FACET-II Workshop
Oct. 17-19, 2016

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

Rafal Zgadzaj & Mike Downer
The University of Texas at Austin

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
- requirements: improved sensitivity; 3D visualization capability

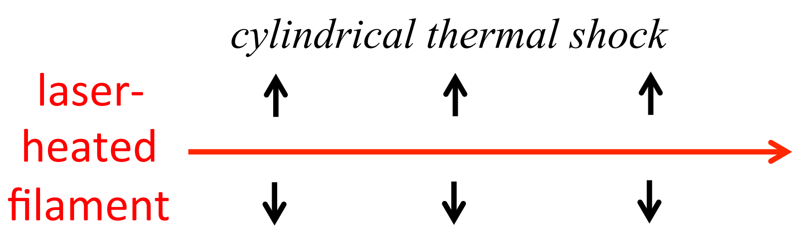
*time delay after e-bunch

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

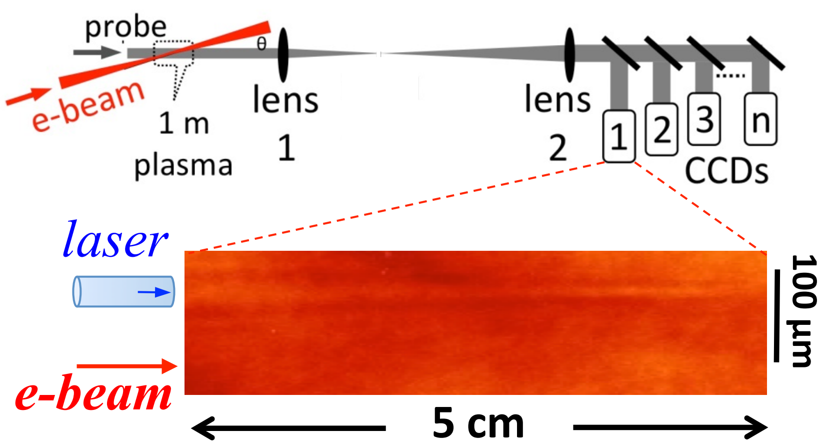
Longitudinally asymmetric e⁻ wakes couple strongly to ion acoustic waves

Sahai, Katsouleas, "Nonlinear ion-wake excitation by ultra-relativistic electron wakes," ArXiv.1504.03735 (2016)

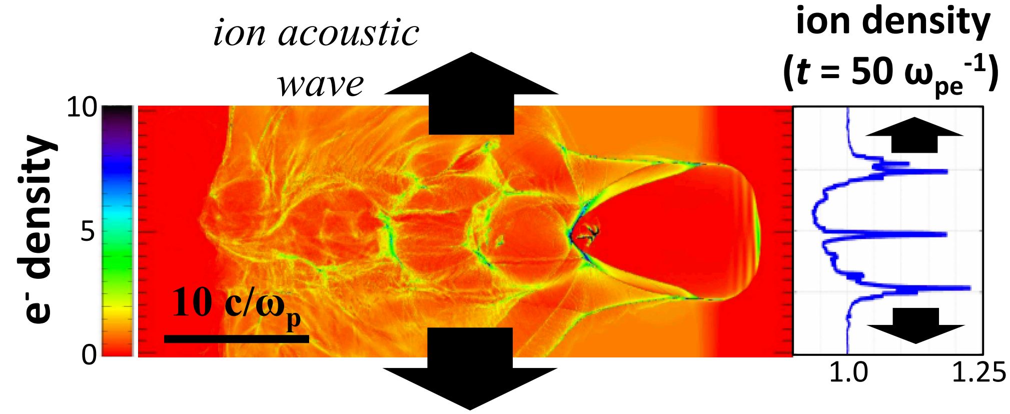
Weak, structureless ion wake

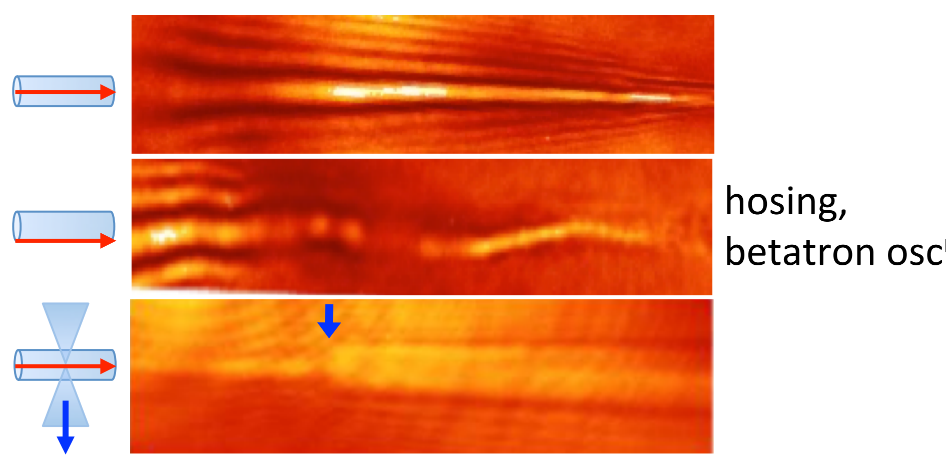


Multi-Object-Plane Imaging (MOPI):



Strong, structured ion wake

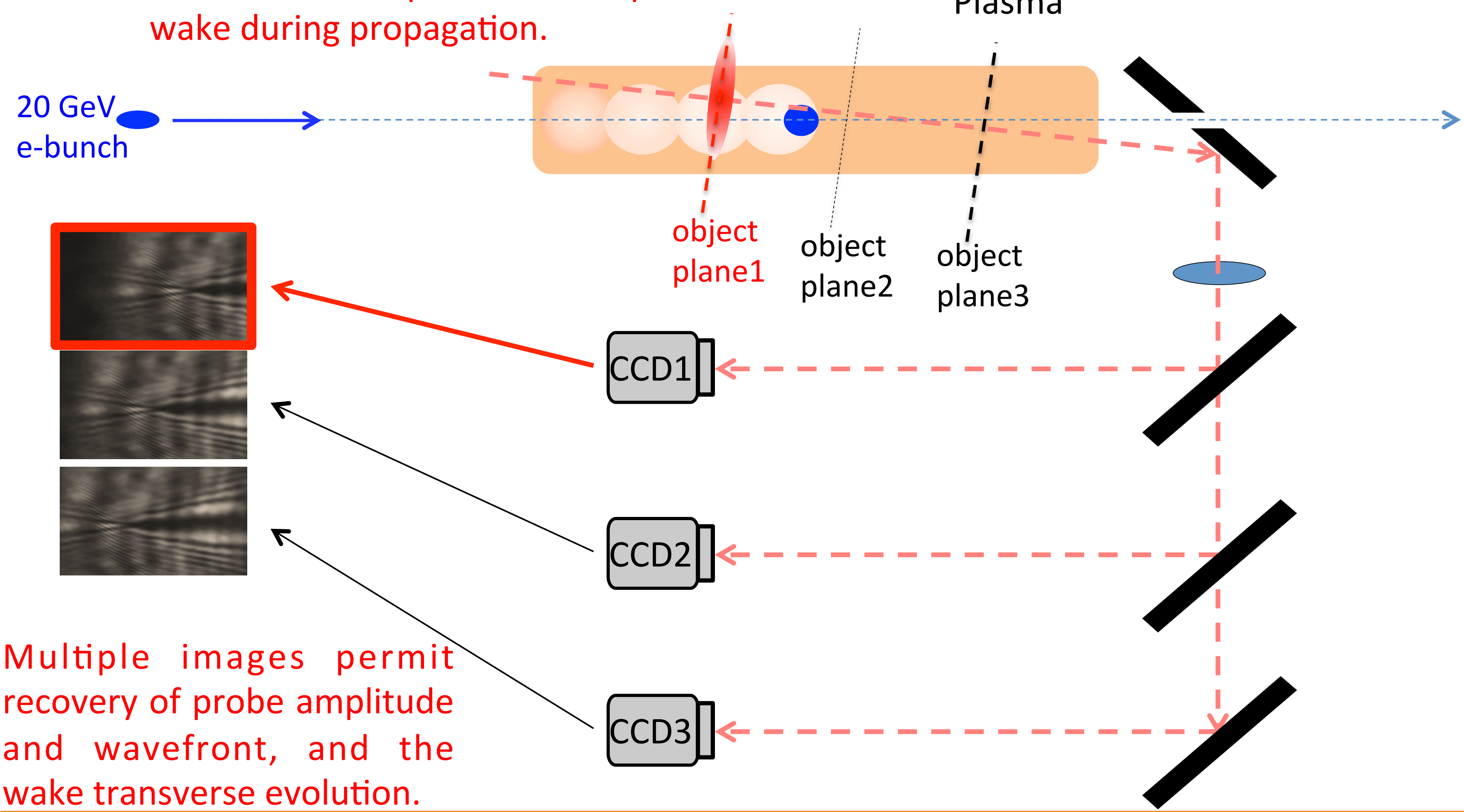




Multiple Object Plane Imaging (MOPI)

Z. Li, et al., Opt. Lett. 38, 5157-5160 (2013).

Short Probe samples the same part of wake during propagation.

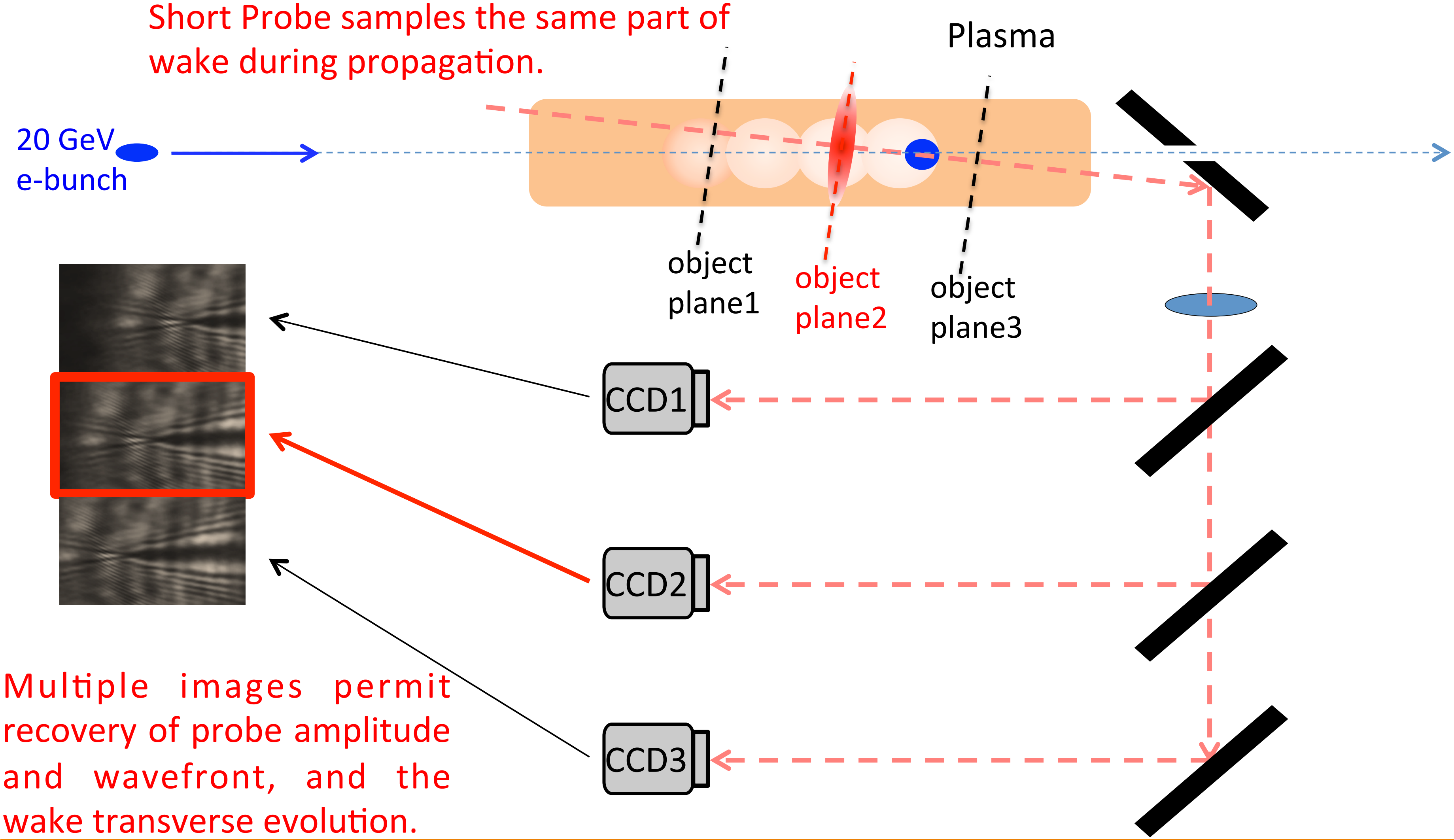


Multiple images permit recovery of probe amplitude and wavefront, and the wake transverse evolution.

