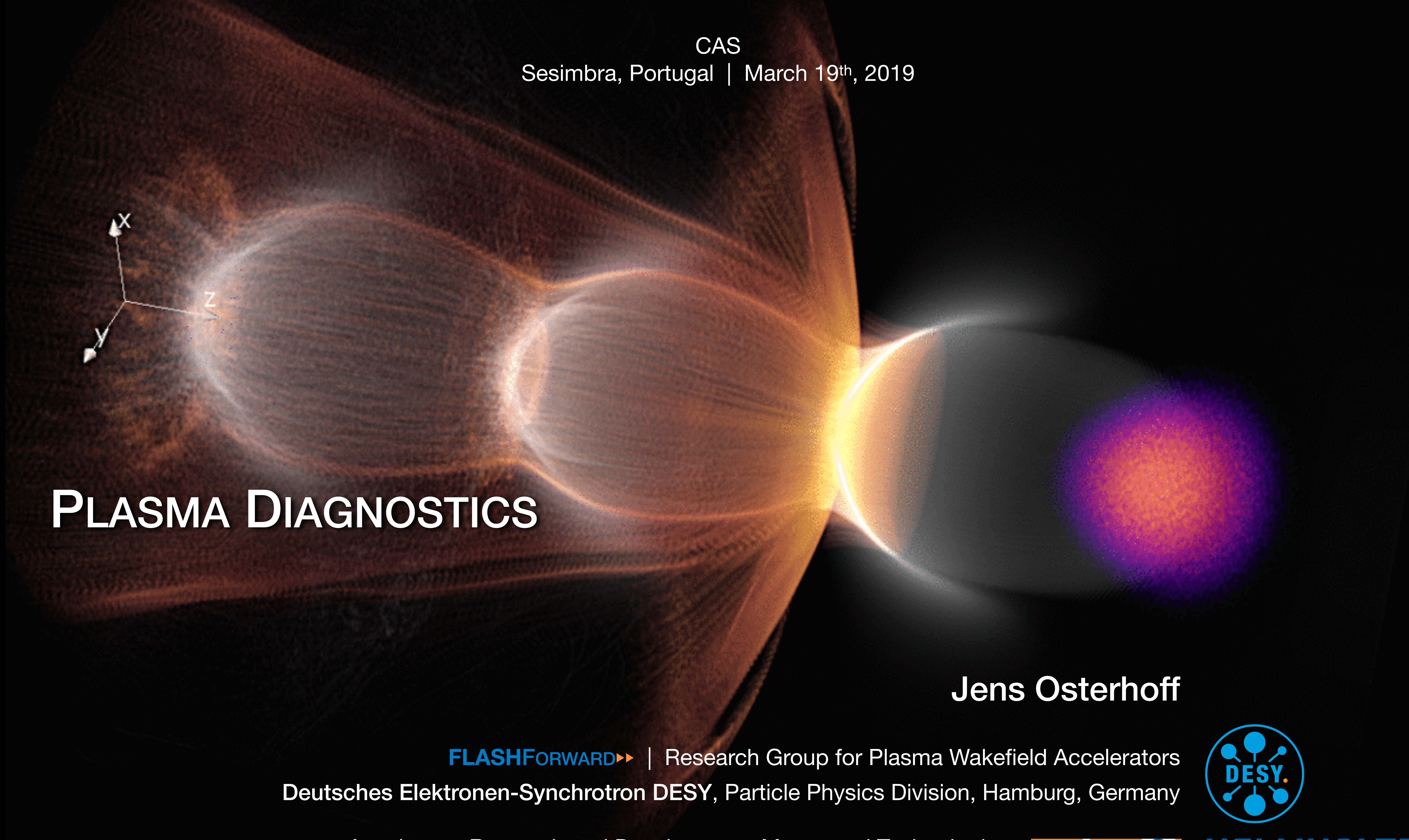
CAS
Sesimbra, Portugal | March 19th, 2019



Plasma Diagnostics

Jens Osterhoff

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simulation by Alberto Martinez de la Ossa

Many thanks for support and material to…

<u>**Malte Kaluza (FSU Jena)**</u>

Gregor Loisch (DESY Zeuthen)

<u>Nicholas Matlis (DESY FS)</u>

Jimmy Garland, Lars Goldberg, Tobias Kleinwächter, Lucas Schaper, Gabriele Tauscher (DESY FH)

<u>Disclaimer:</u> presentation is only an incomplete and subjective snapshot of the field!

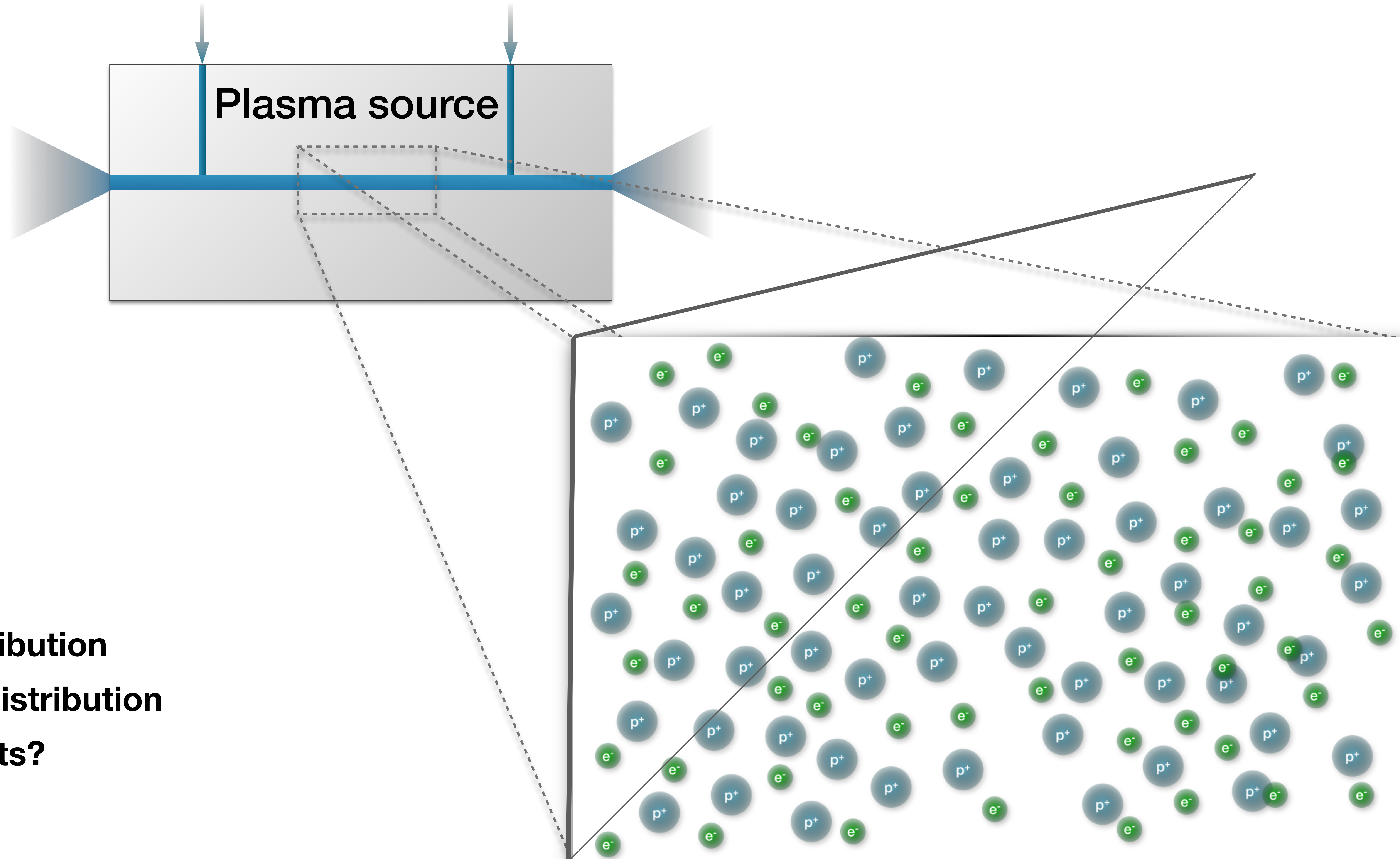
Lecture Series on Plasma Sources and Diagnostics

> **Plasma Sources I**
  - Thursday, March 14, 9:00 - 10:00
  - **Conceptual aspects**

> **Plasma Sources II**
  - Friday, March 15, 9:00 - 10:00
  - **Technical aspects**

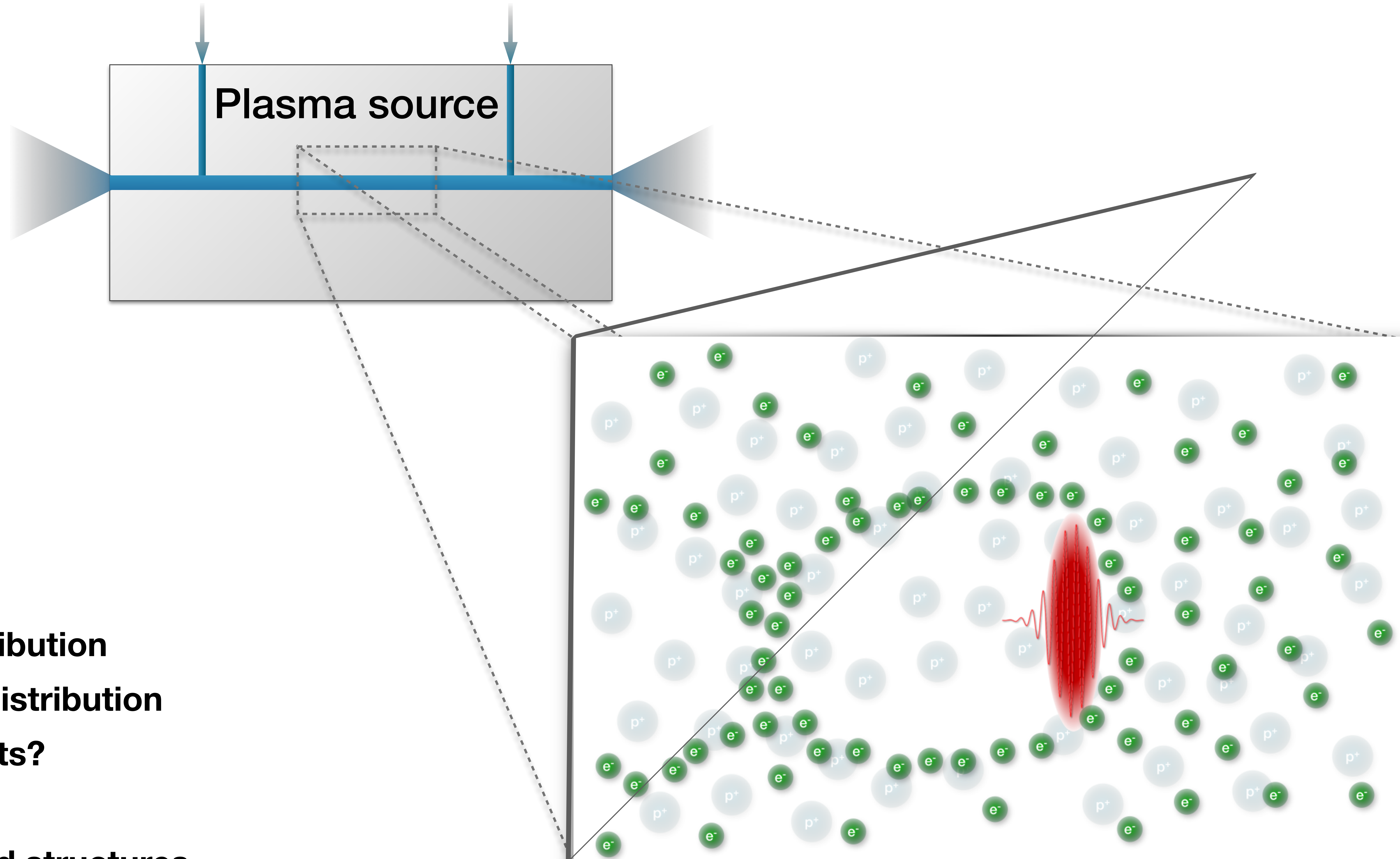
> **Plasma Diagnostics**
  - Tuesday, March 19, 10:00 - 11:00
  - **Diagnostics:** how to measure what is going on in plasmas

Outline - Plasma Diagnostics - What to measure?



- Gas density distribution
- Plasma density distribution
- Other constituents?
- Temperature

Outline - Plasma Diagnostics - What to measure?



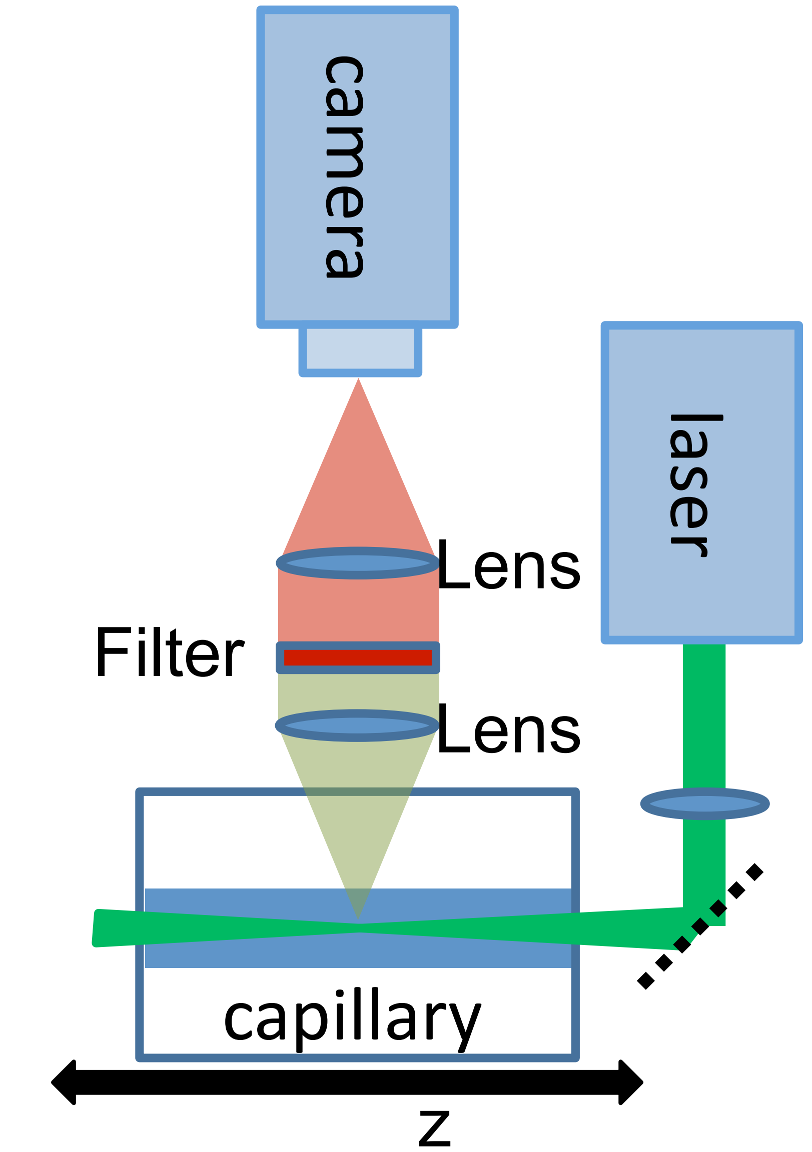
- **Gas density distribution**
- **Plasma density distribution**
- **Other constituents?**
- **Temperature**
- **Internal fields and structures**

Initial gas density distribution

- Raman scattering
- Laser interferometry
  → plasma density measurements

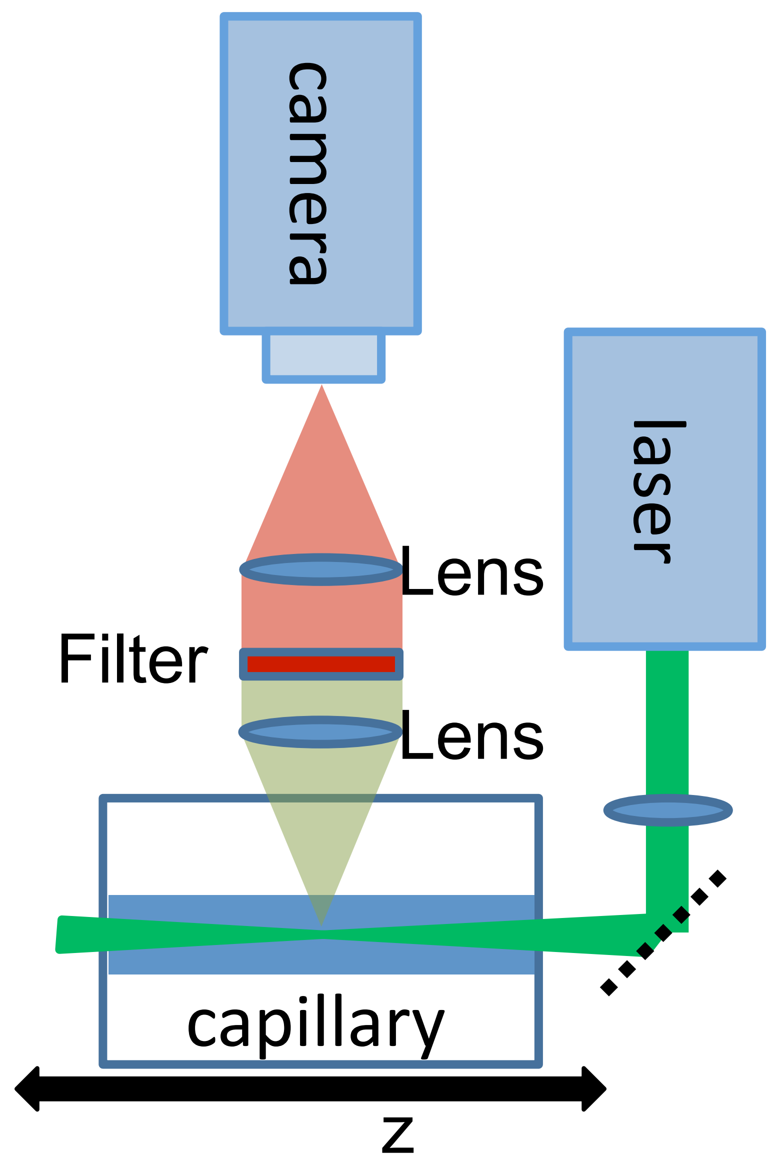
Laser scattering

- Scattering of (laser) light on bound electrons (gas, plasma) can be used as density diagnostic



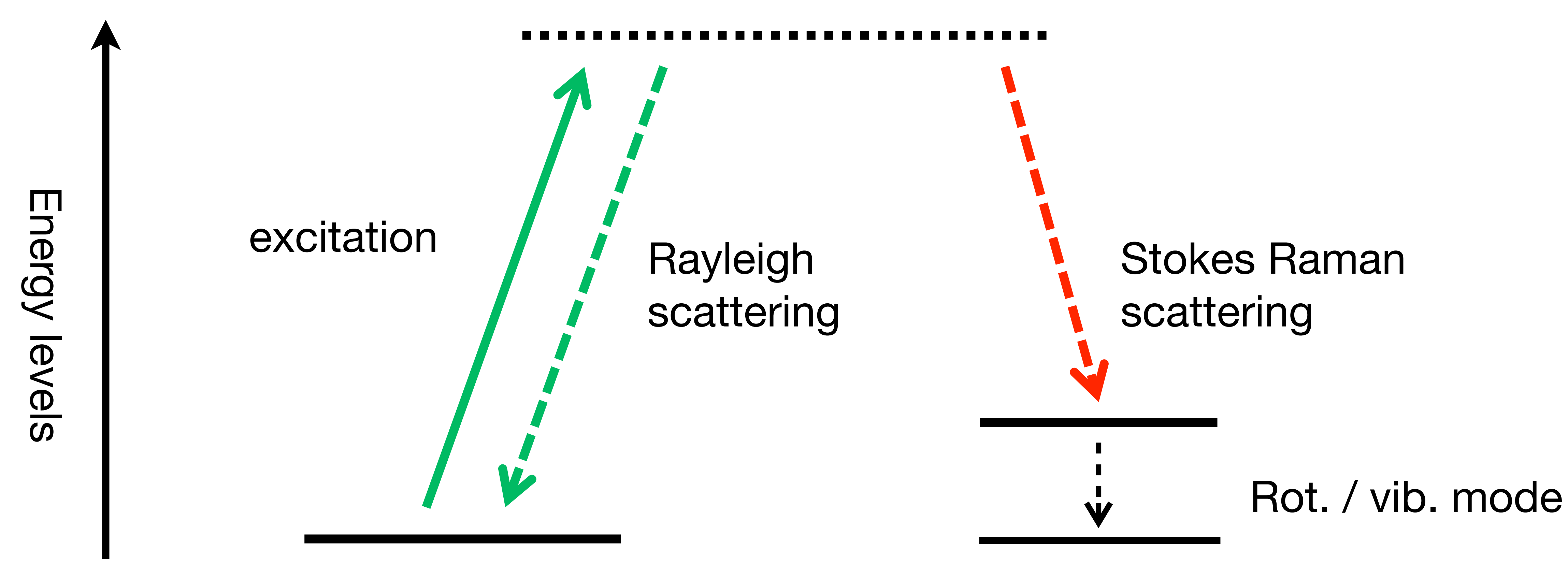
Laser scattering

- Scattering of (laser) light on bound electrons (gas, plasma) can be used as density diagnostic

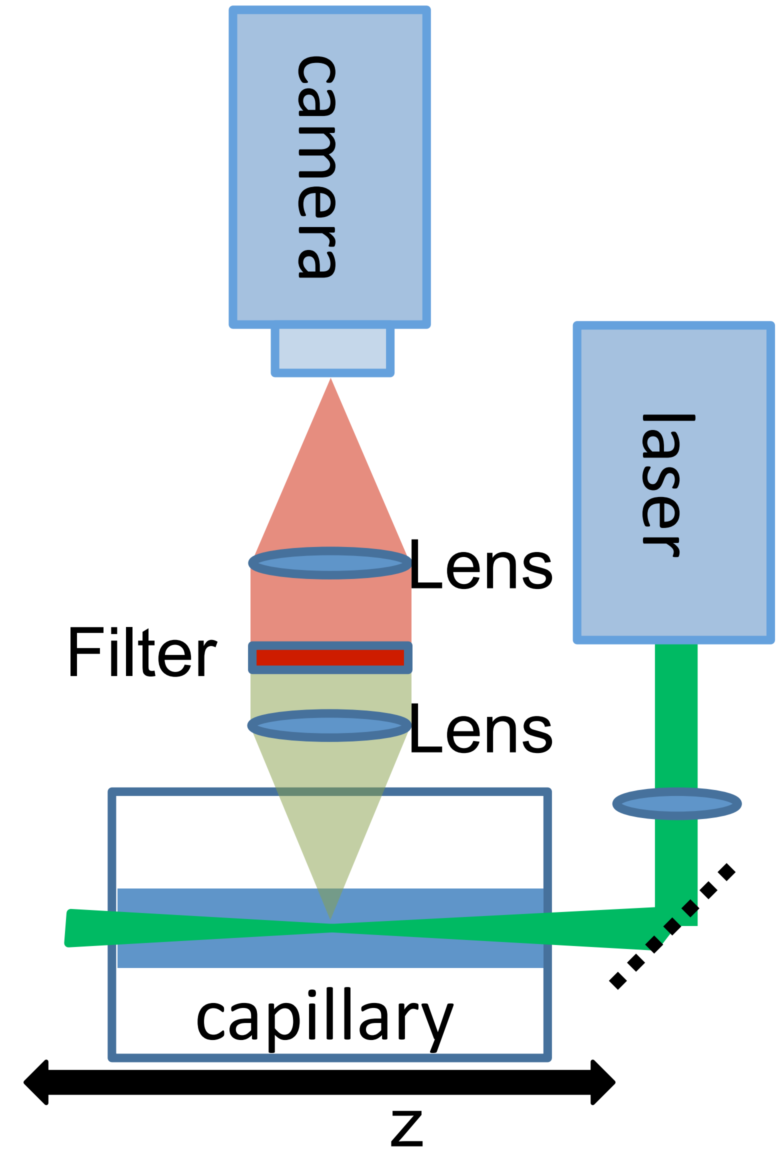


Elastic scattering (Rayleigh)
leaves species in same quantum state
scattered photons of same energy

Inelastic scattering (Raman)
changes the quantum state of the species
energy difference excitation to emission



Laser scattering



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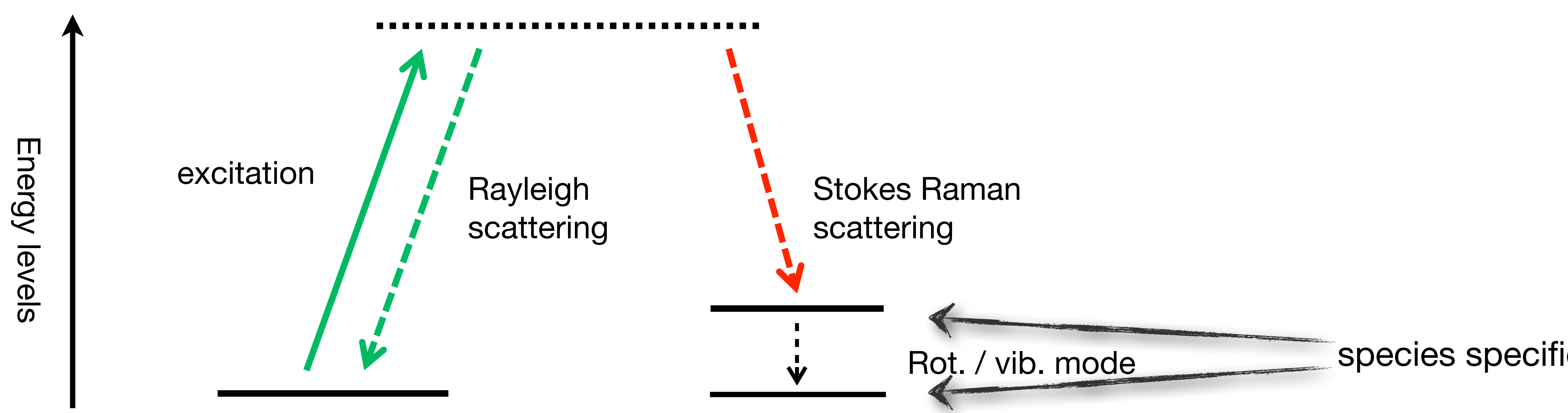


- **Rayleigh scattering** allows in principle for measuring densities, but scattering off plasma difficult to distinguish from scattering off walls (+ much more intense!)
- **Raman scattering** photons at species specific wavelength → differentiation between scattering sources

Raman scattering

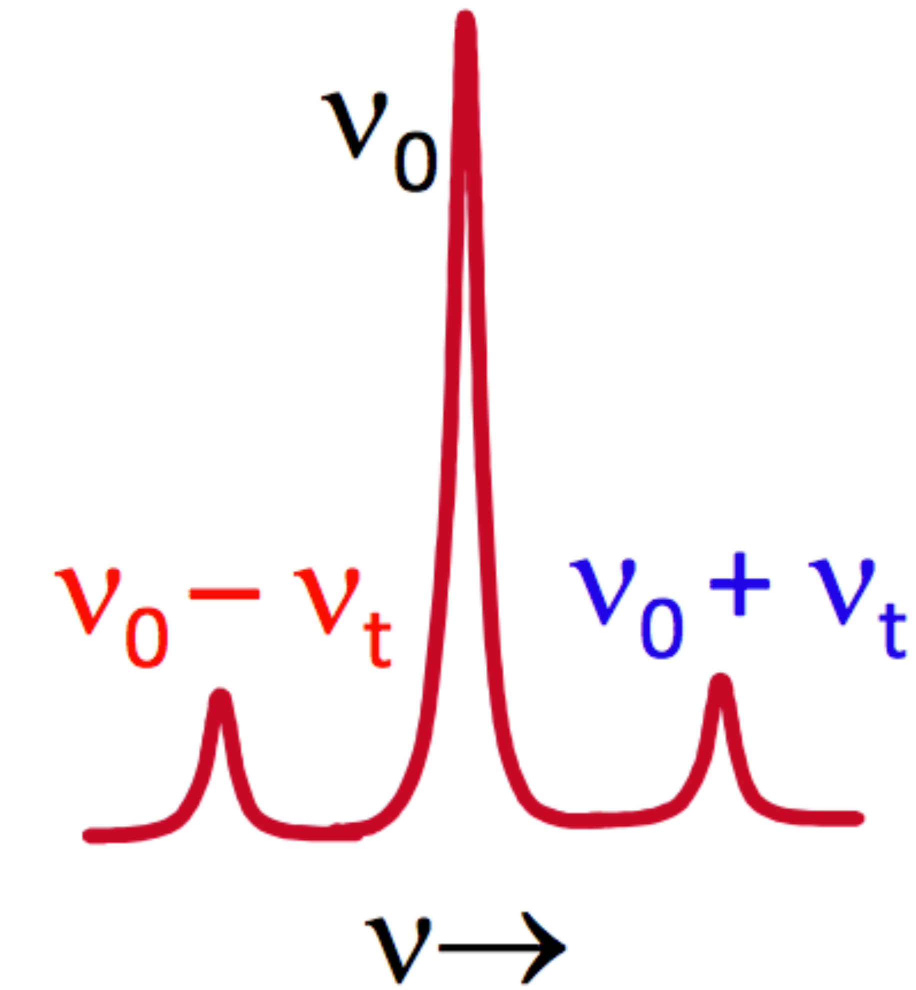
- Inelastic process in which energy can be transferred to or from the scatterer
- When energy is transferred to the scatterer: Stokes lines $\nu_s = \nu_0 - \nu_t$
- When energy is transferred from the scatterer: Anti-Stokes lines $\nu_{as} = \nu_0 + \nu_t$
- Raman scattering cross section larger than Rayleigh scattering cross section

$$I_{Raman} = I_0 \frac{\partial \sigma}{\partial \Omega} n \, \Omega_{eff}$$

Ω_{eff}: Optics and detector efficiency

T. Weineisen *et al.*, Phys. Rev. ST Accel. Beams **14**, 050705 (2011)

- Rotational and vibrational Raman scattering modes exist
- Upper state can be virtual or real electronic transition (resonance Raman spectroscopy)

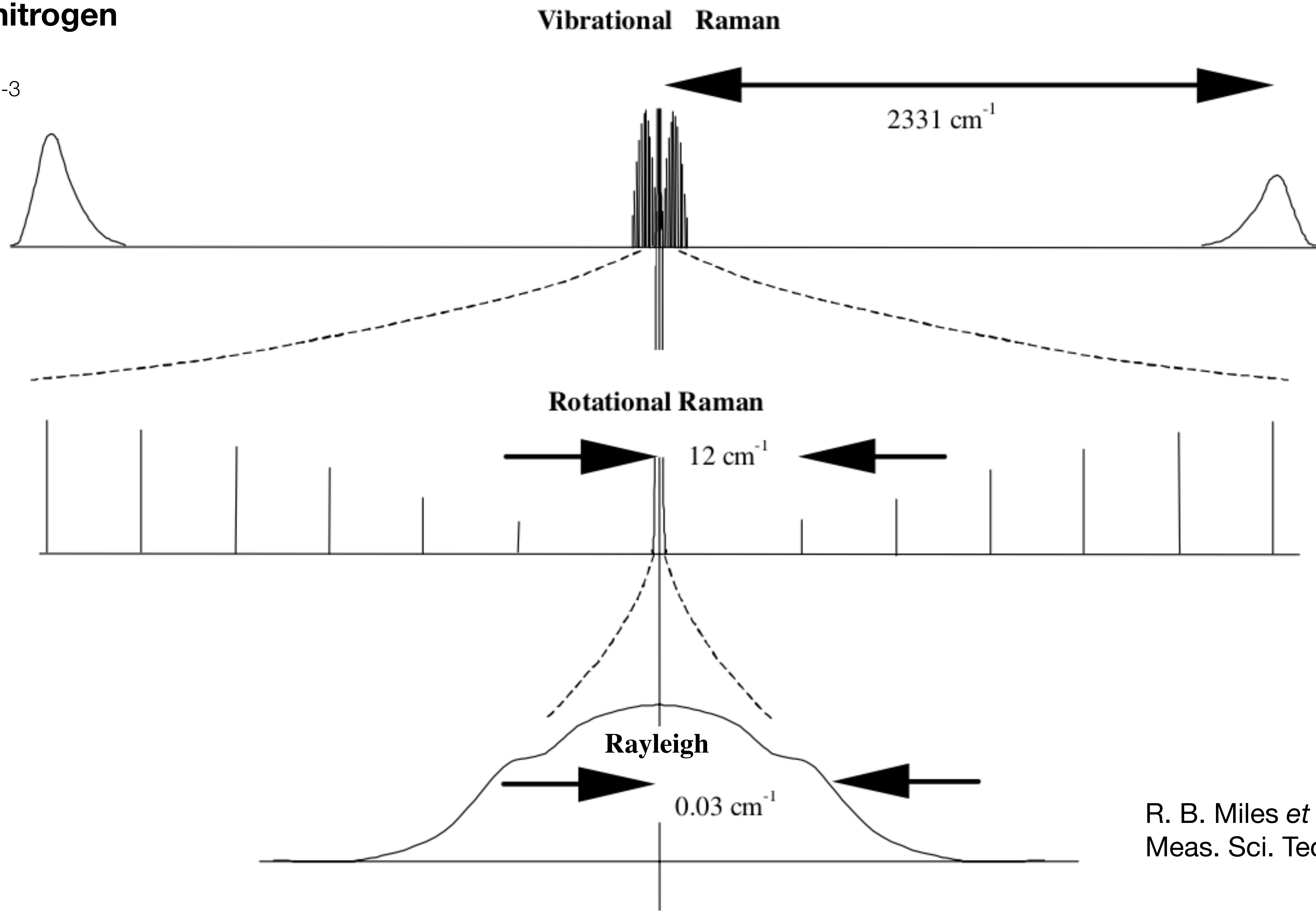


Raman scattering

Molecular nitrogen

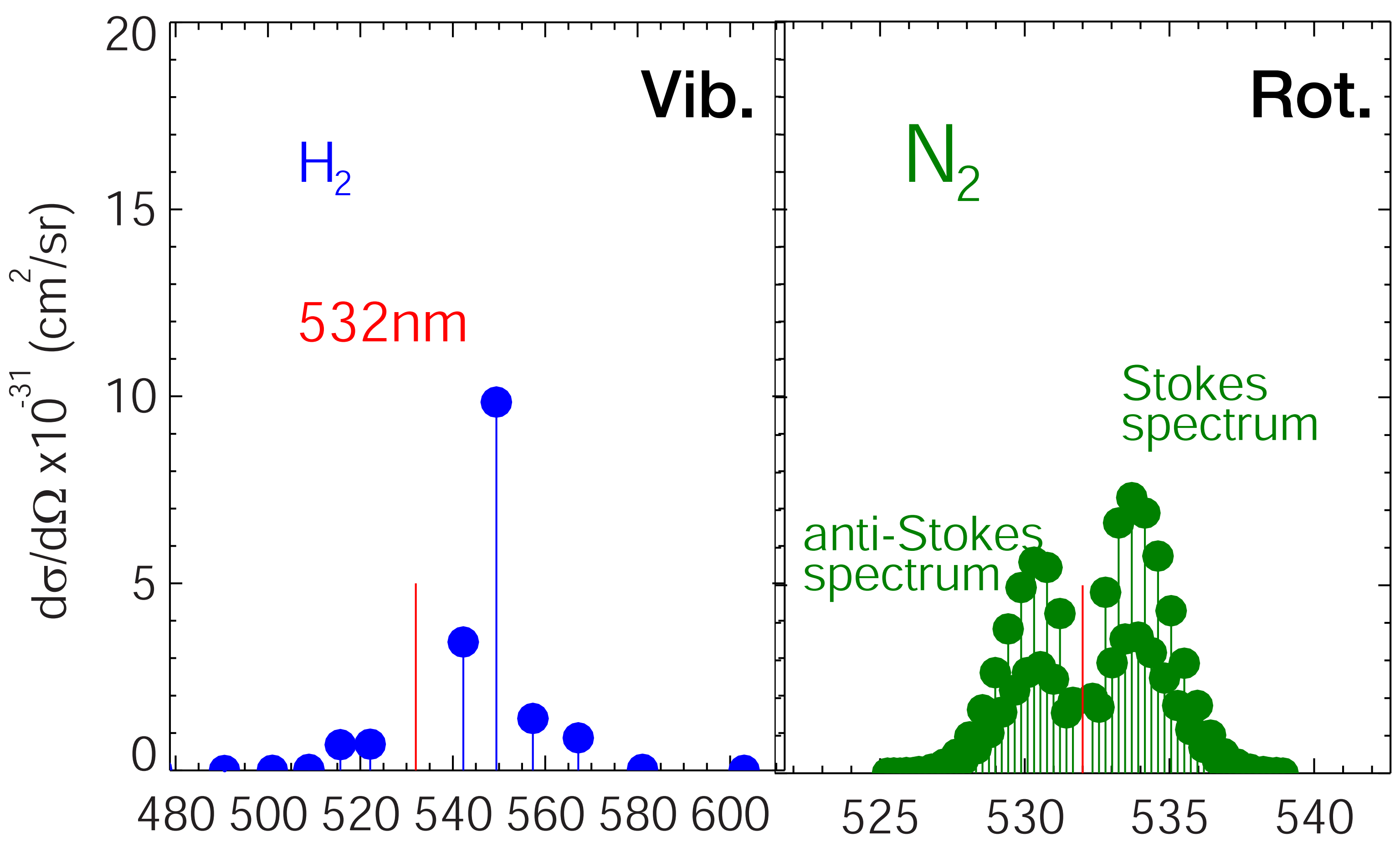
T = 300K

n = 10^{25} m^{-3}



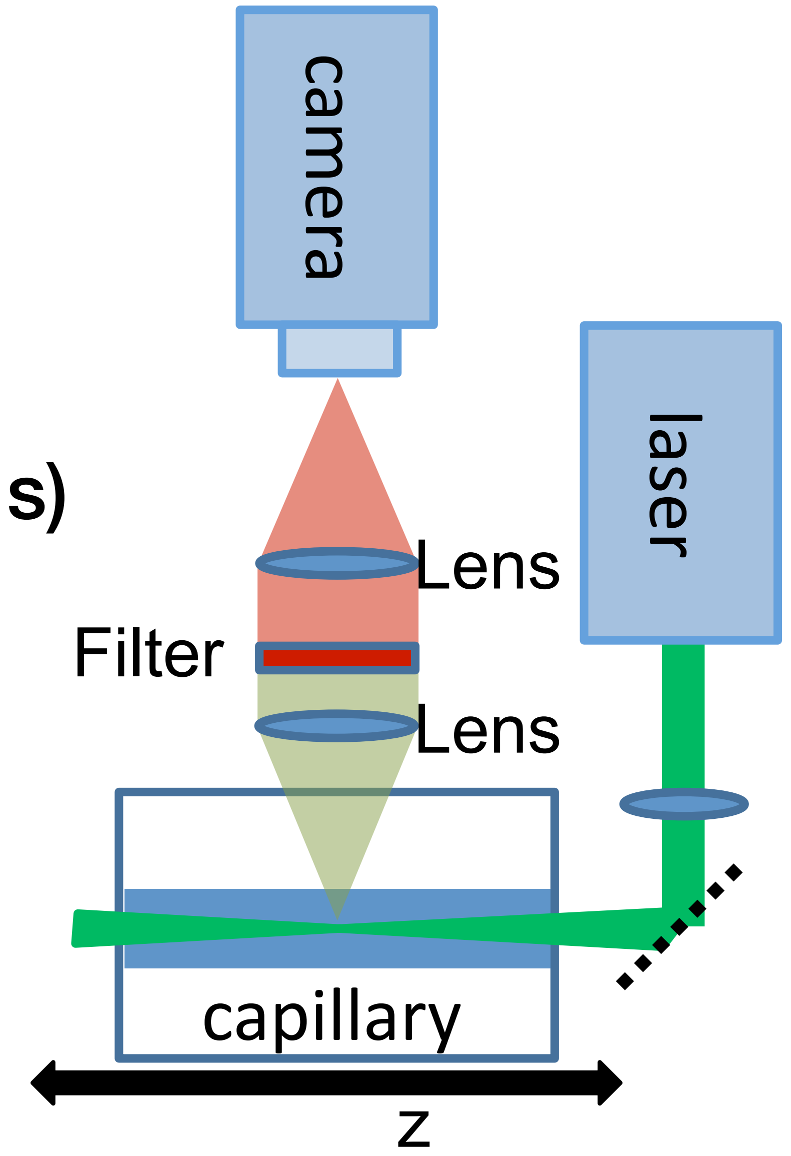
R. B. Miles *et al.*,
Meas. Sci. Technol. **12**, R33-R51 (2001)

Raman scattering

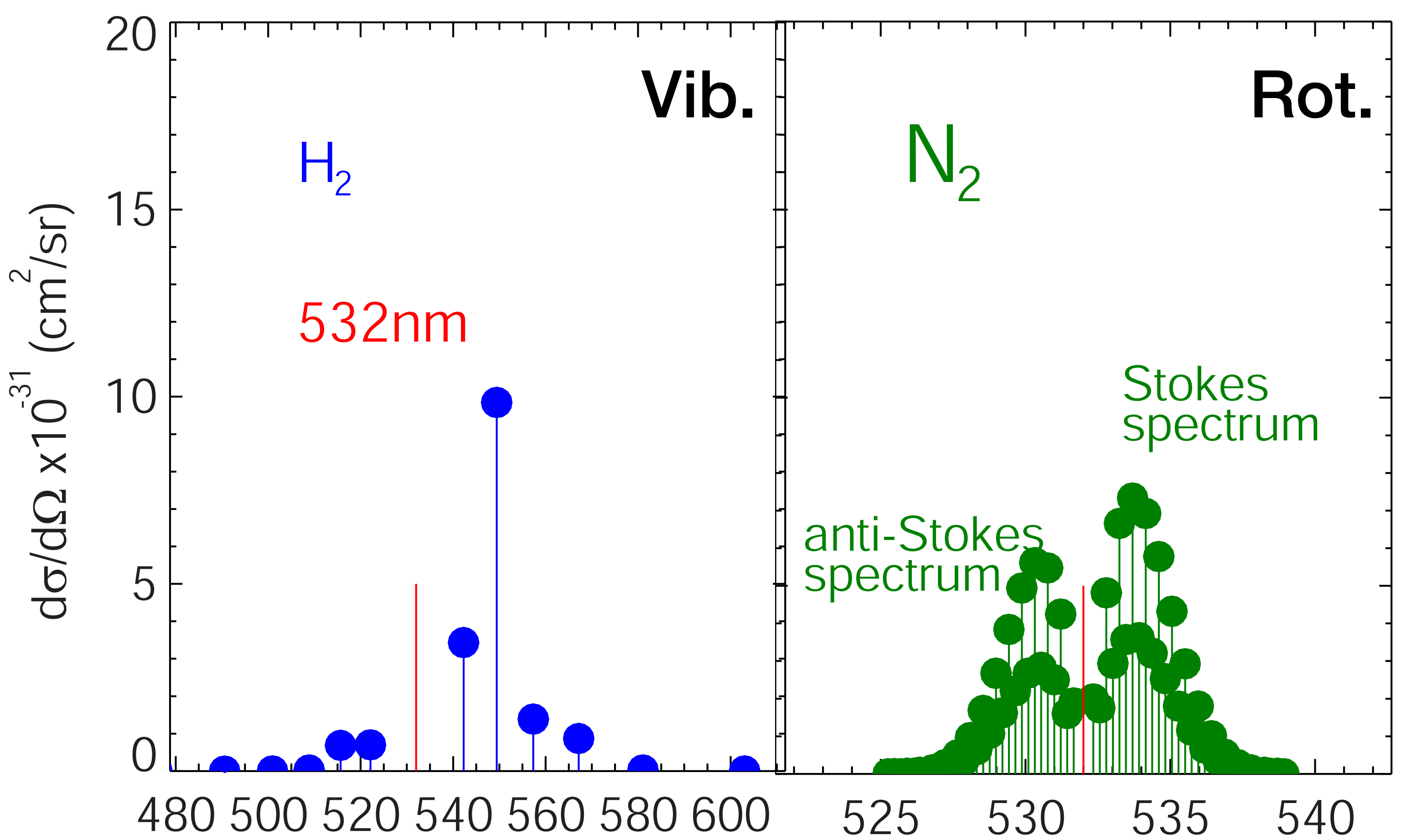


- Weak signals require long interaction times (~ 1s)
- Raman scattering allows for species discrimination
- Raman scattering only works for molecules, no atoms

R. Scannell *et al.*,
Rev. Sci. Instrum. **81**, 045107 (2010)



Raman scattering



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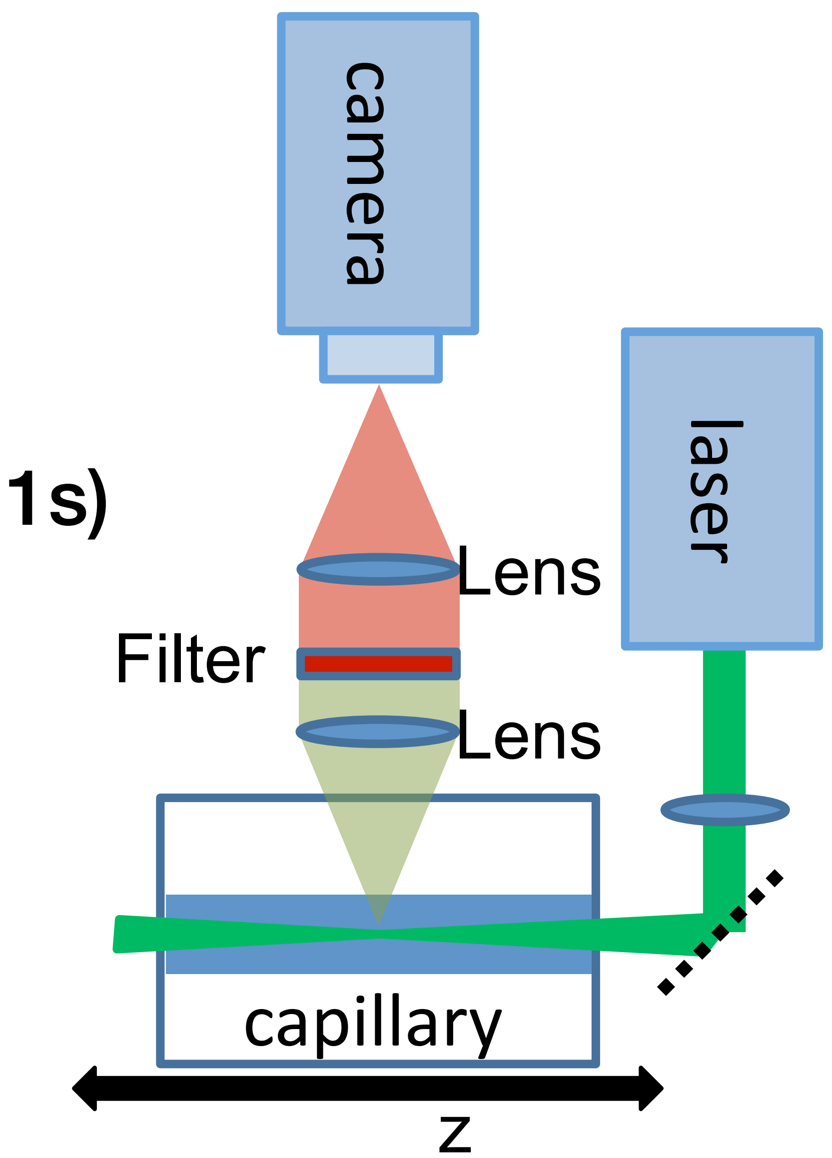
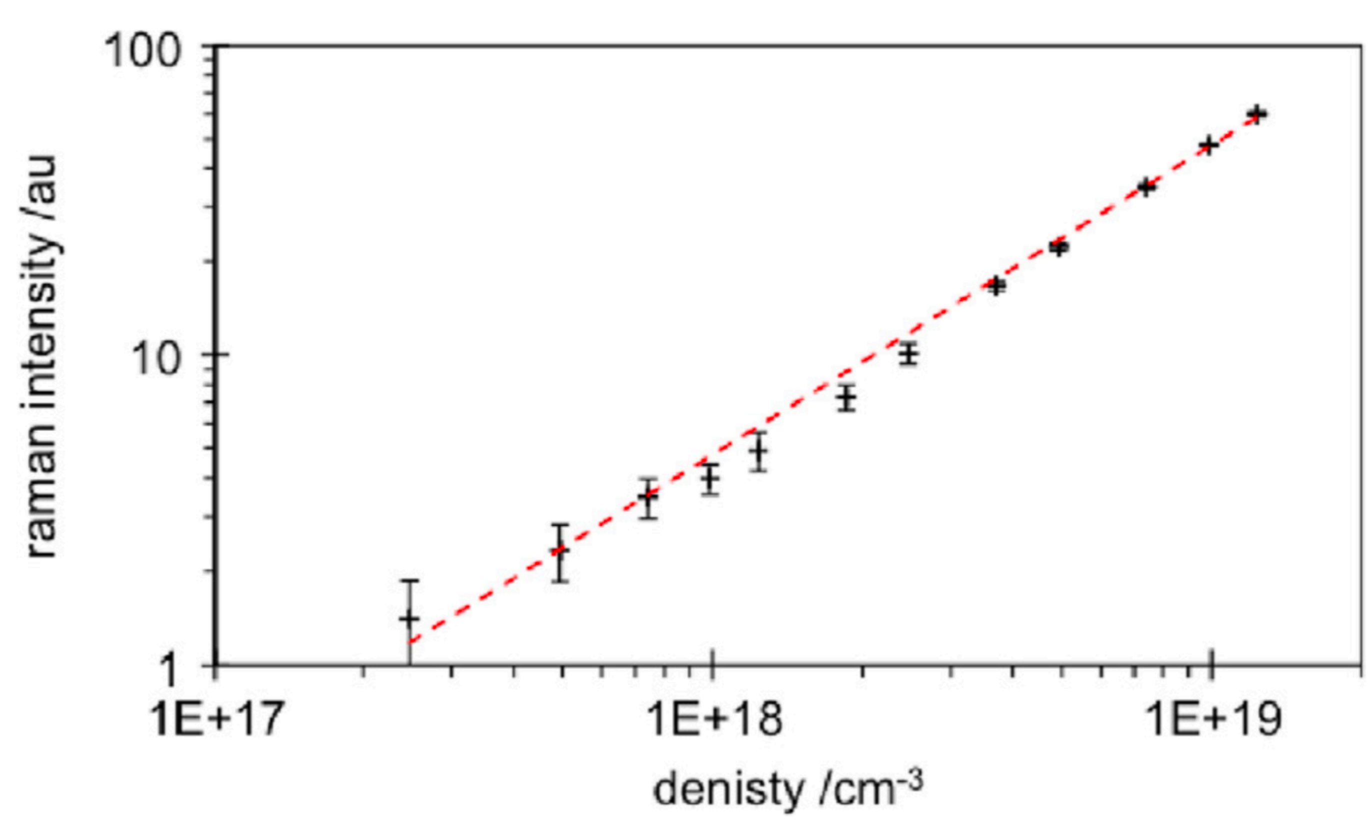
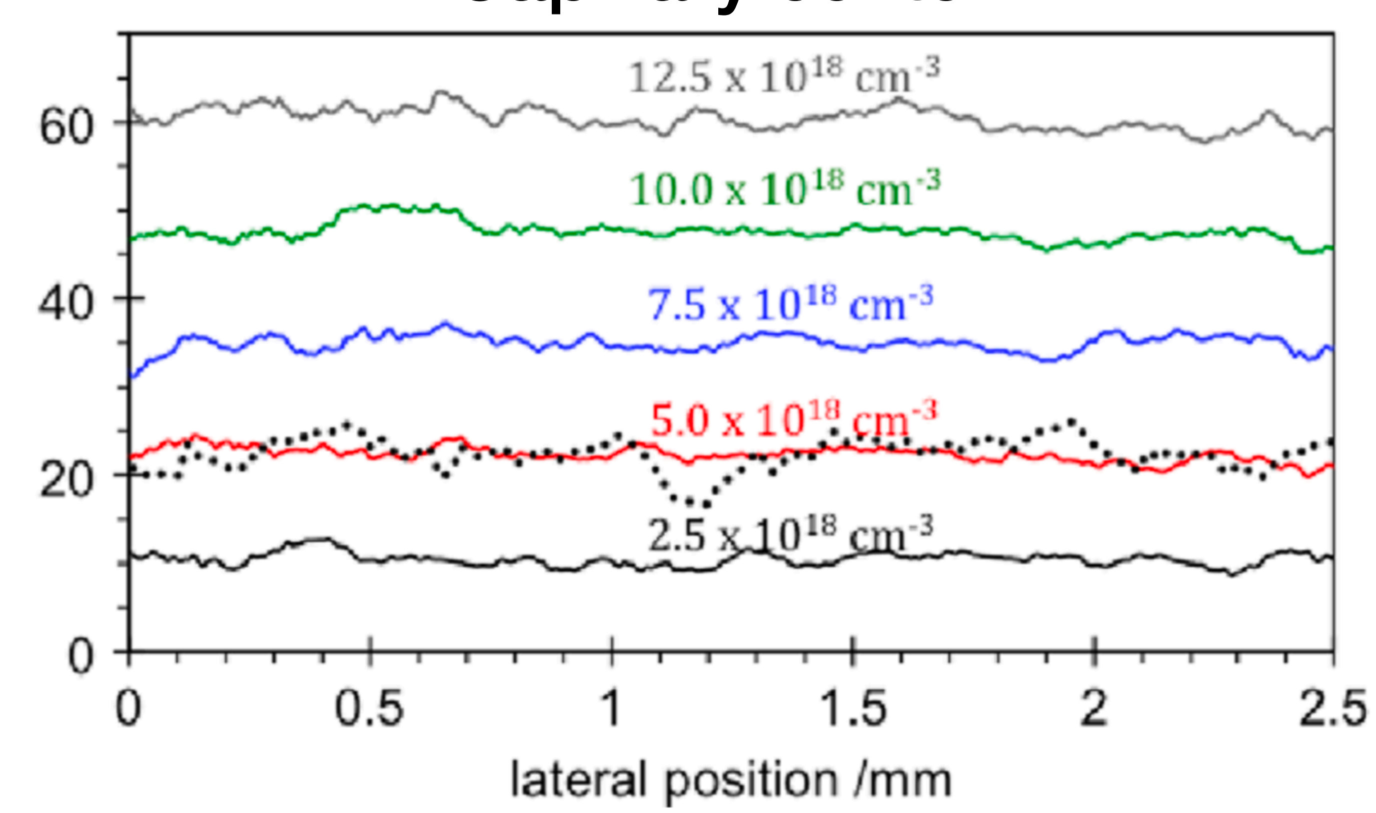
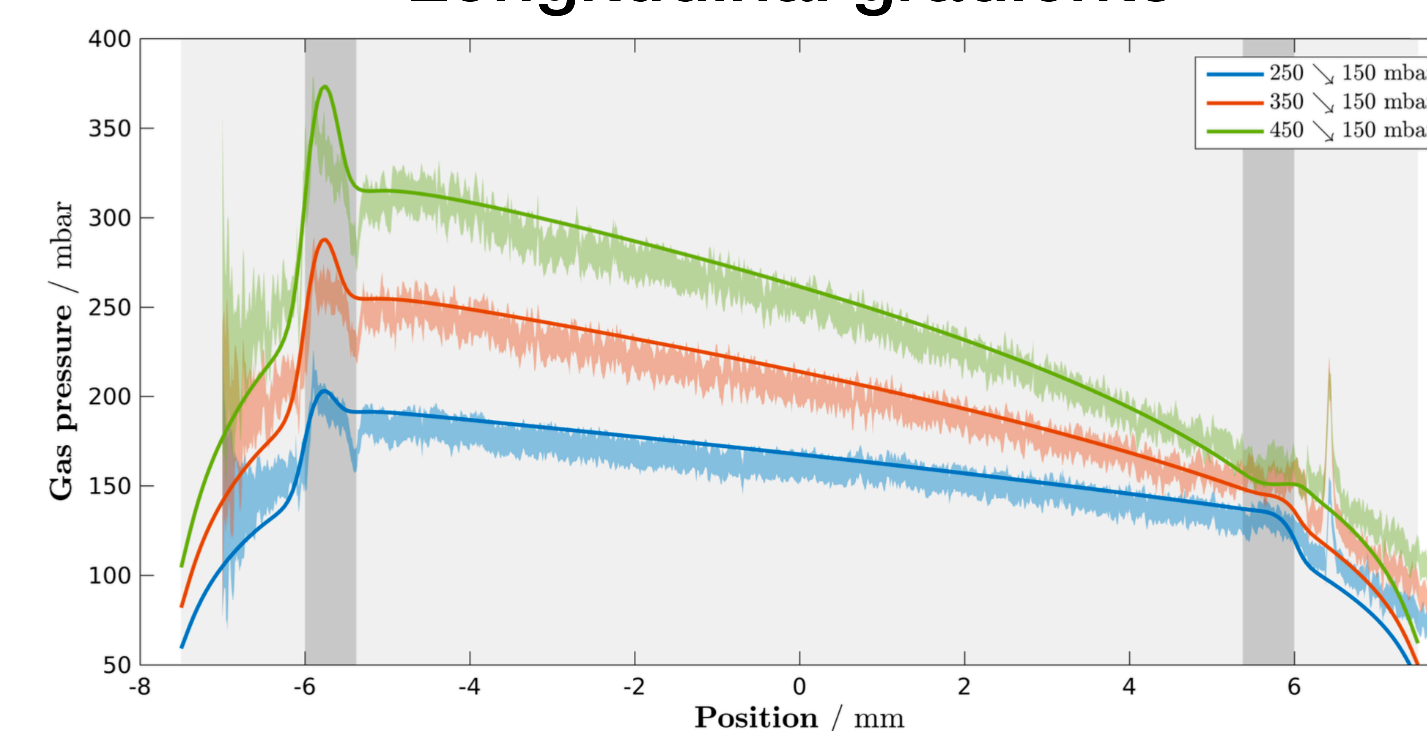




