Plasma Wakefield Acceleration and the AWAKE Experiment

CAS@ ESI: Basics of Accelerator Physics and Technology
7 – 11 October 2019, Archamps, France

Edda Gschwendtner, CERN
Outline

• Motivation

• Introduction to Plasma Wakefield Acceleration

• State of the Art

• The AWAKE Experiment
Discover New Physics

Accelerate particles to even higher energies

→ Bigger accelerators: circular colliders

Future Circular Collider: FCC

Limitations of conventional circular accelerators:

• For hadron colliders, the limitation is magnet strength. Ambitious plans like the FCC call for 16 T magnets in a 100 km tunnel to reach 100 TeV proton-proton collision energy.

• For electron-positron colliders: Circular machines are limited by synchrotron radiation in the case of positron colliders. These machines are unfeasible for collision energies beyond ~350 GeV. 

\[ P_{\text{synch}} = \frac{e^2}{6\pi \varepsilon_0 c^7} \frac{E^4}{R^2 m^4} \]
Discover New Physics

**Linear colliders** are favorable for acceleration of low mass particles to high energies.

**CLIC**, electron-positron collider with 3 TeV energy

**Limitations of linear colliders:**
- Linear machines accelerate particles in a **single pass**. The amount of acceleration achieved in a given distance is the **accelerating gradient**. This number is **limited to 100 MV/m** for conventional copper cavities.
Conventional Acceleration Technology

Radiofrequency Cavities

A voltage generator induces an electric field inside the RF cavity. Its voltage oscillates with a radio frequency of 400 MHz.

Protons in LHC

Protons never feel a force in the backward direction.

Protons always feel a force in the forward direction.

LHC Cavity

(invention of Gustav Ising 1924 and Rolf Wideroe 1927)
Conventional Accelerating Technology

Today’s RF cavities or microwave technology:

• Very successfully used in all accelerators (hospitals, scientific labs,...) in the last 100 years.

• Typical gradients:
  • LHC: 5 MV/m
  • ILC: 35 MV/m
  • CLIC: 100 MV/m

However:

• accelerating fields are limited to <100 MV/m
  • In metallic structures, a too high field level leads to break down of surfaces, creating electric discharges.
  • Fields cannot be sustained, structures might be damaged.

• several tens of kilometers for future linear colliders
Saturation at Energy Frontier for Accelerators

Project size and cost increase with energy

Livingston plot
Plasma Wakefield Acceleration

⇒ Acceleration technology, which obtains ~1000 factor stronger acceleration than conventional technology.
Conventional vs. Plasma

**PLC - Plasma Linear Collider**
(e+e- up to 3 TeV c.m.)

**ILC - International Linear Collider**
(phase 1 to full, e+e- up to 1 TeV c.m.)

**CLIC** (similar footprint for up to 3 TeV c.m.)

**FCC - Future Circular Collider**
(e+e- up to 0.35 TeV c.m., 100 km version)

**SPS** (injector to TLEP)

**LEP/LHC**
(injector to FCC)

**LHeC**
(e+p, ERL)

R&D on feasibility ongoing
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Seminal Paper 1979, T. Tajima, J. Dawson

Use a plasma to convert the transverse space charge force of a beam driver into a longitudinal electrical field in the plasma.
Plasma Wakefield

What is a plasma?

Quasi-neutrality: the overall charge of a plasma is about zero.

Collective effects: Charged particles must be close enough together that each particle influences many nearby charged particles.

Electrostatic interactions dominate over collisions or ordinary gas kinetics.

What is a plasma wakefield?

