FACET-II Science Workshop
Oct. 17-20, 2017

E-224:
Imaging of beam-induced plasma structures: FACET and FACET-II

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The University of Texas at Austin

1. FACET-I: Ion wake visualization (1 ps < Δt < 150 ps)*

- main E224 discovery: ion wakes contain structures seeded by e-wake's "DNA"
- status: simulated e → ion wake conversion; simulating diffraction from wakes
- importance: ion wakes influence emittance; determines collider rep. rate

2. FACET-II: Electron wake visualization (Δt < 100 fs)*

*time delay after e-bunch

- goals: e^- vs. e^+-driven wakes; e-wakes in self- vs. pre-ionized plasma
- requirements: improved sensitivity; 3D visualization capability, low wake-probe time jitter & longitudinal walk-off

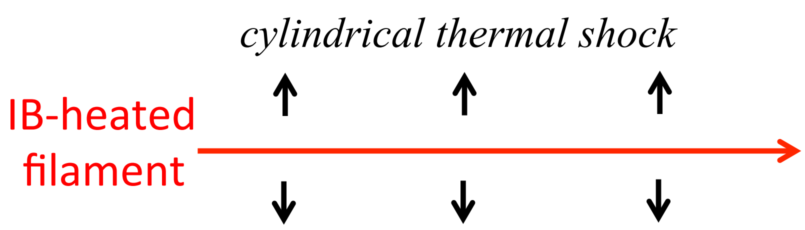
Financial support: NSF-PHY-1416218 "Visualization of e-beam-driven PWFAs"
DOE DE-SC0012444 "Multi-GeV plasma acceleration physics"

Nonlinear PWF creation deposits enormous energy density into plasma electrons…

J. Vieira, *PRL* **109**, 145005 (2012); K. Lotov, *PRL* 112, 194801 (2014);
A. Sahai, ArXiv.1504.03735 (2016)

IB-heated ion wakes

(IB = Inverse Bremsstrahlung)



typical deposited energy density

$k_B T_e \sim 100$ eV

$$n_{e0} k_B T_e \sim 10^{-4} n_{e0}\, mc^2$$

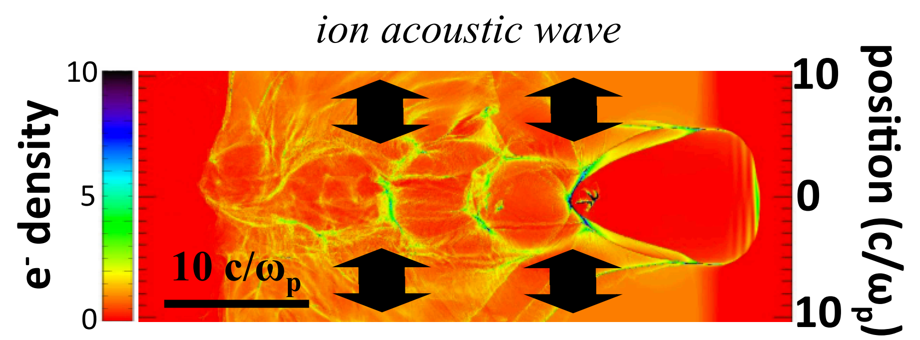
energy deposition rate: $d\varepsilon/dt = 2U_p \nu_{ei}$

e-ion collision frequency: $\nu_{ei} \propto n_i U_p^{-3/2}$

U_p = ponderomotive energy

Durfee, *PRE* **51**, 2368 (1995)

Nonlinear-PWFA-seeded ion wake



energy density of plasma wave

rest energy density of plasma electrons (10^6 eV/e$^-$)

$$(1/2)\varepsilon_0 E_0^2 = (1/2)\, n_{e0} mc^2$$

where $E_0 = mc\omega_p/e$ (wave-breaking field)

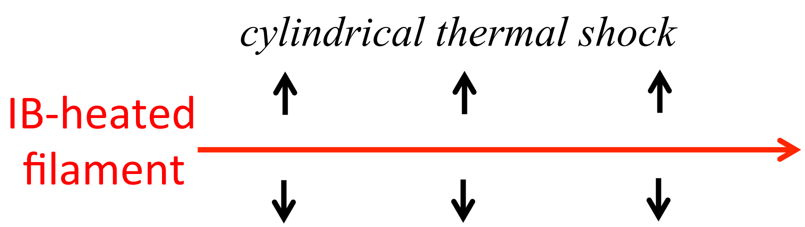
… which drives subsequent ion wakes

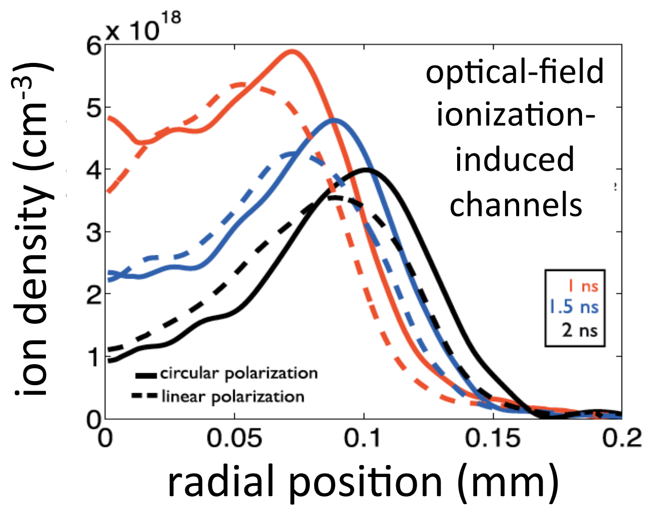
Longitudinally asymmetric e⁻ wakes couple strongly to ion wakes with unique shapes

J. Vieira, *PRL* **109**, 145005 (2012); K. Lotov, *PRL* 112, 194801 (2014);
A. Sahai, ArXiv.1504.03735 (2016)

IB heated ion wakes

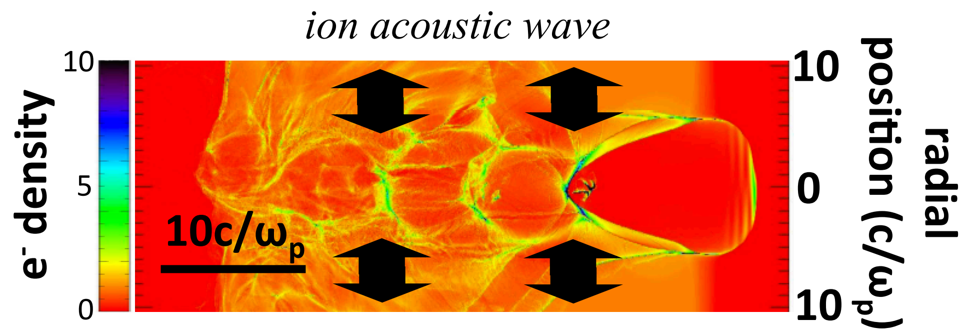
(IB = Inverse Bremsstrahlung)



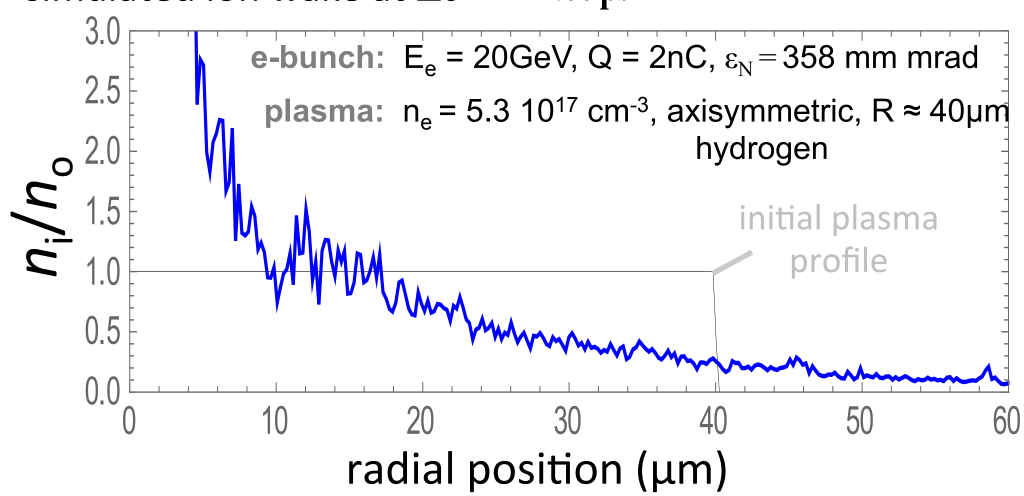


Lemos, *PoP* **20**, 103109 (2013)

