External Injection experiment: first accelerated beam

Jianfei Hua

Tsinghua University

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Acknowledgements

Laboratory of Laser Plasma Physics and Advanced Accelerator Technology

Collaborators

Zheng Zhou, Yingchao Du, Lixin Yan, Jiaru Shi, Chuanxiang Tang

Hsu-Hsin Chu and Jypyng Wang

Weiming An, Chaojie Zhang, Fei Li, Zan Nie, Warren Mori, Chan Joshi

Zhen Wang, Xingtao Wang, Bo Liu, Zhentang Zhao

Dou Wang, Dazhang Li, Jie Gao

Xinlu Xu, Mark Hogan

Yang Wan, Victor Malka
Outline

- External injection from a Linac into a LWFA with ~100% capture efficiency
- Plasma dechriper to achieve 0.1% energy spread
- Ultra-compact turnkey laser development
- High energy plasma based injector for CEPC
- Summary
Two milestones for external injection

Capture efficiency: ~3.5%

Injected charge: ~35pC

Accelerated charge: 1.2pC

Two milestones for external injection


Injected charge: ~650pC

Capture efficiency: <0.1%

Accelerated charge: 0.25pC
Demonstration of external injection

- External injection from a Linac to a LWFA
- Subsequent acceleration
- ~100% capture efficiency

Key challenges

- Ultrashort beam generation ($<\lambda_p$) ~13fs
- Size matching (tightly focused E beam $\sim w_0$) ~20μm
- Synchronization between beam and laser ($<\lambda_p$) ~100fs
- Phase space matching
- Vacuum isolation between Linac and LWFA
- Robust plasma source based on laser ionization
Experimental layout for external injection

**Electron**
- Trans. size: $\sigma_r \sim 20\mu m$
- Bunch length: $\sigma_z \sim 13 fs$
- Charge: 20fC
- Energy: 31.3MeV

**Laser**
- Enclosed Power: 9TW
- Duration: 40fs
- Focus size (FWHM): 12$\mu$m

**Plasma**
- Density: $10^{17} - 10^{18} cm^{-3}$
- Length: 6mm
Achievement of external injection acceleration from a Linac to a LWFA

Focus location:
\[ z_f = -4.5 \text{mm} \]

Density: \( 6 \times 10^{17} \text{cm}^{-3} \)

Jitter: \( \sim 100 \text{fs (rms)} \)

Wavelength: 140fs

unpublished
Achievement of external injection acceleration from a Linac to a LWFA

Focus location: $z_f = -4.5\text{mm}$
Density: $6 \times 10^{17}\text{cm}^{-3}$

Jitter: $\sim 100\text{fs (rms)}$
Wavelength: $140\text{fs}$

Gain: $1.11\text{MeV} (\sim 1.5\text{MeV}) \text{ average(max.)}$

Decel. phase

Unpublished
Two crucial parameters for gain and efficiency:

- **Focus location**: $z_f = -4.5\text{mm}$
- **Density**: $6 \times 10^{17}\text{cm}^{-3}$
Effect of laser focus location

$E_z \propto a_0^2 k_p^2 \exp(-2r^2/w^2)$

Location of focus $z_f$

Beam size $a_0$

Energy gain

$z_f = -3.5 \text{ mm}$
$1.45 \text{ MeV}$

$z_f = -4.5 \text{ mm}$
$1.11 \text{ MeV}$

$z_f = -5.5 \text{ mm}$
$0.77 \text{ MeV}$

unpublished
The plasma density dependent energy gain

\[ E_z \propto a_0^2 k_p^2 \exp(-2r^2/w^2) \]

- Energy gain \( \propto n_p \)
- Lower density: Wavelength \( \uparrow \) Energy spread

\[ 6 \times 10^{17} \text{ cm}^{-3} \]
\[ 0.77 \text{ MeV} \]
\[ 2 \times 10^{17} \text{ cm}^{-3} \]
\[ 0.26 \text{ MeV} \]
How to improve capture efficiency?

- Size matching between wakefield and electron beam
  - Tight beam focusing
  - Large laser spot size

\( z_f \): Location of laser focus

![Plasma density profile](image)

![Graphs](image)
Non-optimized capture efficiency

Low capture efficiency

$z_f = -1.5 \text{ mm, } n_p = 6 \times 10^{17} \text{ cm}^{-3}$
Phase space dynamics

Transverse wakefield:

\[ E_r - B_\theta \propto (4a_0^2 k_p r / w^2) \exp(-2r^2 / w^2) \sin(k_p \xi) \]

- Linear in \( r \) in the beam region
- Preserve the slice emittance
- Rotation of slice phase ellipses

