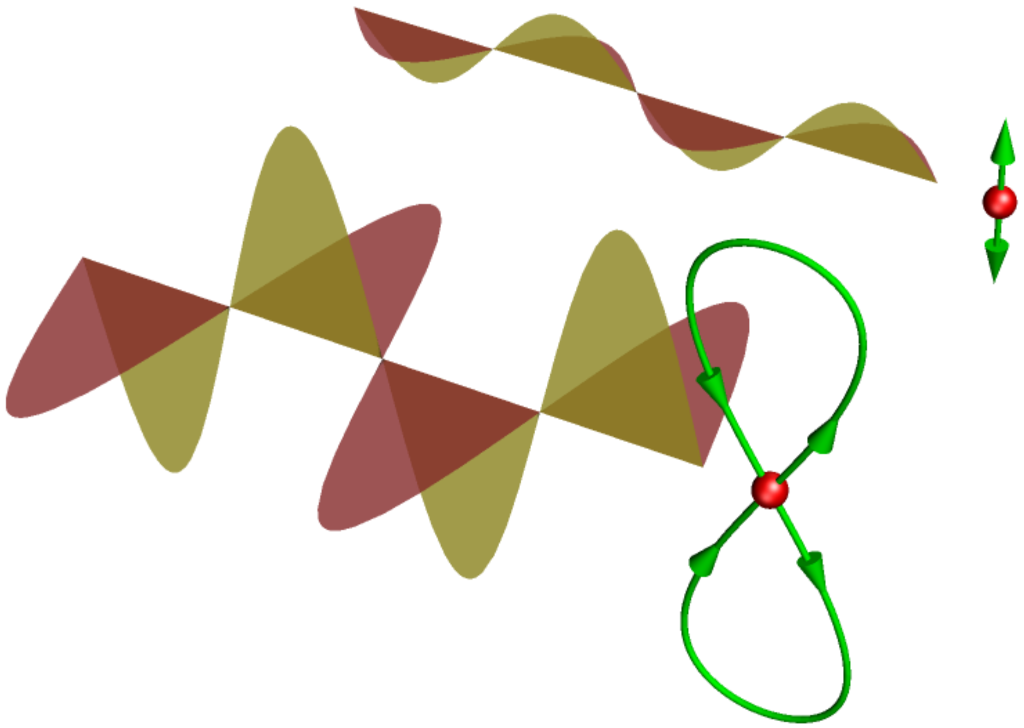
The plasma volume modifies the air refractive index, changing the optical path of a light beam that goes through it