Fields created by collective motion of plasma particles are called plasma wakefields.
Plasma Baseline Parameters

• A plasma of density \( n_{pe} \) is characterized by the plasma frequency

\[
\omega_{pe} = \sqrt{\frac{n_{pe} e^2}{m_e \varepsilon_0}} \rightarrow \frac{c}{\omega_{pe}} \quad \text{... unit of plasma [m]} \quad k_{pe} = \frac{\omega_{pe}}{c}
\]

Example: \( n_{pe} = 7 \times 10^{14} \text{ cm}^{-3} \) (AWAKE) \( \Rightarrow \) \( \omega_{pe} = 1.25 \times 10^{12} \text{ rad/s} \) \( \Rightarrow \) \( \frac{c}{\omega_{pe}} = 0.2 \text{mm} \) \( \Rightarrow \) \( k_{pe} = 5 \text{ mm}^{-1} \)

• This translates into a wavelength of the plasma oscillation

\[
\lambda_{pe} = 2\pi \frac{c}{\omega_{pe}} \rightarrow \lambda_{pe} \approx 1 \text{ mm} \sqrt{\frac{10^{15} \text{ cm}^{-3}}{n_{pe}}}
\]

\( \lambda_{pe} = 1.2 \text{ mm} \) \( \Rightarrow \) Produce cavities with mm size!
How to Create a Plasma Wakefield?

Analogy:
water → plasma
Boat → particle beam (drive beam)
Surfer → accelerated particle beam (witness beam)
How to Create a Plasma Wakefield?

**What we want:**
Longitudinal electric field to accelerate charged particles.

**Our Tool:**
List of ions forming a plasma.

Using plasma to convert the **transverse electric field** of the drive bunch into a **longitudinal electric field in the plasma**. The more energy is available, the longer (distance-wise) these plasma wakefields can be driven.

**Charged particle bunches** carry almost purely transverse Electric Fields.
Principle of Plasma Wakefield Acceleration

- **Laser drive beam**
  - ➔ Ponderomotive force

- **Charged particle drive beam**
  - ➔ Transverse space charge field
    - Reverses sign for negatively (blow-out) or positively (suck-in) charged beam

- Plasma wave/wake excited by relativistic particle bunch

- Plasma e⁻ are expelled by space charge force

- Plasma e⁻ rush back on axis

- Ultra-relativistic driver – ultra-relativistic wake ➔ no dephasing

- Acceleration physics identical for LWFA, PWFA

\[ \text{plasma wavelength } \lambda_{pe} \]
Where to Place the Witness Beam (Surfer)?

Accelerating for $e^-$
Decelerating for $e^-$
Focusing for $e^-$
Defocusing for $e^-$

Diagram showing the relations between $E_{z,\text{max}}$, $g_{\text{max}}$, and the phase of the beam. The beam experiences different forces at different phases of its cycle.
How strong can the fields be?

- The plasma oscillation leads to a longitudinal accelerating field. The maximum accelerating field (wave-breaking field) is:

\[ e E_{WB} = 96 \frac{V}{m} \sqrt[n_{pe}]{cm^{-3}} \]

- The ion channel left on-axis, where the beam passes, induces an ultra-strong focusing field:

\[ g = 960 \pi \frac{n_{pe}}{10^{14} \text{ cm}^{-3}} \frac{T}{m} \]

Example: \( n_{pe} = 7 \times 10^{14} \text{ cm}^{-3} \) (AWAKE) \( \Rightarrow eE_{WB} = 2.5 \text{ GV/m} \Rightarrow g = 21 \text{kT/m} \)

Example: \( n_{pe} = 7 \times 10^{17} \text{ cm}^{-3} \) \( \Rightarrow eE_{WB} = 80 \text{ GV/m} \Rightarrow g = 21 \text{MT/m} \)
Plasma Wakefield, Linear Theory


When drive beam density is smaller than plasma density \( n_b << n_p \) \( \rightarrow \) linear theory.