Capillary center



Longitudinal gradients

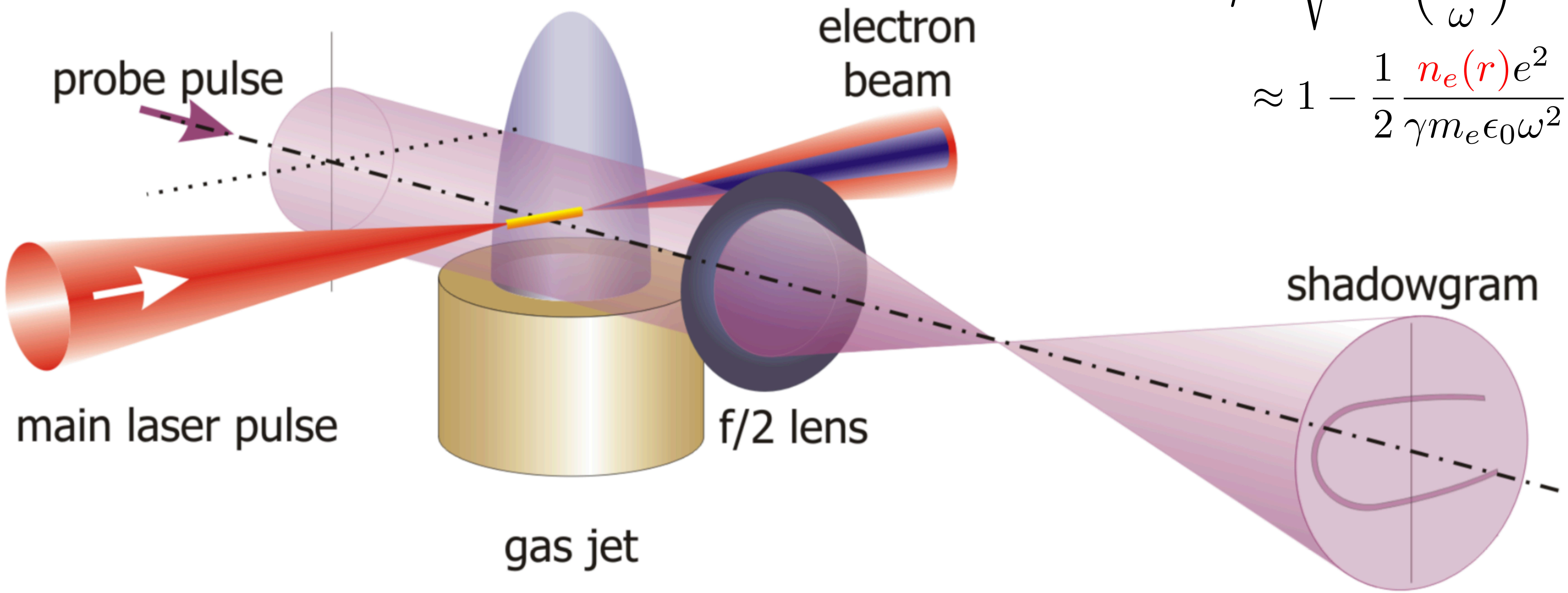


L. Schaper *et al.*, NIM A **740**, 208 (2014)

Plasma density distribution and constituents

- Schlieren/dark-field imaging
- Laser interferometry
- Two-color phase delay spectral interferometry
- Plasma spectroscopy

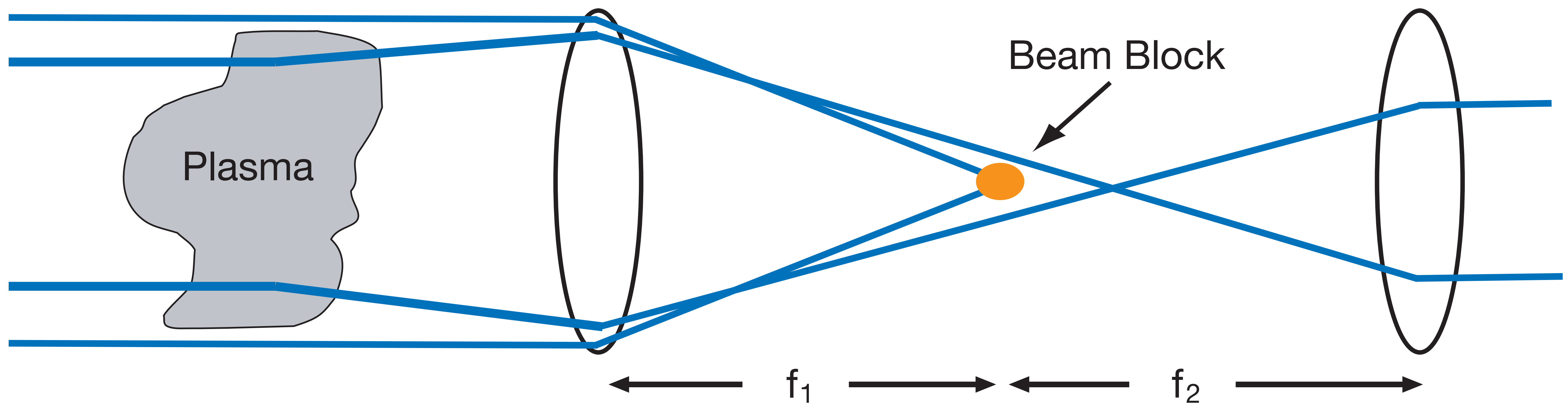
Schlieren/dark-field imaging or shadowgraphy



$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2}$$
$$\approx 1 - \frac{1}{2}\frac{n_e(r)e^2}{\gamma m_e \epsilon_0 \omega^2}$$

- Index of refraction gradients cause distortion of probe phase front → intensity structures in beam

Schlieren/dark-field imaging or shadowgraphy

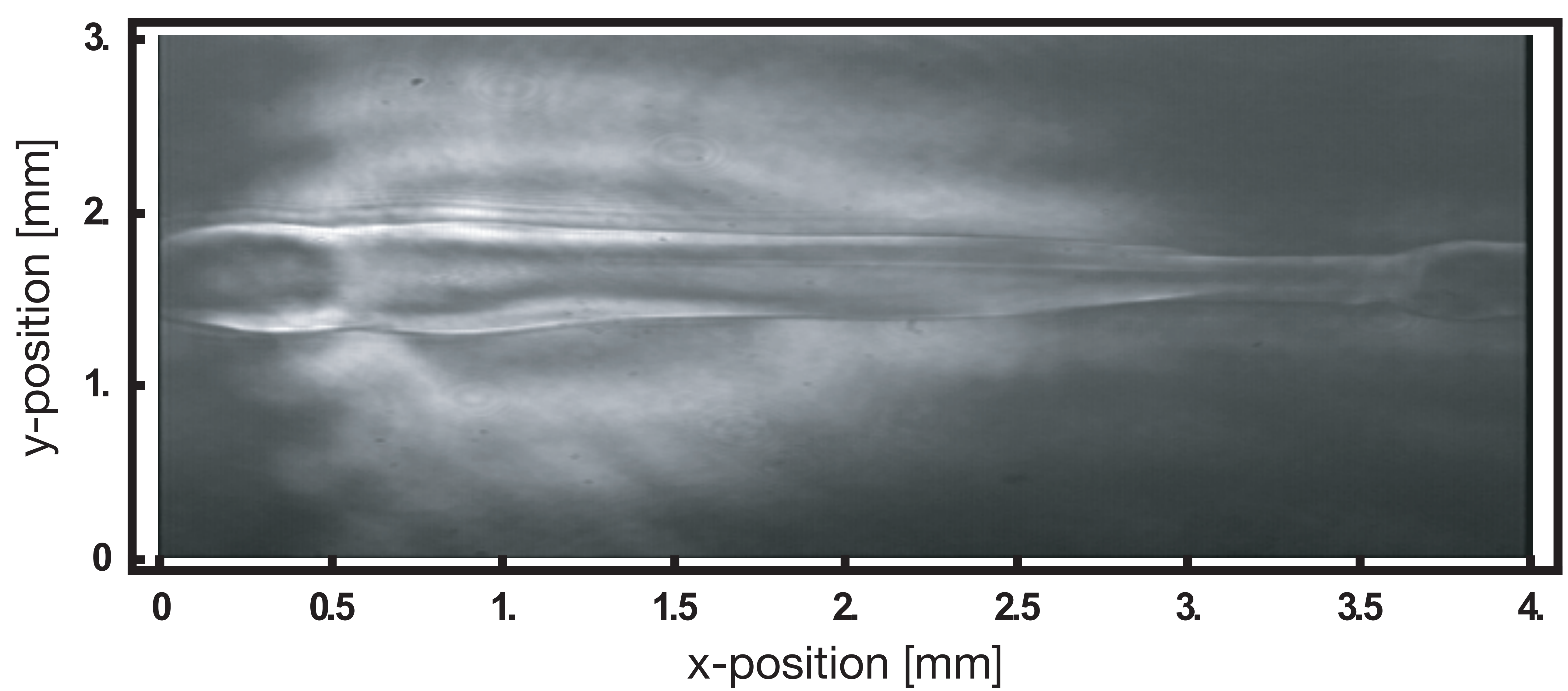


$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2}$$
$$\approx 1 - \frac{1}{2}\frac{n_e(r)e^2}{\gamma m_e \epsilon_0 \omega^2}$$

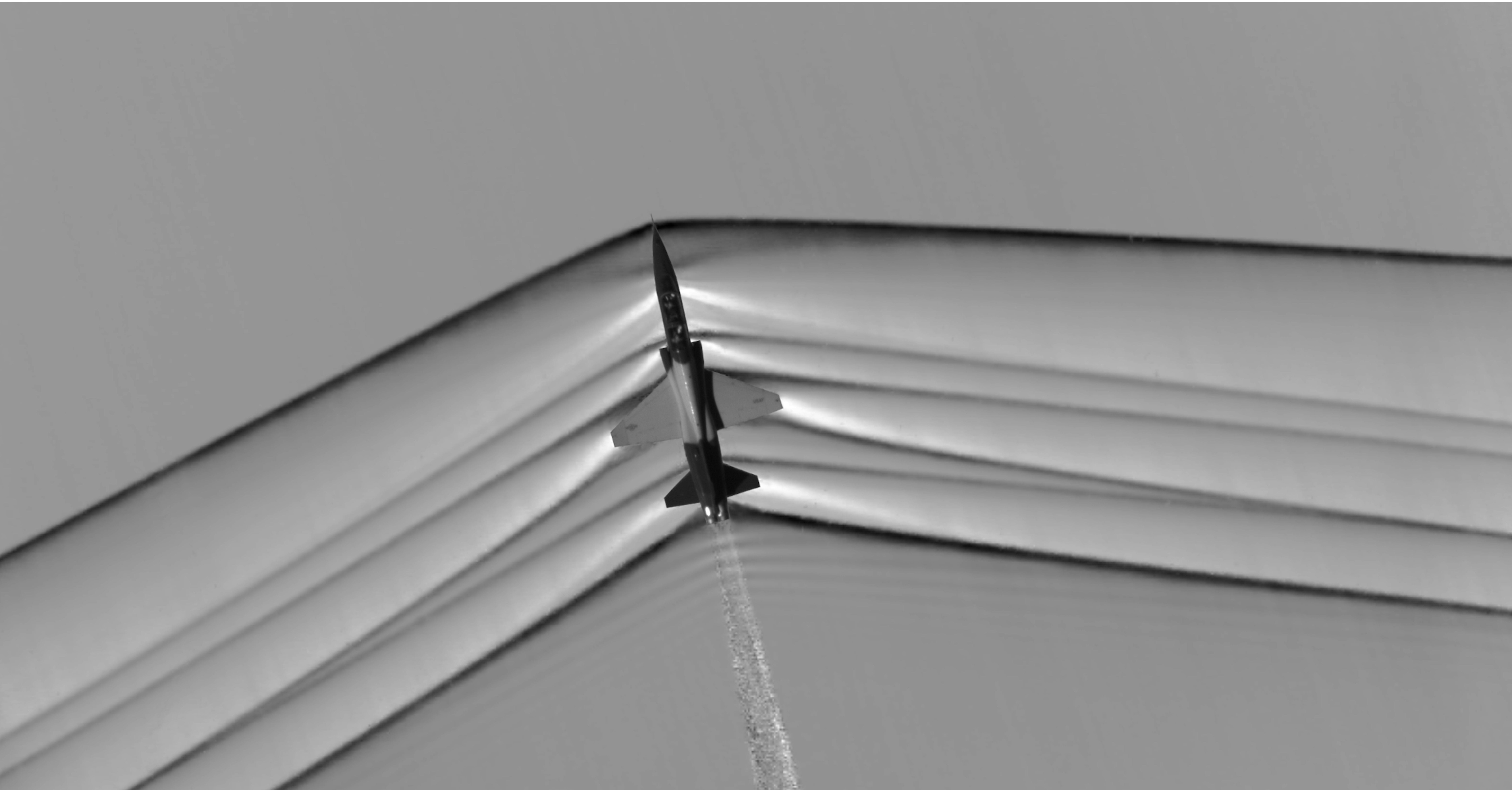
- Angular deviation of ray

$$\varepsilon_y = \frac{1}{n}\int \frac{\partial n}{\partial y} dz$$

- Sensitive to density gradients
- Absolute density measurements not straightforward

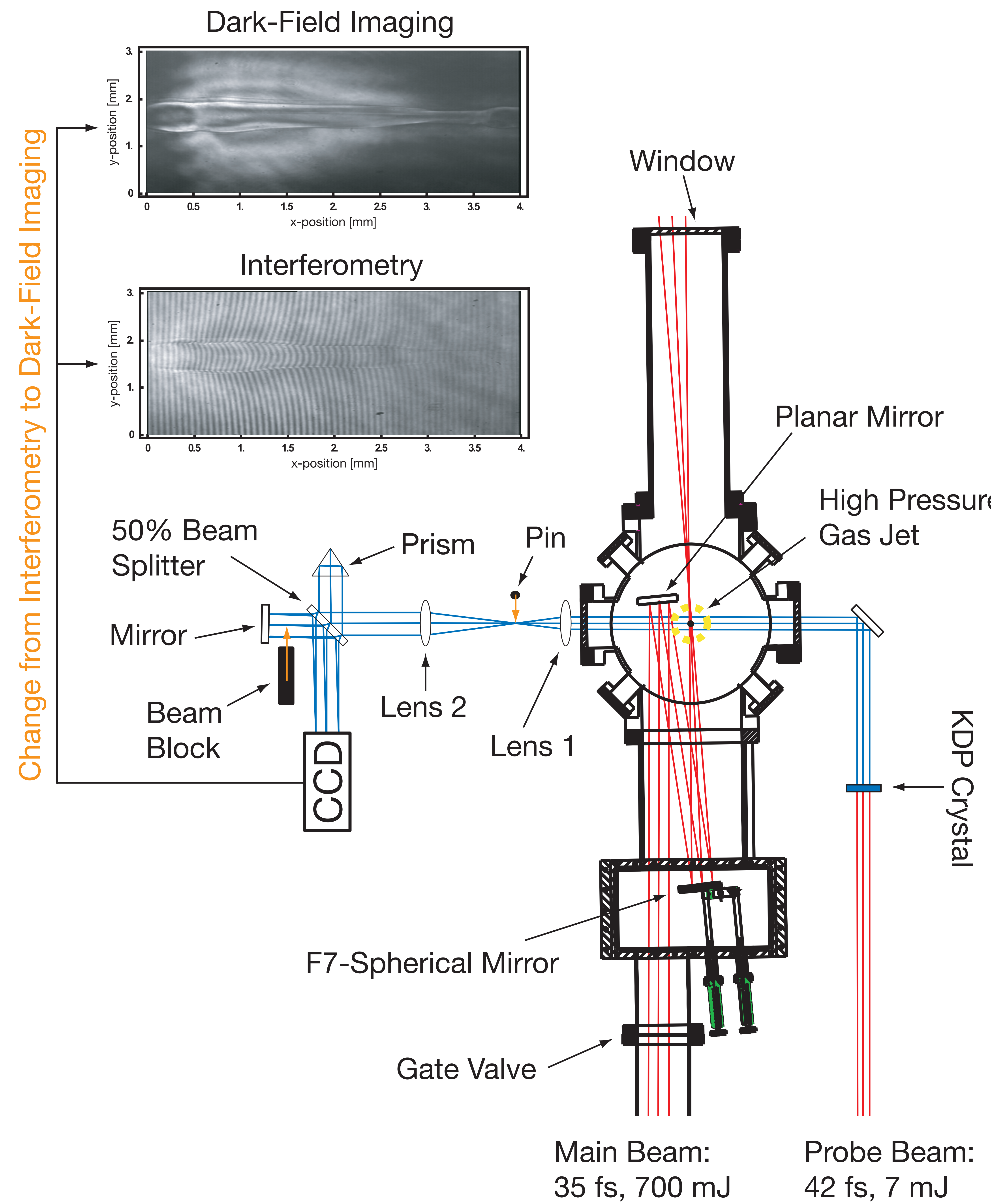


Schlieren/dark-field imaging or shadowgraphy



Laser interferometry

- Laser interferometry allows for absolute density measurements
- *Here:* setup compatible with dark-field imaging



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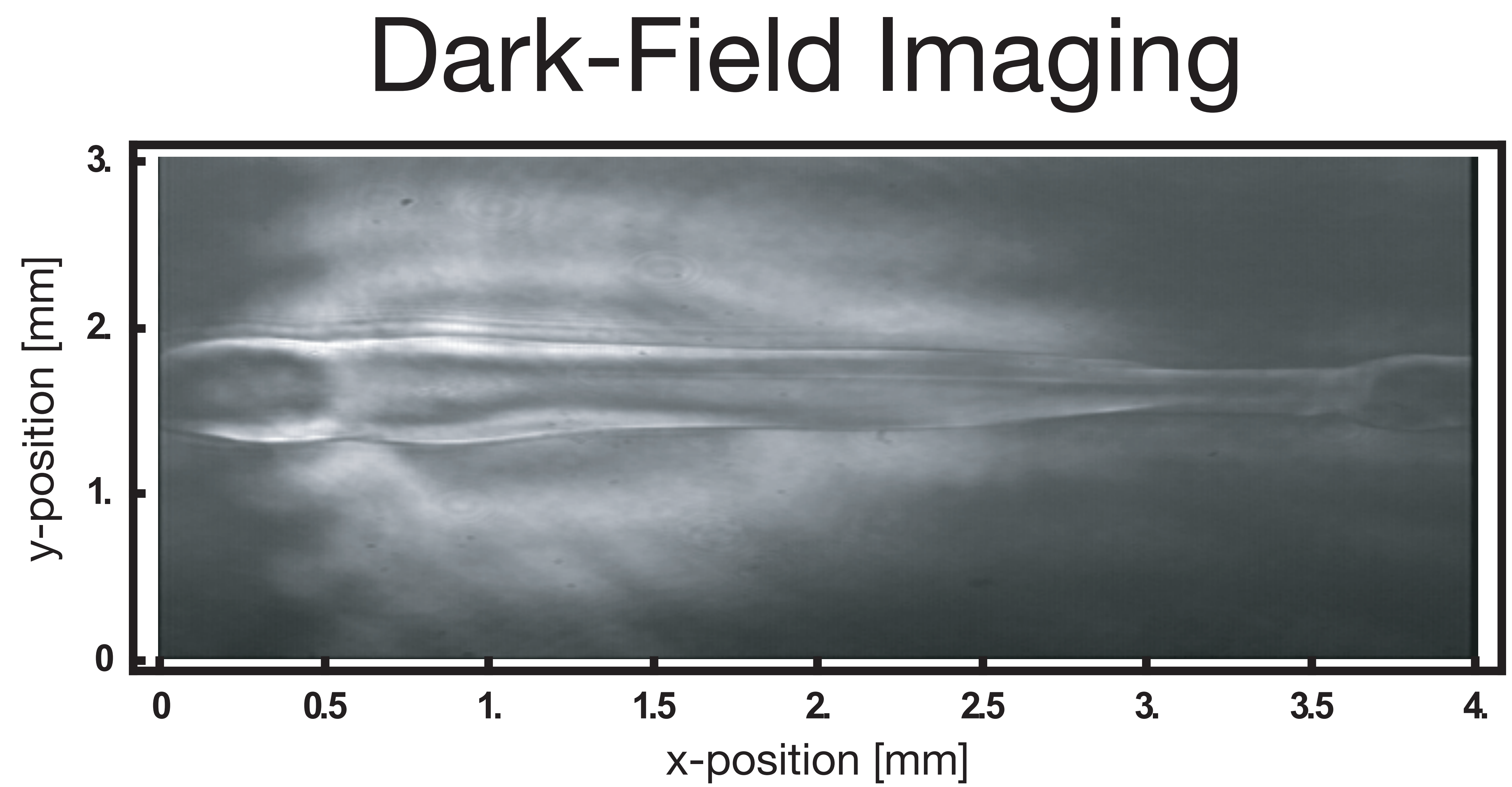
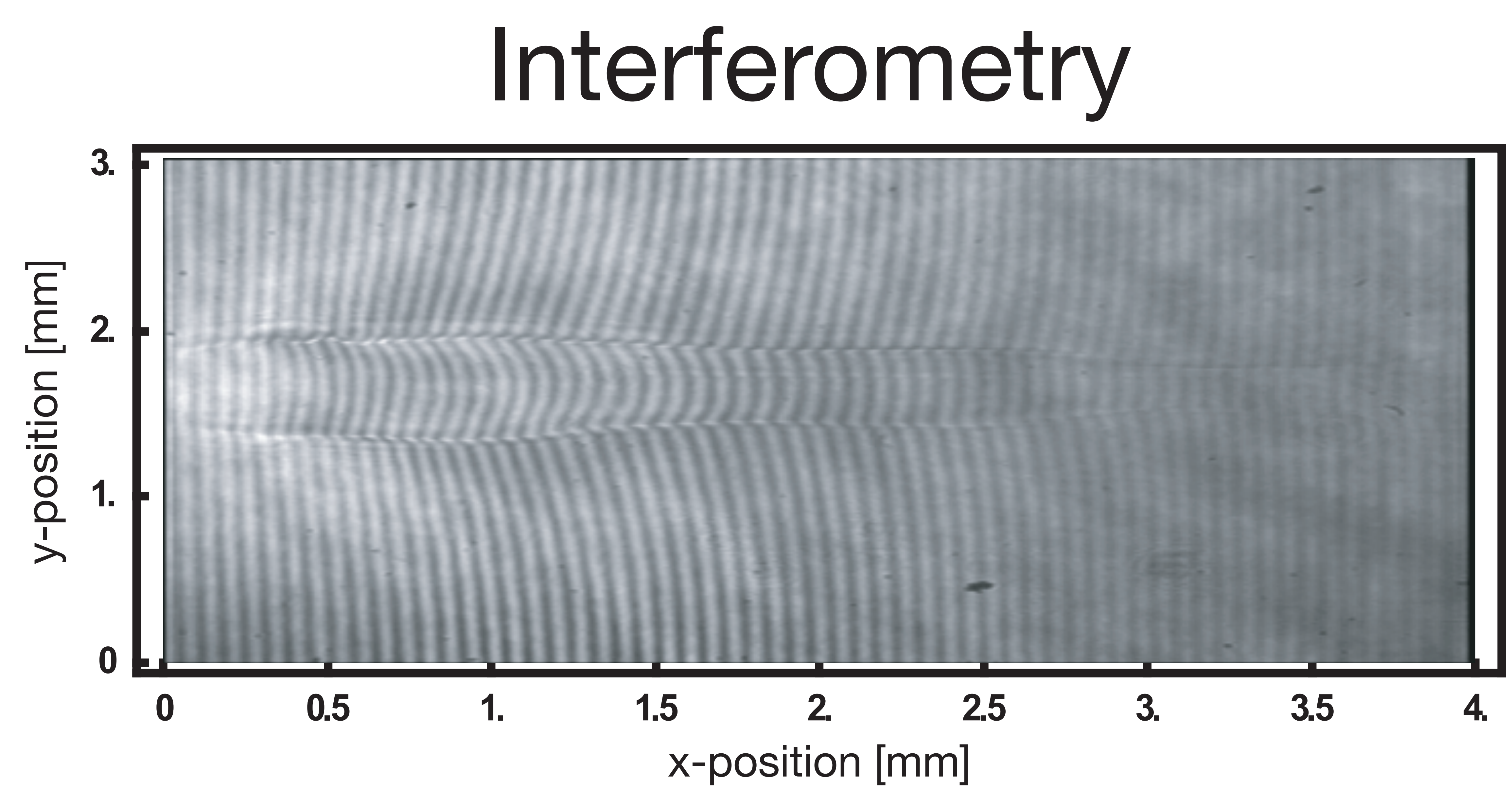
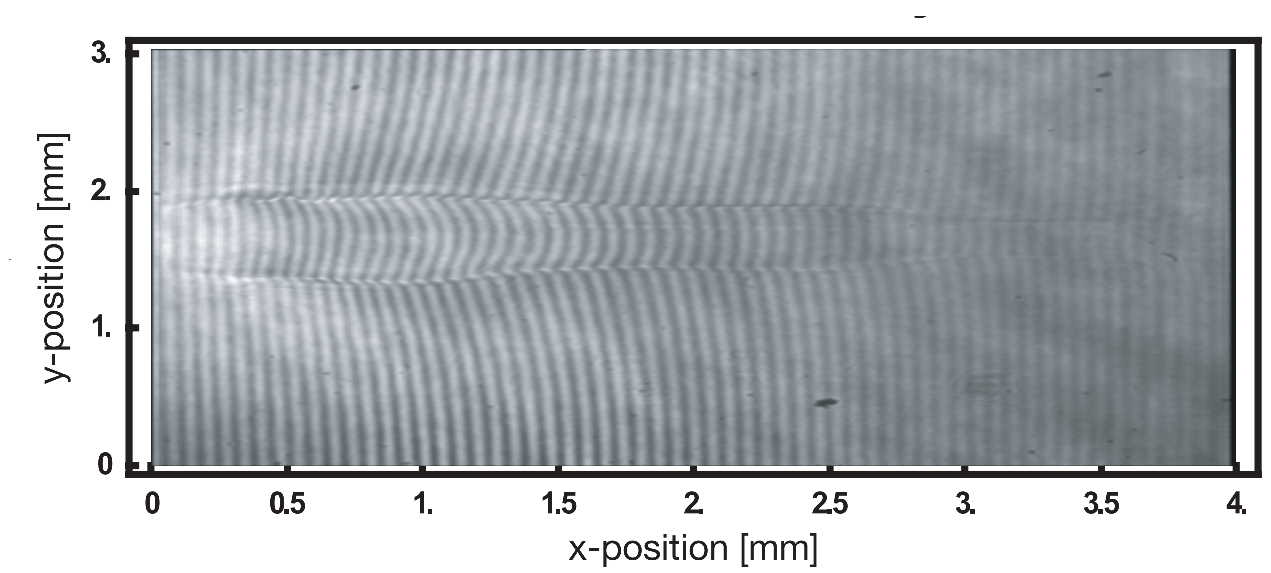
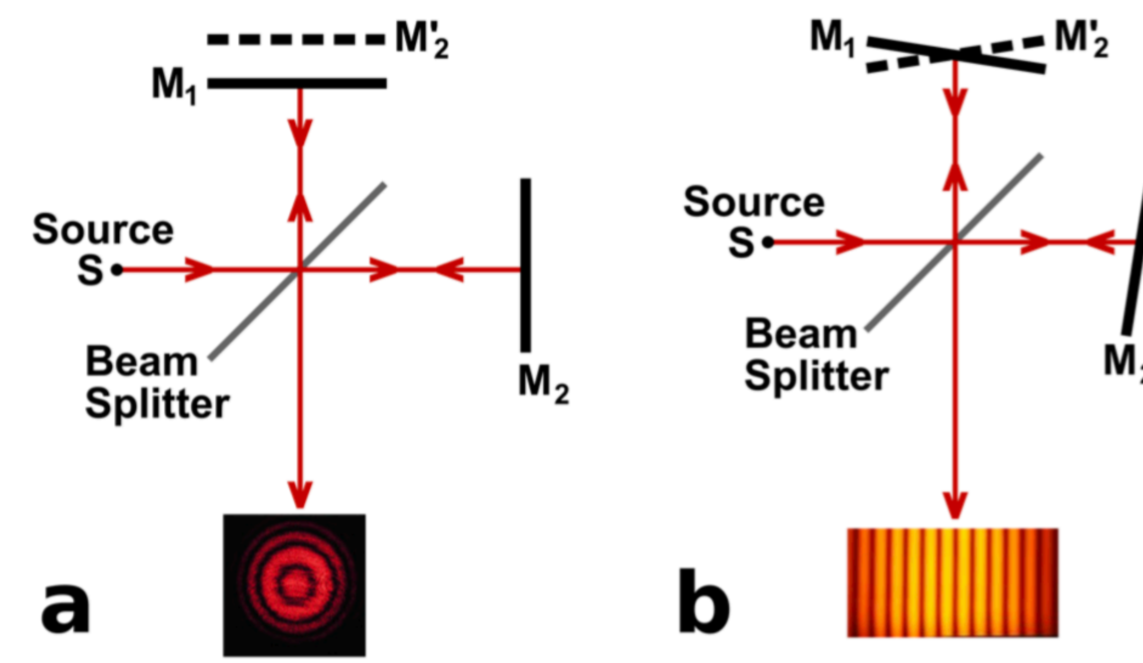




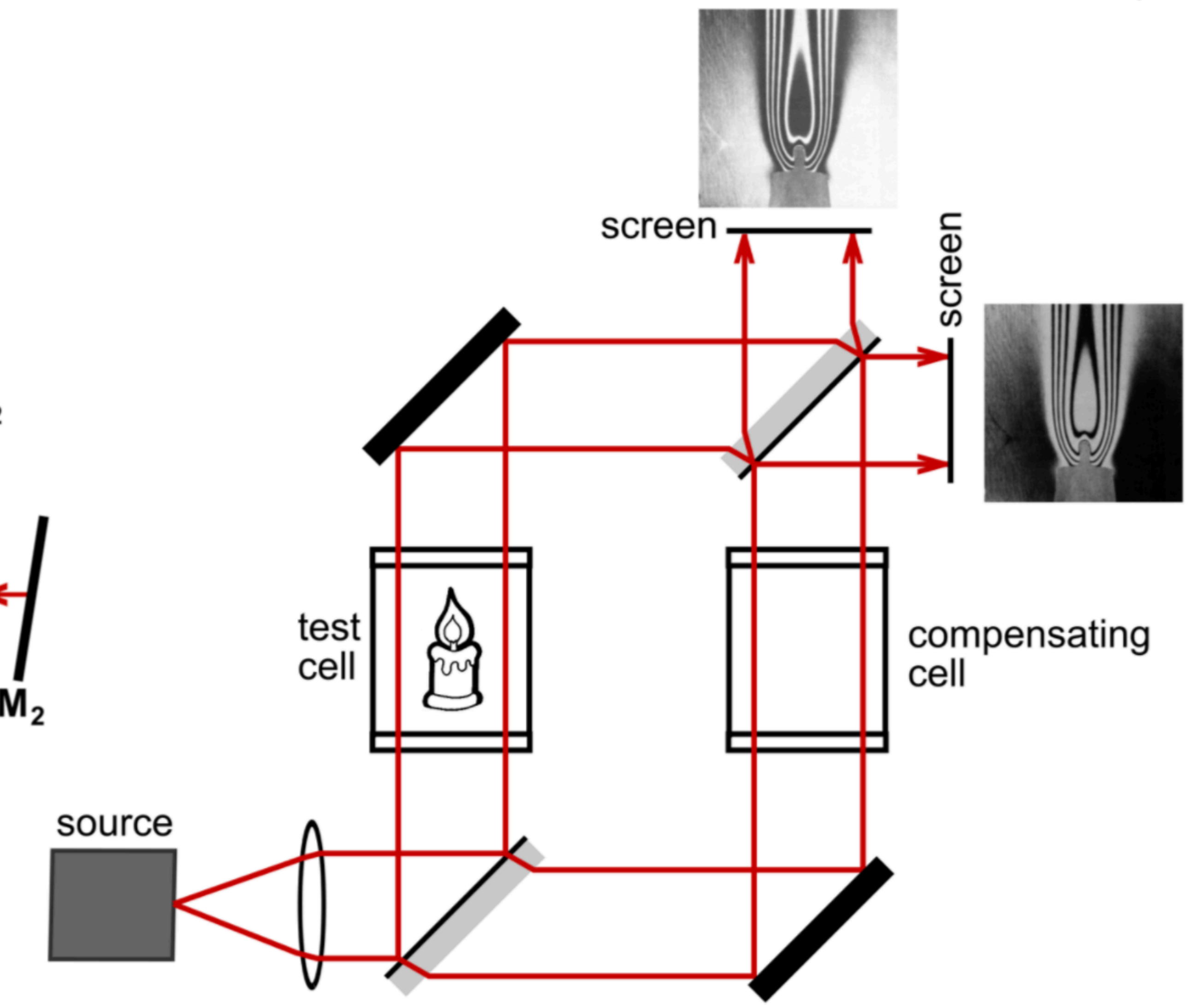
Laser interferometry

- > Laser interferometry allows for absolute density measurements





Michelson interferometer

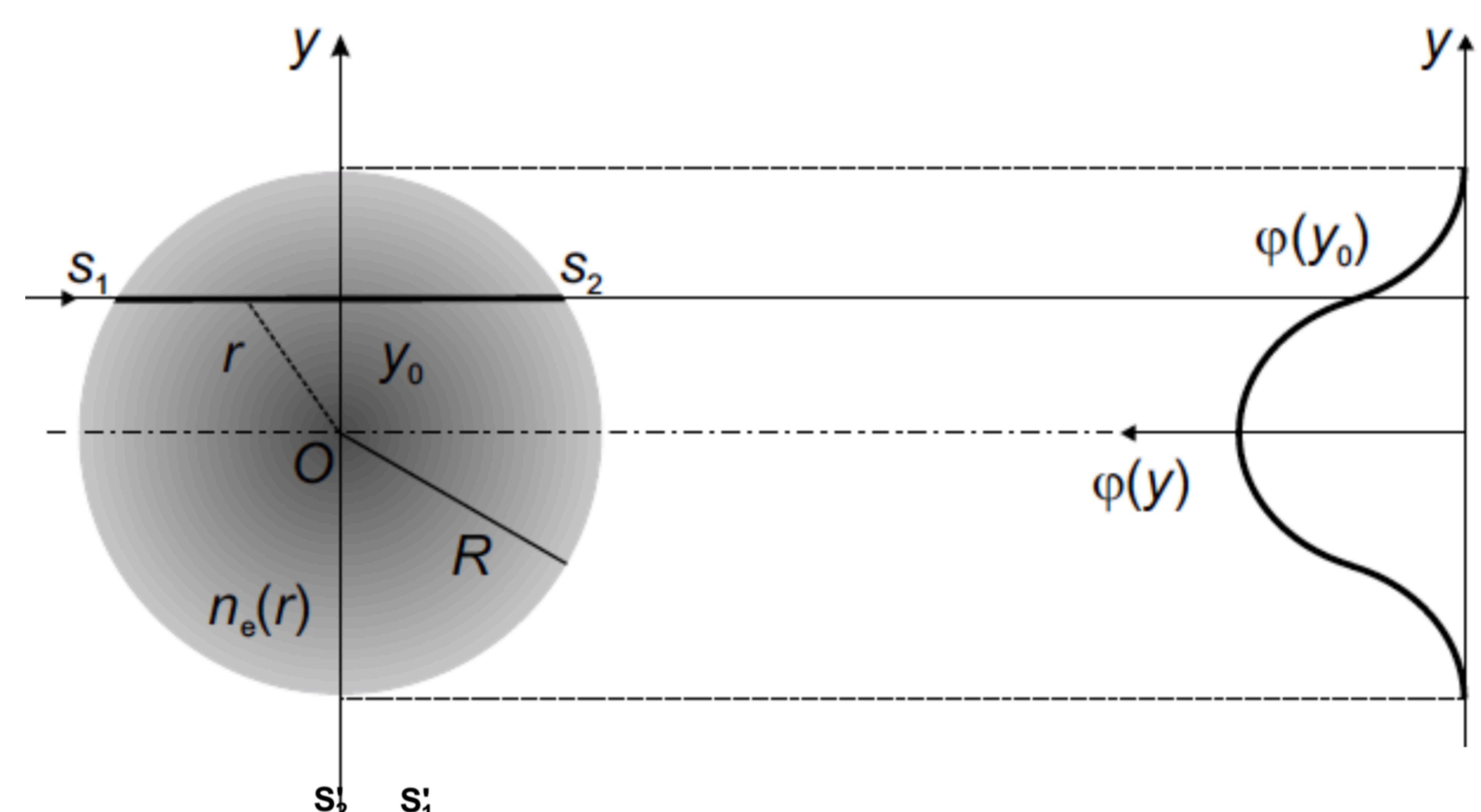


Mach-Zehnder interferometer

- > Integrated optical path length or phase ϕ depends on integrated index of refraction

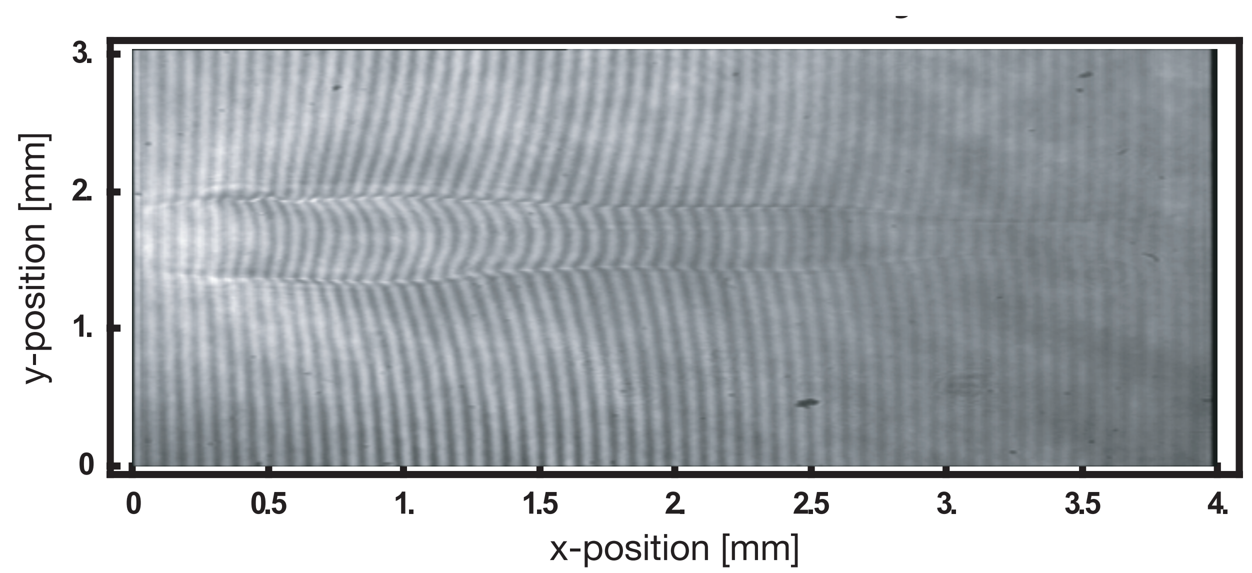
$$\eta = \sqrt{1 - (\omega_{\rm p}/\omega_{\rm L})^2} = \sqrt{1 - n_{\rm e}/n_{\rm c}}$$

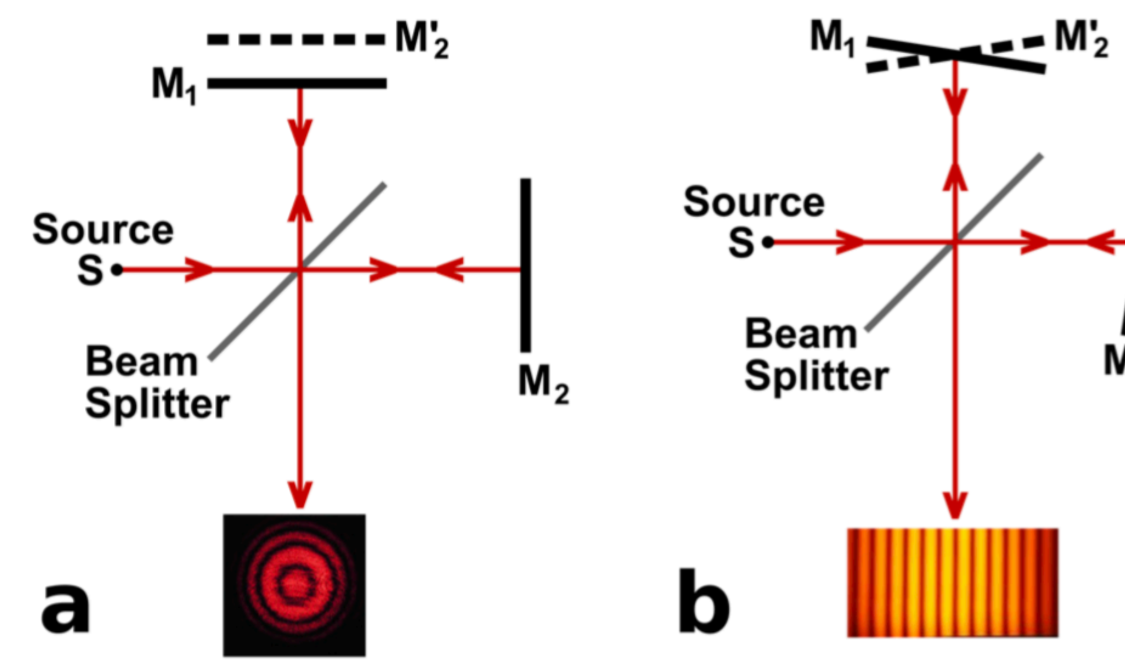
- > Visualize phase difference to unaffected reference by interference



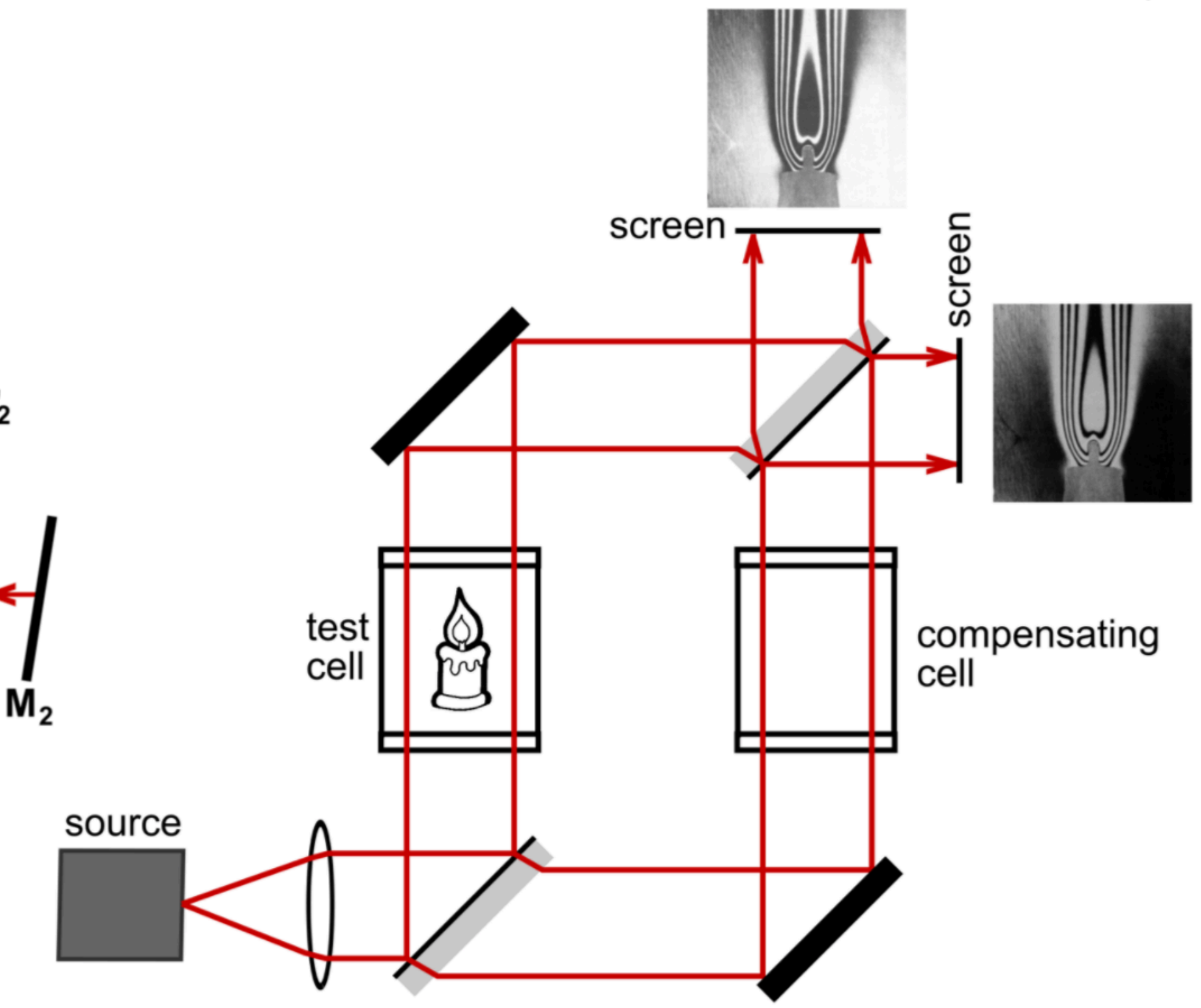
Laser interferometry

> Path lengths need to be within laser coherence length (typical ~ few μm), otherwise no fringes





Michelson interferometer



Mach-Zehnder interferometer

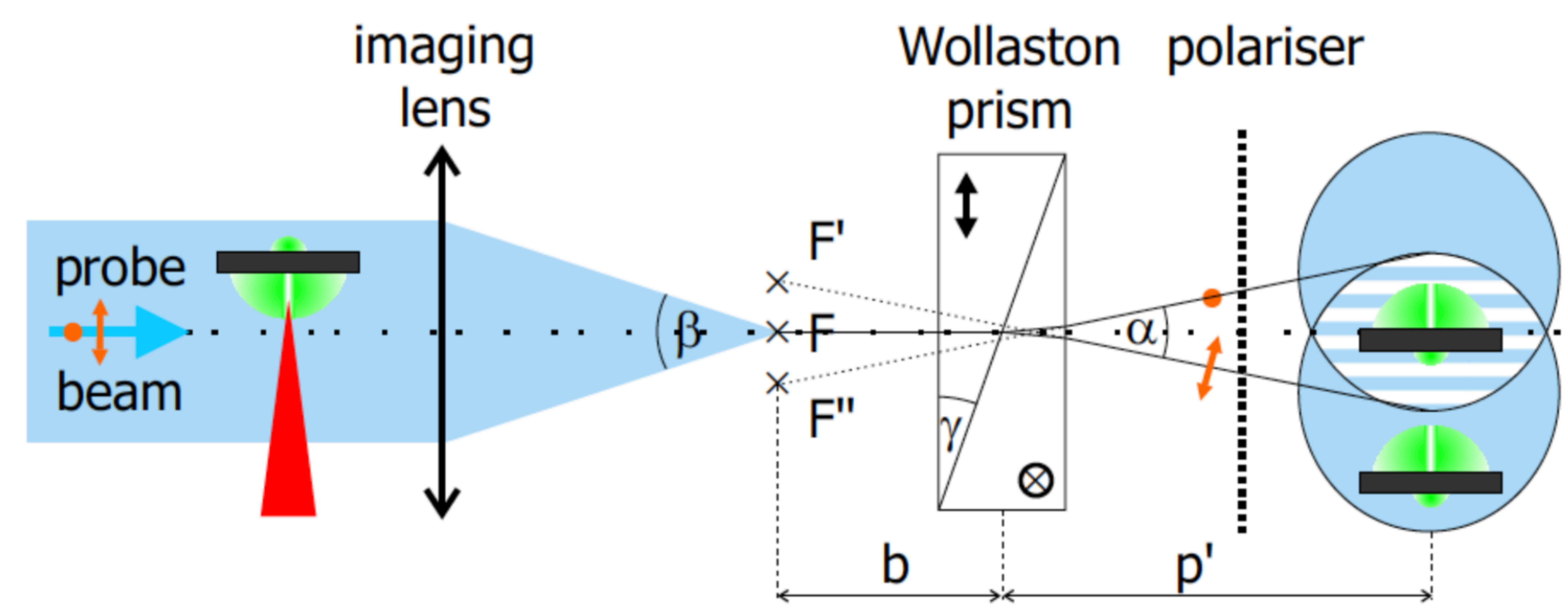
> Simple-to-align alternative: Wollaston prism (polarizing beam splitter, combination of two birefringent prisms)

> Probe is polarized under 45° wrt optical axes

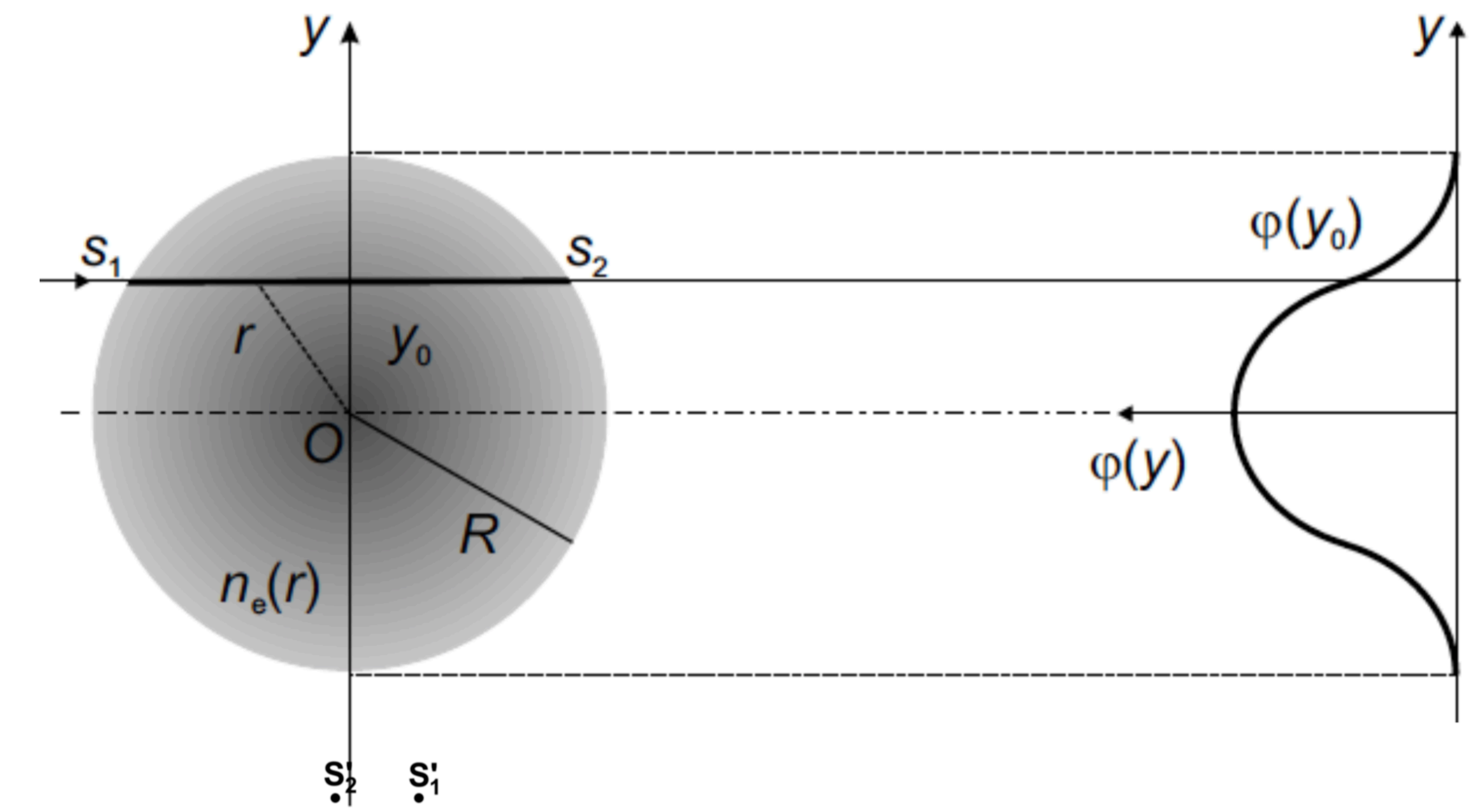
> Two replica, separated by α, polarized ⊥