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

Forces acting on electrons

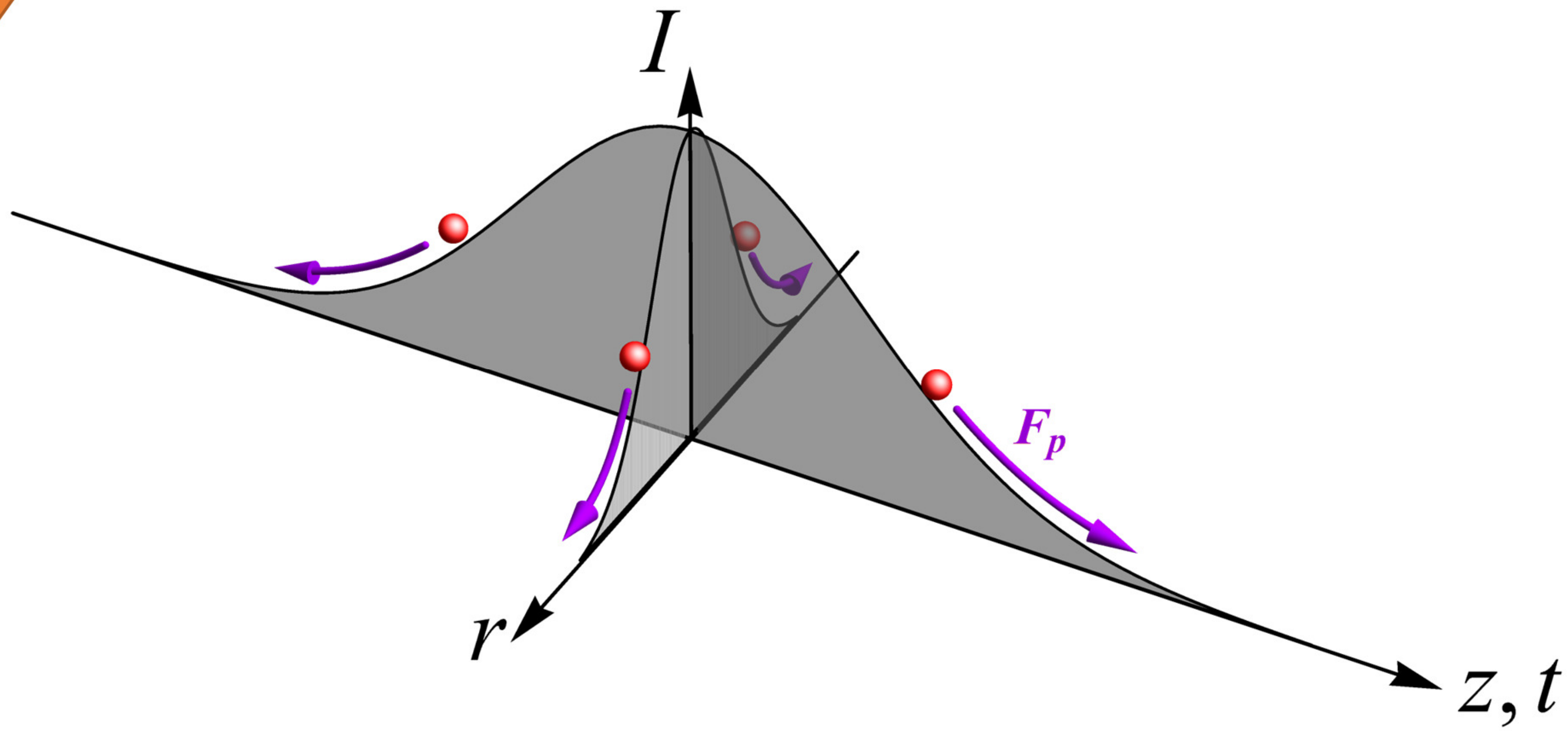
Lorentz Force

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

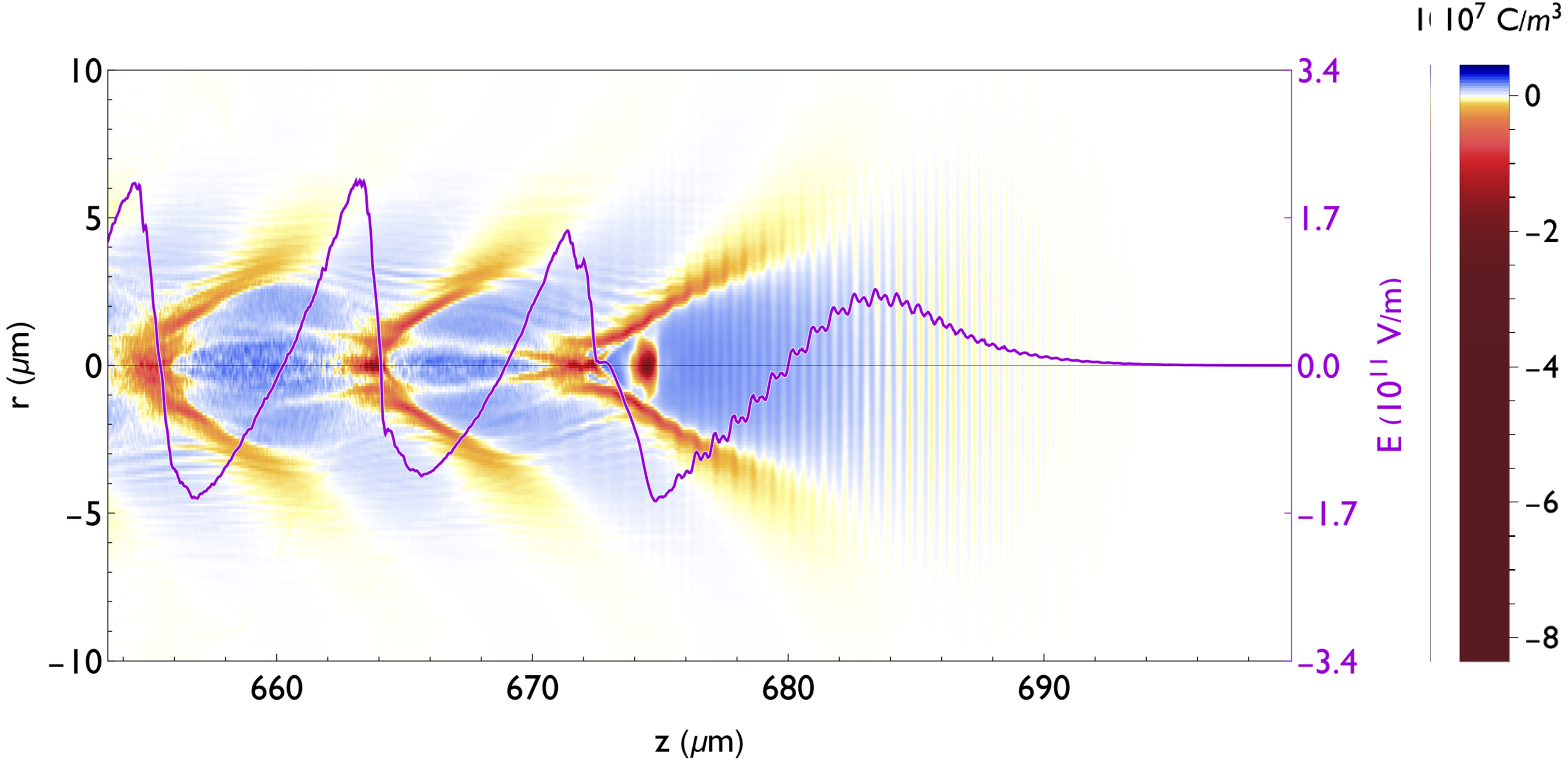


Ponderomotive Force (at high intensities)

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



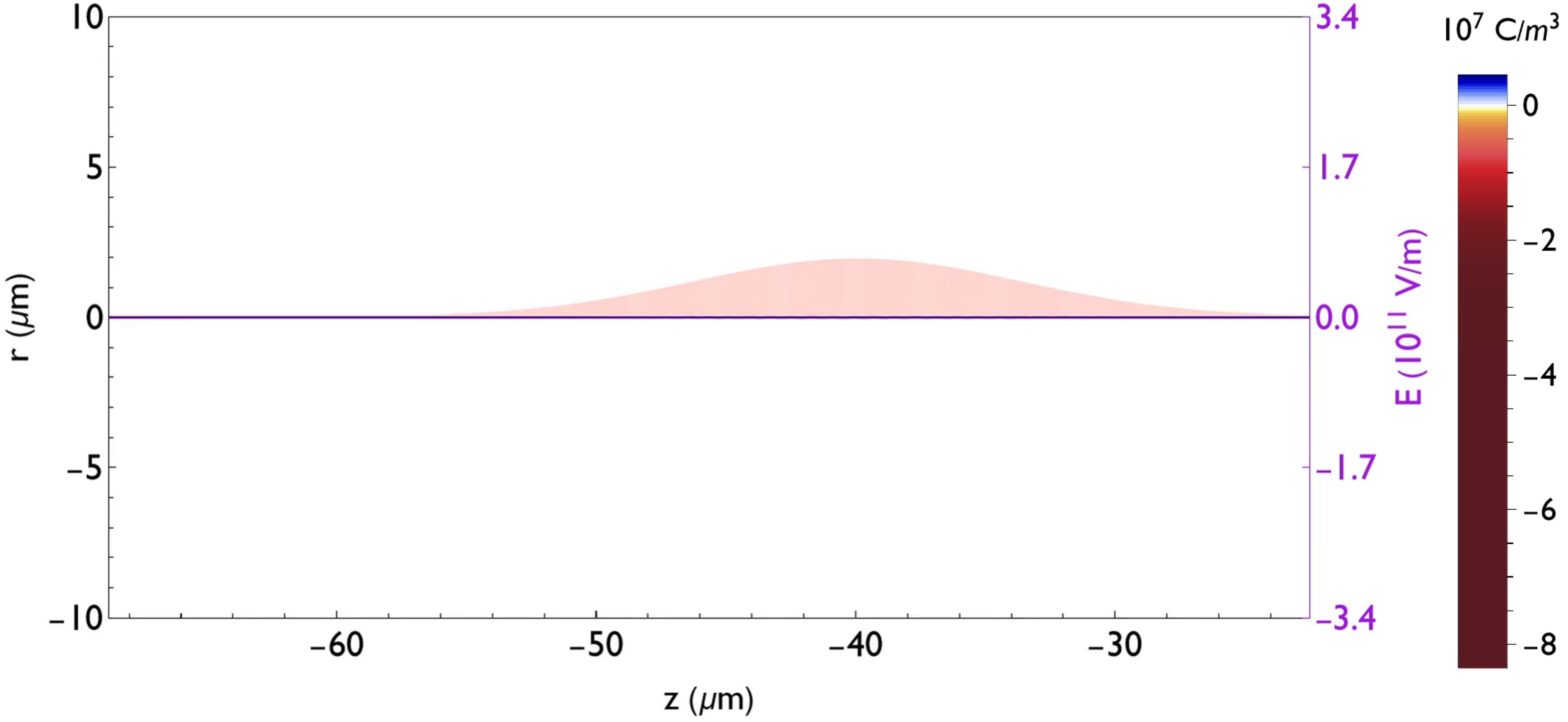
Longitudinal Electric Field (Wakefield)



2TW pulse on He+N2 target

PIC simulation results

Charge density and Wakefield (longitudinal electric field)



