AWAKE: Advanced Proton Driven Plasma Wakefield Acceleration Experiment at CERN

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for the AWAKE Collaboration

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Outline

• Motivation

• Plasma Wakefield Acceleration

• AWAKE at CERN

• AWAKE Experimental Program

• Components of the AWAKE Experiment

• Installation of the AWAKE Facility

• Summary
Motivation – Cavities vs. Plasma

Today’s RF cavities or microwave technology: accelerating fields is limited to <100 MV/m

➔ several tens of kilometers for future linear colliders

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

Use plasma as ‘cavity’!

• Plasma can sustain up to three orders of magnitude higher gradients
  – SLAC experiment: 50 GV/m

➔ much shorter linear colliders!
Motivation – Cavities vs. Plasma

• ILC Cavity: 35 MV/m

• Plasma cell: 35 GV/m $\rightarrow$ 35 MV/mm!!

1 mm (Not to scale!)
Motivation – Linear Colliders

ILC

Plasma based Linear Collider

500 GeV: 31 km

500 GeV: 3 km (3000 GeV: 8 km)
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Plasma Wakefield Acceleration

Wakefield excitation

Particle acceleration
**Principle of Plasma Wakefield Acceleration**

- 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.

⇒ Produce ‘mini cavities’ (~1mm) inside the plasma cell

⇒ Proton beam produces *(drives)* accelerating wakefield in the plasma

⇒ Injected electron beam *surfs (witnesses)* on that wakefield and gets accelerated.

⇒ Size of the accelerating structure is set by the plasma density: plasma wavelength $\lambda_p = 1\text{mm}$, (for typical plasma density of $n_p = 10^{15}\text{cm}^{-3}$)

⇒ Gradients at several GV/m

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

$$E_{z,\text{max}} \approx 2 \text{ GeV/m} \cdot \left(\frac{N_b}{10^{10}}\right) \cdot \left(\frac{100 \text{ \mu m}}{\sigma_z}\right)^2$$
First Results: Electron Beam Driven PWA

- Experimental results show success of PWFA and its research
- **SLAC beam:**
  - 42 $\rightarrow$ 84 GeV in 85 cm!
  - 50 GV/m
High-Efficiency acceleration of an electron beam in a plasmas wakefield accelerator
M. Litos et al., doi, Nature, 6 Nov 2014, 10.1038/nature 13992

Result

- Total efficiency is <29.1%> with a maximum of 50%.
- Final energy spread of 0.7 % (2% average)
There is a **limit to the energy gain** of a witness bunch in the plasma:

- Today’s electron beams usually < 100 J level.
- Limitation of the energy carried by the drive beam (< 100J) and the propagation length of the driver in the plasma (<1m).

To reach TeV scale with electron driven PWA: also need **several stages**, but need to have
- relative timing in 10’s of fs range
- many stages
- effective gradient reduced because of long sections between accelerating elements....
Proton Beam Driven PWA

Proton beams carry 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.

