AWAKE : A proton-driven plasma wakefield acceleration experiment

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On behalf of the AWAKE Collaboration

- Motivation : particle physics; large accelerators
- General concept : proton-driven plasma wakefield acceleration
- AWAKE experiment at CERN
- Outlook
Motivation
Big questions in particle physics

 Particle accelerators have been crucial in elucidating the Standard Model.

 Culmination in 27-km long LHC (pp); a future $e^+e^-$ collider is planned to be 30–50-km long.

 Can we reduce their size and their costs?

 Ultimately, can we build a (up to) TeV-scale $e^+e^-$ collider of a few km in length?

The Standard Model is amazingly successful, but some things remain unexplained:

• what are the consequences of the “Higgs” particle discovery?
• why is there so much matter (vs anti-matter)?
• why is there so little matter (5% of Universe)?
• can we unify the forces?
Collider history

- t quark
- W/Z bosons
- Gluon
- $N_v = 3$

Diagram showing the history of collider experiments over time.
## Collider parameters e⁻ beam

<table>
<thead>
<tr>
<th></th>
<th>ILC</th>
<th>LHeC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy (GeV)</td>
<td>125</td>
<td>60</td>
</tr>
<tr>
<td>Bunch population</td>
<td>$2 \times 10^{10}$</td>
<td>$2 \times 10^9$</td>
</tr>
<tr>
<td>Number of bunches</td>
<td>1312</td>
<td></td>
</tr>
<tr>
<td>Bunch separation (ns)</td>
<td>554</td>
<td>25 or 50</td>
</tr>
<tr>
<td>Collision rate (Hz)</td>
<td>5</td>
<td>-</td>
</tr>
<tr>
<td>Energy spread</td>
<td>0.19%</td>
<td>0.03%</td>
</tr>
<tr>
<td>Horizontal emittance</td>
<td>10 µm</td>
<td>50 µm</td>
</tr>
<tr>
<td>Vertical emittance</td>
<td>35 nm</td>
<td>50 µm</td>
</tr>
<tr>
<td>Beam size</td>
<td>$729 \times 7.7$ nm²</td>
<td>$7 \times 7$ µm²</td>
</tr>
<tr>
<td>Luminosity $\times 10^{34}$ cm⁻²s⁻¹</td>
<td>0.75</td>
<td>0.1 (~1)</td>
</tr>
</tbody>
</table>

ILC TDR, June 2013
LHeC CDR, June 2012
Proton-driven plasma wakefield acceleration
PDPWA concept*

- Electrons ‘sucked in’ by proton bunch.
- Continue across axis creating a depletion region.
- Transverse electric fields focus witness bunch.
- Maximum accelerating gradient of 3 GV/m.

PDPWA concept

Proton beam impacting on a plasma to accelerate and electron witness beam

\[ E_e = 0.6 \ TeV \text{ from } E_p = 1 \ TeV \text{ in } 500 \ m \]
PDPWA concept

- Needs significant bunch compression < 100 µm (or new proton source).
- Challenges include: sufficient luminosities for an $e^+e^-$ machine, repetition rate, focusing, accelerating positrons, etc.

### Table 1 | Table of parameters for the simulation.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protons in drive bunch</td>
<td>$N_P$</td>
<td>$10^{11}$</td>
<td></td>
</tr>
<tr>
<td>Proton energy</td>
<td>$E_P$</td>
<td>1</td>
<td>TeV</td>
</tr>
<tr>
<td>Initial proton momentum spread</td>
<td>$\sigma_p/p$</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>Initial proton bunch longitudinal size</td>
<td>$\sigma_z$</td>
<td>100</td>
<td>µm</td>
</tr>
<tr>
<td>Initial proton bunch angular spread</td>
<td>$\sigma_\theta$</td>
<td>0.03</td>
<td>mrad</td>
</tr>
<tr>
<td>Initial proton bunch transverse size</td>
<td>$\sigma_{x,y}$</td>
<td>0.43</td>
<td>mm</td>
</tr>
<tr>
<td>Electrons injected in witness bunch</td>
<td>$N_e$</td>
<td>$1.5 \times 10^{10}$</td>
<td></td>
</tr>
<tr>
<td>Energy of electrons in witness bunch</td>
<td>$E_e$</td>
<td>10</td>
<td>GeV</td>
</tr>
<tr>
<td>Free electron density</td>
<td>$n_p$</td>
<td>$6 \times 10^{14}$</td>
<td>cm$^{-3}$</td>
</tr>
<tr>
<td>Plasma wavelength</td>
<td>$\lambda_p$</td>
<td>1.35</td>
<td>mm</td>
</tr>
<tr>
<td>Magnetic field gradient</td>
<td></td>
<td>1,000</td>
<td>T m$^{-1}$</td>
</tr>
<tr>
<td>Magnet length</td>
<td></td>
<td>0.7</td>
<td>m</td>
</tr>
</tbody>
</table>
The AWAKE experiment at CERN
Self-modulation of the proton beam

