Novel Acceleration Techniques
Plasma Wakefield Acceleration

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Edda Gschwendtner, CERN
Outline

• Motivation

• Introduction to Plasma Wakefield Acceleration

• Key Challenges of Plasma Wakefield Acceleration and Experimental Results
Discover New Physics

Accelerate particles to even higher energies

→ Bigger accelerators: circular colliders

Future Circular Collider: FCC

Limitations of conventional circular accelerators:

• For hadron colliders, the limitation is magnet strength. Ambitious plans like the FCC call for 16 T magnets in a 100 km tunnel to reach 100 TeV proton-proton collision energy.

• For electron-positron colliders: Circular machines are limited by synchrotron radiation in the case of positron colliders. These machines are unfeasible for collision energies beyond ~350 GeV.

\[ P_{\text{synchr}} = \frac{e^2}{6\pi\varepsilon_0 c^7} \frac{E^4}{R^2 m^4} \]
Discover New Physics

Linear colliders are favorable for acceleration of low mass particles to high energies.

CLIC, electron-positron collider with 3 TeV energy

Limitations of linear colliders:
• Linear machines accelerate particles in a single pass. The amount of acceleration achieved in a given distance is the accelerating gradient. This number is limited to 100 MV/m for conventional copper cavities.
Conventional Acceleration Technology

Radiofrequency Cavities

A voltage generator induces an electric field inside the RF cavity. Its voltage oscillates with a radio frequency of 408 MHz.

Protons in LHC

Protons never feel a force in the backward direction.

Protons always feel a force in the forward direction.

LHC Cavity

(invention of Gustav Ising 1924 and Rolf Wideroe 1927)
Conventional Accelerating Technology

Today’s RF cavities or microwave technology:

• Very successfully used in all accelerators (hospitals, scientific labs,...) in the last 100 years.

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

However:

• accelerating fields are limited to <100 MV/m
  • In metallic structures, a too high field level leads to break down of surfaces, creating electric discharge.
  • Fields cannot be sustained, structures might be damaged.

• several tens of kilometers for future linear colliders
Saturation at Energy Frontier for Accelerators

→ Project size and cost increase with energy
Plasma Wakefield Acceleration

Wakefield excitation

Particle acceleration
Outline

• Motivation

• Introduction to Plasma Wakefield Acceleration

• Key Challenges of Plasma Wakefield Acceleration and Experimental Results
Seminal Paper 1979, T. Tajima, J. Dawson

Use a plasma to convert the transverse space charge force of a beam driver into a longitudinal electrical field in the plasma.
Many, Many Electron and Laser Driven Plasma Wakefield Experiments…!

Now first Proton Driven Plasma Wakefield Experiment
Motivation for PWFA

• Short term perspective of PWFA (< 10 years):
  • Compact FEL based: 5 – 10 GeV energy range
  • Compact X-ray sources: electron accelerated in strong transverse field of plasma emit betatron radiation
    ➔ applications in medicine, radiobiology, material science

• Long term perspective of PWFA (>20 years):
  • High energy physics applications: Plasma-based high energy linear collider
    ➔ depends strongly on progress in many fields.

The most demanding application of plasma wakefield acceleration is to build a compact, efficient, Plasma-Based Linear Collider.
Plasma Wakefield

What is a plasma?

Quasi-neutrality: the overall charge of a plasma is about zero.

Collective effects: Charged particles must be close enough together that each particle influences many nearby charged particles.

Electrostatic interactions dominate over collisions or ordinary gas kinetics.

Example: Single ionized rubidium plasma

What is a plasma wakefield?

Fields created by collective motion of plasma particles are called plasma wakefields.
Plasma Baseline Parameters

• A plasma of density $n_{pe}$ is characterized by the plasma frequency

$$\omega_{pe} = \sqrt{\frac{n_{pe} e^2}{m_e \varepsilon_0}} \Rightarrow \frac{c}{\omega_{pe}} \text{ ... unit of plasma [m]} \quad k_{pe} = \frac{\omega_{pe}}{c}$$

Example: $n_{pe} = 7 \times 10^{14}$ cm$^{-3}$ (AWAKE) $\Rightarrow$ $\omega_{pe} = 1.25 \times 10^{12}$ rad/s $\Rightarrow$ $\frac{c}{\omega_{pe}} = 0.2$ mm $\Rightarrow$ $k_{pe} = 5$ mm$^{-1}$

• This translates into a wavelength of the plasma oscillation

$$\lambda_{pe} = 2\pi \frac{c}{\omega_{pe}} \Rightarrow \lambda_{pe} \approx 1 \text{ mm} \sqrt{10^{15} \text{ cm}^{-3}} \frac{1}{n_{pe}}$$

$\lambda_{pe} = 1.2$ mm $\Rightarrow$ Produce cavities with mm size!
**How to Create a Plasma Wakefield?**

**What we want:**
Longitudinal electric field to accelerate charged particles.

**Our Tool:**
Single ionized rubidium plasma

Using plasma to convert the **transverse electric field** of the drive bunch into a **longitudinal electric field in the plasma**. The more energy is available, the longer (distance-wise) these plasma wakefields can be driven.

