AWAKE—
A proton-driven plasma wakefield acceleration experiment at CERN

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CockcroA Ins8tute and the University of Manchester
Evolution of accelerators

R. Wideroe (1928)

E. Lawrence (1931)

E. Rutherford (1911)

E.M. McMillan (1950)

J. Cockcroft (1932)

Huddersfield Accelerator Symposium
Todays HEP machines

SLC

RHIC

HERA

Tevatron

02/05/2014  Huddersfield Accelerator Symposium
Large Hadron Collider

- **LHC**: the world biggest accelerator, both in energy and size
- First collisions in late 2009 (2.36 TeV)
- 7 TeV collisions in March 2010
- 5.6 fm⁻¹ luminosity accumulated in 2011
- Higgs-boson like particles discovered (July 4th, 2012)!
- ~23 fb⁻¹ luminosity accumulated (8 TeV) end of 2012
- Higgs boson confirmed in early 2013
- Physics Noble Prize in 2013
Complex machines
International Linear Collider-ILC

The next big thing. After LHC, a Linear Collider of over 30 km length, will probably be needed.
The New Livingston Plot

- Plot showing the progression of particle accelerators and related energy technologies over time.
- Key elements include the Livingston Plot, major accelerators, and significant milestones.

References:
- Scientific American
- Nature
- CERN Courier
- Physical Review Letters

Events:
- 02/05/2014
- Huddersfield Accelerator Symposium
- Joshi & Katsouleas Physics Today 2003
Motivation
Plasma accelerators
Proton-driven PWFA
AWAKE experiment at CERN
Colliders based on proton-driven PWFA
Summary
Motivation

- With an increase of beam energy, the size and cost of modern high energy particle accelerators reach the limit (material break down, RF power).
- Plasma can sustain very large electric fields, a few orders of magnitude higher than the fields in metallic structures.
- The plasma accelerators (laser driven--LWFA or beam driven--PWFA) have been developed rapidly in last 20 years, 50--100GV/m accelerating gradients have been demonstrated in labs.
- The novel plasma accelerators can potentially minimize the size and cost of future machines.
Plasma accelerators

I) Generate homogeneous plasma channel

II) Send intense laser pulse or particle beam towards plasma

Ionization of gas via:
- Laser
- Beam
- RF or DC voltage

Beam density $n_b$
Gas density $n_p$
Plasma accelerators

III) Excite plasma wakefields

Electrons are expelled

Ion channel

\[ \omega_p = \sqrt{\frac{n_p}{\varepsilon_0 m}} \]

\[ \lambda_p \approx 1 \text{mm} \cdot \sqrt{\frac{10^{15} \text{cm}^{-3}}{n_p}} \]

Space charge force of beam ejects all plasma electrons promptly along radial trajectories

Pure ion channel is leA: Ion-focused regime, underdense plasma
Plasma accelerators

**driving force:** Space charge or ponderomotive force of drive pulse displaces plasma electrons.

**restoring force:** Plasma ions exert restoring force

Longitudinal fields can both accelerate and decelerate!

Structure size: approximately sub-millimeter!

Space charge oscillations (Harmonic oscillator)

\[
E\left[\frac{V}{m}\right] = \frac{! m_e c^2}{\# \varepsilon_0} \frac{\varepsilon_0}{\%} n_p^{1/2} \approx 100\sqrt{n_p (\text{cm}^{-3})}
\]
Plasma "structures" are also super-strong "quadrupoles"!
(many thousand T/m)

Plasma ions move relatively little

\[ \frac{W_r}{r} = 2\pi \cdot n_p \cdot e^2 = 960\pi \frac{T}{m} \left( \frac{n_p}{10^{14} \text{cm}^{-3}} \right) \]

Constant focusing gradient

need to handle acceleration and focusing!

acceleration and focusing!
**Electron beam** (beam energy 42 GeV, bunch length 50 fs, bunch charge 2.9 nC)

