Status and Prospects for the AWAKE Experiment

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Outline of this Talk

- Introduction
  - Concept of plasma wakefield acceleration
  - AWAKE experiment
  - Seeded self-modulation

- Status of the AWAKE experiment
  - Seeded self-modulation measurements results
  - 2018: electron acceleration

- Prospects
  - AWAKE run 2

- Summary
Concept of plasma wakefield acceleration
Why plasma wakefield acceleration?

The general **goal** of the work done in our field is to:

- use plasma wakefields for **charged particle acceleration**;
- accelerate to **higher energies** in **shorter distances** than with RF cavities.
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Particle acceleration in **radiofrequency** cavities limited to fields ~100 MV/m due to electrical **breakdown** in the structure.

Accelerate charged particles with **plasma wakefields**, because plasma can sustain higher electric fields. Estimate of the achievable accelerating gradient is the cold plasma wave-breaking field ($E$):

$$ eE = m_e \omega_{pe} c \sim 100 \frac{eV}{m} \sqrt{n_{pe} \text{[cm}^{-3}] $$

i.e. ~1 GeV/m for a plasma electron density $n_{pe}$ of $10^{14}$ cm$^{-3}$

~100 GeV/m for $10^{18}$ electrons/cm$^3$
How to Create a Plasma Wakefield?

Plasma: Quasi-neutral plasma in which electrostatic interactions dominate and charged particles are close enough to support collective behaviour.

Drive bunch or pulse: Typically a relativistic charged particle bunch or laser pulse/s.
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**Plasma wavelength** $\lambda_{pe}$

- Accelerating for $e^-$
- Decelerating for $e^-$
- Defocusing for $e^-$
- Focusing for $e^-$
How to Create a Plasma Wakefield?

Plasma:
Quasi-neutral plasma in which electrostatic interactions dominate and charged particles are close enough to support collective behaviour.

Drive bunch or pulse:
Typically a relativistic charged particle bunch or laser pulse/s.

Larger plasma e\(^-\) density implies smaller plasma e\(^-\) wavelength ⇒ smaller structures

\[ \lambda_{pe} = \frac{2\pi c}{\omega_{pe}} \propto \frac{1}{\sqrt{n_{pe}}} \]
AWAKE and the Seeded Self-Modulation (SSM)
What is AWAKE?

- AWAKE stands for: Advanced Proton Driven Plasma WAKefield Experiment.

- AWAKE is a R&D project to study proton driven plasma wakefields at CERN.

- Final Goal: Design high quality & high energy electron accelerator.

Proton bunches have the potential to drive wakefields that can accelerate a witness bunch to TeV energies in a single plasma.

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The seeded self-modulation

Why protons?

The length over which wakefields can be sustained depends on the drive bunch energy
The seeded self-modulation

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The length over which wakefields can be sustained depends on the drive bunch energy
Laser pulses: \(~40\) J, Electron drive beam: 30 J/bunch, Proton drive beam: SPS 19 kJ/bunch, LHC 300 kJ/bunch.

To effectively excite wakefields (from linear plasma wakefield theory):

\[
k_{pe} \sigma_z \approx \sqrt{2} \quad k_{pe} \sigma_r \approx 1
\]

\(\Rightarrow\) In order to create plasma wakefields effectively, the drive bunch length has to be in the order of the plasma wavelength \(\Rightarrow\) mm scale proton bunches do not exist.
The seeded self-modulation

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⇒ In order to create plasma wakefields effectively, the drive bunch length has to be in the order of the plasma wavelength ⇒ mm scale proton bunches do not exist.

CERN SPS proton bunch: very long!
Longitudinal beam size (\( \sigma_z = 6-15 \text{ cm} \)) is much longer than plasma wavelength (\( \lambda_{pe} = 1 \text{ mm}, n_{pe} = 7 \times 10^{14} \text{ e}^-/\text{cm}^3 \))
⇒ Seeded Self-Modulation (SSM)

Before self modulation:

\( \sigma_z = 12 \text{ cm} \)
\( \lambda_p = 1.2 \text{ mm} \)
The seeded self-modulation

1) When entering the plasma, the bunch drives wakefields at the initial seed value.

2) The initial wakefields act back on the proton bunch itself. The on-axis density is modulated. The contribution to the wakefields is $\propto n_b$.

3) **Density modulation** on axis (Micro-bunches).

   Micro-bunches separated by $\lambda_{pe}$. Drive wakefields resonantly.
The seeded self-modulation

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Micro-bunches separated by $\lambda_{pe}$. Drive wakefields resonantly.

We seed the instability by:

- Placing the laser close to the center of the proton bunch
- Sudden onset of the proton density

$\Rightarrow$ Seeded self-modulation (SSM)
Counts / a.u.

$s = 0.2 \text{ m}$
The AWAKE experimental setup
1. 10 m long **rubidium vapour source** with a vapour density adjustable from $10^{14}$-$10^{15}$ atoms/cm$^3$ and a density uniformity of 0.2%.

2. **Laser** system that produces a 120 fs, 450mJ laser pulse.

3. **Proton** beam line that transfers a 400 GeV/c proton bunch with a RMS length of 6-15 cm, a radial RMS size of 0.2 mm and $3 \times 10^{11}$ protons/bunch from the CERN SPS to AWAKE.

