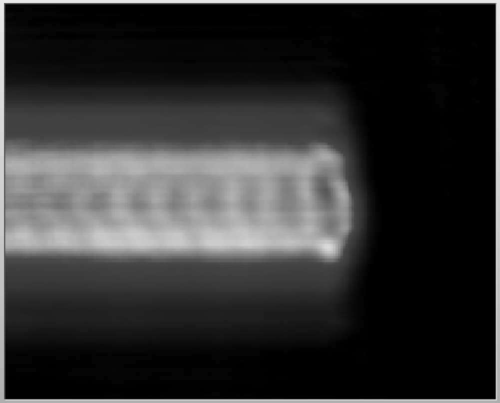
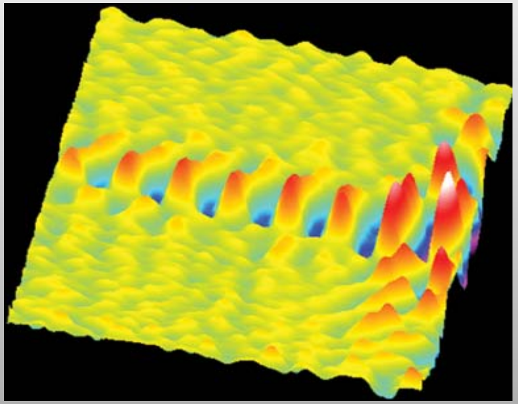
Holographic Snapshots of Laser Wakefields





Nicholas Matlis

M. Downer

Femtosecond Spectroscopy Laboratory
University of Texas at Austin

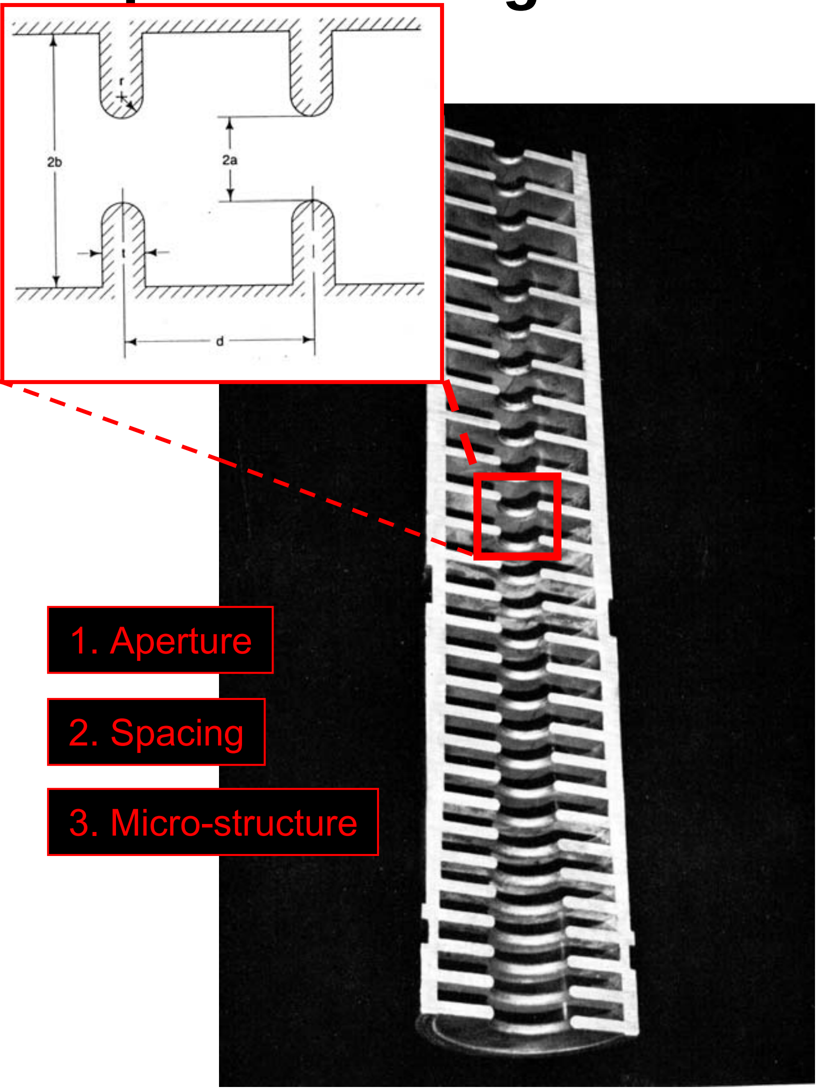
Collaborators

S. Kalmykov, G. Shvets
University of Texas at Austin

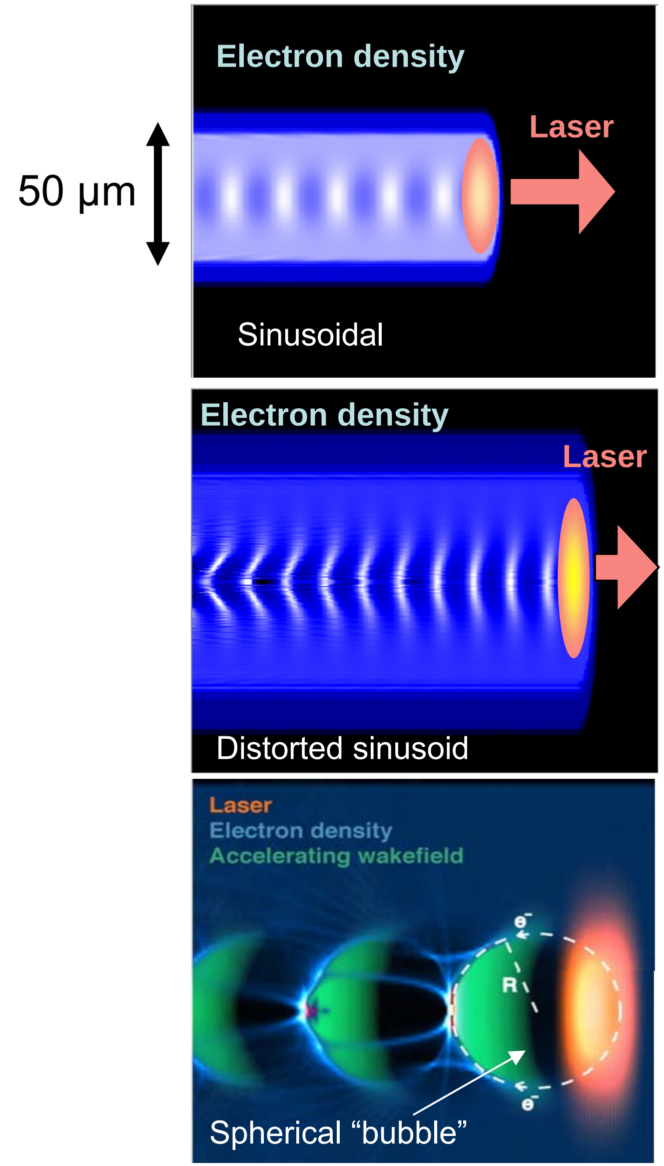
S. Reed, S. S. Bulanov, V. Chvykov,
G. Kalintchenko, P. Rousseau, T. Matsuoka,
A. Maksimchuk and V. Yanovsky

FOCUS Center and Center for Ultrafast Optical Science
University of Michigan

Copper RF accelerator cavities must be precision-engineered



Simulations show widely varying plasma wake structures...

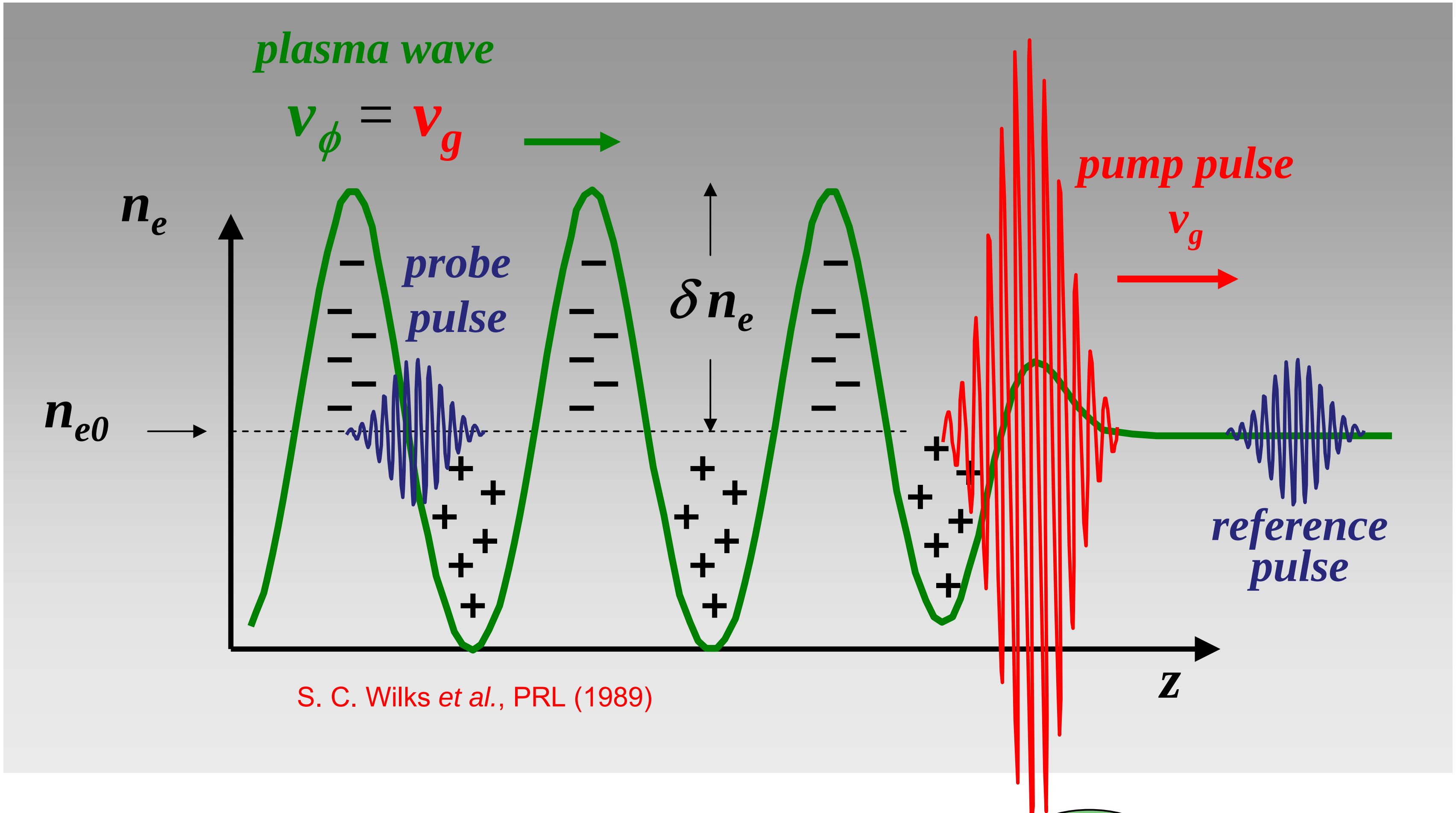


...BUT we can’t even see them!