**Charged particle bunches** carry almost purely transverse Electric Fields.
How to Create a Plasma Wakefield?
How to Create a Plasma Wakefield?

Different ways to excite the wakes-
Most commonly used:
- Laser bunches
- Electron beams
- Protons bunches (first time to be done at CERN)
Principle of Plasma Wakefield Acceleration

- Laser drive beam
  - \(\text{Ponderomotive force}\)

- Charged particle drive beam
  - \(\text{Transverse space charge field}\)
    - Reverses sign for negatively (blow-out) or positively (suck-in) charged beam

- Plasma wave/wake excited by relativistic particle bunch
- Plasma e\(^-\) are expelled by space charge force
- Plasma e\(^-\) rush back on axis
- Ultra-relativistic driver – ultra-relativistic wake \(\rightarrow\) no dephasing
- Acceleration physics identical for LWFA, PWFA

\(\lambda_{pe}\) - plasma wavelength
Where to Place the Witness Beam (Surfer)?

Accelerating for $e^-$
Decelerating for $e^-$
Focusing for $e^-$
Defocusing for $e^-$
Wakefields

How strong can the fields be?

• The plasma oscillation leads to a longitudinal accelerating field. The maximum accelerating field (wave-breaking field) is:

\[ e E_{WB} = 96 \frac{V}{m} \sqrt{\frac{n_{pe}}{\text{cm}^{-3}}} \]

Example: \( n_{pe} = 7 \times 10^{14} \text{ cm}^{-3} \) (AWAKE) \( \Rightarrow \) \( eE_{WB} = 2.5 \text{ GV/m} \) \( \Rightarrow \) \( g = 21 \text{kT/m} \)

Example: \( n_{pe} = 7 \times 10^{17} \text{ cm}^{-3} \) \( \Rightarrow \) \( eE_{WB} = 80 \text{ GV/m} \) \( \Rightarrow \) \( g = 21 \text{MT/m} \)

• The ion channel left on-axis, where the beam passes, induces an ultra-strong focusing field:

\[ g = 960 \pi \frac{n_{pe}}{10^{14} \text{ cm}^{-3}} \frac{T}{m} \]
Linear Theory

When drive beam density is smaller than plasma density \((n_b \ll n_p) \Rightarrow \text{linear theory.}\)

- Peak accelerating field in plasma resulting from drive beam with Gaussian distribution:

\[
e_{E_z} = \sqrt{n_p} \frac{n_b}{n_p} \frac{\sqrt{2\pi k_p \sigma_z}}{1 + \frac{k_p^2 \sigma_r^2}{4}} \sin k_p(z - ct) \quad (eV/cm)
\]

\(\Rightarrow e_{E_z} \approx N/\sigma_z^2\)

B.E. Blue 2003

- **Wakefield** excited by bunch oscillates **sinusoidally** with frequency determined by plasma density
- **Accelerating gradient** increases linearly with \(N/\sigma_z\)
- Fields excited by electrons and protons/positrons are **equal in magnitude but opposite in phase**
- The **accelerating field is maximized** for a value of

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

Example: \(n_{pe} = 7 \times 10^{14} \text{ cm}^{-3} \) (AWAKE), \(k_{pe} = 5 \text{ mm}^{-1}\) \(\Rightarrow\) drive beam: \(\sigma_z = 300\mu m, \sigma_r = 200\mu m\)
Linear Theory: Maximum accelerating electric field reached with drive beam of $N$ and $\sigma_z$:

$$E_{acc} = \frac{110 \text{ MV/m}}{\frac{N}{(2 \times 10^{10})} \left(\frac{\sigma_z}{0.6 \text{mm}}\right)^2}$$

- Driver must be short compared to plasma wavelength, easy for laser and electron bunches.

