Ultrafast Diagnostics for Electron Beams from Laser Plasma Accelerators

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June 16, 2010

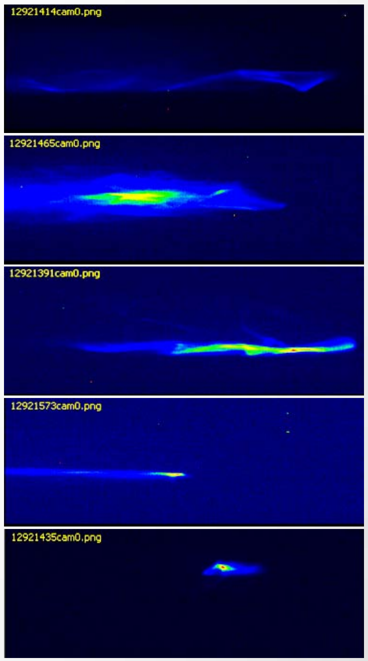
http://loasis.lbl.gov/

Motivation: e-beam Diagnostics for Laser Plasma Accelerators

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

High brightness beams

Electron Spectra

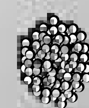


Large Energy Spread & Variability

Charge
- ICT
- Scintillating Screen
- Nuclear Activation

Emittance
- Undulator Radiation

Electron Bunch



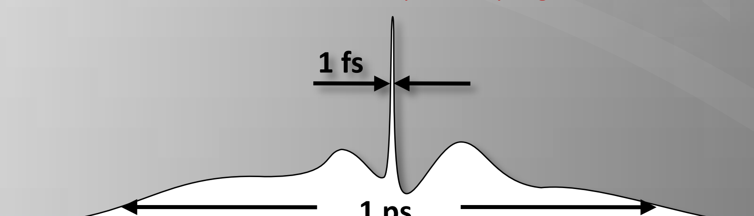
Properties

Energy
- Magnetic Spectrometer

Source Size
- Betatron Radiation

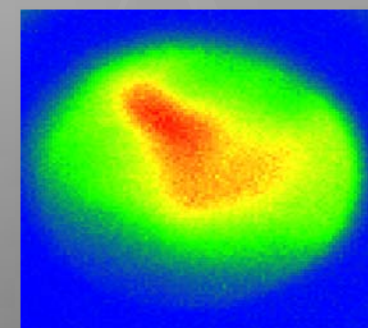
Energy Spread
- Undulator Radiation

Bunch Length
- THz Electro-Optic Sampling



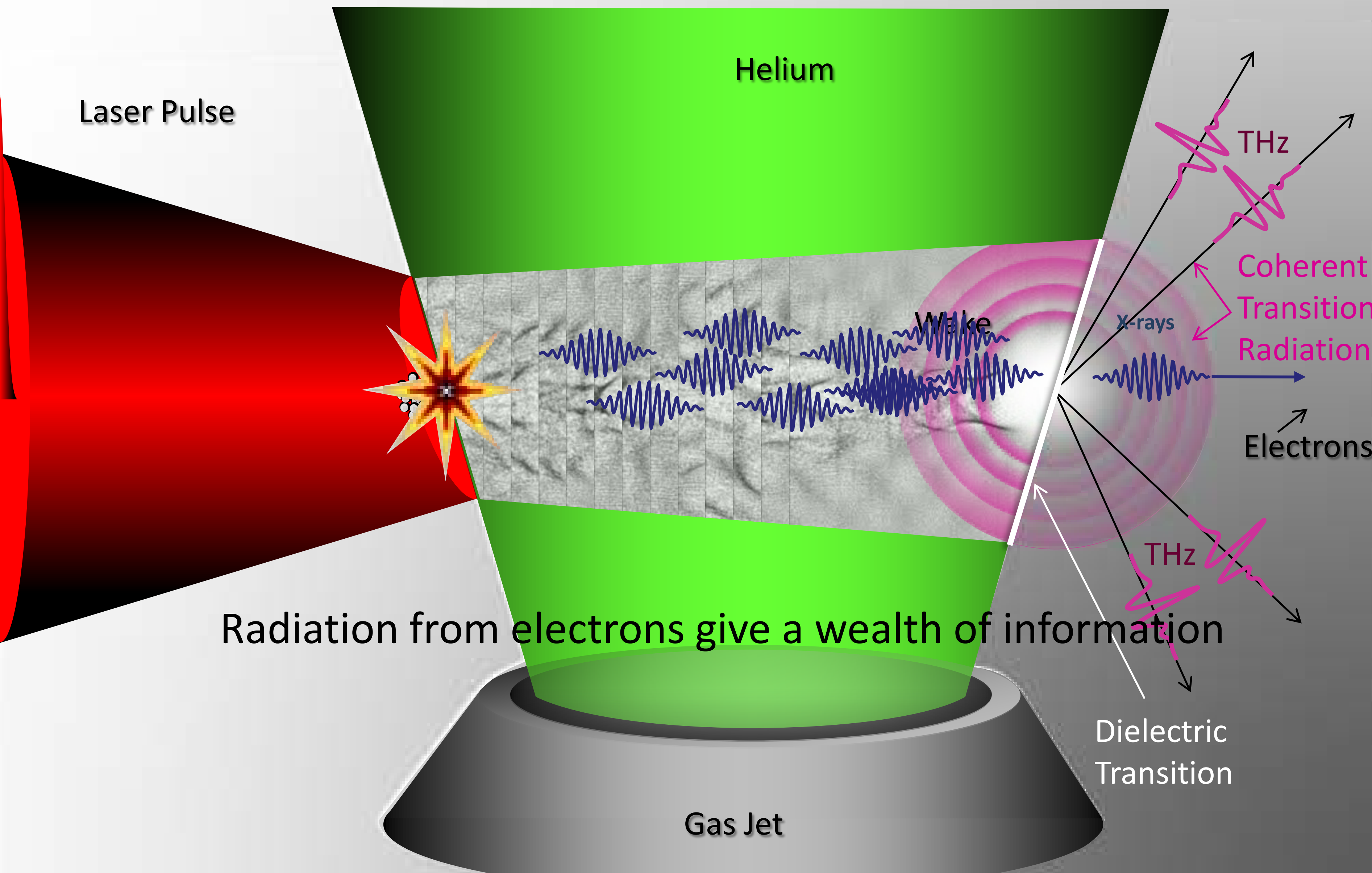
Complex Bunch Temporal Structure

Electron Beam



Multiple components

Need Single-shot, non-destructive diagnostics



Radiation from electrons give a wealth of information

CHARGE DIAGNOSTICS

3 Methods to Measure Charge

1. Integrating Current Transformer

Pros: ICTs are useful charge diagnostic

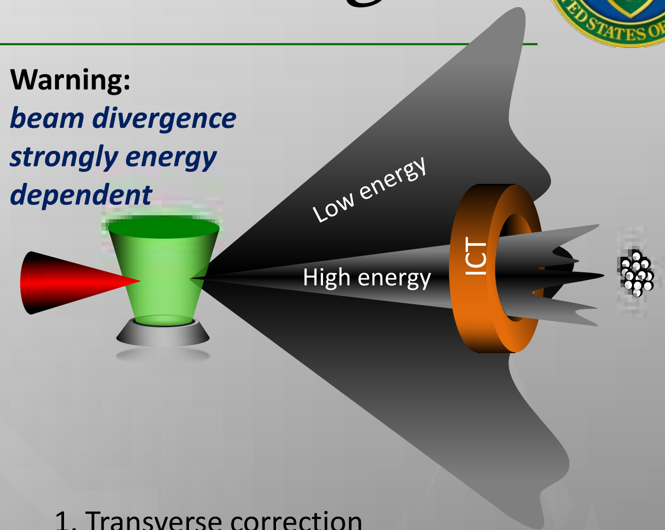
- Nondestructive
- Easy to use
- Work over broad range of energies and bunch durations