Outline

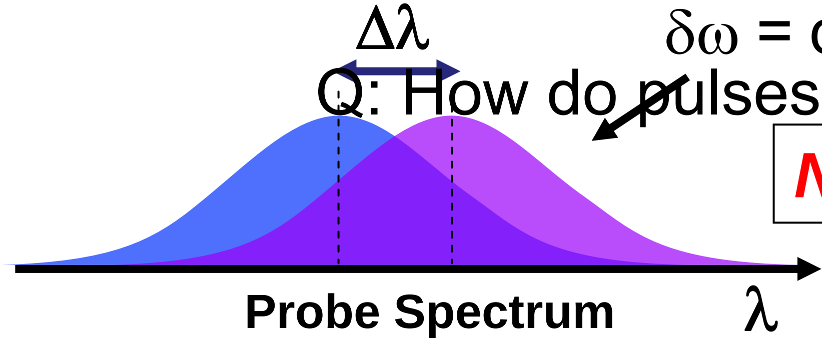
- Overview on Frequency Domain Wakefield Diagnostic
- New Single-shot Wakefield Measurements
- Applications of FD Holography to Accelerator Issues

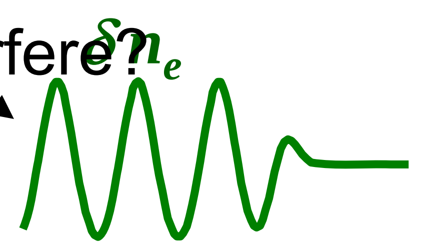
Photon Acceleration



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

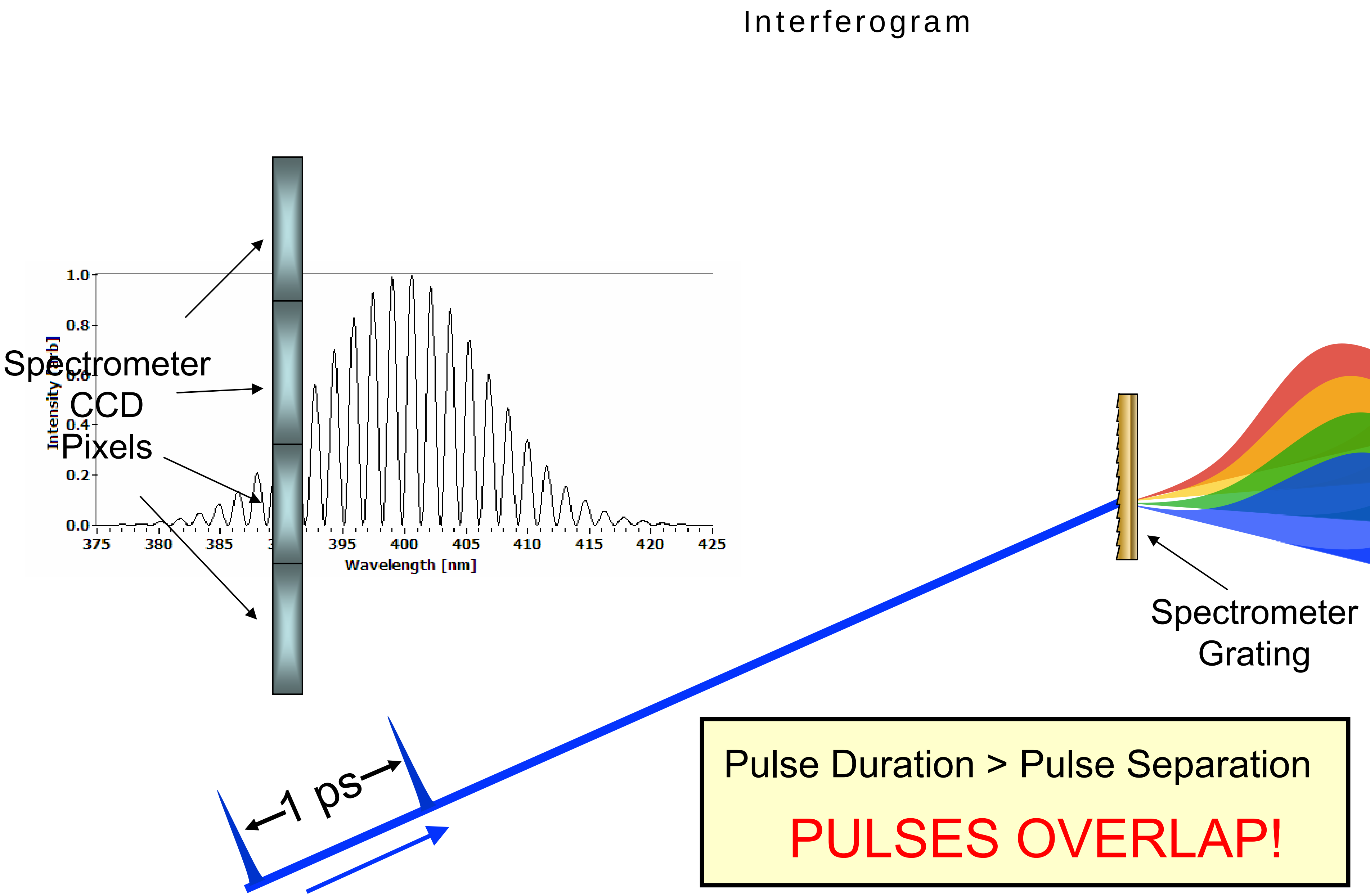
Q: How do pulses that don't overlap interfere?





Not very sensitive

FDI: Temporal Overlap in Spectrometer



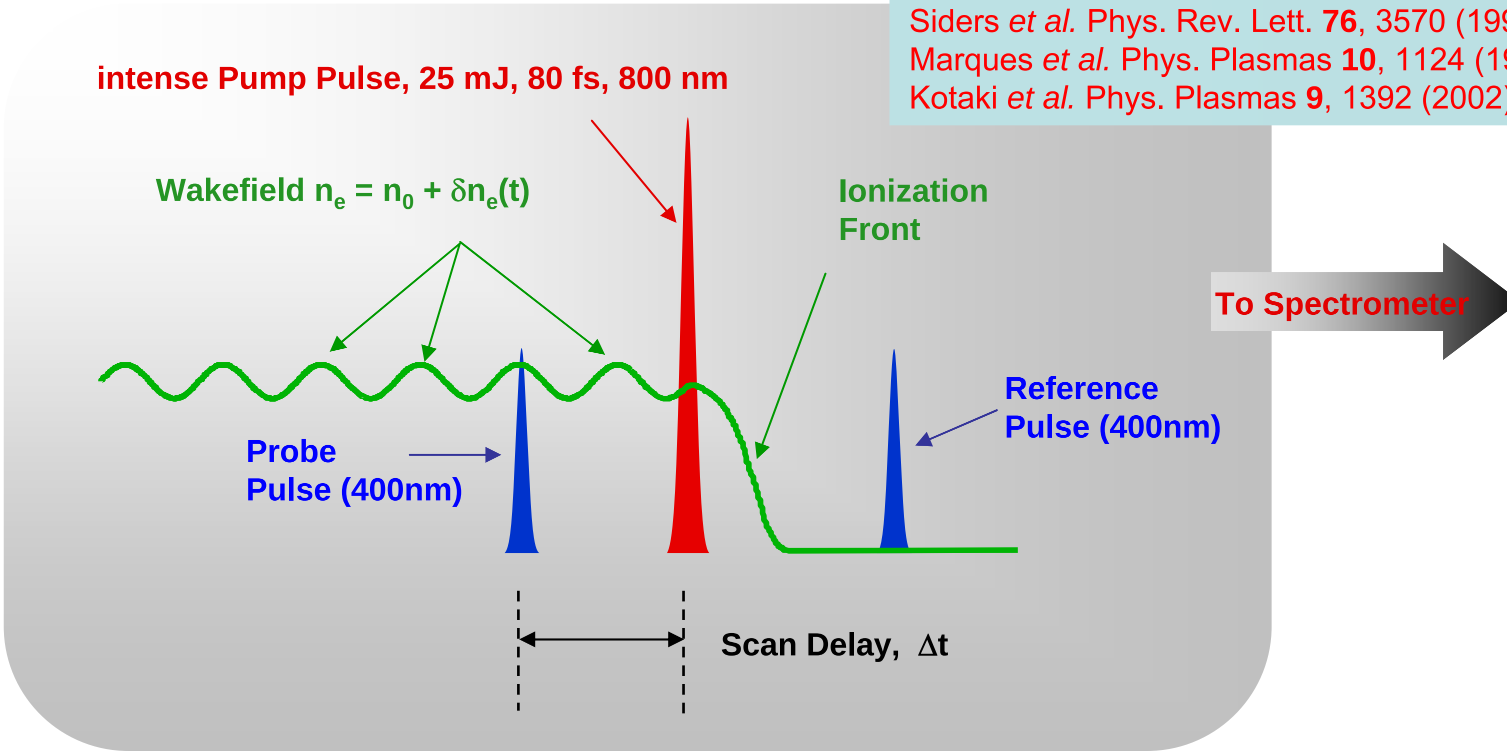
Pulse Duration > Pulse Separation

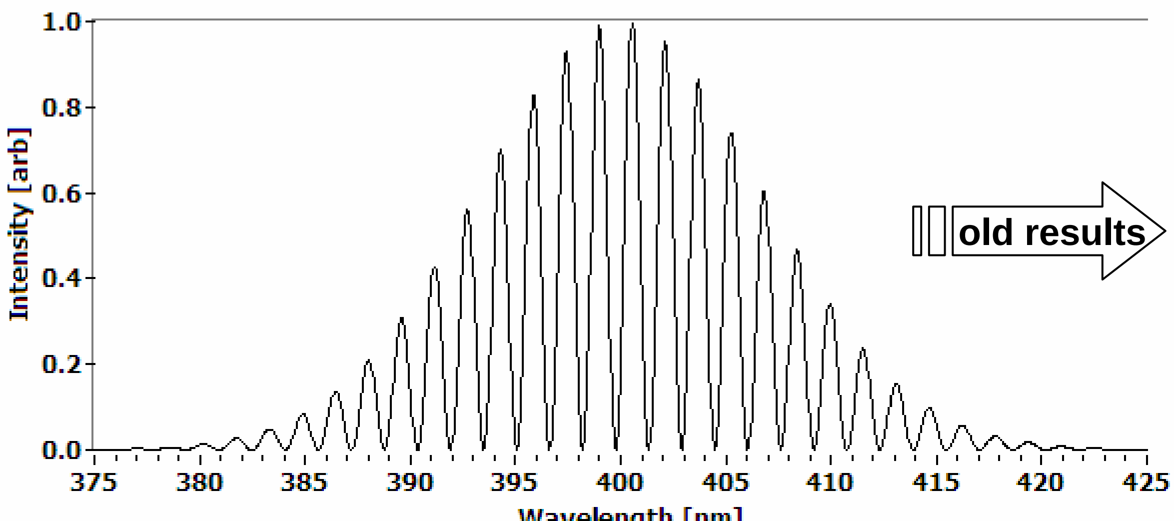
PULSES OVERLAP!

