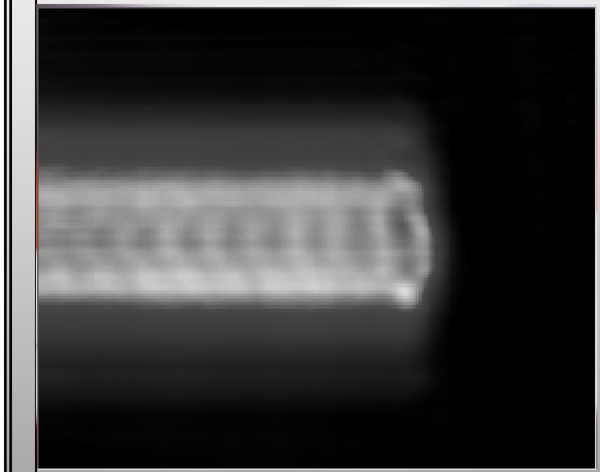
Seeing is Believing:

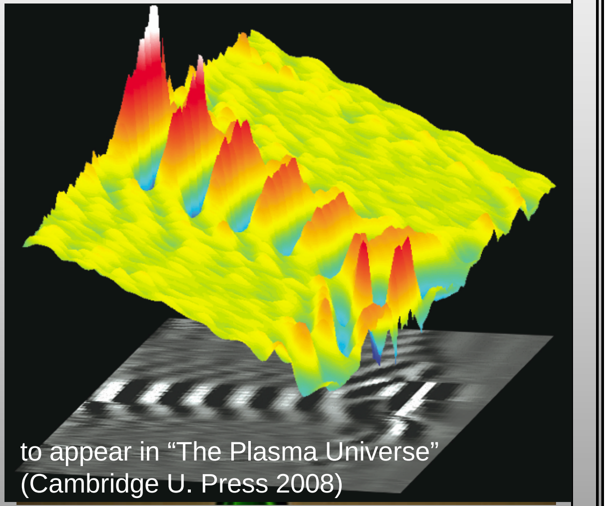
Laboratory Visualization of Laser Wakefields

Lasers and Accelerators: Particle Acceleration with High Intensity Lasers
Stellenbosch Institute of Advanced Study Stiαs
15 January 2009



Mike Downer

Laser-plasma experiments:
lecture 4 of 4



to appear in “The Plasma Universe”
(Cambridge U. Press 2008)

Collaborators

**Nicholas Matlis,* Peng Dong,
Steve Reed, Xiaoming Wang,
S. Kalmykov, G. Shvets**
University of Texas at Austin
*Ph.D. ‘06, currently at LBNL

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

Center for Ultrafast Optical Science, University of Michigan

Laser-Plasma Electron Accelerator

Tajima & Dawson, Phys. Rev. Lett. ***43,*** *267 (1979)*

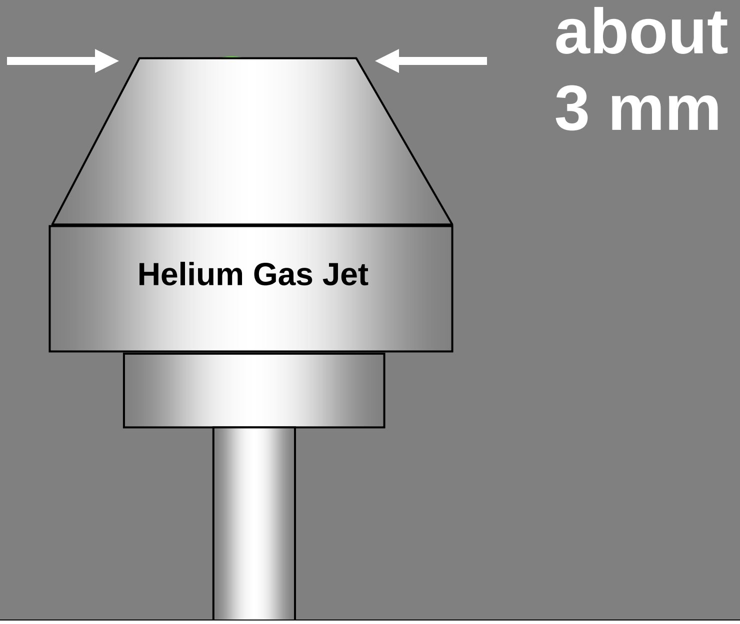
INVISIBLE

Gas Jet Fires

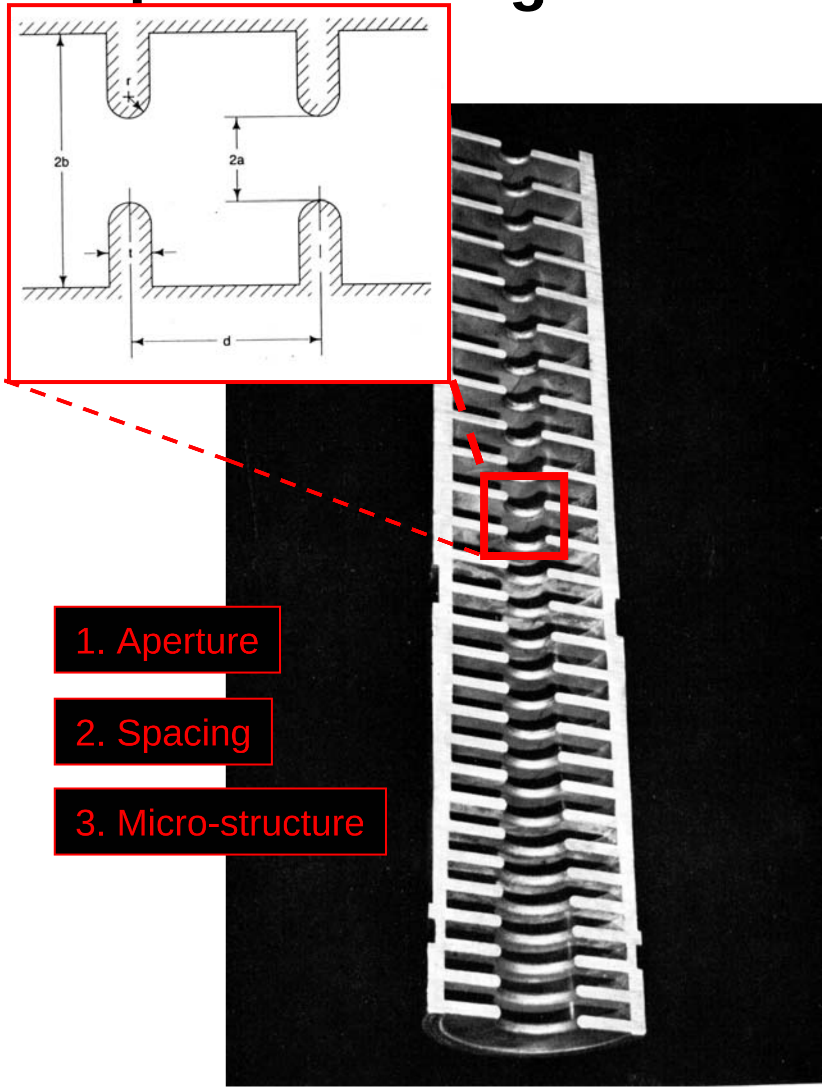
Laser Pulse Focuses

Ionize Gas & Make Wave

Wave Captures and
Accelerates Electrons



Copper RF accelerator cavities must be precision-engineered

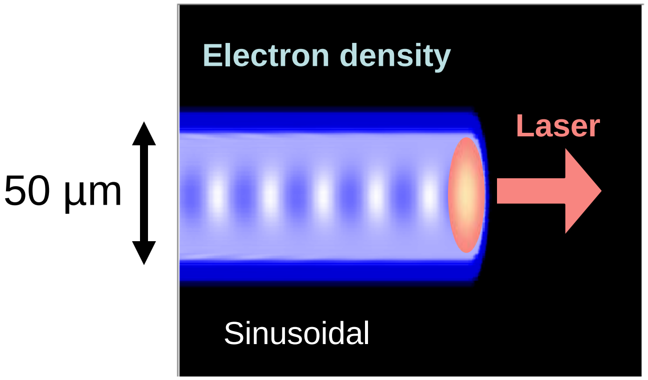


1. Aperture

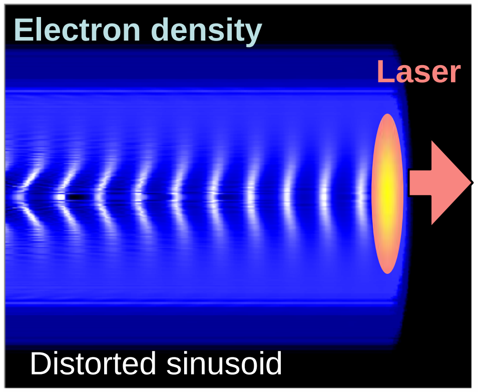
2. Spacing

3. Micro-structure

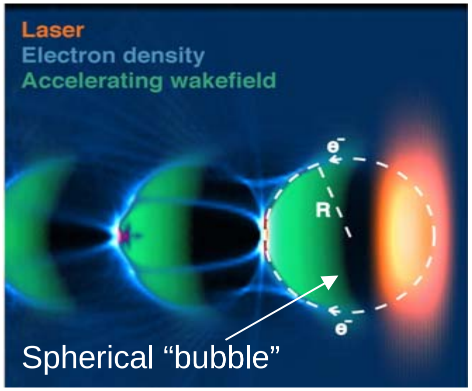
Simulations show widely varying plasma wake structures...



Sinusoidal



Distorted sinusoid



Spherical “bubble”

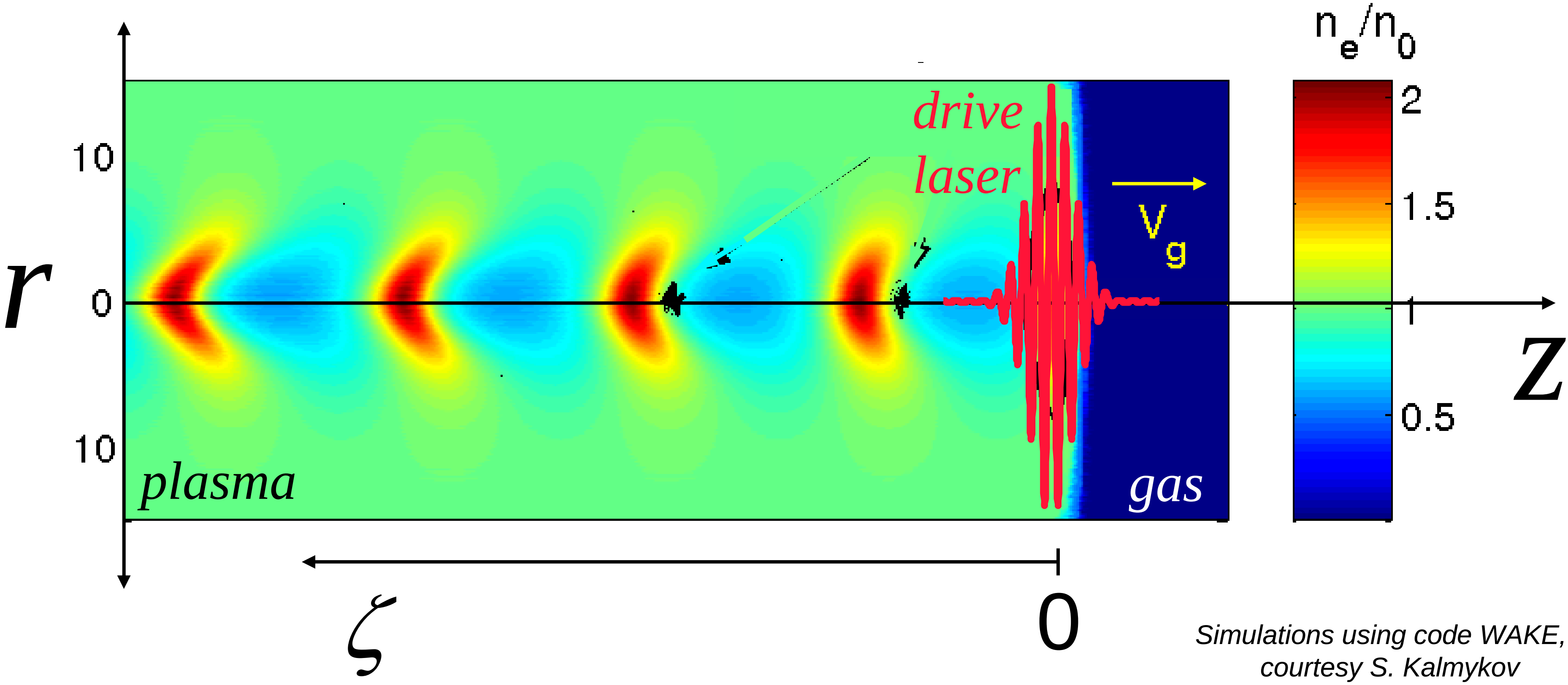
...BUT we can’t even see them!

DoE’s $0.5 M challenge
to me (ca. 1995):

Take a picture of a wakefield

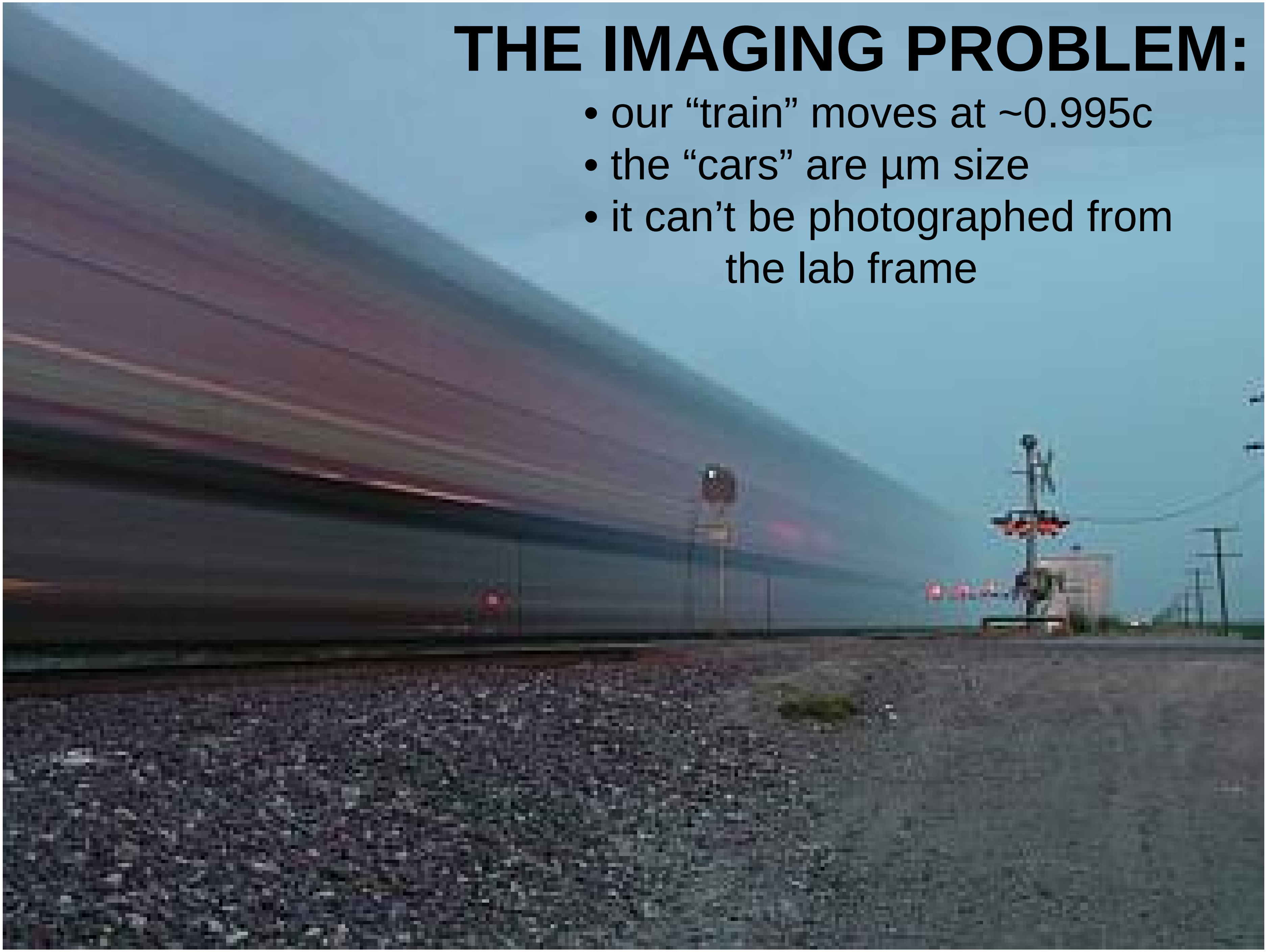
Visualization of quasi-static plasma structures:

$$n_e(r,\zeta,z) \approx n_e(r,\zeta)$$



*Simulations using code WAKE,**
courtesy S. Kalmykov

***Mora & Antonsen, *Phys. Plasmas* 4, 217 (97)**



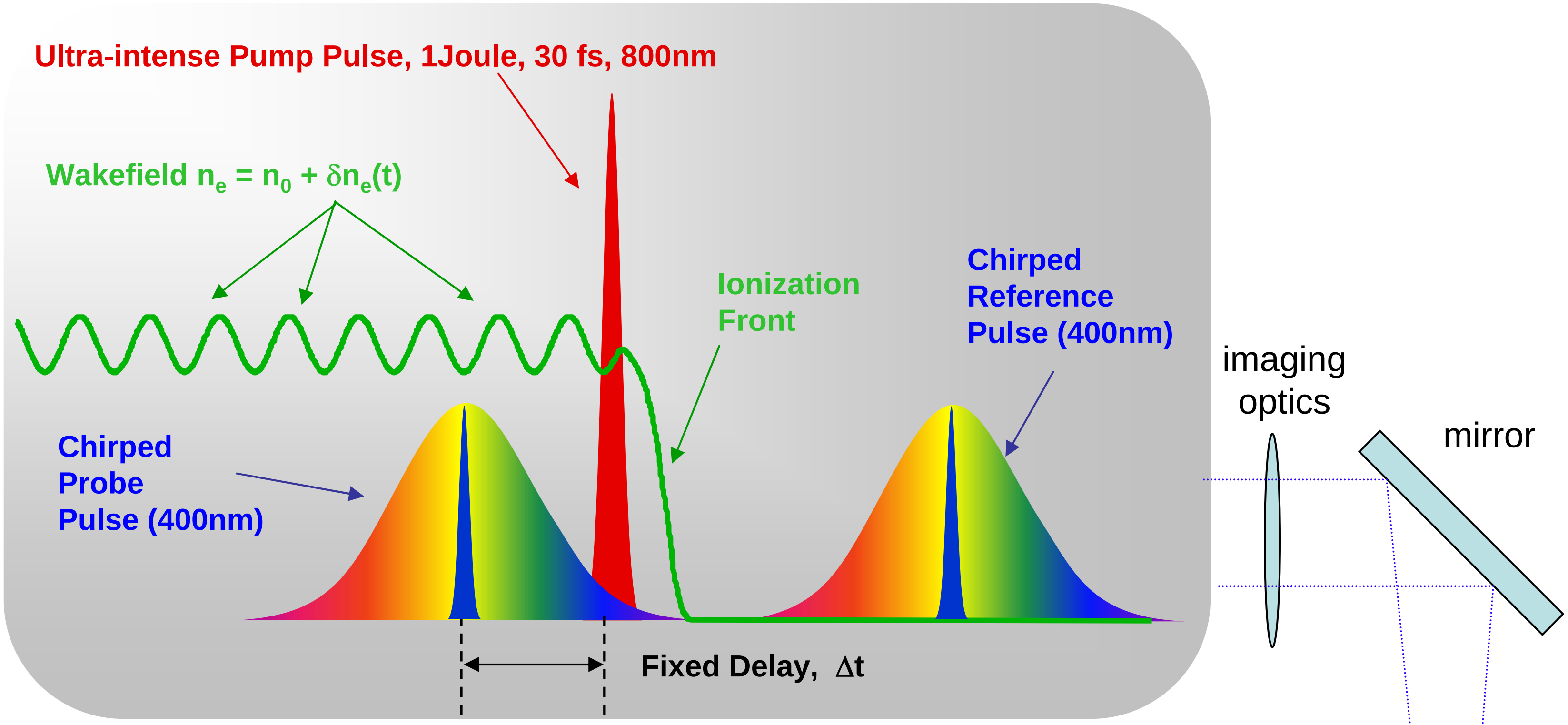
THE IMAGING PROBLEM:

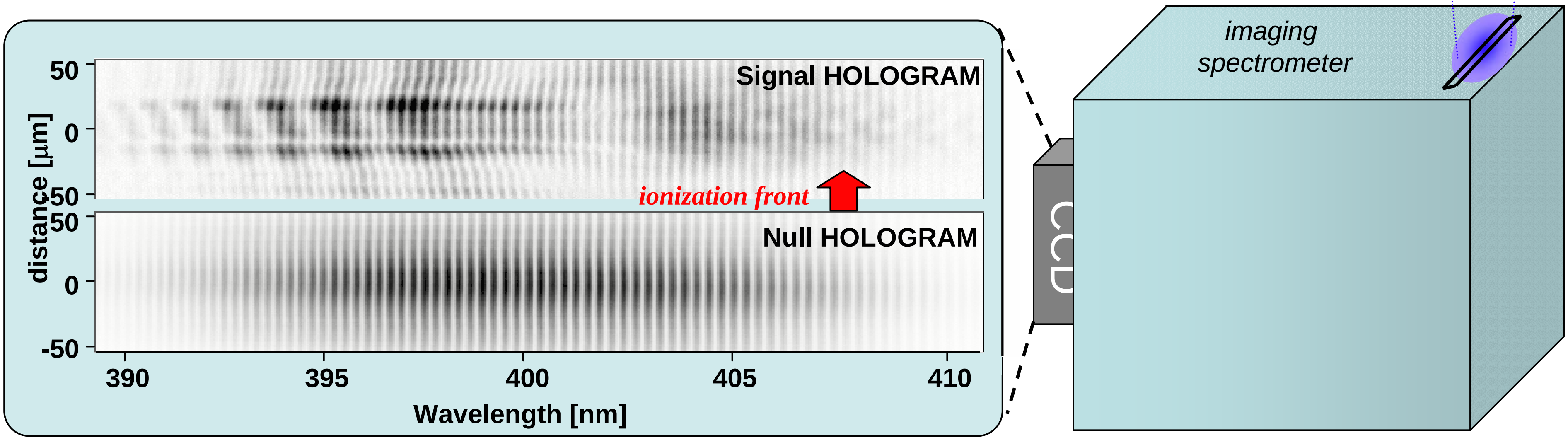
- our “train” moves at ~0.995c
- the “cars” are μm size
- it can’t be photographed from the lab frame

SOLUTION: Ride the train!!

“Frequency Domain Holography” measures Wakefields in a Single-Shot

Nicholas
Matlis
Ph.D.’06

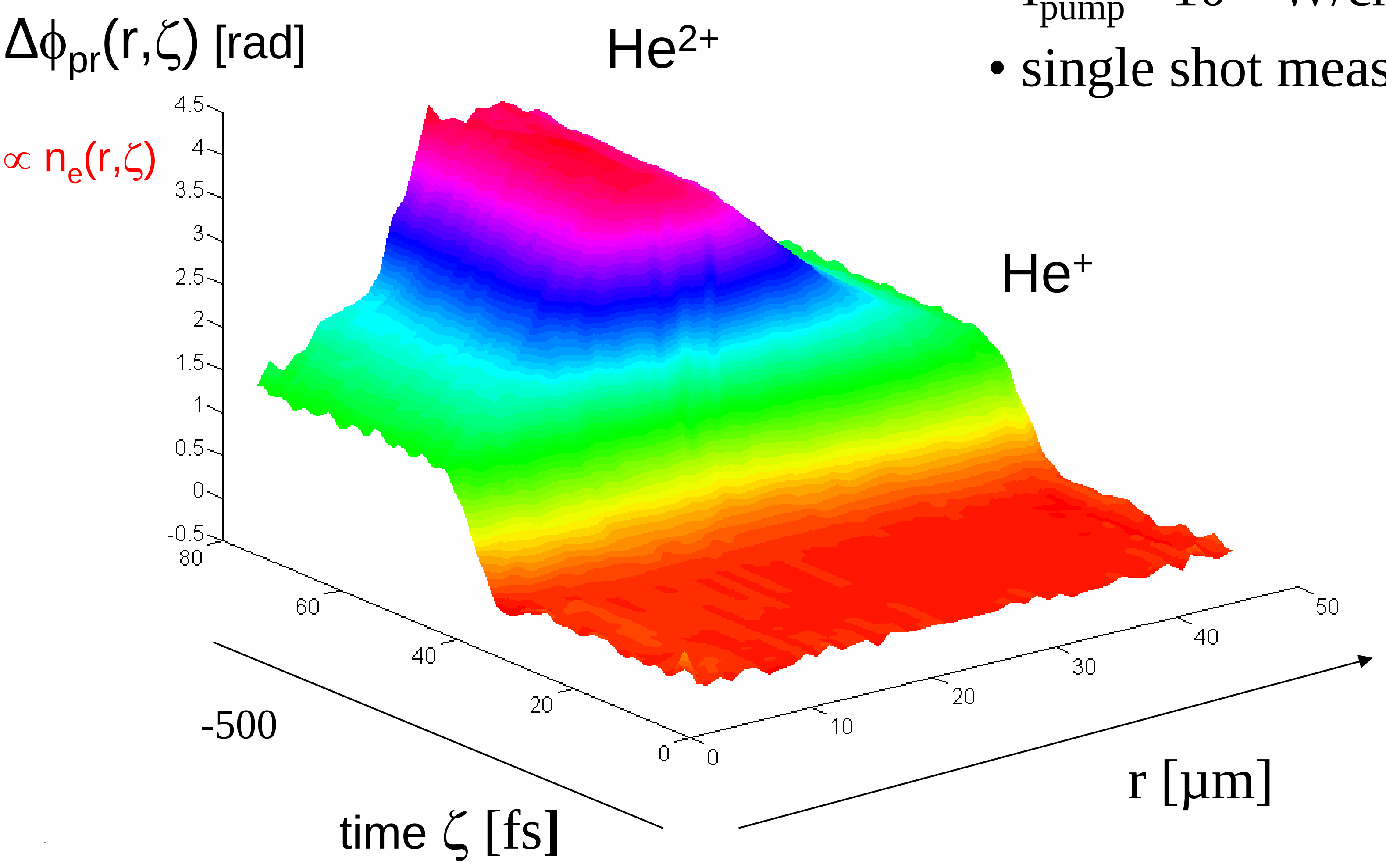




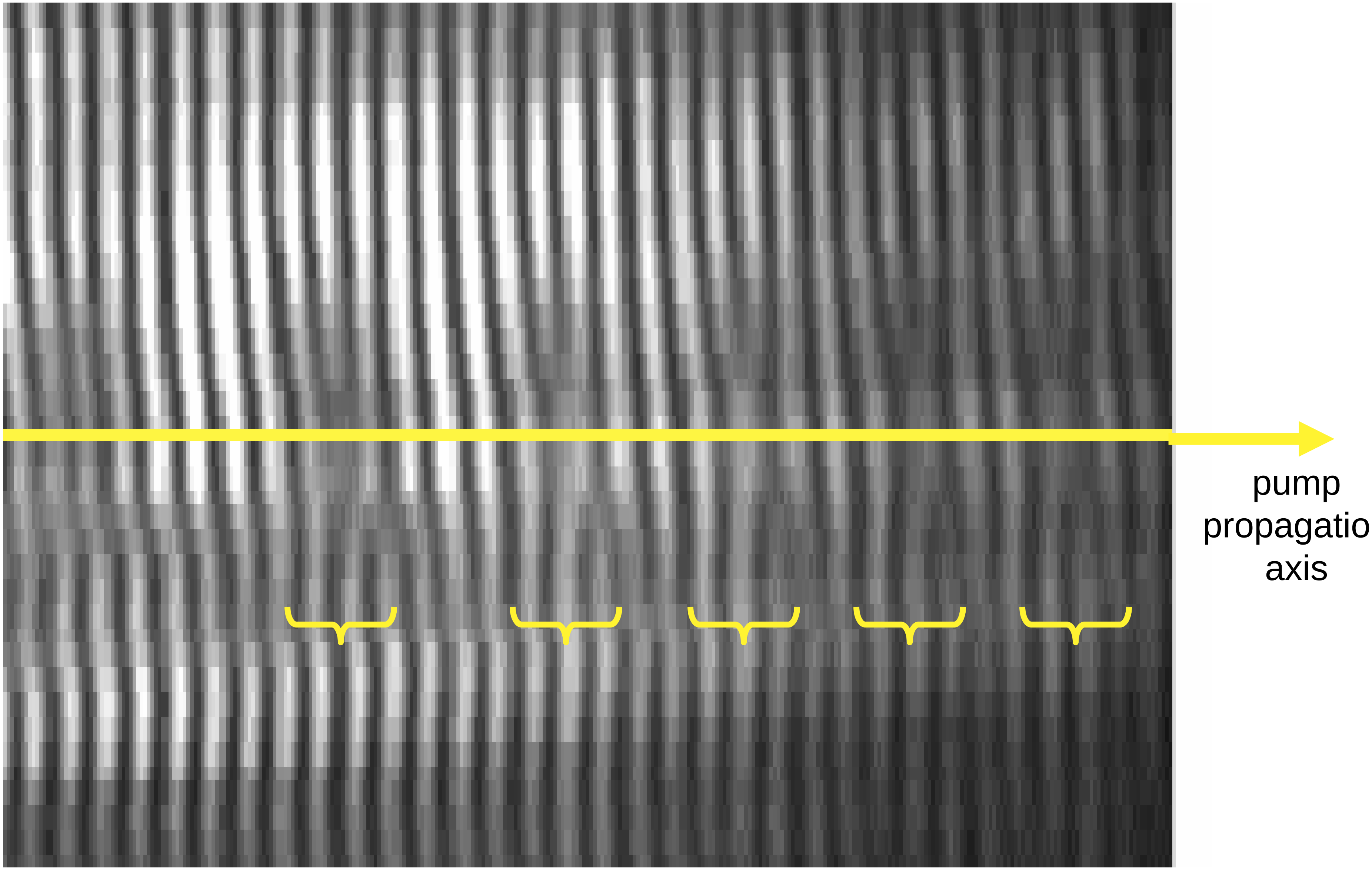
Holographic snapshot of an ionization front

LeBlanc, Matlis, MCD, *Optics Letters* **25**, 764 (2000)