Cons: *none*

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

Reliability confirmed
Nakamura et al, in preparation

Warning:
beam divergence strongly energy dependent



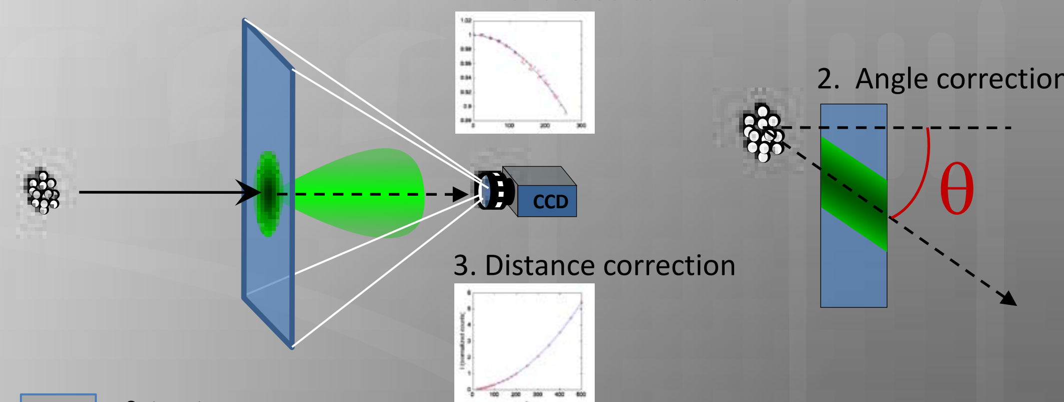
2. Scintillating Screen (e.g. Lanex)

Pros:

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

Cons:

- Destructive
- Calibration requires several steps



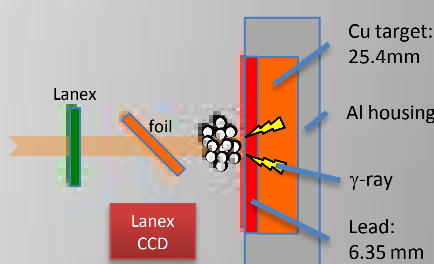
3. Nuclear Activation

Pros:

- Reliable

Cons:

- Destructive
- Not single-shot
- Requires Monte Carlo Analysis

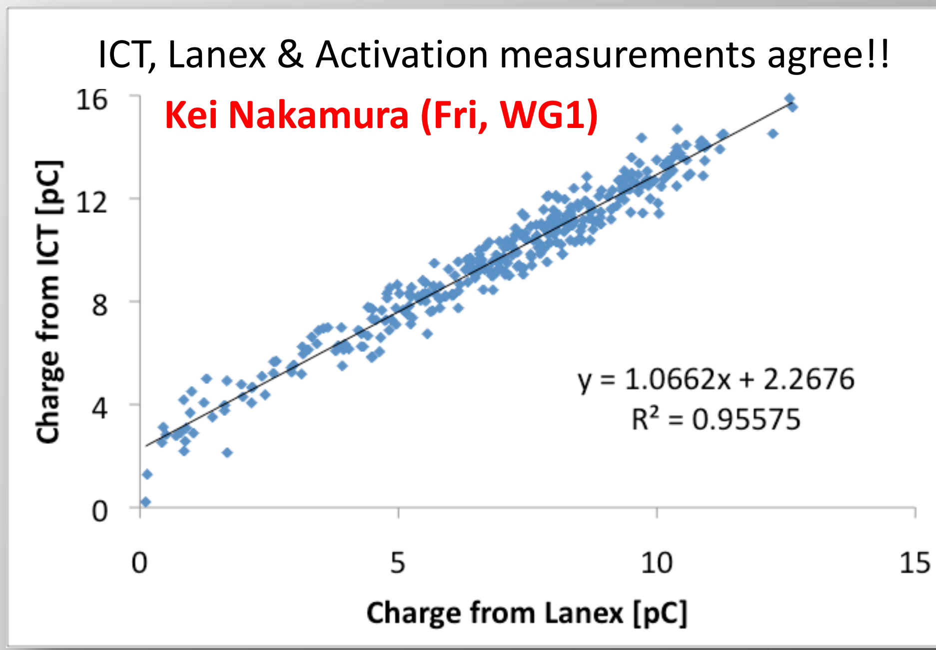


$^{65}Cu\ (\gamma,1n) \rightarrow {}^{64}Cu$

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

ICT Charge Measurements Agree with Lanex

Nakamura et al, in preparation



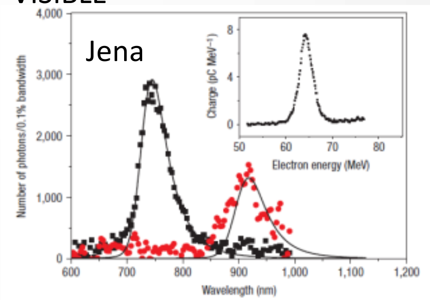
UNDULATOR DIAGNOSTICS

Measurement of Energy, Energy-spread, Emittance

Application: Laser – Plasma FEL

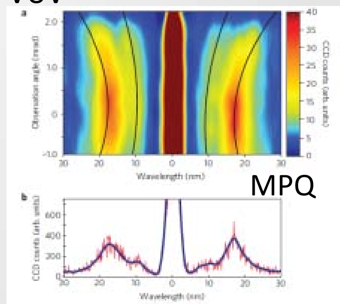
(tunable, coherent, ultrashort source)

VISIBLE



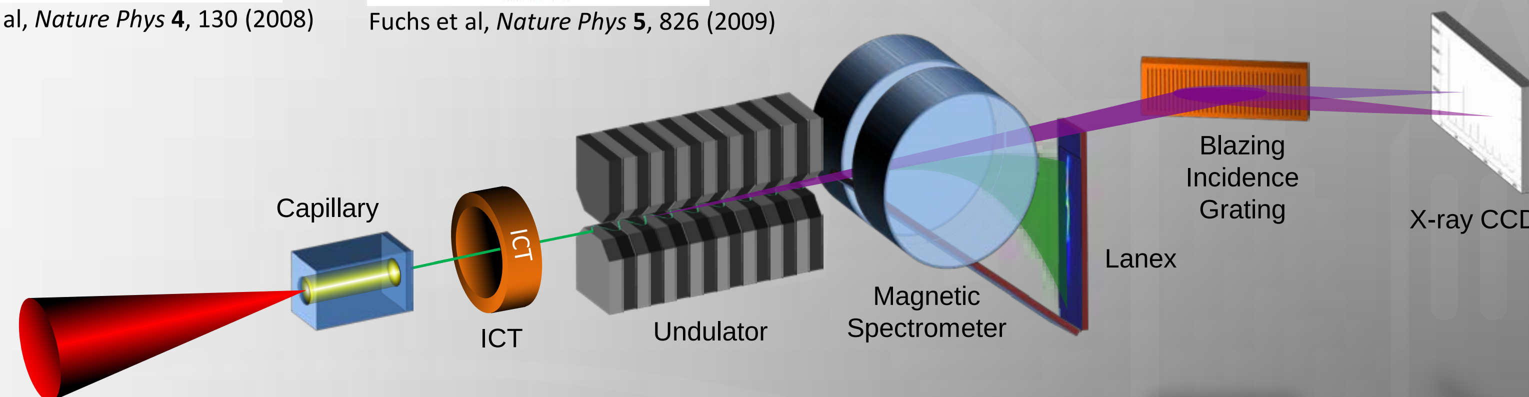
Schlenvoigt et al, *Nature Phys* **4**, 130 (2008)

VUV

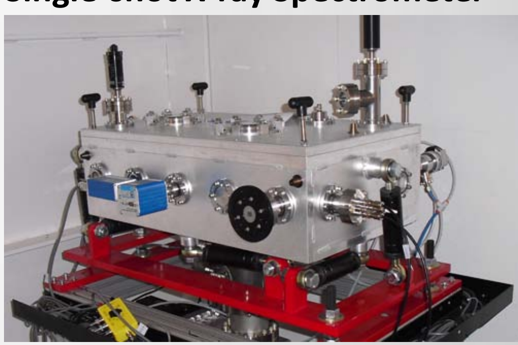


Fuchs et al, *Nature Phys* **5**, 826 (2009)

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



Single-shot X-ray Spectrometer



LOASIS Experiment

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

Also supported by:

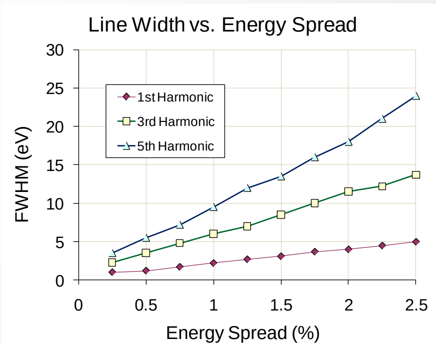
Defense Threat Reduction Agency

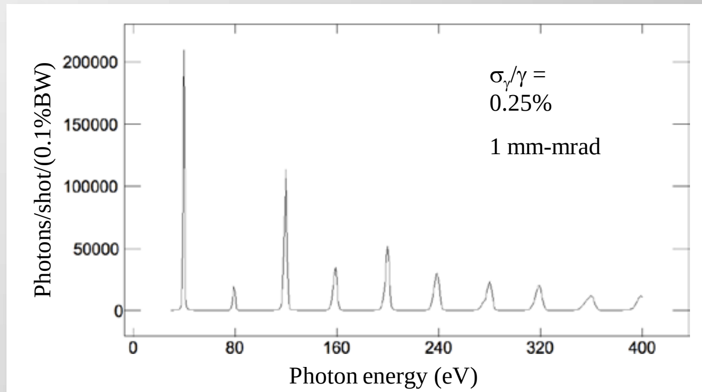
Undulator: Ready to go

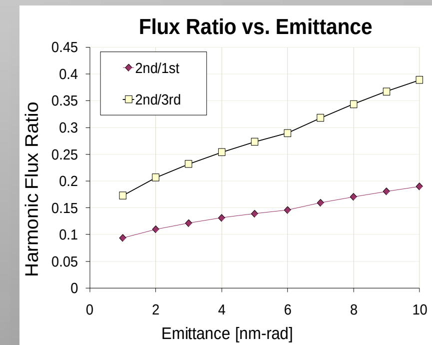
K. Robinson et al, IEEE Quant Elect (1987)

Undulator Diagnostic Provides Energy-Spread, Emittance Measurement

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

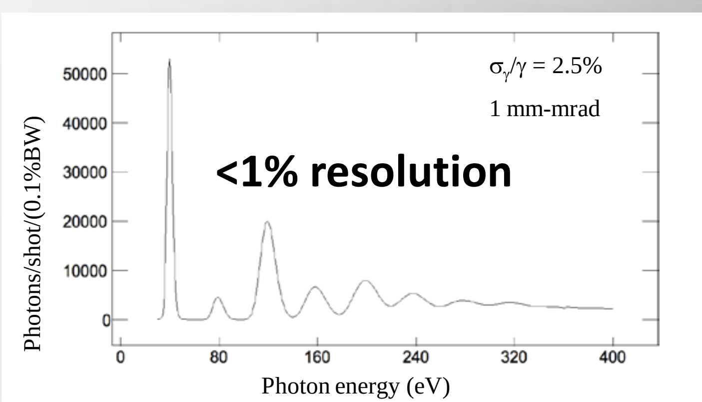


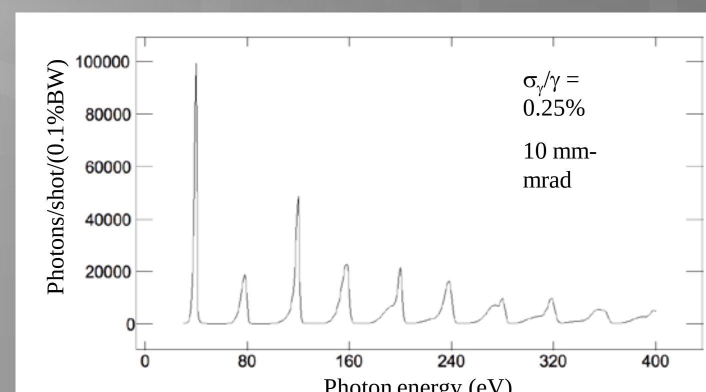




Energy spread x10

Emittance x10



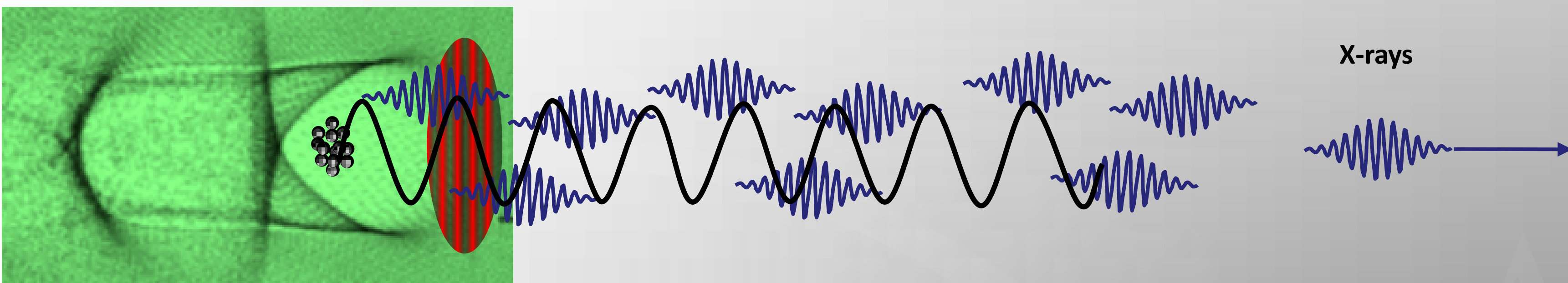


BETATRON DIAGNOSTICS

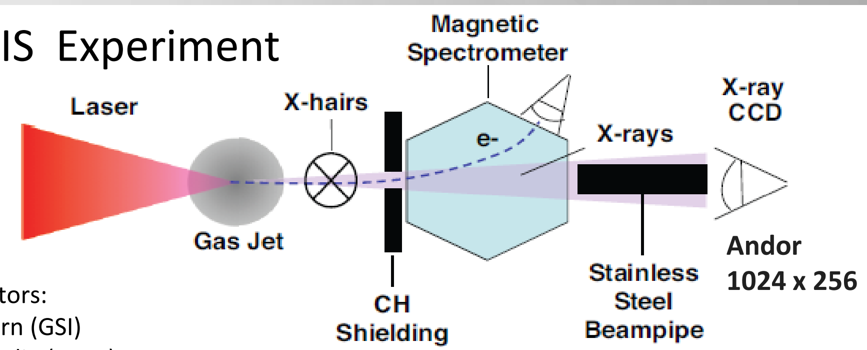
Measurement of Source size, acceleration Dynamics

Production of Betatron X-rays

Esarey et al *Phys Rev E* **65**, 056505 (2002)