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

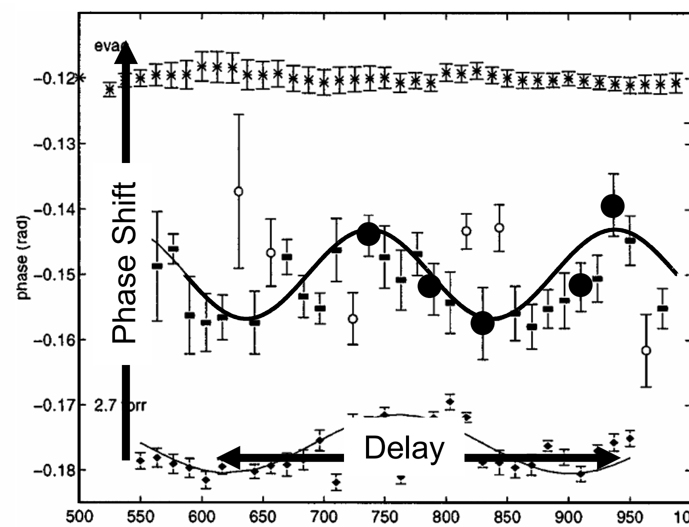
Siders *et al.* Phys. Rev. Lett. **76**, 3570 (1996)
Marques *et al.* Phys. Plasmas **10**, 1124 (1998)
Kotaki *et al.* Phys. Plasmas **9**, 1392 (2002)

Craig Siders
now at LLNL





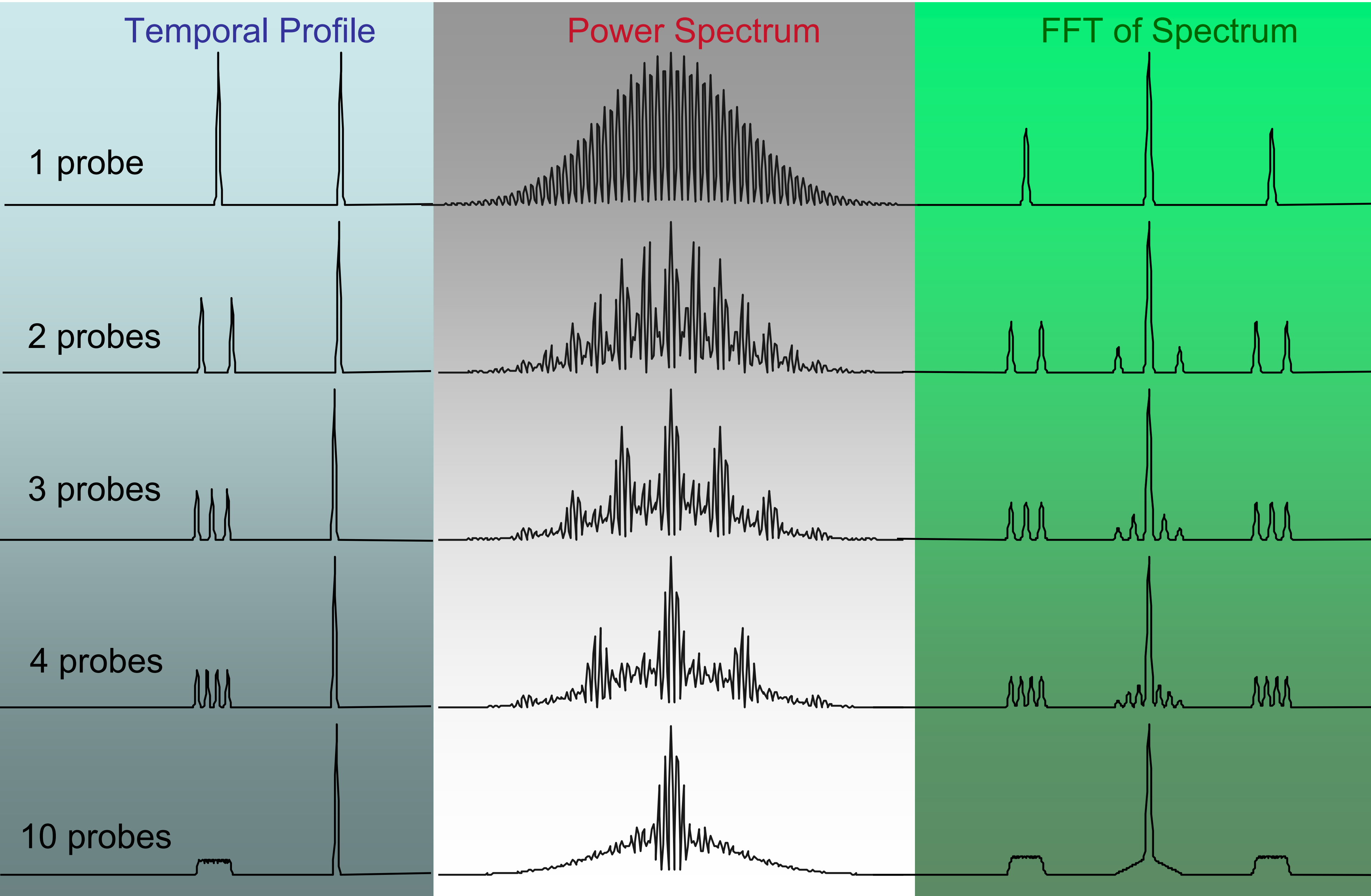
old results



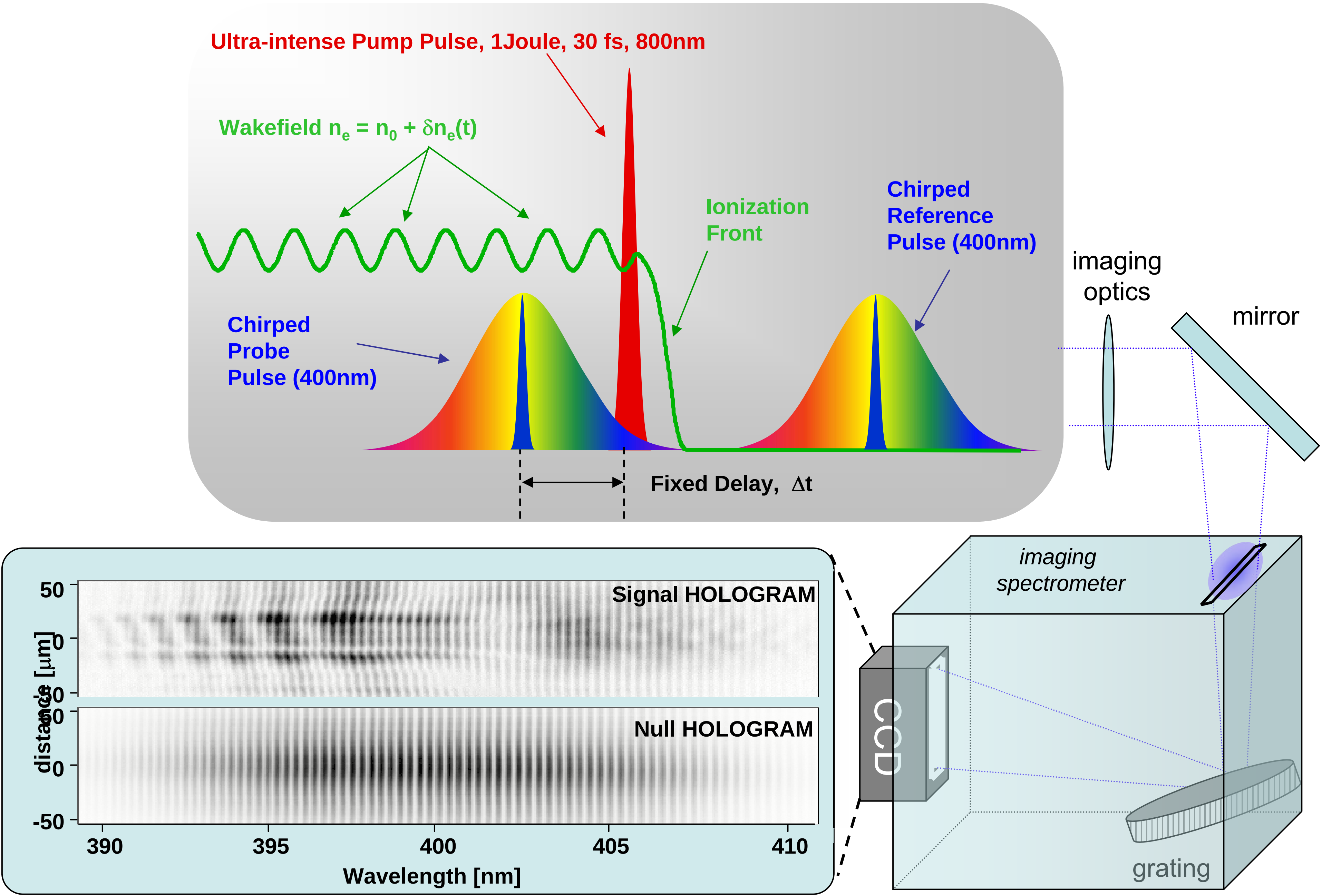
FD Interferometry → FD Holography

C. W. Siders *et al. Phys. Rev. Lett.* 76, 3570 (1996)

S. P. LeBlanc *et al. Opt. Letters* 25, 764 (2000)



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



“Reading” the Hologram

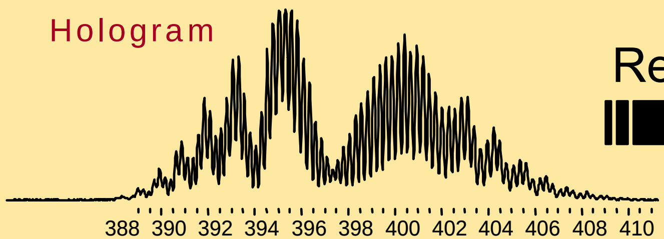
(Full Electric Field Reconstruction)

BASIC SCHEME

RECONSTRUCTION

TIME DOMAIN

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



Read →

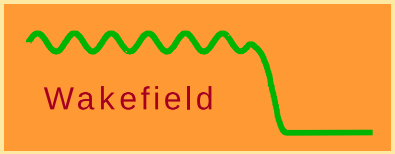
$E_{probe}(\omega) = |E(\omega)|\, e^{-i\phi(\omega)}$

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

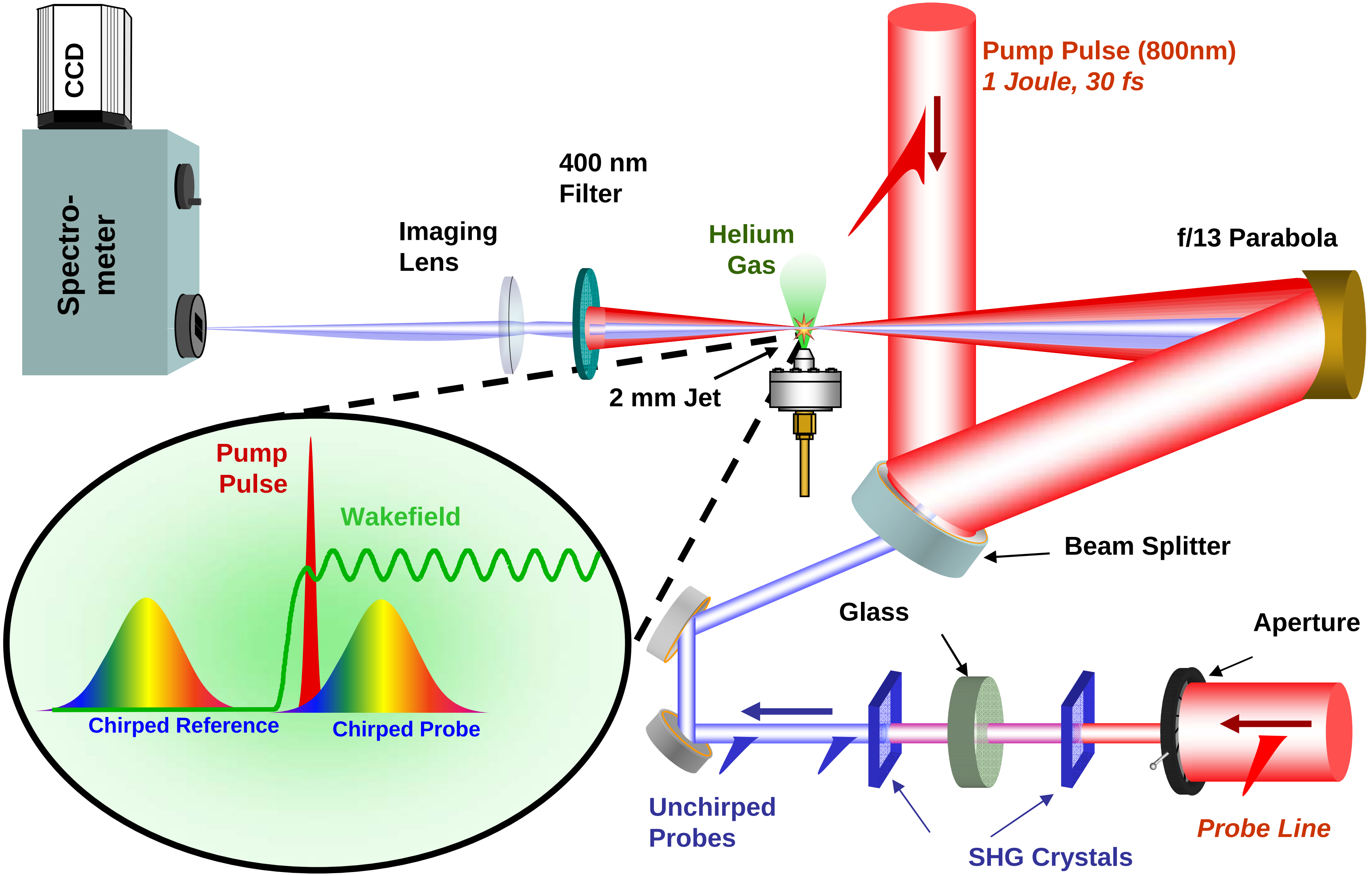
$E_{probe}(\omega)$ —FFT→ $E_{probe}(t) = |E(t)|\, e^{-i\delta\phi(t)}$

