Beam-driven, Plasma-based Particle Acceleration

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Work supported by US Dept. of Energy
OUTLINE

- Motivation - Introduction to PWFA (Plasma Wakefield Accelerator)
- PWFA experimental results @ SLAC
  
  *P. Muggli and M.J. Hogan, Comptes Rendus Physique, 10(2-3), 116 (2009).*
- Low energy PWFA @ ATF-BNL
- Proton driven PWFA @ CERN (for e⁻ acceleration)
- Self-modulation-driven PWFA
- Summary and Conclusions

*Focus on acceleration all the way through!*
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Summary and Conclusions

Focus on acceleration all the way through!
Some of the largest and most complex (and most expensive) scientific instruments ever built!

All use rf technology to accelerate particles

Can we make them smaller (and cheaper) and with a higher energy?
Is there a high-gradient alternative to rf technology? Could it be plasmas?

- Linear accelerator to avoid synchrotron radiation limitation ($\sim \gamma^4/r^2 \sim E^4/m^4r^2$)
- Energy frontier: 0.5-3 TeV, $e^-/e^+$
- Accelerator length with (cold) rf technology:
  
  $\frac{1 \text{ TeV}}{<50 \text{ MeV/m}} > 20 \text{ km}$

ILC

FUTURE LEPTON ($e^-/e^+$) COLLIDER

≈25 km site?
What About Plasmas?

Relativistic Electron Electrostatic Plasma Wave (Electrostatic, $E_z$):

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \quad k_p E_z = \frac{\omega_{pe}}{c} E_z = \frac{n_e e}{\varepsilon_0} \quad \omega_{pe} = \left(\frac{n_e e^2}{\varepsilon_0 m_e}\right)^{1/2}$$

Plasma Frequency

$$E_z = \left(\frac{m_e c^2}{\varepsilon_0}\right)^{1/2} n_e^{1/2} \approx 100 \sqrt{n_e (cm^{-3})} = 1 \text{ GV/m}$$

Cold Plasma “Wavebreaking” Field

Collective response!

- Plasmas can sustain very large (collective) $E_z$-field, acceleration
- Wave, wake phase velocity = driver velocity (~c when relativistic)
- Plasma is already (partially) ionized, difficult to “break-down”
- Plasmas wave or wake can be driven by:
  - Intense laser pulses (LWFA)
  - Short particle bunch (PWFA)
4 PLASMA ACCELERATORS*

- **Plasma Wakefield Accelerator (PWFA)**
  A high energy particle bunch \((e^-, e^+, \ldots)\)

- **Laser Wakefield Accelerator (LWFA)**
  A short laser pulse (photons)

- **Plasma Beat Wave Accelerator (PBWA)**
  Two frequencies laser pulse, i.e., a train of pulses

- **Self-Modulated Laser Wakefield Accelerator (SMLWFA)**
  Raman forward scattering instability in a long pulse

\[ \sigma_z \approx \frac{\lambda_{pe}}{4} \]

4 PLASMA ACCELERATORS

The plasma:
• Converts transverse into longitudinal fields (ES wave)
• Supports the relativistic ($v_z \sim c$) plasma wave with $E_z = 1-100$ GV/m
• Supports the accelerating structure
• Suppresses need for cavity fabrication
• Needs only one wave period
• Overcomes the breakdown limit

Linear theory $(n_b << n_e)$ scaling:

$$E_{acc} \equiv 110 (MV / m) \frac{N/2 \times 10^{10}}{(\sigma_z / 0.6 mm)^2} \approx \frac{N}{\sigma_z^2}$$

@ $k_{pe} \sigma_z \approx \sqrt{2}$ (with $k_{pe} \sigma_r << 1$)

Focusing strength:

$$B_\theta = \frac{1}{2} \frac{n_e}{\epsilon_0 c} = \frac{3kT}{m \times n_e (10^{14} \text{ cm}^{-3})} \quad (n_b > n_e)$$

$N = 2 \times 10^{10}$: $\sigma_z = 600 \mu m$, $n_e = 2 \times 10^{14} \text{ cm}^{-3}$, $E_{acc} \sim 100 \text{ MV/m}$, $B_\theta / r = 6 \text{ kT/m}$

