Frequency Domain Streak Camera for Ultrafast Imaging of EVOLVING Wakefields

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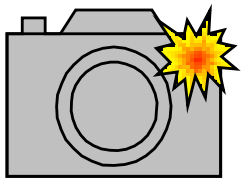
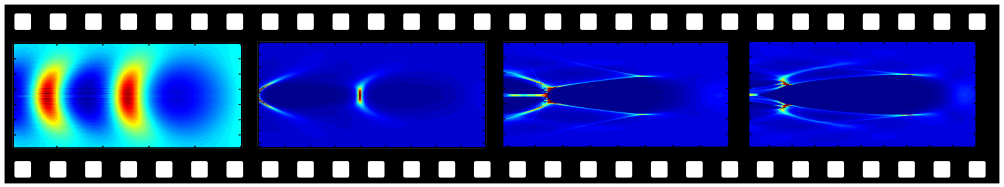
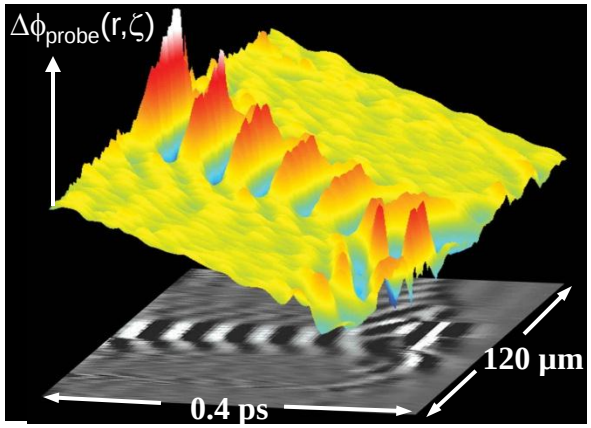




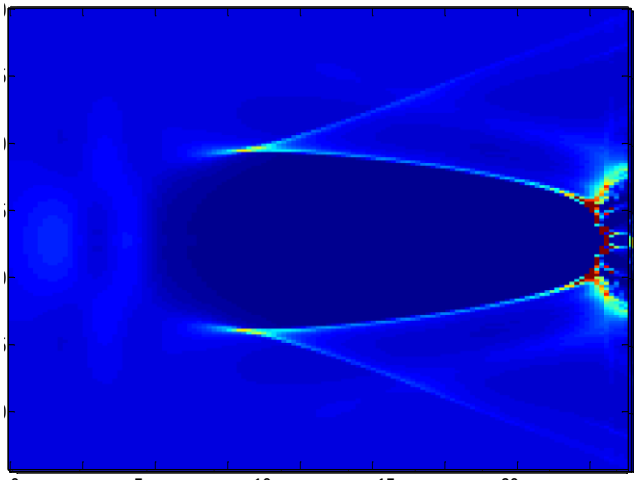
Snapshots of Quasi-static Wakes



N. H. Matlis *et al*., Nature Phys. **2**, 749 (2006)
P. Dong *et al*., Phys. Rev. Lett.**104**, 134801 (2010)

aim of this work

Movies of Evolving Wakes...

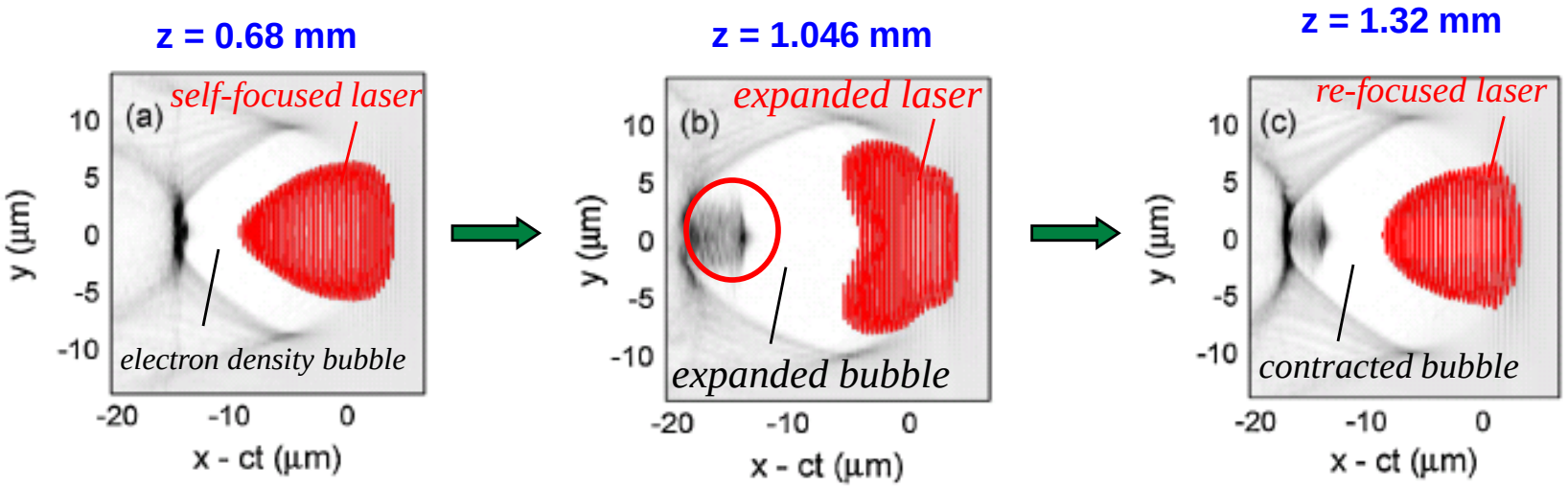


...all in one laser shot !

