CHiP Annual Meeting on 2024

Frequency-Domain Interferometry for Measuring Plasma Density Produced by Femtosecond Laser Pulses in a Gas-Filled Capillary Waveguide

Speaker : Jia-Wen Gu

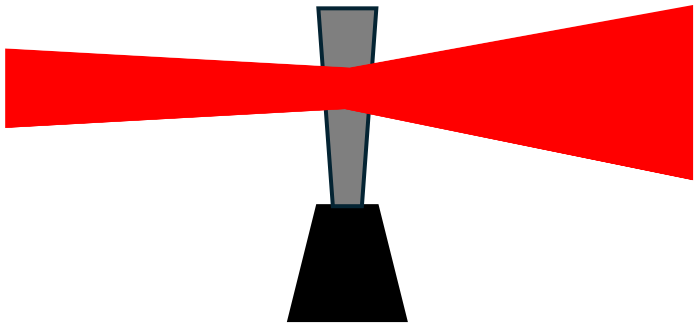
Adviser : Hsu-Hsin Chu

Gas-Filled Capillary Waveguide

The laser-plasma interaction:

- High-order Harmonic Generation (HHG)
- Laser-Wakefield Acceleration (LWFA)

Gas Jet



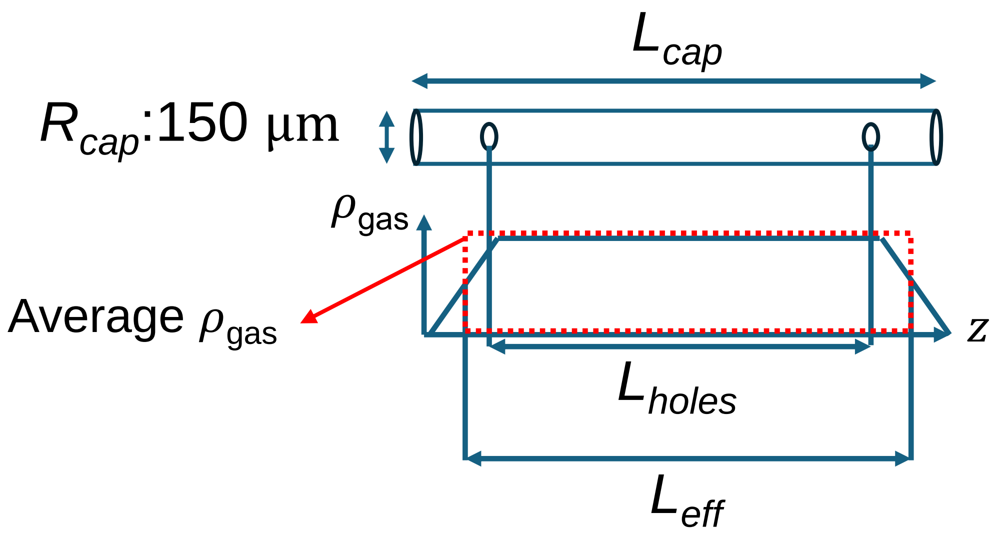
Natural diffraction limits the interaction length

Gas-Filled Capillary Waveguide

Waveguide confines the propagated beam size / Extend the interaction length

Plasma Diagnosis inside Gas-Filled Capillary Waveguide

- Frequency Domain Interferometry (FDI) can be employed to diagnose the plasma density along the longitudinal axis of the capillary.
  - Femtosecond scale time resolution
  - Average plasma density



$$L_{eff} = L_{holes} + \frac{L_{cap} - L_{holes}}{2}$$

The length referred to in the following slides is all effective length.

Frequency Domain Interferometry (FDI)