Examples of accelerating fields for different beam parameters and plasma parameters fields:

- $N = 3 \times 10^{10}$, $\sigma_z = 300 \mu\text{m}$, $n_{pe} = 7 \times 10^{14} \text{ cm}^{-3} \Rightarrow E_{acc} = 600 \text{ MV/m}$
- $N = 3 \times 10^{10}$, $\sigma_z = 20 \mu\text{m}$, $n_{pe} = 2 \times 10^{17} \text{ cm}^{-3} \Rightarrow E_{acc} = 15 \text{ GV/m}$
From Linear to Non-Linear

Electron density :

Longitudinal fields :

- $n_b << n_{pe}$
  - linear regime
- $n_b \approx n_{pe}$
  - non-linear wakes
- $n_b >> n_{pe}$
  - blow-out regime

- lower wakefields
- transverse forces not linear in $r$
- Symmetric for positive and negative witness bunches
- Well described by theory
+ Higher wakefields
+ Transverse forces linear in $r$ (emittance preservation)
+ High charge witness acceleration possible
- Requires more intense drivers
- Not ideal for positron acceleration

W. Mori (UCLA)
Blow-out Regime

- Space-charge force of the driver blows away all the plasma electrons in its path, leaving a uniform layer of ions behind (ions move on a slower time scale).
- Plasma electrons form a narrow sheath around the evacuated area, and are pulled back by the ion-channel after the drive beam has passed.
- An accelerating cavity is formed in the plasma.
- The back of the blown-out region: ideal for electron acceleration.

→ High charge witness acceleration possible → charge ratio to witness of same order
→ Linear focusing in r, for electrons; very strong quadrupole (MT/m)
→ High transformer ratios (>2) can be achieved by shaping the drive bunch
→ $E_r$ independent of $x$, can preserve incoming emittance of witness beam
Self-Injection Scheme

4.25 GeV beams obtained from 9cm plasma channel powered by 310TW laser pulse (15 J)

W.P.Leemans et al., PRL 2014
Example of FACET-II Experiment ‘Trojan Horse’: High Brightness Beam

**Plasma photocathode:** Tunable production of electron bunches of ultrahigh quality by laser release from higher ionization threshold inside the electron-driven plasma wave

Released electrons are rapidly accelerated and form bunch with ultralow emittance

Synchronized laser pulse tunnel ionizes in focus and releases ultracold electron population

Two plasma components:

- Beam-driven plasma wakefield using low-ionization-threshold gas such as Li
- Laser-controlled electron injection via ionization of high-ionization threshold gas such as He

Ultra-high brightness beams:

- Sub-µm spot size
- fs pulses
- Small emittance (nm mrad)

\[
B_{6D} = \frac{I}{\epsilon_n^2 \cdot 0.1\% \sigma_w \text{ energy spread}}
\]

B. Hidding et al., PRL 108, 035001 (2012)
# Laser-Driven Plasma Acceleration Facilities

## Table 2.2: Laser facilities ($\geq 100$ TW) performing LWFA R&D in Europe.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Institute</th>
<th>Location</th>
<th>Energy (J)</th>
<th>Peak power (PW)</th>
<th>Rep. rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ELBE [16]</td>
<td>HZDR</td>
<td>Dresden, Ge</td>
<td>30</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>GEMINI [17]</td>
<td>STFC, RAL</td>
<td>Didcot, UK</td>
<td>15</td>
<td>0.5</td>
<td>0.05</td>
</tr>
<tr>
<td>LLC [18]</td>
<td>Lund Univ</td>
<td>Lund, Se</td>
<td>3</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>Salle Jaune [19]</td>
<td>LOA</td>
<td>Palaiseau, Fr</td>
<td>2</td>
<td>0.07</td>
<td>1</td>
</tr>
<tr>
<td>UH1100 [20]</td>
<td>CEA Saclay</td>
<td>Saclay, Fr</td>
<td>2</td>
<td>0.08</td>
<td>1</td>
</tr>
<tr>
<td>CALA* [21]</td>
<td>MPQ</td>
<td>Munchen, Ge</td>
<td>90</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>CILEX* [22]</td>
<td>CNRS-CEA</td>
<td>St Aubin, Fr</td>
<td>10-150</td>
<td>1-10</td>
<td>0.01</td>
</tr>
<tr>
<td>ELIbeamlines* [23]</td>
<td>ELI</td>
<td>Prague, TR</td>
<td>30</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>ILIL* [24]</td>
<td>CNR-INO</td>
<td>Pisa, It</td>
<td>3</td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td>SCAPA* [25]</td>
<td>U Strathclyde</td>
<td>Glasgow, UK</td>
<td>8</td>
<td>0.3</td>
<td>5</td>
</tr>
<tr>
<td>ANGUS</td>
<td>DESY</td>
<td>Hamburg, Ge</td>
<td>5</td>
<td>0.2</td>
<td>5</td>
</tr>
</tbody>
</table>