In the "Bubble" regime, evolution of the LPA structure is essential to the accelerator's function

S. Kalmykov, S. A. Yi, V. Khudik, G. Shvets, Phys. Rev. Lett. **109**, 135094 (2009);
G. Shvets, AAC WG1, Thursday, June 17; S. Y. Kalmykov, AAC WG1, Thursday, June 17

Simulated pictures…

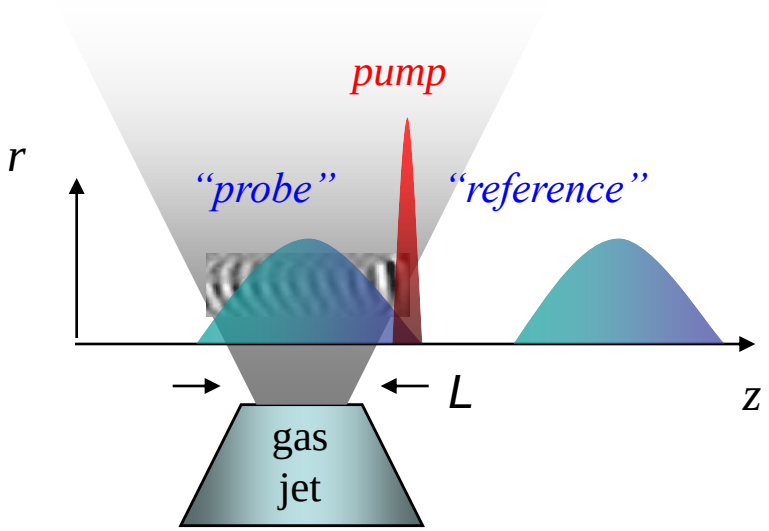


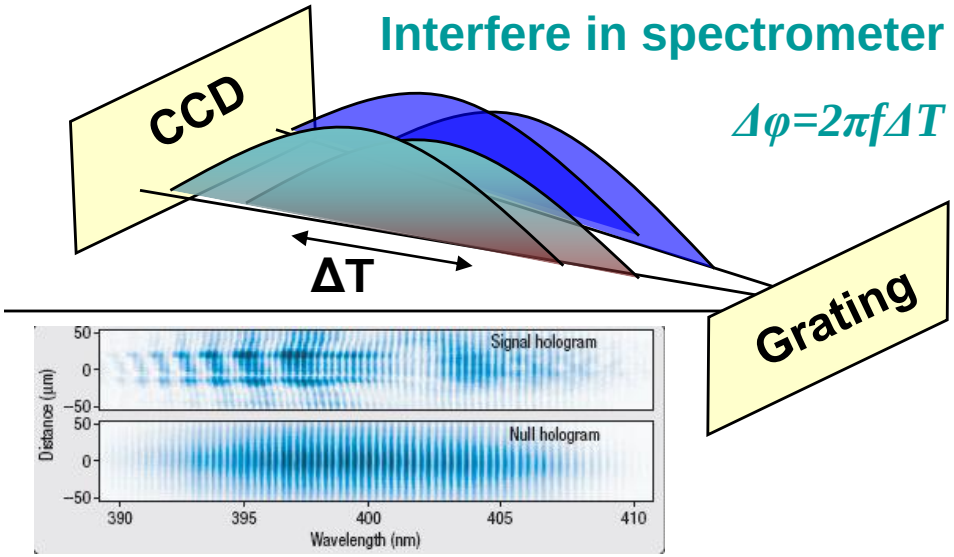
- **Bubble Formation**
- **Bubble Expansion:** election self-injection
- **Bubble Contraction:** e^- injection terminated, mono-energetic electron

We aim to visualize such evolution in the laboratory on each laser shot in order to better understand and optimize LPA function

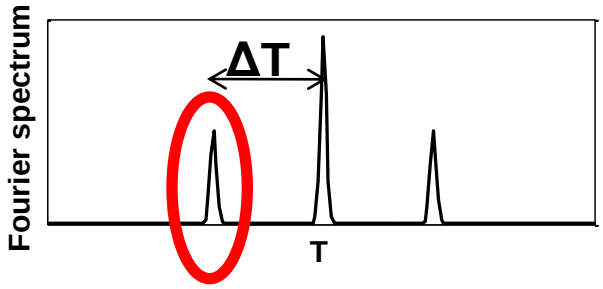
Basic method we developed to visualize weakly evolving wakefields: Frequency Domain Holography (FDH)* …

* Le Blanc *et al*., Opt. Lett. (2000)

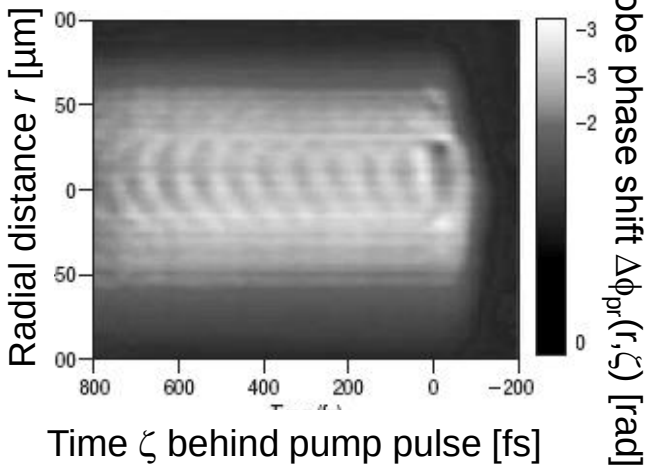




$$\Delta\phi_{pr}(r,\zeta) = \frac{2\pi}{\lambda_{pr}} \int_0^L [1 - \eta(r,\zeta,z)]dz$$