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

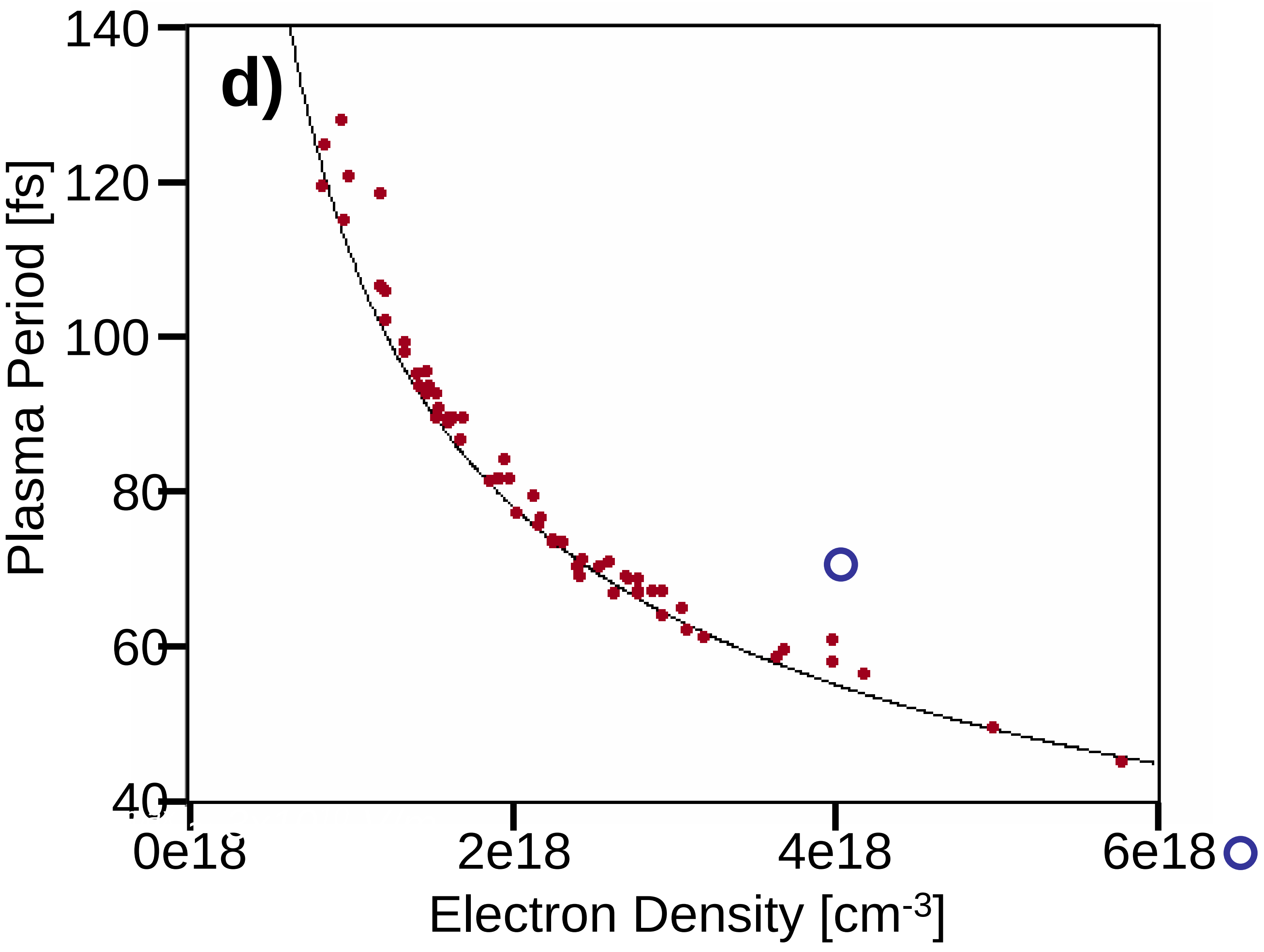


Wake appears as periodic bunching of interference fringes in the Frequency Domain Hologram



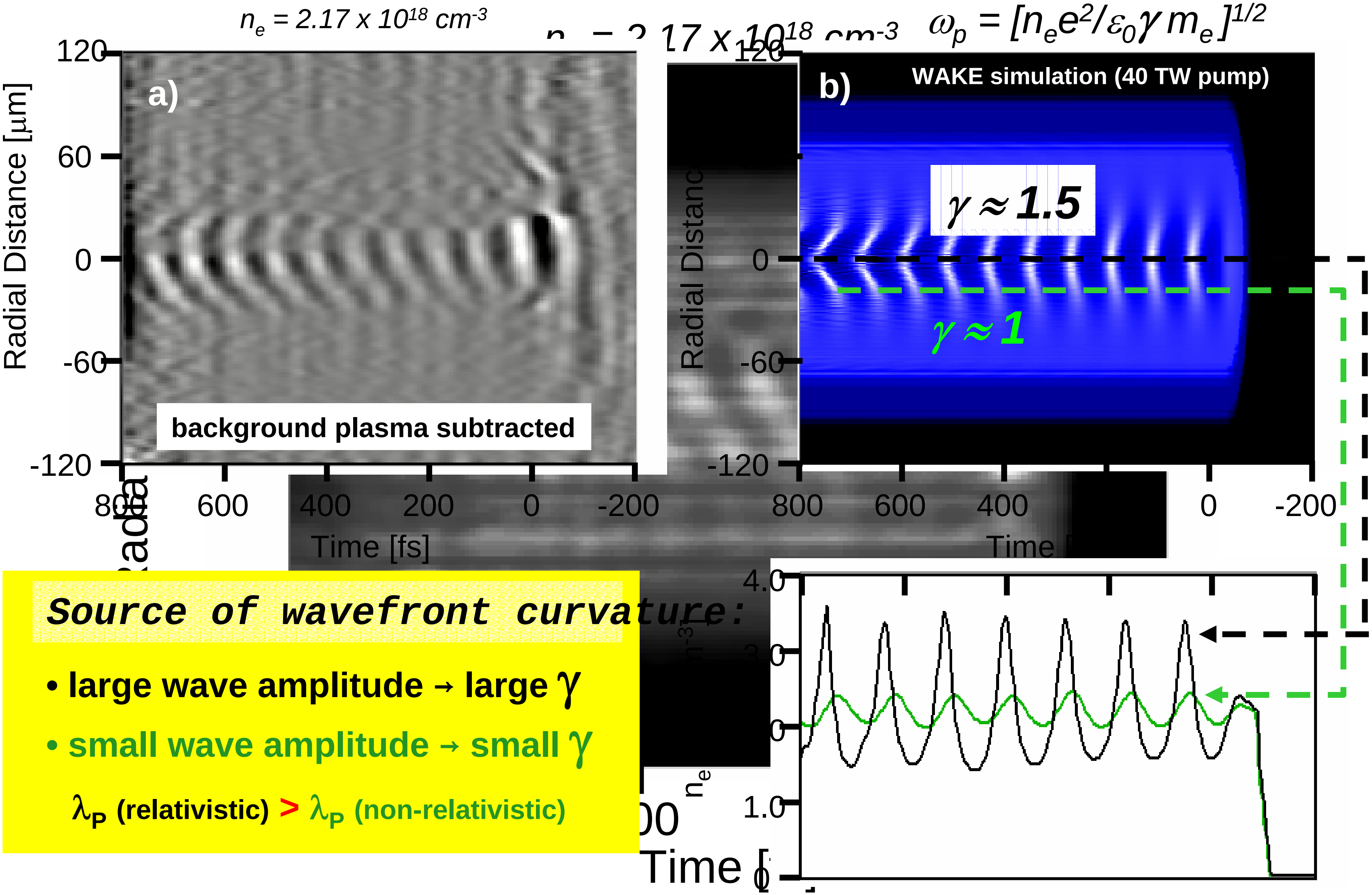
Holographic snapshots of laser wakefields

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



Strong wakes have curved wavefronts

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



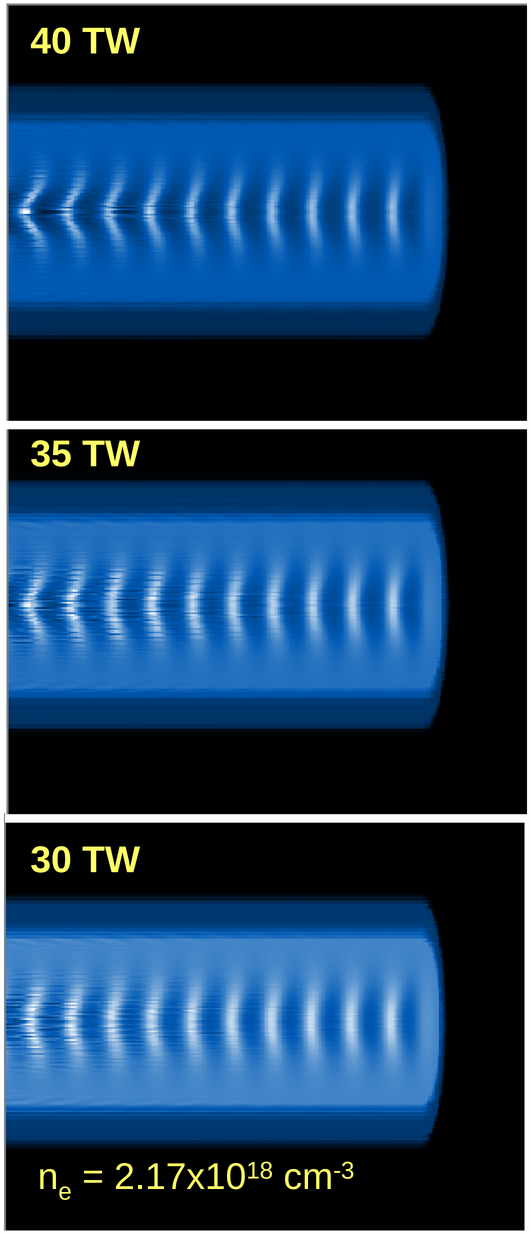
$\omega_p = [n_e e^2/\varepsilon_0 \gamma m_e]^{1/2}$

Source of wavefront curvature:

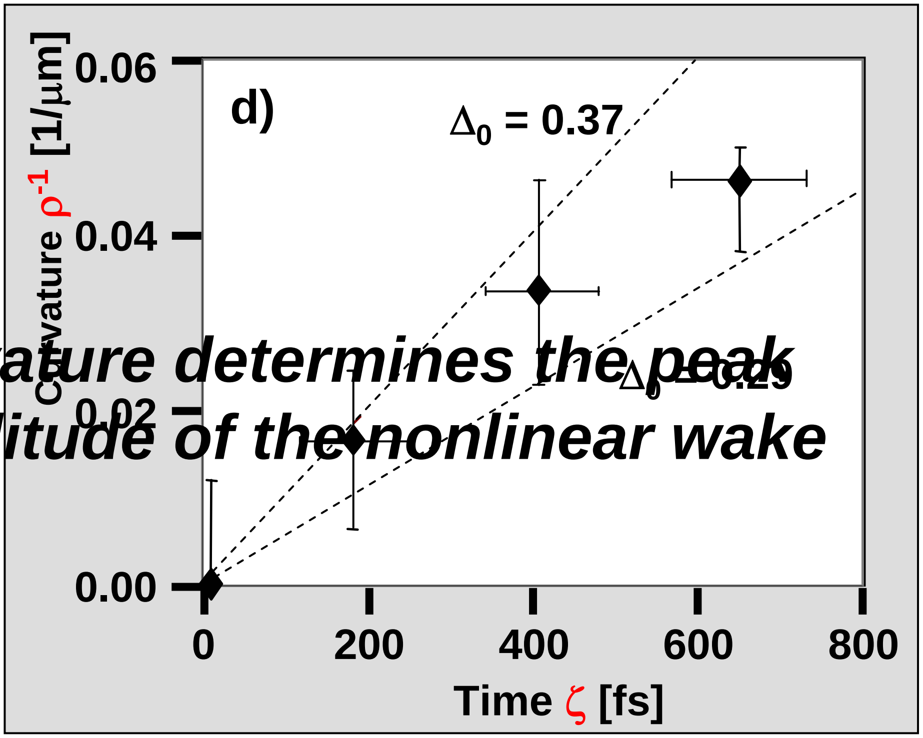
- **large wave amplitude → large γ**
- **small wave amplitude → small γ**

λ_P (relativistic) > λ_P (non-relativistic)

Significance of Wavefront Curvature



Simulated Wakefields



Curvature determines the peak amplitude of the nonlinear wake

$$\rho^{-1}(\zeta) \approx 0.45\,\zeta\,[\,\Delta_0/r_0\,]^2\,{}^{*}$$

Benefits of Curvature for Electron Beam

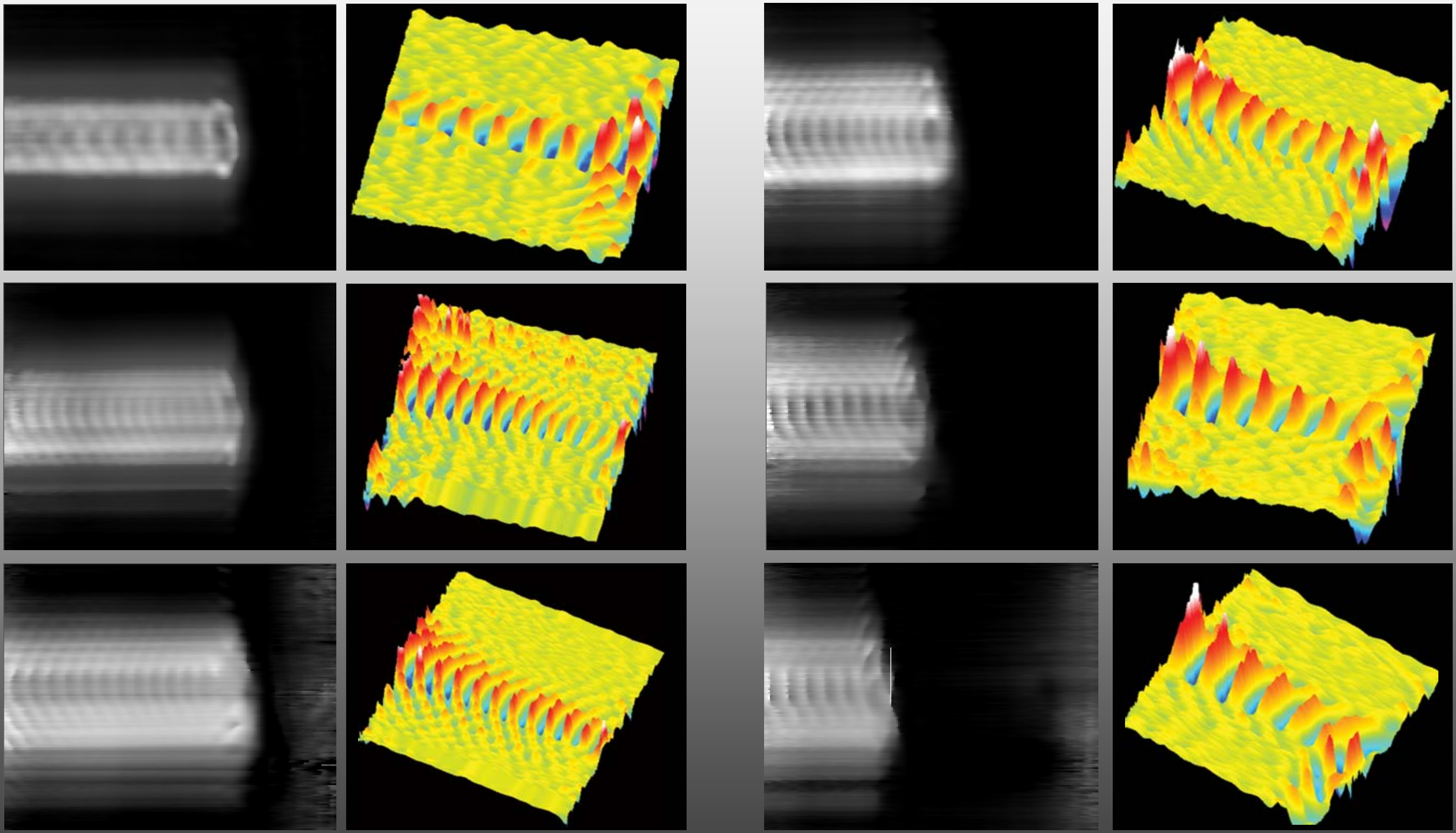
- **Precipitates wavebreaking (electron injection)**
- **Collimates beam**
- **Helps compress bunch energy spectrum**

* S. Kalmykov *et al.*, *Phys. Plasmas* **13**, 113102 (2006)

Wakefield Photo Gallery

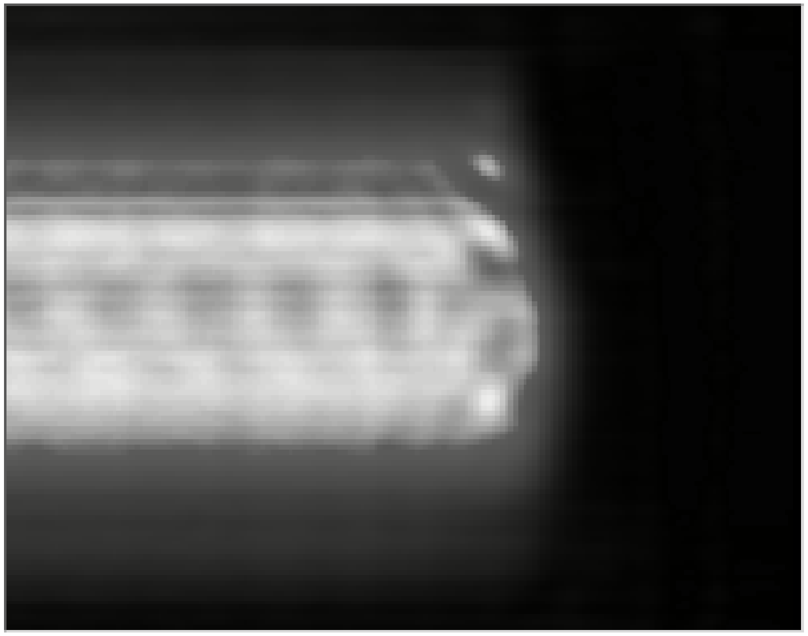
Matlis *et al*., Nature Physics **2**, 749 (2006).

http://www.nature.com/nphys/index.html (Supplementary Fig. 1)



Greyscale Image 3D Map Greyscale Image 3D Map

GALLERY of WORLD-FAMOUS PHOTOGRAPHS ?



