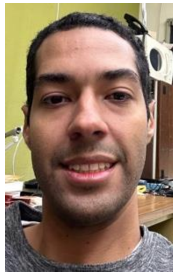
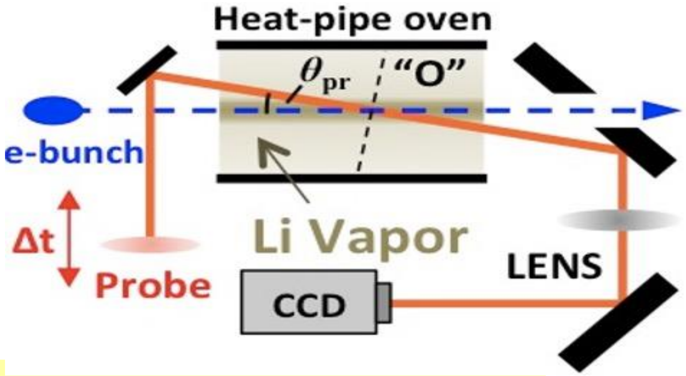
Jason Brooks
PhD 2025



Timothy Araujo
PhD student

Rafal Zgadzaj
Research Scientist



E-324: "Optical visualization of beam-driven plasma wakefield accelerators"

Mike Downer, Jason Brooks, Rafal Zgadzaj, Timothy Araujo,
Robert Ariniello, Brendan O'Shea, Mark Hogan, et al.…

E-224 publications: ($0.1 \lesssim \Delta t \lesssim 1$ ns)

- Zgadzaj *et al.*, "Dissipation of electron-beam-driven plasma wakes," *Nature Commun.* **11**, 4753 (2020).
- Khudyakov *et al.*, "Ion dynamics driven by strongly nonlinear plasma wake," *PPCF* **64**, 045003 (2022).
- Chang *et al.*, "Faraday rotation study of plasma bubbles in GeV wakefield accelerators," *PoP* **28**, 123105 (2021).
- Silva *et al.*, "Stable positron acceleration in thin, warm, hollow plasma channels," *PRL* **127**, 104801 (2021)

E324 Goals: observe, analyze, understand **post-wake plasma recovery** ($1 \text{ ns} \leq \Delta t \leq$ tens of μs) relevant to accelerator repetition rate,
and **ion-wake formation** ($\Delta t \leq 0.1$ ns) relevant to positron acceleration.

E324: High-Level Scientific Goals & Target Publications

1. Clarify fundamental limits to PWFA repetition rate (GHz? MHz? kHz?) set by post-wake plasma recovery time (ns? μs? ms?).

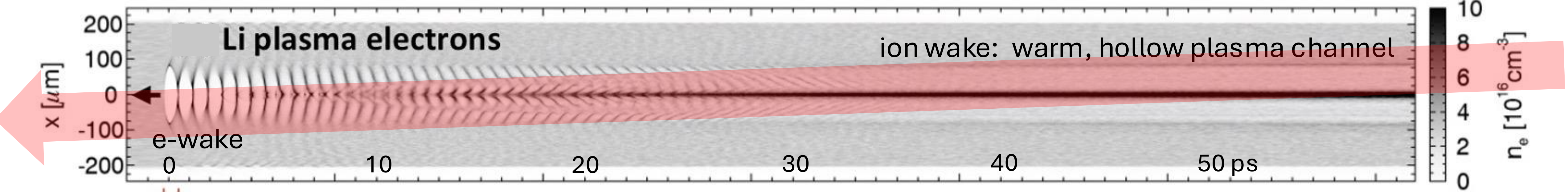
- Community understanding currently dominated by DESY and INFN experiments:
  - D'Arcy *et al.* *"Recovery time of a plasma-wakefield accelerator." Nature* **603**, 58 (2022). **16 MHz, 60 ns**
  - Pompili *et al.*, *"Recovery of hydrogen plasma at the sub-nanosecond time scale in a PWFA," Commun. Phys.* **7**, 241 (2025). **> 1 GHz, < 1 ns**
- E324 results at FACET-II are poised to correct this understanding significantly… *
  - J. Brooks *et al.*, "Measurements of lifetime of beam-driven wakes at FACET-II" (PhD dissertation 2025). **< 10s of kHz, > 100s of μs**
  - J. Brooks *et al.*, "Optical signatures of plasma wake lifetimes," in preparation for *Nat. Commun.* or *PRX.*

*…but there are some gaps to fill.

Target publication 1 (2026)

2. Visualize electron- and ion-density wake structures relevant to electron- and positron-acceleration

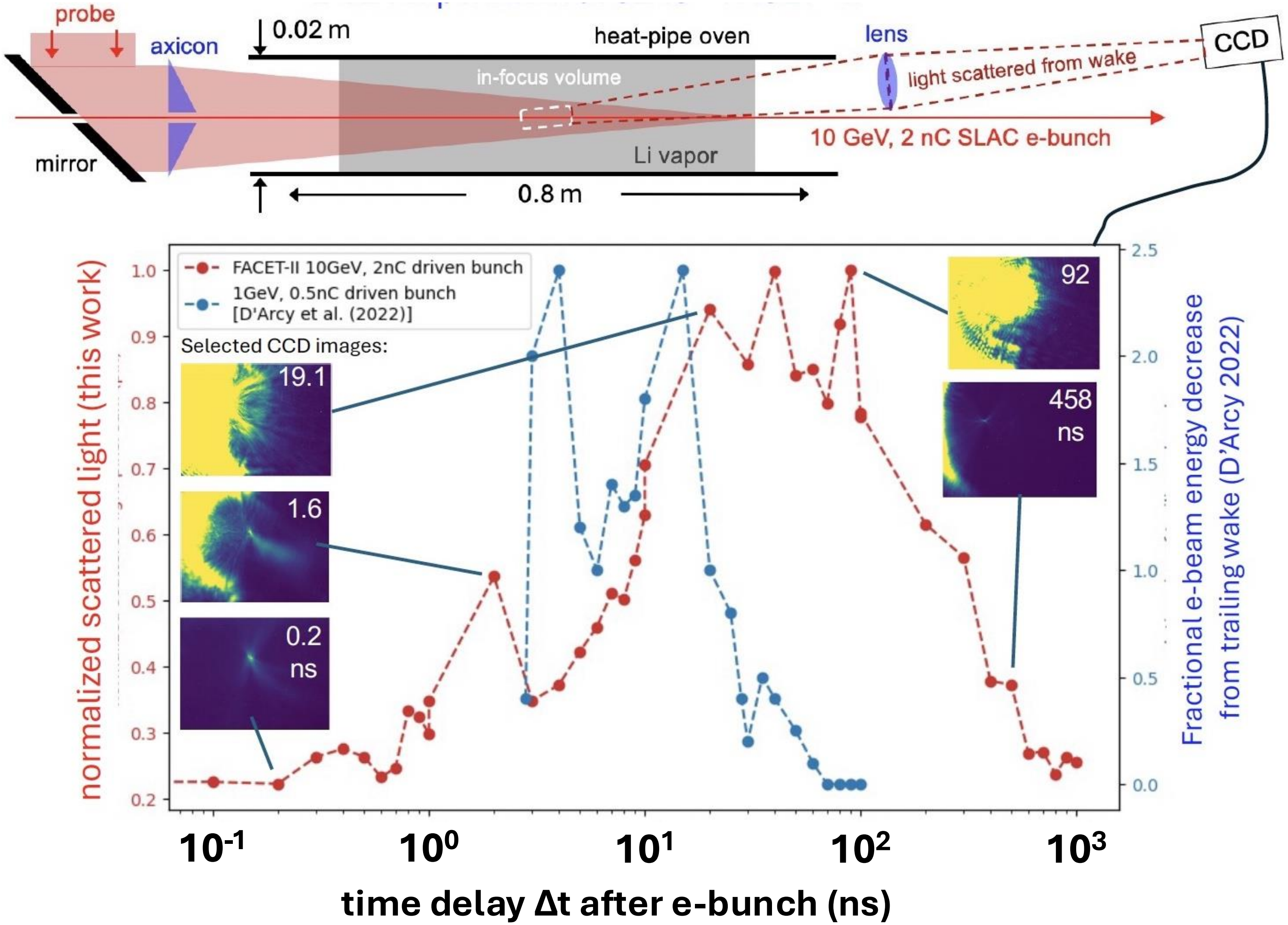
T. Silva *et al.*, "Stable positron acceleration in thin, warm, hollow plasma channels," *Phys. Rev. Lett.* **127**, 103801 (2021)



- T. Araujo sees "suggestive" signatures of these structures from grazing-incidence probe measurements.
- A new collinear probe experiment is needed for definitive publishable results. **Target publication 2 (2027)**

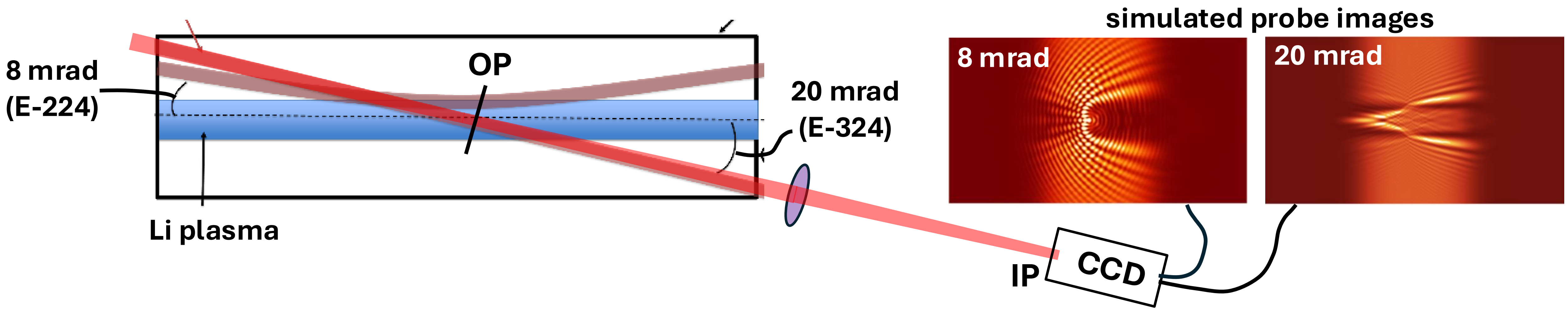
Data & Analysis in Hand I: Time-resolved near-forward probe scatter

- J. Brooks *et al.*, "Measurements of lifetime of beam-driven wakes at FACET-II" (PhD dissertation 2025).
- J. Brooks *et al.*, "Optical signatures of plasma wake lifetimes," in preparation for *Nat. Commun.* or *PRX*.

