AWAKE: The Proton Driven Plasma Wakefield Acceleration Experiment at CERN

Alexey Petrenko
on behalf of the AWAKE Collaboration
• 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
What is the AWAKE experiment?

- **AWAKE**: Advanced Proton Driven Plasma Wakefield Acceleration Experiment
  - Use SPS proton beam as drive beam (Single bunch 3e11 protons at 400 GeV)
  - Inject electron beam as witness beam

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

- **AWAKE Collaboration**: 14 Institutes world-wide:
Motivation

• Accelerating field of today’s RF cavities is limited to <100 MV/m
  – Several tens of kilometers for future linear colliders

• Plasma can sustain up to three orders of magnitude higher gradient
  – SLAC (2007): electron energy doubled from 42 GeV to 85 GeV over 0.8 m → 52 GV/m gradient
  – However to reach 1 TeV energy with 50 GeV drive beam will require 20 stages. Similar staging problem exists for laser-driven plasma wakefield accelerators.

Why protons?
• There are proton beams available at CERN with TeV scale energy per particle and huge total stored energy. For example:

LHC nominal beam parameters:
(2808 bunches)*(1.15e11 protons)*(7 TeV) = 360 MJ

Fully loaded A320 (80 t) at take-off speed (300 km/h) carries similar amount of kinetic energy (280 MJ).
(However the momentum of the airplane is ~ c/v ~ 10⁶ times larger than the LHC beam momentum)

Single LHC proton bunch (7 TeV, 1.2e11 protons) carries 130 kJ
Single SPS proton bunch (0.4 TeV, 3e11 protons) carries 19 kJ
Single ILC electron bunch (0.5 TeV, 2e10 e+/e-) carries 1.6 kJ

Using LHC beam as a driver it’s possible to obtain TeV-level (e-/e+/muons) in a single stage!
Motivation


Proton bunch driver: 1 TeV, $\sigma_z = 0.1$ mm

Witness bunch of $1.5 \cdot 10^{10}$ electrons

Unfortunately compressing 12 cm long LHC bunch down to $\sigma_z = 0.1$ mm is very challenging and expensive (although technically possible).
Motivation

Self-modulation instability of a long proton bunch in plasma
(Very similar to Raman self-modulation of long laser pulses -- LWFA with long laser beams, before the invention of chirped pulse compression)

The beam as is seen by the plasma

Wakefield

Electrons

L = 4 m

$\lambda_p = 1.2$ mm

Laser pulse

Self-modulated proton bunch resonantly driving plasma wakefields.
The AWAKE experiment configuration & baseline parameters:

- Rb gas uniformity should be better than 0.2%

Fast valve, 15 msec / 1 sec, 220 °C, Ø4 cm, 40000 cycles

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plasma density, $n_0$</td>
<td>$7 \times 10^{14}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Plasma length, $L_{\text{max}}$</td>
<td>10 m</td>
</tr>
<tr>
<td>Atomic weight of plasma ions, $M_i$</td>
<td>85.5</td>
</tr>
<tr>
<td>Plasma skin depth, $c/\omega_p \equiv k_p^{-1}$</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Initial plasma radius, $r_0$,</td>
<td>1.5 mm</td>
</tr>
<tr>
<td>Final plasma radius, $r_1$,</td>
<td>1 mm</td>
</tr>
<tr>
<td>Wavebreaking field, $E_0 = mc\omega_p/e$,</td>
<td>2.54 GV/m</td>
</tr>
<tr>
<td>Proton bunch population, $N_b$</td>
<td>$3 \times 10^{11}$</td>
</tr>
<tr>
<td>Proton bunch length, $\sigma_{zb}$</td>
<td>12 cm</td>
</tr>
<tr>
<td>Proton bunch radius, $\sigma_{rb}$</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Proton bunch energy, $W_b$</td>
<td>400 GeV</td>
</tr>
<tr>
<td>Proton bunch energy spread, $\delta W_b$</td>
<td>0.35%</td>
</tr>
<tr>
<td>Proton bunch normalized emittance, $\epsilon_{nb}$</td>
<td>3.6 mm mrad</td>
</tr>
<tr>
<td>Proton bunch maximum density, $n_{bo}$</td>
<td>$4 \times 10^{12}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Electron bunch population, $N_e$</td>
<td>$1.25 \times 10^9$</td>
</tr>
<tr>
<td>Electron bunch length, $\sigma_{ze}$</td>
<td>1.2 mm</td>
</tr>
<tr>
<td>Electron bunch radius, $\sigma_{re}$</td>
<td>0.25 mm</td>
</tr>
<tr>
<td>Electron bunch energy, $W_e$</td>
<td>16 MeV</td>
</tr>
<tr>
<td>Electron bunch energy spread, $\delta W_e$</td>
<td>0.5%</td>
</tr>
<tr>
<td>Electron bunch normalized emittance, $\epsilon_{ne}$</td>
<td>2 mm mrad</td>
</tr>
<tr>
<td>Electron bunch delay, $\xi_e$</td>
<td>16.4 cm</td>
</tr>
</tbody>
</table>
Outline