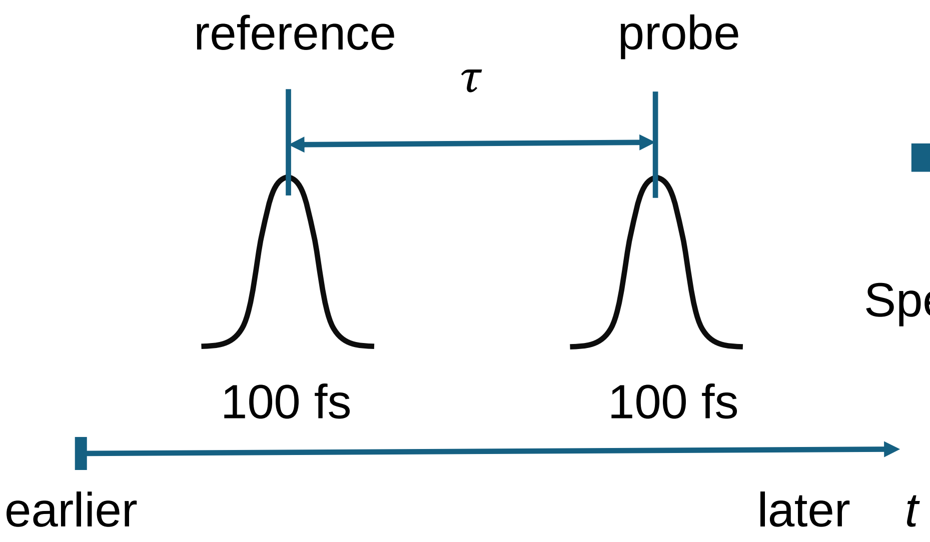
$$E_{reference}(t) = |E_0|e^{i\omega_0 t}$$

$$E_{probe}(t) = |E_0|e^{i\omega_0 (t-\tau)}$$

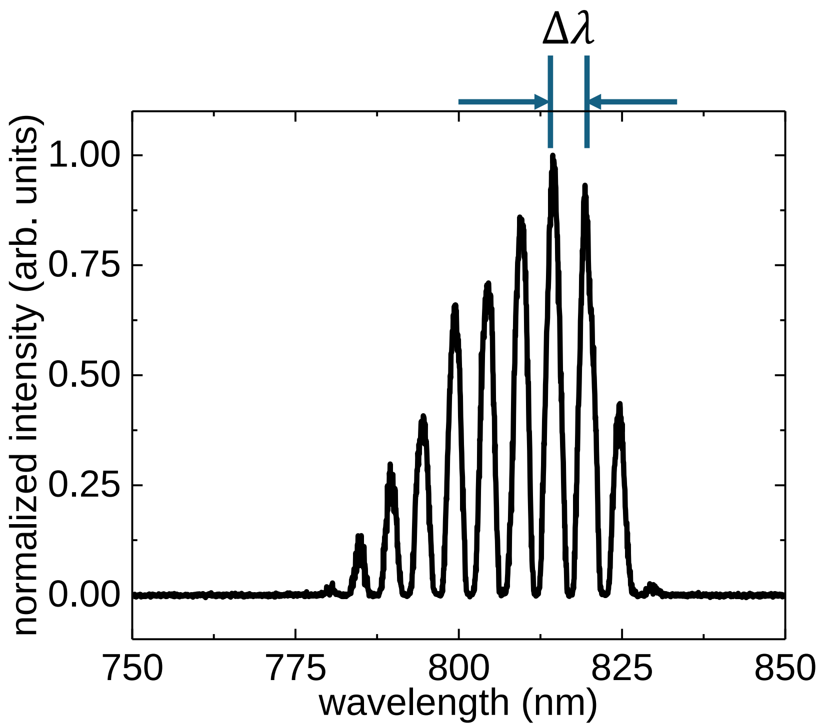
$$E_{total}(t) = |E_0|(e^{i\omega_0 (t-\tau)} + e^{i\omega_0 t})$$

$$E_{total}(\omega) = FT\big(E_{total}(t)\big) \propto 1 + \cos(\omega\tau)$$

$$\Delta\omega = \left|\frac{2\pi c}{\lambda^2}\right| \Delta\lambda \propto \frac{1}{\tau}$$



Sent to Spectrometer



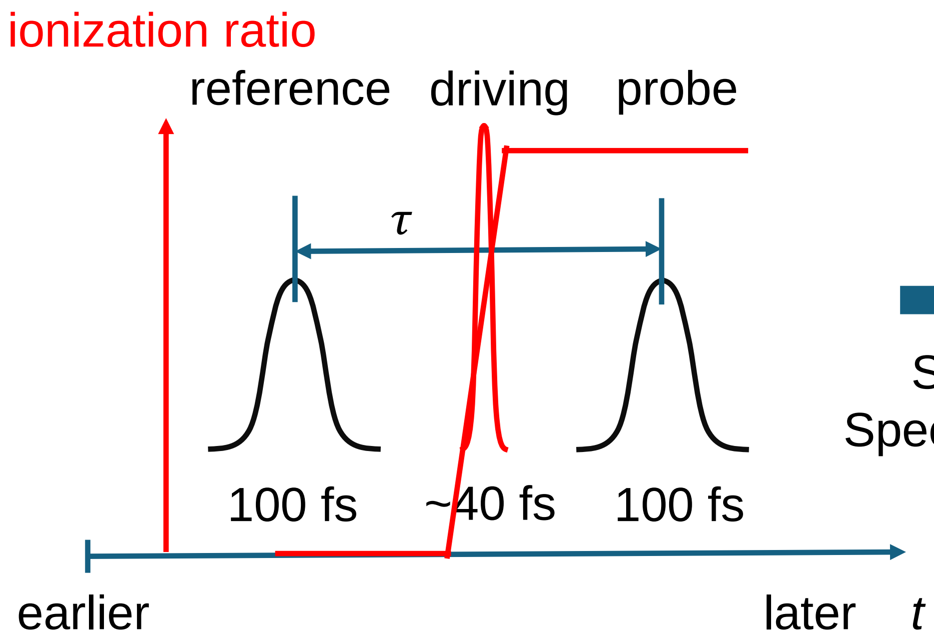
Frequency Domain Interferometry (FDI)