- Peak accelerating field in plasma resulting from drive beam with Gaussian distribution:

  \[
  eE_z = \sqrt{n_p \frac{n_b}{n_p}} \frac{\sqrt{2\pi} k_p \sigma_z e^{-k_p^2 \sigma_r^2/2}}{1 + \frac{1}{k_p^2 \sigma_r^2}} \sin k_p (z - ct) \quad (eV/cm)
  \]

  \[\Rightarrow eE_z \approx N/\sigma_z^2\]

  B.E. Blue 2003

- **Wakefield** excited by bunch oscillates **sinusoidally** with frequency determined by plasma density

- **Accelerating gradient** increases linearly with \( N/\sigma_z \)

- Fields excited by electrons and protons/positrons are **equal in magnitude but opposite in phase**

- The **accelerating field is maximized** for a value of

  \[k_p \sigma_z \approx \sqrt{2}\]

  \[k_p \sigma_r \leq 1\]

**Example:** \( n_{pe} = 7 \times 10^{14} \text{ cm}^{-3} \) (AWAKE), \( k_{pe} = 5 \text{ mm}^{-1} \) \( \Rightarrow \) drive beam: \( \sigma_z = 300\mu m, \sigma_r = 200\mu m \)
Plasma Wakefield, Linear Theory

Linear Theory: Maximum accelerating electric field reached with drive beam of $N$ and $\sigma_z$:

$$E_{\text{acc}} = 110 \frac{\text{MV}}{\text{m}} \frac{N/(2 \times 10^{10})}{(\sigma_z / 0.6\text{mm})^2}$$

$\leftarrow$ Driver must be short compared to plasma wavelength, easy for laser and electron bunches.

Examples of accelerating fields for different beam parameters and plasma parameters fields:

- $N = 3 \times 10^{10}$, $\sigma_z = 300\mu\text{m}$, $n_{pe} = 7 \times 10^{14} \text{ cm}^{-3}$ $\Rightarrow E_{\text{acc}} = 600 \text{ MV/m}$
- $N = 3 \times 10^{10}$, $\sigma_z = 20\mu\text{m}$, $n_{pe} = 2 \times 10^{17} \text{ cm}^{-3}$ $\Rightarrow E_{\text{acc}} = 15 \text{ GV/m}$
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• The AWAKE Experiment
Many, Many Electron and Laser Driven Plasma Wakefield Experiments…!

Now first Proton Driven Plasma Wakefield Experiment
Laser-Driven Plasma Acceleration Facilities

Table 2.2: Laser facilities (≥100 TW) performing LWFA R&D in Europe.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Institute</th>
<th>Location</th>
<th>Energy (J)</th>
<th>Peak power (PW)</th>
<th>Rep. rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELBE [16]</td>
<td>HZDR</td>
<td>Dresden, Ge</td>
<td>30</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>GEMINI [17]</td>
<td>STFC, RAL</td>
<td>Didcot, UK</td>
<td>15</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>LLC [18]</td>
<td>Lund Univ</td>
<td>Lund, Se</td>
<td>3</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>Salle Jaune [19]</td>
<td>LOA</td>
<td>Palaiseau, Fr</td>
<td>2</td>
<td>0.07</td>
<td>1</td>
</tr>
<tr>
<td>UHI100 [20]</td>
<td>CEA Saclay</td>
<td>Saclay, Fr</td>
<td>2</td>
<td>0.08</td>
<td>1</td>
</tr>
<tr>
<td>CALA* [21]</td>
<td>MPQ</td>
<td>Munchen, Ge</td>
<td>90</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>CILEX* [22]</td>
<td>CNRS-CEA</td>
<td>St Aubin, Fr</td>
<td>10-150</td>
<td>1-10</td>
<td>0.01</td>
</tr>
<tr>
<td>ELIbeamlines* [23]</td>
<td>ELI</td>
<td>Prague, TR</td>
<td>30</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>ILIL* [24]</td>
<td>CNR-INO</td>
<td>Pisa, It</td>
<td>3</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>SCAPA* [25]</td>
<td>U Strathclyde</td>
<td>Glasgow, UK</td>
<td>8</td>
<td>0.3</td>
<td>5</td>
</tr>
<tr>
<td>ANGUS</td>
<td>DESY</td>
<td>Hamburg, Ge</td>
<td>5</td>
<td>0.2</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 2.3: Laser facilities (≥100 TW) performing LWFA R&D in Asia

