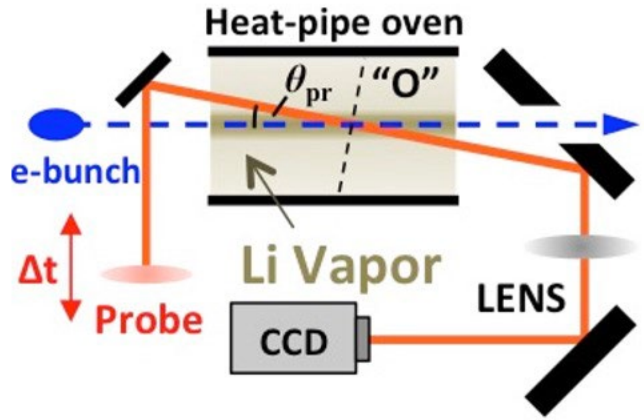
THE UNIVERSITY OF TEXAS AT AUSTIN

*FACET-II User's Meeting*
*October 18, 2023*




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


Project leaders: Rafal Zgadzaj & Mike Downer

Ph.D. students: Jason Brooks, Timothy Araujo


**E-224 publications**: 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).
[2] Chang *et al*., "Faraday rotation study of plasma bubbles in GeV wakefield accelerators," *PoP* **28**, 123105 (2021).
[1] Silva *et al*., "Stable positron acceleration in thin, warm, hollow plasma channels," *PRL* **127**, 104801 (2021)

**E-324 Goal**: **observe, analyze, understand *on-axis* PWFA structures** that were invisible to us in FACET-I, where the small $\theta_{pr}$ and $\Delta t$ (< 1.5 ns), and large $\lambda_{pr}$ (1 µm) prevented probe light from reaching them.

- 2024: µs, ms post-wake plasma recovery dynamics
- 2025: formation of warm, hollow plasma channels for $e^+$ acceleration[1]
- 2026: in-line visualization of PWFA accelerator structures[2]


**NSF support: PHY-2308921**, "Optical visualization of beam-driven plasma wakefield accelerators" (2023-26)

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SLAC NATIONAL ACCELERATOR LABORATORY

# In FACET-I we documented the first 1.5 ns of NL-wake → plasma energy-transfer physics

Zgadzaj et al., "Dissipation of e-beam-driven plasma wakes," *Nat. Commun.* **11**, 4753 (2020)

Khudyakov *et al*., "Ion dynamics driven by strongly nonlinear plasma wake," *PPCF* **64**, 045003 (2022).

OSIRIS[1] | LCODE[2]

[1] Fonseca, *PPCF* **55**, 124011 (2013)

[2] Lotov, *NIM*-A **829**, 350 (2016).

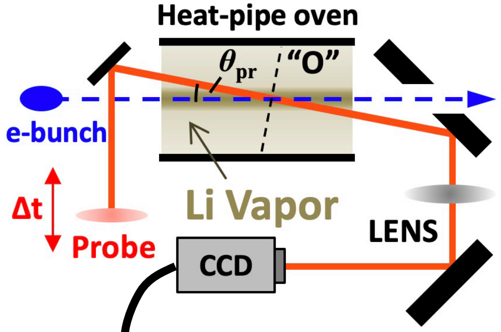
drive bunch → (< 1ps) → PWFA → (~10 ps) → wake breaks, ejects fast e⁻ → (10s ps) → on-axis ion-density structures form → (100s ps) → 10s keV ions stream radially outward → (1.5 ns) → ion-impact ionization → ?

