AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN

Edda Gschwendtner
on behalf of the AWAKE Collaboration
Outline

• Motivation
• AWAKE at CERN
• AWAKE Experimental Layout: 1\textsuperscript{st} Phase
• AWAKE Experimental Layout: 2\textsuperscript{nd} Phase
• Experimental Facility at CERN
• Planning
• Next Steps
• Summary
• AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  – Use SPS proton beam as drive beam
  – Inject electron beam as witness beam

• Proof-of-Principle Accelerator R&D experiment at CERN
  – First proton driven wakefield experiment worldwide
  – First beam expected in 2016

• AWAKE Collaboration: 14 Institutes world-wide
Motivation

- Accelerating field of today’s RF cavities or microwave technology is limited to <100 MV/m
  - Several tens of kilometers for future linear colliders

- Plasma can sustain up to three orders of magnitude much higher gradient
  - SLAC (2007): electron energy doubled from 42GeV to 85 GeV over 0.8 m → 52GV/m gradient

Why protons?

- Energy gain is limited by energy carried by the laser or electron drive beam (<100J) and the propagation length of the driver in the plasma (<1m).
  - Staging of large number of acceleration sections required to reach 1 TeV region.

- Proton beam carries much higher energy: 19kJ for 3E11 protons at 400 GeV/c.
  - Drives wakefields over much longer plasma length, only 1 plasma stage needed.

Simulations show that it is possible to gain 600 GeV in a single passage through a 450 m long plasma using a 1 TeV p+ bunch driver of 10e11 protons and an rms bunch length of 100 μm.
Motivation

- Plasma wave is excited by a relativistic particle bunch
- Space charge of drive beam displaces plasma electrons.
- Plasma electrons attracted by plasma ions, and rush back on-axis

$\lambda_p = \frac{2\pi}{k_p} = 1\text{mm} \sqrt{\frac{1 \cdot 10^{15} \text{ cm}^{-3}}{n_p}}$

$E_{z,\text{max}} \approx 2 \text{ GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right) \cdot \left(\frac{100 \mu\text{m}}{\sigma_z}\right)^2$

$\rightarrow$ plasma wavelength $\lambda_p = 1\text{mm}$, (for typical plasma density of $n_p = 10^{15}\text{cm}^{-3}$)

$\rightarrow$ To excite large amplitude wakefields, proton bunch length $\sigma_z \sim \lambda_p = 1\text{mm}$

SPS beam: $\sigma_z \sim 12\text{cm}$

$\rightarrow$ Way out: Self-Modulation Instability (SMI):
Modulate long SPS bunch to produce a series of ‘micro-bunches’ in a plasma with a spacing of plasma wavelength $\lambda_p$.

$\rightarrow$ Strong self-modulation effect of proton beam due to transverse wakefield in plasma

$\rightarrow$ Starts from any perturbation and grows exponentially until fully modulated and saturated.

$\rightarrow$ Immediate use of CERN SPS beam
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AWAKE at CERN

AWAKE in CNGS Facility (CERN Neutrinos to Gran Sasso)

CNGS physics program finished in 2012
  - CNGS approved for 5 years: 2008 – 2012
  - Expect ~8 tau-neutrinos, 4 published so far
• Running underground facility
• Desired beam parameters
⇒ adequate site for AWAKE
AWAKE at CERN

- Running underground facility
- Desired beam parameters

adequate site for AWAKE

~1100m
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AWAKE Experimental Layout: 1st Phase

- Perform **benchmark experiments using proton bunches** to drive wakefields for the first time ever.
- Understand **the physics of self-modulation instability** processes in plasma.
• Perform **benchmark experiments using proton bunches** to drive wakefields for the first time ever.
• Understand **the physics of self-modulation instability** processes in plasma.

→ **SPS proton bunch experiences** **Self-Modulation Instability** (SMI) in the plasma.
→ **Laser ionizes** the plasma and **seeds the SMI** in a controlled way.
→ **10 m long plasma cell**: **Rubidium vapor** source, \( n_e = 7 \times 10^{14} \text{ cm}^{-3} \).

<table>
<thead>
<tr>
<th>Proton Beam</th>
<th>Laser Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum</td>
<td>Laser type</td>
</tr>
<tr>
<td>400 GeV/c</td>
<td>Pulse wavelength</td>
</tr>
<tr>
<td>3 ( \times 10^{11} )</td>
<td>Pulse length</td>
</tr>
<tr>
<td>0.5 Hz (ultimate: 0.14 Hz)</td>
<td>Pulse energy (after compr.)</td>
</tr>
<tr>
<td>( \sigma_z = 0.4 \text{ ns (12 cm)} )</td>
<td>Laser power</td>
</tr>
<tr>
<td>( \sigma^*_{x,y} = 200 \text{ \mu m} )</td>
<td>Focused laser size</td>
</tr>
<tr>
<td>3.5 mm mrad</td>
<td>Energy stability</td>
</tr>
<tr>
<td>( \Delta p/p = 0.35% )</td>
<td>Repetition rate</td>
</tr>
<tr>
<td>( \beta^<em>_{x} = \beta^</em>_{y} = 4.9m )</td>
<td></td>
</tr>
<tr>
<td>( D^<em>_{x} = D^</em>_{y} = 0 )</td>
<td></td>
</tr>
</tbody>
</table>
Laser and proton beam synchronized at the 100 ps level.

