A Perspective on Plasma Accelerators

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OSIRIS simulation by F. Tsung UCLA
Talk based on

Perspectives on the generation of electron beams from plasma-based accelerators and their near and long term applications
C. Joshi, S. Corde, W.B. Mori, Phys. Plasmas 27, 070602 (2020)

Special Thanks to
V. Yakimenko, R. Siemann, J.M. Dawson
All our former students, postdocs and Colleagues
Accelerator based Experiments are necessary to address Important Science Questions in this Century.

Are there additional dimensions of space?

Why is there matter-antimatter imbalance?

How did the universe begin?

What is dark matter?

How were heavy elements created?
Particle colliders 21st Century

Other Contenders:

FCC : CERN e-e or p-p
CEPC: China e-e+

International Linear e-e+ Collider

Energy Frontier of particle Physics 500 GeV CM
Very large 30 km (<20 MeV/m)
Very Expensive $20+ B (DOE Estimate)

Can we make accelerators at energy frontier smaller and cheaper?
Can high electric fields of laser pulses or beams be used to accelerate particles?

a) At ultra high gradients?
b) To very high energies?
Relativistic Wakes in Plasmas as particle accelerators?

- **Plasma Wake Field Accelerator**
  A high energy electron bunch

- **Laser Wake Field Accelerator**
  A single short-pulse of photons

Leonardo de Vinci
Study of Wakes:1509

Wake – disturbance left behind by a piston moving thru fluid

• Drive beam
  \( v_p \sim c \)

• Trailing beam
RF and Plasma Accelerators

Conventional

- TM mode in a SW Structure
- $E_z$, $E_r$, and $B_\theta$
- 20 MeV/m
- 3-30 cm diameter permanent Cu structure

Plasma: Holographic Interferometry

- TM mode in Plasma
- $E_z$, $E_r$, and $B_\theta$
- 20 GeV/m
- 30-300 um diameter transient structure

Courtesy M. Downer
Multi-stage Plasma based Linear Collider
(basic design follows the ILC collider concept)

E. Adli et al. Snowmass Proc. 2013
A. Seryi et al. 23rd PAC Conf. Proc.

Courtesy; S. Corde
Why Use Wakes in Plasmas for Acceleration?

1D-Linear Plasma Wakefield Theory

\[
(\partial_t^2 + \omega_p^2) \frac{n_1}{n_o} = -\omega_p^2 \left( \frac{n_b}{n_o} + k_p^2 \nabla^2 \sqrt{1 + a_o^2} \right)
\]

For \( \tau_{\text{pulse}} \) of order \( \pi \omega_p^{-1} \sim 100 \text{fs} \ (10^{17}/n_o)^{1/2} \) and spot size \( c/\omega_p \)

**Large wake for a laser amplitude** \( a_o = eE_o/m\omega_oc \sim 1 \) or a beam density \( n_b \sim n_o \)

Wakes are said to be linear when \( n_1 < n_o \)

\[
\nabla \cdot E = -4\pi en_1 \Rightarrow \quad eE = \frac{n_1}{n_o} \sqrt{\frac{n_o}{10^{16} \text{cm}^{-3}}} \times 10 \text{GeV/m} \cos \omega_p(t - z/c)
\]
Linear Wakes can Accelerate both e- & e+

Linear Wake when $n_1 < n_o$

Sinusoidal longitudinal electric field

Longitudinal and transverse field out of phase by $\frac{\pi}{2}$ rads.

The e- and e+ can be accelerated in a region $\frac{\lambda}{4}$ wide but $\frac{\lambda}{2}$ apart.
What about positron driven wakes?
Nonlinear dynamics of positron plasma interactions

28 GeV Positron Beam at SLAC propagates through a dilute plasma

Positron beams at SLAC

Plasma electrons

Focusing force

Accelerating field

Initial beam at plasma entrance
E 162 Collaboration
P. Muggli et al PRL 2008

Central core surrounded by a halo

Beam exiting plasma
FULL/REDUCED PIC CODES VALIDATED BY NUMEROUS EXPTS and USED TO DESIGN EXPT.s AND CONFIRM NEW IDEAS

