Electro-optic techniques in beam diagnostics

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Electron accelerators:
• Experiments utilizing electron bunches
  • Electron diffraction
  • Colliders
  • Magnetic switching
• Generation of radiation
  • X-rays
  • VUV radiation
  • THz and FIR

IMPORTANT:
Quality of electron bunch

Quality of electron bunch
• Charge
• Divergence
• Energy
• Energy spread
• Transverse profile
• Longitudinal/temporal profile
Charge profile analysis:
Time or frequency domain

- Charge profile in the time domain:
  - Profile 1
  - Profile 2

- Form factor:
  - Amplitude
  - Amplitude + Phase

- Phase ignored:
  - Profile 1
  - Profile 2

- Phase not ignored:
  - Profile 1
  - Profile 2
E-bunch and coherent radiation: Close correlation

- Transition rad.
- Smith-Purcell rad.
- Diffraction rad.
- Synchrotron rad.

- μJ’s of energy
- ~1 MV/cm

Why analysis on coherent radiation?
- Setup away from electron path (air)
- Setup can be used for THz applications
- THz beam path adds complications (alignment, aberrations, spectral change)

\[ E_{CTR}(\omega) \propto N\varepsilon(u)D(\omega, u, \rho)F(\omega) \]
Talk outline

- Overview of diagnostic techniques
- Introduction to electro-optic sampling (EOS)
- EOS in time domain
- EOS in laser’s frequency domain
- Summary
Overview of diagnostic techniques

Bunch diagnostic techniques

- Direct e-beam
  - EO sampling
  - Pump/probe scattering
  - RF zero-phasing

- Convert e-beam to radiation
  - Incoherent Radiation
    - Fluctuation Interferometry
    - Streak camera
  - Coherent Radiation (THz regime)
    - Bolometer spectrum
    - Interferometry
    - EO sampling
    - Angular emission pattern

EO sampling
- Resolution of 10's of fs
- Exact charge profile
- Non-destructive
- Single-shot
- Relative timing for pump/probe
- Room temperature
Electro-optic sampling: Mix laser + THz fields in EO crystal

Crystal axis (z axis)

Index ellipse

$E_{THz}$

Laser polarization

Index ellipse

EO Crystal

Change index $\Delta n(t) \sim E_{THz}(t)$

$E_m(t) = E_L(t) \cdot e^{i\Gamma_{THz}(t)}$

Measurement of $\Gamma_{THz}(t)$:
Use a probe laser and cross-polarizer
Phase modulation $\rightarrow$ amplitude modulation $|E_m(t)|$

Time domain laser

Frequency domain laser
Electro-optic sampling
Measuring polarization change

(b) Overlap in positive THz field

(c) Overlap in negative THz field
Electro-optic sampling
Crystal effects on spectral bandwidth

Crystal effects:
• Absorption
• Dispersion
• Mismatch laser – THz

CTR 50 fs e-beam

Modeled EO measurement

\[ S_{EO}(f) \propto Q(f) \cdot D(f) \cdot E_{L, envelope}(f) \cdot T_{crystal}(f) \]

Charge bunch
Diffraction (radiation)
EO crystal
Spectrum envelope laser
Multi-shot EOS
(use short laser pulse)

Advantages
• Complete profile
• Works for low fields

Challenges
• Takes many shots
• Reproducibility

van Tilborg et al., PRL 96, 014801 (2006)
1) Single-shot EOS
Spatio-temporal mixing

Advantages
• Complete profile
• Single-shot

Challenges
• Complex imaging
• Availability echelons
• Resolution >30 fs

Non-collinear cross-correlation

\[ I_L(x_1) \propto \int E_L(t)E_{THz}(t - \tau_1)dt \]

\[ I_L(x_2) \propto \int E_L(t)E_{THz}(t - \tau_2)dt \]

\[ E_{THz}(\tau) \propto I_L(x) \propto \int E_L(t)E_{THz}(t - \tau)dt \]
2) Single-shot spatial encoding
Non-collinear cross-correlation between laser and THz

Advantages
- Complete profile
- Single-shot

Challenges
- Transverse effects
- Weak THz fields

3) Single-shot spatial encoding

Non-collinear cross-correlation laser and THz-modulated laser

![Diagram showing laser and THz pulse envelope](image-url)
3) Single-shot spatial encoding

Non-collinear cross-correlation laser and THz-modulated laser


3) Single-shot spatial encoding
Non-collinear cross-correlation laser and THz-modulated laser

- Model (red curve) is based on a 45-fs e-bunch
- E-field of 0.4 MV/cm

Advantages
- Complete profile
- Single-shot

Challenges
- Two laser beams
- Complex power balance
- 2 nonlinear crystals

4) Single-shot spectral encoding
Direct relation laser wavelength and time

For $\tau_{ebeam} > \sqrt{\tau_{L,chirp} \cdot \tau_{L,FL}}$

Example
$\tau_{L,chirp} = 2.8$ ps
$\tau_{L,FL} = 40$ fs
Yields $\tau_{ebeam} = 330$ fs

Advantages
- Complete profile
- Single-shot
- Only low-power laser beam

Challenges
- Poor resolution

Direct relation $\lambda$ to time
$\omega_{inst}(t) = \omega_0 + \frac{b}{2 \tau_{FL}^2 (1 + b^2 / 4)} t$

Graphs showing THz field $E_{thz}(t)$ and spectral modulation $M$ with wavelength $\lambda$.
4) Single-shot spectral encoding
Direct relation laser wavelength and time

Loos et al., Proceedings PAC 2003


Bunch duration 1.7 ps
Limited time resolution
Complex spectral modulations

For $\tau_{e\text{beam}} > \sqrt{\tau_{L,\text{chirp}} \cdot \tau_{L,\text{FL}}}$

For $\tau_{e\text{beam}} < \sqrt{\tau_{L,\text{chirp}} \cdot \tau_{L,\text{FL}}}$
Examples of spectral modulations....


5) Single-shot spectral encoding

spectral envelope only

Advantages
• Single-shot
• Only low-power laser beam
• High resolution

Challenges
• Limited information

Transverse (2D) electro-optic sampling

Conclusion

• Many variations of EOS available
• Time resolution (~ laser pulse length)
• Single- vs. multi-shot
• Minimum THz field strength (weak to stronger)
  • Number of laser pulses (1 or 2)
  • Number of nonlinear crystals (1 or 2)
  • Full or limited charge profile retrieval
• Future: resolution ~10 fs
  • Shorter laser pulses
  • Thinner EO crystal
• EOS has now been proven to be a very reliable technique in many labs worldwide
Template....