A Proton-driven Plasma Wakefield Experiment
At CERN

Swapan Chattopadhyay
Laboratori Nazionali di Frascati, INFN Colloquium
6 July, 2016
OUTLINE

• Prologue

• Motivation for Plasma Wakefield acceleration

• Why Proton-driven?

• AWAKE Experiment and Global Collaboration

• AWAKE Experimental Set-up

• AWAKE Installation, Time-table and Phases

• Outlook
Acknowledgments

• Allen Caldwell (MPI Munich, Germany) ➔ Spokesperson
• Matthew Wing (UCL, UK) ➔ Deputy-Spokesperson
• Edda Gschwendtner (CERN) ➔ Technical Project Leader

Colleagues from Cockcroft Institute (UK)
• G. Xia, Oznur Mete, Carsten Welsch, Graeme Burt

Thanks to David Alessini, Massimo Ferrario, Marica Biagini (LNF/INFN)

And

Luigi Palumbo and Andrea Mostacci (Sapienza Univ. di Roma)

For the invitation!!!
“Nothing tends so much to the advancement of knowledge as the application of a new instrument”

from

Elements of Chemical Philosophy (1812)

→ “High Energy Particle Beams and Colliders” are indeed “Grand Instruments of Science”, playing a historically critical role in advancing our knowledge of elementary particles and forces
When I think about how we got into this small-scale region, I must say that the most important contributors have been the entire machine team --- I am reminded of the voyage of Columbus. There were those hardy ship builders, who knew not how far or where to or for how long the ships had to sail, but that they should withstand all tests of the unknown sea. These are our accelerator builders of today. Then we had those folks who jumped onto the ships and sailed away, landed at the first island they could reach and noted down everything they saw in great detail. These are our experimental colleagues. Finally there were those fellows so dear to us who stayed back in Madrid and told the expedition crew that they were going to land in India! 

“ The Structure of Matter and Elementary Particles ” CERN (1978)
Innovative Particle Accelerators of Ever Increasing Size and Cost in 20\textsuperscript{th} – 21\textsuperscript{st} Century

Nobel Trio: Walton, Rutherford, Cockcroft

Cyclotron

Cockcroft-Walton

Wideröe Linac

Bevatron

SLAC

Tevatron

LEP/LHC

FCC/ILC ??
Particle Accelerators and Colliders have helped us piece together the entire Standard Model of Particles and Associated Interactions from Quarks to Leptons to Gauge Bosons
## Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two quarks separated by the specified distances.

<table>
<thead>
<tr>
<th>Property</th>
<th>Gravitational Interaction</th>
<th>Weak Interaction (Electroweak)</th>
<th>Electromagnetic Interaction</th>
<th>Strong Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acts on:</td>
<td>Mass – Energy</td>
<td>Flavor</td>
<td>Electric Charge</td>
<td>Color Charge</td>
</tr>
<tr>
<td>Particles experiencing:</td>
<td>All</td>
<td>Quarks, Leptons</td>
<td>Electrically Charged</td>
<td>Q/A, Gluons</td>
</tr>
<tr>
<td>Particles mediating:</td>
<td>Graviton (not yet observed)</td>
<td></td>
<td></td>
<td>Gluons</td>
</tr>
<tr>
<td>Strength at 10^{-18} m</td>
<td>10^{-41}</td>
<td></td>
<td></td>
<td>25</td>
</tr>
<tr>
<td>Strength at 3x10^{-17} m</td>
<td>10^{-41}</td>
<td></td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

### FERMIONS

Fermions are the building blocks of matter, with spin = 1/2, 3/2, 5/2...:

#### Leptons, spin = 1/2

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$</td>
<td>(0.0-0.13)x10^{-9}</td>
<td>0</td>
</tr>
<tr>
<td>$e$</td>
<td>0.000 11</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_M$</td>
<td>(0.009-0.13)x10^{-9}</td>
<td>0</td>
</tr>
<tr>
<td>$\mu$</td>
<td>0.106</td>
<td>-1</td>
</tr>
<tr>
<td>$\nu_H$</td>
<td>(0.04-0.1)x10^{-9}</td>
<td>0</td>
</tr>
<tr>
<td>$\tau$</td>
<td>1.777</td>
<td>-1</td>
</tr>
</tbody>
</table>