**Osiris framework**
- Massively Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris consortium ⇒ UCLA + IST

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http://epp.tecnico.ulisboa.pt/
http://plasmasim.physics.ucla.edu/
Linear wake formation, energy loss and energy gain of a positron bunch in plasma

**Experiment**

- Energy gain of 80 MeV in 1m
- Typical e+ acceleration gradient < 20 MeV/m
- Ref. B. Blue et al. PRL 2002
- Expt. Done on FFTB @ SLAC

**PIC Simulation**

- Energy evolution over time
Nonlinear Wakes in the blowout regime driven by laser pulse or e-bunch

Need $< 100$fs (FWHM) driver beams with $a_0 > 2$ or $a > 10$ KA electron beam

Ref. T. Tajima and J.M, Dawson PRL 1979
Nonlinear wakes: Rosenzweig, Katsouleas, Mori, Lu, etc.
Longitudinal and transverse fields in blowout regime
(ideal for preserving emittance or beam quality)
BREAKING THE 1 GeV BARRIER
With 15 micron long bunches

\[ n_e \approx 3.5 \times 10^{17} \text{ cm}^{-3} \ L \approx 10 \text{ cm}, \ N \approx 1.8 \times 10^{10} \]

Charge Fraction > \( E_0 \) 0.8% 25pC of charge

Ref. M. Hogan et al. PRL 2005
Energy Doubling with a Plasma Wakefield Accelerator in the FFTB

Drive Electron Beam 42 GeV

Particles in the tail gained 43 GeV in just 85 cm

Acceleration gradient of 50 GeV/m sustained over 85 cm

Beam head erosion limited the propagation of the beam to a distance less than pump depletion length.

C. Joshi, CERN Courier 2007
Compact and Cheaper High-Energy Colliders a Grand Challenge for Science and Engineering in the 21st century

Particle Physics Project Prioritization Panel (P5) Report 2014: Building for Discovery

“A primary goal, therefore, is the ability to build the future generation accelerators at dramatically lower cost. ...For e⁺e⁻ colliders, the primary goals are improving the accelerating gradient and lowering the power consumption”

NAE Grand Challenges for Engineering
Engineer Tools of Scientific Discovery

“..engineers will be able to devise smaller, cheaper but more powerful atom smashers, enabling physicists to explore realms beyond the reach of current technology.”
Acceleration of a distinct trailing bunch and beam loading of the Wake

Acceleration of Trailing Bunch of Electrons

M. Litos et al. PPCF 2016

Max. Energy gain 9 GeV in 1.3m, energy spread <5%, 25% energy extraction efficiency
Acceleration of positrons in nonlinear wakes


e+ beam produces wake & a dense region of plasma electrons that traps e+

4 GeV in 1.3 m
1.8% energy spread
Low beam divergence
Jet Age of Laser-wakefield Acceleration-LWFA Takes off
RAL/IC, LBNL and LOA Expts show ~ 10% energy spreads

Monoenergetic beams of relativistic electrons from intense laser-plasma interactions

G. R. D. Geden 1, D. Toff 1, J. van Tilburg 2, J. E. Evers 1, A. B. Schröder 1, D. Brincker 1, C. Müller 2, J. Cruy 2 & W. P. Leeman 2

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A laser-plasma accelerator producing monoenergetic electron beams

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3Département de Physique Théorique et Appliquée, CEA/DSIM, En de Préval, 80460 Boulogne-Billancourt, France

High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding

C. R. Geddes 1, C. Toff 1, J. van Tilburg 2, J. E. Evers 1, A. B. Schröder 1, D. Brincker 1, C. Müller 2, J. Cruy 2 & W. P. Leeman 2

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Maximum energy gain of 8 GeV seen at BELLA.
Percent level energy spreads
@4 hour operation of a LWFA in Germany

Numerous new ideas: colliding pulse injection, self beam loading, Photon acceleration and deceleration, overcoming dephasing, DLA wake assisted relativistic guiding. Ionization injection

A phenomenological theory for nonlinear wakes, nonlinear beam loading, beam matching, transverse beam instabilities -essential to our understanding and charting a path forward.
Plasma Accelerator Progress

“Accelerator Moore’s Law”

[Graph showing the progress of plasma accelerator technology over time, with key milestones and experiments labeled.]
Can critical physics issues for a multi-stage e+e- collider be quantified via experiments and/or simulations in the next decade: 2017-2027?