A. Caldwell, K. Lotov, Physics of Plasma, 18,103101 (2011)
# Beam-Driven Wakefield Acceleration: Landscape

<table>
<thead>
<tr>
<th>Facility</th>
<th>Where</th>
<th>Drive (D) beam</th>
<th>Witness (W) beam</th>
<th>Start</th>
<th>End</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>AWAKE</td>
<td>CERN, Geneva, Switzerland</td>
<td>400 GeV protons</td>
<td>Externally injected electron beam (PHIN 15 MeV)</td>
<td>2016</td>
<td>2020+</td>
<td><strong>Use for future high energy e-/e+ collider.</strong></td>
</tr>
<tr>
<td></td>
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<td></td>
<td>- Study Self-Modulation Instability (SMI).</td>
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<td></td>
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<td></td>
<td>- Accelerate externally injected electrons.</td>
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<td></td>
<td></td>
<td></td>
<td>- Demonstrate scalability of acceleration scheme.</td>
</tr>
<tr>
<td>SLAC-FACET</td>
<td>SLAC, Stanford, USA</td>
<td>20 GeV <em>electrons</em> and <em>positrons</em></td>
<td>Two-bunch formed with mask (e/e* and e-e* bunches)</td>
<td>2012</td>
<td>Sept 2016</td>
<td>- Acceleration of witness bunch with high <strong>quality and efficiency</strong></td>
</tr>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td>- Acceleration of positrons</td>
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<td></td>
<td></td>
<td></td>
<td>- FACET II proposal for 2018 operation</td>
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<tr>
<td>DESY-Zeuthen</td>
<td>PITZ, DESY, Zeuthen, Germany</td>
<td>20 MeV <em>electron</em> beam</td>
<td>No witness (W) beam, only D beam from RF-gun.</td>
<td>2015</td>
<td>~2017</td>
<td>- Study Self-Modulation Instability (SMI)</td>
</tr>
<tr>
<td>DESY-FLASH Forward</td>
<td>DESY, Hamburg, Germany</td>
<td>X-ray FEL type <em>electron</em> beam 1 GeV</td>
<td>D + W in FEL bunch. Or independent W-bunch (LWFA).</td>
<td>2016</td>
<td>2020+</td>
<td><strong>Application (mostly) for x-ray FEL</strong></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>- Energy-doubling of Flash-beam energy</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>- Upgrade-stage: use 2 GeV FEL D beam</td>
</tr>
<tr>
<td>Brookhaven ATF</td>
<td>BNL, Brookhaven, USA</td>
<td>60 MeV <em>electrons</em></td>
<td>Several bunches, D+W formed with mask.</td>
<td>On going</td>
<td></td>
<td>- <strong>Study quasi-nonlinear PWFA regime.</strong></td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td>- Study PWFA driven by multiple bunches</td>
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<td></td>
<td>- Visualisation with optical techniques</td>
</tr>
</tbody>
</table>
Outline

• Motivation

• Plasma Wakefield Acceleration

• AWAKE at CERN

• AWAKE Experimental Program

• Components of the AWAKE Experiment

• Installation of the AWAKE Facility

• Summary
• **Advanced Proton Driven Plasma Wakefield Acceleration Experiment**
  – Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.

• **Proof-of-Principle Accelerator R&D experiment at CERN**
  – *First proton driven wakefield experiment worldwide*
  – Demonstration of high-gradient acceleration of electrons
  – Approved in 2013
  – First beam expected in **2016**

• **AWAKE Collaboration: 16 Institutes world-wide**
AWAKE installed in
CNGS Facility (CERN Neutrinos to Gran Sasso) ➔ CNGS physics program finished in 2012

- Running underground facility
- Desired beam parameters
  ➔ adequate site for AWAKE
• Drive beam for AWAKE: 400 GeV/c SPS proton beam
• SPS longitudinal beam size ($\sigma_z = 12$ cm) is much longer than plasma wavelength ($\lambda = 1$ mm)

⇒ AWAKE Experiment is based on self-modulation instability
  – Modulate long bunch to produce a series of ‘micro-bunches’ in a plasma with a spacing of plasma wavelength $\lambda_p$.
    ⇒ Strong self-modulation effect of proton beam due to transverse wakefield in plasma
    ⇒ Starts from any perturbation and grows exponentially until fully modulated and saturated.

⇒ Immediate use of CERN SPS beam
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AWAKE Experimental Program

Phase 1: Understand the physics of self-modulation instability processes in plasma.
Phase 1: Understand **the physics of self-modulation instability** processes in plasma.

**Plasma cell**

→ Rb vapour source
Phase 1: Understand the physics of self-modulation instability processes in plasma.

Plasma cell
→ Rb vapour source

Proton beam
→ drives the plasma wakefield + undergoes self-modulation instability.
→ LHC-type proton beam, 400 GeV/c, 3E11 protons/bunch, σ = 400 ps long
Phase 1: Understand the **physics of self-modulation instability** processes in plasma.

**Plasma cell**
- Rb vapour source

**Proton beam**
- drives the plasma wakefield + undergoes self-modulation instability.
- LHC-type proton beam, 400 GeV/c, 3E11 protons/bunch, σ = 400 ps long

**Laser beam:**
- ionizes the plasma + seeds the self-modulation instability of the proton beam.
- 4.5 TW laser, 100 fs
Phase 1: Understand the **physics of self-modulation instability** processes in plasma.

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**Diagnostics**
- BTVs, OTR, CTR
Phase 1: Understand **the physics of self-modulation instability** processes in plasma.

