Positron Transport, Focusing and Acceleration Using Plasma Techniques

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Work supported by US Dept. of Energy
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OUTLINE

♦ Plasma Wakefield Accelerator (PWFA), collider, $e^-$

♦ $e^+$ beam transport and focusing

♦ $e^+$ acceleration

♦ Conclusions
Plasma Wakefield Accelerator* 101

♦ Two-beam, co-linear, plasma-based accelerator

♦ Deceleration, acceleration, focusing by plasma

♦ Accelerating field/gradient scales as $n_e^{1/2}$

♦ Typical: $n_e \approx 10^{16}-10^{17}$ cm$^{-3}$, $\lambda_p \approx 150$ µm, $f_p \approx 2$ THz, $E > 10$ GV/m

♦ High-gradient, high-efficiency energy transformer
PWFA-LC Concept (an example)

- TeV CM Energy
- 10’s MW Beam Power for Luminosity
- Electron & Positron Acceleration in plasmas
- Conventional technology for particle generation & focusing

July 7, 2008

FACET Program will demonstrate most of a single stage

♦ FACET* @ SLAC: single, 1m-long, +25 GeV stage, e⁻ and e⁺
PWFA-LC Concept (an example)

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FACET Program will demonstrate most of a single stage PWFA-LC Concept (an example)

- $e^-$
  - Energy doubling of 42 GeV $e^-$
  - Plasma length: 85 cm
  - Accelerating gradient: 50 GeV/m
  - Agreement with simulations

FACET*@SLAC: single, 1m-long, +25 GeV stage, $e^-$ and $e^+$

*Facilities for Accelerator Science and Testing

e+ at SLAC only!
PWFA-LC Concept (an example)

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*Facilities for Accelerator Science and Technology

PRL 93, 014802 (2004)

nde, matched = 1.6-2.5×10^{14} \text{ cm}^{-3}

Linear focusing force n_b > n_e

Emittance preservation

The case of e- bunches in PWFA is well understood and favorable
PWFA-LC Concept (an example)

♦ e^+

Less studied
♦ e^+ beams not widely available!
♦ More challenging!
e⁻ & e⁺ BEAM NEUTRALIZATION, “FOCUSING”

- Transverse dynamics, emittance preservation?

3-D QuickPIC simulations, plasma e⁻ density:

- e⁻: \( n_{e0} = 2 \times 10^{14} \text{ cm}^{-3} \), \( c/\omega_p = 375 \mu\text{m} \)
- e⁺: \( n_{e0} = 2 \times 10^{12} \text{ cm}^{-3} \), \( c/\omega_p = 3750 \mu\text{m} \)

- Uniform focusing force \((r,z)\)
- Free of geometric aberrations
- Emittance preserved

- Non-uniform focusing force \((r,z)\)
- Emittance growth?

\[ \sigma_r = 35 \mu\text{m} \]
\[ \sigma_r = 700 \mu\text{m} \]
\[ N = 1.8 \times 10^{10} \]
\[ L = 2 \text{ mm} \]
**e^- & e^+ FOCUSING FIELDS**

QuickPIC

- $\sigma_{x0} = \sigma_{y0} = 25 \, \mu m$
- $\sigma_z = 730 \, \mu m$
- $N = 1.9 \times 10^{10} \, e^+/e^-$
- $n_e = 1.5 \times 10^{14} \, cm^{-3}$

Non-linear, aberrations

Linear, no aberrations

P. Muggli, PAC 09. 05/04/09
e\(^-\) & e\(^+\) FOCUSING FIELDS

QuickPIC: \(\sigma_x \approx \sigma_y \approx 25 \mu m, \varepsilon_Nx \approx 390 \times 10^{-6}, \varepsilon_{Ny} \approx 80 \times 10^{-6} \) m-rad, \(N = 1.9 \times 10^{10} \) e\(^+\), \(\sigma_z \approx 730 \mu m, n_e = 1.5 \times 10^{-6}, L \approx 1.1 \) cm

- Uniform focusing force \((r,z)\)
- Non-uniform focusing force \((r,z)\)
- Weaker focusing force
- Stronger focusing force

\[ E_x \times B_z \]  
\[ E_y \times B_x \]  

\* e\(^+\): focusing fields vary along \(r\) and \(z\)!

