Advanced

Future Linear Collider Concepts

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Some of the largest and most complex (and most expensive) scientific instruments ever built!

All use radio frequency (RF) technology to accelerate particles

Can we make them smaller (and cheaper) and with a higher energy?
PARTICLE COLLIDERS

The future is ...

... large and larger...

(... because of higher and higher energies)
OUTLINE

✧ Introduction

✧ Novel Acceleration Techniques

✧ Summary
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PARTICLE COLLIDERS

“The 2.4-mile circumference RHIC ring is large enough to be seen from space.”

Hadron accelerators energy limited by magnetic field:

\[ r_{Larmor} = \frac{\gamma mc}{qB_0} = r_{accelerator} \]

\( B_0 \sim 8\text{T for LHC} \)  
\((p^+, 7\text{TeV, C=27km})\)

\( B_0 \sim 16\text{T for FCC} \)  
\((p^+, 50\text{TeV, C=100km})\)

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Some of the largest and most complex (and most expensive) scientific instruments ever built!

Light particles (e⁻/e⁺) accelerator
Limited by synchrotron radiation

\[ P_{\text{synchr}} = \frac{e^2}{6\pi\varepsilon_0 c^7} \frac{E^4}{R^2 m^4} \]

Linear for high energy!
Energy limited by the accelerating gradient:

\[ L = \frac{E(\text{eV})}{G(\text{eV} / \text{m})} \]

Can we make them smaller (and cheaper) and with a higher energy?

- e⁻/e⁺ 0-50GeV in 3km SLC
- e⁻/e⁺ 0-20GeV in 2km FACET
- e⁻ 0-14GeV in 1km LCLS

“The 2.4-mile circumference RHIC ring is large enough to be seen from space”
ACCELERATING STRUCTURES

✧ All HEP accelerators use (metallic) RF structures … maximize gradient …

✧ Cold, superconducting structures

✧ Warm structures

ILC cavities, 1.3GHz
 Field < 50MV/m

SLAC, 2.856GHz

CLIC, 12GHz
 Lecture: Walter Wuensch

Field < 200MV/m
ACCELERATING FIELD/GRADIENT LIMITATIONS

- Gradient/field limit in (warm) RF structures: <100MV/m
- RF break down (plasma!!) and pulsed heating fatigue
- Accelerating field on axis, damage on the surface
- Material limit, metals in the GHz freq. range (Cu, Mo, etc.)
- Does not (seem to) increase with increasing frequency

Pulsed heating fatigue
Pritzkau, PRSTAB 5, 112002 (2002)

RF break down
Braun, PRL 90, 224801 (2003)
ACCELERATING FIELD/GRADIENT LIMITATIONS

- Gradient/field limit in (warm) RF structures: <100MV/m
- RF break down (plasma!!) and pulsed heating fatigue
- Accelerating field limited to <100MV/m (low break-down rate)
- Does not (seem to) increase with increasing frequency

RF-accelerators:
Accelerating field limited to <100MV/m (low break-down rate) by metal damage:
- RF-breakdown
- pulsed heating

Copper: low damage threshold

Pulsed heating fatigue
Pritzkau, PRSTAB 5, 112002 (2002)

Braun, PRL 90, 224801 (2003)
Search for a new technology to accelerate particles at high-gradient (>100MeV/m) and reduce the size and cost of a future linear e⁻/e⁺ collider or of a x-ray FEL.

Some of the largest and most complex (and most expensive) scientific instruments ever built!

All use radio frequency (RF) technology to accelerate particles.

Can we make them smaller (and cheaper) and with a higher energy?
ADVANCED & NOVEL ACCELERATORS (ANAs)

Dielectric Laser Accelerator

Laser Wakefield Accelerator

Structure Wakefield Accelerator

Plasma Wakefield Accelerator

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P. Muggli, CAS 03/02/2016
ADVANCED & NOVEL ACCELERATORS (ANAs)

“Advanced”

“High-gradient”

>1 GeV/m (ICFA-ANA)

Average gradient over m-scale

GeV to TeV or beyond $e^-/e^+$

*do not include laser vacuum/direct acceleration
ADVANCED & NOVEL ACCELERATORS (ANAs)

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Average gradient over m–scale

GeV to TeV or beyond e–/e+

Novel materials with higher damage threshold:

- Dielectrics (~GV/m)
- Plasmas (10-100GV/m or ∞)

Novel drivers:

- Laser pulse(s)*
- Charged particle bunch(es)

*do not include laser vacuum/direct acceleration
**Advanced & Novel Accelerators (ANAs)**

- **“Advanced”**
- **“High-gradient”**
- $>1\text{GeV/m}$ (ICFA-ANA)
- Average gradient over m-scale
- GeV to TeV or beyond $e^-/e^+$

