Using the AWAKE acceleration scheme for beam-dump experiments

Matthew Wing (UCL)

• Introduction and motivation for AWAKE
• Possible physics experiments
  • Possible ideas
  • Search for dark photons, NA64-like
• Summary and discussion

Introduction: limits on accelerators

- The use of (large) accelerators has been central to advances in particle physics.
- Culmination in 27-km long LHC ($pp$); e.g. a future $e^+e^-$ collider planned to be 30–50-km long.
- The high energy frontier is (very) expensive; can we reduce costs? Can we develop and use new technologies?
- Accelerators using RF cavities limited to ~100 MV/m; high energies → long accelerators.
- The Livingston plot shows a saturation …
Plasma wakefield acceleration as a solution

- Plasma wakefield acceleration is a promising scheme as a technique to realise shorter or higher energy accelerators in particle physics.
- Accelerating gradients achieved in the wakefield of a plasma are very high (3 orders of magnitude more than RF acceleration and up to 100 GV/m).
- Proton-driven plasma wakefield acceleration* is well-suited to high energy physics applications. Higher stored energy, ability to drive wakefields over long lengths.

\[ E_e = 0.5 \text{ TeV from } E_p = 1 \text{ TeV in 300 m} \]

Note proton bunch length, 100 µm; cf LHC, bunch length, ~10 cm

Plasma wakefield acceleration

- Electrons ‘sucked in’ by proton bunch
- Continue across axis creating depletion region
- Oscillation of plasma electrons creates strong electric fields
- Longitudinal electric fields can accelerate particles in direction of proton bunch
- Transverse electric fields can focus particles
- A ‘witness’ bunch of e.g. electrons placed appropriately can be accelerated by these strong fields
- But proton bunches are not “short” …
Long proton bunches?

Use self-modulation instability where micro-bunches are generated by a transverse modulation of the bunch density.


- Micro-bunches are spaced $\lambda_p$ apart and have an increased charge density.
- Micro-bunches constructively reinforce to give large wakefields, $GV/m$.
- Self-modulation process allows current beams to be used.
AWAKE experiment at CERN

- Demonstrate for the first time proton-driven plasma wakefield acceleration.

- Advanced proton-driven plasma wakefield experiment.

- Using 400 GeV SPS beam in former CNGS target area.

Direct measurement of self-modulation

Laser off, no plasma

• Events stitched together.
• Clear modulation of the proton bunch.
• Highly reproducible phase between the bunches (and events).
• Crucial for injection of electrons.
Electron acceleration

Clear signals

AWAKE Coll. (E. Adli et al.),

Reproducible acceleration
Electron acceleration energy dependence

- Acceleration to 2 GeV is a great achievement.
- Simulation/theory predicted similar energy gains.
- Experiment not optimised for electron injection: accelerated charge (~0.25 pC) is low; already increased value.

**AWAKE Run 1 achieved all of its original goals and more**
AWAKE Run 2

  - Accelerate electron bunch to higher energies (~10 GeV).
  - Demonstrate beam quality preservation.
  - Demonstrate scalability of plasma sources.

Preliminary Run 2 electron beam parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acc. gradient</td>
<td>&gt;0.5 GV/m</td>
</tr>
<tr>
<td>Energy gain</td>
<td>10 GeV</td>
</tr>
<tr>
<td>Injection energy</td>
<td>≥ 50 MeV</td>
</tr>
<tr>
<td>Bunch length, rms</td>
<td>40–60 μm (120–180 fs)</td>
</tr>
<tr>
<td>Peak current</td>
<td>200–400 A</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>67–200 pC</td>
</tr>
<tr>
<td>Final energy spread, rms</td>
<td>few %</td>
</tr>
<tr>
<td>Final emittance</td>
<td>≤ 10 μm</td>
</tr>
</tbody>
</table>

- Goal: after Run 2, in a position to provide beam for particle physics experiments
- Are there experiments that require an electron beam of up to $O(50 \text{ GeV})$?
- Using the LHC beam as a driver, TeV electron beams are possible.