> Polarizer under 45°, so interference possible

> Probe and reference sides overlapp



Laser interferometry



> Phase shift difference between probe and reference ray

$$\Delta\varphi(y_0) = \Phi(y_0) = \frac{2\pi}{\lambda_L}\int_{x_1}^{x_2}[1-\eta(x)]\,\mathrm{d}x$$

$$\approx \frac{\pi}{n_{cr}\lambda_L}\int_{x_1}^{x_2} n_e(x)\mathrm{d}x = \frac{2\pi}{n_{cr}\lambda_L}\int_{y_0}^{R}\frac{n_e(r)r}{\sqrt{r^2-y_0^2}}\mathrm{d}r$$

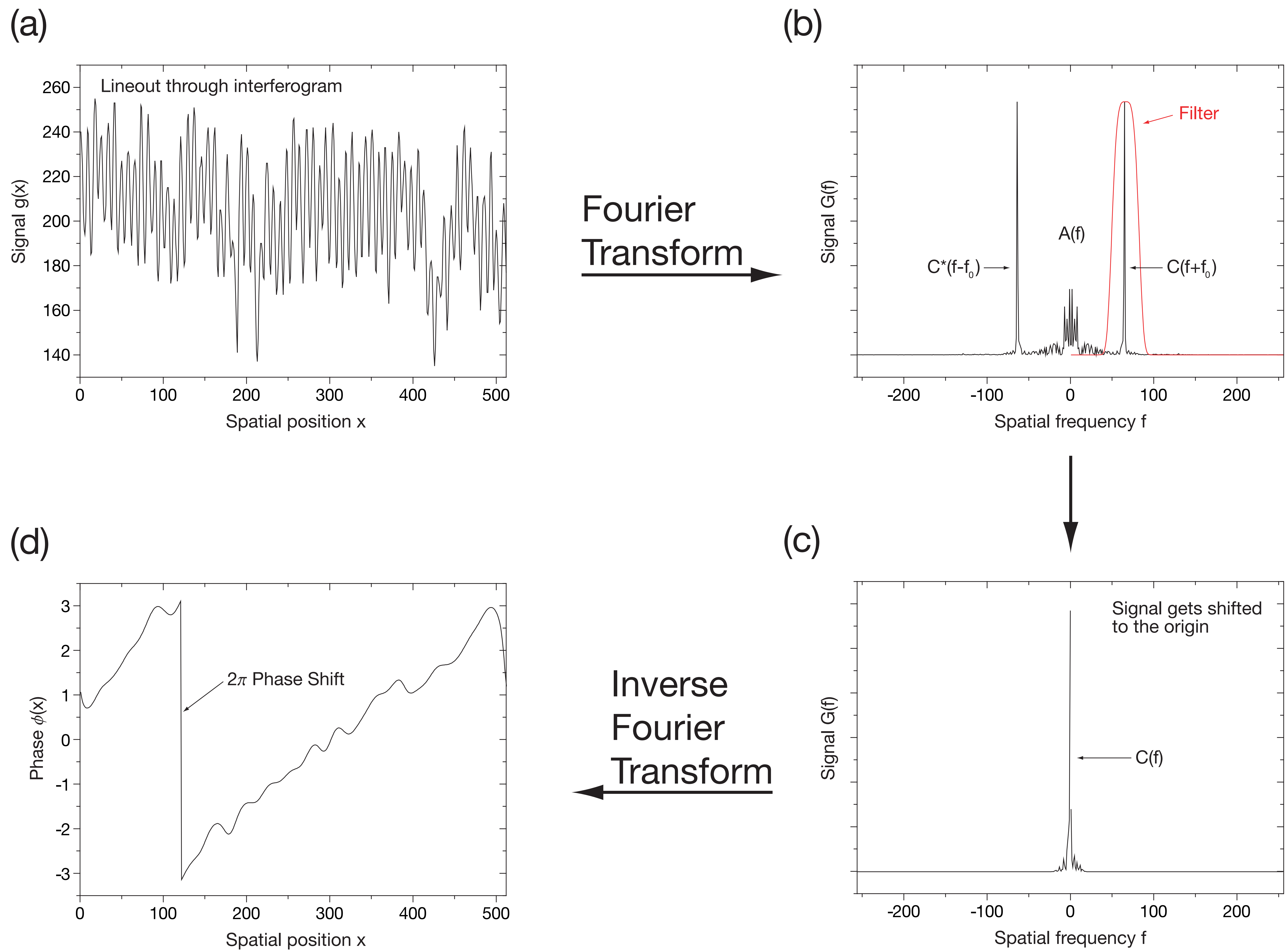
> If cylindrical symmetry can be assumed → density reconstruction by Abel inversion (otherwise tomography)

$$n_e(r) = -\frac{n_{cr}\lambda_L}{\pi^2}\int_r^R \frac{\mathrm{d}\Phi(y)}{\mathrm{d}y}\cdot\frac{\mathrm{d}y}{\sqrt{y^2-r^2}}.$$

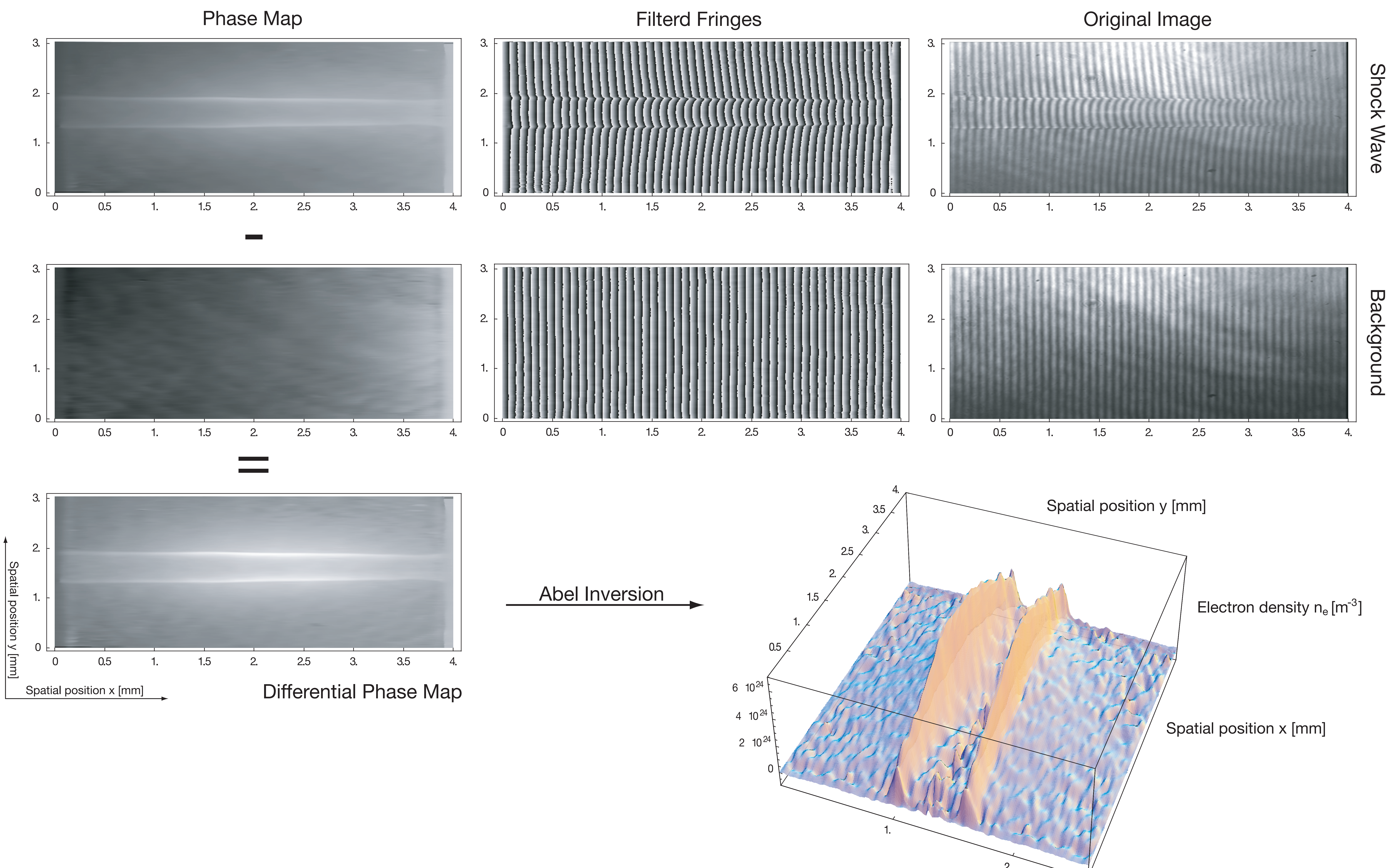
> *Important:* Phase shift needs to be measurable, i.e. λ_L needs to see significant phase shift, not too far away from critical density n_{cr} or long plasma

> *In practice:* densities below 10^{18} cm^{-3} difficult to diagnose in transverse geometry with 1 μm lasers

Laser interferometry

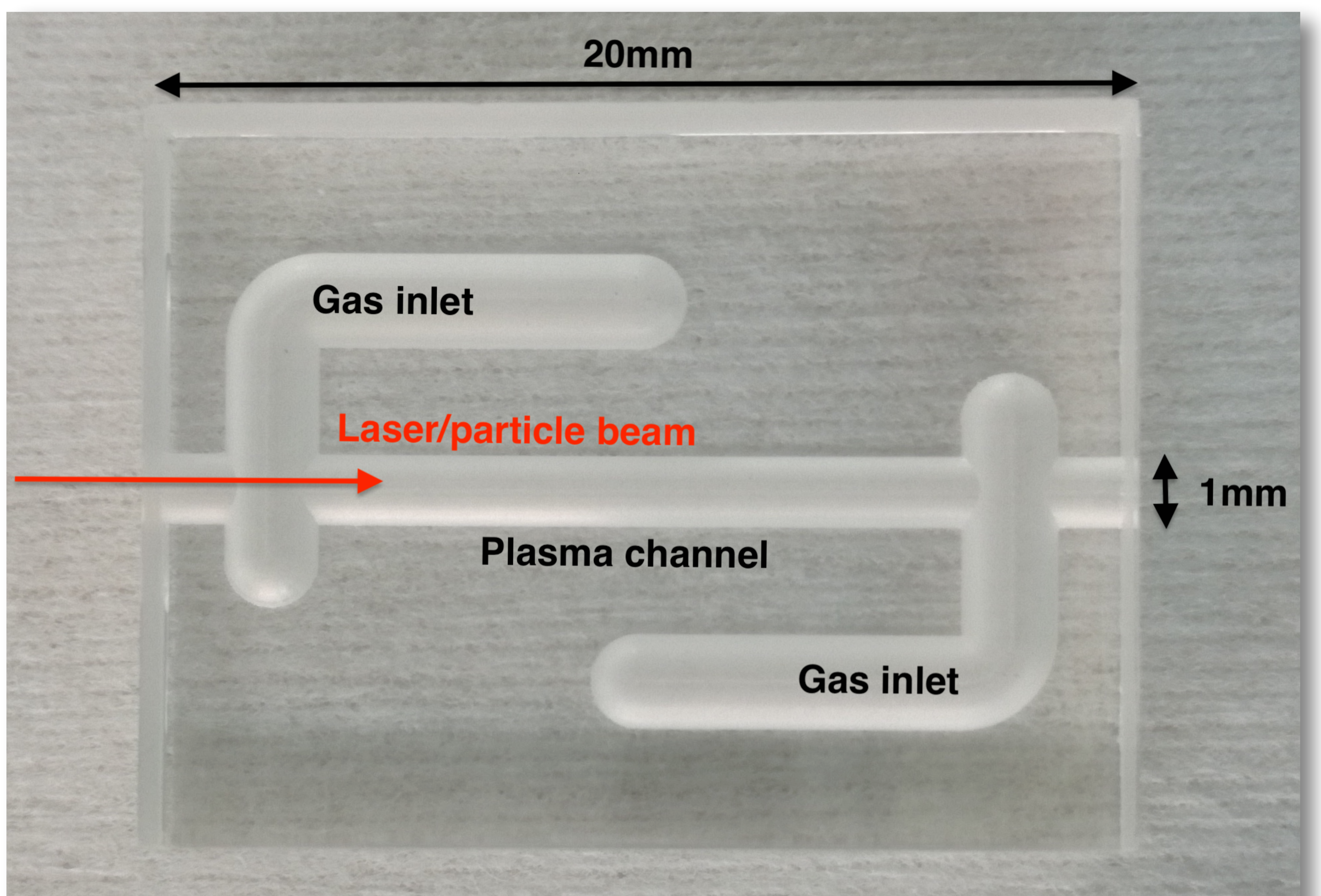


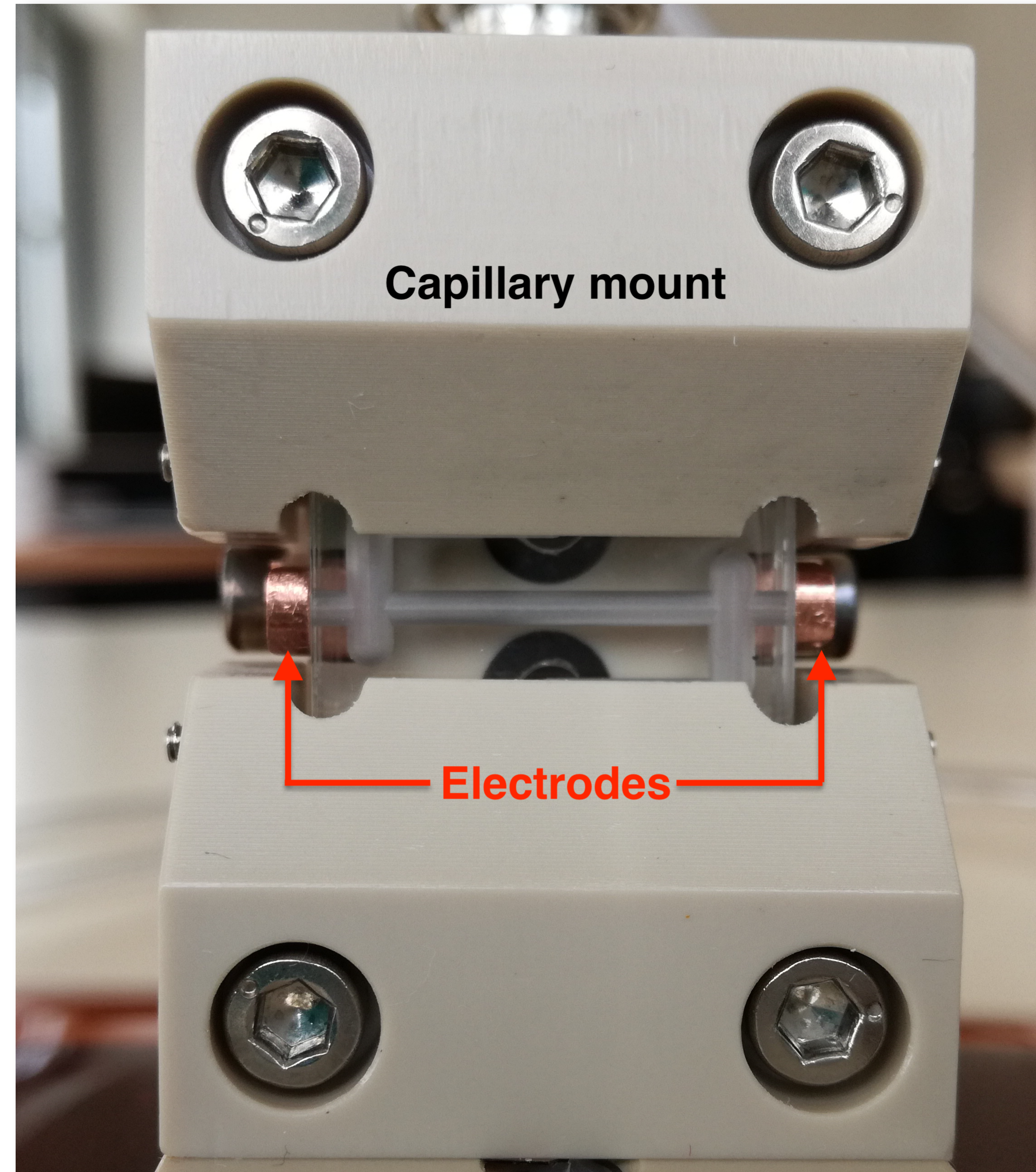
Laser interferometry



Two-color phase delay spectral interferometry

- **System to be investigated: discharge capillary**
  - Cylindrical, sapphire milled channel
  - Length: 20 mm; Diameter: 1.0 mm
  - Electrically discharge-ignited plasma





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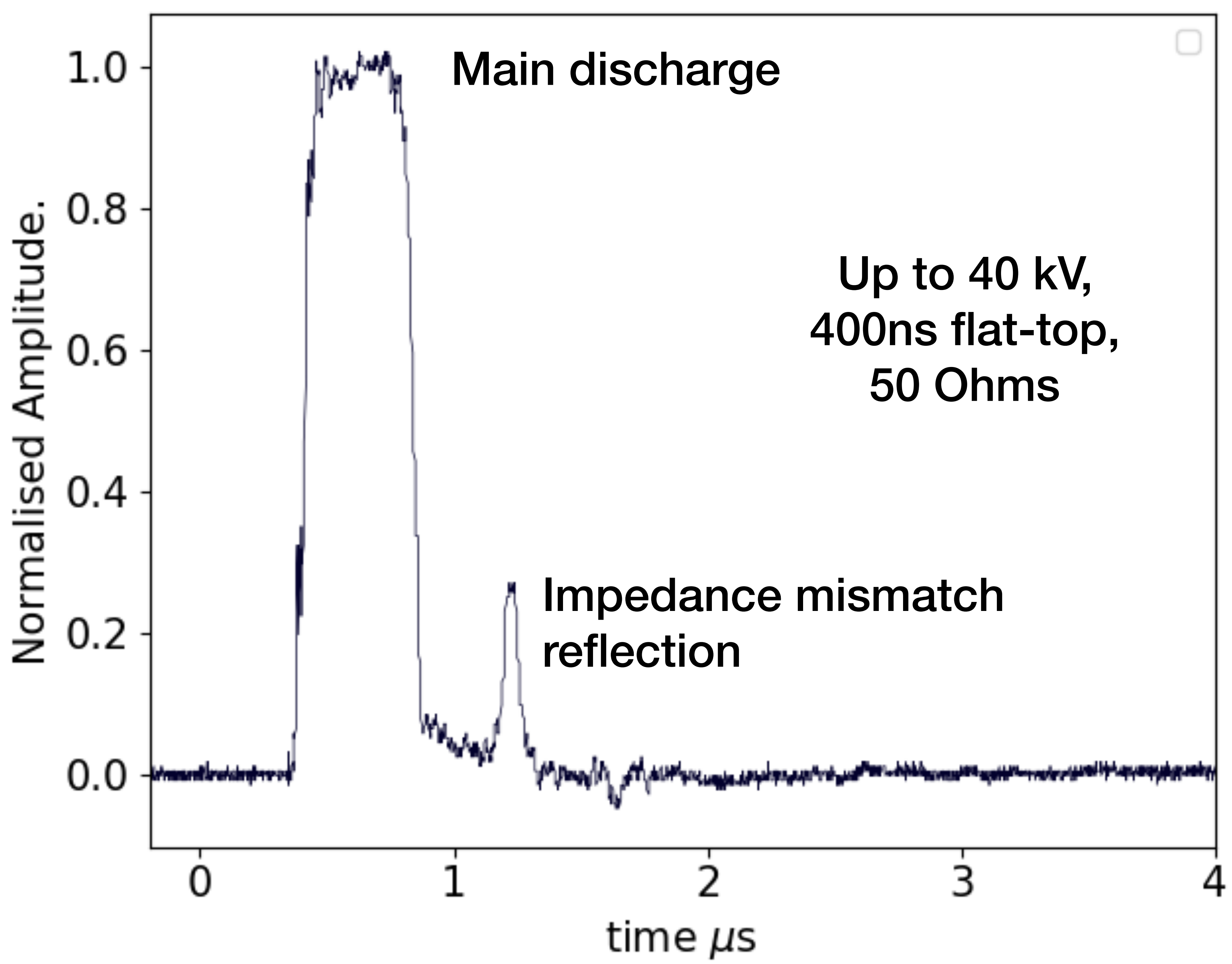
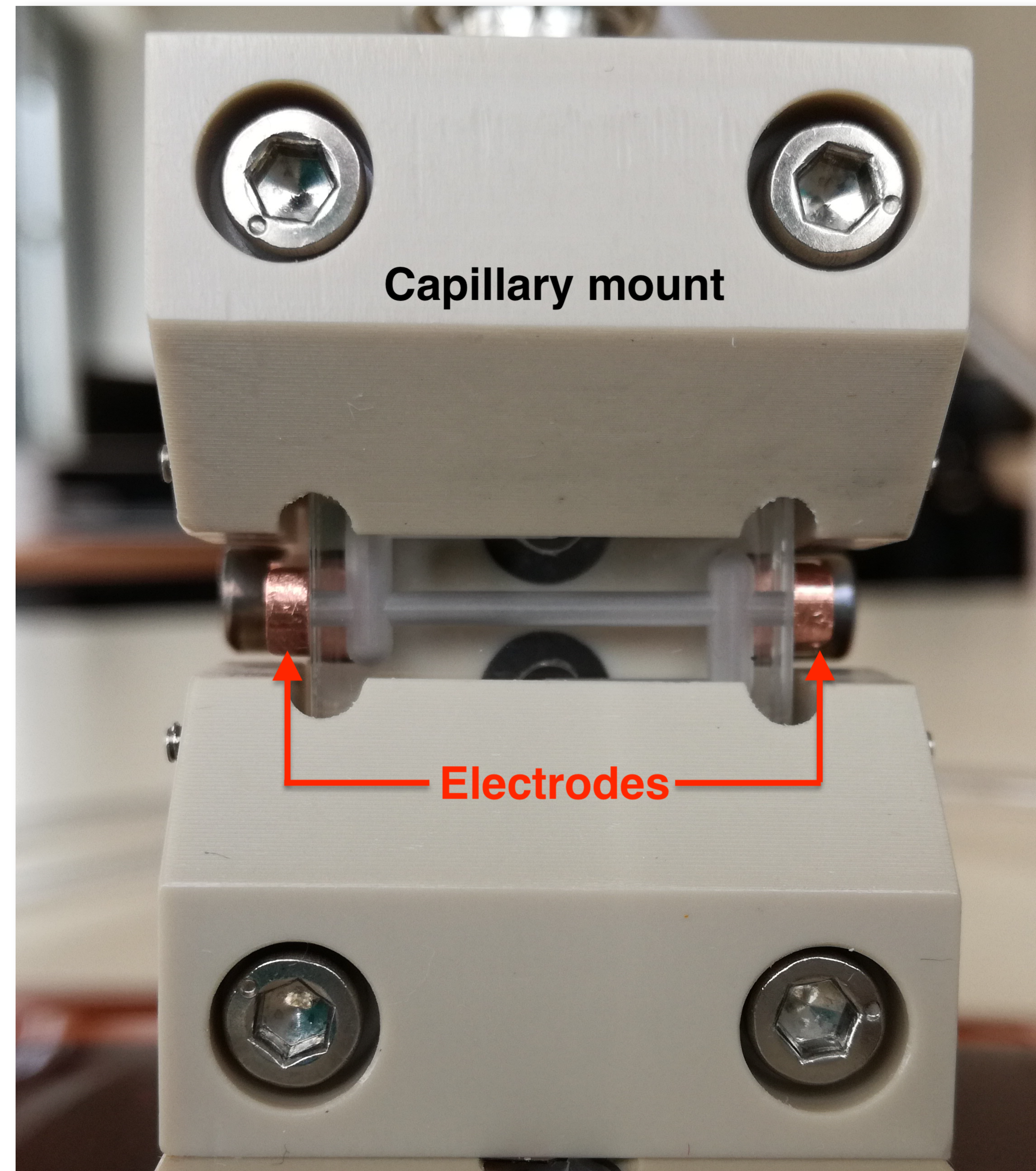
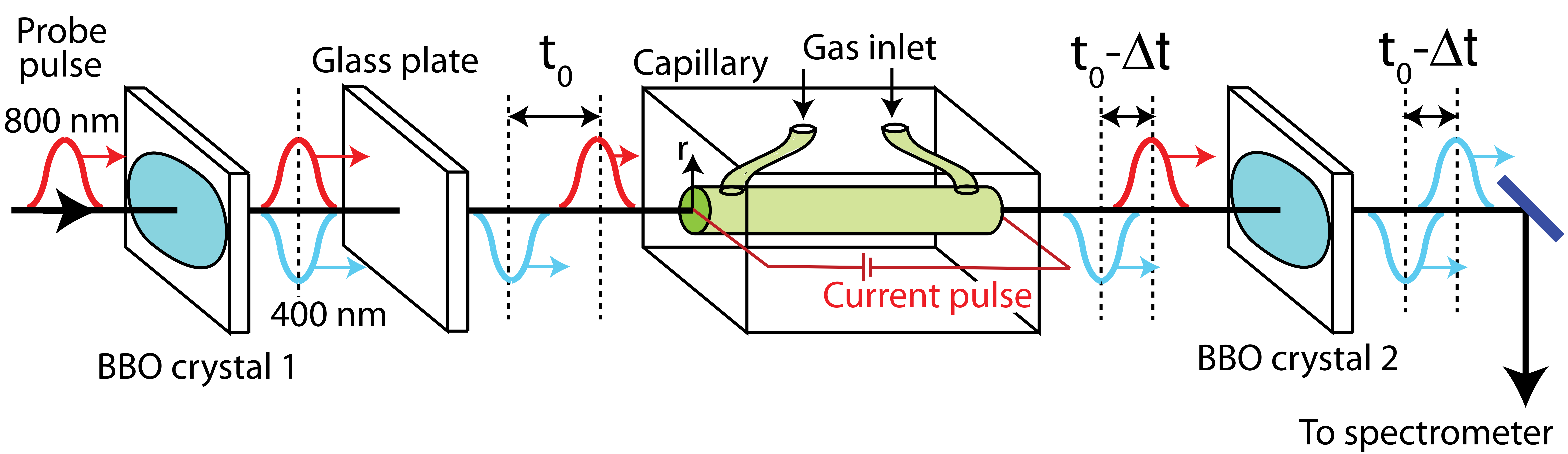




Two-color phase delay spectral interferometry

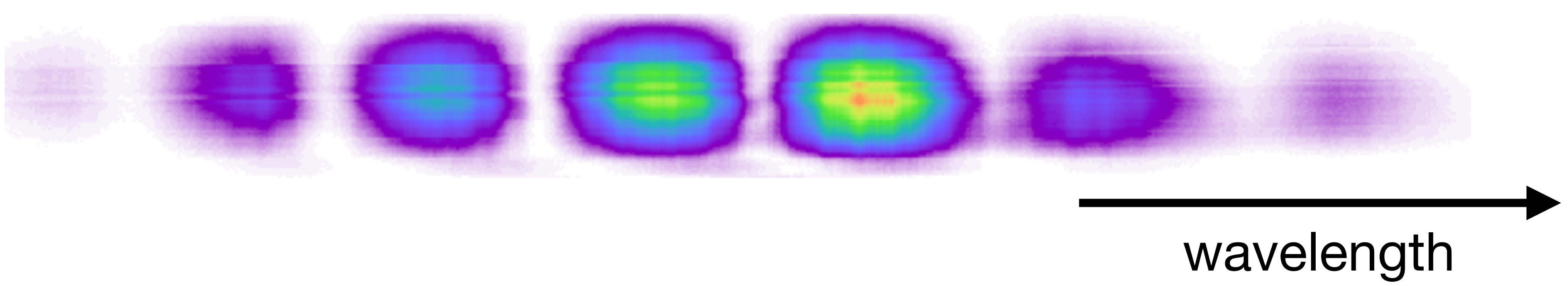
- Single laser pulse frequency doubled → two co-propagating harmonics at 800 and 400 nm (red and blue)
- Two pulses have different group and phase velocities in plasma → the pulses acquire a *Δt* and phase shift
- On exiting the plasma, remaining 800 nm pulse is also doubled (all blue)
- Spectral interference pattern reveals information about temporal delay, phase shift, and the plasma density

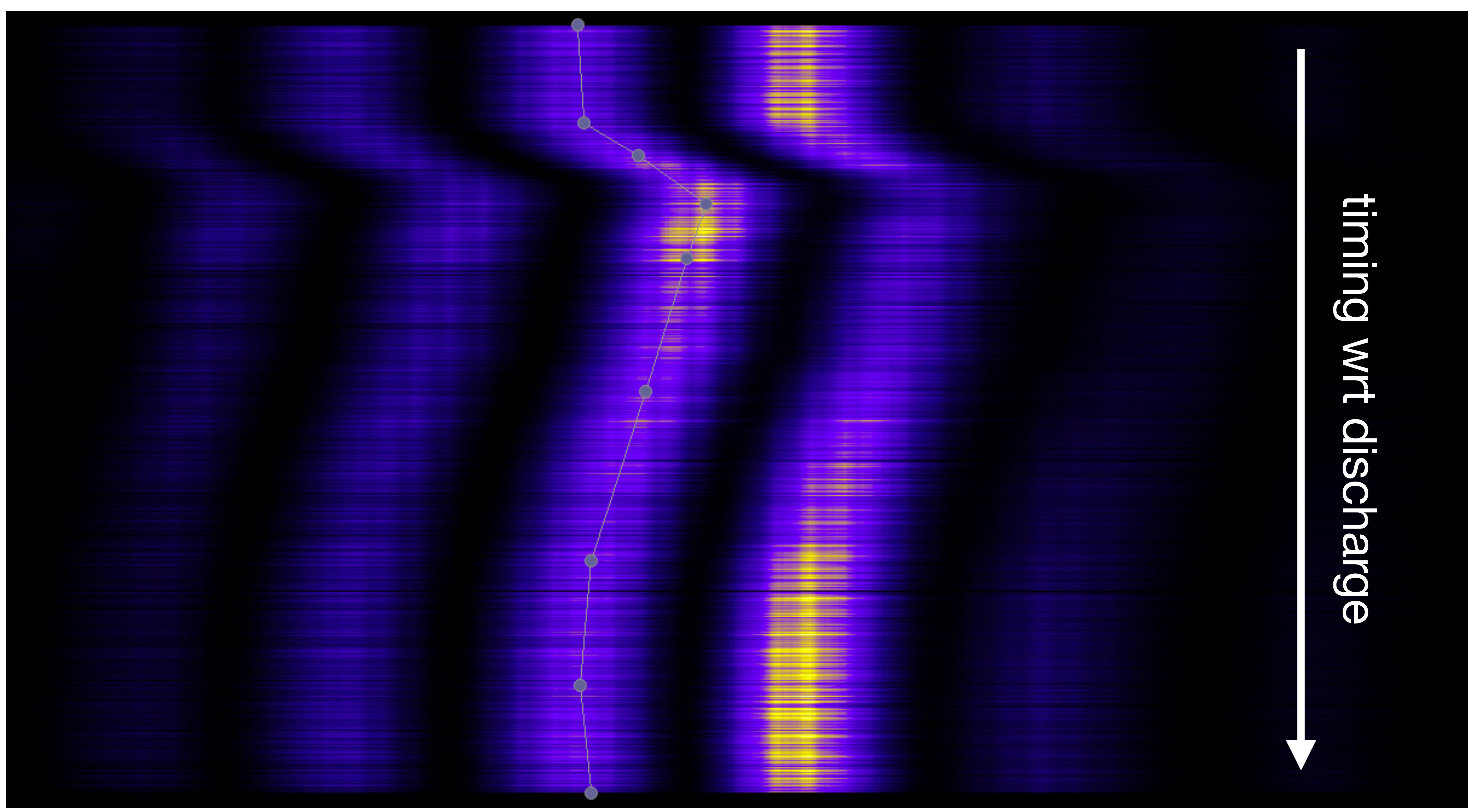


J. Van Tilborg *et al*, Optics Letters **43**, 12 (2018)

Two-color phase delay spectral interferometry

- Interference pattern



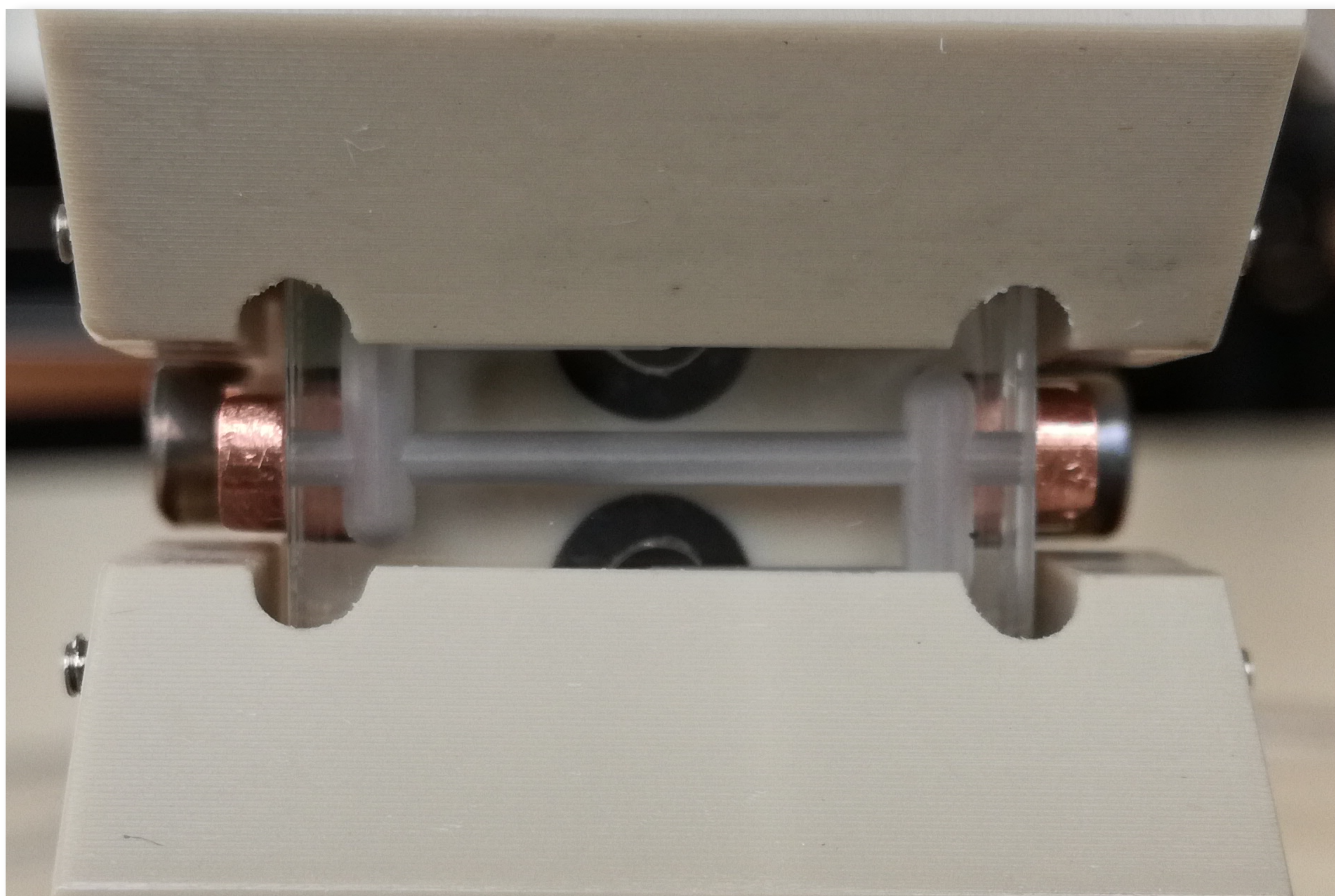


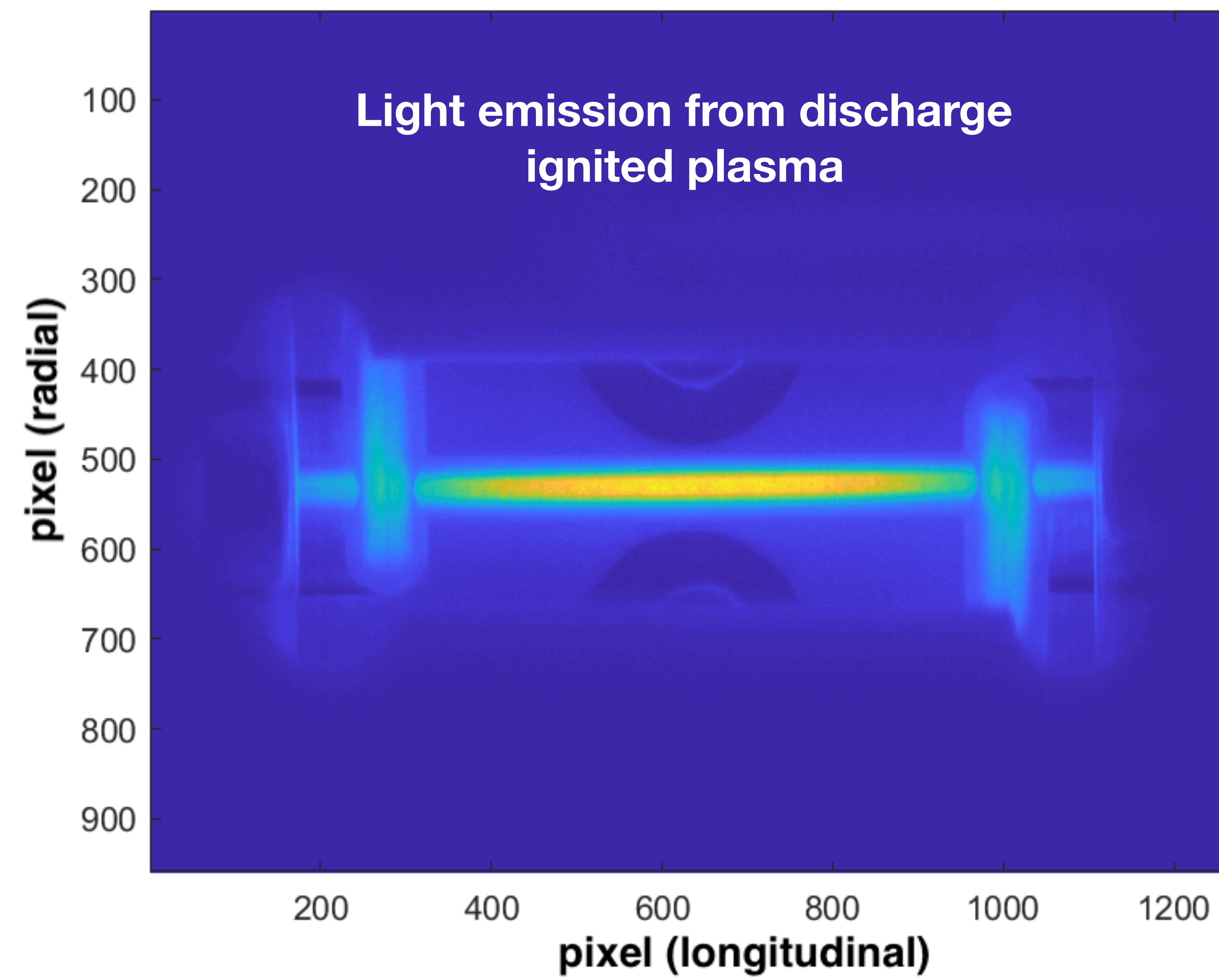
- Fringe frequency → pulse separation
- Fringe position → phase delay

- Spatial resolution:
  longitudinally integrated
- Temporal resolution:
  sub-ns (depending on capillary traversal time)

Plasma spectroscopy

> Plasma emission may be used to acquire information about plasma

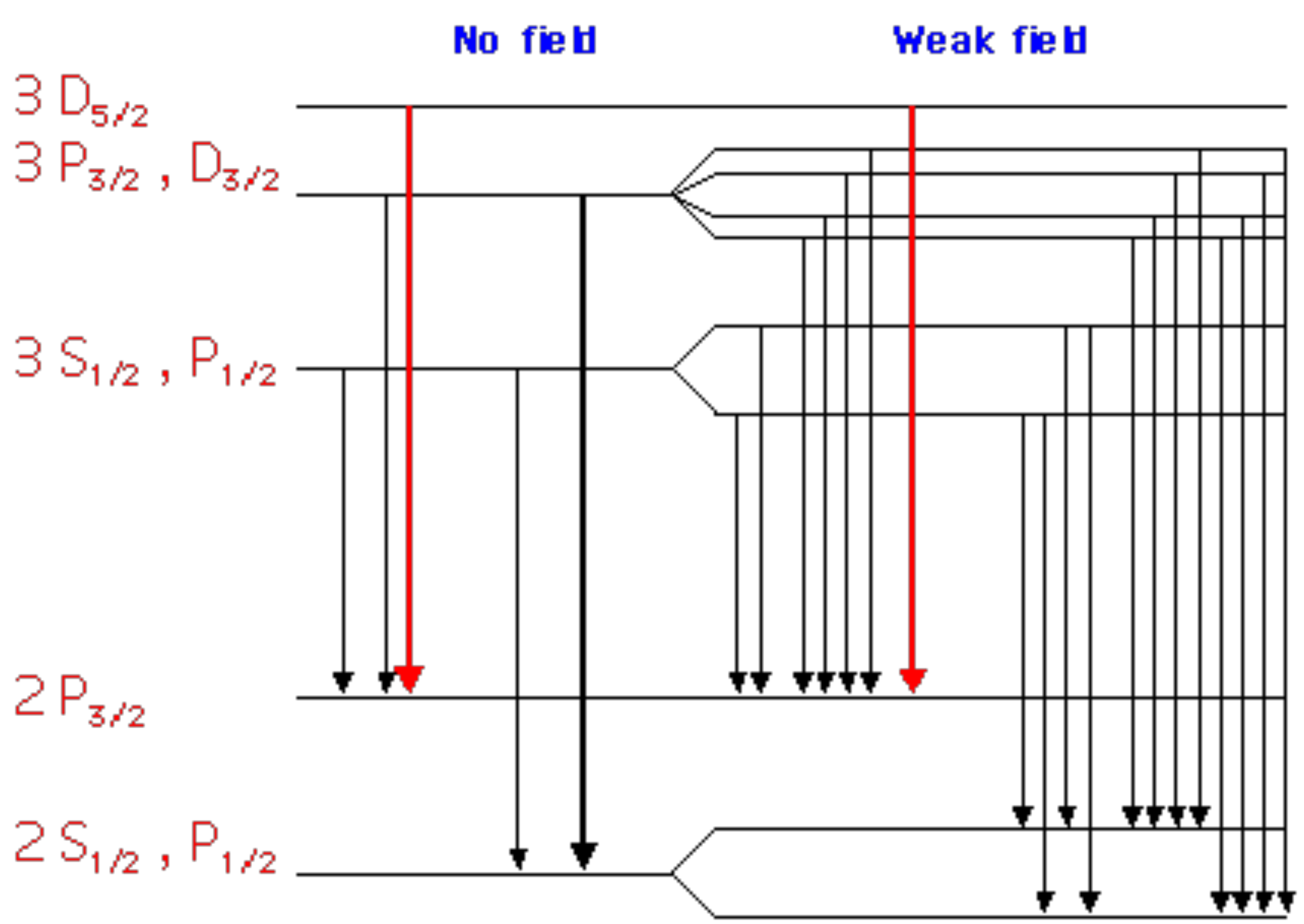




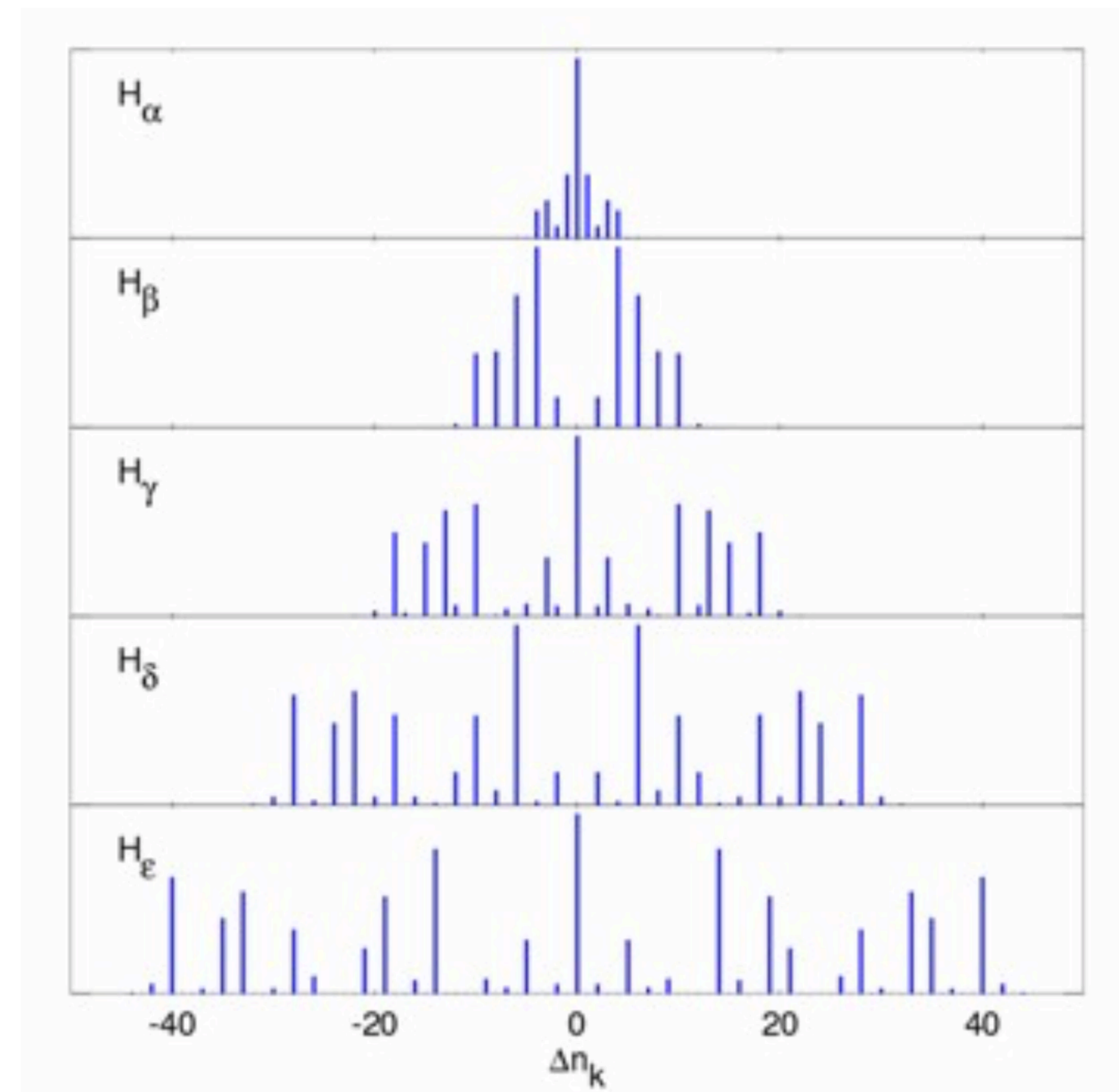
Plasma spectroscopy

> Stark broadening of electric relaxation lines depends on local electric field strength in plasma (Debye shielding)
→ contains information about local plasma electron density

Stark effect for Hydrogen H_α



Line splitting of Balmer Series of Hydrogen

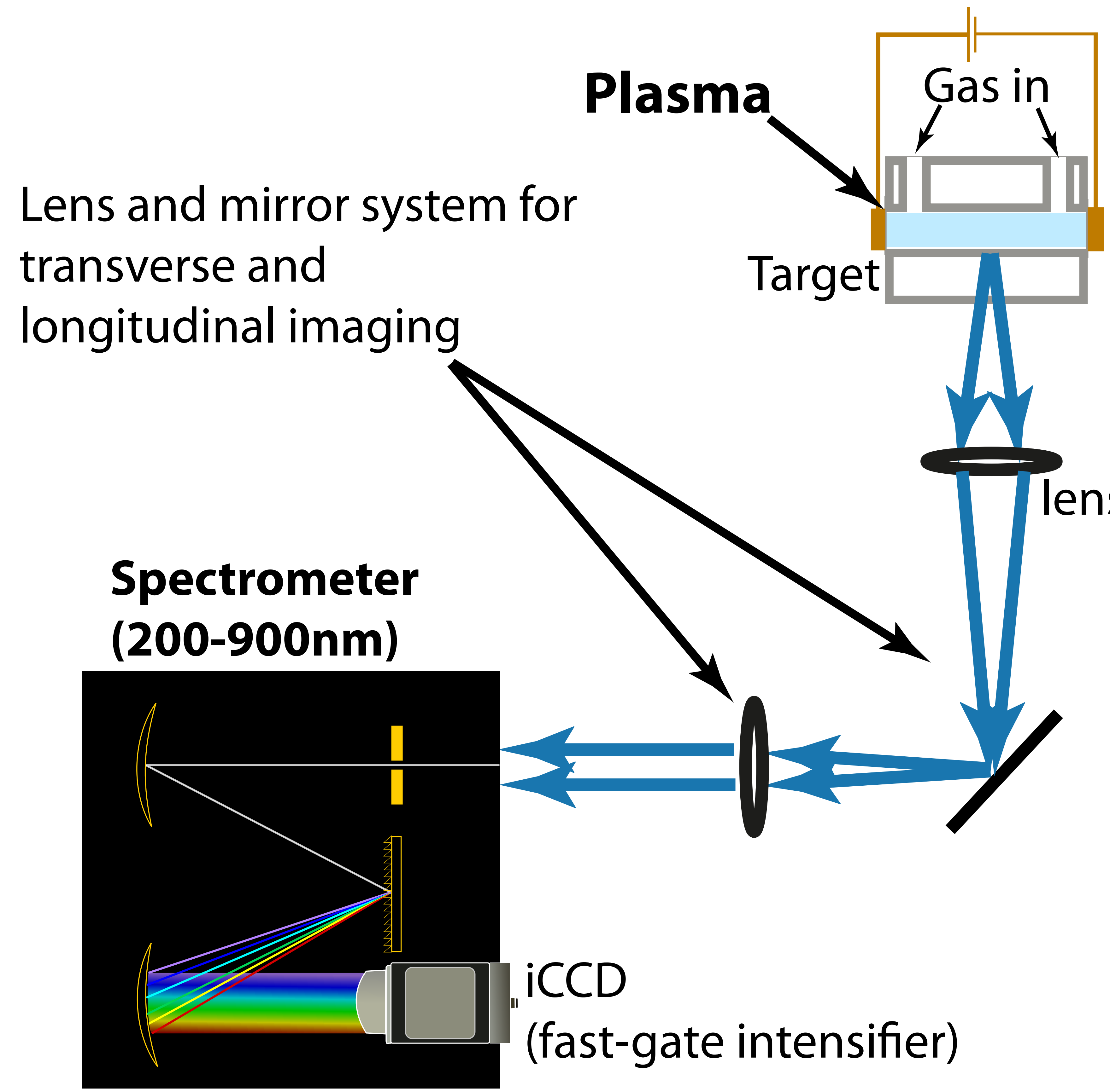


> Number of degenerate states: $g = 2\sum_{l=0}^{n-1}(2l+1)$

Plasma spectroscopy

> Stark broadening of electric relaxation lines depends on local electric field strength in plasma (Debye shielding)
  → contains information about local plasma electron density

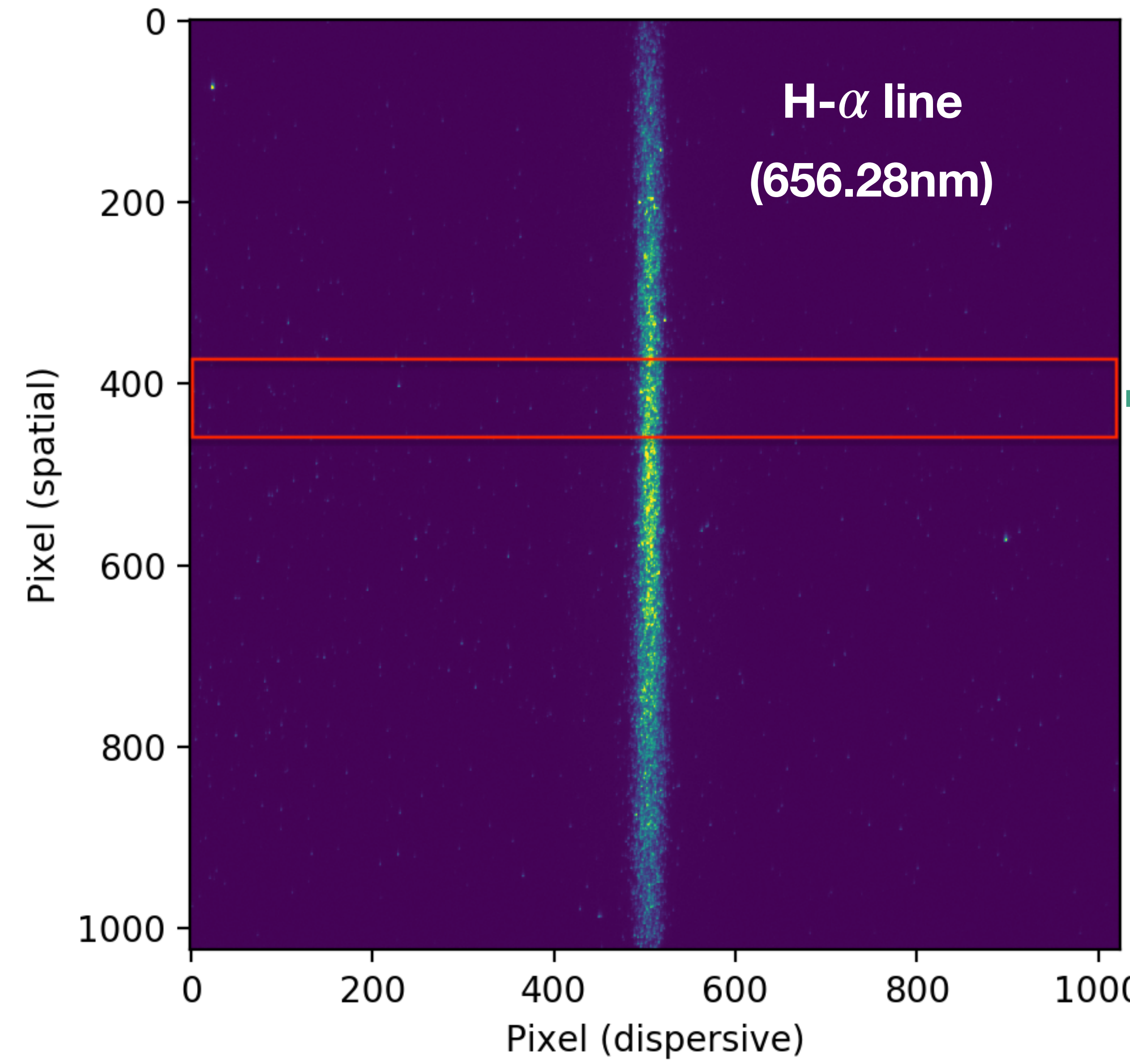
- Observe spectroscopic light emission from atoms in plasma
- Fast-gate intensifier (2 - 50 ns) before CCD camera
- Width of spectral lines reveals information about plasma density