**Novel materials with higher damage threshold:**
- ✝ Dielectrics ($\sim \text{GV/m}$)
- ✝ Plasmas ($10-100\text{GV/m or } \infty$)

**Novel drivers:**
- ✝ Laser pulse(s)*
- ✝ Charged particle bunch(es)

<table>
<thead>
<tr>
<th>Medium</th>
<th>Dielectric</th>
<th>Plasma</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Driver</strong></td>
<td><strong>Dielectric Laser Accelerator</strong></td>
<td><strong>Laser Wakefield Accelerator</strong></td>
</tr>
<tr>
<td>Laser Pulse</td>
<td>DLA</td>
<td>LWFA</td>
</tr>
<tr>
<td>Particle Bunch</td>
<td>Structure Wakefield Accelerator</td>
<td>Plasma Wakefield Accelerator</td>
</tr>
<tr>
<td></td>
<td>SWFA</td>
<td>PWFA</td>
</tr>
</tbody>
</table>

*do not include laser vacuum/direct acceleration
**Advanced & Novel Accelerators (ANAs)**

Role of the novel structure / challenge: convert (some of) the transverse fields ($E_\perp$) of the novel driver (laser pulse, particle bunch) into a longitudinal ($E_z$) component for acceleration ($E_z > 1$ GV/m)

**Advantage of novel material:**
Sustain higher fields
- $E \sim 1$-10 GV/m for dielectrics
- $E \sim 100\,\infty$ GV/m for plasmas 😊

**Novel materials with higher damage threshold:**
- Dielectrics (~GV/m)
- Plasmas (10-100 GV/m or $\infty$)

**Novel drivers:**
- Laser pulse(s)*
- Charged particle bunch(es)

---

*do not include laser vacuum/direct acceleration*
**Advanced & Novel Accelerators (ANAs)**

**Laser Pulse:**
(Plane wave)

\[
\text{Intensity} \approx \frac{1}{2} \varepsilon_0 c E_\perp^2
\]

Example:
\( E_\perp = 1 \text{GV/m} \)
\( I \approx 10^9 \text{W/cm}^2 \)

**Charged Particle Bunch:**
(tri-Gaussian, relativistic)

\[
E_{\perp,\text{max}} \approx \frac{1}{2(2\pi)^{3/2}} \frac{e}{\varepsilon_0} \frac{N}{\sigma_r \sigma_z} \left(1 - e^{-1/2}\right)
\]

Example:
\( N = 2 \times 10^{10} \text{e}^-, \, \sigma_r = 10 \mu\text{m}, \, \sigma_z = 20 \mu\text{m} \)
\( E_\perp = 11 \text{GV/m} \)

**Poynting Vector:**
\[
\mathbf{S} = \frac{\mathbf{E} \times \mathbf{B}^*}{\mu_0}
\]

**Challenge / function of the accelerating structure:**
Convert a fraction of \( E_\perp \) into \( E_z \) (accel. \( \sim \int E_z \, dz \))
OUTLINE

✧ Introduction

✧ Novel Acceleration Techniques

✧ Directly use the laser E-field in a ~$\lambda^3$ (micro) structure

✧ Summary
Dielectric Laser Accelerator (DLA)
DiELECTric LASER ACCELERATOR (DLA)

- Take advantage of large laser E-field
- Take advantage of large damage threshold (SiO$_2$, Si, etc.)
- Structure = phase mask for velocity matching

DLA RESULTS

- Beam not bunches at $\lambda_{\text{laser}}$ scale -> broad spectrum ... possible bunching: IFEL
- Inferred accelerating gradient in excess of 300MeV/m
- Need sub-$\left(\lambda_{\text{laser}}\right)^3$ beams, naturally low emittance and charge
- Operate at very high rep-rate
DLA RESULTS

Demonstration of electron acceleration in a laser-driven dielectric microstructure

- Beam not bunches at $\lambda_{\text{laser}}$ scale -> broad spectrum ... possible bunching: IFEL
- Inferred accelerating gradient in excess of 800MeV/m
- Need sub-$(\lambda_{\text{laser}})^3$ beams, naturally low emittance and charge
- Operate at very high rep-rate

Presented by D. Cesar (UCLA) @ EAAC 2017
Novel Acceleration Techniques

- Directly use the laser E-field in a ~\(\lambda^3\) (micro) structure

**Introduction**

- Demonstrated ~1GeV/m
- Takes advantage of \(\mu\)-fabrication
- Takes advantage of rapid progress in fiber lasers
- Symmetric e\(^-\)/e\(^+\)
- Low emittance, low charge, high rep. rate
OUTLiNE

✧ Introduction

✧ Novel Acceleration Techniques

✧ Summary

✧ Cherenkov wakes in dielectric layers
**DiELECTRiC WAKEfiELD ACCELERATOR (DWA)**