Multiple Object Plane Imaging (MOPI)

Z. Li, et al., Opt. Lett. 38, 5157-5160 (2013).

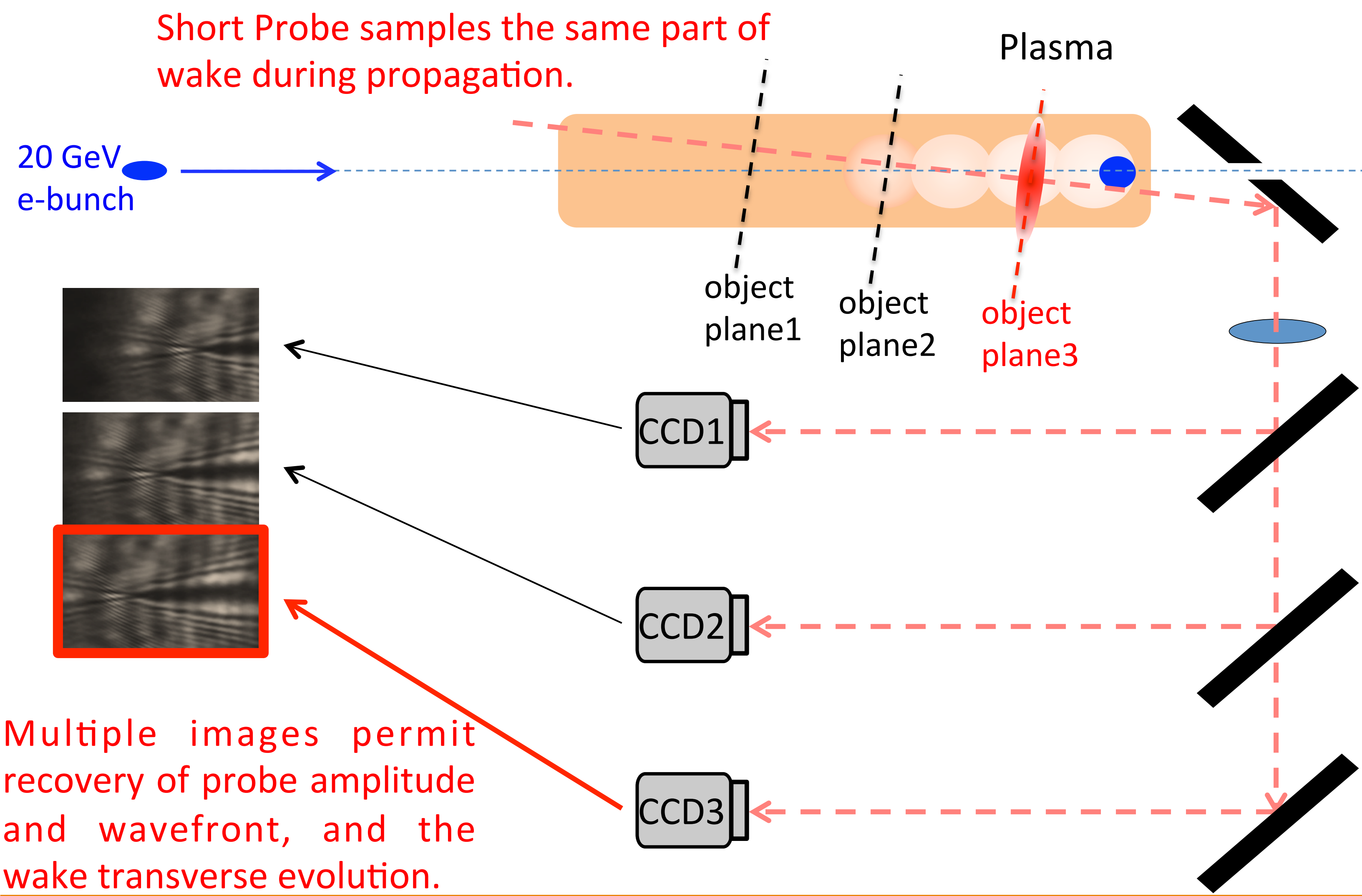
Short Probe samples the same part of wake during propagation.



Multiple images permit recovery of probe amplitude and wavefront, and the wake transverse evolution.

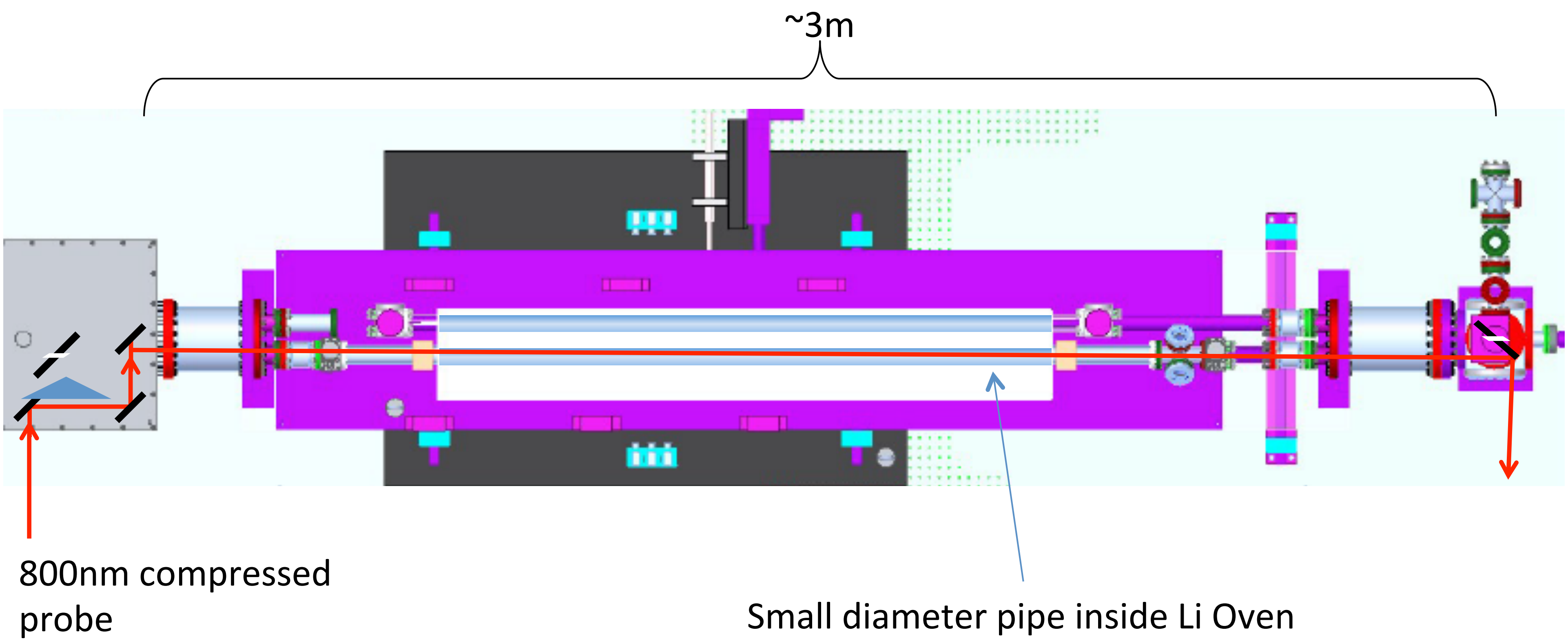
Multiple Object Plane Imaging (MOPI)

Z. Li, et al., Opt. Lett. 38, 5157-5160 (2013).

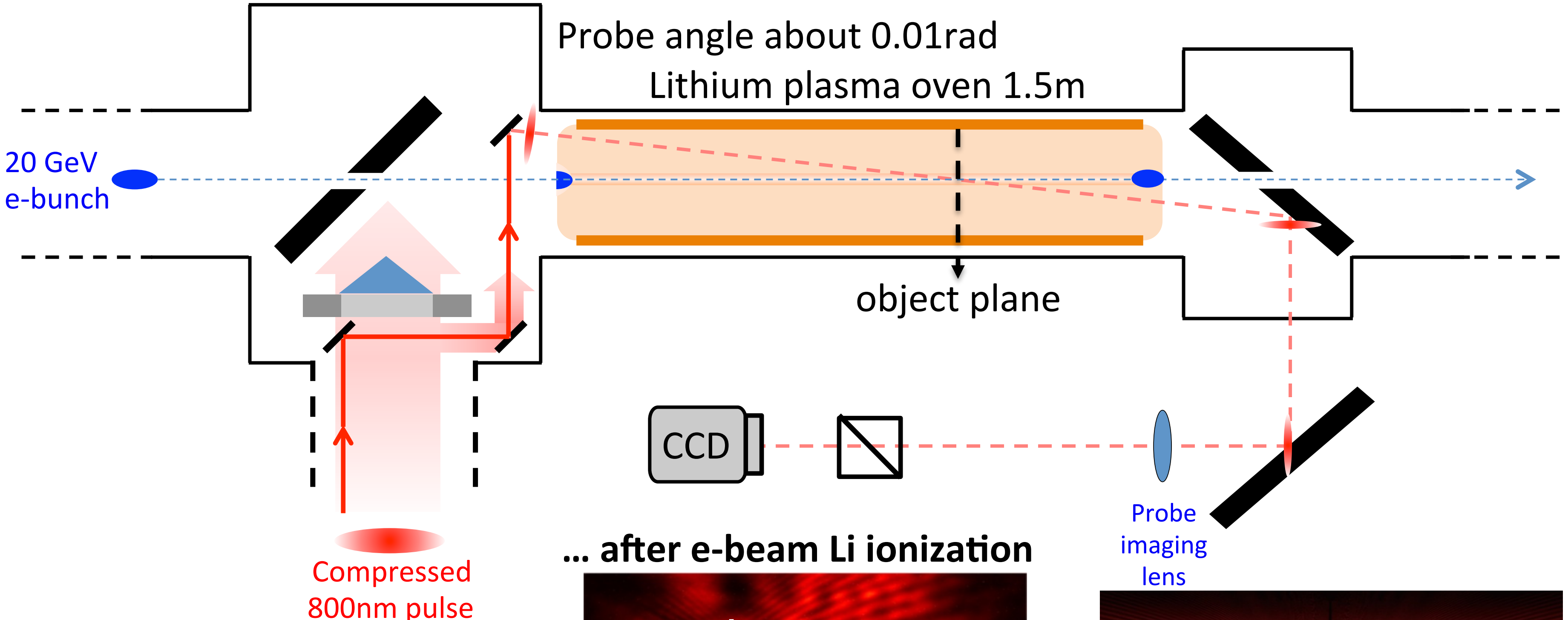


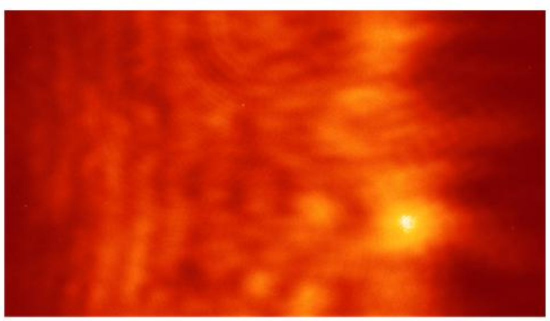
Multiple images permit recovery of probe amplitude and wavefront, and the wake transverse evolution.