E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008).
Possible particle physics experiments I

- Use of electron beam for test-beam campaigns.
  - Test-beam infrastructure for detector characterisation often over-subscribed.
  - Also accelerator test facility. Also not many world-wide.
  - Characteristics: variation of energy, provide pure electron beam, short bunches.
- Fixed-target experiments using electron beams, e.g. deep inelastic electron–proton scattering.
  - Measurements at high $x$, momentum fraction of struck parton in the proton, with higher statistics than previous experiments. Valuable for LHC physics.
  - Polarised beams and spin structure of the nucleon. The “proton spin crisis/puzzle” is still a big unresolved issue.
- Investigation of strong-field QED at the Schwinger limit in electron–laser interactions.
  - New regime for QED.
  - Can constrain more exotic physics (e.g. dark photons).
Possible particle physics experiments II

- **Search for dark photons à la NA64**

- **High energy electron–proton collider**
  - A low-luminosity LHeC-type experiment: $E_e \sim 50$ GeV, beam within 50–100 m of plasma driven by SPS protons; low luminosity, but much more compact.
  - A very high energy electron–proton (VHEeP) collider with $\sqrt{s} = 9$ TeV, $\times 30$ higher than HERA. Developing physics programme.

- **Acceleration of muons.**

These experiments will probe exciting areas of physics and will really profit from an AWAKE-like electron beam.

Interested to hear of other possibilities.

- **Demonstrate an accelerator technology also doing cutting-edge particle physics**

Using a new technology

Fixed-target → High $E$ $ep$ collider → High $E$, high lumi $e^+e^-$ collider
The hidden / dark sector

- Baryonic (ordinary) matter constitutes ~5% of known matter.
  - What is the nature of dark matter? Why can we not see the dominant constituent of the Universe?

- LHC Run 1 (and previous high energy colliders) have found no dark matter candidates so far.

- LHC Run 2 to continue that search looking for heavy new particles such as those within supersymmetry.

- Also direct detection experiments looking for recoil from WIMPs

- There are models which postulate light (GeV and below) new particles which could be candidates for dark matter.

- There could be a dark sector which couples to ordinary matter via gravity and possibly other very weak forces.

- Could e.g. explain $g-2$ anomaly between measurement and the Standard Model.
Dark photons

A light vector boson, the “dark photon”, $A'$, results from a spontaneously broken new gauge symmetry, $U(1)_D$.

The $A'$ kinetically mixes with the photon and couples primarily to the electromagnetic current with strength, $\varepsilon e$

Growing field of experiments with many running or starting or proposed at JLab, SLAC, INFN, Mainz, etc.

\[
\Delta \mathcal{L} = \frac{\varepsilon}{2} F_{\mu \nu}^{Y, \mu \nu} F'_{\mu \nu}
\]
NA64 experimental programme

- Initial run in SPS beam focusing on $A' \rightarrow \text{invisible}$ channel.
- Also programme measuring $A' \rightarrow e^+ e^-$ channel.

Signature:
- Initial 100 GeV $e^-$ track
- Final < 50 GeV $e^-$ shower in ECAL
- No energy in the veto or HCAL

- NA64 detector for $A' \rightarrow \text{invisible}$ channel.
- Backgrounds essentially zero.
- Similar detector for $A' \rightarrow e^+ e^-$ channel with signature of two EM showers after gap when initial $e^-$ hits target.
NA64 searches

Invisible mode, $A' \rightarrow \chi \bar{\chi}$

Visible mode, $A' \rightarrow e^+ e^-$

NA64 searches covering significant areas and addressing “new physics” issues.


Electrons on target using AWAKE scheme

NA64 receives about $10^6$ $e^-$/spill or $2 \times 10^5$ $e^-$/s from SPS secondary beam:

- $N_e \sim 10^{12}$ $e^-$ for 3 months running.
- Optimisation of SPS beam could lead to up to NA64: $N_e \sim 5 \times 10^{12}$ $e^-$.  

AWAKE-like beam with bunches of $(1-5) \times 10^9$ $e^-$:  

- 16 or 320 bunches every 40 s.
- 3 months running with 70% efficiency  
- **AWAKE+NA64**: $N_e \sim 2 \times 10^{15} - 2 \times 10^{17}$ $e^-$

Will assume that an AWAKE-like beam could provide an effective upgrade to the NA64 experiment, increasing the intensity by a factor of > 1000.
An experiment in the AWAKE area

About 100 m available in old CNGS target area. Would need a clean out.
Possible ways to reduce accelerator length:

- Try to use high plasma density with existing proton beam.
- Improved SPS beam transverse emittance: higher beam density means higher wakefields in more dense plasma.
- Use more efficient micro-bunching technique.

