AWAKE: A Proof of Principle
Proton-driven, PWFA
R&D Experiment @ CERN

presented by:
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for the AWAKE Collaboration
Some of the largest and most complex (and most expensive) scientific instruments ever built!

- **CERN LHC**: 8.6 km, 5.3 mi
- **BNL RHIC**: R=621 m
- **SLAC SLC**:
  - $e^-/e^+$ 0-50GeV in 3km SLC
  - $e^-/e^+$ 0-20GeV in 2km FACET
  - $e^-$ 0-14GeV in 1km LCLS

"The 2.4-mile circumference RHIC ring is large enough to be seen from space"

Could plasmas be used to accelerate particles at high-gradient (>100MeV/m) and reduce the size and cost of a future collider or of a x-ray FEL?

Litos, Nature 515(6) 92 (2014)

ΔE/E~% η~30%

SLAC FACET

E200

“quantity” 42 => 84GeV in 85cm! 50GeV/m

“quality” Relativistic Electron Bunch

Defocusing Accelerating Decelerating ($E_r$, $E_z$)
PLASMA WAKEFIELD ACCELERATOR (e−)


SLAC FACET

E200

Litos, Nature 515(6) 92 (2014)

ΔE/E~% η~30%

“quantity”

“quality”

42 => 84GeV in 85cm! 50GeV/m

E0 2E0

E0 = 2.3x10^{17} \text{cm}^{-3} \quad \sigma_z \sim 20\text{μm}

n_e = 2.3 \times 10^{17} \text{cm}^{-3}

ΔE/E ~ %

η ~ 30%

−12 −10 −8 −6 −4 −2 0 2 4 6 8 10 12 14 16

Position [mm]

Energy Loss Energy Gain

Scalloping of the Beam

Experiment

Relativistic Electron Bunch

e− Driver
e− Witness
PLASMA WAKEFIELD ACCELERATOR (e−)

S. Gessner
 TUYC1
 Tues. 2pm

“quantity”


42 => 84GeV in 85cm! 50GeV/m

“quality”

SLAC FACET

E200

E0

2E0

ΔE/E~% η~30%

Litos,
Nature 515(6) 92 (2014)

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P. Muggli, IPAC’15 05/04/2015
Proton-driven PWFA

Blue. PRL 90, 214801 (2003)

Existing $p^+$ bunches carry 10’s-100’s kJ ($\gg e^-$ bunches)

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 $n_e$ ($6 \times 10^{14}$ cm$^{-3}$), larger ($\lambda_{pe}$)$^3$, easier life …
Short (100μm) bunches with $10^{11}$ p+ do not exist!!!

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

- E/$E_0$ ~ $10^{-2}$
- $\Delta E/E \sim 1\%$
- Energy ~ 0.5 TeV
- L ~ 300 m

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- $\Delta E/E \sim 1\%$
- Energy ~ 0.5 TeV
- L ~ 300 m

- Existing p+ bunches carry 10’s-100’s kJ ($\gg$ e− bunches)
- Accelerate an e− bunch on the wakefields of a p+ bunch
- Single stage, no gradient dilution
- Gradient ~1 GV/m over 100’s m
- Operate at lower $n_e$ ($6 \times 10^{14}$ cm$^{-3}$), larger ($\lambda_{pe}$)$^3$, easier life …
**SELF-MODULATION INSTABILITY** (SMI)

\[ \mathcal{N}_{\text{exp}} \approx \frac{3\sqrt{3}}{4} \left( \frac{n_b}{n_e} \frac{m_e}{\gamma M_b} \left( k_p \xi \right) \left( k_p \sigma_z \right) \right)^{2/3} \]

- **Grows along the bunch & along the plasma**
- **Initial small transverse wakefields modulate the bunch density with \( \sim \lambda_{pe} \) period**
- **Associated longitudinal wakefields reach large amplitude through resonant excitation**

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

\*Kumar, PRL 104, 255003 (2010)
SELF-MODULATION INSTABILITY (SMI)

z=0, e⁻  \( k_p \sigma_z \approx 45 \)

Exponential Growth
Saturation

Radial!
NOT longitudinal!

z=5cm, e⁻  J. Vieira, IST

Distance (z) [cm]

Time = 0.00 [1/\( \omega_p \)]

\( x_z [c/\omega_p] \)
\( x_t [c/\omega_p] \)
SELF-MODULATION INSTABILITY (SMI)

Radial! NOT longitudinal!