**Start with physics Q4 2016!**

Self-modulated proton bunch resonantly driving plasma wakefields.

J. Vieira et al PoP 19063105 (2012)
AWAKE Experimental Program

- Phase 1: Understand **the physics of self-modulation instability** processes in plasma.
- Phase 2: **Probe the accelerating wakefields** with externally injected electrons.

**Plasma cell**
- $\rightarrow$ Rb vapour source

**Proton beam**
- $\rightarrow$ drives the plasma wakefield + undergoes self-modulation instability.
- $\rightarrow$ LHC-type proton beam, 400 GeV/c, 3E11 protons/bunch, $\sigma = 400$ ps long

**Laser beam:**
- $\rightarrow$ ionizes the plasma + seeds the self-modulation instability of the proton beam.
- $\rightarrow$ 4.5 TW laser, 100 fs

**Diagnostics**
- $\rightarrow$ BTVs, OTR, CTR

**Electron source and beam**
- $\rightarrow$ Witness beam to ‘surf’ on the wakefield and get accelerated
- $\rightarrow$ 16 MeV/c, 1.2 E9 electrons/ bunch, $\sigma = 4ps$ long
AWAKE Experimental Program

- Phase 1: Understand the **physics of self-modulation instability** processes in plasma.
- Phase 2: **Probe the accelerating wakefields** with externally injected electrons.

**Plasma cell**
- Rb vapour source

**Proton beam**
- drives the plasma wakefield + undergoes self-modulation instability.
- LHC-type proton beam, 400 GeV/c, 3E11 protons/bunch, $\sigma = 400$ ps long

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- BTVs, OTR, CTR

**Electron source and beam**
- Witness beam to ‘surf’ on the wakefield and get accelerated
- 16 MeV/c, 1.2 E9 electrons/ bunch, $\sigma = 4$ps long

**Electron spectrometer system**
Phase 1: Understand the physics of self-modulation instability processes in plasma.

Phase 2: Probe the accelerating wakefields with externally injected electrons.

Maximum amplitude of the accelerating field $E_z$ as a function of position along the plasma. Saturation of the SMI at ~4m.
AWAKE Experimental Program

- Phase 1: Understand the physics of self-modulation instability processes in plasma.
- Phase 2: Probe the accelerating wakefields with externally injected electrons.

Start with physics Q4 2017!

Energy of the electrons gained along the 10 m long plasma cell.
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Plasma Source: Rubidium Vapor Source

- Density adjustable from $10^{14} - 10^{15} \text{ cm}^{-3}$
- 10 m long, 4 cm diameter

- Plasma formed by field ionization of Rb
  - Ionization potential $\Phi_{\text{Rb}} = 4.177 \text{ eV}$
  - above intensity threshold ($I_{\text{ioniz}} = 1.7 \times 10^{12} \text{ W/cm}^2$) 100% is ionized.

- Plasma density = vapor density

- System is oil-heated: 150° to 200° C
  - keep temperature uniformity
  - Keep density uniformity

Required:
$\Delta n/n = \Delta T/T \leq 0.002$
Plasma Source: Rubidium Vapor Source

3m prototype at MPI Munich

10m plasma source for AWAKE

Grant Instruments
Laser intensity must exceed ionization intensity at the plasma end (L=10m) over a plasma radius of \( r > 3\sigma = 600 \, \mu m \).

### 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 ( \lambda_0 )</td>
<td>780 nm</td>
</tr>
<tr>
<td>Pulse length</td>
<td>100-120 fs</td>
</tr>
<tr>
<td>Pulse energy (after compr.)</td>
<td>450 mJ</td>
</tr>
<tr>
<td>Laser power</td>
<td>4.5 TW</td>
</tr>
<tr>
<td>Focused laser size ( \sigma_{x,y} )</td>
<td>1 mm</td>
</tr>
<tr>
<td>Rayleigh length ( Z_R )</td>
<td>5 m</td>
</tr>
<tr>
<td>Energy stability</td>
<td>±1.5% r.m.s.</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
</tr>
</tbody>
</table>
Indirect SMI Measurement: Defocusing of the proton beam

Direct SMI Measurement: Radiation emitted by bunch when traversing dielectric material → Streak camera