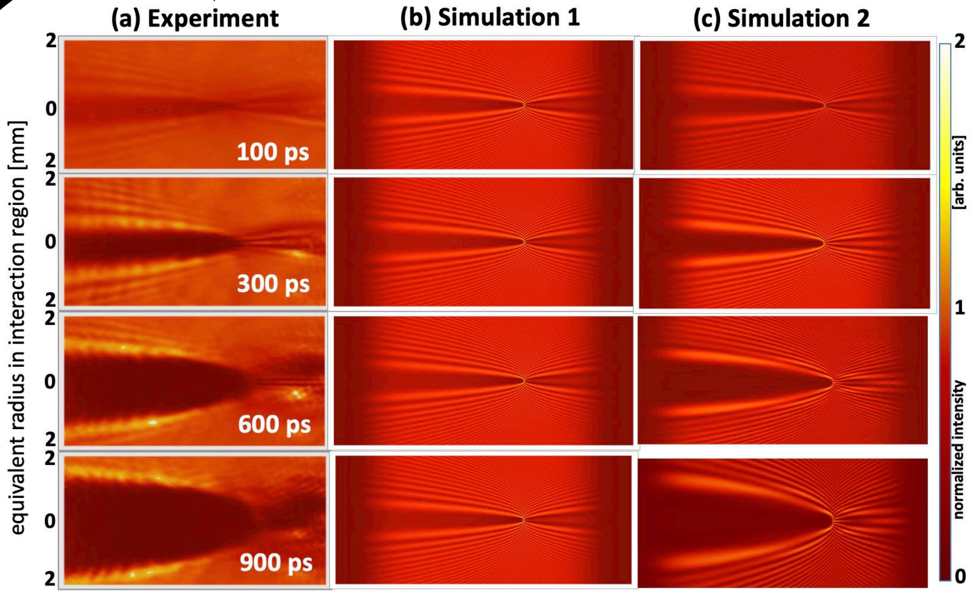
PWFA: 2026 expts

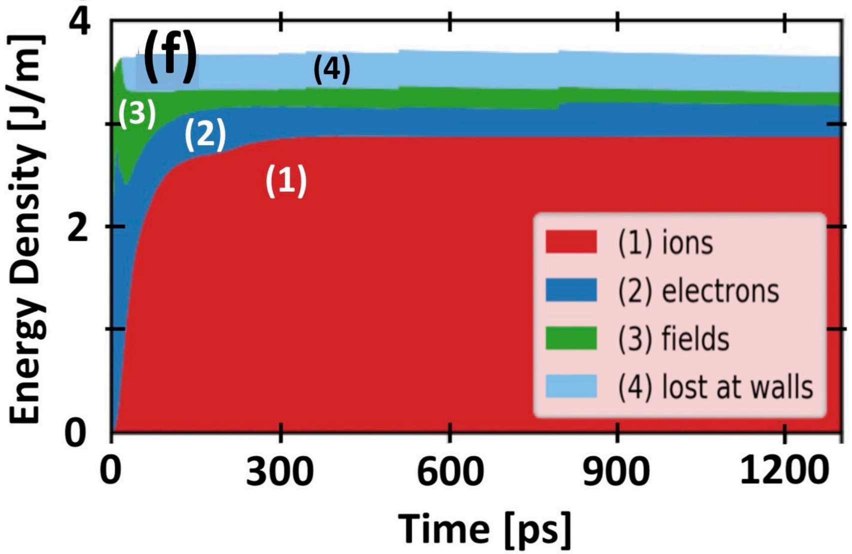
on-axis ion-density structures form: 2025 expts