<table>
<thead>
<tr>
<th>Facility</th>
<th>Institute</th>
<th>Location</th>
<th>Energy (J)</th>
<th>Peak power (PW)</th>
<th>Rep. rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLAPA</td>
<td>PKU</td>
<td>Beijing, PRC</td>
<td>5</td>
<td>0.2</td>
<td>5</td>
</tr>
<tr>
<td>CoReLS [28]</td>
<td>IBS</td>
<td>Gwangju, Kr</td>
<td>20-100</td>
<td>1-4</td>
<td>0.1</td>
</tr>
<tr>
<td>J-Karen-P* [29]</td>
<td>KPSI</td>
<td>Kizugawa, Jn</td>
<td>30</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>LLP [30]</td>
<td>Jiao Tong Univ</td>
<td>Shanghai, PRC</td>
<td>5</td>
<td>0.2</td>
<td>10</td>
</tr>
<tr>
<td>SILEX*</td>
<td>LFRC</td>
<td>Myanyang, PRC</td>
<td>150</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>SULF* [31]</td>
<td>SIOM</td>
<td>Shanghai, PRC</td>
<td>300</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>UPHILL [32]</td>
<td>TIFR</td>
<td>Mumbai, In</td>
<td>2.5</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>XG-III</td>
<td>LFRC</td>
<td>Myanyang, PRC</td>
<td>20</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

Table 2.1: US laser facilities (>100 TW) performing LWFA R&D.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Institute</th>
<th>Location</th>
<th>Gain media</th>
<th>Energy (J)</th>
<th>Peak power (PW)</th>
<th>Rep. rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BELLA [7]</td>
<td>LBNL</td>
<td>Berkeley, CA</td>
<td>Ti:sapphire</td>
<td>42</td>
<td>1.4</td>
<td>1</td>
</tr>
<tr>
<td>Texas PW [8]</td>
<td>U. Texas</td>
<td>Austin, TX</td>
<td>Nd:glass</td>
<td>182</td>
<td>1.1</td>
<td>single-shot</td>
</tr>
<tr>
<td>Diocles [9]</td>
<td>U. Nebraska</td>
<td>Lincoln, NE</td>
<td>Ti:sapphire</td>
<td>30</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Hercules [10]</td>
<td>U. Michigan</td>
<td>Ann Arbor, MI</td>
<td>Ti:sapphire</td>
<td>9</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Jupiter [11]</td>
<td>LLNL</td>
<td>Livermore, CA</td>
<td>Nd:glass</td>
<td>150</td>
<td>0.2</td>
<td>single-shot</td>
</tr>
</tbody>
</table>
# Beam-Driven Plasma Acceleration Facilities

