Advanced Accelerator Concepts

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Accelerators for Basic Research and Applications

Present Technologies

Dielectric Structures

Plasma Wakefield Accelerators
History of Electron Accelerators
Livingston Plot

![Graph showing the history of electron accelerators with markers for different accelerators and their beam energies and years of completion.](image-url)
Applications of Accelerators
Basic Requirements for Electron Accelerators beyond ILC

- **Energy**
  \[ W \geq 5 \ldots 10 \text{ TeV} \]
  \[ W = E \cdot e \cdot L \quad \text{(Linac)} \]

- **Luminosity**
  \[ \mathcal{L} \approx 10^{36} \text{ cm}^{-2} \text{ s}^{-1} \]
  \[ \mathcal{L} = \frac{N^2 f}{4\pi \sigma_x \sigma_y} \]
  \[ P = U \cdot I \]
  \[ P \approx 100 \text{ MW} \]

- **Cost**
  \[ C \approx 5 \cdot 10^9 \]

- High accelerating fields
- Low emittance (small diameter)
- High bunch charge
- Good efficiency
Luminosity

- Cross section for $e^+e^-$ collisions goes as $1/E^2$
  \[ \Rightarrow \text{Need a luminosity of } \mathcal{L} \geq 10^{36} \text{ cm}^{-2} \text{ s}^{-1} \]

- Just increasing the number of particles at constant phase space density will lead to a prohibitive AC power
  \[ \Rightarrow \text{Need to improve} \]
  - The particle density at the source (the source emittance)
  - Control emittance growth in the linacs
  - Final focus optics (considering beam–beam interactions)
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: $3 \times 10^{10}$

Therefore

- Need to increase the accelerating fields (without increasing the cost by the same factor)
- Explore alternative acceleration techniques
How to Accelerate Charged Particles

Assume:

- an ultrarelativistic particle of charge $e$
- moving along the $z$ axis
- accelerated by a plane electromagnetic wave that propagates at an angle $\theta$ to the $z$ axis
How to Accelerate Charged Particles

Then:
• Position of the electron

\[ \vec{r}(t) = \begin{pmatrix} 0 \\ 0 \\ ct \end{pmatrix} \]

• Electric field

• Energy gradient

\[ E_{\parallel} = \sin \vartheta \cos \left( \omega t - \frac{z}{2\pi \lambda \cos \vartheta} \right) \]

\[ \frac{\Delta W}{L} = \int_L eE_{\parallel} \, dz = \int_L \sin \vartheta \cos(kz(1 - \sec \vartheta)) \, dz \]

\[ = \frac{\sin \vartheta \sin(kL(1 - \sec \vartheta))}{k(1 - \sec \vartheta)} \frac{1}{L} \]

\[ \underset{L \to \infty}{\longrightarrow} 0 \]
Lawson Woodward Theorem

- 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

Woodward, J. IEE 93 (1947)
RF Acceleration

- Using a resonant cavity at radio frequencies (RF) (~GHz)
- Electromagnetic field provided by external source (e.g. klystron)

Resonating RF Cavity

Electrical field

Cu

electron

Travelling Wave Structure

11.4 GHz 2π/3 Mode \( E_{\text{acc}} \geq 50 \text{ MV/m} \)

adapted from H. Weise
Superconducting RF

Resonant Circuit:

\[ f_o = \frac{1}{2\pi \sqrt{LC}} \]

\[ Q_o = \frac{f}{\Delta f} = \frac{G}{R_s} \]

\[ \Rightarrow Q_0 \approx 10^9 - 10^{10} \]
Limits to the Accelerating Field

- Normal-conducting accelerators
  - Breakdown on the surface

- Superconducting accelerators
  - Critical magnetic field

http://hyperphysics.phy-astr.gsu.edu/hbase/solids/scbc.html
# 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>Metallic</td>
<td>$2 \cdot 10^8$</td>
<td>solid state: 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>Plasma</td>
<td>$\geq 10^{11}$</td>
<td>laser</td>
</tr>
</tbody>
</table>

Plus: Inverse FEL, disposable structures, excited atoms, muon colliders
Dielectric Structures
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

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

\[ \lambda = 1.5 \, \mu m \]
Dielectric Accelerator Structures

Photonic Band Gap Structures
Setup of an Experiment

- Generation of 200 nm long electron bunches:
  - Energy modulation in IFEL
  - Pulse forming in chicane
Results

Generation of attosecond pulses

![Graphs showing generation of attosecond pulses](image)

Acceleration

Energy Gain/Loss (keV)

![Graph showing energy gain/loss](image)
Acceleration on Metallic Surfaces

- Inverse transition radiation on a metallic surface

Above the damage threshold, indeed!
Dielektric Structures

Generation of the accelerating field by an electron beam
Studies on the Maximum Fields

Emission of Cherenkov light

Calculated surface fields

100 µm pulse length
20 µm pulse length

Cracks in the dielectric
Plasma Wakefield Acceleration
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:
  
  - Limit:

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

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

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

Laser \((I > 0.2I_0)\), density, Trapped particles
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