Our current experiments focus on correlating wake structures with generated electrons at $n_e > 10^{19}$ cm^{-3}

wake reconstructions

QuickTime™ and a
decompressor
are needed to see this p

QuickTime™ and a
decompressor
are needed to see this picture.

multiple buckets

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

3 buckets

QuickTime™ and a
decompressor
are needed to see this picture.

QuickTime™ and a
decompressor
are needed to see this picture.

single bucket
(bubble?)

electron spectra

wide continuous spectrum

QuickTime™ and a
decompressor
are needed to see this picture.

3 quasi-monoenergetic peaks

QuickTime™ and a
decompressor
are needed to see this picture.

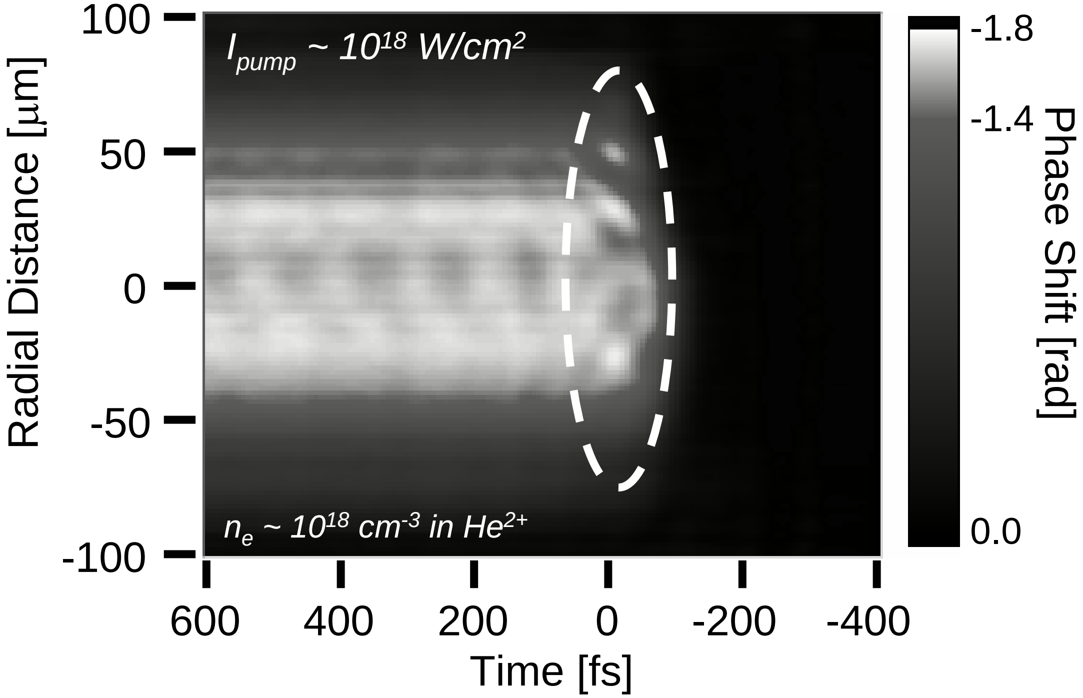
quasi-monoenergetic peak

QuickTime™ and a
decompressor
are needed to see this picture.

Laser: 30 TW, 30 fs

data of 1/15/09

At $n_e > 10^{19}$ cm^{-3}, relativistic nonlinear optical radiation begins to influence FDH data



- relativistic nonlinear index modulation*: $n = n_0 + n_2 I$

* Max *et al.*, *Phys. Rev. Lett.* **33**, 209 (1974)

- pump second-harmonic & continuum generation

Chen, *Nature* **396**, 53 (1998); *Phys. Rev. Lett.* **84**, 5528 (2000)

"artifacts" in reconstructed $\Delta\phi_{pr}(r,\zeta)$ ⇔ additional diagnostic opportunity

SHG by diverging pump produces elliptical "Newton rings" in the FD hologram

unchirped, diverging SH of pump:

$$\exp\left[-\frac{(\omega-\omega_0)^2}{a_{pu}} - ik\frac{r^2}{2R}\right]$$

$$+$$

chirped collimated probe:

$$\exp\left[-\frac{(\omega-\omega_0)^2}{a_{pr}} - i\frac{(\omega-\omega_0)^2}{b_{pr}}\right]$$

$$\Downarrow$$

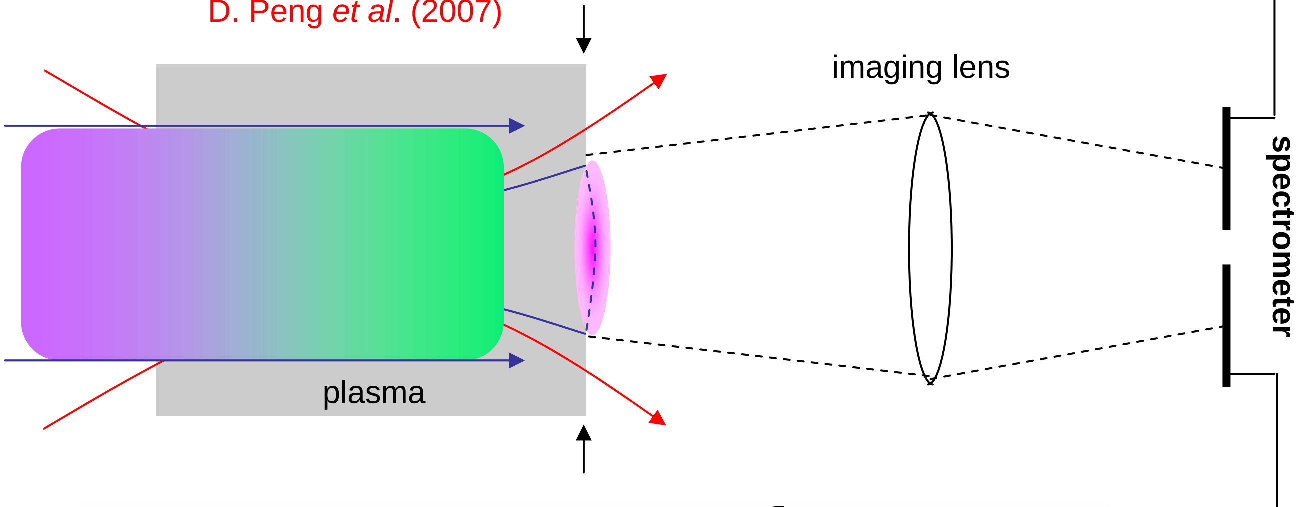
elliptical Newton ring:

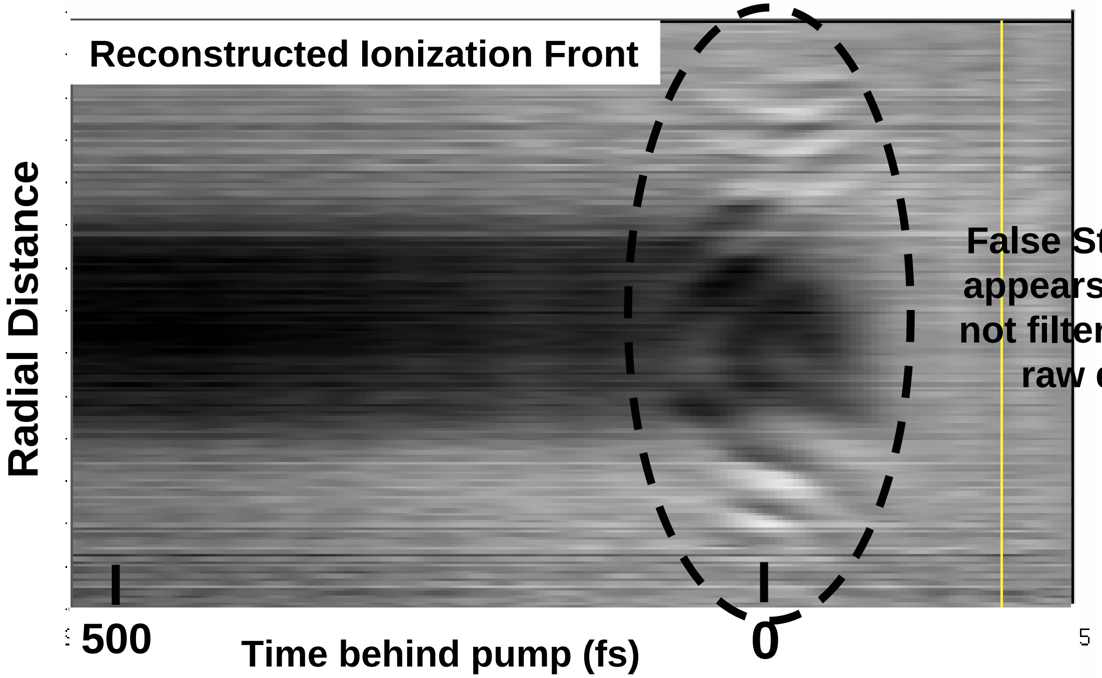
$$\cos\left[\frac{(\omega-\omega_0)^2}{b_{pr}} + k\frac{r^2}{2R}\right]$$

Useful to characterize:

- **relativistic pump propagation**
- **relativistic harmonic generation**

D. Peng *et al.* (2007)

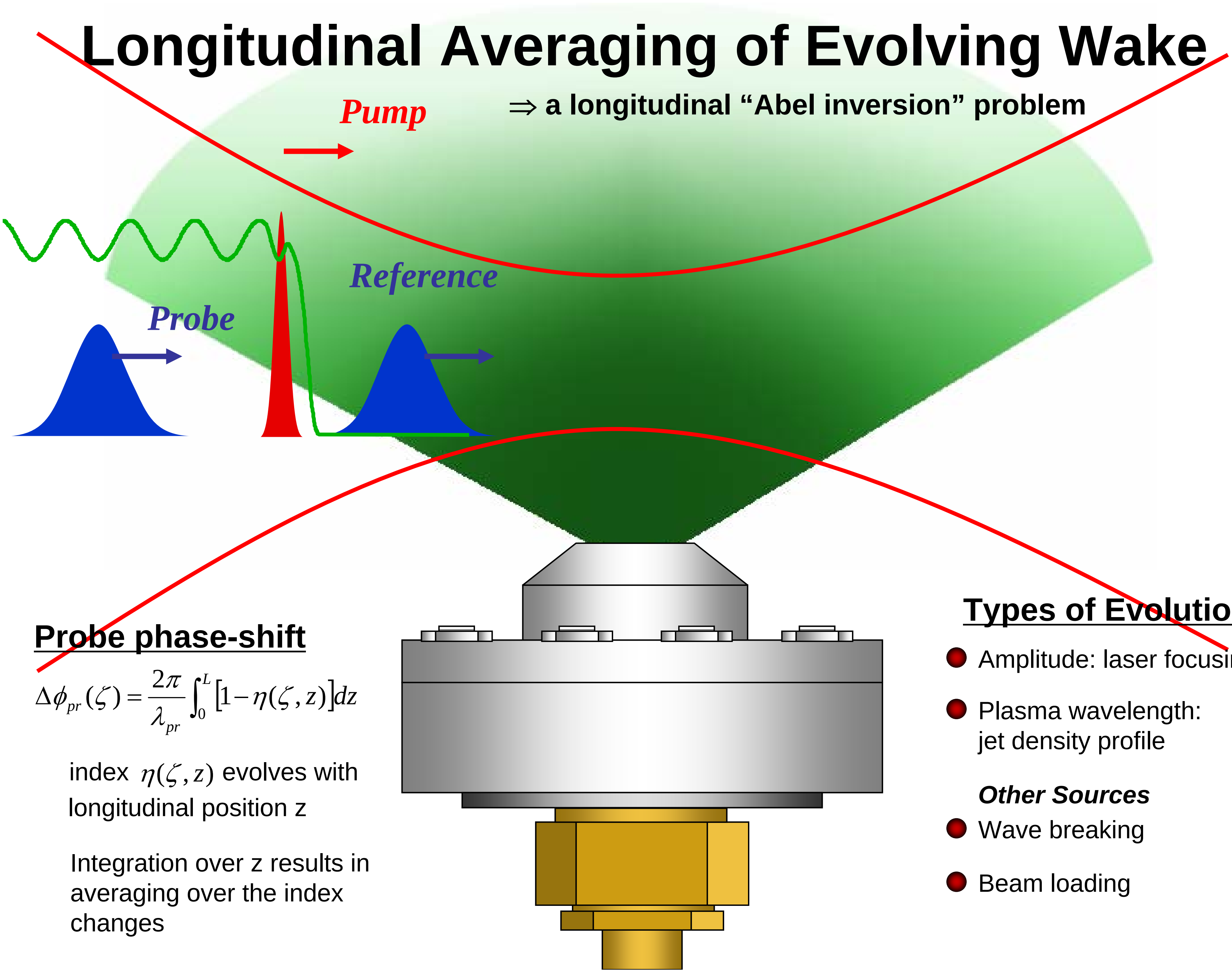




False Structure appears if rings not filtered from raw data.

Longitudinal Averaging of Evolving Wake

⇒ a longitudinal “Abel inversion” problem



Probe phase-shift

$$\Delta\phi_{pr}(\zeta) = \frac{2\pi}{\lambda_{pr}} \int_0^L \left[1-\eta(\zeta,z)\right]dz$$

index $\eta(\zeta,z)$ evolves with longitudinal position z

Integration over z results in averaging over the index changes

Types of Evolution

- Amplitude: laser focusing
- Plasma wavelength: jet density profile

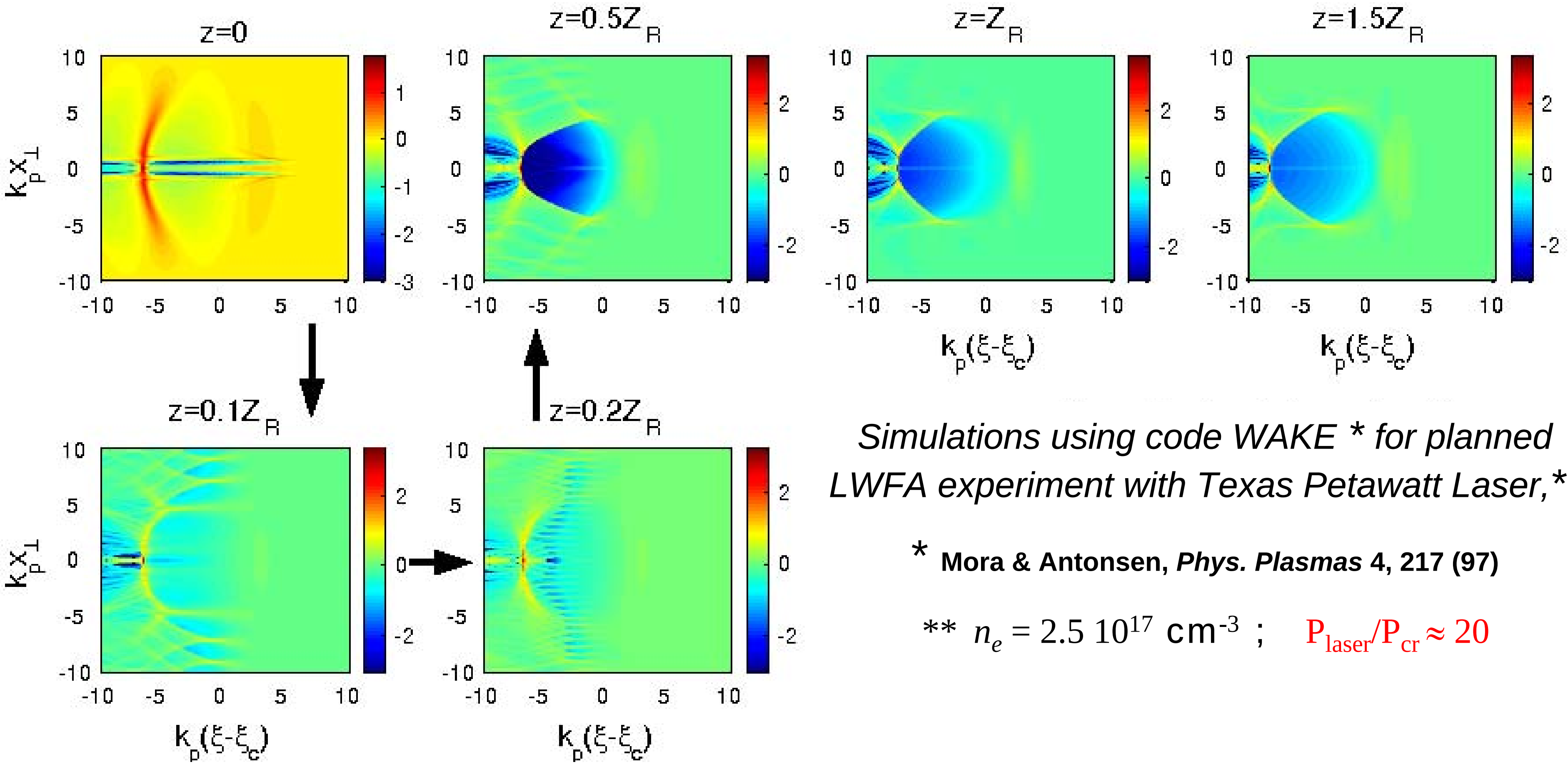
Other Sources

- Wave breaking
- Beam loading

Plasma “bubble”*: example of a strongly evolving laser-plasma structure

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

- Plasma bubble accelerators can produce nearly mono-energetic electrons
- Bubbles have been simulated, but not seen in the laboratory
- Bubble & laser pulse evolve considerably during jet transit.