## Table 3.1: Overview of PWFA facilities

<table>
<thead>
<tr>
<th>Operation Start</th>
<th>AWAKE</th>
<th>CLEAR</th>
<th>FACET-II</th>
<th>FF &gt;&gt;</th>
<th>SparcLAB</th>
<th>EuPR@Sparc</th>
<th>CLARA</th>
<th>MAX IV</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Current Status</th>
<th>running</th>
<th>running</th>
<th>construction</th>
<th>commissioning</th>
<th>PWFA, LWFA</th>
<th>commissioning</th>
<th>CDR ready??</th>
<th>construction</th>
<th>design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unique Contribution</td>
<td>rapid access and</td>
<td>high energy peak-current</td>
<td>MHz rep rate</td>
<td>100kW average power</td>
<td>PWFA with COMB beam,</td>
<td>PWFA with COMB beam,</td>
<td>ultrashort</td>
<td>short pulse,</td>
<td>low emittance,</td>
</tr>
<tr>
<td>Protons</td>
<td>operation cycle</td>
<td>electrons, positrons</td>
<td>1 fs resolution</td>
<td>bunch diag,</td>
<td>LWFA external injection,</td>
<td>test FEL</td>
<td>e^- bunches</td>
<td>high-density</td>
<td>e^- beam</td>
</tr>
<tr>
<td>Research Topic</td>
<td>HEP instrumentation</td>
<td>high intensity e^-, e^+ beam driven exp.</td>
<td>high average power</td>
<td>PWFA</td>
<td>PWFA, LWFA, FEL, other applications</td>
<td>PWFA, Soft</td>
<td>X-FELs</td>
<td></td>
<td></td>
</tr>
<tr>
<td>User Facility</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>partially</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Drive Beam</td>
<td>p^+</td>
<td>e^-</td>
<td>e^-</td>
<td>e^-</td>
<td>e^-</td>
<td>e^-</td>
<td>e^-</td>
<td>e^-</td>
<td></td>
</tr>
<tr>
<td>Driver Energy</td>
<td>400 GeV</td>
<td>200 MeV</td>
<td>10 GeV</td>
<td>0.4—1.5 GeV</td>
<td>150 MeV</td>
<td>600 MeV</td>
<td>240 MeV</td>
<td>3 GeV</td>
<td></td>
</tr>
<tr>
<td>Ext. Inject. Witness Energy</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>no</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td></td>
</tr>
<tr>
<td>Plasma Density [cm^-3]</td>
<td>1—10E14</td>
<td>1E16—1E18</td>
<td>1E15—1E18</td>
<td>1E15—1E18</td>
<td>1E16—1E18</td>
<td>1E16—1E18</td>
<td>1E15—1E18</td>
<td>1E15—1E18</td>
<td></td>
</tr>
<tr>
<td>Plasma Length</td>
<td>10 m</td>
<td>5—20 cm</td>
<td>10—100 cm</td>
<td>1—30 cm</td>
<td>3 cm</td>
<td>&gt; 30 cm</td>
<td>10—30 cm</td>
<td>10—50 cm</td>
<td></td>
</tr>
<tr>
<td>Plasma Tapering</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td></td>
</tr>
<tr>
<td>Acc. Gradient</td>
<td>1 GeV/m average</td>
<td>na</td>
<td>10 GeV/m peak</td>
<td>10 GeV/m peak</td>
<td>&gt; 1 GeV/m??</td>
<td>&gt; 1 GeV/m??</td>
<td>na</td>
<td>10 GeV/m peak</td>
<td></td>
</tr>
<tr>
<td>Exp. E Gain</td>
<td>1+ GeV</td>
<td>na</td>
<td>≈10 GeV</td>
<td>≈1.5 GeV</td>
<td>40 MeV??</td>
<td>&gt; 500 MeV</td>
<td>na</td>
<td>3 GeV</td>
<td></td>
</tr>
</tbody>
</table>
Premier R&D facility for PWFA: Only facility capable of e⁺ acceleration

- Timeline:
  - Commissioning (2011)
  - Experimental program (2012-2016)

- Key PWFA Milestones:
  ✓ Mono-energetic e⁻ acceleration
  ✓ High efficiency e⁻ acceleration
  ✓ First high-gradient e⁺ PWFA
  ✓ Demonstrate required emittance, energy spread

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator
→ gradient of 52 GV/m

High-Efficiency acceleration of an electron beam in a plasma wakefield accelerator, 2014
M. Litos et al., doi, Nature, 6 Nov 2014, 10.1038/nature 13882

70 pC of charge accelerated, 2 GeV energy gain, 5 GeV/m gradient ➔ Up to 30% transfer efficiency, ~2% energy spread

9 GeV energy gain in a beam-driven plasma wakefield accelerator
Positron Acceleration, FACET

Positrons for high energy linear colliders: high energy, high charge, low emittance.

First demonstration of positron acceleration in plasma (FFTB)

Energy gain of 5 GeV. Energy spread can be as low as 1.8% (r.m.s.).

Two-bunch positron beam: First demonstration of controlled beam in positron-driven wake

Hollow plasma channel: positron propagation, wake excitation, acceleration in 30 cm channel.

Measurements of transverse wakefields in a hollow plasma channel due to off-axis drive bunch propagation.