Nonlinear-PWFA-seeded ion wake



simulated ion wake at Δt = 114.66 ps



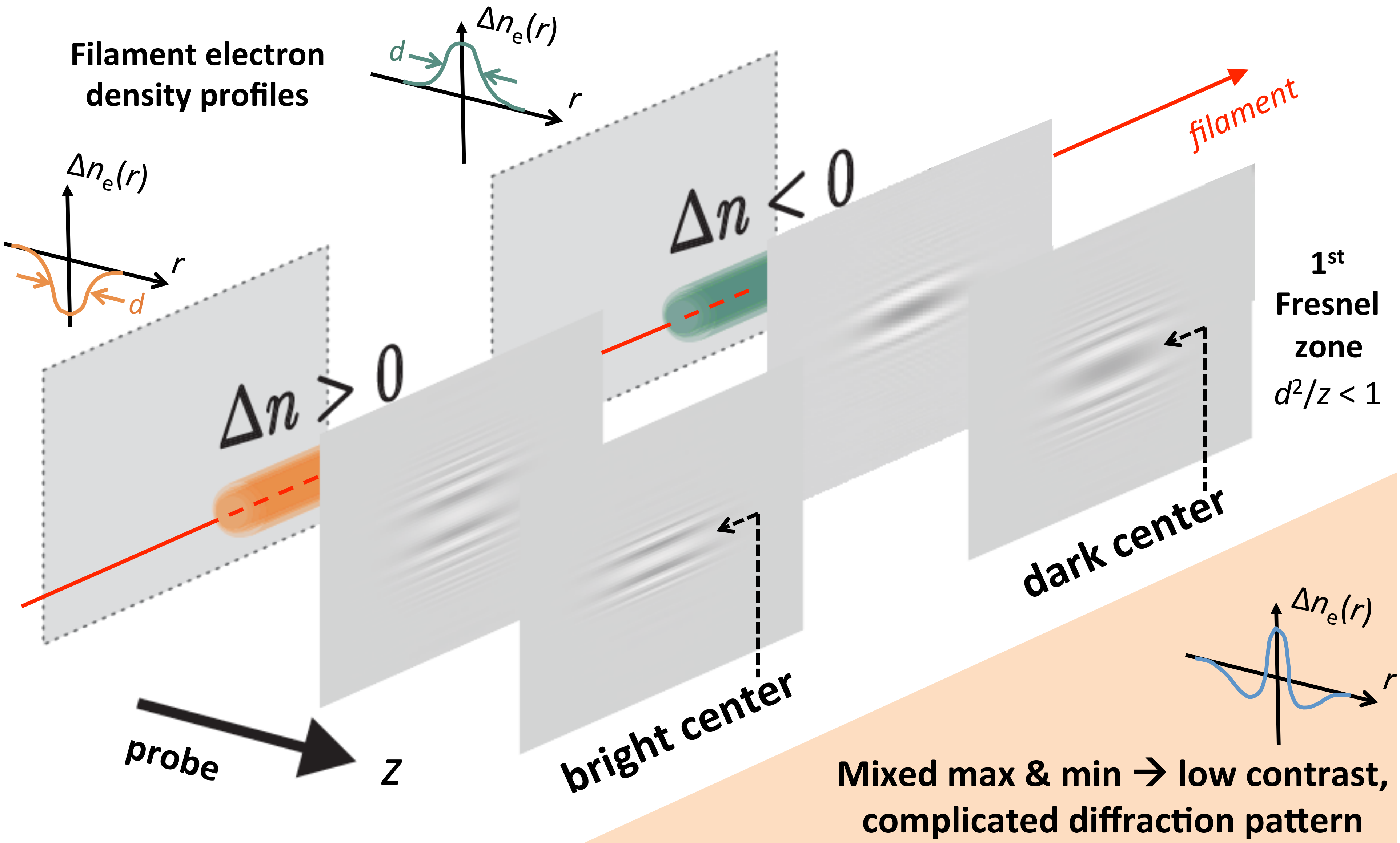
L-CODE simulations, courtesy K. V. Lotov

LCODE is a quasi-static axisymmetric 2d3v code

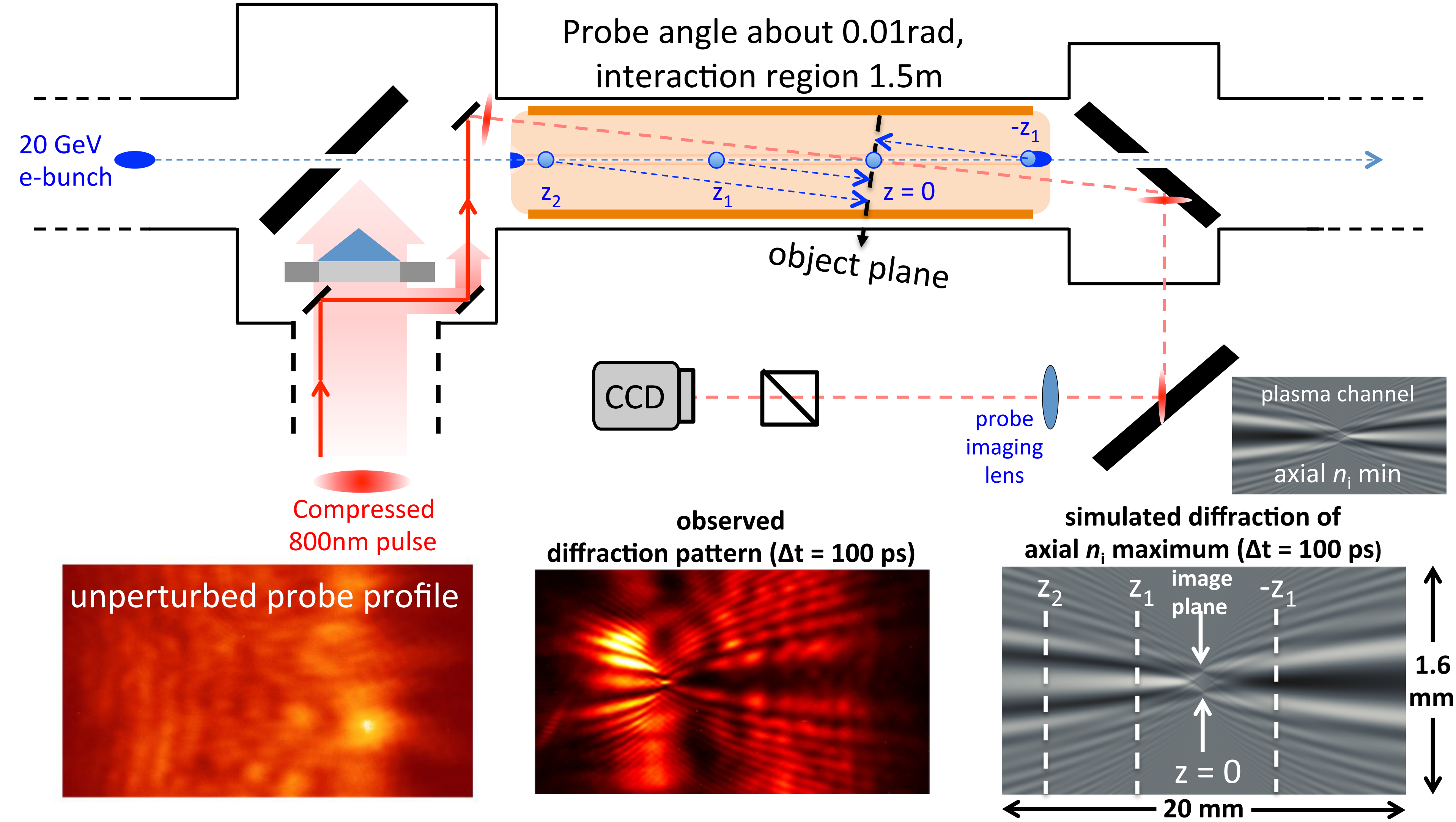
- **Kinetic solver for plasma electrons, plasma ions, & beam e$^-$**
- **LCODE used to simulate long-term evolution of broken wake-fields for the AWAKE project.**
- **We are simulating probe diffraction from the simulated density profiles. The initially sharp plasma edge must be softened to get realistic results for Δt < ~30 ps.**
- **References:** K. V. Lotov, *PRL* **112**, 194801 (2014)
  , Phys. Plasmas 5, 785 (1998)
  , Phys. Rev. ST Accel. Beams 6, 061301 (2003)
  , Plasma Phys. Controlled Fusion 52, 065001 (2010)
- **Strong ion wakes motivate use of auxiliary "energy recovery" laser pulses/e-bunches to cancel un-needed parts of wake.**
  See Cowley, Hooker, *PRL* **119**,044802 (2017) for details.
- **We remain interested in complementary simulation support from others!**

Near-field transverse-probe diffraction distinguishes axial n_e max & min

Abdollahpour, *Phys. Rev. A* **84**, 053809 (2011)

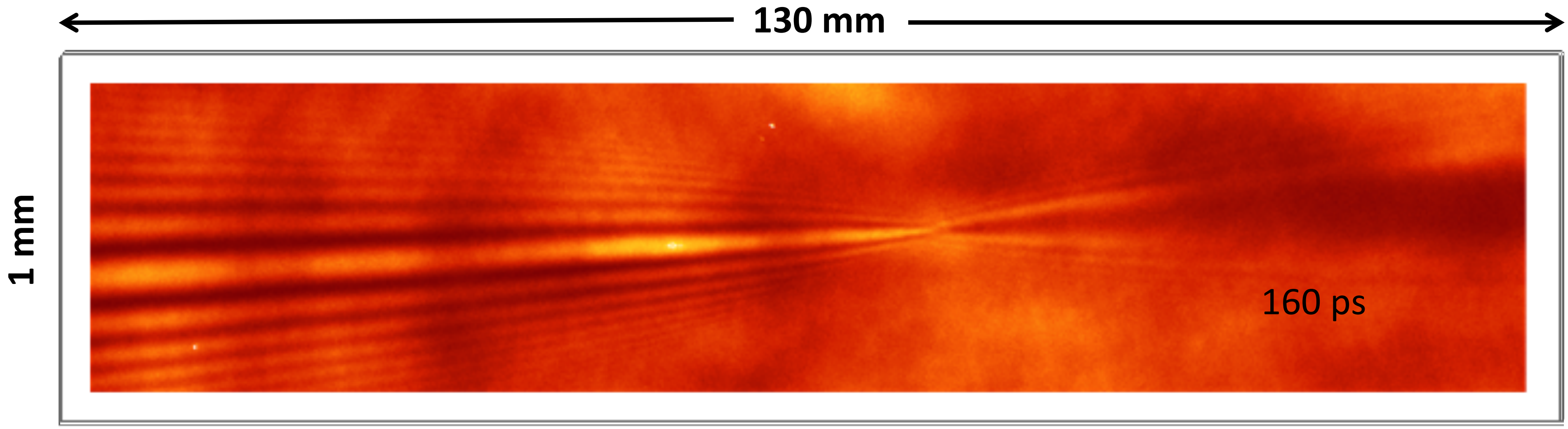


At FACET, we imaged a continuous series of near-field diffraction patterns of an ion wake in a single shot



We observed time evolution of the ion wake's diffraction pattern in hydrogen plasma.