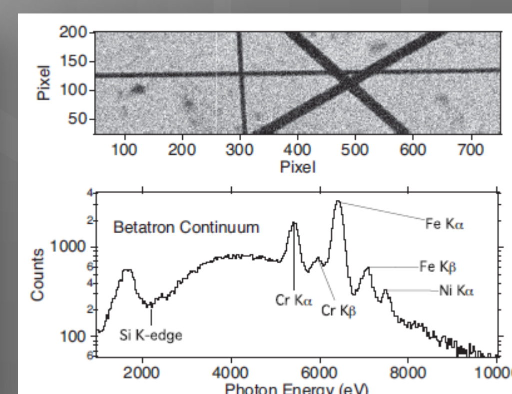


LOASIS Experiment



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

Thorn et al, submitted to RSI



Single shot simultaneous measurement of Electron and Xray spectra

Ebeam spectra

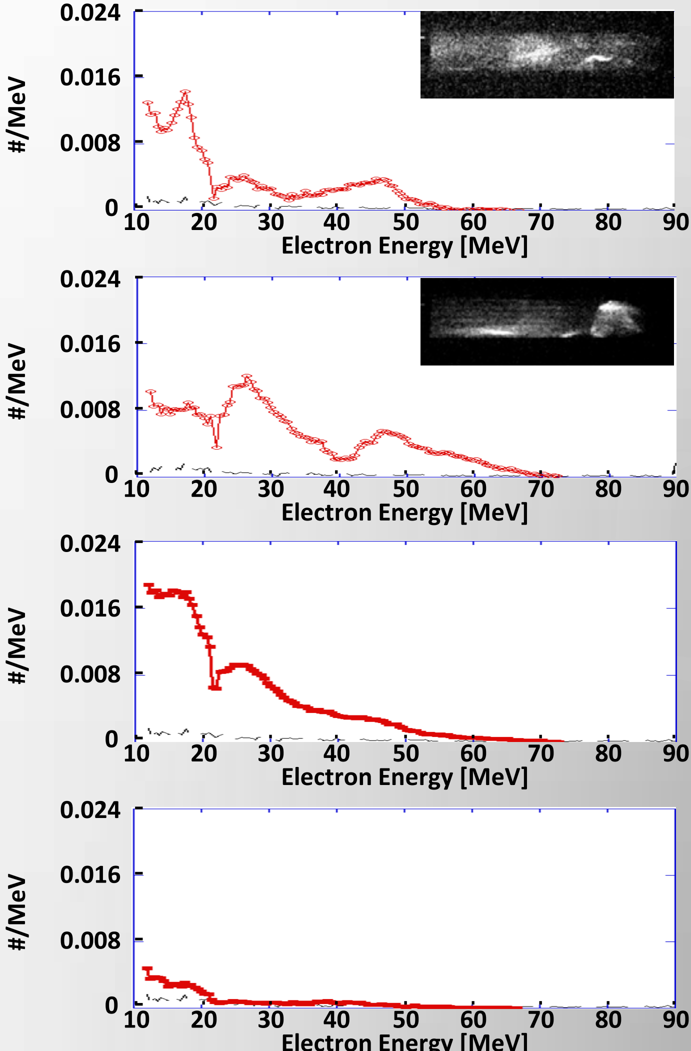
Xray spectra

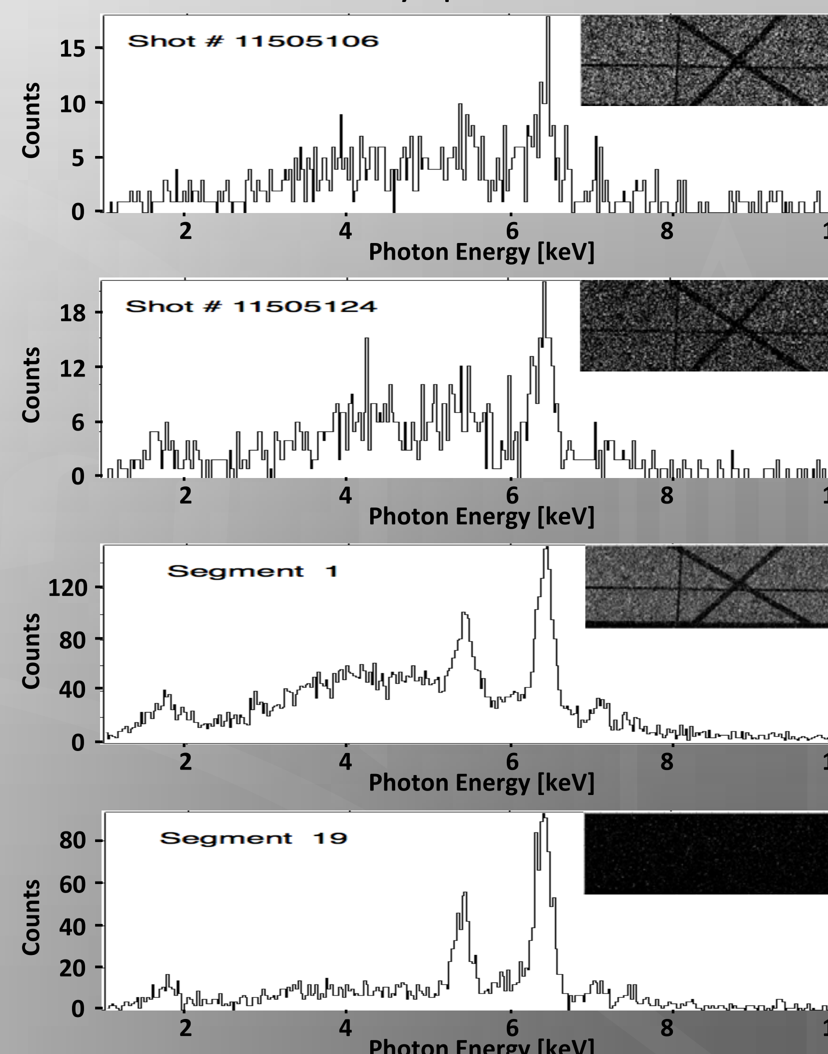
Shots

High

Group

Low



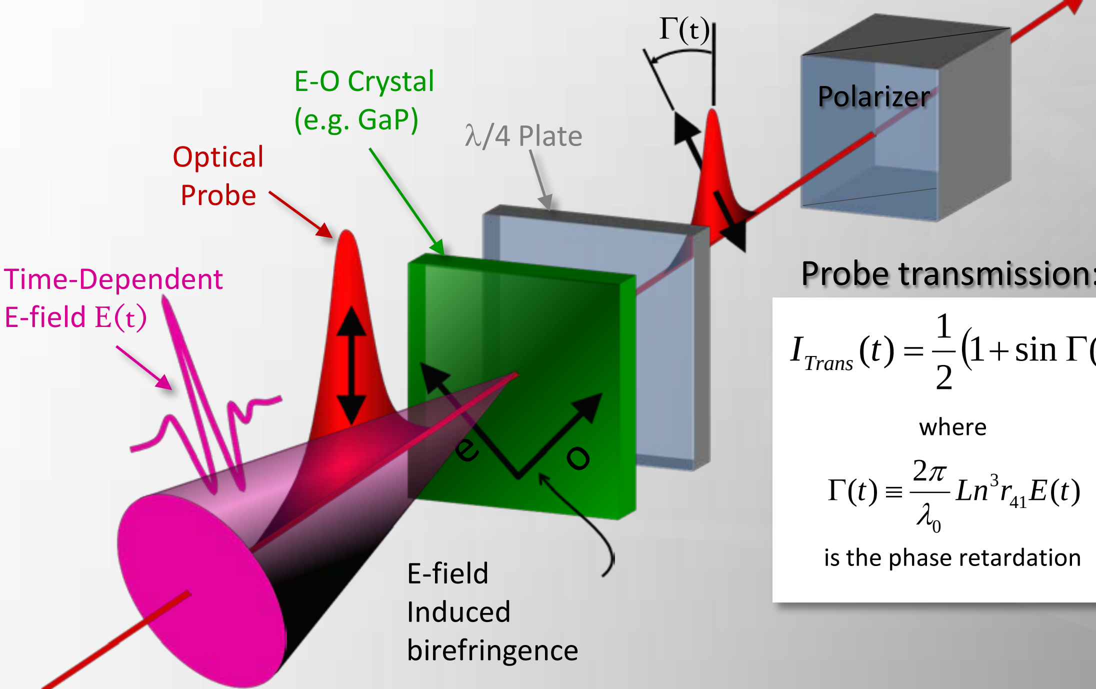


- *Extraction of low-E spectrum with Si dead layer in progress*

ELECTRO-OPTIC DIAGNOSTICS

Measurement of electron bunch temporal structure

Electro-Optic Sampling Method



Probe transmission:

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

where

$$\Gamma(t) \equiv \frac{2\pi}{\lambda_0} L n^3 r_{41} E(t)$$

is the phase retardation

Two halves of EO Sampling:

1. Configuration of the encoding
(setting up the E-fields)

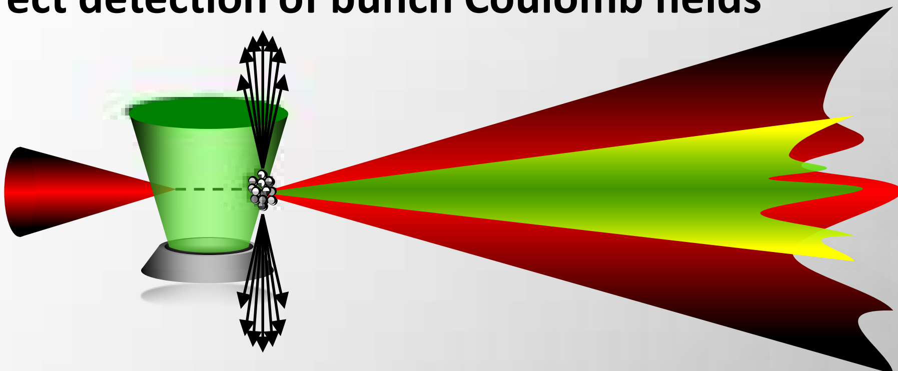
- Coulomb E-fields of the bunch
  Cavalieri *et al*, *PRL* ***94***, *114801 (2005)*
- Transition radiation from a foil
- Transition radiation from the plasma-vacuum boundary
  Leemans *et al*, *PRL* ***91***, *074802 (2003)*

2. Method of retrieval of Information
(configuring the probes)

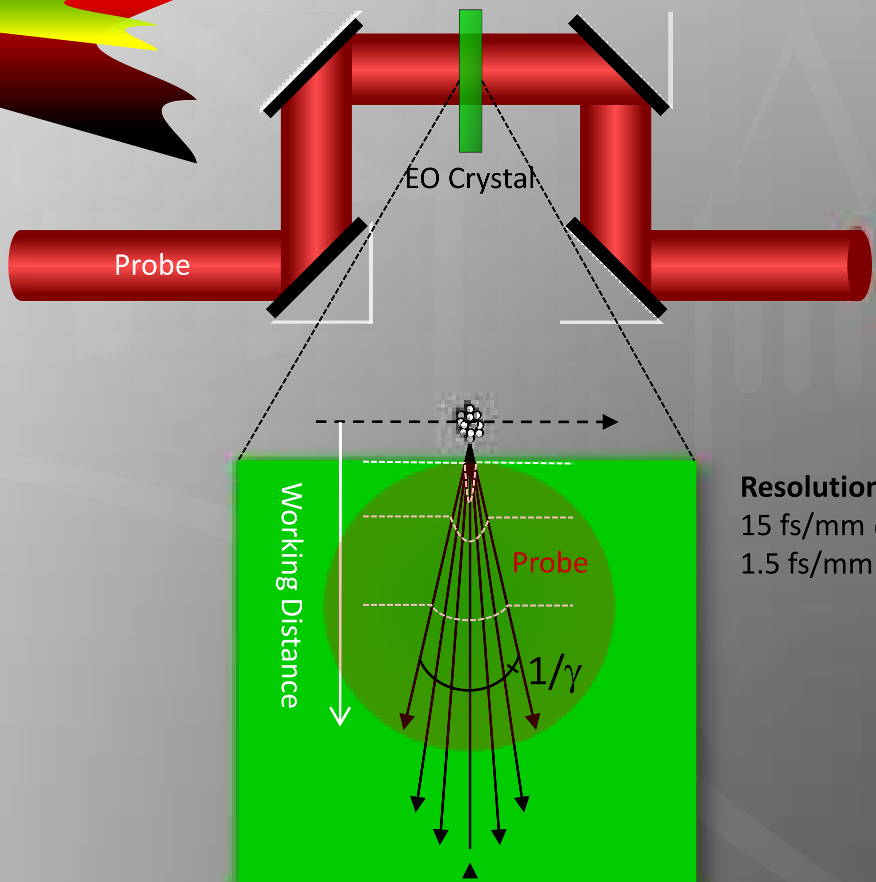
- Spectral Encoding
- Second-Harmonic Cross-correlation
- Temporal Electric-field Cross-correlation (New)

3 Encoding Configurations

1. Direct detection of bunch Coulomb fields



$$E_0 = \frac{Q}{(2\pi)^{3/2}\epsilon_0 r c \sigma}.$$



Implemented at SLAC:
Cavalieri *et al*, *PRL* ***94***, *114801 (2005)*

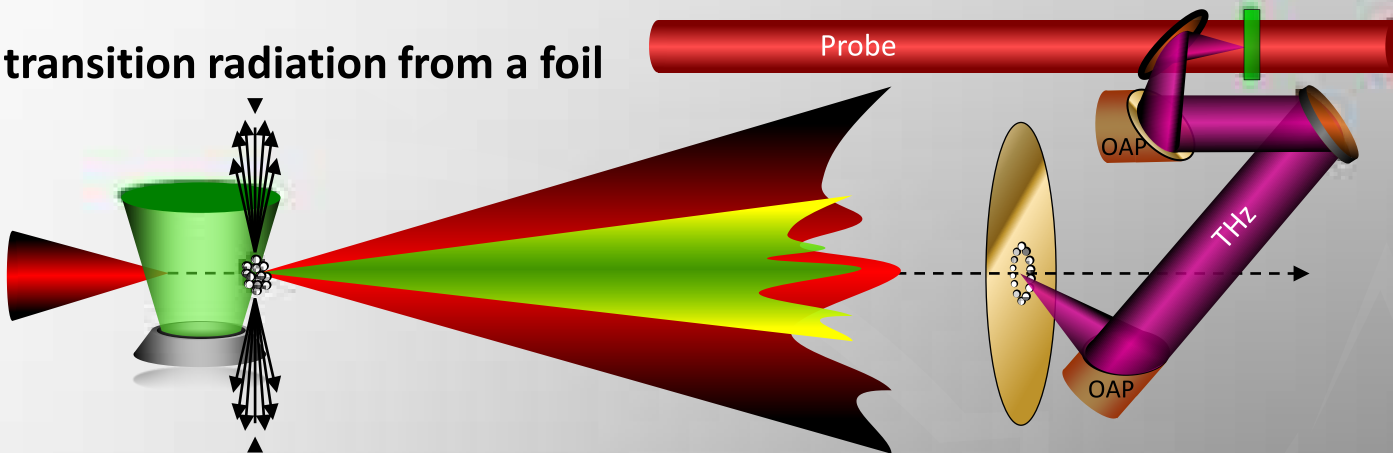
Resolution loss:
15 fs/mm @ 100 MeV
1.5 fs/mm @ 1 GeV

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)

3 Encoding Configurations

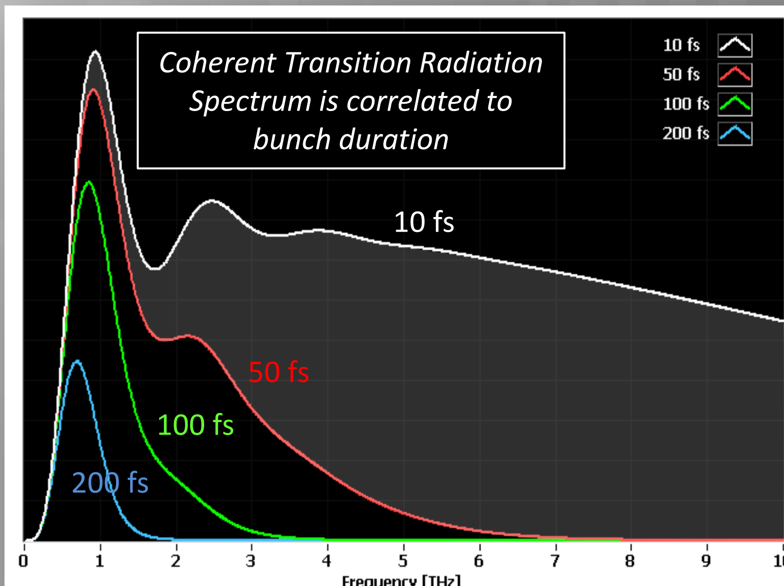
2. Coherent transition radiation from a foil



Fiorito et al. NIMPR Sect. B **173**, 67 (2001)
Debus et al. PRL **104**, 084802 (2010)