3. Calculate electron density from extracted temporal phase

$\delta\phi(t)$ —index→ $\delta n_e(t)$



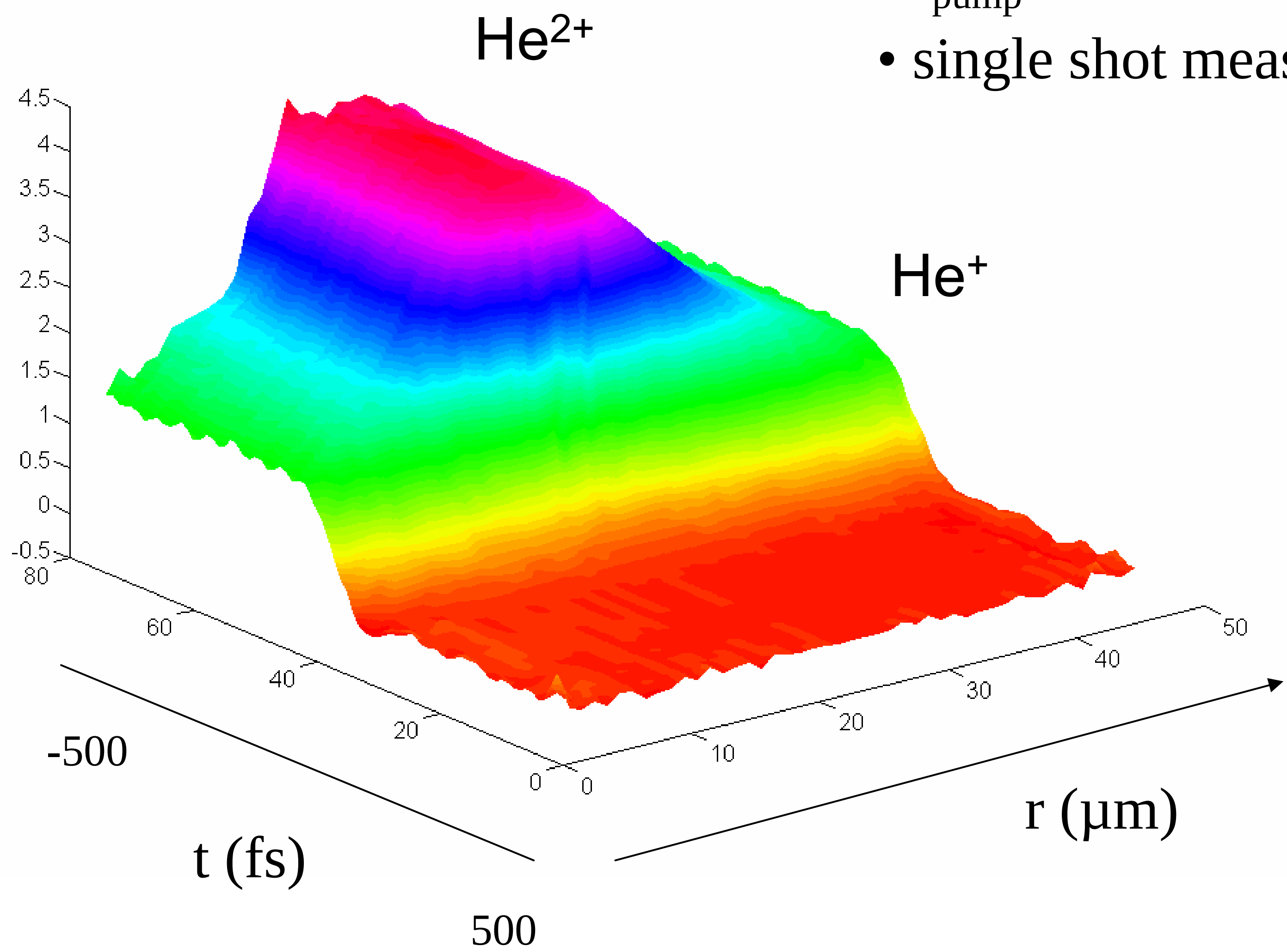
Experimental Layout



Holographic snapshot of an ionization front

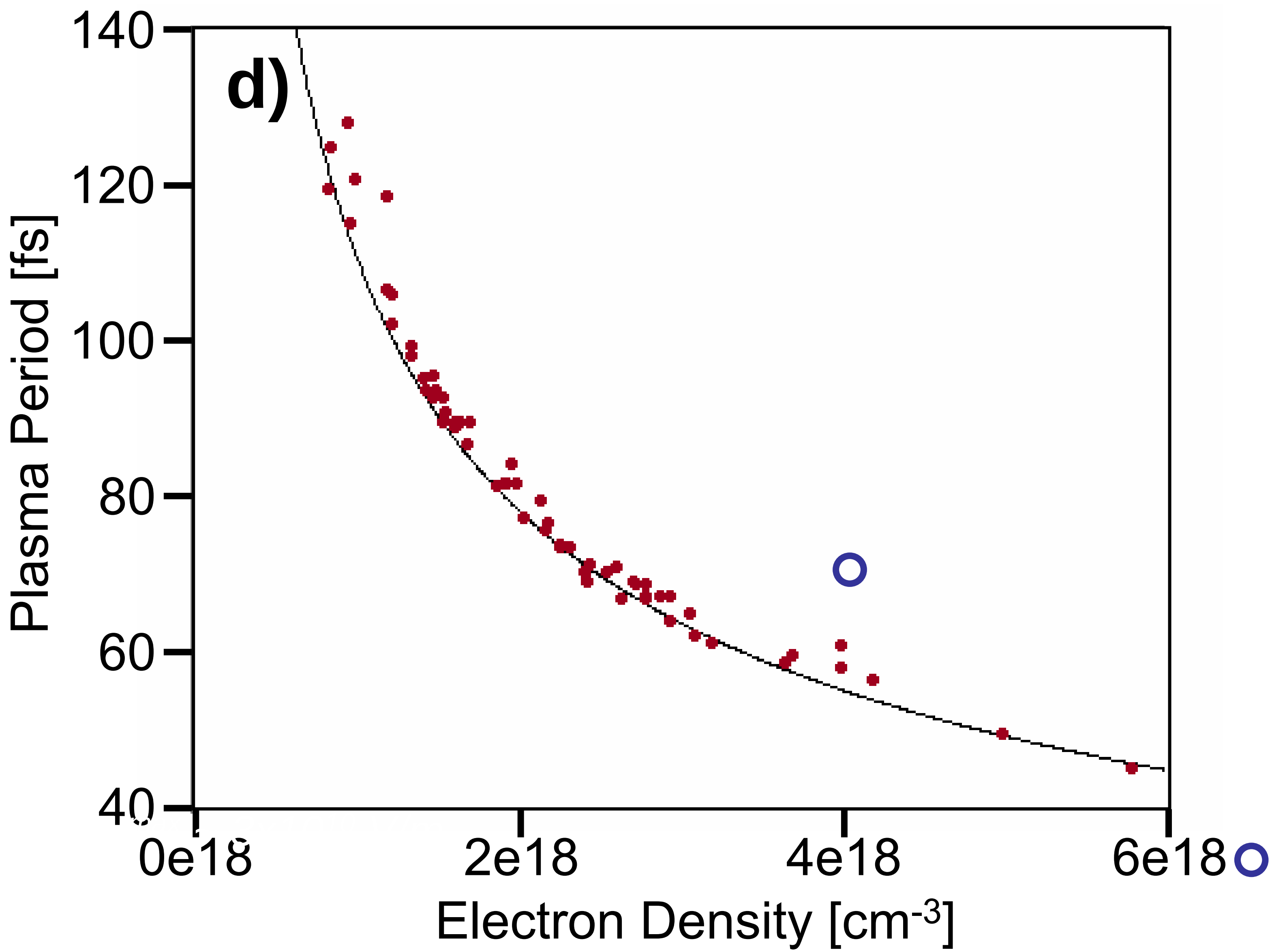
LeBlanc, Matlis, MCD, *Optics Letters* **25**, 764 (2000)
Kim, Alexeev, Milchberg, *Appl. Phys. Lett.* **81**, 4124 (2002)

