Beam Driven Plasma Acceleration
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Egham – September 9th 2017
Conventional RF accelerating structures
Typical breakdown and pulse heating damage is standing-wave structure cell
Performance summary at CLIC specifications

\[ BDR = \frac{E_{\text{surf}}^{30}}{\tau^5} \left( \frac{15}{\omega^2} \right) \]

CLIC BDR Criteria

Unloaded Accelerating Gradient [MV/m]

- T18-CERN-SLAC
- T18-KEK-KEK
- T18-KEK-SLAC
- TD18-KEK-KEK
- TD18-KEK-SLAC
- T24-KEK-KEK
- T24-Tsinghua-KEK
- TD24-KEK-KEK
- TD24r05#4-KEK-KEK
- TD26cc-CERN-CERN

- meas.
- \( E_0 \) scaled to 180 ns
- \( E_0 \) scaled to 180 ns & BDR = 3x10^{-7}

100 MV/m
Future of Accelerators

- **FCC**: Conceptual Design started
- **ILC**: Technical Design exists Waiting funding decision
- **muons**
- **ESS**
- **SwissFEL**
- **LBNL LWFA 2014**

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**Hadron acc. project**

**Lepton acc. project**

**Hadron acc. proposal**

**Lepton acc. proposal**

R. Assmann, EAAC 2015, 9/2015
Laser Electron Accelerator

T. Tajima and J. M. Dawson

*Department of Physics, University of California, Los Angeles, California 90024*

(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density $10^{18}$ W/cm$^2$ shone on plasmas of densities $10^{18}$ cm$^{-3}$ can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulseres are examined.

Acceleration of Electrons by the Interaction of a Bunched Electron Beam with a Plasma

Pisin Chen$^{(a)}$

*Stanford Linear Accelerator Center, Stanford University, Stanford, California 94305*

and

J. M. Dawson, Robert W. Huff, and T. Katsouleas

*Department of Physics, University of California, Los Angeles, California 90024*

(Received 20 December 1984)

A new scheme for accelerating electrons, employing a bunched relativistic electron beam in a cold plasma, is analyzed. We show that energy gradients can exceed 1 GeV/m and that the driven electrons can be accelerated from $\gamma_0 me^2$ to $3\gamma_0 me^2$ before the driving beam slows down enough to degrade the plasma wave. If the driving electrons are removed before they cause the collapse of the plasma wave, energies up to $4\gamma_0 me^2$ are possible. A noncollinear injection scheme is suggested in order that the driving electrons can be removed.
\[ \lambda_p \approx 1 \text{mm} \cdot \sqrt{\frac{10^{15} \text{ cm}^{-3}}{n_0}} \]

\[ \omega_p = \sqrt{\frac{n_0 e^2}{\varepsilon_0 m_e}} \]

0.3 mm for \( n_0 = 10^{16} \text{ cm}^{-3} \)

Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield

S. Corde\textsuperscript{1,2}, E. Adli\textsuperscript{1,3}, J. M. Allen\textsuperscript{1}, W. An\textsuperscript{4,5}, C. I. Clarke\textsuperscript{1}, C. E. Clayton\textsuperscript{4}, J. P. Delahaye\textsuperscript{1}, J. Frederico\textsuperscript{1}, S. Gessner\textsuperscript{1}, S. Z. Green\textsuperscript{1}, M. J. Hogan\textsuperscript{1}, C. Joshi\textsuperscript{4}, N. Lipkowitz\textsuperscript{1}, M. Litos\textsuperscript{1}, W. Lu\textsuperscript{6}, K. A. Marsh\textsuperscript{4}, W. B. Mori\textsuperscript{4,5}, M. Schmelitz\textsuperscript{1}, N. Vafaie-Najafabadi\textsuperscript{4}, D. Walz\textsuperscript{1}, V. Yakimenko\textsuperscript{1} & G. Yocky\textsuperscript{1}
CONCEPTUAL DESIGN OF THE DRIVE BEAM FOR A PWFA-LC*

S. Pei*, M. J. Hogan, T. O. Raubenheimer, A. Seryi, SLAC, CA 94025, U.S.A.
H. H. Braun, R. Corsini, J. P. Delahaye, CERN, Geneva

Fig. 1: Concept for a multi-stage PWFA Linear Collider.
### Table 1: Key Parameters of the Conceptual Multi-Stage PWFA-based Linear Collider