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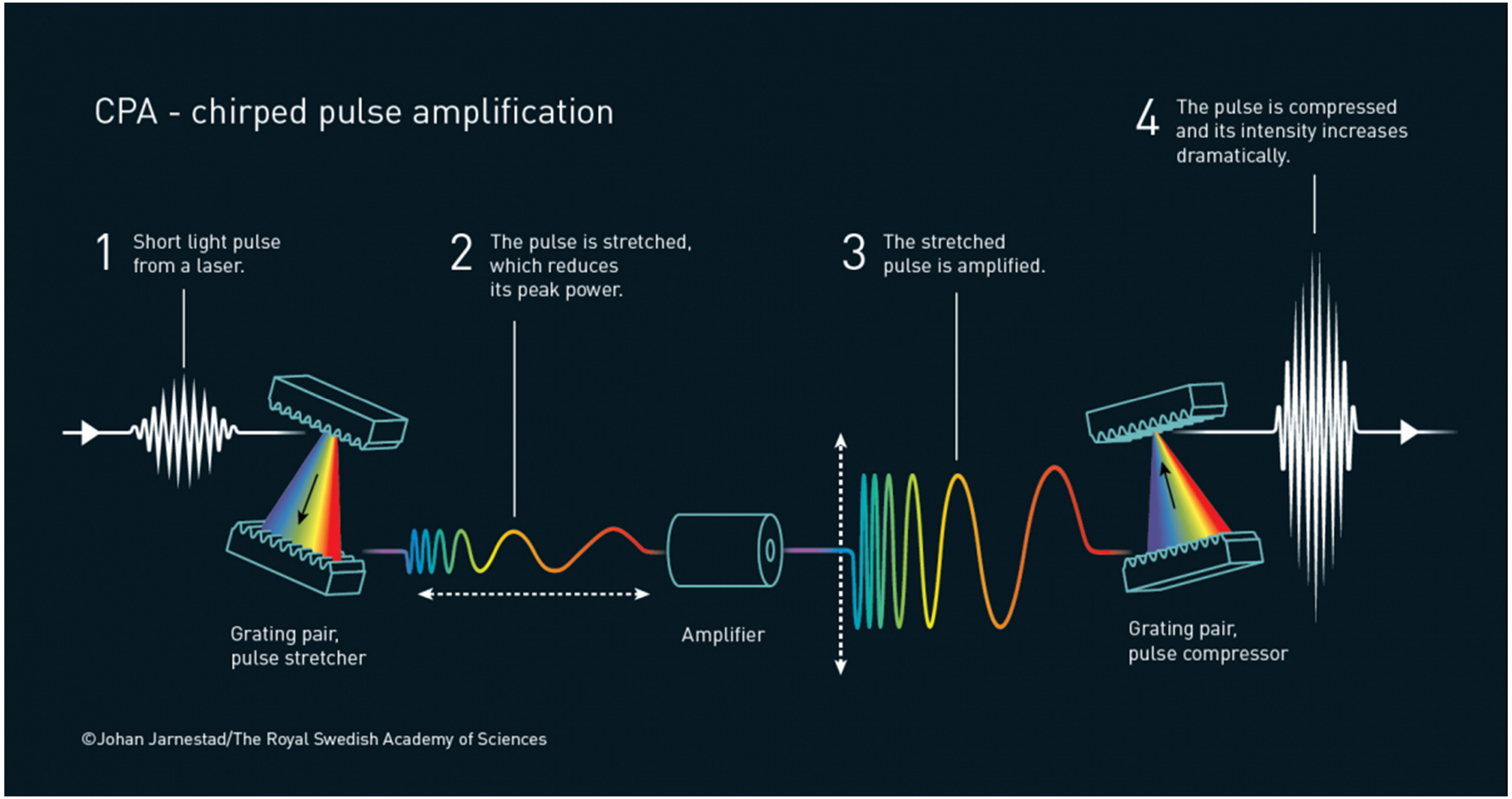
CPA Lasers required to accelerate electrons

