Electro-Optic and THz Diagnostics

Daniel Gordon,
Michael Helle*, Dmitri Kaganovich, Antonio Ting

Naval Research Laboratory, Plasma Physics Division, Washington DC
*Georgetown University, Washington, DC

2010 Advanced Accelerator Concepts Workshop, Annapolis, MD, June 13-19

Supported by Department of Energy and Office of Naval Research
Outline

- Background
- Three Dimensional Effects
- Short Bunches
- Conclusions
Electro-optic sampling is a well established technique for measuring THz waveforms.

Short electron bunches produce THz fields:
- Radiatively through, e.g., CTR
- Self fields

Electro-optic sampling of THz fields due to short bunches gives information about the bunch.
Electro-Optic Effect

DC electric field induces birefringence
EO Bunch Diagnostic

Induced Principle Axes

Output Polarization

Input Polarization

Optical Beam

Bunch Field

e-Bunch

EO Crystal
Upon input, laser is x-polarized. THz field is y-polarized. Principle axes $(u,v)$ are at 45°.

Upon output, $E_u$ and $E_v$ are shifted in phase by

$$\Gamma = \frac{\omega}{c} (n_u - n_v) L$$

Phase shift gives THz field through

$$n_u - n_v \propto E_T$$
Balanced Diode Technique

The differential signal on the diodes gives THz field

$$|E_x|^2 - |E_y|^2 \propto \Gamma$$

Scanning a delay line produces the THz waveform.
Cross Correlation Technique

Image of SHG crystal gives THz Intensity via

\[ \Delta t = \frac{\Delta x}{c} \sin \theta \]

\[ |E_y|^2 \propto \Gamma^2 \]
Thin crystal has flatter response:

- L=50 µm
- L=100 µm
- L=200 µm

|G(ω)/r(ω)|

Frequency (THz)
Characterization of Photoinjector Bunches at FLASH* (DESY)

- Resolution of 40 fs achieved
- Benchmarked against deflecting cavity method

Characterization of Bunches from LWFA* (LBL)

Established 50 fs maximum bunch length

Characterization of Bunches From LWFA* (RAL)

- Inferred bunch duration < 38 fs

Simulation Model: Extension of TurboWAVE

• 3D PIC combined with nonlinear optics model
• Massively Parallel
• Arbitrary crystal orientations and parameters
• Fully explicit fields and material polarization
• All orders of dispersion, optical + THz
• All second order effects (electro-optic effect, sum generation, difference generation, etc.)
Nonlinear Lorentz Model

Model dielectric as population of anharmonic oscillators:

\[ \ddot{r}_i + \nu_{ij} \dot{r}_j + (\Omega^2)_{ij} r_j + a_{ijk} r_j r_k = \frac{q}{m} E_i \]

Typically use two oscillators: one in the UV, one in the THz.

Form polarization and compute effective current density and charge density for use in PIC algorithm:

\[ P = \sum_s q_s n_s f_s \cdot r_s \]

\[ \rho_{\text{eff}} = \rho - \nabla \cdot P \]

\[ J_{\text{eff}} = J + \frac{\partial P}{\partial t} \]

(f is an oscillator strength, typically the identity matrix)
Simulations of 3D Bunch Fields in a Crystal

- Pass bunch over crystal
- Examine field in crystal
- Speed of light frame
- PML boundaries
**3D Bunch Fields in GaP Crystal**

<table>
<thead>
<tr>
<th>Crystal Dimensions</th>
<th>$300 \times 180 \times 170 \ \mu m^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch Size</td>
<td>$8.4 \ \mu m$ radius, $80$ fs long</td>
</tr>
<tr>
<td>Bunch Energy</td>
<td>$250$ MeV</td>
</tr>
</tbody>
</table>

**$E_y$ - Longitudinal Cut**

$x = 0$

**$E_y$ - Transverse Cut**

$z - ct = -158 \ \mu m$
Animation of 3D Bunch Fields

<table>
<thead>
<tr>
<th>Crystal Dimensions</th>
<th>300 x 180 x 170 µm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch Size</td>
<td>8.4 µm radius, 80 fs long</td>
</tr>
<tr>
<td>Bunch Energy</td>
<td>250 MeV</td>
</tr>
</tbody>
</table>
Consider coherent radiation emitted by $10^9$ electrons at 250 MeV propagating parallel to the surface of a dielectric at a distance $d$:

There is an azimuthal dependence which is strongly peaked along normal to surface.
1D vs. 3D Models

Waveforms offset for clarity
1D Simulations of EO Decoding

- 800 nm, 500 fs optical probe*
- THz Half-Wave
- Boundaries absorb all radiation coming from inside simulation box
- To cross correlator
- 50 µm
- peak ~ 500 kV/cm
- * wavelength not to scale
Cross Correlation with 50 fs Gate

\[
R = \frac{\int_{\text{opt}} |E_y(\omega)|^2 d\omega}{\int_{\text{opt}} |E_x(\omega)|^2 d\omega}
\]

\(120 \text{ fs Bunch}^* \)

\(60 \text{ fs Bunch}^* \)

\(R = 0.022\)

\(R = 0.009\)

*pulse width defined by FWHM of I(t)*
Even with delta-function gate (black curve), the bunch cannot be resolved. Red curve uses 50 fs gate.
Overall Output Spectra from 15 fs Bunch

x-polarization

y-polarization

Scattered THz
Phonon Resonance

Phonon Resonance
Scattered Light
Detail of Optical Spectra from 15 fs Bunch

Initial polarization (x)  
Scattered polarization (y)

spectral modulation due to etalon effect

\[
\mathcal{R} = \frac{\int_{\text{opt}} |E_y(\omega)|^2 d\omega}{\int_{\text{opt}} |E_x(\omega)|^2 d\omega} = 0.00075
\]
Gabor Transform of Optical Pulse from 15 fs Bunch

Can be done experimentally via X-FROG
X-FROG Diagnostic

1 THz Modulation

3 THz Modulation

10 THz Modulation

(Experimental Data)
Synthesis of THz Pulses

Oscillator → Stretcher → Regen

M1

M2

Slits

Amplifier

Compressor

$\lambda/2$ GaSe

G1

G2

Bolometer

F1

$0.7 \text{ THz}$

$1.0 \text{ THz}$

$2.0 \text{ THz}$
Experimental and Simulated Phase Matching Curves at 1.0 THz
Conclusion

- Phonon resonance limits time resolution of standard EO diagnostics to about 50 fs.

- 3D simulation model developed
  - Modeling shows superposition of CTR and Cherenkov wakes in EO crystal
  - Reduced 1D models work if probe pulse is spatially separated from Cherenkov wakes

- EO Response above phonon resonance may lead to observable frequency shift