Plasma Accelerators (III)---
Proton-driven plasma wakefield acceleration

Guoxing Xia

Cockcroft Institute and the University of Manchester
Outline

- Why proton-driven PWFA
- Short proton bunch production
- AWAKE experiment at CERN
- Colliders based on PD-PWFA
- Summary
List of people discussing project

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Motivation

• With an increase of beam energy, the size and cost of modern high energy particle accelerators reach the limit (break down + power)
• Plasma can sustain very large electric fields, a few orders of magnitude higher than the fields in metallic structures
• The plasma accelerators (laser driven-LWFA or beam driven-PWFA) have been developed rapidly in last 20 years, 50-100GV/m accelerating gradients have been demonstrated in labs
• The novel plasma accelerators can potentially minimize the size and cost of future machines
• Very high energy proton beams are available nowadays, why not use these proton beam to excite wakefield for the electron acceleration?
Energy gain

\[ E = 240(\text{MeV/m}) \left( \frac{N}{4 \times 10^{10}} \right) \left( \frac{0.6}{\sigma_z(\text{mm})} \right)^2 \]

In the linear regime, the maximum achievable field scales as the bunch charge divided by bunch length squared, high intensity and short bunch length are required for high field production.

Transformer ratio limit *

\[ R = \frac{E_{\text{witness}}}{E_{\text{max}}^{\text{drive}}} \leq 2 \]

for longitudinal symmetric bunch

*R.D. Ruth et al, SLAC-PUB-3374
PWFA-based linear collider*

*M. Hogan et al., Proceedings of PAC09 (TU1GRI01)
*A. Seryi et al., Proceedings of PAC09 (WE6PFP081)
## Existing proton machines

<table>
<thead>
<tr>
<th></th>
<th>HERA</th>
<th>TEVATRON</th>
<th>LHC</th>
</tr>
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<tbody>
<tr>
<td>Circumference [km]</td>
<td>6.336</td>
<td>6.28</td>
<td>26.659</td>
</tr>
<tr>
<td>Maximum energy [TeV]</td>
<td>0.92</td>
<td>0.98</td>
<td>7.0</td>
</tr>
<tr>
<td>Energy spread [$10^{-3}$]</td>
<td>0.2</td>
<td>0.14</td>
<td>0.113</td>
</tr>
<tr>
<td>Bunch length [cm]</td>
<td>8.5</td>
<td>50</td>
<td>7.55</td>
</tr>
<tr>
<td>Transverse emit. [$10^{-9}$ $\pi$ m rad]</td>
<td>5</td>
<td>3</td>
<td>0.5</td>
</tr>
<tr>
<td>Particles per bunch [$10^{10}$]</td>
<td>7</td>
<td>26</td>
<td>11.5</td>
</tr>
</tbody>
</table>
high energy proton beam as driver

- Hugh energy stored in current proton machines like Tevatron, HERA, SPS and LHC
- For example, the SPS/LHC beam carries significant stored energy for driving plasma waves
  - SPS (450 GeV, 1.3e11 p/bunch) ~ 10 kJ
  - LHC (1 TeV, 1.15e11 p/bunch) ~ 20 kJ
  - LHC (7 TeV, 1.15e11 p/bunch) ~ 140 kJ
  - SLAC (50 GeV, 2e10 e-/bunch) ~ 0.1 kJ
- However, the current proton bunches are quite longer to use as driver directly. Need much effort to compress the beam
- How to couple the energy of driver to the plasma and the witness beam efficiently?
PWFA and PDPWA

Pros. of PWFA
Plasma electrons are expelled by space charge of beam, a nice bubble will be formed for beam acceleration and focusing.
The short electron beam is relatively easy to have (bunch compression).
Wakefield phase slippage is not a problem.

Cons. of PWFA
One stage energy gain is limited by transformer ratio, therefore maximum electron energy is about 100 GeV using SLC beam.
Easy to be subject to the head erosion due to small mass of electrons

Pros. of PDPWA
Very high energy proton beam are available today, the energy stored at SPS, LHC, Tevatron, HERA
SPS (450 GeV, 1.3e11 p/bunch) ~ 10 kJ
LHC (1 TeV, 1.15e11 p/bunch) ~ 20 kJ
LHC (7 TeV, 1.15e11 p/bunch) ~ 140 kJ
SLAC (50 GeV, 2e10 e-/bunch) ~ 0.1 kJ

Cons. of PDPWA
Flow-in regime responds a relatively low field vs. blow-out regime.
Long proton bunches (tens centimeters), bunch compression is difficult.
Wave phase slippage for heavy mass proton beam (small γ factor), especially for a very long plasma channel
The linear theory of PWFA holds for either negatively charged or positively charged beams.

The maximum achievable gradient scales as $N/\sigma_z^2$, therefore we need high current and short bunch for proton bunch driven PWFA.

Transformer ratio (the gained energy of witness beam / the energy of driver beam) is limited to 2 for longitudinal symmetric driven bunches.

2D and 3D Particle-in-cell (PIC) simulations have given us very promising results for proton driven PWFA.

One of the biggest hurdles is to produce the short proton beam, in the scale of 100 micron.
Schematics of PD-PWFA

A thin tube containing Li plasma is surrounded by quadrupole magnets with alternating polarity. The magnification shows the plasma bubble created by the proton bunch (red). The electron bunch (yellow) undergoing acceleration is located at the back of the bubble. Note that the dimensions are not to scale.