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

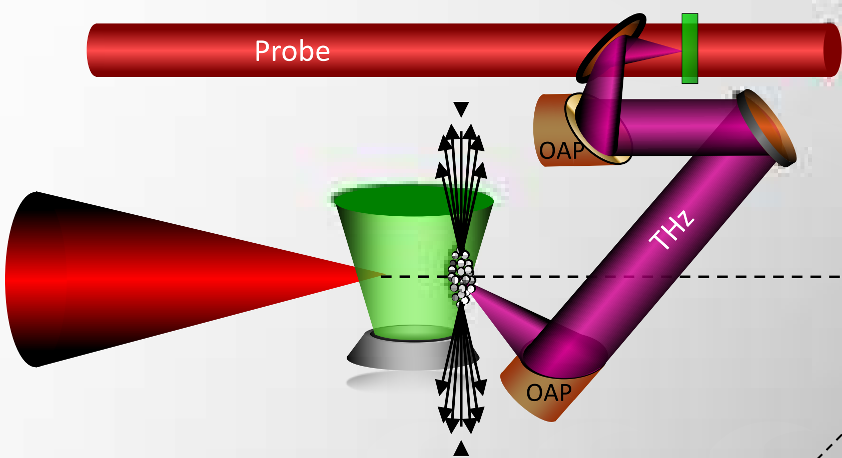
Cons:
- Still have harsh environment (laser & plasma)
  (can not put foil close to interaction)
- Still have bunch expansion
  (may reduce coherence for high frequencies)
- Detection is indirect
  (THz emission must be correlated to bunch properties)
- Bandwidth of Electro-optic detection is limited



Schroeder et al. PRE 69, 016501 (2004)

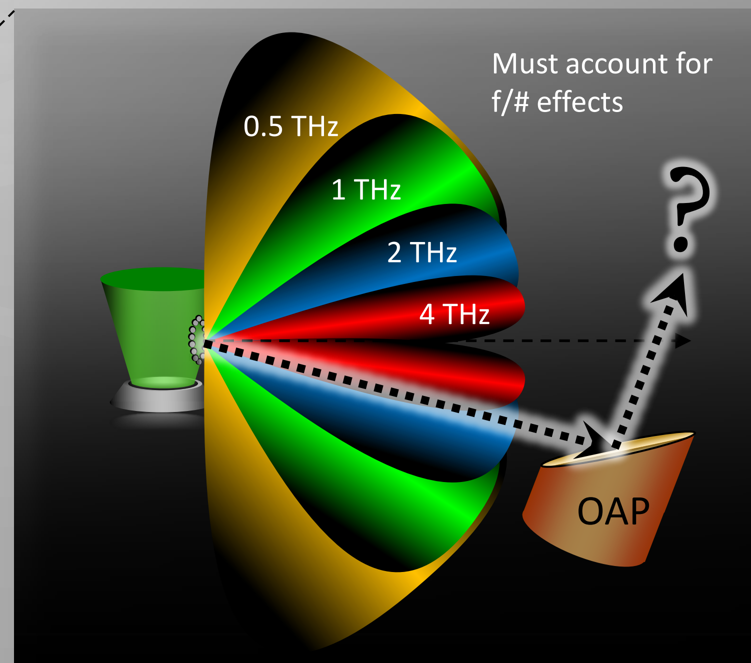
3 Encoding Configurations

3. Coherent transition radiation directly from the plasma boundary



Leemans *et al.*, Phys. Rev. Lett. **91**(7) 074802 (2003)
Schroeder *et al.*, Phys. Rev. E **69**, 016501 (2004)
van Tilborg *et al.*, Phys. Rev. Lett. **96**, 014801 (2006)

THz emission is *very* wavelength dependent



Pros:

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

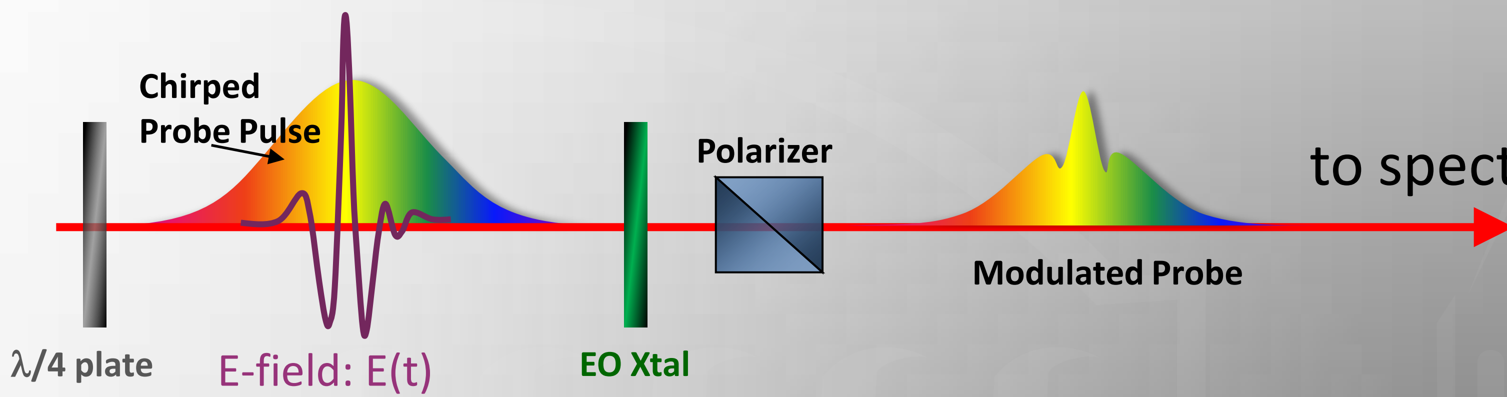
Cons:

- 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

3 Detection Techniques

1. “Spectral Encoding”

Z. Jiang et al, Appl Phys Lett ***72****, 1945 (1998)*

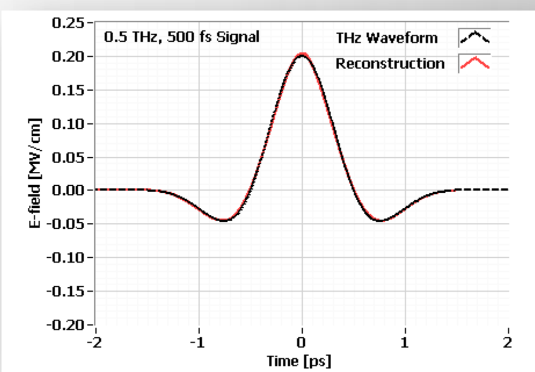


Pros:

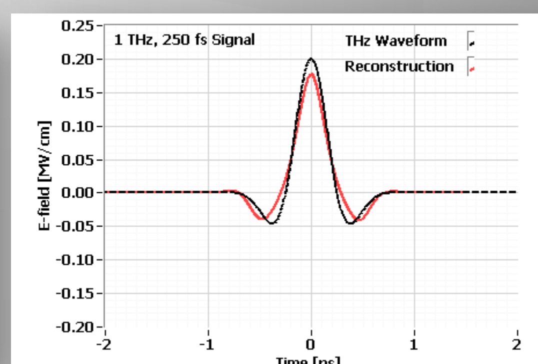
- Simple to implement

Cons:

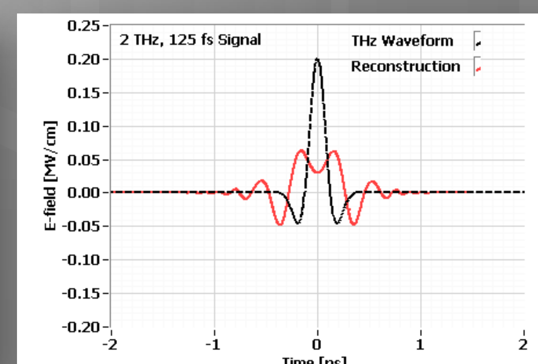
- Recovery is unreliable for short pulses due to distortion