Emittance blow-up is an issue! Use hollow-channel, so no plasma on-axis, no complicated forces from plasma electrons streaming through the plasma but then strong transverse wakefields when beams are misaligned.
Multistage coupling of independent laser-plasma accelerators

S. Steinke, Nature 530, 190 (2016)

Staging demonstrated at 100MeVs level.

Petawatt laser guiding and electron beam acceleration to 8 GeV in a laser-heated capillary discharge waveguide


Electron spectra, up to 6-8 GeV

Laser heater added to capillary

→ path to 10 GeV with continued improvement of guiding in progress
What about a proton beam as a driver?
Energy Budget for High Energy Plasma Wakefield Accelerators

Drive beams:
Lasers: ~40 J/pulse
Electron drive beam: 30 J/bunch
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

Witness beams:
Electrons: $10^{10}$ particles @ 1 TeV ~few kJ

To reach TeV scale:

• **Electron/laser driven PWA**: need several stages, and challenging wrt to relative timing, tolerances, matching, etc...
  • effective gradient reduced because of long sections between accelerating elements....

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E. Adli et. al., arXiv:1308.1145 [physics.acc-ph]

Energy Budget for High Energy Plasma Wakefield Accelerators

**Drive beams:**
Lasers: ~40 J/pulse
Electron drive beam: 30 J/bunch
Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

**Witness beams:**
Electrons: $10^{10}$ particles @ 1 TeV ~few kJ

- **Proton drivers:** large energy content in proton bunches $\rightarrow$ allows to consider single stage acceleration:
  - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.

**Dephasing:**
SPS: ~70 m
LHC: ~few km
FCC: $\sim \infty$

---

Dephasing:
SPS: ~70 m
LHC: ~few km
FCC: ~ $\infty$
Seeded Self-Modulation of the Proton Beam

In order to create plasma wakefields efficiently, the drive bunch length has to be in the order of the plasma wavelength.

**CERN SPS proton bunch: very long!** ($\sigma_z = 12$ cm) $\rightarrow$ much longer than plasma wavelength ($\lambda = 1\text{mm}$)

N. Kumar, A. Pukhov, K. Lotov, PRL 104, 255003 (2010)

**Self-Modulation:**

a) Bunch drives wakefields at the initial seed value when entering plasma.
   - **Initial wakefields act back** on the proton bunch itself. $\rightarrow$ On-axis density is modulated. $\rightarrow$ Contribution to the wakefields is $\propto n_b$.

b) Density modulation on-axis $\rightarrow$ **micro-bunches**.
   - Micro-bunches separated by plasma wavelength $\lambda_{pe}$.
   - drive wakefields resonantly.
**Advanced WAKEfield Experiment**

- Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.
- Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
- Approved in August 2013
- First proton beam sent to plasma end 2016
- First electron acceleration in 2018
AWAKE

AWAKE Collaboration: 22 institutes world-wide:

- University of Oslo, Oslo, Norway
- CERN, Geneva, Switzerland
- University of Manchester, Manchester, UK
- Cockcroft Institute, Daresbury, UK
- Lancaster University, Lancaster, UK
- Oxford University, UK
- Max Planck Institute for Physics, Munich, Germany
- Max Planck Institute for Plasma Physics, Greifswald, Germany
- UCL, London, UK
- UNIST, Ulsan, Republic of Korea
- Philipps-Universität Marburg, Marburg, Germany
- Heinrich-Heine-University of Düsseldorf, Düsseldorf, Germany
- University of Liverpool, Liverpool, UK
- ISCTE - Instituto Universitário de Lisboa, Portugal
- Budker Institute of Nuclear Physics SB RAS, Novosibirsk, Russia
- Novosibirsk State University, Novosibirsk, Russia
- GoLP/Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal
- TRIUMF, Vancouver, Canada
- Ludwig-Maximilians-Universität, Munich, Germany
- University of Wisconsin, Madison, US
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL, Lausanne, Switzerland
AWAKE Run 1: Proof-of Concept
2016/17: Seeded Self-Modulation of proton beam in plasma
2018: Electron acceleration in plasma

AWAKE Run 2: proposed for after LS2:
achieve high-charge bunches of electrons accelerated to high energy, about 10 GeV, while maintaining beam quality through the plasma and showing that the process is scalable.