- **Peak decelerating field**
  
  \[ eE_{z,\text{dec}} \approx \frac{-4N_b}{a} \frac{m_e c^2}{\sqrt{8\pi \left(\frac{\epsilon}{\epsilon - 1}\right) \sigma_z + a}} \]

- **Transformer ratio (unshaped beam)**
  
  \[ R = \frac{E_{z, \text{acc}}}{E_{z, \text{dec}}} \leq 2 \]
**DiELECTRIC WAKEFIELD ACCELERATOR (DWA)**

- **Peak decelerating field**
  
  \[ eE_{z,\text{dec}} \approx \frac{-4N_{m}e\mu_{m}c^{2}}{a\left[\frac{8\pi}{\varepsilon - 1}\sigma_{z} + a\right]} \]

- **Transformer ratio (unshaped beam)**
  
  \[ R = \frac{E_{z,\text{acc}}}{E_{z,\text{dec}}} \leq 2 \]

- \( \sigma_{z} = 100-10\mu m, \ N = 2 \times 10^{10} \ e^{-} \)
- \( a = 50 \mu m, \ b = 162 \mu m, \ \text{fused silica, } \varepsilon \approx 3, \ f_{1} \approx 470 \text{GHz} \)
- **Breakdown field at** 13.8±0.7 GV/m
- **Estimated max. decelerating field**: 11 GV/m
- **Estimated max. accelerating field**: 17 GV/m
DWA RESULTS

O’Shea et al., Nat. Comm. 7, 12763 (2016)

9.4\times10^9 e\n\nonlineq{G_d}{=252\pm14\text{MeV/m}}\n
6\times10^9 e^-\n\nonlineq{G_a}{=320\pm17\text{MeV/m}}\n\nonlineq{E_{\text{extraction}}}{=80\%}\n
2a=300\mu m\n2b=400\mu m\nSiO_2, \varepsilon=3-4?\nCu cladding

\nonlineq{\Delta E}{=220\pm3\text{MeV in 15 cm}}\n\nonlineq{G}{=1.347\pm0.020\text{GeV/m}}

\\\\
\begin{itemize}
\item GV/m demonstrated
\item Energy gain by W bunch!
\item Lack of proper beams
\end{itemize}
**DWA RESULTS**

**Acceleration in slab symmetric DWA**

- **Structure:**
  - SiO$_2$, planar geometry, beam gap 240µm
- **BNL ATF**
  - Flat beam
  - Long bunch structure with two peaks
- **Acceleration of trailing peak**
- **Robust start-to-end simulations for benchmarking**

**Slab geometry allows for:**
- Reduced transverse wakefields \( W'_{\text{per}} \sim k^3 \rightarrow 0 \) when \( \sigma_{//} \gg a \)
- More charge per bunch
- Demonstration of energy gain!

**Appropriate for “flat” collider beams?**

---

**Slab geometry:**
- \( \text{SiO}_2 \), \( a = 2.5 \mu\text{m} \), and beam loading quality factor \( Q = 1000 \); only the lowest frequency dipole-like mode is considered, with \( \sigma_{//} = 100 \mu\text{m} \) in the slab case.
- Comparison parameters: average current \( eN/eX \), transverse wake strength \( W'_{\text{per}}/eX \), and BBM growth length \( L_z \).

**Table 1.** Comparison of slab and cylindrical BBU with an average accelerating gradient of 1 GeV/m, fundamental wavelength \( \lambda_0 = 2 \pi/k_0 = 10.6 \mu\text{m} \), and beam loading quality factor \( Q = 1000 \); only the lowest frequency dipole-like mode is considered, with \( \sigma_{//} = 100 \mu\text{m} \) in the slab case.

<table>
<thead>
<tr>
<th>Slab case</th>
<th>Cylindrical case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average current</td>
<td>490 mA</td>
</tr>
<tr>
<td>Transverse wake (dominant dipole)</td>
<td>30 V/(mm²·FC)</td>
</tr>
<tr>
<td>Multibunch BBU growth length</td>
<td>15 cm</td>
</tr>
</tbody>
</table>

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Tremaine
PRE 56 7210 (1997)

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**Image:**
- Slab geometry:
  - \( L_z \approx 1.2 \text{mm} \)
  - \( \varepsilon_N = 2 \text{mm}-\text{mrad} \)
  - \( E_0 = 59 \text{MeV} \)
  - \( Q = 100 - 900 \text{pC} \)
  - \( L_z \approx 1.2 \text{mm} \)
  - \( \varepsilon_N = 2 \text{mm}-\text{mrad} \)

**Graph:**
- Energy Gain
  - \( G \approx 7 \text{MeV/m} \)
  - Slab Exp.
  - No Slab Exp.
  - Slab Sim.
  - No Slab Sim.