$\sigma_z = 20 \mu m$, $n_e = 2 \times 10^{17} \text{ cm}^{-3}$, $E_{acc} \sim 10 \text{ GV/m}$, $B_\theta / r = 6 \text{ MT/m}$

Frequency: 100GHz to $>1$THz, “structure” size 1mm to 100µm

Conventional accelerators: MHz-GHz, $E_{acc} < 150 \text{ MV/m}$, $B_\theta / r < 2 \text{ kT/m}$

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Focus on acceleration all the way through!
Long-bunch Experiments

\( e^-/e^+ \) 28.5 GeV
\( \sigma_z \approx 700 \mu m \)
\( \sigma_r \approx 30 \mu m \)
\( n_e \approx 2 \times 10^{14} \text{ cm}^{-3} \)
\( L_p \approx 1.4 \text{ m} \)
Pre-ionized

\( k_{pe} \sigma_z \approx \sqrt{2} \)
\( 0.1-100 \text{ GV/m} \)

Short-bunch experiments

\( e^- \) 28.5, 42 GeV
\( \sigma_z \approx 30-20 \mu m \)
\( \sigma_r \approx 10 \mu m \)
\( n_e \approx 1-3 \times 10^{17} \text{ cm}^{-3} \)
\( L_p \approx 10, 20, 30, 60, 90, 120 \text{ cm} \)
Field-ionized

Linear Theory
**PLASMA WAKEFIELD FIELDS (e⁻)**

\[ \sigma_z \approx 700 \mu m \]

**2-D PIC Simulation QUICPICK**

- \( n_e = 1.5 \times 10^{14} \text{ cm}^{-3} \)
- \( N = 1.8 \times 10^{10} \text{ e}^- \)
- \( k_p \sigma_z \sim \sqrt{2} \)

**Experiment**

- Measure energy gain/loss not wakefield amplitudes

- **Simulation Parameters**
  - \( E_0 = 28.5 \text{ GeV} \)
  - \( n_b = 4 \times 10^{14} \text{ cm}^{-3} \)
  - \( N = 2 \times 10^{10} \text{ e}^- \text{ or e}^+ \)
  - \( \sigma_z = 0.63 \text{ mm (2.1 ps)} \)
  - \( \varepsilon_{xN} = 5 \times 10^{-5} \text{ m-rad} \)
  - \( \sigma_x = \sigma_y = 70 \mu m \)
  - \( \varepsilon_{yN} = 0.5 \times 10^{-5} \text{ m-rad} \)

- **Graphical Elements**
  - **Current**
  - **Energy Gain**
  - **Energy Loss**
  - **Blow-Out**
  - **Focusing** (\( E_r \))
  - **Decelerating** (\( E_2 \))

- **Cartoon Illustration**

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2-D PIC Simulation QUICPICK

$n_e = 1.5 \times 10^{14} \text{ cm}^{-3}, N = 1.8 \times 10^{10} \text{ e}^-$

$E_0 = 28.5 \text{ GeV}$

$N = 2 \times 10^{10} \text{ e}^- \text{ or e}^+$

$\sigma_z = 0.63 \text{ mm (2.1 ps)}$

$\sigma_x = \sigma_y = 70 \mu\text{m}$

$\epsilon_x N = 5 \times 10^{-5} \text{ m-rad}$

$\epsilon_y N = 0.5 \times 10^{-5} \text{ m-rad}$

$\epsilon_x N = 0.63 \times 10^{-5} \text{ m-rad}$

$\epsilon_y N = 0.5 \times 10^{-5} \text{ m-rad}$

$k_p \sigma_z \approx \sqrt{2}$

**Peak energy gain:** 279 MeV, $L = 1.4 \text{ m}$, $\approx 200 \text{ MeV/m}$

**Shows the physics**

**Similar results with positron bunch**


PLASMA NUMBERS (e⁻)

Focusing ($E_r$)

Defocusing

Accelerating

Decelerating ($E_z$)