100s ps to ion-impact ionization: Zgadzaj et al. FACET-I experiments

?: 2024 expts



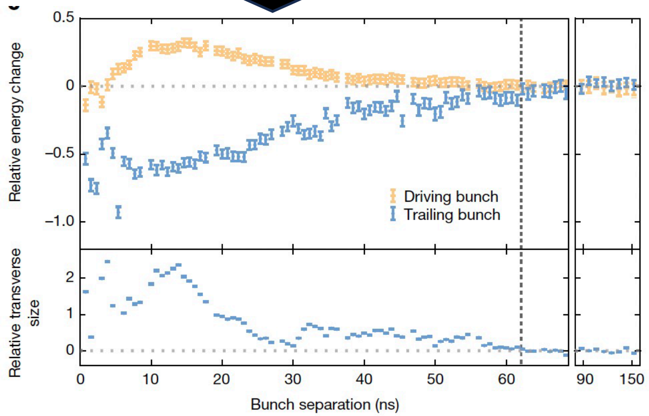



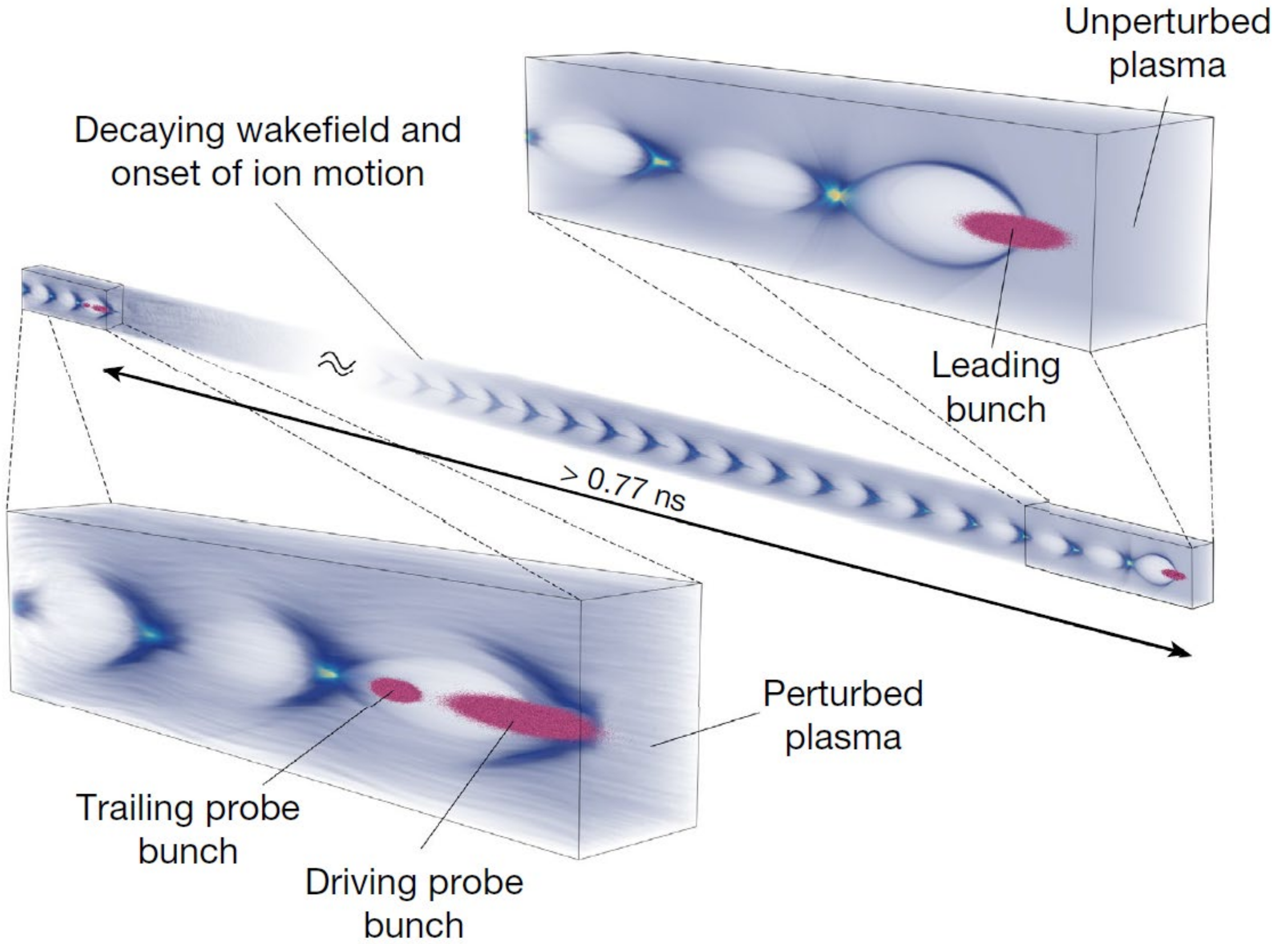
# A recent DESY experiment reported ~60 ns plasma recovery time (lower limit)

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

**FlashForward parameters:**

- drive bunch: 1 GeV, 0.5 nC
- plasma: 1.75 x $10^{16}$ $cm^{-3}$ Ar
- probe: secondary PWFA driver at 1 ns < $\Delta t$ ≤ 150 ns + trailing witness bunch
- "recovery" measured after single shots only. No account of cumulative plasma heating.