*Simulations using code WAKE * for planned LWFA experiment with Texas Petawatt Laser,***

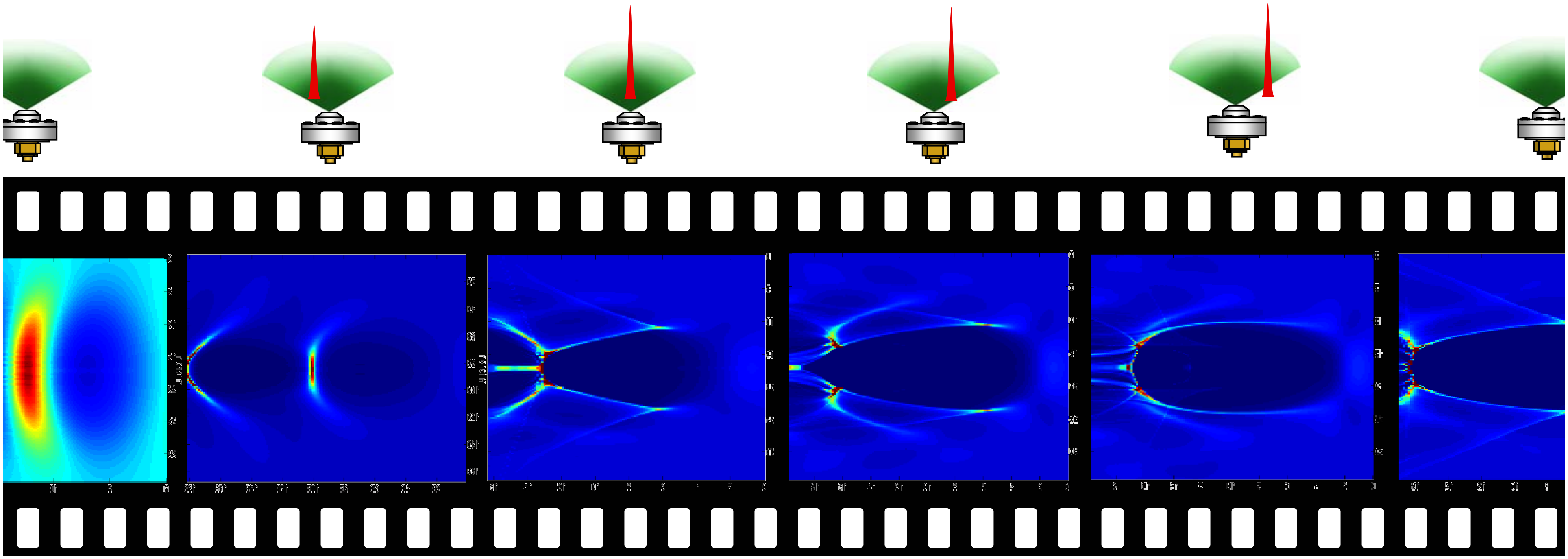
* **Mora & Antonsen, *Phys. Plasmas* 4, 217 (97)**

** $n_e = 2.5\ 10^{17}$ cm^{-3} ; $P_{laser}/P_{cr} \approx 20$

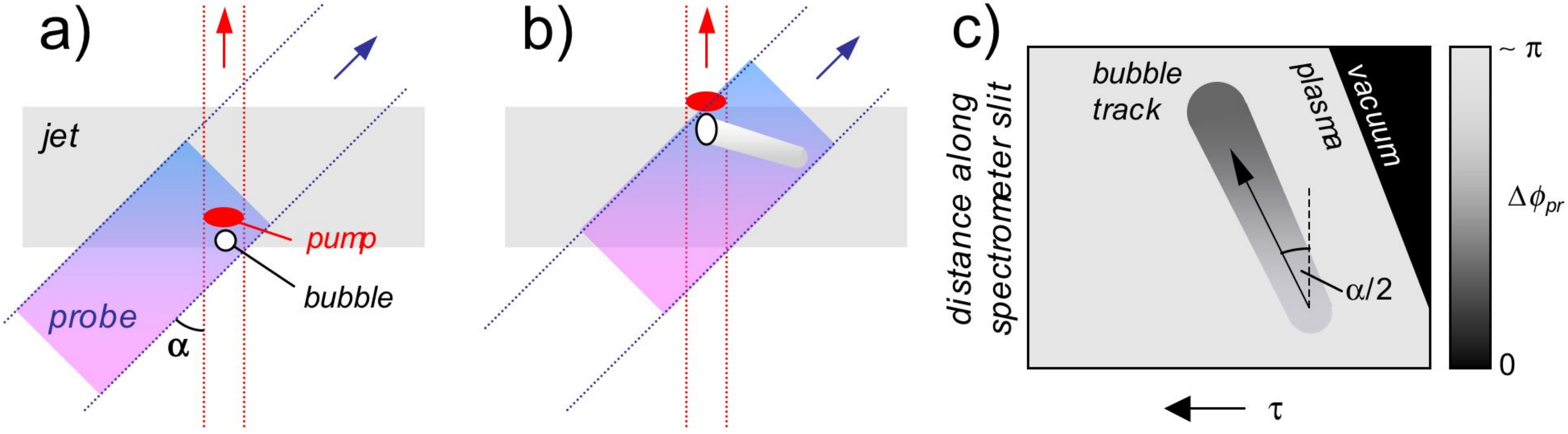
Visualization of evolving laser-plasma structures

$$n_e(r,\zeta,z)$$

SNAPSHOTS → MOVIES



Frequency-Domain “Streak Camera” Records Evolution of Plasma Bubble



- Oblique probe measures bubble evolution
- Collinear probe records longitudinally-averaged bubble structure

Simulated Phase Streak of a Plasma Bubble

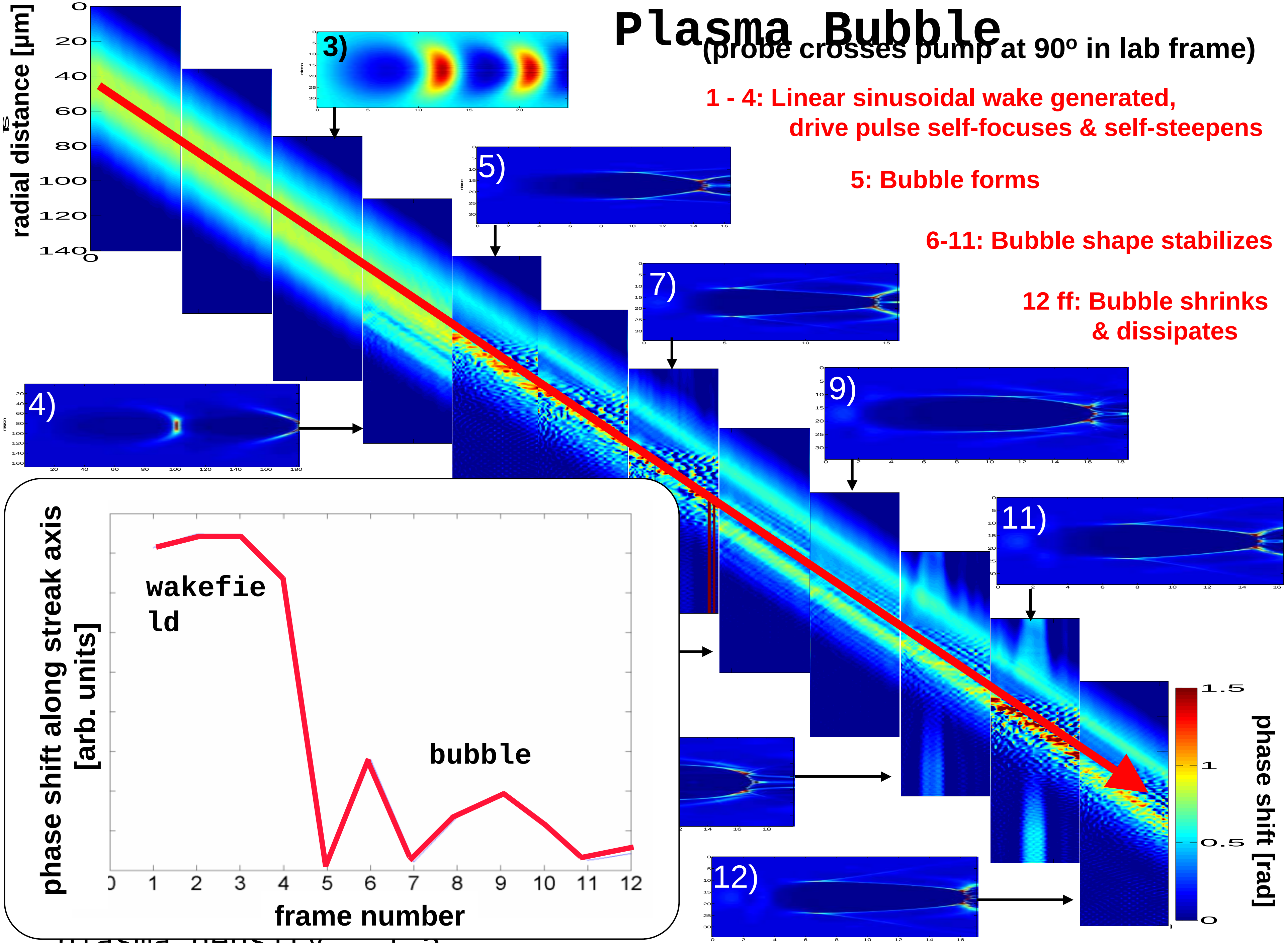
(probe crosses pump at 90º in lab frame)

1 - 4: Linear sinusoidal wake generated, drive pulse self-focuses & self-steepens

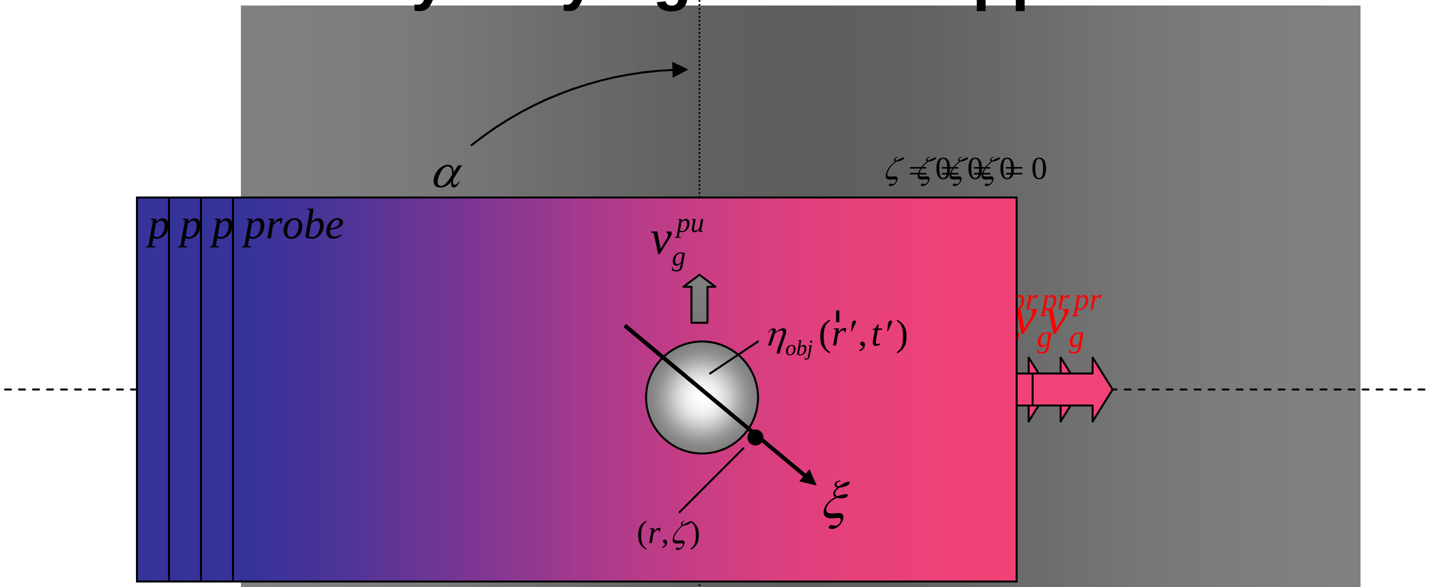
5: Bubble forms

6-11: Bubble shape stabilizes

12 ff: Bubble shrinks & dissipates



Slowly varying bubble approximation



- If bubble is quasi-static during time $\tau_{obj}^{transit} \approx \dfrac{R_{obj}}{2c\sin\alpha/2} \approx 10\, fs << \tau_{jet}^{transit}$

  for point (r,ζ) to sweep across object in direction ξ ...

... then [2] $\phi_{pr}(r,\zeta) = \dfrac{2\pi}{\lambda_{pr}} \int_{\xi} \eta_{obj}(\vec{r}')d\xi$, exactly as if probe had propagated

  across **stationary** object in direction ξ.

- The problem becomes equivalent to conventional computer-aided tomography (CAT) of stationary object.