$$E_{reference}(t) = |E_0|e^{i\omega_0 t}$$

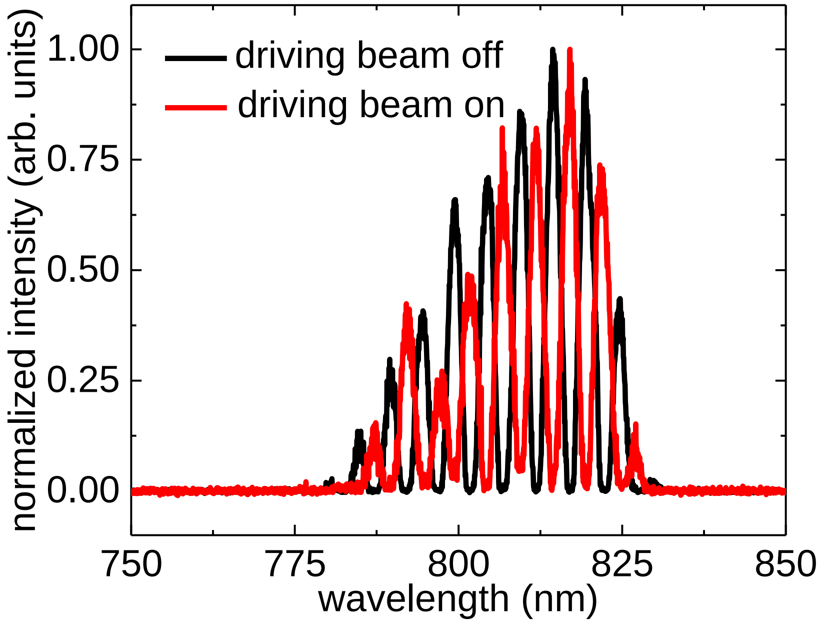
$$E_{probe}(t) = |E_0|e^{i\omega_0(t-\tau)+\mathrm{i}\Delta\phi}$$

$$E_{total}(t) = |E_0|(e^{i\omega_0(t-(\tau+\Delta\tau))+\mathrm{i}\Delta\phi} + e^{i\omega_0 t})$$

$$E_{total}(\omega) = FT\big(E_{total}(t)\big) \propto 1 + \cos(\omega\tau - \phi)$$



Sent to Spectrometer



1. *Journal of the Optical Society of America B* 12, no. 5 (May 1, 1995): 753.
2. Memorandum - Frequency Domain Interferometry, Hsu-Hsin Chu, (June 21, 2022)

Frequency Domain Interferometry (FDI)

$$E_{reference}(t) = |E_0|e^{i\omega_0 t}$$

$$E_{probe}(t) = |E_0|e^{i\omega_0(t-\tau)+\mathrm{i}\Delta\phi}$$

$$E_{total}(t) = |E_0|(e^{i\omega_0(t-(\tau+\Delta\tau))+\mathrm{i}\Delta\phi} + e^{i\omega_0 t})$$