---

**Courtesy G. Andonian**
DWA RESULTS

Acceleration in slab symmetric DWA

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  - SiO$_2$, planar geometry, beam gap 240µm
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In cylindrical coordinates the field decreases as $1/r$:

$$E_r(r) = \frac{1}{2\pi\varepsilon_0} Q_{lin} \frac{1}{r}$$

In Cartesian coordinates the field is constant:

$$E_y(x) = \frac{1}{\varepsilon_0} Q_{lin} = cst$$

Appropriate for “flat” collider beams?

Courtesy G. Andonian
Dielectric "CLIC"
Demonstrated >1GeV/m

OUTLINE

✧ Introduction

✧ Novel Acceleration Techniques

✧ Summary

✧ Simple structure to fabricate
✧ Demonstrated >1GeV/m
✧ Demonstrated energy transfer efficiency
✧ Symmetric e⁻/e⁺
✧ Dielectric “CLIC”
OUTLINE

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✧ Summary
Novel Acceleration Techniques

Mmmmm … plasmas, is there anything they can’t do? (adapted from H. J. Simpson)
Relativistic Electron, Electrostatic Plasma Wave \((E_z/k, B=0)\):

First plasma wave discovered: Langmuir wave

Dispersion relation: \(\omega^2 = \omega_{pe}^2 = n_e e^2/\varepsilon_0 m_e\), \(\omega_{pe}\) plasma frequency, \(n_e\) plasma electron density

Longitudinal electric field, \(E_z/k, B=0\) – electrostatic wave

Erwin Langmuir, Nobel Prize in chemistry(!), 1932

Hannes Alfvèn, 1970, MHD

Wikipedia Plasma: (from Greek πλάσμα, "anything formed") is one of the four fundamental states of matter, the others being solid, liquid, and gas. A plasma has properties unlike those of the other states.

Plasma: "Gas" of charged (ionized) particles (e\(^-\), ions) that exhibits a collective behavior (screening, waves, etc.)
Relativistic Electron, Electrostatic Plasma Wave \((E_z / k, B=0)\):

\[
\nabla \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \quad \omega_{pe} = \left( \frac{n_e e^2}{\varepsilon_0 m_e} \right)^{1/2} \quad k_p E_z = \frac{\omega_{pe}}{c} E_z = \frac{n_e e}{\varepsilon_0} \quad E_z = \left( \frac{m_e c^2}{\varepsilon_0} \right)^{1/2} n_e^{1/2} \approx 100 \sqrt{n_e \left( \text{cm}^{-3} \right)} = 1 \text{ GV} / \text{m} \quad n_e = 10^{14} \text{ cm}^{-3}
\]

Cold Plasma “Wavebreaking” Field

\[
E_{WB} = m_e c \omega_{pe} / e
\]

Dawson, PRL (1959)
**PLASMAS**

✧ Relativistic Electron, Electrostatic Plasma Wave \((E_z//k, B=0)\):

\[
\vec{\nabla} \cdot \vec{E} = \frac{\rho}{\varepsilon_0} \\
\omega_{pe} = \left( \frac{n_e e^2}{\varepsilon_0 m_e} \right)^{1/2} \text{Plasma Frequency} \\
k_p E_z = \frac{\omega_{pe}}{c} E_z = \frac{n_e e}{\varepsilon_0}
\]

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

\[
E_{WB} = m_e c \frac{\omega_{pe}}{e}
\]

Dawson, PRL (1959)

✧ Plasmas can sustain very large (collective) \(E_z\)-field, acceleration

✧ Wave, wake phase velocity = driver velocity (\(\sim c\) when relativistic, \(\omega^2=\omega_{pe}^2\))

✧ Plasma is already (partially) ionized, difficult to “break-down”

✧ No structure to build …. Wave in a uniform medium …

✧ Plasmas wave or wake can be driven by:

- Intense laser pulse (LWFA)
- Dense particle bunch (PWFA)
Plasmas

Relativistic Electron, Electrostatic Plasma Wave \((E_z/k, B=0)\):

\[ \mathbf{\nabla} \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0} \]

\( \omega_{pe} = \left( \frac{n_e e^2}{\varepsilon_0 m_e} \right)^{1/2} \)

Plasma Frequency

\[ k_p E_z = \frac{\omega_{pe}}{c} E_z = \frac{n_e e}{\varepsilon_0} \]

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

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

Cold Plasma “Wavebreaking” Field

\[ E_{WB} = m_e c \omega_{pe} / e \]

Dawson, PRL (1959)

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- Dense particle bunch (PWFA)
4 Plasma-based Accelerators*

• Plasma Wakefield Accelerator (PWFA)
  A high energy particle bunch ($e^-, e^+, ...$)

• Laser Wakefield Accelerator (LWFA) *
  A short laser pulse (photons, ponderomotive)

• 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 (LWFA of 20th century)