- $I_{pump} = 10^{16}$ W/cm^2
- single shot measurement



Holographic snapshots of laser wakefields

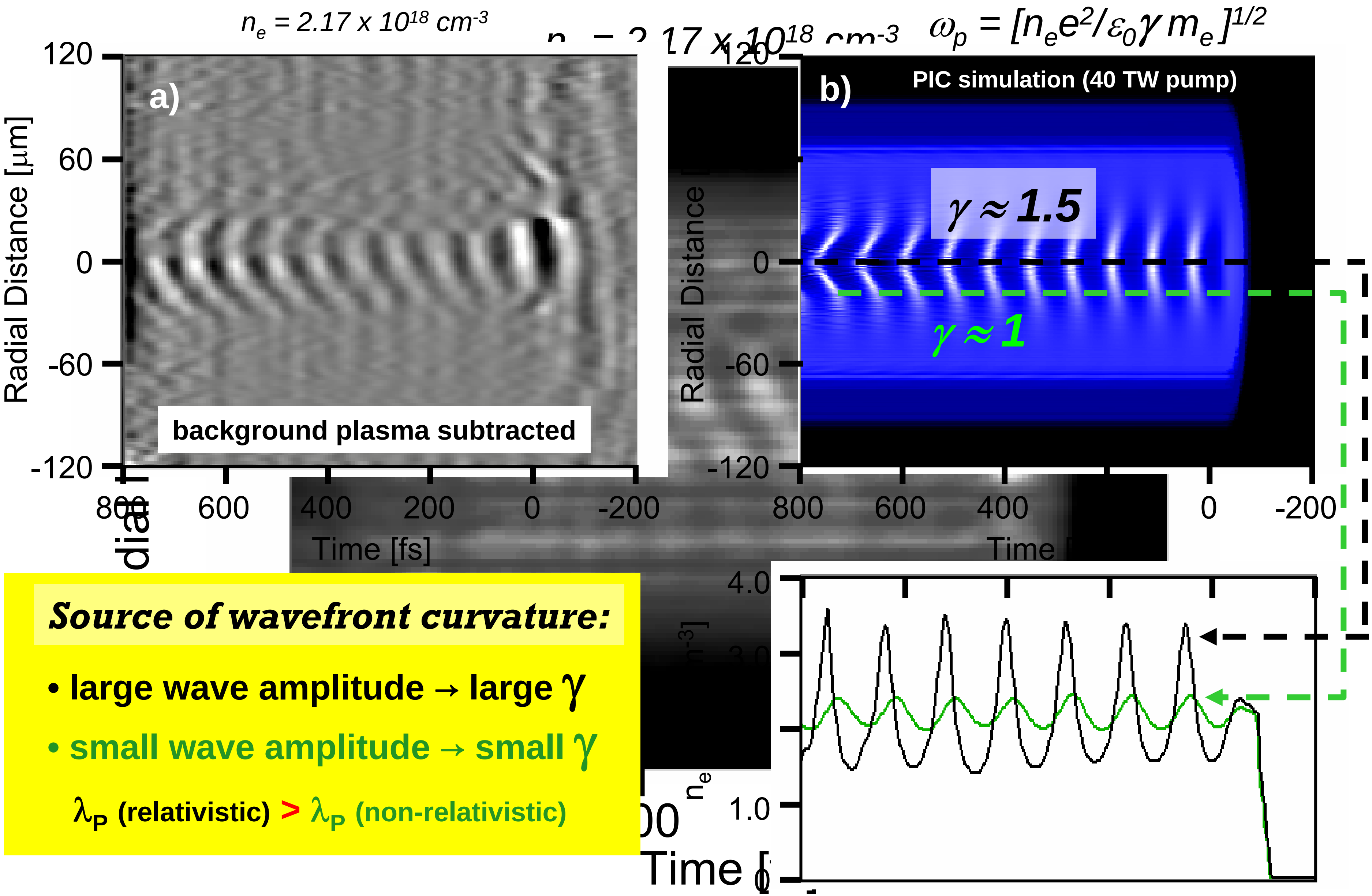
P ~10 TW, I ~ 10^{18} W/cm²



Strong wakes have curved wavefronts

P ~30 TW, I ~ 3 x 10^{18} W/cm²

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

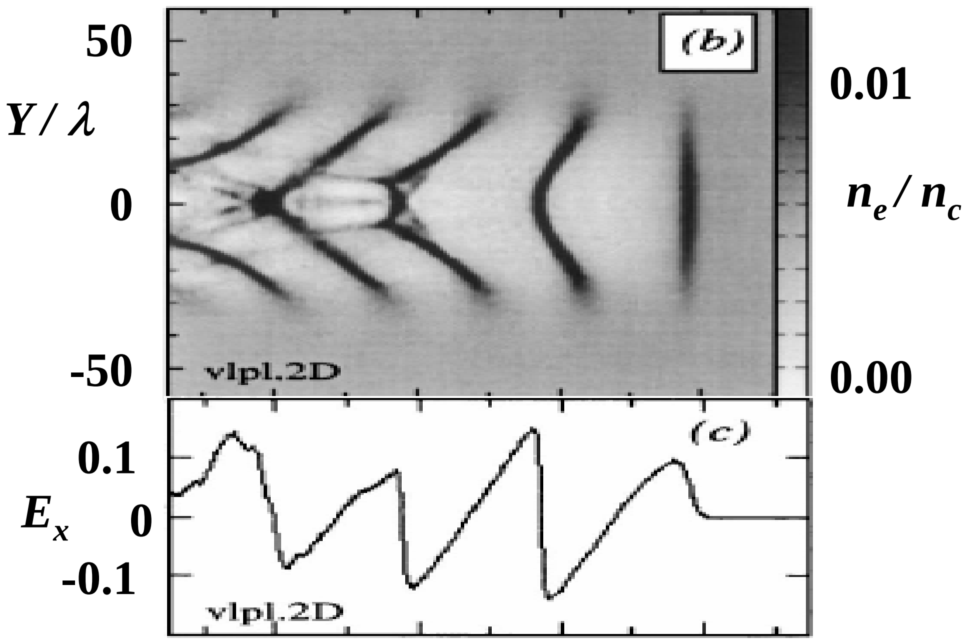


Source of wavefront curvature:

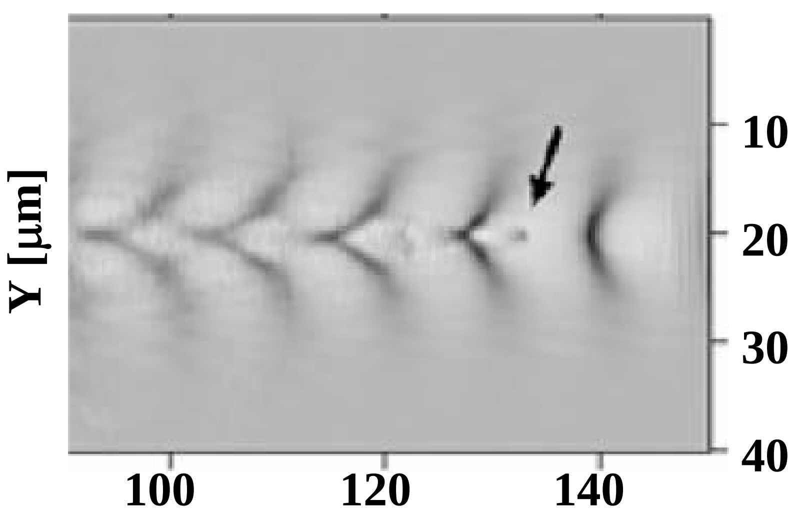
- **large wave amplitude → large γ**
- **small wave amplitude → small γ**

λ_P (relativistic) > λ_P (non-relativistic)

Importance of Wavefront Curvature



S. V. Bulanov et al, PRL **78**, 4205 (1997)



P. Tomassini et al, Phys Rev ST-AB, **6,** 121301 (2003)

- **relativistic dependence of ω_p on the plasma wave amplitude**

  (yields estimate of γ – factor of wave)

- **Crossing of e- trajectories leads to wavebreaking**

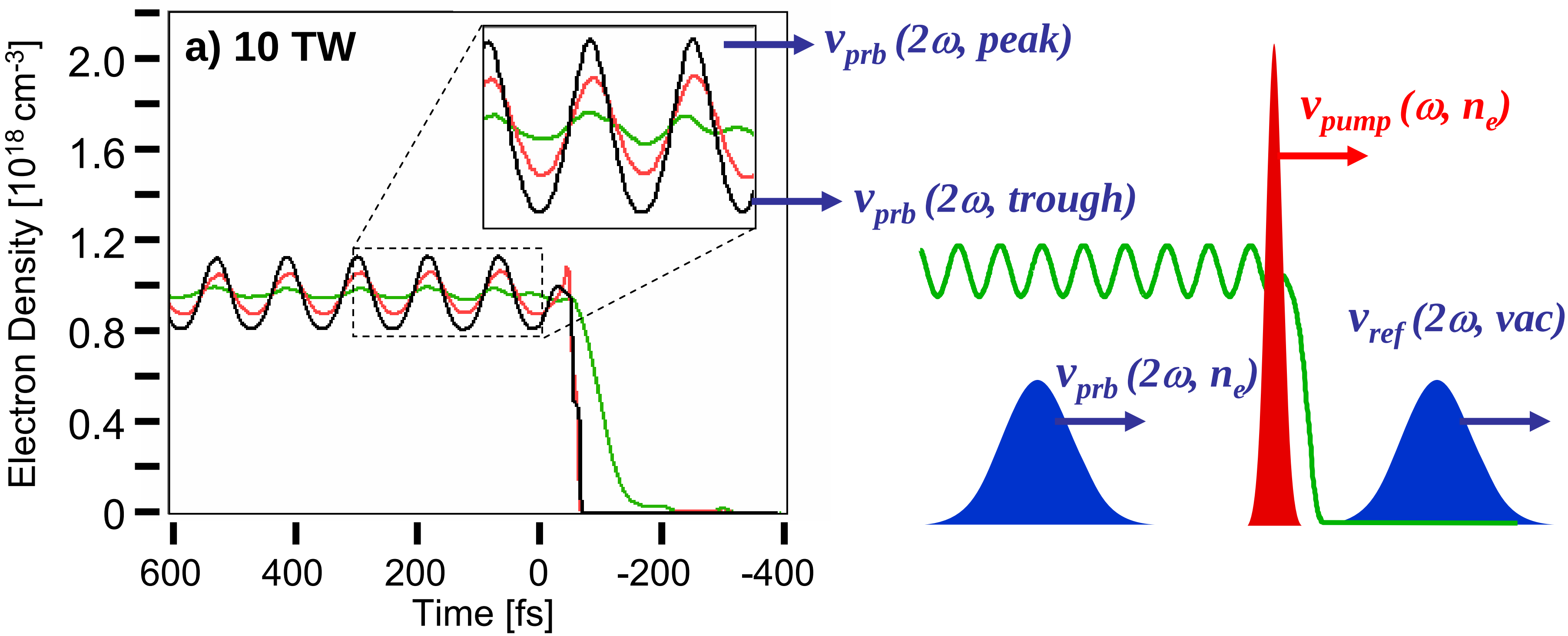
- **electron injection**

- **Curvature increases the overlap between the accelerating and focusing regions of the wave**

- **e – bunch can reach dephasing without defocusing**

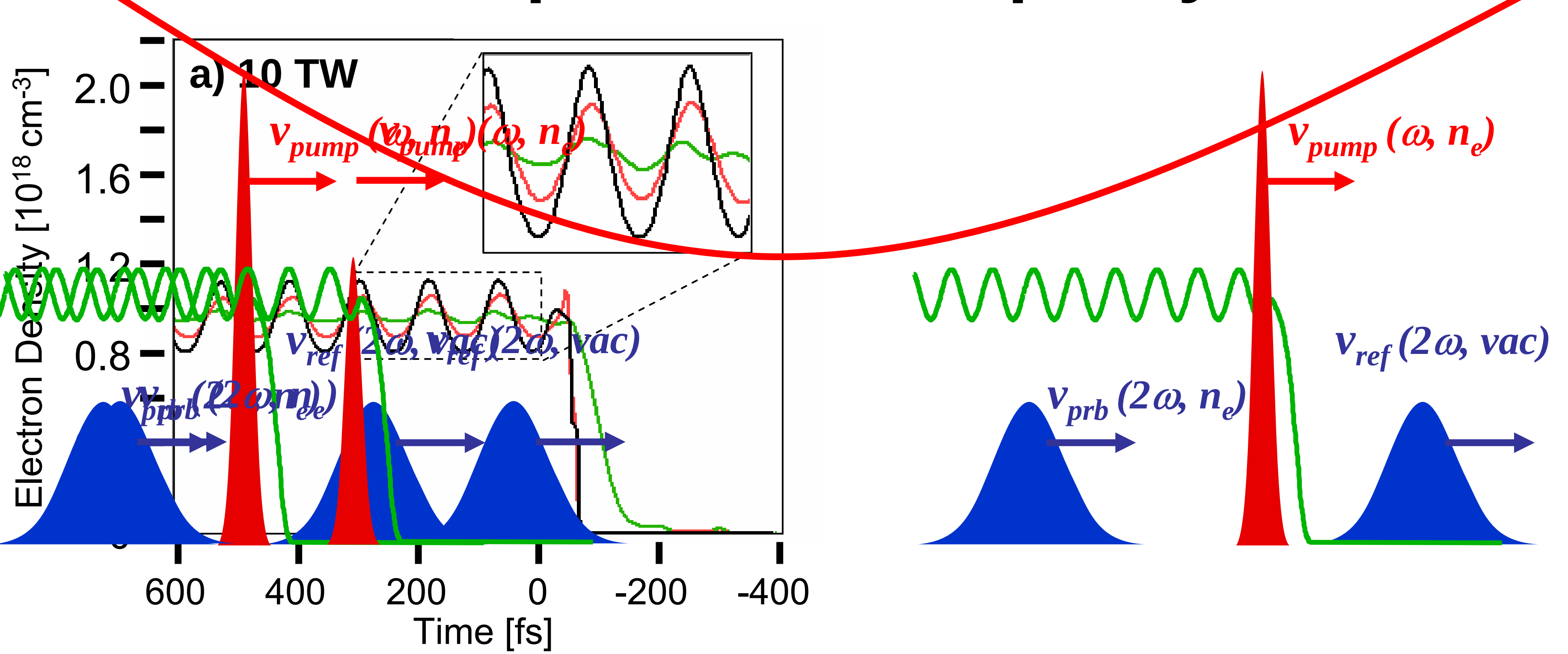
  (compresses bunch energy spectrum)