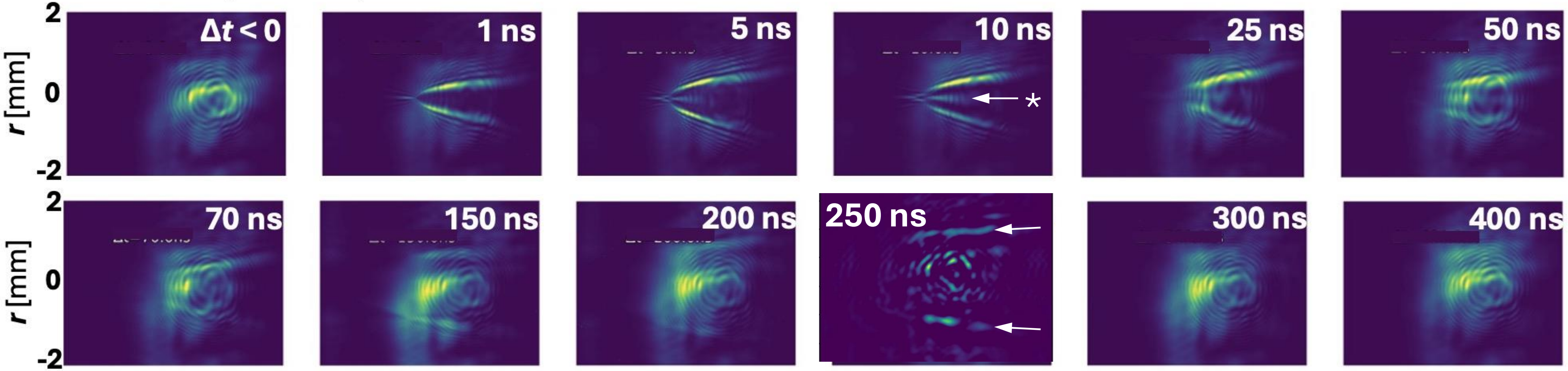


Jason Brooks
PhD 2025

Data & Analysis in Hand I: Time-resolved grazing-angle shadowgraphy



1 Torr Ar plasma, e-beam-ionized (same gas/plasma used in D'Arcy (2022))



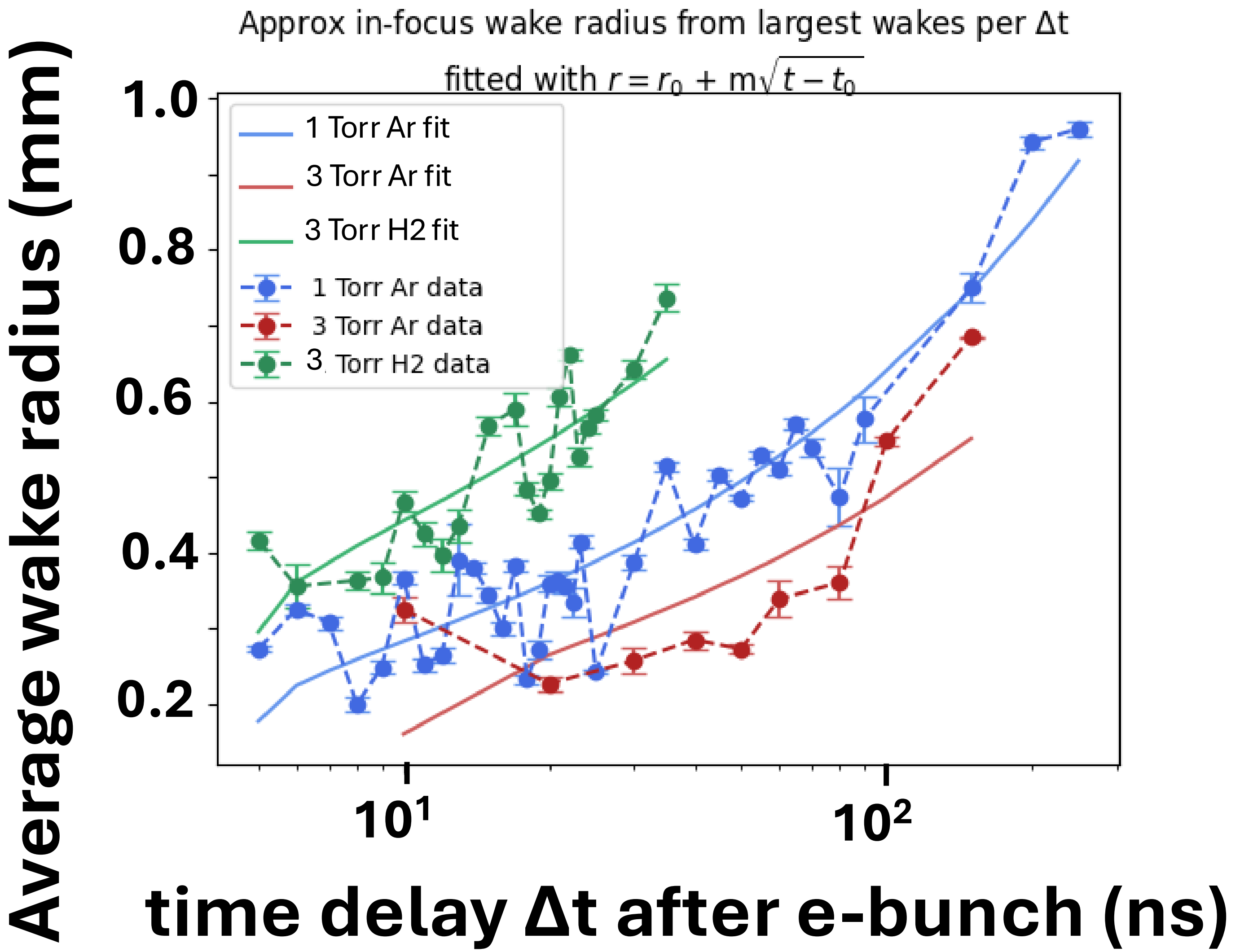
background-subtracted, spatially-filtered

- expanding plasma observed out to $\Delta t \sim 300$ ns...

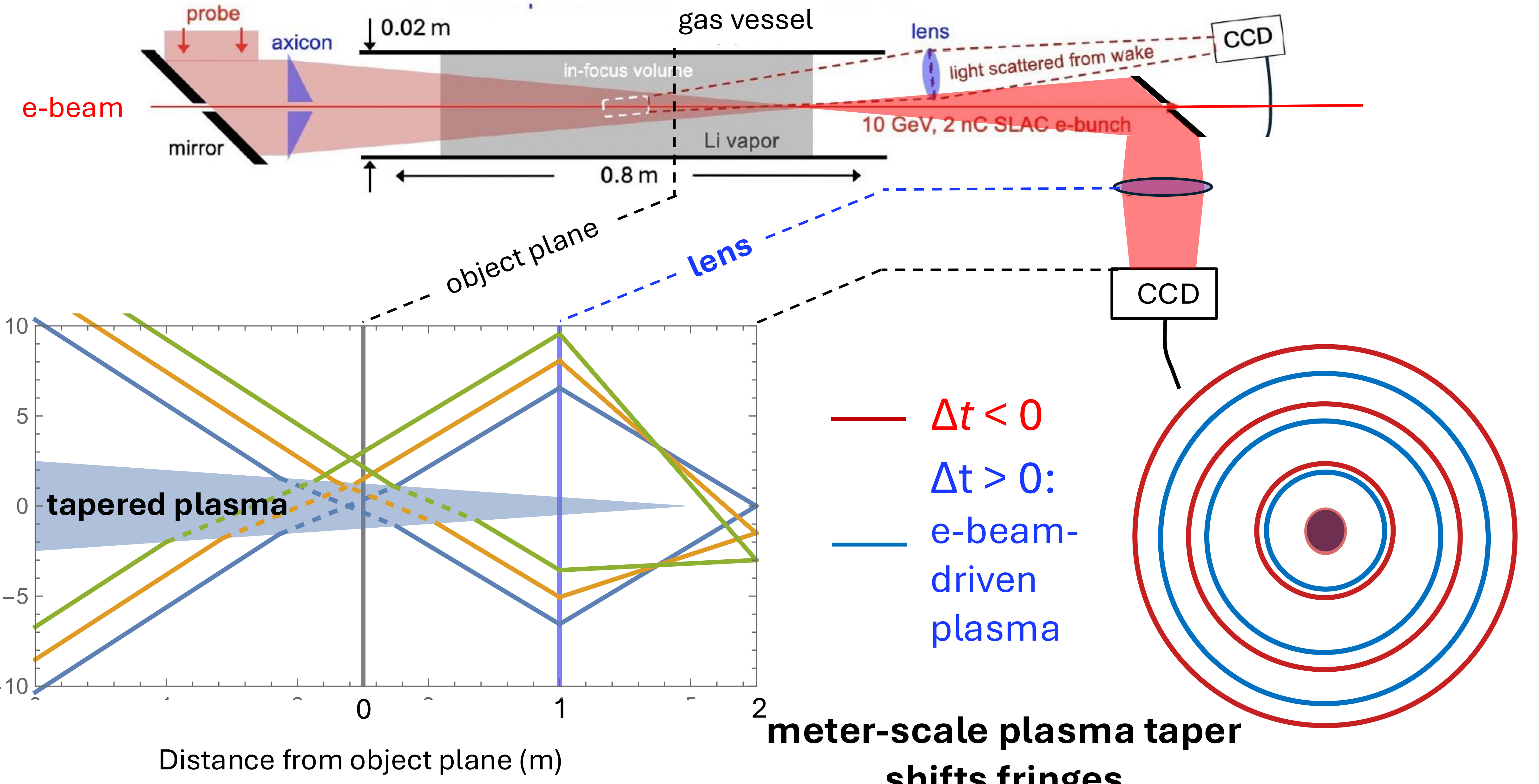
Data & Analysis in Hand I: Ion wake radius vs time