The E-224 current setup

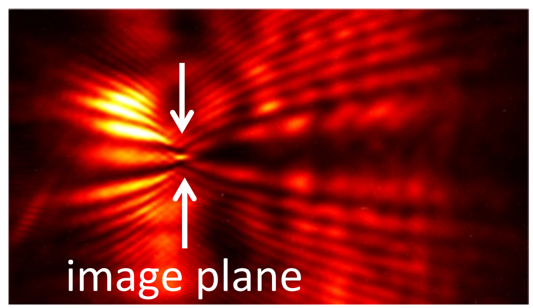


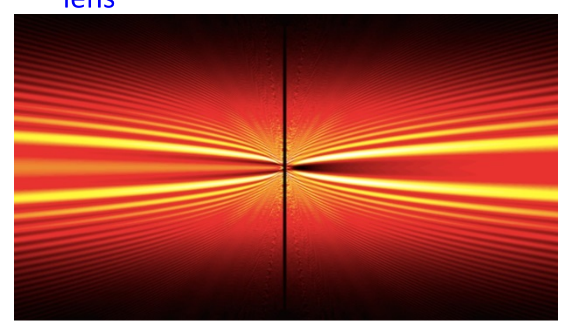
E-224 setup in the Lithium oven





… after e-beam Li ionization

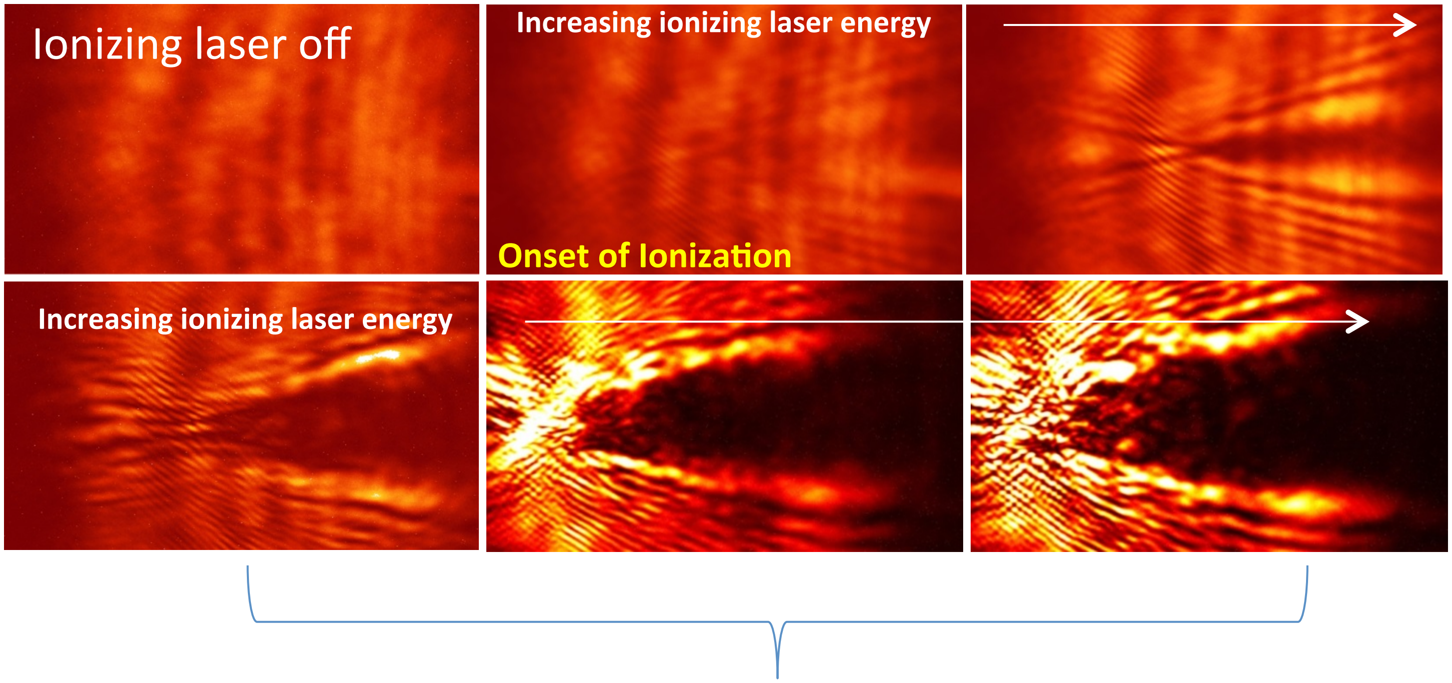




Simulation Margaux Schmeltz

Phase-contrast images of probe profile…

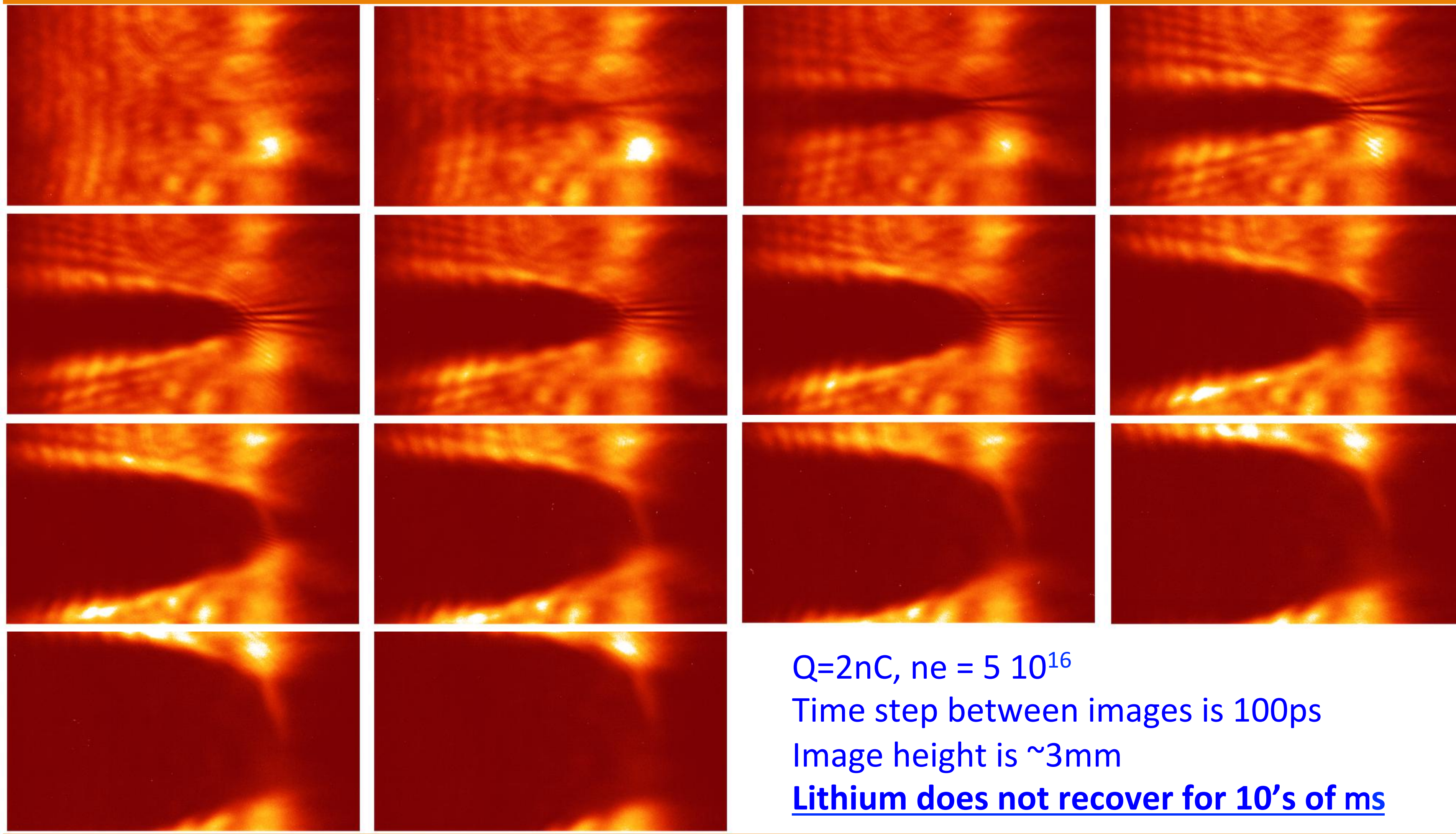
Stability regime for laser preionized lithium plasma