* A. Caldwell et al., Nature Physics 5, 363 (2009)
## Parameter settings

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Drive Beam</strong></td>
<td></td>
</tr>
<tr>
<td>Protons in drive bunch [$10^{11}$]</td>
<td>$N_p$</td>
</tr>
<tr>
<td>Proton energy [TeV]</td>
<td>$E_p$</td>
</tr>
<tr>
<td>Initial proton momentum spread</td>
<td>$\sigma_p/p$</td>
</tr>
<tr>
<td>Initial longitudinal spread [$\mu$m]</td>
<td>$\sigma_z$</td>
</tr>
<tr>
<td>Initial angular spread [mrad]</td>
<td>$\sigma_\theta$</td>
</tr>
<tr>
<td>Initial bunch transverse size [mm]</td>
<td>$\sigma_{X,Y}$</td>
</tr>
<tr>
<td><strong>Witness Beam</strong></td>
<td></td>
</tr>
<tr>
<td>Electrons in witness bunch [$10^{10}$]</td>
<td>$N_e$</td>
</tr>
<tr>
<td>Energy of electrons [GeV]</td>
<td>$E_e$</td>
</tr>
<tr>
<td><strong>Plasma Parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Free electron density [cm$^{-3}$]</td>
<td>$n_p$</td>
</tr>
<tr>
<td>Plasma wavelength [mm]</td>
<td>$\lambda_p$</td>
</tr>
<tr>
<td><strong>External Field</strong></td>
<td></td>
</tr>
<tr>
<td>Magnetic field gradient [T/m]</td>
<td>1000</td>
</tr>
<tr>
<td>Magnetic length [m]</td>
<td>0.7</td>
</tr>
</tbody>
</table>
Simulations

- 2 D and 3 D Particle-In-Cell (PIC) codes are employed to simulate the interactions between plasma and beams.

Fig.a-d), Simulation results for the unloaded (no witness bunch) case (a,b) and in the presence of a witness bunch (c,d). The witness bunch is seen as the black spot in the first wave bucket in d). d) also shows the driving proton bunch at the wavefront (red). e) The on-axis accelerating field of the plasma wave for the unloaded (blue curve) and loaded (red curve) cases.

* A. Caldwell et al., Nature Physics 5, 363 (2009)
Simulation results

- **Energy gain**

1 TeV

10 GeV

phase
Phase space of driver & witness

Fig. a-h), Snapshots of the combined longitudinal phase space of the driver and the witness bunches (energy versus coordinate) (a–d) and corresponding energy spectra (e–h). The snapshots are taken at acceleration distances $L=0, 150, 300, 450$ m. The electrons are shown as blue points and the protons are depicted as red points.

* A. Caldwell et al., Nature Physics 5, 363 (2009)
Energy gain & energy spread

Fig. a,b), The mean electron energy in TeV (a) and the r.m.s. variation of the energy in the bunch as a percentage (b) as a function of the distance travelled in the plasma.

* A. Caldwell et al., Nature Physics 5, 363 (2009)
Simulation results

- Proton bunch can indeed be used as the drive beam for exciting a large amplitude wakefield.
- Proton-driven PWFA can bring a bunch of electrons to the energy frontier in only one stage.
- An unsolved question: short beam!
Short proton bunch production

• Laser striking thin foil can produce short and low energy proton beam
• Emittance exchange technique, exchanges the longitudinal emittance to horizontal emittance
• Fast quads tuning for low momentum compaction factor before extraction in the ring
• Fast nanochoppers to get microbeam
• Conventional magnetic bunch compression*
• Plasma wakefield beam slicing via modulation
Magnetic bunch compression

- Beam compression can be achieved:
  1. by introducing an energy-position correlation along the bunch with an RF section at zero-crossing of voltage
  2. and passing beam through a region where path length is energy dependent:
     this is generated by bending magnets to create dispersive regions.

- To compress a bunch longitudinally, trajectory in dispersive region must be shorter for tail of the bunch than it is for the head.

![Diagram showing magnetic bunch compression](image)
### Bunch compressor design

For a thousand-fold compression, one stage compression looks infeasible

We expect that the ring could compress the bunch by a factor of 10 and the rest will be realized via magnetic chicane

\[
\begin{aligned}
\begin{pmatrix}
 z(s_2) \\
 \delta(s_2)
\end{pmatrix} &=
\begin{pmatrix}
 1 & R_{56} & 0 \\
 0 & R_{65} & 1
\end{pmatrix}
\begin{pmatrix}
 z(s_0) \\
 \delta(s_0)
\end{pmatrix} =
\begin{pmatrix}
 1 + R_{56}R_{65} & R_{56} & R_{65} \\
 R_{65} & 1 & 0
\end{pmatrix}
\begin{pmatrix}
 z(s_0) \\
 \delta(s_0)
\end{pmatrix}
\end{aligned}
\]

\[
1 + R_{56}R_{65} = 0
\]

\[
R_{65} = \frac{\delta}{z} = \frac{1}{z} \frac{\Delta E}{E} = \frac{eV_0}{E} \frac{\omega}{\beta c}
\]

\[
R_{56} = -2E_B \left( \frac{1}{3} L_B + \Delta L \right)
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch charge</td>
<td>(10^{11})</td>
</tr>
<tr>
<td>Proton energy [TeV]</td>
<td>1</td>
</tr>
<tr>
<td>Initial energy spread [%]</td>
<td>0.01</td>
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<tr>
<td>Initial bunch length [cm]</td>
<td>1.0</td>
</tr>
<tr>
<td>Final bunch length [(\mu m])]</td>
<td>165</td>
</tr>
<tr>
<td>RF frequency [MHz]</td>
<td>704.4</td>
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<tr>
<td>Average gradient of RF [MV/m]</td>
<td>25</td>
</tr>
<tr>
<td>Required RF voltage [MV]</td>
<td>65,000</td>
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<tr>
<td>RF phase [degree]</td>
<td>-102</td>
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<tr>
<td>Compression ratio</td>
<td>~60</td>
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<tr>
<td>Momentum compaction (MC) [m]</td>
<td>-1.0</td>
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<tr>
<td>Second order of MC [m]</td>
<td>1.5</td>
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<tr>
<td>Bending angle of dipole [rad.]</td>
<td>0.05</td>
</tr>
<tr>
<td>Length of dipole [m]</td>
<td>14.3</td>
</tr>
<tr>
<td>Drift space between dipoles [m]</td>
<td>190.6</td>
</tr>
<tr>
<td>Total BC length [m]</td>
<td>4131</td>
</tr>
<tr>
<td>Final beam energy [GeV]</td>
<td>986.5</td>
</tr>
<tr>
<td>Final energy spread [%]</td>
<td>0.93</td>
</tr>
</tbody>
</table>
Phase space of beam