#### Quarks, spin = 1/2

<table>
<thead>
<tr>
<th>Flavor</th>
<th>Approx. Mass GeV/c²</th>
<th>Electric charge</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u$</td>
<td>0.002</td>
<td>2/3</td>
</tr>
<tr>
<td>$d$</td>
<td>0.005</td>
<td>-1/3</td>
</tr>
<tr>
<td>$c$</td>
<td>1.3</td>
<td>2/3</td>
</tr>
<tr>
<td>$s$</td>
<td>0.1</td>
<td>-1/3</td>
</tr>
<tr>
<td>$t$</td>
<td>173</td>
<td>2/3</td>
</tr>
<tr>
<td>$b$</td>
<td>4.2</td>
<td>-1/3</td>
</tr>
</tbody>
</table>

The most important tool for this development was the particle accelerator.
TODAY’S HIGHEST ENERGY PARTICLE COLLIDER: Large Hadron Collider at CERN, Geneva

→ Enabled Major Discovery of the Early 21st century

HIGGS!

LHC

→ NEXT?
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs "for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subconfirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider".
Particle physicists are convinced there are more discoveries to come: many things not explained in the standard model:

- why three families
- matter/antimatter imbalance
- neutrinos and neutrino masses
- hierarchy problem/unification
- dark matter, dark energy......
- Inflationary cosmology and connection with gravity
SCALES of FUTURE POSSIBILITIES IN PARTICLE PHYSICS: Time, Effort, Cost

LHC HIGGS?

- v Programme (≈ $1B)
- Muons (< $1B)
- Brighter LHC (<$1B)
- Linear e+e- Collider Options "Higgs factory" (~400 GeV) (~ $10B - $30B)

Even Larger Circular Colliders (FCC) E (I)
100 TeV pp / 400 GeV e+e- (~$10B - 40B)
→ Other Colliders?
Are their new ways to explore physics at higher energy scales in an earth-based laboratory environment in a manner acceptable fiscally, geo-politically and socially?

- New cost-effective, compact acceleration technology!

- Focus of this talk, “speculative”, future promise depending on laboratory demonstration!!

- Alternative technologies as laboratory-based “precision” probes to “sense” very “weak” effects e.g. BSM, the “Dark Universe”: exploring the energy frontier without colliders but exploiting collider technologies augmented by emerging “Quantum Sensors” technologies: cavities, high magnetic fields and vacuum, lasers, atomic beam interferometers, qubit-sensing of photons, etc.

- Promising but needing implementation!! Focus of yesterday’s talk at Sapienza Univ. di Roma and INFN Rome
The inverse of Acceleration (energy gain) is Radiation (energy loss) and vice-versa:

Detection of faint \( \rightarrow \) Acceleration of High Radiation

"Reciprocity"
ACCELERATOR OPTIONS for Far Future:
*Creating artificial periodic structures for rapid and efficient acceleration*

- **New Materials**
  - Dielectrics
  - Photonic structures and Metamaterials

- **Plasmas**
  - Laser Driven
  - Electron Beam Driven
  - Proton Beam Driven
A bit of Digression:

Superposition, Acceleration and Radiation

- Superposition with Radiation
- Linear Acceleration and Deceleration
- Fundamental limit to acceleration from radiation
Superposition and Radiation of beam

\[ E_s(t, r) = \sum e_s(t - \tau_i, \vec{r} - \vec{r}_i) \]

\[ E_s(\omega, \vec{k}) = e_s(\omega, \vec{k}) \sum e^{i \vec{k} \cdot \vec{r}_i - i \omega \tau_i} \]

If

\[ k a \theta \ll 1 \quad a \ll d_c \]

Incoherent radiation \( \omega \tau_b >> 1 \)

Bunch length >> radiation wavelength

amplitude \( E_s(\omega, \theta) \sim N^{1/2} \)

intensity \( \sim |E_s(\omega, \theta)|^2 \sim N \)

Coherent radiation \( \omega \tau_b << 1 \)

Bunch length << radiation wavelength

amplitude \( E_s(\omega, \theta) \sim N \)

intensity \( \sim |E_s(\omega, \theta)|^2 \sim N^2 \)
Linear acceleration/ deceleration

If in the far field region one has fields from an external source and fields from spontaneous emission from particles

\[ E = E_{\text{ex}}(\omega, \theta) + e_s(\omega, \theta) \]

where \( \eta \) is the overlap of external and spontaneous fields

\[ E(\omega) \sim \int_{-\infty}^{\infty} E(t) e^{i \omega t} dt \]

\[ E(0) \sim \int_{-\infty}^{\infty} E(t) dt t \equiv 0 \]

where \( \eta \) is the overlap of external and spontaneous fields

Acceleration/ deceleration linear with external field always is interference of spontaneous radiation with external field.