4 PLASMA-BASED ACCELERATORS*

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

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  Raman forward scattering instability in a long pulse (LWFA of 20\(^{th}\) century)
  
OUTLINE

✿ Introduction

✿ Novel Acceleration Techniques

✿ Summary

✿ Intense laser pulse to drive wakefields in a plasma

U. Oxford
Laser pulse ponderomotive force (~light pressure) drives the wakefields

Typical parameters:
Laser: $I=10^{18}-10^{20}\text{W/cm}^2$, ~40fs, $w_0=10\mu\text{m}$
Plasma: $n_e=10^{18}-10^{20}\text{cm}^{-3}$

- Most active field
- Availability of TW Ti:Sapphire laser systems
- Few TW for 10-100MeV $e^-$ in a few mm
- Medical, THz/x-ray source, …
**LASER WAKEFIELD ACCELERATOR (LWFA)**

- Wakefields driven by ponderomotive force of an intense laser beam
  \[ a_0 = \frac{v_{osc}}{c} = eE_0/mc\omega_0^2 \approx 1 \quad a_0 = \frac{v_{osc}}{c} = 8.5 \times 10^{-10} \lambda_0 [\mu m] I_0^{1/2} [Wcm^{-2}] \]

- "Forced" or "bubble" regime
  \[ a_0 \sim 1 \]

- "Monoenergetic" bunches (self-trapped)
- Short laser pulse \( (a_0 > 1) \)

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S. P. D. MANGLES et al. (IC)
C. G. R. GEDDES et al. (LBNL)
J. FAURE et al. (LOA)
_Nature_ 431, 2004

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P. Muggli, CAS 03/02/2016
Laser Wakefield Accelerator (LWFA)

- Wakefields driven by ponderomotive force of an intense laser beam
  \[ a_0 = \frac{v_{osc}}{c} = \frac{eE_0}{mc\omega_0^2} \approx 1 \]
  \[ a_0 = \frac{v_{osc}}{c} = 8.5 \times 10^{-10} \lambda_0 [\mu m] I_0^{1/2} [W/cm^2] \]

- "Forced" or "bubble" regime

- Finite energy spread with the "forced" or "bubble" regime

- "Monoenergetic" bunches (self-trapped)
- Short laser pulse \((a_0 > 1)\)
LWFA RESULTS

- PW laser pulse (300TW)
- Peak energy gain 4.2GeV in <10cm
- Self-trapped plasma $e^-$

- LWFA does NOT need conventional injector
- $e^-$ trapped from the plasma

$E_{\text{av}}=4.2$ GeV, $\Delta E/E_{\text{RMS}}=6\%$
$Q=6$ pC
$\Theta_{\text{rms}}=0.3$ mrad
$L_p=9$cm, $n_e=7\times10^{17}$cm$^{-3}$
Capillary discharge
$P_{\text{laser}}\approx0.3$PW
$W=16$J, $\alpha_r=52\mu$m, $\tau=42$fs
1) Wave breaking: drive the wave very non linearly (Dawson, PRL, 1956)

2) Ionization trapping
(Oz, PRL 98, 084801 (2007), Hidding, PRL 108 035001 (2012))

3) Three- two laser beams

4) Density step (Suk PRL 86, 1011)

5) Density down-ramp

6) Shock in a gas jet (Schmid PRST-AB 13, 091301 (2010)

7) External injection

Overview of plasma-based accelerator concepts, E. Esarey et al., IEEE TPS, 24(2), 252 (1996)
1) Wave breaking: drive the wave very non linearly (Dawson, PRL, 1956)

2) Ionization trapping
(Oz, PRL 98, 084801 (2007), Hidding, PRL 108 035001 (2012))

3) Three- two laser beams

4-5) Density step

6) Shock in a gas jet (Schmid PRST-AB 13, 091301 (2010)

7) External injection

LWFA is also an e⁻ injector

Overview of plasma-based accelerator concepts, E. Esarey et al., IEEE TPS, 24(2), 252 (1996)
**OUTLINE**

✦ Introduction

✦ Novel Acceleration Techniques

![Diagram](image)

✦ Summary

✧ No structure to fabricate
✧ Demonstrated >100 GeV/m
✧ Demonstrated large energy gain
✧ LWFA is also the injector (e−)
✧ Not symmetric e−/e+

✧ Intense laser pulse to drive wakefields in a plasma

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Introduction

Novel Acceleration Techniques

Dense, relativistic particle bunch ($e^-$, $e^+$, $p^+$, ...) to drive wakefields in plasma

Summary
Plasma wave/wake excited by a relativistic particle bunch

Plasma e\(^{-}\) expelled by space charge force $\Rightarrow$ deceleration + focusing (MT/m)

Plasma e\(^{-}\) rush back on axis $\Rightarrow$ acceleration, GV/m

Ultra-relativistic driver $\Rightarrow$ ultra-relativistic wake
$\Rightarrow$ no dephasing