a) Initial phase space

b) Phase space after RF section

c) Final phase space

G. Xia, A. Caldwell et al., Proceedings of PAC09 (FR5RFP011)
Phase space of beam

G. Xia, A. Caldwell et al., Proceedings of PAC09 (FR5RFP011)
Fitting data show that the bunch length of 170 micron and the relative energy spread of 9e-3 can be achieved.

Plasma wakefield slicing via modulation

- Magnetic bunch compression: formidable RF power for energy chirp!
- Self-modulation via plasma wakefield (the transverse instability modulates the long bunch into many ultra short beamlets at plasma wavelength.

SPS beam at 5m Plasma @ 1e14 cm⁻³

on-axis (X = 0) beam density profile after 5 m propagation in plasma


G. Xia, F. Zimmermann, et al., Proceedings of PAC09, (FR5RFP004)
Demonstration experiment at CERN

PS (East Hall Area) and SPS (West Area) could be used for our demonstration experiment
Long bunch modulation by wakefield

VLPL3D simulation
PS-beam:
10cm, 10e11 p
Plasma: 10e13 1/cc
SPS beam for a test experiment

Super Proton Synchrotron-SPS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Momentum [GeV/c]</td>
<td>450</td>
</tr>
<tr>
<td>Maximum protons/bunch [10^{11}]</td>
<td>1.15</td>
</tr>
<tr>
<td>rms bunch length [cm]</td>
<td>12</td>
</tr>
<tr>
<td>rms energy spread [10^{-4}]</td>
<td>2.8</td>
</tr>
<tr>
<td>rms transverse emittance [μm]</td>
<td>3.5</td>
</tr>
<tr>
<td>Bunch spacing [ns]</td>
<td>25</td>
</tr>
</tbody>
</table>

11/05/2015 Cockcroft Institute Lecture

I. Efthymiopoulos, EN/MEF - CERN
SPS beam for a test experiment

- large space available for SPS tunnel
- The SPS/LHC proton bunch has **excellent properties:**
  - Very stiff beam: can drive plasma without too much beam deterioration.
  - Well controlled and maintained (for LHC, CNGS, HiRadMat, …).
  - Variable in intensity (2e9-3.0e11) and emittance.
  - Carries significant stored energy for driving plasma waves:

- The issue is **how to couple** the proton energy to the plasma (via modulation):
  - CERN proton bunches are very long (120 mm), compared to the electron bunches used at SLAC (< 0.1 mm).
  - Plasma wavelength is at the 1 mm scale.
  - How do we couple the proton beam energy into the plasma and then to the witness electron beam?
Various particle-in-cell (PIC) codes are used to benchmark the results based on the same parameter set. Presently they show very good agreement.
Seeding the instability

- Seed the instability via laser or electron beam prior to the proton beam (the instability will not start from random noise, rather from a well-defined seeded field)
- The instability is seeded via half-cut beam (beam density abruptly increases)

For SPS half-cut beam, at plasma density \( n_p = 10^{14} \text{ cm}^{-3} \) (\( \lambda_p \approx 3.33 \text{ mm} \))
A strong beam density modulation is observed,
A nice wakefield structure is excited and
the wakefield amplitude is around 100 MV/m at 5 m plasma.

VLPL results from A. Pukhov
Simulations of SPS beam-driven PWFA

Beam density modulation

QuickPIC results

Half-cut SPS beam @ 4.8 m plasma ($n_p = 10^{14}$ cm$^{-3}$)

Full SPS beam @ 10 m plasma ($n_p = 10^{14}$ cm$^{-3}$)

Maximum longitudinal e field is ~120 MV/m

Simulations of SPS beam-driven PWFA

Simulation from 2D OSIRIS

nominal SPS beam

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch population, $N_p$</td>
<td>$1.15 \times 10^{11}$</td>
</tr>
<tr>
<td>Bunch length, $\sigma_z$</td>
<td>12 cm</td>
</tr>
<tr>
<td>Beam radius, $\sigma_{x,y}$</td>
<td>200 $\mu$m</td>
</tr>
<tr>
<td>Beam energy, $E$</td>
<td>450 GeV</td>
</tr>
<tr>
<td>Energy spread, $dE/E$</td>
<td>0.03%</td>
</tr>
<tr>
<td>Normalized emittance, $\varepsilon_{x,y}$</td>
<td>3 $\mu$m</td>
</tr>
<tr>
<td>Angular spread, $\sigma_\theta$</td>
<td>0.02 mrad</td>
</tr>
</tbody>
</table>

Electron acceleration

$\rho_n = 1 \times 10^{14} \text{ cm}^{-3}$

$\rho_n = 7 \times 10^{14} \text{ cm}^{-3}$

VLPL3D hydro-dynamic code (A. Pukhov)

10 MeV continuous e- beam to sample the wakefield
### Electron acceleration

- **Plasma density in use:** $7 \times 10^{14} \text{ cm}^{-3}$

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy [GeV]</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>Bunch population [$10^{11}$]</td>
<td>1.15</td>
<td>3.0</td>
</tr>
<tr>
<td>Beam radius [$\mu$m]</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Angular spread [mrad]</td>
<td>0.04</td>
<td>0.04</td>
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<tr>
<td>Normalized emittance [$\mu$m]</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Bunch length [cm]</td>
<td>12</td>
<td>12.4</td>
</tr>
<tr>
<td>Energy spread [%]</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>
**Demonstration experiment at CERN**

**Scientific Goal of Experiments:**
- Initial goal is to observe the energy gain of 1 GeV in 10 m plasma.
- A plan for reaching 100 GeV within 100 m plasma will be developed based on the initial round of experiments.
- The very high energy electron beam achieved by using the LHC-like high energy beam.