Laser and proton beam co-axial over the full length of the plasma cell:
- 100μm and 15 rad pointing accuracy
- High resolution diagnostics to perform and monitor relative alignment

Plasma density uniformity better than 0.2%

Maximum amplitude of the accelerating field $E_z$ as a function of position along the plasma. Saturation of the SMI at ~4m.
• Laser and proton beam synchronized at the **100 ps level**.
• Laser and proton beam **co-axial** over the full length of the plasma cell:
  – 100 μm and 15 μrad pointing accuracy
  – High resolution diagnostics to perform and monitor relative alignment
• Plasma density uniformity better than **0.2%**

**Self-modulated proton bunch** resonantly driving plasma wakefields.
AWAKE Experimental Layout: 1st Phase

- Laser and proton beam synchronized at the **100 ps level**.
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• **Probe the accelerating wakefields with externally injected electrons**, including energy spectrum measurements for different injection and plasma parameters.
**AWAKE Experimental Layout: 2nd Phase**

- **Probe the accelerating wakefields with externally injected electrons**, including energy spectrum measurements for different injection and plasma parameters.

```
<table>
<thead>
<tr>
<th>Electron beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum</td>
</tr>
<tr>
<td>Electrons/bunch (bunch charge)</td>
</tr>
<tr>
<td>Bunch length</td>
</tr>
<tr>
<td>Bunch size at focus</td>
</tr>
<tr>
<td>Normalized emittance (r.m.s.)</td>
</tr>
<tr>
<td>Relative energy spread</td>
</tr>
<tr>
<td>Beta function</td>
</tr>
<tr>
<td>Dispersion</td>
</tr>
</tbody>
</table>
```

```
<table>
<thead>
<tr>
<th>Laser beam for electron source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser type</td>
</tr>
<tr>
<td>Pulse wavelength</td>
</tr>
<tr>
<td>Pulse length</td>
</tr>
<tr>
<td>Pulse energy (after compr.)</td>
</tr>
<tr>
<td>Electron source cathode</td>
</tr>
<tr>
<td>Quantum efficiency</td>
</tr>
<tr>
<td>Energy stability</td>
</tr>
</tbody>
</table>
```
• Laser and electron beam synchronized at the < 1 ps level.
• Electron bunch is externally injected into the plasma cell, on-axis and collinearly with the proton and laser beam.
• On-axis injection point is upstream the plasma cell.
• Electrons are trapped from the very beginning by the wakefield of seed perturbation
• Trapped electrons make several synchrotron oscillations in their potential wells
• After $z=4\text{ m}$ the wakefield moves forward in the light velocity frame
- Laser and electron beam synchronized at the $< 1 \text{ ps level}$.
- **Electron bunch is externally injected** into the plasma cell, on-axis and collinearly with the proton and laser beam.
- **On-axis injection** point is upstream the plasma cell.

Energy of the electrons gained along the 10 m long plasma cell.
• Laser and electron beam synchronized at the \(< 1 \text{ ps level}\).
• **Electron bunch is externally injected** into the plasma cell, on-axis and collinearly with the proton and laser beam.
• **On-axis injection** point is upstream the plasma cell.

- Trapping efficiency: 10 – 15 %
- Average energy gain: 1.3 GeV
- Energy spread: ± 0.4 GeV
- Angular spread up to ± 4 mrad

Large acceptance spectrometer (aperture and magnetic field)
Laser and electron beam synchronized at the < 1 ps level.
Electron bunch is externally injected into the plasma cell, on-axis and collinearly with the proton and laser beam.
On-axis injection point is upstream the plasma cell.

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**Ti: Sapphire laser system:**

- Laser with 2 beams (for plasma and e-gun)
- Delay line in either one of both beams
- Focusing telescope (lenses, in air) before compressor
- 35 meter focusing
- Optical compressor (in vacuum)
- Optical in-air compressor and 3rd harmonics generator for electron gun

Complete UHV vacuum system up to $10^{-9}$ mbar starting from optical compressor
Proton Beam Line

Change of the proton beam line only in the **downstream part (~80m)**

Present CNGS Layout (end of the line)

Future AWAKE Layout

→ **Displace existing magnets** of the final focusing to fulfill optics requirements at plasma cell
→ Move existing dipole and **4 additional dipoles** to create a chicane for the laser mirror integration.