Above a threshold energy the plasma channel becomes very non-uniform

Evolution of e-beam ionized and heated lithium plasma

Plasma recovery time affects the maximum repetition rate of a PWFA



Q=2nC, ne = 5 10^{16}

Time step between images is 100ps

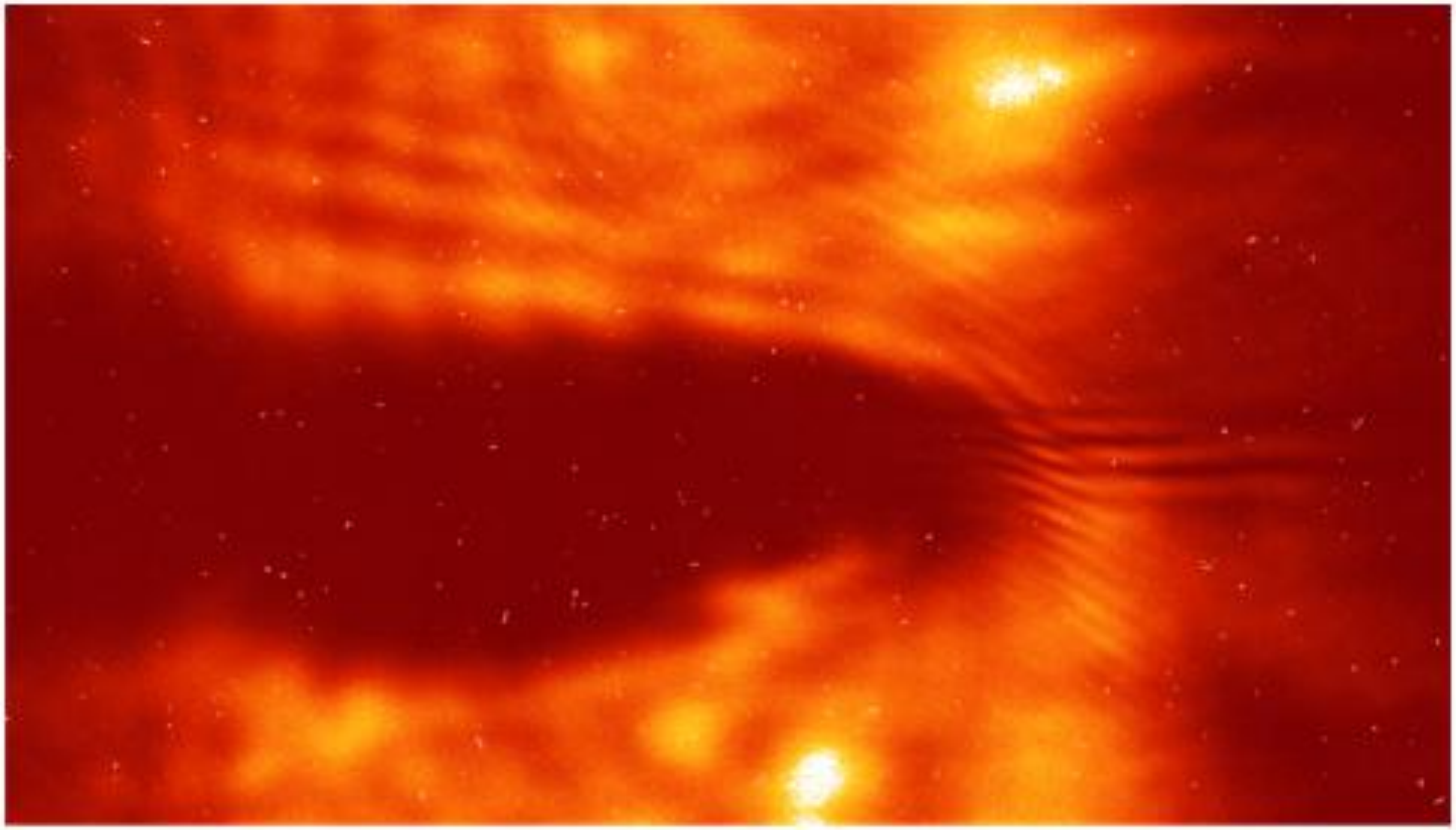
Image height is ~3mm

Lithium does not recover for 10's of ms

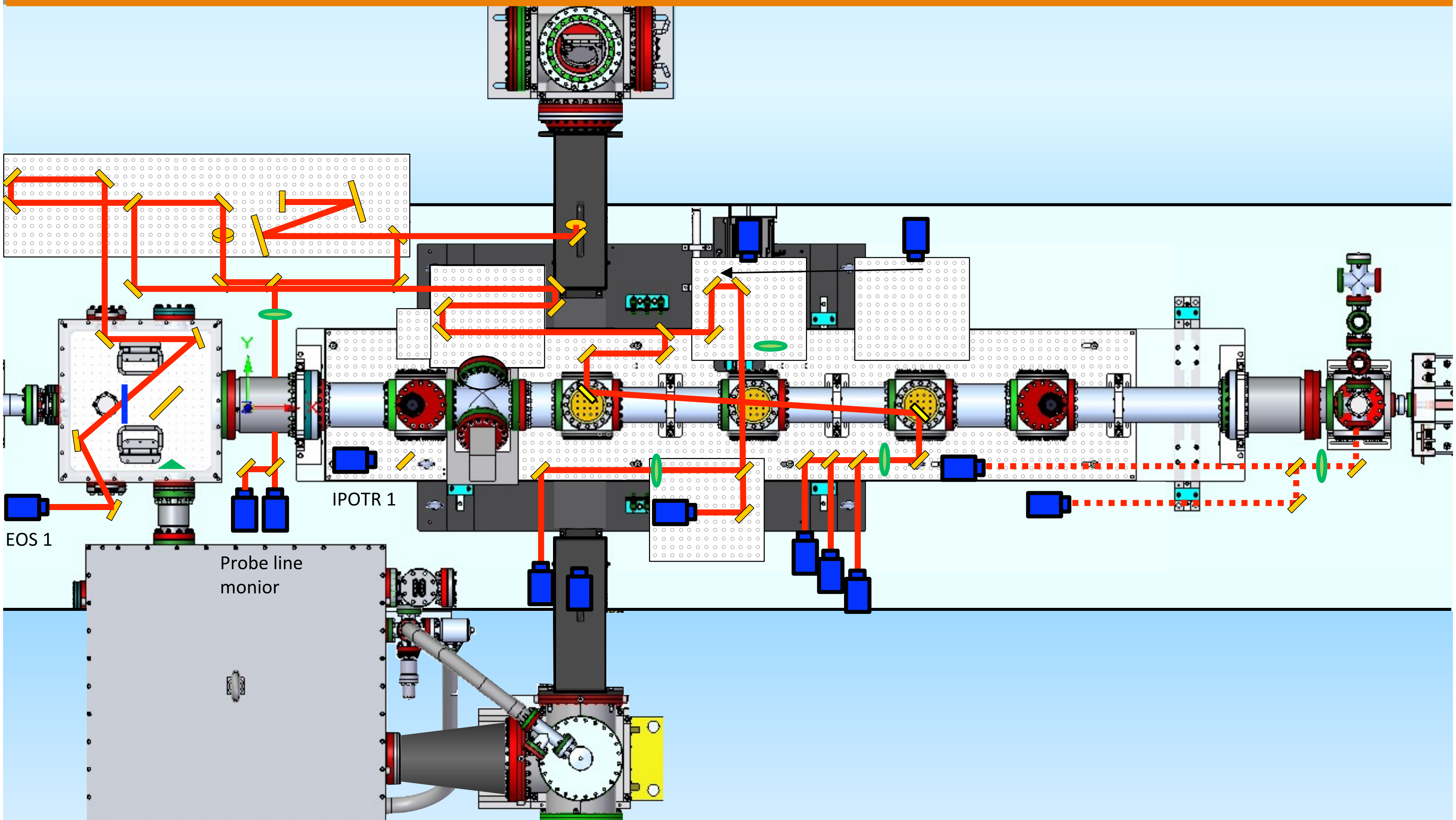
THE UNIVERSITY OF TEXAS AT AUSTIN

FACET

Evolution of e-beam ionized and heated plasma with increasing bunch charge

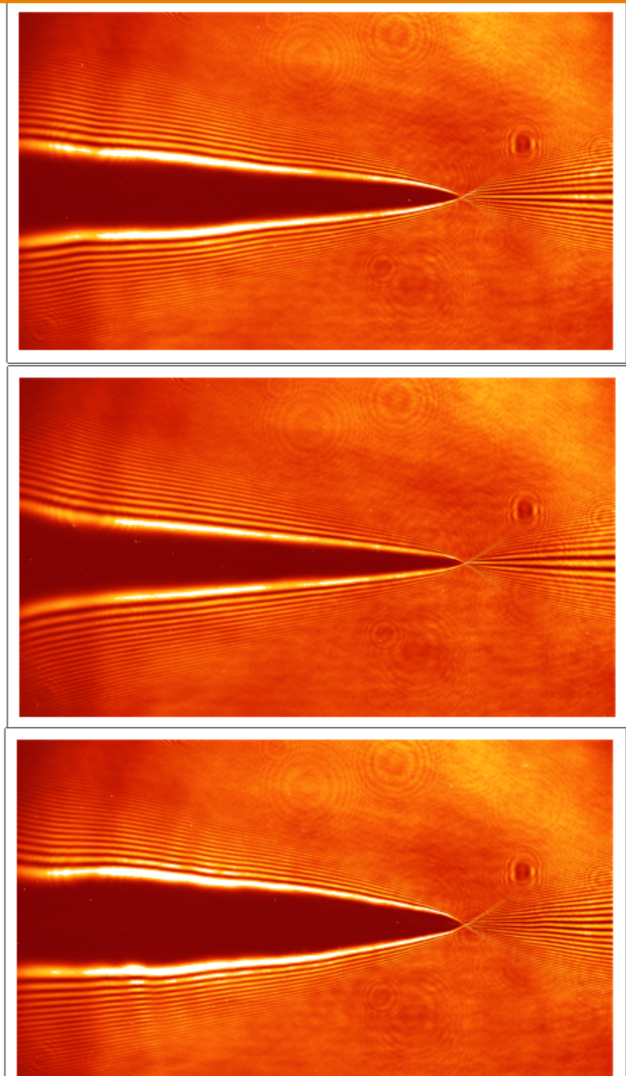


E-224 experimental setup in the Hydrogen chamber

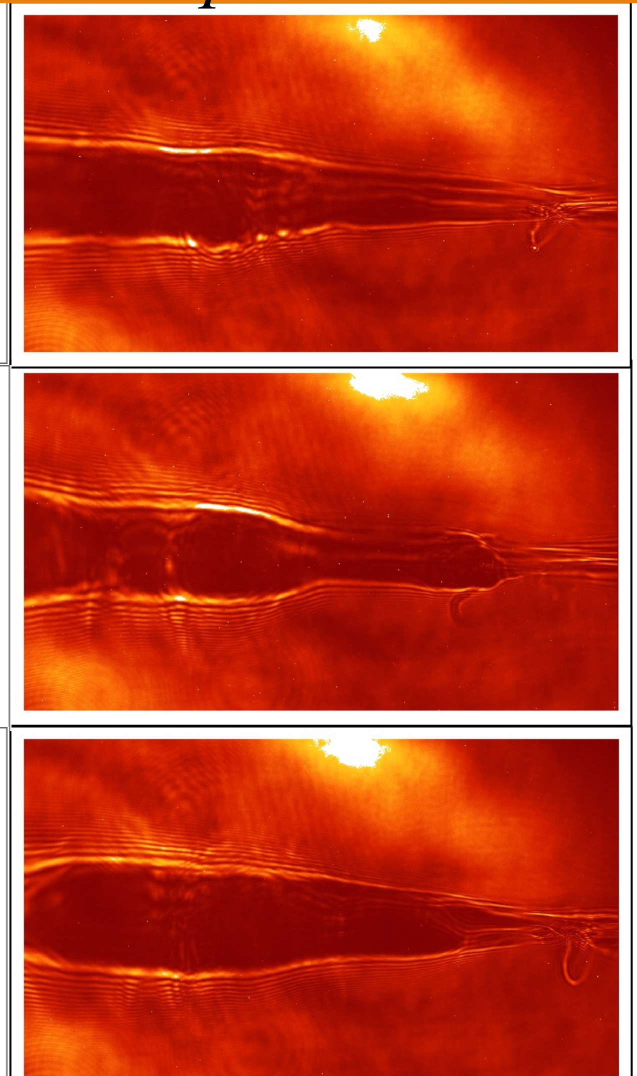


Argon 27Torr

e-beam ionization

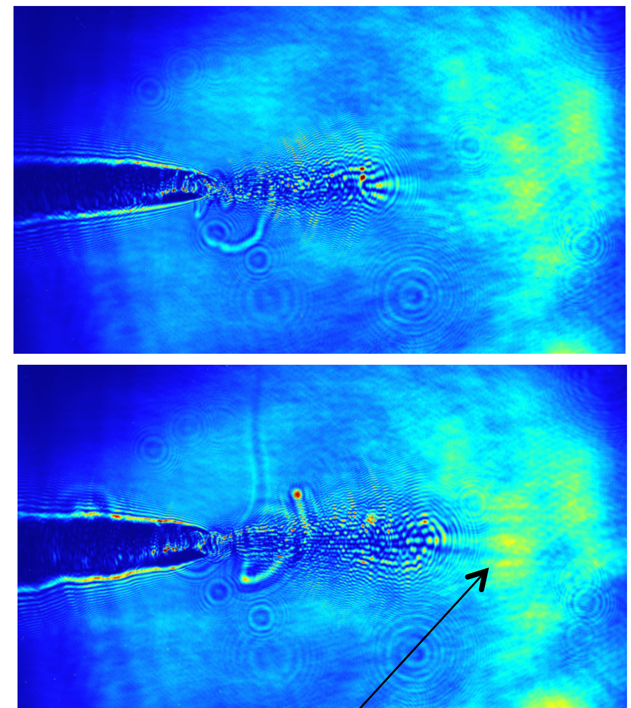


Axicon pre-ionization



Hydrogen 27 Torr

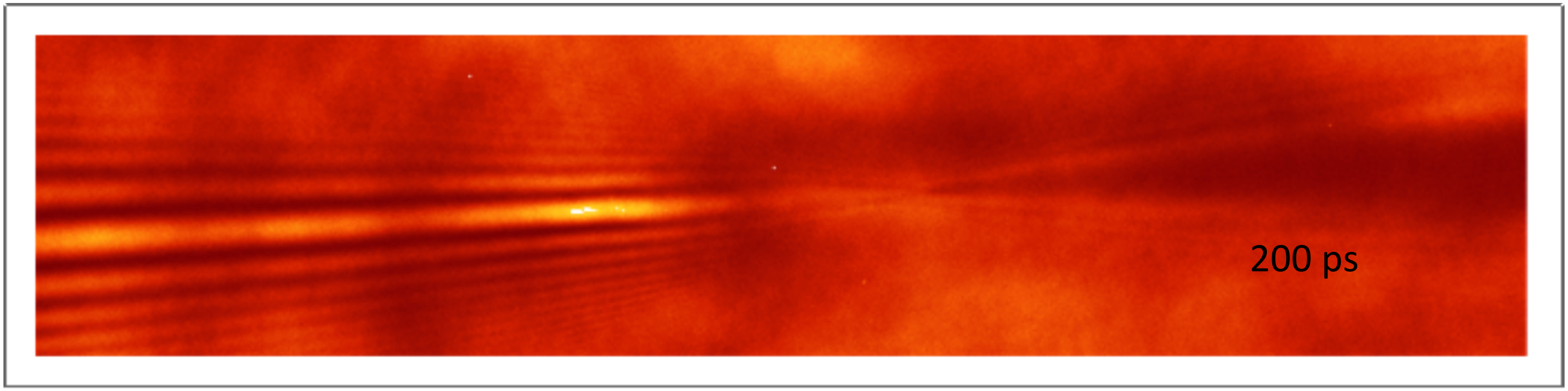
e-beam ionization



Probe delay 750ps

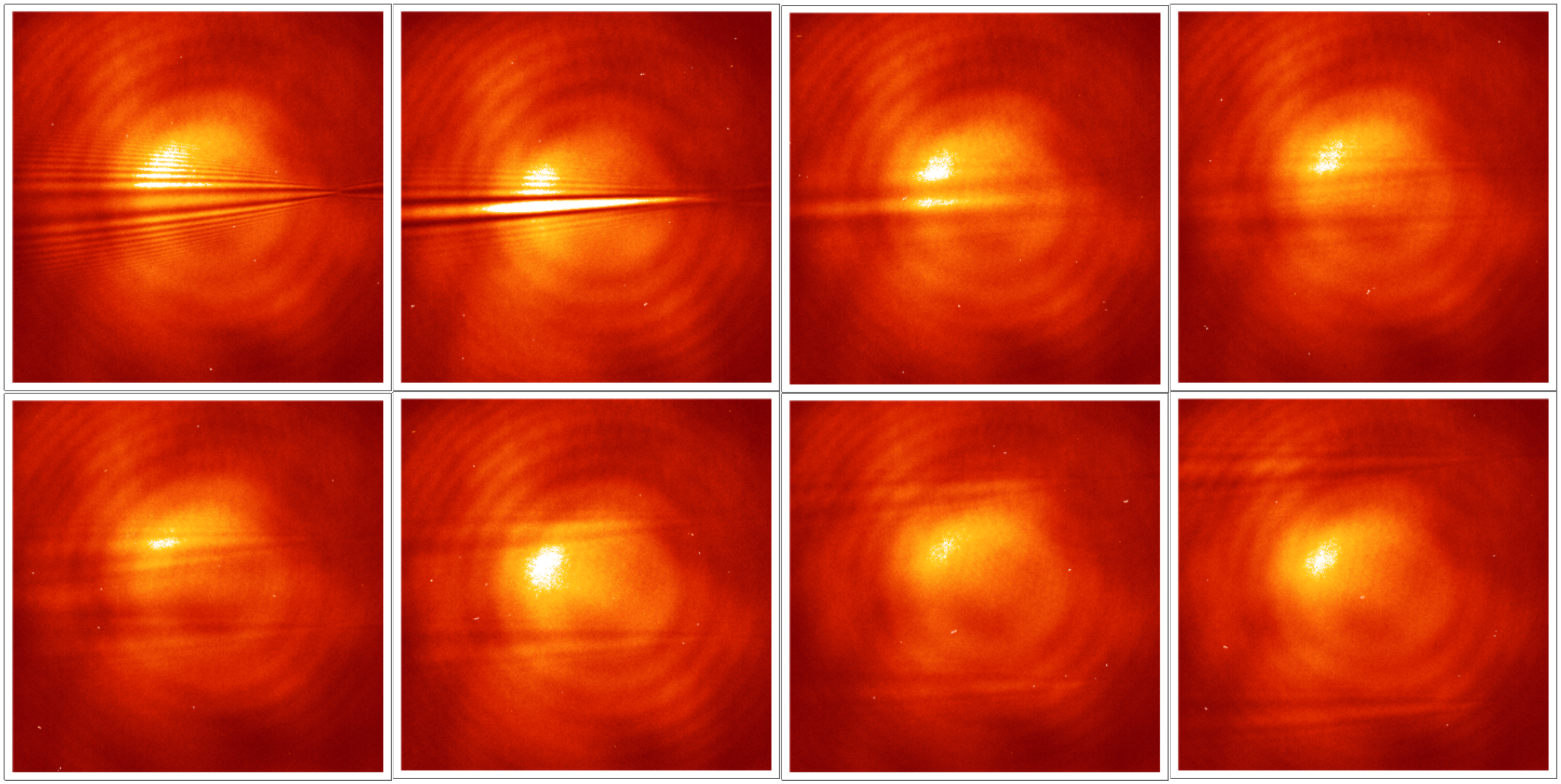
Evolution of ion channel in Hydrogen.

e-beam arrival 3ps after ionizing laser, which was focused by and axicon in 20Torr H2. Probe delay scan from 0 to 200ps



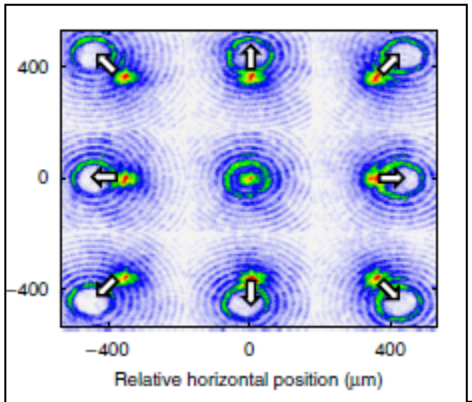
Evolution of e-beam ionized and heated hydrogen plasma

E224 probe images of plasma expansion from ~0 to 500ns.
27Torr H_2, 2e10e



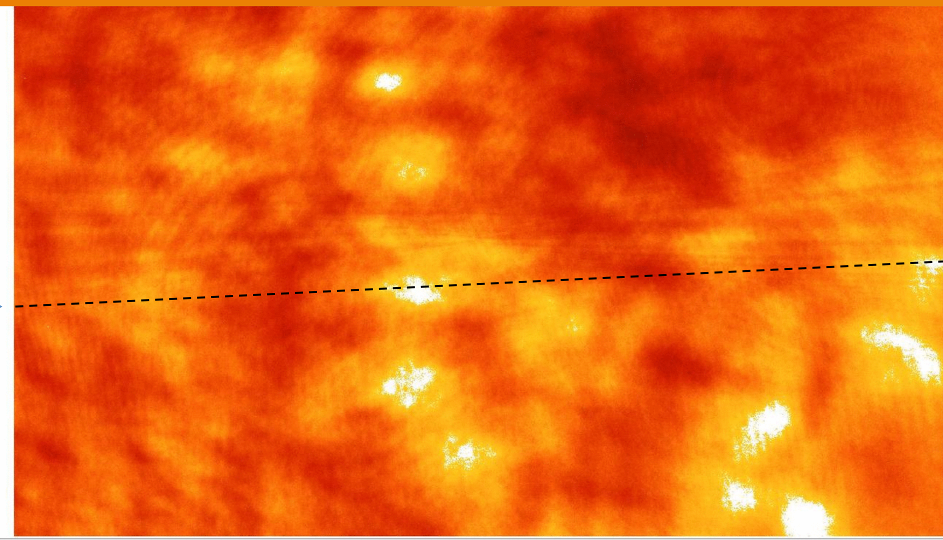
Vertical scan of hollow plasma channel vs. e-beam

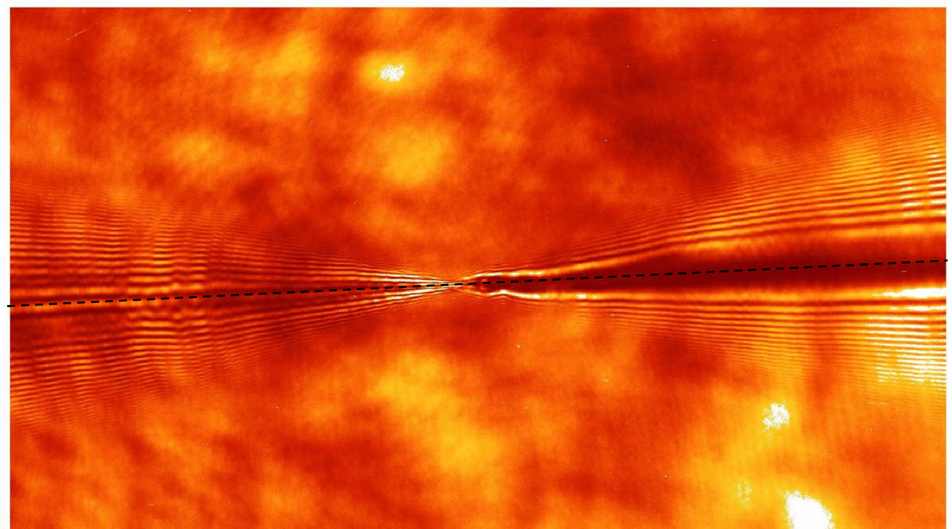
E225

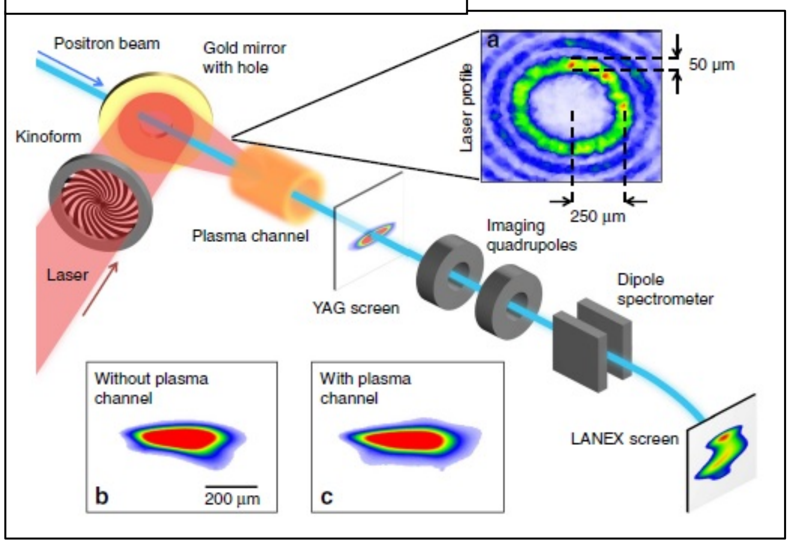


Probe ~100ps after e-beam
np~9 10^{17} cm^{-3}
Ebunch charge ~1.2 10^{10}
Ebunch size 30x23x24
Kinoform pulse ~1ps before e-bunch

e-beam axis







Gessner, S. et al., Nat. Commun., 11785 (2016)

Vertical scan of axicon plasma relative to the e-beam propagation axis

Beam hosing observed for offset from axial alignment.

axicon focus is shifted here at ~50micron steps relative to the electron beam axis.