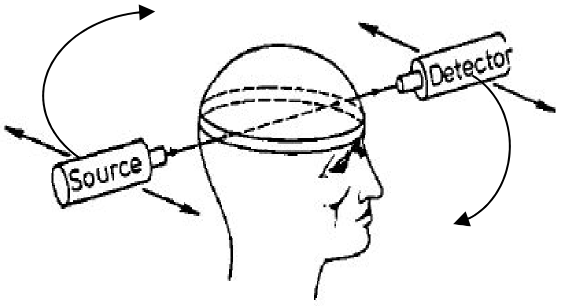
Frequency Domain Tomography (FDT)

borrows reconstructive algorithms of medical CAT scans

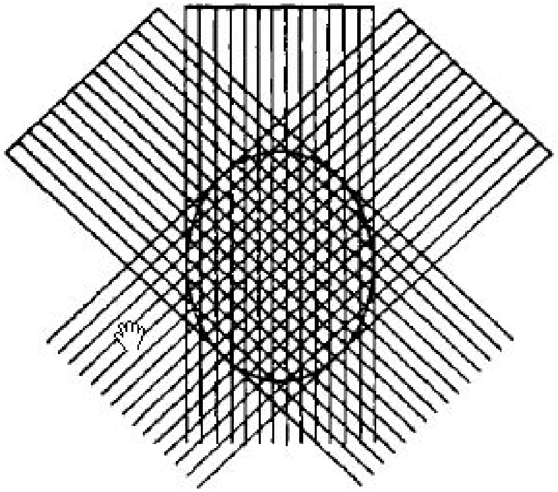
Ledley *et al.*, “Computerized axial tomography of the human body,” Science **186** (1974)

Brooks & Di Chiro, “Principles of Computer Assisted Tomography” *Phys. Med. Biol*. **21**, 689 (1976)

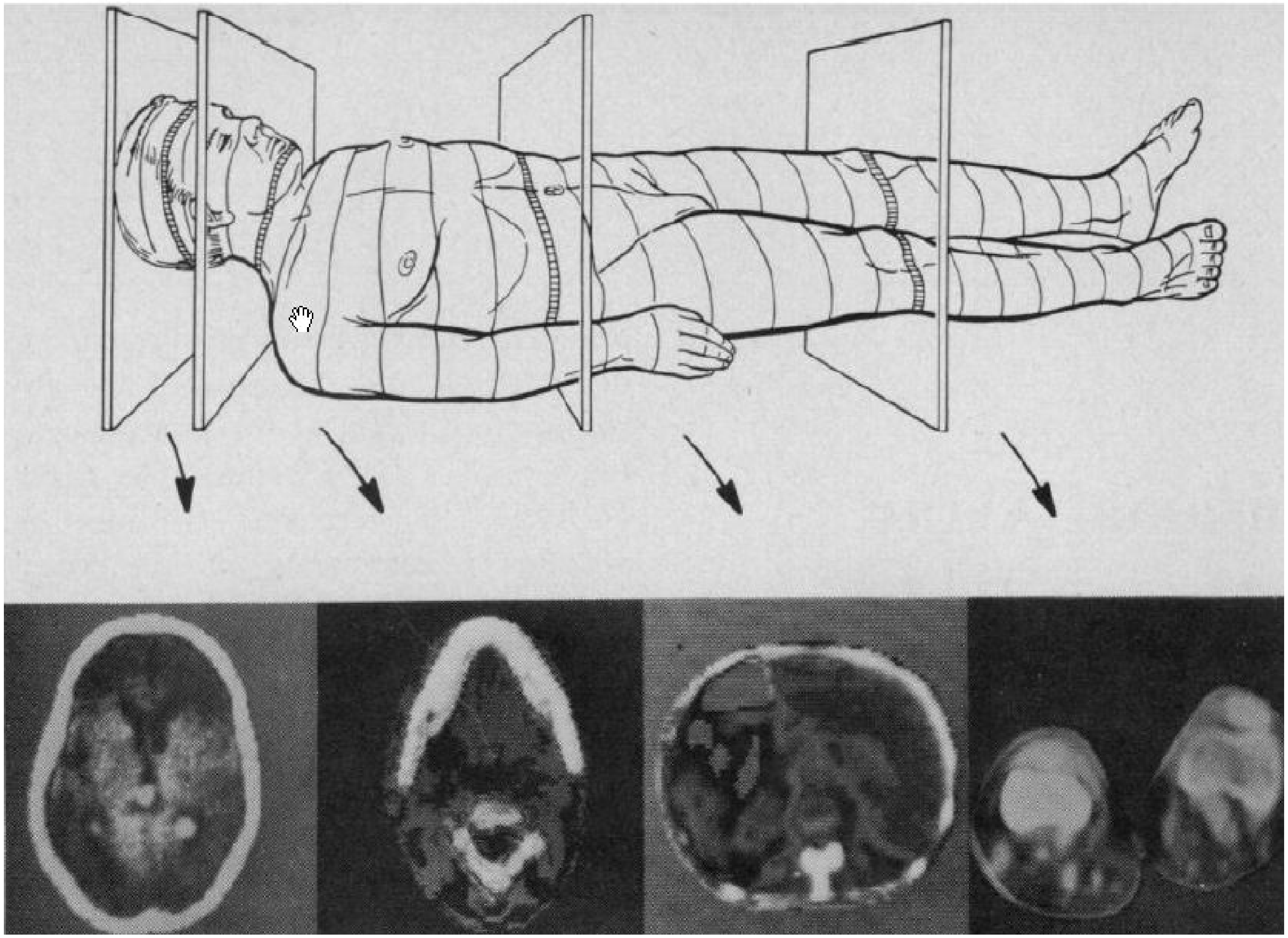
Reconstructive tomography



(a) transmission imaging

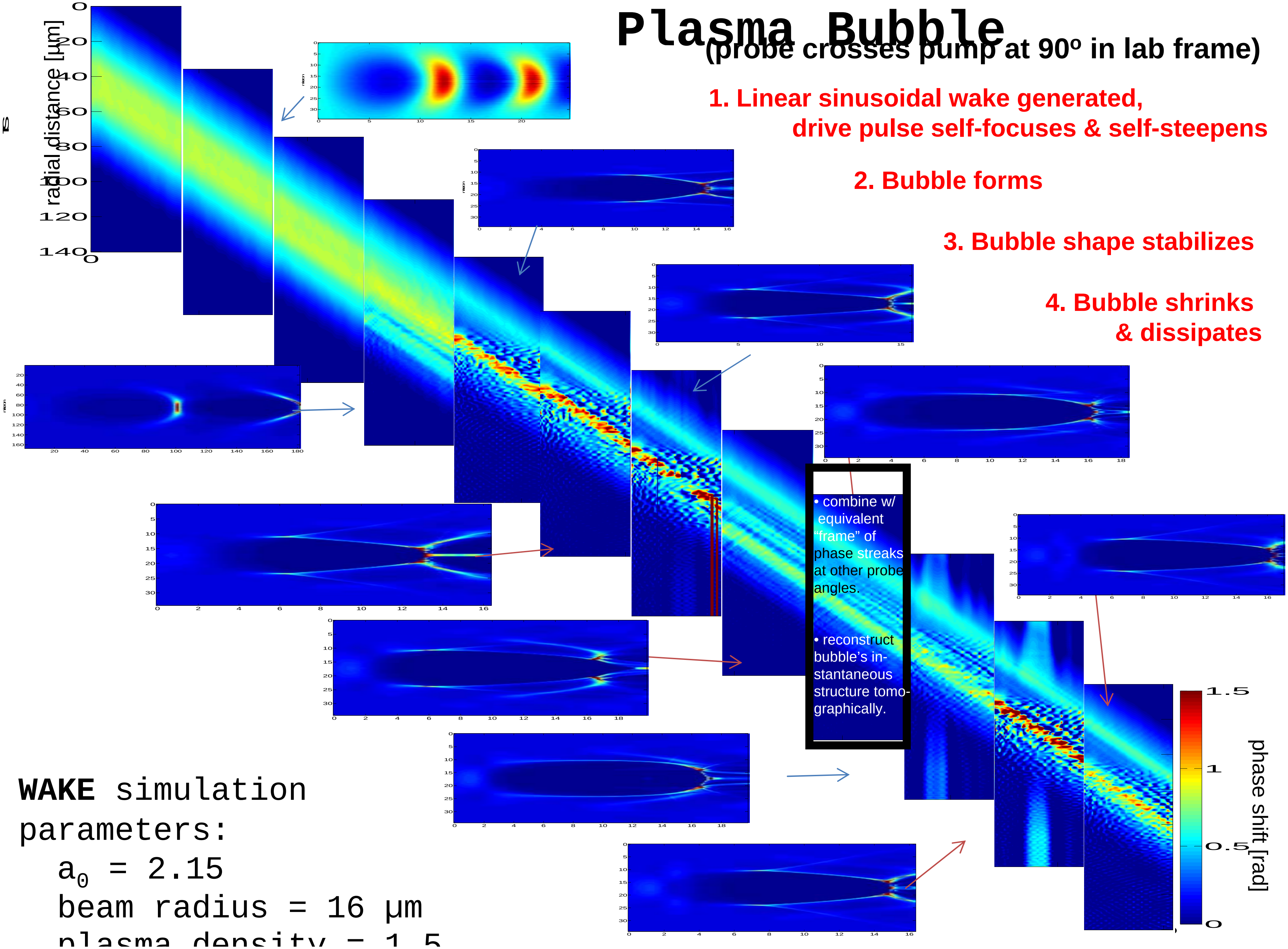


(b) scan pattern



Simulated Phase Streak of a Plasma Bubble

(probe crosses pump at 90º in lab frame)



1. Linear sinusoidal wake generated, drive pulse self-focuses & self-steepens

2. Bubble forms

3. Bubble shape stabilizes

4. Bubble shrinks & dissipates

- combine w/ equivalent "frame" of phase streaks at other probe angles.
- reconstruct bubble's instantaneous structure tomographically.

WAKE simulation parameters:

a_0 = 2.15

beam radius = 16 μm

plasma density = 1.5

Simulations show that evolving, luminal-velocity plasma structures can be reconstructed tomographically from multiple-angle phase streaks

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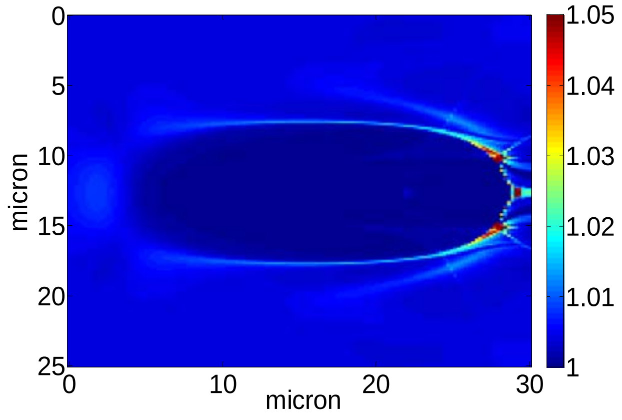
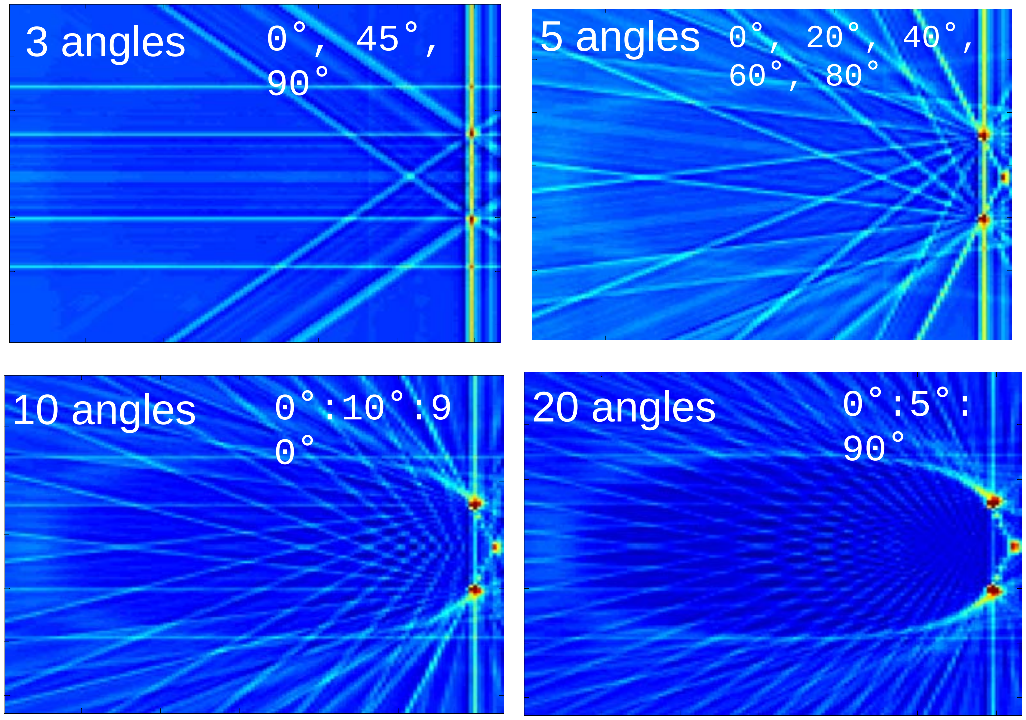
Single “frame” of bubble “movie”



Tomographic reconstructions of this frame from multi-angle phase streaks

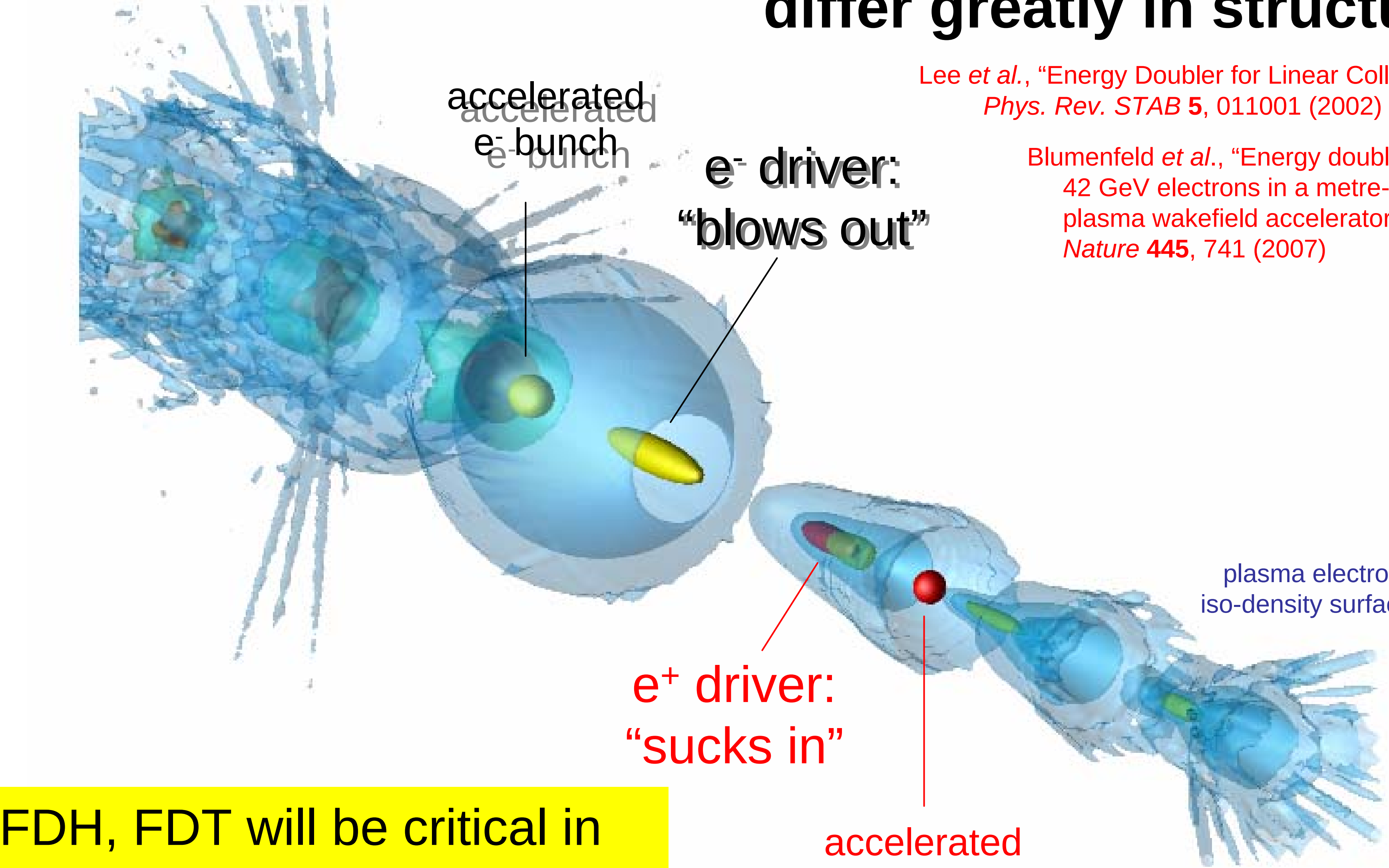


This approach will be essential for visualizing **channeled wakes**, which cannot be imaged by conventional collinear FDH.