Amplitude Discrepancy



- **Group Velocity Dispersion:** $v_{group}(\omega, n_e) \neq$ ***constant***
  - **Pulse Walk-off:** $v_{pump}(\omega, n_e) \neq v_{prb}(2\omega, n_e) \neq v_{ref}(2\omega, vac)$
  - **Density Dependent Velocity:** $v_{prb}(2\omega, peak) \neq v_{prb}(2\omega, trough)$
  - **Velocity Dependent Index:** $\eta = \eta(\gamma)$
- **Longitudinal Averaging:** $\delta n_e(\zeta, z) \neq$ ***constant***
  - **Pump Evolution** **(i.e. focusing)**
  - **Density Evolution** **(i.e. gas jet profile)**
  - **Wake Evolution** **(e.g. wave breaking & beam loading)**

Amplitude Discrepancy



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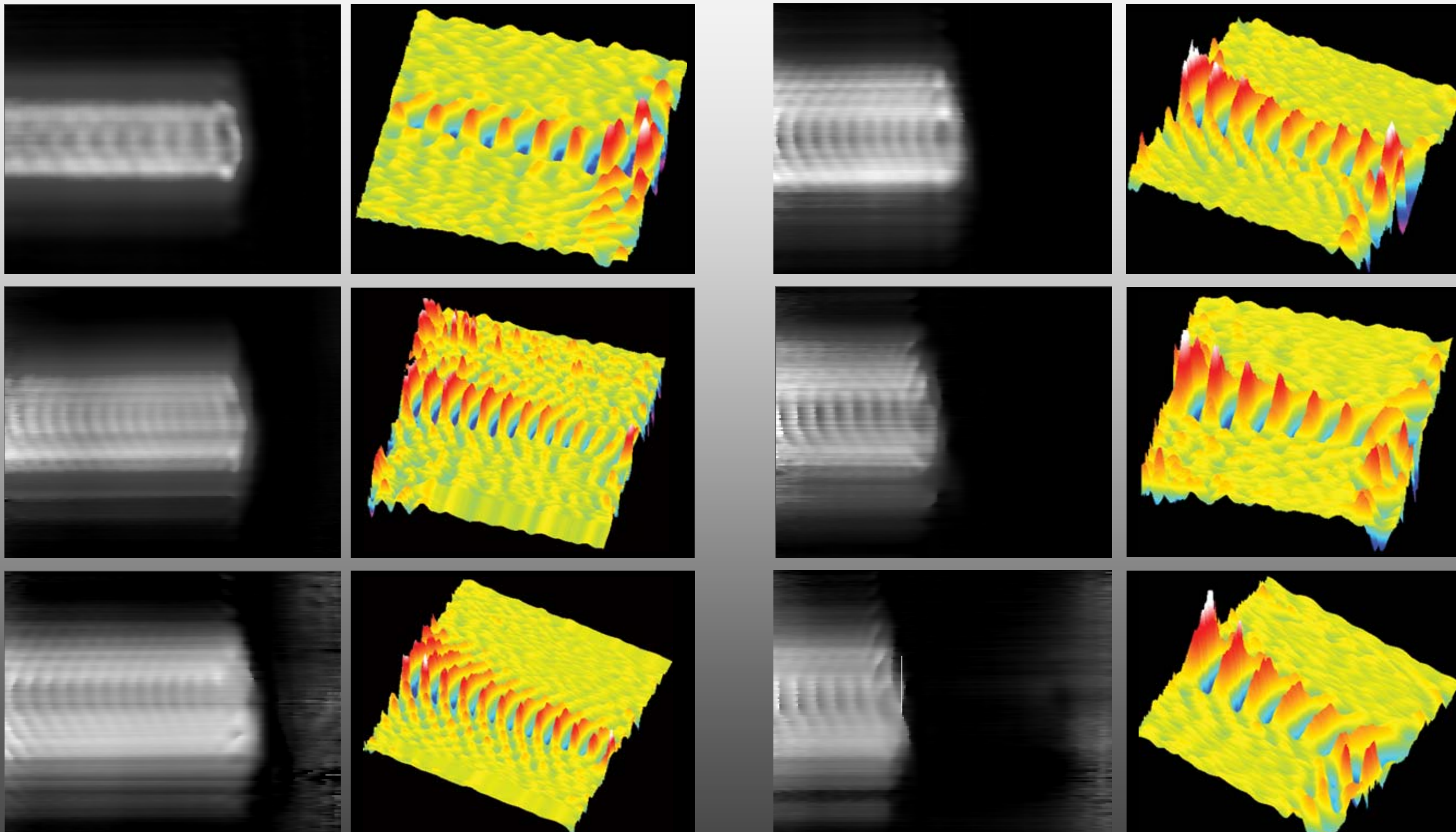
  - **Wake Evolution** **(e.g. wave breaking & beam loading)**
  - **Density Evolution** **(i.e. gas jet profile)**

Wakefield Photo Gallery

Density Graph	3D Map	Density Graph	3D Map



Applying FDH to other accelerator issues

- ❑ **Compare Simulation and Measurement of Wake Structure (WG1)**
- ❑ **Correlate Wake Structure with Beam Properties (WG5)**
- ❑ **Characterize Beam-driven Wakefields (WG4)**
- ❑ **Characterize Channeled Wakefields (WG6b)**

(WG1) Comparing Simulation and Observation

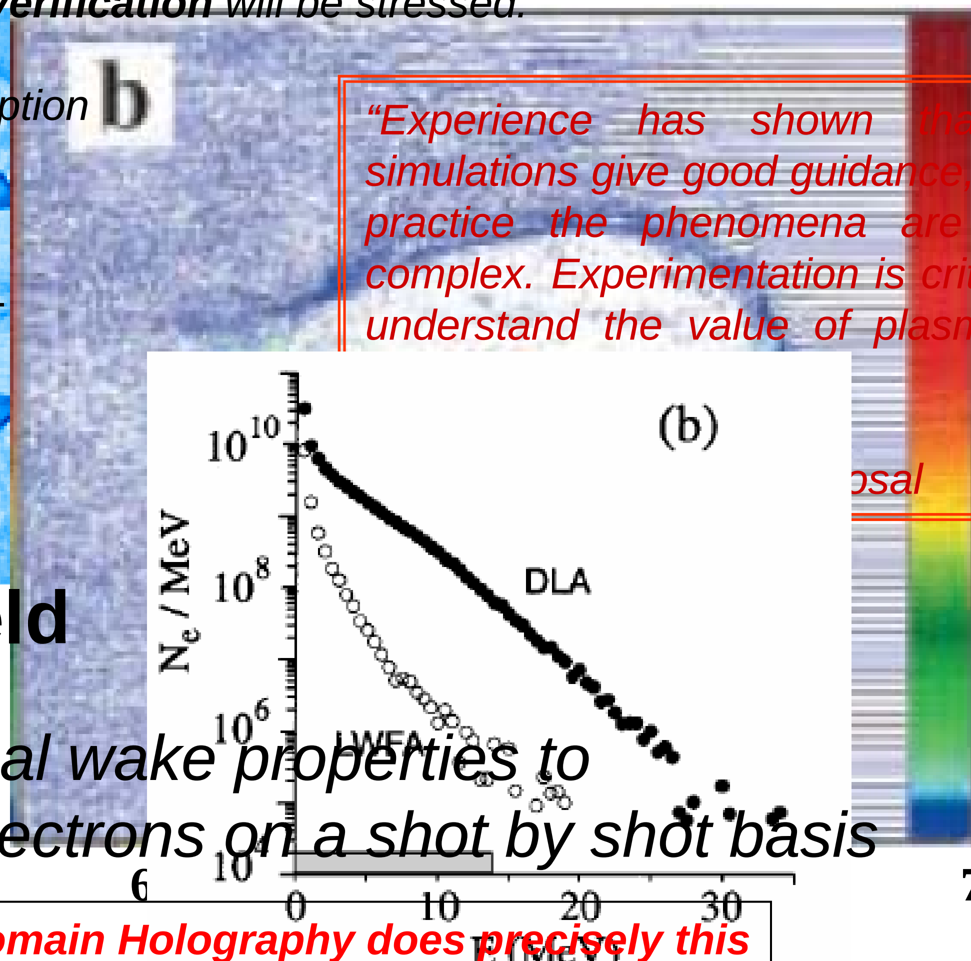
*"…we will emphasize the important connections between **simulation**, **theory** and **experimental data**. In particular, the vital and difficult issues of **code validation and verification** will be stressed."*

-Working Group 1 Description

• Wavebreaking

Courtesy S.S. Bulanov

- **Bubble Formation**
- **Direct vs. Wakefield Acceleration**



"Experience has shown that the simulations give good guidance, but in practice the phenomena are more complex. Experimentation is critical to understand the value of plasmas to …osal

Correlate actual wake properties to accelerated electrons on a shot by shot basis