## Table 2.3: Laser facilities ($\geq 100$ TW) performing LWFA R&D in Asia

<table>
<thead>
<tr>
<th>Facility</th>
<th>Institute</th>
<th>Location</th>
<th>Energy (J)</th>
<th>Peak power (PW)</th>
<th>Rep. rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLAPA</td>
<td>PKU</td>
<td>Beijing, PRC</td>
<td>5</td>
<td>0.2</td>
<td>5</td>
</tr>
<tr>
<td>CoReLS [28]</td>
<td>IBS</td>
<td>Gwangju, Kr</td>
<td>20-100</td>
<td>1-4</td>
<td>0.1</td>
</tr>
<tr>
<td>J-Karen-P* [29]</td>
<td>KPSI</td>
<td>Kizugawa, Jn</td>
<td>30</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>LLP [30]</td>
<td>Jiao Tong Univ</td>
<td>Shanghai, PRC</td>
<td>5</td>
<td>0.2</td>
<td>10</td>
</tr>
<tr>
<td>SILEX*</td>
<td>LFRC</td>
<td>Myanyang, PRC</td>
<td>150</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>SULF* [31]</td>
<td>SIOM</td>
<td>Shanghai, PRC</td>
<td>300</td>
<td>10</td>
<td>1</td>
</tr>
<tr>
<td>UPHILL [32]</td>
<td>TIFR</td>
<td>Mumbai, In</td>
<td>2.5</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td>XG-III</td>
<td>LFRC</td>
<td>Myanyang, PRC</td>
<td>20</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

## Table 2.1: US laser facilities (>100 TW) performing LWFA R&D.

<table>
<thead>
<tr>
<th>Facility</th>
<th>Institute</th>
<th>Location</th>
<th>Gain media</th>
<th>Energy (J)</th>
<th>Peak power (PW)</th>
<th>Rep. rate (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BELLA [7]</td>
<td>LBNL</td>
<td>Berkeley, CA</td>
<td>Ti:sapphire</td>
<td>42</td>
<td>1.4</td>
<td>1</td>
</tr>
<tr>
<td>Texas PW [8]</td>
<td>U. Texas</td>
<td>Austin, TX</td>
<td>Nd:glass</td>
<td>182</td>
<td>1.1</td>
<td>single-shot</td>
</tr>
<tr>
<td>Diocles [9]</td>
<td>U. Nebraska</td>
<td>Lincoln, NE</td>
<td>Ti:sapphire</td>
<td>30</td>
<td>1</td>
<td>0.1</td>
</tr>
<tr>
<td>Hercules [10]</td>
<td>U. Michigan</td>
<td>Ann Arbor, MI</td>
<td>Ti:sapphire</td>
<td>9</td>
<td>0.3</td>
<td>0.1</td>
</tr>
<tr>
<td>Jupiter [11]</td>
<td>LLNL</td>
<td>Livermore, CA</td>
<td>Nd:glass</td>
<td>150</td>
<td>0.2</td>
<td>single-shot</td>
</tr>
</tbody>
</table>
## Beam-Driven Plasma Acceleration Facilities

### Table 3.1: Overview of PWFA facilities

<table>
<thead>
<tr>
<th>Operation Start</th>
<th>AWAKE</th>
<th>CLEAR</th>
<th>FACET-II</th>
<th>FF &gt;&gt;</th>
<th>SparcLAB</th>
<th>EuPR@Sparc</th>
<th>CLARA</th>
<th>MAX IV</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Current Status</th>
<th>Running</th>
<th>Running</th>
<th>Construction</th>
<th>Commissioning</th>
<th>PWFA, LWFA Commissioning</th>
<th>CDR ready??</th>
<th>Construction</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unique Contribution</td>
<td>Protons</td>
<td>Operation</td>
<td>Cycle</td>
<td>Positrons</td>
<td>1 fs resolution</td>
<td>PWFA with COMB beam,</td>
<td>LWFA external injection,</td>
<td>test FEL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>FEL gain tests</td>
<td>PWFA with COMB beam,</td>
<td>LWFA ext. inj.</td>
<td></td>
</tr>
<tr>
<td>Research Topic</td>
<td>HEP</td>
<td>Instrumentation</td>
<td>High intensity</td>
<td>e⁻, e⁺ beam</td>
<td>High average power</td>
<td>PWFA</td>
<td>PWFA, LWFA,</td>
<td>FEL, other applications</td>
</tr>
<tr>
<td>User Facility</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Partially</td>
</tr>
<tr>
<td>Drive Beam</td>
<td>p⁺</td>
<td>e⁻</td>
<td>e⁻</td>
<td>e⁻</td>
<td>e⁻</td>
<td>e⁻</td>
<td>e⁻</td>
<td>e⁻</td>
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<tr>
<td>Driver Energy</td>
<td>400 GeV</td>
<td>200 MeV</td>
<td>10 GeV</td>
<td>0.4–1.5 GeV</td>
<td>150 MeV</td>
<td>600 MeV</td>
<td>240 MeV</td>
<td>3 GeV</td>
</tr>
<tr>
<td>Ext. Inject.</td>
<td>Yes</td>
<td>No</td>
<td>No/Yes</td>
<td>Tb upgraded</td>
<td>0.4–1.5 GeV</td>
<td>150 MeV</td>
<td>600 MeV</td>
<td>na</td>
</tr>
<tr>
<td>Plasma Density [cm⁻³]</td>
<td>1-10E14</td>
<td>1E16-1E18</td>
<td>1E15-1E18</td>
<td>1E15-1E18</td>
<td>1E16-1E18</td>
<td>1E16-1E18</td>
<td>1E16-1E18</td>
<td>1E15-1E18</td>
</tr>
<tr>
<td>Plasma Length</td>
<td>10 m</td>
<td>5-20 cm</td>
<td>10-100 cm</td>
<td>1-30 cm</td>
<td>3 cm</td>
<td>&gt; 30 cm</td>
<td>10-30 cm</td>
<td>10-50 cm</td>
</tr>
<tr>
<td>Plasma Tapering</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Acc. Gradient</td>
<td>1 GeV/m average</td>
<td>na</td>
<td>10+ GeV/m peak</td>
<td>10+ GeV/m peak</td>
<td>10+ GeV/m peak</td>
<td>&gt; 1 GeV/m??</td>
<td>&gt; 1 GeV/m??</td>
<td>na</td>
</tr>
<tr>
<td>Exp. E Gain</td>
<td>1 GeV</td>
<td>na</td>
<td>10+ GeV/m peak</td>
<td>10+ GeV/m peak</td>
<td>10+ GeV/m peak</td>
<td>&gt; 1 GeV/m??</td>
<td>&gt; 1 GeV/m??</td>
<td>na</td>
</tr>
</tbody>
</table>