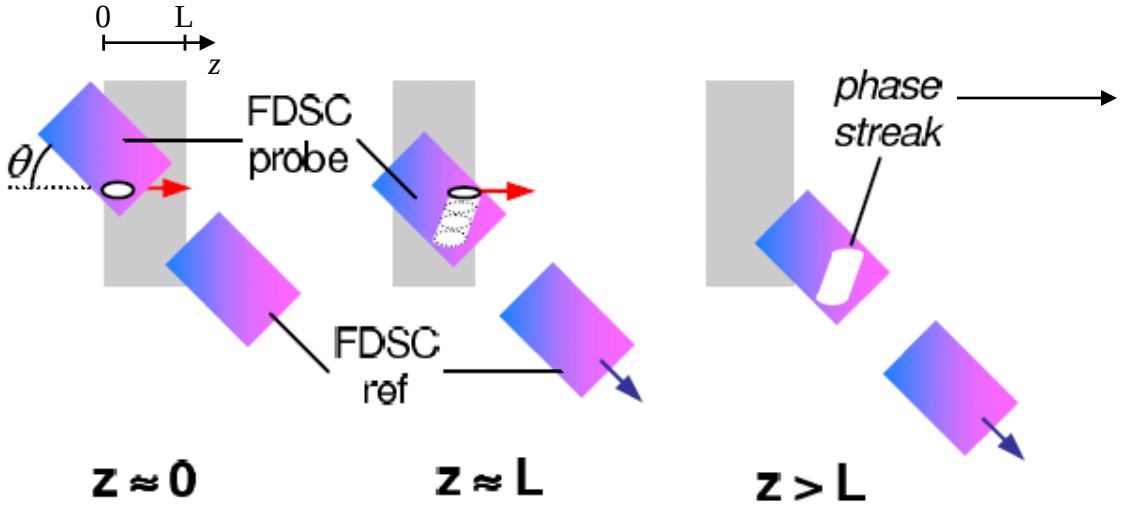


FM (phase) reconstruction

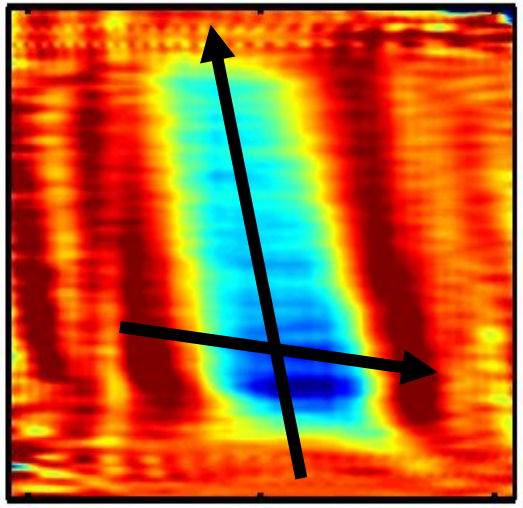


AM (amplitude) reconstruction by P. Dong, AAC WG1 Th, 6/17.

Frequency Domain Streak Camera (FDSC) records evolution of the “bubble” by probing at an oblique angle



Measured Streak…



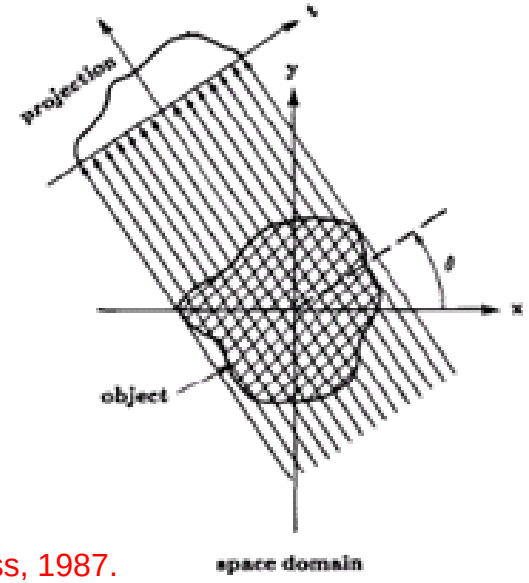
Conventional X-ray CT projection: **static object, moving probe**

In reference frame of FDSC probe …

Static probe, moving object

Transverse line-out: “projection” of object at z

Longitudinal line-out: refractive index evolution as pump propagates.