\* Emittance growth expected
**EXPERIMENTAL SET UP**

- **Optical Transition Radiation (OTR)**
  - 1:1 imaging, spatial resolution <9 µm

- **CHERENKOV (aerogel)**
  - Spatial resolution ≈100 µm
  - Energy resolution ≈30 MeV
  - Time resolution: ≈1 ps

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P. Muggli, PAC 09. 05/04/09
FOCUSING OF $e^-/e^+$

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

$n_e=0$

- Ideal Plasma Lens in Blow-Out Regime

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

- Plasma Lens with Aberrations, Halo Formation

- Qualitative differences
**EXPERIMENT/SIMULATIONS: BEAM SIZE**

\[ \sigma_{x_0} = \sigma_{y_0} = 25 \mu m, \ \varepsilon_{N_x} = 390 \times 10^{-6}, \ \varepsilon_{N_y} = 80 \times 10^{-6} \text{ m-rad}, \ N = 1.9 \times 10^{10} \text{ e}^+, \ L = 1.4 \text{ m} \]

Downstream OTR

Experiment

Simulations: QuickPIC

- Excellent experimental/simulation results agreement!
- The beam is \approx round with \( n_e \neq 0 \)
EXPERIMENT/SIMULATIONS: HALO FORMATION

\[
\sigma_x \approx \sigma_y \approx 25 \, \mu m, \quad \varepsilon_{N_x} \approx 390 \times 10^{-6}, \quad \varepsilon_{N_y} \approx 80 \times 10^{-6} \, \text{m-rad}, \quad N = 1.9 \times 10^{10} \, e^+, \quad L \approx 1.4 \, m
\]

- **Very nice qualitative agreement**
- **Simulations to calculate emittance**

P. Muggli, PAC 09. 05/04/09
\( e^+ : \text{SLICE EMITTANCE (SIMULATIONS)} \)

\[ \sigma_{x0} \approx \sigma_{y0} \approx 25 \, \mu\text{m}, \varepsilon_{Nx} \approx 390 \times 10^{-6}, \varepsilon_{Ny} \approx 80 \times 10^{-6} \, \text{m-rad}, \, N=1.9 \times 10^{10} \, e^+, \, L \approx 1.4 \, \text{m} \]

\[ n_e = 2 \times 10^{14} \, \text{cm}^{-3} \]

\[ x \text{-emittance} \]

\[ y \text{-emittance} \]

\[ \text{Slices contain 20\% of charge} \]

\[ \text{The } e^+ \text{ beam exits the plasma with } \approx \text{equal emittances and } \approx \text{equal transverse sizes} \]

\[ \text{FR8RPF025} \]

P. Muggli, PAC 09. 05/04/09

BEAM/FIELD EVOLUTION

$\sigma_{x0} = \sigma_{y0} = 25\mu m$, $\varepsilon_{Nx} = 390 \times 10^{-6}$, $\varepsilon_{Ny} = 80 \times 10^{-6}$ m-rad, $N = 1.9 \times 10^{10}$

Initial focusing for small $n_eL$

Hogan, PRL 90 (2003)

♦ Dynamic focusing, beam becomes non Gaussian
♦ Beam size and focusing field “stop” at $z \approx 0.7$ m, “self matching”
$e^+: ACCELERATION$

- Possible?

3-D QuickPIC simulations, plasma $e^-$ density:

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

- $e^+$: $n_{e0} = 2 \times 10^{12} \text{ cm}^{-3}$, $c/\omega_p = 3750 \text{ } \mu\text{m}$

- Plasma $e^-$ density spike “pushes” beam $e^-$

- Plasma $e^-$ density spike “pulls” beam $e^+$

- YES!

