CO2-laser-driven laser-wakefield acceleration experiments at Brookhaven’s Accelerator Test Facility

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BNL/ATF experiment AE-71
CO2-laser-driven laser-wakefield acceleration experiments at Brookhaven’s Accelerator Test Facility

**Accelerator Test Facility (ATF):**
- 70 MeV, sub-ps, 3kA S-band linac
- TW, 10μm few-ps CO₂ laser
- fs synchronization
Our Vision: Quasi-mono-energetic LWFA's based on large, controlled mid-IR laser-driven bubbles

injection with ΔE/E ~ 0.1% from external linac or μm-focused UV ionizing laser

\( \lambda_{\text{drive}} = 0.8 \, \mu \text{m (UT)} \)

25 TW, 30 fs

\( n_e = 2 \times 10^{19} \text{cm}^{-3} \)

\( \lambda_{\text{drive}} = 10 \, \mu \text{m} \)

25 TW, 500 fs

\( n_e = 1 \times 10^{16} \text{cm}^{-3} \)

simulations courtesy G. Shvets
Our experiments use ATF’s TW CO₂ laser, linac, & e-compression/synchronization capabilities.

1) ~10 fs jitter

2) emittance-preserving zig-zag chicane compressor

3) CPA at λ = 10μm (Ref. 3)

Large plasma bubbles
→ easy external injection,
→ high-resolution diagnostics

300 μm
nₑ = 1e16 cm⁻³ plasma:

low-emittance
electron bunch

Bubble driven by 1μm, 25 TW laser in nₑ = 1e19 cm⁻³ plasma:

1 Sydlo et al., Proc. FEL 2014
3 Babzien et al., Optica (2016)
Upgraded ATF CO2 laser is needed for bubble LWFAs; meanwhile we study SM-LWFA with ATF I pulses.

### 3 CO2 LWFA experiments:

<table>
<thead>
<tr>
<th></th>
<th>(n_e) (cm(^{-3}))</th>
<th>(\tau) (ps)</th>
<th>(P) (TW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bubble Regime LWFA</td>
<td>(10^{16})</td>
<td>0.5</td>
<td>25</td>
</tr>
<tr>
<td>Self-Modulated LWFA</td>
<td>(~10^{18})</td>
<td>4</td>
<td>0.5</td>
</tr>
<tr>
<td>Plasma Beat-Wave Accelerator</td>
<td>(&lt;10^{16})</td>
<td>300</td>
<td>0.2</td>
</tr>
</tbody>
</table>

**25TW CO2 pulse**

- \(0.3\) mm pulse
- \(n_e = 10^{16}\) cm\(^{-3}\)
- \(\tau = 0.5\) ps
- \(P = 25\) TW

**simulations:**

- Clayton et al., *PRL 70*, 37 (1992)
We modeled CO$_2$ SM-LWFA experiments after prior expts with $\lambda = 1 \, \mu \text{m}$, 400 fs drive pulses in $n_e \sim 10^{19} \, \text{cm}^{-3}$ plasma.


- $P \sim 2 \, \text{TW}$
- $\lambda_{pr} = 0.5 \, \mu \text{m}$
- self-focus ($P > P_{cr}$, $6 < \lambda_p < 12 \, \mu \text{m}$)

Critical power for relativistic self-focusing:

$$P_{cr} [\text{GW}] = 17 \left( \frac{n_{cr}}{n_e} \right)$$
$n_e$-dependent probe spectral shifts
0.5 TW, 4 ps CO$_2$ laser pulse ($\lambda = 10\mu$m) drives SM-LWFA

CO$_2$ laser pulse drives SM-LWFA
4 ps, 0.53 µm pulse probes wake via forward collective Thomson scatter as $n_e$, $\Delta t$ and $P_{CO2}$ vary.

Lower limit: Notch filter blocking region

Upper $n_e$ limit: CO$_2$ laser reflection from jet

BNL/ATF experiment AE-71
Δt-dependent probe spectral shifts show wake decays 90% in ~10 ps, remnants observable at Δt > 25 ps


\[ n_e = 1.5 \times 10^{18} \text{ cm}^{-3} \]
Onset of self modulation is observed near $P/P_{crit} \sim 1$

Edge of notch filter blocking region has been moved closer to the probe wavelength, 532nm, by slight rotation.

$\text{n}_e \sim 1.3 \times 10^{18} \text{cm}^{-3}$

BNL/ATF experiment AE-71
1st generation 3D OSRIS$^1$ PIC simulations confirmed 5 observations qualitatively ...

(1) initial self-focusing

(2) wake forms ...

(3) ... with few ps lifetime

(4) ... and multiple oscillation frequencies

(source of side-band spectral structure?)

(5) no e- produced

CO$_2$ pulse:
- 0.5 TW, 2 ps
- $w_0 = 25 \mu$m

plasma:
- $n_e = 6e17$ cm$^{-3}$

simulations courtesy Chaojie Zhang & Wei Lu


... but did not study the pump or probe spectra structure
Ionization is critical to reproducing approximate Stokes/anti-Stokes symmetry \(^2\)

Simulations using SPACE\(^1\) code: P. Kumar, R. Samulyak, Stony Brook University

3D parallel, relativistic particle-in-cell code for simulating EM fields, relativistic particles, plasma & atomic processes

2. P. Kumar, “Role of ionization in mid IR laser-plasma interaction simulations”, SUBMITTED

PRE-IONIZED PLASMA

- Ionization seeds the forward Raman instability

DYNAMIC IONIZATION
Pump and probe included in the SPACE code PIC simulation. Synthetic diagnostic.