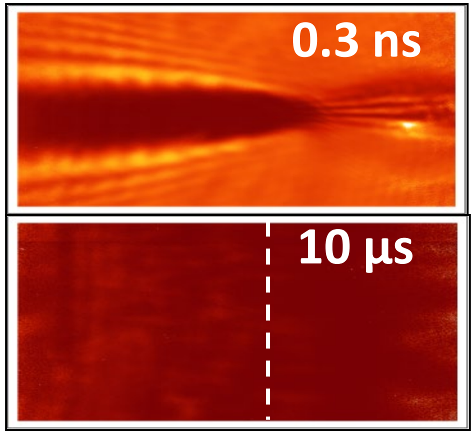

**FACET-II is uniquely positioned to resolve current orders-of-magnitude uncertainty in plasma recovery time**

**FACET-II parameters:**

- drive bunch: 10 GeV, 2 nC
- plasma: 1 x $10^{16}$ $cm^{-3}$ Li
- E-324 optical probe at 1 ns < Δt < ms
- Two SLAC observations:

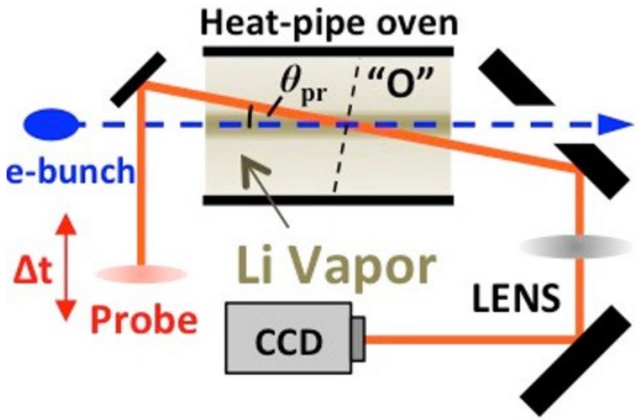
**a)** 20 GeV, 2 nC e-bunches @ 10 Hz heated Li oven tens °C within minutes.

**b)** "Hail Mary" E-224 result (Zgadaj, 2020):



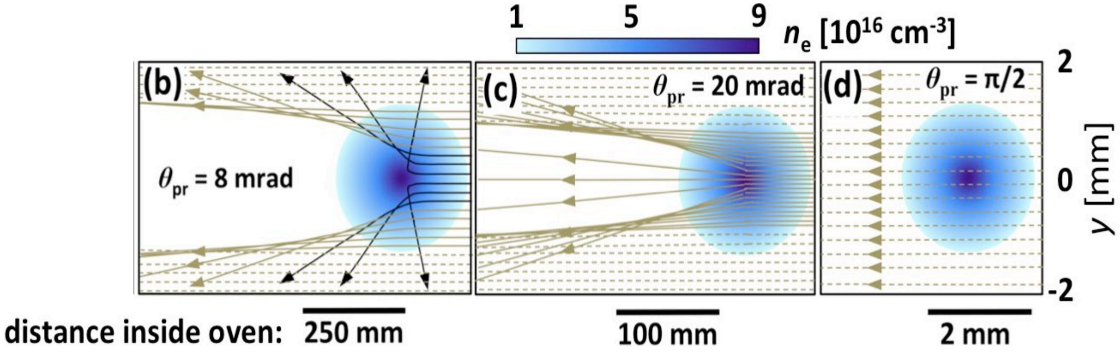
# Specific 2024 goals of E-324:

## things we didn't/couldn't do in E-224




1) Widen probe parameter range:

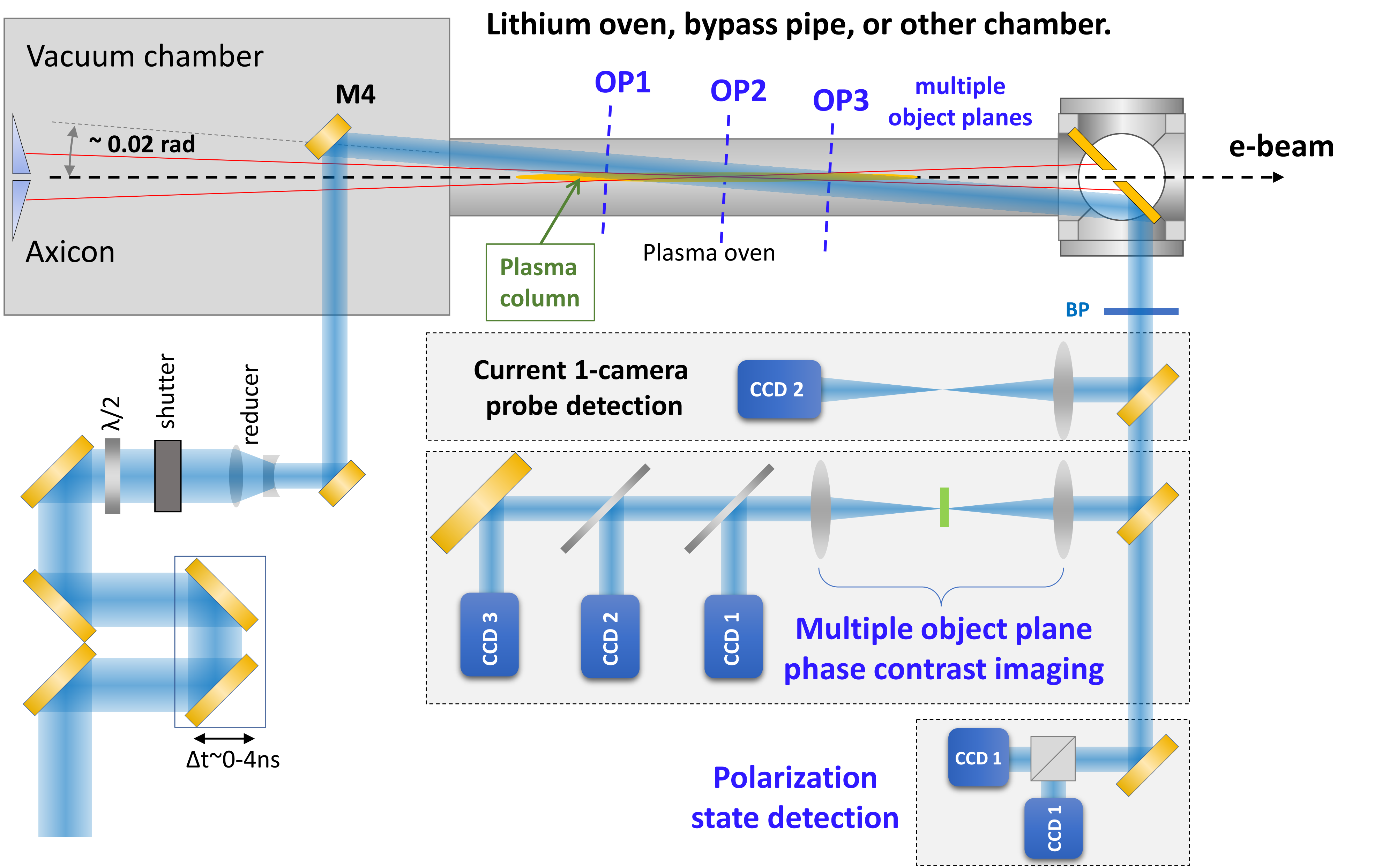
- $\Delta t_{pr}$: 1 ns → milliseconds (electronic delay)
  - observe plasma recovery dynamics
- $\theta_{pr}$: 8 → 20 mrad
  - enabled by shorter FACET-II pipe
  - deeper optical penetration into plasma column
- $\lambda_{pr}$: 1 → 0.5 µm
  - better spatial resolution
  - deeper penetration, observe two Δt's simultaneously, reduce lost probe light




2) Widen plasma excitation conditions

- Drive bunch only → drive + witness: observe reduced plasma heating due to witness acceleration
- Beam-ionized → laser pre-ionized plasma: enabled by 0.5 µm probe, issue in Nat. Comms reviews
- Single-bunch excitation → 10 Hz excitation: observe cumulative heating

