PARTICLE DRIVEN PLASMA WAKEFIELD ACCELERATORS

by

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• Space charge of drive beam displaces plasma electrons

• Plasma ions exert restoring force => Space charge oscillations

• Wake Phase Velocity = Beam Velocity (like wake on a boat)

• Wake amplitude \( \propto \frac{N_b}{\sigma_z^2} \)

• Transformer ratio \( \frac{E_z, \text{acell}}{E_z, \text{decell}} \)

Wakefield Fields for $e^- \& e^+$

$n_e = 1.5 \times 10^{14} \text{ cm}^{-3}$

homogeneous, QUICKPIC

- Blow-Out
- Accelerating “Spike”
- Fields vary along $r$, stronger
- Less Acceleration
**e⁻ & e⁺ FOCUSING FIELDS**

- **e⁻**
  - $\sigma_x = \sigma_y = 25$ µm
  - $\sigma_z = 730$ µm
  - $N = 1.9 \times 10^{10}$ e⁺/e⁻
  - $n_e = 1.5 \times 10^{14}$ cm⁻³

- **e⁺**

*QuickPIC*

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**Graphs:**

- **Linear, no abberations**
- **Non-linear, abberations**
# Physical Effects of Plasma Fields on the Beam

## TRANSVERSE ($E_r$)

- **Deflection**
- **Focusing/Defocusing**
- **Periodic Oscillations**
- **Emission of Betatron Radiation**

## APPLICATION

- **Beam Steering**
- **Plasma Lenses**
- **Plasma Wigglers**
- **Positron Production**

## LONGITUDINAL ($E_z$)

- **Acceleration**
- **Deceleration**

## APPLICATION

- **High Gradient Accelerators**
- **Beam Dumps**
Proof of Principle PWFA Experiment @ ANL

- Performed in 1987 at ANL at AATF
- Drive and witness beam configuration
- 1.6 MeV/m acceleration fields
- Transverse deflection of witness beam by driver wake also observed

The plasma flow in the main capillary is turbulent. The time of the plasma propagation through the main capillary can be estimated as:

\[
    t = \frac{d}{k\xi c_s(0)} \exp \left( \frac{KL}{d} \right)
\]

Where \( k \) and \( \xi \) are dimensionless turbulent heat conductivity and viscosity. \( k = 0.048, \xi = 0.25, c_s = 4 \times 10^5 \text{ cm/s}. \)

For \( d = 300 \mu\text{m}, L = 1.4 \text{ cm} \)

\( t = 60 \mu\text{s}. \)

Discharge (plasma) off

Discharge (plasma) on

Energy distribution and transverse beam phase space dramatically changed after a 60 MeV, 0.5 nC, 3 ps (FWHM) e-beam passes through 17 mm of \( \sim 10^{17} \) plasma.
First measurement of PWFA in the “blowout regime”

- Measurement at ANL AWA facility in 1999
- First creation of witness and drive beams in RF photogun
- Average acceleration of 25 MV/m in 12 cm of $10^{13}$ cm$^{-3}$ plasma, with $n_b > 2.5n_p$

High gradient PWFA with compressed beam @ A0

Spectrometer image of beam after 8 cm of plasma

- First use of compressed beam in PWFA experiment at FNAL A0 photoinjector (2001)
- Deceleration observed at 150 MeV/m, with beam nearly stopped in plasma
- Acceleration recently observed at 132 MeV/m (2003)
- New experiments with witness beam
E-162/E-164/E-164X

Collaborations:


Stanford Linear Accelerator Center


University of California, Los Angeles

T. Katsouleas, S. Lee, P. Muggli, E. Oz

University of Southern California
PWFA Experiments @ SLAC

Located in the FFTB

- Ionizing Laser Pulse (193 nm)
  - N = 1.2 \cdot 10^{10}
  - \sigma_z = 0.1 \text{ mm}
  - E = 30 \text{ GeV}

- Li Plasma
  - n_e = 6 \cdot 10^{15} \text{ cm}^{-3}
  - L = 30 \text{ cm}

- Streak Camera
  - (1\text{ps resolution})

- Spectrometer
- Cerenkov Radiator
- X-Ray Diagnostic
- Dump

Not to scale!
FOCUSING OF e⁺

OTR Images
(≈1m downstream from plasma)