More work ongoing on infrastructure issues and accelerator configuration.
Sensitivity with increased electrons on target

- Have taken plots of mixing strength, $\varepsilon$, versus mass, $m_{A'}$, from NA64 studies/proposals and added curves to show increased sensitivity.
- Simulation from NA64 (theory and experimental layout)
- Modified detector for different configuration; note that this idea uses bunches, rather than single electrons
- Considered $A' \rightarrow e^+ e^-$ channel.
- Analysis based on well separated tracks (due to dipole) on trackers (MM1–3).
- Vertex reconstruction and invariant mass.

![Diagram of experiment setup]

50 GeV
$5 \times 10^9$ electron bunch
Tungsten target width, 10 cm
decay volume ~ 10 m

MM1  MM2  MM3
Magnet
ECAL

23 cm
Limits on dark photons, $A' \rightarrow e^+ e^-$ channel

- For $10^{10} - 10^{13}$ electrons on target with NA64.
- For $10^{16}$ electrons on target with AWAKE-like beam.
- Using an AWAKE-like beam would extend sensitivity further:
  - around $\varepsilon \sim 10^{-3} - 10^{-5}$.
  - to high masses $\sim 0.1$ GeV.
- Input into the CERN Physics Beyond Colliders study:
  - in combined plots assembling all possible experiments.
  - submit to European Strategy process.

A. Hartin (UCL)
Further studies

- More study of backgrounds needed.
- More study of possible detector configurations.
- Could consider other channels, e.g. \( A' \rightarrow \mu^+ \mu^-, A' \rightarrow \pi^+ \pi^- \).
- More careful study of optimal beam energy needed.

According to simulations, TeV region is possible.

TeV electrons would have more applications, including dark photons.


Summary and discussion

• The AWAKE collaboration has demonstrated acceleration of electrons in proton-driven plasma wakes.

• AWAKE has an exciting programme of R&D aiming to develop a useable accelerator technology.

• Have started to consider realistic applications to novel and interesting particle physics experiments:
  - Investigation of strong-field QED.
  - Fixed-target/beam-dump experiments in particular those sensitive to dark photons.
    - Electron–proton collider up to very high energies.

• Emphasis what can be done with proton-driven scheme using CERN infrastructure.

• Work ongoing studying boundary conditions / possibilities from physics, technical and integration side, e.g. de-phasing limit, repetition rate, tunnel space, etc..

• A high-energy high-charge electron bunch complements other dark photon searches.

• Welcome other ideas on what could be done with AWAKE scheme.
Back-up
Plasma considerations

Based on linear fluid dynamics:

\[ \omega_p = \sqrt{\frac{n_p e^2}{\varepsilon_0 m_e}} \]

\[ \lambda_p \approx 1 \text{[mm]} \sqrt{\frac{10^{15} \text{[cm}^{-3}] }{n_p}} \quad \text{or} \quad \approx \sqrt{2 \pi \sigma_z} \]

\[ E \approx 2 \text{[GV m}^{-1}] \left( \frac{N}{10^{10}} \right) \left( \frac{100 \text{[}\mu\text{m}]}{\sigma_z} \right)^2 \]

Relevant physical quantities:

- Oscillation frequency, \( \omega_p \)
- Plasma wavelength, \( \lambda_p \)
- Accelerating gradient, \( E \)

where:

- \( n_p \) is the plasma density
- \( e \) is the electron charge
- \( \varepsilon_0 \) is the permittivity of free space
- \( m_e \) is the mass of electron
- \( N \) is the number of drive-beam particles
- \( \sigma_z \) is the drive-beam length

High gradients with:

- **Short drive beams** (and short plasma wavelength)
- **Pulses with large number of particles** (and high plasma density)

