Dream Beams Based on Implanting Ultracold Electrons into Beam-driven Plasma Waves

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5th Generation Light Source needs a 4th or 5th Generation Electron Source

1st
10's of MV/m fields, thermionic cathode (e.g. SLAC)

2nd
10's of MV/m fields, photocathode (e.g. FLASH, LCLS, XFEL)

3rd
10's of GV/m fields in plasmas & various injection methods (LWFA and PWFA)

4th/5th
GV/m fields in dielectric wakefield accelerators & photocathodes

10's of GV/m fields in plasmas & underdense photocathode PWFA

a.k.a Trojan Horse: combining the tunability of photocathodes w/ plasma fields
LWFA vs. PWFA

- Laser pulses: transversally oscillating wave, electron bunch: unipolar transverse fields
- Relativistic electrons move with \( \sim c \), no dephasing
- Much longer acceleration distances with relativistic electron bunches (emittance vs. diffraction)
- Lasers can easily ionize matter, but intensities required to drive a plasma “bubble” orders of magnitude higher
- Electron bunches can drive a plasma “blowout”, but intensities required to self-ionize orders of mag. higher

\[ \omega(z) = \omega_0 \sqrt{1 + \left( \frac{z}{Z_R} \right)^2} \quad Z_R = \frac{\pi \omega_0^2}{\lambda} \]

\[ e.g., \ Z_R \approx 400 \mu m \quad \text{at} \ \omega_0 = 10 \mu m \]

\[ \sigma_r(z) = \sigma_{r0} \sqrt{1 + \left( \frac{z}{\beta^*} \right)^2} \quad \beta^* = \frac{\sigma_{r0}^2 \gamma}{\epsilon_n} \]

\[ e.g., \ \beta^* \approx 20 \, \text{cm} \quad \text{at} \ \sigma_{r0} = 10 \mu m, \ \gamma = 2000, \ \epsilon_n = 10^{-6} \, \text{mrad} \]
Hybrid LWFA & PWFA

Rethink LWFA and PWFA: laser pulses are great for ionization, while electron bunches are better drivers

Use the best of both worlds!

Use oscillating fields from laser pulse to ionize and to generate low-transverse momentum electrons

ionization @~10^{14} W/cm^2, produced electrons will receive very low transverse momentum (Lawson-Woodward)

Use unidirectional transverse fields from e-bunch to kick out electrons and to excite blowout

ionization if $E_r > 5$ GV/m
blowout if $n_b > n_e$
Combine both in media w/ Low-ionization-threshold (LIT) and High-ionization-threshold (HIT) component

Synchronized laser pulse is strongly focused to HIT, releases HIT electrons in focus

Driver bunch ionizes/expels LIT electrons, only, and excites plasma blowout

Beyond Injection: Trojan Horse Plasma Wakefield Acceleration, AAC 2012, Austin, APS proc. 2012

Injection: 1590–1600: Latin *injectus* past participle of *in (j) icere* to throw in, equivalent to *in-* + *-jec-* (combining form of *jac-* throw) + *-tus* past participle suffix
What’s needed:
- LIT/HIT medium
- reliable electron bunch driver to set up LIT blowout
- synchronized, low-intensity laser pulse to release HIT electrons within blowout
Released electrons are compressed, trapped and then co-propagate dephasing-free at the end of the blowout.

Both accelerating cavity and photocathode are co-moving in phase with the released electrons.

Release laser: Ti:Sapph, 800 nm, 25 fs, $a_0=0.015$, self-ionization of LIT medium by electron bunch.

All simulations w/
Laser pulse intensity is crucial

Focus laser pulse intensity has to be just above the ionization threshold of the HIT medium (here, helium).

In contrast to LWFA schemes (~$10^{18}$-$10^{19}$ W/cm$^2$), here the laser pulse intensity is of the order of ~$10^{14}$-$10^{15}$ W/cm$^2$, only. ➔ Transverse momentum of bunch electrons is very low ➔ direct consequences for divergence & emittance!
Works w/ self-ionization and w/ preionization:
Preionized hydrogen plasma (LIT)
and photoionized helium (HIT)
Photocathode + Space Charge Screening

Space charge screening during low-$\gamma$ transit due to simultaneously born LIT+ ions on axis

Transient space charge shielding by ions at low $\gamma$
What’s the obtainable emittance?