The charge must be able to radiate in the mode that we want to use for accelerating it.
**FUNDAMENTAL THEOREM OF ACCELERATION AND DECELERATION**

For optimal acceleration/deceleration, linear or otherwise in $\hat{E}_{\text{ext}}$, there must be optimal overlap of 'acceleration' mode $\hat{E}_{\text{ext}}(w,k)$ with 'radiation' mode $\tilde{E}_s(w,k)$. The particles are accelerated if the coherent radiation loss is less than the energy gain, leading to the restriction:

$$N \leq \left( |E_{\text{ext}}|/e \right) e^{2}$$

on the number of particles in a bunch that can be effectively accelerated before losses start to dominate, leading to deceleration ($\chi \equiv \lambda/2\pi$ is the reduced wavelength of accelerating mode).
ACCELERATOR OPTIONS for Far Future:

Creating artificial periodic structures for rapid and efficient acceleration

• **New Materials**
  
  Dielectrics
  
  Photonic structures and Metamaterials

• **Plasmas**
  
  Laser Driven
  
  Electron Beam Driven
  
  Proton Beam Driven
**ISSUES AND QUESTIONS:**

**Gradient:** <0.3-1 GeV/m (?) – **NOT** sufficient for compact very high energy colliders but can be explored for low intensity, low energy ‘accelerator-on-a-chip’

**Staging:** VERY inefficient to stack acceleration modules

**Cost:** Unknown, probably prohibitive from laser power, efficiency structure integrity and clean-room logistics

**Power:** 430 MW for 3 TeV (est.)!

**Luminosity:** Very low!! (many issues, dE/E)

NB - at >1 TeV electrons radiate even in a linear collider!
Plasma Waves


Plasma wave: electron density perturbation

Laser/beam pulse \( \sim \lambda_p/c \)

Option B:
Short intense laser pulse
\( \sim 10^{17} \text{cm}^{-3}, 30 \text{ GV/m}, \lambda_p \sim 100 \mu\text{m} \)

Option A:
Short intense e-/e+/\( p \) bunch
\( 10^{18} \text{cm}^{-3}, 100 \text{ GV/m}, \lambda_p \sim 30 \mu\text{m} \)

\[ E_0 = \frac{m_e c \omega_p}{e} \approx 100 \left[ \frac{\text{GeV}}{m} \right] \cdot \sqrt{n_0 [10^{18} \text{cm}^{-3}]} \]
Plasmas: Laser Driven Wakefield

**ISSUES AND QUESTIONS:**

**Gradient**: $<10-100 \text{ GV/m} - \text{Sufficient for compact colliders!}$

**Staging**: VERY difficult at relativistic energies

**Efficiency**: Lasers are still very inefficient, more than an order of magnitude less efficient than RF Sources: Need R&D on fiber lasers, power combining,...! Many decades away.

**Cost and Power**: Prohibitive today!

**Luminosity**: Unknown but probably very low!

**Beam Physics**: Scattering, luminosity, positrons,...??????
Plasmas: Electron Beam Driven Wakefield

**ISSUES AND QUESTIONS:**

**Gradient:** $<10-100$ GV/m — **Sufficient for compact colliders**

**Staging and Transformer Ratio (TR):** $[(2 - 3)]$

→ requiring too many inefficient stages
→ Pulse shaping to improve TR a challenge!

**Cost:** Unknown but probably very high as requires conventional electron beam linear accelerator infrastructure as driver!!!

**Power:** OK with the after-burner concept!

**Luminosity:** too low, $L \times e^(-n)$!! And all the Beam Physics issues scattering, positrons,..??
Plasmas: Proton Beam Driven Wakefield

**ISSUES AND QUESTIONS:**

**Gradient:** <10-100 GV/m – Sufficient for compact colliders!

**Staging and Transformer Ratio:** OK, requiring only one or two stages (transform 100-200 kilojoules of multiple TeV proton beams into TeV class electron beams!).

**Cost:** Unknown but depends on existing TeV-class proton beam infrastructure (e.g. CERN!)

**Power:** OK with availability of 1-10 TeV proton beams

**Luminosity:** Unknown! Positron plus beam stability?
Proton Drivers for PWFA

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

**DRIVERS:**
- Peta-Watt lasers today: ~40 J/Pulse
- FACET facility @SLAC: ~30 J/bunch
  - SPS: ~20 kJ/bunch !!
  - LHC: ~300 kJ/bunch !!