0.5 THz, 500 fs signal



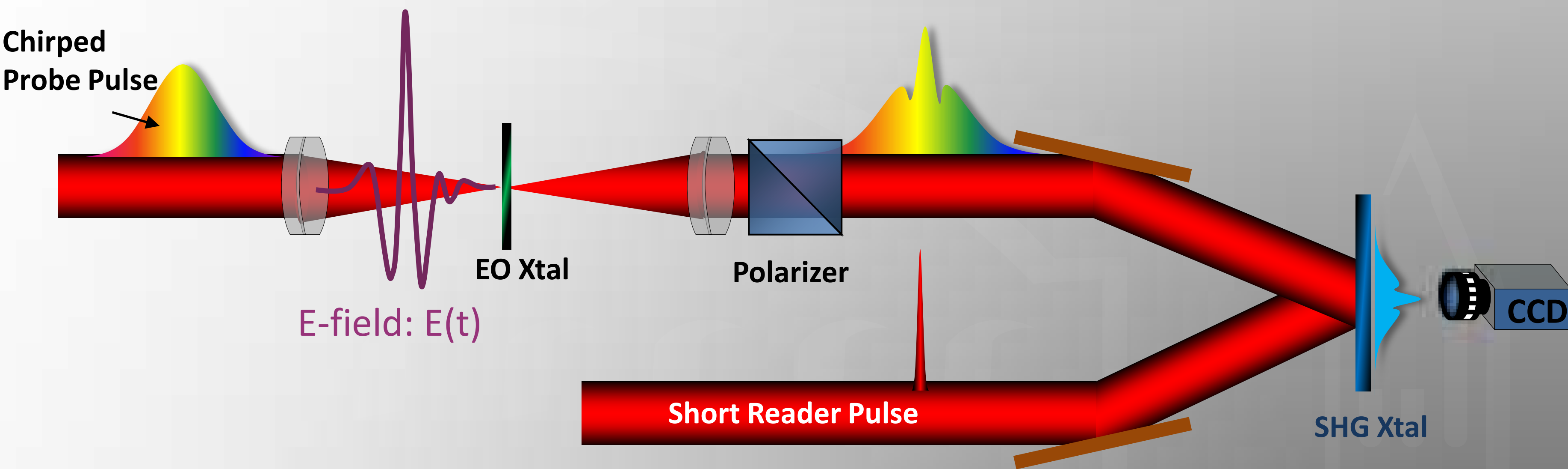
1 THz, 250 fs signal



2 THz, 125 fs signal

2. Second-Harmonic Cross-correlation

*S.P. Jamison et al, Opt Lett **28**, 1710 (2003)*



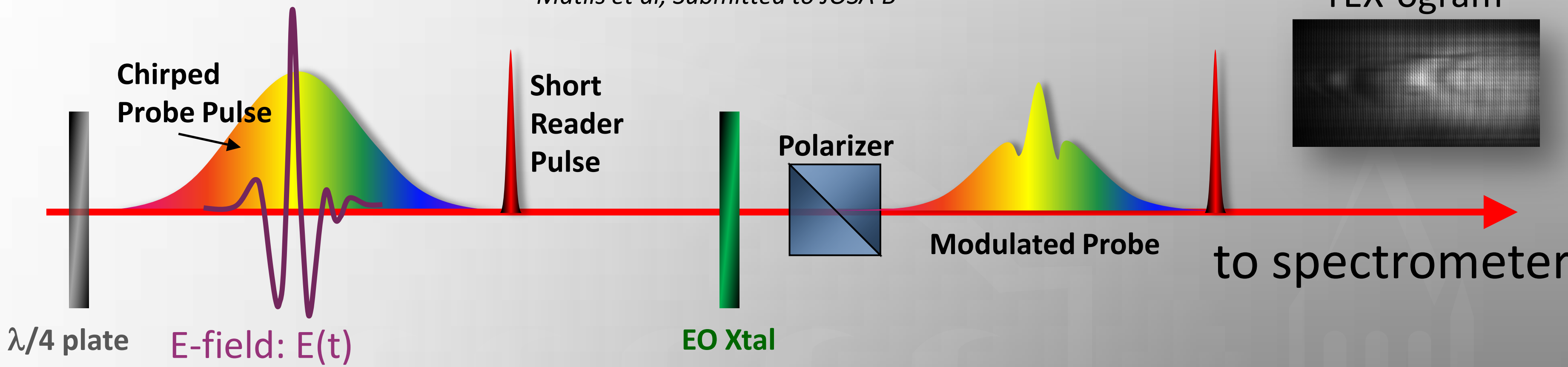
Pros:
- High temporal resolution

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

3 Detection Techniques

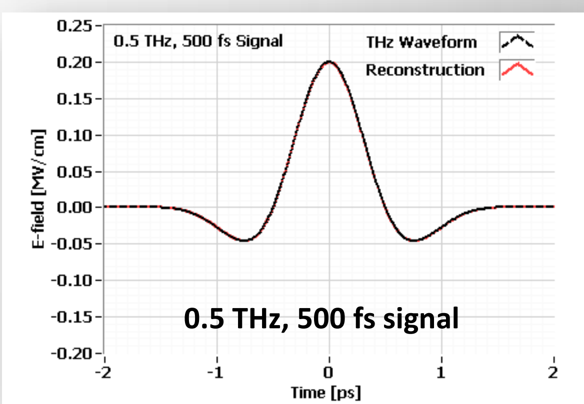
3. Temporal Electric-field Cross-correlation (TEX)