**Experimental Setup:**

Expected Results:
- A long SPS drive beam (without compression) will be used in the first experiment. A self-modulation of the beam due to two-stream instability which produces many ultrashort beam slices at plasma.
- The modulation resonantly drives wakefield in the 200-500 MV/m with CERN SPS beam.
- Simulation shows with the optimum beam and plasma parameters, ≥ 1 GV/m field can be achieved in the experiment.
Demonstration experiment at CERN

- PD-PWFA has the potential to accelerate electron beam to the TeV scale in a single stage. As a first step, we would like to demonstrate the scaling laws of PD-PWFA in an experiment with an existing beam
- kick-off meeting-PPA09 held at CERN in December 2009
- A spare SPS tunnel is available for demonstration experiment
- With no bunch compression in the beginning

http://indico.cern.ch/conferenceDisplay.py?confId=74552
http://cerncourier.com/cws/article/cern/41714

G. Xia et al, Proceedings of PAC11 (TUOBN5), New York, 2011
CERN’s interest

PDPWFA collaboration:
• Several workshops, biweekly phone meeting, and site visit at CERN, strong collaboration team.
• Submitted the LoI in June to CERN
• Proposal defense at 102 SPSC meeting on June 28, 2011

Steve Myers
CERN Director of Accelerators & Technology

"CERN is very interested in following and participating in novel acceleration techniques, and has as a first step agreed to make protons available for the study of proton-driven plasma wakefield acceleration."
AWAKE

• **Advanced Proton Driven Plasma Wakefield Acceleration Experiment**
  – Final Goal: Design high quality & high energy electron accelerator based on acquired knowledge.

• **Proof-of-Principle Accelerator R&D experiment at CERN**
  – First proton driven wakefield experiment worldwide
  – Study the Self-Modulation Instability
  – Demonstration of high-gradient acceleration of electrons
  – Approved in 2013
  – First beam expected in 2016

• **AWAKE Collaboration: 16 Institutes world-wide**
  – Spokesperson: Allen Caldwell, MPI Munich
  – Deputy Spokesperson: Matthew Wing, UCL
  – Physics and Experiment Coordinator: Patric Muggli, MPI Munich
  – Simulation Coordinator: Konstantin Lotov, BINP
  – Technical Coordinator and CERN AWAKE Project Leader: Edda Gschwendtner, CERN
  – Deputy: Chiara Bracco, CERN
In 2011:

- $5.3 \times 10^{16}$ protons to LHC
- $1.37 \times 10^{20}$ protons to CERN's Non-LHC Experiments and Test Facilities
Drive Beam: which proton energy?

Variation of driver energy at constant normalized emittance

SPS-AWAKE parameters

K. Lotov et al., Physics of Plasma, 21, 083107 (2011)
AWAKE will be installed in the CNGS, CERN Neutrinos to Gran Sasso, experimental facility. CNGS physics program finished in 2012.

Proton beam for AWAKE requires:
- High charge
- Short bunch length
- Small emittance
Drive Beam: proton beam sensitivity

Proton beam population

- The baseline regime is close to the limit (~40% of wave-breaking field)
- Further increase of population does not result in proportional field growth.

Proton beam radius

- Wide beams are not dense enough to drive the wave to the limiting field.
- Narrow beams are quickly diverging due to the transverse emittance.

Baseline radius is the optimum one for this emittance.

K. Lotov et al., Physics of Plasma, 21, 083107 (2014)
# Proton Beam Specifications

<table>
<thead>
<tr>
<th>Nominal SPS Proton Beam Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Momentum</strong></td>
</tr>
<tr>
<td>400 GeV/c</td>
</tr>
<tr>
<td><strong>Protons/bunch</strong></td>
</tr>
<tr>
<td>$3 \times 10^{11}$</td>
</tr>
<tr>
<td><strong>Bunch length</strong></td>
</tr>
<tr>
<td>$\sigma_z = 0.4$ ns (12 cm)</td>
</tr>
<tr>
<td><strong>Bunch size at plasma entrance</strong></td>
</tr>
<tr>
<td>$\sigma_{x,y}^* = 200$ μm</td>
</tr>
<tr>
<td><strong>Normalized emittance (r.m.s.)</strong></td>
</tr>
<tr>
<td>3.5 mm mrad</td>
</tr>
<tr>
<td><strong>Relative energy spread</strong></td>
</tr>
<tr>
<td>$\Delta p/p = 0.35%$</td>
</tr>
</tbody>
</table>

Long proton beam $\sigma_z = 12$ cm! ↔ Compare with plasma wavelength of $\lambda = 1$ mm. ➔ Experiment based on Self-Modulation Instability!

**Self-modulation instability of the proton beam:** modulation of a long (SPS) beam in a series of ‘micro-bunches’ with a spacing of the plasma wavelength.
Plasma Source: Requirements

- Reach a strong wakefield
  - $E_z \propto (n_e)^{-1/2}$

- Seeding of the SMI is necessary
  - Seeding shortens the length in the plasma
    $\rightarrow$ until the SMI reaches saturation.
  - Fixes the phase of the wakefields
    $\rightarrow$ deterministically inject the witness electron beam.

