Starting Up the AWAKE Experiment at CERN

Edda Gschwendtner, CERN
For the AWAKE Collaboration

IPAC17, Copenhagen, Denmark, 14-19 May 2017
Outline

• Introduction
• The AWAKE Experiment
• Commissioning of AWAKE
• First Beam Results
• Electron Acceleration Status
• What’s Next
• Summary
Proton Drivers for Plasma Wakefield Acceleration

Proton bunches as drivers of plasma wakefields are interesting because of the very large energy content of the proton bunches.

**Drive beams:**
- Lasers: $\sim$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 $\sim$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....
- **Proton drivers:** large energy content in proton bunches $\Rightarrow$ allows to consider single stage acceleration
Self-Modulation Instability

- 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!**
- Longitudinal beam size ($\sigma_z = 12 \text{ cm}$) is much longer than plasma wavelength ($\lambda = 1 \text{ mm}$)

**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
  - Resonantly drives the longitudinal wakefield

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

Fukhov et al., PRL 107, 184003 (2011)
Schroeder et al., PRL 107, 185002 (2011)
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AWAKE at CERN

Advanced Proton Driven Plasma Wakefield Acceleration Experiment

• Proof-of-Principle Accelerator R&D experiment at CERN
• Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.
• AWAKE Collaboration: 16 institutes + 3 associate

• Approved in August 2013
• First beam end 2016

Run 1 – until LS2 of the LHC.

After LS2 – proposing Run 2 of AWAKE (during Run 3 of LHC)

After Run 2 – kick off particle physics driven applications
AWAKE Experimental Program Run 1, 2016/17

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

**Self-modulated proton bunch** resonantly driving plasma wakefields.

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

Second half of the proton bunch sees plasma

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A. Petrenko, CERN

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K. Riegler, MPP
Phase 1: Understand the physics of self-modulation instability processes in plasma.

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

- Trapping efficiency: 10 – 15 %
- Average energy gain: 1.3 GeV
- Energy spread: ± 0.4 GeV
- Angular spread up to ± 4 mrad
The AWAKE Facility
**AWAKE Proton Beam Line**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Protons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum [MeV/c]</td>
<td>400 000</td>
</tr>
<tr>
<td>Momentum spread [%]</td>
<td>±0.035</td>
</tr>
<tr>
<td>Particles per bunch</td>
<td>3·10^{11}</td>
</tr>
<tr>
<td>Charge per bunch [nC]</td>
<td>48</td>
</tr>
<tr>
<td>Bunch length [mm]</td>
<td>120 (0.4 ns)</td>
</tr>
<tr>
<td>Norm. emittance [mm-mrad]</td>
<td>3.5</td>
</tr>
<tr>
<td>Repetition rate [Hz]</td>
<td>0.033</td>
</tr>
<tr>
<td>1σ spot size at focal point [μm]</td>
<td>200 ±20</td>
</tr>
<tr>
<td>β-function at focal point [m]</td>
<td>5</td>
</tr>
<tr>
<td>Dispersion at focal point [m]</td>
<td>0</td>
</tr>
</tbody>
</table>

Change of the proton beam line in the **downstream part (~80m)** → e.g. create a chicane for the laser merging integration.

Protons from SPS

Laser Merging Point

Electron Source (Phase 2)

Start of Plasma Cell

Proton beam line upstream

Proton beam line downstream
Laser and Laser Line

- **Laser beam line to plasma cell**
  - $\lambda = 780$ nm
  - $t_{\text{pulse}} = 100-120$ fs
  - $E = 450$ mJ

- **Diagnostic beam line ("virtual")**
  - $\lambda = 780$ nm
  - $t_{\text{pulse}} = 100-120$ fs,
  - $E \approx 5$ mJ

- **Laser beam line to electron gun (2017)**
  - $\lambda = 260$ nm
  - $t_{\text{pulse}} = 0.3-10$ ps
  - $E = 0.5$ mJ

Requirements
This installation requires Adobe Acrobat Reader 7.0 or Adobe Acrobat 7.0. You must install one of these products before installation of the plug-in. Adobe products are available on Adobe website: www.adobe.com

Contact: infos@seemage.com
The AWAKE Plasma Cell

- **10 m long, 4 cm diameter**
- Rubidium vapor, field ionization threshold $\sim 10^{12}$ W/cm$^2$
- Density adjustable from $10^{14}$ – $10^{15}$ cm$^{-3}$ $\Rightarrow 7 \times 10^{14}$ 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
Indirect SMI diagnostics:
Image protons that got defocused by the strong plasma wakefields.

Two imaging stations (IS) to measure the radial proton beam distribution 2 and 10 m downstream the end of the plasma.