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



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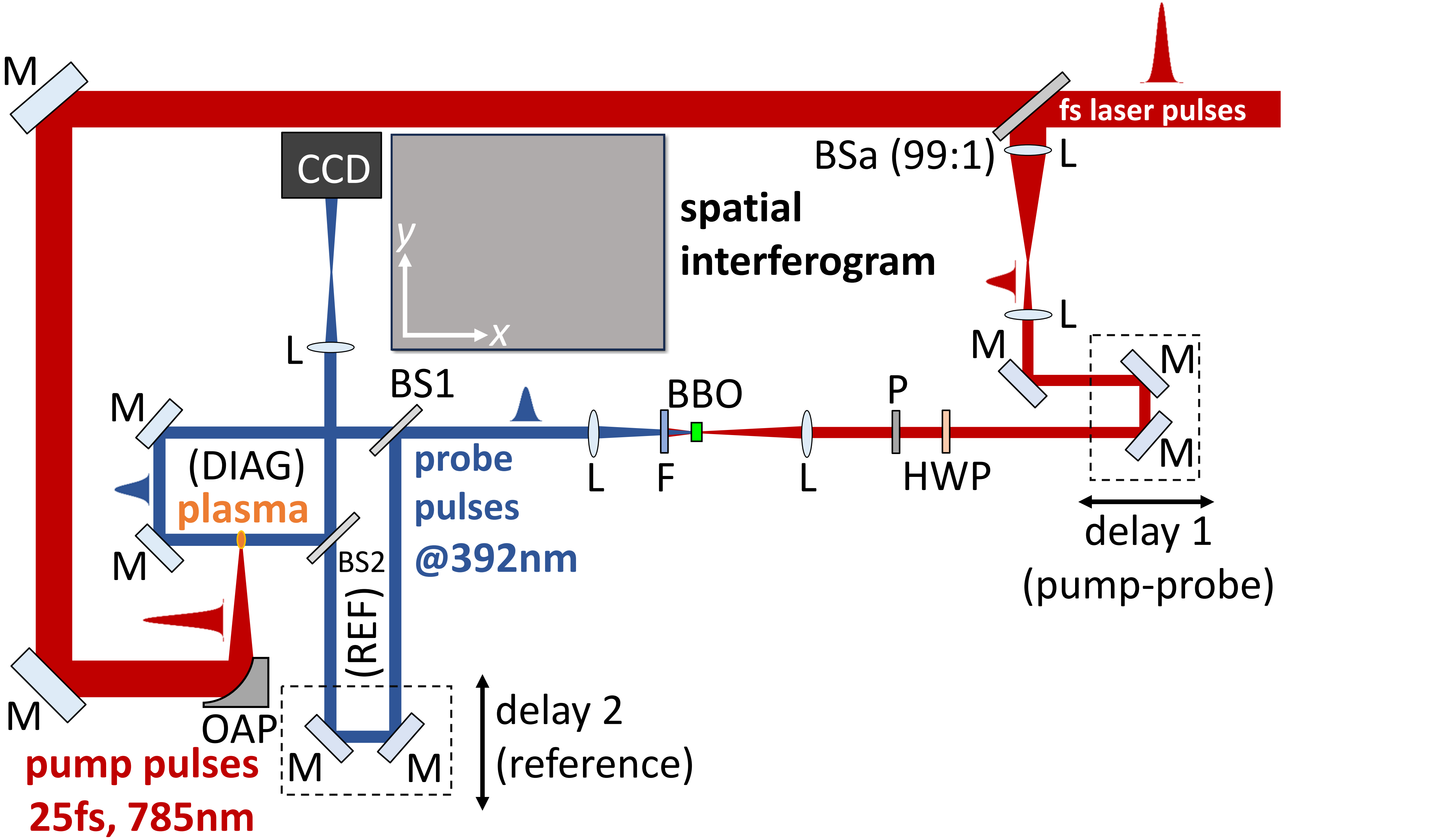
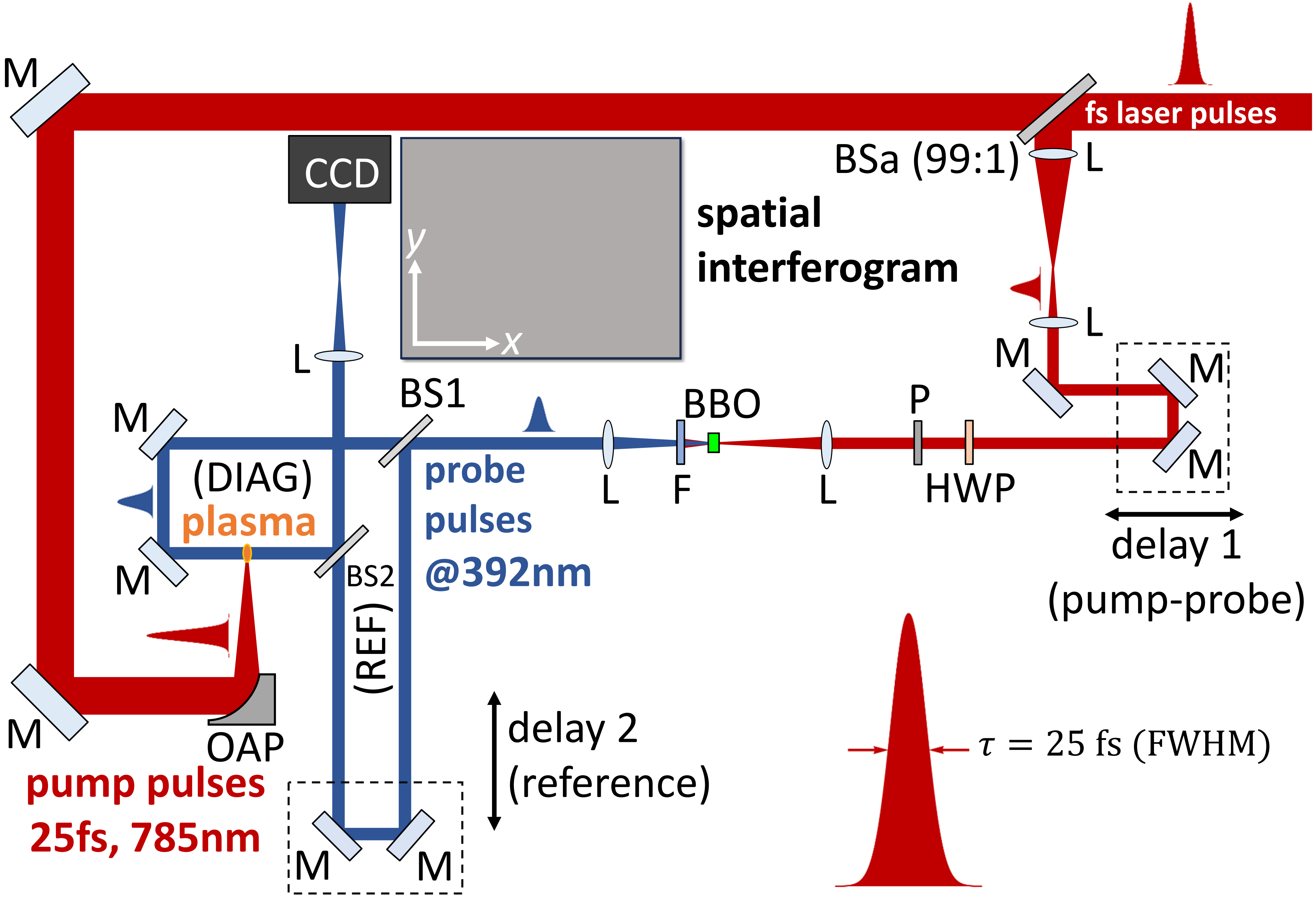
Time-Resolved Mach-Zehnder Like Interferometer



Time-Resolved Mach-Zehnder Like Interferometer



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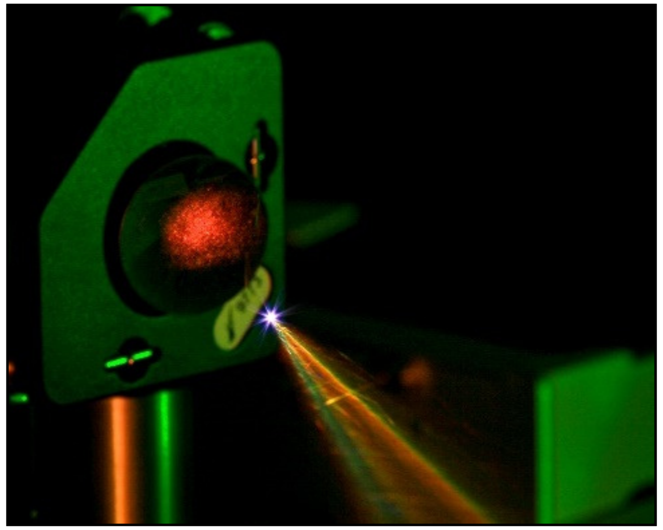
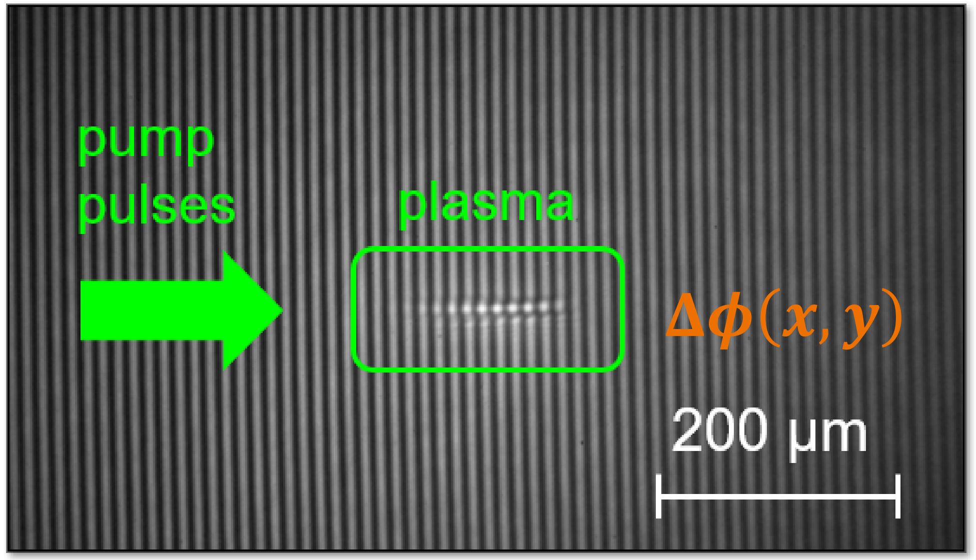
Laser-induced Plasma Characterization

25fs laser pulses, ~100μJ, focused in **air** by a parabolic mirror to **10^{16} W/cm²**



