The AWAKE Proton-Driven Plasma Wakefield Acceleration Experiment at CERN

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For the AWAKE Collaboration
Ultra-relativistic driver $\Rightarrow$ ultra-relativistic wake $\Rightarrow$ no dephasing

Plasma wave/wake excited by a relativistic particle bunch

Plasma e$^-$ expelled by space charge forces $\Rightarrow$ deceleration + focusing

Plasma e$^-$ rush back on axis $\Rightarrow$ acceleration

Particle bunches have long "Rayleigh lengths" $\Rightarrow$ large energy gain

$\beta$ function $\beta = \sigma^2 / \varepsilon \sim \text{cm, m}$

Acceleration physics identical PWFA, LWFA

Figure 8. Most probable energy of witness bunch particles as a function of propagation distance in plasma.

Energy spectrum of drive and witness bunch after 85 cm of plasma. Drive bunch particles lose a significant fraction of their energy and actually begin to slow down. The position of the peak decelerating field rapidly moves back in the speed of light frame. At the same time, its magnitude drops. However, the position of the peak accelerating field and the spike in figure 7 on the right and more importantly the plateau in the acceleration field where most of the witness bunch particles reside does not change in this frame. The witness bunch moves with the wakefield without dephasing.

3.6. Efficiency

Figure 8 shows energy gain defined as the most probable energy of the witness bunch particles as a function of propagation distance for the simulations of figure 7. The energy gain is almost linear up to a distance of $\approx 65$ cm. At a distance of $85$ cm, the initially $5$ GeV witness bunch has doubled in energy with an $\approx 3$ m energy spread, as seen in figure 8. While the witness bunch is monoenergetic, much of the drive bunch has lost nearly all its energy. We have estimated various efficiencies in the simulations. The energy transfer efficiency from the wake to the witness bunch is almost $56\%$. The efficiency from the drive to the witness bunch is greater than $3\%$.

The overall drive to witness bunch transfer energy efficiency can be improved by using bunches with longitudinal current profiles tailored such that all longitudinal slices of the drive bunch lose energy at the same rate (except for the very first and the last ones). This is accomplished by ramping up the current along the bunch. The optimum longitudinal current shape is trapezoidal $[33]$ with a long rise time and a sharp fall time. In that case, the peak decelerating wakefield remains constant along the drive bunch, while the peak accelerating field left behind the bunch keeps increasing with the bunch length. The transformer ratio then scales as $\pi$ times the number of plasma wavelengths covered by the bunch, and can be much larger than $2\pi$. More sophisticated bunch profiles can lead to even larger enhancements of $R_w$.

E$_0$ $\Rightarrow$ $84$ GeV in $85$ cm! $\sim 50$ GeV/m
p$^+\text{-DRIVEN PWFA? WHY?}$

- ILC, 0.5TeV bunch with $2 \times 10^{10}$e$^-$ ~1.6kJ
- SLAC, 20GeV bunch with $2 \times 10^{10}$e$^-$ ~60J
- SLAC-like driver for staging (FACET= 1 stage, collider 10$^+$ stages)
- SPS, 400GeV bunch with $10^{11}$p$^+$ ~6.4kJ
  - LHC, 7TeV batch with $10^{11}$p$^+$ ~112kJ
- A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
- Large average gradient! ($\geq$1GeV/m, 100’s m)
- Wakefields driven by e$^+$ bunch: Blue, PRL 90, 214801 (2003)
PROTON-DRIVEN PWFA


- Accelerate an $e^-$ bunch on the wakefields of a $p^+$ bunch
- Single stage, no gradient dilution
- Gradient $\sim 1$ GV/m over 100’s m
- Operate at lower $n_e$, larger $(\lambda_{pe})^3$, easier life ...

$e^-$: $E_0=10$GeV
$p^+$: $E_0=1$TeV
$\sigma_z=100$µm
$N=10^{10}$
$W_0=16$J
$W_f=1$kJ

$\Delta E/E \sim 1\%$

$\sim 0.5$TeV
$\sim 300$m
PROTON-DRIVEN PWFA


Short (100µm) bunches do not exist!!!