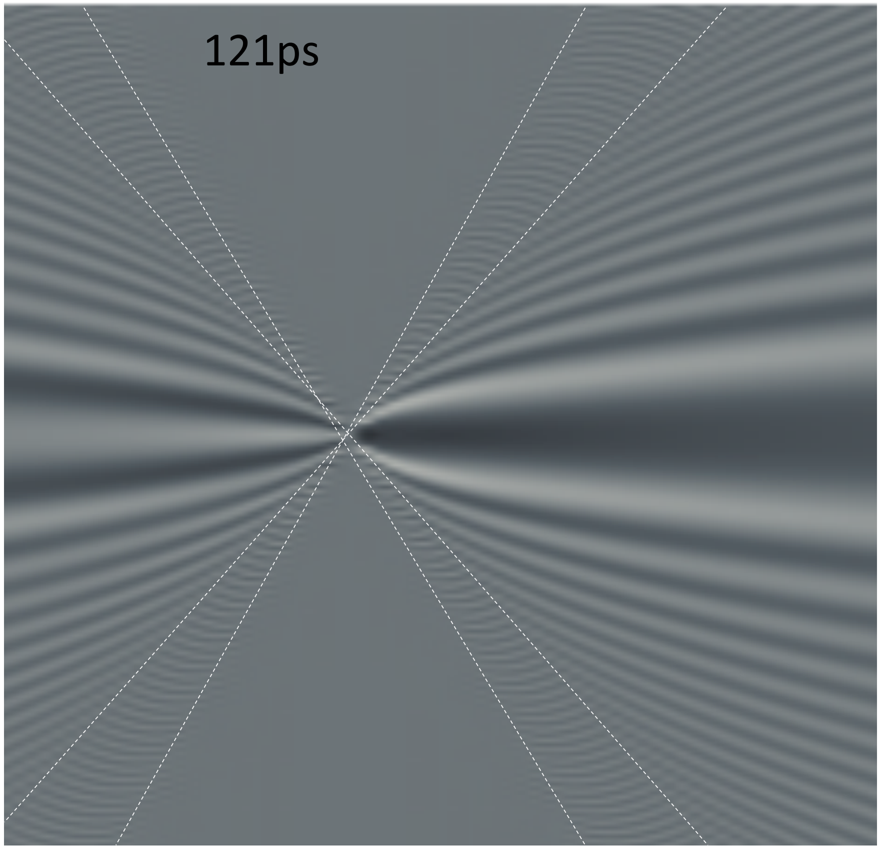
e-beam arrives 3ps after ionizing laser, which was focused by an axicon in 20 Torr H_2.
Probe delay Δt scanned from 0 to 200ps



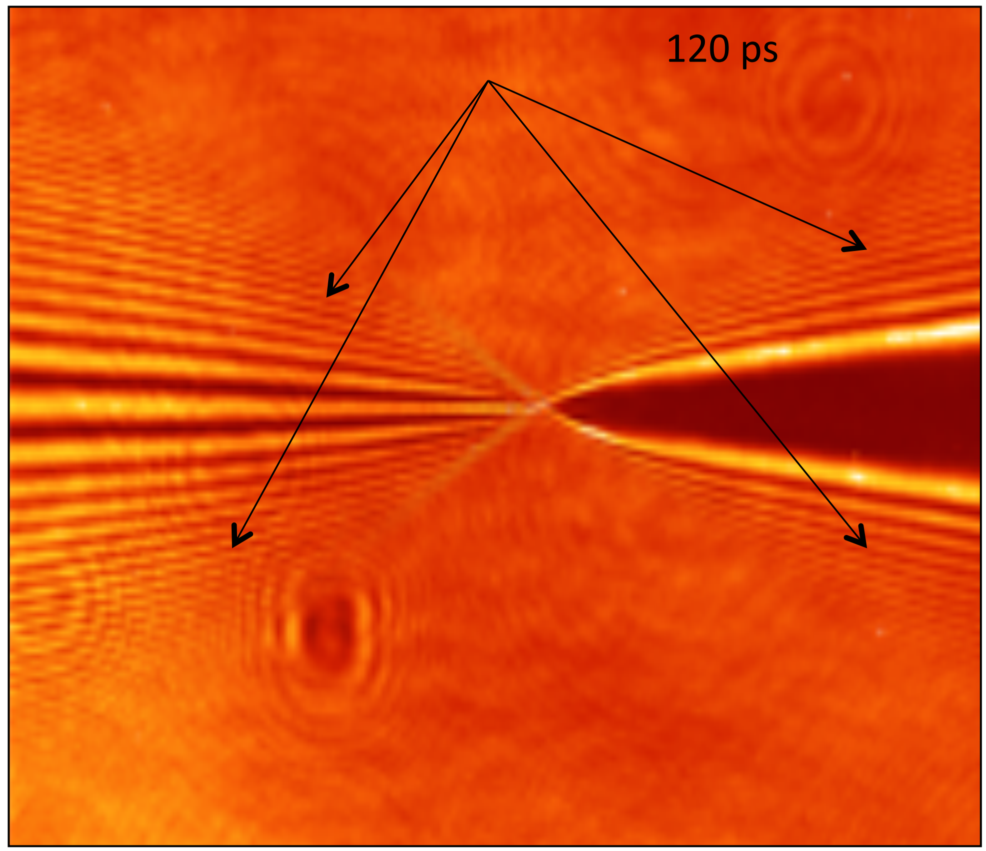
Strengthening of the diffraction pattern tracks growth of central ion density maximum.
The ~100 ps time scale of this growth is consistet with simulations.

Fine-scale structure appears in simulated & measured diffraction patterns at Δt > 80 ps

Simulation

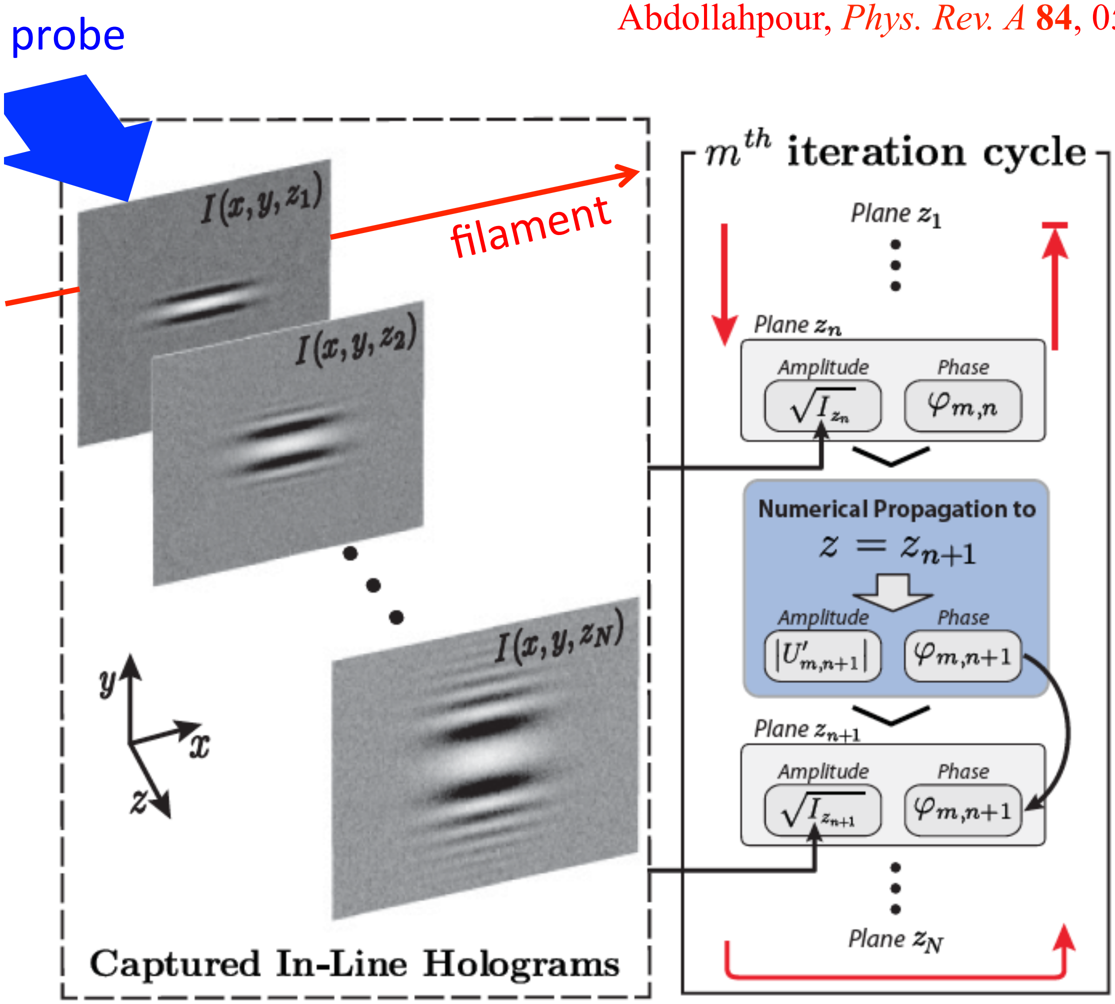


Measurement

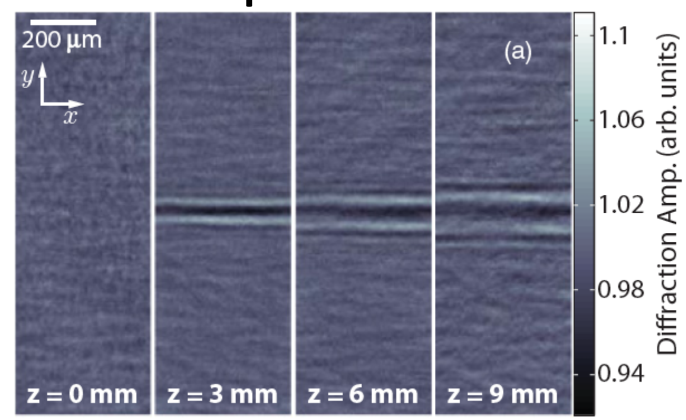


Multi-Plane Optical Diffractometry (M-POD) recovers transverse profile of filaments ...