- **Cylindrical blast wave:**
  - $R(t) = A\left(\frac{E_{th}}{\rho_0}\right)^{1/4} t^{1/2}$
  - E_{th} = energy per unit length
  - ρ_0= mass density
  - A= dimensionless; function of the specific heat ratio

- **Ions dissipate most of the wake's stored energy.**

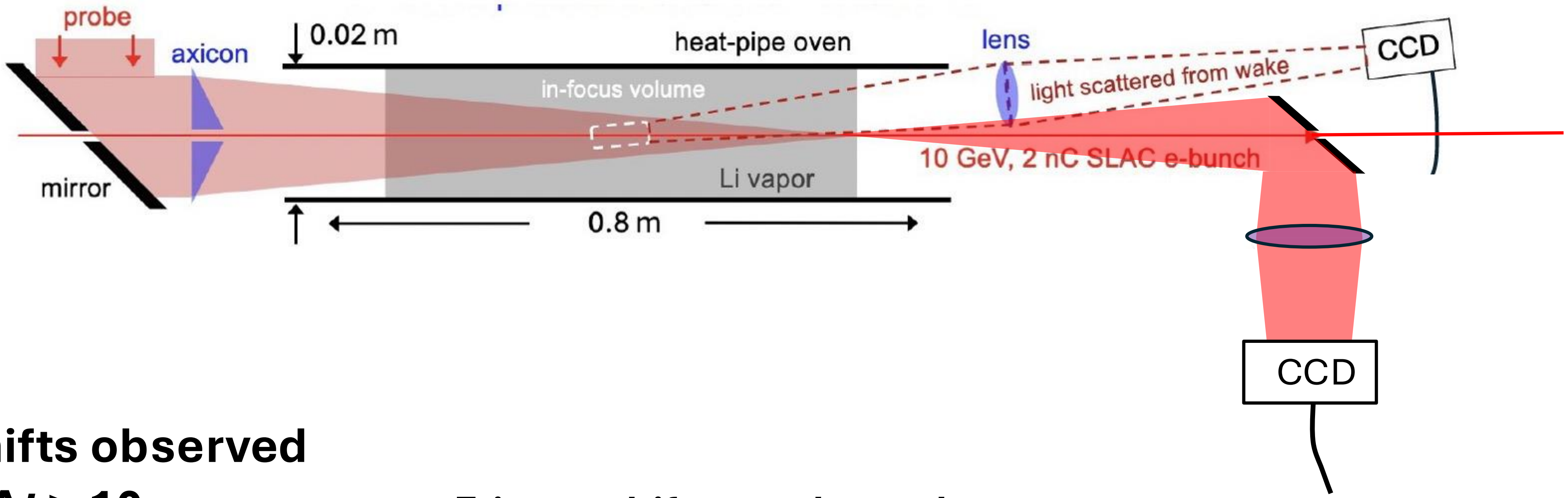


Data & Analysis in Hand I: Bessel-beam interferometry

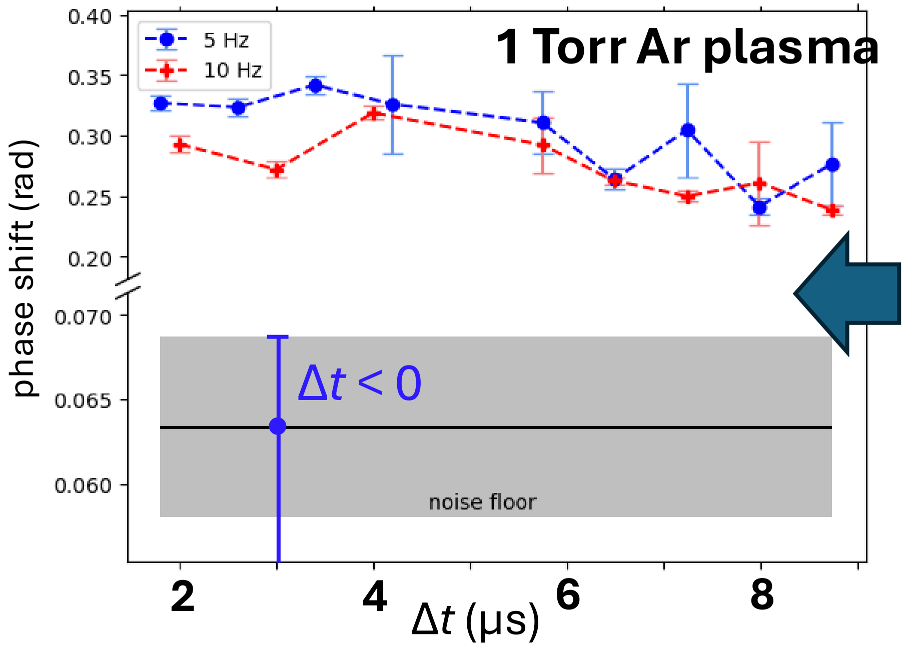


meter-scale plasma taper shifts fringes

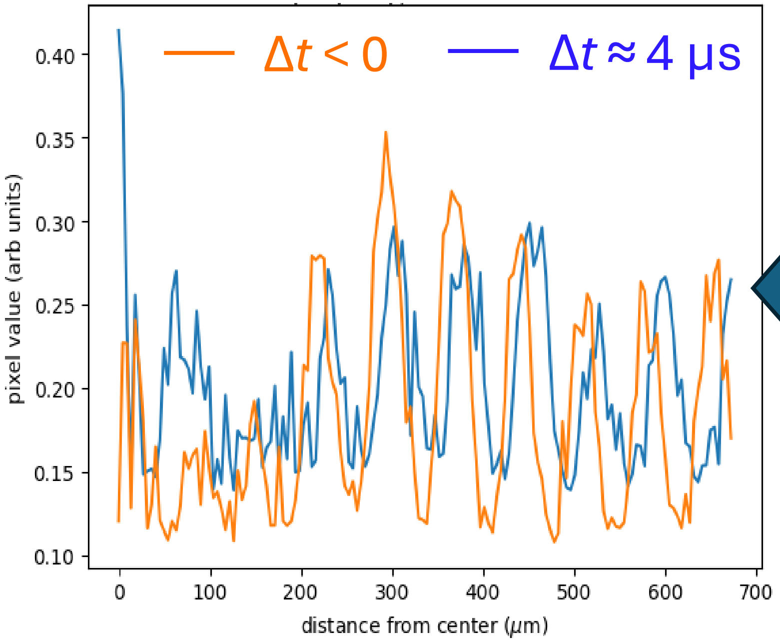
Data & Analysis in Hand I: Bessel-beam interferometry



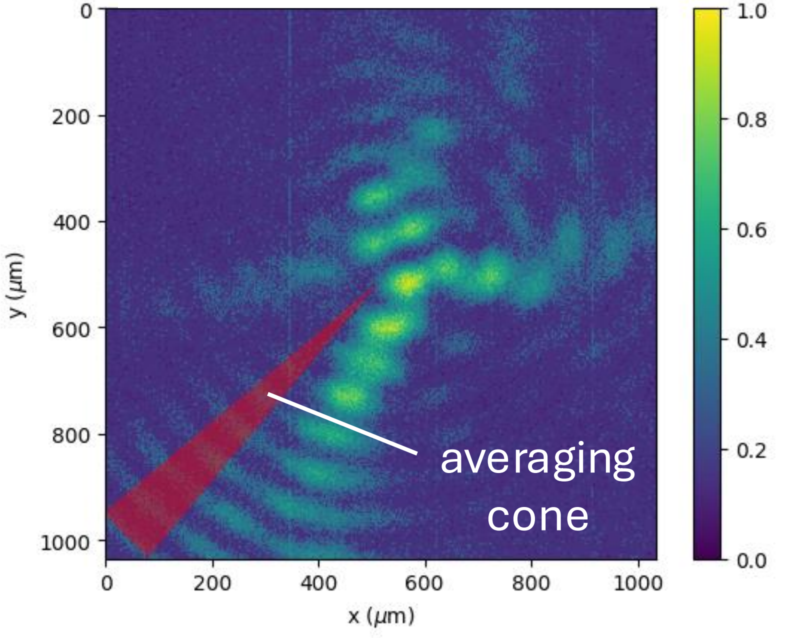
Residual shifts observed out to $\Delta t > 10$ μs



Fringes shift as wake evolves



Bessel beam fringes



Missing data/analysis for high-impact publication (Part I)

- Calibrate optical methods for conditions* of Refs. 1 and/or 2

Done! not yet done

*plasma species	*drive bunch	Probe method	$\tau_{recovery}$
Ar	1 GeV, 0.5 nC [1]	recovery of wake-accelerated e- properties	0.06 μs [1]
Ar	10 GeV, 2 nC [3]	grazing-incidence shadowgraphy	> 0.3 μs [3]
Ar	10 GeV, 2 nC [3]	Bessel-beam interferometry	>10s of μs [3]
pre-ionized Ar	<10 GeV and/or <2 nC and/or w. witness	either of above	??
and/or H_2	0.084 GeV, 0.5 nC [1]	recovery of e- probe properties	0.0007 μs [2]
H_2	10 GeV, 2 nC [3]	grazing-incidence shadowgraphy	>0.07 μs [3]
H_2	10 GeV, 2 nC [3]	Bessel-beam interferometry	??
H_2	<10 GeV and/or <2 nC	either of above	??