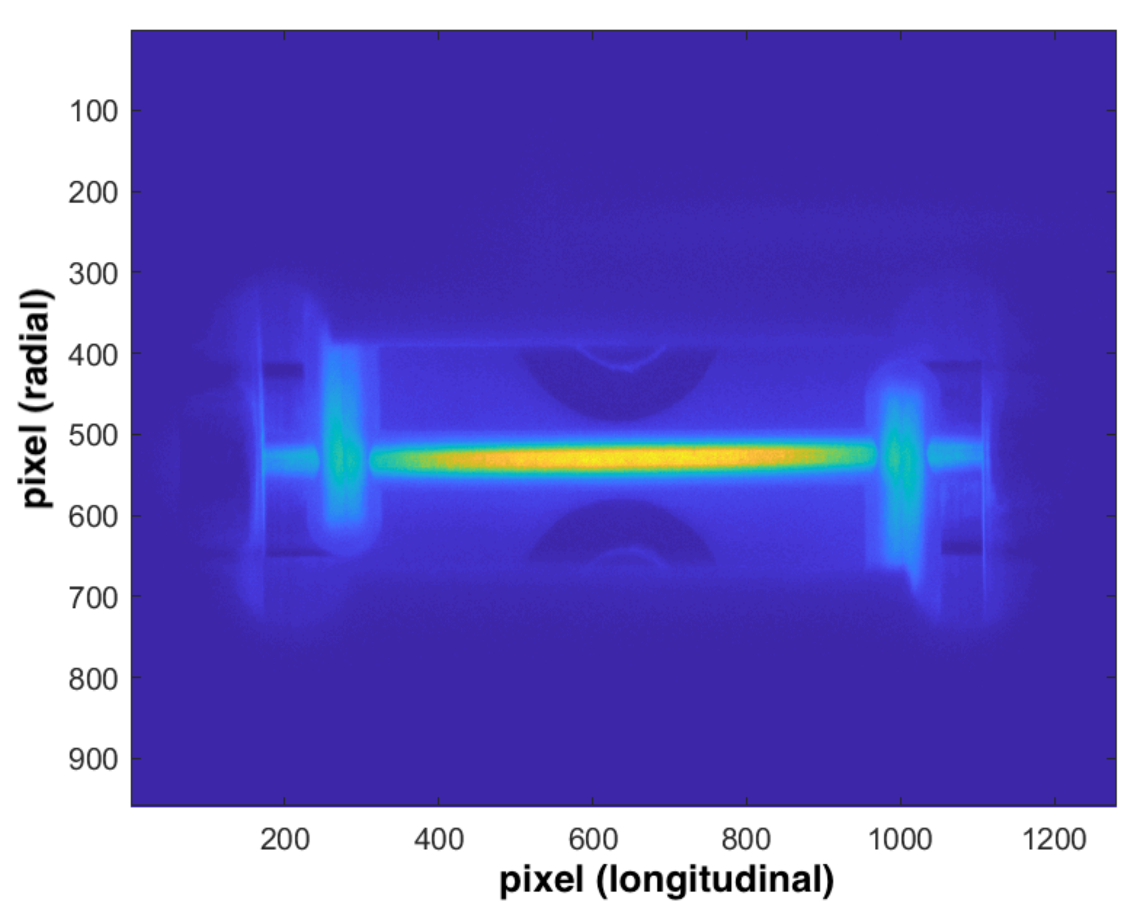
Methodology references: M.A. Gigosos *et al*, **Spectrochimica Acta B 58** (2003)
P. Kepple and H.R. Griem, **Phys. Rev. 173** (1968)

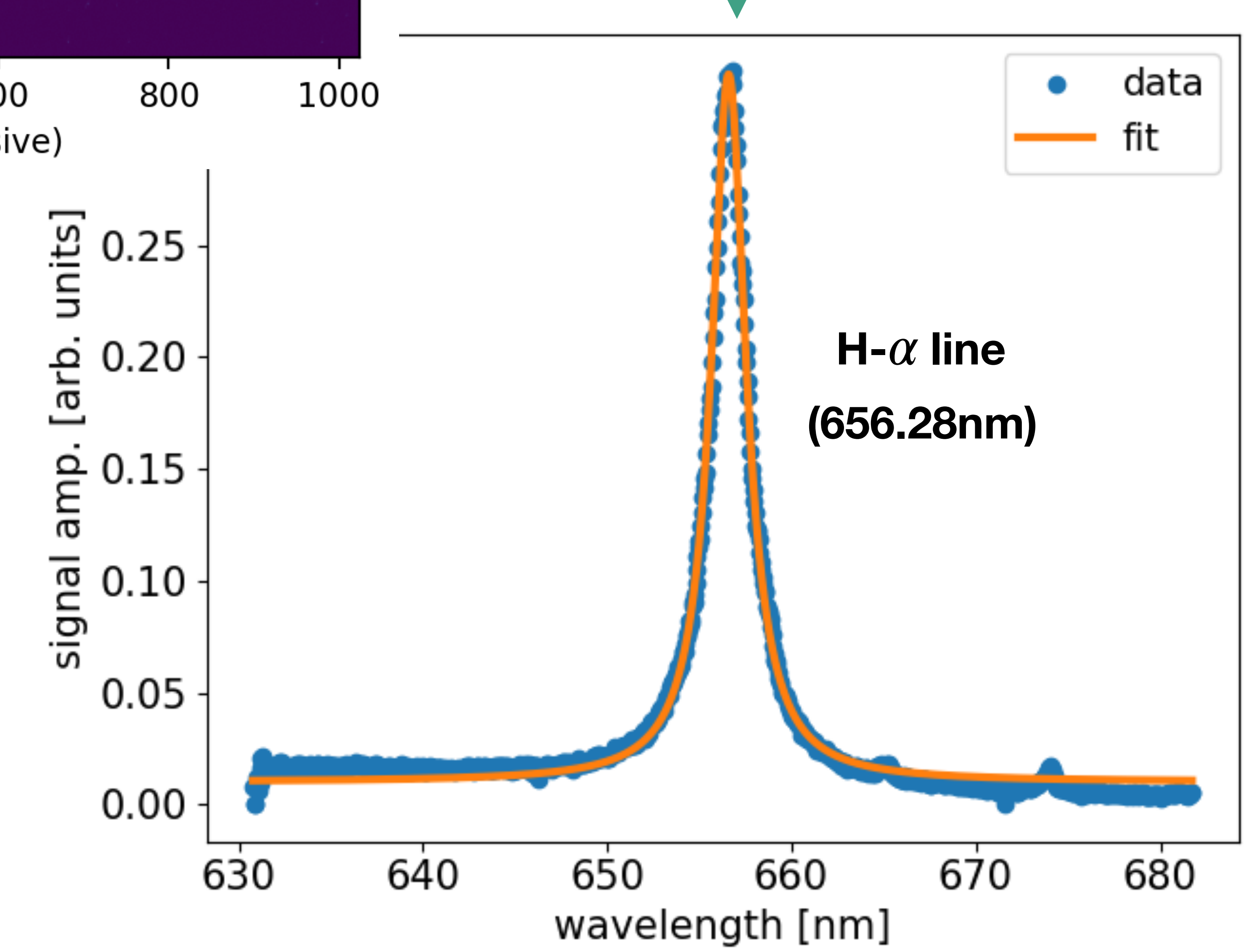
Plasma spectroscopy

- Spatial resolution:
  longitudinally xor radially
  resolved density slices, ~ 10 µm resolution
- Temporal resolution:
  shortest gating time over which
  S/N is sufficient (typically 2 - 50 ns)

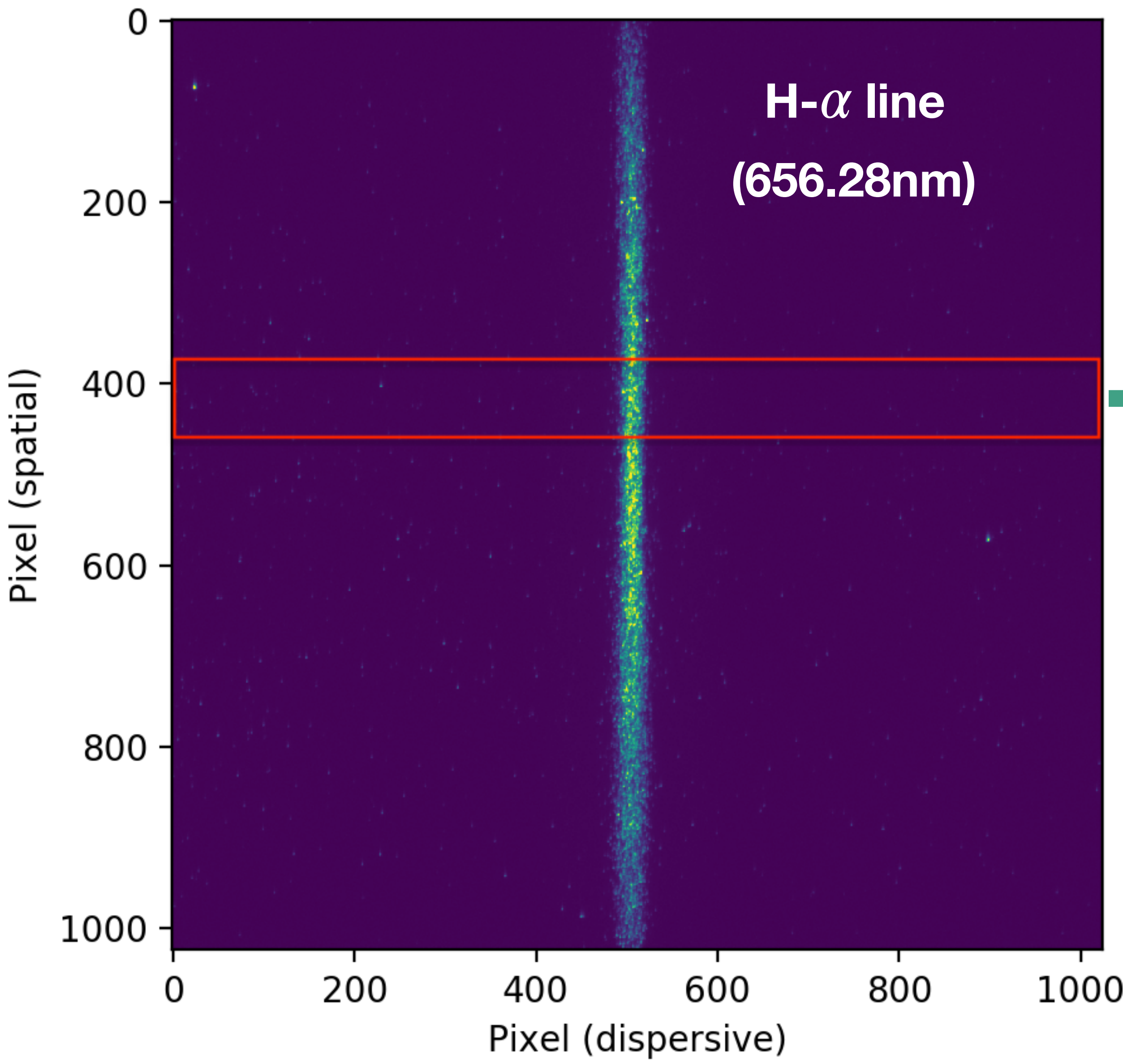


Hydrogen-Balmer series alpha line has high relative intensity - easily identifiable

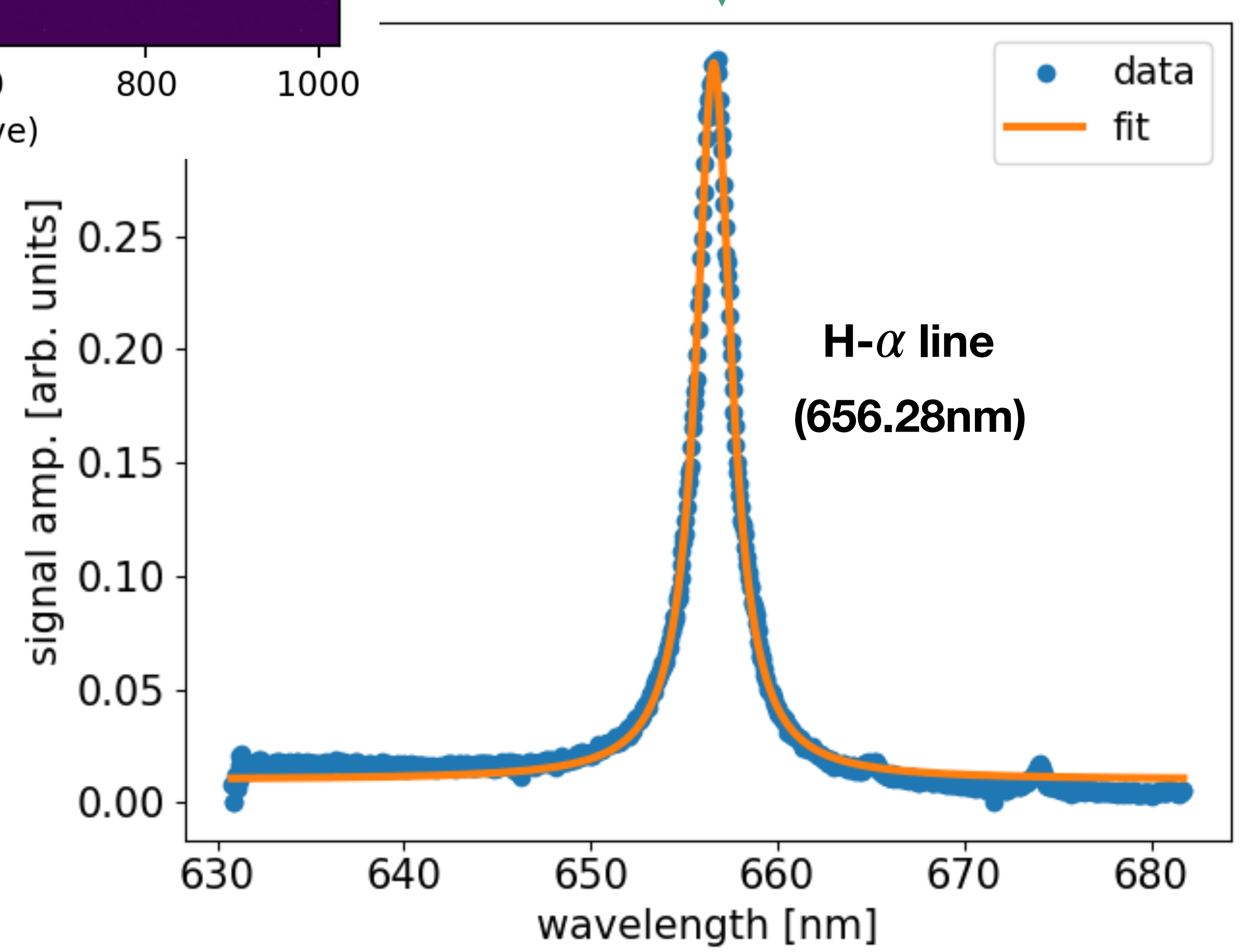


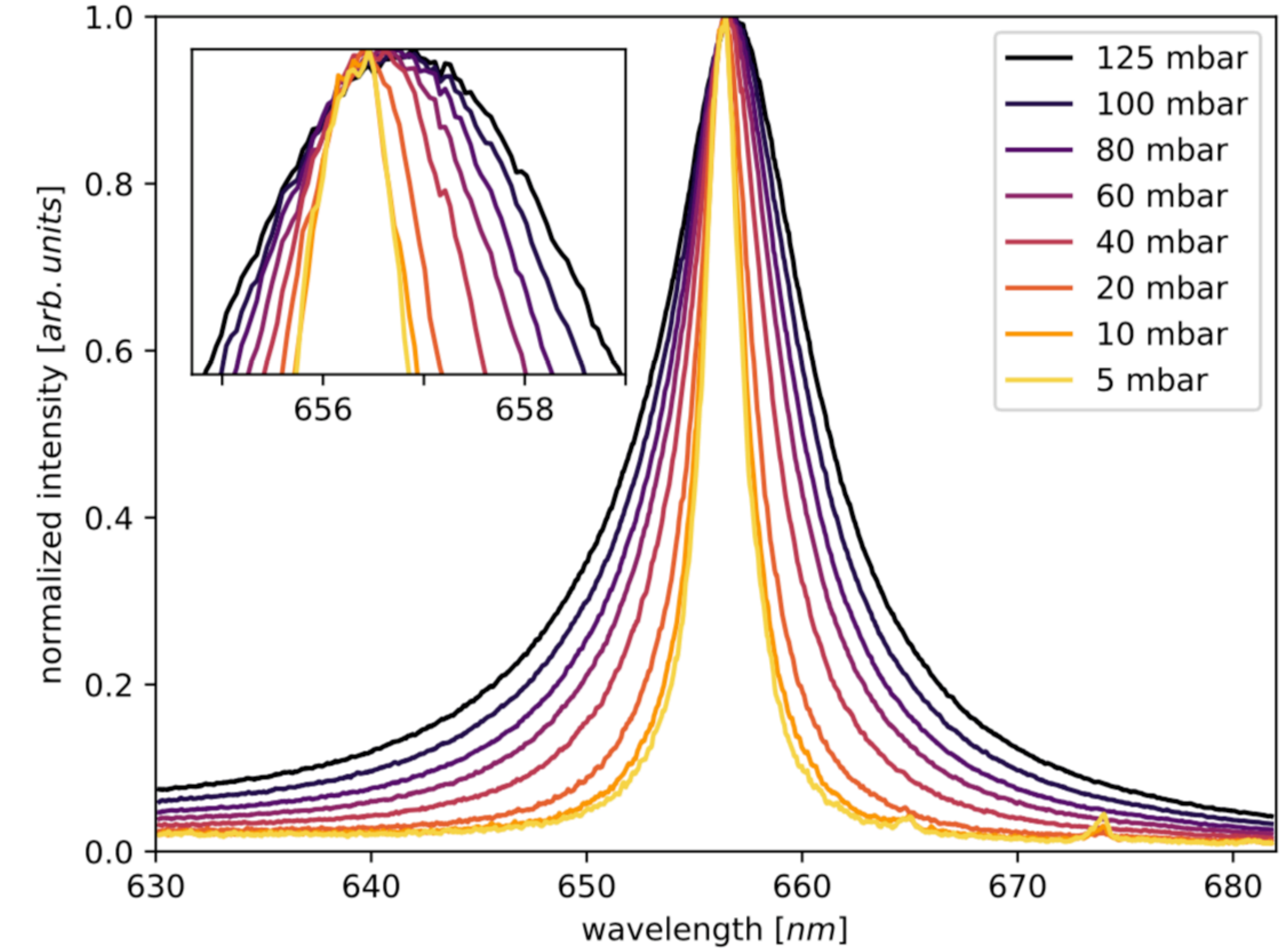


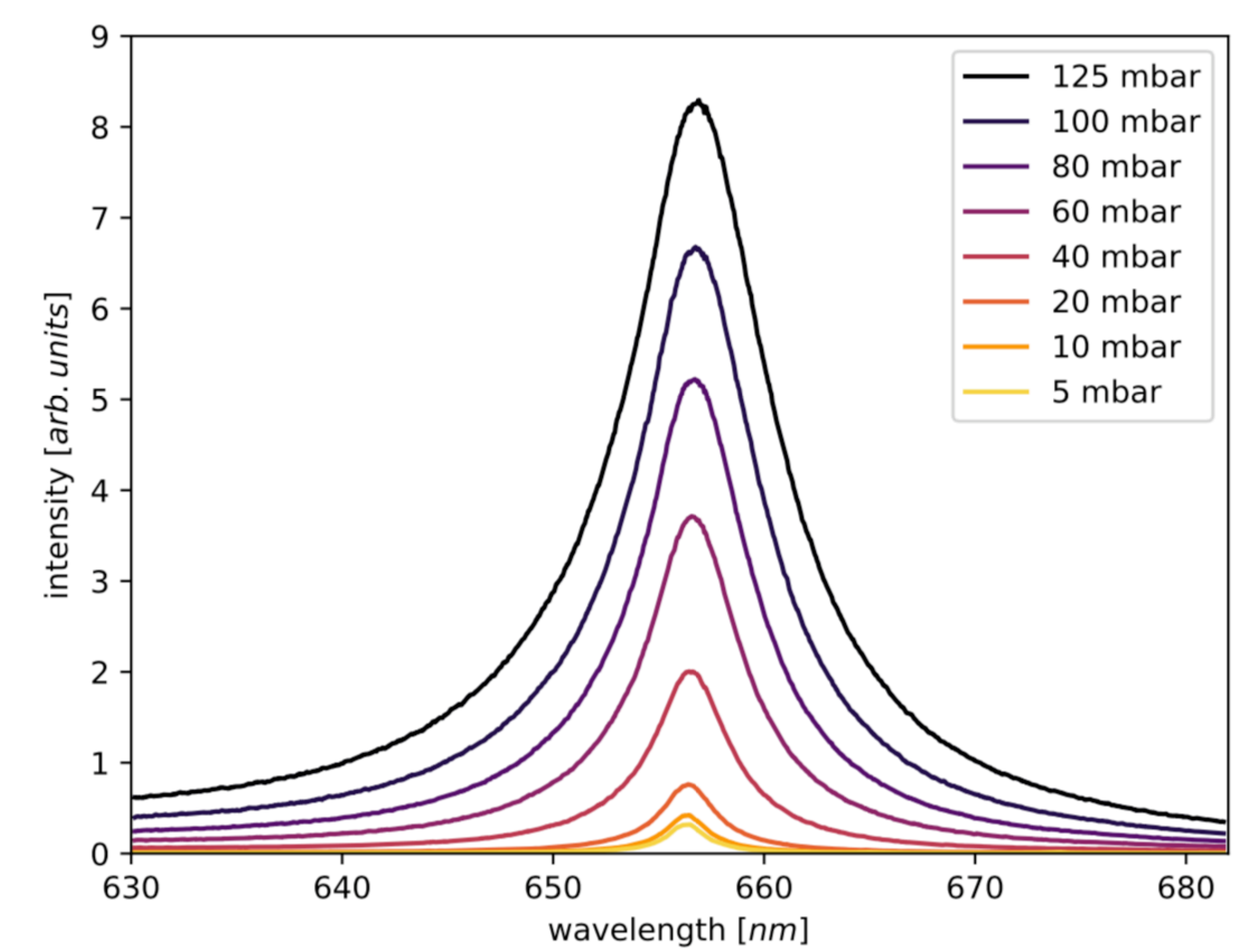
Plasma spectroscopy



Hydrogen-Balmer series alpha line has high relative intensity - easily identifiable



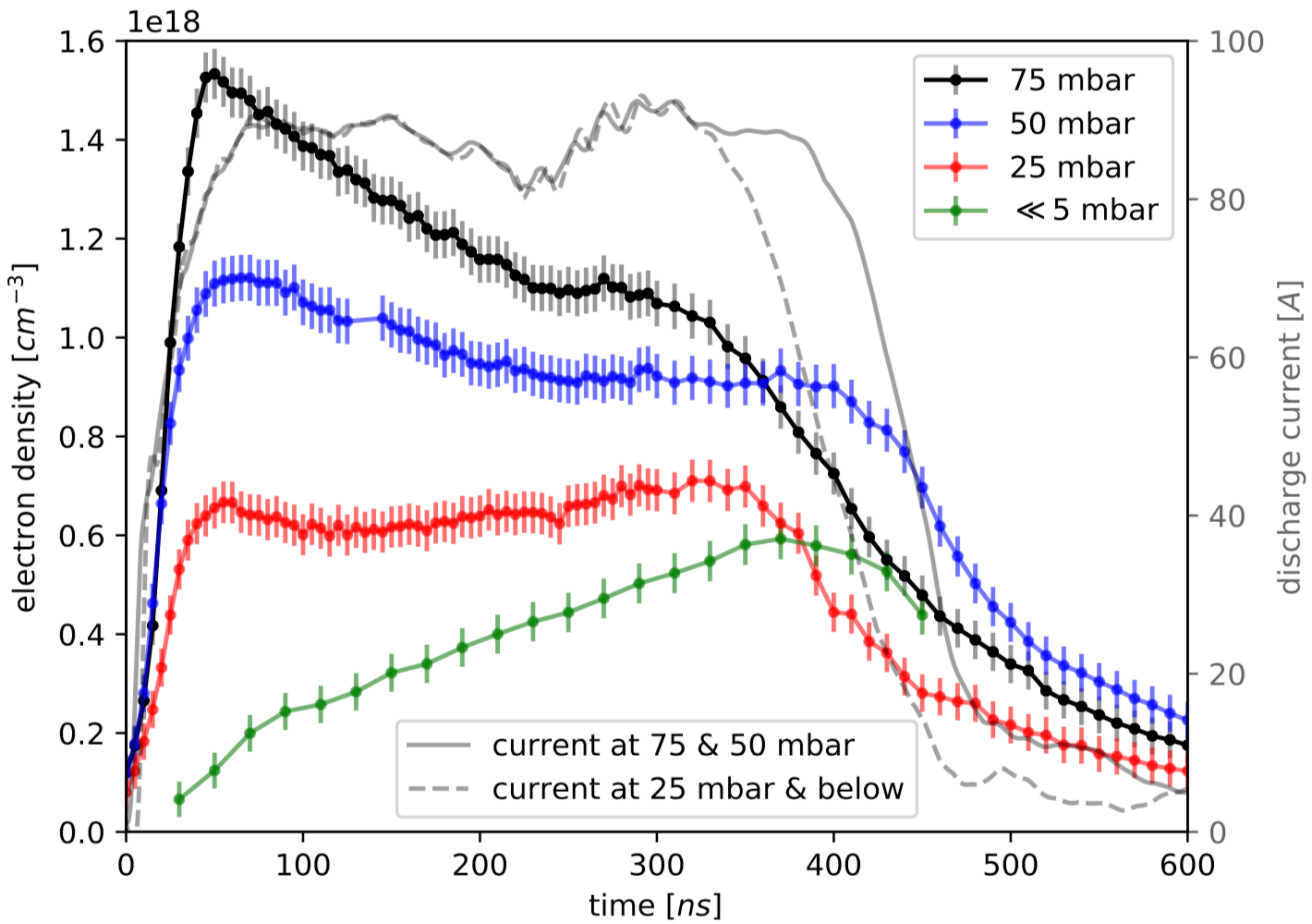




Plasma spectroscopy

- Different capillary with 300 µm inner diameter capillary

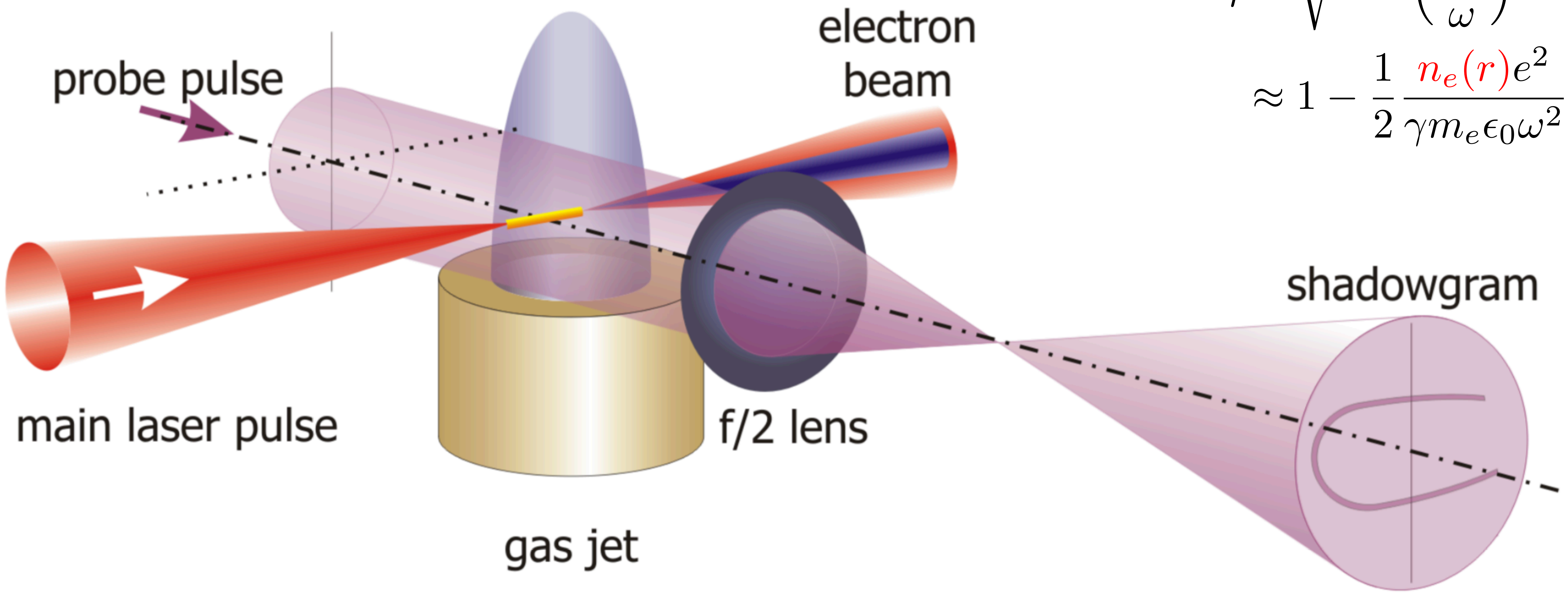
“100%” Hydrogen temporal evolution



Internal E- & B-fields, and wake structures

- Polarimetry
- Particle beam probes
- Frequency Domain Holography

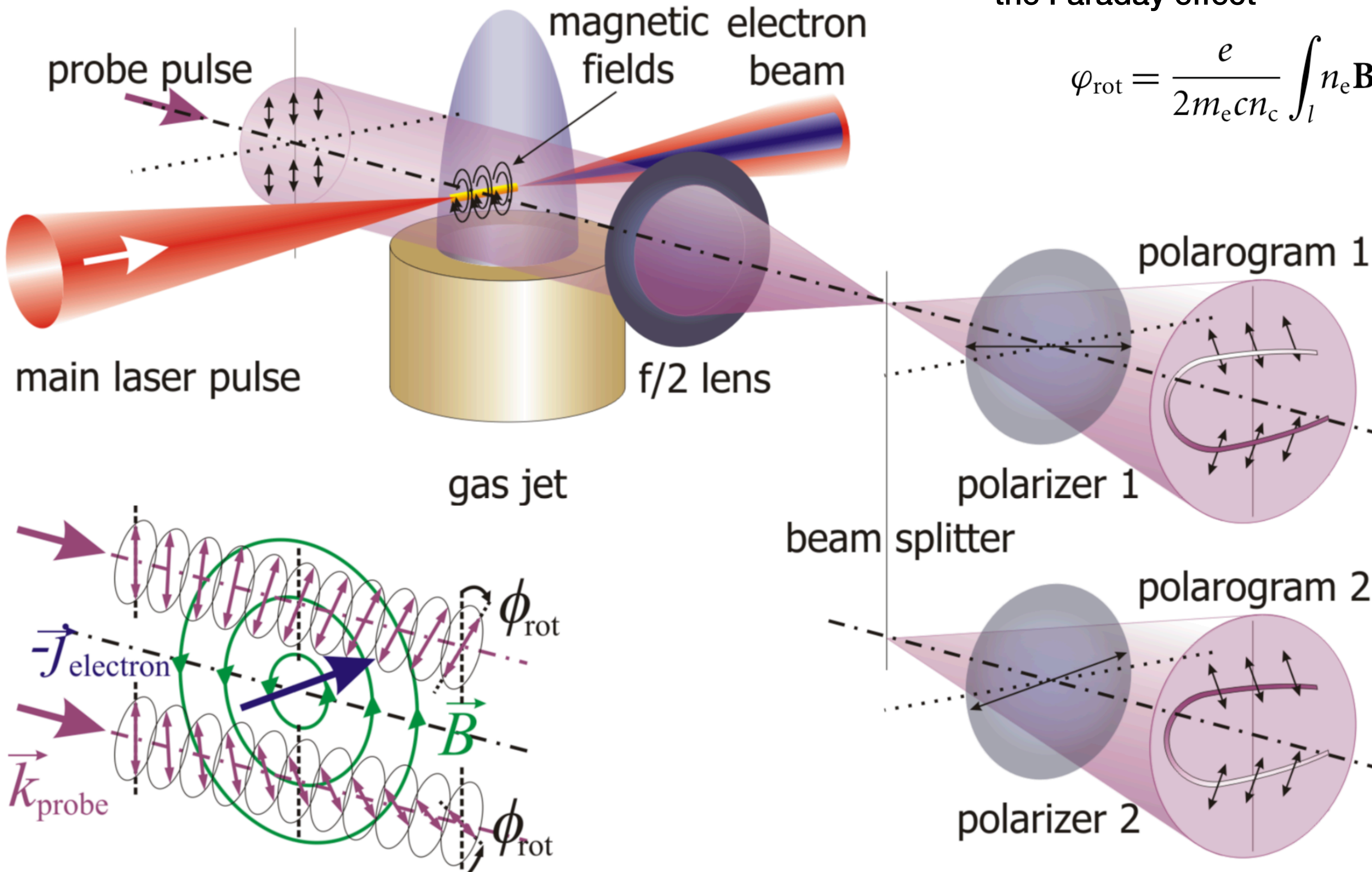
Reminder: Shadowgraphy



$$\eta = \sqrt{1 - \left(\frac{\omega_p}{\omega}\right)^2} \approx 1 - \frac{1}{2}\frac{n_e(r)e^2}{\gamma m_e \epsilon_0 \omega^2}$$

> Index of refraction gradients cause distortion of probe phase front → intensity structures in beam

Polarimetry



- Plasma can be an active medium for the Faraday effect

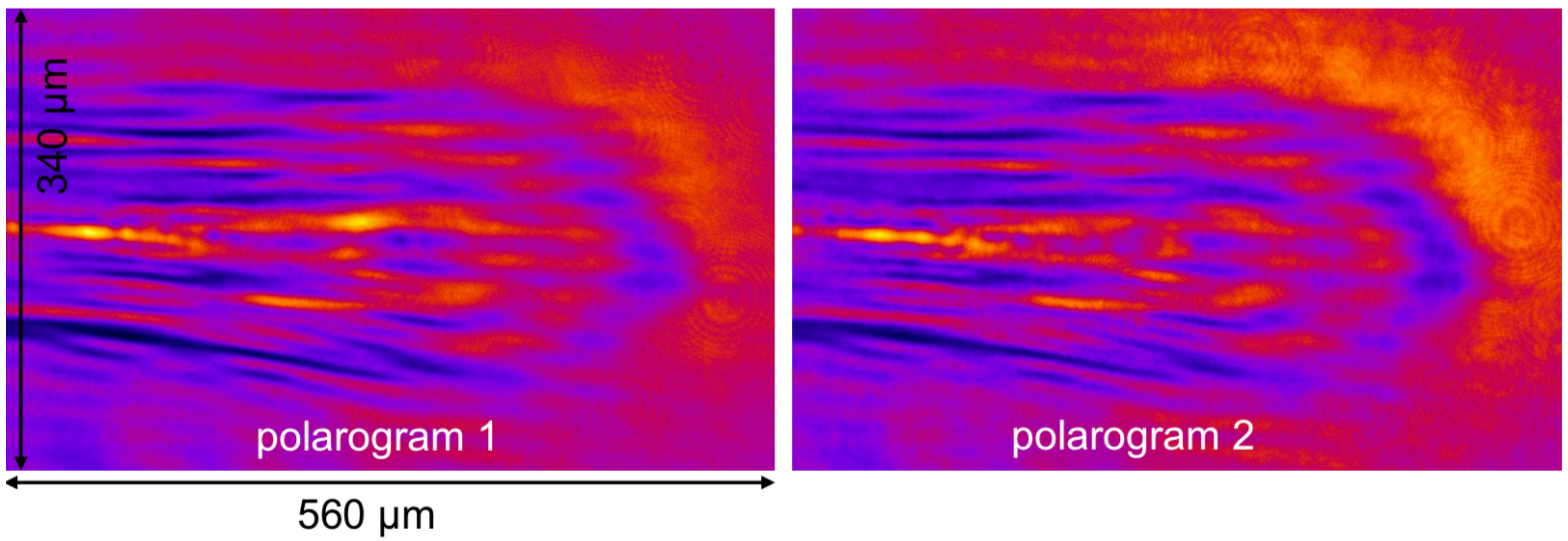
$$\varphi_{\text{rot}} = \frac{e}{2m_e c n_c} \int_l n_e \mathbf{B}_\varphi \cdot \mathrm{d}\mathbf{s}$$

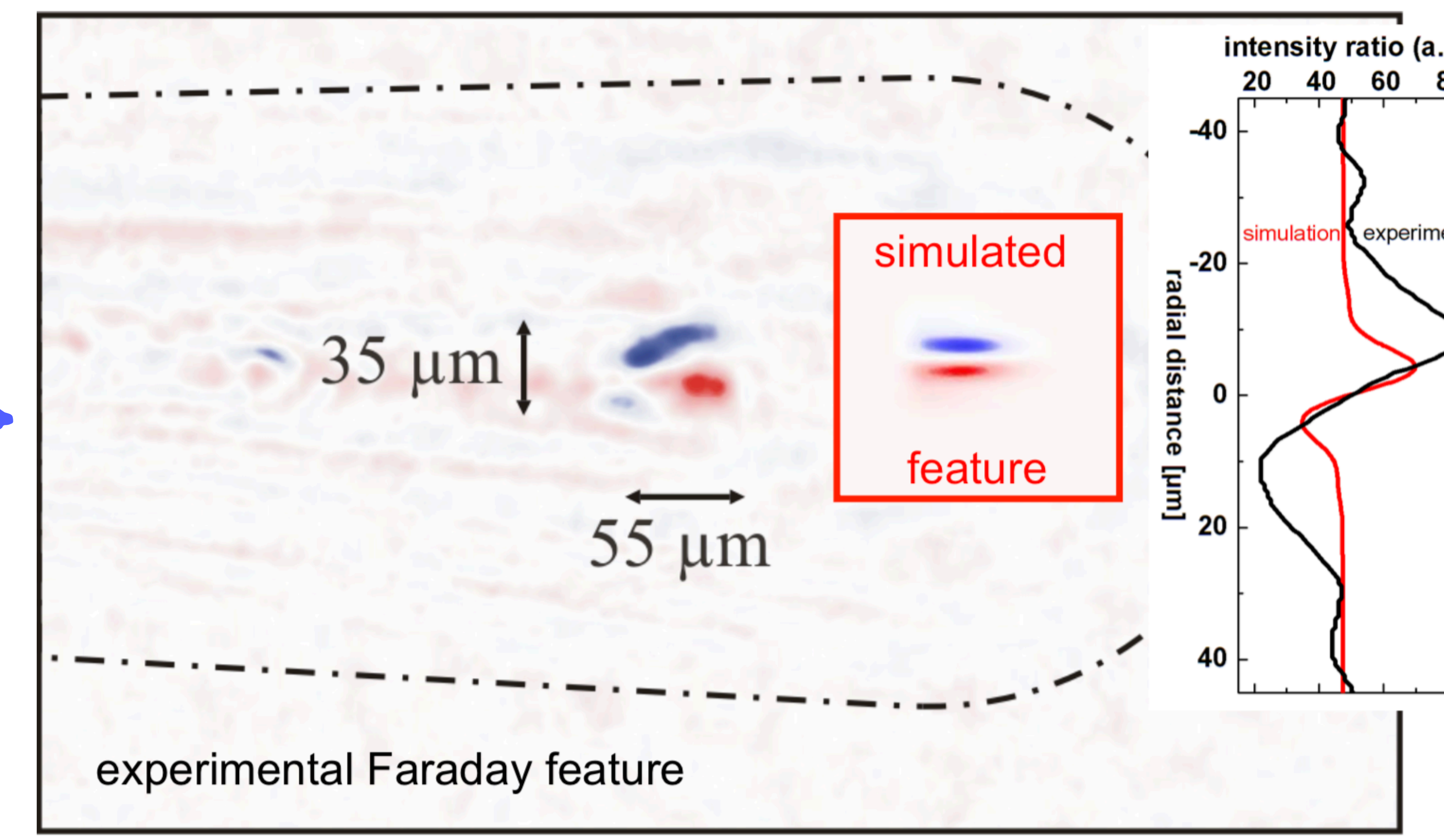
Polarimetry

> Plasma can be an active medium for the Faraday effect

$$\varphi_{\mathrm{rot}} = \frac{e}{2 m_e c n_c} \int_l n_e \mathbf{B}_\varphi \cdot d\mathbf{s}$$

Two polarograms from two (almost) crossed polarizers:





Experimental evidence for B-fields from MeV electrons and bubble!

MCK *et al.*, Physical Review Letters **105,** 115002 (2010)

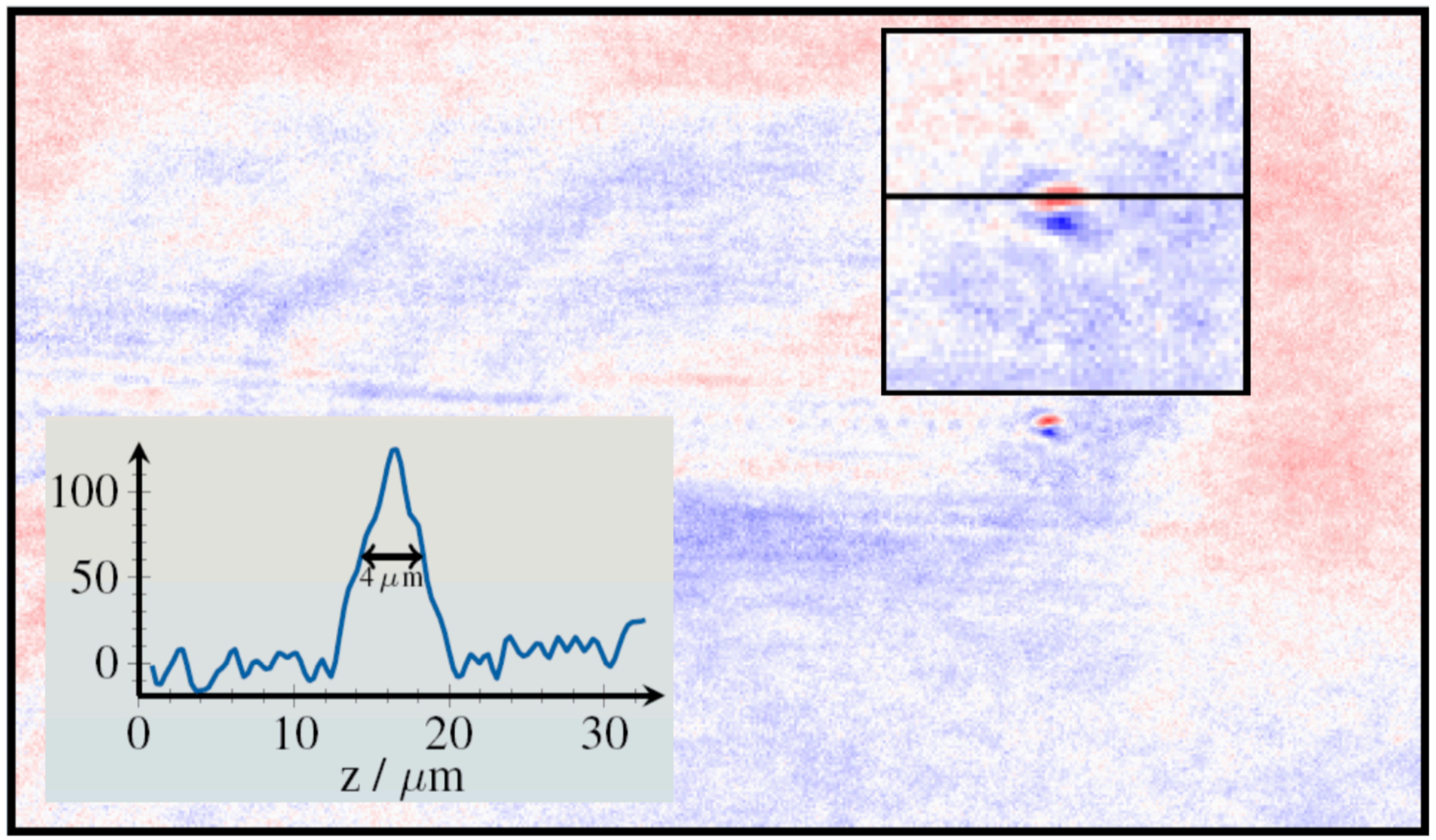
$$I_{\mathrm{pol1}} = I_0 \left[1 - \beta_1 \sin^2(90^\circ - \theta_{\mathrm{pol1}} - \phi_{\mathrm{rot}})\right] \quad I_{\mathrm{pol2}} = I_0 \left[1 - \beta_2 \sin^2(90^\circ + \theta_{\mathrm{pol2}} - \phi_{\mathrm{rot}})\right]$$

Deduce rotation angle ϕ_{rot} from pixel-by-pixel division of polarogram intensities:

$$I_{\mathrm{pol1}}(x,y)/I_{\mathrm{pol2}}(x,y)$$

Polarimetry

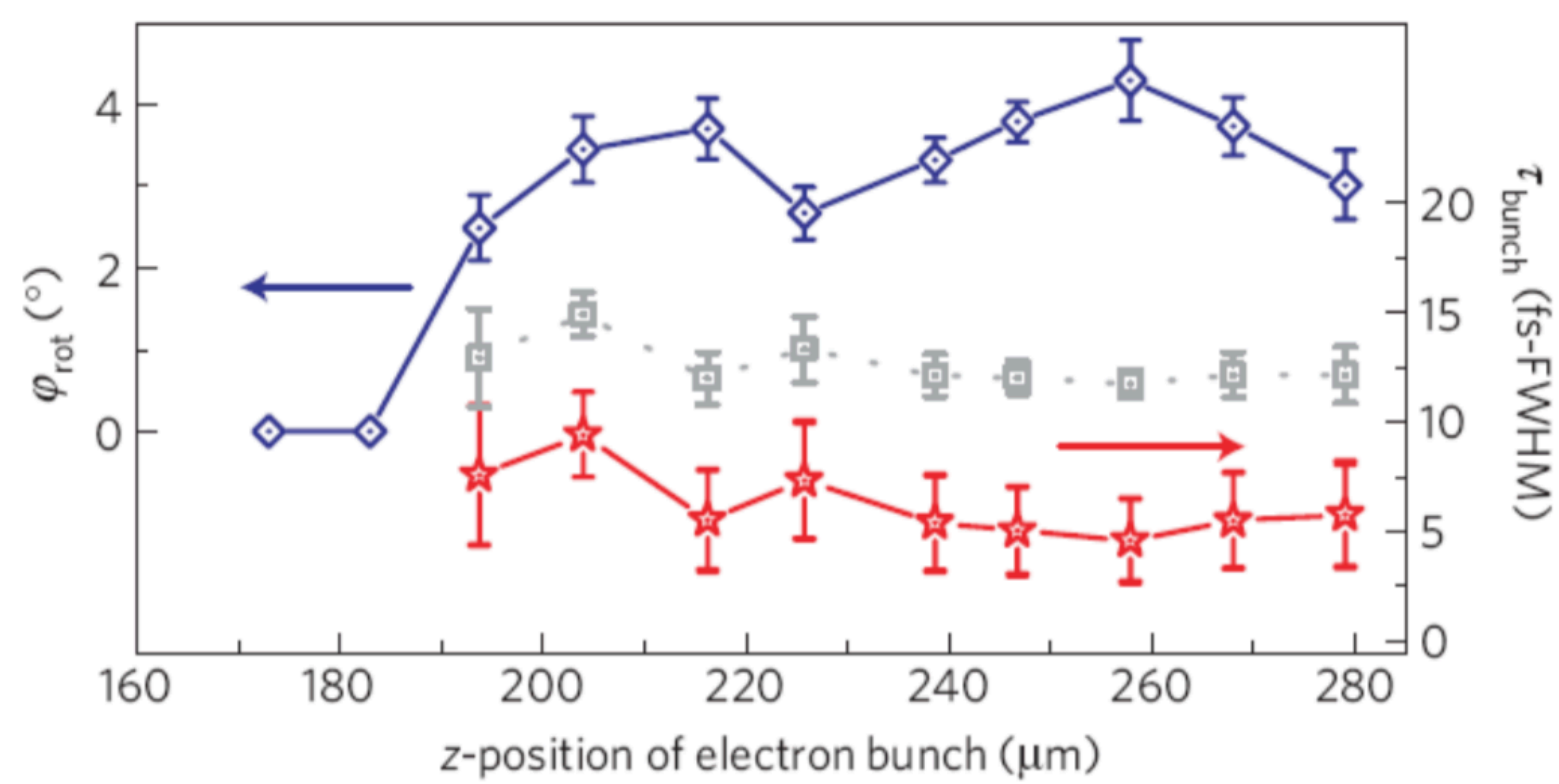
- Bunch length measurements with few cycle laser pulses



Electron bunch length: $\Delta z = 4\ \mu m$

τ_{FWHM}= (6±2) fs, **τ_{RMS}= (2.5±0.9) fs**

- Online observation of electron bunch formation in an LWFA

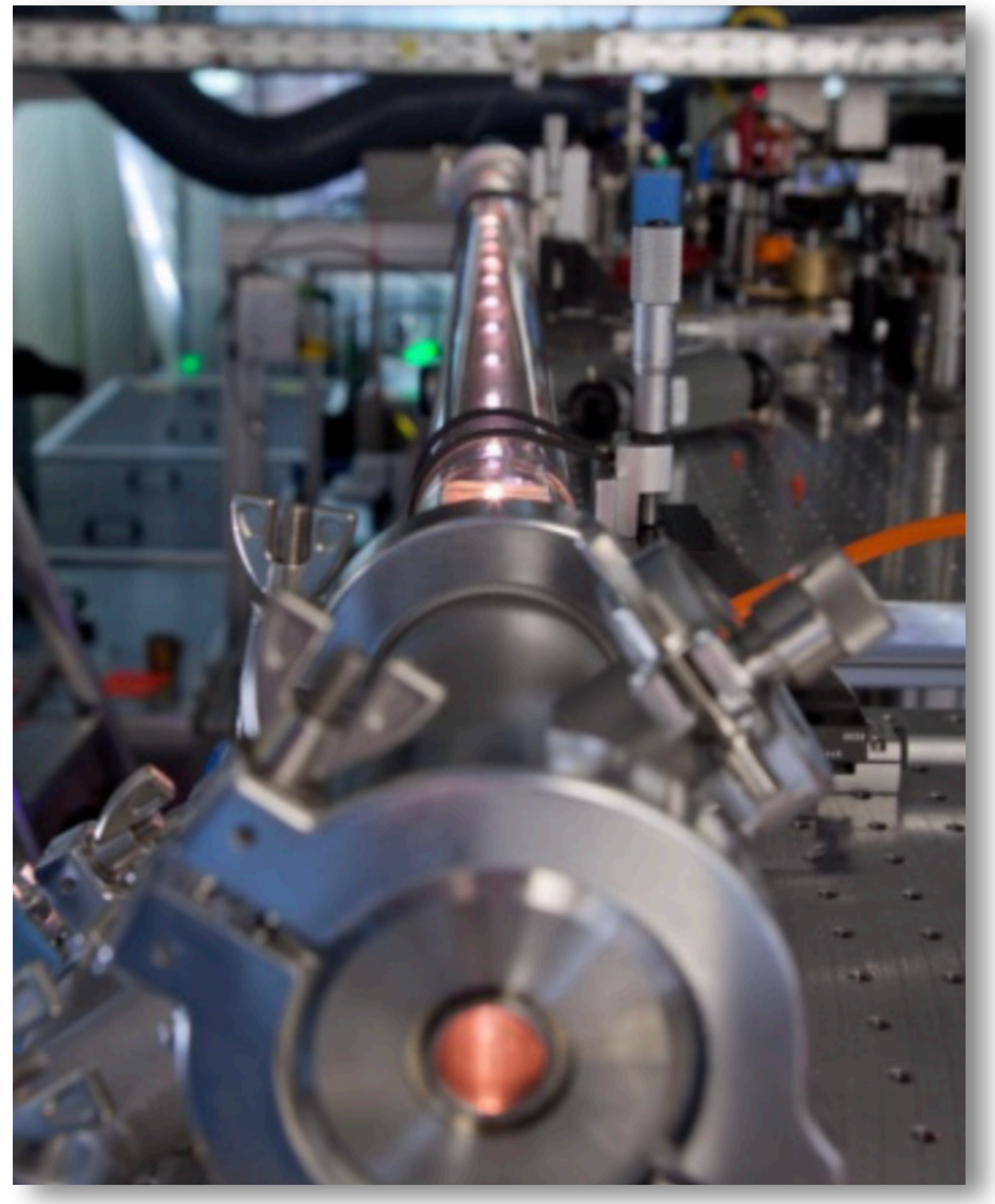


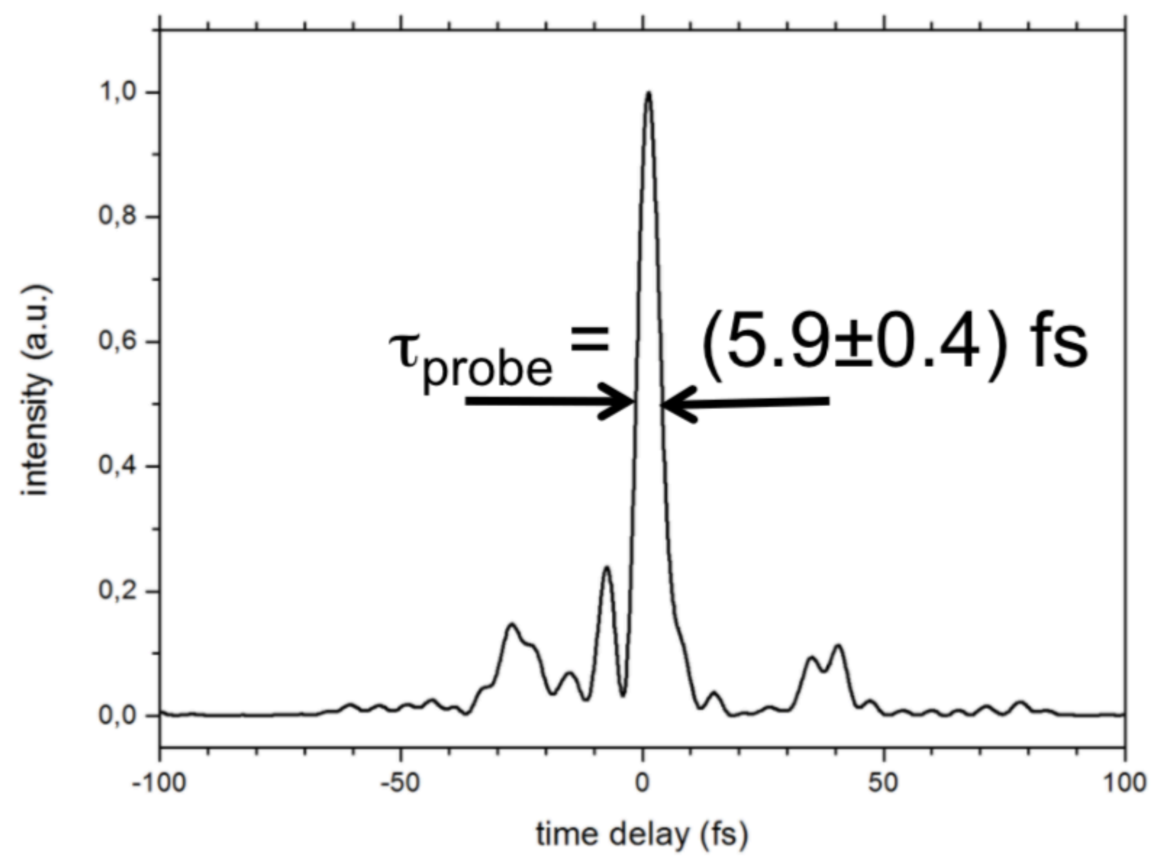
A. Buck *et al.*, Nature Physics 7, 543 (2011)