CERN SPS-LHC $\sigma_z \sim 12$cm

- Operate at lower $n_e$, larger $(\lambda_{pe})^3$, easier life...
- Gradient ~1 GV/m over 100’s m
- Gradient, no gradient dilution
- Accelerate an $e^-$ bunch on the wakefields of a $p^+$ bunch
- $\Delta E/E \sim 1\%$

$e^-$: $E_0=10$GeV
$e^-$: $N=10^{10}$ $W_0=16$J $\sigma_z=100$µm
$p^+$: $E_0=1$TeV $N=10^{11}$ $W_0=16$kJ $\sigma_z=43$µm

$\Delta E/E \sim 1\%$
SELF-MODULATION INSTABILITY (SMI)

Kumar, PRL 104, 255003 (2010)

Grows along the bunch & along the plasma
Convective instability

Radial focusing/defocusing with longitudinal period!

Initial small transverse wakefields modulate the bunch density

Pukhov et al., PRL 107, 145003 (2011)
Schroeder et al., PRL 107, 145002 (2011)

SMI-PWFA SIMULATIONS

OSIRIS 2.0

osiris framework
- Massively Parallel, Fully Relativistic Particle-in-Cell (PIC) Code
- Visualization and Data Analysis Infrastructure
- Developed by the osiris.consortium
  - UCLA + IST

New Features in v2.0
- Bessel Beams
- Binary Collision Module
- Tunnel (ADK) and Impact Ionization
- Dynamic Load Balancing
- PML absorbing BC
- Optimized higher order splines
- Parallel I/O (HDF5)
- Boosted frame in 1/2/3D

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Benchmarking with (for AWAKE only!):
- **VLPL A**: Pukhov, J. Plasma Phys. 61, 425 (1999)
CERN Industrial Beam Complex

**PROTON BEAMS @ CERN**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PS</th>
<th>SPS</th>
<th>SPS Opt</th>
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<tr>
<td>$E_0$ (GeV)</td>
<td>24</td>
<td>400</td>
<td>400</td>
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<tr>
<td>$N_p \times 10^{10}$</td>
<td>13</td>
<td>10.5</td>
<td>30</td>
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<td>$\Delta E/E_0$ (%)</td>
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<td>0.03</td>
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<tr>
<td>$\sigma_z$ (cm)</td>
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<td>12</td>
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<tr>
<td>$\varepsilon_N$ (mm-mrad)</td>
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<td>3.6</td>
<td>3.6</td>
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<tr>
<td>$\sigma_r^*$ ($\mu$m)</td>
<td>400</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>$\beta^*$ (m)</td>
<td>1.6</td>
<td>5</td>
<td>5</td>
</tr>
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- SPS beam: high energy, low $\sigma_r^*$, long $\beta^*$
- Initial goal: ~GeV gain by externally injected $e^-$, in 5-10m of plasma in self-modulated $p^+$ driven PWFA

$n_e \approx 7 \times 10^{14} \text{cm}^{-3}$ for $k_p \sigma_r \approx 1$

$\lambda_{pe} \approx 1.3 \text{mm} \ll \sigma_z$

$f_{pe} \approx 240 \text{GHz}$

$L_p \approx 10 \text{m} \sim 2 \beta^*$
**AWAKE EXPERIMENT @ CERN**

- **Laser**
- **Final Focus**
- **Ionizing Laser Pulse**
- **Plasma**
  - 10m, $10^{14}$-$10^{15}$ cm$^{-3}$
- **p* dump**
- **p* from SPS**
- **SMI Acceleration**
- **EOS Diagnostic**
- **Laser dump Diagnostics**
- **OTR/CTR Diagnostics**

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*Kumar, Phys. Rev. Lett. 104, 255003 (2010)*
Short laser pulse creates the plasma and seeds the SMI

\[ \sigma_z \sim 12\text{cm} \gg \lambda_{pe} \sim 1.2\text{mm} \left( n_e \sim 10^{14}\text{cm}^{-3} \right) \Rightarrow \text{Self-modulation Instability (SMI)}^{*} \]

The plasma for the AWAKE experiment must have a number of characteristics:

- **Length**: $L \approx 10 \text{ m}$
- **Radius**: $R_p$ larger than approximately three $p^+$ bunch rms radii or $\approx 1 \text{ mm}$
- **Density**: $n_e$ within the $10^{14} - 10^{15} \text{ cm}^{-3}$ range
- **Density Uniformity**: $\delta n_e/n_e$ on the order of $0.2\%$ or better
- **Allow for seeding of the self-modulation instability (SMI)**