Plasma Afterburner: e^- and e^+ driven wakes differ greatly in structure

Lee *et al.*, “Energy Doubler for Linear Collider,” *Phys. Rev. STAB* **5**, 011001 (2002)

Blumenfeld *et al.*, “Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator,” *Nature* **445**, 741 (2007)

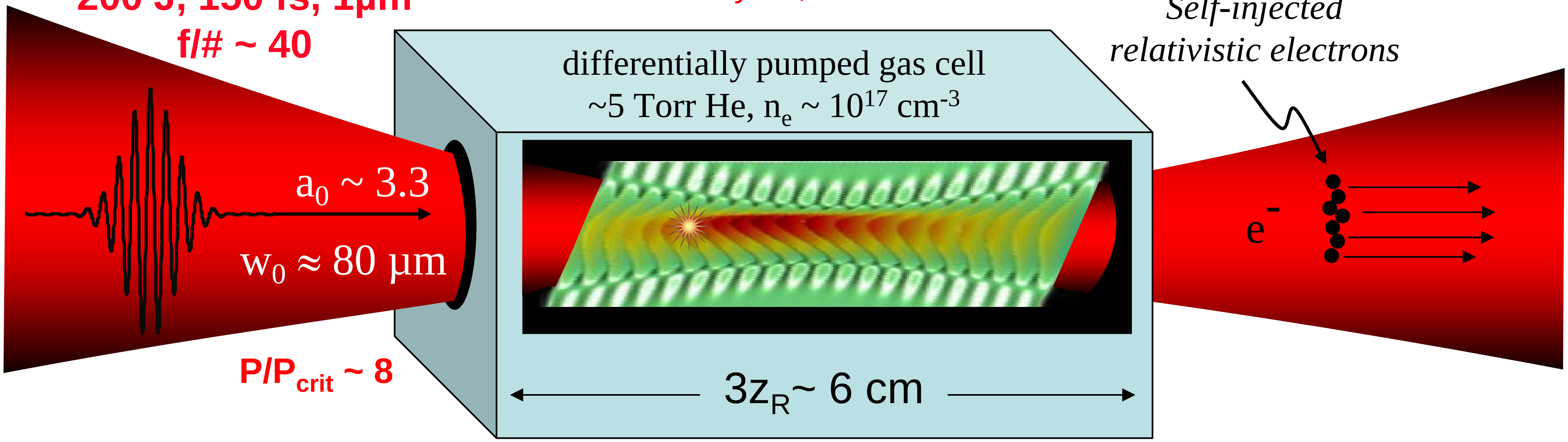


courtesy Frank Tsung (UCLA)

FDH, FDT will be critical in characterizing & optimizing these accelerating structures

Petawatt laser wakefield accelerator PIC simulations

S. Kalmykov, G. Shvets



200 J, 150 fs, 1μm
f/# ~ 40

$a_0 \sim 3.3$

$w_0 \approx 80\ \mu m$

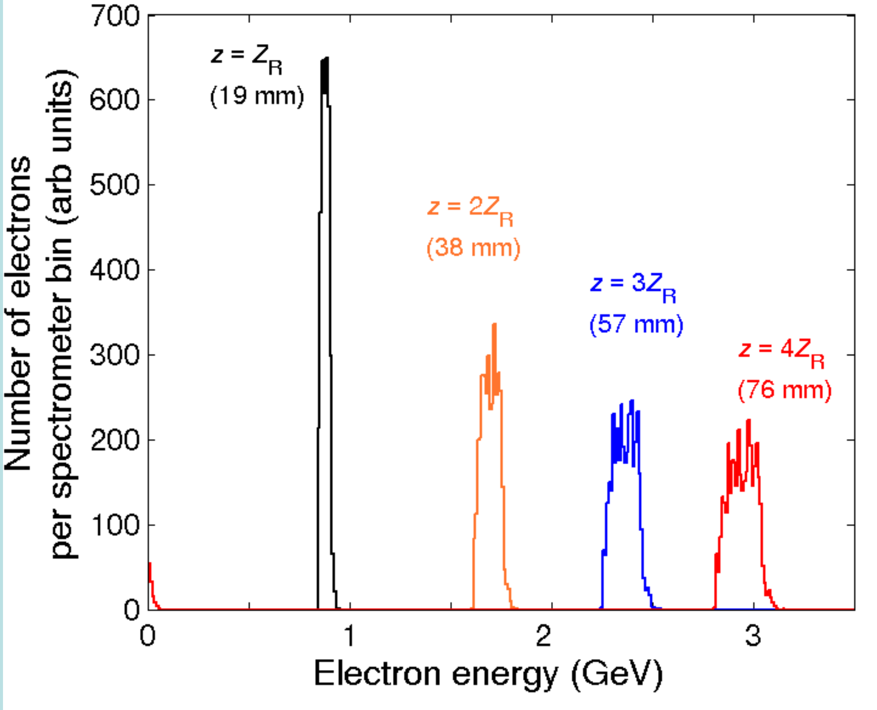
$P/P_{crit} \sim 8$

differentially pumped gas cell
~5 Torr He, $n_e \sim 10^{17}$ cm^{-3}

$3z_R \sim 6$ cm

Self-injected relativistic electrons

Self-injected electrons reach 3 GeV after $3z_R \approx 7.6$ cm propagation



2.5 million hours on NERSC*

(National Energy Research Scientific Computer)

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

30 September 2004

International weekly journal of science

nature

Dream beam

The dawn of compact particle accelerators

Disease control
Europe plays catch-up

The Earth's hum
Sounds of air and sea

Protein folding
Escape from the ribosome

Human ancestry
One from all and all from one

---

* consuming ~ 30 MW of electrical power

SUMMARY

1) Holographic snapshots of LWFAs

- first direct laboratory visualization of LWFAs

Matlis *et al*., *Nature Phys*. **2**, 749 (2006)
Maksimchuk et al., *Phys. Plasmas* **15**, 056703 (2008)

2) LWFA movies by Frequency Domain Tomography

- evolving plasma “bubbles”
- the only way to “see” channel-guided LWFA

3) Future applications

- particle-bunch- and petawatt-laser-driven wakes
- fast igniter tracks in laser fusion targets

Seeing is believing,
but seeing is not always easy

“Reading” the Hologram

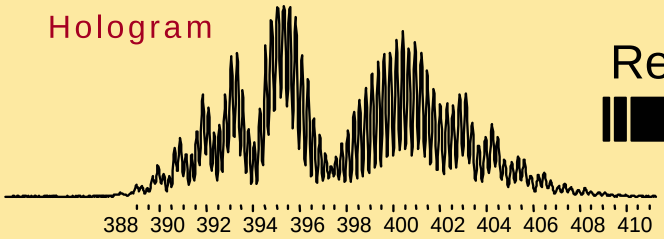
(Full Electric Field Reconstruction)

BASIC SCHEME

RECONSTRUCTION

TIME DOMAIN

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



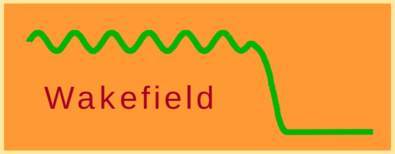
$$\xrightarrow{\text{Read}} \quad E_{probe}(\omega) = |E(\omega)|\, e^{-i\phi(\omega)}$$

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

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

3. Calculate electron density from extracted temporal phase

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



“Reading” the Hologram

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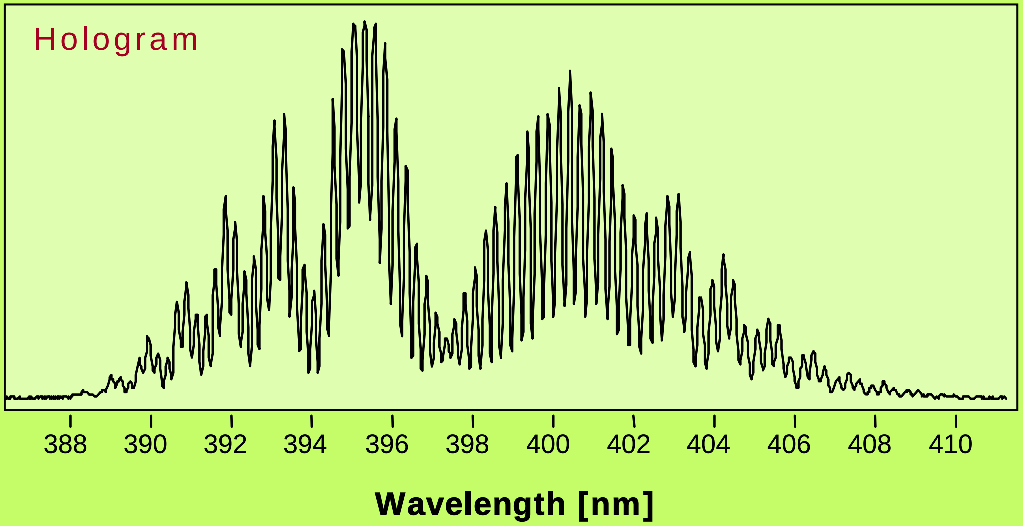
BASIC SCHEME

RECONSTRUCTION

TIME DOMAIN



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

$$= |E|^2 + |E|^2 + |E|$$

$$e^{i\phi_{signal}(\omega)}$$

from FFT side peak

Separate Measurement

FFT of Hologram

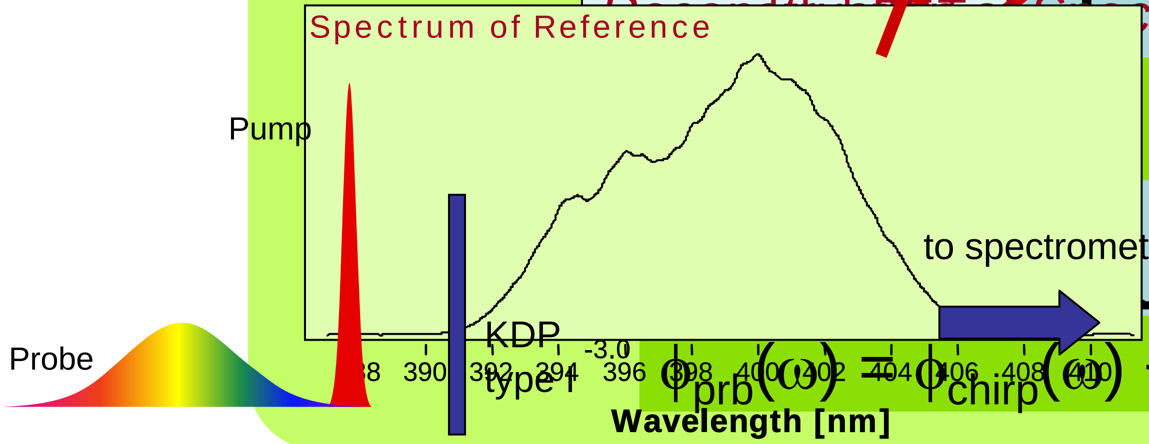
FFT

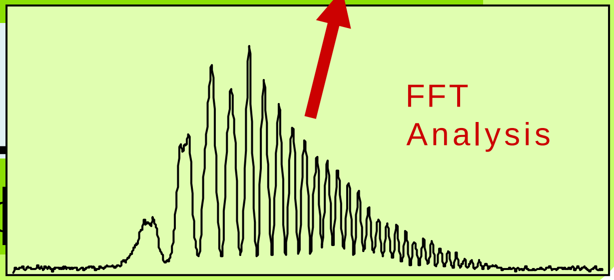
Spectral Electric Field

FFT^{-1}

$$e^{-i[\phi_{signal}(\omega) + \phi_{chirp}(\omega)]}$$

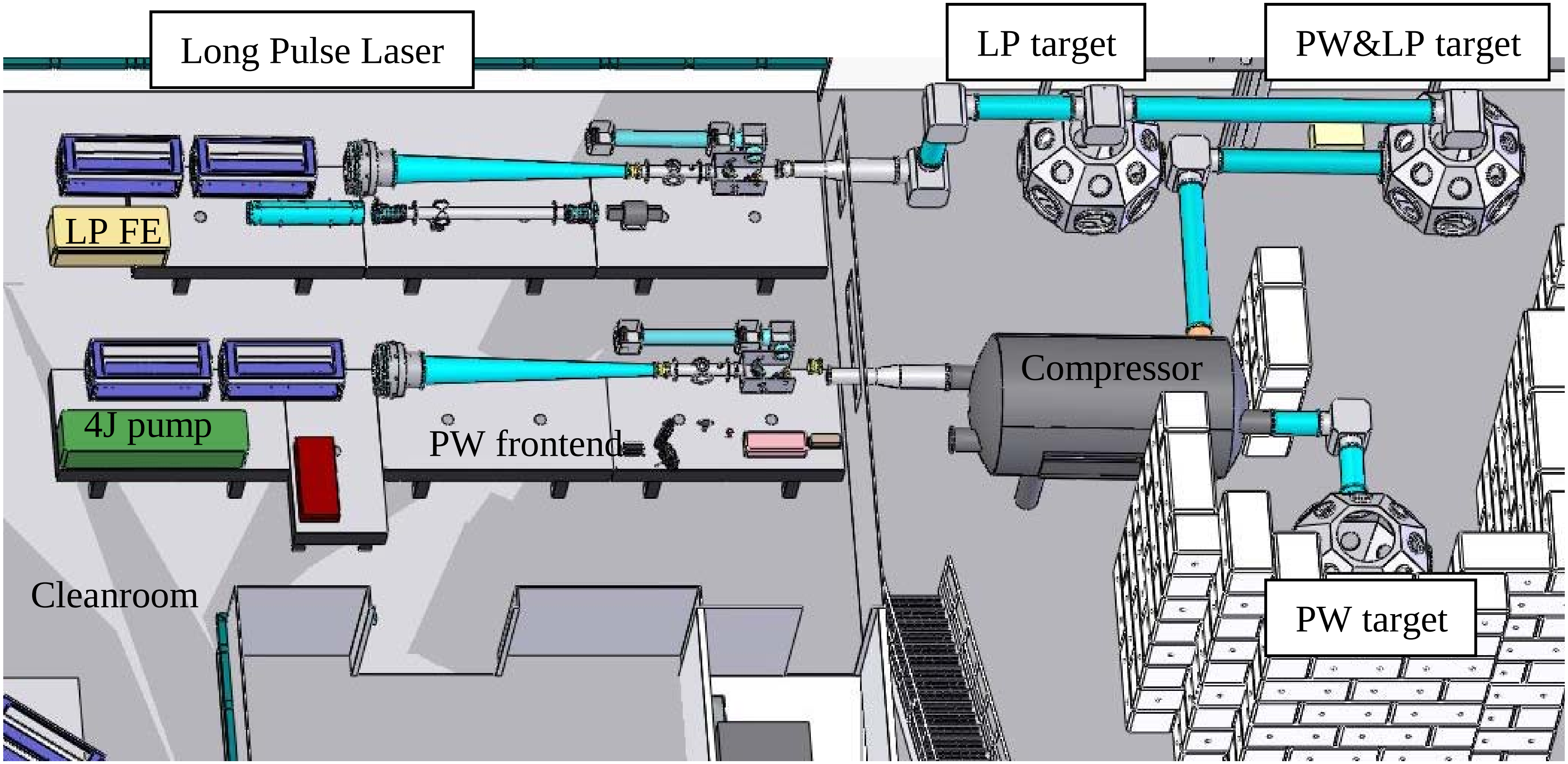
$$\phi_{prb}(\omega) = \phi_{chirp}(\omega) + \delta\phi$$





