VHEeP (and PEPIC)
very high energy eP and eA colliders

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DIS2018 Workshop
Kobe, Japan
Novel accelerators based on plasma wakefields, dielectric structures or direct laser acceleration will bring new scientific opportunities.

With AWAKE and proton-driven wakefield acceleration, we aim to use existing infrastructure for the wakefield driver to accelerate electrons to high energy. We want to develop the program of particle physics applications in parallel.

First ideas:

➢ Fixed target experiments
➢ Low luminosity eP/eA using SPS driver : PEPIC
➢ Low luminosity eP/eA using LHC driver : VHEeP
➢ For-purpose built proton driver
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:
PW lasers today, ~40 J/Pulse
FACET (e beam, SLAC), 30J/bunch
SPS@CERN 20kJ/bunch
LHC@CERN 300 kJ/bunch

Witness:
$10^{10}$ particles @ 1 TeV ≈ few kJ

Energy content of driver allows to consider single stage acceleration. Need short drivers to create strong wakefields.

Seeded self-modulation

Short high energy bunches do not exist. But, a self-modulation can be seeded by a sharp start of the beam (or beam-plasma interaction).

The ‘microbunches’ then drive strong wakes.

A. Petrenko, CERN
AWAKE Result - 2017

Streak camera Images

Laser Off/no plasma (5 sets, 2 events, saturated)

Front

Defocused p⁺ ~σ_z/c ~200ps

Streak camera Images

“Ionizing” Laser Pulse Marker Laser Pulse Marker Laser Pulse Marker Laser Pulse Marker Laser Pulse

50ps 50ps 50ps 50ps 50ps

Front

~σ_z
AWAKE Experimental Program

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

Program for 2018

Demonstrate GeV scale gradients with proton driven wakefields.

Maximum amplitude of the **accelerating field** $E_z$ as a function of position along the plasma. Saturation of the SMI at $\sim$4m.
Run II (2021-2024)

**Goals:**
- Stable acceleration of bunch of electrons with high gradients over long distances
- Good electron bunch emittance at plasma exit

**Require:**
- Compressed proton beam in SPS
- Possibly short electron bunch with higher energy for loading wakefield
- Density step in plasma for freezing modulation
- Alternative plasma cell developments

O. Grülke, IPP
O. Schmitz, Wisconsin
Started considering:

- **Physics with a high energy electron beam**
  - E.g., search for dark photons

- **Physics with an electron-proton or electron-ion collider**
  - Low luminosity version of LHeC
  - Very high energy electron-proton, electron-ion collider

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**Are there fundamental particle physics topics for high energy but low luminosity colliders?**

I believe – yes! Particle physicists will be interested in going to much higher energies, even if the luminosity is low.

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In general – start investigating the particle physics potential of an AWAKE-like acceleration scheme.
QCD at high energies

With VHEeP - clearly enter into a new regime that will allow to study and understand the high energy behavior of cross sections. This is fundamental physics, which today lacks understanding. Different targets can be probed (eA as well as eP).

Workshop: June 1-2, 2017 at the Max Planck Institute for Physics (titles paraphrased)

A. Mueller  eA physics and nonlinear effects in parton densities
G. Dvali  Classicalization and energy dependence of cross sections
J. Erdmenger  Applying AdS/CFT to very low-x physics
A. Stasto  low-x physics and high-energy neutrino physics
L. Stodolsky  Formation-zone physics
J. Bartels  HERA lessons and perspectives for small-x physics
H. Kowalski  BFKL and dipoles
D. Schildknecht  Color dipoles at small-x
H. Mantysaari  eA physics at very high energies
E. Aschenauer  Polarized eP and eA physics
V. Myronenko  What we know from HERA
F. Keeble  VHEeP kinematics study
S. Plaetzer  Physics simulators for very high energy eP and eA
VHEeP
Munich Workshop, June 1-2, 2017

Alfred Mueller, Columbia University
Approach to saturation in eA collisions

Georgi Dvali, Max Planck Institute for Physics
Alternative high energy theory - classicalization
PEPIC: SPS Driver

Focus on QCD:

- Large cross sections – low luminosity (HERA level) enough
- Many open physics questions!
- Consider high energy ep collider with E_e up to O(100 GeV), colliding with LHC proton; e.g. E_e = 10 GeV, E_p = 7 TeV, √s = 530 GeV already exceeds HERA cm energy.