It must also be easily ionized and reproducible. In the AWAKE context, we are currently exploring three options for the plasma (see below). However, the source for the first experiments will be a rubidium vapor source ionized by a short and intense laser pulse. The general laser and plasma parameters for the source are listed in Table 1. This source does not scale well to much longer lengths. Therefore, we are investigating discharge plasma sources and a helicon source for plasma lengths longer than ten meters.
The long ($\sigma_z \sim 12\text{cm}$) $p^+$ bunch self-modulates with period $\lambda_{pe} \sim 1.2\text{mm}$ ($n_e \sim 10^{14}\text{cm}^{-3}$).
SMI Diagnostics

Electro-optic Sampling
in Frequency Domain
(O. Reimann, MPP)

Streak Camera
≤1ps resolution

from Pukhov, PRST-AB 2012

Laser
Ionizing Laser Pulse

Final Focus

p⁺ from SPS

SMI Acceleration

10m, 10^{14}-10^{15} \text{ cm}^{-3}

Not modulated

Fully self-modulated, \nu_e \nu_p \Rightarrow injection

\lambda_{pe}=1.2\text{mm} 
\Rightarrow 4\text{ps} 
for n_e=7\times 10^{14}\text{cm}^{-3}

\nu_e \nu_p
The SM $p^+$ bunch resonantly drives wakefields.
AWAKE EXPERIMENT @ CERN

Final Focus
- Laser Pulse
- Ionizing Laser Pulse
- p+ from SPS

Plasma
- 10 m, 10^{14}-10^{15} cm^{-3}

EOS Diagnostic
- Laser dump Diagnostics
- OTR/CTR Diagnostics

SMI Acceleration
- Laser dump

Propagation direction
- Long beam: \( \alpha_z \approx 100 \lambda_p \)

On-axis \( E_z \) field
- Inject e-
- 1\( \sigma_z \) p+
- 980 MV/m
- 500 MV/m

Large amplitude wakefields: 0.1-1 GeV/m
- 11 meters

\( p^+ \) Vapor
The wake is slowed down. Its phase velocity of wakefield is \( \sim 40 \) in the growth phase. External injection \( \sim 460 \) electron bunch injection system – the gun and booster – is shown in Fig. 2.5. This injector is based on preliminary design of the first section of the 21–31 MeV electron beam is transported along a WAKEFIELDS experiment that will allow the acceleration of an externally injected witness beam of electrons. The electron injector system (see the Technical Note [63] for more details) is a critical component of the accelerator at STF, Daresbury Laboratory, UK [64], a design which has also been used for the 'LPH' 3.6ycell Syband RF gun currently being commissioned at the Versatile Electron Linear accelerator. Accelerated electron bunch has little effect on the resolution of the measurement. Consequently, it can be seen that the energy reconstructed with the spectrometer system agrees well with the input spectrum and demonstrated the suitability of this setup. It can be seen that the energy reconstructed with the spectrometer system agrees well with the input spectrum and demonstrated the suitability of this setup. Therefore, it can be seen that the energy reconstructed with the spectrometer system agrees well with the input spectrum and demonstrated the suitability of this setup. Therefore, it can be seen that the energy reconstructed with the spectrometer system agrees well with the input spectrum and demonstrated the suitability of this setup. Therefore, it can be seen that the energy reconstructed with the spectrometer system agrees well with the input spectrum and demonstrated the suitability of this setup. Therefore, it can be seen that the energy reconstructed with the spectrometer system agrees well with the input spectrum and demonstrated the suitability of this setup. Therefore, it can be seen that the energy reconstructed with the spectrometer system agrees well with the input spectrum and demonstrated the suitability of this setup. Therefore, it can be seen that the energy reconstructed with the spectrometer system agrees well with the input spectrum and demonstrated the suitability of this setup. Therefore, it can be seen that the energy reconstructed with the spectrometer system agrees well with the input spectrum and demonstrated the suitability of this setup. Therefore, it can be seen that the energy reconstructed with the spectrometer system agrees well with the input spectrum and demonstrated the suitability of this setup.
CERN team already translated our dreams into CAD drawings

Next step: make it real!
Laser ionization of a metal vapor (Rb), 3-4m plasma for p⁺ self-modulation only, SEEDING NECESSARY!