Particle bunches have long “Rayleigh length”
(beta function $\beta^* = \sigma^2/\varepsilon \sim \text{cm, m}$)

Acceleration physics identical PWFA, LWFA
PWFA NUMBERS (e⁻)

Defocusing
Accelerating
Decelerating (∂E/∂z)
Neutral Plasma
Relativistic e⁻ bunch

✧ Linear theory
(n_b<<n_e) scaling:

\[ E_{\text{acc}} \cong 110 \text{(MV/m)} \frac{N/2 \times 10^{10}}{\left(\sigma_z / 0.6\text{mm}\right)^2} \approx N/\sigma_z^2 \]

@ \( k_{\text{pe}} \sigma_z \approx \sqrt{2} \) (with \( k_{\text{pe}} \sigma_r \ll 1 \))

\[ k_{\text{pe}} = \frac{\omega_{\text{pe}}}{c} \propto n_e^{1/2} \]

✧ Focusing strength:

\[ B_\theta = \frac{1}{2} \frac{n_e e}{\varepsilon_0 c} \]

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

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

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

✧ Conventional accelerators: MHz-GHz, \( E_{\text{acc}} < 150 \text{ MV/m}, B_\theta / r < 2 \text{ kT/m} \)
**PWFA NUMBERS ($e^-$)**

**Focusing ($E_r$)**

**Decelerating ($E_z$)**

**Defocusing**

**Accelerating**

Neutral Plasma

Relativistic $e^-$ bunch

**Linear theory**

$(n_b << n_e)$ scaling:

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

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

\[ k_{pe} = \frac{\omega_{pe}}{c} \propto n_e^{1/2} \]

**Focusing strength**:

\[ \frac{B_\theta}{r} = \frac{1}{2} \frac{n_e e}{\varepsilon_0 c} \]

\((n_b > n_e)\)

**Neutral Plasma**

\[ B_\theta r = \frac{1}{2} n_e e \varepsilon_0 c \]

**Neutral and Plasma**

\[ k_{pe} = \frac{\omega_{pe}}{c} \propto n_e^{1/2} \]

**Conventional accelerators**

MHz-GHz, \( E_{\text{acc}} < 150 \text{ MV/m}, B_\theta / r < 2 \text{ kT/m} \)

**Frequency**

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

**N=2\times10^{10}**:

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

\( \sigma_z = 20 \mu m, n_e = 2 \times 10^{17} \text{ cm}^{-3}, E_{\text{acc}} \sim 10 \text{ GV/m}, B_\theta / r = 6 \text{ MT/m} \)
Drive/witness bunch experiment
Low wakefield amplitudes (low $n_e$, long bunches, ...)

FIG. 1. Schematic of Argonne National Laboratory AATF layout.

FIG. 2. Scan 1: Witness-beam energy-centroid change $\delta E$ vs time delay behind driver. Total driver-beam charge $Q = 2.1$ nC; plasma parameters $L = 28$ cm and $n_e = 8.6 \times 10^{12}$ cm$^{-3}$. Theoretical predictions are given by the dashed line.

Rosenzweig, PRL 61, 98 (1988)

$\tau \approx 38$ ps = $\frac{2\pi}{\omega_{pe}}$

$\sim$ MV/m
PLASMA WAKEFIELD ACCELERATOR (e⁻)

Focusing ($E_r$)
Defocusing
Accelerating
Decelerating ($E_z$)

Relativistic $e^-$ bunch


Hogan, Phys. Rev. Lett. 95, 054802 (2005)
Muggli, Hogan, Comptes Rendus Physique, 10 (2-3), 116 (2009)

$n_e=2.3\times10^{17}\text{cm}^{-3}$
$\sigma_z\sim\sigma_r\sim20\mu\text{m}$
$N=2\times10^{10}$
$E_0=42\text{GeV}$
$I\sim10\text{kA}$

$42 \Rightarrow 84\text{GeV in 85cm!} \ 50\text{GeV/m}$
Figure 8. The most probable energy of witness bunch particles as a function of propagation distance in plasma is shown in the figure. The energy spectrum of the drive and witness bunch after 85 cm of plasma is also depicted.

The drive bunch particles lose a significant fraction of their energy and actually begin to slow down as the position of the peak decelerating field rapidly moves back in the speed of light frame. At the same time, its magnitude drops. However, the position of the peak accelerating field, the spike in figure 7, and more importantly the plateau in the acceleration field where most of the witness bunch particles reside, does not change in this frame, and the witness bunch moves with the wakefield without dephasing.