[1] D'Arcy et al. *"Recovery time of a plasma-wakefield accelerator." Nature* ***603****, 58 (2022).*

[2] *Pompili et al., "Recovery of hydrogen plasma at the sub-nanosecond timescale in a plasma-wakefield accelerator" Commun Phys* ***7****, 241(2025).*

[3] This work

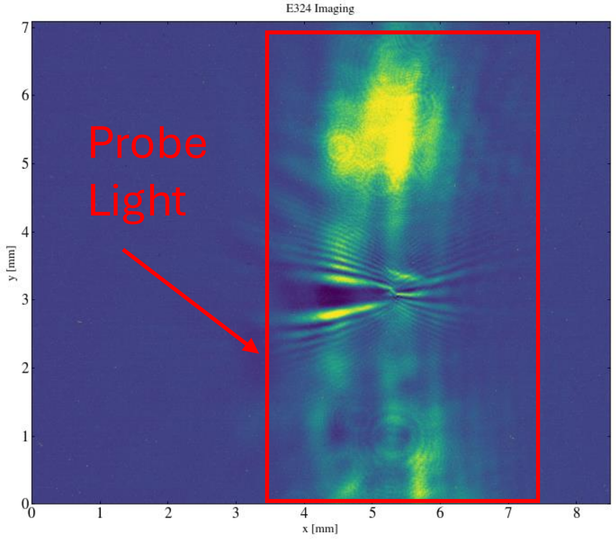
- Address **cumulative plasma heating** question:
  - Some measurements of **vessel heating** at **5 & 10 Hz** done; more needed.
  - Theoretical modeling of cumulative heating needed.

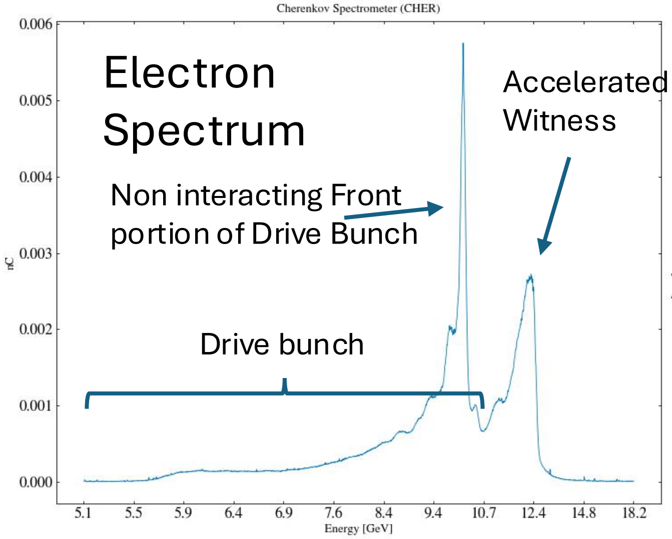
Optical Injection Light from Decelerating Witness Bunch

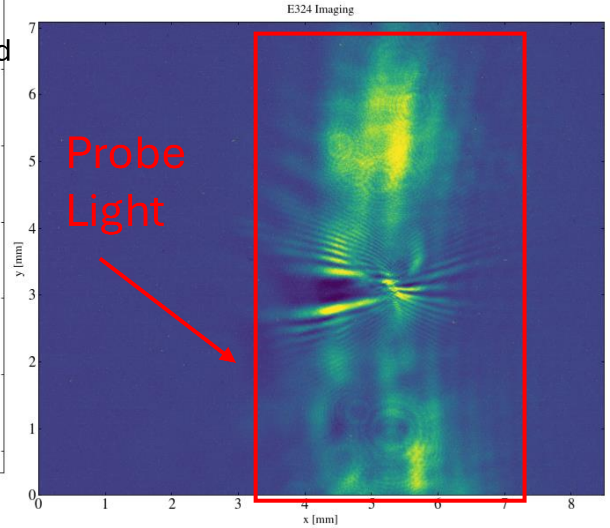
Timothy Araujo

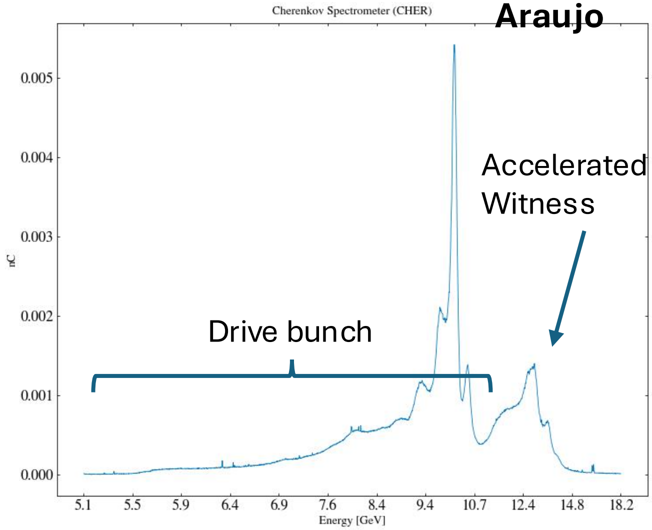
Unexpected Result

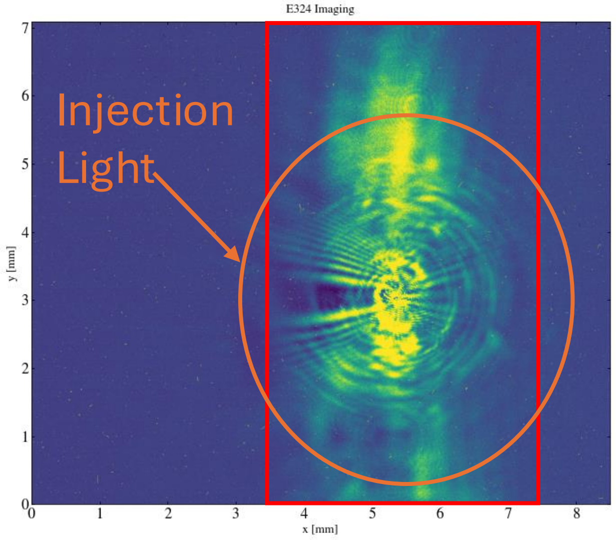
When witness accelerated no optical flashes
When witness decelerated optical flashes are present

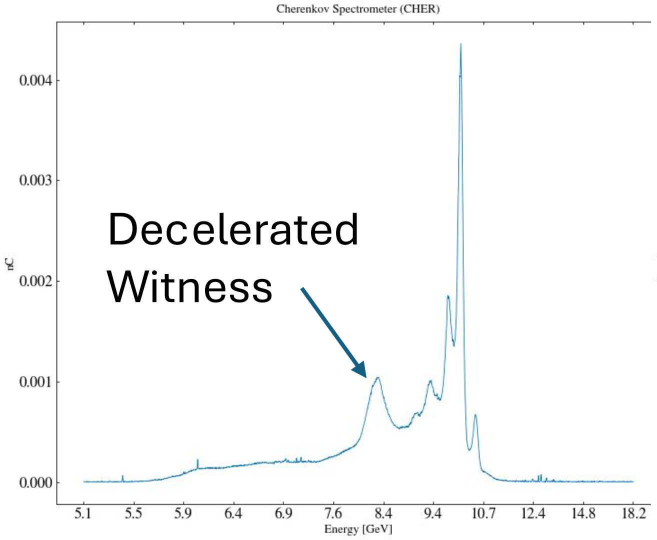


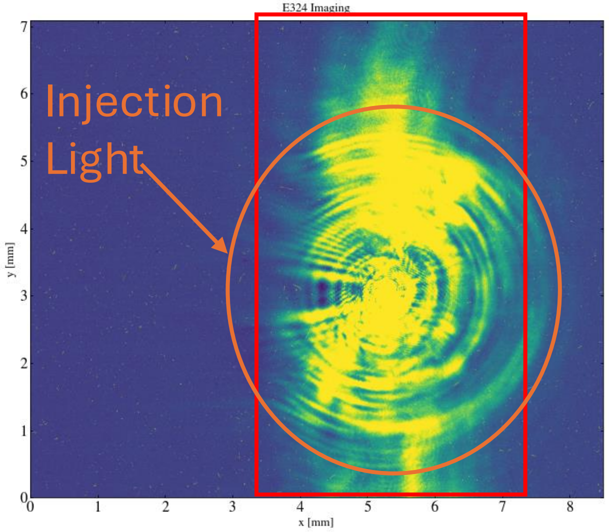


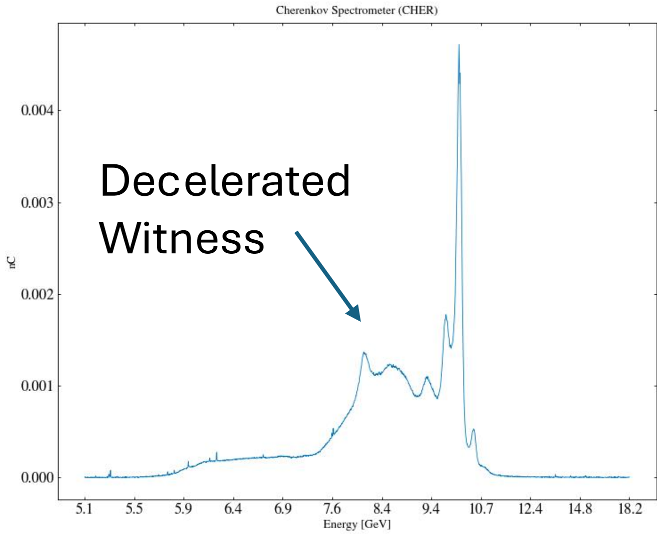






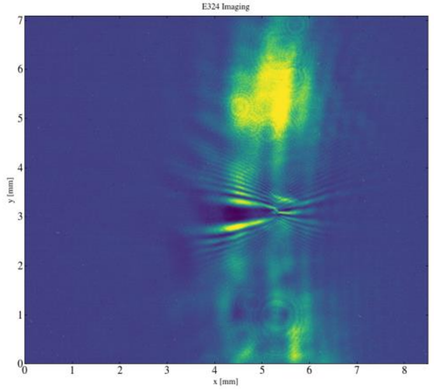


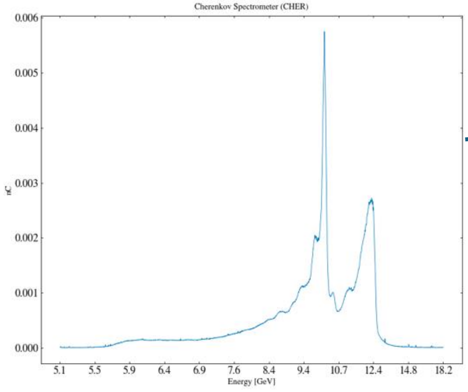


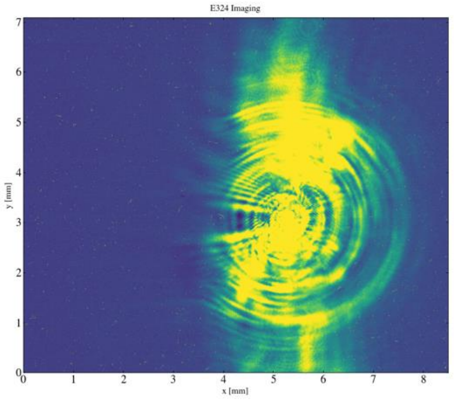


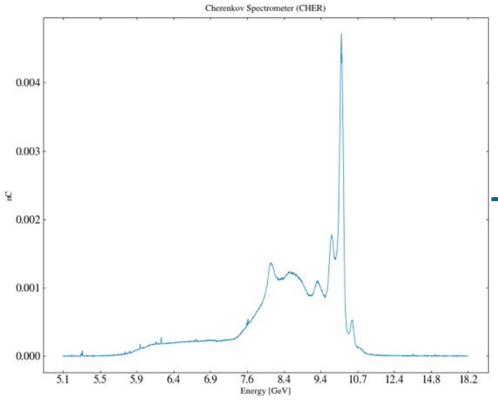
Correlation between Total Camera Signal (Probe light + Injection Light) and weighted electron energy

