Application of AWAKE acceleration scheme to high energy physics experiment

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• Introduction to AWAKE
• Beam properties and “Luminosity” for the SPS as a driver
• Possible experiments with AWAKE scheme
• Search for dark photons
• $ep$ colliders
• Summary
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.

- AWAKE was approved as a CERN project in August 2013.
- Demonstrate and understand self-modulation of long proton bunch [2016–8].
- Sample high-gradient wakefields with electron bunch and accelerate to \(O(\text{GeV})\) [2018].
- AWAKE Run 2 [2021–4].
- Then HEP applications …
Modulation of proton bunch
• Clear defocusing of proton bunch.
• Clear modulation of proton bunch.
  › Met first milestone of demonstration of self-modulation of long proton bunch.


Electron acceleration in AWAKE


- Observed up to 2 GeV
- Data taken in May and published in Nature in August
- Meeting of other major milestone.
- Other studies and measurements ongoing as is preparing for AWAKE Run 2…
AWAKE Run 2

  - Accelerate electron bunch to higher energies.
  - 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).
Input to the European Particle Physics Strategy Update

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Using the SPS for high energy electrons

- Bunches of electrons with $O(50 \text{ GeV})$ each accelerated in 50–100 m plasma.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AWAKE-upgrade-type</th>
<th>HL-LHC-type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton energy $E_p$ (GeV)</td>
<td>400</td>
<td>450</td>
</tr>
<tr>
<td>Number of protons per bunch $N_p$</td>
<td>$3 \times 10^{11}$</td>
<td>$2.3 \times 10^{11}$</td>
</tr>
<tr>
<td>Longitudinal bunch size protons $\sigma_z$ (cm)</td>
<td>6</td>
<td>7.55</td>
</tr>
<tr>
<td>Transverse bunch size protons $\sigma_r$ ($\mu$m)</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>Proton bunches per cycle $n_p$</td>
<td>8</td>
<td>320</td>
</tr>
<tr>
<td>Cycle length (s)</td>
<td>6</td>
<td>20</td>
</tr>
<tr>
<td>SPS supercycle length (s)</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Electrons per cycle $N_e$</td>
<td>$2 \times 10^9$</td>
<td>$5 \times 10^9$</td>
</tr>
</tbody>
</table>

Table 2: Potential achievable number of electrons on target for an AWAKE-based fixed target experiment for two different drive beam configurations. Assumes a 12 week experimental period with a 70% SPS duty cycle.

- Estimate of number of electrons on target for dark photon searches.
- Can also be used for other experiments, e.g. deep inelastic scattering, etc.
- If use LHC as a driver, can have $O(\text{TeV})$ electron beams.
Possible experiments

- Searches for dark photons (à la NA64) with high energy electrons.
- Investigation of strong-field QED
  - Can measure non-linear QED, e.g. $\gamma + n\gamma \rightarrow e^+e^-$ in $e\gamma$ or $\gamma\gamma$ collisions in which a laser provides a strong field.
  - Complement efforts at EuXFEL, FACET-II and in laser wakefield studies
- Deep inelastic $ep/eA$ collisions with:
  - $\sqrt{s} = 1.2$ TeV for $E_e = 50$ GeV using SPS as a plasma driver
  - $\sqrt{s} = 9.2$ TeV for $E_e = 3$ TeV using LHC as a plasma driver
  - or fixed-target variants with these electron beams
- The FCC protons would be very effective plasma drivers.
  - Introduce plasma cells in straight section for multi-TeV electrons.
  - Possible to have $> 50$ GeV electrons with minimal disturbance of protons.
- Acceleration of muons to high energies.
  - “Fast” (> GV/m) acceleration could get muons to high energies.
  - Should be considered further.
- More ideas welcome…
Search for dark photons using an AWAKE-like beam

• NA64 are making great progress investigating the dark sector:
  ‣ Dark sectors with light, weakly-coupling particles are a compelling possibility for new physics.
  ‣ Search for dark photons, \( A' \), up to 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.

• An AWAKE-like beam will have higher intensity than the SPS secondary beam.
• Provide upgrade/extension to NA64 programme.
• Using NA64 software and similar detectors.
Dark photons search, $A' \rightarrow e^+ e^-$ channel

- For $10^{10} - 10^{13}$ electrons on target with NA64.
- For $(10^{15}$ and $)10^{16}$ 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.
- At 1 TeV goes to even higher masses:
  - similar $\varepsilon$ values.
  - approaching 1 GeV.
  - beyond any other planned experiments.
Dark photons search

Global plots

• Expect significant development in the field in the next decade.
• AWAKE can play a role.