M. Turner, A. Petrenko, E.G, CERN

K. Rieger, P. Muggli, MPI
Phase 2: Electron Witness Beam – Electron Source

PHIN Photo-injector for CTF3/CLIC:
→ Program will stop end 2015

→ Fits to requirements → used as electron beam source for AWAKE
Phase 2: Electron Witness Beam

<table>
<thead>
<tr>
<th>Electron beam for AWAKE</th>
<th>Baseline</th>
<th>Range for upgrade phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum</td>
<td>16 MeV/c</td>
<td>10-20 MeV</td>
</tr>
<tr>
<td>Electrons/bunch (bunch charge)</td>
<td>1.25 E9</td>
<td>0.6 – 6.25 E9</td>
</tr>
<tr>
<td>Bunch charge</td>
<td>0.2 nC</td>
<td>0.1 – 1 nC</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z = 4\text{ps}$ (1.2mm)</td>
<td>0.3 – 10 ps</td>
</tr>
<tr>
<td>Bunch size at focus</td>
<td>$\sigma_{x,y}^* = 250 \mu\text{m}$</td>
<td>0.25 – 1mm</td>
</tr>
<tr>
<td>Normalized emittance (r.m.s.)</td>
<td>2 mm mrad</td>
<td>0.5 – 5 mm mrad</td>
</tr>
<tr>
<td>Relative energy spread</td>
<td>$\Delta p/p = 0.5%$</td>
<td>&lt;0.5%</td>
</tr>
</tbody>
</table>
Electron Beam Trapping and Acceleration in the Plasma Wakefield

• Electrons are trapped from the very beginning by the wakefield.
• Trapped electrons make several synchrotron oscillations in their potential wells.
• After $z=4$ m the wakefield moves forward in the light velocity frame.

K. Lotov, LCODE
Phase 2: Electron Witness Beam Acceleration Diagnostics

Probe the accelerating wakefields with externally injected electrons → Electron spectrometer

8.5 ton, 1.2 T, 1.3 Tm, L=1.6 m, W=1.3 m

Dispersed electron impact on scintillator screen. Resulting light collected with intensified CCD camera.
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AWAKE Installation

Protons from SPS are sent through a tunnel and a dump, then through a distance of ~1100m to the LHC. The AWAKE experiment is located along this path.
AWAKE Experimental Facility

- Laser
- RF gun
- SPS protons
- Proton diagnostics: BTV, OTS, CTR
- Laser dump
- Proton beam dump
- Laser room
- Proton beam
- plasma cell
- electron source, klystron
- diagnostics
AWAKE Facility Preparation
Proton Beam Line

Proton beam line from SPS extraction to ~80 m upstream the AWAKE facility.
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## AWAKE Time Line

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</thead>
<tbody>
<tr>
<td>Proton and laser beam-line</td>
<td>Study, Design, Procurement, Component preparation</td>
<td>Installation</td>
<td>Commissioning</td>
<td>Data taking</td>
<td>Study, Design, Procurement, Component preparation</td>
<td>Modification, Civil Engineering and installation</td>
<td>Phase 1</td>
</tr>
<tr>
<td>Experimental area</td>
<td>Study, Design, Procurement, Component preparation</td>
<td>Fabrication</td>
<td>Installation</td>
<td>Commissioning</td>
<td>Study, Design, Procurement, Component preparation</td>
<td>Phase 2</td>
<td></td>
</tr>
<tr>
<td>Electron source and beam-line</td>
<td>Studies, design</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Continue data taking after LS2</td>
<td></td>
</tr>
</tbody>
</table>

- AWAKE 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
Next Steps (Phase 3)

- **Split-cell mode**: SMI in 1\(^{st}\) plasma cell, acceleration in 2\(^{nd}\) 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 ($\sim 300\text{fs}$) $\rightarrow$ bunch compression $\rightarrow$ Almost 100% capture efficiency

![Plasma density profile](image)

![Maximum wakefield amplitude](image)
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.
  - Strong motivation of the community: long-term prospects for proton-driven PWA exiting
    - Provide a design for a particle physics frontier machine by 2022
    - Needs extensive experimental program NOW, results with electrons, ...

- 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)
  - Reach higher gradients, develop long scalable and uniform plasma cells, production of shorter electron and proton bunches (2020)