Simulations using SPACE code: P. Kumar, R. Samulyak, Stony Brook University

3D parallel, relativistic particle-in-cell code for simulating EM fields, relativistic particles, plasma & atomic processes


**CO2 pump spectrum**

![CO2 pump spectrum graph]

Strong side band asymmetry in pump laser spectrum after interaction.

**1064nm Probe spectrum**

![1064nm Probe spectrum graph]

Probe side band structure is much more symmetric than in the pump spectrum.

This agrees with observations. Sidebands are symmetric in the data.
SPACE\textsuperscript{1} simulations elucidated previously unexplained $n_e$-dependence of sideband amplitudes

Simulations: P. Kumar, R. Samulyak, Stony Brook University

- At high $n_e$, the drive laser overfocuses, preventing sustained wake propagation.

- Spectral structure in sidebands agrees with observations.

Measured average Stokes/anti-Stokes amplitude


Probing of Linear Wakes Using a Relativistic LWFA Electron Beam

W. Lu - Tsinghua University, Beijing

Zhang, C.J. et.al., Scientific Reports | 6:29485 | DOI: 10.1038/srep29485

Electron radiography is sensitive to electromagnetic fields of the plasma wave and of the accelerated charge.

-Easily scaled to low densities.

-NAVID VAFAEI-NAJAFABADI
DIAGNOSTICS WG5 MONDAY 18:00

**Measurement**

**Simulation**
ATF’s CO₂ LWIR Laser upgrades continue, latest configuration: 9.2 μm with mixed isotopes in regen and amplifier

M. Polyanskiy, I. Pogorelsky, ATF-BNL

New compressor gratings
Line density: 75 → 100 lines/mm
Coating: Al → Au
Blaze wavelength: 10.0 → 9.3 μm
Diffraction Efficiency: 84 → 92%
Compressor Efficiency (4x): 50 → 70%
Damage threshold: 0.5 → 2 J/cm²

Compressor (~3 m)

10 mJ, 60 ps
20 J, 60 ps

Regenerative CO₂ amplifier (10 bar)

16O: 57%
18O: 43%

16O: 53%
18O: 47%

1.83 ps

Single shot Autocorrelation

Pulse duration remains constant as pulse energy grows.

2 μJ, 120 ps

March 2019: 5 TW

14 J, 2.3 ps
5 TW

2 μJ, 120 ps

Final CO₂ amplifier (8 bar)

Laser Pulse Energy [Joule]

March 2019: 5 TW

Peak Power [TW]

Laser Pulse Energy [Joule]

15 μJ, 0.4 ps @ 9.2 μm

OPA Osc

Ti:Sapphire amplifier

ATF’s unique expertise
- First mixed-isotope picosecond CO₂ laser
- First gas laser with CPA
- Solid-state seed laser
OSIRIS and SPACE simulations predict self-injection, relativistic e- production at $P_{CO2} > 1$ TW...

Pre-experimental safety approval test. The readings below are in Rad’s, after 100 shots, behind ¾ inch steel. The angle covered by the detectors is within the predicted electron emission cone.

Pump parameters

- $w_0 = 20$ micron
- 2 ps
- 4J

1.2 mm H$_2$ jet

$ne = 7.5 \times 10^{17}$ cm$^{-3}$

Simulation: Prbhat Kumar, SBU

Simulation: Lidia Pinto de Almeida Amorim, SBU

Summary

1) Plasma wakes produced by BNL/ATF’s 0.5 TW, 10mm, 2J CO₂ laser in the self-modulated regime.
2) Wakes detected and characterized by collective Thomson scatter of a 532nm, 4ps probe.
3) Confirmed injection and acceleration of electrons to multi MeV energy with ~2TW, 2ps pump pulses.
4) OSIRIS¹ and 3D SPACE² PIC simulations explain ne dependent trend, show key role of ionization front seeding in the self-modulation, qualitatively reproduce the complex structure of sidebands often seen in the data, and suggest origin of sum/difference frequency peaks in CTS spectra.
5) Moved experiment to new location in the linac experimental hall. System has gone though most validations and approvals, allowing to shortly begin radiographic probing of wake fields.

Future Plans

1) probe wake’s internal fields transversely with synchronous, few-fs e-bunches from the ATF linac³, and longitudinal optical probe experiments.
2) Characterization of accelerated electrons: OSIRIS and SPACE simulations predict self-injection, relativistic e- production at $P_{CO₂} > 1$ TW...
3) Addition of newer optical probing techniques, such as Frequency Domain Holography (FDH)⁴, Multiple Object plain Imaging (MOP)⁵, Faraday rotation for magnetic field measurement, et al. Characterize wake structure and evolution in single shot.
4) Develop on shot diagnostics for the CO2 laser beam input and output parameters. On shot profile, spectrum, duration etc.
5) Pave way for bubble regime. Reachable within the next 2-3 years.