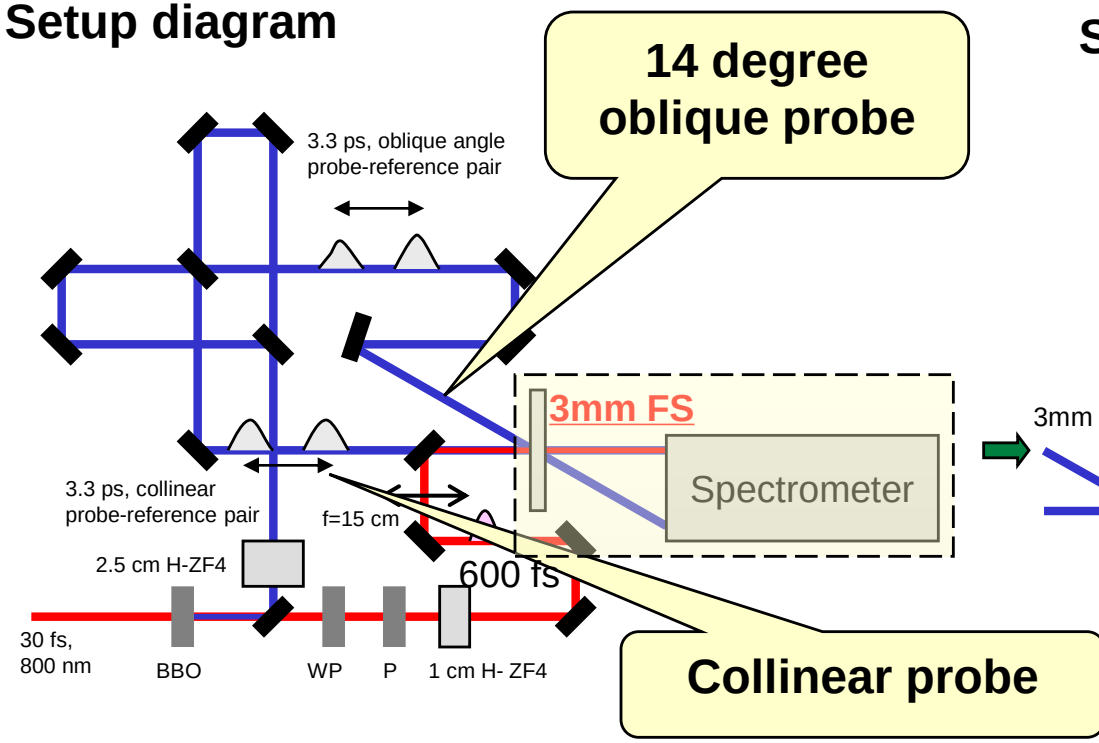


FDSC is a Time Sequence of Projections (TSP)!

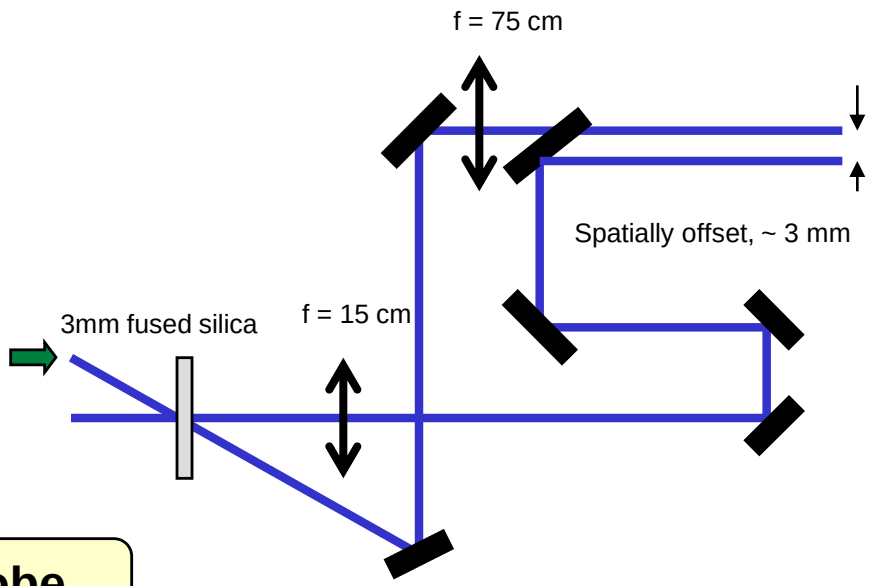
A. C. Kak, M. Slaney, Principles of Computerized Tomographic Imaging, IEEE Press, 1987.

To demonstrate the FDSC method, we performed *prototype* experiment with μJ pump in glass…