Can the then remaining critical issue be solved by 2032?

Can an important enough first application of a plasma accelerator be identified?

Can a plasma accelerator built for this application (for \(< \sim 1B\)) serve as a prototype for a LC by 2035?

Can the community come up with a CDR for a Plasma-Based LC by 2035?
Next big challenge for Plasma-Accelerators is demonstration of All the necessary parameters for a single stage of a multi-stage collider

No single experimental facility is suitable such a demonstration
So must rely on a combination of experiments and 1:1 PIC simulations

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Simulations</th>
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<tbody>
<tr>
<td>More than 90% energy extraction From the pump to the wake</td>
<td>Generation and acceleration of ultra-low emittance beams</td>
</tr>
<tr>
<td>Extraction of 90% of the energy from the wake by the accelerating beam</td>
<td>Generation and acceleration of highly polarized e- and e+ beams</td>
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<tr>
<td>Emittance preservation at 1um level</td>
<td>Techniques for high quality beam generation in linear wakes</td>
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<td>Nearly 100% charge throughput</td>
<td>Staging, radiation loss</td>
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<td>Less than 1% energy spread</td>
<td>Transverse beam instabilities</td>
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<td>0.5 nC charge accelerated per shot</td>
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<tr>
<td>Do all this with both e- and e+</td>
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Energy Doubling (10-20+ GeV) with <1% Energy Spread, Pump Depletion and > 40% energy transfer efficiency

Plasma and beam density with on-axis Ez line out

Beam Energy

Simulations by W. An UCLA, Joshi et al. PPCF 2018
Beam Matching in and out of plasma accelerator
And emittance preservation

Simulation Results: Weiming An
Colliders and 5\textsuperscript{th} Generation Light Sources both need Cheaper and more Compact Accelerators

A true 5\textsuperscript{th} Gen. Light Source that will compete with X-FELs may be the 1\textsuperscript{st} grand application of the advanced accelerator concepts technology.

<table>
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<tr>
<th>COLLIDERS</th>
<th>5th Gen Light Source</th>
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<tr>
<td>e and e+ TeV beams</td>
<td>e</td>
</tr>
<tr>
<td>Spin polarization</td>
<td>1GeV beams</td>
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<tr>
<td>Multiple stages</td>
<td>10 pC charge per beam</td>
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<tr>
<td>High Luminosity</td>
<td>Single stage</td>
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<tr>
<td>-nC charge per beam</td>
<td>High beam brightness</td>
</tr>
<tr>
<td>-nm emittance</td>
<td>-Extremely low energy spread</td>
</tr>
<tr>
<td>-kHZ Rep. rate</td>
<td>-nm emittance</td>
</tr>
<tr>
<td>-&gt;20 MW Average power</td>
<td>-kHZ Rep. rate</td>
</tr>
<tr>
<td>-&gt; need 90% driver beam</td>
<td></td>
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<td>accelerated bunch energy extraction efficiency</td>
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Synchrotrons and X-FELs poised to be Breakthrough Tools of Discovery in 21st century

Deciphered by Venky Ramakrishnan’s Team: Nobel in Chemistry 2009

100,000 proteins in human body
75,000 enzymes
25,000 Genes in each cell

structure analysis with highest resolution
Ribosome molecule
Conclusions

1) Developing plasma accelerators that will disrupt an established technology is a long-term endeavor. Beautiful science but limited resources.

2) A team that has diverse expertise, bright young people eager to make their mark and good leadership is essential to success.

3) Long term funding and access to facilities is essential

4) Important to have goals to judge progress but must also have the freedom to pursue unexpected avenues as they open up.

5) The prognosticators must come up with a “killer app” such as 5th Generation Light Source to secure funding for continued R&D within 10 years.