Laser-induced plasma interferogram

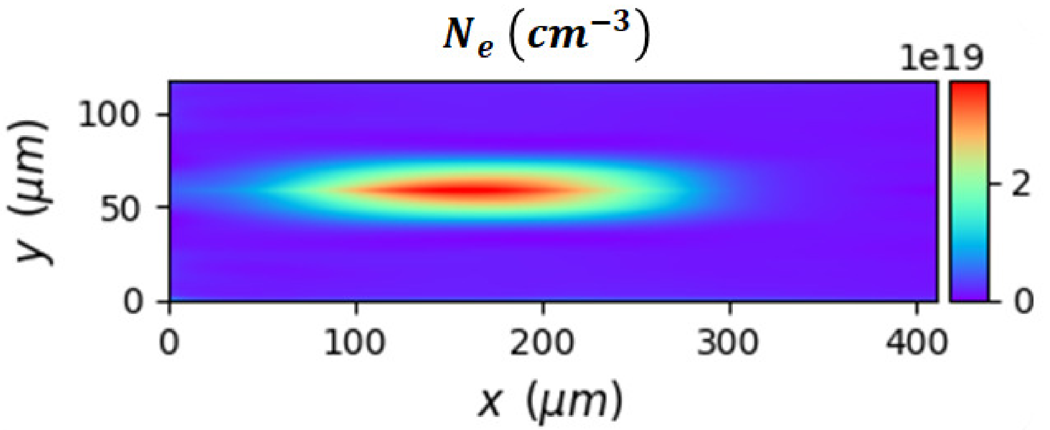


Plasma (electronic) density

$$n_e(x,y) = \frac{4\pi^2 c^2 \varepsilon_0 m_e}{e^2\lambda^2}\left\{1 - \left[1 + \frac{\Delta\phi(x,y)\lambda}{2\pi l}\right]^2\right\}$$

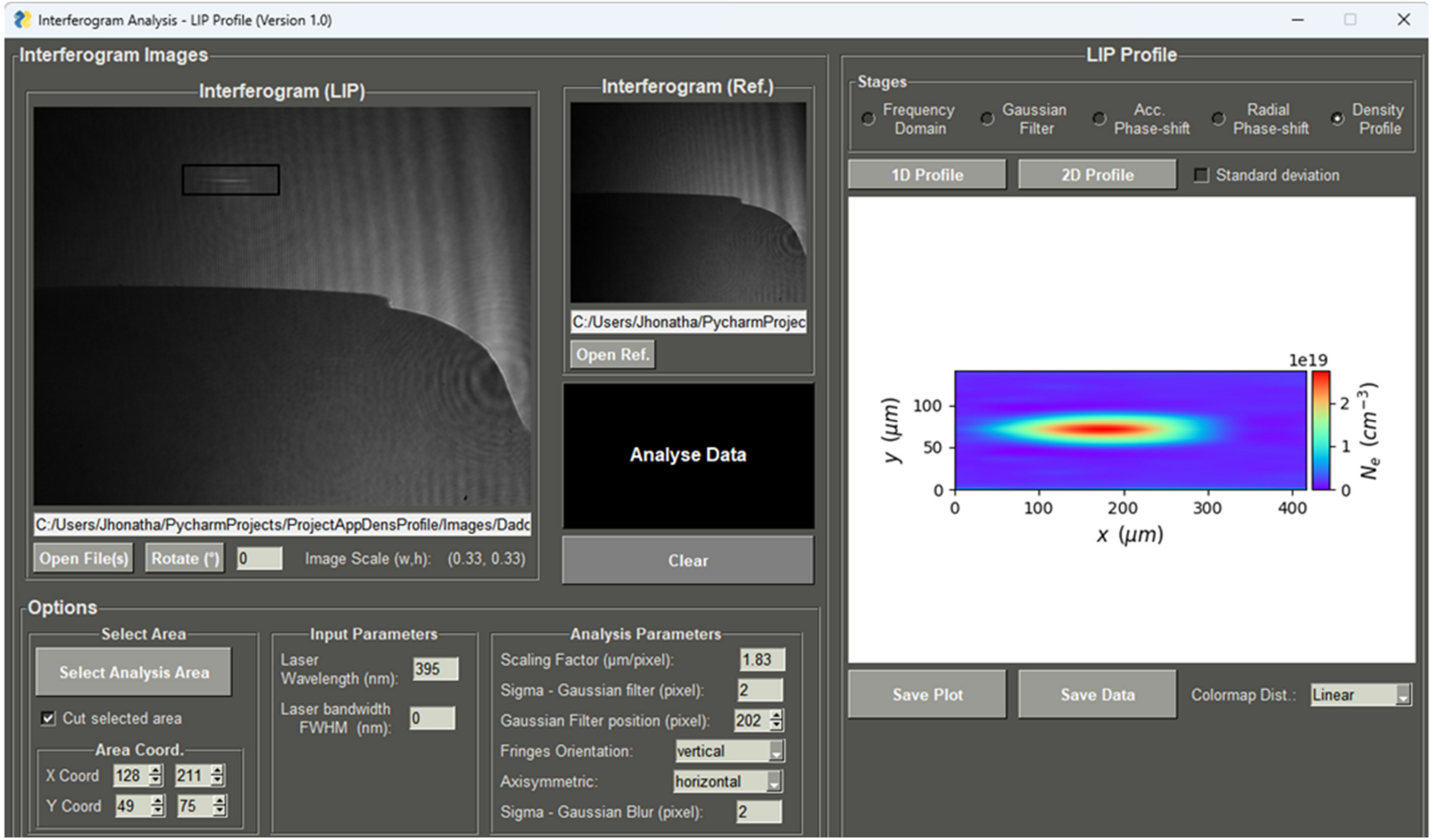
Fourier Transform + Frequency filtering + Inverse FT + phase difference + phase unwrap + Abel inversion