Probe ~750ps after e-beam

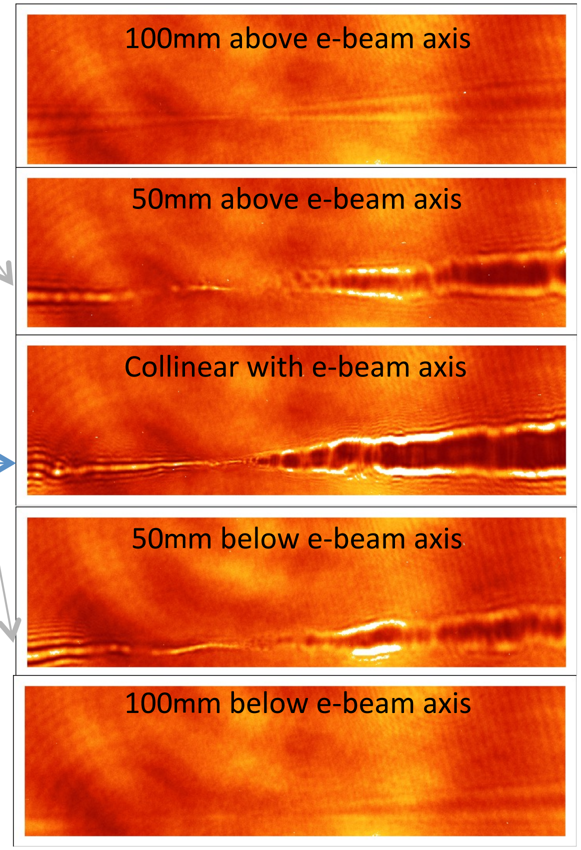
np~2.6 10^{17} cm^{-3} (at 1.3 10^{17} cm^{-3} channel was stable)

Ebunch charge ~1.2 10^{10}

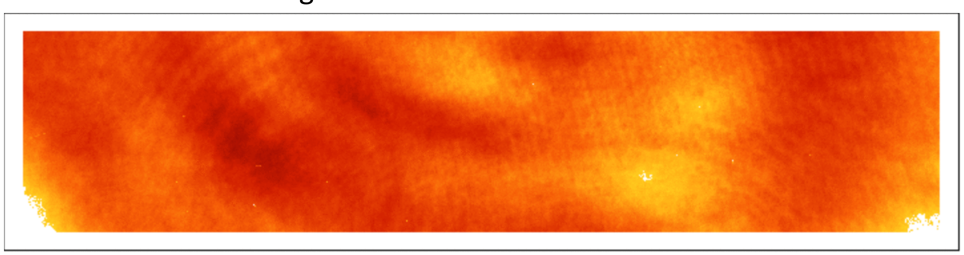
Ebunch size 30x23x24

Axicon pulse ~1ps before e-bunch

e-beam axis



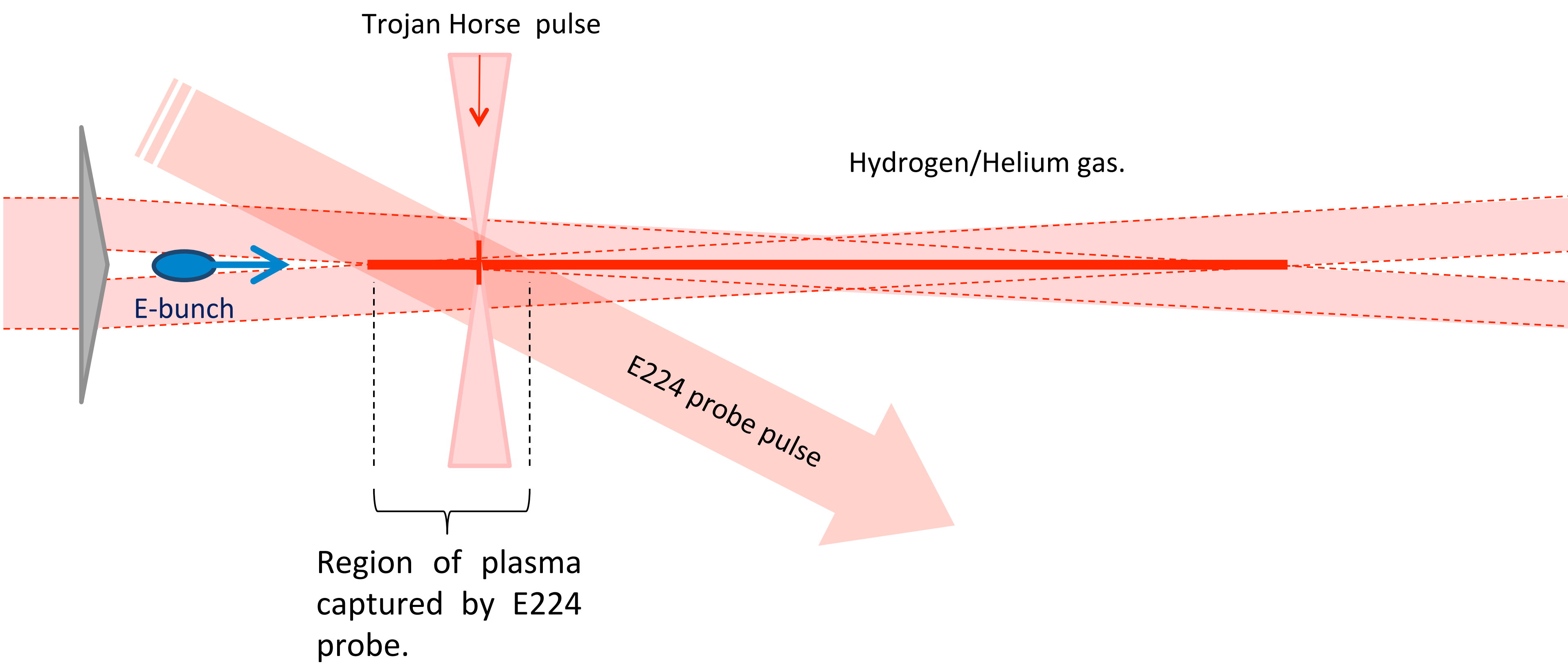
750 ps probe delay sequence with nominally axial alignment of axicon focus and e-beam.



E210 "Trojan Horse" PWFA

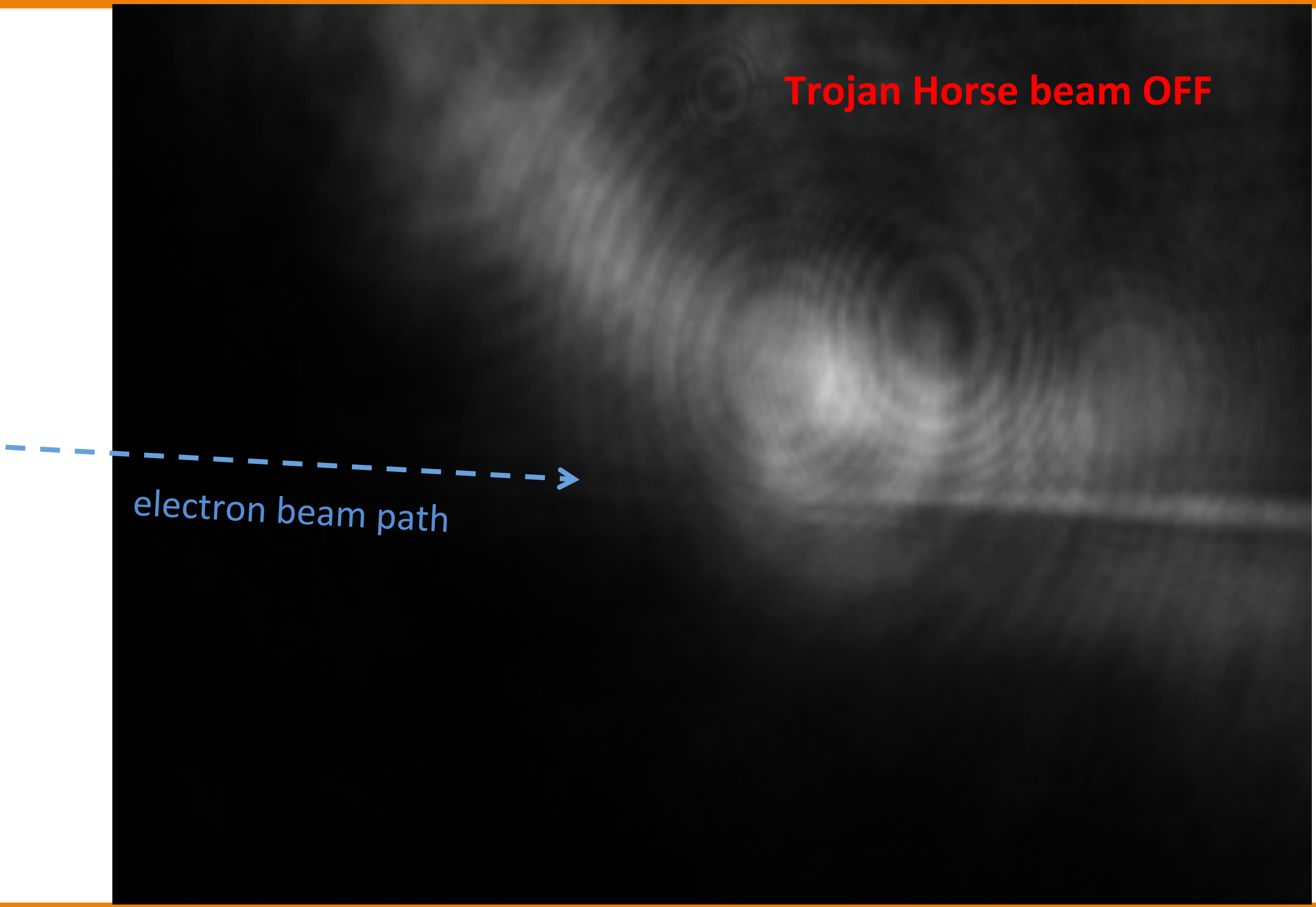
Transverse laser OFF

Transverse laser ON



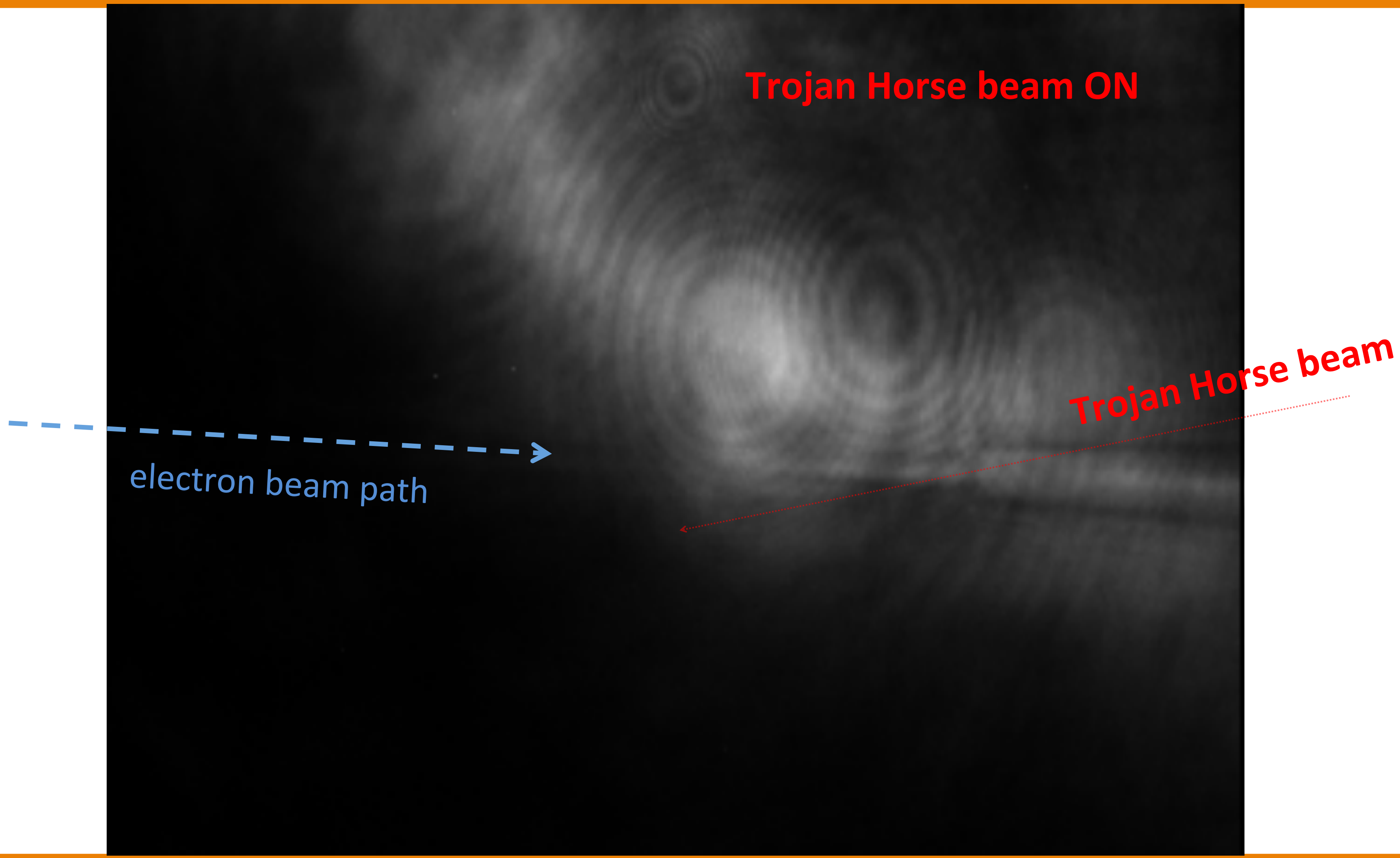
E210 "Trojan Horse" PWFA

Transverse laser OFF Transverse laser ON



E210 "Trojan Horse" PWFA

Transverse laser OFF Transverse laser ON



FACET-II Workshop
Oct. 17-19, 2016

E-224:

"Visualization of lepton-driven plasma wakefield accelerators"

Rafal Zgadzaj & Mike Downer
The University of Texas at Austin

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

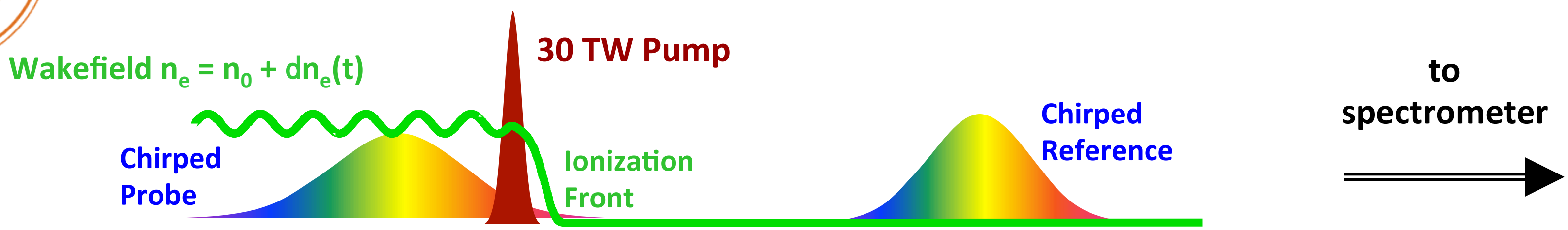
2. FACET-II: Electron wake visualization (Δt < 100 fs)*

- goals: e^- vs. e^+-driven wakes; e-wakes in self- vs. pre-ionized plasma
- requirements: improved sensitivity; 3D visualization capability

*time delay after e-bunch

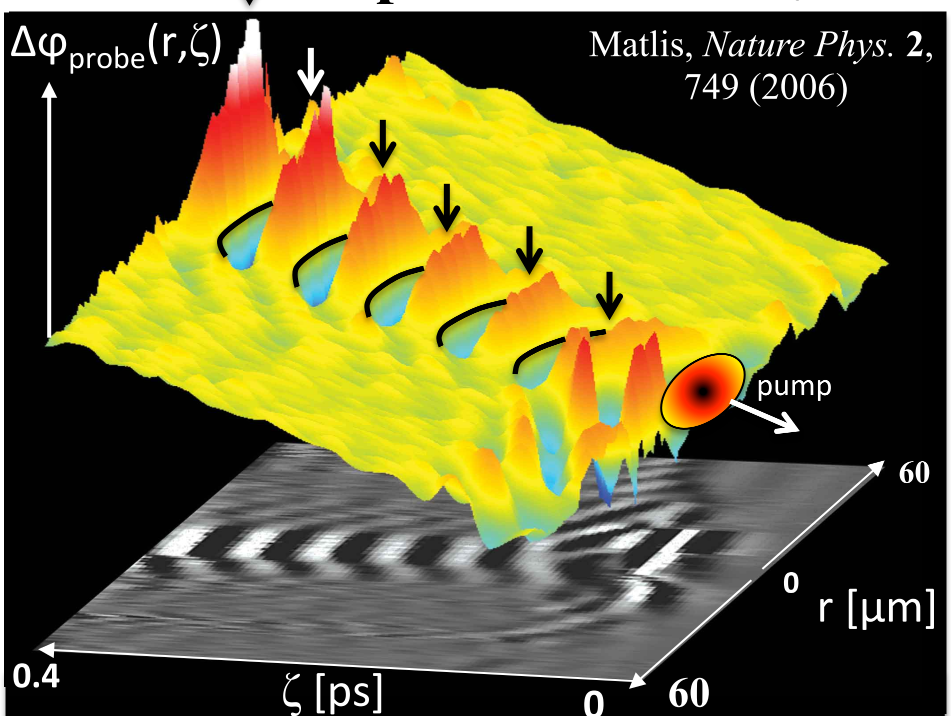
Financial support: NSF-PHY-1416218 "Visualization of e-beam-driven PWFAs"
DOE DE-SC0012444 "Multi-GeV plasma acceleration physics"

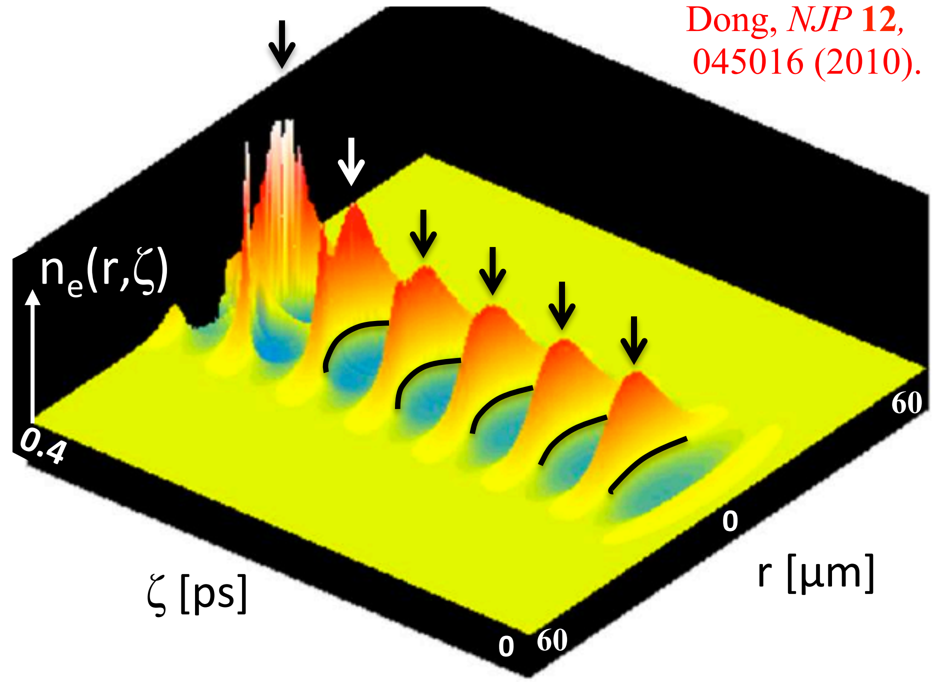
"Frequency Domain Holography" Imaged Quasi-Static Wakes in One Shot



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

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



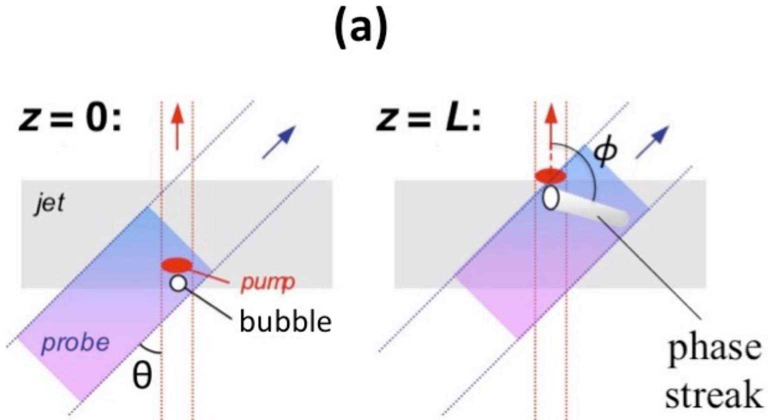


Dong, *NJP* **12**, 045016 (2010).

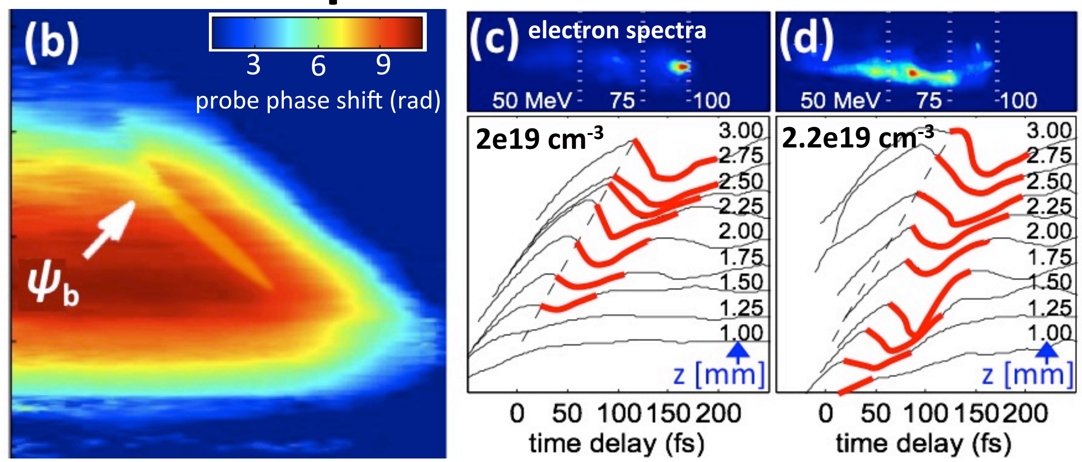
We've observed formation, propagation, collapse of plasma bubbles with an all-optical streak camera

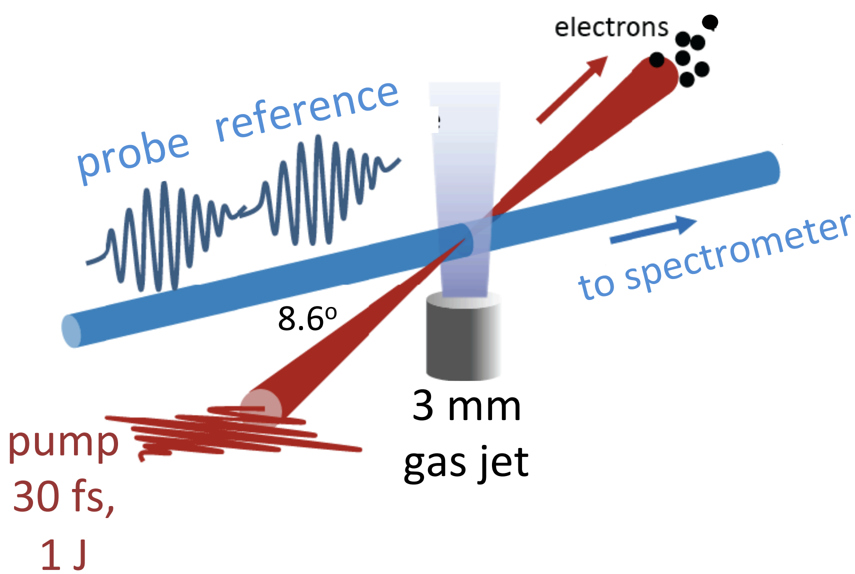
Li *et al.*, *Phys. Rev. Lett.* **113**, 085001 (2014)