**WITNESS ACCELERATED BUNCH REQUIREMENT:**

- $10^{10}$ electrons @ 1 TeV ≈ few kJ

Energy content of driver allows to consider single stage acceleration !!!
Multiple Stage Laser-driven and/or Electron Beam-driven Plasma Wakefield Accelerator vs. Single Stage Proton-driven Plasma Wakefield Accelerator
In Summary: Motivation for PDPWA

• Laser-plasma wakefield acceleration has made great advances producing GeV class electron beams in compact setting;

• Electron beam-driven plasma wakefield acceleration has also shown high gradients and energy-doubling of 42 GeV to 85 GeV in a single pass;

• However, both have limitations: laser-plasma approach being limited by the multiple staging needed for reaching high energies relevant for particle physics, while electron beam-plasma approach being limited by the energy of the drive beam and maximum possible “transformer ratio”;

• Proton beams such as in the 7 TeV LHC carry significant stored energy (>140 kilojoules per pulse) that can be transformed into a TeV class electron beam using a plasma channel as the wakefield transformer. Hence using a proton driver is the best option for particle physics; can we model the interaction?
Proton-driven Plasma Wakefield Acceleration

Short beam enters plasma
Free e- pulled towards beam
e- reach beam, and overshoot
Ion region is left behind beam
e- pulled back towards axis by ions
‘bubble’ structure formed
High electric fields created
Many ‘bubbles’ trail beam
Inject e- into bubble to accelerate them
Here is a simulation of the cartoon (electric field plotted)
The side view shows how the ‘bubbles’ get noisier further behind the beam
Circled is the electric field of the proton beam driving the wakefield

Can also drive wakefields with:
• Electrons
• Photons
• Positrons
• Muons (in principle)
Simulation Results: $E_e = 0.6$ TeV from $E_p = 1$ TeV in 500 m

**Drive beam: $p^+$**
- $E = 1$ TeV, $N_p = 10^{11}$
- $\sigma_z = 100$ μm, $\sigma_r = 0.43$ mm
- $\sigma_\theta = 0.03$ mrad, $\Delta E/E = 10\%$

**Witness beam: $e^-$**
- $E_0 = 10$ GeV, $N_e = 1.5 \times 10^{10}$

**Plasma: $Li^+$**
- $n_p = 6 \times 10^{14}$ cm$^{-3}$

**External magnetic field:**
- Field gradient: 1000 T/m
- Magnet length: 0.7 m

PROMISE:

- Proton-driven plasma wakefield acceleration (PD-PWFA) can accelerate electron bunch to the energy frontier (TeV) in a single stage, while the transverse electric fields focus the accelerating bunch;

CHALLENGE:

- This requires ultra-short proton beams not yet achievable in practice: typical proton beams are ‘nanoseconds’ long, not ‘pico-seconds’ short!

COMPROMISE for Proof-of Principle Demonstration:

- Compromise can be reached by using plasma-modulated protons beams as a driver exploiting SMI (Self-Modulation Instability)
Self-modulation instability of a long proton bunch in plasma resonantly driving plasma wakefields.

The microbunches are generated by a transverse modulation of the bunch density (transverse two-stream instability). The microbunches are naturally spaced at the plasma wavelength, and act constructively to generate a strong plasma wake. Investigated both numerically and analytically.
The Self-Modulation Instability

Affects long drive beams.

- Long beam enters plasma
- Free e- pulled towards proton beam
- E- overshoot the proton beam
- Ion region left behind head of proton beam
- E- pulled back on axis by ions
- Impinge on proton beam
- Weak wakefield co-propagates with beam
- Ion regions force beam protons away
- E- regions focus beam and keep on axis

After some time, half the proton beam is discarded, leaving micro-bunches

- Microbunches are spaced $\lambda_p$ apart.
- Charge density increased.
- Micro bunch lengths are much closer to the ideal driver length of:
  \[ \sigma_{\text{ideal}} = \frac{\lambda_p}{\pi \sqrt{2}} \]

These properties then allow the modulated beam to drive a wakefield much more effectively.
• [http://www.cern.ch/awake](http://www.cern.ch/awake)
Proton-beam modulation

CERN SPS proton beam

- Proton bunch population, \( N_b \)
- Proton bunch length, \( \sigma_z \)
- Proton bunch radius, \( \sigma_r \)
- Proton energy, \( W_b \)
- Proton bunch relative energy spread, \( \delta W_b / W_b \)
- Proton bunch normalized emittance, \( \epsilon_{bn} \)