CERN SPS proton beam

- Proton bunch population, \( N_b \)
- Proton bunch length, \( \sigma_z \)
- Proton bunch radius, \( \sigma_r \)
- Proton energy, \( W_b \)
- Proton bunch relative energy spread, \( \delta W_b / W_b \)
- Proton bunch normalized emittance, \( \epsilon_{bn} \)

\[ \begin{align*}
3 \times 10^{11} \\
12 \text{ cm} \\
0.02 \text{ cm} \\
400 \text{ GeV} \\
0.35\% \\
3.5 \text{ mm mrad}
\end{align*} \]
Injection of witness electrons

Table 9) Baseline parameters of the AWAKE experiment

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notation</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma density</td>
<td>$n_e$</td>
<td>$7 \times 10^{14}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Plasma ion to electron mass ratio</td>
<td>$M_i$</td>
<td>9.777</td>
</tr>
<tr>
<td>Proton bunch population</td>
<td>$N_b$</td>
<td>$3 \times 10^{11}$</td>
</tr>
<tr>
<td>Proton bunch length</td>
<td>$\sigma_z$</td>
<td>90 cm</td>
</tr>
<tr>
<td>Proton bunch radius</td>
<td>$\sigma_r$</td>
<td>75 \mu m</td>
</tr>
<tr>
<td>Proton energy</td>
<td>$W_b$</td>
<td>77 GeV</td>
</tr>
<tr>
<td>Proton bunch relative energy spread</td>
<td>$\delta W_b / W_b$</td>
<td>75.0 %</td>
</tr>
<tr>
<td>Proton bunch normalized emittance</td>
<td>$\epsilon_{bn}$</td>
<td>0.5 mm mrad</td>
</tr>
<tr>
<td>Electron bunch population</td>
<td>$N_e$</td>
<td>1.25 $\times 10^9$</td>
</tr>
<tr>
<td>Electron bunch length</td>
<td>$\sigma_{ze}$</td>
<td>0.25 cm</td>
</tr>
<tr>
<td>Electron bunch radius at injection point</td>
<td>$\sigma_{re}$</td>
<td>0.02 cm</td>
</tr>
<tr>
<td>Electron energy</td>
<td>$W_e$</td>
<td>16 MeV</td>
</tr>
<tr>
<td>Electron bunch normalized emittance</td>
<td>$\epsilon_{en}$</td>
<td>2 mm mrad</td>
</tr>
<tr>
<td>Injection angle for electron beam</td>
<td>$\phi$</td>
<td>9 mrad</td>
</tr>
<tr>
<td>Injection delay relative to the laser pulse</td>
<td>$\xi_0$</td>
<td>13.6 cm</td>
</tr>
<tr>
<td>Intersection of beam trajectories</td>
<td>$z_0$</td>
<td>3.9 m</td>
</tr>
</tbody>
</table>

