Intense Broadband Terahertz from FACET at SLAC

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Workshop on Terahertz Sources
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Purpose

- Longitudinal diagnostics of compressed electron bunches
- High peak fields for THz science
The FACET User Facility at SLAC

- Facility for Advanced Accelerator Experimental Tests
  - Provides highly compressed $e^-$ (and soon $e^+$) bunches at high energy and with high charge
  - Uses the first 2 km of the SLAC linac

- Experiments include:
  - Plasma wakefield acceleration
  - Dielectric wakefield acceleration
  - Ultrafast magnetic switching
  - Smith-Purcell radiation
  - Terahertz radiation
## FACET Beam Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>2012 Run Typical</th>
<th>2012 Run Best</th>
<th>Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy</td>
<td>20.35</td>
<td>21.1</td>
<td>23 GeV</td>
</tr>
<tr>
<td>Charge</td>
<td>2.5–2.9</td>
<td>3.2</td>
<td>3.2 nC</td>
</tr>
<tr>
<td>Size at focus $(\sigma_x)$</td>
<td>35</td>
<td>20</td>
<td>20 µm</td>
</tr>
<tr>
<td>$(\sigma_y)$</td>
<td>35</td>
<td>23</td>
<td>20 µm</td>
</tr>
<tr>
<td>Bunch length $(\sigma_z)$</td>
<td>25–30</td>
<td>&lt;25</td>
<td>&lt;20 µm</td>
</tr>
<tr>
<td>$(\sigma_t)$</td>
<td>83–100</td>
<td>&lt;83</td>
<td>&lt;67 fs</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10</td>
<td>10</td>
<td>30 Hz</td>
</tr>
</tbody>
</table>
THz source: Coherent transition radiation from two 1-μm-thick Ti foils
- 10–14 m before main focus at experiments on the IP Table
- Allows parasitic operation and use of THz for beam diagnostics
- But e-beam at THz foil is larger than at IP
Upstream IP Table
IP Tables
THz Table with Dry-Air Enclosure
Layout of the THz Table

Top View

From bunch compressor
1-µm Ti foil
Visible
Insertable silicon plate
THz
OAP
Knife-edge (Sample stage)
Total-energy Detector
Pyro
Pyro
Reference Detector
Michelson Detector
Michelson Interferometer

Side View

To IP
Optics for Upstream Foil

- OAP
- Foil
- Knife edge
- Joulemeter
- To Michelson
Finding the Peak Electric Field

- Electric field at the focus modeled as a Gaussian
  \[ E = E_0 \exp \left[ -\frac{1}{2} \left( \frac{x^2}{\sigma_x^2} + \frac{y^2}{\sigma_y^2} + \frac{z^2}{\sigma_z^2} \right) \right] \]

- Energy in the pulse
  \[ W = \iiint \frac{1}{2} \varepsilon_0 E^2 dx \, dy \, dz = \frac{1}{2} \pi^{3/2} \varepsilon_0 E_0^2 \sigma_x \sigma_y \sigma_z \]

- Dependence on bunch charge \( q \), bunch compression \( \sigma_z \):
  - Field \( E_0 \sim q/\sigma_z \)
  - Energy \( W \sim E_0^2 \sigma_z \sim q^2/\sigma_z \)

- Coherence
  - Less energy, due to incoherent emission, for wavelengths \( \lambda \leq \sigma_{x,y,z} \)

- Measurements needed:
  - Knife-edge scans, for widths of focus \( \sigma_{x,y} \)
  - Michelson interferometer, for pulse duration \( \sigma_t = \sigma_z/c \)
  - Pyroelectric joulemeter, for pulse energy \( W \)
Knife-Edge Scans at a THz Focus

Horizontal Profile

Vertical Profile

Knife-Edge Scan and Fit to Error Function

\[ \mu = 14.721 \text{ mm} \]
\[ \sigma = 1.357 \text{ mm} \]

Knife-Edge Scan and Fit to Error Function

\[ \mu = 16.879 \text{ mm} \]
\[ \sigma = 1.085 \text{ mm} \]
Standard Electron Optics near the THz Table

Large $x$ beam size at THz table: Reduces power.

Minimum beam size at experimental IP:
Transverse $e$-Beam Size

Simulated beam with standard optics:

$$\sigma_x = 1.2 \text{ mm}, \sigma_y = 6 \mu\text{m}$$

Measured with optical transition radiation
Refocus to Reduce Transverse $e$-Beam Size

Simulation comparing standard optics to a circular 85-µm beam

“Double Waist”: Focus remains at IP, but $x$ size at foil is reduced:

$$\sigma_x = 317 \, \mu\text{m}, \sigma_y = 36 \, \mu\text{m}$$
Scan of the Michelson Interferometer

Interferogram

Spectrum

Reflections from detector layers lead to spectral modulation.
Restoring Low Frequencies and Phase

- Model low-frequency loss as a filter:
  \[ 1 - \exp\left(-f^2/f_0^2\right) \]
- Divide by filter, except very near \( f = 0 \)
  - Just fit a parabola near \( f = 0 \)
  - Result is not very sensitive to fit

Kramers-Kronig relations give phase from magnitude of form factor \( f(\omega) \)
- Inverse transform gives distribution \( f(t) \)
Profiles at Three Bunch Compressions

High Compression

- Gaussian width for points >= 10% of peak
- $\sigma_1 = 95$ fs
- $\sigma_2 = 26 \mu m$