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>3 \times 10^{11}</td>
<td>12 cm</td>
</tr>
<tr>
<td>12 cm</td>
<td>0.02 cm</td>
</tr>
<tr>
<td>400 GeV</td>
<td>0.35%</td>
</tr>
<tr>
<td>3.5 mm mrad</td>
<td></td>
</tr>
</tbody>
</table>

\[ E_z, \text{ GV/m} \]

\[ z, \text{ m} \]
Injection of witness electrons

Electron bunch population, $N_e$
Electron bunch length, $\sigma_{ze}$
Electron bunch radius at injection point, $\sigma_{re}$
Electron energy, $W_e$
Electron bunch normalized emittance, $\epsilon_{en}$
Injection angle for electron beam, $\phi$
Injection delay relative to the laser pulse, $\xi_0$
Intersection of beam trajectories, $z_0$

1.25 $\times$ 10$^9$
0.25 cm
0.02 cm
16 MeV
2 mm mrad
9 mrad
13.6 cm
3.9 m
An international collaboration (AWAKE) has been set up for experimental study of proton-driven PWFA using SPS beam.

AWAKE Collaboration

Spokesperson: Prof. Allen Caldwell, MPI, Munich (Germany)

Deputy Spokesperson: Prof. Matthew Wing, UCL (UK)

Technical Project Manager: Dr. Edda Gschwendner (CERN)
AWAKE Collaboration: 16 Institutes world-wide:

- Budker Institute of Nuclear Physics & Novosibirsk State University
- CERN
- Cockcroft Institute
- DESY
- Heinrich Heine University, Düsseldorf
- Instituto Superior Tecnico
- John Adams Institute
- Imperial College
- Ludwig Maximilian University
- Max Planck Institute for Physics
- Max Planck Institute for Plasma Physics
- Rutherford Appleton Laboratory
- TRIUMF
- University College London
- University of Oslo
- University of Strathclyde

Requests under consideration:
- Ulsan National Institute of Science and Technology (UNIST), Korea
- Wigner Institute, Budapest
- Swiss Plasma Center group of EPFL
- Northern Illinois University, USA

Further groups have also expressed their interest to join AWAKE.

A fully approved CERN project; on their Medium-Term Plan and significant funding.
In the News

SPSC Meeting, October 2015

Just kidding – but there was a Spiegel article!
AWAKE: to high energies in a single leap

Proton-driven plasma wakefield acceleration could accelerate electrons to the terascale in a single plasma stage. The AWAKE project is set to verify this novel technique using proton beams at CERN.

To complement the results that will come from the LHC at CERN, the particle-physics community is looking for options for future lepton colliders at the tera-electron-volt energy scale. These will need to be large circular or linear colliders. With the accelerating gradients of today’s RF cavity or microwave technology limited to about 100 MV/m, the length of the linear machines would be tens of kilometres. However, plasma can sustain much higher gradients and the idea of harnessing them in plasma wakefield acceleration is gathering momentum. One attractive idea is to use a high-energy proton beam as the driver of a wakefield in a single plasma section.

Fig. 1. Simulation of a self-modulated proton bunch resonantly driving plasma wakefields sustained by the plasma-density perturbation. The plasma density is shown increasing from white to blue and the proton density increasing from yellow to dark red.

A proposed demonstration of an experiment of proton-driven plasma wakefield acceleration based on CERN SPS

G. XIA1, R. ASSMANN2, R. A. FONSECA3, C. HUANG4, W. MORI5, L. O. SILVA3, J. VIEIRA3, F. ZIMMERMANN2 and P. MUGGLI1

for the PPWFA Collaboration

1Max Planck Institute for Physics, Munich, Germany (xianguo@mpp.mpg.de)
2CERN, Geneva, Switzerland
3GoLP/Instituto de Plasmas e Fusao Nuclear-Laboratório Associado, IST, Lisboa, Portugal
4Los Alamos National Laboratory, Los Alamos, NM, USA
5University of California, Los Angeles, CA, USA

(Received 20 September 2011; accepted 2 January 2012)
Scientific goals

1. Demonstrate self-modulation effect of a long proton bunch and realize 1 GeV electron energy gain with a ~10 m plasma;
2. Develop and test the diagnostic equipments for the first and later experiments;
3. Benchmark data against simulation results;
4. Provide inputs for future experiment for 100 GeV energy gain in 100 m plasma.
Phase 1: Understand the physics of self-modulation instability processes in plasma.
Phase 1: Understand the physics of self-modulation instability processes in plasma.