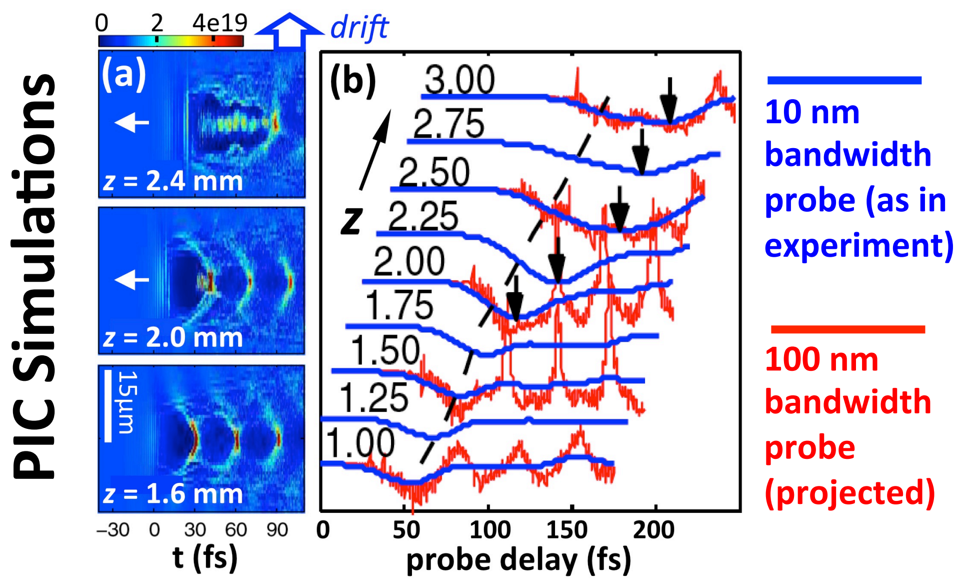
Experimental Setup



Experimental Results

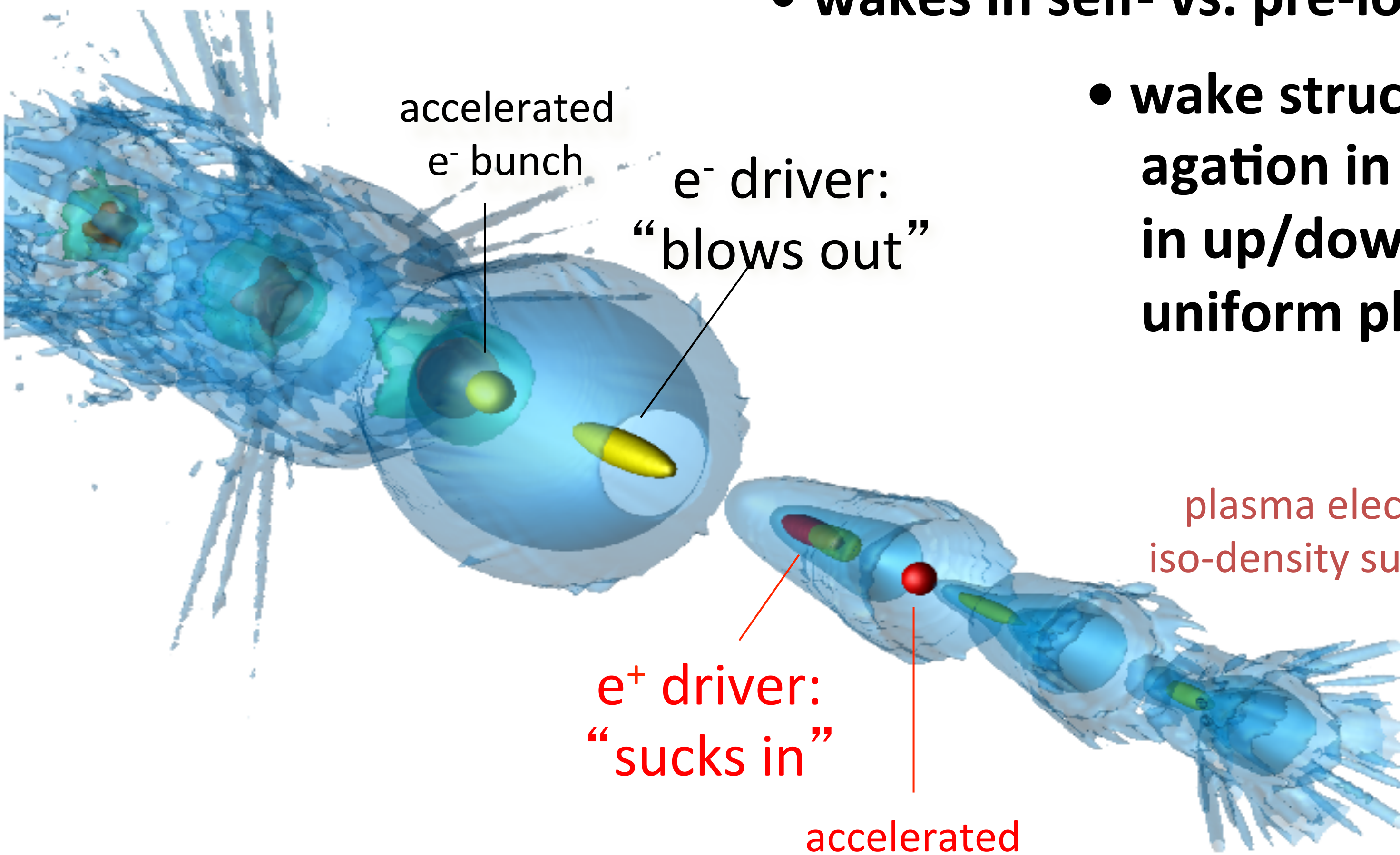






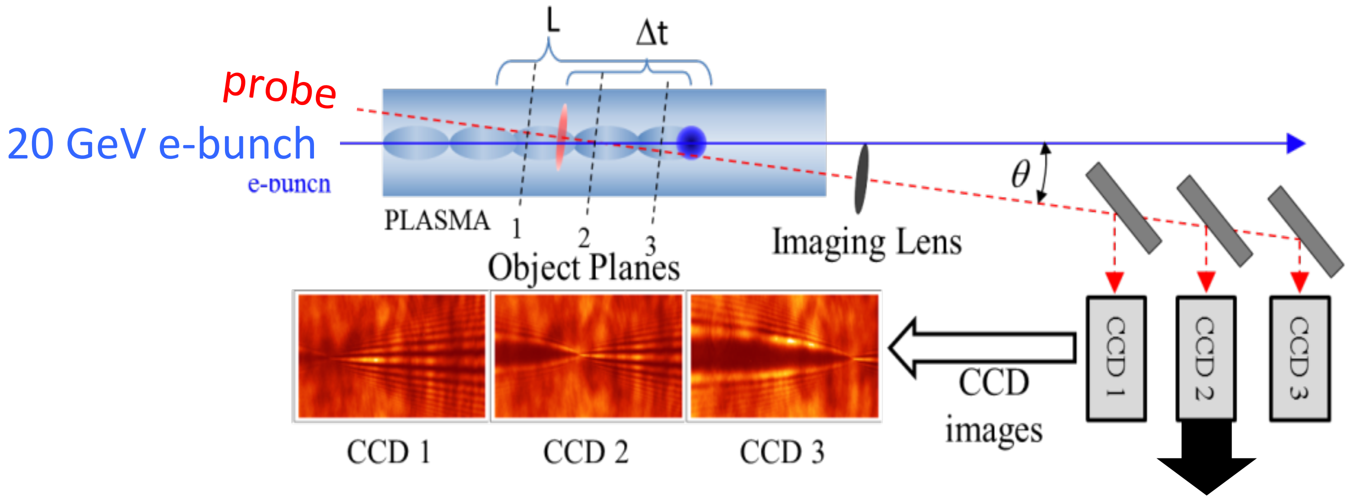
In FACET-II, we aim to visualize beam-driven electron wakes directly

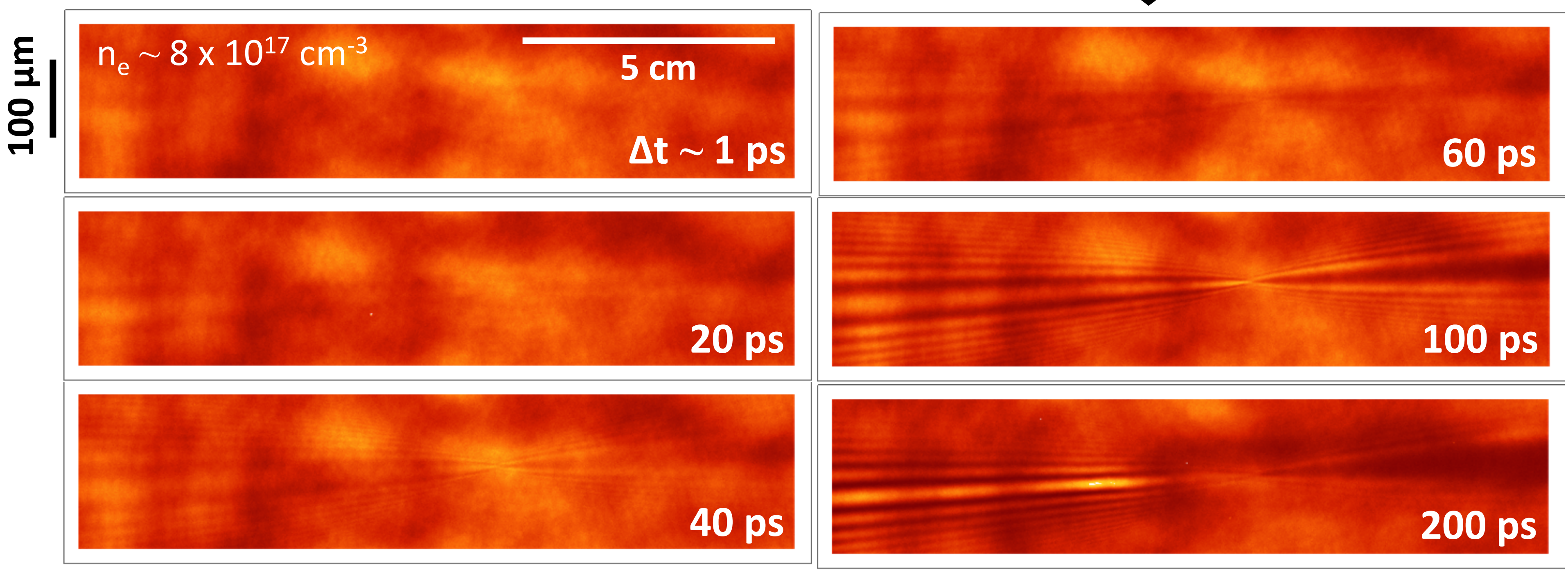
- e^- vs. e^+-driven plasma wakes
- wakes in self- vs. pre-ionized plasma
- wake structure & propagation in one shot, in up/down-ramps + uniform plasma



courtesy Frank Tsung (UCLA)

With MOPI, visibility of early e-wakes is low; structural information is lacking





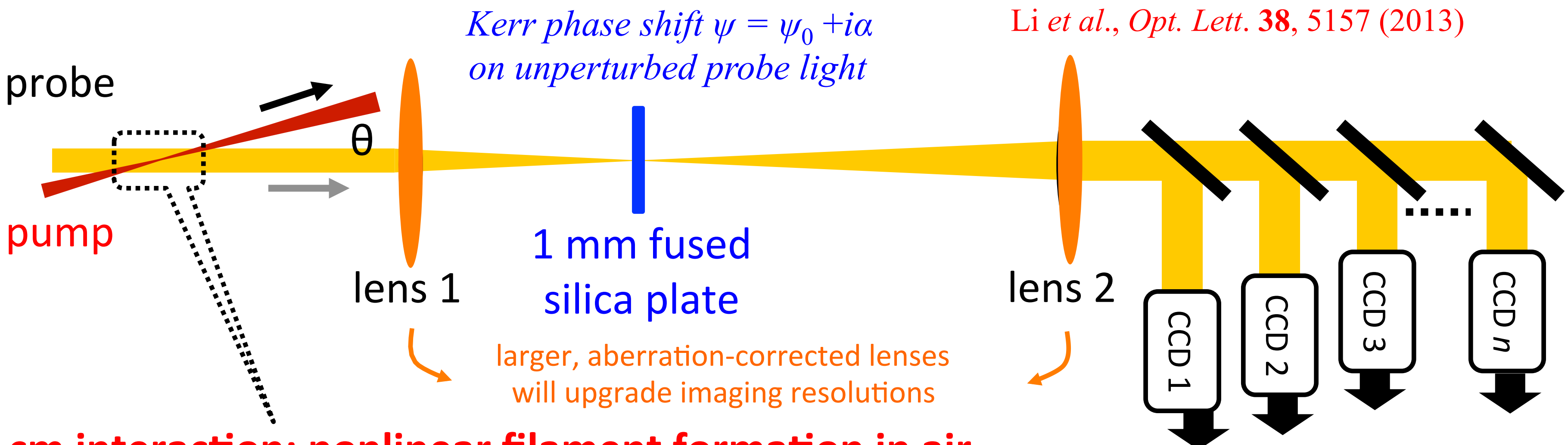
We propose 3 upgrades to FACET's plasma imaging capability

- **MOP - Phase-Contrast Imaging** [F. Zernike, *Physica* **9**, 686 (1942)]
  - sensitivity to $n_e \sim 10^{16}$ cm^{-3} plasma structures
  - Li *et al.*, *Opt. Lett*. **38**, 5157 (2013)
- **Faraday rotation** [M. Faraday, *Diary* **IV**, #7504-7718 (1845)]
  - selective, sensitive imaging of dense bubble walls in tenuous plasma
  - kT **B** field of drive & accelerating GeV e^- bunch magnetizes selected components of plasma bubble
  - Chang, AAC (2016)
- **Computerized Tomography ^ w. Multiple Probes** [J. Radon, *Ber. Saechsische Akad. Wiss*. **29**, 262 (1917)]
  - 4D visualization of evolving plasma structures
  - Li *et al.*, *Nature Comm*. **5**, 3085 (2014)

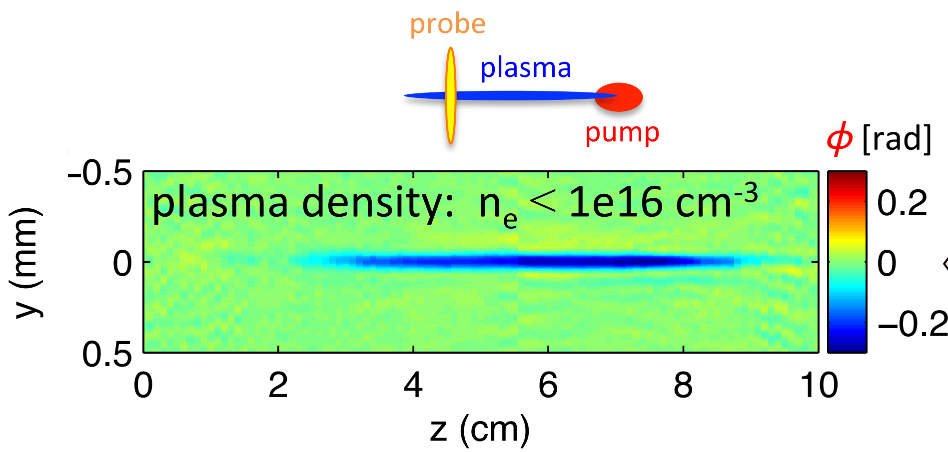
We have successfully tested each of these ideas on LASER-driven plasma structures in our Texas lab

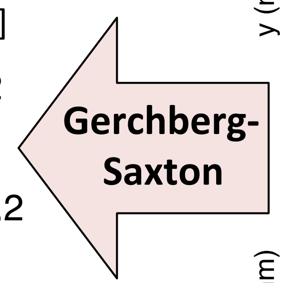
MOP-Phase-Contrast Imaging detects $n_e < 10^{16}$ cm^{-3} plasma structures

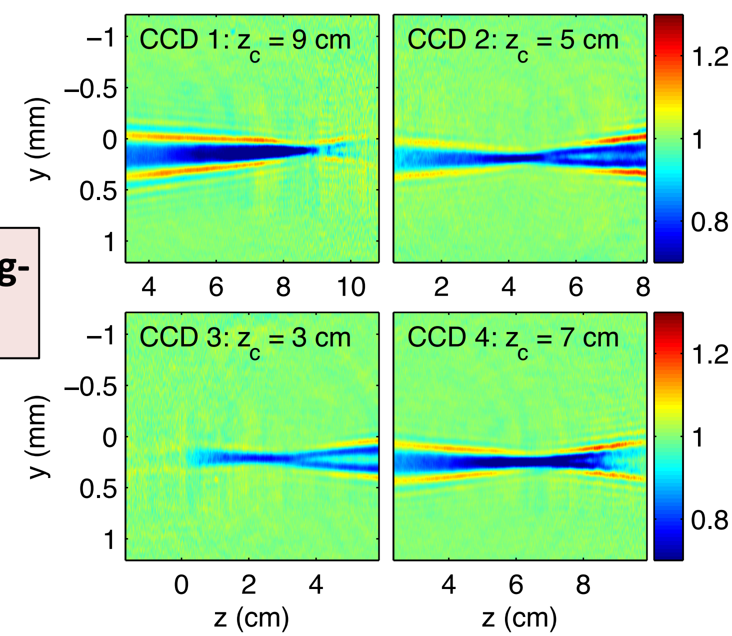
Li *et al.*, *Opt. Lett.* **38**, 5157 (2013)