### Parameter Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>PS</th>
<th>SPS</th>
<th>SPS Opt</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_0$ (GeV)</td>
<td>24</td>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>$N_p$ ($10^{10}$)</td>
<td>13</td>
<td>10.5</td>
<td>30</td>
</tr>
<tr>
<td>$\Delta E/E_0$ (%)</td>
<td>0.05</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>$\sigma_z$ (cm)</td>
<td>20</td>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>$\epsilon_N$ (mm-mrad)</td>
<td>2.4</td>
<td>3.6</td>
<td>3.6</td>
</tr>
<tr>
<td>$\sigma_r^*$ (μm)</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>
</tbody>
</table>

**SPS beam:** high energy, small $\sigma_r^*$, long $\beta^*$

**Experimental area:**

**Plasma:**

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

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

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

$L_p \sim 10\text{m} \approx 2\beta^*$

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AWAKE EXPERIMENT @ CERN

First experiments: 2016

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

Laser dump Diagnostics
OTR/CTR Diagnostics

p^+ from SPS

Final Focus

Ionizing Laser Pulse

SMI Acceleration

EOS Diagnostic

Laser dump

p^+ dump

"Sharp" (<<\lambda_{pe}) start of the beam/plasma interaction for SMI seeding
AWAKE: will seed with ionization front!

◊ No seed no SMI (over 10m)
Short laser pulse creates the plasma and seeds the SMI

\( \sigma_z \sim 12 \text{cm} \gg \lambda_{pe} \sim 1.2 \text{mm} \ (n_e \sim 7 \times 10^{14} \text{cm}^{-3}) \Rightarrow \text{Self-modulation Instability (SMI)}\)

\( \sigma_{z \text{ laser}} \sim 30 \mu\text{m} (100 \text{fs}) \ll \lambda_{pe} \Rightarrow \text{good seed} \)

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

- $\sigma_z \sim 12\text{cm} >> \lambda_{pe} \sim 1.2\text{mm}$ ($n_e \sim 7 \times 10^{14}\text{cm}^{-3}$) => Self-modulation Instability (SMI)*
- $\sigma_{z,\text{laser}} \sim 30\mu\text{m}(100\text{fs}) << \lambda_{pe}$ => good seed

First experiments: 2016

The wakefields grow …

Simulation by K. Lotov
The long ($\sigma_z \sim 12\text{cm}$) $p^+$ bunch self-modulates with period $\lambda_{pe} \sim 1.2\text{mm}$ ($n_e \sim 7 \times 10^{14}\text{cm}^{-3}$)
SMI DIAGNOSTICS

2016

Laser

Final Focus

Ionizing Laser Pulse

p⁺ from SPS

OTR

SMI Acceleration

CTR

Plasma, Rb vapor

10m, 10^{14}-10^{15} cm⁻³

EOS Diagnostic

p⁺ dump

OTR/CTR Diagnostics

Heterodyne Measurement

Streak Camera

≤1ps resolution

Schottky Diode

2016

\( \lambda_{pe} = 1.2 \text{mm} \Rightarrow 4 \text{ps} \)

for \( n_e = 7 \times 10^{14} \text{cm}^{-3} \)

\( \tau_{RF} = 1/f_{IF} \)
The SM p+ bunch resonantly drives wakefields
AWAKE EXPERIMENT @ CERN

Laser

Final Focus

Ionizing Laser Pulse

p⁺ from SPS

Plasma

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

EOS Diagnostic

p⁺ dump

Laser dump Diagnostics

OTR/CTR Diagnostics

SMI Acceleration

Long beam: \(\alpha_z \sim 100 \lambda_p\)

Propagation direction

Invert e⁻

On-axis \(E_z\) field

\(E_{acc}\) [MV/m]

Position [cm]

500MV/m

1σ \(p⁺\)

\(~GV/m\) accelerating field

Vapor

Laser

\(~GV/m\) accelerating field

Large amplitude wakefields: 0.1-1 GeV/m

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The wake is slowed down. Its minimum gamma-factor is 
\[ \gamma_{\text{min}} \approx 40 \]
This is order of magnitude below that of the beam. 