Plasma cell

→ Rb vapour source
Phase 1: Understand the physics of self-modulation instability processes in plasma.

Plasma cell
- Rb vapour source

Proton beam
- drives the plasma wakefield + undergoes self-modulation instability.
- LHC-type proton beam, 400 GeV/c, 3E11 protons/bunch, σ = 400 ps long
Phase 1: Understand the physics of self-modulation instability processes in plasma.

**Plasma cell**
- Rb vapour source

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- drives the plasma wakefield + undergoes self-modulation instability.
- LHC-type proton beam, 400 GeV/c, 3E11 protons/bunch, \( \sigma = 400 \) ps long

**Laser beam:**
- ionizes the plasma + seeds the self-modulation instability of the proton beam.
- 4.5 TW laser, 100 fs
Phase 1: Understand the physics of self-modulation instability processes in plasma.

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**Diagnostics**
- BTVs, OTR, CTR
AWAKE: Experimental Program

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

Start with physics Q4 2016!

Self-modulated proton bunch resonantly driving plasma wakefields.

J. Vieira et al PoP 19063105 (2012)
AWAKE Experimental Program

- Phase 1: Understand the physics of self-modulation instability processes in plasma.
- Phase 2: Probe the accelerating wakefields with externally injected electrons.

**Plasma cell**
- Rb vapour source

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- Drives the plasma wakefield + undergoes self-modulation instability.
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- 4.5 TW laser, 100 fs

**Diagnostics**
- BTVs, OTR, CTR

**Electron source and beam**
- Witness beam to ‘surf’ on the wakefield and get accelerated
- 16 MeV/c, 1.2 E9 electrons/bunch, $\sigma = 4$ps long
AWAKE Experimental Program

- Phase 1: Understand the physics of self-modulation instability processes in plasma.
- Phase 2: Probe the accelerating wakefields with externally injected electrons.

**Plasma cell**
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**Electron source and beam**
- Witness beam to ‘surf’ on the wakefield and get accelerated
- 16 MeV/c, 1.2 E9 electrons/ bunch, $\sigma = 4$ps long

**Electron spectrometer system**
AWAKE Experimental Program

• Phase 1: Understand **the physics of self-modulation instability** processes in plasma.
• Phase 2: **Probe the accelerating wakefields** with externally injected electrons.

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![Diagram of AWAKE experimental setup](attachment:image.png)

Maximum amplitude of the **accelerating field** $E_z$ as a function of position along the plasma. Saturation of the SMI at $\sim 4$ m.
**AWAKE Experimental Program**

- **Phase 1:** Understand the physics of self-modulation instability processes in plasma.
- **Phase 2:** Probe the accelerating wakefields with externally injected electrons.

Start with physics Q4 2017!

K. Lotov et al., arXiv: 1408.4448

Energy of the electrons gained along the 10 m long plasma cell.
AWAKE at CERN

AWAKE is installed in
**CNGS Facility** (CERN Neutrinos to Gran Sasso)
→ CNGS physics program finished in 2012

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**Nominal SPS Proton Beam Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum</td>
<td>400 GeV/c</td>
</tr>
<tr>
<td>Protons/bunch</td>
<td>$3 \times 10^{11}$</td>
</tr>
<tr>
<td>Bunch length</td>
<td>$\sigma_z = 0.4 \text{ ns (12 cm)}$</td>
</tr>
<tr>
<td>Bunch size at plasma entrance</td>
<td>$\sigma^*_{x,y} = 200 \mu\text{m}$</td>
</tr>
<tr>
<td>Normalized emittance (r.m.s.)</td>
<td>3.5 mm mrad</td>
</tr>
<tr>
<td>Relative energy spread</td>
<td>$\Delta p/p = 0.35%$</td>
</tr>
</tbody>
</table>
Electron acceleration based on modulated proton driven wakefield acceleration!
Electron acceleration based on modulated proton driven wakefield acceleration!

Electron bunch
Proton bunch
Electron beam line
Laser & proton beam junction
Laser power supplies
Access gallery

Proton beam line
Luminescent Laser power supplies
Access gallery

Electron gun
Klystron system

Electron spectrometer
Experimental Diagnostics
CNLS target area

Items in dark blue: ventilation ducts
Items in light blue: AWAKE electronic racks
Items in cyan: existing CNGS equipment (cable trays, pipes,...)