Fig 5) Energy spectrum of electrons side injected near $z \sim 4$ m with 9 MeV energy and accelerated until $z = 10$ m. The spectrum is narrow, $\sim 3\%$ width, and centered around 0 GeV. Gradients. Once trapped by the plasma wave, the electron bunch is very sensitive to the wakefield phase in which it resides. The wakefield phase is determined by the plasma density that must be constant with an accuracy $\propto \lambda_{pe} / 4 \sigma_z$ or $\sim 0.2\%$ for our baseline parameters. To provide this accuracy, instant ionization of a thermal equilibrium gas was chosen as the baseline design of the plasma cell. The final electron bunch parameters are not very sensitive to the injection parameters; see the Technical Note for more details. Injection at angles or energies which are $\pm 30\%$ of the optimum values results in roughly twofold reduction of the bunch charge. The good window in the other two parameters is $\sim \pm 0.25$ m for the injection point along the plasma and $\sim \pm 1$ cm for the injection delay with respect to the ionizing laser pulse.

Layout of AWAKE experiment

- Laser power supplies
- Access gallery
- Lasers
- Electron gun
- Klystron system
- Proton beam line
- Laser & proton beam junction
- Electron beam line
- Plasma cell (10m long)
- Electron spectrometer
- Experimental Diagnostics
- CNGS target area

Items in **dark blue**: ventilation ducts
Items in **light blue**: AWAKE electronic racks
Items in **cyan**: existing CNGS equipment (cable trays, pipes, …)
Plasma source

Three possibilities:
• Rubidium vapour
• Helicon cell
• Discharge cell

Must satisfy:
• length ~ 10 m
• density $10^{14} - 10^{15}$ cm$^{-3}$
• uniformity ~ 0.2%

• Synthetic oil surrounding Rb for temperature stability
• Vacuum tube surrounding oil suppressing heat loss
• Need 1 – 2 TW laser with 30 – 100 fs pulse
Diagnostics

Electron spectrometer

Some examples, also looking at others, CTR, photon acceleration, THz diagnostics, ...

OTR and TCTR

- Use 1 m, 1.8 T magnet.
- Can measure wide range of energies.

AWAKE Collaboration and practicalities

Collaboration of accelerator, plasma and particle physicists and engineers formed.

AWAKE Design Report

A Proton-Driven Plasma Wakefield Acceleration Experiment at CERN

AWAKE Collaboration

Abstract

The AWAKE Collaboration has been formed in order to demonstrate proton-driven plasma wakefield acceleration for the first time. This technology could lead to future colliders of high energy but of a much reduced length compared to proposed linear accelerators. The SPS proton beam in the CNGS facility

9.2.1 Institutes Committed to AWAKE

- ASTeC, STFC Daresbury Laboratory, Warrington, UK
- Budker Institute of Nuclear Physics (BINP), Novosibirsk, Russia
- CERN, Geneva, Switzerland
- Cockroft Institute (CI), Daresbury, UK
- Heinrich Heine University, Düsseldorf (D), Germany
- Instituto Superior Técnico, Lisboa (IST), Portugal
- Imperial College (IC), London, UK
- Ludwig Maximilian University (LMU), Munich, Germany
- Max Planck Institute for Physics (MPP), Munich, Germany
- Max Planck Institute for Plasma Physics (IPP), Greifswald, Germany
- Rutherford Appleton Laboratory (RAL), Chilton, UK
- University College London (UCL), London, UK
- University of Strathclyde (S), Glasgow, Scotland, UK

More institutes committing.

Now a (fully) approved CERN project; on their Medium-Term Plan and significant funding.

- Expect first protons to plasma cell end of 2016
- Expect electron injection end of 2017
- Periods of running for 3 – 4 years
Outlook
The future

- Consider intermediate stage to possible “full” experiment.
- Consider compressing proton beam—magnetic compression, cutting the beam into slices, etc..
- Ultimate goal of application to future collider.

Could be used for:

- $ep$ ($60 \times 7000$ GeV) LHeC collider
- TeV-scale $e^+e^-$ collider

**Electron energy gain**

Summary

- Plasma wakefield acceleration could have a huge impact on many areas of science and industry using particle accelerators.
- Presented an idea to have a high energy lepton collider based on proton-driven plasma wakefield acceleration.
- Proof-of-principle AWAKE experiment at CERN.
- To realise a TeV-scale lepton collider a factor of ~ 10 shorter than current designs.