Back to Shadowgraphy with few-cycle beams

- Few-cycle probe pulse generation with hollow-core-fiber chirped mirror compressor
- 5.9 fs beam generated from 35 fs FWHM Ti:sa pulse

M. Schwab *et al.*,
Appl. Phys. Lett. 103, 191118 (2013)





Back to Shadowgraphy with few-cycle beams

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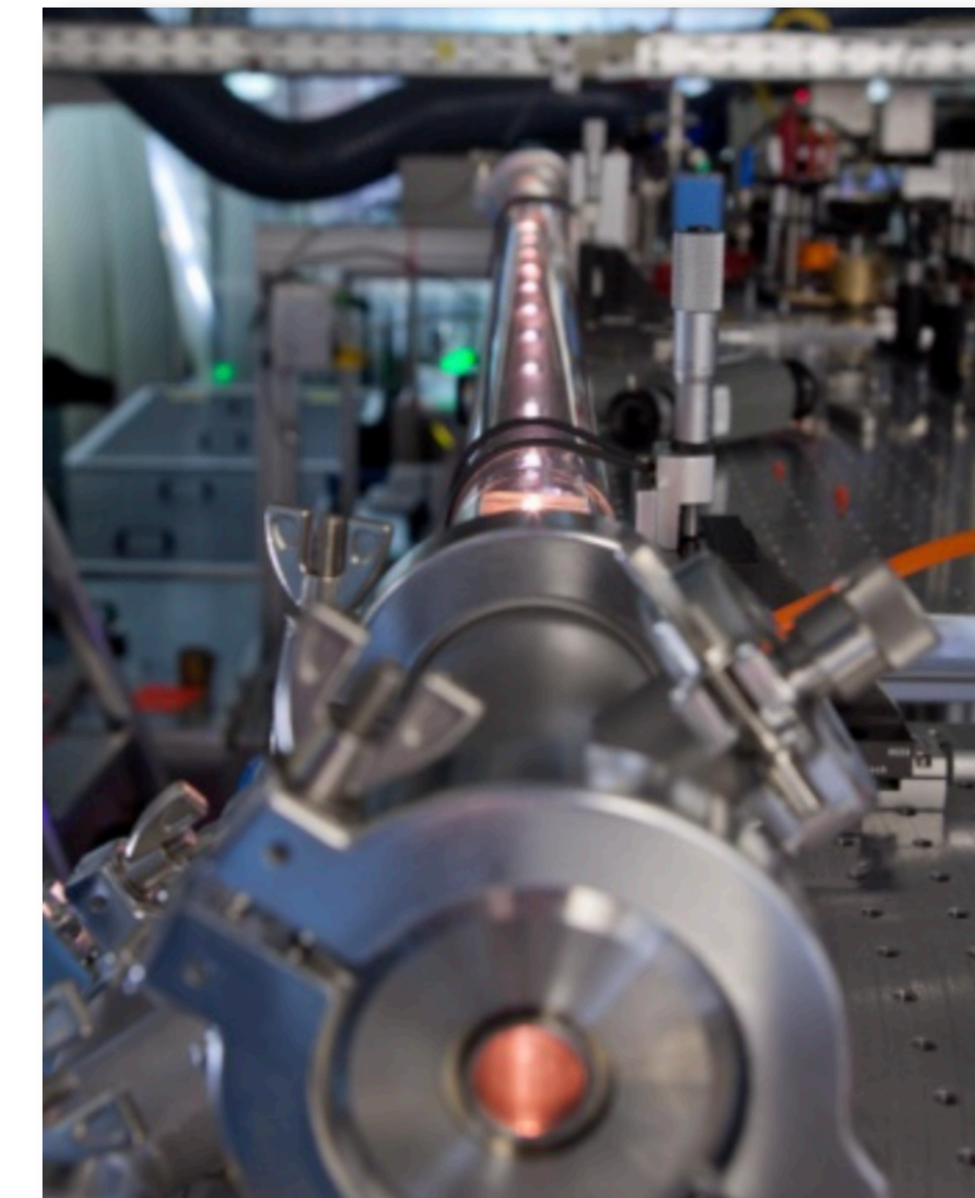
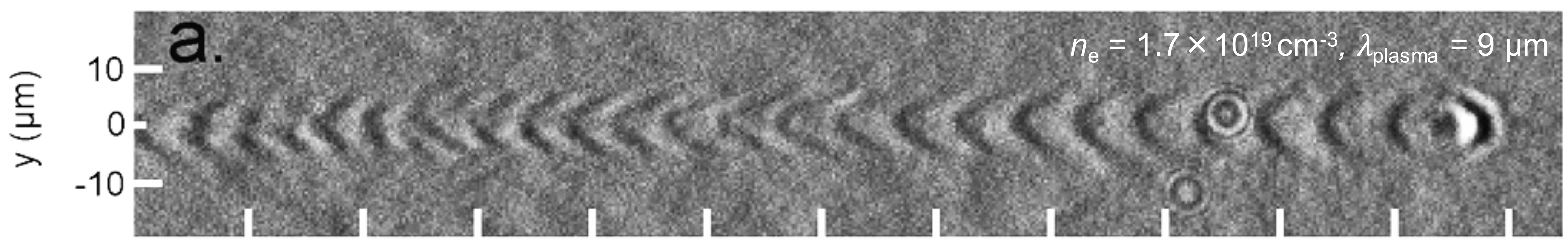
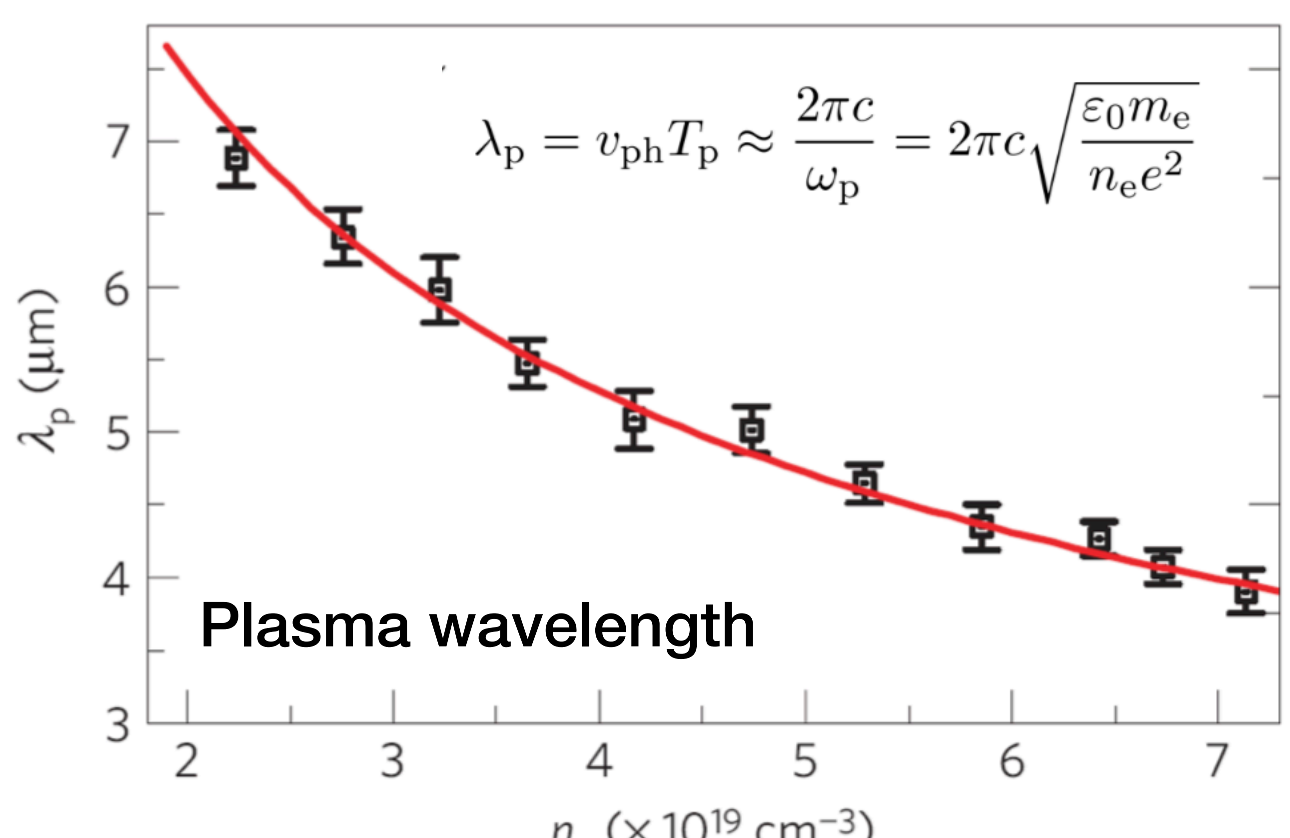
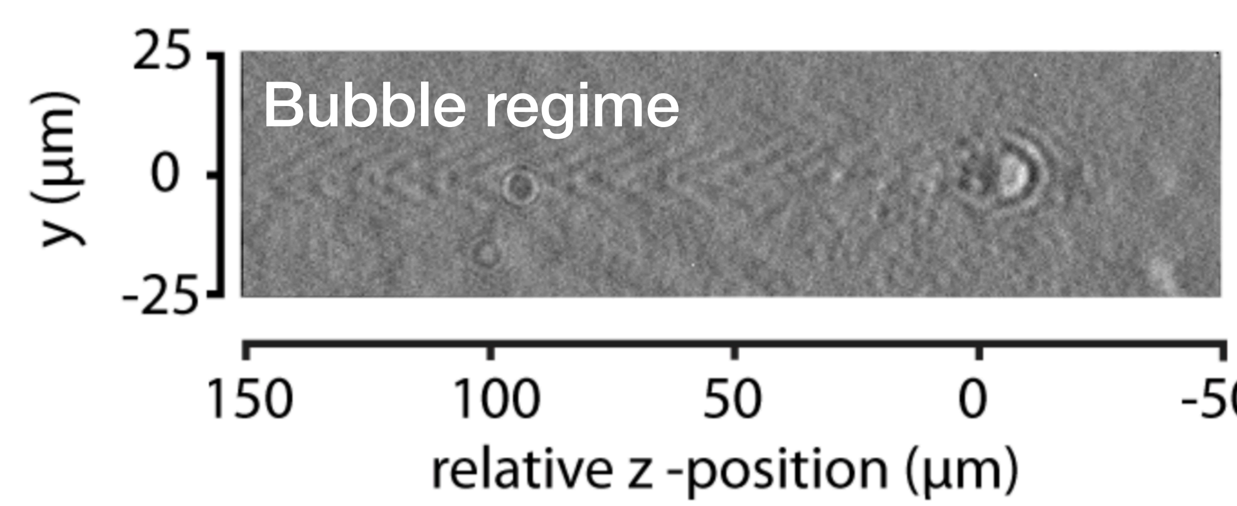


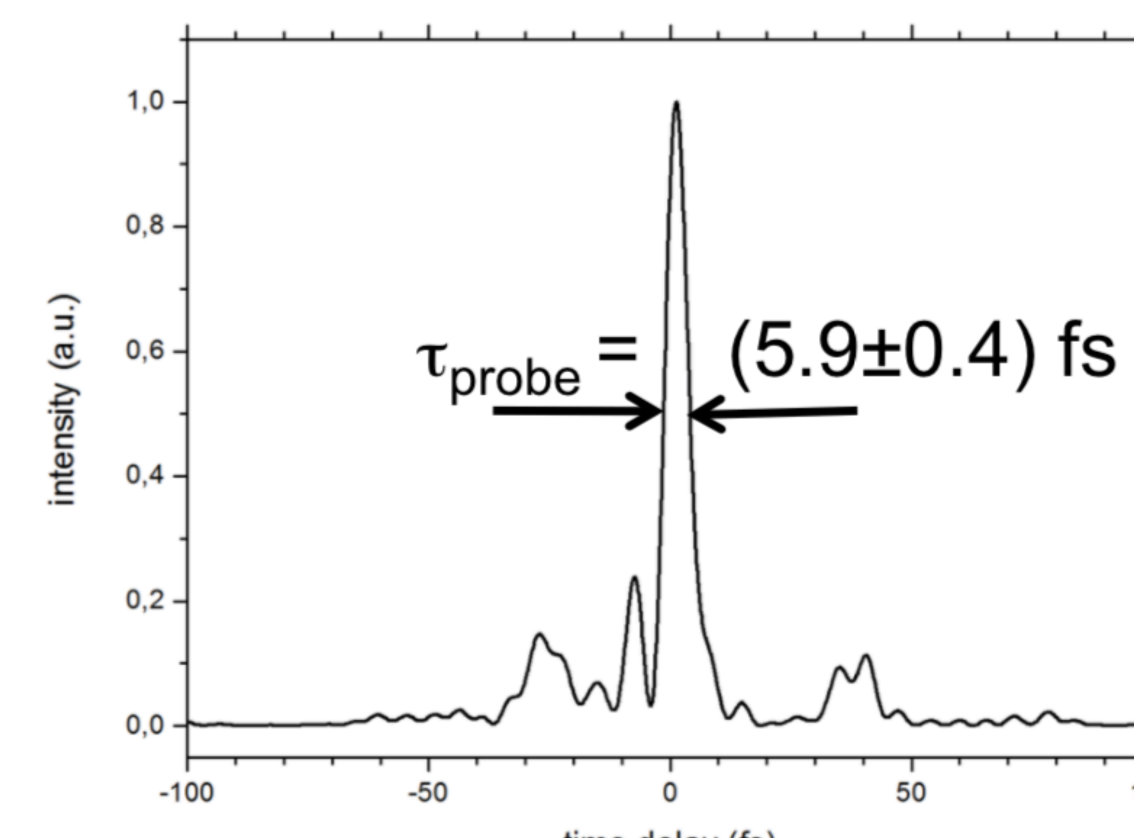
- Visualize wakefield structure



M. Schnell *et al.*, Nat. Comm. 4, 2421 (2013)

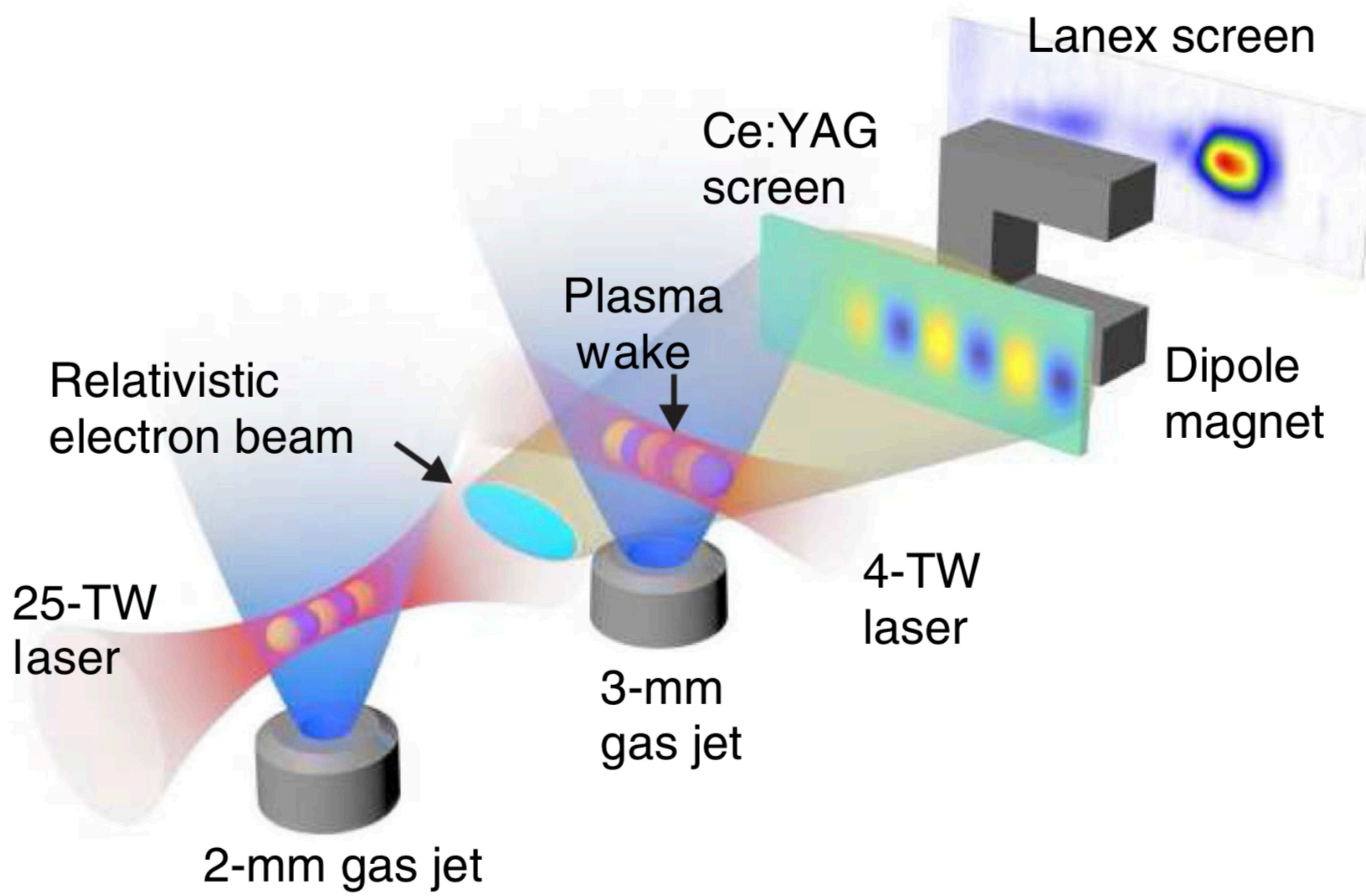


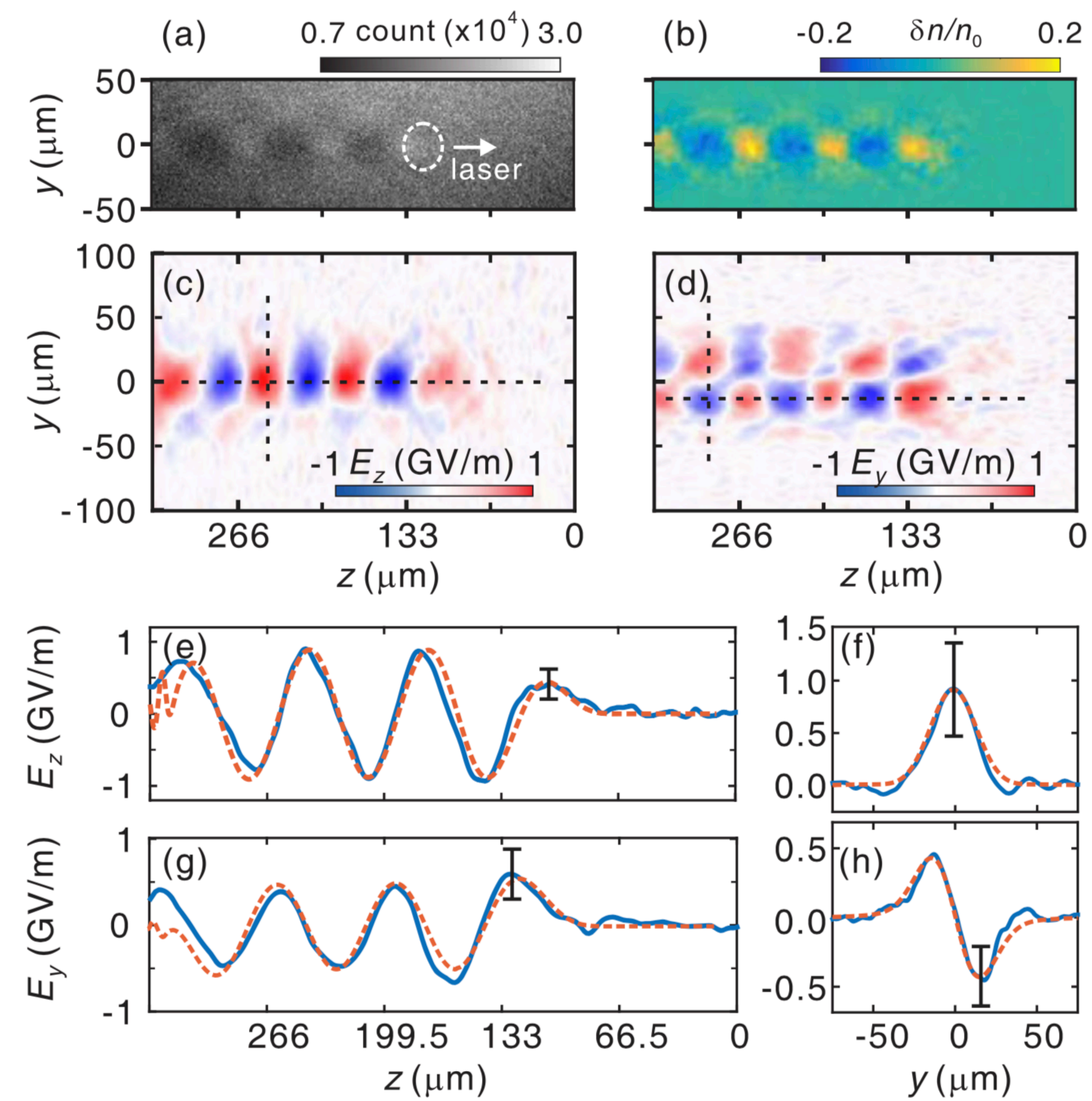




Electron beams: electric field probes

> Relativistic electron beams can act as femtosecond transverse probes to measure electric fields

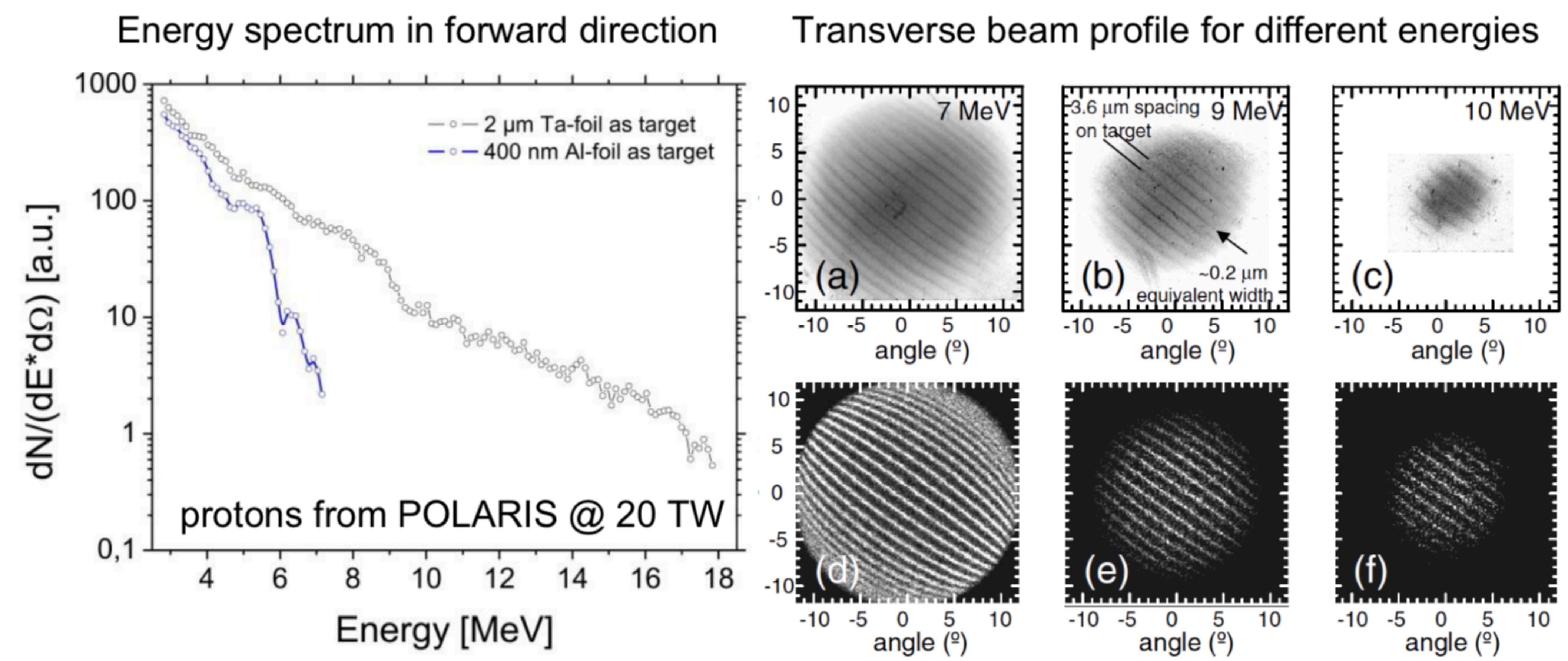




C. J. Zhang *et al.,* PRL **119**, 064801 (2017)

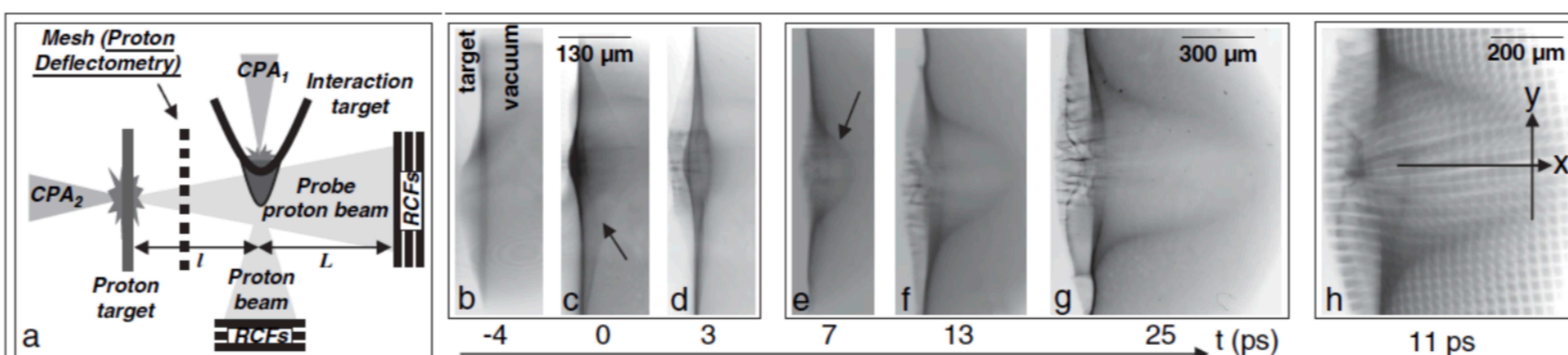
Proton beams: electric field probes

- **>** Probing with laser-accelerated proton beams
  - broad energy spectrum (up to 10s of MeV)
  - laminar flow → excellent imaging properties
  - different energies arrive at target at different times → single-shot movie



T. E. Cowan, PRL (2004)

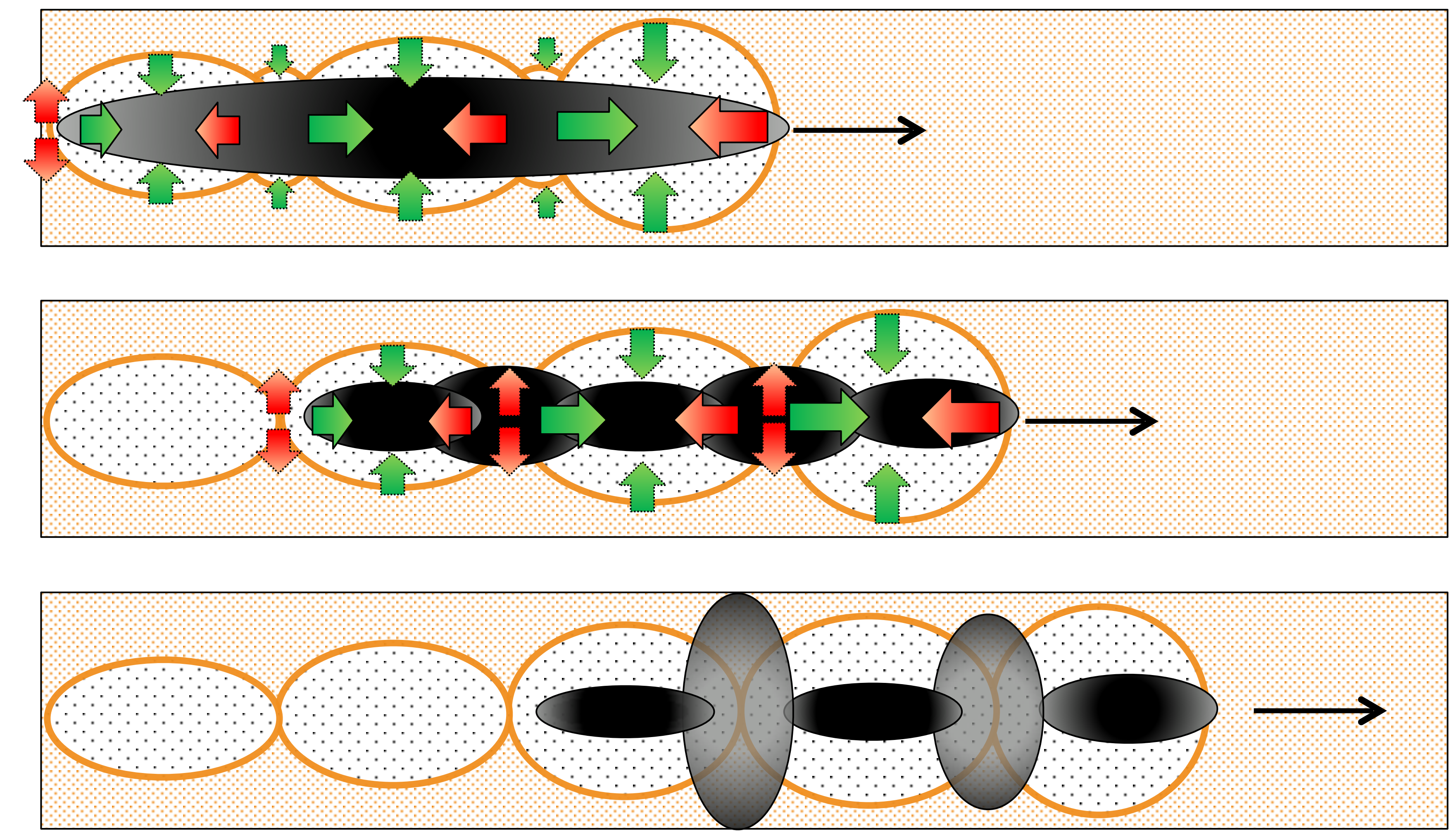
- **>** *Example:* record TNSA-sheath evolution in a single shot
  deduce sheath-field strength from mesh warping $E_{TNSA} \geq 3\times10^{10}$ V/m



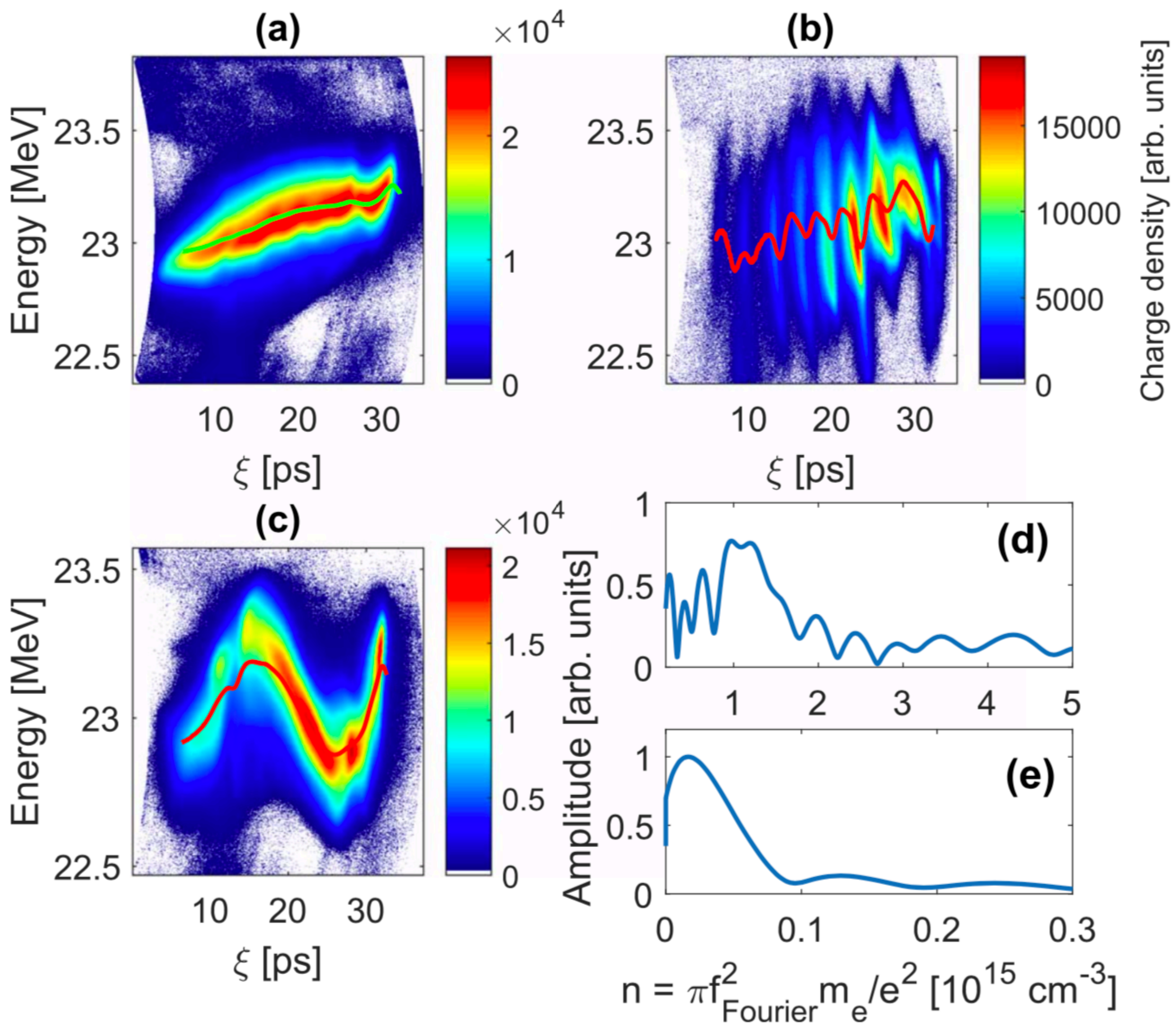
L. Romagnani, PRL (2005)

Particle beams: self-modulation instability as a probe

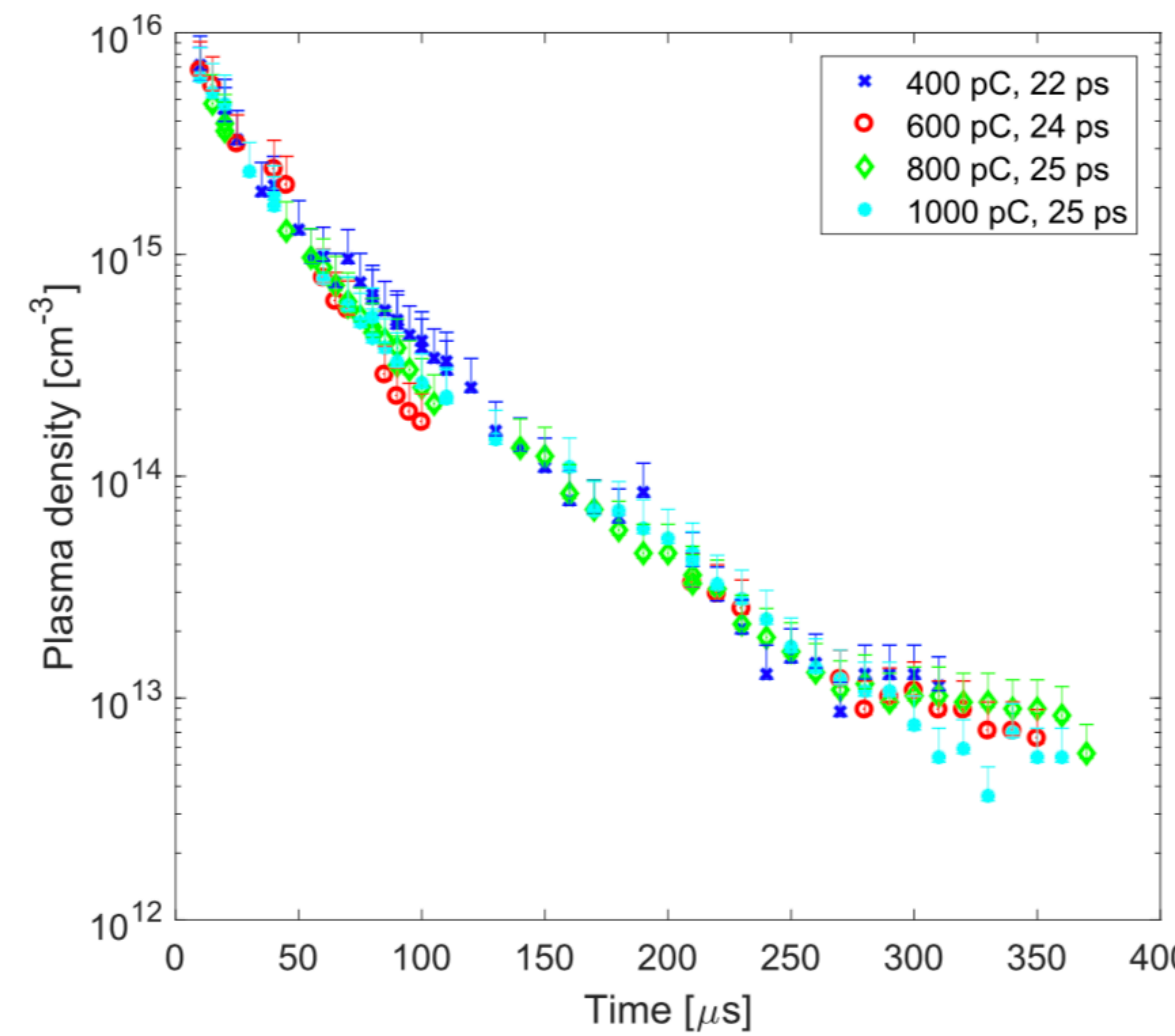
- Transverse modulation of long bunches ($L_{bunch} > \lambda_{plasma}$)
- Initiated by inhomogeneities in focusing forces
- Provides proton driver trains for AWAKE
- Length scales are plasma density dependent → diagnostic
  - Observe periodicity of longitudinal phase space
  - Dominant Fourier components reflect λ_p
  - Longitudinally integrating technique
  - Works over large range of n_e



Particle beams: self-modulation instability as a probe



G. Loisch *et al.,* Plasma Phys. Control. Fusion **61,** 045012 (2019)

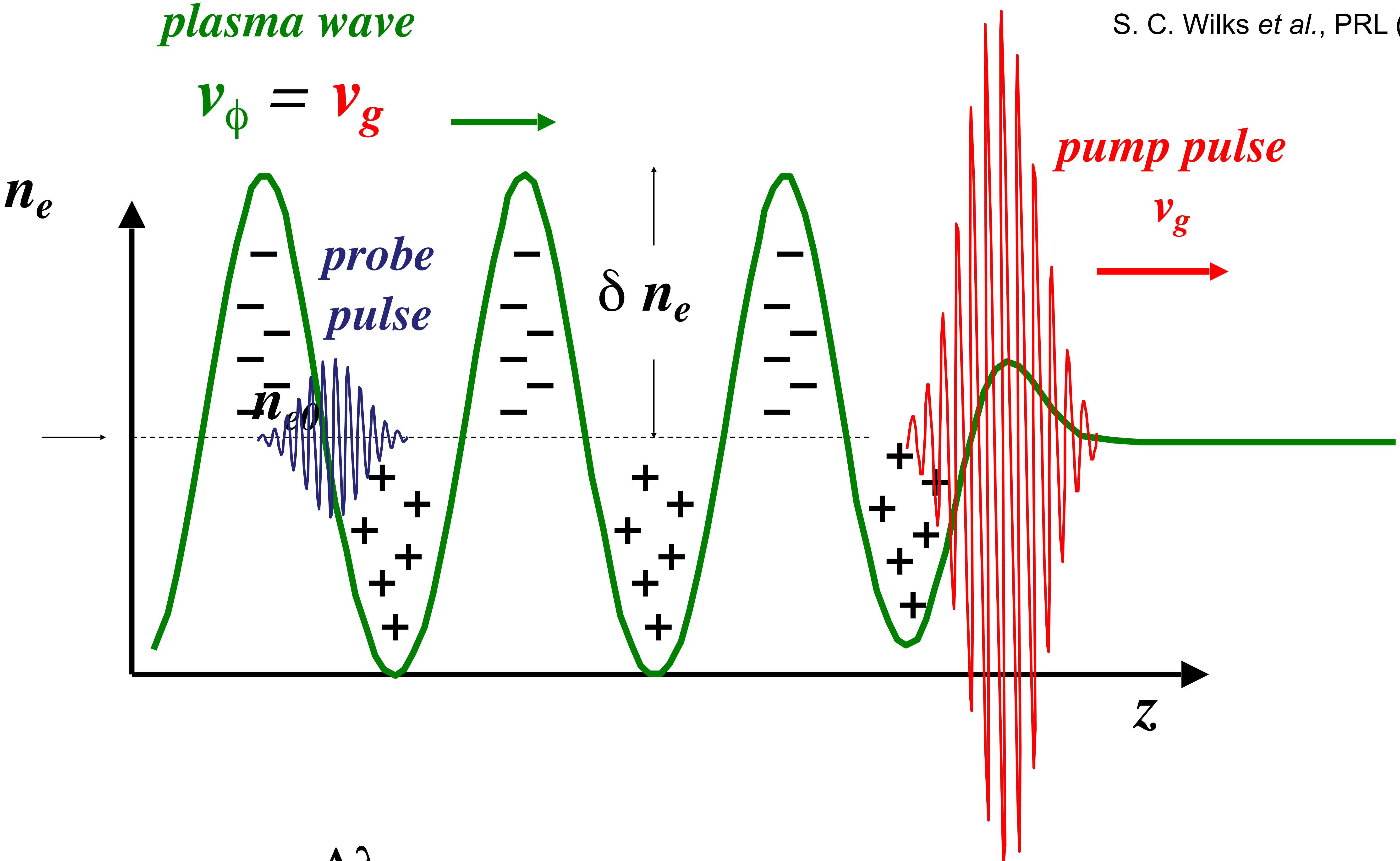


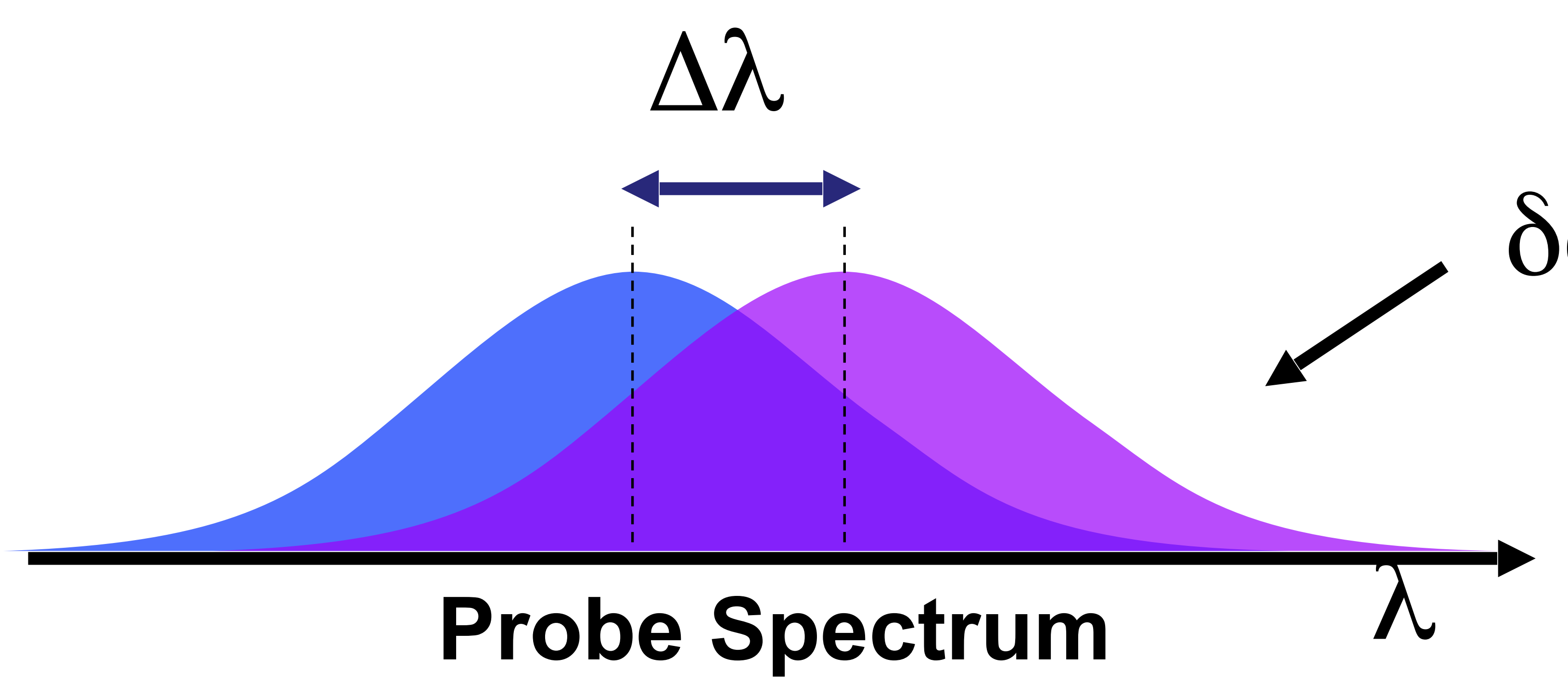
Frequency Domain Holography

- Thanks to Nicholas Matlis (DESY) for providing the following slides
- For detailed info on FDH and its variants TEX and TESS, please refer to
  - FDH: N. H. Matlis *et al.,* Nature Physics 2, 749 (2006)
  - TEX: N. H. Matlis *et al.*, JOSA B 28, 23 (2011)
  - TESS: N. H. Matlis et al., Optics Letters 41, 5503 (2016)

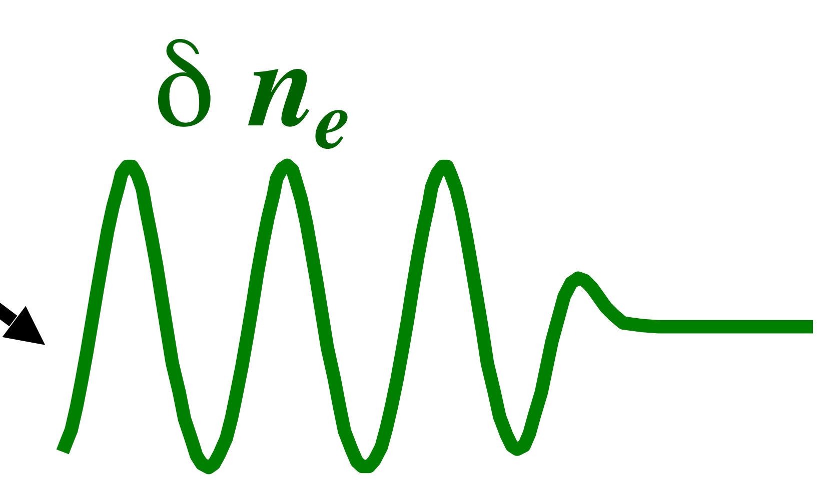
Photon Acceleration

S. C. Wilks *et al.*, PRL (1989)





$\delta\omega = d\phi/d\zeta = 2\pi\ (L/\lambda)\ d\eta/d\zeta$



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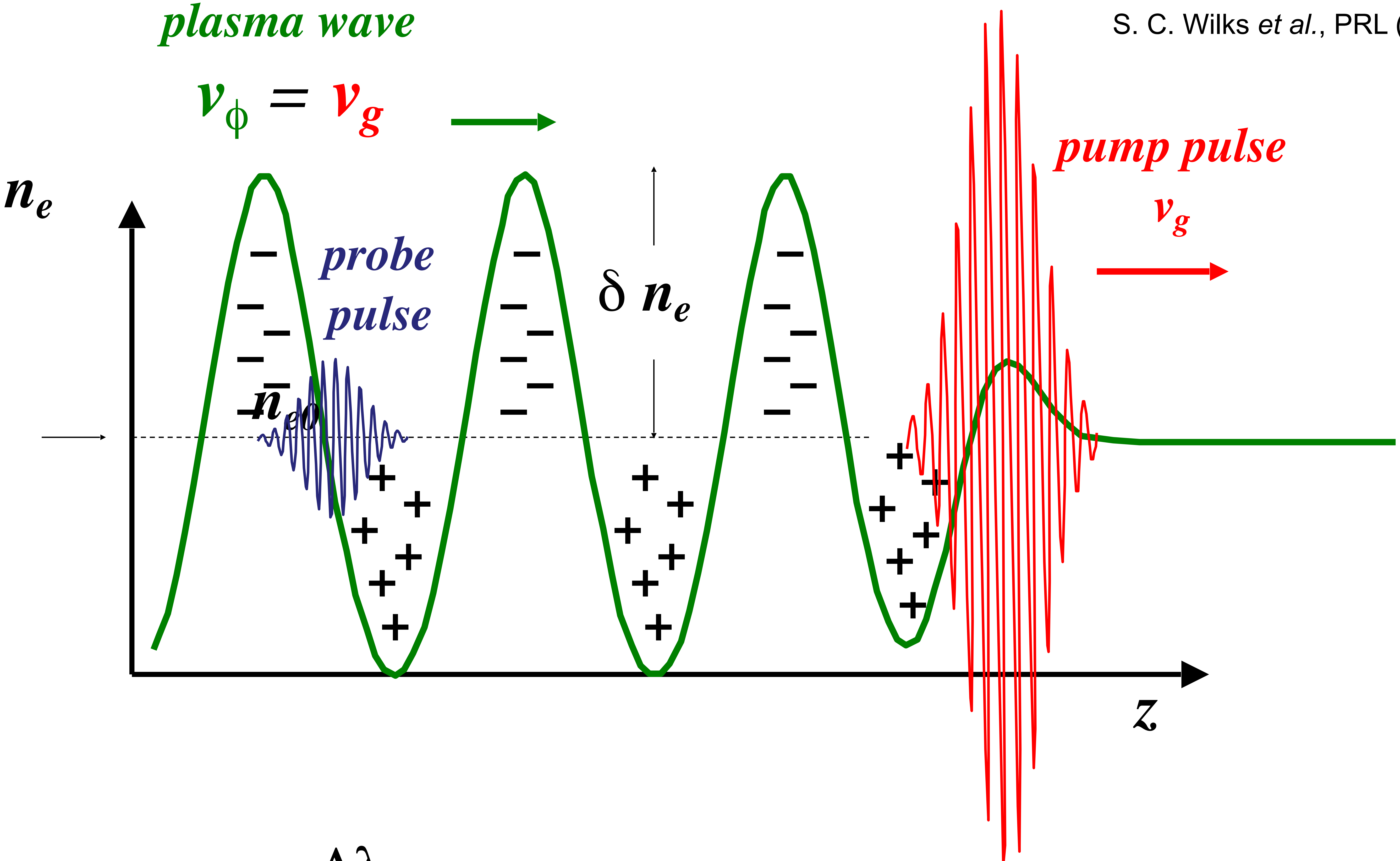
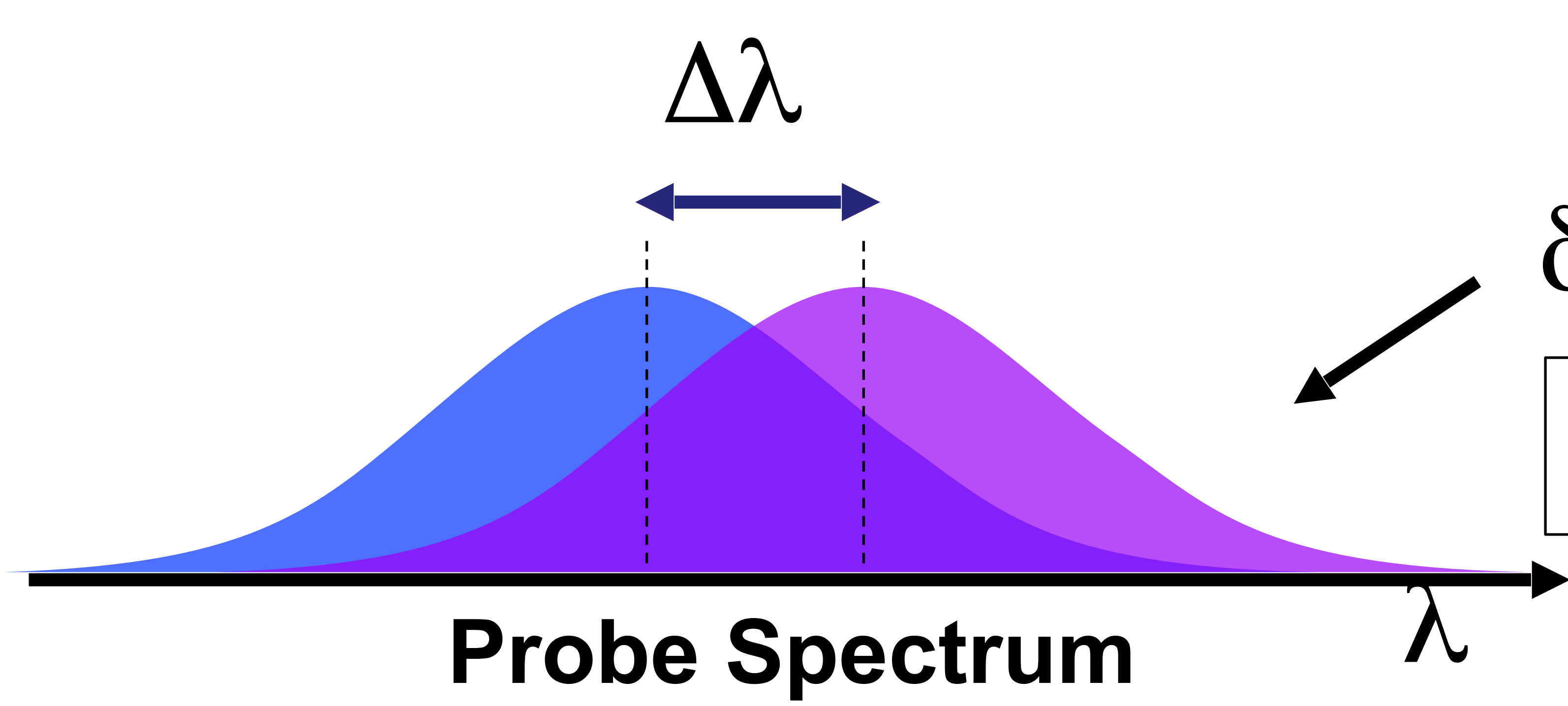
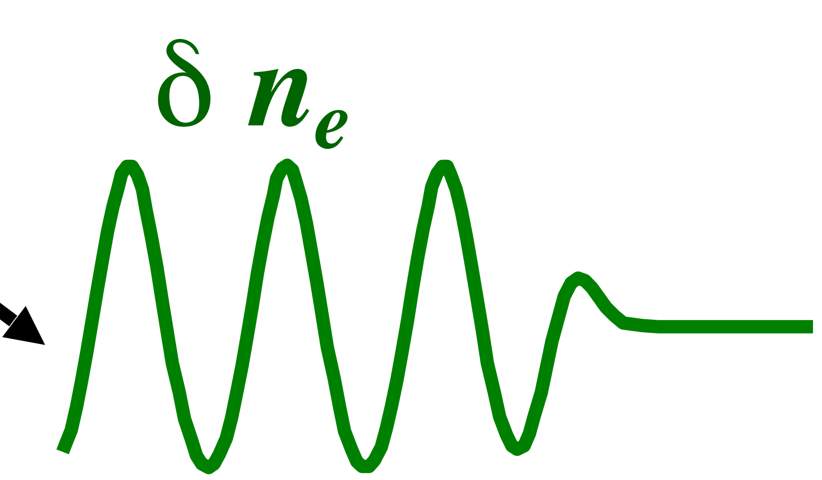