Laser-induced plasma density map



Plasma Density Retrieval

- Interferograms analysis by Fourier Transforms and Abel Transforms



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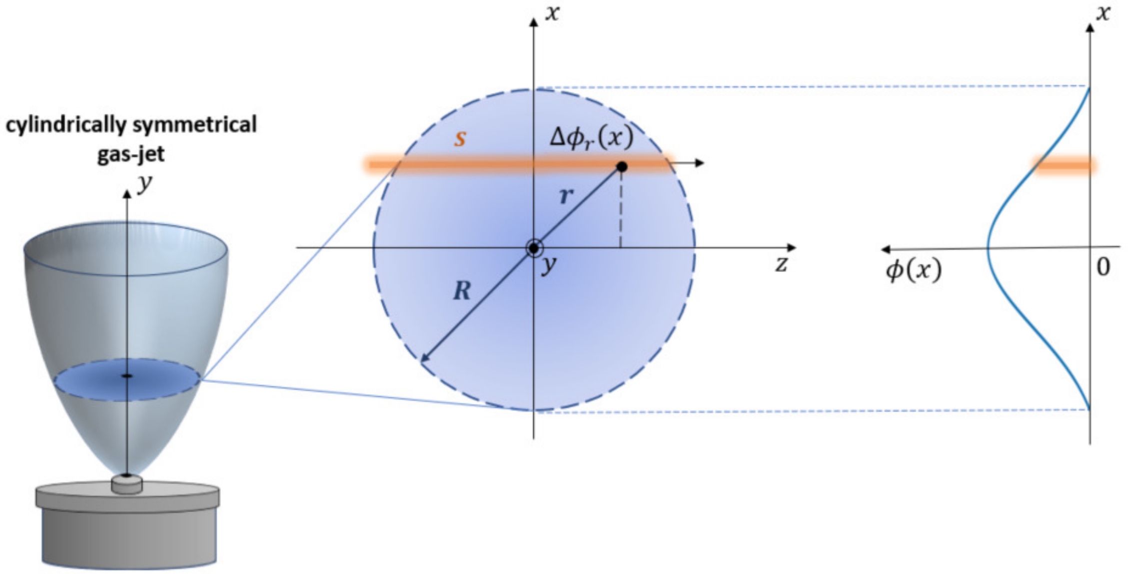
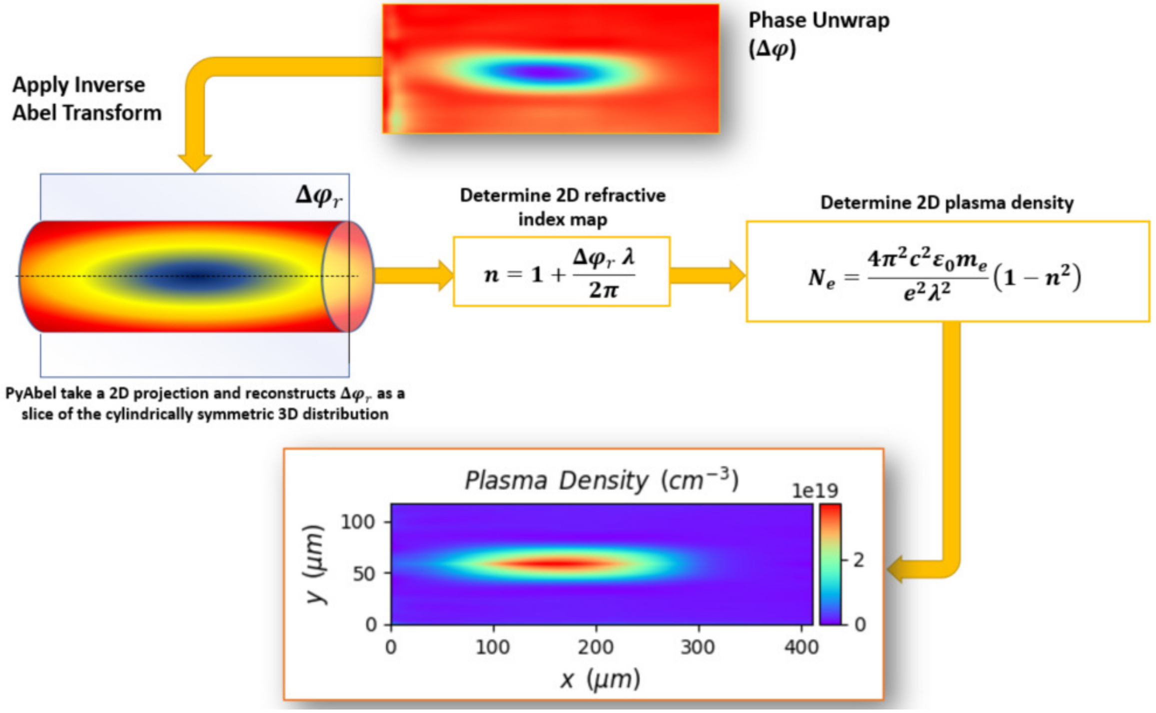
Inverse Abel Transform

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.



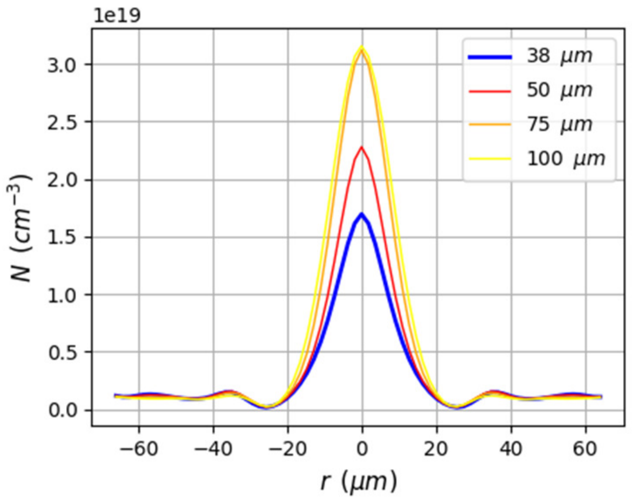


inverse Abel transform takes a 2D projection and reconstructs cylindrically symmetric 3D distribution

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:

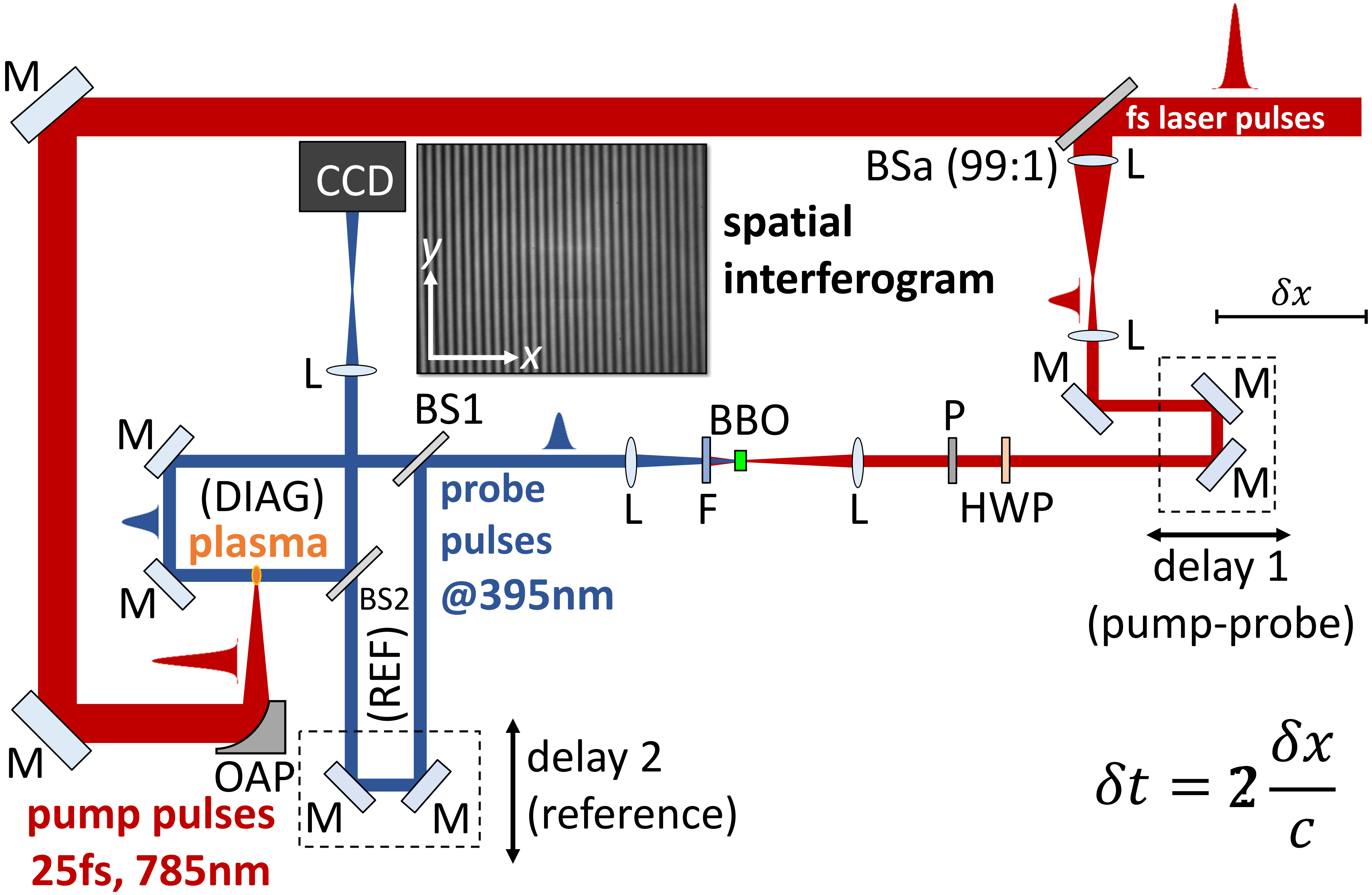
$$\Delta\phi_r = -\frac{1}{\pi}\int_r^{\infty} \frac{d[\Delta\phi]}{dx}\frac{dx}{\sqrt{r^2 - x^2}}$$