  → Seeding

- Witness beam: very sensitive to the wakefield phase.
  - If $\lambda_p$ changes locally, the witness electrons will be defocussed
    $\rightarrow$ Wakefield phase is determined by the plasma density:
    $\rightarrow$ Density must be constant with an accuracy of $\lambda_{pe}/4\sigma_z$
    $\rightarrow$ $\Delta n/n \leq 0.002$
Plasma Sources: different types

- Metal Vapor Source (Li, Cs, Rb) → SLAC experiments
  - Very uniform, very well known
  - Ionization with laser. Scaling to long lengths?

- Discharge plasma source
  - Simple, scalable
  - Uniformity? Density?

- Helicon source
  - Scalable, density recently achieved.
  - Uniformity?
Various sources

Maximum wakefield amplitude vs ion mass

Rubidium is heavy enough to have no problems with ion motion
Rubidium Vapor Source

• Density adjustable from $10^{14} - 10^{15} \text{ cm}^{-3}$
• 10 m long, 4 cm diameter

• Plasma formed by field ionization of Rb
  – Ionization potential $\phi_{\text{Rb}} = 4.177 \text{ eV}$
  – above intensity threshold ($I_{\text{ioniz}} = 1.7 \times 10^{12} \text{ W/cm}^2$) 100% is ionized.

• Plasma density = vapor density

• System is oil-heated: 150° to 200
  → keep temperature uniformity
  → Keep density uniformity

Required:
$\Delta n/n = \Delta T/T \leq 0.002$
Plasma Source: Rubidium Vapor

3m prototype at MPI Munich

- Fast valves at both ends
  - Separation of plasma from SPS beam vacuum.
  - Must be opened when laser/electron/proton passes through.

Ultra-fast (15 ms) valves
> 40,000 cycles!
Plasma Source

• Rubidium Vapor Source is used
  – Ionization with laser beam

• Density uniformity of 0.2% required

• Seeding of SMI is needed in the plasma cell
  – Use laser beam for seeding
Laser Beam

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

<table>
<thead>
<tr>
<th>Laser Beam</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser type</td>
</tr>
<tr>
<td>Pulse wavelength</td>
</tr>
<tr>
<td>Pulse length</td>
</tr>
<tr>
<td>Pulse energy (after compr.)</td>
</tr>
<tr>
<td>Laser power</td>
</tr>
<tr>
<td>Focused laser size</td>
</tr>
<tr>
<td>Rayleigh length ( Z_R )</td>
</tr>
<tr>
<td>Energy stability</td>
</tr>
<tr>
<td>Repetition rate</td>
</tr>
</tbody>
</table>

- **Summary:** ➔ 4.5 TW Laser for ionization and seeding
Proton Bunch Modulation

Self-Modulation Instability (SMI):
- Laser beam co-moving within the proton bunch effectively seeds the SMI
  - Laser pulse creates the ionization front
  - Ionization front acts as if long proton bunch is sharply cut
  - Laser pulse excites wakes to directly seed the self-modulation instability
  - grows exponentially until fully modulated and saturated.

Self-modulated proton bunch resonantly driving plasma wakefields.
AWAKE: 1st Experimental Phase

- Perform benchmark experiments using proton bunches to drive wakefields for the first time ever.
- Understand the physics of self-modulation instability processes in plasma.

Self-modulated proton bunch resonantly driving plasma wakefields.
Drive Beam Diagnostics

Direct Measurement of self-modulation instability of the proton beam

- results in radial modulation of the proton beam (micro-bunches)
  - Measured by using the radiation emitted by the bunch when traversing a dielectric interface or by directly sampling the bunch space charge field. → streak-camera.

Indirect Measurement by observing the proton bunch defocusing downstream the plasma

- Proton bunch: 1mrad divergence
Witness Beam

Externally injected electron beam

→ Which energy?

Area (grey) where wakefields are both accelerating and focusing for the witness electrons

→ Electrons must be trapped in the accelerating/focusing wakefield

SMI: grows in the first ~4 m and is then fully developed.

– Wakefield phase velocity is slower than that of the drive beam.
– Approaches light velocity at z ~4m.
Witness Beam

→ Optimal electron energy is 10-20 MeV
  – Electron energy = wakefield phase velocity at self-modulation stage.

→ Electron bunch length:
  – Should be small to be in phase with high field region.

→ Electron beam should have small enough size and angular divergence to fit into high capture efficiency region.

→ Electron beam intensity: get good signal in diagnostics!

<table>
<thead>
<tr>
<th>Electron beam</th>
<th>Baseline</th>
<th>Range for upgrade phase</th>
</tr>
</thead>
<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=$4ps (1.2mm)</td>
<td>0.3 – 10 ps</td>
</tr>
<tr>
<td>Bunch size at focus</td>
<td>$\sigma_{xy}^*= 250 \mu m$</td>
<td>0.25 – 1mm</td>
</tr>
<tr>
<td>Normalized emittance (r.m.s.)</td>
<td>2 mm mrad</td>
<td>0.5 – 5 mm mrad</td>
</tr>
<tr>
<td>Relative energy spread</td>
<td>$\Delta p/p = 0.5%$</td>
<td>&lt;0.5%</td>
</tr>
</tbody>
</table>
Electrons are trapped from the very beginning by the wakefield.

- Trapped electrons make several synchrotron oscillations in their potential wells.
- After \( z=4 \) m the wakefield moves forward in the light velocity frame.

K. Lotov, LCODE
Electron Source

PHIN Photo-injector for CTF3/CLIC:
- Charge/bunch: 2.3 nC
- Bunch length: 10 ps
- 1800 bunches/train, 1.2 μs train-length
→ Program will stop end 2015

→ Fits to requirements of AWAKE
→ Photo-injector laser derived from low power level of plasma ionization laser system.