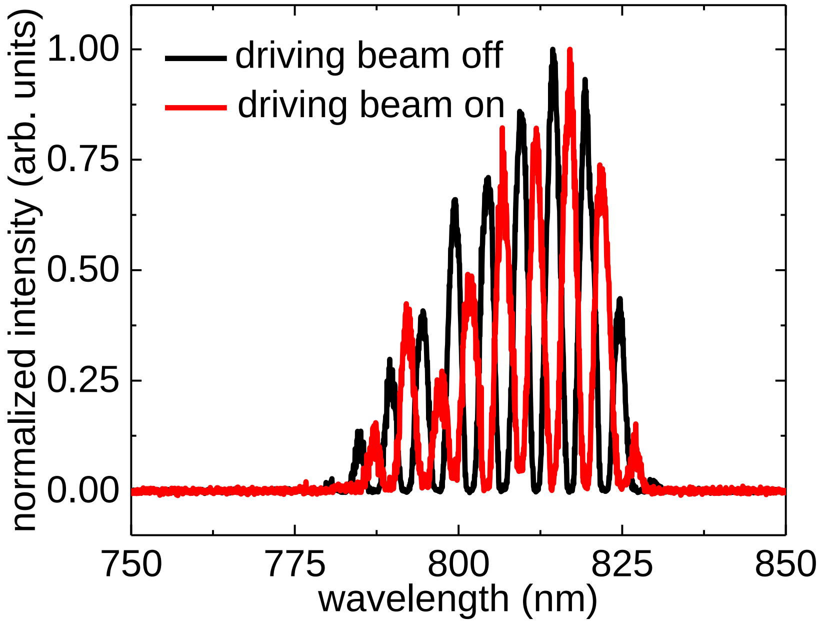
$$E_{total}(\omega) = FT\big(E_{total}(t)\big) \propto 1 + \cos(\omega\tau - \phi)$$

Plasma dispersion

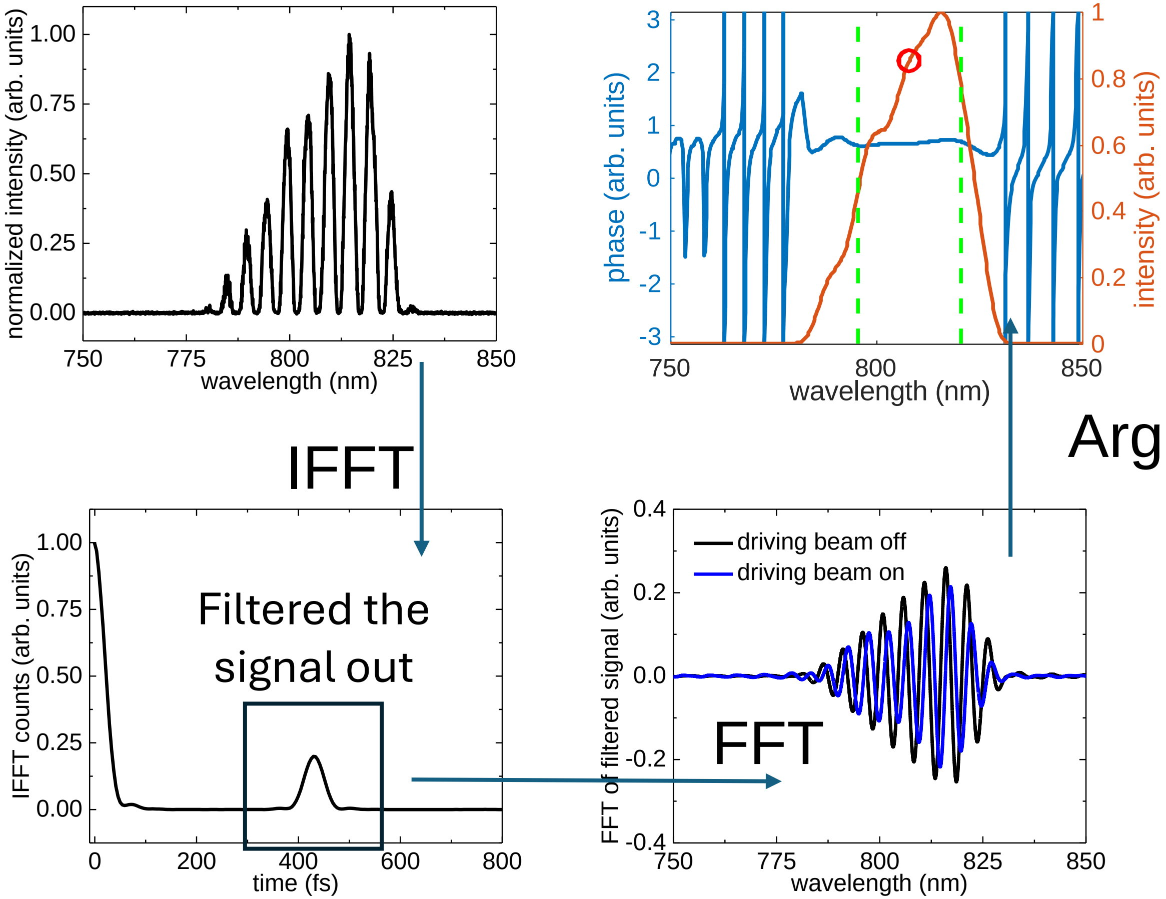
$$n(N_e, \omega) = \sqrt{1 - \frac{N_e e^2}{\epsilon_0 m_e \omega^2}}$$