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• Introduction to Plasma Wakefield Acceleration

• Key Challenges of Plasma Wakefield Acceleration and Experimental Results
Key Challenges for Plasma Wakefield Acceleration

- Accelerating gradient
- Accelerated energy
- Beam quality
- Transformer ratio
- Positron acceleration
- Protons as drive beam
First Beam Driven Acceleration 1988

**Experimental Observation of Plasma Wake-Field Acceleration**


High Energy Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

Received 21 March 1988

We report the first experimental test of the physics of plasma wake-field acceleration performed at the Argonne National Laboratory Advanced Accelerator Test Facility. Megavolt-per-meter plasma wake fields are excited by a intense 21-MeV, multipicosecond bunch of electrons in a plasma of density \( n_e = 10^{13} \text{cm}^{-3} \), and probed by a low-intensity 15-MeV witness pulse with a variable delay time behind the intense bunch. Accelerating and deflecting wake-field measurements are presented, and the results compared to theoretical predictions.

**Argonne National Lab**

- Drive beam: 21 MeV, witness beam: 15 MeV
  \( \sigma_z = \sigma_r = 2.4\text{mm}, \text{charge: } 2-3nC \)
- DC plasma source, Argon, \( n_e = 0.7-7\times10^{13}\text{cm}^{-3} \)

Linear theory: \( n_e = 8\times10^{12}\text{cm}^{-3} \)

\( \Rightarrow \) Result: **Wakefields of order 1 MV/m**

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Theoretical paper for beam driven PWFA 1985

**Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma**

J. M. Dawson, Robert W. Holt, and T. Katsouleas

Department of Physics, University of California, Los Angeles, California 90024

Received 10 December 1984

A new scheme for accelerating electrons by bunching relativistic electron beams in a cold plasma, is analyzed. We show that energy gains can exceed 1 GeV/m and that the driven electrons can be accelerated from \( \gamma = 10 \) to \( \gamma = 10^2 \) before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to 4 GeV/m are possible. A nonlinear injection scheme is suggested in order that the driving electrons can be removed.
Record Acceleration, at SLAC: 42 GeV

Final Focus Test Beam Facility, FFTB at SLAC


Gaussian electron beam with 42 GeV, 3nC @ 10 Hz, $\sigma_x = 10\mu$m, 50 fs

85cm Lithium vapour source, $2.7 \times 10^{17}$ cm$^{-3}$

➔ Accelerated electrons from 42 GeV to 85 GeV in 85 cm.
➔ Reached accelerating gradient of 52 GeV/m
Key Challenges for Plasma Wakefield Acceleration

- Accelerating gradient
- Accelerated energy
- Beam quality
- Transformer ratio
- Positron acceleration
- Protons as drive beam
The maximum accelerating field (wave-breaking field) is:

\[ e E_{WB} = 96 \frac{V}{m} \sqrt{\frac{n_{pe}}{cm^{-3}}} \]