# Experimental layout




**Probe pulse control**:

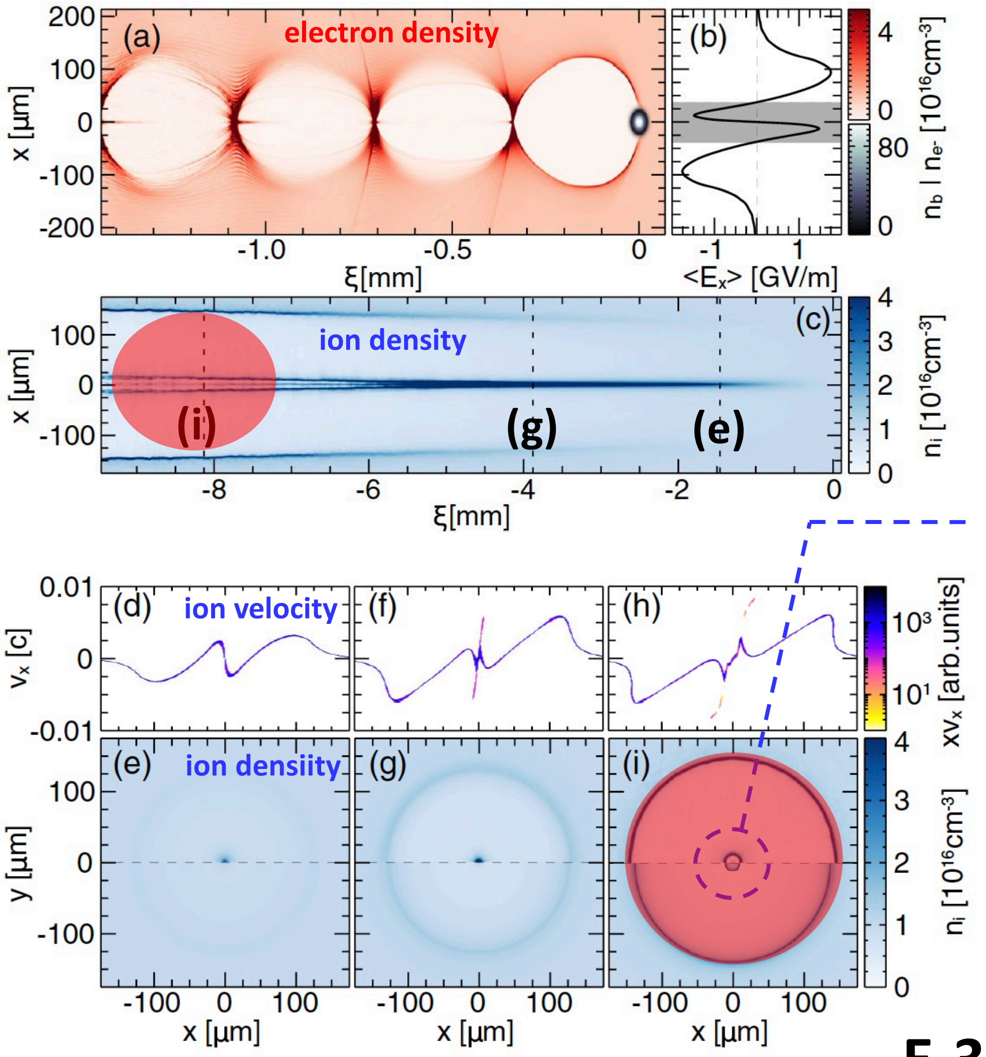
- time delay Δ*t*
- polarization
- beam size & shape
- color

# 2025: Thin, warm, hollow plasma channels for stable positron acceleration

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

Related work: Diedrichs, *Phys. Rev. Accel. Beams* **22**, 081301 (2019) + many others