4. Experiment **diagnostics**.

5. **Electron** photoinjector and transfer line that produces a 10-20 MeV electron bunch with a RMS length of 1 mm a RMS size of $\sim$0.2 mm and $\sim 10^9$ electrons/bunch.
Alignment of $p^+$, $e^-$ and laser pulse

Temporal alignment:

- $p^+$
- Laser pulse
- Space
- $e^-$
- Laser pulse
- Time
- MPP

Status last Dec.

I. Gorgisyan, this proceeding

M. Turner, CERN for the AWAKE collaboration
Alignment of p⁺, e⁻ and laser pulse

Temporal alignment:

Spatial alignment:

~2m upstream the plasma
1. **Self-modulate** a long (compared $\lambda_{pe}$) 400 GeV/c proton bunch in plasma.
The AWAKE experiment (Run 1)

1. **Self-modulate** a long (compared $\lambda_{pe}$) 400 GeV/c proton bunch in plasma.

First results of the AWAKE experiment

M. Turner, CERN for the AWAKE collaboration
Did the bunch self-modulate?

Generally we measure what is going into the plasma and what is coming out of the plasma ⇒ what has happened inside the plasma.
OTR Streak camera measurement

Streak camera imaging OTR light ⇒ time resolved image of the proton bunch.

1) Simulation, Image K. Rieger

- no plasma
- plasma

Self-modulated proton bunch
45° tilted metal screen

Backward CTR / OTR
Forward CTR / OTR
The imaging stations

2 Imaging stations ⇒ Transverse time integrated bunch profile.

Goal: Detect protons that got defocused by the strong plasma wakefields.

No plasma:
No ionizing laser pulse; bunch propagates through rb vapor

Log scale!
The imaging stations

2 Imaging stations ⇒ Transverse time integrated bunch profile.

Goal: Detect protons that got defocused by the strong plasma wakefields.

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

Log scale!
Seeded Self-Modulation

- **Effect** starts at the laser position.
- **Micro-bunches** are visible on a fast time-scale.

$N_{pe} = 2.1 \times 10^{14}/\text{ccm}$
Seeded Self-Modulation

- Single streak camera measurement
- Time scale ~73 ps
- Streak camera trigger jitter (~20ps rms): Marker laser pulsed synchronized with ionization laser pulse at the 10 ps time scale.
- **10 consecutive events** aligned to marker laser pulse

- Bunches add:
  - Modulation fixed wrt *ionizing laser pulse*
  - Modulation fixed wrt to *seed*
Seeded Self-Modulation

- 5 sets of 10 events each
- Possible because: **marker laser** pulsed synchronized with ionization laser pulse at the ps time scale

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$\rho_{Bb} = 2.1 \times 10^{14} \text{cm}^{-3}$
Seeded Self-Modulation

- **Micro-bunches** present over long time scale from seed point
- “Stitching” demonstrates **reproducibility** of the micro-bunch process against bunch parameters variations ($N=2.5\times10^{11}\pm10\%$, $s_{2t}=220\pm10\text{ps}$, $s_r$)
- **Phase stability** essential for $e^-$ external injection!
Detection of defocused protons

Two consecutive measurements:

- Close to **AWAKE** baseline parameters.

- 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/cm³.

- Halo symmetric ⇒ **no hose instability**.
Electron acceleration
The AWAKE electron bunch

- The electron gun and transport line has been installed in 2017.

- The electron system is now under commissioning.
Electron injection

AWAKE is getting ready for electron acceleration:

- **Challenge:**
  - During the SSM the proton bunch distribution evolves
  - Short plasma density ramp at the entrance of the plasma
    ⇒ change of wakefield phase

*M. Turner, CERN for the AWAKE collaboration*
AWAKE is getting ready for electron acceleration:

- **Challenge:**
  - During the *SSM* the proton bunch distribution evolves
  - Short plasma density ramp at the entrance of the plasma
    ⇒ change of wakefield phase

- Instead of injecting bunches co-linear
  ⇒ **Cross** the electron and proton bunch at a defined location inside the plasma.

- Radial bunch size:
  - proton : ~150 um
  - electron : ~200 um
Electron injection diagnostics

**Goal:** see the electron bunch in presence of the protons and the ionizing laser pulse
What is the energy of accelerated electrons?

Accelerated electrons are sent through an imaging spectrometer and deposit energy on a scintillating screen which is imaged by a camera.

B = 0.1 - 1.5 T
Magnetic length = 1m

We can detect electrons with energies ranging from: 30 MeV - 8.5 GeV

See Keeble F et al., The AWAKE electron Spectrometer, this proceedings

Calibration image of the spectrometer

Spectrometer fully commissioned

Expected measurement
L. Deacon (UCL)
Prospects
Goal: The next big step for AWAKE is to demonstrate scalability of the AWAKE concept and that we can control the parameters of the accelerated electron bunch to the level where it can be used for first applications:

- a micron-level normalized emittance
- a percent level relative energy spread
- high charge

After Run 2: get ready for first HEP applications:
Use bunches from SPS with 3.5 E11 protons every ~5sec, electron beam of up to O (50GeV).
The AWAKE Collaboration!
Conclusions and Summary

- The goal of the AWAKE experiment is to: accelerate electrons with plasma wakefields driven by a self-modulated proton bunch.
- We demonstrated that the SSM develops over the 10m of plasma and that its physics properties scale as expected.
- The electron beam system has been installed and is under commissioning.
- Electron acceleration experiments are foreseen for 2018.