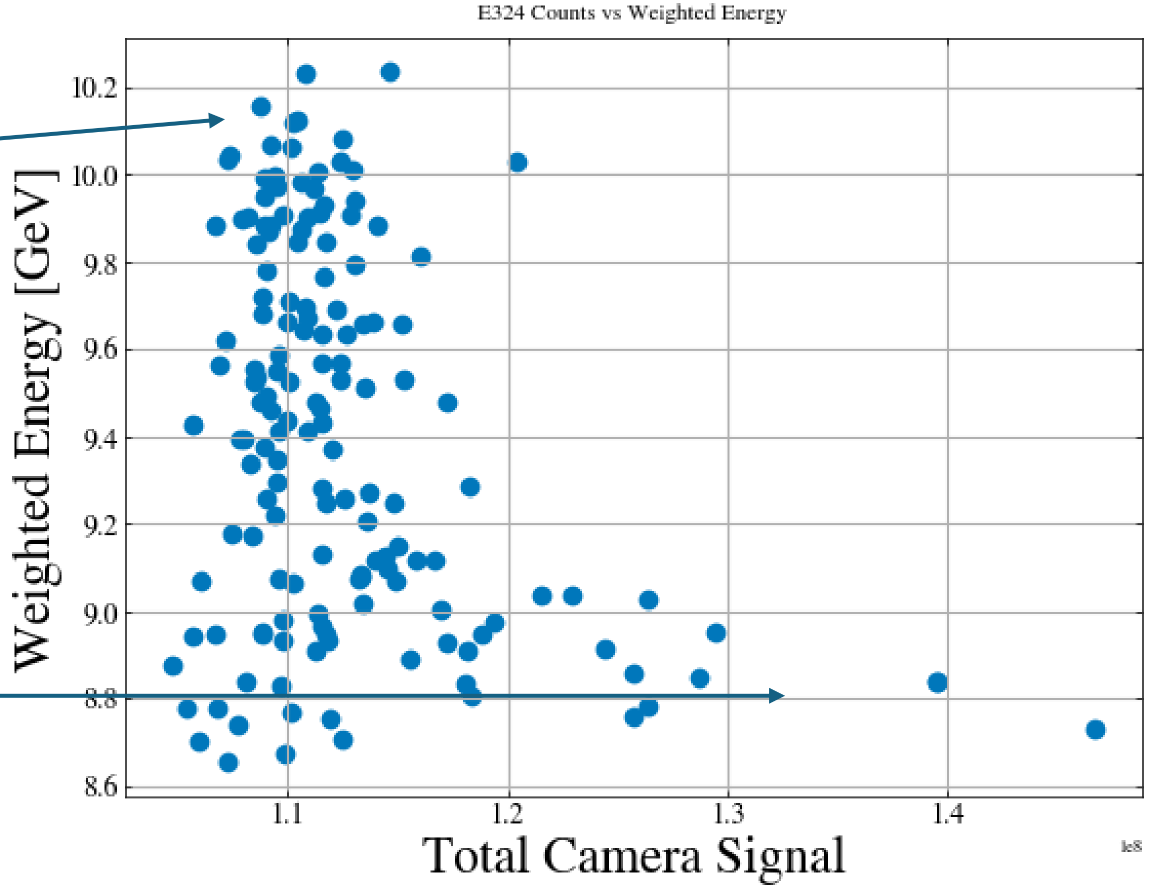
Sequence of data was captured for two bunch experiment in which drive witness delay was varied. When delay was smaller than half plasma period then both bunches contributed to driving the wake and Witness bunch was decelerated. Under these conditions strong injection flashes were visible. When witness delay was greater than half plasma period and experiencing gain no flashes were observed.







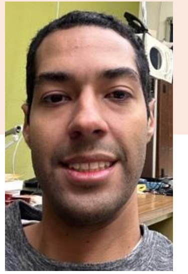




Current Interpretation:
When Witness delay is small the fields of the witness enhance the drive fields enabling ionization of He in Li oven leading to ionization injection

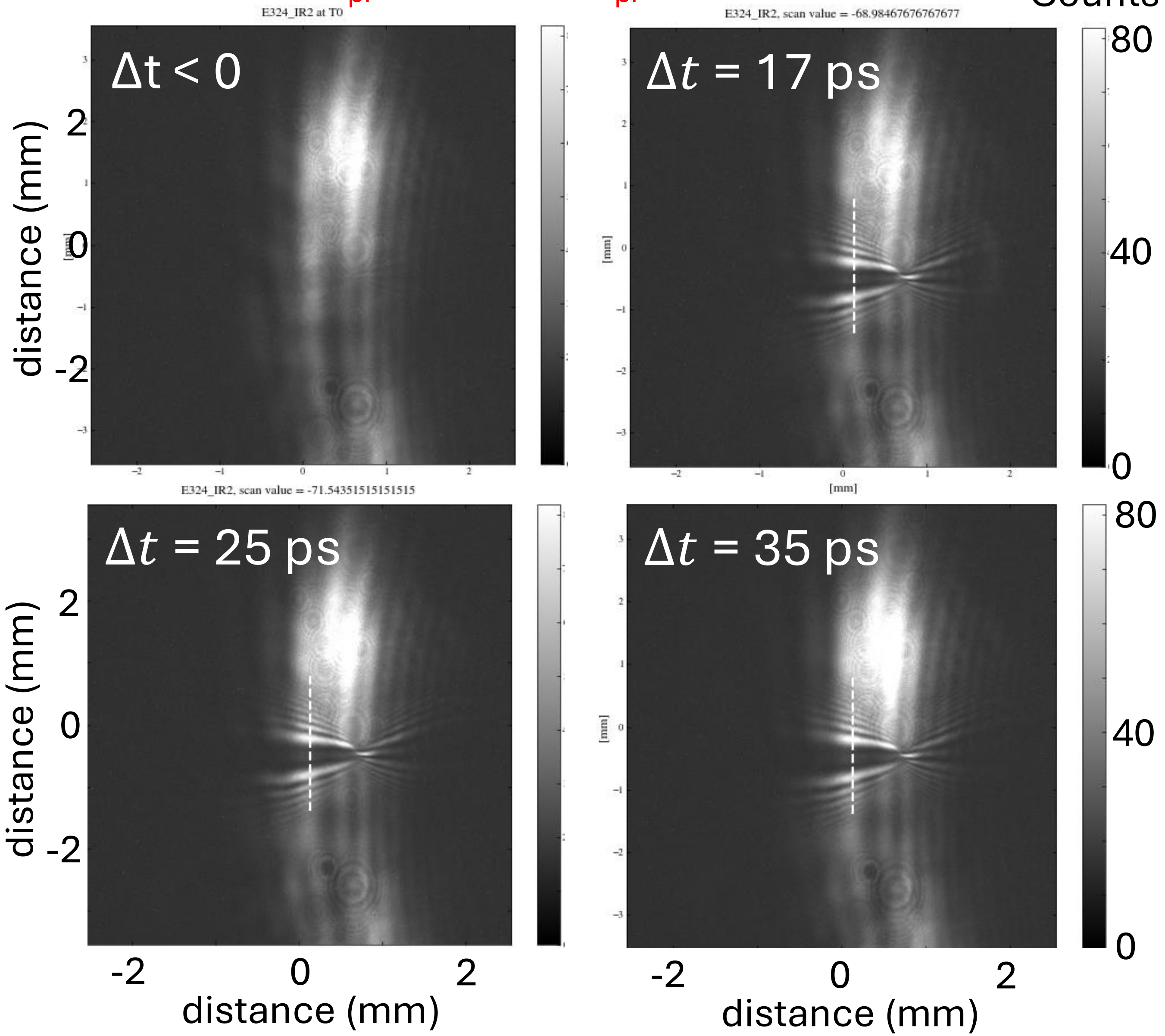
Weighted electron energy = Total Energy of electron bunch (obtained by weighted integrated of spectra shown on previous slide) after interaction with plasma

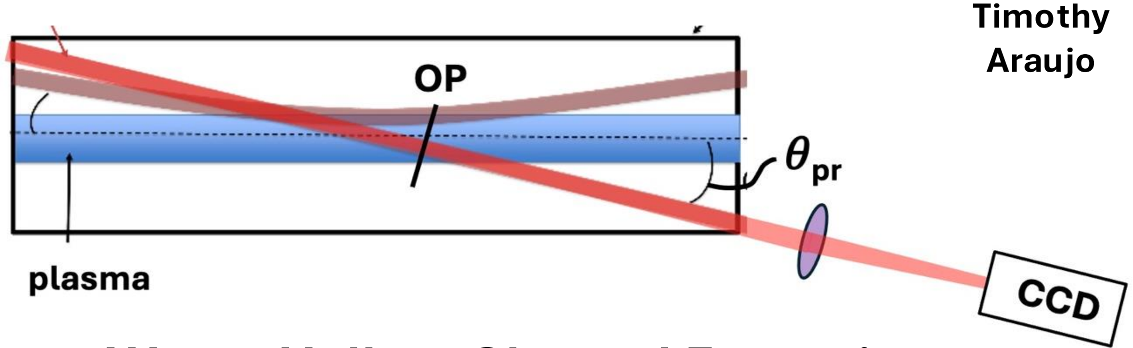
Data & Analysis in Hand II: Grazing-angle shadowgraphy at Δt < 35 ps