3D OSIRIS simulations

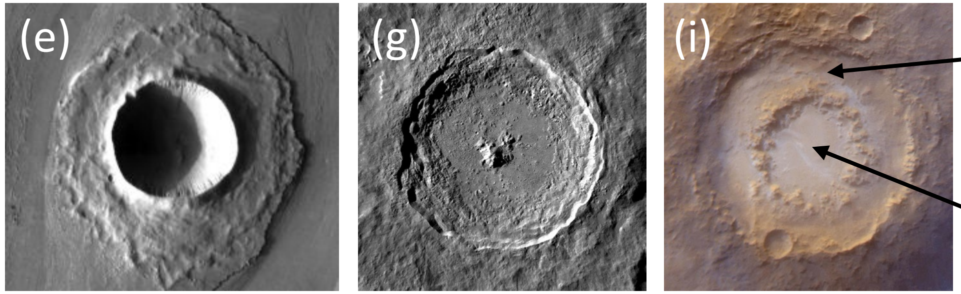



1) $e^-$ bunch (3 nC, 10 GeV, 10μm$^3$) or laser pulse generates nonlinear wake in $n_e = 10^{16}$ cm$^{-3}$ hydrogen plasma. Plasma $e^-$ warm to $2 < kT_e < 9$ keV, rendering them mobile.

2) Ponderomotive force of wake pulls some ions into axis, pushes others outward, forming 2 concentric hollow plasma channels.

3) Inner ($r \sim 10$ μm) hollow ion channel forms ~1 cm behind driver. Attracts & traps warm plasma $e^-$ → charges negatively → focusing force.

**simple crater** | **central peak crater** | **peak ring crater**




common | Tycho (earth moon) | Lowell (Mars)

generate NL wake filling outer channel

inject $e^+$ into inner channel

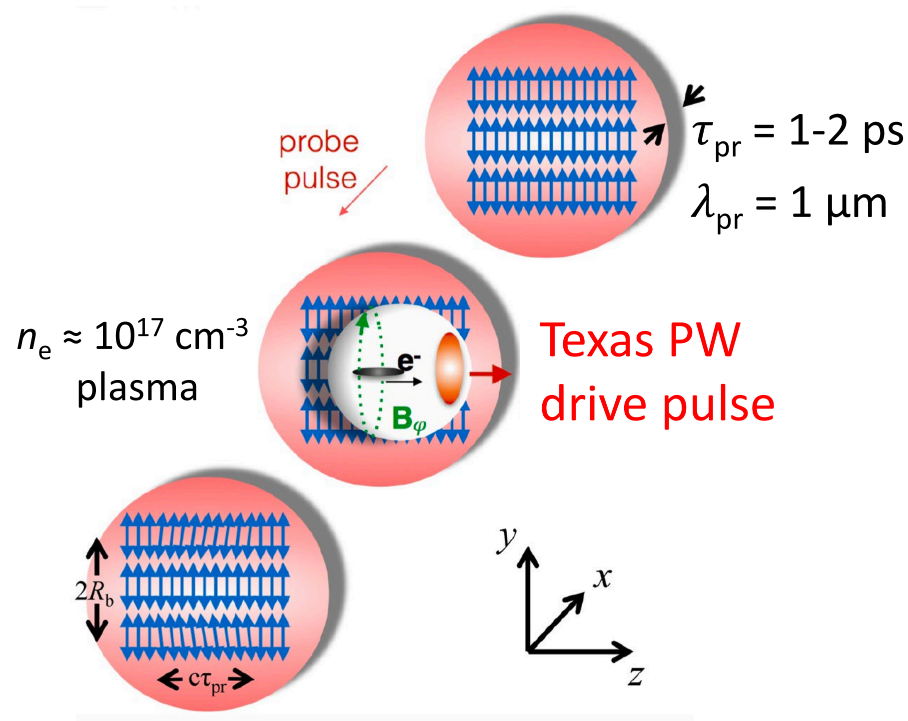
**E-324 is uniquely positioned to observe these ion channels**

# 2026: Faraday rotation to image plasma bubbles in low-$n_e$ plasma

Texas Petawatt

$n_e \approx 10^{17}$ cm$^{-3}$: [1] Chang *et al.*, "Faraday rotation study of plasma bubbles in GeV wakefield accelerators," *Phys. Plasmas* **28**, 123105 (2021)