Tightly focused laser ionized gas jet & drove wake

Laser self modulation to plasma period drives wake to trapping

Acceleration to 50 MeV in ~1 mm

Drive beam
10 TW, 500mJ 50fs, 10^{19}W/cm^2

Hydrogen gas jet

nC charge
few % > 10 MeV

Cameron Geddes
Hydrodynamic Plasma Channels

Main beam <500mJ >50fs
Ignitor Beam 20mJ
Heater beam 150mJ 250ps

Plasma ionized by ignitor heated by heater
Expansion shock yields guiding profile

Channel profile
Channel only

No channel leakage
Guided drive beam
Unchanneled drive beam

Guiding over > 10 ZR ~ 2mm relativistic intensity
High quality guiding up to 4TW
C.G.R. Geddes et al, PRL, 2005

Rasmus Ischebeck – Advanced Accelerator Concepts. 2009–04–29
Cameron Geddes
Plasma Waveguides

Phase Images from transverse probe

(d) Nitrogen

50 µm

(c) Air

500 µm

650 µm

(b) Argon

200 µm

1000 µm

(e) 13 µm

Modulated plasma waveguide

Radially modulated 100ps Nd:YAG laser pulse

70fs Ti:Sapphire laser pulse

Axicon

70 fs transverse interfer. probe

Andrew York
Plasma Acceleration in Capillaries

Jens Osterhoff, Stefan Karsch
“Monoenergetic” Particle Bunches

High quality, intense beams*

2e9 electrons
Energy Spread < 4 MeV

Divergence 3 mrad
Normalized Geometric Emittance 2π mm-mrad

Laser = 9TW, 50 fs, Z_R=200μm
Plasma = 1.8e19 cm⁻³, 1.7mm

Peak energies 150-170 MeV

>153 MeV
>134 MeV
>115 MeV

Rasmus Ischebeck – Advanced Accelerator Concepts. 2009–04–29
Cameron Geddes
Particle Energies up to 1 GeV

- $a_0 \approx 1.46$ (40 TW, 37 fs)
- $n_e \approx 4 \times 10^{18} \text{ cm}^{-3}$, $P_{\text{crit}} \approx 7$ TW

1 GeV BEAM

| Divergence (rms): 1.6 mrad |
| Energy spread (rms): 2.5% |
| Resolution: 2.4% |
| Charge: 35 pC |

Rasmus Ischebeck – Advanced Accelerator Concepts. 2009–04–29

Cameron Geddes
Plasma Wakefield Acceleration with Electron Bunches

Energy source: electron beam
- 42 GeV particle energy
- 3.2 nC bunch charge
- Beam power: $\sim 10^{15}$ W = 1 TW
- Power density: $\sim 10^{24}$ W/m$^2$ = 1 YW/m$^2$

Plasma source: Lithium oven
- Particle density: $\sim 10^{23}$ / m$^3$
Plasma Wakefield Acceleration at SLAC

Acceleration, compression and focussing of bunches to reach a peak power density of 5 YW/m²

P. Emma et al., PAC (2005)
Experimental Setup

- **e⁻ beam from SLAC linear accelerator**
- **e⁻ spectrum**
  - X-ray based spectrometer
  - optical transition radiation (OTR)
- **e⁻ bunch length**
  - autocorrelation of coherent transition radiation (CTR)
- **Čerenkov spectrometer magnet**
- **Čerenkov light in air gap**
- **Čerenkov monitor**
- **trapped particles**
- **plasma oven**
- **notch collimator**
- **beam stopper**
First Results

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

<table>
<thead>
<tr>
<th>No Plasma</th>
<th>13 cm FWHM</th>
<th>22.5 cm FWHM</th>
<th>30.5 cm FWHM</th>
</tr>
</thead>
</table>

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Patric Muggli
1 m Long Plasma

Longer plasma oven

New spectrometer

Diagnostics for low-energy particles

Increased the energy in the drive beam
Images from both Spectrometer Planes
800 Consecutive Events
Energy Doubling

- Plasma length: 85 cm
- Density: $2.7 \times 10^{17}$ cm$^{-3}$
- Entrance energy: 42 GeV
- Peak energy: 85 GeV

Trapping of Plasma Electrons

- Very small angle of emission at the plasma exit: \( \langle \alpha^2 \rangle \approx 33 \mu \text{rad} \)

- Limited by camera resolution
Trapping of Plasma Electrons (Short Plasma)

- Imaging the angle of Čerenkov radiation
- Light intensity is increased by more than three orders of magnitude

\[ E \approx 25 \text{ GV/m} \cdot L \]

N. Kirby et al., AIP Conf Proc 877 (2006)

Neil Kirby
There is More to Accelerating Structures than the Accelerating Field

- Power sources
- Beam loading
- Emittance preservation

There is Much More to an Accelerator than Accelerating Structures

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

Demonstrated Once does not mean Available for Users
But

- Future particle accelerators cannot be built with today’s technologies
Livingston Plot
An Unfair Comparison

![Graph showing the comparison of beam energy and year of completion of various accelerators.]
Thank You!

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http://people.web.psi.ch/ischebeck

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