AWAKE++: After Run 2: kick-off particle physics driven applications
The AWAKE beamline is designed to deliver a high-quality beam to the experiment. The proton beam must be steered around a mirror which couples a terawatt class laser into the beamline. Further downstream, the witness electron beam will injected into the same beamline.
AWAKE Plasma Cell

- 10 m long, 4 cm diameter
- Rubidium vapor, field ionization threshold $\sim 10^{12} \text{ W/cm}^2$
- Density adjustable from $10^{14} - 10^{15} \text{ cm}^{-3} \rightarrow 7 \times 10^{14} \text{ cm}^{-3}$
- Requirements:
  - density uniformity better than 0.2%
    - Fluid-heated system (~220 deg)
    - Complex control system: 79 Temperature probes, valves
  - Transition between plasma and vacuum as sharp as possible
AWAKE Plasma Cell

Plasma cell in AWAKE tunnel
AWAKE uses a short-pulse Titanium:Sapphire laser to ionize the rubidium source.

→ Seeding of the self-modulation with the ionization front.

The laser can deliver up to 500 mJ in a 120 fs pulse envelope.
A Photo-injector originally built for a CLIC test facility is now used as electron source for AWAKE producing **short electron bunches at an energy of ~20 MeV/c.**

A **completely new 12 m long electron beam line** was designed and built to connect the electrons from the e-source with the plasma cell.

**Challenge:** cross the electron beam with the proton beam inside the plasma at a precision of ~100 µm.
Outline

• Introduction to Plasma Wakefield Acceleration

• AWAKE, The Advanced Wakefield Experiments

• AWAKE Results

• What’s Next
Seeded Self-Modulation Results

\[ \lambda_p = 1.2 \text{ mm} \]

Second half of the proton bunch sees plasma
Diagnostics for Seeded Self-Modulation

Direct SSM Measurement:
Measure longitudinal structure of self-modulated proton bunch.
→ Image OTR light onto the slit of a streak camera.
→ Time resolved measurement.
Results: Direct Seeded Self-Modulation Measurement

- Effect starts at laser timing → SM seeding
- **Density modulation** at the ps-scale visible
- Micro-bunches **present over long time scale** from seed point
- **Reproducibility** of the µ-bunch process against bunch parameters variation
- **Phase stability** essential for e⁻ external injection.

⇒ **1st AWAKE Milestone reached**

Electron Acceleration Results 2018

Electron acceleration after 10m:
What we expect with the AWAKE Run 1 setup:

with baseline parameters: ~1.6 GeV

A. Petrenko, CERN

Electron Acceleration Diagnostics

Electrons will be accelerated in the plasma. To measure the energy the electrons pass through a dipole spectrometer and the dispersed electron impact on the scintillator screen. The resulting light is collected with an intensified CCD camera.

Spectrometer:
Dipole: $B = 0.1 - 1.5$ T, Magnetic length = 1m
→ detect electrons with energies ranging from $30\text{MeV} - 8.5\text{GeV}$
Electron Acceleration Results

Event at $n_{pe} = 1.8 \times 10^{14}$ cm$^{-3}$ with 5%/10m density gradient.

- Acceleration to 800 MeV.

• **Acceleration up to 2 GeV** has been achieved.
• **Charge capture up to 20%**.

Outline

• Introduction to Plasma Wakefield Acceleration

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• AWAKE Results

• What’s Next
**Goal:**

- **Accelerate an electron beam to high energy** (gradient of 0.5-1 GV/m)
- **Preserve electron beam quality** as well as possible (emittance preservation at 10 mm mrad level)
- **Demonstrate scalable** plasma source technology (e.g. helicon prototype)

- Freeze the modulation with **density step** in first plasma cell
- For emittance control: need to work in **blow-out regime** and do **beam-loading**
- **R&D on different plasma source technologies**

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**E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)**
AWAKE Run 2

X-band electron source

Accelerating plasma cell

Helicon plasma cell

E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)
Applications with AWAKE-Like Scheme

Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, so first experiments in not-too far future!