Laser-proton merging 20m upstream the plasma cell
Rubidium Vapour Plasma Cell

- Density adjustable from $10^{14} - 10^{15}$ cm$^{-3}$
- 10 m long, 4 cm diameter
- Plasma formed by field ionization of Rb vapour using laser pulse (~$1.7 \times 10^{12}$ W/cm$^2$)
- System is oil-heated $\rightarrow$ keep temperature uniformity $\rightarrow$ density uniformity $\Delta n/n = \Delta T/T \leq 0.002$

3m prototype

Ultra-fast (15 ms) valves $> 40\,000$ cycles!

Temperature profiles along the heat exchanger
Measurements remain $< \pm 0.1$ K
Self-Modulation-Instability Diagnostics

Measure the **characteristics of the proton** beam after propagating through the plasma cell.

- **Optical Transition Radiation (OTR):**
  - Time-resolve bunch radius variation with streak-camera (~100fs resolution)
  - Measure relative phasing of laser pulse, proton bunch and electron bunch
- **Coherent Transition Radiation (CTR) and Transverse Coherent Transition Radiation (TCTR)**
  - High frequency (\(\sim f_p = 237.5\) GHz)
  - Broadband detection scheme (500 GHz)

\[ \sigma_p \sim 400\,\text{ps} \]

\[ \sigma_y \sim 4\,\text{ps} \]

\[ \text{Look at cut-off frequency} \]

\[ \text{237.5 GHz Filter} \]

\[ \text{Broadband Detector} \]

\[ \text{Real-time Oscilloscope} \]
Electron – Source

• Baseline:
  – Photo injector (PHIN) from CTF2 at CERN (5 MeV electrons)
  – Klystron and modulator from CTF3
  – Booster from Cockcroft/Lancaster 5 MeV → 20 MeV
• Optimize and test performance of complex system.
  – use as test area after 2015.
Electron Beam Line

- Completely **new beam line and tunnel**:
  - Horizontal angle of 60 deg,
  - 20% slope of the electron tunnel $\rightarrow$ 1m level difference
  - 7.2% slope of the plasma cell
  - $\sim$5 m common beam line between electron and proton

- **Common diagnostics** for proton (high intensity, $3E11$ p) and electron beam (low intensity, $1.2E9$ e)
- **Flexible electron beam optics**: focal point can be varied by up to 6 m inside the plasma cell

![Electron beam envelope (H, V)](image)
Electron Beam Line

Status 4 weeks ago
Electron Beam Line

Status 1 week ago
Electron Spectrometer

- Measure **peak energy and energy spread** of electrons.
- Spectrometer magnet separates electrons from proton beam-line.
- Dispersed electron impact on scintillator screen.
- Resulting light collected with intensified CCD camera.

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MBPS magnet (CERN): 15 ton
1.84 T, 3.80 Tm
Vert. aperture: 110-200 mm
Horiz. Aperture: 300 mm
L=1670 mm, W=1740 mm
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AWAKE was approved in August 2013

1st Phase: First proton and laser beam in 2016

2nd Phase: first electron beam in 2017

Physics program for 3 – 4 years

<table>
<thead>
<tr>
<th>Run-scenario</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of run-periods/year</td>
<td>4</td>
</tr>
<tr>
<td>Length of run-period</td>
<td>2 weeks</td>
</tr>
<tr>
<td>Total number of beam shots/year (100% efficiency)</td>
<td>162000</td>
</tr>
<tr>
<td>Total number of protons/year</td>
<td>$4.86 \times 10^{16}$ p</td>
</tr>
<tr>
<td>Initial experimental program</td>
<td>3 – 4 years</td>
</tr>
</tbody>
</table>
Next Steps

- **Split-cell mode**: SMI in 1\textsuperscript{st} plasma cell, acceleration in 2\textsuperscript{nd} one.
- New scalable uniform plasma cells (helicon or discharge plasma cell)
- Step in the plasma density $\rightarrow$ maintains the peak gradient
- Need ultra-short electron bunches ($> 300\text{fs}$) $\rightarrow$ bunch compression $\rightarrow$ Almost 100% capture efficiency
Summary

• AWAKE is proof-of-principle accelerator R&D experiment currently being built at CERN.
  – First proton-driven wakefield acceleration experiment
  – The experiment opens a pathway towards plasma-based TeV lepton collider.
  – 400 GeV SPS proton beam as drive beam
  – 10-20 MeV electrons as witness beam
  – 2 TW laser beam for plasma ionization and seeding of the SMI

• AWAKE program
  – Study the physics of self-modulation instability as a function of plasma and proton beam parameters (1\textsuperscript{st} Phase, 2016)
  – Probe the longitudinal accelerating wakefields with externally injected electrons (2\textsuperscript{nd} Phase, 2017-2018)
  – Develop long scalable and uniform plasma cells, production of shorter electron and proton bunches (2020)