Overview

- Brief introduction to laser-plasma acceleration

- Motivation for study of THz
  1. Noninvasive diagnostic for accelerator performance
  2. High-intensity source is good for applications

- THz generation and Characterization
  1. Coherent Transition Radiation (CTR)
  2. Electro-Optic Sampling
  3. Single-shot detection
Conventional accelerators are big and expensive!

SLAC: $114 Million, 3 Km

Fermilab: $250 Million, 6 Km

LHC: $8 Billion, 27 Km!

We need a technology to make high energy physics accessible!
Acceleration in a conventional RF Accelerator

Copper Accelerator Structure

~ 1"

3.2 Km

• electron

Radio Frequency electric field ($E_{\text{accel}}$)

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Particle physics can be done in a lab. Laser Wakefield Accelerator (LWA) is a technique that utilizes laser-generated electron beams to create a strong electric field, which accelerates particles. This method is particularly advantageous in typical university labs due to its low divergence, low energy spread (ΔE/E ~ 5 – 10%), high peak energy (E_{pk} > 1 GeV), and low charge (0.1 – 0.5 nC).

Compared to conventional accelerators like the Stanford Linear Accelerator Center (SLAC), the LWA approach is significantly more compact. For instance, the electron beam energy is given as

$$E_{\text{WF}} \sim 10,000 E_{\text{SLAC}}$$

This equation shows the wakefield energy in the LWA scenario, which is much shorter (35 cm) compared to the SLAC's 3.5 km. The wakefield energy strategy leverages the electric field generated by the laser to accelerate electrons, making it a powerful tool for experimental particle physics.

Geddes et al., Nature 431, 538 (2004) provides further insights into the effectiveness and potential applications of LWA in particle physics research.
Electrons surf on a plasma wave

- Injected Electrons
- Self Injection
- Injected Out of Phase

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Laser Wakefield Generation:

\[ \frac{d^2 \omega_p}{dt^2} + \omega_p^2 \frac{\delta n}{n_0} = \frac{c^2}{2} \nabla^2 a(r, z, t) \]

Laser Pulse

neutral Helium plasma

ponderomotive force

e^-

plasma frequency

wake amplitude

laser vector potential

35 GeV \implies \text{in 35 cm}

E \sim 100 \text{ GV/m}

30 TW

\[ I_0 = 1 \times 10^{19} \text{ W/cm}^2 \]

\[ \tau_p = 30 \text{ fs} \]

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Using Wakefields to Accelerate Electrons

Laser Pulse

Helium

Wake

Plasma

Gas Jet

Electrons

THz

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Recent Progress in Laser Plasma Acceleration

2004

9 TW: 86 MeV/c
\[ \Delta p = 4 \text{ MeV/c FWHM}^* \]


2006

40 TW, 1 GeV/c,
\[ \Delta p = 25 \text{ MeV/c rms}^{**} \]

1. THz as a bunch diagnostic:
   Measurements of THz waveform allow characterization of accelerated e\(^{-}\) bunch

2. THz as a unique source:
   - Remote Sensing
   - Rapid 2D Imaging of biological and semiconductor samples
   - Pump-Probe Experiments
     - \(E_{\text{THz}} \sim 0.01-10\) MV/cm (traditional sources: \(E_{\text{THz}} \sim 0.1\) MV/cm)
     - intrinsic synchronization with laser, electrons, x-rays, etc.
THz Radiation as an Electron Bunch Diagnostic

Measurement of electron bunch temporal structure
Transition Radiation is Emitted by electrons passing an Interface

**Diffraction Condition**  
(low cutoff)  
\[ D_{\text{source}} > \lambda_{\text{THz}} \]

**Coherence Condition**  
(high cutoff)  
\[ \lambda_{\text{THz}} > \tau_{\text{e-bunch}} \]

THz Spectrum

- \( \rho = 1000 \, \mu m \)
- \( \rho = 400 \, \mu m \)
- \( \rho = 100 \, \mu m \)

rms e-beam = 50 fs  
(FWHM = 118 fs)
THz Collection Geometry

800 nm Probe Beam

Electrons

Gas Jet

Helium

OAP

Polarizer

Foil

GaP Xtal

To Detector

Electro-Optic Effect

Electrons

PLasma

Gas Jet

THz

OAP

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Electro-Optic Sampling Method

**Electro-Optic Sampling:**

1. High electric field of THz polarizes crystal atoms, inducing birefringence

2. Optical probe (laser pulse) “samples” the birefringence.

3. Amplitude modulation is recorded

**Probe transmission:**

\[ I_{\text{Trans}}(t) = \frac{1}{2} \left( 1 + \sin \Gamma(t) \right) \]

where

\[ \Gamma(t) \equiv \frac{2\pi}{\lambda_0} L n^2 r_{41} E(t) \]

is the phase retardation
TEX Detection Method

Temporal Electric-field Cross-correlation (TEX)

Matlis et al, Submitted to JOSA B

1. Variation of THz E-field in space and time is mapped onto probe
2. Spectral interference of probe and reader pulses allow waveform recovery:

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How TEX works

\[ S(\omega) = |E_p(\omega)|^2 + |E_r(\omega)|^2 + E_p(\omega)E_r^*(\omega) + c.c. \]

\[ C(t) = \int_{-\infty}^{\infty} E_p(\tau)E_r^*(\tau - t)dt \]

TEX Recovers temporal amplitude and phase information!
THz resolves variation in accelerator performance during parameter scans

Focus on Gas Jet Leading Edge
* higher energy e-bunches
  • higher n,γ production
  • less Coulombic expansion
  • expect higher THz frequencies

Focus on inside Gas Jet
* lower energy e-bunches
  • lower n,γ production
  • more Coulombic expansion
  • expect lower THz frequencies

Example: scan of gas-jet position

Geddes et al. PRL (2008)
Leemans et al. Phys Plasmas (2001)
THz spectrum correlates with accelerator performance

Bunch Charge

Neutron Yield

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Bunch properties can be inferred from spatio-temporal model

- Physics of THz emission is elucidated by spatio-temporal coupling
- Spatio-spectral analysis of THz waveform indicates presence of two bunch structure (90% at 420 fs, 10% at 150 fs, rms)
Summary

1. Laser Plasma Accelerators offer potential for a low-cost alternative for electron acceleration

2. Coherent THz Transition Radiation is generated at plasma boundary
   - Source of high-field THz pulses for applications
   - THz emission provides a non-invasive bunch diagnostic

3. Temporal Electric-field Cross-correlation (TEX) introduced
   - TEX provides high-resolution spatial & temporal single-shot measurements of THz waveforms for the 1st time
   - TEX used to determine 2-component structure of e-beam
THE END