$\delta\omega = d\phi/d\zeta = 2\pi\,(L/\lambda)\,d\eta/d\zeta$

Not very sensitive



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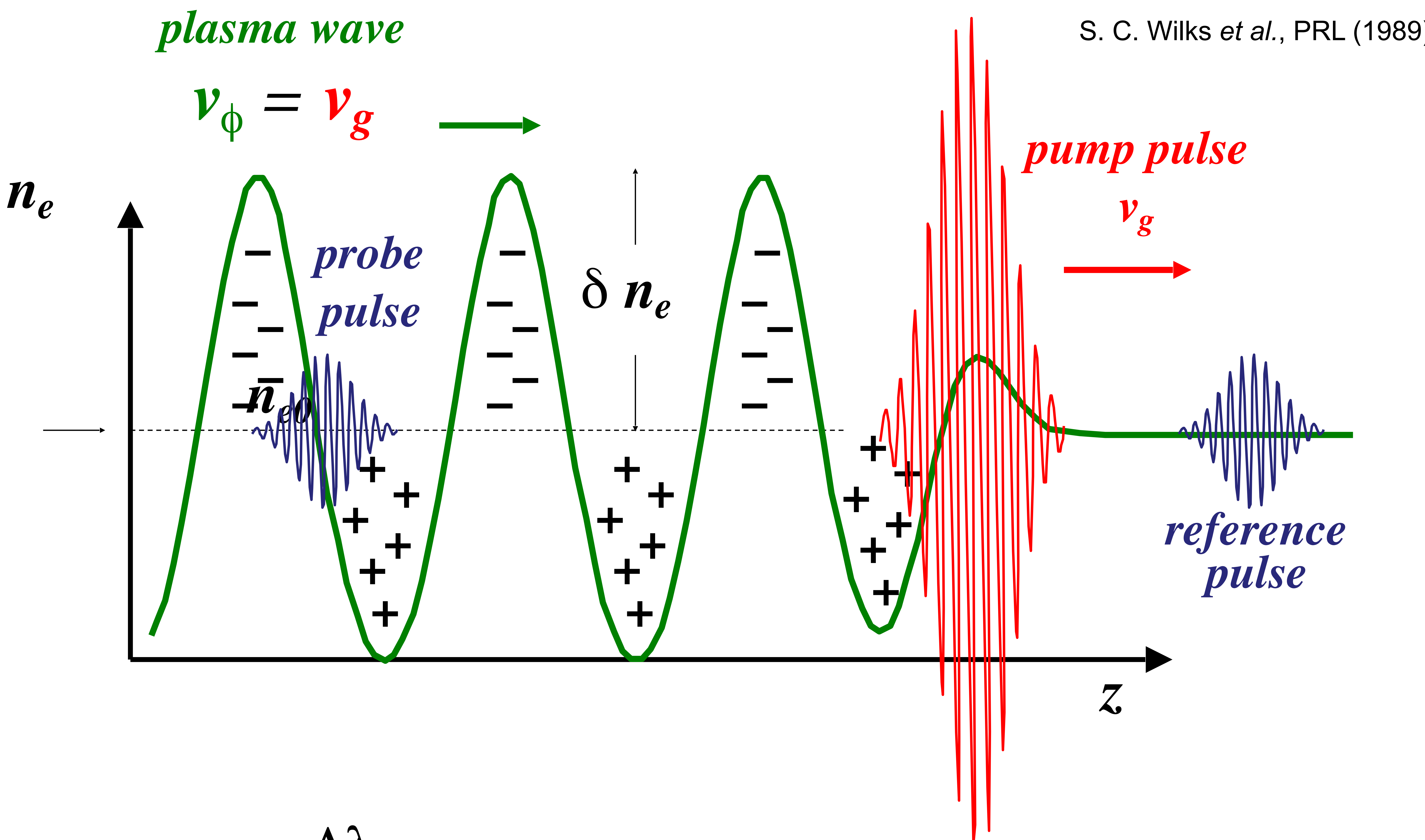
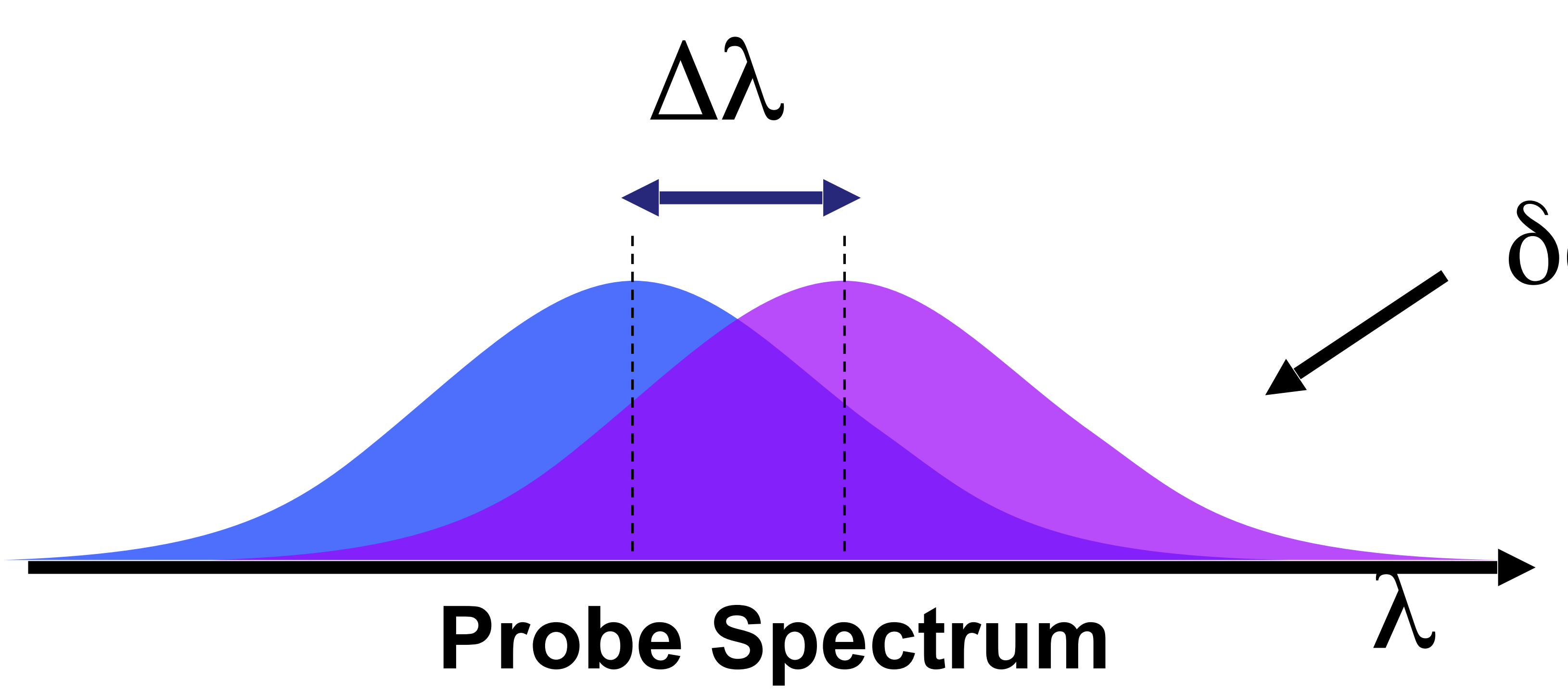


How do pulses that don't overlap interfere?



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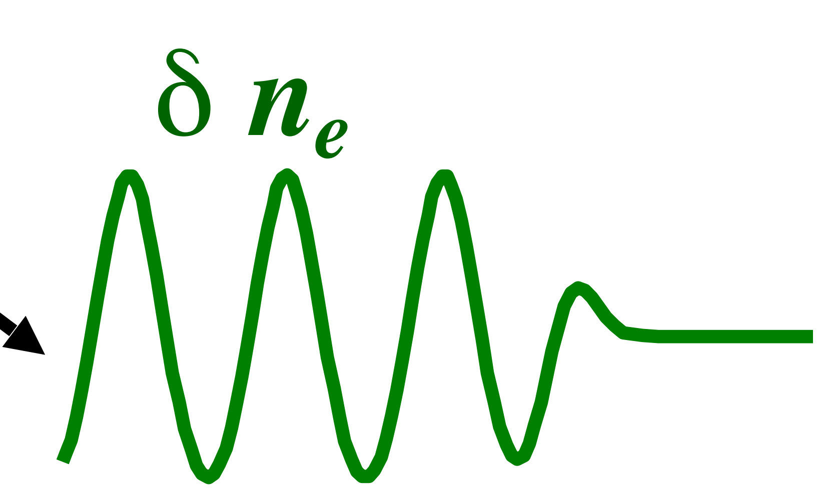
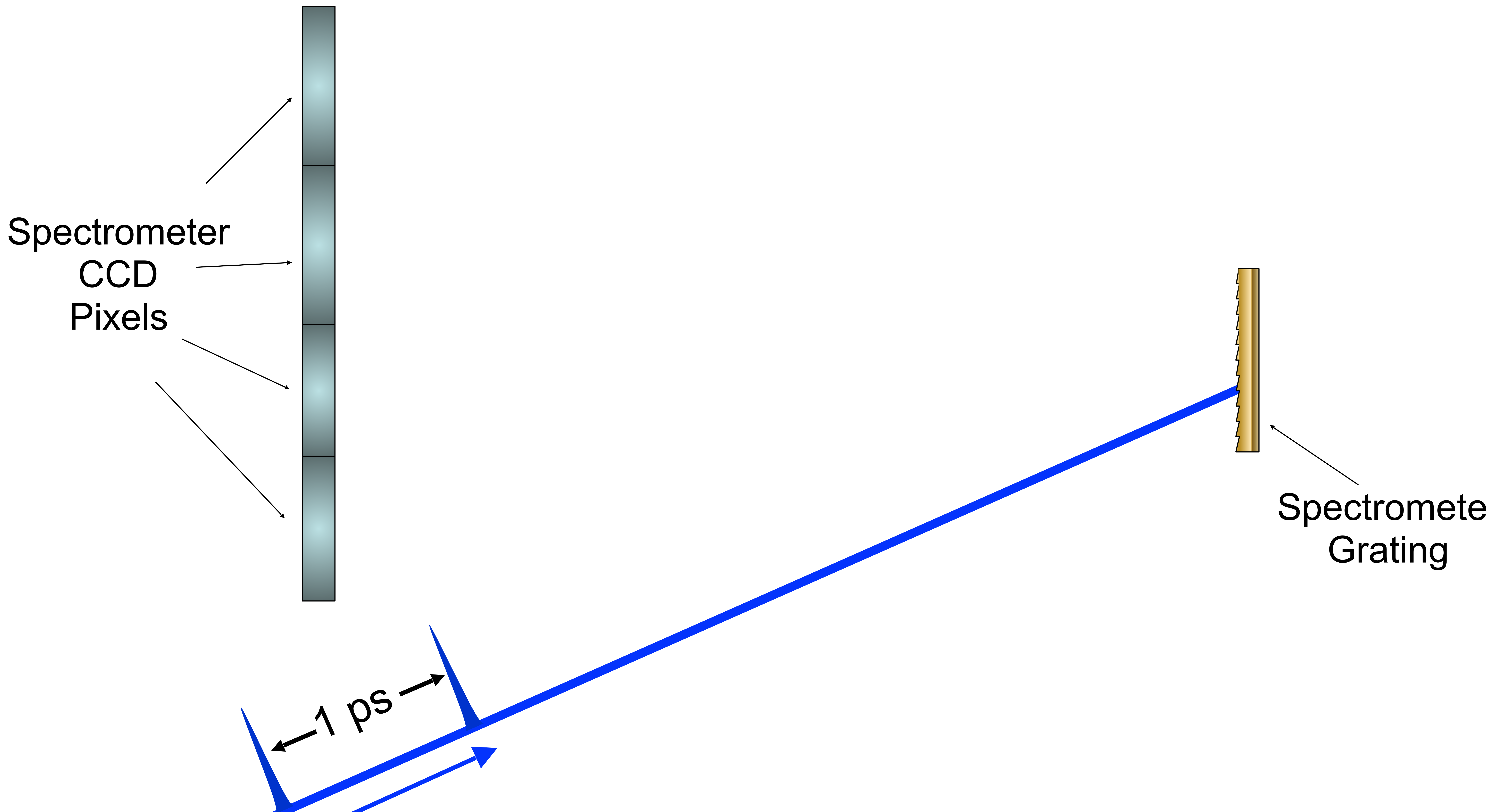


FDI: Temporal Overlap in Spectrometer



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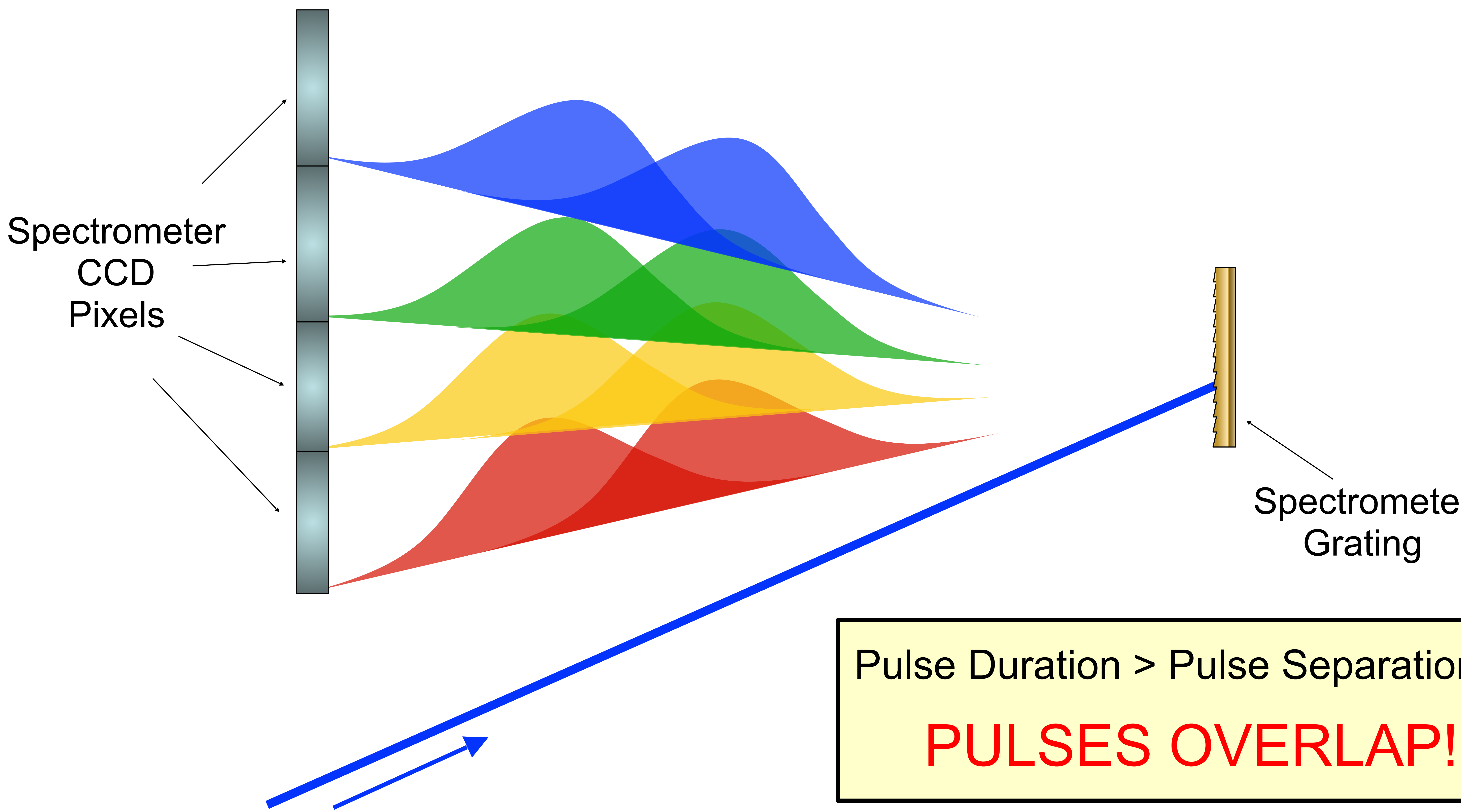
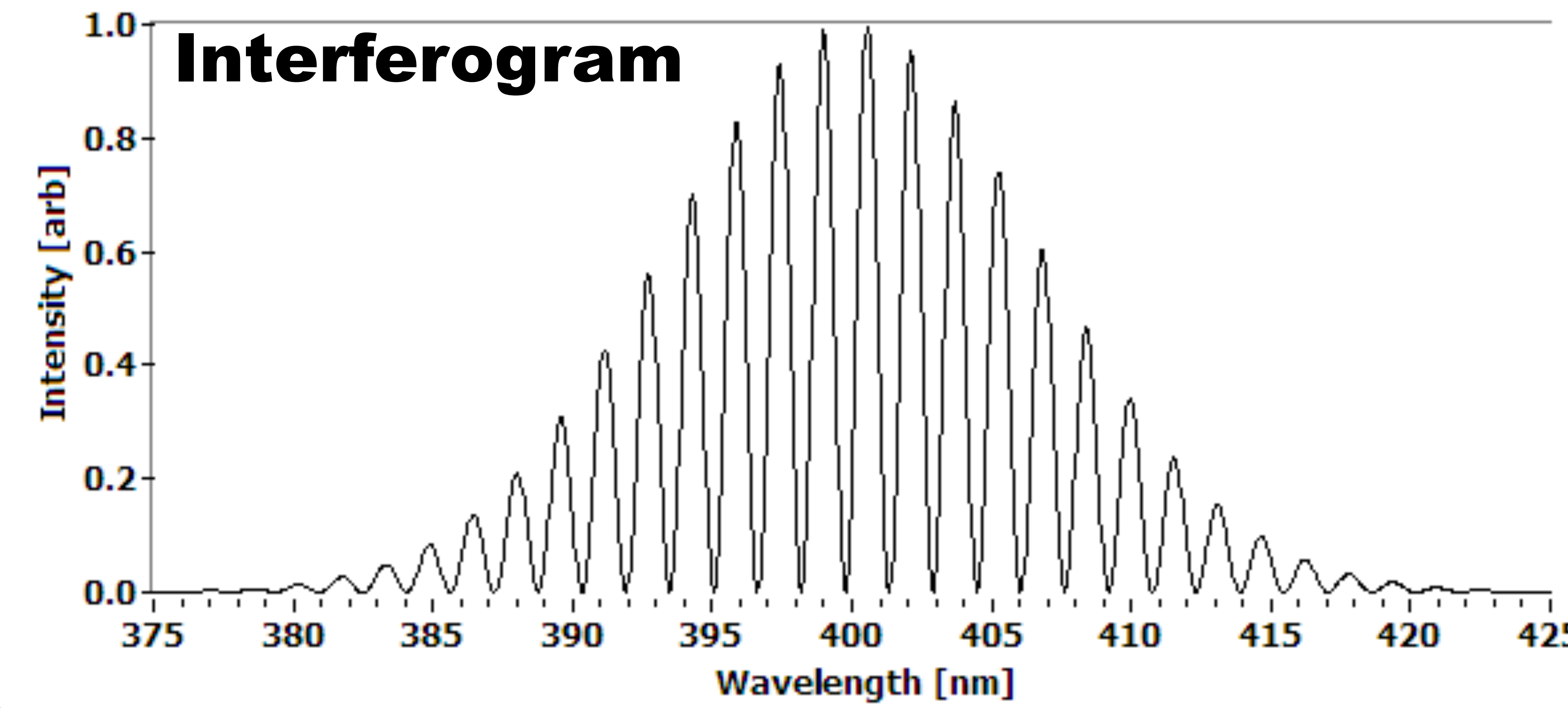
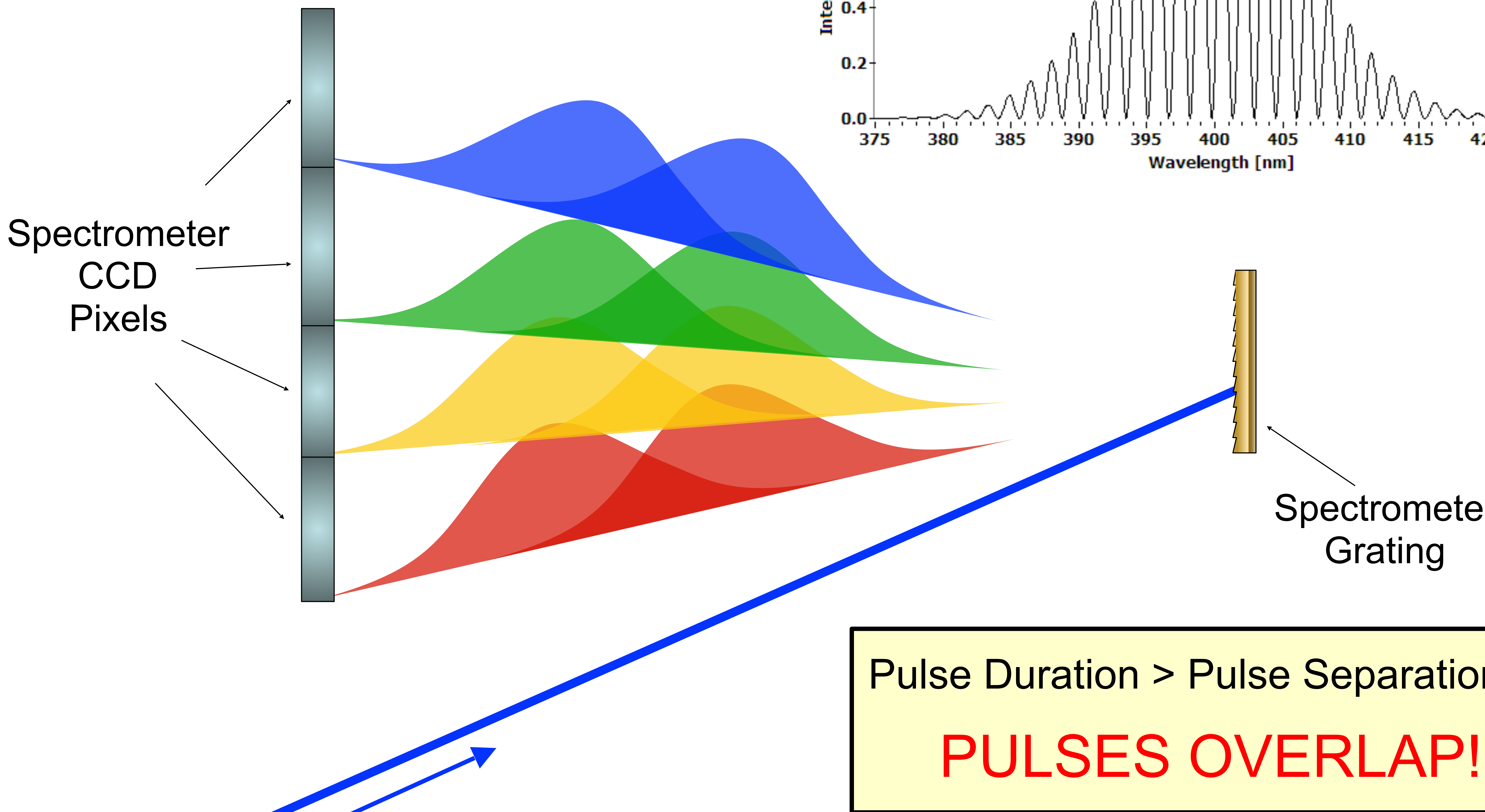


Pulse Duration > Pulse Separation

PULSES OVERLAP!

FDI: Temporal Overlap in Spectrometer



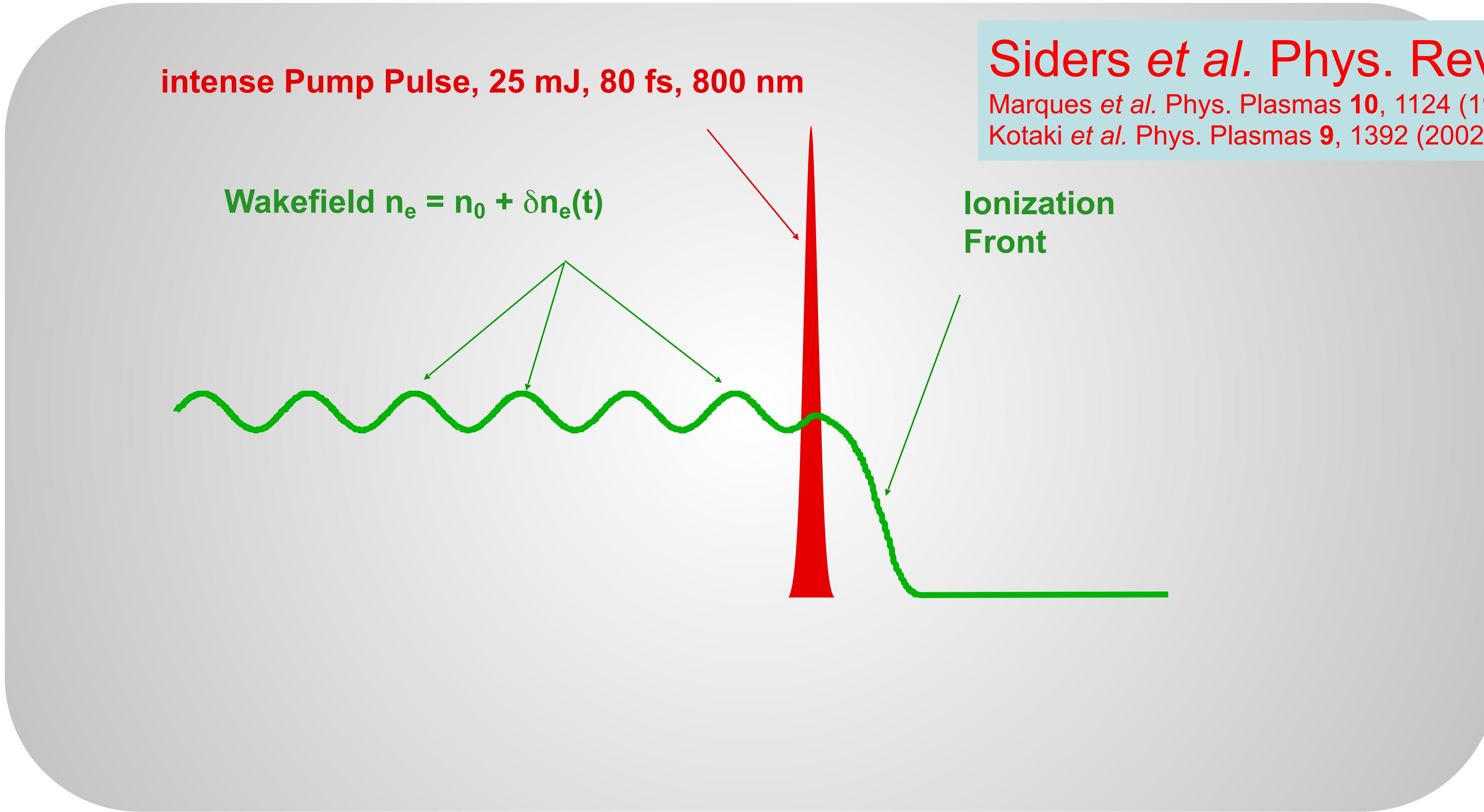


Pulse Duration > Pulse Separation

PULSES OVERLAP!

“Frequency Domain Interferometry” probes Wakefields one point at a time

Siders *et al.* Phys. Rev. Lett. **76**, 3570 (1996)
Marques *et al.* Phys. Plasmas **10**, 1124 (1998)
Kotaki *et al.* Phys. Plasmas **9**, 1392 (2002)



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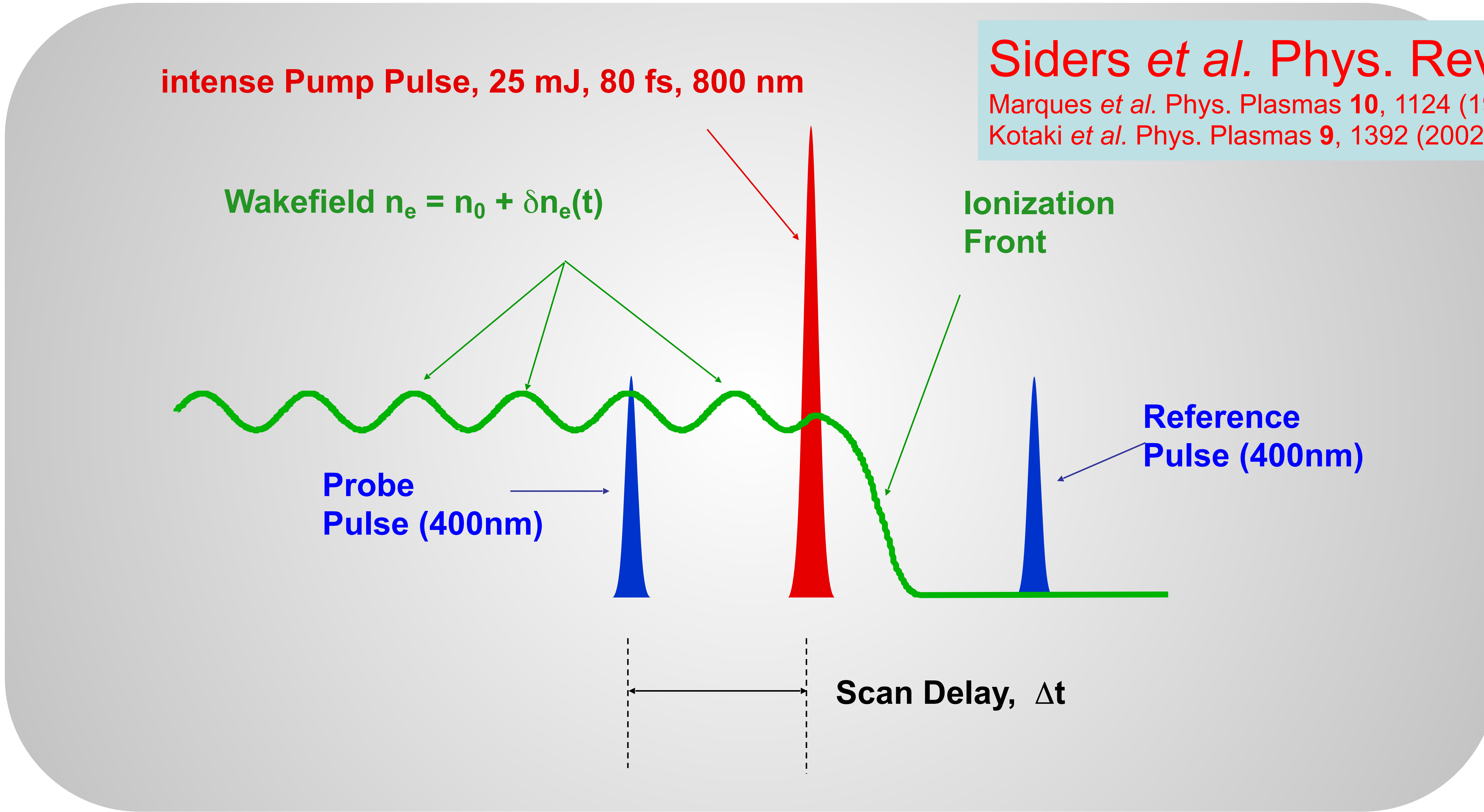

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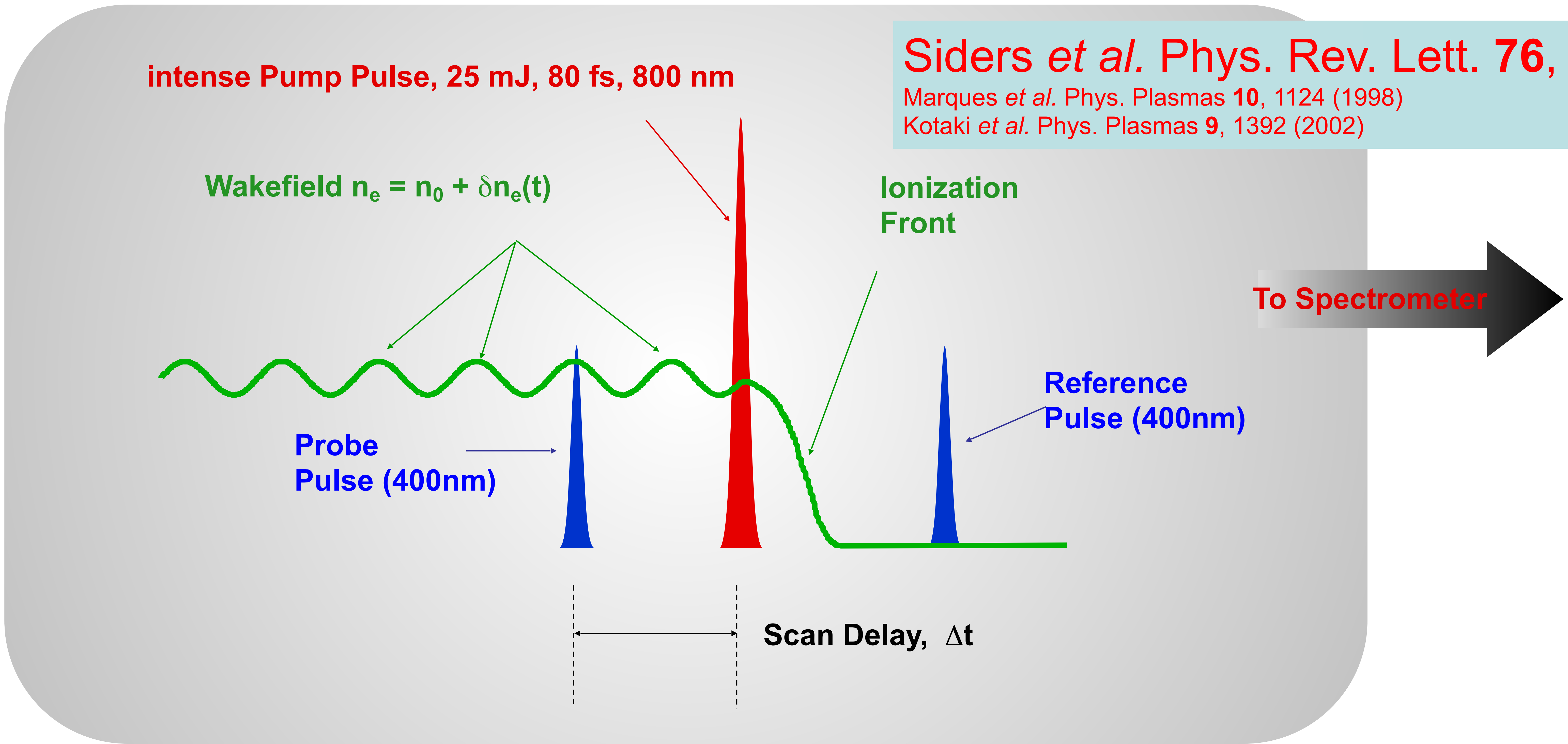

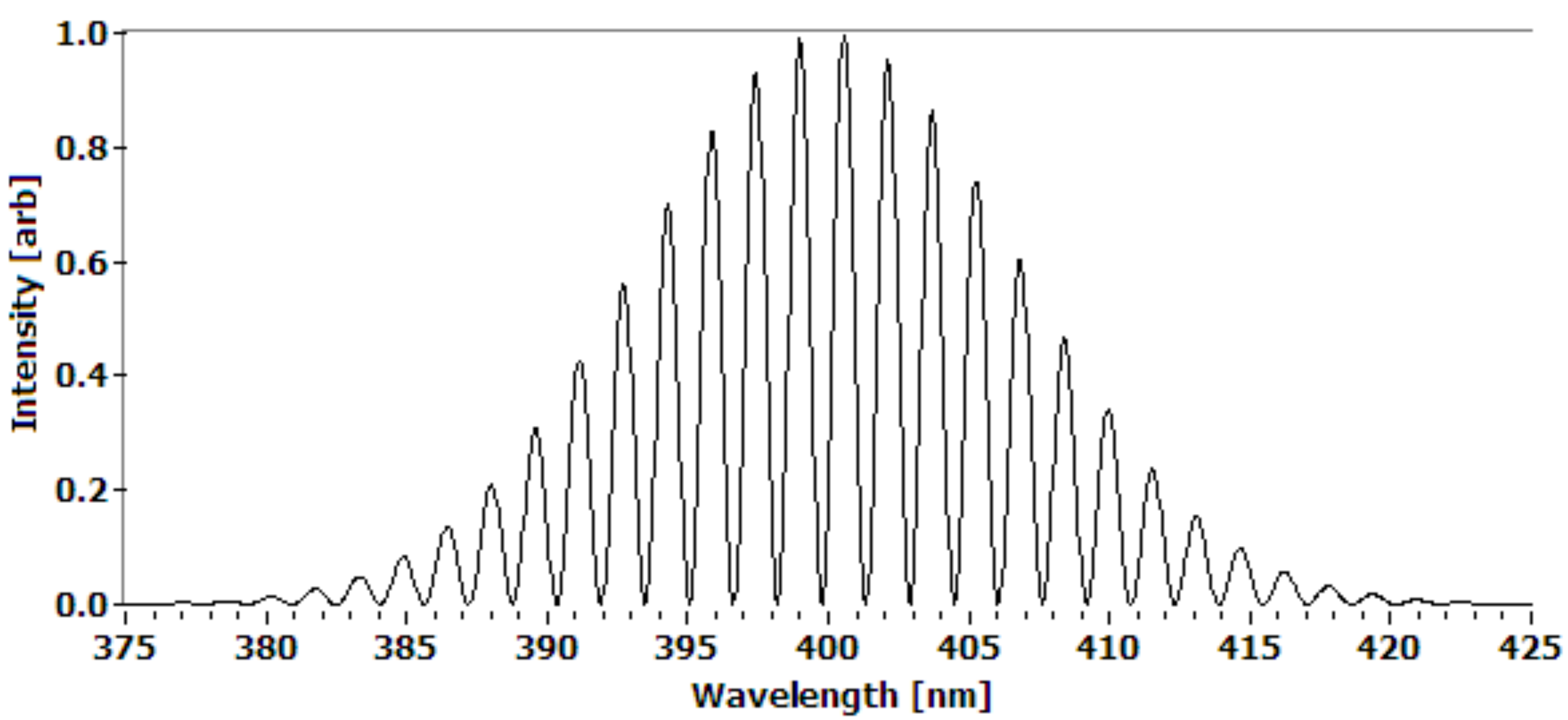

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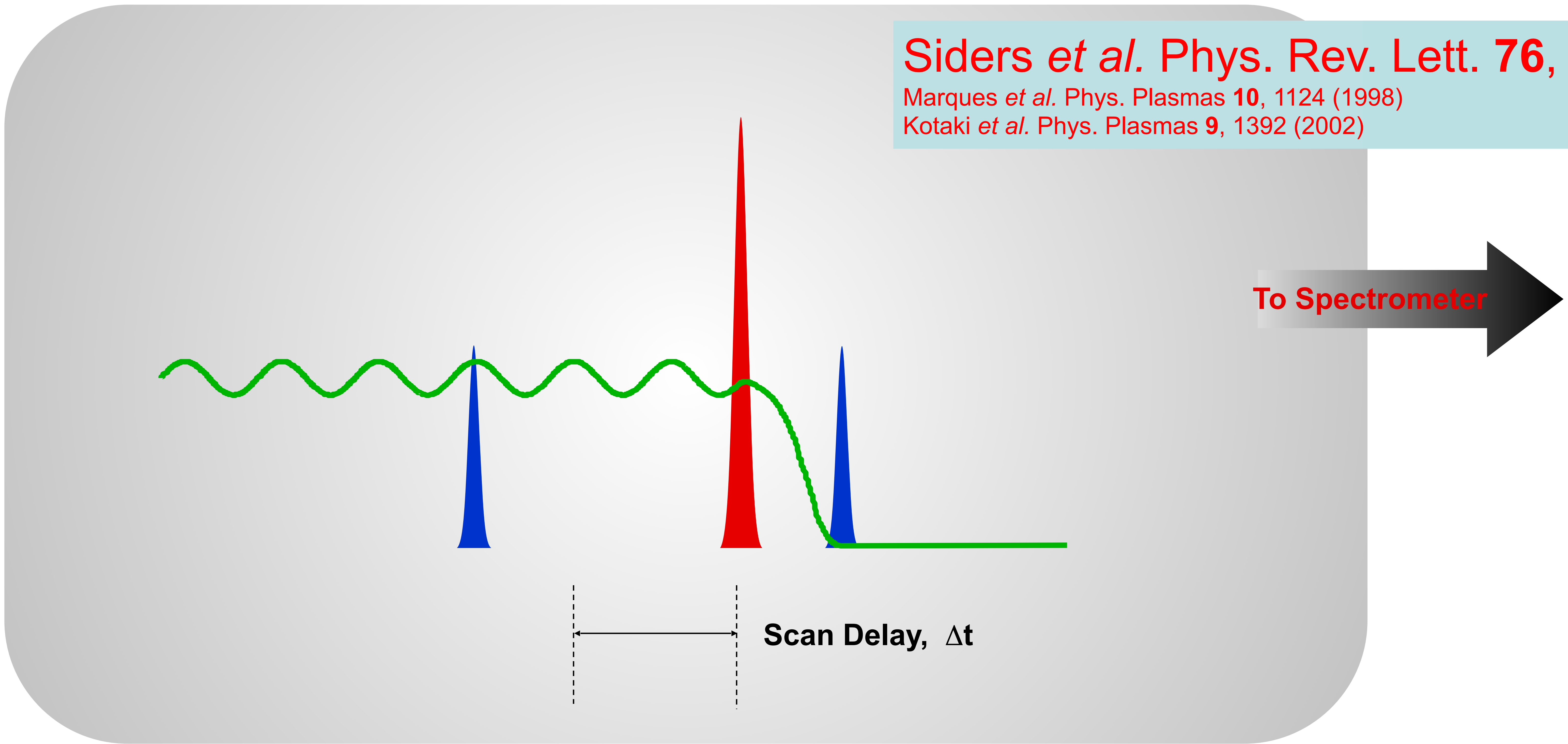

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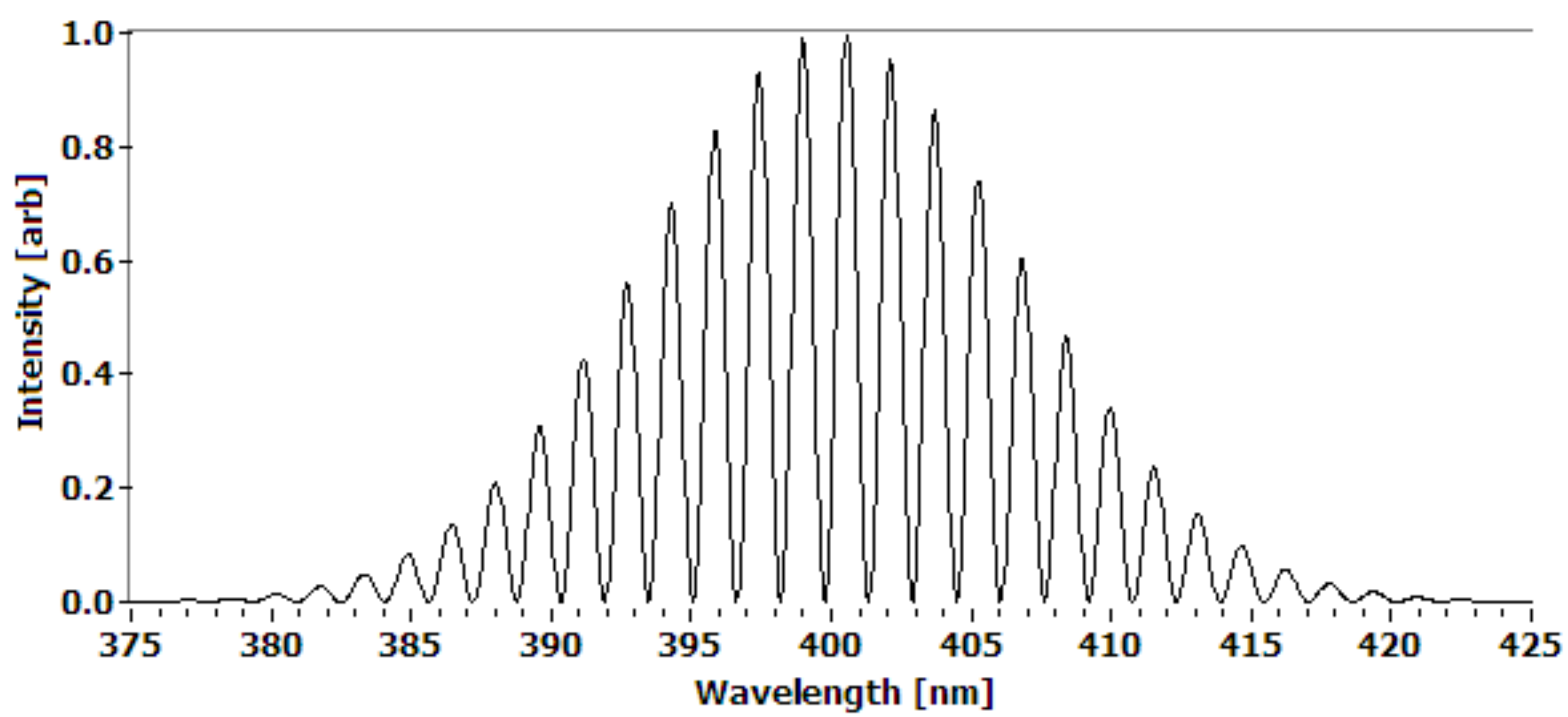

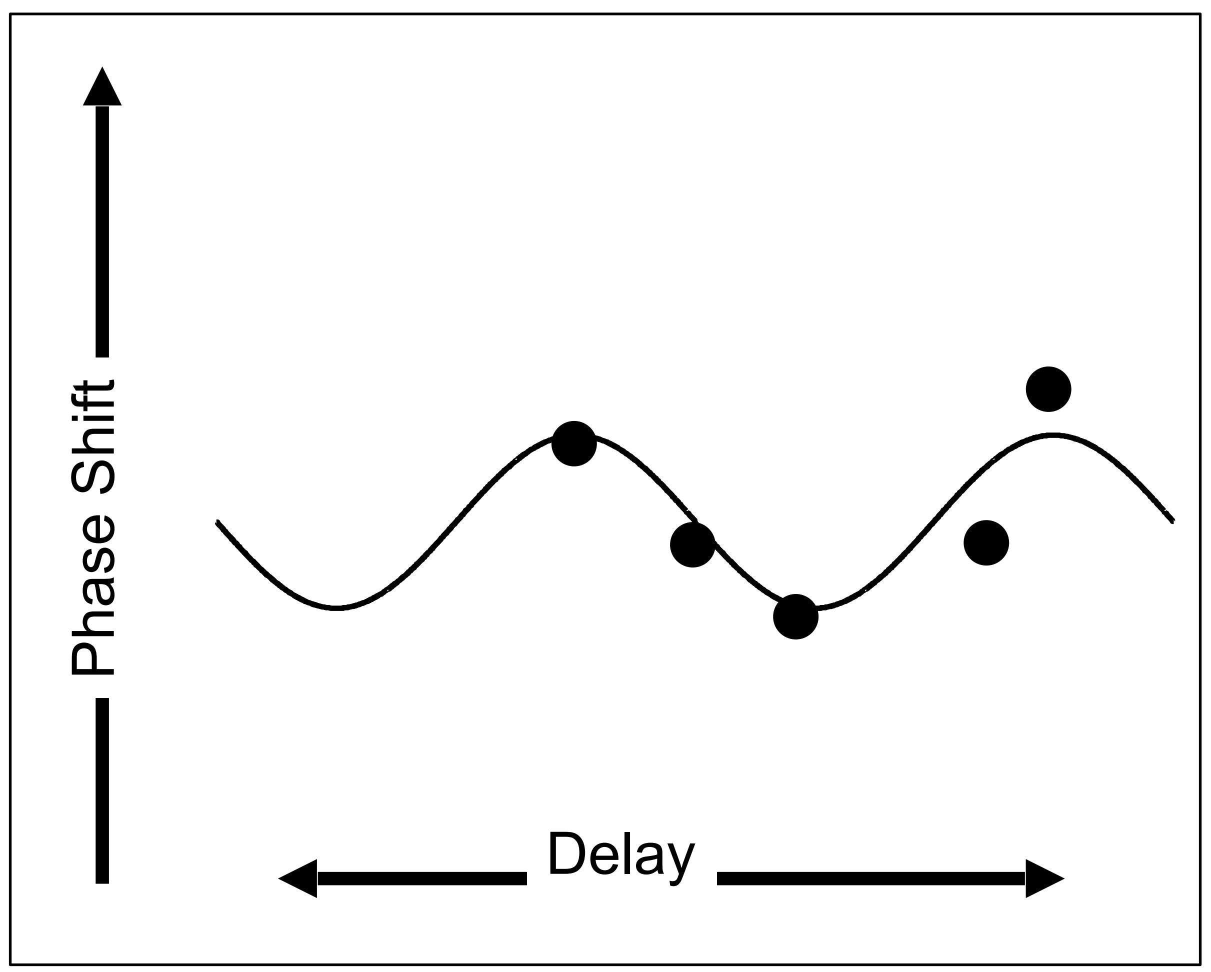

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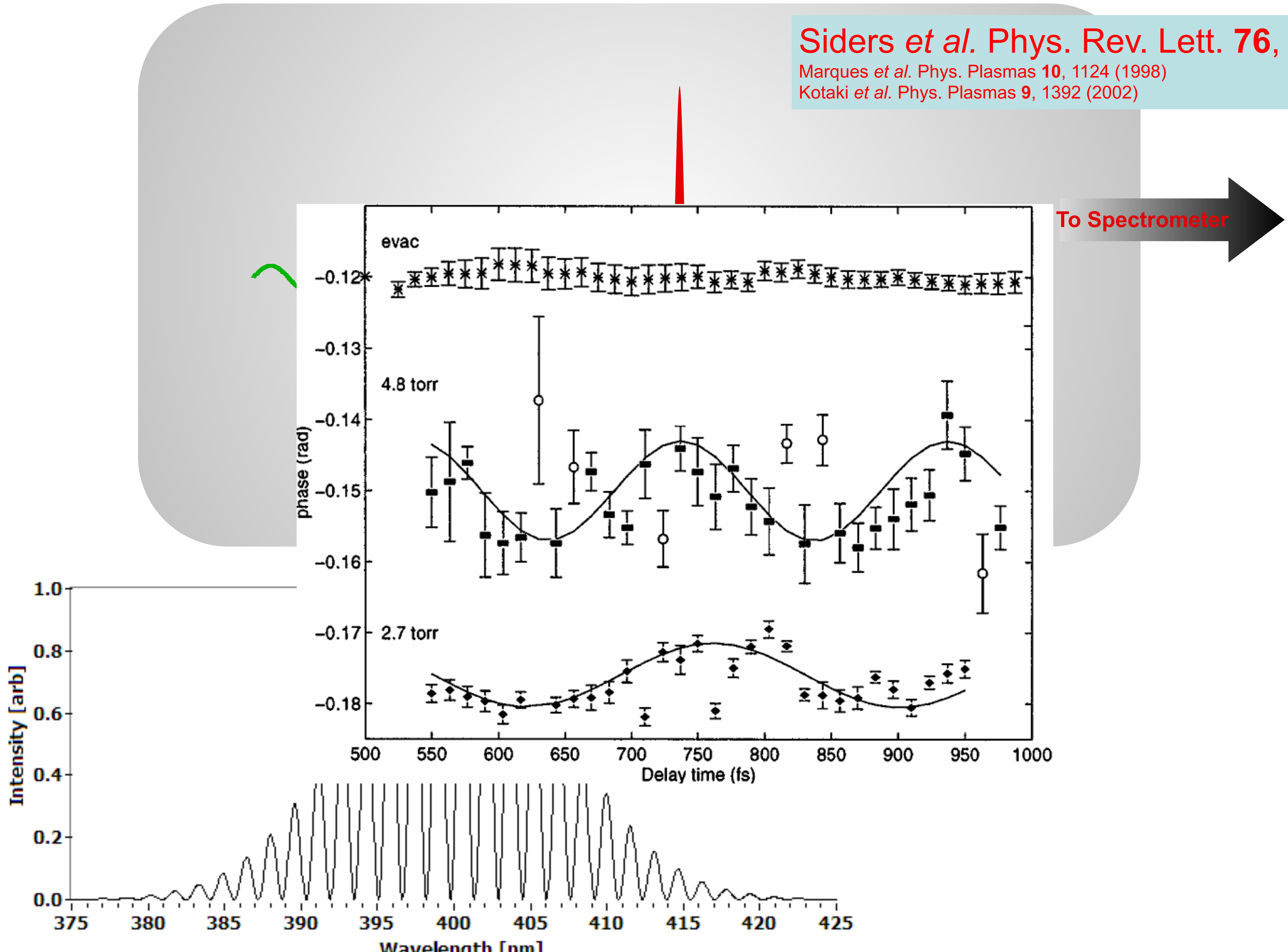
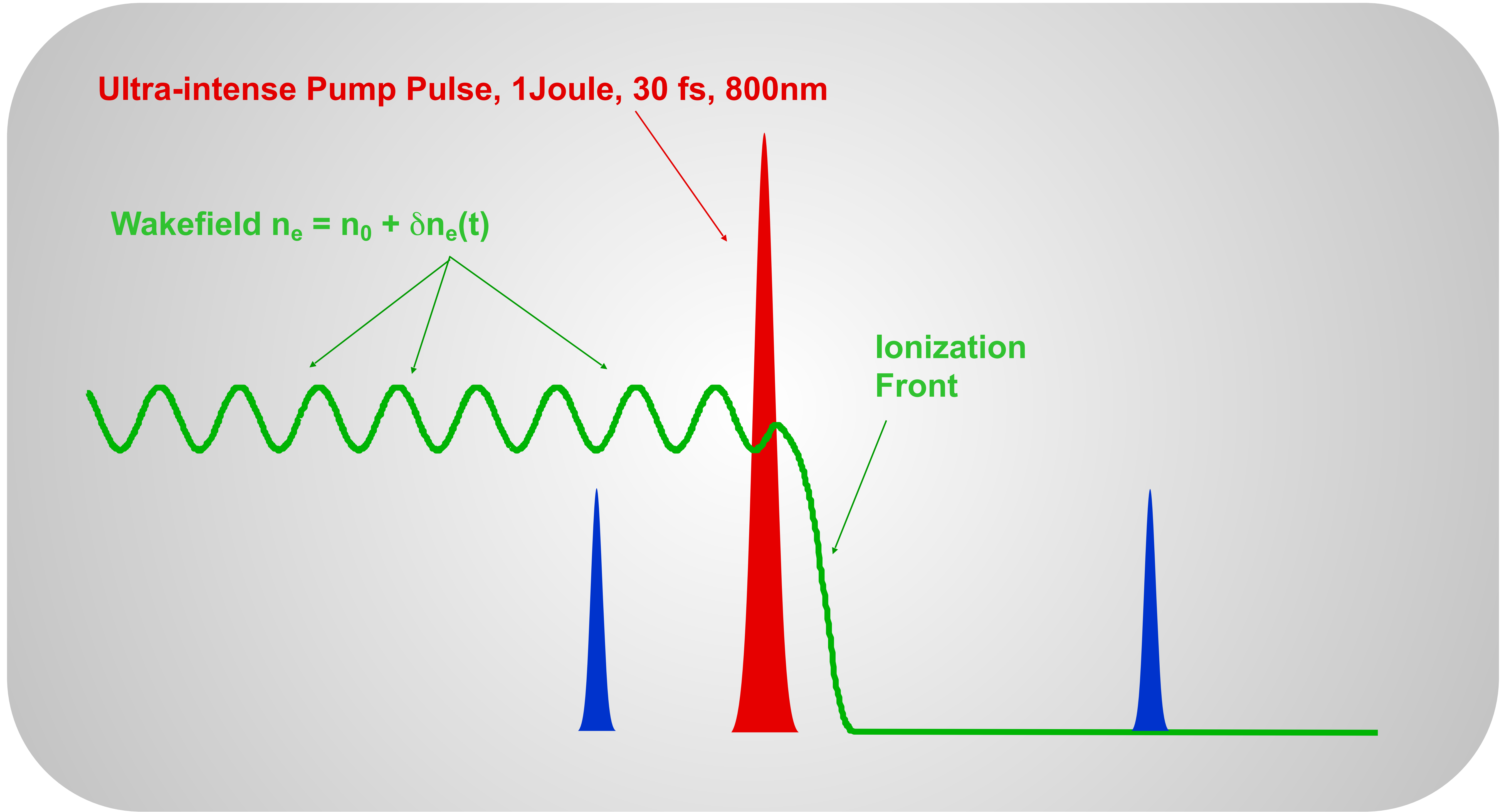