Frequency Domain Holography does precisely this

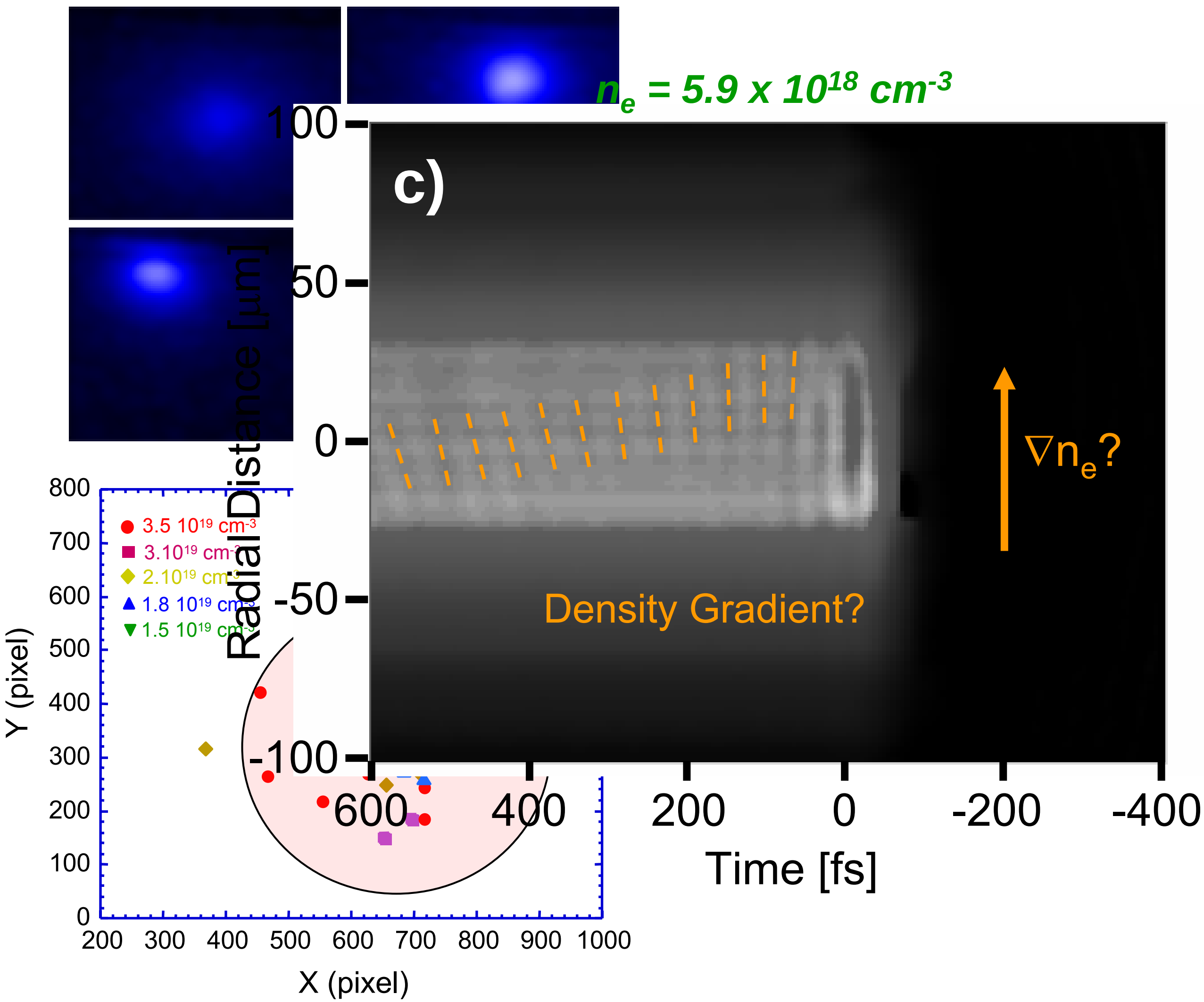
A. Pukhov et al, App Phys B, **74**, 355 (2002)

C. Gahn et al, PRL **83**, 4772 (1999)

2.5 million hours on NERSC
(National Energy Research Scientific Computer)

Estimated computing power required for 3D PIC simulation of 1 GeV channel-guided LWFA

(WG5) Correlating Wakefield Morphology to Electron Beam Characteristics



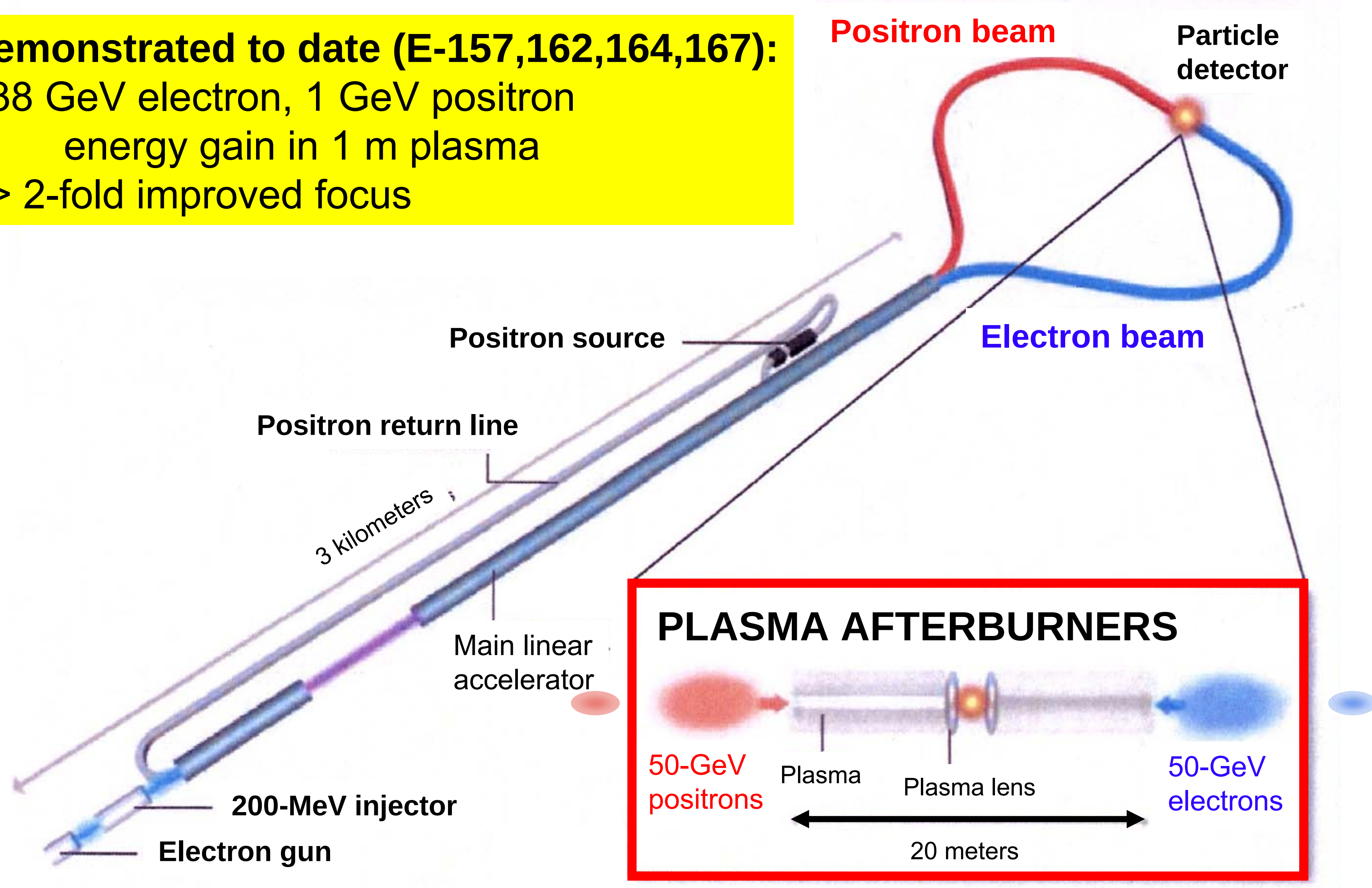
Hercules Laser System
courtesy, A. Maksimchuk

Wake diagnostics will be critical in fine-tuning plasma afterburners

Goal: Energy Doubling

C. Joshi, *Scientific American* (Feb 2006)

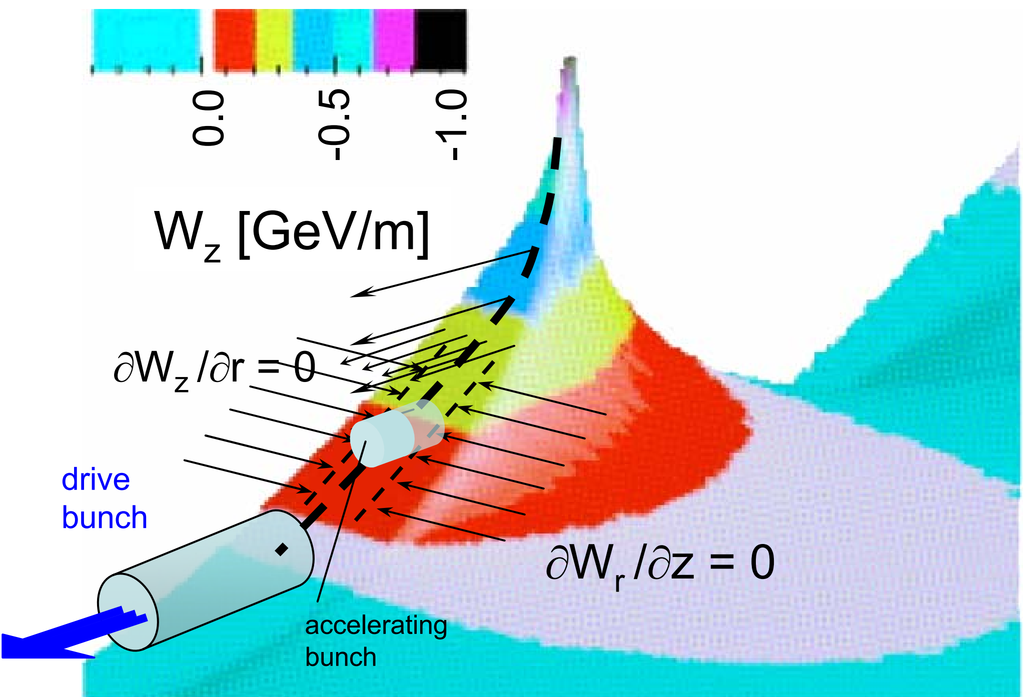
Demonstrated to date (E-157,162,164,167):
- 38 GeV electron, 1 GeV positron
  energy gain in 1 m plasma
- > 2-fold improved focus

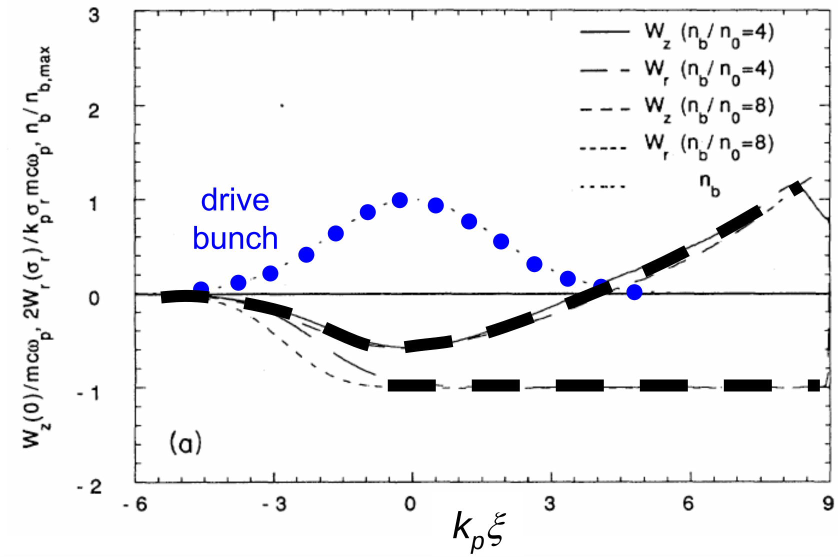


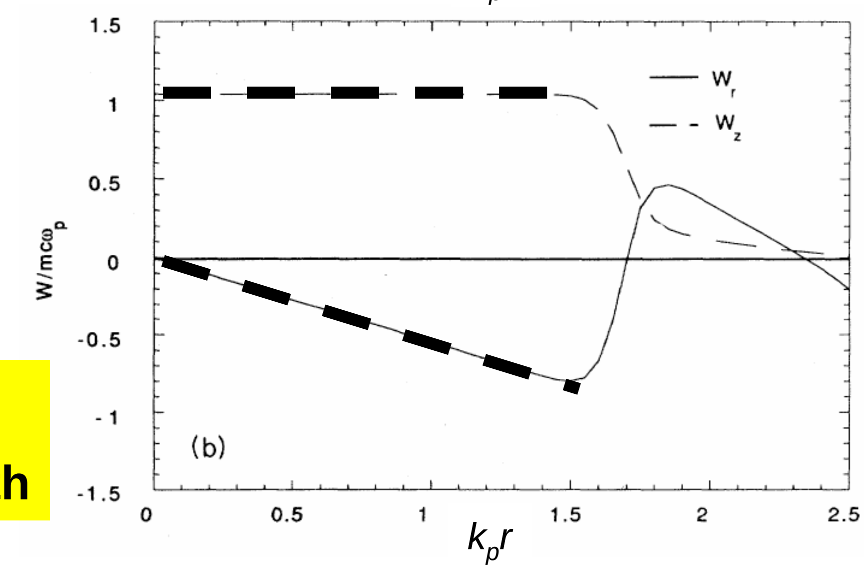
SLAC / UCLA / USC collaboration

For optimized bunch length $k_p\sigma_z = \sqrt{2}$, best PWFA is realized in the nonlinear "blowout" regime: $n_b >> n_0$ AND $k_p\sigma_r < 1$