Phase: $\Delta\phi(N_e, \omega) = k_0(n(N_e, \omega) - 1)L_{eff}$

Group Delay: $\Delta\tau(N_e, \omega) = \frac{L_{eff}}{c}\left(\frac{1}{n(N_e,\omega)} - 1\right)$

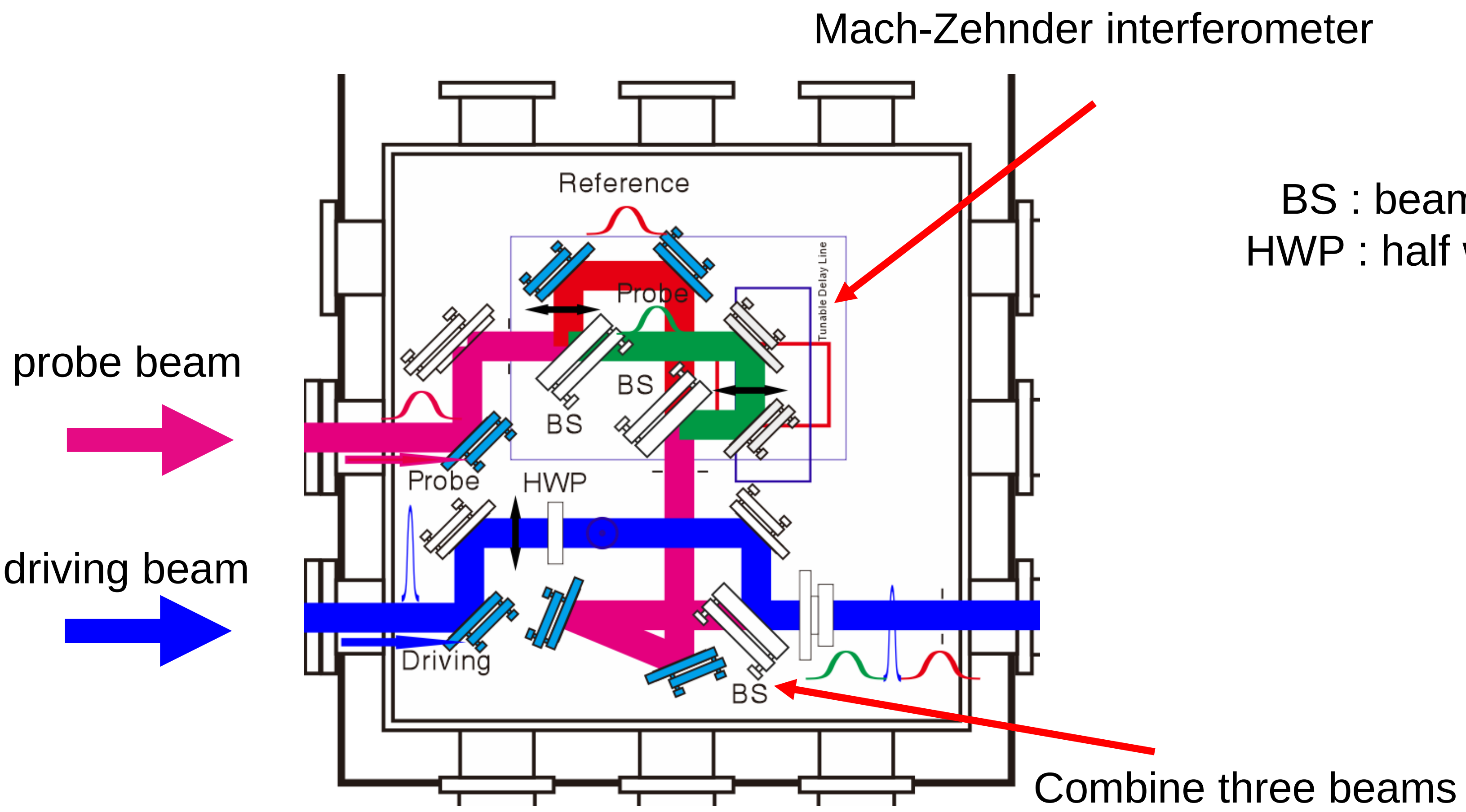


Frequency Domain Interferometry – Phase Retrieving



$$\mathrm{Arg}\left(\frac{I_{driving\ beam\ on}}{I_{driving\ beam\ off}}\right)$$