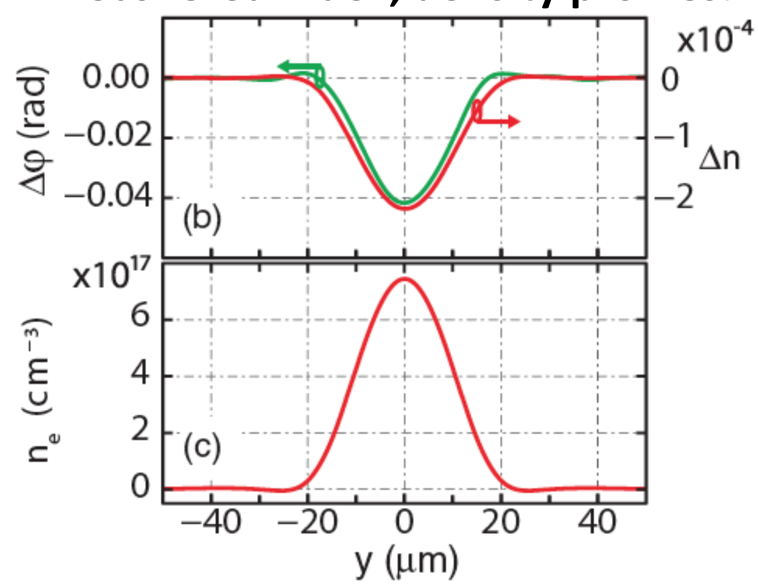
Abdollahpour, *Phys. Rev. A* **84**, 053809 (2011)



sample data:



recovered index, density profiles:

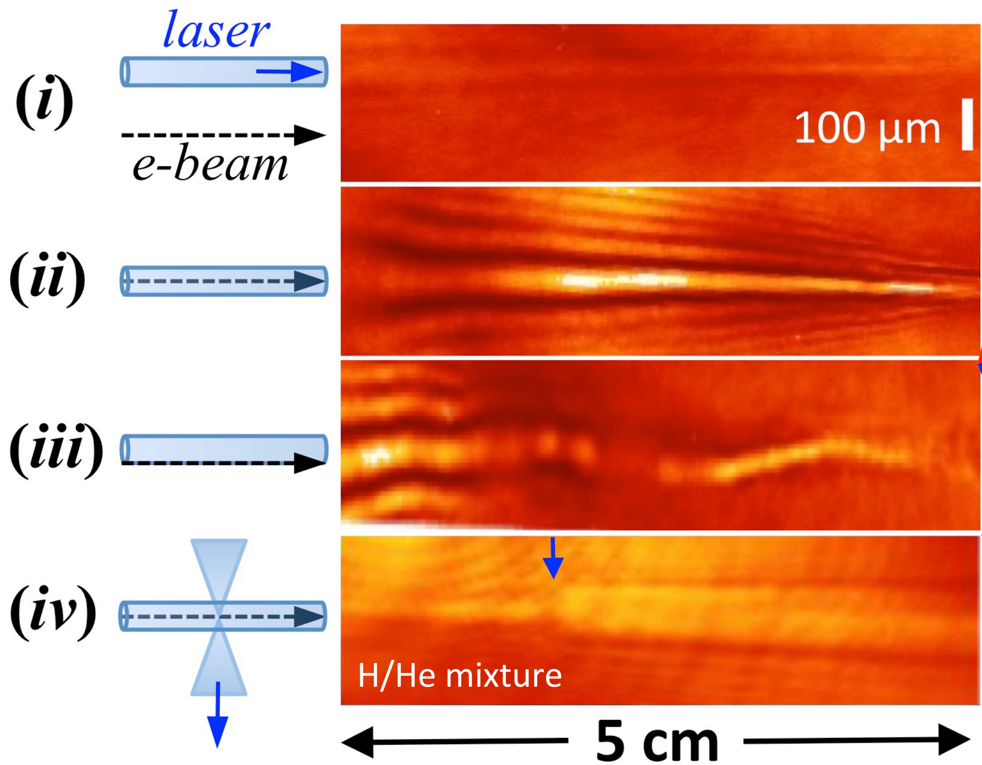


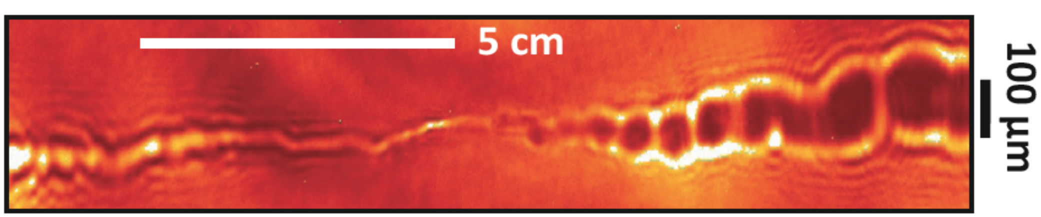
... Usuallly requires multiple-shots.

We can do it in one!

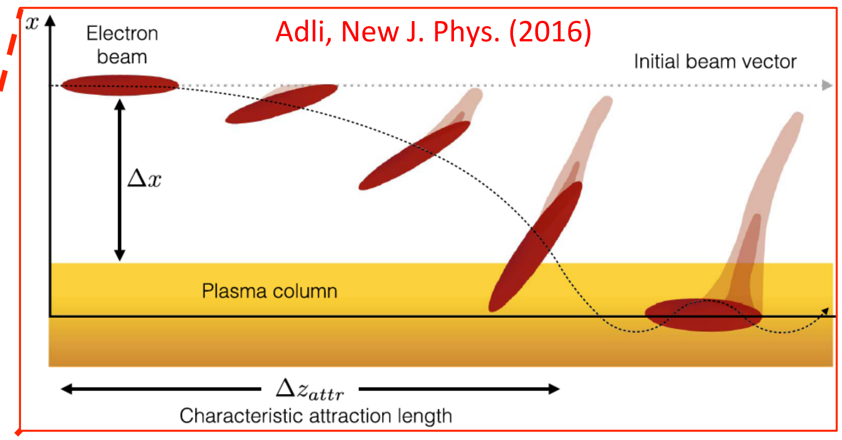
E-224 also observed wake dynamics

e-bunch: 2 nC, 30x23x24 µm, 20 GeV, 1 ps after ionizing laser
probe: Δt = 100 ps
plasma: $n_e = 5 \times 10^{17}$ cm^{-3}

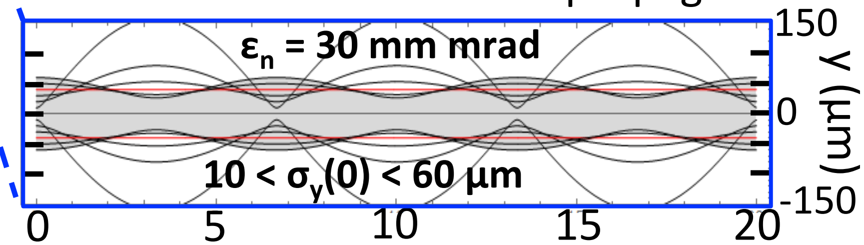




cm-period transverse oscillation of e-beam attracted to its image charge in plasma



mm-period longitudinal oscillations due to mis-matched beam propagation



$$\sigma_r''(z) + \left[k^2 - \varepsilon_n^2/\gamma^2\sigma_r^4(z)\right]\sigma_r(z) = 0$$

Clayton, *PRL* **88**, 154801 (2002)

FACET-II Workshop
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SLAC

FACET

E-224:
"Visualization of lepton-driven plasma wakefield accelerators"

Mike Downer & Rafal Zgadzaj
The University of Texas at Austin

*time delay after e-bunch

1. FACET-I: Ion wake visualization (Δt > 100 ps)*

- main E224 discovery: ion wakes contain structures seeded by e-wake's "DNA"
- current effort: modeling e → ion wake conversion
- importance: source of emittance growth; determines collider rep. rate

