Working Group 1 Summary: Laser-Plasma Wakefield Acceleration

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Injection • Guiding • Diagnostics • 10um-driven • Applications
Stable injector allowed demonstration of staged LPA. Large energy spread leads to low efficiency. Optimizing density tailored target to reduce energy spread.
Improved electron beam quality from shock-induced density downramp injection

$E = 130 \pm 2.8 \text{ MeV}$
$Q = 4.5 \pm 1 \text{ pC}$

$E = 65 \pm 4 \text{ MeV}$
$Q = 16 \pm 2 \text{ pC}$

Swanson, K. et al., in progress
Control and Steering of quasi-monoenergetic electron beams from Laser Plasma Accelerator

- Stable and tunable e-beam is produced from straightened shock injection.
- E-beam divergence (2mrad), pointing (0.6mrad), energy tunable (30-300MeV), energy spread (5%).
- Two major parameters in shock structure:
  1. shock angle
  2. up-ramp width
- Shock angle affects the steering of the electron beam. Up-ramp density width affects the e-beam energy spread.
- Adjusting the shock profile tuned the energy spread from 15% to 5%.
- Next generation jet+blade design in progress

Hai-En Tsai et al.
Low energy spread beams at Tsinghua University & NCU

Low-energy spread beams with high density jet

Pulse Energy: ~300mJ
Pulse Duration: 60fs
$W_0 \approx 12 \mu m$
$N_e = 3 \times 10^{19} \text{ cm}^{-3}$
2mm He jet

Single-stage self-guided LWFA via self-injection

Pulse Energy: ~2J
Pulse Duration: 36fs
$W_0 \approx 27 \mu m$
$N_e = 5.6 \times 10^{18} \text{ cm}^{-3}$
4mm He jet
Simulations show super-high Brightness beams from Density Downramp Injection

Xinlu Xu et al. from UCLA and Tsinghua University

Key physics:
1. Phase velocity reduction due to downramp
2. Transverse momentum reduction due to sheath dynamics near the bubble tail

High quality beams achievable:
- High charge: 0.5nC
- High brightness: >0.5*10^20A/m^2/rad^2
- Low energy spread: <0.5MeV
Full 3D PIC simulations of realistic laser mode less charge and lower energy

At the electron maximal energy:

- High differences in electron charge and energy.
- The gaussian beam overestimates the electron charge and energy.

Pulse Energy: \( \sim \) J
Pulse Duration: 30fs
Laser Focal spot \( W_0 \sim 18\mu m \)
\( N_e = 6 \times 10^{18} \text{ cm}^{-3} \)
5mm He jet

3.5 mm

\[ \text{d}N/\text{d}E \left[ 10^5 \right] \text{ part/MeV} \]
Experiments (Texas Petawatt): > 10x charge with two separated hot spots in focal plane

- ‘Single’ spot: 35 pC FWHM, 190 pC total
- Two hot spots: 617 pC FWHM, 1921 pC total

(2D) simulation: up to 17x charge yield by modeling hot spots as intersecting pulses

- 1° intersection enhances charge
- π phase between pulses (shown at start of interaction)
- Injection occurs near time of merged wake

LWFA charge yield can be increased by using far-from-Gaussian laser pulses
Conclusions and outlook

- Experimentally measured peak accelerating fields of 100s GV/m
- Extended electron energy beyond 2 GeV with 250 TW laser in self-guided, self-injected regime by employing $f/40$ focussing
Non-linear scaling laws for 10-100J pulses verified using quasi-3D OSIRIS

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

\[ \tau = \mathcal{F} 2 \sqrt{a_0 \omega_p}^{-1} \]

\[ \Delta E = \frac{2}{3} \frac{m_e c^2}{\alpha^{2/3}} \left[ \frac{4 \omega_0}{A} \right]^{2/3} \frac{E_L^{2/3}}{\mathcal{F}^{2/3} a_0^{4/3}} \]

\[ [A = 17 \text{ GW}] \]

[\dagger] W. Lu et al., PRSTAB 10 (2007) 061301

Davidson et al.
Self-Guiding accompanied by spatio-temporal optical vertices

- Slowly varying envelope $E_0$ can be extracted from $E_x$
- Complex envelope can be visualized with phase represented by a cyclic colormap, and magnitude represented by the opacity (color saturation).
Demonstration of the Excitation and Control of Plasma Wakefields by Multiple Laser Pulses

- Multi-pulse laser wakefield acceleration may offer route to high repetition rate plasma accelerators driven by trains of low-energy laser pulses
- Proof-of-principle experiments
  - Ti:sapphire laser
  - FDH and TESS to measure wakefield
- Two-pulse expts
  - Wakefield interference clearly observed
  - Cancellation of wakefield by second pulse is first step to “energy recovery”
- Multi-Pulse expts (N = 7):
  - Strong resonance when pulse separation matches plasma period
  - Excellent agreement with linear theory

Cartoon of MP-LWFA scheme

FDH and TESS are in excellent agreement with each other and expected plasma period

Expected wake amplitude:

\[
\frac{\delta n_e}{n_{e0}} \propto \left( \frac{\delta n_e}{n_{e0}} \right)_{N=1} \times \frac{\sin \left( \frac{1}{2} N \omega_{pe} \delta \tau \right)}{\sin \left( \frac{1}{2} \omega_{pe} \delta \tau \right)}
\]

Preliminary analysis!
Capillary discharge diagnostics and control shape the path towards 10 GeV electron beams on BELLA