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main beam: bunch population, bunches per train, rate</td>
<td>$1 \times 10^{10}$, 125, 100 Hz</td>
</tr>
<tr>
<td>Total power of two main beams</td>
<td>20 MW</td>
</tr>
<tr>
<td>Drive beam: energy, peak current and active pulse length</td>
<td>25 GeV, 2.3 A, 10 µs</td>
</tr>
<tr>
<td>Average power of the drive beam</td>
<td>58 MW</td>
</tr>
<tr>
<td>Plasma density, accelerating gradient and plasma cell length</td>
<td>$1 \times 10^{17}$ cm$^{-3}$, 25 GV/m, 1 m</td>
</tr>
<tr>
<td>Power transfer efficiency drive beam $\rightarrow$ plasma $\rightarrow$ main beam</td>
<td>35%</td>
</tr>
<tr>
<td>Efficiency: Wall plug $\rightarrow$ RF $\rightarrow$ drive beam</td>
<td>50% $\times$ 90% = 45%</td>
</tr>
<tr>
<td>Overall efficiency and wall plug power for acceleration</td>
<td>15.7%, 127 MW</td>
</tr>
<tr>
<td>Site power estimate (with 40MW for other subsystems)</td>
<td>170 MW</td>
</tr>
<tr>
<td>Main beam emittances, x, y</td>
<td>2, 0.05 mm-mrad</td>
</tr>
<tr>
<td>Main beam sizes at Interaction Point, x, y, z</td>
<td>0.14, 0.0032, 10 µm</td>
</tr>
<tr>
<td>Luminosity</td>
<td>$3.5 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
<tr>
<td>Luminosity in 1% of energy</td>
<td>$1.3 \times 10^{34}$ cm$^{-2}$s$^{-1}$</td>
</tr>
</tbody>
</table>

**Fig. 1:** Concept for a multi-stage PWFA Linear Collider.
Proton-driven Plasma Wakefield Acceleration Collaboration: Accelerating $e^-$ on the wake of a $p^+$ bunch
**WHY p⁺-DRIVEN PWFA?**

- ILC, 0.5TeV bunch with $2 \times 10^{10} e^-$ ~ 1.6kJ
- SLAC, 20GeV bunch with $2 \times 10^{10} e^-$ ~ 60J
- SLAC-like driver for staging (FACET = 1 stage, collider 10+ stages)
- SPS, 400GeV bunch with $10^{11} p^+$ ~ 6.4kJ
- LHC, 7TeV bunch with $10^{11} p^+$ ~ 112kJ
- A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!
- Large average gradient! ($\geq 1$GeV/m, 100's m)
Discharge configuration II

preliminary tests with the AWAKE 3 meter test tube at IC - 2016

very promising results

... reliable, low jitter plasma formation

scalability of electric circuit for plasmas > 10 m seem achievable...
EUROPEAN PLASMA RESEARCH ACCELERATOR WITH EXCELLENCE IN APPLICATIONS

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under grant agreement No 653782.
Motivations

PRESENT EXPERIMENTS

Demonstrating 100 GV/m routinely
Demonstrating GeV electron beams
Demonstrating basic quality

EuPRAXIA INFRASTRUCTURE

Engineering a high quality, compact plasma accelerator
5 GeV electron beam for the 2020’s
Demonstrating user readiness
Pilot users from FEL, HEP, medicine, ...

PRODUCTION FACILITIES

Plasma-based linear collider in 2040’s
Plasma-based FEL in 2030’s
Medical, industrial applications soon

Courtesy R. Assmann
EuPRAXIA Design Study
Approved as HORIZON 2020 INFRADEV, 4 years, 3 M€
Coordinator: Ralph Assmann (DESY)

First idea – very preliminary
PWFA accelerating field

\[ E_z(r, \xi) \approx (\alpha)(k_p^2 \sigma_z) e^{-k_p^2 \sigma_z^2/2} \cos k_p \xi R(r) \]

\[ \alpha = \frac{n_b}{n_0} \]

\[ \sigma_z \approx \frac{\lambda_p}{\pi \sqrt{2}} \]

\[ R(0) = -\left( \frac{k_p^2 \sigma_r^2}{2} \right) \left( e^{k_p^2 \sigma_r^2/2} \right) \Gamma \left( 0, \frac{k_p^2 \sigma_r^2}{2} \right) \]

\[ E_z \propto \frac{n_b}{n_o} \sigma_z \sigma_r^2 \propto Q \]
Regimes: Linear & Non-Linear

FIG. 8. Time-averaged density variation $\delta n / n_0$ (dashed curve) and axial electric field $E_z / E_0$ (solid curve) in an LWFA driven by a Gaussian laser pulse (pulse is moving to the right, centered at $k_p \zeta = 0$ with rms intensity length $L_{rms} = k_p^{-1}$) for (a) $a_0 = 0.5$ and (b) $a_0 = 2.0$. 