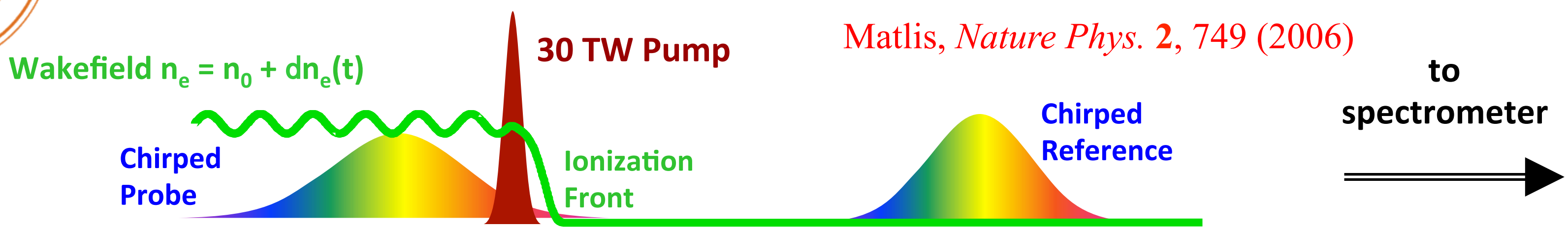
2. FACET-II: Electron wake visualization (Δt < 100 fs)*

- goals: e^- vs. e^+-driven wakes; e-wakes in self- vs. pre-ionized plasma, subtle ion motion dynamics that govern ε_n
- requirements: improved sensitivity; 3D visualization capability

Financial support: NSF-PHY-1416218 "Visualization of e-beam-driven PWFAs"
DOE DE-SC0012444 "Multi-GeV plasma acceleration physics"

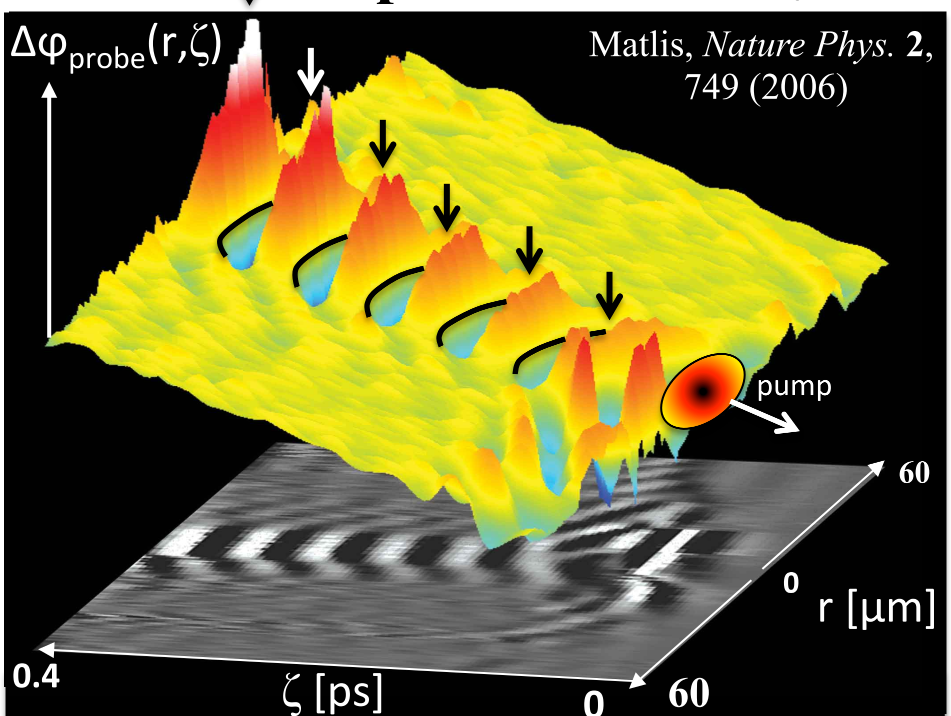
"Frequency Domain Holography" Imaged Quasi-Static Wakes in One Shot

Matlis, *Nature Phys.* **2**, 749 (2006)

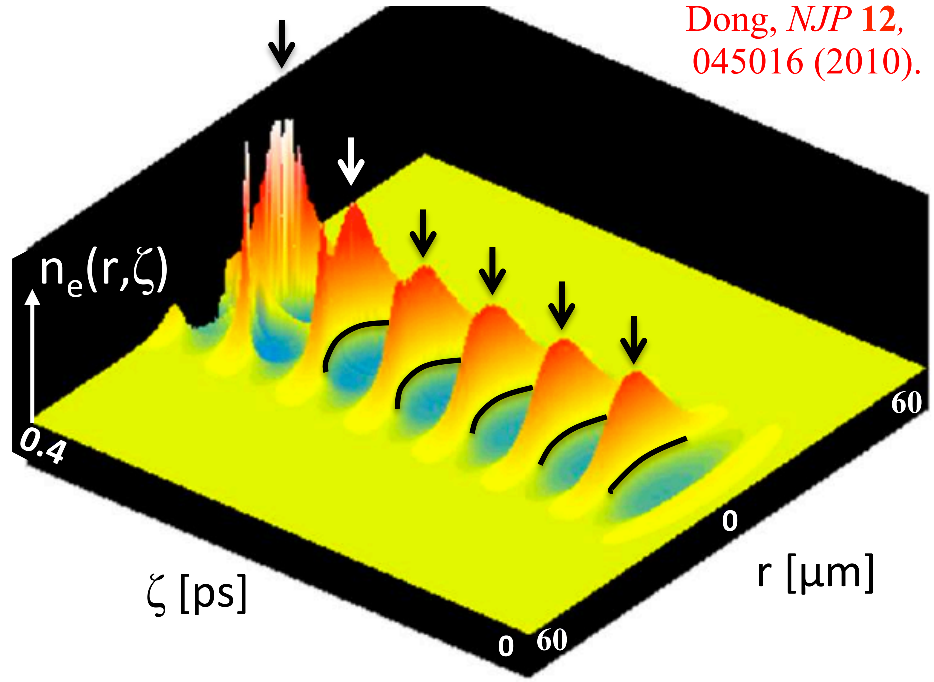


- wave fronts curve relativistically
- waves compress & break behind pump

Experiment ($n_e = 3 \cdot 10^{18}$ cm^{-3}) **Simulation**



Dong, *NJP* **12**, 045016 (2010).

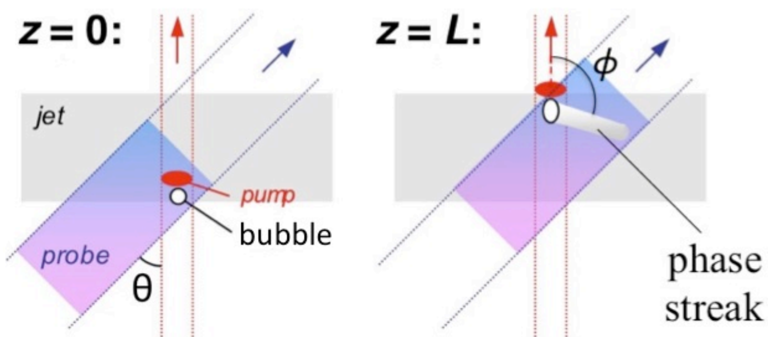


We've observed formation, propagation, collapse of plasma bubbles with an all-optical streak camera

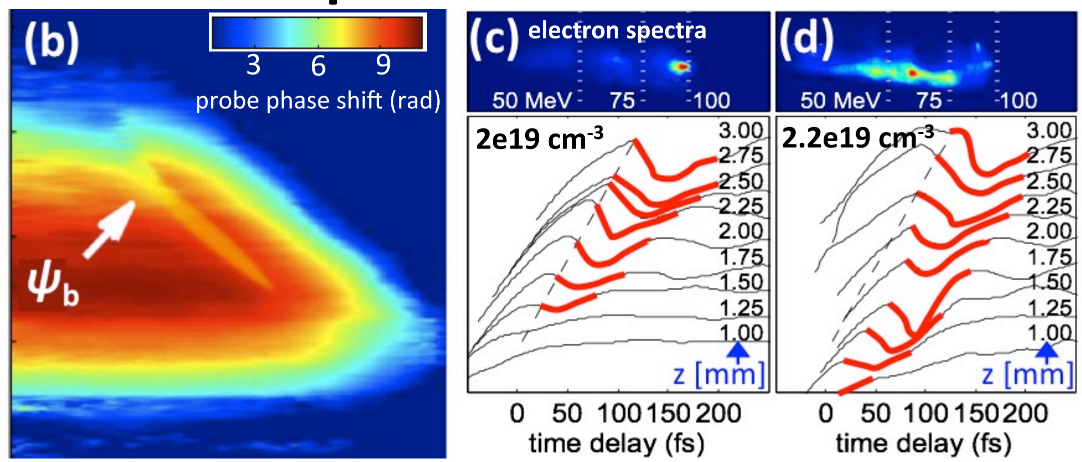
Li *et al.*, *Phys. Rev. Lett.* **113**, 085001 (2014)