**Plasma** (heat Li oven, length 85 cm, density 2.7e17 cm⁻³)

**Max. energy gain**
43 GeV (85 cm column) = 52 GeV/m!

Energy spectrum of the electrons in the 35-100 GeV range as observed in plane 2

2nd generation PWFA

Physical mechanism of the Plasma Wakefield Accelerator for previous single bunch experiments in the FFTB (top) and the two bunch case proposed for FACET (bottom)
# Existing proton synchrotrons

<table>
<thead>
<tr>
<th></th>
<th>HERA</th>
<th>TEVATRON</th>
<th>LHC</th>
</tr>
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<tbody>
<tr>
<td>Circumference [km]</td>
<td>6.336</td>
<td>6.28</td>
<td>26.659</td>
</tr>
<tr>
<td>Maximum energy [TeV]</td>
<td>0.92</td>
<td>0.98</td>
<td>7.0</td>
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<tr>
<td>Energy spread [10^{-3}]</td>
<td>0.2</td>
<td>0.14</td>
<td>0.113</td>
</tr>
<tr>
<td>Bunch length [cm]</td>
<td>8.5</td>
<td>50</td>
<td>7.55</td>
</tr>
<tr>
<td>Transverse emit. [10^{-9} \pi m rad]</td>
<td>5</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>Particles per bunch [10^{10}]</td>
<td>7</td>
<td>26</td>
<td>11.5</td>
</tr>
</tbody>
</table>
high energy proton beam as driver

- Huge energy stored in current proton machines like Tevatron, HERA, SPS and LHC
- For example, the SPS/LHC beam carries significant stored energy for driving plasma waves
  - SPS (450 GeV, 1.3e11 p/bunch) ~ 10 kJ
  - LHC (1 TeV, 1.15e11 p/bunch) ~ 20 kJ
  - LHC (7 TeV, 1.15e11 p/bunch) ~ 140 kJ
  - SLAC (50 GeV, 2e10 e-/bunch) ~ 0.1 kJ
- However, the current proton bunches are quite longer to use as drive beam directly. Need much effort to compress the bunch length
- How to couple the energy of driver to the plasma and to the witness beam efficiently?
Proton driven PWFA

- The linear theory of PWFA holds for either negatively charged or positively charged beams
- The maximum achievable gradient scales as $N/\sigma_z^2$, therefore we need high current and short bunch for proton bunch driven PWFA
- Transformer ratio (the gained energy of witness beam / the energy of driver beam) is limited to 2 for longitudinal symmetric driven bunches
- 2D and 3D Par8cle-in-cell (PIC) simulations have given us very promising results for proton driven PWFA

A thin tube containing Li plasma is surrounded by quadrupole magnets with alternating polarity. The magnification shows the plasma bubble created by the proton bunch (red). The electron bunch (yellow) undergoing acceleration is located at the back of the bubble. Note that the dimensions are not to scale.

*S. Chen et al., Nature Physics 5, 363 (2009)*
## Parameter settings

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
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<tbody>
<tr>
<td><strong>Drive Beam</strong></td>
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<tr>
<td>Protons in drive bunch [10^{11}]</td>
<td>$N_p$</td>
</tr>
<tr>
<td>Proton energy [TeV]</td>
<td>$E_p$</td>
</tr>
<tr>
<td>Initial proton momentum spread</td>
<td>$\sigma_p/p$</td>
</tr>
<tr>
<td>Initial longitudinal spread [µm]</td>
<td>$\sigma_z$</td>
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<tr>
<td>Initial angular spread [mrad]</td>
<td>$\sigma_\theta$</td>
</tr>
<tr>
<td>Initial bunch transverse size [mm]</td>
<td>$\sigma_{X,Y}$</td>
</tr>
<tr>
<td><strong>Witness Beam</strong></td>
<td></td>
</tr>
<tr>
<td>Electrons in witness bunch [10^{10}]</td>
<td>$N_e$</td>
</tr>
<tr>
<td>Energy of electrons [GeV]</td>
<td>$E_e$</td>
</tr>
<tr>
<td><strong>Plasma Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Free electron density [cm^{-3}]</td>
<td>$n_p$</td>
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<tr>
<td>Plasma wavelength [mm]</td>
<td>$\lambda_p$</td>
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<tr>
<td><strong>External Field</strong></td>
<td></td>
</tr>
<tr>
<td>Magnetic field gradient [T/m]</td>
<td></td>
</tr>
<tr>
<td>Magnetic length [m]</td>
<td></td>
</tr>
</tbody>
</table>
**Simulations**

- 2D and 3D Par8cle-In-Cell (PIC) codes are employed to simulate the interactions between plasmas and beams.