3.6. Efficiency

Figure 8 shows energy gain defined as the most probable energy of the witness bunch particles as a function of propagation distance for the simulations of figure 7. The energy gain is almost linear up to a distance of \( \approx 65 \) cm. At a distance of \( 85 \) cm, the initially \( 5 \) GeV witness bunch has doubled in energy with an \( \approx 3 \) GeV energy spread, as seen in figure 8. While the witness bunch is monoenergetic, much of the drive bunch has lost nearly all its energy. We have estimated various efficiencies in the simulations. The energy transfer efficiency from the wake to the witness bunch is almost \( 56\% \). The efficiency from the drive to the witness bunch is greater than \( 3\% \).

The overall drive to witness bunch transfer energy efficiency can be improved by using bunches with longitudinal current profiles tailored such that all longitudinal slices of the drive bunch lose energy at the same rate, except for the very first and the last ones. This is accomplished by ramping up the current along the bunch. The optimum longitudinal current shape is trapezoidal \([33]\) with a long rise time and a sharp fall time. In that case, the peak decelerating wakefield remains constant along the drive bunch, while the peak accelerating field left behind the bunch keeps increasing with the bunch length. The transformer ratio then scales as \( \pi \) times the number of plasma wavelengths covered by the bunch, and can be much larger than \( tw \). More sophisticated bunch profiles can lead to even larger enhancements of \( Rw \).


SLAC FACET

E200

Hogan, NJP 12, 055030 (2010)

42 => 84GeV in 85cm! 50GeV/m
**PLASMA WAKEFIELD ACCELERATOR (e⁻)**

- **e⁻ Witness**
- **e⁻ Driver**
- **e⁻ bunch**

"quantity"

"quality"


**SLAC FACET**

**E200**

**Litos, Nature 515(6) 92 (2014)**

**Experiment**

- Energy Loss
- Energy Gain
- $n_e = 2.3 \times 10^{17} \text{ cm}^{-3}$
- $\sigma_z = 20 \mu m$

**Scalloping of the Beam**

- $E_0$
- $2E_0$

42 => 84GeV in 85cm! 50GeV/m

$\Delta E/E \sim %$

$\eta \sim 30\%$
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)
**p+-DRiven PWFA? YES BUT WHY?**

- 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)

- Wakefields driven by $e^+$ bunch: Blue, PRL 90, 214801 (2003)
Accelarate an $e^-$ bunch on the wakefields of a $p^+$ bunch

- Single stage, no gradient dilution
- Gradient $\sim 1$ GV/m over 100’s m
- Operate at lower $n_e (6 \times 10^{14} \text{cm}^{-3})$, larger $(\lambda_{pe})^3$, easier life …

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
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<tbody>
<tr>
<td>Protons in drive bunch</td>
<td>$N_p$</td>
<td>$10^{11}$</td>
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</tr>
<tr>
<td>Proton energy</td>
<td>$E_p$</td>
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<td>TeV</td>
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<tr>
<td>Initial proton momentum spread</td>
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<td>Initial proton bunch longitudinal size</td>
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<tr>
<td>Initial proton bunch angular spread</td>
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<tr>
<td>Initial proton bunch transverse size</td>
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<tr>
<td>Electrons injected in witness bunch</td>
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<tr>
<td>Energy of electrons in witness bunch</td>
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<td>10</td>
<td>GeV</td>
</tr>
<tr>
<td>Free electron density</td>
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<td>$\text{cm}^{-3}$</td>
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<tr>
<td>Plasma wavelength</td>
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<tr>
<td>Magnetic field gradient</td>
<td>$B$</td>
<td>1,000</td>
<td>T m$^{-1}$</td>
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<tr>
<td>Magnet length</td>
<td>$L$</td>
<td>0.7</td>
<td>m</td>
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</table>

$E_0=10\text{GeV}$

$e^-:
N=10^{10}$
$W_0=16\text{J}$

$p^+:
E_0=1\text{TeV}$
$\sigma_z=100\mu$m
$N=10^{11}$
$W_0=16\text{kJ}$

$\sigma_z=100\mu$m
$N=10^{11}$
$W_0=16\text{kJ}$

$\Delta E/E \sim 1\%$

Energy (TeV)

- $\sim 0.5\text{TeV}$
- $\sim 300\text{m}$
Short (100µm) bunches with $10^{11}$ p+ do not exist!!!

CERN PS-SPS-LHC $\sigma_z \sim 6$-12cm

Operate at lower $n_e$ ($6 \times 10^{14}$cm$^{-3}$), larger $\lambda_{pe}^3$, easier life …
Use a long ($\sigma_z \gg \lambda_{pe}$), relativistic (400GeV/p\(^+\)), high energy (~20kJ) p\(^+\) bunch to resonantly drive large amplitude wakefields ($E_z \sim 1$GV/m) in a long (~10\(^+\)m) plasma.