$$N_e = \frac{4\pi^2\, c^2\, \varepsilon_0 m_e}{e^2\lambda^2}(1 - n^2\,)$$



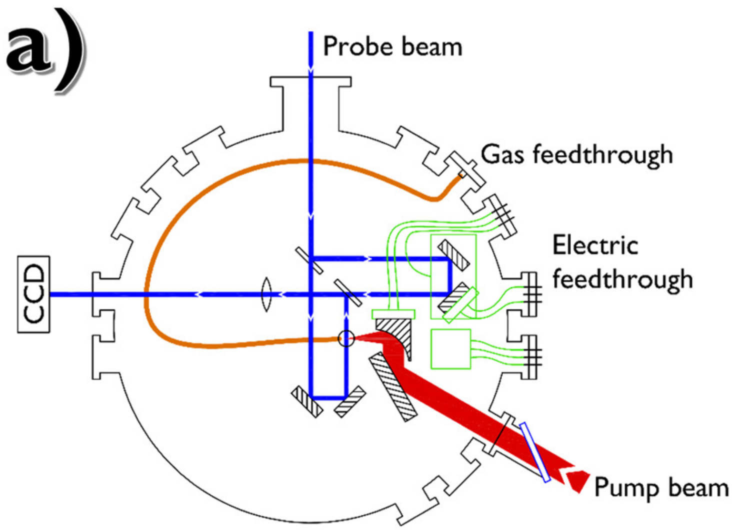
In our code, the radial phase-shift map is constructed from the application of a PyAbel algorithm on the accumulated phase-shift map Δφ . PyAbel is a Python package that provides efficient implementations of several forward and inverse Abel transform algorithms.

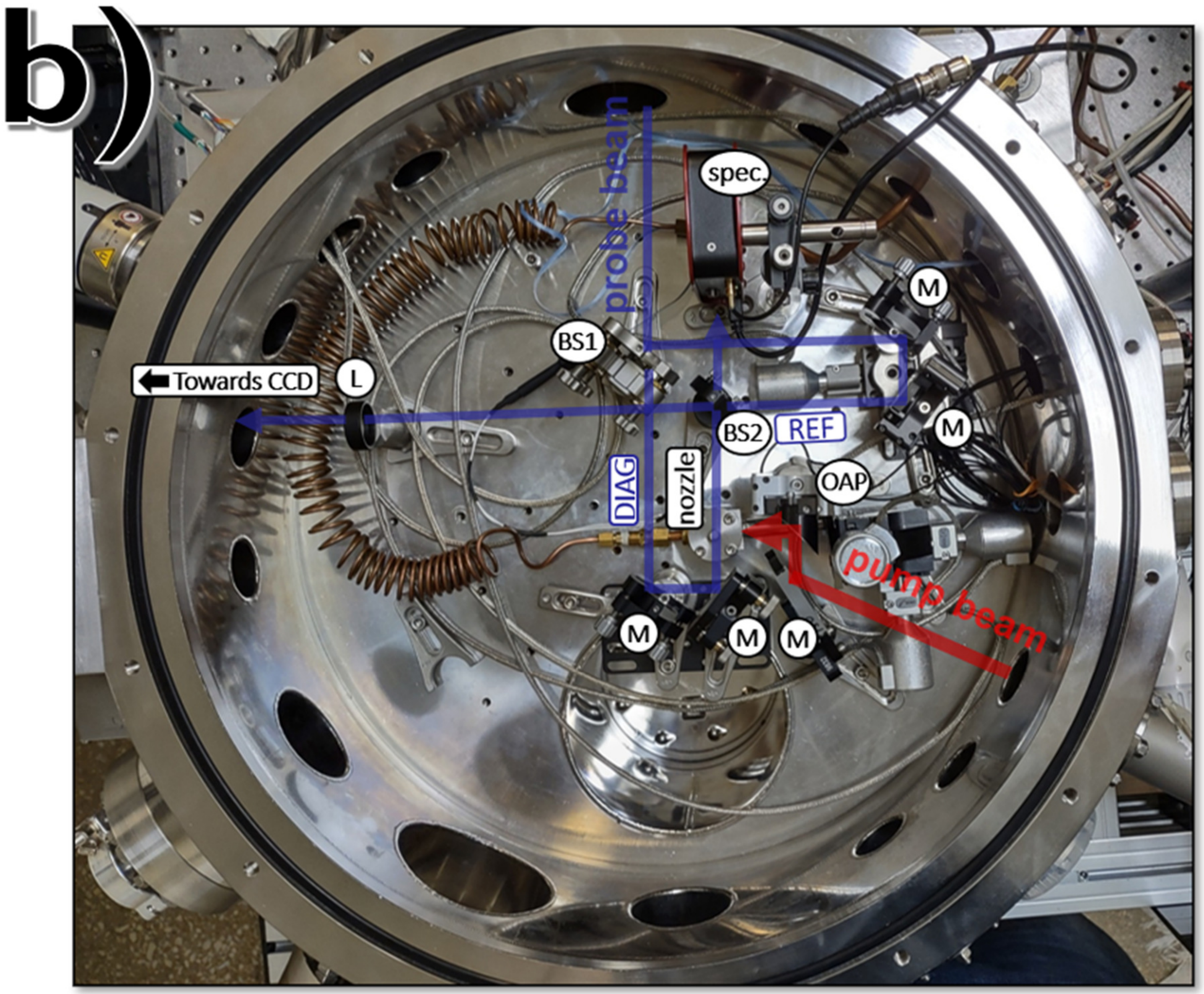
Time-Resolved Mach-Zehnder Like Interferometer