Experimental Configuration

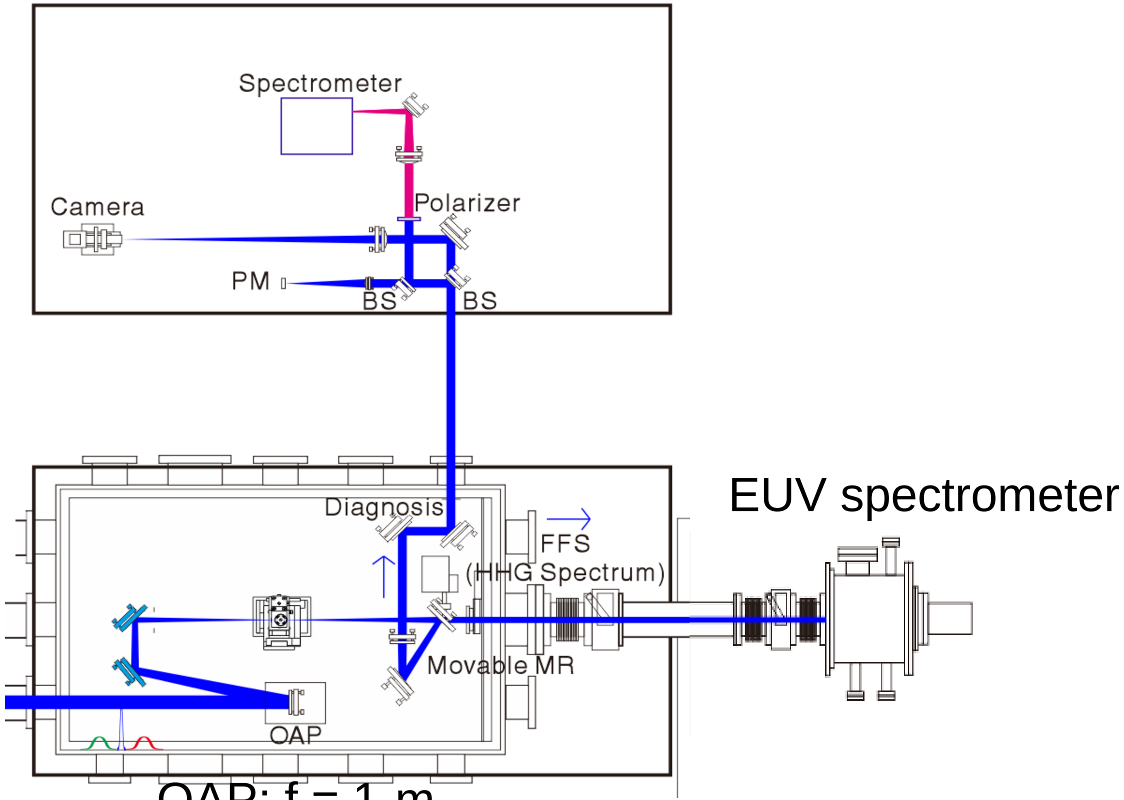


BS : beam splitter
HWP : half waveplate

Experimental Configuration

Diagnostic System:

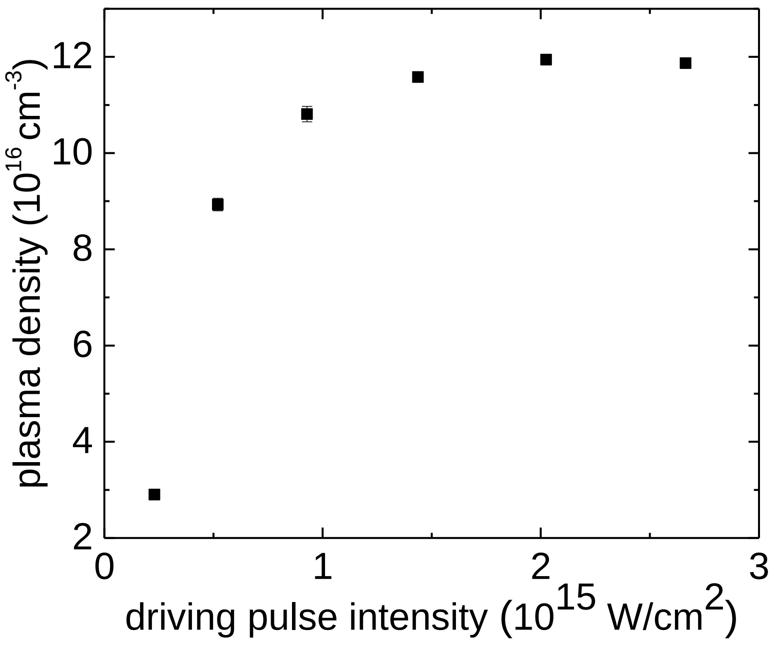
- Beam Profile
- Energy
- Spectrum
- Plasma Density