Timothy Araujo

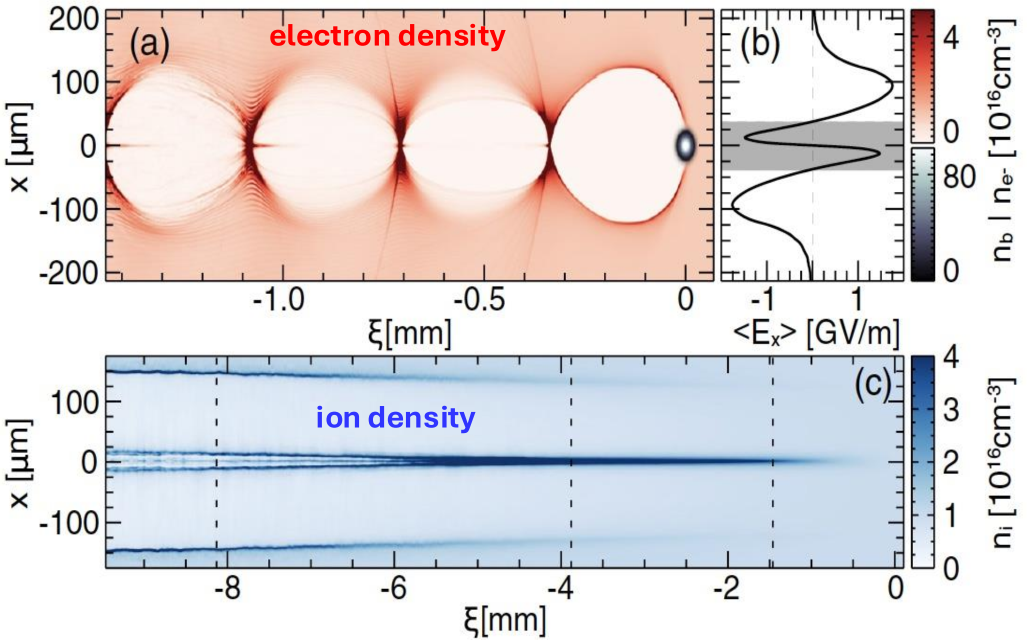
λ_{pr} = 800 nm; θ_{pr} = 17 mrad





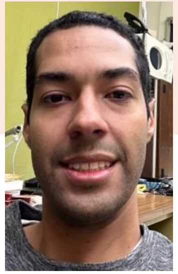
Warm, Hollow-Channel Formation in Hydrogen Plasma (0 < Δt < 35 ps)

T. Silva *et al.*, *Phys. Rev. Lett.* **127**, 103801 (2021)



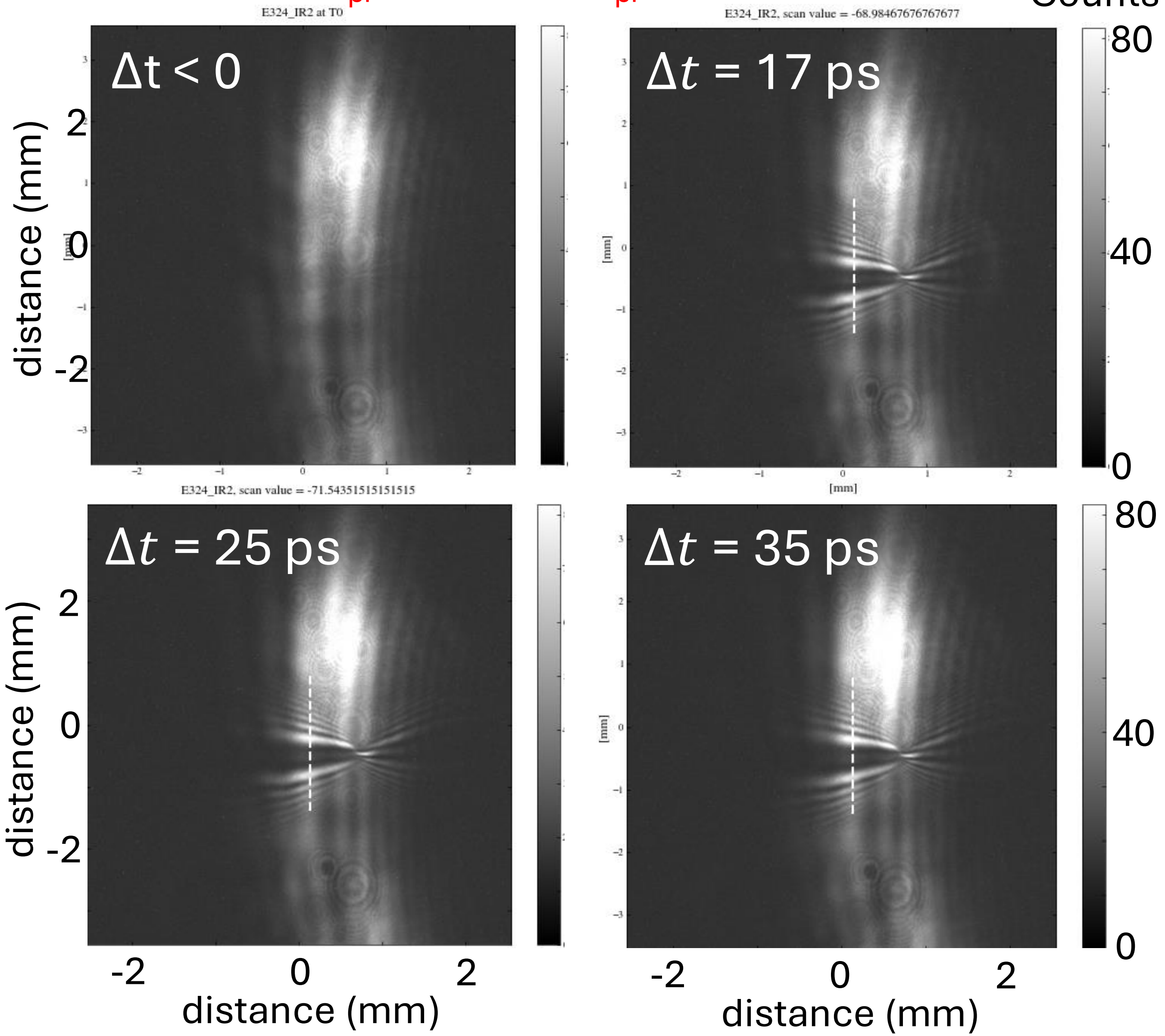
Data & Analysis in Hand II:

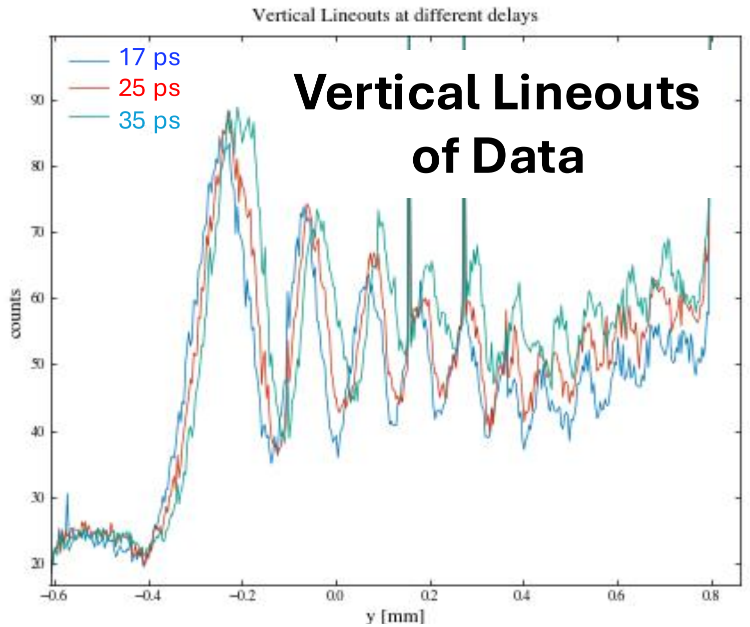
Grazing-angle shadowgraphy at $\Delta t < 35$ ps