"Frequency Domain Holography" measures Wakefields in a Single-Shot



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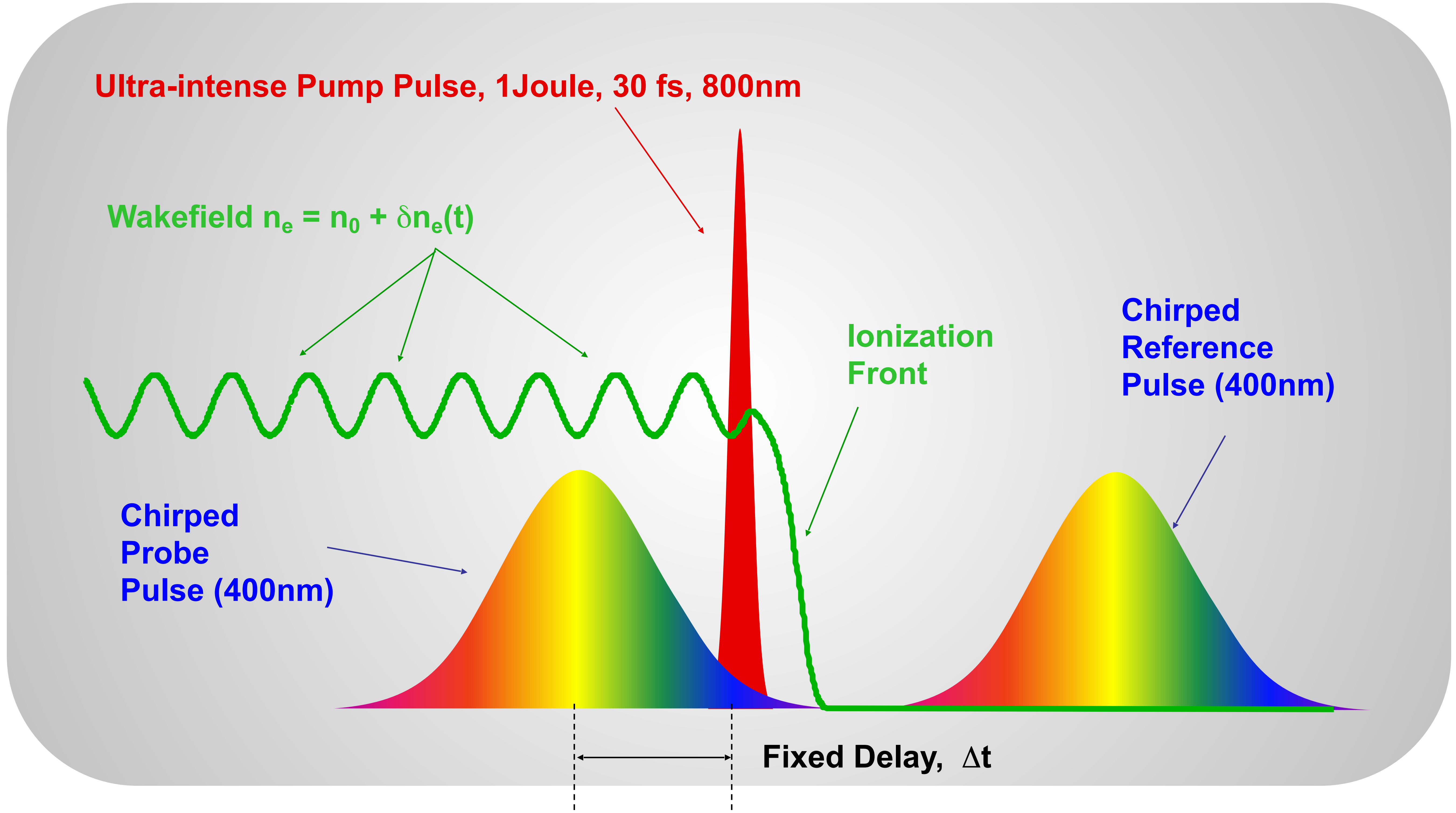

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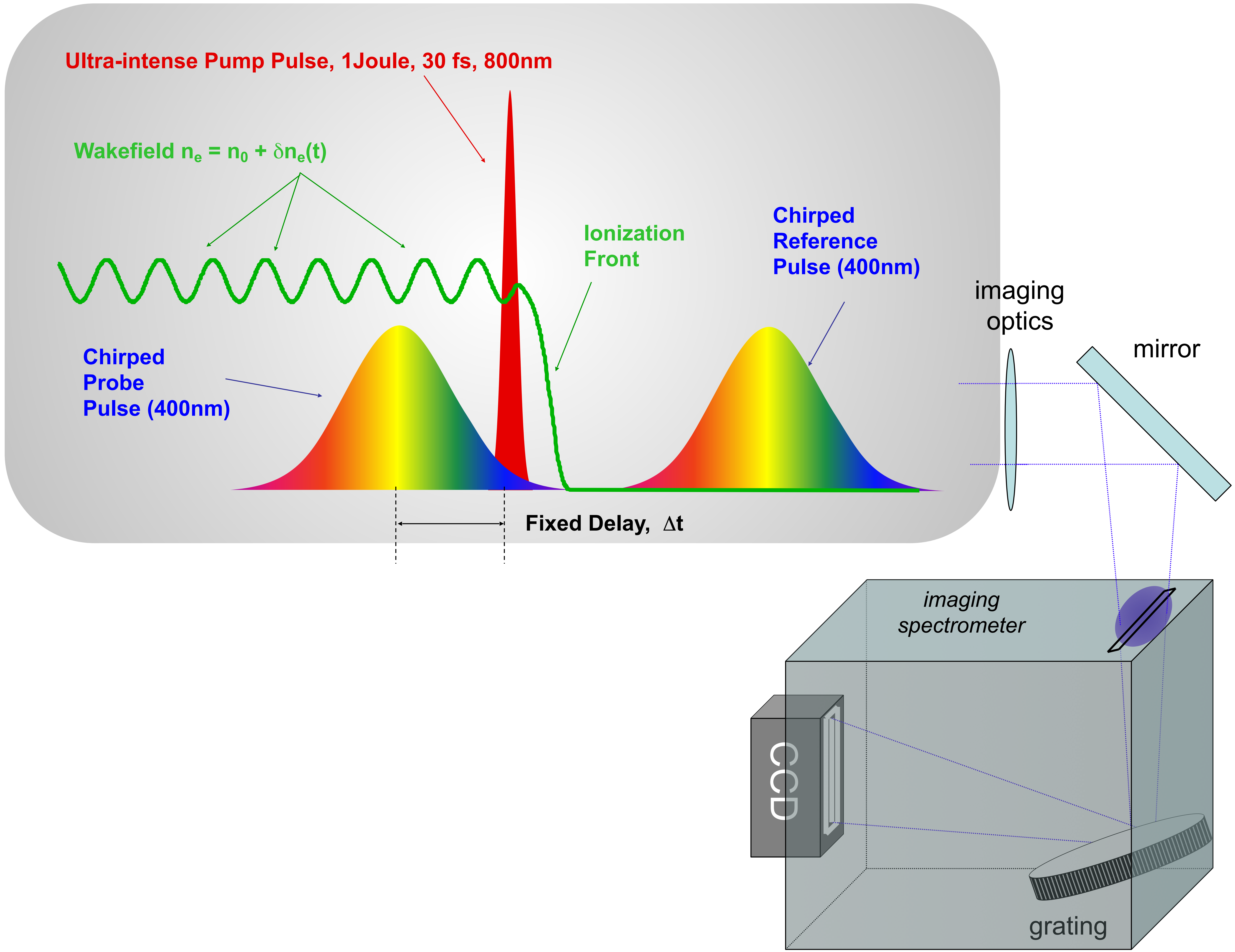

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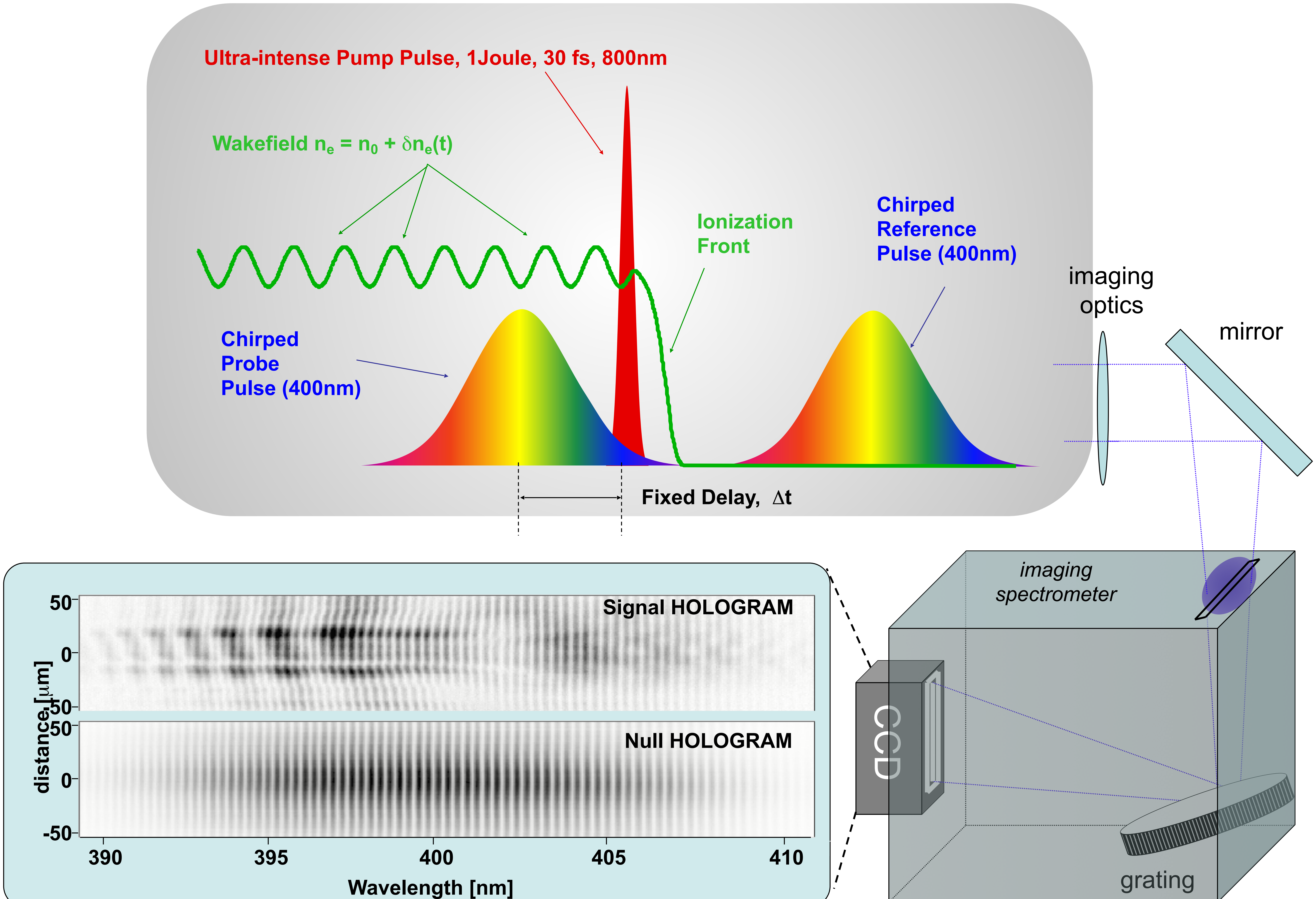
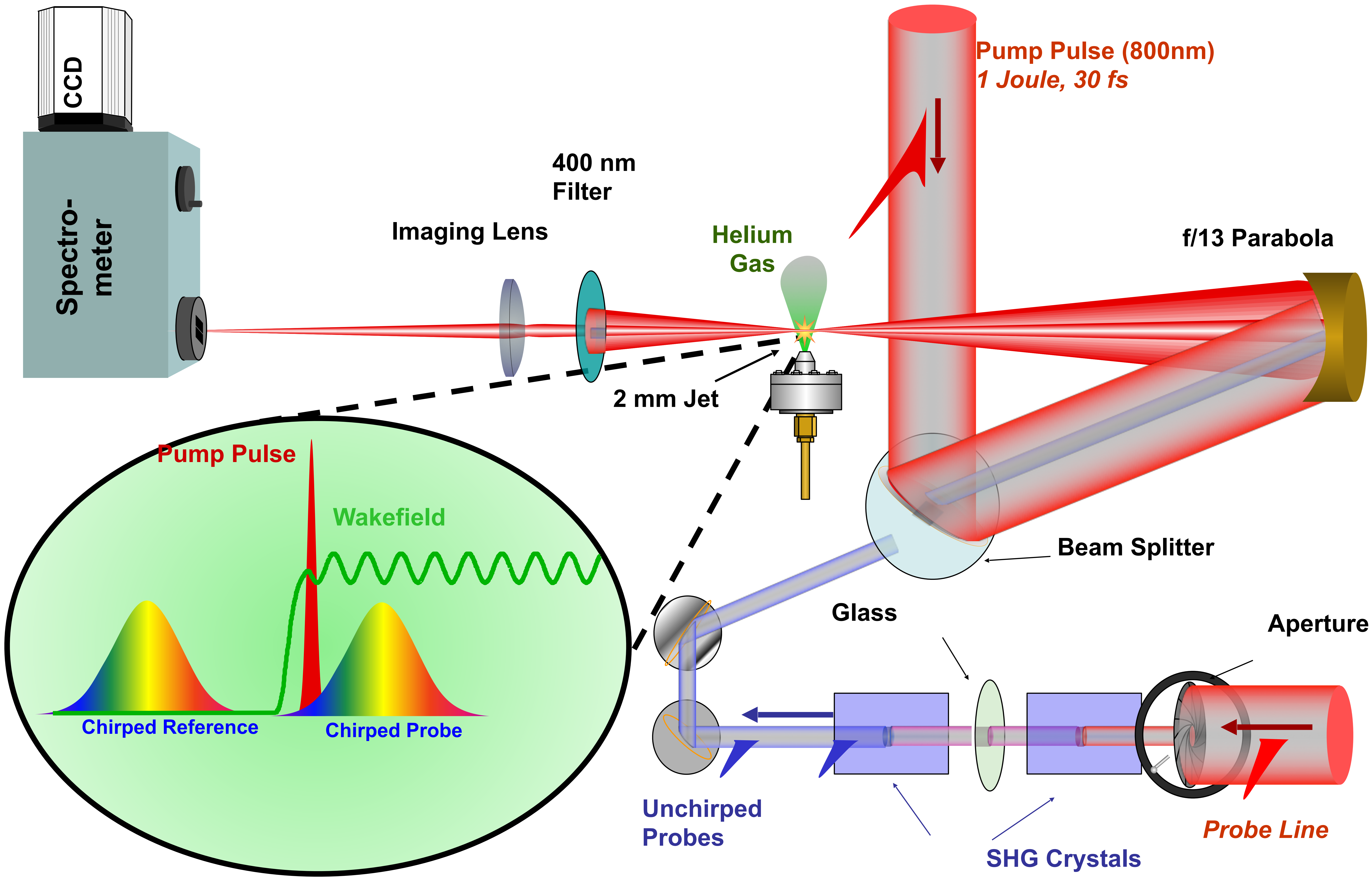


Experimental Layout



"Reading" the Hologram

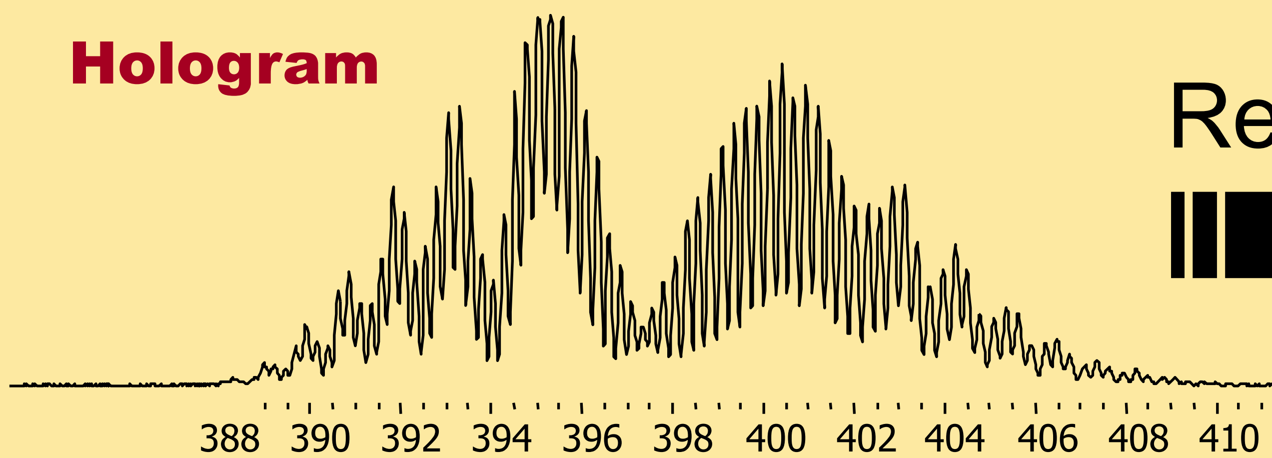
(Full Electric Field Reconstruction)

BASIC SCHEME

RECONSTRUCTION

TIME DOMAIN

1. Reconstruct spectral E-field of probe pulse from holographic spectrum



Read

$$E_{probe}(\omega) = |E(\omega)|\, e^{-i\phi(\omega)}$$

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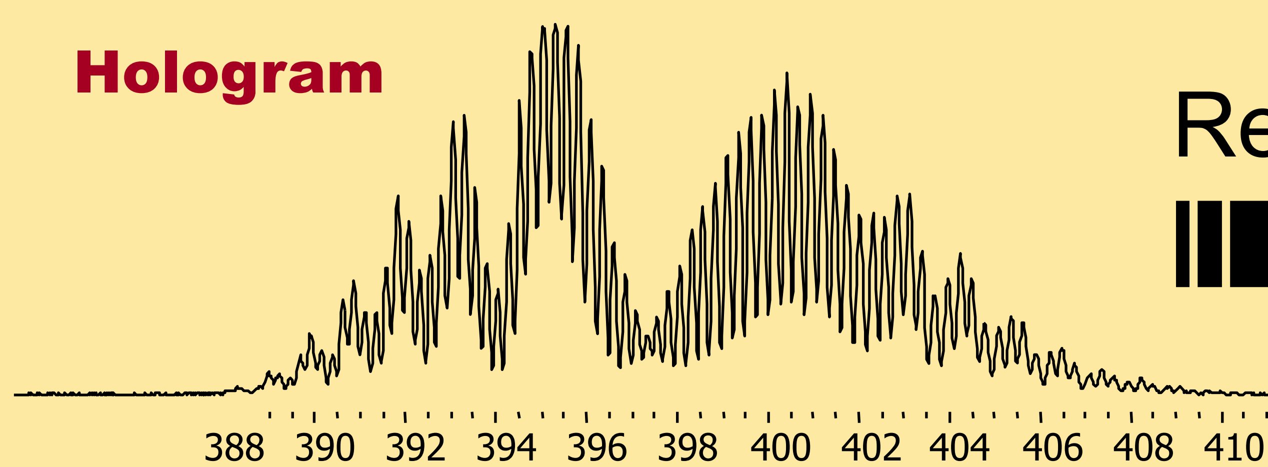

Read

$$E_{probe}(\omega) = |E(\omega)|\, e^{-i\phi(\omega)}$$

2. Fourier Transform to the time-domain to recover temporal phase

$$E_{probe}(\omega) \xrightarrow{\text{FFT}} E_{probe}(t) = |E(t)|\, e^{-i\delta\phi(t)}$$

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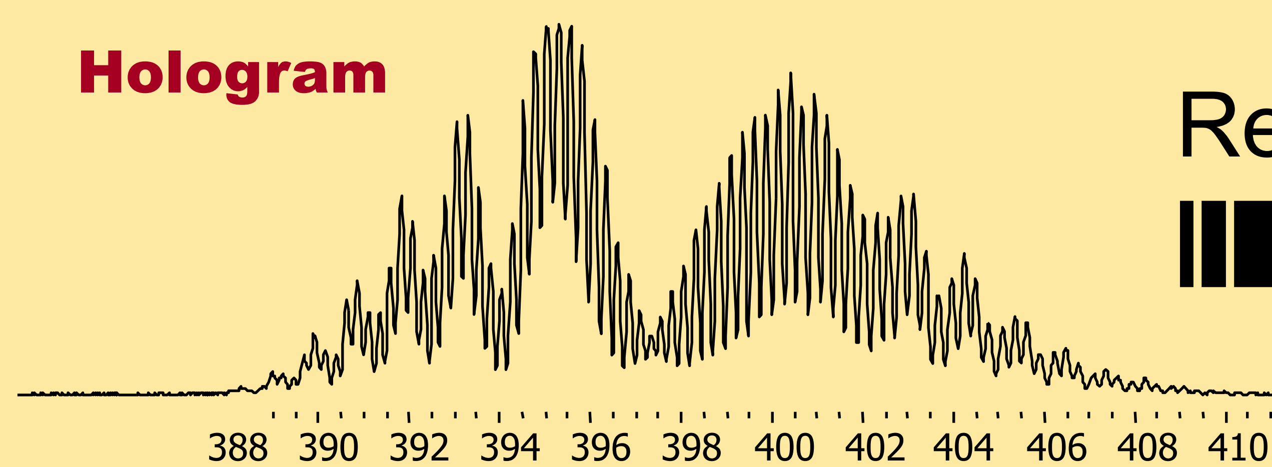

Read

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2. Fourier Transform to the time-domain to recover temporal phase

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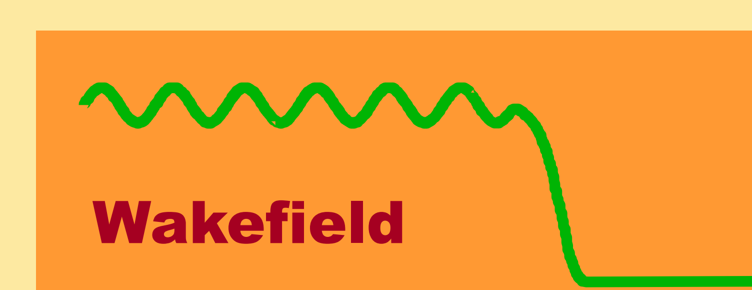
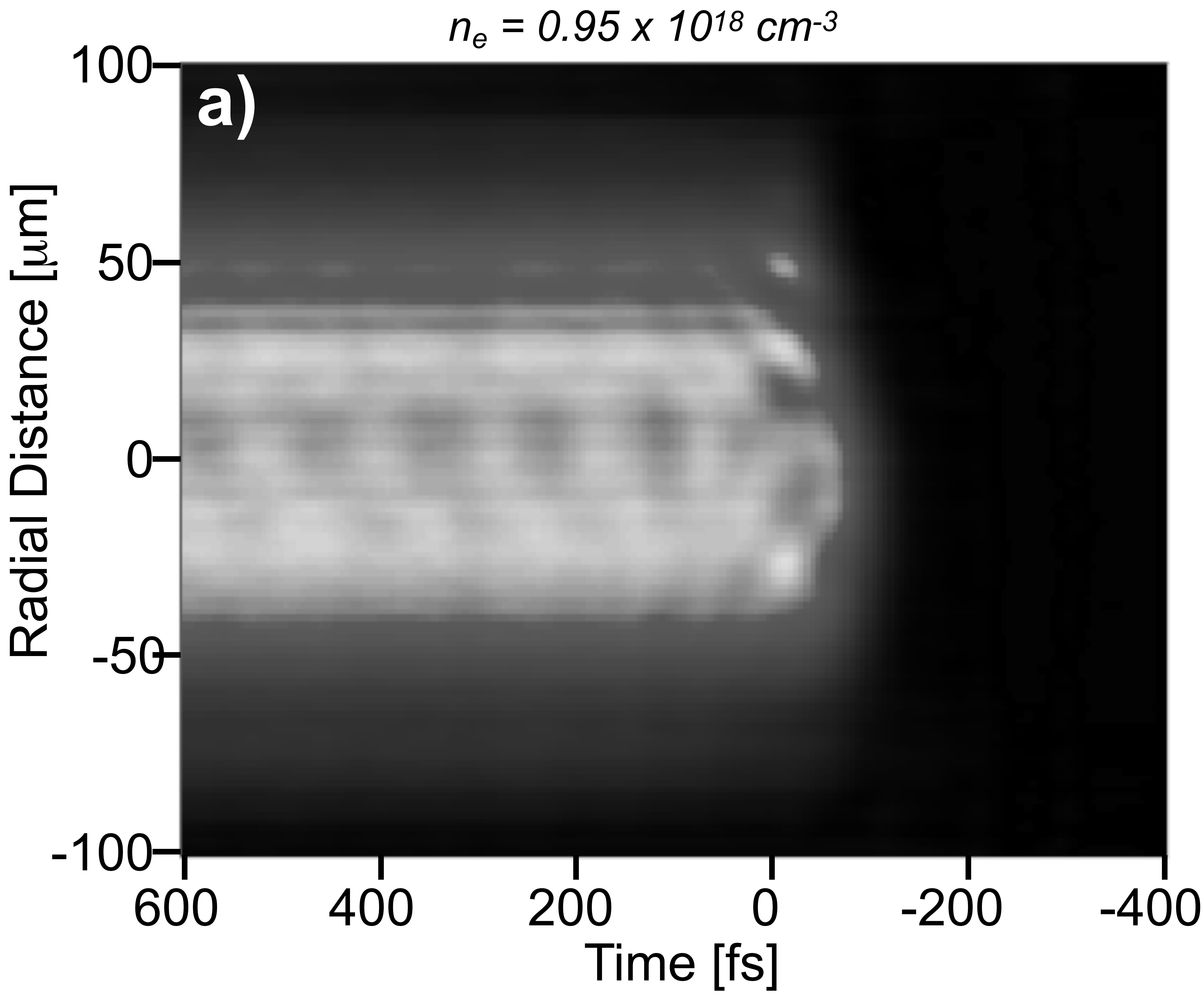
3. Calculate electron density from extracted temporal phase

$$\boldsymbol{\delta\phi(t)} \xrightarrow{\text{index}} \boxed{\boldsymbol{\delta n_e(t)}}$$



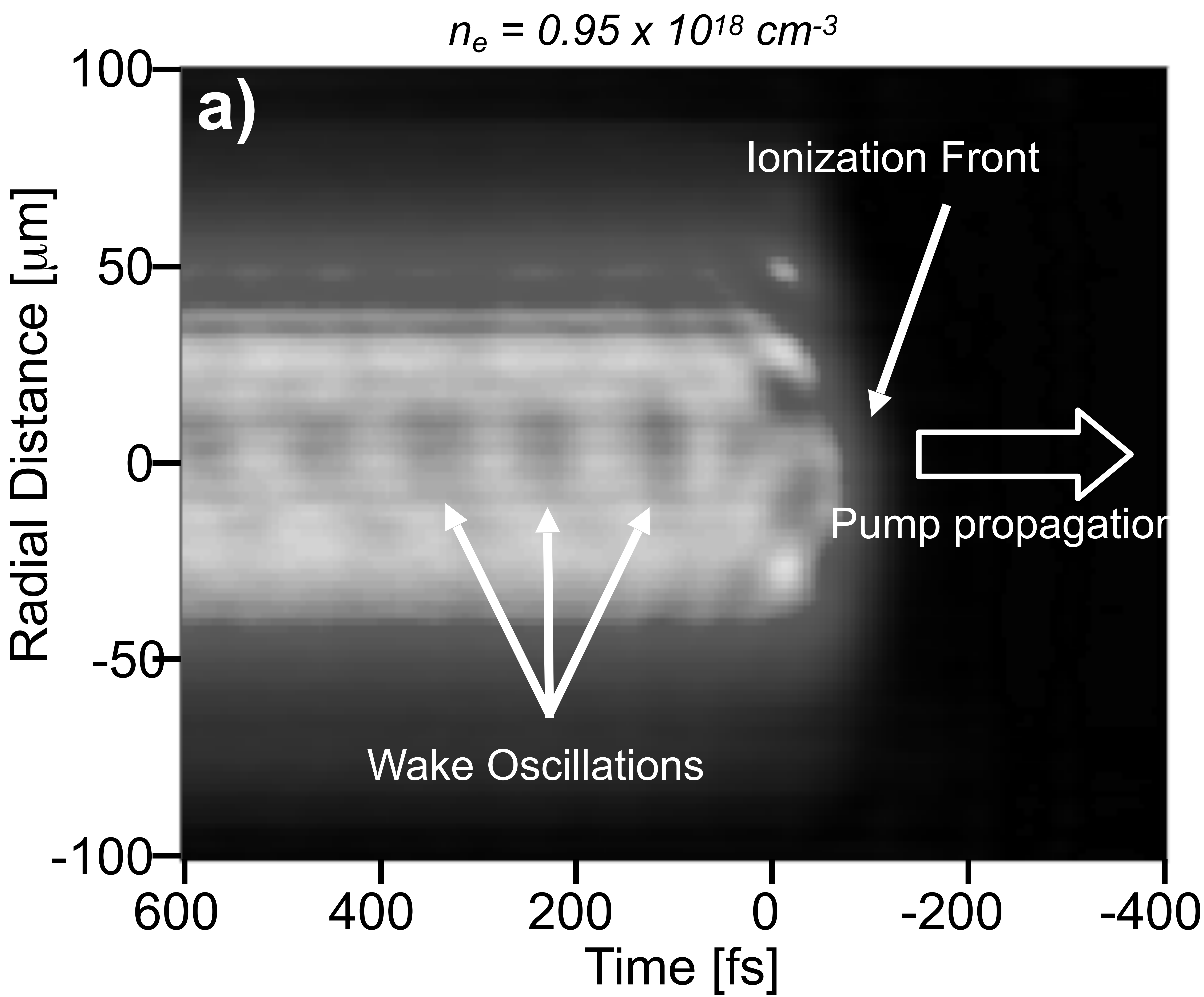
Holographic snapshots of laser wakefields

P ~10 TW, I ~ 10^{18} W/cm^2



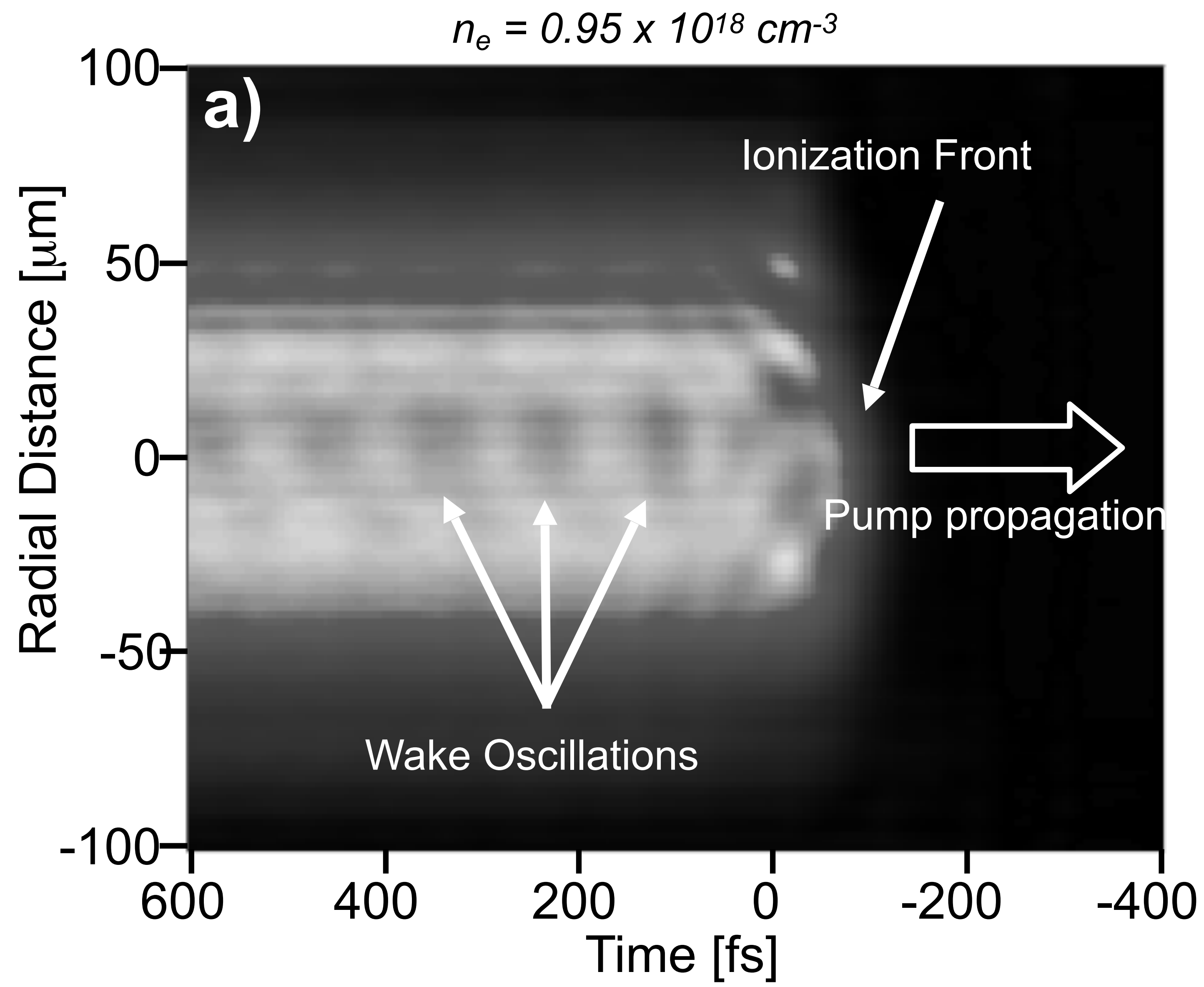
Holographic snapshots of laser wakefields

P ~10 TW, I ~ 10^{18} W/cm^2



Holographic snapshots of laser wakefields

$P \sim 10$ TW, $I \sim 10^{18}$ W/cm^2



Holographic snapshots of laser wakefields

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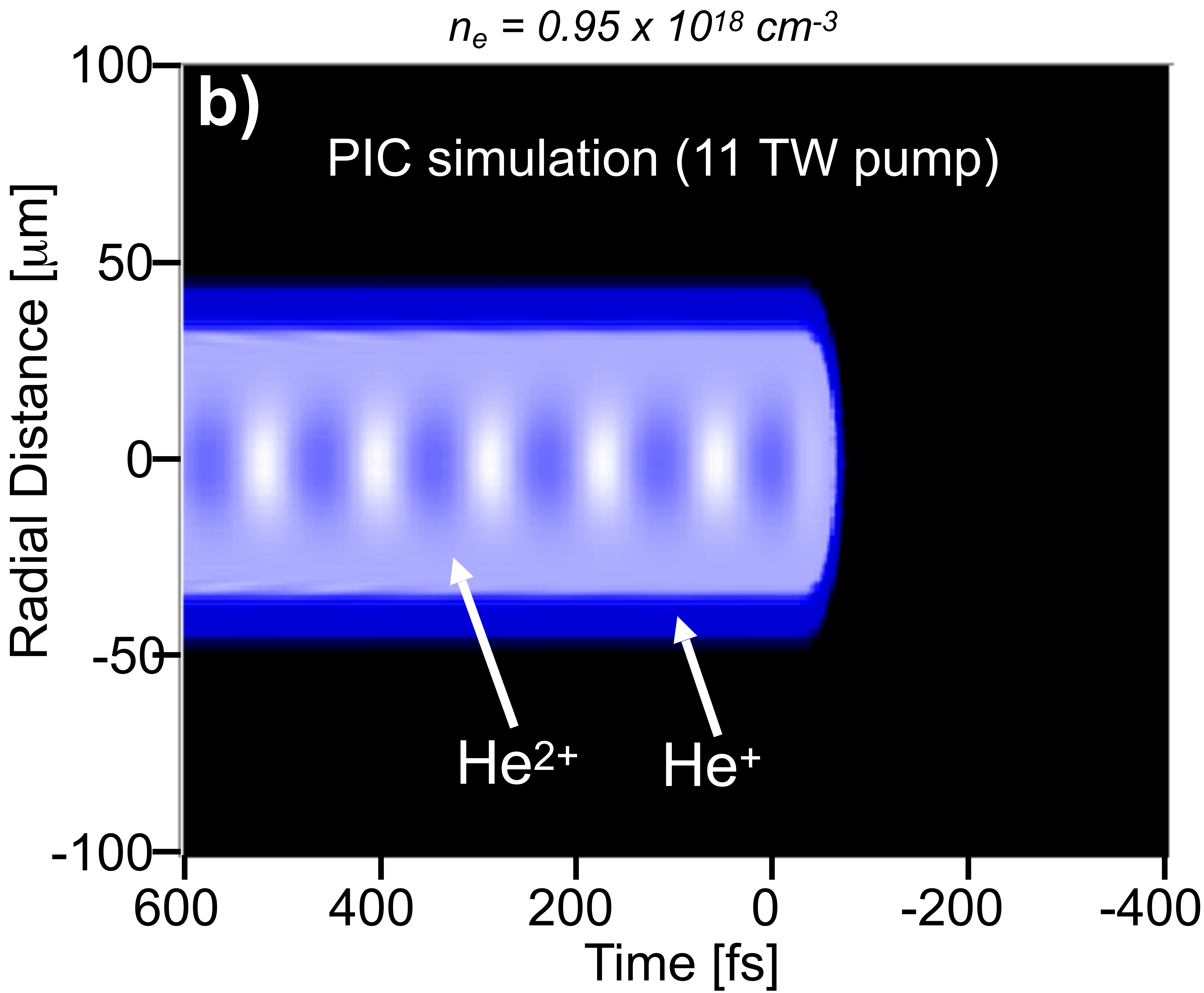

Holographic snapshots of laser wakefields

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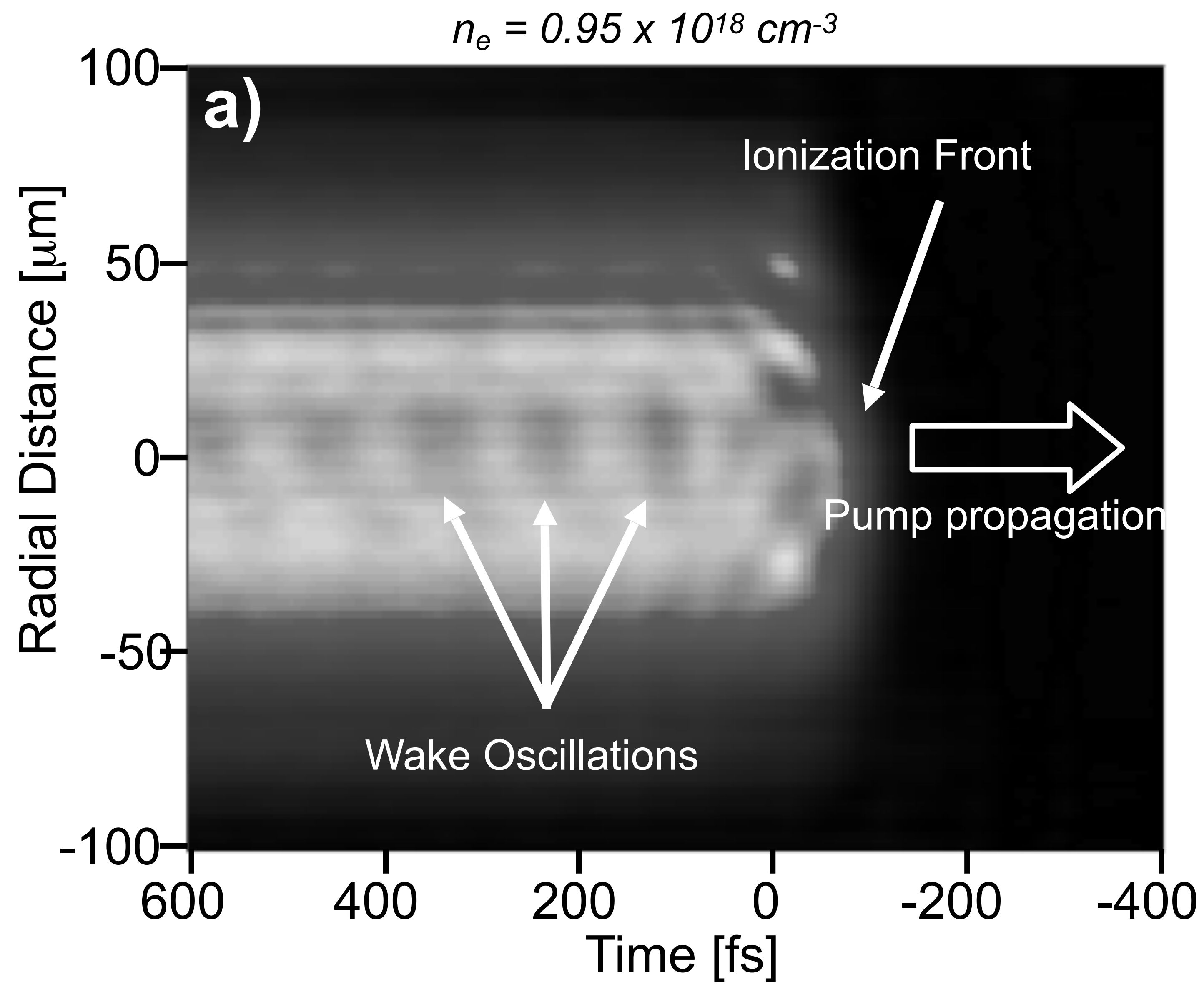
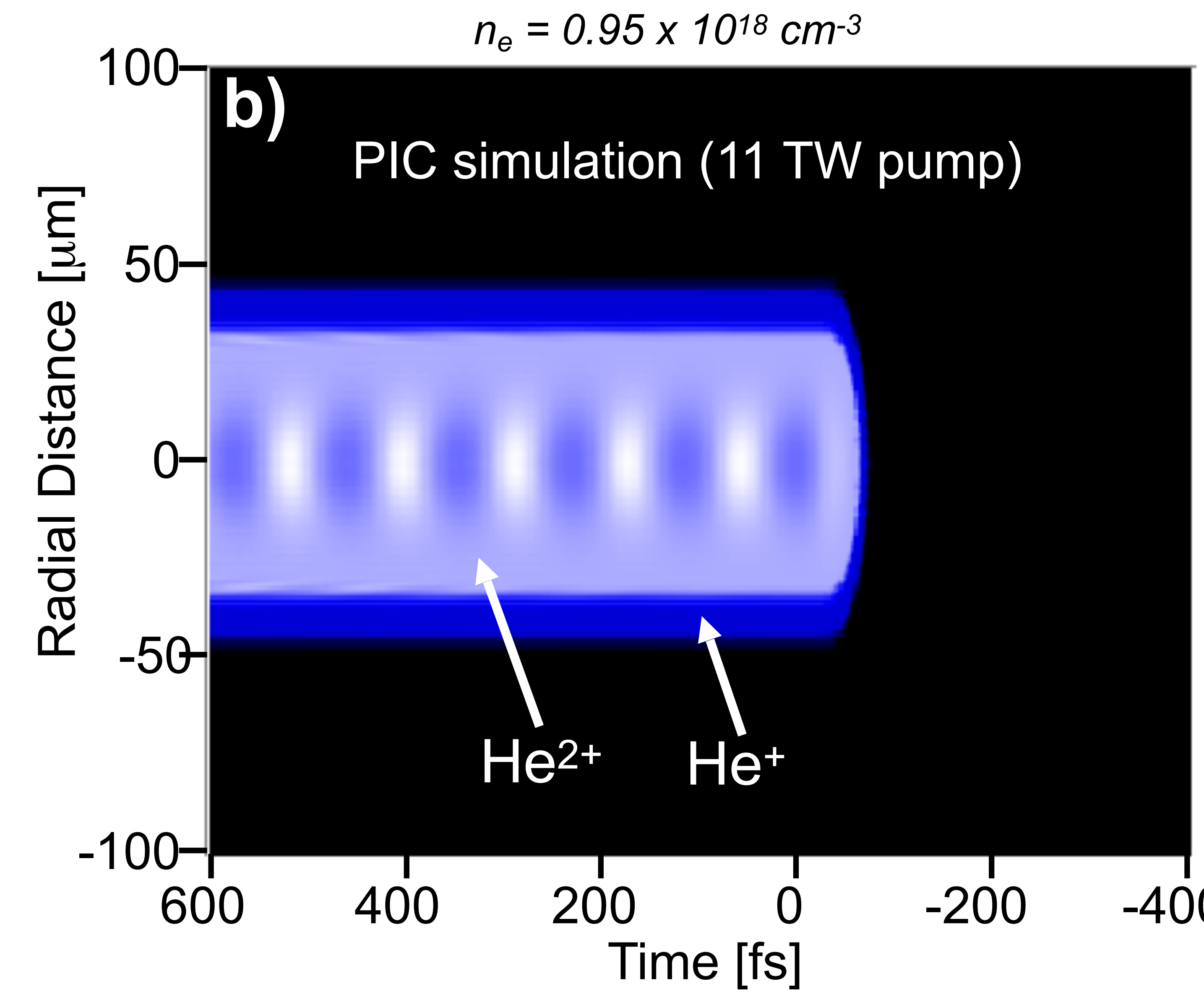
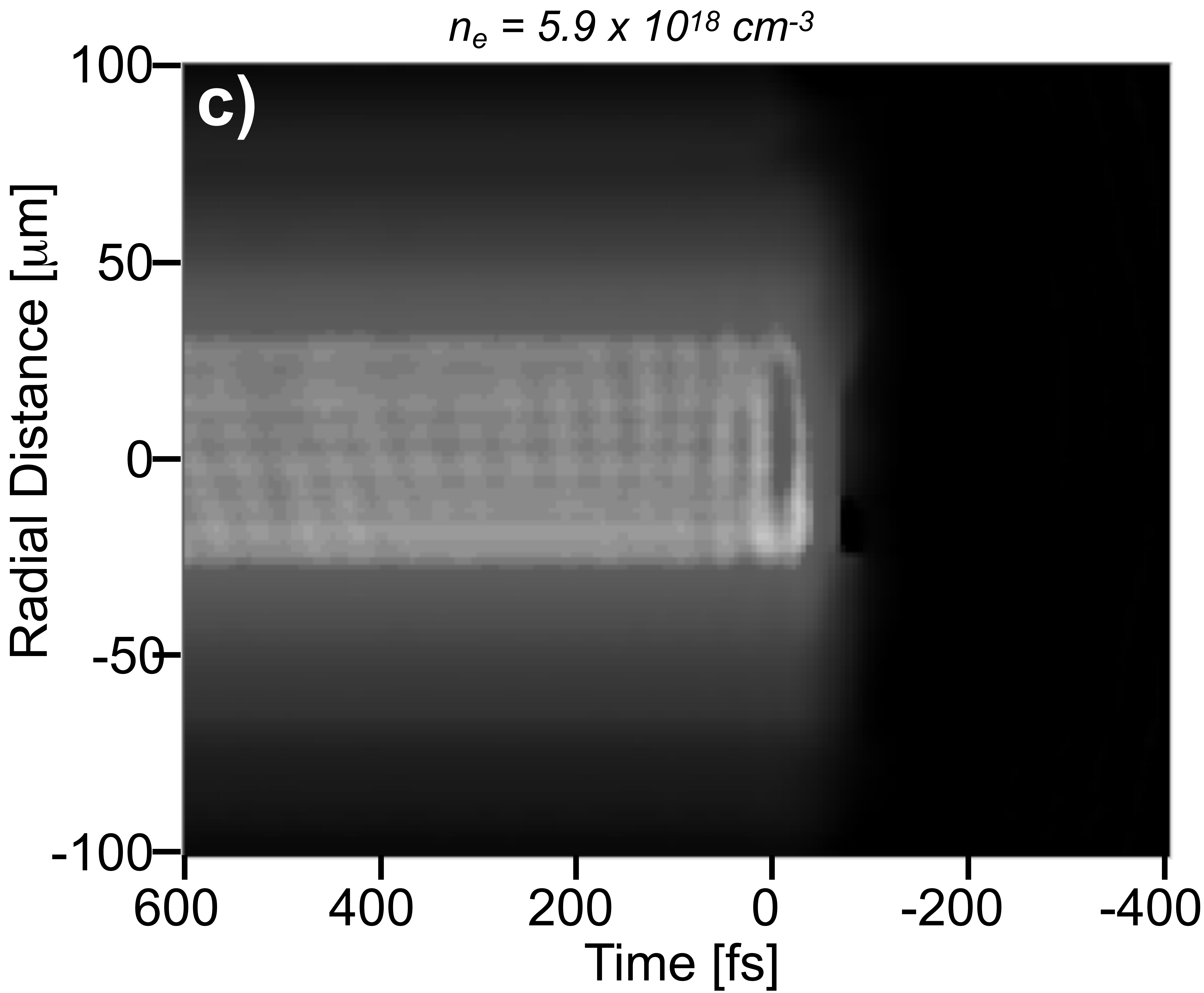