Linear

Non-Linear
Breakdown limit?

\[ E_0 = \frac{m_e c \omega_p}{e} \approx 100 \left[ \frac{GeV}{m} \right] \cdot \sqrt{n_0 \left[ 10^{18} \ cm^{-3} \right]} \]
Self-injection
External-injection
Wilson theorem for collinear wake field acceleration

Energy lost by an infinitely short bunch: \( U_d = -q_d^2 w_{//}(0) \)

Energy change of the second bunch \( U_w = -q_w^2 w_{//}(0) + q_d q_w w_{//}(z_w) \)

The sum of the energy exchange by the two bunches must be smaller or equal to zero:

\[
U_d + U_w = -q_d^2 w_{//}(0) - q_w^2 w_{//}(0) + q_d q_w w_{//}(z_w) \leq 0
\]

\[
w_{//}(z_w) \leq \frac{q_d^2 + q_w^2}{q_d q_w} w_{//}(0)
\]

This relation has to be true for all values of charges (the \( w \)-potential doesn’t depend on \( q \)), also when \( q_d = q_w \) which minimize the r.h.s, we obtain:

\[
w_{//}(z_w) \leq 2w_{//}(0)
\]
The transformer ratio $R_T$ is a figure of merit of the accelerating field.

According to previous discussion is defined as the ratio between the peak accelerating field behind drive bunch and the peak decelerating field within drive bunch:

$$R_T = \frac{E_+}{E_-}$$

$R_T \leq 2$
**Fig. 5:** Linear beam loading example: (a) drive bunch density profile (red line) and longitudinal wakefield $E_z$ (green line), (b) same for the witness bunch, (c) same for the drive and witness bunches together. The field of the drive bunch only is shown as the blue line in panel (c). A zoom around the witness bunch is shown in panel (d). The bunches move to the left.
Energy gain and efficiency

Assuming $R_T=2$ and that the Driver will lose all its energy in the plasma, the active length can be defined as:

$$\Delta T_d = eE_- L_{act}$$

$$L_{act} = \frac{\Delta T_d}{eE_-} = \frac{2\Delta T_d}{eE_+}$$

The Witness energy gain is:

$$\Delta T_w = eL_{act} E_+ - eL_{act} E_-$$

Where the second term on the r.h.s is the energy lost in the plasma by the witness itself.

Substituting the definition of $L_{act}$, and using the field scaling $E_z \propto Q$ w.r.t the charge it results:

$$\Delta T_w = 2\left(1 - \frac{E_-}{2E_+}\right)\Delta T = \left(2 - \frac{q_w}{Q_d}\right)\Delta T_d$$

And the efficiency of the process is given by:

$$\eta = \frac{q_w \Delta T_w}{Q_d \Delta T_d} = \left(2 - \frac{q_w}{Q_d}\right)\frac{q_w}{Q_d}$$
\[ \Delta T_w \propto \left(2 - \frac{q}{Q}\right) \Delta T_d \]

- \( q = 30 \text{ pC} \)
- \( Q = 200 \text{ pC} \)
- \( \frac{q}{Q} = 0.15 \)
\[ \eta = \frac{\Delta U_w}{\Delta U_d} = R \left( 1 - \frac{q}{2Q} \right) \frac{q}{Q} \]

In progress at SPARC_LAB
Transformer Ratio: \( R = \frac{E_+}{E_-} \)

Energy Gain: \( \leq RE_0 \)

\[ \alpha_r = 125 \mu m, \ n_e = 1.8 \times 10^{16} \text{ cm}^{-3}, \ \lambda_p = 250 \mu m \]

\( Q = 30 \text{ pC/bunch}, \ \Delta z = 250 \mu m \approx \lambda_p \)

Bunch Train

\[ R = 1.11 \]

\( \Delta z = 375 \mu m \approx 1.5 \lambda_p \)

Ramped Bunch Train*

\[ Q = 15, 45, 75 \]

\[ R = 7.89 \]

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Linear (2D) theory for \( n_b \ll n_e \)!

\( R = 7.9 \) => multiply energy by \( \sim 8 \) in a single PWFA stage!

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*Tsakanov, NIMA, 1999

Kallos, PAC'07 Proceedings

P. Muggli, 06/07/2010, INFN Frascati
High Brightness Photo-Injector
Velocity bunching concept (RF Compressor)

If the beam injected in a long accelerating structure at the crossing field phase and it is slightly slower than the phase velocity of the RF wave, it will slip back to phases where the field is accelerating, but at the same time it will be chirped and compressed.
Laser Comb technique: generation of a train of short bunches

Laser Pulse Train Generation

\[ \Delta \tau = \left| \frac{1}{v_{ge}} - \frac{1}{v_{go}} \right| L_{\text{crystal}} \]

- Ti:sapphire oscillator
- Chirped Pulse Amplifier
- Regen. amplifier
- Multipass amplifiers
- UV conversion
- IR pulse
- Single UV pulse
- Half waveplate + \( \alpha \)-BBO
- Crystal 4 ps
- Crystal 2 ps
- UV pulses
- Streak camera
- Streak camera
Overcompression
Laser COMB: experimental results