Create ~70 GeV beam within 100 m of plasma driven by SPS protons and have an LHeC-type experiment.

Clear difference is that luminosity currently expected to be < 10^{30} cm^{-2} s^{-1}.

VHEeP
(Very High Energy electron-Proton collider)

One proton beam used for electron acceleration to then collide with one bunch from other proton beam.

Luminosity $\sim 10^{28} - 10^{29}$ cm$^{-2}$ s$^{-1}$ gives $\sim 1$ pb$^{-1}$ per year.

Electron energy from wakefield acceleration by LHC bunch

Choose $E_e = 3$ TeV as a baseline for a new collider with $E_p = 7$ TeV yields $\sqrt{s} = 9$ TeV. Can vary.
- Center-of-mass energy $\sim 30$ higher than HERA.
- Reach in (high) $Q^2$ and (low) Bjorken $x$ extended by $\sim 1000$ compared to HERA.
- Opens new physics perspectives


Total Photon-Proton Cross Section

- Data
- \(\ln^2(W^2)\) Regge fits:
  - DL 1992
  - DL 2004

- VHEeP reach

Huge cross section - no statistical uncertainty even at \(10^{28}\) cm\(^{-2}\)s\(^{-1}\)

Rises - as power of energy, or \(\ln^2s\) (Unitarity Constraint)? Why?
High energy behavior needed to understand cosmic ray interactions
Vector Meson Cross Section

\[ \sigma(\gamma p \rightarrow V p) \text{ (nb)} \]

Photon-proton centre-of-mass energy, \( W \) (GeV)

\[ \sigma_{\text{tot}} \]

\[ \phi \]

\[ \Omega \]

\[ \psi(2S) \]

\[ J/\psi \]

\[ Y(1S) \]

VHEeP reach

H1/ZEUS

fixed target

ALICE/LHCb

VHEeP, \( \sqrt{s} \)

VHEeP W range

\[ \sigma(\gamma p \rightarrow J/\psi p) \approx \sigma(\gamma p \rightarrow \rho p) \]

Expect to see change in energy dependence
Cross sections increasing with energy -> do not require large luminosity to probe this physics. PEPIC & VHEeP will distinguish the important physics.
Leptoquarks are predicted in many models for Beyond-the-Standard-Model physics. Electron-proton colliders are the ideal tool to look for this kind of process.

Fixed mass of LQ means fixed $x$.

$$\sigma_{LQ}^{NWA} = (J + 1) \frac{\pi}{4s} \lambda^2 q(x_0, M_{LQ}^2)$$

Sensitivity depends mostly on CM energy.
At the LHC

Figure 1: The s-channel resonant LQ production diagram.

Figure 2: The t-channel LQ production diagrams with non-resonant components. The diagram
VHEeP Study

100 pb\(^{-1}\)

Require \(Q^2 > 10000 \text{ GeV}^2\) and \(y > 0.1\)

Use Standard Model prediction (no LQ)

Sensitivity goes far beyond what is expected to be reached at LHC. (Currently \(\sim 1\) TeV, later 2–3 TeV)
There are detector challenges!

Very forward electron detector required.  

F. Keeble, UCL
Path Forward (PEPIC&VHEeP)

**Technology**
- demonstrate electron acceleration
- demonstrate required emittance
- plasma cell scheme

**Realization**
- determine luminosity
- determine range of possible electron energies
- understand how to get rid of defocused protons
- understand how to separate protons from electrons
- beam dump
- IP design
- how fit into CERN infrastructure
- detector studies

**Physics**
- total cross sections (real & virtual photon)
- vector meson production
- other aspects of low-x physics (classicalization, AdS/CFT, ???)
- specific eA physics topics
- BSM opportunities (VHEeP)

- anything interesting in the beam dump. E.g.:
  - search for dark photons, like NA64.
  - strong-field QED by colliding electron bunches with laser beam.

Need to push on all aspects in parallel!