$E_{\text{acc}} \approx 110\text{ (MV/m)} \frac{N/2 \times 10^{10}}{(\sigma_z/0.6\text{mm})^2}$

@ $k_p \sigma_z \approx \sqrt{2}$ (with $k_p \sigma_r << 1$)

Focusing strength:

$B_\theta \approx \frac{1}{2} \frac{n_e}{\varepsilon_0 c} = 3kT / m \times n_e (10^{14} \text{ cm}^{-3})$

$N=2\times10^{10}$: $\sigma_z = 600 \text{ µm}$, $n_e = 2\times10^{14} \text{ cm}^{-3}$, $E_{\text{acc}} \approx 100 \text{ MV/m}$, $B_\theta / r = 6 \text{ kT/m}$

$\sigma_z = 20 \text{ µm}$, $n_e = 2\times10^{17} \text{ cm}^{-3}$, $E_{\text{acc}} \approx 10 \text{ GV/m}$, $B_\theta / r = 6 \text{ MT/m}$

Frequency: 100GHz to >1THz, “structure” size 100 to 10µm

Conventional accelerators: MHz-GHz, $E_{\text{acc}} < 150 \text{ MV/m}$, $B_\theta / r < 2 \text{ kT/m}$
Energy gain scales linearly with plasma length!

Gain ≈14 GeV over (only!) \( L_p = 31 \text{ cm} \)!

\( E_{\text{acc}} \approx 45 \text{ GV/m} \)

\( E_0 = 28.5 \text{ GeV}, \ n_e = 2.7 \times 10^{17} \text{ cm}^{-3} \)

Same incoming beam! \( \sigma_z \approx 25 \mu \text{m} \)

\( \sigma_z \approx 25 \mu \text{m} \)


**e⁻ ENERGY DOUBLING**  

\[ E_0 = 42 \text{ GeV}, \sigma_z \approx 25 \mu\text{m} \]

- Energy doubling of e⁻ over \( L_p \approx 85 \text{ cm}, 2.7 \times 10^{17} \text{ cm}^{-3} \) plasma
- Unloaded gradient \( \approx 52 \text{ GV/m} (\approx 150 \text{ pC accel.}) \)
**SINGLE BUNCH PWFA**

- Large energy gain (42GeV) in only 85cm, but …

- Particles at all phase, large energy spread (100%)

- Particle acceleration, not **bunch** acceleration,
  These wakefields exist and can be sustained over ~ meter!

- Need witness bunch injection behind a drive bunch
2-BUNCH PWFA

Defocusing

Accelerating

Focusing \((E_r)\)

Decelerating \((E_z)\)

Witness Bunch:
\[E_0 \Rightarrow \geq 2E_0\]

Driver Bunch:
\[E_0 \Rightarrow \approx 0\]

Really important experiment! (psychologically)

Witness bunch: lower charge \((N)\), good emittance, shorter beam loading for \(\Delta E/E \ll 1\)

New facility: FACET@SLAC for 20GeV PWFA accelerator module

FACET program starting now

Low energy physics experiments

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*Focus on acceleration all the way through!*
Choose beam parameters with mask and beam parameters: \( N, \Delta z, \sigma_z, Q \)

Test bed for two bunches at FACET

(similar to COMB@SPARC)

© P. Muggli
Transformer Ratio: $R = \frac{E_+}{E_-}$

Energy Gain: $\leq RE_0$

$\sigma_f = 125 \, \mu m$, $n_e = 1.8 \times 10^{16} \, cm^{-3}$, $\lambda_p = 250 \, \mu m$

$E_0$: incoming energy

Q=30 pC/bunch, $\Delta z = 250 \, \mu m \approx \lambda_p$

Bunch Train

Q=15, 45, 75

Ramped Bunch Train*

$\Delta z = 375 \, \mu m \approx 1.5 \lambda_p$

Resonant excitation of wakefields

Large transformer ratio and energy gain (>2)

*Tsakanov, NIMA, 1999
Transformer Ratio: \( R = \frac{E_+}{E_-} \)  
\( \sigma_f = 125 \, \mu m, \, n_e = 1.8 \times 10^{16} \, cm^{-3}, \, \lambda_p = 250 \, \mu m \)  
Energy Gain: \( \leq R E_0 \)  
\( E_0 \): incoming energy