- M. Ferrario et al., Nucl. Inst. and Meth, A 637 (2011)
- A. Mostacci et al., Proc. of IPAC 2011, Spain
PWFA transverse field

\[ E_r(r, \xi) \approx (\alpha)(k_p \sigma_z) e^{-k_p^2 \sigma_z^2/2} \sin k_p \xi R'(r) \]
This works, but the bunch sits on the slope of acceleration. → head gets lower energy than tail → energy spread.
Fig. 5: Linear beam loading example: (a) drive bunch density profile (red line) and longitudinal wakefield $E_z$ (green line), (b) same for the witness bunch, (c) same for the drive and witness bunches together. The field of the drive bunch only is shown as the blue line in panel (c). A zoom around the witness bunch is shown in panel (d). The bunches move to the left.
Transverse beam dynamics inside the plasma

Envelope evolution

Transverse normalized emittance

Courtesy P. Tomassini
matching condition with the plasma:

\[ \sigma_x'' + \frac{k_p^2}{3\gamma} \sigma_x = \frac{\varepsilon_n^2}{\gamma^2 \sigma_x^3} \]

\[ k_p^2 = \frac{e^2 n_1}{\varepsilon_o m c^2} \]

\[ \sigma_\varepsilon = 4 \sqrt{\frac{3}{\gamma}} \sqrt{\frac{\varepsilon_n}{k_p}} \]

- **\( \varepsilon_n = 2 \mu m \)**
- **\( n [\text{cm}^{-3}] \)**
- **\( \text{sigma}_r [\text{um}] \)**
\[ \sigma_\varepsilon = \sqrt[4]{\frac{3}{\gamma}} \sqrt[4]{\frac{\varepsilon_n}{k_p}} \]
Beam Manipulation
Capillary Discharge at SPARC_LAB
Plasma Source

$P_{H_2} = 10 \text{ mbar}$
Total discharge duration: 800 ns
Voltage: 20 kV
Peak current: 200 A
Capacitor: 6 nF

Courtesy of M. P. Anania, A. Biagioni, D. Di Giovenale, F. Filippi, S. Pella
Active Plasma Lens

Magnetic Field ($B_\varphi$) vs Force on electrons ($F$)

e⁻ bunch

$B_\varphi$ F

Current

HV
Preliminary results

Discharge OFF

Discharge current profile
Experimental characterization of active plasma lensing for electron beams


[Graph showing current, emittance, and spot size over delay]
Results vs simulations

- **a** Discharge OFF
- **b** Discharge ON (45 A)
- **c** Discharge ON (93 A) with Spherical aberrations
- **d**
- **e**
- **f**
Nonlinear focusing field

45 A discharge current

- Current density
- Magnetic field
- Ionization degree
- Bunch profile

Magnetic field (mT), Ionization degree (%)

Input bunch profile

Radius (μm)

Current density (A/m²)
Ramps effects on emittance without discharge

- with External ramps
- only internal ramps

emittance (mm·mrad)

$Z_0$ (cm)
In order to see the real expansion of the plasma we have to mount the capillary of 3 cm length so that we will not see the cutting due to the supports.
velocity of plasma

Delay: 20 images separated by 100 ns = 2 µs
Gate: 10 ns
Area: 1000 x 500 pixel
Photocathode side: POSITIVE

0 ns

200 ns

400 ns

700 ns

1000 ns

1300 ns

1600 ns

2000 ns

Current (A)

Time (μs)

20 kV
The CERN Accelerator School is organizing a course on

PLASMA WAKE ACCELERATION

23-29 November, 2014
CERN, Geneva, Switzerland

The course will be of interest to staff and students in accelerator laboratories, university departments and companies working in or having an interest in the field of new acceleration techniques. Following introductory lectures on plasma and laser physics, the course will cover the different components of a plasma wake accelerator and plasma beam systems. An overview of the experimental studies, diagnostic tools and state of the art wake acceleration facilities both present and planned, will complement the theoretical part. Topics remain and a visit of CERN will complete the programme.

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3rd European Advanced Accelerator Concepts Workshop

Supported by EU/ARIES via EuroNNAc3
24-30 September 2017, La Biodola - Isola d'Elba – Italy

Laser technology for advanced accelerators
Dielectric structures and other novel technologies
Advanced and novel accelerators for high energy physics
High gradient and multibunch acceleration in metallic structures
C-X-band and beyond with innovative power generation schemes

Plasma accelerators driven by: modern lasers, electron beams, proton beams
Computations for accelerator physics advanced beam diagnostics for beams and plasma
Novel schemes using advanced technologies (table-top FEL, medical imaging...)

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Workshop Organizing Committee

Philippe Sauvanet (HEF, Germany), CO-CHAIR

Ulfen Brägger (DESY, Germany), Proceedings Editor

Programme Committee

Tiberius T. W. J. van der Meer (CERN, Switzerland)

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