~10m discharge or helicon source for acceleration only

Helicon plasma source scales well to very long plasmas (>100m)

Maybe able to tune plasma densities to maintain accelerating gradient
First $p^+$-driven PWFA experiment

- Take advantage of large energy ($J$) of $p^+$ bunches; lower gradient, larger size structure approach
- Initially use self-modulation of long ($\sim 12$ cm) of $p^+$ bunches in dense plasma ($\lambda_{pe} \sim 1.2$ mm)
- Study physics of $p^+$ bunch SMI (growth seeding, parametric dependencies, etc.)
- Sample wakefields with externally “side-injected” $e^-$: GeV energy gain
- Accelerator experiments with on axis injection, beam loading, etc.
- Many challenges (plasma, stability, injection, etc.)
- Long term project: short $p^+$ bunches, long plasma sources, etc.
- Collaboration formed ...
- Experiment “corridor-approved” at CERN
- Experiments planned for 2016 ...
Proton-driven Plasma Wakefield Accelerator at CERN

- Proof-of-principle experiment: accelerate in a short distance charged particles
- Candidate for future high energy accelerators
- Toward single-stage TeV lepton accelerator

Thank you!
MOPAC02, Muggli
MOPAC49, Fang
THYAA2, Litos
THOCA1, Marsh
MOPAC37, MOPAC38, MOPAC46, MOPAC49
MAINTAINING HIGH GRADIENT

- Peak gradient can be maintained over long distances with a plasma density step!
- Possibility for ~100GeV in ~100m?

Lotov, Phys. Plasmas 18, 103101 (2011)
◊ SMI-PWFA: instability + resonantly driven

◊ Requirements for SMI growth rate

For a linear gradient:

\[
\frac{n_e(z)}{n_{e0}} = 1 + \frac{z}{L}
\]

Instability suppressed if:

\[
L < \left( \frac{2 \gamma n_{e0} m_p}{n_{b0} m_e} \right)^{1/3} \sigma_z^{2/3} L_p^{1/3}
\]

◊ Requirements witness bunch acceleration

If \( \lambda_{pe} \) changes locally injected electron will be defocused

\[
\Delta \phi = \frac{2 \pi \xi}{\lambda_{pe0}} - \frac{1}{2} \frac{\delta n_e}{n_{e0}} < \frac{\pi}{2} \quad \Rightarrow \quad \frac{\delta n_e}{n_{e0}} < \frac{\lambda_{pe0}}{4 \xi} \approx \frac{\lambda_{pe0}}{4 \sigma_z} \approx 0.25\%
\]

◊ Tight requirement!

Seeding of SMI is NECESSARY

✧ No seed no SMI (over 10m)

✧ Hosing mitigation

✧ Deterministic e- injection

✧ Need to keep laser-ionized source for seeding
SMI SEEDING

◊ SM Instability, grows from noise, “random”
◊ Instabilities can be seeded by a larger-than-noise signal

Preceding e⁻-bunch

“Cut” bunch or plasma

◊ Shortens length to saturation
◊ Suppresses hosing

◊ Generates periodic wakefield
Single, long plasma

Low energy test $e^-$ injected sideways are trapped and bunched in a few wake buckets

$$\alpha_{opt} \sim \frac{v_\phi - v_{e-}}{c} \sim \frac{1}{2\gamma_{e-}^2} \sim \text{mrad}$$

for $E_{e^-}=5\text{-}20\text{MeV}$

Inject in saturated SMI, $v_\phi = v_b \approx c$

Generates narrow final energy spectrum

Trapping efficiency <60%, test particles

Pukhov, Phys. Rev. Lett. 107, 145003 (2011)
**Comparison +/− driven PWFA**

 ромparison positively/negatively charged bunches after SMI saturation

\[ e^+, z=1m \]

\[ e^- \]

\[ n_e=6\times10^{16} \text{cm}^{-3} \]

Propagation direction

\[ 8.3 \text{ meters} \]

\[ p^+ \]

Phase difference, as expected from simple physics

\[ \sigma_r \]

\[ \lambda_{pe} \]

Distance in beam (z)

Distance [mm]

| \(|n_p| \) | \(|n_0| \) |
|---|---|
| 2.0 | 1.0 |
| 1.5 | 0.8 |
| 1.0 | 0.6 |
| 0.5 | 0.4 |
| 0.0 | 0.2 |

| \(|n_{plasma}| \) | \(|n_{beam}| \) |
|---|---|
| 0.0 | 0.65 |
| -1.30 | 1.20 |

\[ e^- \]

\[ z=1m \]

\[ e^- \]