Texas Petawatt Laser

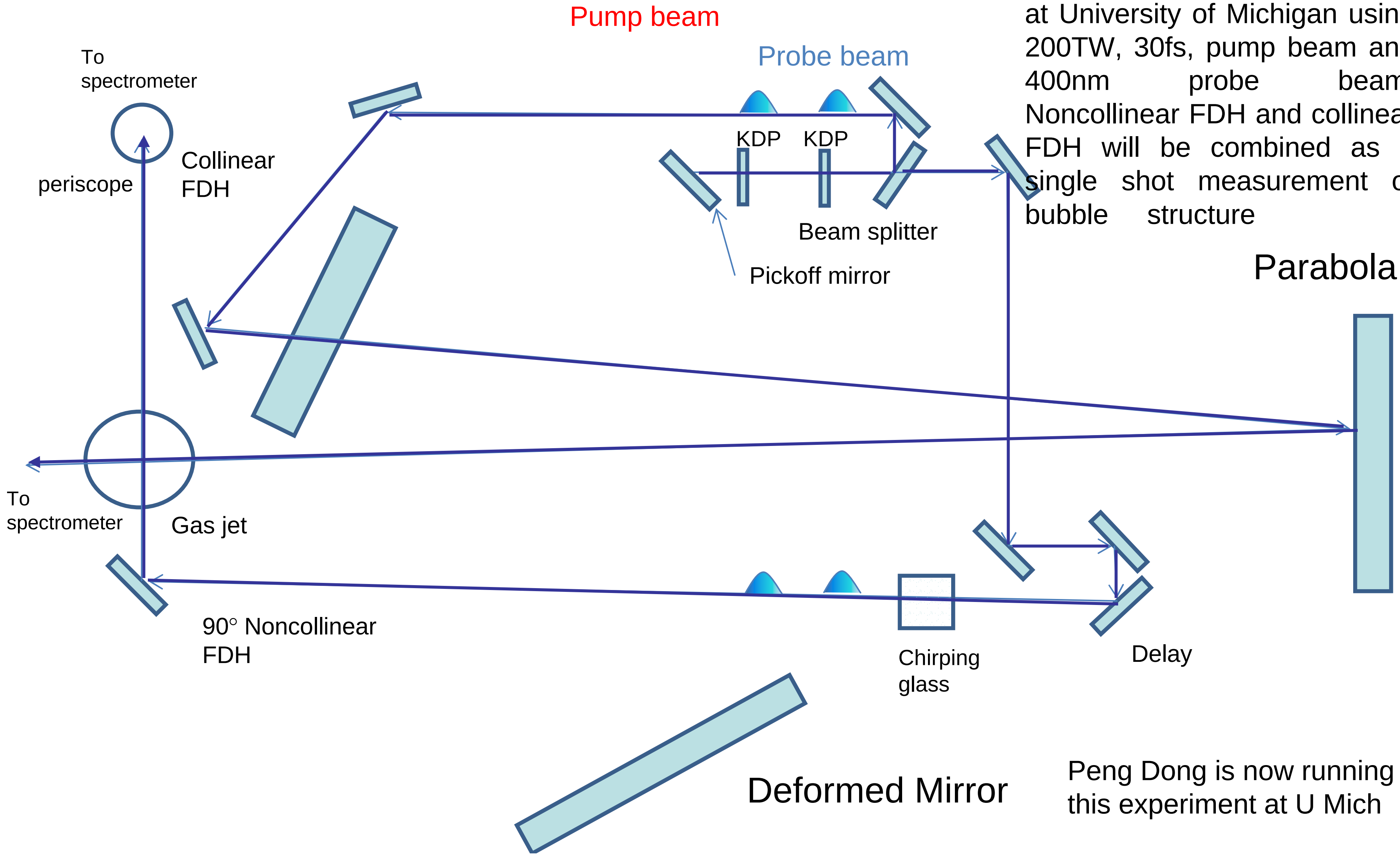
pulse energy: 200 J
pulse duration: 167 fs
peak power: 1.2 PW
1st operation: March 2008



World’s most powerful laser

Todd Ditmire, director

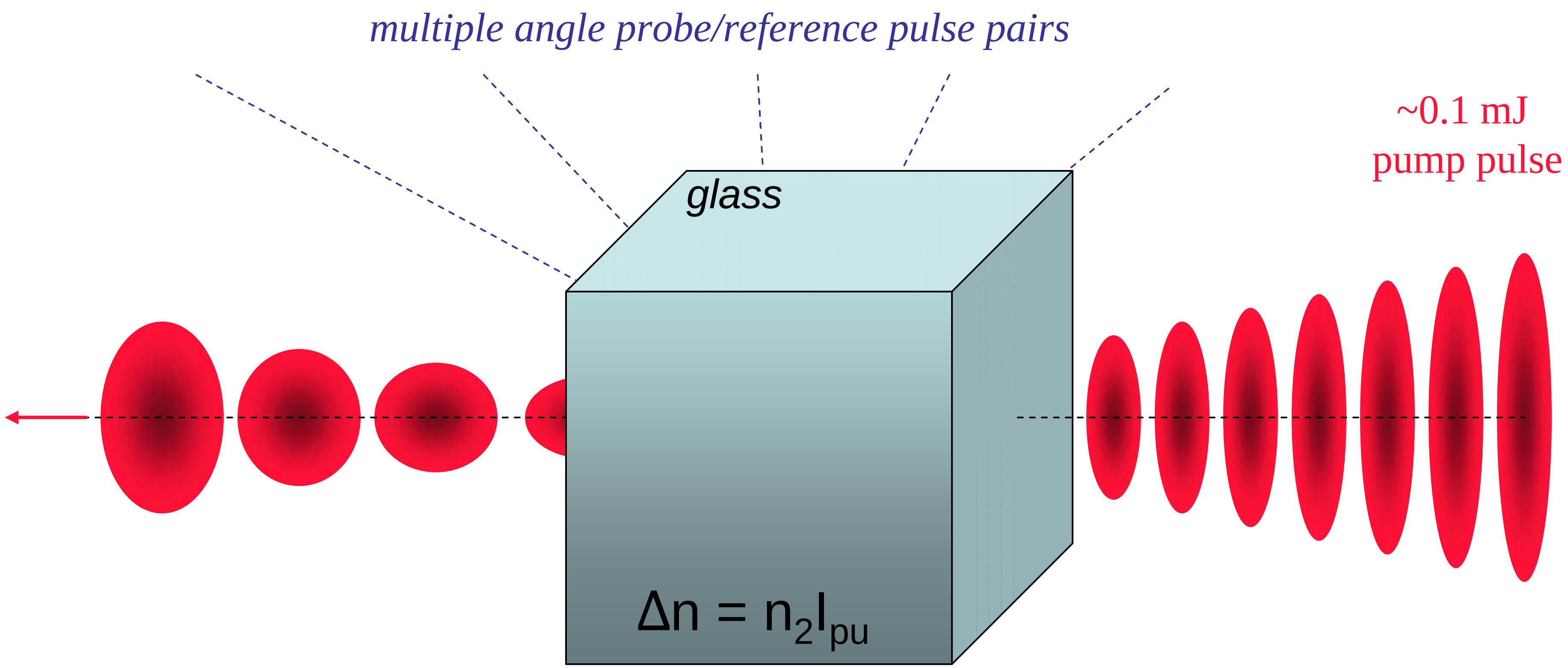
Experimental implementation of Frequency-Domain Streak Camera



Experiments will be performed at University of Michigan using 200TW, 30fs, pump beam and 400nm probe beam. Noncollinear FDH and collinear FDH will be combined as a single shot measurement of bubble structure

Peng Dong is now running this experiment at U Mich

We are setting up a prototype Frequency Domain Tomography experiment based on nonlinear index modulation in glass



As pump self-focuses and broadens temporally by GVD, the $n_2 I_{pu}$ “bubble” changes shape.

Full PIC simulations using Virtual Plasma Laboratory (VPL) code show negligible self-injection by TPW pulse at $n_e \sim 10^{17}$ cm^{-3}

Early simulations had shown efficient self-injection at $n_e \sim 5 \times 10^{17}$ cm^{-3}:

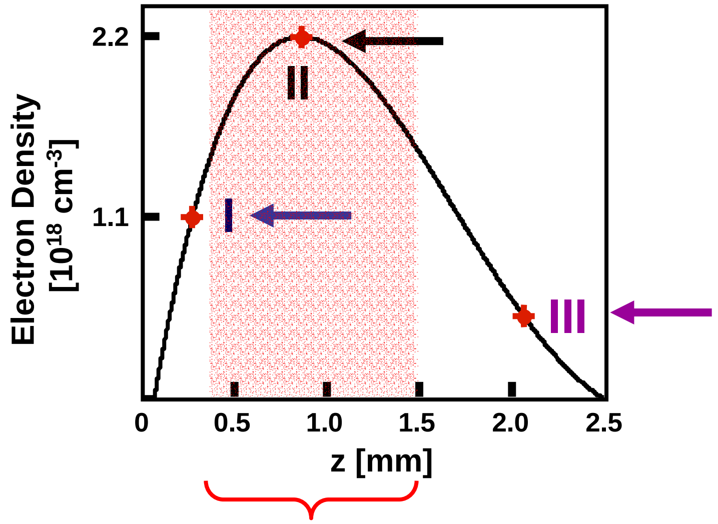
Laser Power [PW]	Pulse Duration [fs]	Plasma Density [cm^{-3}]	Spot Size [µm]	Int. Length [m]	e-charge [nC]	Energy Gain [GeV]	comments
0.02	30	10^{18}	14	0.016	0.18	**0.99**	Leemans (2006)
1.0	**80**	**5x10^{17}**	**34**	**0.08**	**1.3**	**5.7**	**self-guided**
2.0	310	10^{16}	140	16.3	1.8	**99**	**channel-guided**
20	1000	10^{15}	450	500	5.7	999	**channel-guided**

Table entries feature:

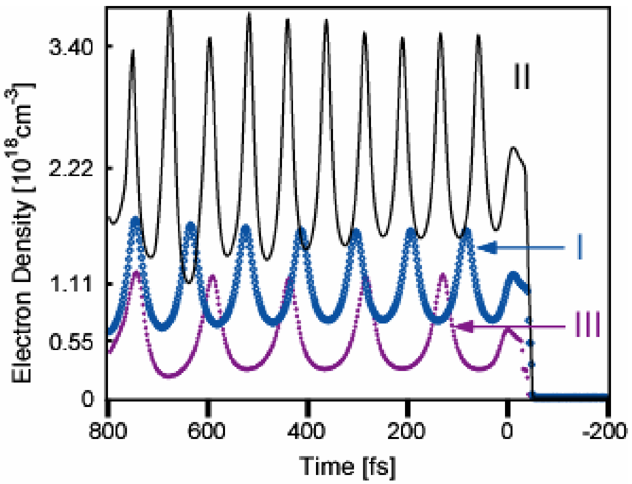
1. *stable plasma structure*
2. *$L_{dephasing} = L_{pump\ depletion}$*
3. *balance between energy extraction & beam quality*

Simulated $\Delta\phi_{pr}(r,\zeta)$ agrees with FDH data

Measured Jet Profile



Simulated Wakefield



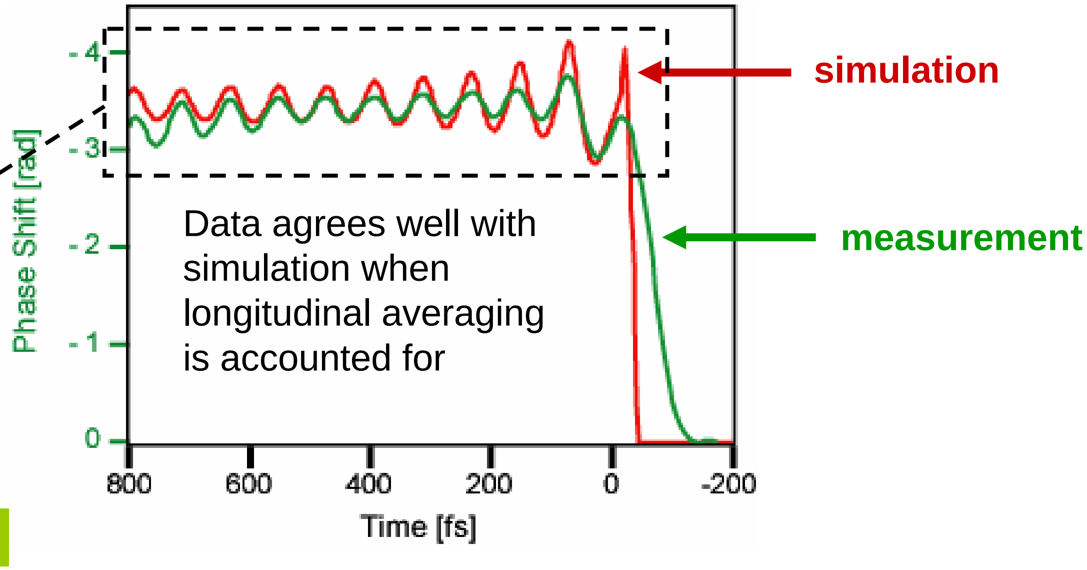
Primary 2D structure $\Delta\phi_{probe}(r,\zeta)$ is imprinted in central L_{eff} ~ L/3, and accurately reflects $n_e(r,\zeta,z\approx1\text{ mm})$ near jet center.

To a good approximation:

$$\left[n_e(r,\zeta,z\approx 1mm)\right]_{oscill} = \frac{mc\omega_{pr}\Delta\phi_{pr}(r,\zeta)}{2\pi e^2 L_{eff}}$$

LONGITUDINAL ABEL INVERSION

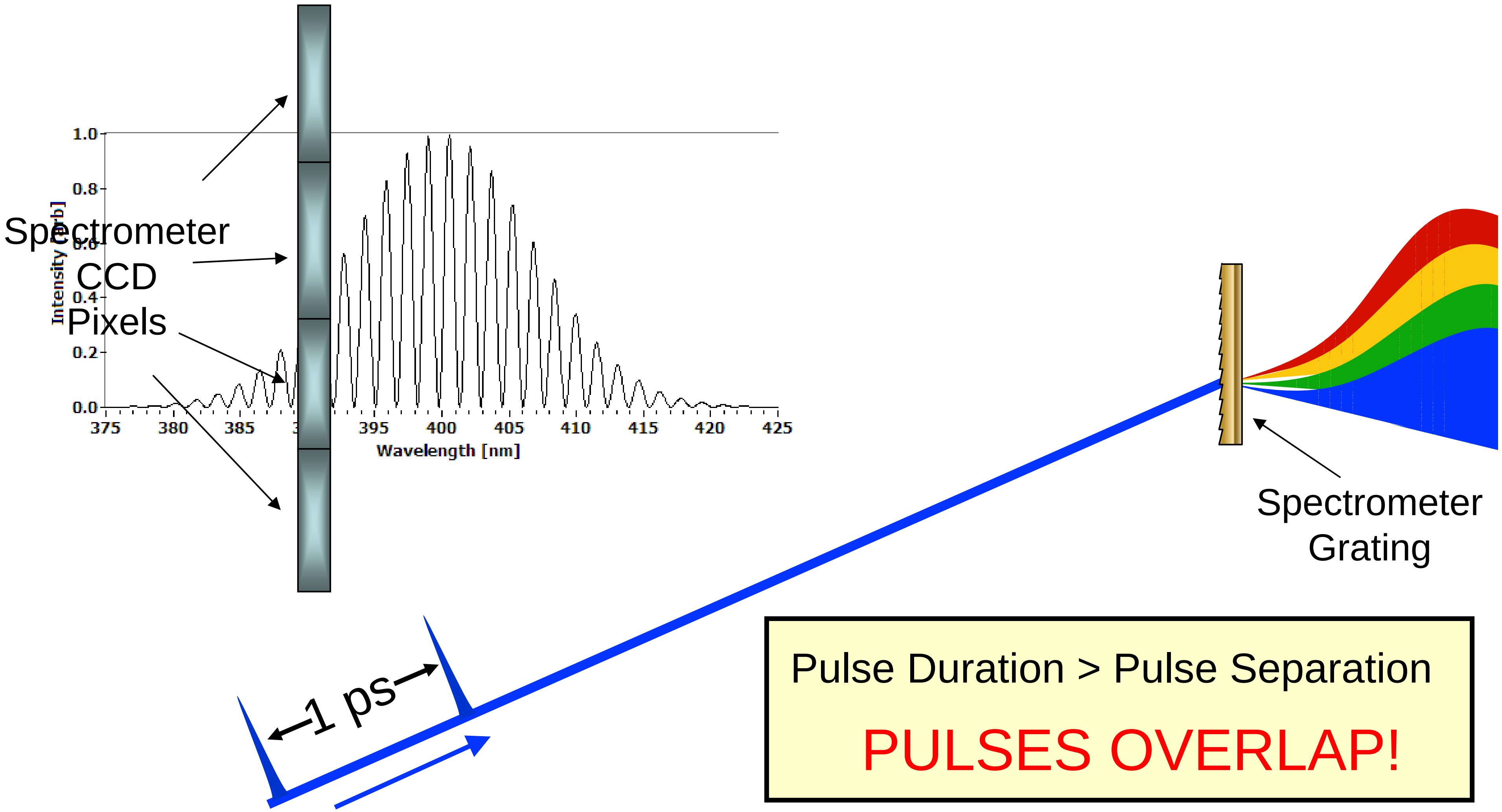
Comparison of Integrated Phase at *r* = 0



Data agrees well with simulation when longitudinal averaging is accounted for

FDI: Temporal Overlap in Spectrometer

Interferogram



Pulse Duration > Pulse Separation

PULSES OVERLAP!