Electron bunch injected off-axis at an angle and some metres... acceleration from 10MeV/c to up to 2000MeV/c

Ingredients
E. Gschwendtner, 4/9/2012
Plasma Source: Rubidium Vapor Source developed simultaneously at MPI Munich, MPI Garching and Imperial College

- Density adjustable from $10^{14} - 10^{15}$ cm$^{-3}$
- 10 m long, 4 cm diameter
- Plasma density = vapor density
- System is oil-heated: 150° to 200° C  
  → keep temperature uniformity  
  → Keep density uniformity

**Required:**  
$\Delta n/n = \Delta T/T \leq 0.002$

Laser

- Laser intensity must exceed ionization intensity at the plasma end (L=10m) over a plasma radius of \( r > 3\sigma = 600 \mu m \).

Laser system in MPI, Munich

<table>
<thead>
<tr>
<th>Laser Beam</th>
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<tbody>
<tr>
<td>Laser type</td>
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<tr>
<td>Pulse wavelength ( \lambda_0 )</td>
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<tr>
<td>Pulse length</td>
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<tr>
<td>Pulse energy (after compr.)</td>
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<tr>
<td>Laser power</td>
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<tr>
<td>Focused laser size ( \sigma_{x,y} )</td>
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<tr>
<td>Rayleigh length ( Z_R )</td>
</tr>
<tr>
<td>Energy stability</td>
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<tr>
<td>Repetition rate</td>
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Laser will be moved to CERN in February 2016
Electron Witness Beam – Electron Source

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<th>Electron beam for AWAKE</th>
<th>Baseline</th>
<th>Range for upgrade phase</th>
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<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>$\sigma_z = 4\text{ps (1.2mm)}$</td>
<td>0.3 – 10 ps</td>
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<tr>
<td>Bunch size at focus</td>
<td>$\sigma_{x,y} = 250 \text{ \mu m}$</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>$\Delta p/p = 0.5%$</td>
<td>$&lt;0.5%$</td>
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PHIN Photo-injector for CTF3/CLIC:
→ Program will stop end 2015 ➔ Fits to requirements ➔ used for AWAKE

- Klystron from CTF3
- e-beam diagnostics
- 1m booster linac (Cockcroft)
- Incident, Reflected, Power and phase
- Laser +Diagnostics
- FCT
- Emittance
- MS
- BPR
- RF GUN
- Corrector
- VP I
- Accelerator
- Matching triplet
- MTV
- Emittance
- Spectrometer E, $\Delta E$

Length ~ 4 m
Electron Witness Beam Acceleration Diagnostics

Probe the accelerating wakefields with externally injected electrons → Electron spectrometer

8.5 ton, 1.2 T, 1.3 Tm, L=1.6 m, W=1.3 m

Dispersed electron impact on scintillator screen. Resulting light collected with intensified CCD camera.

%‐level energy resolution can be achieved with a signal to noise ratio larger than 1000:1
SMI causes angular divergence of the proton beam of the order of ~1 mrad. 

Measure bunch profile at two different scintillator screens at a distance of ~8m.

Growth of tails governed by the transverse fields in the plasma. Will give indication of strong plasma wakefields.

Measure saturation point of SMI
Diagnostics: Direct Measurement of SMI

→ transforming the charge distribution information into a radiation distribution using transition radiation
→ Measured radiation emitted by the bunch when traversing a dielectric interface or by directly sampling the bunch space charge field. → streak-camera.

Use Optical Transition Radiation (OTR) for time-resolved measurement of self-modulation.

- Measure the OTR Light pulse with a streak camera (~ps resolution) while imaging.
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<td>Study, Design, Procurement, Component preparation</td>
<td>Installation</td>
<td>Commissioning</td>
<td>Data taking</td>
<td>Long Shutdown 2 24 months</td>
<td>Continue data taking after LS2</td>
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<tr>
<td>Experimental area</td>
<td>Study, Design, Procurement, Component preparation</td>
<td>Modification, Civil Engineering and installation</td>
<td>Study, Design, Procurement, Component preparation</td>
<td>Fabrication</td>
<td>Installation</td>
<td>Commissioning</td>
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<tr>
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<td>Studies, design</td>
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**Run request:**

**2016:** equivalent of 4 weeks continuous running, but upon demand: $2.4 \times 10^{16}$ protons + some running in the summer for proton beam commissioning

**2017:** equivalent of 8 weeks continuous running, but upon demand: $4.8 \times 10^{16}$ protons
**PHASE 3**

- **Split-cell mode**: SMI in 1\textsuperscript{st} plasma cell, acceleration in 2\textsuperscript{nd} one.
- New scalable uniform plasma cells (helicon or discharge plasma cell)
- Step in the plasma density $\rightarrow$ maintains the peak gradient
- Need ultra-short electron bunches ($\sim 300\text{fs}$) $\rightarrow$ bunch compression $\rightarrow$ Almost 100% capture efficiency

Density step physics better understood; expect to get electrons of few 10’s of GeV using SPS drive beam.
Still far away from any collider scenario.....