Projected emittance growth

\( z_f = -3.5 \text{mm}, \text{Density}=6 \times 10^{17} \text{cm}^{-3} \)
Emittance precompensation by up-ramp

**Up-ramp:**
\[ \frac{\partial (E_r - cB_\theta)}{\partial \xi} > 0 \]

**Plasma plateau:**
\[ \frac{\partial (E_r - cB_\theta)}{\partial \xi} < 0 \]

Reverse the rotation direction of transverse phase space

Compensated by the long plasma up-ramp for the accumulated phase differences in the plasma plateau
Emittance evolutions with or without up-ramp unpublished
3D PIC simulation for high efficiency acceleration

Simulated laser-excited longitudinal wakefields
Feasibility of high-charge external-injected beam into a LWFA

$Q=20 \text{ fC} \rightarrow Q=6 \text{ pC}, 13\text{fs}$

beam excited wakefield ~ laser excited wakefield

unpublished
Feasibility of high-energy gain

\[ z_f = -3.5 \text{mm} (w_0 = 75 \mu\text{m}) \]
\[ n_p = 6 \times 10^{17} \text{cm}^{-3} \]
\[ 9\text{TW@6mm} \]

Laser:
200TW, 40fs, a0=2.2
w0=35μm

Plasma:
\[ 2 \times 10^{17} \text{cm}^{-3} \]
\[ \sim 20 \text{cm plateau} \]

E-beam:
10fs, 20pC, \( \sigma_r = 3.6 \mu\text{m} \)
1mm mrad

1.5MeV gain
\( \sim 250 \text{MV/m} \)

25MeV
Grad: \( \sim 33 \text{GV/m} \)

4.7GeV
unpublished
Outline

- External injection from a Linac into a LWFA with ~100% capture efficiency

- **Plasma dechirper to achieve 0.1% energy spread**
  - Experimental demonstration using uniform plasma dechirper
  - A near ideal dechirper to achieve <0.1% energy spread using hollow channel plasma

- Ultra-compact turnkey laser development

- High energy plasma based injector for CEPC

- Summary
Energy chirp dominated energy spread

- Energy spread ~1% > the requirement of ~0.1% for the applications of FELs and colliders
- Relatively large acceleration phase span leads to large energy chirp (positive linear).

Y. P. Wu, et al., PRL, 122:204804, 2019
PD effect for different beam current profiles

Dechirping strength:

$$S_d = \frac{\Delta E_{z,AB}}{\Delta \xi AB \times Q_{AB}}$$

Dechirping factor:

- 33.3 (flat-top)
- 12.5 (parabolic)
- 8.3 (Gaussian)

Energy spread reduction:

The complex interplay and trade-off among the linear chirp reduction, the nonlinear chirp increase and the slice energy spread growth.

*S. Antipov, et al., PRL, 112, 114801 (2014)*
**Plasma dechirper experimental layout**

**Electron**
- Trans. size: $\sigma_r \sim 40\mu m$
- Bunch length: 1.1ps (FWHM)
- Charge: 40pC
- Energy: 46MeV

**Plasma**
- Density: $10^{14} - 10^{15}$ cm$^{-3}$
- Length: 30mm

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**Beam spot**

**Phase space and parabolic current profile**

**Density profile**

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**Graphs**

- Temp. Res. $\sim 0.4$ps
- Energy Res. $\sim 0.17$MeV
Phase space dynamics for energy spread reduction

Low plasma density

The comparisons use only one parameter to closely match three longitudinal phase spaces and integrated energy spectra.

$P_g = 0.5\, \text{MPa}$
$n_p = 1 \times 10^{14} \, \text{cm}^{-3}$

$P_g = 1\, \text{MPa}$
$n_p = 2 \times 10^{14} \, \text{cm}^{-3}$

$P_g = 2\, \text{MPa}$
$n_p = 4 \times 10^{14} \, \text{cm}^{-3}$

$S_d \approx 1 \,(\text{MV/m})/(\text{mm pC})$
Solution for reducing emittance growth: a hollow channel plasma dechirper

- Transversely uniform $E_z \rightarrow$ negligible slice energy spread increase
- Zero transverse focusing force $\rightarrow$ negligible emittance growth
- Works well for both electron and positron beams