Future studies

- Still much to look at for the dark photon search
  - Optimised beam properties, energy, e.o.t., etc.
  - Look at other channels, e.g. $A' \rightarrow \mu^+\mu^-$, $A' \rightarrow \pi^+\pi^-$, $A' \rightarrow \chi\chi$
  - Optimisation of detector size and parts.
  - Better consideration of backgrounds.

- Work will continue.
PEPIC

- PEPIC: Plasma Electron Proton/Ion Collider

*Figure 5:* Schematic layout of the AWAKE++ PEPIC facility (not to scale).

- Use SPS as driver for $E_e = 50$ GeV and $\sqrt{s} = 1.2$ TeV ($E_p = 7$ TeV), but with modest luminosities, $O(10^{27} \text{ cm}^{-2} \text{ s}^{-1})$; look into ways of increasing luminosity.

- Possible ideas for accelerator design and integration be considered

- Interesting should the LHeC not go ahead.
VHEeP

- VHEeP: Very high energy electron proton collider
- Use LHC as driver for $E_e = 3 \text{ TeV}$ and $\sqrt{s} = 9.2 \text{ TeV}$, but with modest luminosities, $O(10^{28}-10^{29} \text{ cm}^{-2} \text{ s}^{-1})$; looking into ways of increasing.
- Completely new regime; exciting physics potential
- Revolutionise QCD; new theories; links to gravity, cosmic rays, etc..

![Diagram of VHEeP and LHC](image-url)
Summary

• The AWAKE experiment has had a very successful 2018.

• The application of the AWAKE scheme to particle physics experiments has been advancing well:
  - An increased number of electrons on target can lead to a competitive search for dark photons.
  - Facility and integration issues have been addressed for a fixed-target/beam-dump experiment and for an $ep$ collider.
  - There is a novel $ep$ physics programme to be pursued.
  - Other ideas have been proposed and hopefully more will come.

• Work will continue on these studies, also as we learn more from the AWAKE experiment.
Back-up, extra
AWAKE spectrometer
Electron acceleration reproducibility
Very high energy electron–proton collisions, VHEeP

• What about very high energies in a completely new kinematic regime?
• Choose $E_e = 3$ TeV as a baseline for a new collider with $E_p = 7$ TeV ⇒ $\sqrt{s} = 9$ TeV.
• Acceleration of electrons in under 4 km.
• Can vary the energy.
• Centre-of-mass energy $\times 30$ higher than HERA.
• Reach in (high) $Q^2$ and (low) Bjorken $x$ extended by $\times 1000$ compared to HERA.


Idea presented at various workshops and published recently*. Also had a workshop to expand physics case:

https://indico.mpp.mpg.de/event/5222/overview

Vector meson cross sections

Strong rise with energy related to gluon density at low $x$.

Can measure all particles within the same experiment.

Comparison with fixed-target, HERA and LHCb data—large lever in energy.

At VHEeP energies, $\sigma(J/\psi) > \sigma(\phi)$!

Onset of saturation?

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Virtual-photon–proton cross section

- Cross sections for all $Q^2$ are rising; again luminosity not an issue, will have huge number of events.
- Depending on the form, fits cross; physics does not make sense.
- Different forms deviate significantly from each other.
- VHEeP has reach to investigate this region and different behaviour of the cross sections.
- Can measure lower $Q^2$, i.e. lower $x$ and higher $W$.
- Unique information on form of hadronic cross sections at high energy.

VHEeP will explore a region of QCD where we have no idea what is happening.
Some highlights:

• Observe saturation; theory of hadronic interactions (Bartels, Mueller, Stodolsky, etc.)
• Relation of low-x physics to cosmic rays (Stasto); to black holes and gravity (Erdmenger); and to new physics descriptions (Dvali, Kowalski)
• Status of simulations (Plätzer)
• Challenge of the detector (Keeble)
• What understood from HERA data (Myronenko)
**Leptoquark production**

Electron–proton colliders are the ideal machine to look for leptoquarks. 

s-channel resonance production possible up to $\sqrt{s}$.

\[ \sigma^{NWA} = (J + 1) \frac{\pi}{4s} \lambda^2 q(x_0, M_{LQ}^2) \]

Sensitivity depends mostly on $\sqrt{s}$ and $VHE\text{e}P = 30 \times \text{HERA}$
Leptoquark production at VHEeP

- Assumed $L \sim 100 \text{ pb}^{-1}$
- Required $Q^2 > 10,000 \text{ GeV}^2$ and $y > 0.1$

Generated “data” and Standard Model “prediction” using ARIADNE (no LQs).

Sensitivity up to kinematic limit, 9 TeV.

As expected, well beyond HERA limits and significantly beyond LHC limits and potential.