High Quality fs LWFA Beams as Wakefield Probe and External Injector for FACETII

Wei Lu
Tsinghua University
FACETII Scientific Opportunity Meeting
Oct 17-19 2016 at SLAC
Outline

• $L^2PA$: the people, the mission, the facility

• Stable fs LWFA electrons as wakefield probe

• Generation of high quality LWFA beams

• LWFA beams as external injector at FACETII
Laboratory of Laser Plasma Physics and Advanced Accelerator Technology at Tsinghua University (L^2PA)

Yingchao Du
- Accelerator Physics

Jianfei Hua
- Laser-plasma acceleration

Wei Lu
- Laser Plasma Physics and Plasma Acceleration

Chih-Hao Pai
- Laser-plasma Interactions and acceleration

Jiaru Shi
- Accelerator Physics

Lixin Yan
- Accelerator Physics and THz Technology
Current Research Focus

Key physics of high-quality plasma based accelerators

Stable and efficient acceleration structure
- Matched self-guiding, all-optical channel generation, channel assisted matched guiding, arbitrary plasma structures...

High quality controlled injection and 6D phase space manipulation
- Ultralow emittance, high brightness, high charge and current, low energy spread, short pulse duration, controllable profile, phase space matching...

Diagnostics of beams with special space and time structures
- Ultralow emittance, low energy spread, phase space structures...

Diagnostics for acceleration structure and dynamic processes
- Optical probe, electron probe ...
Advanced Acceleration Platform at Tsinghua

40TW Laser + 45MeV Linac

1.4~1.5 J
60 nm

45MeV Linac
National Central University (NCU) 100TW Multi-Beams Facility (led by Prof. Jypying Wang)
Motivation: Detailed mapping of the field structure and its dynamics in low density plasma wakes is highly demanded. But how?

Our solution: Femtosecond Relativistic Electron Probe.

- Concept
- Theory and Simulations
- First Experimental demonstration
- Wakes in a rising density ramp

Conclusion
Why is it important to map the field structure and its dynamics of low density plasma wakes?

1. **Field structure** is critical for achieving high efficiency, high quality acceleration of electron and positron beams.

2. Need to study wakefield dynamics for controllable injection of high quality beams, beam matching and staging.

3. The plasma density goes to $10^{17}$ cm$^{-3}$ for building a 10-GeV single stage plasma based accelerator.
Probing plasma wakes using optical methods

Frequency domain interferometry

Z. Y. Li et al., Nat Commun (2014)

ultrafast shadowgraphy

A. Buck et al., Nat Phys 7, 543–548 (2011)
Probing plasma wakes using optical methods

Frequency domain interferometry

ultrafast shadowgraphy

No field structures
Not yet demonstrated at low densities

Z. Y. Li et al., Nat Commun (2014)

A. Buck et al., Nat Phys 7, 543–548 (2011)
Femtosecond Relativistic Electron Probe

Conceptual illustration of FREP:

- Laser
- e beam
- Wakefield
- Snapshot of the wakefield
Solution: Femtosecond Relativistic Electron Probe

Conceptual illustration of FREP:

Why is it difficult?
1. it is microscopic
2. light speed moving
3. transient
4. intense field
Solution: Femtosecond Relativistic Electron Probe

Conceptual illustration of FREP:

Why is it difficult?
1. it is microscopic
2. light speed moving
3. transient
4. intense field

Requires the probe to be:
1. high energy (>50 MeV)
2. ultrashort (~fs)
3. well synchronised
Motivation: Detailed mapping of the field structure and its dynamics in low density plasma wakes is highly demanded. But how?

Our solution: Femtosecond Relativistic Electron Probe.