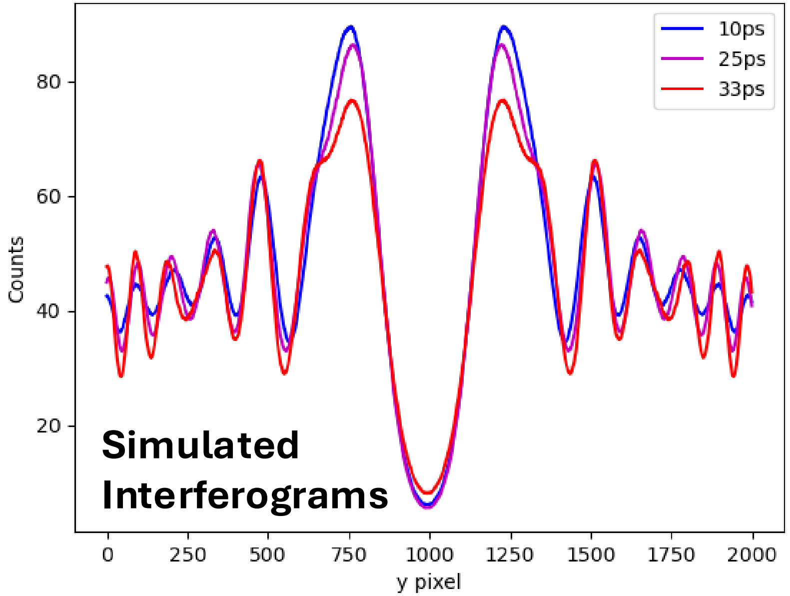


Timothy Araujo PhD student

λ_{pr} = 800 nm; θ_{pr} = 17 mrad

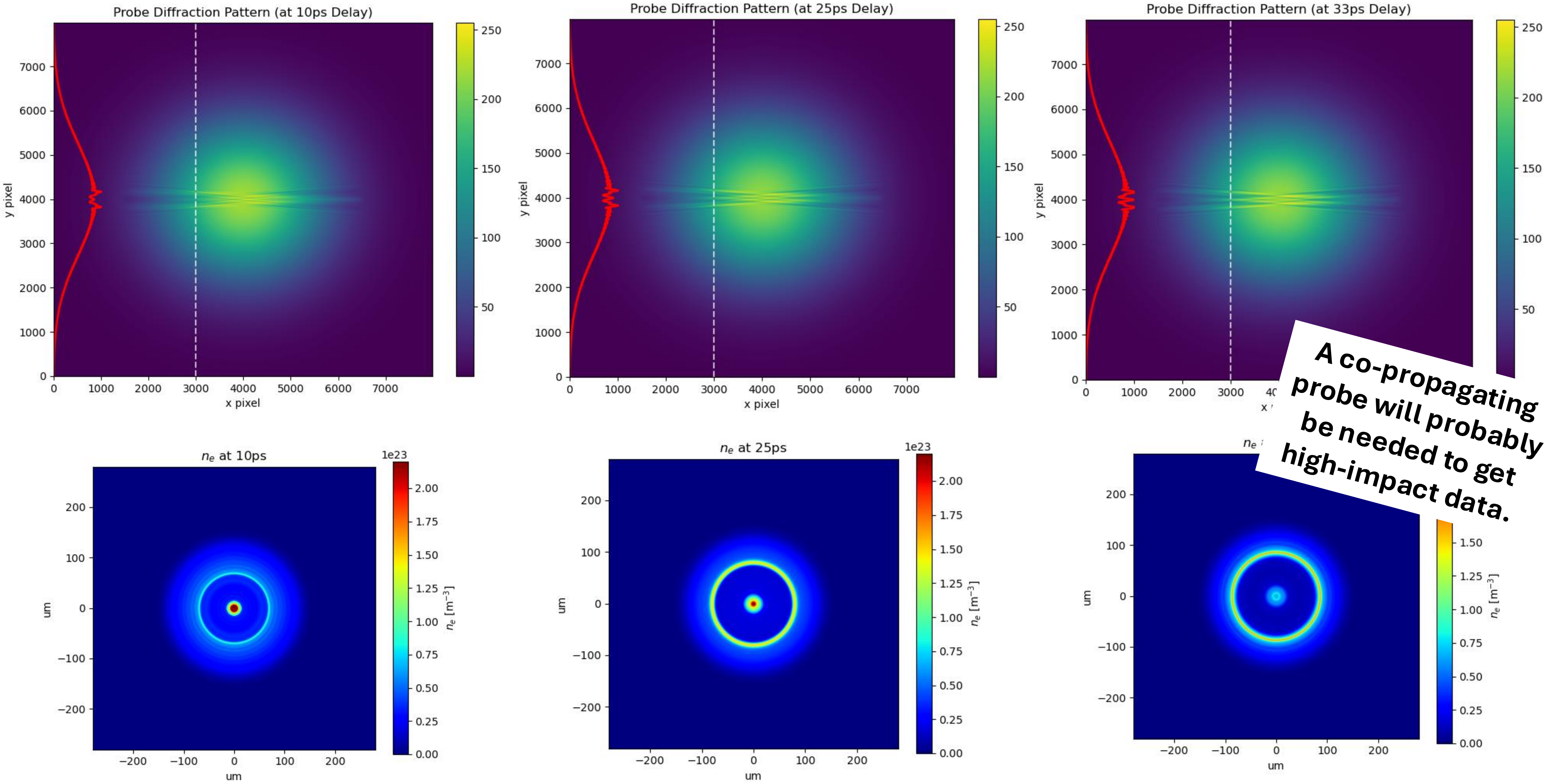






Simulated Grazing Angle Diffraction Patterns for θ_{pr} = 34 mrad and λ_{pr} = 400nm (H plasma)

(simulations by T. Araujo)

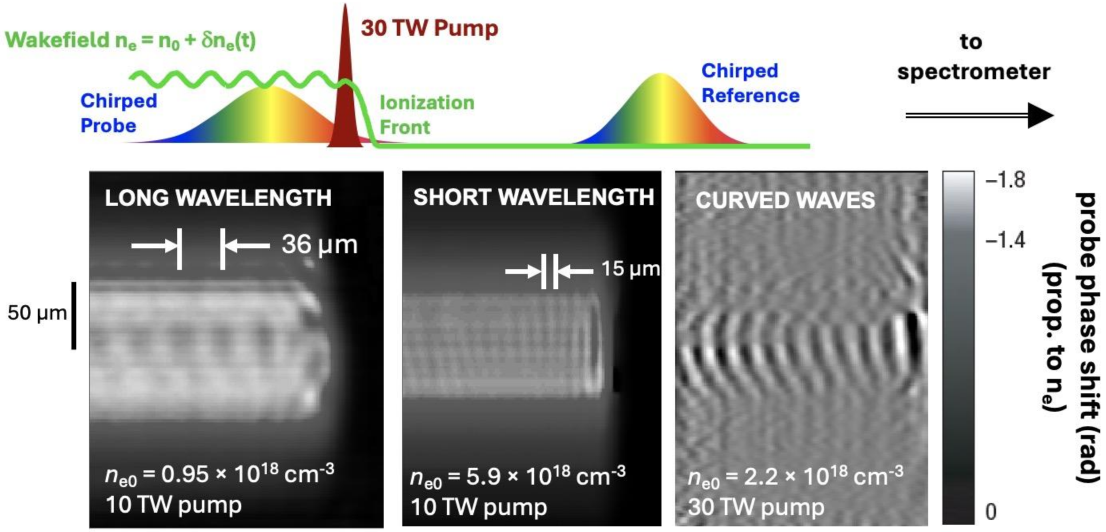


A co-propagating probe will probably be needed to get high-impact data.

Longitudinal Holography of Plasma Wakes

LWFA

Matlis *et al.*, *Nat. Phys.* **2**, 749 (2006)
Cowley *et al.*, *Phys. Rev. Lett.* **119**, 044802 (2017)



<u>Main problems</u>:

- **Forward pump scatter can pollute interferograms**

  ⇒ use $\lambda_{pr} \ll \lambda_{pu}$

- **probe de-phases from pump (& wake evolves) within mm: $v_{pr} < v_{pu} < c$**

⇒ experiments limited to **mm interaction lengths** to avoid "smearing" of wake structure, and thus to $\mathbf{n_e \gtrsim 10^{18}\ cm^{-3}}$

E-beam-driven PWFA

- **Stable wake structure over ~ meter path lengths**
- **No forward pump scatter**
- **Wake and probe propagate nearly at c ($v_{pr} \approx v_{pu} \approx c$)**

⇒ can probe stable wake at $n_e \approx 10^{16}$ cm^{-3} over tens of cm propagation lengths without "smearing"

BUT, new problems emerge:

- **Probe couples onto e-beam path via holed mirror**

  ⇒ annular pupil distorts probe profile downstream

- **Probe evolves over long interaction length**

  ⇒ Guoy phase further distorts probe profile

- **Co-propagating reference pulse requires unacceptably large $\Delta T_{pr\text{-}ref}$ (except for $\Delta t_{pu\text{-}pr} \lesssim 1$ ps)**

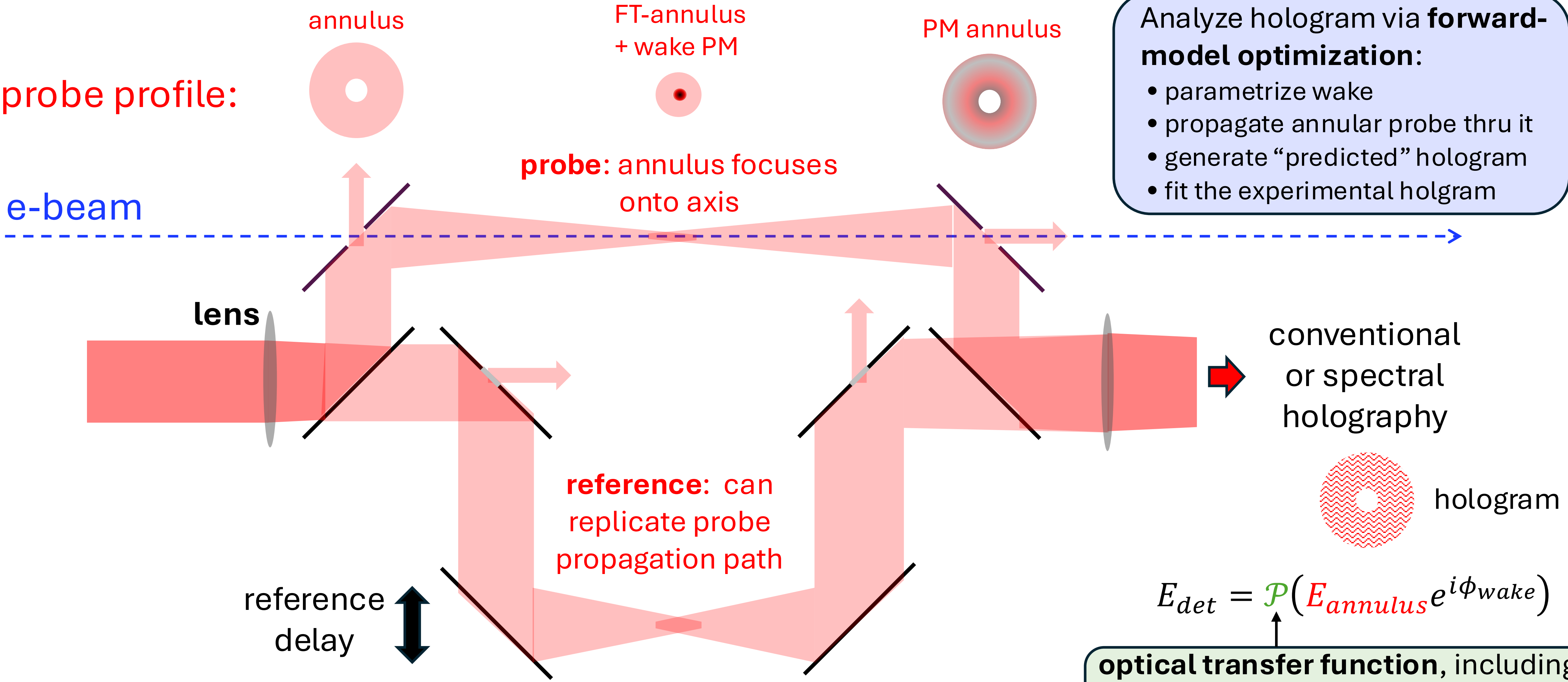
  ⇒ alignment harder than for Matlis-FDH