PIC Simulation for hollow channel dechirper

<table>
<thead>
<tr>
<th>Electron/Positron</th>
<th>Energy</th>
<th>4GeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy chirp</td>
<td>40MeV (rms)</td>
<td></td>
</tr>
<tr>
<td>Slice energy spread</td>
<td>0.4MeV</td>
<td></td>
</tr>
<tr>
<td>Peak current</td>
<td>10kA</td>
<td></td>
</tr>
<tr>
<td>Pulse duration</td>
<td>30μm (100fs)</td>
<td></td>
</tr>
<tr>
<td>Transverse size</td>
<td>σ_r=4μm</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Plasma</th>
<th>Density</th>
<th>5.0 × 10^{15}cm^{-3}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>~55cm</td>
<td></td>
</tr>
<tr>
<td>Inner radius</td>
<td>a=300μm</td>
<td></td>
</tr>
<tr>
<td>Outer radius</td>
<td>b=500μm</td>
<td></td>
</tr>
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40MeV(1%)

\( e^- : 0.76\text{MeV} \quad 0.02\% \)

\( e^+ : 0.72\text{MeV} \quad 0.02\% \)

near flat-top
PIC Simulation for uniform plasma dechirper

- The longitudinal nonlinearity and the transverse nonuniformity of $E_z$

40MeV(1%) $\rightarrow$ e−: 11.58MeV(0.29%) / e+: 12.49MeV(0.31%) 15 (e−)/17 (e+) times larger

- The transverse wakefield depends on the longitudinal position

Emittance increase by a factor of 14 (e−)/83(e+)
Dechirping effects for different current profiles in hollow channel plasma

Initial energy spread

\[
\begin{align*}
&<0.01\% \text{ (Flat-top)} \\
&0.14\% \text{ (sin}^2) \\
&0.22\% \text{ (Gaussian)}
\end{align*}
\]

A flat-top beam current profile has the best effect for linear energy chirp reduction.
Robustness of a hollow channel plasma dechirper

Off-axis injection
A transverse bending field depending on longitudinal position
Steer the beam towards one side
Projected emittance growth

2μm offset: Negligible beam offset growth; Emittance growth <25%

~200mrad tilt: Emittance growth <25%
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- External injection from a Linac into a LWFA with ~100% capture efficiency
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- **Ultra-compact turnkey laser development**
- High energy plasma based injector for CEPC
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Ultra-compact turn-key lasers for application

4 year+ joint effort of Tsinghua, NCU and Qifeng New Light Source Corp.

The Goal: Building turn-key lasers for real application

a laser built by the user and for the user

Single box 1-50TW laser systems:

✓ very compact

- Innovation on high contrast regen amplifier
  
  1.4m*0.8m*0.25m for 1-5TW
  1.4m*1.5m*0.25m for 20-50TW

✓ turn-key performance for long term operation

  - Fully sealed subsystems
  - Independently controlled temperature

More information please contact Prof. Wei Lu(weilu@tsinghua.edu.cn)
Turn-key performance

- Super stable diode pumped frontend (even for air conditioning is off)

<table>
<thead>
<tr>
<th>20-50TW Ti:Sapphire laser (0.6~1.5J 10Hz)</th>
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<tbody>
<tr>
<td><strong>Energy stability (RMS)</strong></td>
</tr>
<tr>
<td><strong>Contrast</strong></td>
</tr>
<tr>
<td><strong>Duration</strong></td>
</tr>
<tr>
<td><strong>Power</strong></td>
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- <1% energy stability for final amplifier
External injection from a Linac into a LWFA with ~100% capture efficiency

Plasma dechriper to achieve 0.1% energy spread

Ultra-compact turnkey laser development

High energy plasma based injector for CEPC

Summary
A possible middle step for AAC towards colliders

Plasma based injector for 100km CEPC

- CEPC (Circular Electron Positron Collider) is a major high energy physics plan under strong promotion in China to build a 100km circular machine for a Higgs Factory.

- A high energy injector (40GeV level) is needed to inject e+/e- beams into the main ring.

- Plasma based schemes (PWFA) may provide a novel and cost effective solution for this injector.

- A joint research group of Tsinghua Univ. and IHEP has been formed since 2017 to study the feasibility of using plasma based acceleration as a novel solution for CEPC injector.
A preliminary design of CEPC plasma based high energy injector

- Driver/trailer beam generation through Photo-injector
- HTR PWFA with good stability (single stage $TR=3-4$, Cascaded stages 6-12, high efficiency)
- Positron generation and acceleration in an electron beam driven PWFA using hollow plasma channel ($TR=1$)

Ref: CEPC CDR
The external injection from a Linac to a LWFA with ~100% capture efficiency has been experimentally demonstrated.

For uniform plasma dechirper, the experimental results, combined with high-fidelity 3D PIC simulations indicate a near tenfold reduction of the beam energy spread from 1.28% to 0.13%.

Next generation ultra-compact turnkey laser systems for application is ready to go. Stay tuned!

The feasibility of using plasma wakefield accelerator as a high energy injector for CEPC is under intense study, a joint effort of Tsinghua Univ and IHEP.

Thank you for your attention!