OAP: f = 1-m
Off-Axis Parabolic Mirror

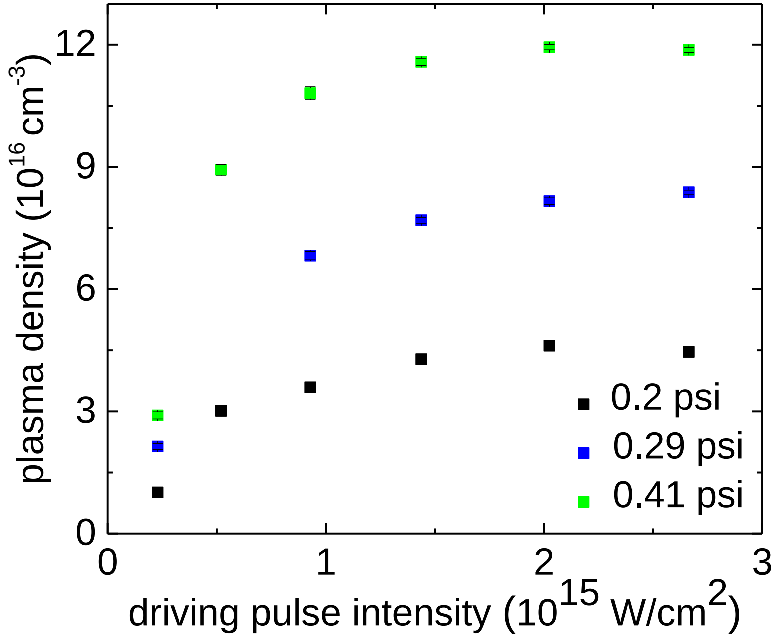
Plasma Density and Gas Density inside Capillary

Gas : H_2
Backing pressure : 0.41 psia
Pulse duration : ~ 40 fs
Center wavelength : 808 nm
Driving beam energy: 3~26 mJ
Effective length: 12.1 mm

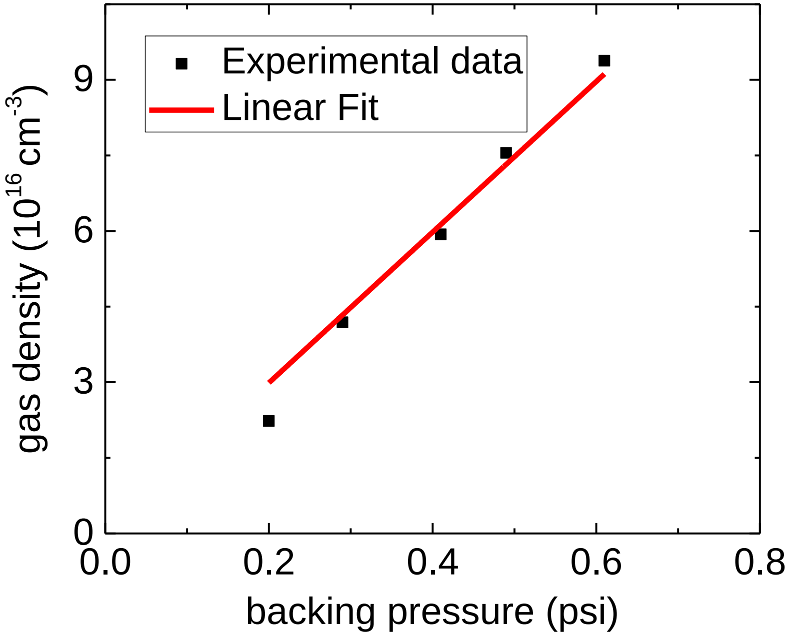


Plasma Density and Gas Density inside Capillary

Gas : H_2
Pulse duration : ~ 40 fs
Center wavelength : 808 nm
Effective length: 12.1 mm