10 cm interaction: nonlinear filament formation in air





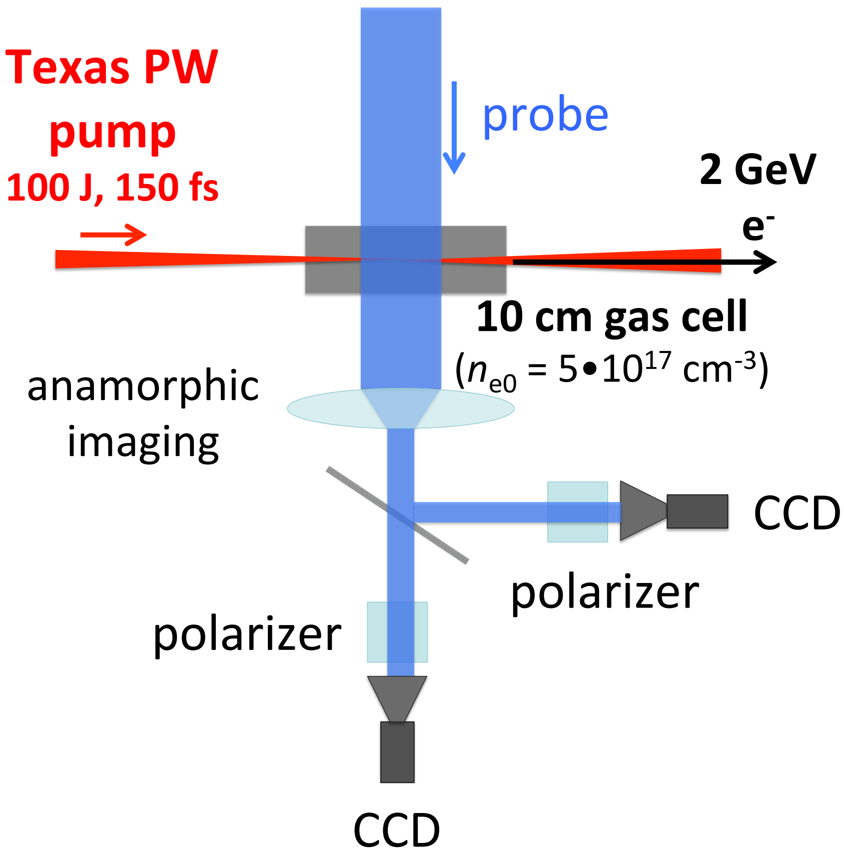


Continuous reconstructed phase shift along *z* due to plasma channel 1.7 ps after pump

Faraday rotation picks out dense bubble wall in tenuous plasma

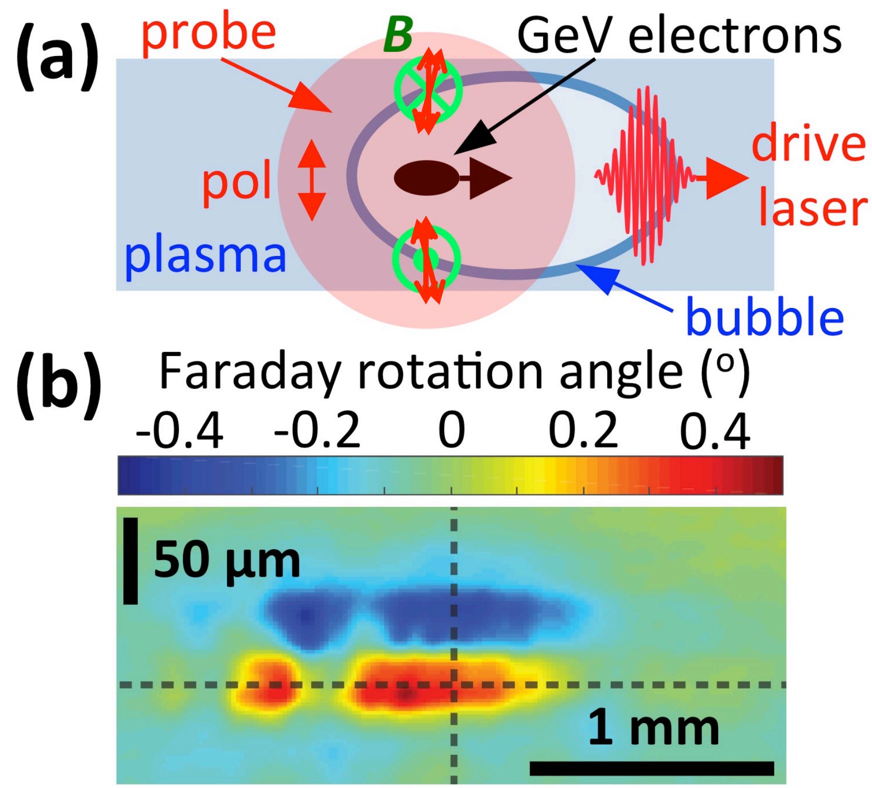
Based on technique developed by: Kaluza, *PRL* **105**, 115002 (2010); Buck, *Nat. Phys*. **7**, 453 (2011) in $n_e > 10^{19}$ cm^{-3} plasma

Faraday probe setup



Results from Chang AAC (2016)

Faraday rotation results

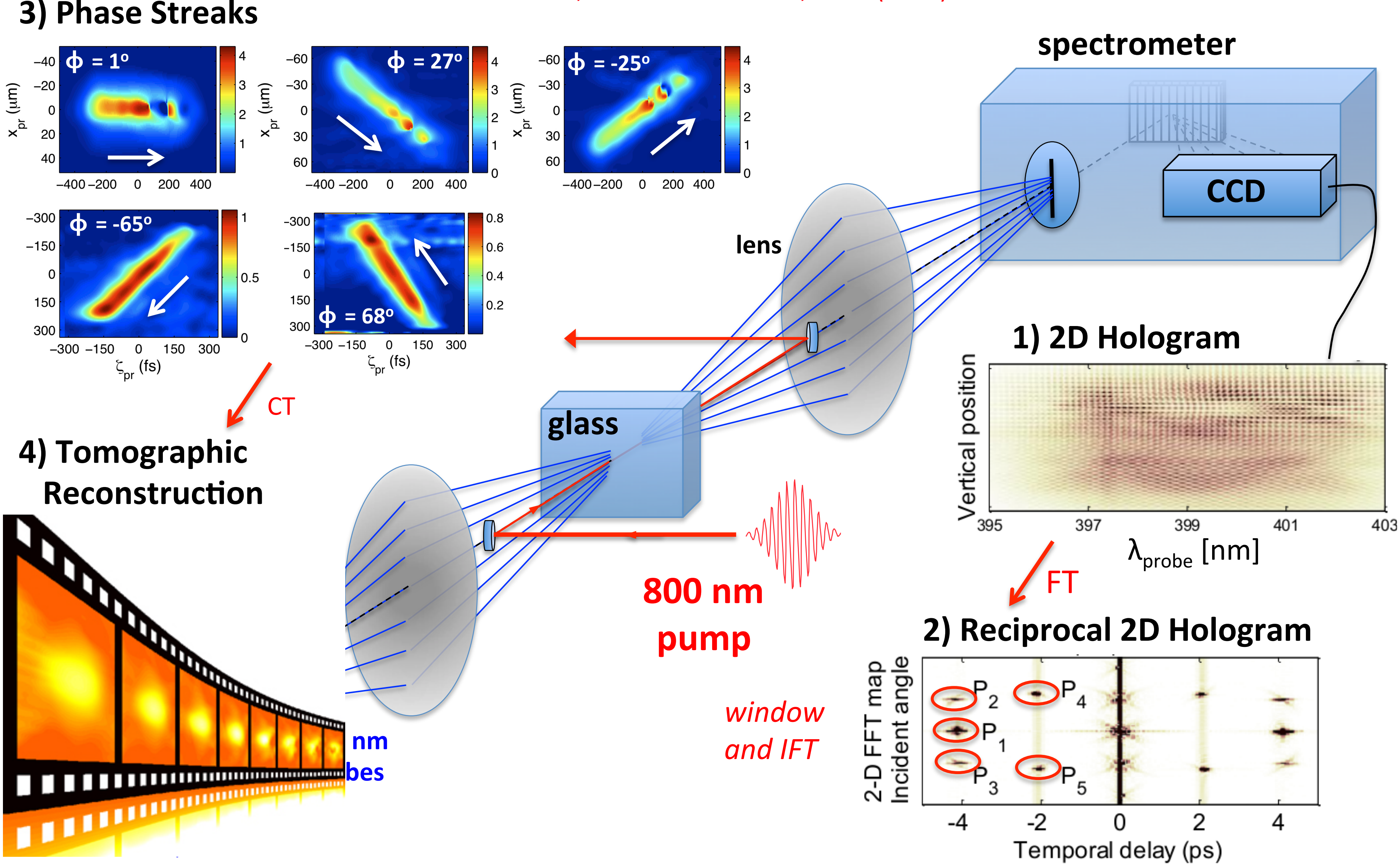


4 measure-ments

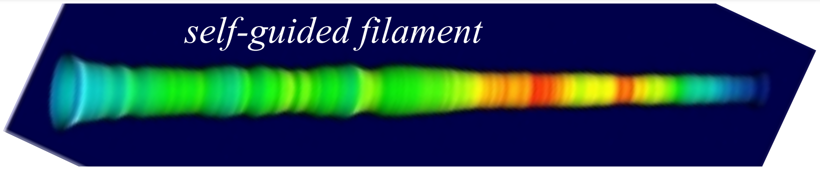
- *separation of ± lobes:* **bubble size**
- $|\Delta\phi_{Faraday}|$: **bubble wall density**
- *width of each lobe:* **bubble wall thickness**
- *longitudinal variations:* **bubble evolution**

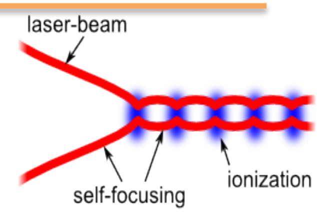
Computerized tomography reconstructs movie from multiple phase streaks in *one shot*...

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



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

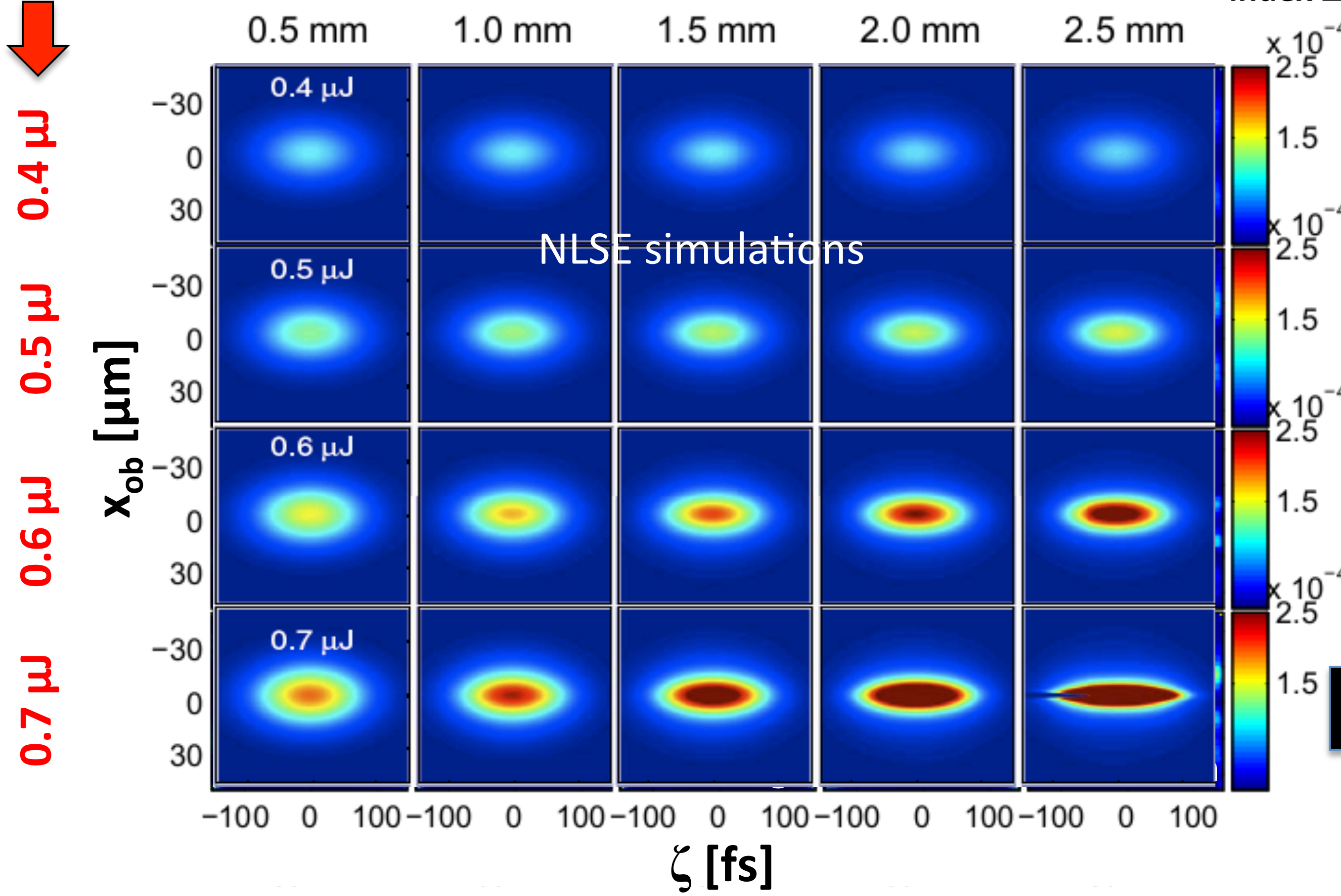




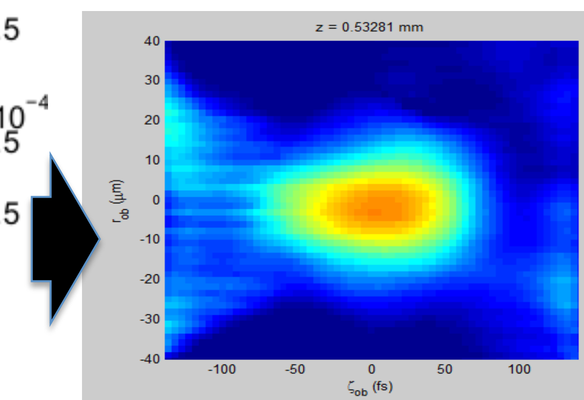
PUMP PULSE ENERGY

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 ion wakes driven by nonlinear electron wakes. Ion wakes depends sensitively on e-wake history, and determine the state of the plasma for subsequent drive bunches.

- We need computational support in interpreting these results.
- 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 phase-contrast and Faraday rotation imaging.

- 3D imaging via multi-probe computerized tomography.

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

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