Plasma on-axis density and matched spot size diagnostic

Inverse Bremsstrahlung heating with additional laser modifies plasma channel

\[
\Delta \rho - \Delta \tau_{\text{beam}}
\]

\[
U_{\text{laser}} = 4.5 \text{ J}
\]

\[
\begin{align*}
Q &= 96 \text{ pC} \\
E &= 8.4 \text{ GeV} \\
dE/E &= 7.0 \% \\
\text{Div} &= 0.33 \text{ mrad}
\end{align*}
\]

J. Daniels et al.
Low Density Plasma Channels Created by Hydrodynamic Expansion of OFI-heated Plasma Columns

- OFI can generate hot plasma columns at arbitrarily low density
  - Heating can be controlled with polarization
- Subsequent hydro expansion could form plasma channels:
  - With low density
  - At multi-kHz repetition rate
- Initial hydro simulations show formation of channels with
  - On-axis densities $2 \times 10^{17}$ cm$^{-3}$
  - Matched spot sizes of tens of microns
- Required laser energy to generate channels is 100s mJ per metre.
  - Most pump energy not absorbed. Could be recycled?
fs optical probe reveals differences between self and ionization injection

Probing plasma wakefield using femtosecond relativistic electron bunches

C. J. Zhang et al.

Wake evolution on a density upramp

$\text{Ne} \approx 10^{17}\text{cm}^{-3}$
High Energy Electron Acceleration from Underdense Plasmas Using the OMEGA EP Laser

- Have measured the electron beam pointing and energy from DLA in an underdense channel at OMEGA EP

- Used proton probe to observe channel formation and behavior in multiple geometries

- By varying heater beam timing, can search for optimum plasma density for electron acceleration in future shot run on OMEGA EP

- In addition, the behavior of the plasma channel in different density profiles will be compared with simulations
• **Ultra-fast CO₂ laser technology on the horizon**

• **It will allow to study LWFA in mid-IR spectral domain**
  • smaller densities – bigger bubble – higher charge

• **Meaningful linear collider LWFA regimes**
  • high-charge LWFA regime good for gamma collider

• **Compton driver for 2-TeV gamma collider**

• **LWFA applications beyond colliders:**
  • seeding/staging studies in big “bubbles”
  • low emittance regimes: two-color LWFA, all-optical “Trojan Horse”

• **Bonus outside LWFA:**
  • ion acceleration, Thomson sources, ...
Towards CO$_2$-laser-driven wake-field accelerator with external injection

- **Final goal:** generating high quality electron beam in LPWA with energy stability and energy spread reaching towards $10^{-4}$. Our final goal will require completions of the CO$_2$-laser power upgrades in progress at ATF, BNL.

- **Current research:** while waiting for the CO$_2$-laser power upgrades to be completed, we are developing and testing the key components necessary for such experiment.
First CO2 self-modulated LWFA

Probe: 1.064 um, 14 ps, 4 mJ, $w_0 = 75$ um

Pump: 10 um, 4 ps, $\sim 0.6$ J, $w_0 = 25$ um

H$_2$ gas jet

0.35 bar $\sim$ 1.75 bar

$5 \times 10^{17} \sim 2 \times 10^{18}$ cm$^{-3}$

1 mm

500 $\mu$m

500 $\mu$m

[ABOVE]: Clean AS shift of 33 nm at 0.75 bar

Welch et al.
Applications for Laser Wakefield Accelerators
Karl Krushelnick, University of Michigan (with LOA, Queen’s Belfast, Imperial College)

**Electrons**

**Gamma-rays**

**X-rays**

Picosecond electron diffraction (Pump-probe measurements)

Positron beams and Pion production

Femtosecond x-ray absorption (Pump-probe measurements)
Our high density gas target lowers the required pulse energy for relativistic self-focusing, enabling the use of high repetition rate lasers for wakefield acceleration.

We have demonstrated kHz repetition rate acceleration of electron bunches with ~pC charge per bunch at MeV scale energies.

Minimum pulse energy required for electron acceleration was 1.3mJ in H₂ gas, yielding ~0.5 MeV electron bunches.

High repetition rate, high charge, short duration electron bunches make our setup an ideal portable source for applications such as ultrafast radiography and diffraction for science and medical applications.
DIRECT LASER ACCELERATION IN LASER WAKEFIELD ACCELERATORS

**LWFA & DLA**

- Electron Density $[e\omega_p^3/c^3]$
  - N6-7
  - He

- DLA occurs when trapped electrons overlap the laser

**DLA Experimental signatures**

- Fork structure for high energy electrons
- Increased electron energy

Jessica L. Shaw, N. Lemos
SM-LWFA as an X-ray source

High energy, long laser pulses - 150, 1ps

Electron spectrum

Generated X-rays

10⁹ photons/eV.Sr at 6.5 keV

X-rays

10 < E_c < 20 keV

Simulations show that the electron acceleration is due to DLA + Wake

Nuno Lemos| AAC 2nd August 2016 | Washington, USA
Staged Laser-Plasma FEL using shaped laser pulses

Accelerate  Cool ε ⊥  Disperse  Zero ΔE/E  Focus  Cool ε ⊥  FEL

Screw-shaped laser pulse

=> Giga-gauss solenoidal field in plasma bubble

=> Fast SR cooling of transverse DOF

=> new approach to design laser-plasma FEL or collider

Screw-shaped laser pulse and trajectories of electrons
A. Seryi, Zs. Lecz, I. V. Konoplev, A. Andreev

Bubble shape (top) and solenoidal field map (bottom)
arXiv:1604.01259
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Thank you for your attention!