Example: \( n_{pe} = 10^{16} \text{ cm}^{-3} \rightarrow E_{WB} = 10 \text{GV/m} \)

Increase gradient by increasing density.

\[ \Rightarrow \text{Advantage of beam-driven PWFA} \]

Higher beam energy needs lower density & more power

For LWFA:

dephasing: laser group velocity depends on plasma density, is slower than \( c \).
- Electron energy reach is limited by dephasing: \( \rightarrow \) move to lower densities and longer accelerators.
- Lower density needs higher laser power
  
  (Significant progress since Chirped Pulse Amplification, CPA, Nobel Prize 2018 to D. Strickland & G. Mourou)
SLAC – FACET

High-Efficiency acceleration of an electron beam in a plasmas wakefield accelerator, 2014

M. Litos et al., doi, Nature, 6 Nov 2014, 10.1038/nature 13882

- Laser ionized Lithium vapour plasma cell:
  - 36 cm long, Density: $5 \times 10^{16} \text{ cm}^{-3}$, $\lambda_p = 200 \mu\text{m}$
- Drive and witness beam:
  - 20.35 GeV, D and W separated by 160 µm
  - 1.02nC (D), 0.78nC (W)

Later the plasma oven was extended from 0.3 to 1.3 meters long.
The accelerated beam had a spectral peak at 9 GeV energy gain.

BELLA, Berkeley Lab

Petawatt laser guiding and electron beam acceleration to 8 GeV in a laser-heated capillary discharge waveguide


Electron spectra, up to 6-8 GeV

→ path to 10 GeV with continued improvement of guiding in progress
Key Challenges for Plasma Wakefield Acceleration

- Accelerating gradient
- Accelerated energy
- Beam quality
- Transformer ratio
- Positron acceleration
- Protons as drive beam
Optimization

• Reduce energy spread:
  • Beam loading (idea: Simon van der Meer, 1985)
    • Shape the witness beam to get optimized fields in the plasma, ie minimize energy spread
    • Extract energy from and flatten the $E_z$ field, while extracting field energy.

Sufficient charge in the witness bunch to flatten the accelerating field
$\rightarrow$ reduce energy spread
High-Efficiency acceleration of an electron beam in a plasmas wakefield accelerator, 2014

M. Litos et al., doi, Nature, 6 Nov 2014, 10.1038/nature 13882

- Laser ionized Lithium vapour plasma cell:
  - 36 cm long, Density: $5 \times 10^{16}$ cm$^{-3}$, $\lambda_{pi} = 200$ µm
- Drive and witness beam:
  - 20.35 GeV, D and W separated by 160 µm
  - 1.02nC (D), 0.78nC (W)

First demonstration of a high-efficiency, low energy-spread plasma wakefield acceleration experiment:

- 70 pC of charge accelerated
- 2 GeV energy gain
- 5 GeV/m gradient
- **Up to 30% transfer efficiency**
- ~2% energy spread
Electric field in plasma wake is **loaded** by presence of trailing bunch

→ Allows efficient energy extraction from the plasma wake
Key Challenges for Plasma Wakefield Acceleration

• Accelerating gradient

• Accelerated energy

• Beam quality

• Transformer ratio

• Positron acceleration

• Protons as drive beam
Transformer Ratio

Would be fantastic to take a 1 GeV electron drive beam with $10^{11}$ electrons to accelerate $10^9$ electrons by 100 GeV. Energy conservation is fulfilled.

BUT: not possible in reality

Limited by the Transformer Ratio $R \leq 2$:

\[
R = \frac{E_+}{E_-} = \frac{\text{Peak accelerating field behind the drive bunch}}{\text{Peak decelerating field within the drive bunch}}
\]

(Short symmetric bunches)

Example:
Assume that $E_- = 10 \text{ GV/m}$
With $R = 2 \Rightarrow E_+ = 20 \text{ GV/m}$

Drive beam ($e^-$) with 30 GeV $\rightarrow$ decelerates 10 GeV/m $\Rightarrow$ 3m total
Witness beam: gains 20 GeV/m $\Rightarrow$ gets 60 GeV in 3m

Of course energy conservation must be fulfilled: $N_D = 3N_W$. 
Increasing the Transformer Ratio

\[ R = \frac{E_+}{E_-} \]

- Adjust the drive beam profile
- Multiple drive beam bunches

Tzoufras, PRL 101, 145002 (2008)
• Photoinjector Test facility at DESY, Zeuthen (PITZ)
• 1.3GHz, 0.01-5nC, up to 25 MeV, $\varepsilon_{\text{norm}} = 0.1 \text{ mmm rad}$
• Drive beam: 508 pC, 20ps
• Witness beam: 10 pC, 0.7ps, delay 10ps.