Rough estimation of laser contribution to normalized emittance:

\[ \epsilon_n \approx \sigma_{rHIT} \sigma_{p_r,HIT} / (mc) \approx \frac{w_0 a_0}{2^{3/2}} \]

\( \omega_0 \): laser focus size, \( a_0 \): laser potential

<table>
<thead>
<tr>
<th>HIT medium</th>
<th>ionization potential</th>
<th>( I_{BSI} )/ W cm(^{-2}) @ 800 nm</th>
<th>( a_0 ) at BSI threshold</th>
<th>( \epsilon_{n,x} \approx \frac{\omega_0 a_0}{2.8} ) ( \omega_0 = 5 \mu m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cs</td>
<td>3.9 eV</td>
<td>9.2 x 10(^{11})</td>
<td>0.00065</td>
<td>1.2 x 10(^{-9}) m rad</td>
</tr>
<tr>
<td>Rb</td>
<td>4.2 eV</td>
<td>1.2 x 10(^{12})</td>
<td>0.00075</td>
<td>1.3 x 10(^{-9}) m rad</td>
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<tr>
<td>Li</td>
<td>5.4 eV</td>
<td>3.4 x 10(^{13})</td>
<td>0.00126</td>
<td>7.1 x 10(^{-9}) m rad</td>
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<tr>
<td>H</td>
<td>13.6 eV</td>
<td>1.4 x 10(^{14})</td>
<td>0.008</td>
<td>1.4 x 10(^{-8}) m rad</td>
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<tr>
<td>Cs+</td>
<td>25.1 eV</td>
<td>4.0 x 10(^{14})</td>
<td>0.01362</td>
<td>2.4 x 10(^{-8}) m rad</td>
</tr>
<tr>
<td>Rb+</td>
<td>27.3 eV</td>
<td>5.6 x 10(^{14})</td>
<td>0.016</td>
<td>2.8 x 10(^{-8}) m rad</td>
</tr>
<tr>
<td>He</td>
<td>24.5 eV</td>
<td>1.4 x 10(^{15})</td>
<td>0.026</td>
<td>4.6 x 10(^{-8}) m rad</td>
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<tr>
<td>Li+</td>
<td>75.6 eV</td>
<td>3.2 x 10(^{16})</td>
<td>0.125</td>
<td>2.2 x 10(^{-7}) m rad</td>
</tr>
</tbody>
</table>

Note:
- **Barrier Suppression Ionization is an upper limit**
- This is all in laser polarization plane \( \Rightarrow \epsilon_n \) further decreased in perpendicular plane
- At 800 nm \( \Rightarrow \epsilon_n \) further decreased w/ higher frequencies

Barrier Suppression Ionization

\[ I_{BSI} \approx 4 \times 10^9 \frac{\xi_i^4 \text{[eV]}}{Z^2} \]

\[ a_0 = \left( \frac{I}{2\epsilon_0 c} \right)^{1/2} \frac{e\lambda}{\pi m_e c^2} \]
Enabling scheme for light sources

**FEL, Thomson, Betatron**

general FEL trend towards low charge

\[ \text{e.g., at } Q \approx 1\mu\text{C}, \sigma_z \approx 2.5 \mu\text{m}, I_p \approx 120 \text{ A} \implies B \approx 2I_p/\epsilon_n^2 \approx 10^{19} - 10^{20} \text{ Am}^{-2}\text{rad}^{-2} \]

minimum theoretical FEL wavelength

\[ \text{e.g., with } \epsilon_n = 1 \times 10^{-9} \text{ m rad at } 1 \text{ GeV} \implies \lambda_{\text{min}} \approx 4\pi \epsilon_n / \gamma < 0.1\text{Å} \]

Unprecedented brightness
Values exceed those of the LCLS by a wide margin

GENESIS calculation for 2 pC bunch, \( \epsilon_n = 3 \times 10^{-8} \text{ m rad} \)
w/ “Finndulator” as in O’Shea et al., PRSTAB 13, 070702 (2010), 4.3 GeV: LCLS performance after 20 m!
EM undulators (GALAXIE, Tantawi et al.)?

- Put into pure plasma wakefields obtained from PIC simulations
- Obtained electron trajectories and emittance via solving equations of motion in plasma superimposed with analytical laser fields
- Obtained flexible tool to predict emittance of generated witness bunches

Detailed numero-analytical analysis shows that $\varepsilon_{n,y}$ is about an order of magnitude lower, and increases slower than $\varepsilon_{n,x}$ as intensity increases. $\varepsilon_{n,y}$ down to the $\varepsilon_{n,y} \approx 10^{-9}$ m rad level.

YI model leads to significantly higher emittance due to inclusion of multiphoton ionization

Y. Xi et al., PRSTAB, to appear (see poster session)
Fishbone electron bunch microstructure observed in 2D simulation reflects peaking ionization yields during laser field maxima

\[ \tau_L \sim 30 \text{ fs} \]

Landau-Lifshitz DC tunneling ionization formula (M. Chen et al., J. Comp. Physics 236, 2013) implemented into VORPAL + variable weighting
Various Potential LIT/HIT media candidates
Applicable w/ conventional acc. and LWFA alike

For example

• gaseous H (13.6 eV)/He (24.6 eV)
• alkali metals Li, Na, Rb, Cs (~5 eV)/He (24.6 eV)
• Rb (4.2 eV)/Rb⁺ (27.3 eV)
• Cs (3.9 eV)/Li (5.4 eV)

You want the lowest ionization thresholds (to decrease the transverse electron momentum), and a reasonable gap between LIT and HIT medium (ionization corridor)