  ⇒ pr-ref interferogram harder than for Matlis-FDH

Solution #1: use grazing-incidence probe

(our FACET solution since 2019)

Solution #2: Computational (FD)H of e-beam-driven wakes



Analyze hologram via **forward-model optimization**:

- parametrize wake
- propagate annular probe thru it
- generate "predicted" hologram
- fit the experimental holgram

$$E_{det} = \mathcal{P}\left(E_{annulus} e^{i\phi_{wake}}\right)$$

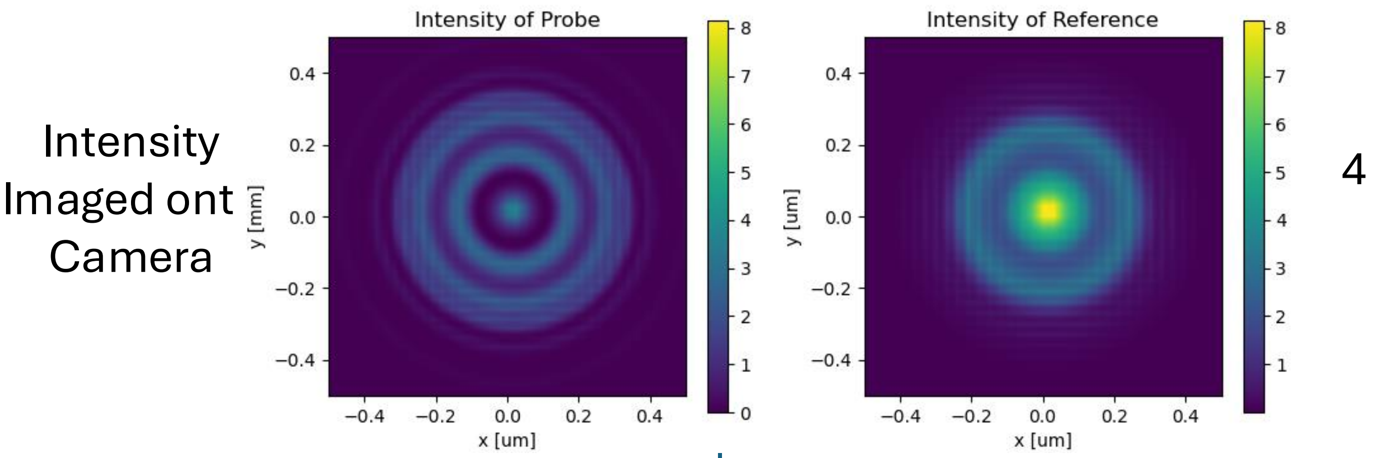
optical transfer function, including:

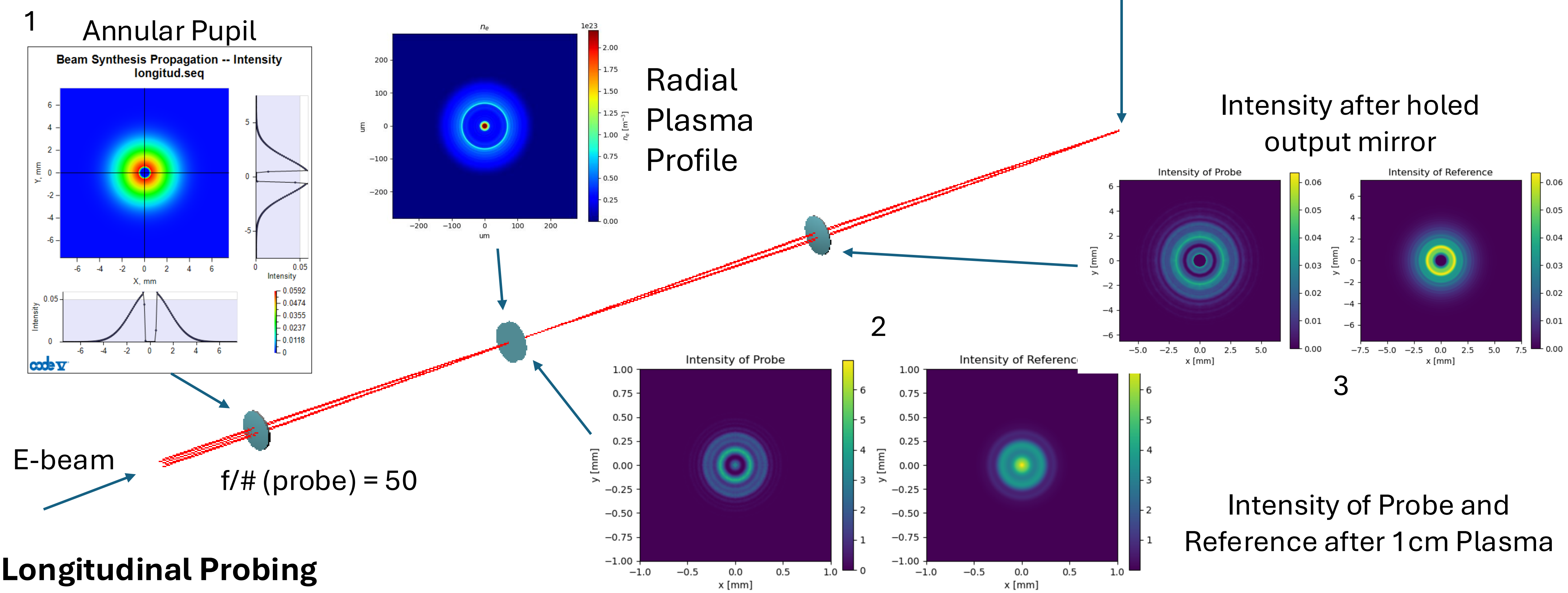
- annular illumination
- focusing, Guoy phase
- extraction thru holed mirror #2
- imaging optics & spectrometer

We are currently simulating this experiment.

Simulated evolution of transverse profile of longitudinal probe and reference coupled in with holed mirror then passing through radially structured plasma 1cm long

Transverse profile of reference & probe are shown at the indicated positions





Summary of E-324 needs

Goal	Request
Calibrate optical wake lifetime measurements for low drive-wake coupling used in DESY/INFN experiments.	Dedicated 1-2 day E-324 data run using grazing-incidence probe correlated with drive-beam energy loss measurements.
Systematic vessel termperature rise measurements at different rep rates up to 30 Hz.	Can be done parasitically with other projects.
Obtain scientifically impactful reconstructions of warm hollow channels ($\Delta t \sim$ tens of ps) and e-wakes ($\Delta t \lesssim 1$ ps).	Implement longitudinal (co-propagating) probe; 1-2 day dedicated E-324 data run with systematic Δt variation.*

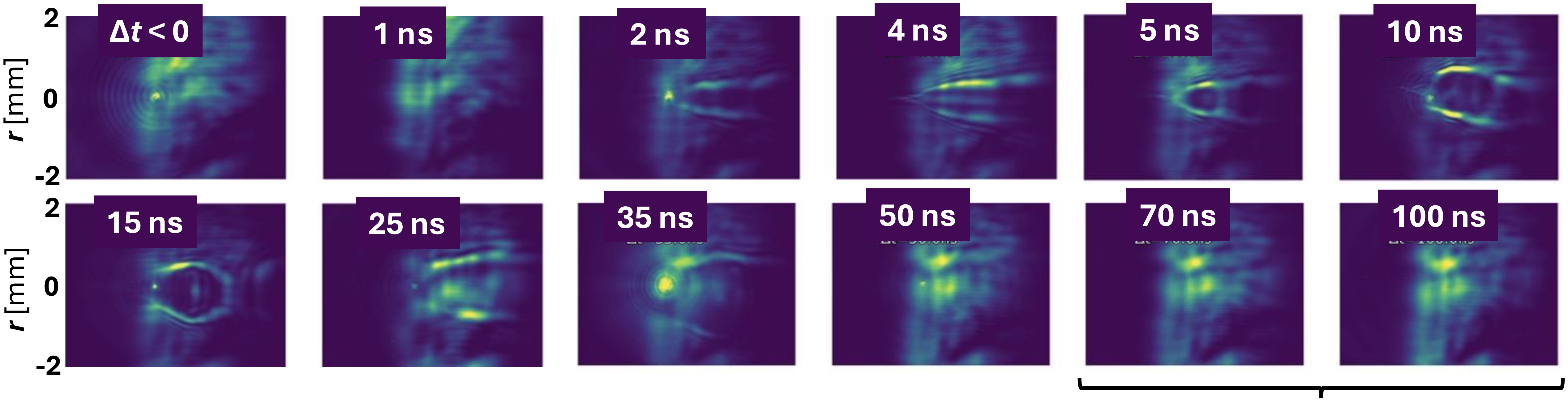
Thank you for your attention!

* pending successful completion of computational modeling of the proposed experiment.

END

We observed 5-6x faster ion wake evolution in H_2 plasma

3 Torr H_2 plasma, e-beam-ionized (June 16-17, 2024 run)



- Plasma structures no longer discernible for $\Delta t \geq 70$ ns

- Faster evolution consistent with ion motion governing plasma dynamics for $\Delta t \gtrsim 0.3$ n

* Zgadzaj *et al.*, *Nature Commun.* **11**, 4753 (2020).