Outline

• Introduction to Plasma Wakefield Acceleration

• AWAKE, The Advanced Wakefield Experiment

• AWAKE Results

• What’s Next
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.

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

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

Accelerating fields are **limited to <100 MV/m**

- In metallic structures, a too high field level leads to **break down** of surfaces, creating electric discharge.
- Fields cannot be sustained, structures might be damaged.

⇒ several tens of kilometers for future linear colliders
Plasma Wakefield Acceleration

- Acceleration technology, which obtains ~1000 factor stronger acceleration than conventional technology.
Use a plasma to convert the transverse space charge force of a beam driver into a longitudinal electrical field in the plasma.
 Plasma is ionized and can sustain electric fields up to three orders of magnitude higher than conventional accelerator technologies. Reach gradients $\rightarrow$ order of $100 \text{ GV/m}$.

Using plasma to convert the transverse electric field of the drive bunch into a longitudinal electric field in the plasma.

The maximum accelerating field (wave-breaking field) is: $e E_{WB} = 96 \frac{V}{m} \sqrt{\frac{n_{pe}}{\text{cm}^3}}$ for $n_{pe} = 10^{16} \text{ cm}^{-3}$, $E_{WB} = 10 \text{ GV/m}$.
Some Highlight Results

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator
I. Blumenfeld et al, Nature 455, p 741 (2007) → 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

9 GeV energy gain in a beam-driven plasma wakefield accelerator

Electron beam driven PFWA

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

First demonstration of positron acceleration in plasma (FFTB)

Positron acceleration with PFWA

Laser driven LFWA

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
Many, Many Electron and Laser Driven Plasma Wakefield Experiments…!

Now first Proton Driven Plasma Wakefield Experiment
Acceleration to HEP Energies

**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

- **Electron/laser driven PWA:** need several stages
  - effective gradient reduced because of long sections between accelerating elements....

  ➔ Challenges: staging, matching, tolerances

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

  ➔ Challenges: long plasma sources

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

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Leemans & Esarey, Phys. Today 63 #3 (2009)


A. Caldwell and K. V. Lotov, Phys. Plasmas 18, 103101 (2011)
In order to create plasma wakefields efficiently, the drive bunch length has to be short compared to the plasma wavelength. → Relatively easy for Laser and Electron bunches.

Proton beam as drive beam: CERN SPS proton bunch: very long! ($\sigma_z = 12$ cm) → much longer than plasma wavelength ($\lambda = 1$ mm), but rely on self-modulation of the proton beam

**Self-Modulation of a Long Proton Beam:**

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

b) Density modulation on-axis → **micro-bunches**. → separated by plasma wavelength $\lambda_{pe}$ → drives wakefields resonantly.

**AWAKE:** Seeding of the instability by
- Placing a laser close to the center of the proton bunch
- Laser ionizes vapour to produce plasma
- Sharp start of beam/plasma interaction
- → Seeding with ionization front
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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 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 Timeline

<table>
<thead>
<tr>
<th>Year</th>
<th>Proton and laser beam-line</th>
<th>Experimental area</th>
<th>e⁻ source and beam-line</th>
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<tr>
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<td>Study, Design, Procurement, Component preparation</td>
<td>Study, Design, Procurement, Component preparation</td>
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<td>2014</td>
<td>Installation</td>
<td>Fabrication</td>
<td>Installation</td>
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<tr>
<td>2015</td>
<td>Study, Design, Procurement, Component preparation</td>
<td>Fabrication</td>
<td>Installation</td>
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<td>2016</td>
<td>Installation</td>
<td>Fabrication</td>
<td>Installation</td>
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<td>2017</td>
<td>Data taking</td>
<td>Data taking</td>
<td>Data taking</td>
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<td>2018</td>
<td>Long Shutdown 2 24 months</td>
<td>LONG SHUTDOWN 2</td>
<td>LONG SHUTDOWN 2</td>
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<td>2019</td>
<td>AWAKE RUN 1 Phase 1</td>
<td>AWAKE RUN 2 Phase 2</td>
<td>AWAKE RUN 2 Phase 2</td>
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<tr>
<td>2020</td>
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<tr>
<td>2022/23/24</td>
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#### 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
AWAKE Experiment
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 ~$10^{12}$ W/cm$^2$
- Density adjustable from $10^{14}$ – $10^{15}$ cm$^{-3}$ $\Rightarrow$ 7x $10^{14}$ 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 $\sim 20$ 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 $\sim 100 \mu$m.
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Seeded Self-Modulation Results

$\lambda_p = 1.2$ mm

Second half of the proton bunch sees plasma

A. Petrenko, CERN
Diagnostics for Seeded Self-Modulation

**Indirect SSM Measurement:**
Measure time integrated transverse bunch distribution.

→ Image protons defocused by the strong plasma wakefields

→ Scintillation light from screen measured with digital camera.
Results: Indirect Seeded Self-Modulation Measurement

From the **radial distribution** of the defocused protons, we learn about the **transverse effects** of SSM.