Fig. a-d), Simulation results for the unloaded (no witness bunch) case (a,b) and in the presence of a witness bunch (c,d). The witness bunch is seen as the black spot in the first wave bucket in d). d) also shows the driving proton bunch at the wavefront (red). e) The on-axis accelerating field of the plasma wave for the unloaded (blue curve) and loaded (red curve) cases.

* A. Caldwell et al., Nature Physics 5, 363 (2009)
Simulation results

- Energy gain

1 TeV

10 GeV

phase
The snapshots are taken at acceleration distances $L=0, 150, 300, 450$ m. The electrons are shown as blue points and the protons are depicted as red points.

* A. Caldwell et al., Nature Physics 5, 363 (2009)
Energy gain & energy spread

Fig. a, b), The mean electron energy in TeV (a) and the r.m.s. variation of the energy in the bunch as a percentage (b) as a function of the distance travelled in the plasma.

* A. Caldwell et al., Nature Physics 5, 363 (2009)
Simulation results

• Proton bunch can indeed to be used as the drive beam for exciting a large amplitude wakefield
• Proton driven PWFA can bring a bunch of electrons to the energy frontier in only one stage.
• An unsolved questions, short beam!
Bunch slicing via wakefield modulation

- Magnetic bunch compression: formidable RF power for energy chirp!
- Self-modulation via plasma wakefield (the transverse instability modulates the long bunch into many ultra short beamlets at plasma wavelength.)

SPS beam at 5m
Plasma @ 1e14 cm\(^{-3}\)

on-axis (X = 0) beam density profile after 5 m propagation in plasma
Plasma density in use: $7 \times 10^{14} \text{ cm}^{-3}$

<table>
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<tr>
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</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>Bunch population [$10^{11}$]</td>
<td>1.15</td>
<td>3.0</td>
</tr>
<tr>
<td>Beam radius [$\mu$m]</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Angular spread [mrad]</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Normalized emittance [$\mu$m]</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Bunch length [cm]</td>
<td>12</td>
<td>12.4</td>
</tr>
<tr>
<td>Energy spread [%]</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Demonstration experiment at CERN

- PDPWA has the potential to accelerate electron beam to the TeV scale in a single stage. As a first step, we would like to demonstrate the scaling laws of PDPWA in an experiment with an existing beam.
- Kick-off meeting-PPA09 held at CERN in December 2009.
- A spare SPS tunnel is available for demonstration experiment.
- With no bunch compression in the beginning.

Kick-off meeting 2009

old beam lines

beam dump

Schematic layout of PDPWA experiment (not to scale)

http://indico.cern.ch/conferenceDisplay.py?confId=745
http://cerncourier.com/cws/article/cern/41714
AWAKE Collaboration

AWAKE collaboration:
• Several workshops, phone meetings, and site visit at CERN, strong international collaboration (communications from plasmas, accelerators and particle physics);
• Submitted the Letter of Intent (LoI) in June 2011 to CERN SPSC;
• Proposal defended at 102 SPSC meeting on June, 2011
• AWAKE approval via CERN Research Board on 28 August, 2013.

"CERN is very interested in following and participating in novel acceleration techniques, and has as a first step agreed to make protons available for the study of proton-driven plasma wakefield acceleration."