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

Kallos, PAC’07 Proceedings

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

Ramped Bunch Train*

*Tsakanov, NIMA, 1999

Resonant excitation of wakefields

Large transformer ratio and energy gain (>2)
Experimental Parameters:

- $E_0=59$ MeV
- $\sigma_r=100$ μm,
- $\Delta z=284$ μm,
- $d=142$ μm
- $\Delta z'=426$ μm
- $Q_{\text{tot}}=140$ pC
- $N_d=3D+W$
- $Q_b=35$ pC
- $L_p=2$ cm
- $n_b\approx 4\times 10^{13}$ cm$^{-3} \ll n_e$

Linear Regime!

- Resonant excitation of wakefield is the main feature
- Chirp such that W enters with highest energy
- $n_{e,\text{res}}\approx 1.4\times 10^{16}$ cm$^{-3} \Leftrightarrow \lambda_{pe}\sim \Delta z$
Resonant excitation of wakefield is the main feature

Chirp such that W enters with highest energy

$n_e,_{res} \approx 1.4 \times 10^{16} \text{ cm}^{-3} \iff \lambda_{pe} \sim \Delta z$
Resonant excitation of wakefield is the main feature.

Chirp such that W enters with highest energy.

\[ n_{e, \text{res}} \approx 1.4 \times 10^{16} \text{ cm}^{-3} \leftrightarrow \lambda_{pe} \approx \Delta z \]
Relative Energy

\[ \Delta z = 284 \mu m, \]
\[ d = 142 \mu m \]
\[ \Delta z' = 426 \mu m \]
\[ Q_{\text{tot}} = 140 \text{ pC} \]
\[ N_d = 3D + W \]
\[ Q_b = 35 \text{ pC} \]
\[ L_p = 2 \text{ cm} \]
\[ n_b \approx 4 \times 10^{13} \text{ cm}^{-3} \ll n_e \]

Linear Regime!

Resonant excitation of wakefield is the main feature

Chirp such that W enters with highest energy

\[ n_{e, \text{res}} \approx 1.4 \times 10^{16} \text{ cm}^{-3} \leftrightarrow \lambda_{pe} \sim \Delta z \]
Relative Energy

Plasma Density $n_e$ (cm$^{-3}$)

$\Delta z = 284$ $\mu$m,
$d = 142$ $\mu$m,
$\Delta z' = 426$ $\mu$m,
$Q_{\text{tot}} = 140$ pC,
$N_d = 3D+W$,
$Q_b = 35$ pC,
$L_p = 2$ cm.

$n_b \approx 4 \times 10^{13}$ cm$^{-3} \ll n_e$,
Linear Regime!

- Resonant excitation of wakefield is the main feature.
- Chirp such that $W$ enters with highest energy.
- $n_e, \text{res} \approx 1.4 \times 10^{16}$ cm$^{-3} \Leftrightarrow \lambda_{pe} \sim \Delta z$. 

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Resonance clearly observed $\leftrightarrow \lambda_{pe} \sim \Delta z$

Large energy loss, $\sim 1.95$ MeV or $\sim 97$ MeV/m (over 2cm)

Energy gain, 0.74 MeV or $\sim 37$ MeV/m
WITNESS BUNCH ACCELERATION

Experiment: $n_e \approx 8 \times 10^{15}$ cm$^{-3}$

- Acceleration of witness bunch
- Large energy loss, $\sim 0.42$ MeV or $\sim 21$ MeV/m (over 2 cm)
- Energy gain, 0.12 MeV or $\sim 6$ MeV/m
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Focus on acceleration all the way through!
Energy considerations (PWFA = energy transformer):

- A SLAC, 28.5GeV bunch with $2 \times 10^{10} e^-$ caries $\sim 90$J
  An ILC, 0.5TeV bunch with $2 \times 10^{10} e^-$ caries $\sim 1.6$kJ

- A SLAC-like driver for staging (FACET, +25GeV)

- A SPS, 450GeV bunch with $10^{11} p^+$ caries $\sim 7.2$kJ
  A LHC, 7TeV bunch with $10^{11} p^+$ caries $\sim 112$kJ

- A single SPS or LHC bunch could produce an ILC bunch in a single PWFA stage!