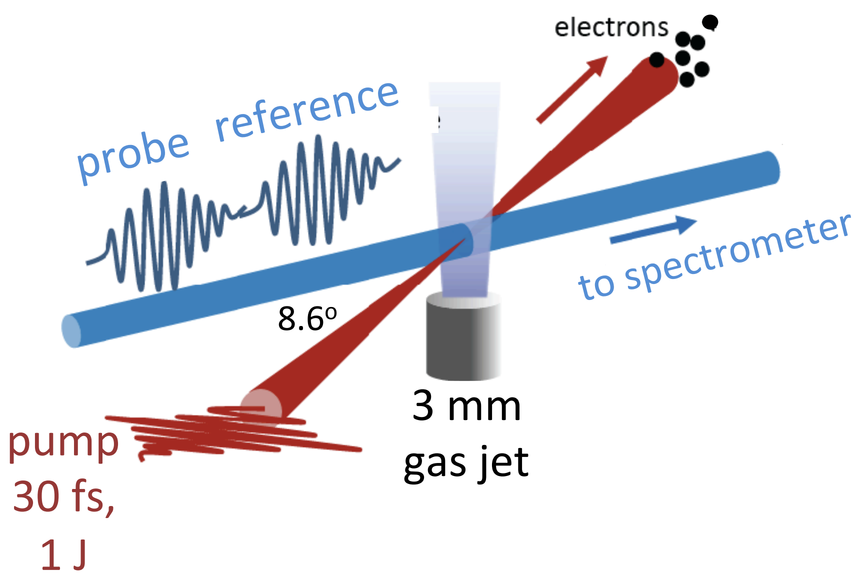
Experimental Setup

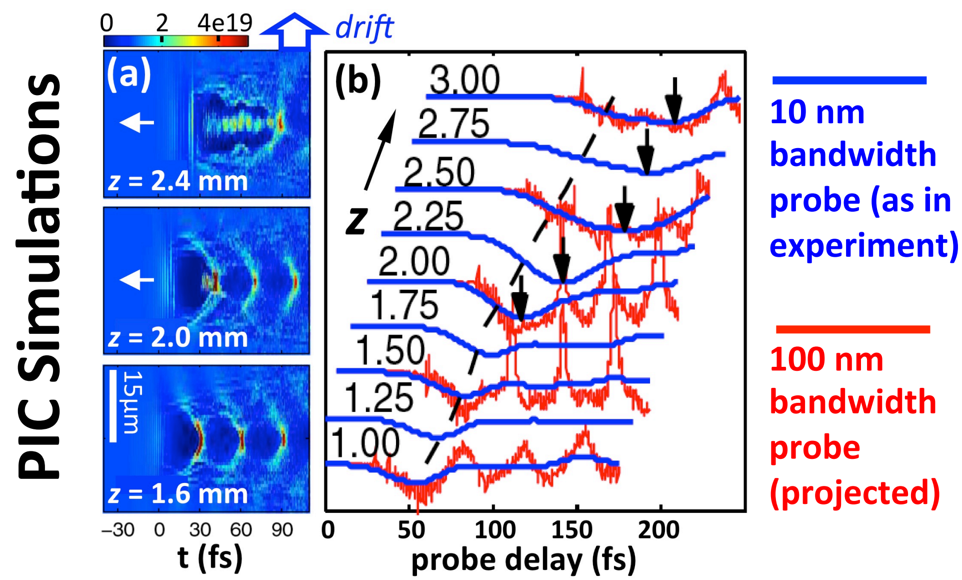
(a)



Experimental Results

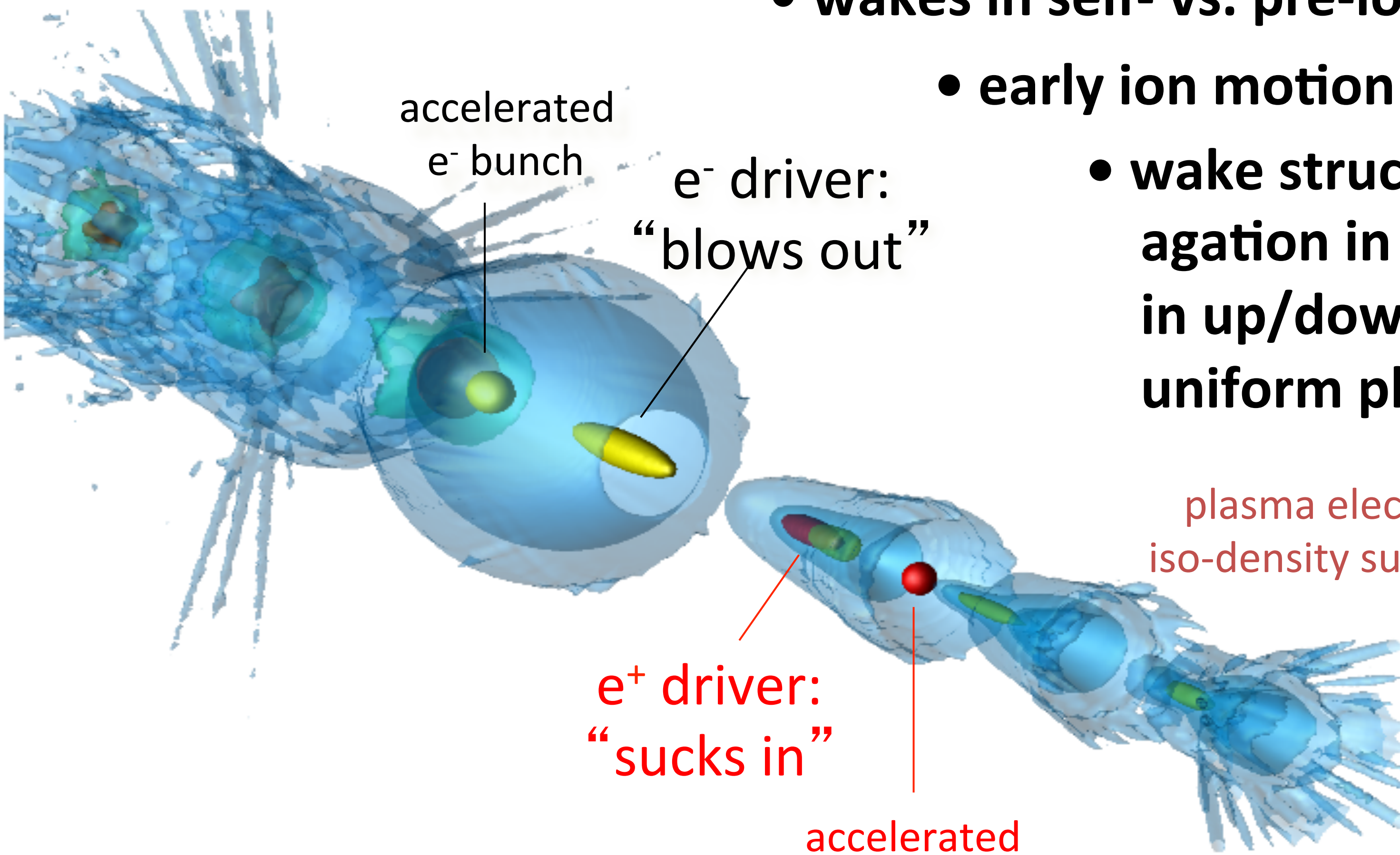






In FACET-II, we aim to visualize beam-driven electron wakes directly

- e^- vs. e^+-driven plasma e-wakes
- wakes in self- vs. pre-ionized plasma
- early ion motion ($\Delta t \sim 1$ ps)
- wake structure & propagation in one shot, in up/down-ramps + uniform plasma



courtesy Frank Tsung (UCLA)

We propose 3 upgrades to FACET's plasma imaging capability

- **Phase-Contrast, *4f* Imaging with tilted probe**
  - PCI increases sensitivity to $n_e \sim 10^{16}$ cm^{-3} plasma structures
  - tilted probe front avoids walk-off from drive bunch
  - *4f* bitelecentric imaging yields better iterative reconstructions
  - Li *et al.*, *Opt. Lett*. **38**, 5157 (2013)

[F. Zernike, *Physica* **9**, 686 (1942)]

- **Faraday rotation** [M. Faraday, *Diary* **IV**, #7504-7718 (1845)]
  - selective, sensitive imaging of dense bubble walls in tenuous plasma
  - K-Tesla **B** field of drive & accelerating GeV e^- bunch magnetizes selected components of plasma bubble
  - Chang et al., submitted (2017)

- **Computerized Tomography w. Multiple Probes**
  - 4D visualization of evolving plasma structures
  - Li *et al.*, *Nature Comm*. **5**, 3085 (2014)

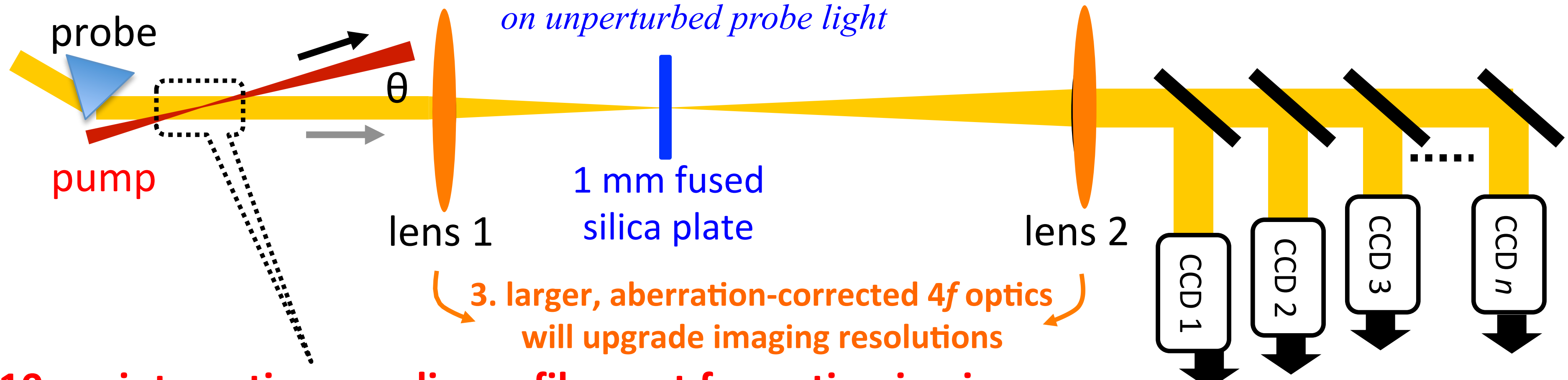
[J. Radon, *Ber. Sächsische Akad. Wiss*. **29**, 262 (1917)]