Medium Compression

- Gaussian width for points >= 10% of peak
- $\sigma_1 = 144$ fs
- $\sigma_2 = 43 \mu m$

Low Compression

- Gaussian width for points >= 10% of peak
- $\sigma_1 = 544$ fs
- $\sigma_2 = 163 \mu m$
Peak Electric Field

- In the case just shown:
  - Charge of 3 nC
  - Energy in the pulse $W = 0.46$ mJ
    - The large $\sigma_x$ of standard electron optics gives 0.35 mJ
  - $\sigma_x = 1.36$ mm, $\sigma_y = 1.08$ mm
  - $\sigma_z = 39$ µm
  - $E = 5.7$ MV/cm

- Measured under other conditions (but not at one time):
  - Energy = 0.7 mJ
  - Bunch length = 25 µm
  - These would give 8.8 MV/cm (≈ 0.088 V/Å)

- Higher fields should be possible with a smaller beam at the foil
  - But not too small: The beam has drilled holes through 1-µm Ti foils at the IP focus
Transporting THz up to the Klystron Gallery

- First stage: Transport THz from the downstream foil to a small table in the Klystron Gallery
  - Now beginning detailed engineering
  - 19-m path, including an 8-m vertical section up through a penetration
  - Characterize pulse before and after transport: energy, focus, spectrum

- Severe diffraction of these long wavelengths
  - Large-diameter mirrors and tubing: 200 mm (8 inches)
  - Frequent refocusing with a lattice of off-axis parabolic (OAP) mirrors
    - Alternately collimating and focusing to a waist
    - Toroidal mirrors may be better for the long focal lengths at bottom and top of penetration
  - Evacuate to remove water vapor and convection (UHV unnecessary)

- Next stage: Another 20 m to the Sector-20 laser building
  - User experiments, including THz pump and laser probe
We have characterized intense THz from CTR at FACET

- Energy \( \sim 0.5 \text{ mJ} \)
- Focus size \( \sim 1 \text{ mm} \)
- Spectrum \( \sim 1 \text{ THz} \)
- Bunch length \( \sim 25 \text{ fs} \)
- Electric fields \( \sim 6 \text{ MV/cm} \)

Higher fields should be possible with more bunch compression and charge, and a smaller transverse beam size

- But foil breakage could be a problem

Upgrades in planning

- Tests of other foil materials
- Tests of other detectors
- THz transport line to a user area above the tunnel
Finding the Form Factor of the Bunch

- Electric field $E$ of a bunch of $N$ electrons at positions $t_j$:

$$E(t) = \sum_{j=1}^{N} E_1(t - t_j) \quad E(\omega) = E_1(\omega) \sum_{j} e^{-i\omega t_j}$$

  - Here $E_1$ is the field of one electron

- Energy in the pulse is related to the longitudinal “form factor” $f(\omega)$:

$$U_0 = \int dt \ E^2(t) = \int \frac{d\omega}{2\pi} |E_1(\omega)|^2 \left| \sum_{j} e^{-i\omega t_j} \right|^2 = N^2 \int \frac{d\omega}{2\pi} |E_1(\omega)|^2 |f(\omega)|^2$$

- Interferometer gives the pulse energy in an autocorrelation with a delay $\tau$:

$$U(\tau) = U_0 + \text{Re} \int \frac{d\omega}{2\pi} |E_1(\omega)|^2 |f(\omega)|^2 e^{i\omega \tau}$$

- The power spectrum $U(\omega)$ is then (neglecting the DC component):

$$U(\omega) = |E_1(\omega)|^2 |f(\omega)|^2$$

- $E_1$ is essentially constant at THz frequencies, and so $U(\omega)$ gives us $|f(\omega)|^2$
If we express $f(\omega)$ in terms of its magnitude $\rho(\omega)$ and phase $\psi(\omega)$, then:

$$\ln f(\omega) = \ln \rho(\omega) + i\psi(\omega)$$

Since $\ln f(t)$ is causal, and since $\rho$ and $\psi$ are real, they obey the Kramers-Kronig relations, which give:

$$\psi(\omega) = -\frac{2\omega}{\pi} \text{P} \int_0^\infty d\omega' \frac{\ln[\rho(\omega')/\rho(\omega)]}{\omega'^2 - \omega^2}$$

The magnitude and phase then let us find $f(t)$.
Detector Response

- THz detectors are poorly calibrated and are not spectrally flat
  - Significant etalon effects (reflections from detector layers)

- Infratec has strong modulation
  - Dip in response near 0.8 THz cuts out part of spectrum
    - Not suitable for interferometer
  - Compare to model (Henrik Loos)

- Gentec has thinner layers
  - 60-GHz modulation
  - When 60 GHz is filtered, 240 GHz becomes visible
    - Better, but not ideal

![Graph showing detector response](image)
Water Vapor

- Before and after adding the dry-air enclosure
  - Compare to transmission through 1-m of humid air

- Without dry-air enclosure
  - Dips near 0.75 and 1.2 THz
  - 3 bunch compressor settings

- With dry-air enclosure
  - Much improved, but there may still be some absorption
  - Will increase flow of dry air
Transport Line

Pumping flange

Flange with mirror mount

Bellows
- Flexibility
- Breaks up reflections from pipe wall

Alignment viewport
- View HeNe alignment beam directly or with a camera

200-mm (8-inch) tubing
This workshop is focused on exploring and defining scientific opportunities associated with THz radiation in a wide range of scientific fields.