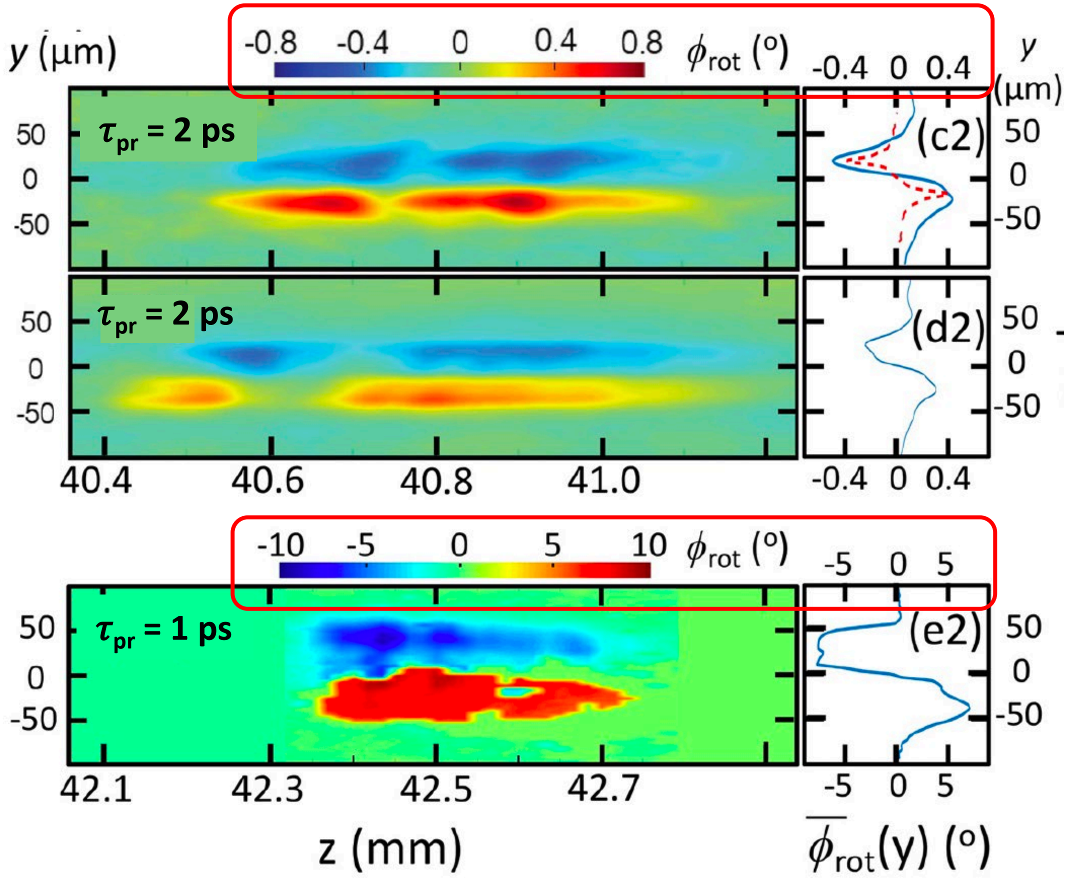
$n_e > 10^{19}$ cm$^{-3}$: [2] Kaluza *et al.*, *Phys. Rev. Lett.* **105**, 115002 (2010);
[3] Buck *et al.*, *Nat. Phys.* **7**, 453 (2011).




$$\phi_{rot} = \frac{e}{2m_e c n_{cr}^{(pr)}} \int_\ell n_e \mathbf{B}_\varphi \cdot d\mathbf{s}$$

large $\mathbf{B}_\varphi$ and $l$ compensate small $n_e/n_{cr}^{(pr)}$

## Faraday "streaks" of magnetized plasma bubble walls in $n_e \approx 10^{17}$ cm$^{-3}$ plasma




**At FACET-II, the drive bunch will magnetize the front end of the bubble.**

# Summary of plans for FACET II E-324

- **2024**: We will extend the study of long term evolution dynamics of post-wake plasma to ms-time scales, to establish full recovery time for a range of parameters.
- **2025**: We will visualize on-axis ion-wake and warm hollow channel structures at $\Delta t \sim 30$ ps, taking advantage of larger $\theta_{pr}$, higher-resolution imaging, lower $n_e$ than in FACET-I.
- **2026**: We will visualize e-wake structure & propagation dynamics at $\Delta t < 1$ ps, using magneto-optic probe techniques developed at UT-Austin.

NSF support: PHY-2308921, "Optical visualization of beam-driven plasma wakefield accelerators" (2023-26)

# Thank You for providing this unique facility!