We have successfully tested each of these ideas on LASER-driven plasma structures in our Texas lab

1. Phase-Contrast Imaging detects $n_e < 10^{16}$ cm^{-3} plasma structures

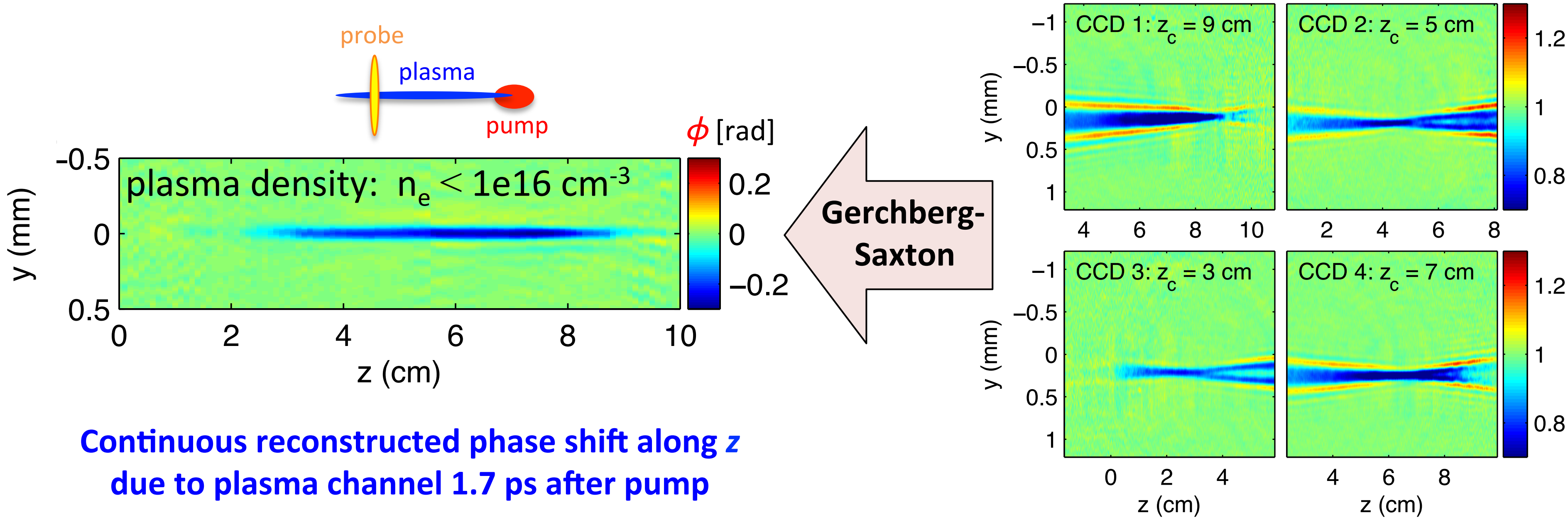
2. Tilt probe pulse

Li *et al.*, *Opt. Lett.* **38**, 5157 (2013)



3. larger, aberration-corrected 4*f* optics will upgrade imaging resolutions

10 cm interaction: nonlinear filament formation in air

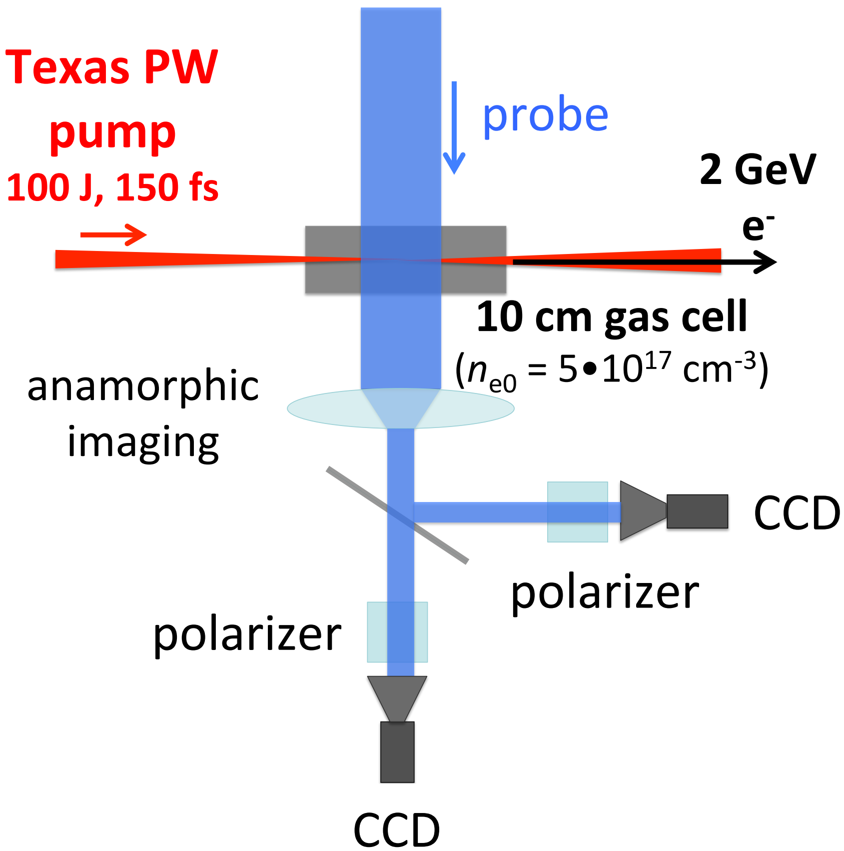


Continuous reconstructed phase shift along *z* due to plasma channel 1.7 ps after pump

Faraday rotation picks out dense bubble wall in tenuous plasma

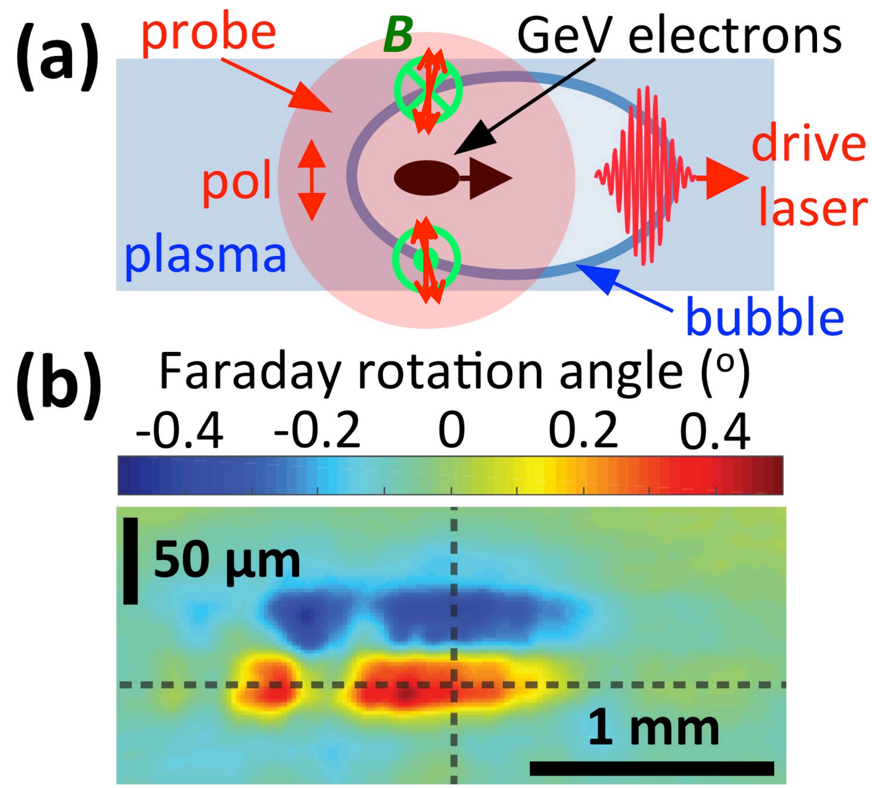
Based on technique developed by: Kaluza, *PRL* **105**, 115002 (2010); Buck, *Nat. Phys*. **7**, 453 (2011) in $n_e > 10^{19}$ cm^{-3} plasma

Faraday probe setup



Probe can be obliquely incident.
In fact, we prefer it that way!

