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

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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)*
   • 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...


**IB-heated ion wakes**

(IB = Inverse Bremsstrahlung)

- cylindrical thermal shock

**Nonlinear-PWFA-seeded ion wake**

- ion acoustic wave

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

$$\left(\frac{1}{2}\right)\varepsilon_0 E_0^2 = \left(\frac{1}{2}\right)n_{e0}mc^2$$

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

- large 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:
  - $d\varepsilon/dt = 2U_p v_{ei}$

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

$U_p =$ ponderomotive energy

- radial position


... which drives subsequent ion wakes
Longitudinally asymmetric e⁻ wakes couple strongly to ion wakes with unique shapes


**IB heated ion wakes**
(IB = Inverse Bremsstrahlung)

- cylindrical thermal shock
- IB-heated filament

**Nonlinear-PWFA-seeded ion wake**

- ion acoustic wave

**Simulated ion wake at ∆t = 114.66 ps**
- e-bunch: $E_e = 20\text{GeV}$, $Q = 2\text{nC}$, $\varepsilon_N = 358 \text{ mm mrad}$
- plasma: $n_e = 5.3 \times 10^{17} \text{ cm}^{-3}$, axisymmetric, $R = 40\mu\text{m}$ hydrogen

- initial plasma profile

**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 $\Delta t < \sim 30$ ps.

• Strong ion wakes motivate use of auxiliary “energy recovery” laser pulses/e-bunches to cancel un-needed parts of wake.
  

• We remain interested in complementary simulation support from others!
Near-field transverse-probe diffraction distinguishes axial $n_e$ max & min


Filament electron density profiles

$\Delta n_e(r)$

$\Delta n(r) > 0$

$\Delta n(r) < 0$

$\Delta n_e(r)$

probe

$z$

$\Delta n_e(r)$

$\Delta n(r)$

$\Delta n_e(r)$

1st Fresnel zone
$d^2/z < 1$

Mixed max & min $\rightarrow$ low contrast, complicated diffraction pattern
At FACET, we imaged a continuous series of near-field diffraction patterns of an ion wake in a single shot.

Probe angle about 0.01 rad, interaction region 1.5 m

Compressed 800 nm pulse

20 GeV e-bunch

unperturbed probe profile

object plane

observed diffraction pattern (Δt = 100 ps)

simulated diffraction of axial $n_i$ maximum (Δt = 100 ps)

FACET-II Science Workshop Oct. 17-20, 2017
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 H₂. 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 consistent with simulations.
Fine-scale structure appears in simulated & measured diffraction patterns at $\Delta t > 80$ ps.
Multi-Plane Optical Diffractometry (M-POD) recovers transverse profile of filaments ... Abdollahpour, Phys. Rev. A 84, 053809 (2011)

Usually 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 x 10^{17} cm^{-3}

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


\[ \varepsilon_n = 30 \text{ mm mrad} \]

\[ 10 < \sigma_y(0) < 60 \mu m \]

H/He mixture

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

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

Electron beam

Initial beam vector

Δz

Plasma column

Characteristic attraction length

Δz_{attr}

beam propagation distance z (mm)

σ''(z)
E-224:

“Visualization of lepton-driven plasma wakefield accelerators”

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

Experiment

\[ \Delta \phi_{\text{probe}}(r, \zeta) \]

Simulation

\[ n_e(r, \zeta) \]

- Wave fronts curve relativistically
- Waves compress & break behind pump

Wakefield

\[ n_e = n_0 + d n_e(t) \]


Dong, NJP 12, 045016 (2010).

Simulation

\[ n_e = 3 \cdot 10^{18} \text{ cm}^{-3} \]
We’ve observed formation, propagation, collapse of plasma bubbles with an all-optical streak camera


Experimental Setup

(a) Experimental Results

Experimental Setup

z = 0:

jet

probe

bubble

θ

z = L:

phase streak

Experimental Results

(c) electron spectra

(d) 2.2e19 cm⁻³

10 nm bandwidth probe (as in experiment)

100 nm bandwidth probe (projected)

Experimental Setup

3 mm gas jet

pump

30 fs,

1 J

Experimental Results

probe phase shift (rad)

probe delay (fs)

50 MeV

75

100

50 MeV

75

100

z [mm]

z [mm]

Experimental Results

PIC Simulations

probe reference

electrons

8.6°

to spectrometer

Experimental Results

9
6
3
probe	
  phase	
  shia	
  (rad)

10

nm

bandwidth

probe (as in experiment)

100 nm bandwidth probe (projected)
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

• 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
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 bитеlecentric imaging yields better iterative reconstructions

- **Faraday rotation**
  - 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

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

Kerr phase shift $\psi = \psi_0 + i\alpha$ on unperturbed probe light

3. larger, aberration-corrected 4f 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

- Texas PW pump
  - 100 J, 150 fs
- 10 cm gas cell
  - \( n_{e0} = 5 \times 10^{17} \) cm\(^{-3}\)
- Anamorphic imaging
- Polarizer
- CCD

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

### Faraday rotation results

#### (a)
- Probe
- GeV electrons
- Drive laser
- Bubble

#### (b)
- Faraday rotation angle (°)
  - -0.4 -0.2 0 0.2 0.4
- Faraday rotation angle
- 50 μm
- 1 mm

**4 measurements**

- Separation of ± lobes: bubble size
- \( |\Delta \Phi_{\text{Faraday}}| \): bubble wall density
- Width of each lobe: bubble wall thickness
- Longitudinal variations: bubble evolution
Computerized tomography reconstructs movie from multiple phase streaks in \textit{one shot}...

Z. Li et al., \textit{Nature Commun.} 5, 3085 (2014)

3) Phase Streaks

4) Tomographic Reconstruction
Single-shot tomographic movies unravel the complex physics of filament formation in Kerr media

Propagation distance $z_{ob}$ into medium

<table>
<thead>
<tr>
<th>$z_{ob}$ [mm]</th>
<th>0.5 mm</th>
<th>1.0 mm</th>
<th>1.5 mm</th>
<th>2.0 mm</th>
<th>2.5 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ [µJ]</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

NLSE simulations

Nonlinear refractive index $\Delta n$

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 4fphase-contrast and Faraday rotation imaging, and tilted probe to reduce probe walk-off from e-wake to < λ_p.
  - 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)

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