ADK ionization rates: \[ W(s^{-1}) \approx 1.52 \times 10^{15} \frac{4^{n^*} \xi_i [eV]}{n^* \Gamma (2n^*)} \left( \frac{20.5 \xi_i^{3/2} [eV]}{E [GV/m]} \right)^{2n^* - 1} \times \exp \left( \frac{-6.83 \xi_i^{3/2} [eV]}{E [GV/m]} \right) \]

Near future @ FACET:

Li (\( \xi_i = 5.4 \) eV/He (\( \xi_i = 24.5 \) eV)

Rb (4.2 eV)/Rb⁺ (27.3 eV)

Ar (15.8 eV)

SLAC and FLASH bunches have bunch parameters which are on the verge of self-ionizing alkali metals: R&D in Hamburg on (partial) preionization of alkali metal vapors w/ excimer lasers \( \rightarrow \) plasma lense \( \rightarrow \) self-ionization
Where/when to realize it?

FACET/SLAC
E-210 “Trojan Horse PWFA“ expt., beamtime for 2013/2014
+ stable driver beam
+ high energy beam
+ most extensive plasma experience
- synchronization difficult
- ionization/preionization difficult

Milestone: If this works, and if also the emittance can be demonstrated (work on back-windowless design of alkali metal oven in HH) → raise funding for Trojan FEL facilitie(s)

Photoinjector facilities (FLASH, FACET-II...)
+ very stable beam, high rep rate
- no facility online yet / no plasma acc. expmts. done yet
- not before 2016 (FLASHforward..)

Laser-Plasma-Accelerators worldwide!
+ availability & cost-effectiveness
+ inherent perfect synchronization between electron bunch and Trojan release pulse
- instable performance
- no purposeful PWFA experiment has been demonstrated yet
- so far low (10 Hz) rep rate for 100 MeV+ beams
Vision: Export Trojan Horse booster section and superior XFEL capability to every LPA!
Beam brightness transformer and stabilizer for Laser-plasma-accelerators

- Bunch quality transformer: energy, energy spread (see “Monoenergetic energy doubling”, PRL 140195002, 2010), emittance

- e.g., LPA: $\Delta E_1 = 20 \%$, $\epsilon_{n1} \sim 10^{-6}$ m rad $\rightarrow$ TROJAN: $\Delta E_2 = 0.1 \%$, $\epsilon_{n2} \sim 10^{-8}$ m rad
Substantially different parameter goals for electron bunches from LWFA to be used for PWFA

- Energy spread does not matter, as long as the energy is sufficiently relativistic: all electrons move with ~c. In first approximation, a 1 GeV bunch with perfect energy spread won’t drive a different plasma wake than a 1 GeV bunch with 30% spread.

- Energy stability not so important: cap acceleration distance via preionization.

- Even in case of current jitter, some stabilization is automatically achieved by the trapping process:

  - Produce compact bunches with a lot of charge (via downramp injection?)
  - Improve pointing
  - Prevent dark current
  - Can we somehow produce current upramp with LPA’s for enhanced transformer ratio? …

Even though the trapping position will be different, the acc. fields can be the same / very similar!
3rd way: All-optically powered TeV accelerator

**PWFA-based:**

- Wake-field modules
- Gamma converter and Detector
- Beam distribution network (rf kickers)
- Heavily Beam-loaded Electron Linac

J.B. Rosenzweig et al., NIMA 410, 1998

**LWFA-based:**

- Laser
- Gas jet
- Capillary
- 1 TeV electrons


**Hybrid LWFA/PWFA-based:**

- LWFA
- PWFA
- LWFA
- PWFA
- LWFA
- PWFA
- LWFA
- PWFA
- LWFA
- PWFA

LWFA/PWFA driven Trojan Horse witness $\varepsilon_n \approx 10^{-9}$ m rad, 5 GeV

e- e+ collider? $\gamma \gamma$-collider?

.. to be submitted

200 stages, 100 TW LWFAs, 1 GeV each, T~5, 5 GeV gain/stage, final energy = 1 TeV 100 kHz, $\varepsilon_n \approx 10^{-8}$ m rad @ 5 pC, focused to100 nm: L~1e33
Highlights

- electron bunches with unprecedented emittance ($\varepsilon_n \sim 10^{-9}$ m rad) and brightness may be possible

- FEL game changer?

- Unprecedented bunch shaping capabilities (more flexible than state-of-the-art photoinjectors)

- Trojan horse a bunch quality transformer (e.g., $\Delta E_1 = 20\%$, $\varepsilon_{n1} \sim 10^{-6}$ m rad $\rightarrow \Delta E_2 = 20\%$, $\varepsilon_{n2} \sim 10^{-8}$ m rad)

- ... and as a bunch energy transformer

- Scheme applicable for most diverse scenarios: hybrid conventional/PWFA accelerator (SLAC/Trojan Horse), hybrid photoinjector/PWFA accelerator (FLASH, FACET-II, etc.), hybrid LWFA/PWFA accelerator

- HEP accelerator applications? TeV accelerator..

- Output stabilizer for LWFA

- Biggest question: emittance preservation & extraction?
Thank you!