- Beam scattering in plasma $\rightarrow$ reduced luminosity
- Positron acceleration a problem in all scenarios, solutions being sought
- I am not advocating a plasma-based particle collider in the future but just pointing to a most promising and serious R&D to date at a laboratory with a major stake in energy frontier particle physics ...CERN....!!!
Future collider design

An $e^+ e^-$ collider

An $e^- p$ collider

Collider design issues based on proton-driven plasma wakefield acceleration

G. Xia$^{a,b,*}$, O. Mete$^{a,b}$, A. Aimidula$^{b,c}$, C.P. Welsch$^{b,c}$, S. Chattopadhyay$^{a,b,c}$, S. Mandry$^{d}$, M. Wing$^{d,e}$

$^*$ School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom
$^b$ The Cockcroft Institute, Sci-Tech Daresbury, Daresbury, Warrington, United Kingdom
$^c$ The University of Liverpool, Liverpool, United Kingdom
$^d$ Department of Physics and Astronomy, University College London, London, United Kingdom
$^e$ Deutsche Elektronen-Synchrotron DESY, Hamburg, Germany

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ABSTRACT

Recent simulations have shown that a high-energy proton bunch can excite strong plasma wakefields and accelerate a bunch of electrons to the energy frontier in a single stage of acceleration. It therefore paves the way towards a compact future collider design using the proton beams from existing high-energy proton machines, e.g., Tevatron or the LHC. This paper addresses some key issues in designing a compact electron–positron linear collider and an electron–proton collider based on the existing CERN accelerator infrastructure.
“VHeP: A very High Energy electron-Proton Collider”,
A. Caldwell and M. Wing, Proceedings of Science,
September 2015
(talks about a 1 TeV electron against a 7 TeV proton collider)

“Path to AWAKE: Evolution of the Concept”, NIMA,
November 2015

“Collider Design Issues based on Proton-driven Plasma Wakefield Acceleration”, NIMPR 2014
Summary

- AWAKE is the first proton-driven plasma wakefield acceleration in the world. It is also the first beam driven plasma wakefield acceleration experiment in Europe.

- AWAKE experiment will study the self modulated proton driven plasma wakefield acceleration; Proton beam from CNGS beam line will be used for the first experiment, expected in 2016.

- The first experiment goal is to demonstrate of 1 GeV electron energy gain @ 10 m plasma, 100 GeV @ 100 m plasma as the second step;

- The AWAKE experiment at CERN may shed light on a future e-e, e-p colliders.
AT THE END of every December, when Father Time’s odometer is ready to click in another year, experts seem compelled to forecast what the coming year will bring. Economists read their econometric entrails and predict hard times or happy days accordingly; psychics announce that this is the year the San Andreas fault will pitch California into the sea. Well, before you believe any of this year’s predictions, consider these vintage prognostications:

—Octave Chanute, aviation pioneer, in 1904: "The (flying) machine will eventually be fast; they will be used in sport, but they are not to be thought of as commercial carriers."

—The Literary Digest, 1889: "The ordinary 'horseless carriage' is at present a luxury for the wealthy; and although its price will probably fall in the future, it will never come into as common use as the bicycle."

—Thomas Edison, on electricity in the home: "Just as certain as death, [George] Westinghouse will kill a customer within six months after he puts in a system of any size."

—Lt. Joseph C. Ives, Corps of Topographical Engineers, 1861, on the Grand Canyon: "[It] is, of course, altogether valueless .... Ours has been the first, and will doubtless be the last, party of whites to visit this profitless locality."

—Science Digest, August 1948: "Landing and moving around on the moon offers so many serious problems for human beings that it may take science another 200 years to lick them."

—Physicist and mathematician Lord Kelvin (1824-1907), who seemed to have a corner on the wrongheaded onliner in his day: "X-rays are a hoax." "Aircraft flight is impossible." "Radio has no future."

-Paul Dickson, The Future File (Rawson Associates)
• http://www.cern.ch/awake