Energy Doubling of 42 GeV Electrons in a Plasma Wakefield Accelerator

Rasmus Ischebeck, Stanford Linear Accelerator Center

Accelerators for TeV–Energy electrons

Present Technologies

Advanced Accelerator Research at SLAC

Electron beam driven Dielectric Structures

Laser–driven Dielectric Structures

Plasma Wakefield Accelerators

Rasmus Ischebeck – Energy Doubling of 42 GeV Electrons, PSI, 2007–09–26
History of Electron Accelerators

Livingston Plot
Basic Requirements for Electron Accelerators beyond ILC

- Energy \( W \gtrsim 5\ldots10 \text{ TeV} \) \( W = E \cdot e \cdot L \) (Linac)

- Luminosity \( \mathcal{L} \gtrsim 10^{36} \text{ cm}^{-2} \text{ s}^{-1} \)

\[ \mathcal{L} = \frac{N^2 f}{4\pi \sigma_x \sigma_y} \]

\( \Rightarrow \) Beam power \( P \approx 100 \text{ MW} \)

- Cost \( C \lesssim 5 \cdot 10^9 \)

- High accelerating fields
- Low emittance (small diameter)
- High bunch charge
- Good efficiency
Not an Option for 10 TeV

- Build a circular accelerator
  - Synchrotron radiation proportional to $E^4$
- Build a linear accelerator based on state-of-the-art RF cavities
  - Accelerating field 0.05 GV/m
  - 300 km long (with focus and beam delivery)
  - Cost: $3 \cdot 10^{10}$

Therefore

- Need to increase the accelerating fields (without increasing the cost by the same factor)
- Explore alternative acceleration techniques
Electromagnetic Waves in Vacuum

- Transverse electric fields
- Moreover, the Lawson–Woodward Theorem states:
  - the total acceleration
    - of ultrarelativistic particles
    - by far-field electromagnetic waves
  - is zero
⇒ Need near-field structures
Possibilities for Accelerating Structures

<table>
<thead>
<tr>
<th>Structure</th>
<th>max. Field (V/m)</th>
<th>Power Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superconducting</td>
<td>$5 \cdot 10^7$</td>
<td>solid state</td>
</tr>
<tr>
<td></td>
<td></td>
<td>electron beams: klystrons</td>
</tr>
<tr>
<td>Metallic</td>
<td>$2 \cdot 10^8$</td>
<td>solid state</td>
</tr>
<tr>
<td></td>
<td></td>
<td>electron beams: klystrons or</td>
</tr>
<tr>
<td></td>
<td></td>
<td>integrated structure</td>
</tr>
<tr>
<td>Dielectric</td>
<td>$10^9$</td>
<td>laser</td>
</tr>
<tr>
<td></td>
<td></td>
<td>electron beams</td>
</tr>
<tr>
<td>Plasma</td>
<td>$10^{11}$</td>
<td>laser</td>
</tr>
<tr>
<td></td>
<td></td>
<td>electron beams</td>
</tr>
</tbody>
</table>

Plus: Inverse FEL, disposable structures, excited atoms, muon colliders
Energy Doubling of 42 GeV Electrons in a Plasma Wakefield Accelerator
Rasmus Ischebeck, Stanford Linear Accelerator Center

Electron beam driven Dielectric Structures

Laser-driven Dielectric Structures

Plasma Wakefield Accelerators
Energy Doubling of 42 GeV Electrons in a Plasma Wakefield Accelerator

Rasmus Ischebeck, Stanford Linear Accelerator Center

Electron beam driven Dielectric Structures

Laser-driven Dielectric Structures

Plasma Wakefield Accelerators
Dielectric Wakefield Acceleration
The T-481 Experiment

- M.C. Thompson, H. Badakov, J. Rosenzweig, and G. Travish (UCLA)
- M.J. Hogan, R. Ischebeck, N. Kirby, R. Siemann, and D. Walz (SLAC)
- P. Muggli (USC)
- A. Scott (UCSB)
- R. Yoder (Manhattan College)
Dielectric Wakefield Acceleration

Experimental Setup
Dielectric Wakefield Acceleration

Breakdown Studies

100 µm bunch length  20 µm bunch length
Dielectric Wakefield Acceleration

Next Experiments

Measure the Cherenkov radiation emitted from the fiber

Try alternative materials (e.g. diamond)