- Concept
- Theory and simulations
- First Experimental demonstration
- Wakes in a rising density ramp

Conclusion
How does FREP work?
How does FREP work?

\[ \frac{\partial I}{\partial z} = \kappa K_m \nabla^2 \int_{-s}^{s} E'_z(r, z) dx \]

\[ \frac{\partial I}{\partial y} = \kappa K_m \nabla^2 \int_{-s}^{s} \frac{y}{r} E'_r(r, z) dx \]

Density modulation of the probe

C. J. Zhang et al., Sci Reports 6, 29485 (2016)
Simulation results (linear wakes)

**plasma density in simulation**

**probe density on the screen**

**reconstructed $E_z$ field**

**reconstructed $E_r$ field**

**simulation parameters:**
- $n_p=1.1 \times 10^{17}$ cm$^{-3}$, $n_b=0.05 n_p$.  
- $\sigma_z=20$ µm, $\sigma_r=17.8$ µm.  
- $\tau=7$ fs, $E=200$ MeV, $\Delta E=0$, $\varepsilon=0$.

**axial lineout of $E_z$**

**radial lineout of $E_z$**

**radial lineout of $E_r$**

C. J. Zhang et al., Sci Reports 6, 29485 (2016)
Simulation results (nonlinear wakes)

plasma density in simulation

probe density on the screen

Reconstructed and Simulated $E_z$

Reconstructed and Simulated $E_r$

axial lineout of $E_z$

radial lineout of $E_z$

radial lineout of $E_r$

C. J. Zhang et al., Sci Reports 6, 29485 (2016)
Tolerance on probe pulse length, energy spread and emittance (correlated divergence)

C. J. Zhang et al., Sci Reports 6, 29485 (2016)
Probing down-ramp injection using realistic beams

Imaging down ramp injection using a realistic probe (τ=30 fs, E=200 MeV, ΔE=10%, ε_g=2.5 μm)

C. J. Zhang et al., Sci Reports 6, 29485 (2016)
FREP also works for positron-driven wakes
Outline

Motivation: Detailed mapping of the field structure and its dynamics in low density plasma wakes is highly demanded. But how?

Our solution: Femtosecond Relativistic Electron Probe.
  -> Concept
  -> Theory and simulations
  -> First experimental demonstration
  -> Wakes in a rising density ramp

Conclusion
The experiment was carried out using the 100 TW laser platform at National Central University, Taiwan.

Experiment setup

The experiment was carried out using the 100 TW laser platform at National Central University, Taiwan.

The experiment was carried out using the 100 TW laser platform at National Central University, Taiwan.

The experiment was carried out using the 100 TW laser platform at National Central University, Taiwan.

Stable electron beams

beam profile:

energy spectra:

Energy 60-80 MeV, ΔE/E~20%

horizontal: 2.1 mrad  vertical: 1.7 mrad

Charge: 2-10 pC

Pulse duration: ~4.2 fs (FWHM)

Quantitative reconstruction of the field structure

Theoretical model for wakefield reconstruction:  

\[
\frac{\partial I}{\partial z} = \kappa K_m \nabla^2 \int_{-s}^{s} E'_z(r, z) \, dx
\]

\[
\frac{\partial I}{\partial y} = \kappa K_m \nabla^2 \int_{-s}^{s} \frac{y}{r} E'_r(r, z) \, dx
\]

C. J. Zhang et al., Sci Reports 6, 29485 (2016)
Quantitative reconstruction of wakefield structure

1. Very good agreement between the measurement and the simulation.
2. The peak $E_z$ is $\sim 1$ GeV/m in this experiment.
3. Sinusoidal form of the $E_z$ field.
4. $r \times \exp(-r^2/\sigma^2)$ form of the $E_r$ field.
5. The +/-8-µm linear portion of the $E_y$ field is critical for preserving the emittance of accelerating electrons and positrons.

First measurement of the field structures in a plasma wake!

This technique also works for nonlinear wakes! (simulation)
Motivation: Detailed mapping of the field structure and its dynamics in low density plasma wakes is highly demanded. But how?

Our solution: Femtosecond Relativistic Electron Probe.
   -> Concept
   -> Theory and simulations
   -> First experimental demonstration
   -> Wakes in a rising density ramp

Conclusion
Characterising wakes produced in density ramps

Upramps for increasing the dephasing length in a LWFA:


Downramps for injection:


Detailed characterising of wakes in density ramps has not been done with existing methods.