Setup diagram



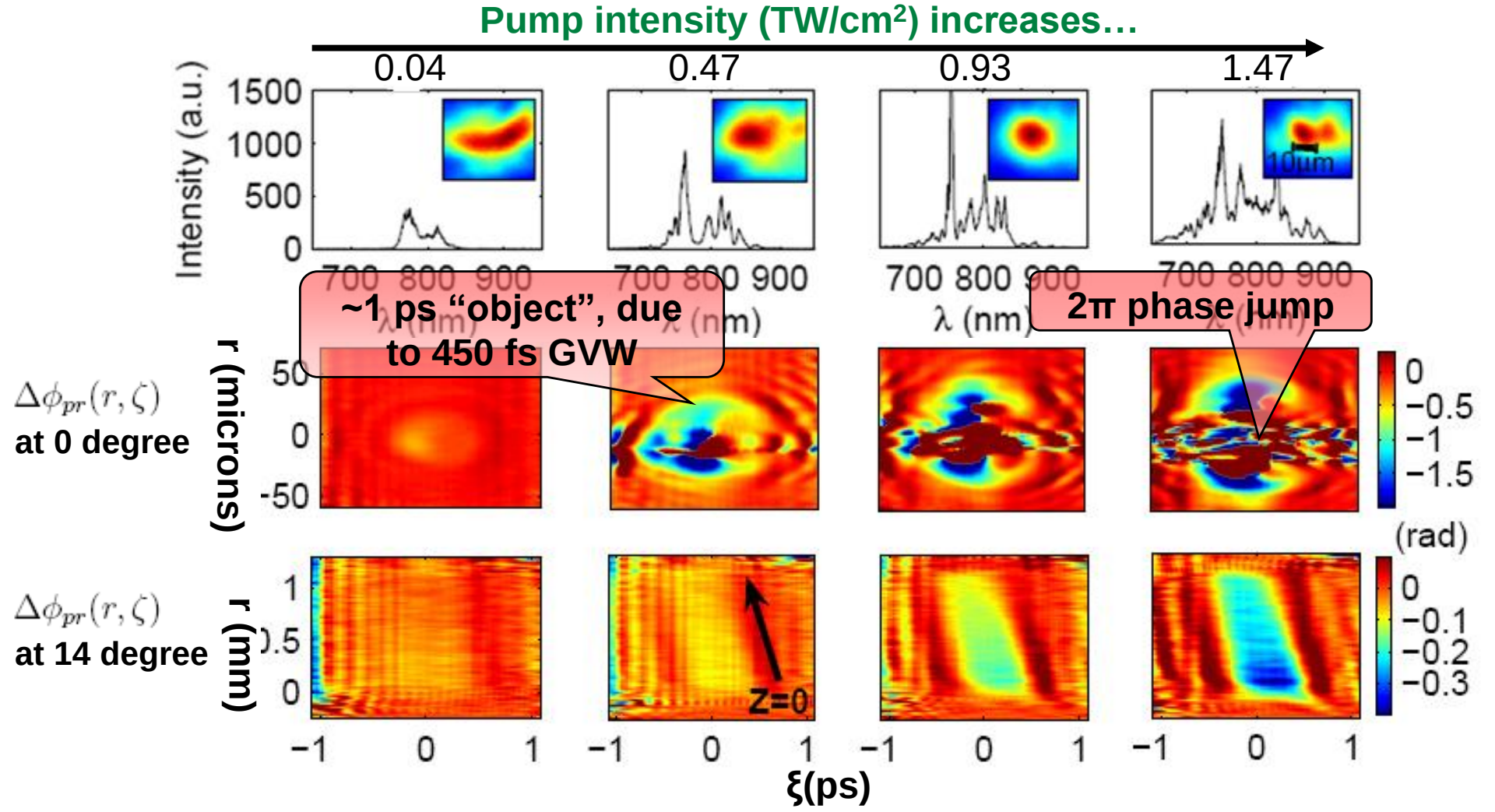
Spatial multiplexing



- $n = n_0 + n_2 I$
- The "object" is space-time profile of pump pulse which is evolving because of diffraction, self-focusing, absorption, etc.

Temporal multiplexing will be discussed later…

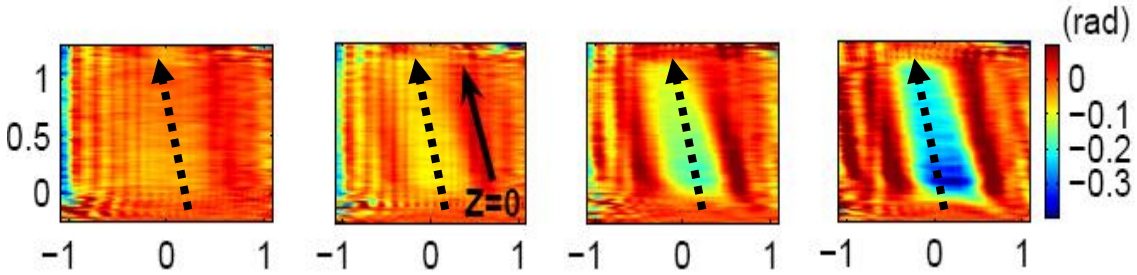
FDSC improves the accuracy of interpreting the object compared to collinear FDH alone…