Faraday rotation results

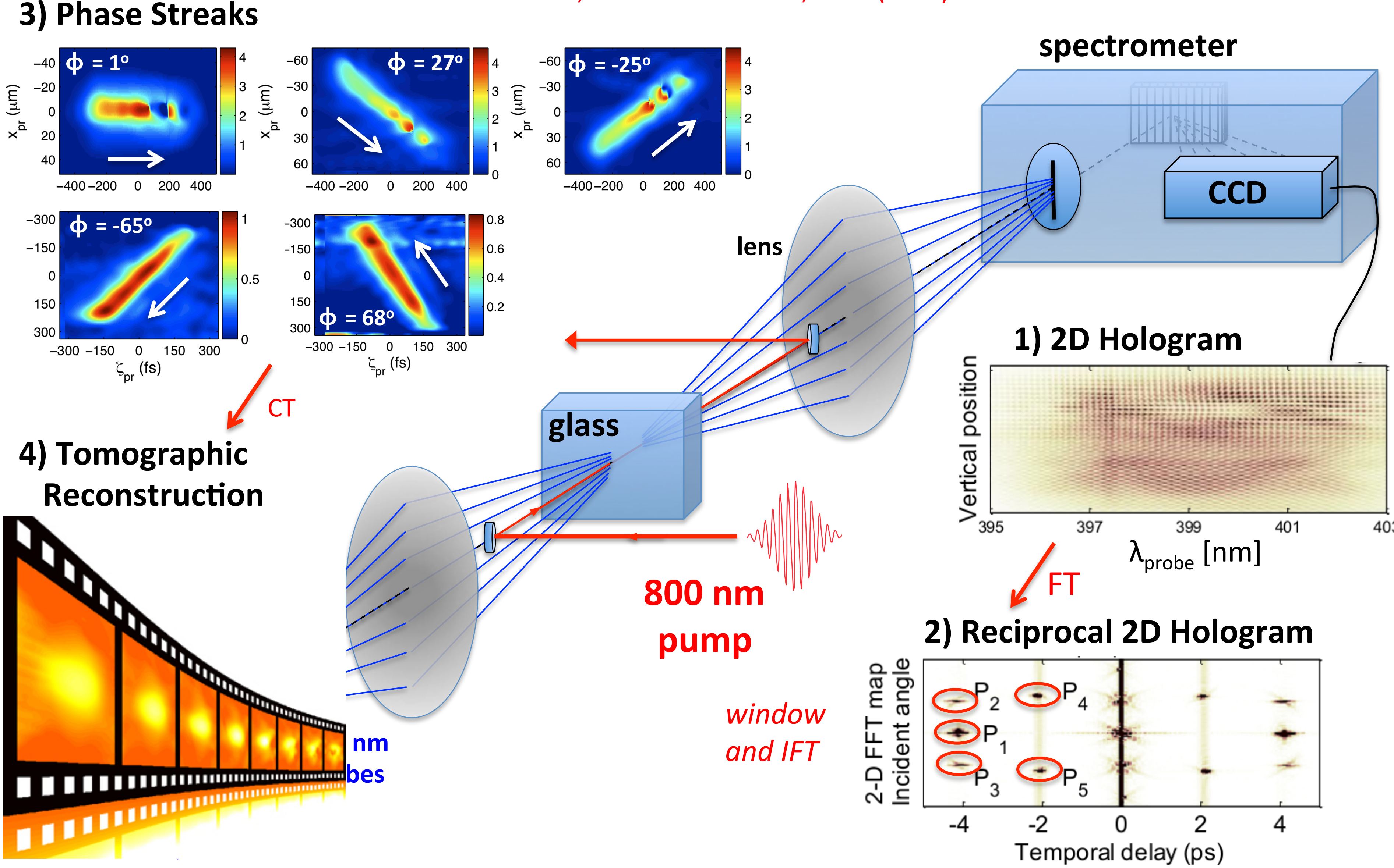


4 measure-ments:

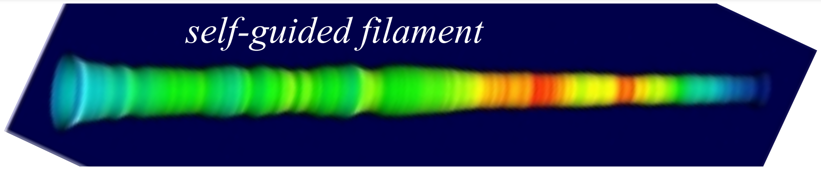
- *separation of ± lobes:* **bubble size**
- $|\Delta\phi_{Faraday}|$: **bubble wall density**
- *width of each lobe:* **bubble wall thickness**
- *longitudinal variations:* **bubble evolution**

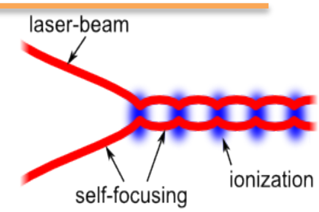
Computerized tomography reconstructs movie from multiple phase streaks in *one shot*…

Z. Li *et al.*, *Nature Commun.* **5**, 3085 (2014)



Single-shot tomographic movies unravel the complex physics of filament formation in Kerr media

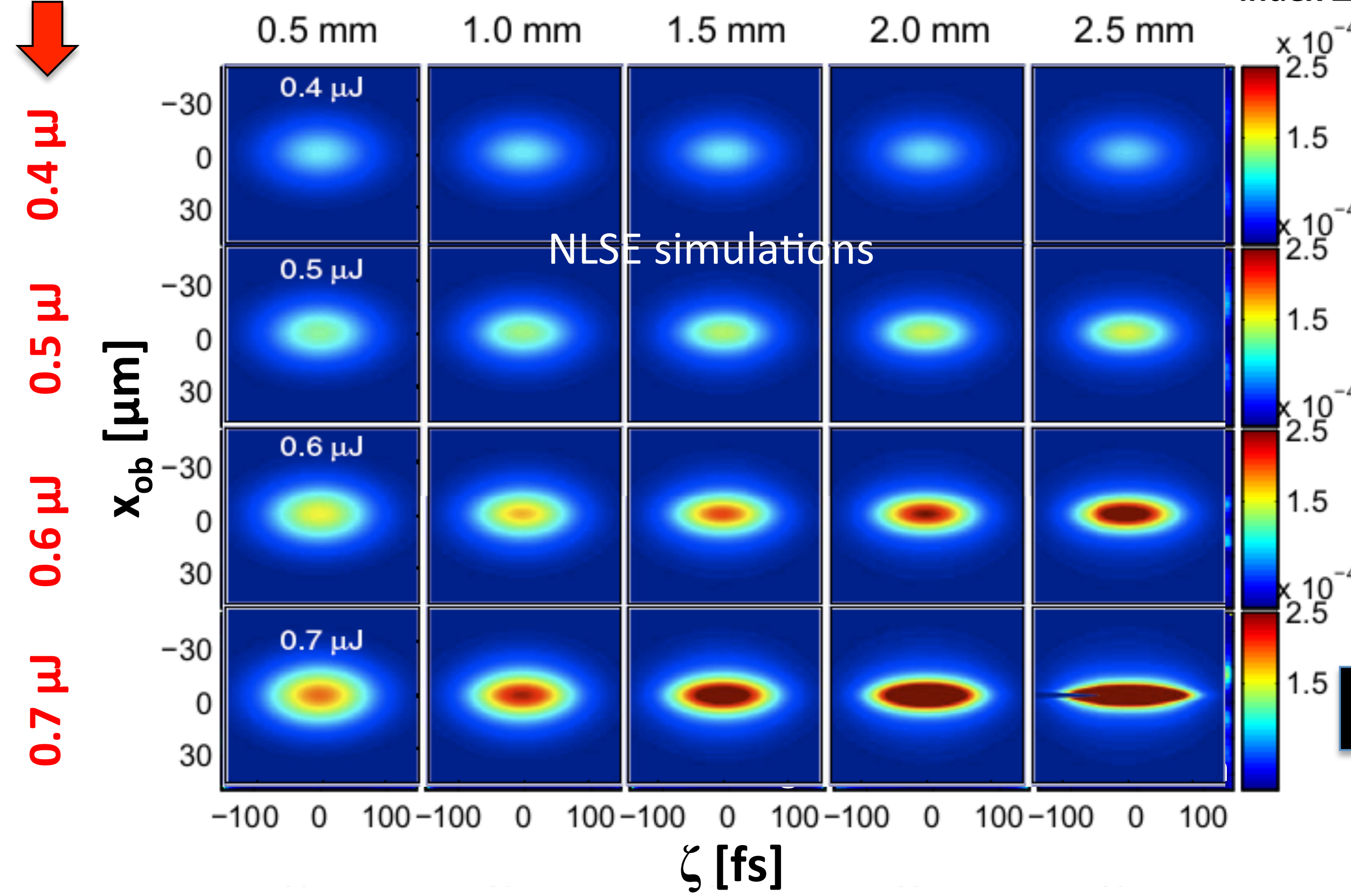




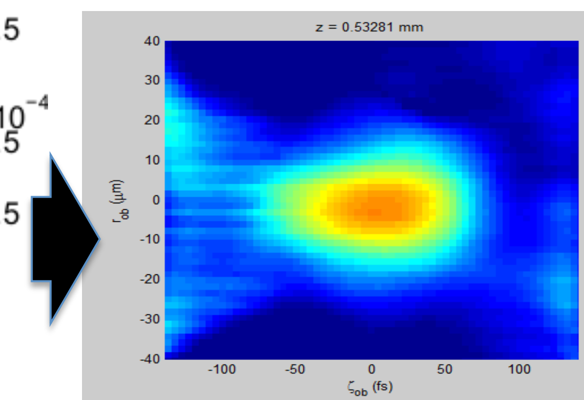
PUMP
PULSE
ENERGY

Propagation distance z_{ob} into medium

nonlinear
refractive
index Δn



Time from peak of pump pulse



Single-shot movie

E224: Conclusions

• E224 has successfully imaged & simulated ion wakes driven by nonlinear electron wakes. Ion wakes depend on e-wake history, & determine the state of the plasma for subsequent drive bunches.

- E224 mostly ran parasitically during companion projects.

• In FACET-II, we propose to visualize e^- and e^+-driven plasma wakes directly, taking advantage of:

- increase sensitivity via <u>*4f* phase-contrast</u> and <u>Faraday rotation</u> imaging, and <u>tilted probe</u> to reduce probe walk-off from e-wake to $< \lambda_p$.

- 3D imaging via <u>multi-probe</u> computerized tomography.

High probe beam quality will be paramount in achieving quality scientific results from these diagnostics (e.g. temperature-controlled transport, pointing stabilization)

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DOE DE-SC0012444 "Multi-GeV plasma acceleration physics"