Plasma Off

1 mm

\[ N = 1.9 \times 10^{10}, \quad \varepsilon_N > 5 \times 10^{-5} \text{ m-rad} \]

- Overall focusing at low plasma densities

M.J. Hogan et al., PRL, 2002
FOCUSING OF $e^-/e^+$

- OTR images $\approx 1$ m from plasma exit ($\varepsilon_x \neq \varepsilon_y$)

- $n_e = 0$

- $n_e \approx 10^{14}$ cm$^{-3}$

- Ideal Plasma Lens in Blow-Out Regime

- Plasma Lens with Aberrations

- $e^+$: halo formation from non uniform focusing (focusing aberrations)
FOCUSING OF $\Theta^-$

OTR Images $\approx 1$ m downstream from plasma

- Focusing of the beam well described by a simple model ($n_b > n_e$):
  Plasma = Ideal Thick Lens
- Channeling of the beam over 1.4 m or $> 12\beta_0$

C.E. Clayton et al., PRL, 2001
• Energy gain by particles \( \approx 279 \text{ MeV} \) in the last (-6 ps) 1 ps slice

• Peak accelerating gradient \( \approx 200 \text{ MeV/m} \) \((L=1.4 \text{ m})\)

P. Muggli et al., PRL, 2004
Energy Gain of a Positron Beam

Excellent agreement between simulation and experiment of a positron beam which has passed through a 1.4 m PWFA

OSIRIS Simulation Prediction: Experimental Measurement:

<table>
<thead>
<tr>
<th>Peak Energy Loss</th>
<th>Peak Energy Gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>64 MeV</td>
<td>78 MeV</td>
</tr>
<tr>
<td>65±10 MeV</td>
<td>79±15 MeV</td>
</tr>
</tbody>
</table>

5x10^8 e^+ in 1 ps bin at +4 ps

EXPECTED GRADIENT / SCALING

- E-164X: \( \sigma_z = 20-10 \, \mu m \): >10 GV/m gradient!
  \((\sigma_r \text{ dependent! } k_p \sigma_r \approx 1)\)
  \(f_p = 2.8 \, \text{THz}, W = 3 \text{MT/m} \) @ \( n_e = 10^{17} \, \text{cm}^{-3} \)
Sub-Picosecond Pulse Source

Damping Ring
\(\varphi_e \approx 30 \text{ \(\mu\)m}\)

20 psec

SLAC Linac

1 GeV

4 psec

0.2 psec

28 GeV

FFTBL Line

<100 fsec

Add 12-meter chicane compressor in linac at 1/3-point (9 GeV)

Existing bends compress to <100 fsec

28 GeV electrons

Or

Existing bends compress to <100 fsec

1.5\(\AA\) photons

10 m undulator

200 periods, K=6

28 GeV

80 fsec FWHM

04/9-11/2003

DOE Program Review
• Short bunch, $E_r \approx 5.2 \times 10^{-19} N/\sigma_z \sigma_r (GV/m) >$ tunneling field (Kyldish, ADK)

Lithium vapor pressure curve

$N=10^{10} e^-, \sigma_z=\sigma_r=20 \mu m$ in Li
• $> 4 \text{ GeV/m}$ Energy Loss in Beam Ionized Plasma (near threshold)
EXPERIMENTAL BEAM-IMAGE AGREES WELL WITH SIMULATION OF SUBPICOSECOND BEAM
E-164 (Run II): First signature of energy gain

**WITHOUT PLASMA**

**WITH PLASMA**

\[ n_e = 3 \times 10^{16} \text{ cm}^{-3}, \ L = 15 \text{ cm}, \ N = 1.8 \times 10^{10} \]

- Energy loss of \(~2.5\text{ GeV}\)
- Energy gain of \(~2\text{ GeV}\)
E164X Breaks GeV Barrier

$L \approx 10 \text{ cm, } N \approx 1.8 \times 10^{10}$

- Energy gain reaches $\approx 4 \text{ GeV}$
- $n_e \approx 2.55 \times 10^{17} \text{ cm}^{-3}$
$n_e \approx 3.5 \times 10^{17}$ cm$^{-3}$ RESULTS

$L \approx 10$ cm, $N \approx 1.8 \times 10^{10}$

Many similar events in a data set

Acceleration with significant charge: 2.5 GeV
$n_e \approx 3.5 \times 10^{17}$ cm$^{-3}$ **ENERGY SPECTRA**

$L \approx 10$ cm, $N \approx 1.8 \times 10^{10}$

Variations from incoming energy spectrum variations

Charge Fraction at $E > 0$: 6.8-7.9% of total charge!