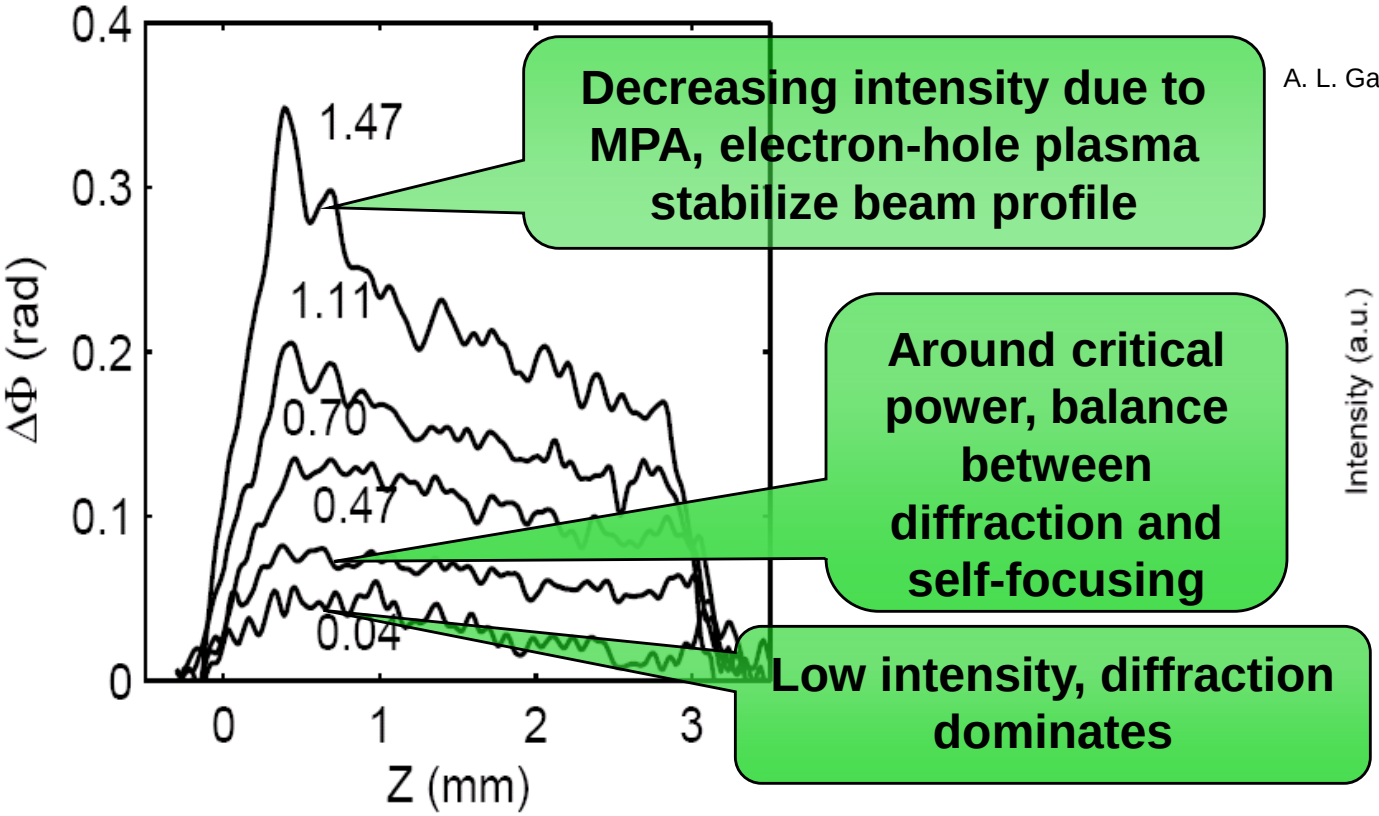


Time-varying phase shift in FDSC reveals pump intensity evolution!

Longitudinal line-outs reveals pump intensity EVOLUTION during propagation…

Longitudinal line-outs of FDSC under different intensities…





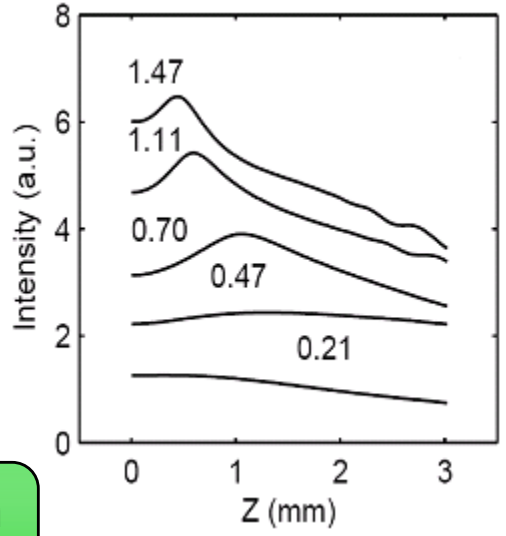
Decreasing intensity due to MPA, electron-hole plasma stabilize beam profile

Around critical power, balance between diffraction and self-focusing

Low intensity, diffraction dominates

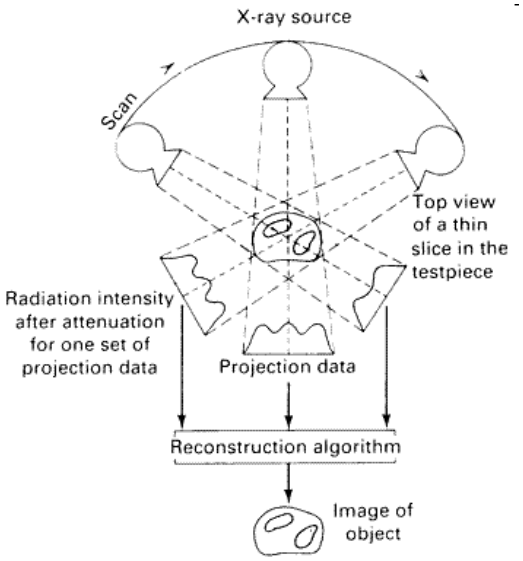
NLSE simulation, including linear diffraction, dispersion, and nonlinear Kerr effect, MPA, electron-hole plasma defocusing and absorption.

A. L. Gaeta, Phys. Rev. Lett. 84, 3582-3585 (2000).



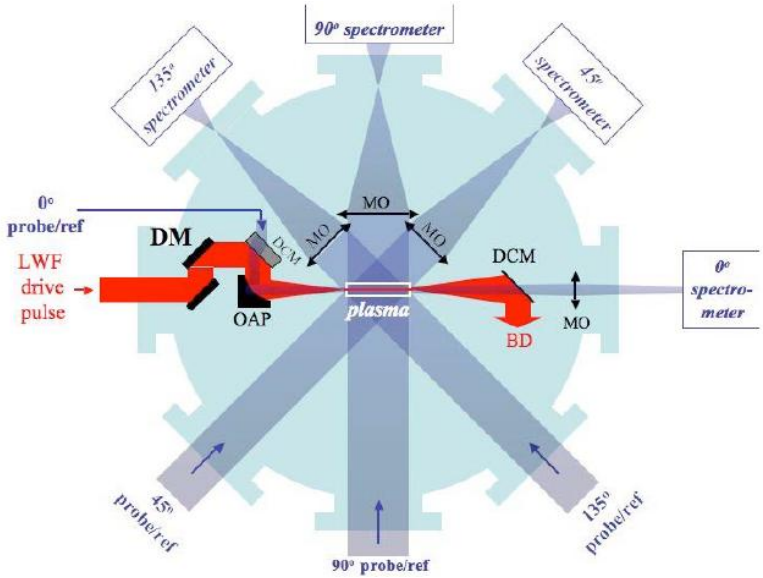
To fully generalize FDH, probes at multiple angles are required: Frequency Domain Tomography (FDT)