Steve Myers
Former CERN Director of Accelerators & Technology
A proposed demonstration of an experiment of proton-driven plasma wakefield acceleration based on CERN SPS

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(Received 20 September 2011; accepted 2 January 2012)
CNGS location
AWAKE experiment @ CERN

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN

- Excavated
- Concreted
- Decay tube (2nd contract)

AWAKE experiment

~1100m

AWAKE beam dump
Layout of AWAKE experiment

Electron acceleration based on modulated proton driven wakefield acceleration!
Scientific goals

1. Demonstrate self-modulation effect of a long proton bunch and realize 1 GeV electron energy gain with a ~10 m plasma
2. Develop and test the diagnostic equipments for the first and later experiments
3. Benchmark data against simulation results
4. Provide inputs for future experiment for 100 GeV energy gain in 100 m plasma

- Inject 10-20 MeV electron beam
- Acceleration of electrons to multi-GeV energy range after the plasma exit.
Collider design based on PDPWA

Recent simulations have shown that a high-energy proton bunch can excite strong plasma wakefields and accelerate a bunch of electrons to the energy frontier in a single stage of acceleration. It therefore paves the way towards a compact future collider design using the proton beams from existing high-energy proton machines, e.g. Tevatron or the LHC. This paper addresses some key issues in designing a compact electron-positron linear collider and an electron-proton collider based on the existing CERN accelerator infrastructure.
Physics at high energies but low luminosity

Particle Physics at High Energies but Low Luminosities

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\textsuperscript{9} IZEST, Ecole Polytechnique, Paris, France

1 Introduction

The main focus of the particle physics community, when considering future accelerators, has been on high luminosity colliders since s-channel cross sections scale as $1/\sqrt{s}$, with $s$ the square of the center-of-mass energy. This focus has led to ILC, CLIC or Muon Collider parameter sets requiring luminosities in excess of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ for center-of-mass energies beyond 1 TeV. This requirement on the luminosity then leads to very demanding requirements on parameters such as beam sizes at the interaction point, repetition rate, etc., and huge power requirements. The former will be difficult to achieve technologically, while the latter will be very hard to justify in an age of diminishing energy resources and increasing energy costs.

Classicalization in electroweak processes; QCD and beyond Standard Model physics; Lorentz invariance and streaking the vacuum; Study of source of high energy cosmic rays; Many others…
Summary

- Simulation shows that proton--driven plasma wakefield acceleration holds promise to accelerate the electron bunch to beyond 500 GeV in one stage.
- Self--modulated proton bunch can drive a large amplitude wakefield for electron beam acceleration.
- AWAKE is the first proton-driven plasma wakefield acceleration in the world. It is also the first beam driven plasma wakefield acceleration experiment in Europe.
- AWAKE experiment will study the self modulated proton driven plasma wakefield acceleration; Proton beam from CNGS beam line will be used for the first experiment, expected in 2016.
- Further investigations are ongoing on the key issues such as accelerating positron beam, high repetition rate for high luminosity, beam instabilities, mobile ions, etc.
Thanks for your attention!
PWFA and PDPWA

Pros. of PWFA
Plasma electrons are expelled by space charge of beam, a nice bubble will be formed for beam acceleration and focusing.
The short electron beam is relatively easy to have (bunch compression). Wakefield phase slippage is not a problem.

Cons. of PWFA
One stage energy gain is limited by transformer ratio, therefore maximum electron energy is about 100 GeV using SLC beam.
Easy to be subject to the head erosion due to small mass of electrons.

Pros. of PDPWA
Very high energy proton beam are available today, the energy stored at SPS, LHC, Tevatron, HERA
SPS (450 GeV, 1.3e11 p/bunch) ~ 10 kJ
LHC (1 TeV, 1.15e11 p/bunch) ~ 20 kJ
LHC (7 TeV, 1.15e11 p/bunch) ~ 140 kJ
SLAC (50 GeV, 2e10 e-/bunch) ~ 0.1 kJ

Cons. of PDPWA
Flow-in regime responds a relatively low field vs. blow-out regime. Long proton bunches (~ ten cen8meters), bunch compression is difficult.
Wave phase slippage for heavy mass proton beam (small γ factor), especially for a very long plasma channel.
Plasma cells

Discharge: IST, Imperial College

Metal vapor, a la SLAC experiment: UCLA, Max Planck Institute for Physics

Helicon – Max Planck Institute for Plasma Physics