Laser beam for electron source

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser type</td>
<td>Ti:Sapphire Centaurus</td>
</tr>
<tr>
<td>Pulse wavelength</td>
<td>$\lambda_0 = 260 \text{ nm}$</td>
</tr>
<tr>
<td>Pulse length</td>
<td>10 ps</td>
</tr>
<tr>
<td>Pulse energy (after compr.)</td>
<td>500 μJ</td>
</tr>
<tr>
<td>Electron source cathode</td>
<td>Copper</td>
</tr>
<tr>
<td>Quantum efficiency</td>
<td>3.00 E-5</td>
</tr>
<tr>
<td>Energy stability</td>
<td>±2.5% r.m.s.</td>
</tr>
</tbody>
</table>

In the diagram:
- Klystron from CTF3
- e-beam diagnostics
- 1m booster linac (Cockcroft)
- Incident, Reflected Power and phase
- Laser + Diagnostics
- Incident, Reflected, transmitted Power
- Spectrometer $E$, $\Delta E$
- Length ~ 4 m

11/05/2015 Cockcroft Institute Lecture
Witness Beam Acceleration

Probe the accelerating wakefields with externally injected electrons

- Electron spectrometer
  - Measure **peak energy and energy spread** of electrons.
  - Spectrometer magnet separates electrons from proton beam-line.

Magnet: 15 ton, 1.84 T, 3.80 Tm, L=1670 mm, W=1740 mm

Dispersed electron impact on scintillator screen. Resulting light collected with intensified CCD camera.
Witness Beam and Diagnostics

• Externally injected electrons

• Electron energy: 10 – 20 MeV

• Energy and number of accelerated electrons depend on injection delay into wakefield

• Use the Photo-injector PHIN from CLIC

• Photo injector laser derived from low power level of the plasma source ionizing system.

• Electron spectrometer is used to probe the accelerating wakefields.
AWAKE: 2nd Experimental Phase

Probe the accelerating wakefields with externally injected electrons, including energy spectrum measurements for different injection and plasma parameters.

- Trapping efficiency: 10 – 15 %
- Average energy gain: 1.3 GeV
- Energy spread: ± 0.4 GeV
- Angular spread up to ± 4 mrad
• **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 ($\sim$ 300fs) $\rightarrow$ bunch compression $\rightarrow$ Almost 100% capture efficiency

![Diagram of plasma system with labels for laser, electron gun, and diagnostic elements.](image)

- **Plasma density profile**
- **Maximum wakefield amplitude**

11/05/2015 Cockcroft Institute Lecture
AWAKE at CERN
AWAKE at CERN

AWAKE experiment

CERN NEUTRINOS TO GRAN SASSO
Underground structures at CERN

AWAKE

protons

SPS

TCV4 sump 30 m³

TSG4 sump 30 m³

TNM41 sump 8 m³

TZ sump 8 m³

TNM42 sump 8 m³

11/05/2015 Cockcroft Institute Lecture

SPS/ECA4

140m

LEP/LHC tunnel

LHC/T1B tunnel

Target chamber

Service gallery

Access galleries

Access shaft

55m

protons

Target chamber

Connection gallery to T1B/LHC

Decay tunnel

~1100m

dump

Hadron stop and first muon detector

muons neutrinos

Second muon detector

neutrinos to Gran Sasso

11/05/2015 Cockcroft Institute Lecture
AWAKE Experimental Facility at CERN
Proton Beam Line

Change of the proton beam line only in the **downstream part** (~80m)

→ **Displace existing magnets** of the final focusing to fulfill optics requirements at plasma cell

**CNGS Layout**

**AWAKE Layout**

→ **Move existing dipole and 4 additional dipoles** to create a **chicane for the laser mirror** integration.

Laser-proton merging 20m upstream the plasma cell

11/05/2015
Cockcroft Institute Lecture
Laser System

New tunnel

**Ti: Sapphire laser system:**
- Laser with 2 beams (for plasma and e-gun)
- Delay line in either one of both beams
- Focusing telescope (lenses, in air) before compressor
- 35 meter focusing
- Optical compressor (in vacuum)
- Optical in-air compressor and 3rd harmonics generator for electron gun

Complete UHV vacuum system up to $10^{-7}$ mbar starting from optical compressor
Electron Beam Line

- Completely new beam line and tunnel:
  - Horizontal angle of 60 deg,
  - 20% slope of the electron tunnel \(\rightarrow\) 1m level difference
  - 7.2% slope of the plasma cell
  - \(\sim\)5 m common beam line between electron and proton
- Common diagnostics for proton (high intensity, 3E11 p) and electron beam (low intensity, 1.2E9 e)
- Flexible electron beam optics: focal point can be varied by up to 6 m inside the plasma cell
Electron Beam Line

Excavation June – October 2014
Electron Beam Line
Proton/Electron/Laser Synchronization

- **Synchronization between proton beam and laser pulse:** ~ 100 ps (cf. proton bunch length 1\(\sigma\)~400ps).
  - SPS beam must synchronize to the AWAKE reference just before extraction.

- **Synchronization between electron beam and laser pulse:** ~ 100 fs (cf. plasma period ~4ps)
  - For deterministic injection of e- bunch into plasma wakefields
  - Achieved by driving the RF-gun of the electron source with a laser pulse derived from same laser system as used for plasma ionization.