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• AWAKE at CERN
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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

AWAKE experiment

- Dump ~1100m
- LHC
- SPS

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN

Excavated
Concrete
Decay tube (2nd contract)

protons
SPS

TNM42 sump 8 m³
TNM41 sump 8 m³
TZ sump 8 m³
TCV4 sump 30 m³
TSG4 sump 30 m³

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• 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, $n_e = 7 \times 10^{14}$ cm$^{-3}$.

### Proton Beam

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum</td>
<td>400 GeV/c</td>
</tr>
<tr>
<td>Protons/bunch</td>
<td>$3 \times 10^{11}$</td>
</tr>
<tr>
<td>Bunch extraction frequency</td>
<td>1/30 Hz</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z = 0.4$ ns (12 cm)</td>
</tr>
<tr>
<td>Bunch size at plasma entrance</td>
<td>$\sigma_{x,y} = 200$ $\mu$m</td>
</tr>
<tr>
<td>Normalized emittance (r.m.s.)</td>
<td>3.5 mm mrad</td>
</tr>
<tr>
<td>Relative energy spread</td>
<td>$\Delta p/p = 0.35%$</td>
</tr>
<tr>
<td>Beta function</td>
<td>$\beta_x^* = \beta_y^* = 4.9 m$</td>
</tr>
<tr>
<td>Dispersion</td>
<td>$D_x^* = D_y^* = 0$</td>
</tr>
</tbody>
</table>

### Laser Beam

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser type</td>
<td>Fiber Ti:Sapphire</td>
</tr>
<tr>
<td>Pulse wavelength</td>
<td>$\lambda_0 = 780$ nm</td>
</tr>
<tr>
<td>Pulse length (FWHM)</td>
<td>200 fs</td>
</tr>
<tr>
<td>Pulse energy (after compr.)</td>
<td>450 mJ</td>
</tr>
<tr>
<td>Laser power</td>
<td>2 TW</td>
</tr>
<tr>
<td>Focused laser size</td>
<td>$\sigma_{x,y} = 1$ mm</td>
</tr>
<tr>
<td>Energy stability</td>
<td>$\pm 1.5%$ r.m.s.</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
</tr>
</tbody>
</table>
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 (~$f_p = 237.5$ GHz)
  - Broadband detection scheme (500 GHz)

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**AWAKE Experimental Layout: 2\(^{nd}\) Phase**

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

### Electron beam

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum</td>
<td>16 MeV/c</td>
</tr>
<tr>
<td>Electrons/bunch (bunch charge)</td>
<td>1.2E9 (0.2 nC)</td>
</tr>
<tr>
<td>Bunch length</td>
<td>(\sigma_z = 4\text{ps} (1.2\text{mm}))</td>
</tr>
<tr>
<td>Bunch size at focus</td>
<td>(\sigma_{x,y}^* = 250,\mu\text{m})</td>
</tr>
<tr>
<td>Normalized emittance (r.m.s.)</td>
<td>2 mm mrad</td>
</tr>
<tr>
<td>Relative energy spread</td>
<td>(\Delta p/p = 0.5%)</td>
</tr>
<tr>
<td>Beta function</td>
<td>(\beta_x^* = \beta_y^* = 0.4,\text{m})</td>
</tr>
<tr>
<td>Dispersion</td>
<td>(D_x^* = D_y^* = 0)</td>
</tr>
</tbody>
</table>