Beam matching

T. Mehrling et al., PRSTAB (2012)
Wake evolution in a density upramp

\[
\begin{align*}
t_0 & \quad \text{(initial)} \\
t_0 + 0.77 \text{ ps} \\
t_0 + 1.54 \text{ ps} \\
t_0 + 2.31 \text{ ps} \\
t_0 + 3.08 \text{ ps} \\
t_0 + 3.85 \text{ ps} \\
t_0 + 4.62 \text{ ps} \\
t_0 + 5.40 \text{ ps}
\end{align*}
\]

Reconstructed 
\( E_z \)
Wake evolution in a density upramp

After the laser has gone, the plasma continues to oscillate at its local frequency $\omega_p(z)$. The phase of the wave is:

$$\phi = \omega_p(z)(t - z/v_d)$$

$$\omega(z,t) \equiv \frac{\partial \phi}{\partial t} = \omega_p(z)$$

$$k(z,t) \equiv -\frac{\partial \phi}{\partial z} = k_p(z) - \frac{\partial \omega_p}{\partial z} t$$

Then we have:

$$-\frac{\partial k}{\partial t} = \frac{\partial \omega_p}{\partial z}$$
Wake evolution in a density upramp

After the laser has gone, the plasma continues to oscillate at its local frequency $\omega_p(z)$. The phase of the wave is:

$$\phi = \omega_p(z)(t - z/v_d)$$

$$\omega(z, t) \equiv \frac{\partial \phi}{\partial t} = \omega_p(z)$$

$$k(z, t) \equiv -\frac{\partial \phi}{\partial z} = k_p(z) - \frac{\partial \omega_p}{\partial z} t$$

Then we have:

$$-\frac{\partial k}{\partial t} = \frac{\partial \omega_p}{\partial z}$$
Wake evolution in a density upramp

After the laser has gone, the plasma continues to oscillate at its local frequency $\omega_p(z)$. The phase of the wave is:

$$\phi = \omega_p(z)(t - z/v_d)$$

$$\omega(z, t) \equiv \frac{\partial \phi}{\partial t} = \omega_p(z)$$

$$k(z, t) \equiv -\frac{\partial \phi}{\partial z} = k_p(z) - \frac{\partial \omega_p}{\partial z} t$$

Then we have:

$$-\frac{\partial k}{\partial t} = \frac{\partial \omega_p}{\partial z}$$
Mapping the profile of a low-density up-ramp
Mapping the profile of a low-density up-ramp
Snapshots of non-ideal wakes
The Feasibility of LWFA probe at FACETII

- With currently available laser (or with minor upgrade), this technique can be relatively simple to implement.

- The laser better has a 30fs short pulse duration with 500mJ or 1J on the gas target, and with good pointing stability.

- Gas targets with open boundary or with thin windows need to be used for PWFA for this tool to be used.

- Synchronization between laser and electron beam driver should be better than few 100fs to get good time resolution.
In a time frame of about 3 years, it can be expected that stable high quality fs electron beams can be relatively easy to obtained:

• 100-500MeV (using a 0.3-2J 30fs laser)
• fs pulse duration (from 0.1-10fs)
• 1-100pC of charge
• high peak current: ~1-10kA
• 0.5-2% energy spread
• small emittance: ~0.1-1 mm mrad
• stable beams (with a stable laser)
Very low energy spread (absolute and relative) electron beams via LWFA

10-40MeV pC, dark current free mono-energetic electron beam generation by a 60fs 5TW laser

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>27.6</td>
<td>0.53</td>
<td>1.9%</td>
<td>5.6</td>
</tr>
<tr>
<td>25.7</td>
<td>0.77</td>
<td>3.0%</td>
<td>2.3</td>
</tr>
<tr>
<td>22.1</td>
<td>0.18</td>
<td>0.8%</td>
<td>3</td>
</tr>
<tr>
<td>21.0</td>
<td>0.87</td>
<td>4.2%</td>
<td>5.8</td>
</tr>
<tr>
<td>17.5</td>
<td>0.20</td>
<td>1.1%</td>
<td>4.6</td>
</tr>
<tr>
<td>16.5</td>
<td>0.53</td>
<td>3.2%</td>
<td>3.1</td>
</tr>
<tr>
<td>14.7</td>
<td>0.45</td>
<td>3.1%</td>
<td>5.5</td>
</tr>
<tr>
<td>14.3</td>
<td>0.39</td>
<td>2.7%</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Acceptance of Slit: 8.6mrad
**300-430 MeV low energy spread (2-5%) electron beams using a 36fs 50TW laser at NCU**