Peak energy gain above the beam head: $\approx 1.5$ GeV

Total gain: 2.5 GeV
$n_e \approx 2.11 \times 10^{17} \text{ cm}^{-3}$

$L \approx 10 \text{ cm}, \ N \approx 1.8 \times 10^{10}$

Gain

$\approx 9 \text{ GeV}$

Very consistent acceleration, varies with incoming parameters
Evidence for plasma $e^-$ trapping:
- Excess charge after the plasma
- Excess light from OTR screen
- Continuum light emission on plasma light spectrum

Dark current limit for the PWFA?
Plasma Accelerators and the Livingston Curve
Beam-Driven Plasma Wakefield Accelerators

**Ultimate Goal**

Double the Energy of a Collider Using Plasma After-Burner Sections Placed Before IP.

Much of the research could be done at SLAC

S. Lee et al., Phys. Rev. STAB, 2001
Critical Issues

- Beam Loading
- Transverse Beam Dynamics (hosing, radiation)
- Beam head Erosion
- Plasma Source Development
- Beginning to end Modeling
- High Gradient Acceleration of Positrons
- High Demagnification plasma Lenses
- Large Transformer Ratio
### First 100 GeV PWFA Simulation: QuickPIC

**C. Huang et al.**

<table>
<thead>
<tr>
<th></th>
<th>E164X</th>
<th>Afterburner</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plasma Density</strong></td>
<td>( n = 1.6 \times 10^{17} \text{cm}^{-3} )</td>
<td>( n = 5.66 \times 10^{16} \text{cm}^{-3} )</td>
</tr>
<tr>
<td><strong>Beam charge</strong></td>
<td>( N = 1.8 \times 10^{10} )</td>
<td>( N_{\text{drive}} = 3 \times 10^{10}, N_{\text{trailing}} = 1 \times 10^{10} )</td>
</tr>
<tr>
<td><strong>Beam Profile</strong></td>
<td>Longitudinal:</td>
<td>Longitudinal:</td>
</tr>
<tr>
<td></td>
<td>Drive beam: wedge shape, ( L = 145 \mu \text{m} = 6.5c/\omega_p )</td>
<td>Trailing beam: Gaussian profile, ( \sigma_z = 10 \mu \text{m} = 0.45c/\omega_p )</td>
</tr>
<tr>
<td></td>
<td>Transverse: Gaussian profile, ( \sigma_r = 12 \mu \text{m} = 0.9c/\omega_p )</td>
<td>Transverse: Gaussian profile, ( \sigma_r = 15 \mu \text{m} = 0.67c/\omega_p )</td>
</tr>
</tbody>
</table>
Drive Beam Erosion and Transverse Stability of Trailing Beam

QuickTime™ and a MPEG-4 Video decompressor are needed to see this picture.
Evolution of Plasma Wake

QuickTime™ and a MPEG-4 Video decompressor are needed to see this picture.
Energy Change of the Drive and Trailing Beams

QuickTime™ and a MPEG-4 Video decompressor are needed to see this picture.
CONCLUSIONS

For the 1st time: gain > 1 GeV in a plasma accelerator!

Maximum energy gain observed: > 4 GeV over 10 cm!

Accelerating gradient > 40 GeV/m over ≈10 cm!

Acceleration very consistent and repeatable

Maximum energy gain limited by the energy acceptance of the FFTB!

Energy gain trends: largest at ≈2.55×10^{17} cm^{-3}, more charge at higher densities.