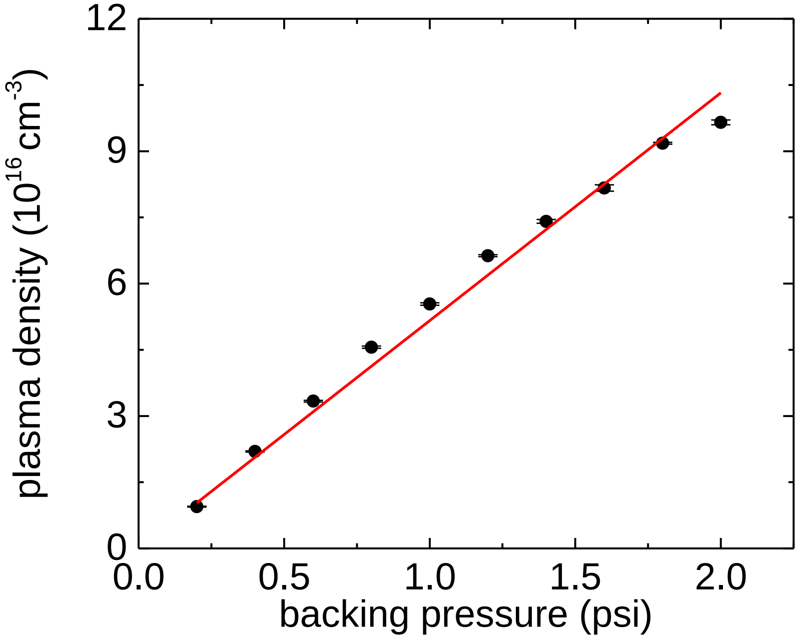
Gas : H_2
Pulse duration : ~ 40 fs
Center wavelength : 808 nm
Driving beam energy : 26 mJ
Effective length: 12.1 mm



Plasma Density through Group Delay and Phase Shift

Low density plasma

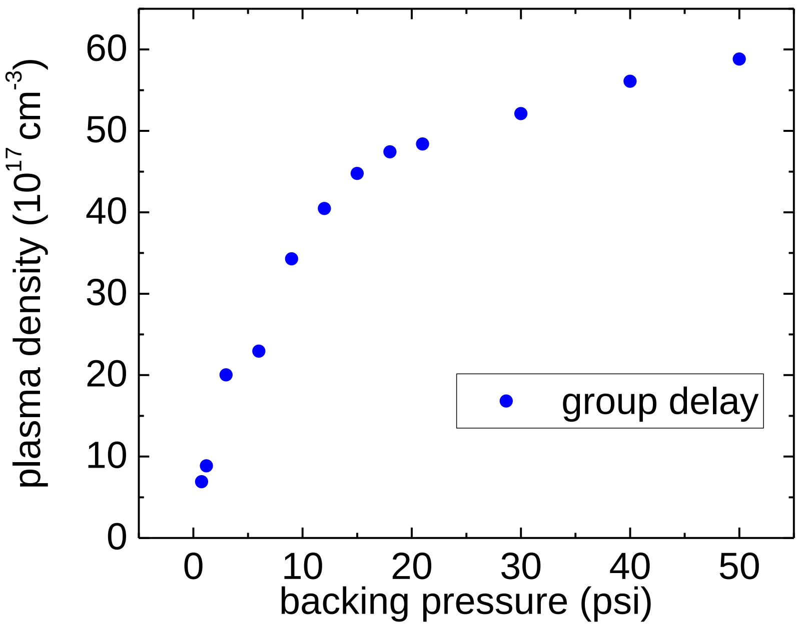
Gas : Ar
Pulse duration : ~ 100 fs
Center wavelength : 808 nm
Effective length: 12.1 mm
Driving beam energy : ~20 mJ
Driving beam intensity: 7.88×10^{14} W/cm^2



Plasma Density through Group Delay and Phase Shift

High density plasma

Gas : Ar
Pulse duration : ~ 40 fs
Center wavelength : 808 nm
Effective Length: 12.1 mm
Driving beam energy : ~3 mJ
Driving beam intensity: 2.76×10^{14} W/cm^2



Conclusion

- FDI technique is successfully used for measuring plasma density inside capillary.
- FDI covers the measurements of plasma density in the range from 10^{16} to 10^{18} cm^{-3}, utilizing phase difference between pulse pairs for lower densities, and group delay between pulse pairs for higher densities.
- This research supports achieving high conversion efficiency HHG by providing powerful plasma diagnosis.

	Phase	Group Delay
Measurable Range(cm^{-3})	1E16-1E17	1E17-1E18

Thanks for your attention