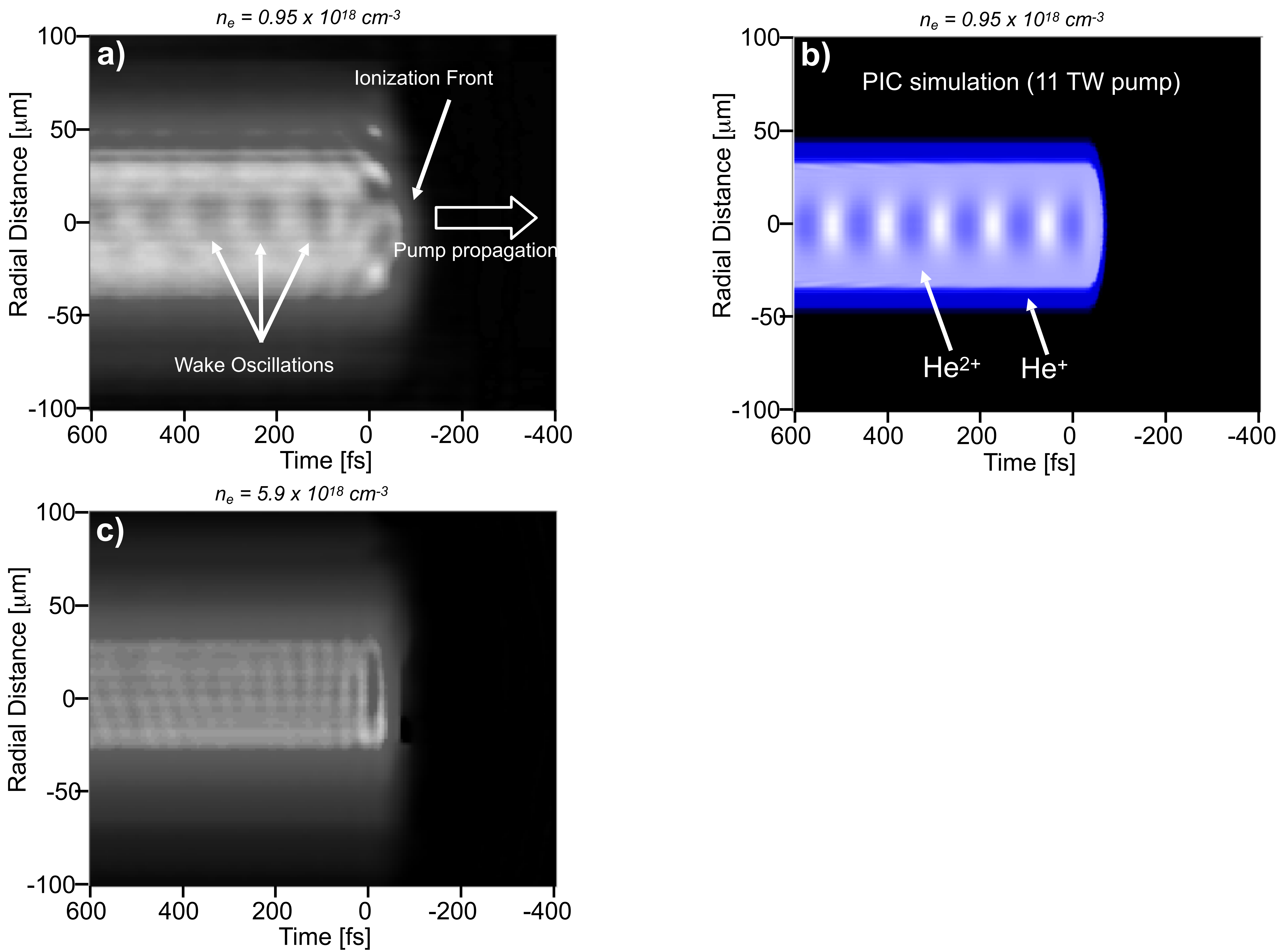
Holographic snapshots of laser wakefields

$P \sim 10$ TW, $I \sim 10^{18}$ W/cm^2



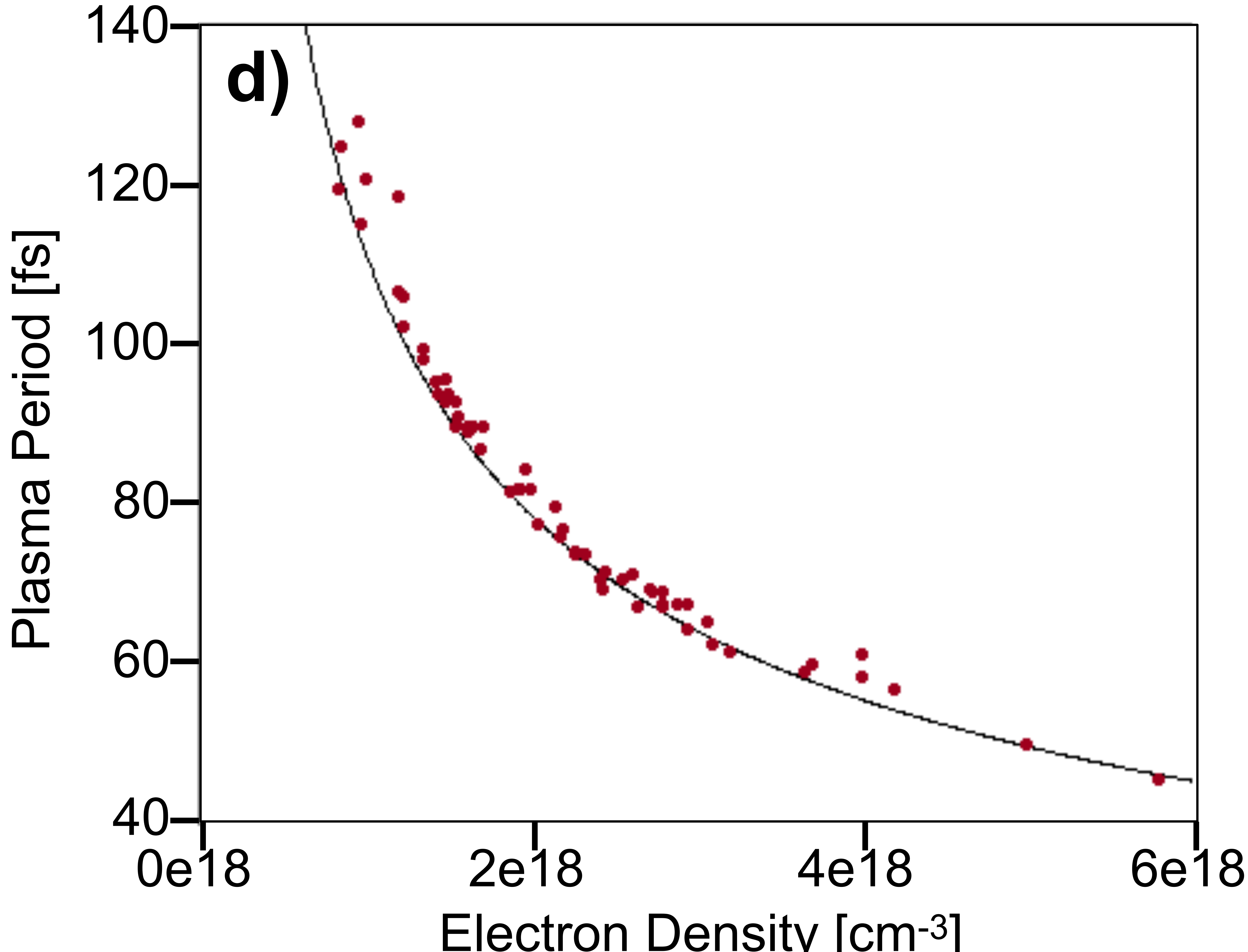
Holographic snapshots of laser wakefields

P ~10 TW, I ~ 10^{18} W/cm^2



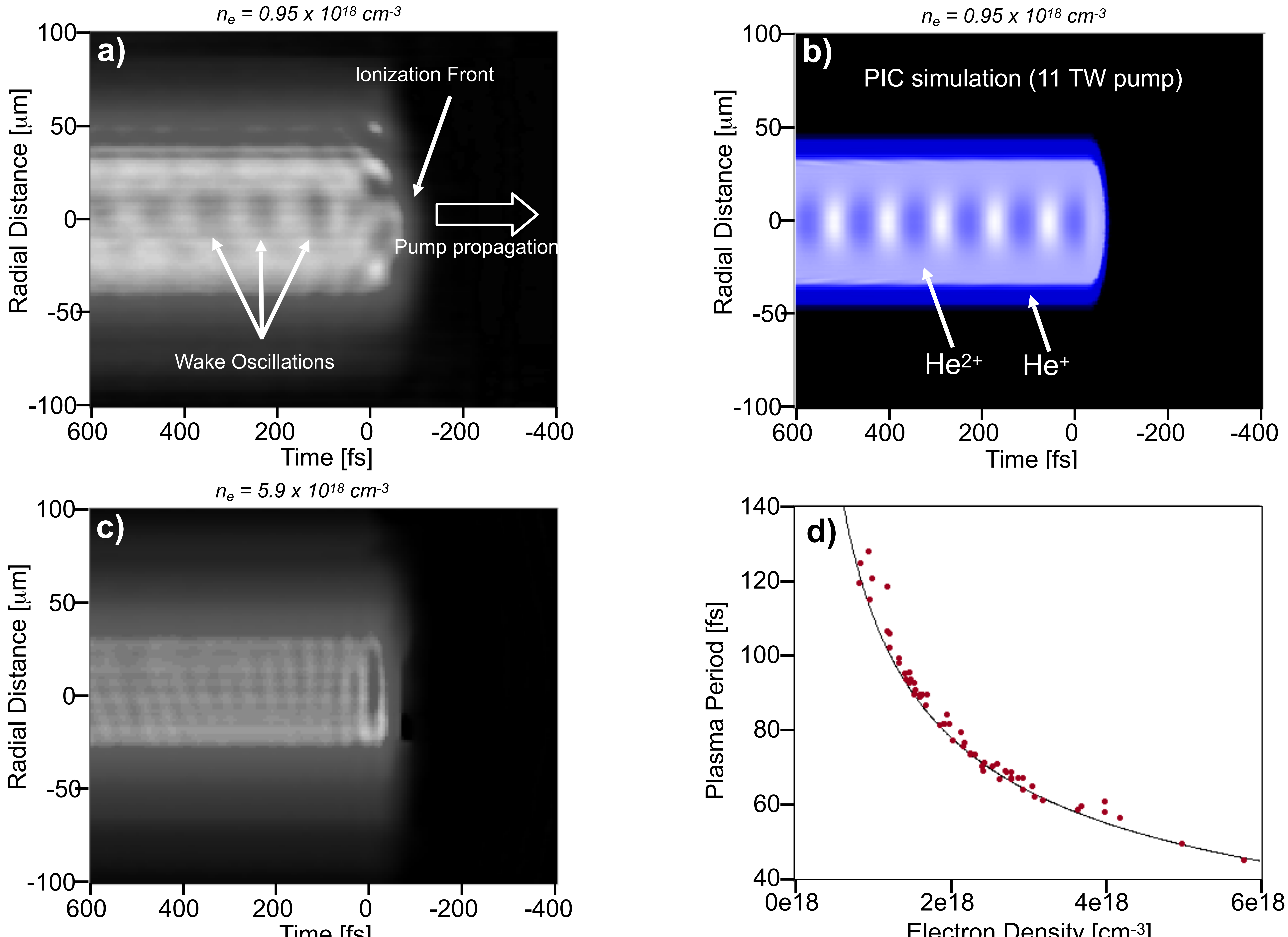
Holographic snapshots of laser wakefields

P ~10 TW, I ~ 10^{18} W/cm^2



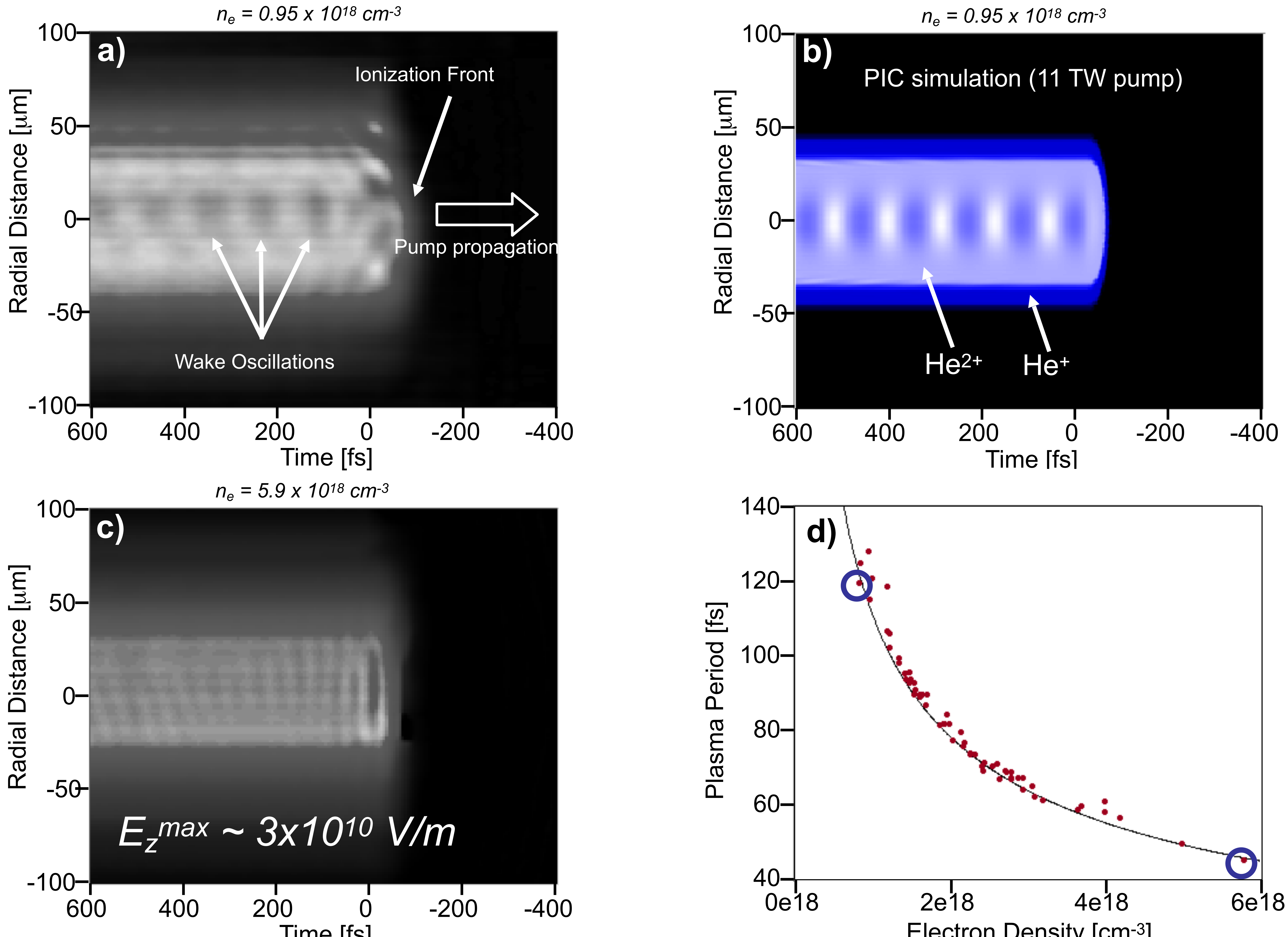
Holographic snapshots of laser wakefields

P ~10 TW, I ~ 10^{18} W/cm^2



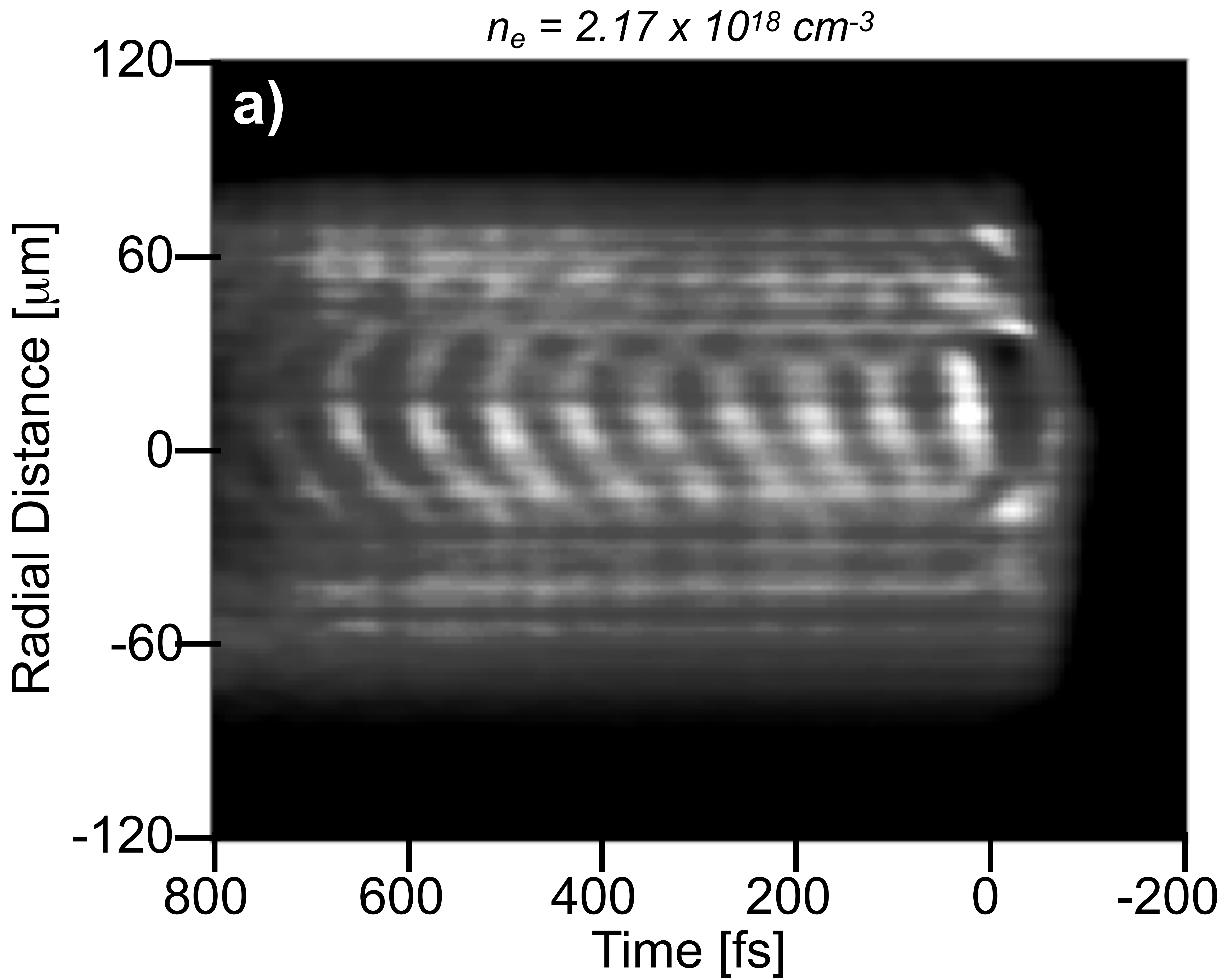
Holographic snapshots of laser wakefields

P ~10 TW, I ~ 10^{18} W/cm²



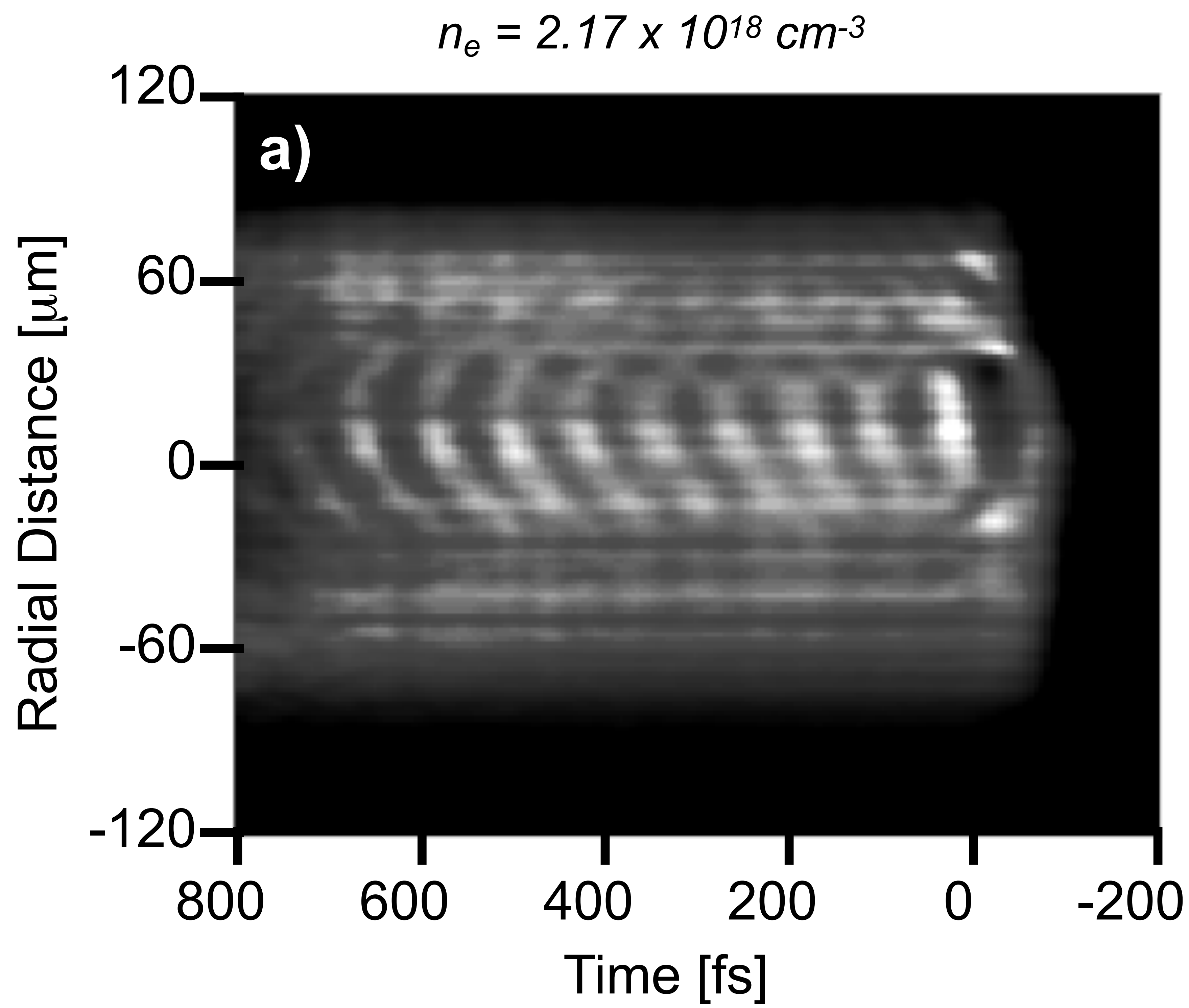
Strong wakes have curved wavefronts

P ~30 TW, I ~ 3 x 10^{18} W/cm^2



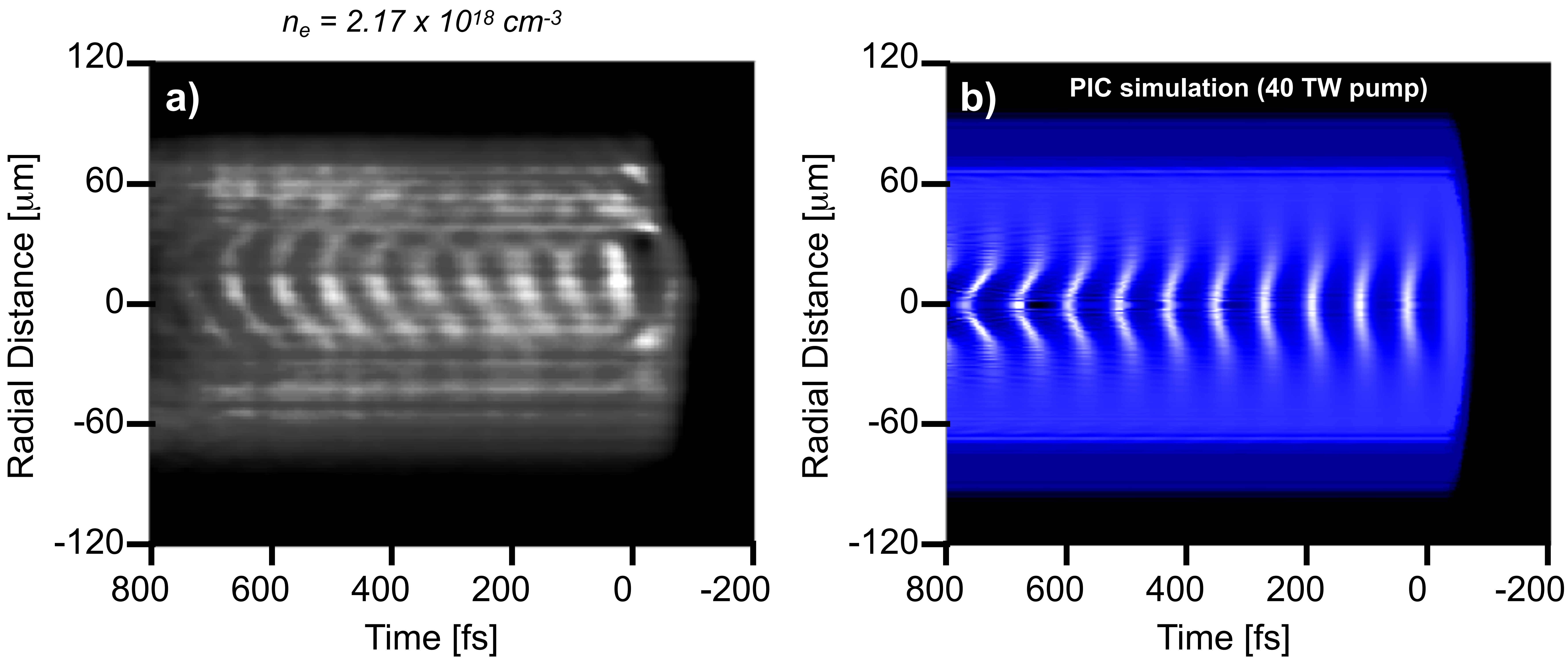
Strong wakes have curved wavefronts

$P \sim 30$ TW, $I \sim 3 \times 10^{18}$ W/cm^2



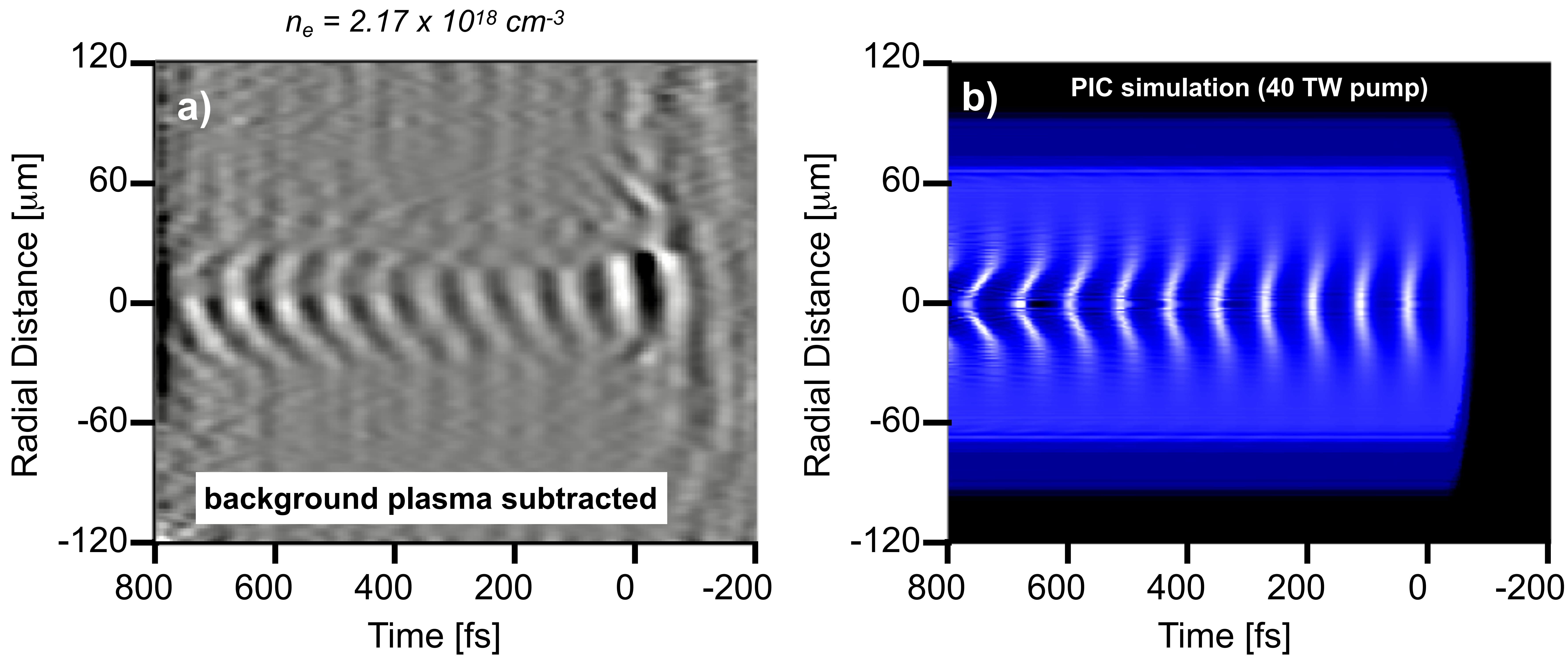
Strong wakes have curved wavefronts

P ~30 TW, I ~ 3 x 10^{18} W/cm^2



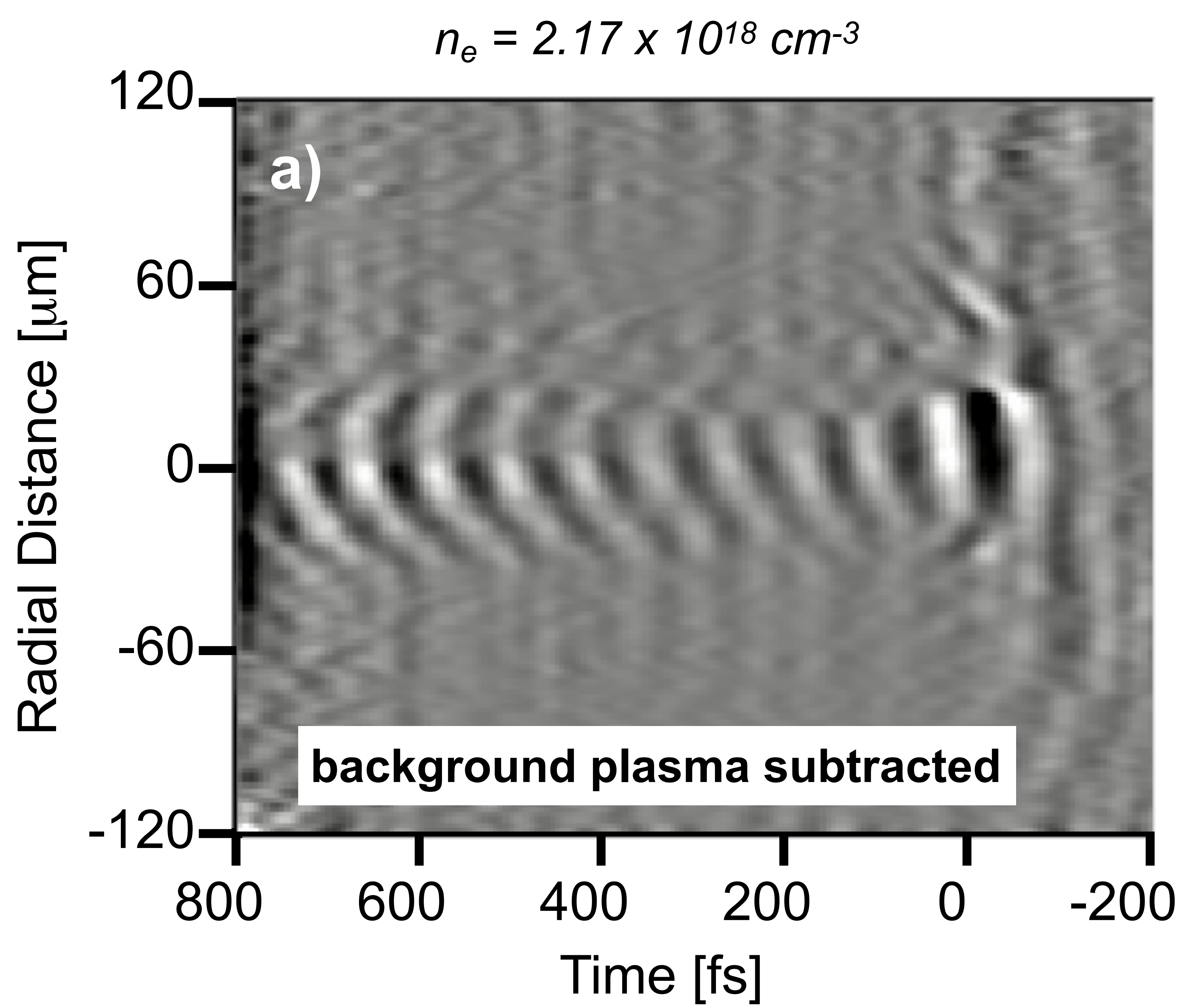
Strong wakes have curved wavefronts

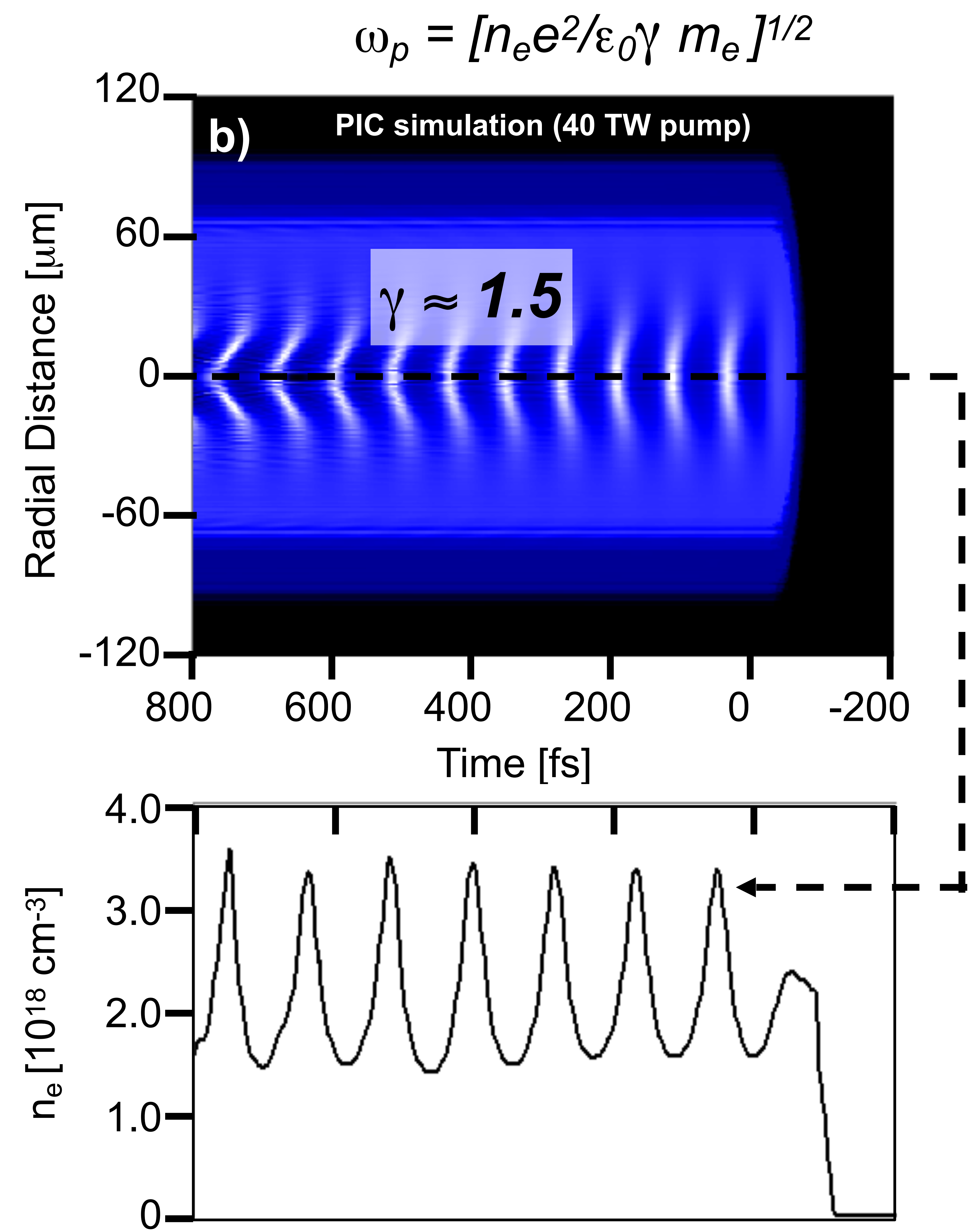
P ~30 TW, I ~ 3 x 10^{18} W/cm^2



Strong wakes have curved wavefronts

$P \sim 30\ TW,\ \ I \sim 3 \times 10^{18}\ W/cm^2$





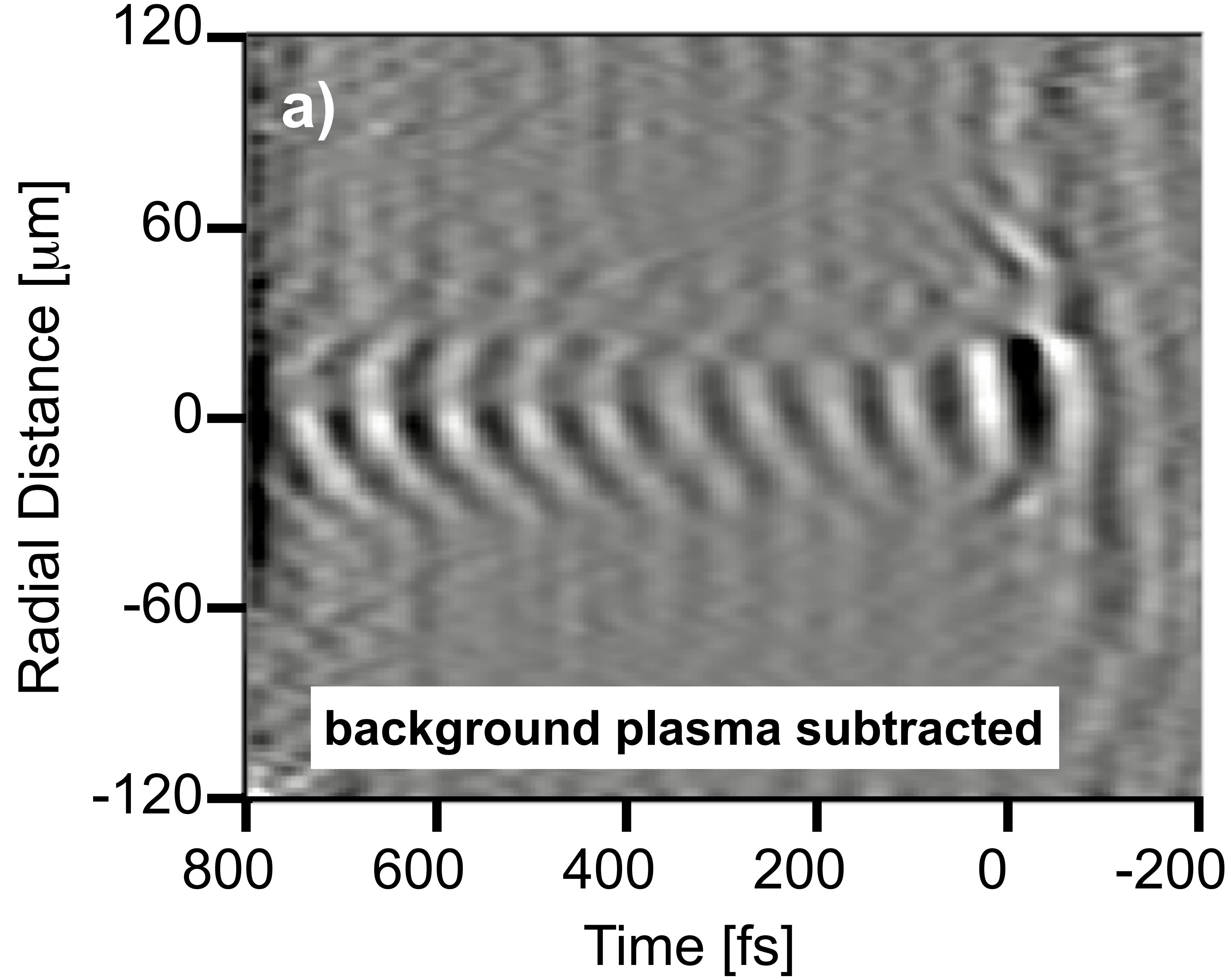
Source of wavefront curvature:

- **large wave amplitude = large γ**

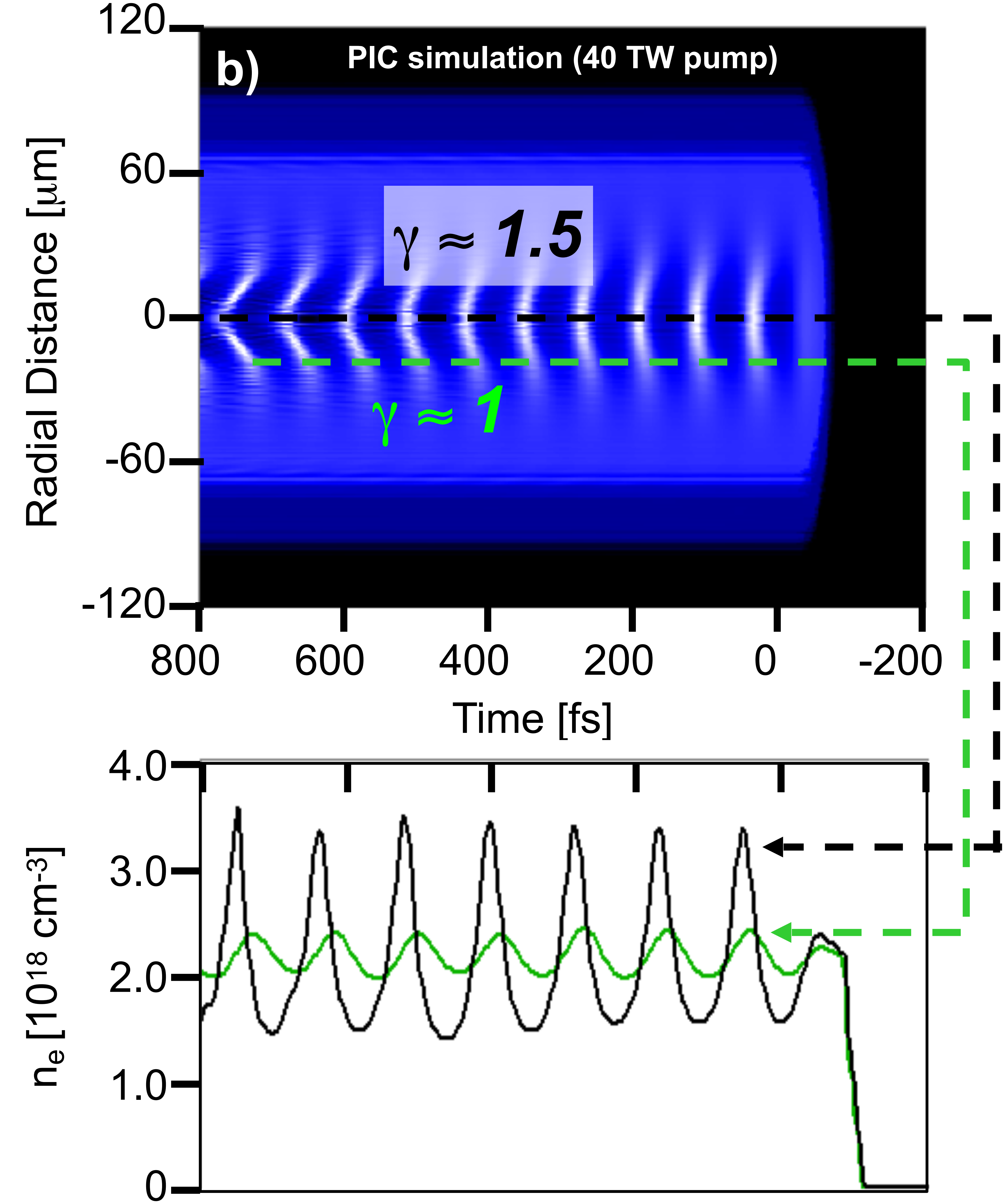
Strong wakes have curved wavefronts

$P \sim 30$ TW, $I \sim 3 \times 10^{18}$ W/cm^2

$n_e = 2.17 \times 10^{18}$ cm^{-3}



$\omega_p = [n_e e^2/\varepsilon_0 \gamma\ m_e]^{1/2}$



Source of wavefront curvature:

- **large wave amplitude = large γ**
- **small wave amplitude = small γ**

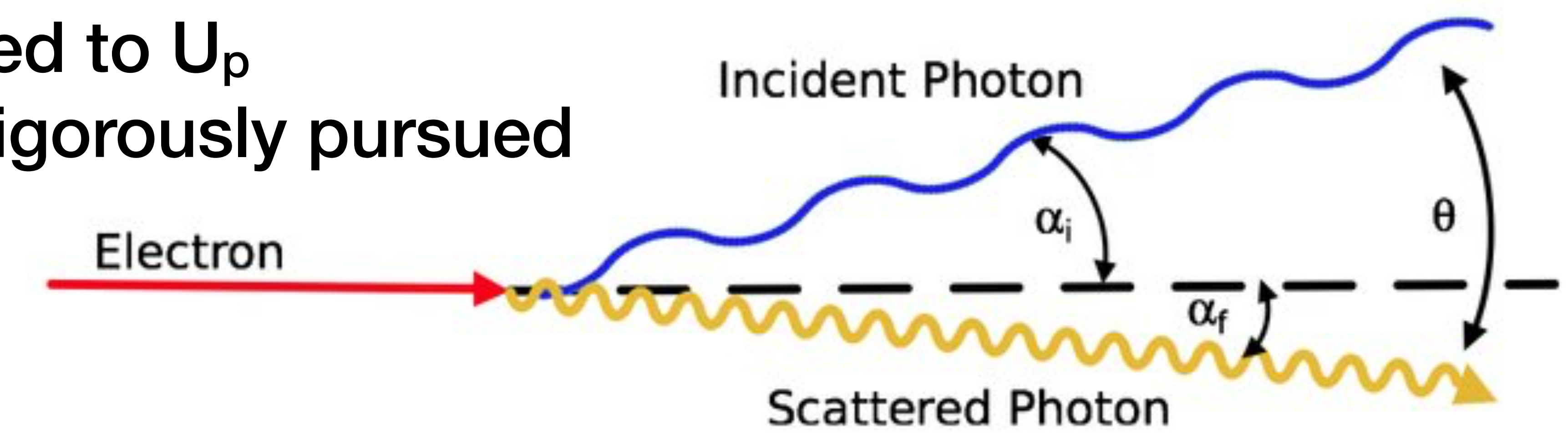
λ_p (relativistic) > λ_p (non-relativistic)

Plasma temperature

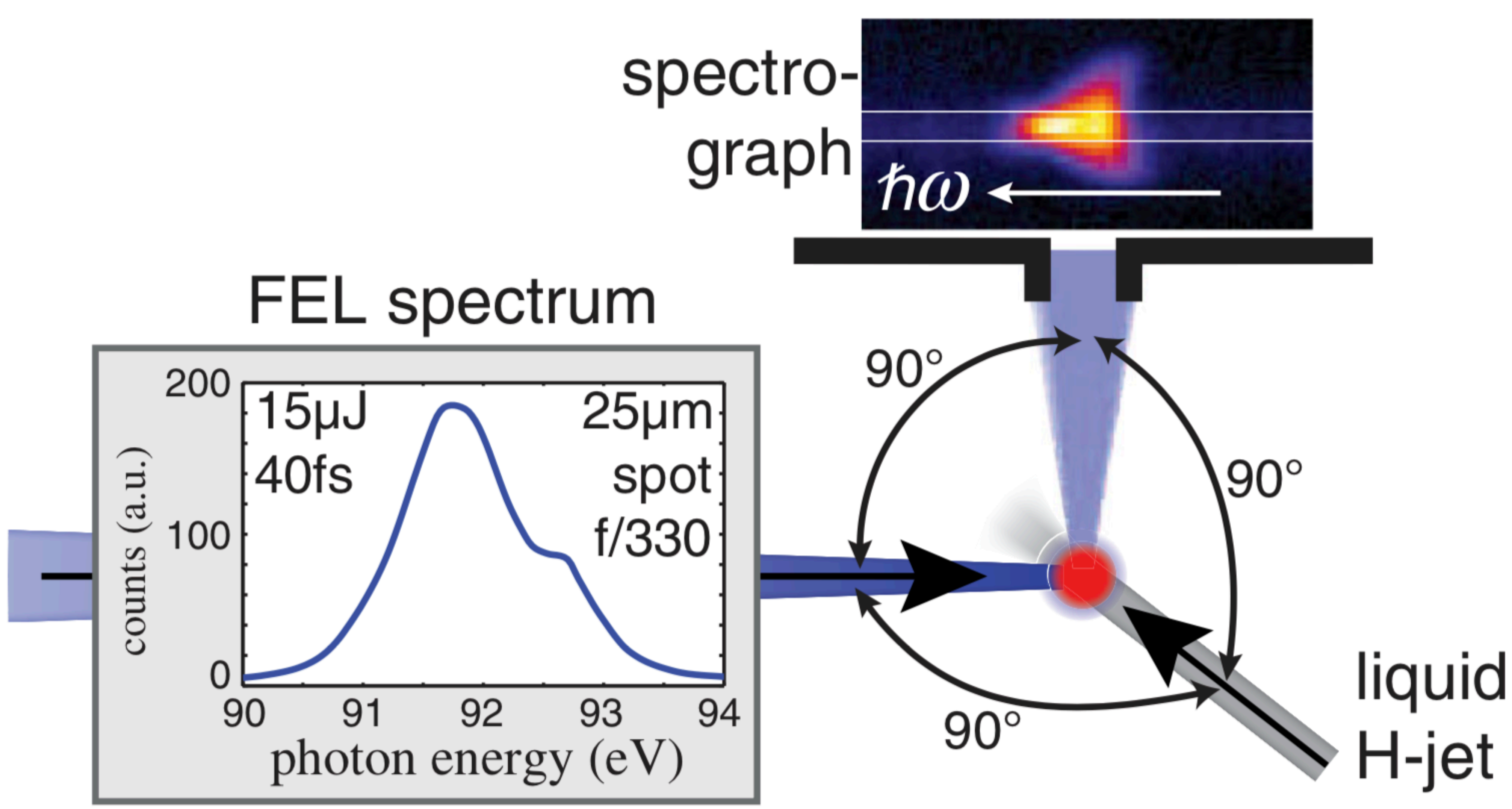
- Inverse compton scattering

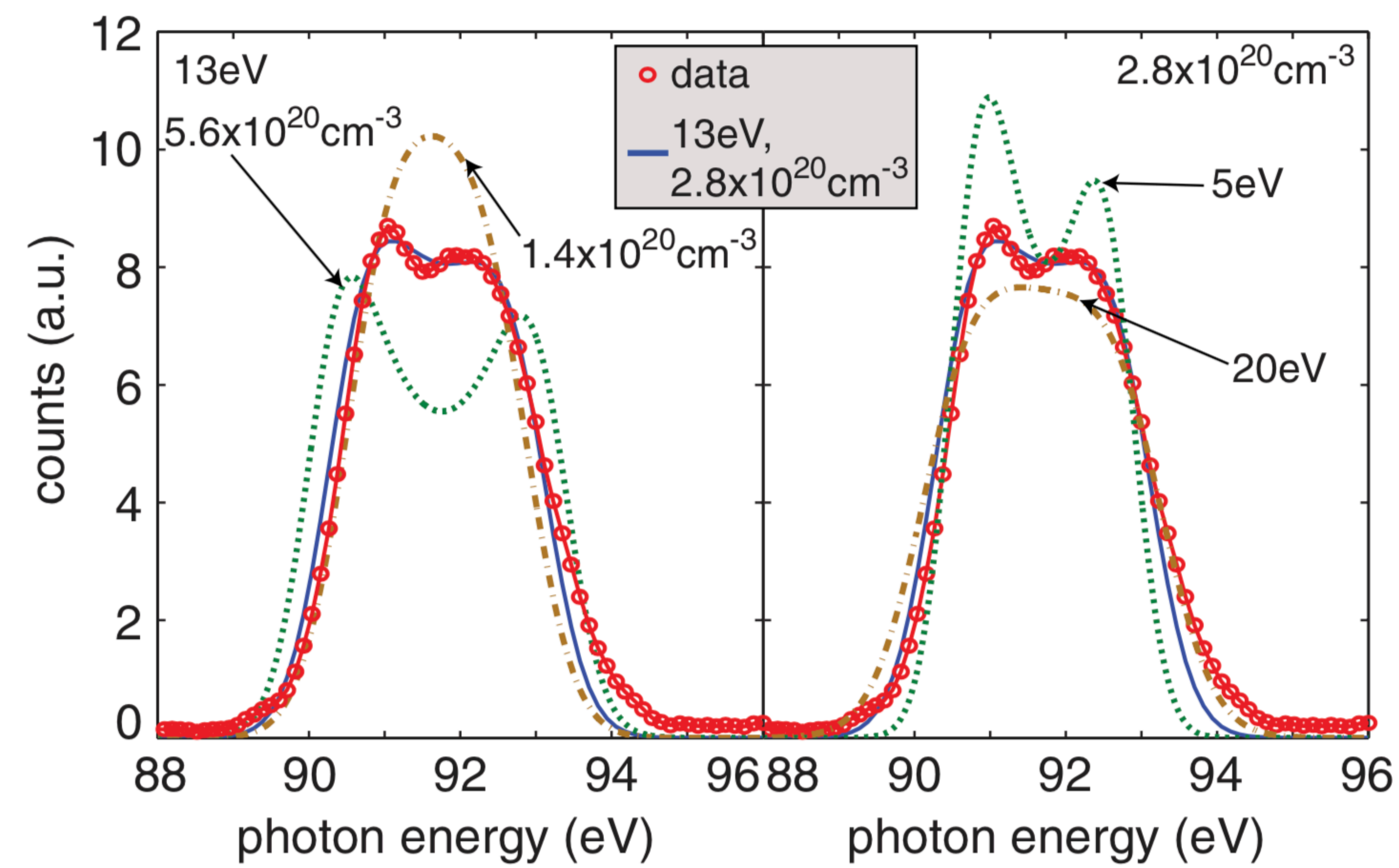
Inverse Compton scattering

- Initial plasma temperature T_e (x,t), T_i (x,t) usually small compared to U_p
  → effects usually neglected, temperature measurements not vigorously pursued
- Possible method **Inverse Compton scattering**



- Example from FLASH FEL





R. R. Fäustlin *et al.,* PRL **104**, 125002 (2010)

Summary of Plasma Diagnostics

> *Gas density*
  - Raman scattering
  - Interferometry

> *Plasma density and constituents*
  - Schlieren/dark-field imaging
  - Laser interferometry
  - Two-color phase delay spectral interferometry
  - Plasma spectroscopy

> *Internal E- & B-fields, and wake structures*
  - *Polarimetry*
  - *Particle beam probes*
  - *Frequency Domain Holography*

> *Plasma temperature*
  - *Inverse Compton Scattering*