Observed trapped particles

Opinion: Energy Doubling with Reasonable Beam Loading Efficiency and Energy Spread @50-100 GeV Level Achievable for Electrons within 2-4 Years
Shaped bunch PWFA can be studied at ORION

Simulated beam phase space and shape

Simulated Wake

Optimum profile
1.2 SLAC Beam Lines Overview

Figure 1. Location of the Instrument Section close to the beginning of the SARC

Courtesy P. Krejcik, P. Emma
Transition trapping injection

- Trapping of plasma electrons based on density transition; phase mixing near boundary
- Density tailored to produce very low energy spread injected beam
- Plasma now installed on beamline at FNAL A0

Observation of nonlinear plasma wakefields @ ANL

• Measurements at AATF
• Wave steepening into sawtooth form
• Wakes persist for 10’s of wavelengths
• Harmonics also observed in transverse deflection wakes

Underdense beam guiding

• Measurement at ANL AWA facility in 1997
• Underdense plasma \( (n_b > n_p) \)
• Guiding shown over 12 times \( \beta^* \)
• First step to blow-out regime of PWFA

e⁻ & e⁺ BEAM NEUTRALIZATION
3-D QuickPIC simulations, plasma e⁻ density:

$e^-$: $n_{e0} = 2 \times 10^{14}$ cm⁻³, $c/\omega_p = 375$ µm

$e^+$: $n_{e0} = 2 \times 10^{12}$ cm⁻³, $c/\omega_p = 3750$ µm

σᵣ = 35 µm
σᵢ = 700 µm
$\mathcal{N} = 1.8 \times 10^{10}$
d = 2 mm

- Uniform focusing force ($r,z$)
- Non-uniform focusing force ($r,z$)
EXPERIMENTAL SET UP

IP0:
- Li Plasma
- Gas Cell: H₂, Xe, NO
- \( n_e \approx 0-10^{18} \text{ cm}^{-3} \)
- \( L \approx 2.5-20 \text{ cm} \)
- Plasma light
- X-Ray Diagnostic, \( e^-/e^+ \) Production
- Cherenkov Radiator
- DUMP
- Imaging Spectrometer
- \( \int Cdt \)
- Coherent Transition Radiation and Interferometer
- Optical Transition Radiators

IP2:
- \( N = 1.8 \times 10^{10} \)
- \( \sigma_z = 20-12 \mu m \)
- \( E = 28.5 \text{ GeV} \)
- Optical Transition Radiation (OTR)
- Coherent Transition Radiation and Interferometer
- Optical Transition Radiators

X-ray Chicane

- Energy resolution \( \approx 60 \text{ MeV} \)
- 1:1 imaging, spatial resolution \( \approx 9 \mu m \)

Optical Transition Radiation (OTR)

- Energy resolution \( \approx 30 \text{ MeV} \)
- Spatial resolution \( \approx 100 \mu m \)

Cherenkov (aerogel)

- Spatial resolution \( \approx 100 \mu m \)
- Energy resolution \( \approx 30 \text{ MeV} \)

Plasma Light

- X-Ray Diagnostic, \( e^-/e^+ \) Production
- Dump
Double the energy of Collider w/ short plasma sections before IP
- 1\textsuperscript{st} half of beam excites wake -- decelerates to 0
- 2\textsuperscript{nd} half of beams rides wake -- accelerates to 2 x $E_0$
- Make up for Luminosity decrease $\propto N^2/\sigma_z^2$ by halving $\sigma$ in a final plasma lens

S. Lee \textit{et al.}, PRST-AB (2001)
E164X simulation results
PIC Simulation of 2 bunch Afterburner Experiment

Hi beam quality requires specialized infrastructure of ORION beamline

(shorter 2nd bunch, precise phasing $\tau$)

Driving bunch only

Proper beam load flattens wake

\[
\begin{align*}
\text{Driving bunch } N &= 3 \times 10^{10} \quad \sigma_z = 0.063\text{mm} \\
\text{Trailing bunch } N^- &= 1 \times 10^{10} \quad \sigma_z(\text{trailing}) = \frac{\sigma_z}{2}
\end{align*}
\]
Energy distribution of driver & trailer

\[ \text{ELECTRON } n_p = 1.749000 \times 10^{16} \text{ cm}^{-3} \]

Energy Change (MeV) [over 0.22\,cm]

\[ \langle E_+ \rangle = \sim 8 \ \text{GeV/m} \]

\[ \langle E_- \rangle = \sim 8 \ \text{GeV/m} \]

\[ \langle dE/E \rangle = \sim 20\% \]

\[ \text{# of } e^- \]

\[ x 10^9 \]

\[ y 10^8 \]

\[ -25.54 \quad -12.77 \quad 0 \quad 12.77 \quad 25.54 \quad 38.31 \]

\[ \text{Energy Change (MeV) [over 0.22cm]} \]

driver

trailer