Accelerate Second Bunch
Energy Doubling of 42 GeV Electrons in a Plasma Wakefield Accelerator
Rasmus Ischebeck, Stanford Linear Accelerator Center

Electron beam driven Dielectric Structures

Laser–driven Dielectric Structures

Plasma Wakefield Accelerators
Laser Acceleration
The E–163 Experiment

• R. Byer, T.I. Smith, Y.C. Huang, T. Plettner, P. Lu, and J.A. Wisdom (Stanford)
• L. Schächter (Techion Israeli Institute of Technology)
• J. Rosenzweig (UCLA)
Dielectric Accelerator Structures

- Using much higher frequencies: THz to optical
- Using dielectrics (e.g. SiO₂)
- Advantages: higher damage threshold
  ⇒ Higher accelerating fields, up to ~GV/m

- Generate the electromagnetic field
  - Cherenkov radiation from an electron beam
  - Laser
- Confine the field
  - Photonic band gap
Photonic Crystals

periodic electromagnetic media

with photonic band gaps: “optical insulators”
Band Gap maps

- Solutions of the wave equation

\[ \vec{\nabla} \times \frac{1}{\varepsilon \varepsilon_0} \times \vec{H} = \left( \frac{\omega}{c} \right)^2 \vec{H} \]

\[
\begin{align*}
\frac{r}{a} &= 0.47 \\
\frac{r}{a} &= 0.4737 \ (r = 1.8 \ \mu m) \\
\frac{r}{a} &= 0.48
\end{align*}
\]

\[ r/a = 0.47 \]

\[ r/a = 0.4737 \ (r = 1.8 \ \mu m) \]

\[ r/a = 0.48 \]

\[ \lambda = 1.5 \ \mu m \]
Dielectric Accelerator Structures
Photonic Band Gap Structures
Laser Acceleration

First Experiments

• Establish interaction between laser and electron beam
Laser Acceleration

First Experiments

• Inverse free electron laser
• Inverse transition radiation
Inverse Transition Radiation

- Scanning the laser timing with respect to the electron beam
Laser Acceleration

Next Steps

• Net acceleration by combining IFEL, chicane and ITR
• Fabricate suitable structures
  • Side–coupled
  • Photonic bandgap fiber
• Measure spectrum emitted from structures
• Accelerate particles
Energy Doubling of 42 GeV Electrons in a Plasma Wakefield Accelerator

Rasmus Ischebeck, Stanford Linear Accelerator Center

Electron beam driven Dielectric Structures

Laser-driven Dielectric Structures

Plasma Wakefield Accelerators
Plasma Wakefield Acceleration
The E–167 Experiment

- C.E. Clayton, C. Huang, D. Johnson, C. Joshi*, W. Lu, K.A. Marsh, W.B. Mori, and M. Zhou (UCLA)
- S. Deng, T. Katsouleas, P. Muggli* and E. Oz (USC)
Plasma Wakes – Theory

• Unlike electromagnetic waves in vacuum, plasma wakes can have a longitudinal electric field

• Tajima & Dawson, *PRL, 43, 267(1979)*

• Linear plasma wake:

\[ \lambda_p \approx \sqrt{\frac{10^{15} \text{cm}^{-3}}{n_p}} \text{ mm} \]

• Limit:

\[ E_0 = \frac{4\pi \varepsilon_0 c m_e}{c} \omega_p \approx \sqrt{\frac{n_p}{\text{cm}^{-3}}} \frac{\text{V}}{\text{cm}} \]
Plasma Wakes – Theory

- Above this limit: non-linear wakes, “Blow-out regime”
- Fields can be calculated only with numerical methods

- Typical wavelength: 50 µm
- Accelerating fields up to 50 GV/m
Plasma Wakes – Reality
Drive the Plasma Wake

- Typical drive beam power: $\sim 10^{15} \text{ W} = 1 \text{ TW}$
- Power density: $\sim 10^{24} \text{ W/m}^2 = 1 \text{ YW/m}^2$
- Drive the plasma wake:
  - Photons
  - Electrons
Plasma Wakefield Acceleration at SLAC
Experimental Setup

e⁻ beam from SLAC linear accelerator

\( e^- \) bunch length autocorrelation of coherent transition radiation (CTR)

\( e^- \) spectrum X-ray based spectrometer

\( e^- \) spatial distribution optical transition radiation (OTR)

plasma oven

\( \text{Čerenkov cell} \)