- Protons are **defocused by the transverse wakefield (SSM)** and form a halo.
- Proton density in core **decreases**, proton density at large radii **increases** (appearance of halo).
- Protons get defocused up to a **maximum radius of 14.5 mm** for a plasma density of \(7.7e14/cm^3\).
- Halo symmetric ⇒ **no hose instability**.
- Estimate of the **transverse wakefields amplitude** (\( JW_{\text{per dr}} \))

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Victor Hess Prize 2019: Marlene Turner

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

Other Studies

• Seeded Self-Modulation (not) Stability

- Whether the phase is stable/not stable depends on the seed level

• Hosing Instability

Hosing is an asymmetric instability. ➔ Important to understand!

- Similarities in simulations and experiment
- Measurements show that HI appears only at low plasma density and proton bunch density.
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 30MeV - 8.5 GeV
Event at $n_{pe} = 1.8 \times 10^{14}$ cm$^{-3}$ with 5%/10m density gradient.

- Acceleration to 800 MeV.
Electron Acceleration Results III

• Acceleration up to 2 GeV has been achieved.
• Charge capture decreases with plasma density $n_{pe}$.

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Goal:

**Accelerate an electron beam to high energy** (gradient of 0.5-1GV/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

![Diagram of electron source and plasma cell](image)

**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>

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 ~5 sec, → electron beam of up to O (50 GeV), **3 orders of magnitude increase in electrons** (compared to NA64)

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>AWAKE-upgrade-type</th>
<th>HL-LHC-type</th>
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</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>
<tr>
<td><strong>Number of electrons on target per 12 weeks run</strong></td>
<td>$4.1 \times 10^{15}$</td>
<td>$2 \times 10^{17}$</td>
</tr>
</tbody>
</table>

50 m: 33 GeV/c e, $\Delta E/E = 2\%$, ~100 pC.
100 m: 53 GeV/c e, $\Delta E/E = 2\%$, ~130 pC.
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 0 (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.

Many encouraging results in the plasma wakefield acceleration technology. Plasma wakefield acceleration is an exciting and growing field with a huge potential.

AWAKE: Proton-driven plasma wakefield acceleration interesting because of large energy content of driver. Modulation process means existing proton machines can be used.

AWAKE has for the first time demonstrated proton driven plasma wakefield acceleration of externally injected electrons.

AWAKE Run 1 was a proof-of-concept experiment. DONE!

Aim of AWAKE Run 2 starting 2021 after CERN’s Long Shutdown 2 is to 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.

Use the AWAKE scheme for particle physics applications such as fixed target experiments for dark photon searches and also for future electron-proton or electron-ion colliders.
Extra slides
# Status of Today and Goals for Collider Application

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Goal</th>
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<tbody>
<tr>
<td>Charge (nC)</td>
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<td>1</td>
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<tr>
<td>Energy (GeV)</td>
<td>9</td>
<td>10</td>
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<tr>
<td>Energy spread (%)</td>
<td>2</td>
<td>0.1</td>
</tr>
<tr>
<td>Emittance (um)</td>
<td>&gt;50-100 (PWFA), 0.1 (LFWA)</td>
<td>&lt;10⁻¹</td>
</tr>
<tr>
<td>Staging</td>
<td>single, two</td>
<td>multiple</td>
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<tr>
<td>Efficiency (%)</td>
<td>20</td>
<td>40</td>
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<td>Rep Rate (Hz)</td>
<td>1-10</td>
<td>10³-4</td>
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<td>Acc. Distance (m)/stage</td>
<td>1</td>
<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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<td>Plasma cell (p-driver)</td>
<td>10 m</td>
<td>100s m</td>
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<tr>
<td>Simulations</td>
<td>days</td>
<td>Improvements by 10⁷</td>
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</table>

Table 1: Facilities for accelerator R&D in the multi-GeV range relevant for ALIC and with emphasis on specific challenges.