P. Muggli, PAC 09. 05/04/09
• Optical Transition Radiation (OTR)
  - 1:1 imaging, spatial resolution <9 µm

• CHERENKOV (aerogel)
  - Spatial resolution ≈100 µm
  - Energy resolution ≈30 MeV
  - Time resolution: ≈1 ps

P. Muggli, PAC 09. 05/04/09
Energy gain and loss $\approx 80$ MeV over 1.4 m (long, $\approx 700 \mu m$ bunches)

Good agreement with numerical simulations

High gradient acceleration not demonstrated
e\(^+\) ACCELERATION ON e\(^-\) Wake

- Test of e\(^+\) acceleration on e\(^-\) wake
- Injection on e\(^+\) on e\(^-\) wake

Wang, PRL 101, 124801 (2008)
CONCLUSIONS

♦ e^+ / plasma interaction much less studied than e^- / plasma

♦ Focusing force on e^+ bunches in nonlinear

♦ Emittance growth for single e^+ bunch in uniform plasma

♦ Possible remedies include hollow plasma channel, linear wake, transverse bunch shaping, drive-witness bunch, …

♦ e^+ can be accelerated in plasmas

♦ e^+ accelerated on e^- or laser wake

♦ Emittance preservation/acceleration more challenging for e^+ than for e^- in plasma-based accelerators

♦ e^+ / plasma interaction @ FACET
♦ Thank you to my collaborators:

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♦ And thank You!

Work supported by US Dept. of Energy
Laser and Plasma Accelerators Workshop
2009

Kardamili, June 22-26 2009

Topics

- Plasma accelerators and the energy frontier
- One to ten GeV laser-plasma accelerator technology
- Computer modelling of laser and plasma accelerators
- Physics and applications of laser/beam - plasma interactions
- Fundamental physics and relativistic astrophysics with intense laser and particle beams

Deadline of May 24th for
- Early registration
- Abstract Submission

International advisory committee

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Local organizing committee

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web: http://cfp.ist.utl.pt/lpaw09/
Fit for Beams with Halo

Beam Size=FWHM (BAB’)
Charge in the Peak=Area(BAB’)
Charge in the Halo=2*Area(CDB)

♦ Use fit to describe:
  - core size
  - relative charge in core and halo
♦ Apply to experimental and simulation images

P. Muggli, PAC 09. 05/04/09
HALO FORMATION

\[ \sigma_x \approx \sigma_y \approx 25 \text{ } \mu\text{m}, \ \varepsilon_{\text{Nx}} \approx 390 \times 10^{-6}, \ \varepsilon_{\text{Ny}} \approx 80 \times 10^{-6} \text{ m-rad}, \ N = 1.9 \times 10^{10} \text{ e}^+, \ L \approx 1.4 \text{ m} \]

- Very similar
Previous work FFTB@SLAC
Studied all aspects of beam-plasma interaction


P. Muggli, PAC 09. 05/04/09
PWFA@FFTB Successes
Generate Two Bunches by Selectively Collimating During Bunch Compression Process

Exploit Position-Time Correlation on e⁻ bunch to create separate drive and witness bunch e⁻/e⁻ or e⁺/e⁺

Adjust final compression

Disperse the beam in energy

\[ x \propto \frac{\Delta E}{E} \propto t \]

...selectively collimate
FACET Experiments will accelerate a discrete bunch of particles with narrow energy spread

- Energy Doubling in \(~1m\)
- Energy Spread \(~\)few percent, \(~30\%\) efficiency
High efficiency and narrow $\Delta E/E_0$ while > energy doubling
Produce Drive/Witness Bunches $e^-/e^+$

♦ Sailboat chicane:

- Extract $e^-$ & $e^+$ from damping rings on same linac pulse
- Accelerate bunches to sector 20, 5cm apart
- Use ‘Sailboat Chicane’ to put them within 100\(\mu\)m at entrance to plasma
- Large beam loading of $e^-$ wakes with high charge $e^+$ beams

♦ True injection of $e^+$ bunch in high gradient plasma wake

♦ High current $e^+$ bunches available at FACET only!!!
Use a combination of 6D particle tracking in ELEGANT combined with EGS4 to simulate the collimator(s).