\( \text{spectrometer magnet} \)

\( \text{Čerenkov monitor} \)

imaging \( \text{Čerenkov monitor} \)

\( e^- \) spectrum Čerenkov light in air gap

beam stopper

notch collimator
Previous Results

More than 3 GeV energy gain in 10 cm plasma length
Increasing the Plasma Length to 30.5 cm

<table>
<thead>
<tr>
<th>Plasma Length</th>
<th>Energy Gain</th>
<th>Energy Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Plasma</td>
<td>13 cm FWHM</td>
<td>22.5 cm FWHM</td>
</tr>
<tr>
<td>30.5 cm FWHM</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Changes to the Experimental Setup

- Longer plasma oven
- New spectrometer
- Diagnostics for low-energy particles
- Increased the energy in the drive beam
Energy Doubling

- Plasma length: 85 cm
- Density: $2.7 \cdot 10^{23} \text{ m}^{-3}$
- Incoming energy: 42 GeV
- Peak energy: $85 \pm 7 \text{ GeV}$
Stability
Peak Energy in 800 Events

≥30 GeV peak energy gain in more than 30% of the events
Simulations

- Particle-In-Cell codes:
  - full PIC code: approximately 132,000 CPU hours for 85 cm plasma
  - QuickPIC: quasi-static approximation, 2760 CPU hours

- Simulation of
  ⇒ field ionization
  ⇒ motion of beam and plasma electrons
  ⇒ wake formation
  ⇒ acceleration
  ⇒ energy spectrum
Comparison to Simulations

![Graph showing charge density vs. electron energy, with experimental and simulated curves.]
Plasma Wakefield Acceleration

There is still Work to Do...

- Understand (and exploit) self-injection
- Scaling to higher energies
  - Hose instability effect
  - Ion motion
- Acceleration of positrons
Livingston Plot

- LEP II
- SLC (SLAC)
- LEP (CERN)
- PETRA (DESY)
- TRISTAN (KEK)
- PEP (SLAC)
- CESR (Cornell)
- VEPP IV
- SPEAR II
- VEPP III (Novosibirsk)
- DORIS (DESY)
- Synchro-Cyclotron (CERN)
- ADONE (Italy)
- SPEAR (SLAC)
- Betatron (Kerst)
- PRIN-STAN (Stanford)
- ACC (France)
- VEPP II (Novosibirsk)
- Alt-Ray (Van de Graaf)
- Rectifier (Cockcroft & Walton)
- Alternating-Field (Wideroe)
An Unfair Comparison
There is More to Accelerating Structures than the Accelerating Field

- Power sources
- Beam loading
- Emittance preservation
  - Non-linear transverse forces
  - Wakefields

There is Much More to an Accelerator than Accelerating Structures

- Particle sources (injectors)
- Bend magnets for storage rings
- Focusing, beam dynamics
- Detectors
Thank You!

- The E-167 Collaboration
  - C.E. Clayton, C. Huang, D. Johnson, C. Joshi*, W. Lu, K.A. Marsh, W.B. Mori, and M. Zhou (UCLA)
  - S. Deng, T. Katsouleas, P. Muggli* and E. Oz (USC)

- The E-163 Collaboration
  - R. Byer, T.I. Smith, Y.C. Huang, T. Plettner, P. Lu, and J.A. Wisdom (Stanford)
  - L. Schächter (Techion Israeli Institute of Technology)
  - J. Rosenzweig (UCLA)

- The GigaWake Dielectric Accelerator Experiment
  - M.C. Thompson, H. Badakov, J. Rosenzweig, and G. Travish (UCLA)
  - M.J. Hogan, R. Ischebeck, N. Kirby, R. Siemann, and D. Walz (SLAC)
  - P. Muggli (USC)
  - A. Scott (UCSB)
  - R. Yoder (Manhattan College)

- Special thanks to
  - H. Weise, F. Tecker, D. Sutter, N. Kirby, E. Oz

- Work supported by Department of Energy contracts DE-AC02-76SF00515 (SLAC), DE-FG03-92ER40745, DE-FG03-98DP00211, DE-FG03-92ER40727, DE-AC-0376SF0098, DE-AC02-76SF00515 and National Science Foundation grants No. ECS-9632735, DMS-9722121 and PHY-0078715.
85 cm Plasma

113 cm Plasma
Simulations

- Determine head erosion as the reason for energy gain limitation