Ultrafast Diagnostics for Electron Beams from Laser Plasma Accelerators

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http://loasis.lbl.gov/
Motivation: e-beam Diagnostics for Laser Plasma Accelerators

Applications (e.g. TeV Colliders, FELs, Coherent Radiation Sources) require:

High brightness beams

Electron Spectra

Charge
- ICT
- Scintillating Screen
- Nuclear Activation

Emittance
- Undulator Radiation

Energy
- Magnetic Spectrometer

Source Size
- Betatron Radiation

Energy Spread
- Undulator Radiation

Bunch Length
- THz Electro-Optic Sampling

Need Single-shot, non-destructive diagnostics

Multiple components

Large Energy Spread & Variability
Laser-Wakefield Interaction

Radiation from electrons give a wealth of information.
CHARGE DIAGNOSTICS
1. Integrating Current Transformer

**Pros:** ICTs are useful charge diagnostic
- Nondestructive
- Easy to use
- Work over broad range of energies and bunch durations

**Cons:** none

Reliability confirmed by: Nakamura et al, in preparation

Reliability questioned by: Glinec et al, RSI 77, 103301 (2006)

2. Scintillating Screen (e.g. Lanex)

**Pros:**
- Can be used real time
- Provide spatial information
- Work over broad range of energies and bunch durations

**Cons:**
- Destructive
- Calibration requires several steps

3. Nuclear Activation

**Pros:**
- Reliable

**Cons:**
- Destructive
- Not single-shot
- Requires Monte Carlo Analysis

65Cu (γ,1n) -> 64Cu

Leemans et al, Phys Plasmas 8, 2510 (2001)

Warning: beam divergence strongly energy dependent
ICT Charge Measurements Agree with Lanex

Nakamura et al, in preparation

ICT, Lanex & Activation measurements agree!!

Kei Nakamura (Fri, WG1)

\[ y = 1.0662x + 2.2676 \]

\[ R^2 = 0.95575 \]
UNDULATOR DIAGNOSTICS

Measurement of Energy, Energy-spread, Emittance
Application: Laser – Plasma FEL
(tunable, coherent, ultrashort source)

Undulator also an excellent single-shot, non-destructive e-beam diagnostic

LOASIS Experiment

Collaborations: Engineering Div., CBP (AFRD-LBNL),
Center for X-Ray Optics (LBNL),
ALS (LBNL),
MPQ (Germany)

Also supported by:


Visible


VUV


Single-shot X-ray Spectrometer

Capillary

ICT

Undulator

Magnetic Spectrometer

Blazing Incidence Grating

Lanex

X-ray CCD

Undulator: Ready to go

Nicholas Matlis: Advanced Accelerator Concepts 2010
Undulator Diagnostic Provides Energy-Spread, Emittance Measurement

Calculated using Synchrotron Radiation Code “SPECTRA”
Tanaka et al. J. Synchrotron Radiation, 8, 1221 (2001)

Energy spread x10

Emittance x10

<1% resolution
Measurement of Source size, acceleration Dynamics
Production of Betatron X-rays


LOASIS Experiment

Collaborators:
• D.B. Thorn (GSI)
• M. Battaglia (LBNL)

Thorn et al, submitted to RSI

Single shot image ~2e5 photons on camera

supported by NA-22
Single shot simultaneous measurement of Electron and Xray spectra

- Extraction of low-E spectrum with Si dead layer in progress

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Measurement of electron bunch temporal structure
Electro-Optic Sampling Method

Two halves of EO Sampling:

1. Configuration of the encoding (setting up the E-fields)
   - Coulomb E-fields of the bunch
     Cavalieri et al, PRL 94, 114801 (2005)
   - Transition radiation from a foil

2. Method of retrieval of Information (configuring the probes)
   - Transition radiation from the plasma-vacuum boundary
   - Spectral Encoding
   - Second-Harmonic Cross-correlation
   - Temporal Electric-field Cross-correlation (New)

Probe transmission:

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

where

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

is the phase retardation
3 Encoding Configurations

1. Direct detection of bunch Coulomb fields

Pros:
- Measurement is direct

Cons:
- Working distance may cause resolution loss
- Harsh environment (laser & plasma) (measurement downstream of interaction)
- Sampling happens after propagation (may have Coulombic & ballistic expansion)

Resolution loss:
- 15 fs/mm @ 100 MeV
- 1.5 fs/mm @ 1 GeV

Implemented at SLAC:
Cavalieri et al, PRL 94, 114801 (2005)
3 Encoding Configurations

2. Coherent transition radiation from a foil

Cons:
• Still have harsh environment (laser & plasma) (can not put foil close to interaction)
• Still have bunch expansion (may reduce coherence for high frequencies)
• Detection is indirect (THz emission must be correlated to bunch properties)
• Bandwidth of Electro-optic detection is limited

Pros:
• Zero working distance
• No interference from plasma emission
• Detection can be outside of vacuum

Debus et al. PRL \textbf{104}, 084802 (2010)

Schroeder et al. PRE 69, 016501 (2004)
3. Coherent transition radiation directly from the plasma boundary

Pros:
- Zero working distance
- No harsh environment
- Minimal propagation before detection
- Detection outside of vacuum

Cons:
- Detection is still indirect
  (THz emission must be correlated to bunch properties)
- Sharpness of boundary
  (plasma-vacuum boundary not as sharp as foil)
- Bandwidth of Electro-optic detection is limited

THz emission is very wavelength dependent

Must account for f/# effects

3 Detection Techniques

1. “Spectral Encoding”


- **Pros:**
  - Simple to implement

- **Cons:**
  - Recovery is unreliable for short pulses due to distortion

![Graph showing spectral encoding](image)

**Graphs:**
- **0.5 THz, 500 fs signal**
- **1 THz, 250 fs signal**
- **2 THz, 125 fs signal**

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**Nicholas Matlis: Advanced Accelerator Concepts 2010**
2. Second-Harmonic Cross-correlation


**Pros:**
- High temporal resolution

**Cons:**
- Susceptible to phase in the reader
- Requires high-intensities for second harmonic
- Does not provide imaging
3 Detection Techniques

3. Temporal Electric-field Cross-correlation (TEX)

Matlis et al, Submitted to JOSA B

- **Pros:**
  - High temporal resolution
  - Provides imaging
  - Linear in probe intensity

- **Cons:**
  - Susceptible to phase in the reader

### Graphs

- **0.5 THz, 500 fs signal**
- **1 THz, 250 fs signal**
- **2 THz, 125 fs signal**
How TEX works

TEX Interferogram without THz

TEX FFT(t) without THz

TEX Interferogram with THz

TEX FFT(t) with THz

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

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

TEX Recovers temporal amplitude and phase information!
TEX can be used for **Amplitude** or **Phase** encoding

- **Amplitude Encoding**
  - Probe polarization *inbetween* birefringence axes

- **Phase Encoding**
  - Probe polarization *along* birefringence axes

- Phase encoding does not restrict by \( \pi/2 \) rotation limit

2D Spatial profile of THz slice at \( t=0 \) showing “over-rotation” at center, measured with amplitude encoding
THz resolves variation in accelerator performance during parameter scans

Geddes et al. PRL (2008)
Leemans et al. Phys Plasmas (2001)

Example: scan of gas-jet position

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
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)

Matlis et al, submitted to JOSA B
OTR DIAGNOSTIC

Measurement of electron bunch micro structure
Evidence for Coherent OTR at 3m

C. Lin et al, in preparation & poster session AAC2010

- First observation of Coherent OTR at meter distances
- Laser completely blocked
- Indicates presence of micro-bunching

Glinec et al, PRL 98, 194801 (2007)

Coherent OTR at 1.5 - 140 mm

LOASIS Experiment
1. ICTs functionality for fs beams confirmed

2. Non-invasive, single-shot radiation-based diagnostics have been developed
   • Energy, energy spread & emittance (Undulator)
   • Bunch source size (Betatron)
   • Bunch temporal structure (THz CTR)

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

4. Coherent Optical Transition Radiation observed
   • indicating micron-scale structure in the e-beam
THE END