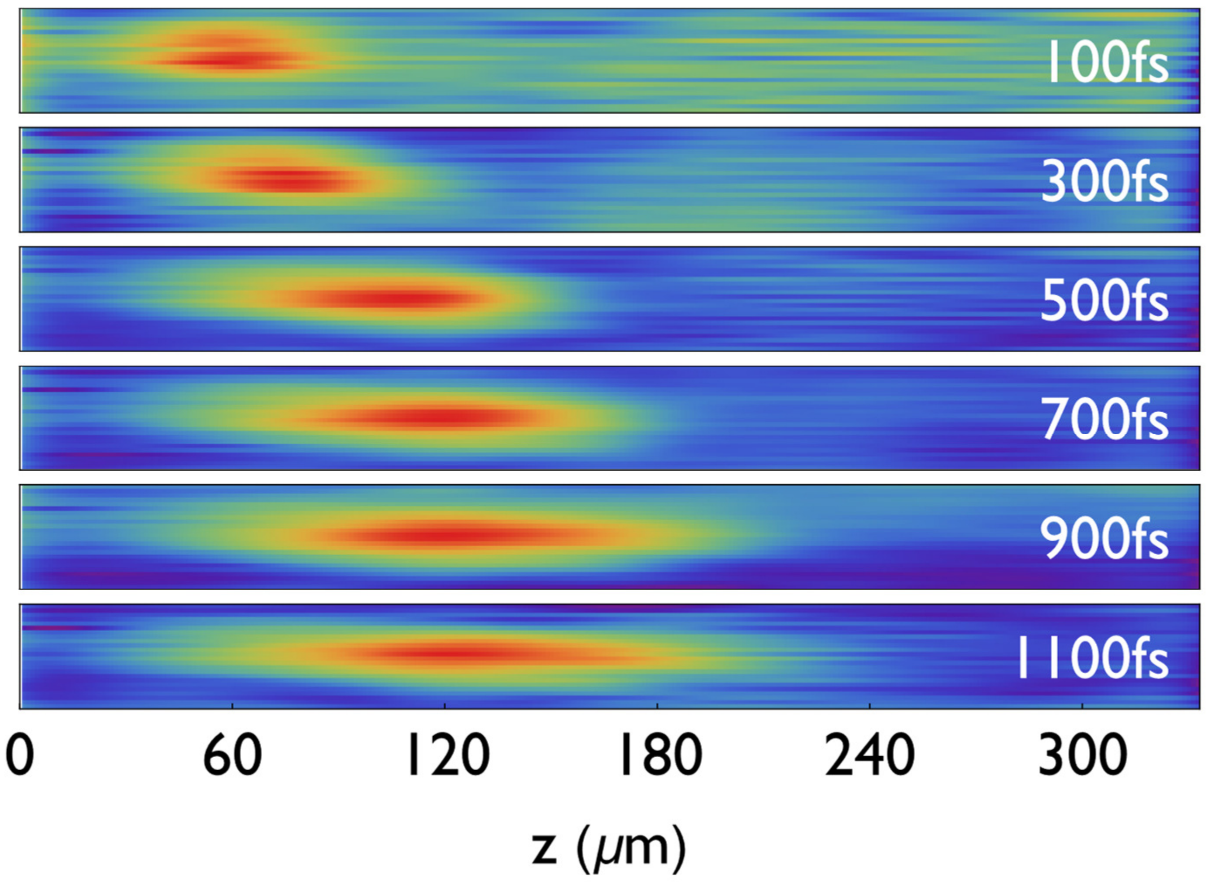
$$\delta t = 2\frac{\delta x}{c}$$

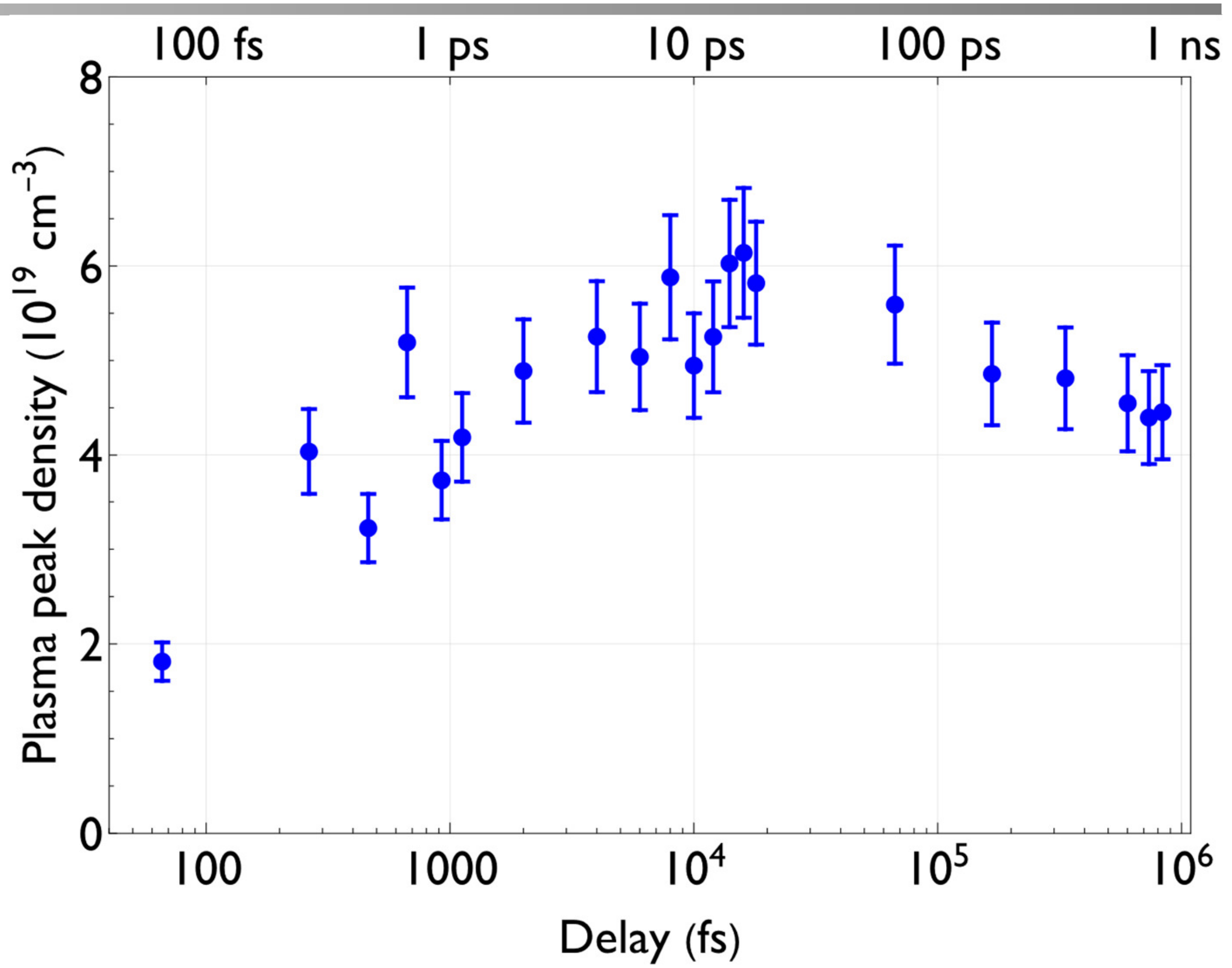
Experimental Setup





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

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