Plasma wakefield experiments

- Pioneering work using a LASER to induce wakefields up to 100 GV/m.
- Experiments at SLAC§ have used a particle (electron) beam:
  - Initial energy $E_e = 42$ GeV
  - Gradients up to $\sim 52$ GV/m
  - Energy doubled over $\sim 1$ m
- Next stage, FACET project (http://facet.slac.stanford.edu)
- Have proton beams of much higher energy:
  - CERN: 450 GeV and 6.5 (7) TeV
  - Can accelerate trailing electron bunch to high energy in one stage

Proton-driven plasma wakefield acceleration concept*

Note proton bunch length, 100 µm; cf LHC, bunch length, ~10 cm

$E_e = 0.5$ TeV from $E_p = 1$ TeV in 300 m

AWAKE experimental programme (Run I)

Phase 1: understand the physics of self-modulation instability process in plasma

Started

Start with physics Q4 2016!

AWAKE experimental programme (Run I)

Phase 2: probe the accelerating wakefields with externally injected electrons.

Demonstrate GeV acceleration of electrons with proton-driven wakefields of GV/m

Start with physics Q4 2017!
Transverse beam profile with **no plasma**

Screen composed of two materials

Transverse blow-up of proton beam indicative of strong electric fields.
Search for dark photons

• Several ways to look for dark photons:
  - A: bump-hunting, e.g. $e^+e^- \rightarrow \gamma A'$
  - B: displaced vertices, short decay lengths
  - C: displaced vertices, long decay lengths

- Search for dark photons, $A'$, up to (and beyond) GeV mass scale via their production in a light-shining-through-a-wall type experiment.
- Use high energy electrons for beam-dump and/or fixed-target experiments.

J. Alexander et al., arXiv:1608.08632
Strong-field QED

- Quantum mechanics and QED has been investigated and measured with amazing precision in many experiments and high-precision predictions describe this well.
  - However the strong-field regime, where QED becomes non-perturbative, has still not been measured.
- The strong field regime was already considered by Heisenberg, Euler et al. in 1930s.
- Characterised by the Schwinger critical field (1951):
  \[ E_{\text{crit}} = \frac{mc^2}{e\chi_C} = \frac{m^2c^3}{e\hbar} = 1.3 \times 10^{16} \text{ V/cm} \]

- This has not been reached experimentally, although they are expected to exist:
  - On the surface of neutron stars.
  - In bunches of future linear $e^+e^-$ colliders.
- Can be reached by colliding photons with a high-energy electron beam
  - Pioneering experiment E144 @ SLAC in 1990s.
- Given increase in laser power, investigate QED in an unexplored region.
Non-linear QED processes

- Initial interest in two strong-field processes in the interaction of electron beam with high-power laser pulse.
  - Non-linear Compton scattering where multiple laser photons are absorbed and a single photon radiated.
  - One or more such Compton scatters happen.
  - Produced photon interacts with laser field to produce electron–positron pair (Breit–Wheeler)

$$e^- + n\gamma \rightarrow e^- + \gamma$$

$$\gamma + n\gamma \rightarrow e^+ + e^-$$

$E_{\text{crit}} = m_e^2 c^3 e \bar{h} = 1.3 \times 10^{16}$ V/cm

$$\lambda = eE / m_e c \approx 2 E / m_e c^2 E_{\text{crit}}$$

$$E_{\text{beam}} (1 - \cos \theta) m_e c^2 E / E_{\text{crit}}$$

Pair production

Compton
E144 experiment at SLAC

- Used 46.6 GeV electron beam (Final Focus Test Beam) with $5 \times 10^9$ electrons per bunch up to 30 Hz.
- Terawatt laser pulses with intensities of $\sim 0.5 \times 10^{18} \text{ W/cm}^2$ and frequency of 0.5 Hz for wavelengths 1053 nm and 527 nm.
- Electron bunch and laser collided with 17° crossing angle.

New strong-field QED experiments

• New experiments being performed/considered
  - In LWFA with few-GeV electrons and laser.
  - Using FACET and EU.XFEL 10–20 GeV electrons and laser.
  - Using higher-power lasers compared to E144@SLAC.

• Could also be an application of an AWAKE-like bunch
  - Unique feature would be the higher electron energies and hence higher $\sqrt{s}$.
  - Sensitive to different processes.
  - Can constrain more exotic physics (e.g. dark photons).