Transformer Ratio: $4.6 \pm 2.2 / -0.7$
Key Challenges for Plasma Wakefield Acceleration

• Accelerating gradient
• Accelerated Energy
• Beam quality
• Transformer Ratio
• Positron acceleration
• Protons as drive beam
Positron Acceleration

- Interested in using positrons for high energy linear colliders:
  - Parameters for positrons: high energy, high charge, low emittance.

Electron-driven blowout wakes:

But the field is defocusing in this region.
High-density, compressed positron beam for non-linear PWFA experiments. 1.3m plasma cell, 20 MeV beam.

New observations:

- Accelerated positrons form a spectrally-distinct peak with an energy gain of 5 GeV.
- Energy spread can be as low as 1.8% (r.m.s.).

Beam loading affects transverse fields for positron driven wakes!


Two-bunch positron beam: First demonstration of controlled beam in positron-driven wake.
Positron Acceleration in Hollow Channel at FACET

- There is no plasma on-axis, and therefore no complicated forces from plasma electrons streaming through the beam.
- Treat the plasma as dielectric
Drive beam transfers energy to witness beam.

Mean $\langle \Delta E \rangle = 19.9$ MeV

Max Energy $33.4$ MeV

Witness beam gains energy from the wake.

Mean $\langle \Delta E \rangle = -11.0$ MeV

Drive beam transfers energy to witness beam.

First Demonstration of Acceleration in Hollow channel

Measurement of transverse wakefields in hollow channel

$\rightarrow$ the result agrees with theoretical calculation:

$10^6 \text{ V/(pC m mm)}$

Or about 10,000 times stronger than the wakefields in CLIC!


Key Challenges for Plasma Wakefield Acceleration

- Accelerating gradient
- Accelerated energy
- Beam quality
- Transformer ratio
- Positron acceleration
- Protons as drive beam
Energy Budget for High Energy Plasma Wakefield Accelerators

**Drive beams:**
- Lasers: ~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, ~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....

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E. Adli et. al., arXiv:1308.1145 [physics.acc-ph]

Energy Budget for High Energy Plasma Wakefield Accelerators

**Drive beams:**
Lasers: ~40 J/pulse
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Proton drive beam: SPS 19kJ/pulse, LHC 300kJ/bunch

**Witness beams:**
Electrons: $10^{10}$ particles @ 1 TeV ~few kJ

- **Proton drivers:** large energy content in proton bunches → allows to consider single stage acceleration:
  - A single SPS/LHC bunch could produce an ILC bunch in a single PDWA stage.

- Dephasing:
  - SPS: ~70 m
  - LHC: ~few km
  - FCC: ~∞
Seeded Self-Modulation of the Proton Beam

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! \((\sigma_z = 12 \text{ cm})\) \(\rightarrow\) much longer than plasma wavelength \((\lambda = 1 \text{mm})\)

Self-Modulation:

a) Bunch drives wakefields at the initial seed value when entering plasma.
   • **Initial wakefields act back** on the proton bunch itself. \(\rightarrow\) On-axis density is modulated. \(\rightarrow\) Contribution to the wakefields is \(\propto n_b\).

b) Density modulation on-axis \(\rightarrow\) **micro-bunches**.
   • Micro-bunches separated by plasma wavelength \(\lambda_{pe}\).
   • Drive wakefields resonantly.

\[\Rightarrow\text{Seeded Self-Modulation}\]

**AWAKE**: **Seeding of the instability** by

• Placing a **laser** close to the center of the proton bunch
• Laser ionizes vapour to produce plasma
• Sharp start of beam/plasma interaction
• \(\rightarrow\) Seeding with ionization front

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

AWAKE has demonstrated during Run 1 (2016-2018) that the seeded self-modulation is a reliable and robust process and that electrons can be accelerated with high gradients.

Seeded self-modulation of the proton bunch:

→ **SSM process is reproducible, reliable and stable.**

---

AWAKE, CERN

AWAKE has demonstrated during Run 1 (2016-2018) that the seeded self-modulation is a reliable and robust process and that electrons can be accelerated with high gradients.