Demonstrated self-modulation of the long proton bunch by the plasma wakefields.
Use a long ($\sigma_z \gg \lambda_{pe}$), relativistic (400GeV/p\(^+\)), high energy (~20kJ) p\(^+\) bunch to resonantly drive large amplitude wakefields ($E_z \sim 1$GV/m) in a long (~10\(^+\)m) plasma

Demonstrated self-modulation of the long proton bunch by the plasma wakefields

External injection of e\(^-\) for acceleration

Development of a physics case and e\(^-\)/p\(^+\) collider design
Novel Acceleration Techniques

- Dense, relativistic particle bunch (e⁻, e⁺, p⁺, …) to drive wakefields in plasma

- No structure to fabricate
- Demonstrated >50GeV/m
- Demonstrated large energy gain
- Not symmetric e⁻/e⁺
- Application to e⁻/e⁺ and e⁻/p⁺ colliders
**INTRODUCTION**

- Introduction

**NOVEL ACCELERATION TECHNIQUES**

<table>
<thead>
<tr>
<th>Driver</th>
<th>Medium</th>
<th>Dielectric</th>
<th>Plasma</th>
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</thead>
<tbody>
<tr>
<td>Laser Pulse</td>
<td>Dielectric</td>
<td>Dielectric Laser Accelerator</td>
<td>Laser Wakefield Accelerator</td>
</tr>
<tr>
<td></td>
<td></td>
<td>DLA</td>
<td>LWFA</td>
</tr>
<tr>
<td>Particle Bunch</td>
<td>Structure</td>
<td>Structure Wakefield Accelerator</td>
<td>Plasma Wakefield Accelerator</td>
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<tr>
<td></td>
<td>Wakefield</td>
<td>SWFA</td>
<td>PWFA</td>
</tr>
</tbody>
</table>

**SUMMARY**
SUMMARY

✧ Advance and novel accelerators (ANAs) have demonstrated very high gradient acceleration (1-100GeV/m)

✧ Large energy gains have been achieved:
  0-4.2GeV in ~ 9cm plasma (LWFA)
  42-84GeV in ~85cm plasma (PWFA)

✧ Schemes based on dielectrics are symmetric for the acceleration of e⁻ and e⁺

✧ Challenges remain in producing beams of collider quality

✧ Concepts/straw-man design of ANA-based colliders exist …
  ✧ e⁻/e⁺ collider, Higgs physics
  ✧ e⁻/p⁺ collider, QED, p⁺ structure physics
  ✧ Reduction in length by a factor of a few

✧ Long term possibility:
  ✧ ANA part of an energy upgrade of a linear collider (CLIC, ILC)
  ✧ ANA replaces “conventional” accelerator parts
  ✧ ANAs need to meet all challenges of colliders
**p⁺-DRIVEN PWFA FOR e⁻/p⁺ COLLIDER**

- Emphasis on using current infrastructure, i.e. LHC beam with minimum modifications.
- Overall layout works in powerpoint.
- Need high gradient magnets to bend protons into the LHC ring.
- One proton beam used for electron acceleration to then collider with other proton beam.
- High energies achievable and can vary electron beam energy.
- What about luminosity?
- Assume
  - ~3000 bunches every 30 mins, gives $f \sim 2$ Hz.
  - $N_p \sim 4 \times 10^{11}$, $N_e \sim 1 \times 10^{11}$
  - $\sigma \sim 4 \mu m$

Simulation of existing LHC bunch in plasma with trailing electrons …


PWFA FOR e⁻/e⁺ COLLIDER

PWFA Research Roadmap for Electron Driver: Goal is to Get to a TeV Scale Collider for High Energy Physics

PWFA-LC concepts highlight key issues and help us prioritize our research programs e.g. efficiency, positrons

Presented at ANAR 2017 WG Summary by M.J. Hogan
PWFA FOR e⁻/e⁺ COLLIDER


2016, Vol. 16 on Advanced Accelerators
Figure 6. A 2-TeV electron–positron collider based on laser-driven plasma acceleration might be less than 1 km long. Its electron arm could be a string of 100 acceleration modules, each with its own laser. A 30-J laser pulse drives a plasma wave in each module’s 1-m-long capillary channel of pre-formed plasma. Bunched electrons from the previous module gain 10 GeV by riding the wave through the channel. The chain begins with a bunch of electrons trapped from a gas jet just inside the first module’s plasma channel. The collider’s positron arm begins the same way, but the 10-GeV electrons emerging from its first module bombard a metal target to create positrons, which are then focused and injected into the arm’s string of modules and accelerated just like the electrons.

Lemmans, Physics Today 62, 3, 44 (2009)

… and concepts for SWFA and DLA also exist …
RF-based acceleration …

… plasma-based acceleration

I. Blumenfeld

Yeah, it’s kinda like that …

… it will change your life!
Thank you!

http://www.mpp.mpg.de/~muggli
muggli@mpp.mpg.de