- Exchange of synchronization signals on ~3 km long fibres between the AWAKE facility and SPS RF Faraday Cage in the control room
2016 Phase 1: Self-Modulation Instability physics
2017-18 Phase 2: Electron acceleration physics

<table>
<thead>
<tr>
<th>Run-scenario</th>
<th>Nominal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of run-periods/year</td>
<td>4</td>
</tr>
<tr>
<td>Length of run-period</td>
<td>2 weeks</td>
</tr>
<tr>
<td>Total number of beam shots/year (100% efficiency)</td>
<td>162000</td>
</tr>
<tr>
<td>Total number of protons/year</td>
<td>$4.86 \times 10^{16}$ p</td>
</tr>
<tr>
<td>Initial experimental program</td>
<td>3 – 4 years</td>
</tr>
</tbody>
</table>
Collider based on proton driven PWFA

Concept for high repetition rate of proton driven plasma wakefield acceleration

3 ring + injectors + recovery

V. Yakimenko, BNL, T. Katsouleas, Duke, LAPW09
Luminosity

\[ L = f \frac{N_1 N_2}{4\pi \sigma_x \sigma_y} \quad \text{Gaussian shaped beams} \]

suppose \( N_1 = N_2 = 10^{11} \)

SPS cycle time 22s 288 bunches
so assume \( f = 15 \text{ Hz} \)

\[ L \approx \left( \frac{1 \mu m^2}{\sigma_x \sigma_y} \right) 10^{30} \text{ cm}^{-2} \text{ s}^{-1} \]

IP beam sizes: 60 nm (horizontal) and 0.7 nm (vertical)

\[ L = 5 \times 10^{32} \text{ cm}^{-2} \text{s}^{-1} \]
Phase slippage

Phase slippage because protons heavy (move more slowly than electrons)

\[
\delta = \frac{\pi L}{\lambda_p} \left[ \frac{1}{\gamma_{1i} \gamma_{1f}} - \frac{1}{\gamma_{2i} \gamma_{2f}} \right] \approx \frac{\pi L}{\lambda_p} \left[ \frac{M_p^2 c^4}{E_{\text{driver},i} E_{\text{driver},f}} \right]
\]

\[
L \leq \frac{1}{2} \left[ \frac{E_{\text{driver},i} E_{\text{driver},f}}{M_p^2 c^4} \right] \lambda_p \approx 300 \text{ m for } E_{\text{driver},i} = 1\text{TeV}, E_{\text{driver},f} = 0.5\text{TeV}, \lambda = 1\text{mm}
\]

Few hundred meters possible but depends on plasma wavelength
Plasma density variation

~ 900 MV/m field propagates stably for 200 m!

Increasing the plasma density properly at the moment of developed instability, the wave shift with respect to the main body of the beam will be stopped and one can obtain a stable bunch train that propagates in plasma for a long distance.

(K. Lotov)
Bunch rotation in the SPS

\[ \text{turn}=0 \quad \text{turn}=90 \quad \text{turn}=162 \]

\[ I (\text{A}) \]

\[ E (\text{GeV}) \]

\[ s (\text{cm}) \]

Bucket

11/05/2015

Cockcroft Institute Lecture
200 MHz RF system in the SPS:

- 4 Travelling Wave cavities:
  - 2 cavities of 5 sections
  - 2 cavities of 4 sections
  - 11 cells/section
  - 2(3) spare sections

- Power/cavity:
  - 700 kW for full ring (FT/CNGS beams) - continuous mode
  - 1.05 MW for half ring (LHC-type beams) - pulsed mode (after some upgrade)

- Voltage:
  - maximum used 8.0 MV

RF-structure quality factor $Q = 200$, filling time $= 600$ ns
(1 beam turn in SPS takes 23 $\mu$s)

Barrier bucket experiments in SPS:

From presentation by E. Shaposhnikova et. al.: https://espace.cern.ch/be-dep/IPAC%20posters/MOPC058.pdf
In order to suppress multibunch instabilities longitudinal emittance in the SPS is blown up by a factor of 2. In the single bunch mode the longitudinal emittance blow-up can be switched off.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>SPS–LHC</th>
<th>SPS–optimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (GeV)</td>
<td>450</td>
<td>450</td>
</tr>
<tr>
<td>Bunch population ($10^{11}$)</td>
<td>1.15</td>
<td>3.0</td>
</tr>
<tr>
<td>Beam radius ($\mu$m)</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>Angular spread (mrad)</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Normalized emittance ($\mu$m)</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Bunch length (cm)</td>
<td>12</td>
<td>12.4</td>
</tr>
<tr>
<td>Energy spread (%)</td>
<td>0.03</td>
<td>0.03</td>
</tr>
</tbody>
</table>
Multi-TeV lepton collider at LHC

(K. Lotov)
A proposed demonstration of an experiment of proton-driven plasma wakefield acceleration based on CERN SPS

G. XIA\textsuperscript{1}, R. ASSMANN\textsuperscript{2}, R. A. FONSECA\textsuperscript{3}, C. HUANG\textsuperscript{4}, W. MORI\textsuperscript{5}, L. O. SILVA\textsuperscript{3}, J. VIEIRA\textsuperscript{3}, F. ZIMMERMANN\textsuperscript{2} and P. MUGGLI\textsuperscript{1}

for the PPWFA Collaboration

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\textsuperscript{2}CERN, Geneva, Switzerland
\textsuperscript{3}GoLP/Instituto de Plasmas e Fusao Nuclear-Laboratório Associado, IST, Lisboa, Portugal
\textsuperscript{4}Los Alamos National Laboratory, Los Alamos, NM, USA
\textsuperscript{5}University of California, Los Angeles, CA, USA

(Received 20 September 2011; accepted 2 January 2012)
UK’s contribution to AWAKE

• Energy spectrometer
• Electron injector
• Discharge plasma source
• Others,
  – plasma simulation, collider design based on proton driven PWFA, radiation calculation, diagnostics, etc.
Energy spectrometer

Wide range of energy acceptance from tens of MeV to more than 2 GeV
Electron injector