→ Compare transverse size of beam with and without plasma.
→ Growth of tails governed by the transverse fields in the plasma.
Self-Modulation Instability Diagnostics II

Direct SMI diagnostics:
Measure frequency of modulation.

OTR: Optical Transition Radiation: Temporal intensity of the OTR carries information on bunch longitudinal structure.

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Temporal intensity of the OTR carries information on bunch longitudinal structure.

Fig. 18: Schematic of the OTR and CTR setup installed on the proton beam line.
Self-Modulation Instability Diagnostics II

Direct SMI diagnostic:
Measure frequency of modulation.

OTR: Optical Transition Radiation: Temporal intensity of the OTR carries information on bunch longitudinal structure.

CTR: Coherent Transition Radiation: Radiation is coherent for \(\sigma\)-bunches (90-300GHz).

Fig. 18: Schematic of the OTR and CTR setup installed on the proton beam line.

![OTR/CTR setup](image-url)
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AWAKE Beam Commissioning 2016

3 periods of commissioning:
June, September, November 2016

Proton beam line **commissioned and running stable** with full intensity and matching specifications

- Optimized trajectory at experiment: Standard deviation during **stability run of ~60 μm**
- **Stable beam** at full intensity 3E11 p/bunch
- **No beam losses** at laser merging mirror
Results Laser Beam Commissioning

Transversal alignment of proton and laser beam (spatial overlap)

J. Moody, MPP; J. Schmidt, CERN

p-beam
Results Laser Beam Commissioning

Transversal alignment of proton and laser beam (spatial overlap)

Laser positioned on proton beam references to within 300 microns (corresponds to 6 µrad pointing jitter)

J. Moody, MPP; J. Schmidt, CERN
SPS proton beam synchronized with AWAKE laser within ~20ps accuracy

S. Mazzoni MOPAB119
J. Schmidt, TUPIK032
V. Olsen, TUPIK061
J. Schmidt, THPAB050
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Indirect SMI Measurement Results

M. Turner, CERN
Turner et al., NIMA 854, 100(2017)

→ $p^+$ defocused by the transverse wakefield (SMI) form a halo
→ $p^+$ focused form a tighter core
→ Estimate of the transverse wakefields amplitude ($\int W_{per} \, dr$)
Direct SMI Measurements, OTR

Timing at the ps scale
Effect starts at laser timing
Density modulation at the 10ps-scale visible

 Successful first SMI physics run: 48h
Operation at low plasma density: ~1.5x10^{14} \text{cm}^{-3}
SMI signal detected on all three diagnostics (IS, OTR, CTR)

2017: further investigation of SMI
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Electron Source and Beam Line

### Electron beam

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<thead>
<tr>
<th>Parameter</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>σ_z = 4 ps (1.2 mm)</td>
<td>0.3 – 10 ps</td>
</tr>
<tr>
<td>Bunch size at focus</td>
<td>σ^2_{xy} = 250 μm</td>
<td>0.25 – 1 mm</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>Δp/p = 0.5%</td>
<td>&lt;0.5%</td>
</tr>
</tbody>
</table>

**Completely new beam line and tunnel:**
- Horizontal angle of 60 deg,
- 20% slope of the electron tunnel \(\Delta = 1.16\text{m}\)
- 5.66% slope of the plasma cell
- ~5 m common beam line of e^- and p.
Dispersed electron impact on scintillator screen. Resulting light collected with intensified CCD camera. %-level energy resolution achieved with a S/N ratio larger than 1000:1

Start commissioning end 2017
Physics in 2018
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AWAKE Proposal Run 2

Goals:

• Accelerate an electron beam to high energy
• Preserve electron beam quality as well as possible
• Demonstrate scalability of the AWAKE concept

After Run 2: get ready for first applications:

• Use bunches from SPS with 3.5 E11 protons every ~5sec, electron beam of up to O (50GeV).
• Using the LHC beam as a driver, TeV electron beams are possible.
Summary

• AWAKE is a **proton driven** plasma wakefield experiment at CERN

• AWAKE aims accelerating electrons with $\sim 1$ GV/m gradient using self-modulation instability of a long proton bunch in a plasma ($\sigma_z > \lambda_{pe}$)

• The AWAKE facility was **successfully commissioned**

• **First signs of SMI** were seen on all three diagnostics during a 48hr run in December 2016 $\rightarrow$ further investigation in 2017

• **Electron acceleration experiment**: commissioning end 2017, physics in 2018

• **Run 2** is proposed for after 2020: preserve electron beam quality, scalability

• First studies on **applications** of p-driven PWFA