X-ray CT scan…



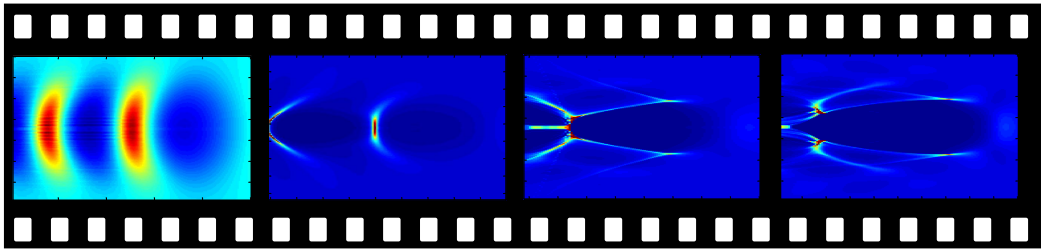
http://qnde.org/ct.html

Probes at multiple angles…



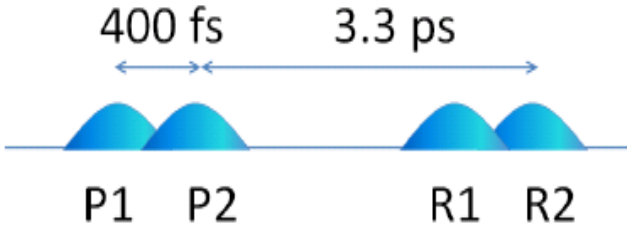
Time Sequences of Projections(TSsP)

FDT reconstruction…

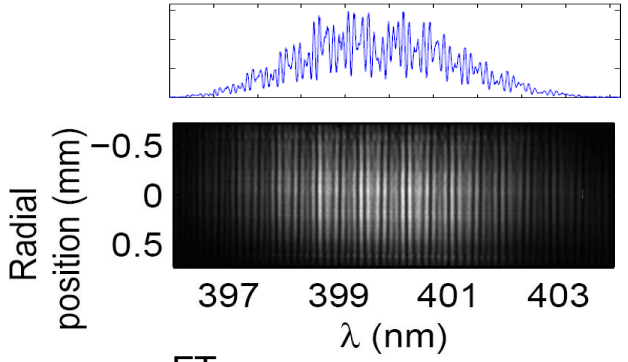


The first difficulty comes in mind: EXPENSIVE spectrometers!!! ***$$$!!!***

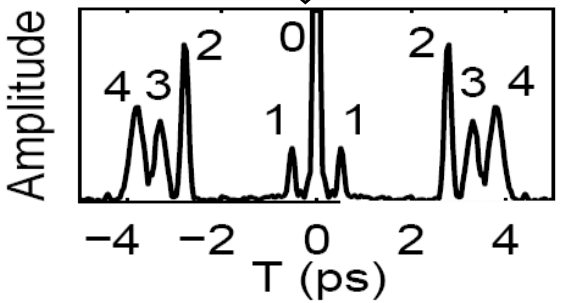
Analyzing a dozen of probes with a SINGLE spectrometer is possible by temporally multiplexing those probes…



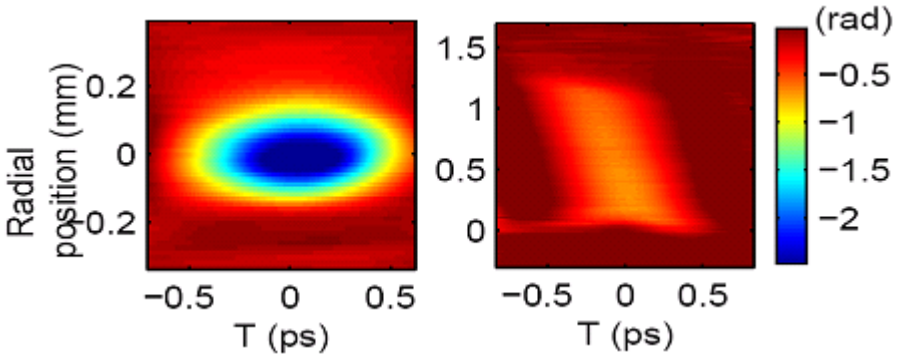
Interference



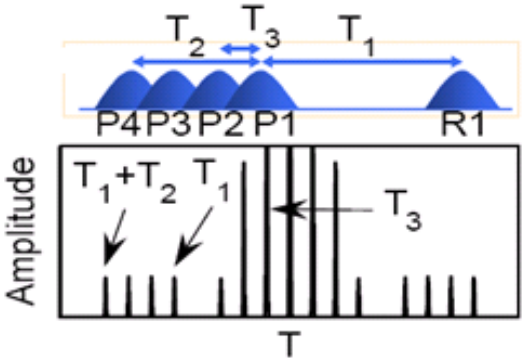
FT transform



Cross-talk free Reconstruction

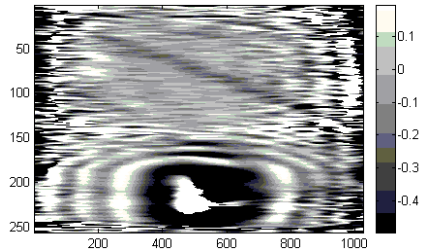


Current more efficient setup allowing more probes…

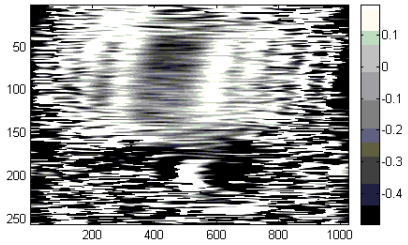


Measured streaks in a single shot with both SM and TM…

0 & ~50 degree

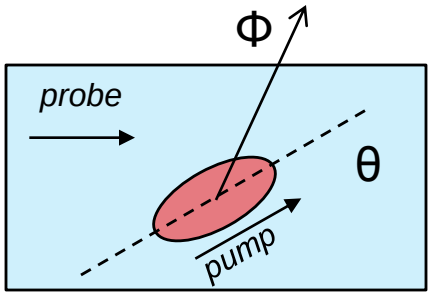


14 degree



~ 15 probes analyzed by a SINGLE spectrometer by combing spatial and temporal multiplexing!