Rosenzweig *et al*., Phys. Rev. A **44**, R6189 (1991)
Hemker *et al*., Phys. Rev. ST-AB **3**, 061301 (2000)





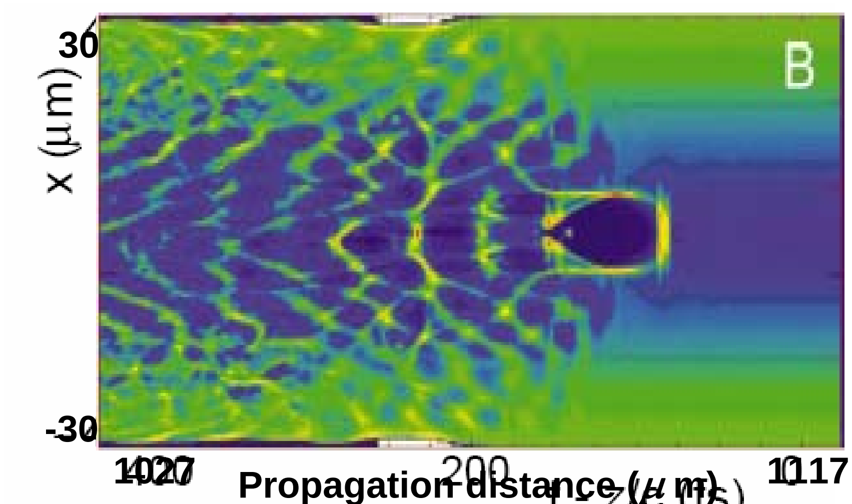


Desirable properties:

- **uniform accelerating field profile**
- **linear focusing force, independent of z**

⇒ drive pulse & trailing accelerating bunch propagate stably, w/ low emittance growth

FDH in a Channel

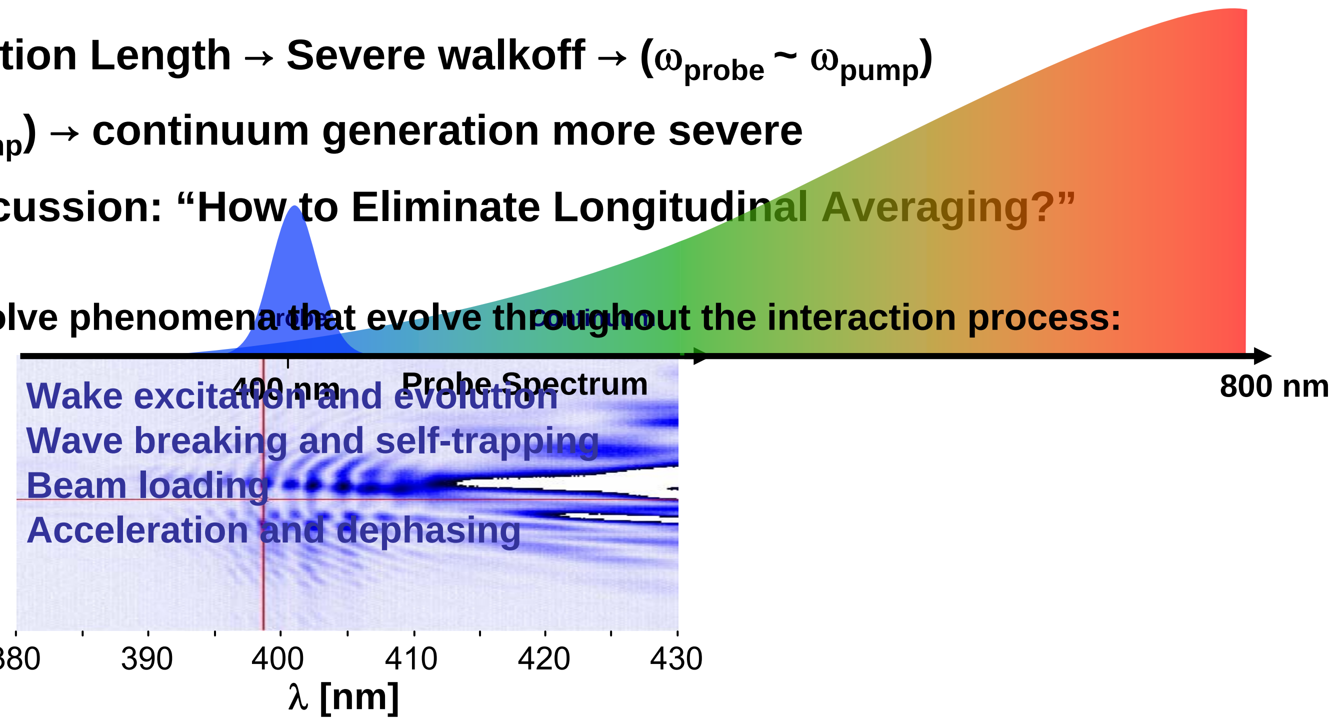


Geddes et al. Phys. Plasmas **12** 056709 (2005)

Reitsma et al., PRST-AB v5 p051301 (2002)

- Long Interaction Length → Severe walkoff → ($\omega_{probe} \sim \omega_{pump}$)
- ($\omega_{probe} \sim \omega_{pump}$) → continuum generation more severe
- Topic of Discussion: “How to Eliminate Longitudinal Averaging?”

Want to resolve phenomena that evolve throughout the interaction process:



- Wake excitation and evolution
- Wave breaking and self-trapping
- Beam loading
- Acceleration and dephasing

Summary of Experiment Results

1. **We have demonstrated the first real-time "snapshots" of laser wakefields**
   - up to 15 oscillations with sub- λ_P spatial resolution
   - wavefront evolution and curvature
   - dependence of wake morphology on laser-plasma conditions

2. **These features never previously observed, and determine key electron bunch properties:**
   - energy
   - energy spread
   - divergence
   - charge

Applying FDH to other accelerator issues

- **Comparison of Simulation and Experimental Data (WG1)**
- **Beam Control Analysis (WG5)**
- **Characterizing Beam-driven Wakefields (WG4)**
- **Extending FDH to channeled wakefields (WG6b)**
- **Application to exotic accelerator schemes (WG3)**

END

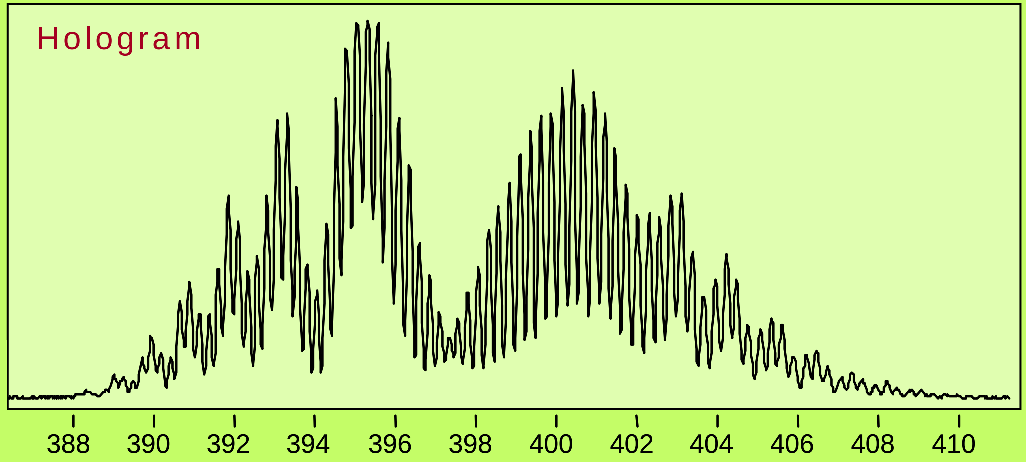
“Reading” the Hologram

(Full Electric Field Reconstruction)

BASIC SCHEME

RECONSTRUCTION

TIME DOMAIN



$$S_{holo}(\omega) = |E_{prb}(\omega)|^2 + |E_{ref}(\omega)|^2 + E_{prb}^*(\omega)E_{ref}(\omega) + E_{prb}(\omega)E_{ref}^*(\omega)$$

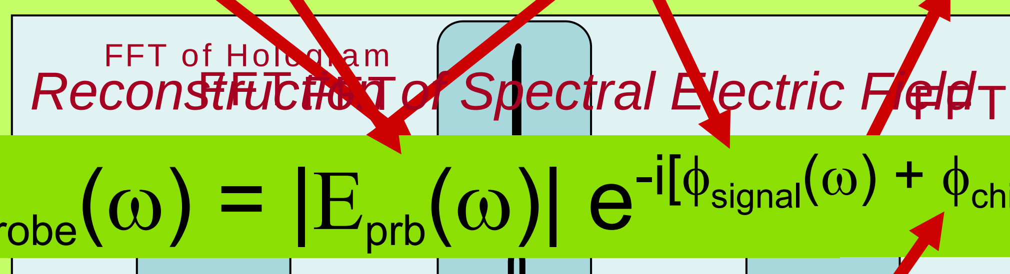
$$= |E_{prb}||E_{ref}|\,e^{i\phi_{signal}(\omega)}$$

from FFT side peak

Reconstruction of Spectral Electric Field

FFT

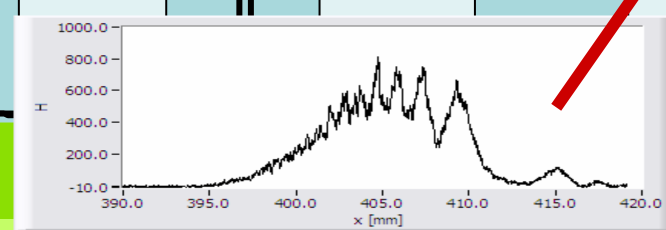
FFT^{-1}



$$E_{probe}(\omega) = |E_{prb}(\omega)|\, e^{-i[\phi_{signal}(\omega) + \phi_{chirp}(\omega)]}$$

separate XPM measurement

$\phi_{prb}(\omega)$



“Reading” the Hologram

(Full Electric Field Reconstruction)

BASIC SCHEME

RECONSTRUCTION

TIME DOMAIN

$$E_{probe}(\omega) = |E_{prb}(\omega)|\, e^{-i[\phi_{signal}(\omega) + \phi_{chirp}(\omega)]}$$

Time-Domain ↓ FFT

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

Index of Refraction ↓

$$\delta\eta(t) = \frac{c}{\omega L_{INT}} \delta\phi(t)$$

electron density ↓

$$n_e(t) = n_{crit}[1 - \eta^2(t)]$$

Probe and Electron Beam Imaging Layout