<table>
<thead>
<tr>
<th>Energy (MeV)</th>
<th>RMS energy spread</th>
<th>Charge (pC)</th>
<th>Divergence angle (mrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>265</td>
<td>2.1%</td>
<td>4.9</td>
<td>1.3</td>
</tr>
<tr>
<td>334</td>
<td>2.3%</td>
<td>0.89</td>
<td>0.83</td>
</tr>
<tr>
<td>367</td>
<td>5.2%</td>
<td>3.4</td>
<td>1.0</td>
</tr>
<tr>
<td>377</td>
<td>5.5%</td>
<td>11</td>
<td>1.6</td>
</tr>
<tr>
<td>408</td>
<td>2.3%</td>
<td>2.3</td>
<td>1.0</td>
</tr>
<tr>
<td>435</td>
<td>3.6%</td>
<td>0.96</td>
<td>1.6</td>
</tr>
</tbody>
</table>

\[ \Delta E [\text{GeV}] \approx 1.7 \left( \frac{P [\text{TW}]}{100} \right)^{1/3} \left( \frac{10^{18}}{n_p [\text{cm}^{-3}]} \right)^{2/3} \left( \frac{0.8}{\lambda_0 [\mu m]} \right)^{4/3} = 0.45 \]

Laser Parameters:
- Pulse Energy: ~2J
- Pulse Duration: 36fs
- Laser Focal spot: 4mm He jet
- \( N_e = 5.6 \times 10^{18} \text{ cm}^{-3} \)

LWFA Electron Beams as Option of External Injector at FACET II

Advantages:
- Short pulse with high current: good for beam loading
- Large energy chirp: could be good for energy spread reduction
- Compact and relatively cheap

Challenges:
- Matching between the injector and the PWFA stage
- Timing jitter between laser and electron beam
Longitudinally tailored plasma density profiles

- Linear focusing forces from nonlinear wakes
- Control phase space matching between sections with negligible emittance growth
- Match the initial $\beta_i$ of the bunch to the $\beta_{\text{goal}}$ of the PBA
- Transport the bunch from its waist ($\alpha_i = 0$) at 1st stage to another waist ($\alpha_{\text{goal}} = 0$) at the end of the matching section

Parameters for exact matching

\[ l = \beta_{p0} \sqrt{\left[ \frac{(N + 1)\pi}{\ln \beta_{\text{goal}}/\beta_i} \right]^2 + \frac{1}{4}}, \quad \frac{L}{l} = \left( \frac{\beta_{\text{goal}}}{\beta_i} - 1 \right) \]
Two possible Schemes for matching

- Density down and up ramps in-between at mm-cm distance:
  - need combined design of plasma target with very different density:

- Adding PMQs in between to increase the distance between injector and PWFA stage:
  - could be tested in small facility independently
  - PWFA driver going through PMQs
One Possible Method: laser machined plasma structure

The machining pulse plays both the roles of ionizing the gas through optical-field ionization and heating the plasma

Experimental result of Plasma structures

Intensity of machining beam with mask

\[ n_e = 6 \times 10^{18} \text{cm}^{-3} \text{ at 300psi, 1200\mu m, H}_2 \]

Gas jet’s side scattering images
(The minimal laser energy: 15mJ)

OAP: \( f=30\text{cm}; \ d=5\text{cm} \)
CL1, CL2: \( f=25\text{cm} \)

Latest results in 2015

Periodic length: 237\text{um}
Works need to do to evaluate the feasibility

• Proper designs for short (mm-cm) plasma matching stage

• Independent tests of matching through plasma ramps and PMQs
Thanks for your attentions!