First Application:

- **Fixed target test facility**: Use bunches from SPS with 3.5 E11 protons every ~5sec, → electron beam of up to O (50GeV), 3 orders of magnitude increase in electrons (compared to NA64)

- deep inelastic scattering, non-linear QED, **search for dark photons a la NA64**

![Diagram showing energy-mass relation and plasma cell with electron and proton beams](image)
Applications with AWAKE-Like Scheme

Requirements on emittance are moderate for fixed target experiments and e/p collider experiments, so first experiments in not-too far future!

Using the SPS or the LHC beam as a driver, TeV electron beams are possible → Electron/Proton or Electron/Ion Collider

- **PEPIC**: LHeC like collider: $E_e$ up to O (70 GeV), colliding with LHC protons → exceeds HERA centre-of-mass energy
- **VHEeP**: choose $E_e = 3$ TeV as a baseline and with $E_p = 7$ TeV yields $\sqrt{s} = 9$ TeV. → CM ~30 higher than HERA. Luminosity $\sim 10^{28} - 10^{29}$ cm$^{-2}$ s$^{-1}$ gives $\sim 1$ pb$^{-1}$/yr.

Summary and Outlook

多项令人鼓舞的结果表明，等离子体尾波加速技术有巨大的潜力。等离子体尾波加速是一个令人兴奋且正在发展的领域。

AWAKE: 等离子体尾波加速技术有趣是因为驱动器中的能量很大。调制过程意味着现有的质子机器可以使用。

AWAKE第一次演示了从外部注入的电子驱动等离子体尾波加速到GeV级别。下一步是加速高品质、高能量电子。

Outlook:

近期目标：激光/电子等离子体尾波加速技术可能提供近期内的解决方案，如FELs和医学应用等。

中期目标：AWAKE技术将可用于粒子物理学应用。

长期目标：设计一个基于等离子体尾波加速的高能量电子/正电子/伽马线性加速器。
## Status of Today and Goals for Collider Application

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Goal</th>
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</thead>
<tbody>
<tr>
<td>Charge (nC)</td>
<td>0.1</td>
<td>1</td>
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<tr>
<td>Energy (GeV)</td>
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<td>10</td>
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<tr>
<td>Energy spread (%)</td>
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<td>0.1</td>
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<tr>
<td>Emittance (um)</td>
<td>&gt;50-100 (PWFA), 0.1 (LFWA)</td>
<td>&lt;10^{-1}</td>
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<tr>
<td>Staging</td>
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<tr>
<td>Efficiency (%)</td>
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<td>40</td>
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<td>Rep Rate (Hz)</td>
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<td>10^{3-4}</td>
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<tr>
<td>Acc. Distance (m)/stage</td>
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<td>1-5</td>
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<tr>
<td>Positron acceleration</td>
<td>acceleration</td>
<td>emittance preservation</td>
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<tr>
<td>Proton drivers</td>
<td>SSM, acceleration</td>
<td>emittance control</td>
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<tr>
<td>Plasma cell (p-driver)</td>
<td>10 m</td>
<td>100s m</td>
</tr>
<tr>
<td>Simulations</td>
<td>days</td>
<td>improvements by 10^{7}</td>
</tr>
</tbody>
</table>
Outlook

- Short term perspective of PWFA (< 10 years):
  - Compact FEL based: 5 – 10 GeV energy range
  - Compact X-ray sources: electron accelerated in strong transverse field of plasma emit betatron radiation
    ➔ applications in medicine, radiobiology, material science

- Long term perspective of PWFA (>20 years):
  - High energy physics applications: Plasma-based high energy linear collider
    ➔ depends strongly on progress in many fields.

The most demanding application of plasma wakefield acceleration is to build a compact, efficient, Plasma-Based Linear Collider.