- **Electrons accelerated to 2 GeV in 10m.**
- **Energy is as expected from simulations**

Seeded self-modulation of the proton bunch:

- **SSM process is reproducible, reliable and stable.**
## Status of Today and Goals for Collider Application

<table>
<thead>
<tr>
<th></th>
<th>Current</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Charge (nC)</strong></td>
<td>0.1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Energy (GeV)</strong></td>
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<td>10</td>
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<tr>
<td><strong>Energy spread (%)</strong></td>
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<td>0.1</td>
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<tr>
<td><strong>Emittance (um)</strong></td>
<td>&gt;50-100 (PWFA), 0.1 (LFWA)</td>
<td>&lt;10^{-1}</td>
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<tr>
<td><strong>Staging</strong></td>
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<td>multiple</td>
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<td><strong>Efficiency (%)</strong></td>
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<td>40</td>
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<tr>
<td><strong>Rep Rate (Hz)</strong></td>
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<td>10^{3-4}</td>
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<tr>
<td><strong>Acc. Distance (m)/stage</strong></td>
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<td>1-5</td>
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<tr>
<td><strong>Positron acceleration</strong></td>
<td>acceleration</td>
<td>emittance preservation</td>
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<td><strong>Proton drivers</strong></td>
<td>SSM, acceleration</td>
<td>emittance control</td>
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<tr>
<td><strong>Plasma cell (p-driver)</strong></td>
<td>10 m</td>
<td>100s m</td>
</tr>
<tr>
<td><strong>Simulations</strong></td>
<td>days</td>
<td>improvements by 10^{7}</td>
</tr>
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</table>
Summary

• Remarkable progress in the last decades in beam driven plasma wakefield acceleration.

• Much progress needs to be made to reach realistic collider beam parameters.
  • Many facilities will offer new potential for meeting the challenges.

⇒ Lots of opportunities for young students and scientists!!
Facilities – AWAKE
AWAKE at CERN

**Advanced WAKEfield Experiment**

- **Proof-of-Principle Accelerator R&D experiment at CERN to study proton driven plasma wakefield acceleration.**
- **Final Goal:** Design high quality & high energy electron accelerator based on acquired knowledge.
- **Approved in August 2013**
- **First beam end 2016**
AWAKE Proton and Laser Beam Line

The AWAKE beamline is designed to deliver a high-quality beam to the experiment.

The proton beam must be steered around a mirror which couples a terawatt class laser (Ti:Saph, 500mJ, 120fs) into the beamline.

Further downstream, a trailing electron beam will be injected into the same beamline.
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 (\(\sim 220\) deg)
    - Complex control system: 79 Temperature probes, valves
  - Transition between plasma and vacuum as sharp as possible

E. Öz et al., NIM A 740(11), 197 (2014)
E. Öz et al., NIM A829, 321 (2016)
F. Batsch et al., NIM A, 909, 359 (2018)
AWAKE Plasma Cell

Plasma cell in AWAKE tunnel
A Photo-injector originally built for a CLIC test facility is now used as electron source for AWAKE producing short electron bunches at an energy of ~20 MeV/c.
A completely new 12 m long electron beam line was designed and built to connect the electrons from the e-source with the plasma cell.

**Challenge:** cross the electron beam with the proton beam inside the plasma at a precision of ~100 µm.
Electrons will be accelerated in the plasma. To measure the energy the electrons pass through a dipole spectrometer and the dispersed electron impact on the scintillator screen. The resulting light is collected with an intensified CCD camera.
AWAKE Run 2

Proposing Run 2 for 2021 after CERN Long Shutdown 2

- AWAKE Run 1: Proof-of-Concept
- AWAKE Run 2: Accelerate electron beam to high energy while preserving beam quality so that it can be used for first physics application.

- Acceleration of an externally injected e⁻ bunch with small final $\varepsilon$ and $\Delta E/E$ @ GeV

**OLSEN, ADLI, and MUGGLI**

**PHYS. REV. ACCEL. BEAMS 21, 011301 (2018)**

Typical parameters:
- $\sigma_z=60\mu$m
- $\sigma_x=5.25\mu$m
(matched for $\epsilon_N=2\text{mm-mrad}$, $n_e=7\times10^{14}\text{cm}^{-3}$, $-\epsilon_N^\text{14}$)
- $Q=100\text{pC}$
- Blow-out and beam loading
- $\sim73\%$ charge with $\Delta E_N/\epsilon_N<5\%$, $\Delta E/E\sim\%$

- Challenging parameters to produce with low energy particles ($\sigma_x, \sigma_z$)
- Challenging to measure ($\sigma_r$)
AWAKE Run 2

Goals:

- Accelerate an electron beam to high energy (gradient of 0.5-1 GV/m)
- Preserve electron beam quality as well as possible (emittance preservation at 10 mm mrad level)
- Demonstrate scalability of the AWAKE concept (R&D plasma sources)

Proposing Run 2 for 2021 after CERN Long Shutdown 2

A diagram illustrating the proposed X-band electron source, including laser, RF gun, optimized SPS protons, BTV, OTR, CTR, and an e- spectrometer. The diagram shows the process of accelerating and compressing the electron beam, with parameters such as energy gain, bunch length, and final emittance.

E. Adli (AWAKE Collaboration), IPAC 2016 proceedings, p.2557 (WEPMY008)