- Long plasmas required ($\sim 100$’s m)

- Requires short ($\sim 100\mu$m) p+ bunch
Use “pancake” $p^+$ bunch to drive non-linear wake (cylinder for $e^-$ driver)

- Gradient $\sim 1.5$GV/m (av.), efficiency $\sim 10$

ILC-like $e^-$ bunch from a single $p^+$-driven PWFA
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Self modulation of long (~12cm), 450GeV SPS bunch in $\lambda_p = 1.5\text{mm}$ plasma

- Growth of instability / $p^+$ density modulation / $E_z$
- Resonantly drives large amplitude (1-2GV/m) accelerating fields
- Injected $e^-$ gain $\sim 1\text{GeV}$ in 5-10m plasma
- Injected of short $e^-$ bunch would produce narrow $\Delta E/E$

Simulations: J. Vieira

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Letter of intent favorably reviewed by CERN SPSC

Detailed technical proposal due in one year

Experiments 2015-… for 1GeV in a few meters, self modulated

Program for TeV class e- from p⁺-driven PWFA, driven by MPP
TEST SELF-MODULATION @ SLAC

- Send long SLAC $e^-$ bunches ($\sigma_z \sim 700\mu$m) in plasma for short bunches ($n_e \sim 10^{17}\text{cm}^{-3}$)
- $E_0=20\text{GeV}$, $\sigma_r \sim 10\mu$m, $N=2\times10^{10}$
- $Z=10\text{cm}$
- S-M after $<10\text{cm}$
- $E_z > 20\text{MV/m}$
- Reach “blowout”
- Multi-GeV gain/loss
- Experiment will be proposed to SAREC for experiments in Summer 2012
- All components available (tinker toy experiment)
First evidence of self-modulation (in energy) in a plasma?

Coherent transition radiation energy ($\sim 1/\sigma_z$) measurements indicate S-M

Encouraging preliminary results

Will repeat next week ….
Test Self-modulation @ ATF-BNL

- $E_0=60\text{MeV}$, $\sigma_r \sim 100\mu\text{m}$, $N\sim 4\times10^9$, $L_z \sim 1500\mu\text{m}$

- Coherent transition radiation energy ($\sim 1/\sigma_z$) measurements indicate S-M

- First evidence of self-modulation (in energy) in a plasma?

- Encouraging preliminary results

- Will repeat next week ….
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  Two frequencies laser pulse, i.e., a train of pulses

- **Self-Modulated Laser Wakefield Accelerator (SMLWFA)**
  Raman forward scattering instability in a long laser pulse

- **Self-Modulated PWFA (SMPPWFA)**

SUMMARY AND CONCLUSIONS

- PWFA made remarkable progress
  - 42 GeV energy gain in 85 cm of plasma @ SLAC
- PWFA is well understood
  - [Link](http://www-rcf.usc.edu/~muggli/publications.html)
- FACET@SLAC will address PWFA collider issues
  - Acceleration of witness bunch ($\Delta E/E_0\sim1\%$), $e^+$, single $e^-/e^+$
  - +25 GeV PWFA stage
- Test the physics in low energy experiments (BNL-ATF)
- Proton-driven PWFA proposed to CERN, by MPP, first PWFA experiment in EU, only $p^+$ PWFA in the world (Fermilab???)
- PWFA at DESY, in Japan, Italy (COMB@Frascati), …
- $p^+$-PWFA will use self-modulation initially
- Exciting new self-modulation experiments with $e^-$ (SLAC-FACET, ATF, DESY, Diamond (UK), Russia. …)
- PWFA could be a technology candidate for future more compact (cheaper) colliders and light sources
Collaborations:

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Thank you!
Thank You!

The PWFA:

turning this … … into that!

RF-based acceleration

Plasma-based acceleration

Review of High-energy Plasma Wakefield Experiments:


Work supported by US Dept. of Energy