Tomography reconstruction of the EVOLVING “bubble” with “streaks” from multiple angle probes…

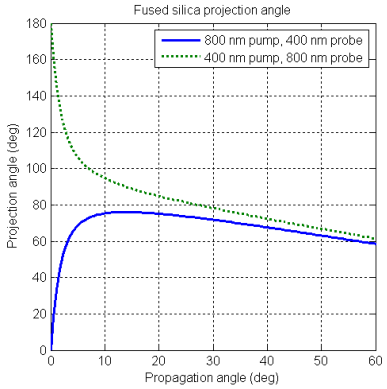


θ: *angle between pump & probe*

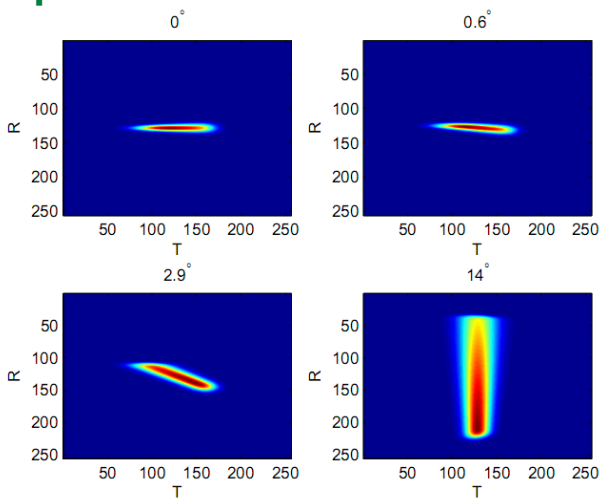
Φ : *streak axis angle*

δ =φ-θ: *projection angle*

δ -θ relation



The evolving object propagation writes “streaks” on probe profiles…

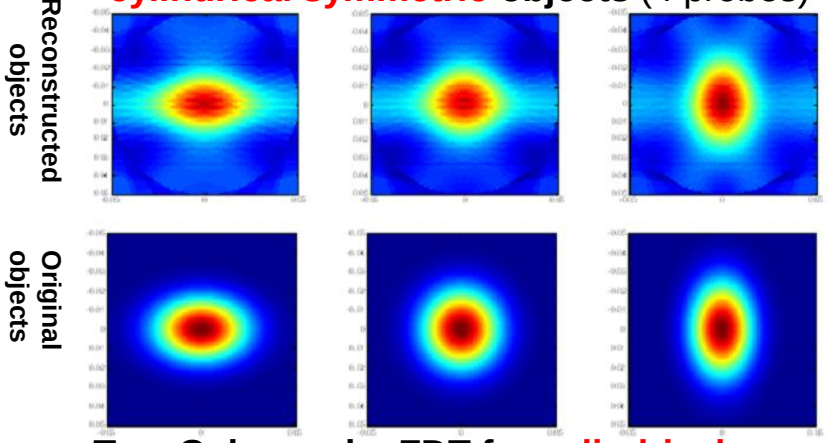


Reconstructions with tomography algorithm…

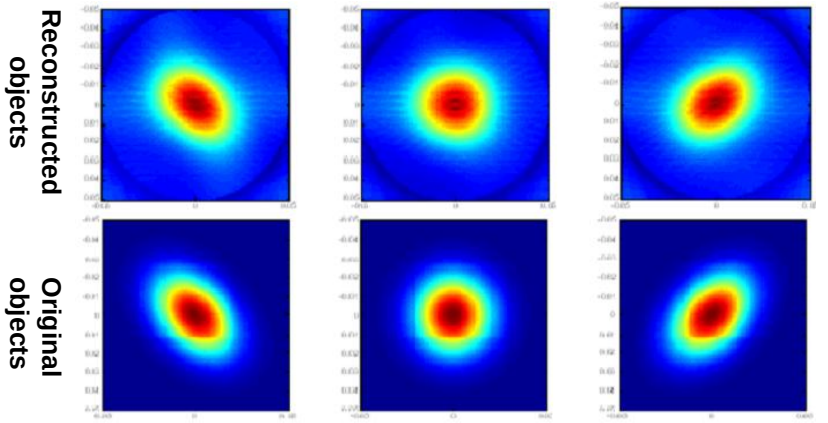
Numerical experiments…

Z = 0.5mm Z = 1.5mm Z = 2.5mm

800nm pump/400nm probe FDT for cylindrical symmetric objects (4 probes)



Two-Color probe FDT for cylindrical asymmetric objects (10+10 probes)*



* F.B.Grigsby, et al. J. Opt. Soc. Am. B **25**, 346 (2008)

Conclusion

- We demonstrated **Frequency Domain Streak Camera (FDSC),** which is a Time Sequence of Projections (TSP), revealing time-varying properties of evolving laser plasma wakefields.
- We also proposed **Frequency Domain Tomography (FDT),** with probes at multiple angles spatially and temporally multiplexed, yielding a movie of evolving wakefields.
- **FDSC/FDT application for several types of advanced accelerators**
  1. Channeled LPA, where longitudinal probing is impossible
  2. Particle beam driven LPA, where longitudinal probing is inconvenient.
  3. Visualization of evolving LPA.

This work was supported by U.S. DoE grants DE-FG02-07ER54945 and DE-FG03-96ER40954 and NSF grant PHY-0936283.

Z. Li, R. Zgadzaj, X. Wang, S. Reed, M. C. Downer, *"Frequency-Domain Streak Camera for Ultrafast Imaging of Evolving Light-Velocity Object,"* submitted to Optics Letters.

Thank you!