**Challenges:**
- Drive bunch needs to both ionize the vapor and drive a large amplitude wake.
- Witness bunch needs to be half-plasma period behind the drive bunch (~100µm for $10^{17}$ e$^-$/cm$^3$ plasma).
- Must work for e$^-$ & e$^+$. 

Two bunches:
- Sigma z 18µm ea.
- Separation ~150µm
- Charge ratio ~ 3:1

NDR exit to FACET IP
VISION

♦ Beam-driven, Plasma Wakefield Acceleration (PWFA) as a new technology for a future e⁻/e⁺ Plasma-based LC or PWFA-LC

♦ Demonstrated Accelerating Gradient: 50 GV/m over 85 cm

  Energy doubling of 42 GeV e⁻

♦ Build single, e⁻/e⁺ 25 GeV stage of a (possible) multi-stage PWFA-LC

♦ Vision: reduce the price of a future e⁻/e⁺ linear collider to 2-4 b$ (target) by merging the high efficiency of conventional beam generation with the large accelerating gradient of the PWFA
e\(^+\) ACCELERATION ON e\(^-\) WAKE

♦ Asymmetry

♦ Injection of e\(^+\) on e\(^-\) wake (or laser wake!)

X. Wang, PRL (2008)
e\(^+\) FROM e\(^-\) β-TRON RADIATION IN PLASMAS

- Demonstration of a plasma wiggler e\(^+\) source
- Excellent experiment/calculations agreement

Johnson, PRL 97, 2006

Johnson, AAC 06, Proceedings

P. Muggli, PAC 09. 05/04/09
**β-tron Radiation in Plasmas**

**Large Beam Size ($K \geq 1/\beta_0$)**

- $L = 1.4 \text{ m}$
- $\sigma_0 = 50 \mu\text{m}$
- $\varepsilon_N = 12 \times 10^{-5} \text{ m-rad}$
- $\beta_0 = 1.16 \text{ m}$
- $\alpha_0 = -0.5$

Ion column:

$$\lambda_\beta = \frac{\sqrt{8\gamma \pi c}}{\omega_{pe}} \propto \frac{1}{n_e^{12/2}}$$

$$\omega_c = \frac{3}{2} \frac{\gamma^3}{c} \omega_\beta \sigma_r \propto n_e$$

- $n_e = 1.5 \times 10^{14} \text{ cm}^{-3}$
- $\lambda_\beta \approx 0.91 \text{ m}$
- $N_{\lambda_\beta} \approx 1.5$
- $\hbar \omega_c \approx \text{keV}$

◆ x-rays from a plasma wiggler (e⁻)

Wang, PRL 88, 2002
**e^+ FROM e^- β-TRON RADIATION IN PLASMAS**

- $n_e = 10^{17} \text{ cm}^{-3}$
- $\lambda_\beta \approx 0.035 \text{ m}$
- $N_\beta \approx 24 \left( L_p = 30 \text{ cm} \right)$
- $\hbar \omega_e \approx 10 \text{ MeV} > 2m_e c^2$
- Produce e^−/e^+ pairs!

- Demonstration of a plasma wiggler e^+ source
- Excellent experiment/calculations agreement

Johnson, AAC 06, Proceedings

![Diagram](image)

Spectrum (x10^5 e^+/MeV/Sr)

Positron Energy (MeV)

Johnson, PRL 97, 2006

P. Muggli, PAC 09. 05/04/09