### Laser beam for electron source

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser type</td>
<td>Ti:Sapphire Centaurus</td>
</tr>
<tr>
<td>Pulse wavelength</td>
<td>(\lambda_0 = 260,\text{nm})</td>
</tr>
<tr>
<td>Pulse length</td>
<td>10 ps</td>
</tr>
<tr>
<td>Pulse energy (after compr.)</td>
<td>50 (\mu\text{J})</td>
</tr>
<tr>
<td>Electron source cathode</td>
<td>Copper</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>3.00E-5</td>
</tr>
<tr>
<td>Energy stability</td>
<td>(\pm 2.5%,\text{r.m.s.})</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.
On-axis injection: animation of electron trapping and acceleration

- Electrons are trapped from the very beginning by the wakefield of seed perturbation
- Trapped electrons make several synchrotron oscillations in their potential wells
- After $z=4$ m the wakefield moves forward in the light velocity frame
The baseline AWAKE accelerated electron beam:

Typical trajectory of accelerated electron:

Final energy & angle distributions in e-beam:
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AWAKE Experimental Facility at CERN

- Laser
- RF gun
- SPS protons
- e^+ spectrometer
- Proton beam dump
- Laser dump
- Proton diagnostics
- OTR, CTR, TCTR
- Protons
- SMI
- Acceleration
- Laser dump
- Proton diagnostics
- e^-
spectrometer
- Protons
- Laser dump
- Laser room
- Electron source, klystron
- Plasma cell, 10m
- Diagnostics
- Proton-laser-merging
- Proton beam-line
- Protons
- Proton-laser-merging
- Laser room
- Electron beam line
- Proton beam-line
- Laser room
- Laser room
Laser System

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

750m proton beam line
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 $10^{12}$ 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
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

About two months ago:

Now:

Laser tunnel has been excavated recently also.
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.

### Specifications

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight</td>
<td>15 t, 8.5 t</td>
</tr>
<tr>
<td>Power consumption</td>
<td>60 kW, 15 kW rms &amp; 24 kW cycled</td>
</tr>
<tr>
<td>Integrated field (B*L)</td>
<td>1.9 T<em>m, 1.3 T</em>m rms &amp; 1.6 T*m cycled</td>
</tr>
<tr>
<td>Max. magnetic field</td>
<td>1.65 T, 1.2 T rms &amp; 1.5 T cycled</td>
</tr>
<tr>
<td>Horizontal aperture</td>
<td>52 cm, 32 cm</td>
</tr>
<tr>
<td>Vertical aperture</td>
<td>11 cm, 8 cm</td>
</tr>
<tr>
<td>Iron length</td>
<td>1 m, 1 m</td>
</tr>
<tr>
<td>Total length</td>
<td>1.7 m, 1.6 m</td>
</tr>
<tr>
<td>Total width</td>
<td>1.2 m, 1.3 m</td>
</tr>
<tr>
<td>Current</td>
<td>545 A, 400 A rms &amp; 500 A cycled</td>
</tr>
</tbody>
</table>
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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 (> 300fs) $\rightarrow$ bunch compression $\rightarrow$ Almost 100% capture efficiency

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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 (1st Phase, 2016)
  - Probe the longitudinal accelerating wakefields with externally injected electrons (2nd Phase, 2017-2018)
  - Develop long scalable and uniform plasma cells, production of shorter electron and proton bunches (2020)

Many thanks to all members of the AWAKE collaboration, especially to Allen Caldwell and Edda Gschwendtner!