Table 1: Specifications for the simulation studies.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>Range of interest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam energy (MeV)</td>
<td>16</td>
<td>10-20</td>
</tr>
<tr>
<td>Energy spread (σ, %)</td>
<td>0.5</td>
<td>-</td>
</tr>
<tr>
<td>Bunch length, (σ, ps)</td>
<td>4</td>
<td>0.3-10</td>
</tr>
<tr>
<td>Beam focus size, (σ, μm)</td>
<td>250</td>
<td>250-1000</td>
</tr>
<tr>
<td>Norm. emittance (rms, mm-mrad)</td>
<td>2</td>
<td>0.5-5</td>
</tr>
<tr>
<td>Bunch charge, (nC)</td>
<td>0.2</td>
<td>0.1-1</td>
</tr>
</tbody>
</table>

Specifications for AWAKE e⁻ beam.
Discharge plasma source
Future collider based on PDPWA

- A self-consistent e⁻ e⁺ collider (multi-TeV CoM energy) or an e⁻ p⁺ collider (> 2 TeV CoM) have been designed based on existing CERN infrastructure;
- The key issues for collider design have been studied (e.g. positron acceleration, efficiency, CoM energy, luminosity, dephasing, plasma channel, efficiency, etc.).
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.
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

^a 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

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.

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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 in the end of 2016.

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

The AWAKE experiment at CERN will shed light on a future compact Higgs factory or next generation energy frontier collider design.

UK is the strong partner to the AWAKE project and give key contributions to the experiment, e.g. the discharge plasma source, diagnostics, simulations, electron injector, energy spectrometer, etc.

The collaborated institutes include: CI, UCL, IC, RAL, JAI, Strathclyde University, etc.
**Phase slippage**

- Due to the heavy mass of proton, the relativistic factor $\gamma$ of a TeV proton beam is smaller than that of an electron beam with energy of 1 GeV. Therefore the electrons may overrun the wakefield (the group velocity of the wakefield is the same as the velocity of the driver) and the acceleration process will cease.

\[
\frac{d(\gamma_i m_i c^2)}{dt} = -q E_{\text{dec}} v_i \\
\frac{d(\gamma_e m_e c^2)}{dt} = e E_{\text{acc}} v_e \\
\Delta d = \int_0^T (v_e - v_i) dt = \frac{m_e c^2}{e} \left[ \frac{\gamma_e - \gamma_{e 0}}{E_{\text{acc}}} + \frac{m_i}{m_e q} \frac{\gamma_i - \gamma_{i 0}}{E_{\text{dec}}} \right]
\]

\[
\frac{d(\gamma_i m_i v_i)}{dt} = -q E_{\text{dec}} \\
\frac{d(\gamma_e m_e v_e)}{dt} = q E_{\text{acc}} \\
\Delta d = \frac{m_e c^2}{e E_{\text{acc}}} (\gamma_e - \gamma_{e 0}) \left[ 1 - \frac{(\sqrt{\gamma_e^2 - 1} - \sqrt{\gamma_{e 0}^2 - 1})(\gamma_i - \gamma_{i 0})}{(\sqrt{\gamma_i^2 - 1} - \sqrt{\gamma_{i 0}^2 - 1})(\gamma_e - \gamma_{e 0})} \right] \\
\text{For } \gamma_e >> \gamma_i \quad \Delta d \approx \frac{m_e c^2}{e E_{\text{acc}}} (\gamma_e - \gamma_{e 0}) \left[ 1 - \frac{(\gamma_i - \gamma_{i 0})}{(\sqrt{\gamma_i^2 - 1} - \sqrt{\gamma_{i 0}^2 - 1})} \right]
\]

G. Xia et al., IPAC11 (WEPZ024)
Phase slippage

\[ \delta = k_p \Delta d = \frac{1}{eE_{ac}/m/ec_\omega_p} (\gamma_e - \gamma_{e0}) \left[ 1 - \frac{(\gamma_i - \gamma_{i0})}{(\sqrt{\gamma^2_i - 1} - \sqrt{\gamma^2_{i0} - 1})} \right] \]

For a single stage PDPWA with a 1 TeV proton drive beam that accelerates electrons to 500 GeV energy (assuming electron injection energy far less than 500 GeV), \( \gamma_{i0} = 1000 \), \( \gamma_e - \gamma_{e0} \approx 10^6 \). If we assume that the wakefield amplitude is \( eE_{ac}/m_ec_\omega_p \sim 1 \), then the phase slippage is \( k_p \Delta d = 10^6 \left[ 1 - (\gamma_i - 1000)/\left(\sqrt{\gamma^2_i - 1} - \sqrt{1000^2 - 1}\right) \right] \), which has to be smaller than \( \pi \). Fig.1 shows the phase slippage as a function of the final energy of the proton for a 1 TeV drive beam. It can be seen that the final energy of a 1 TeV proton beam has to be larger that 160 GeV in order to satisfy the phase slippage requirement. Using the average accelerating (decelerating) field of \( \sim 1.4 \text{ GV/m} \), the maximum dephasing length is about 600 m. And the transformer ratio of such a single stage PDPWA is about 0.6. This provides the basic parameter to design such an acceleration stage.

G. Xia et al., IPAC11 (WEPZ024)
Plasma cells

Discharge: IST, Imperial College

Metal vapor, a la SLAC experiment:
UCLA, Max Planck Institute for Physics

Helicon – Max Planck Institute for Plasma Physics
Plasma cells

Helicon cell prototype – Greifswald (Olaf Grülke)

Nelson’s discharge cell @ MPP

Heat pipe oven concept + vapor cell
E. Öz, P. Muggli
Status and outlook

- AWAKE experiment will be the first proton-driven plasma wakefield accelerator worldwide.
- Simulation shows that working in self-modulation regime, SPS beam can excite the field around ~ 1 GV/m with a high density plasma.
- Future experiment will be carried out based upon the first round experiments for even higher energy electron beam acceleration.
- AWAKE experiment will give input to the future design for a compact, more affordable, multi-TeV lepton collider.
Thanks to Edda for many nice pictures!

Thanks for your attention!