**Phase velocity of the wake**

\[ v_{\text{ph}} - c \]

\[ 10^{-4} \]

\[ Z, m \]

\[ (v_{\text{ph}} - c) / c, x 10^{-4} \]

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**Figure:**
- Laser
- Ionizing Laser Pulse
- e⁻ gun
- e⁻ injection
- Plasma
- 10m, \( 10^{14} - 10^{15} \) cm⁻³
- Final Focus
- p⁺ from SPS
- SMI Acceleration
- Injection experiments: 2017
- e⁻ → λ_{pe}
- \( \sigma_{\text{ze}} \)
- Laser dump
- OTR/CTR Diagnostics
- e⁻ spectrometer
- 0.1 → 2 GeV
- Pukhov et al., Phys Rev Lett (2011)

**Parameters:**
- \( E_0 = 15 \text{ MeV} \)
- \( \varepsilon_N = 2 \text{ mm-mrad} \)
- \( \xi_{\text{inj}} \approx 1.5 \delta_{zp} \approx 18 \text{ cm} \)
- \( \sigma_{\text{ze}} \approx 3 \text{ mm} \approx 1.5 \lambda_{pe} \)
- \( \eta_{\text{trap}} \approx 40\% \)
- \( E_{\text{mean}} \approx 1.3 \text{ GeV} \)
- \( \Delta E / E_{\text{mean}} \approx 12\% \)

**Notes:**
- Accelerate e⁻ to multi-GeV energies with \( \sim \) GeV/m gradient
The wake is slowed down. Its minimum gamma-factor is \( \gamma_{\text{min}} \approx 40 \), which is an order of magnitude below that of the beam. This can be calculated using the equation:

\[
\frac{v_{\text{ph}} - c}{c} \times 10^{-4}
\]

where \( v_{\text{ph}} \) is the phase velocity of the wakefield. 

In the growth phase, \( v_{\text{ph}} \approx c \) in the saturation phase. External injection after the saturation of SMI can be used to accelerate electrons to multi-GeV energies with \( \sim \) GeV/m gradient. 

- **Injection Point**
- **Elec. gun**
- **Laser**
- **H-Q-VLPL3D simulation**
- **Phase velocity of wakefield < \( v_{\text{ph}} \approx c \) in the growth phase**
- **External injection after saturation of SMI**
- **Pukhov et al., Phys Rev Lett (2011)**
- **F. M. Velotti, J. S. Schmidt, WEPWA039**
- **O. Mete, WEPWA059**
- **U. Dorda, WEPWA007**
- **L.C. Deacon, WEPWA045**

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- \( \sigma_0 = 200 \mu\text{m} \)
- \( \sigma_0 = 300 \mu\text{m} \)
AWAKE EXPERIMENT @ CERN

- CERN team already translated dreams into CAD and more
- SMI experiments Q4 2016 …
p⁺ bunches interesting because they carry large amounts of energy (10-100’s kJ)

2016: study the physics of p⁺ bunch SMI (radial modulation, seeding, …)

2017: probe the accelerating wakefields with externally injected e⁻

2017: study accelerator physics

Set-up a comprehensive and long term p⁺-driven plasma-based accelerator program at CERN

Develop long, scalable and uniform plasma cells

Develop schemes for the production of short p⁺ bunches

Explore applications for a p⁺-driven PWFA
SUMMARY

✧ **p⁺** bunches interesting because they carry large amounts of energy (10-100’s kJ)

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**Equation**

\[ E_\text{0} = 15 \text{MeV} \]
\[ E_\text{N} = 2 \text{mm-mrad} \]
\[ \zeta_\text{inj} \sim 1.5 \sigma_{z, p} \sim 18 \text{cm} \]
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2017⁺: study accelerator physics
p+ bunches interesting because they carry large amounts of energy (10-100’s kJ)

2016: study the physics of p+ bunch SMI (radial modulation, seeding, …)

2017: probe the accelerating wakefields with externally injected e-

2017+: study accelerator physics

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✧ Set-up a comprehensive and long term p⁺-driven plasma-based accelerator program at CERN
✧ Develop long, scalable and uniform plasma cells
✧ Develop schemes for the production of short p⁺ bunches
✧ Explore applications for a p⁺-driven PWFA
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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http://cfp.ist.utl.pt/golp/epp/
http://exodus.physics.ucla.edu/

Benchmarking with:

THANK YOU!

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THANK YOU