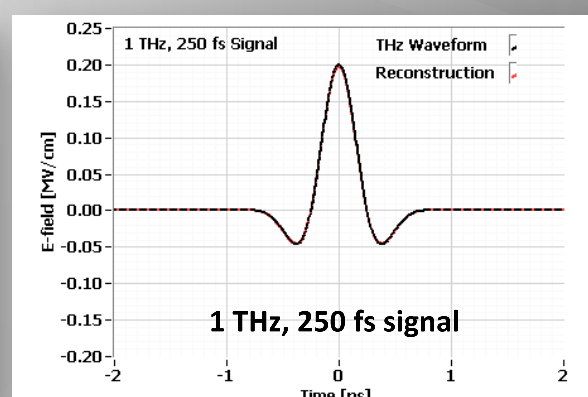
Matlis et al, Submitted to JOSA B

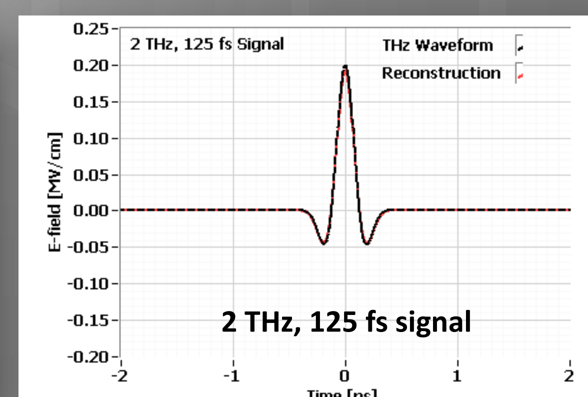


Pros:
- High temporal resolution
- Provides imaging
- Linear in probe intensity

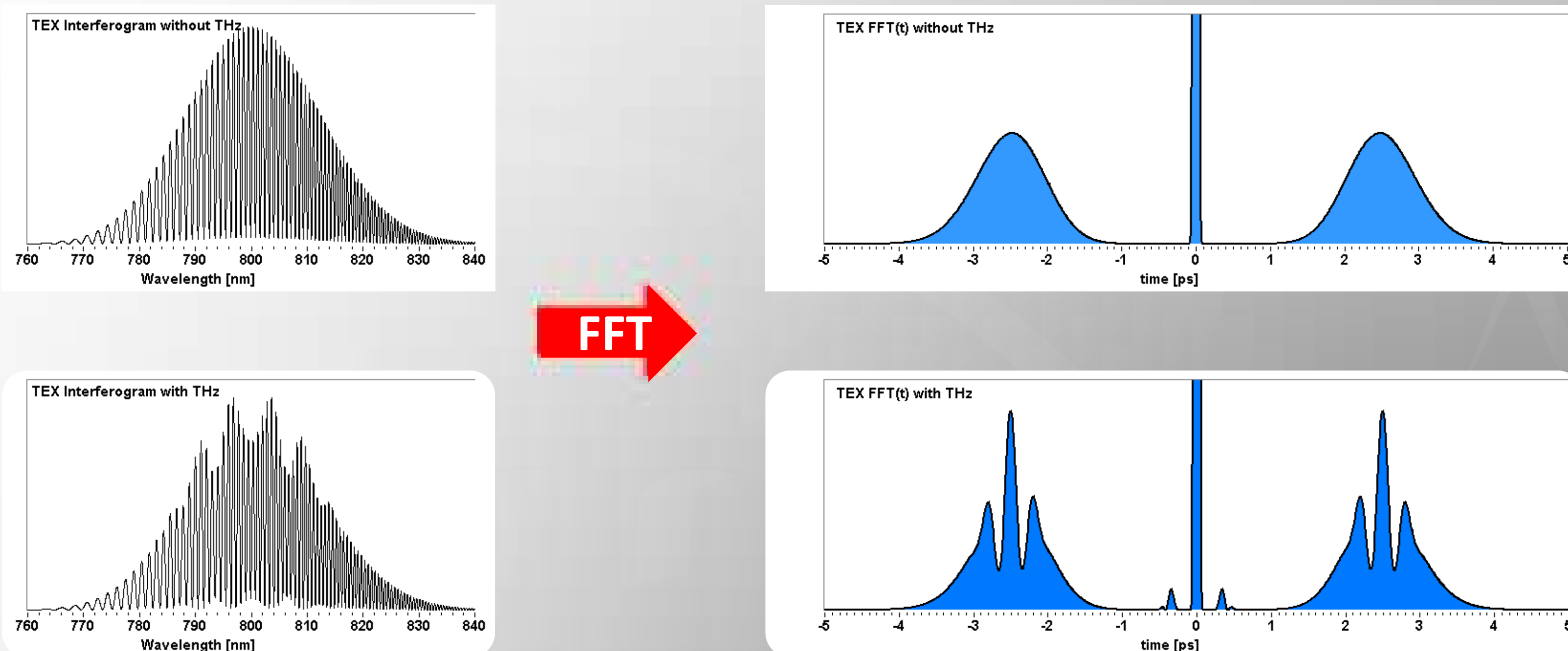
Cons:
- Susceptible to phase in the reader







How TEX works



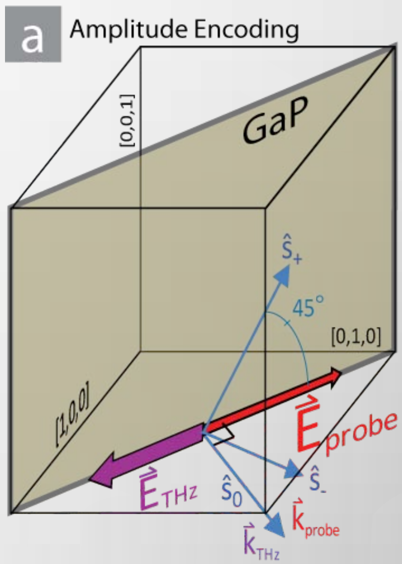
$$S(\omega) = \left|E_p(\omega)\right|^2 + \left|E_r(\omega)\right|^2 + E_p(\omega)E_r^*(\omega) + c.c.$$

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

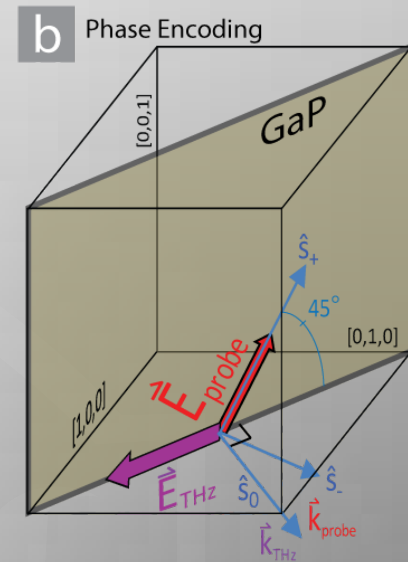
FFT

TEX Recovers temporal amplitude and phase information!

TEX can be used for *Amplitude* or *Phase* encoding



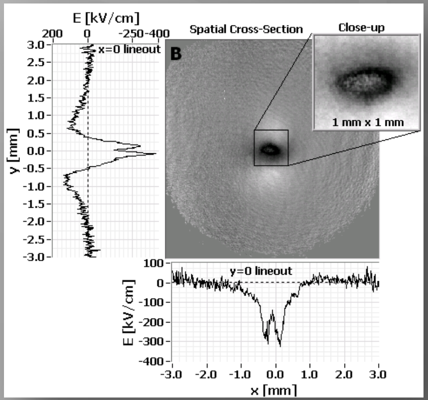
Probe polarization *inbetween* birefringence axes



Probe polarization *along* birefringence axes

- Phase encoding does is not restricted by $\pi/2$ rotation limit

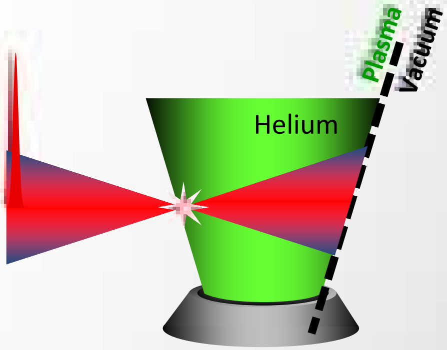
2D Spatial profile of THz slice at t=0 showing "over-rotation" at center, measured with amplitude encoding

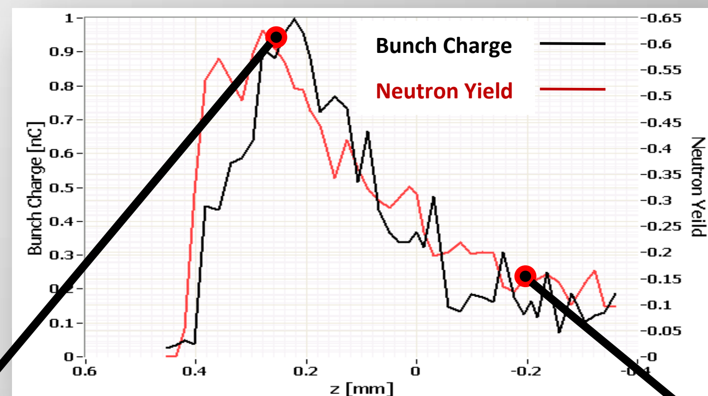


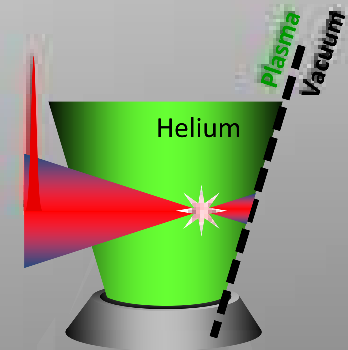
THz resolves variation in accelerator performance during parameter scans

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***

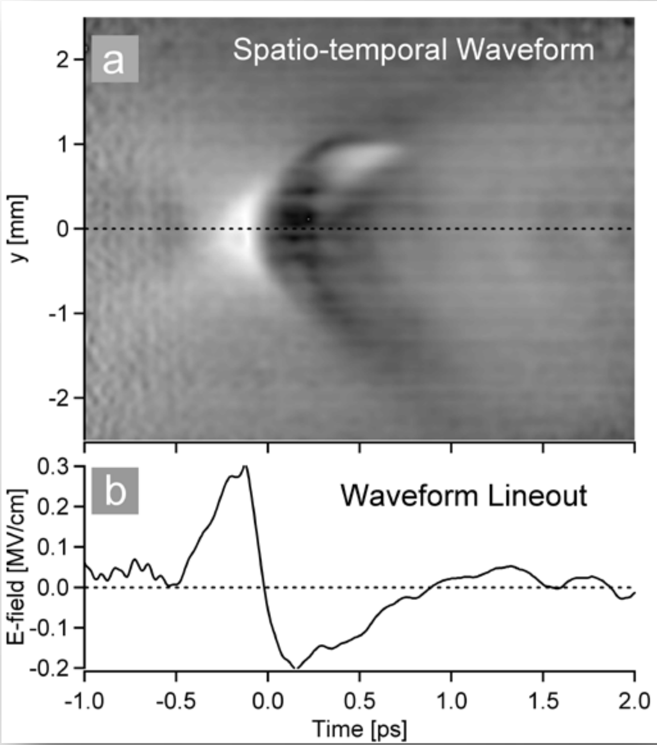
- higher n,γ production
- less Coulombic expansion
- *expect* higher THz frequencies

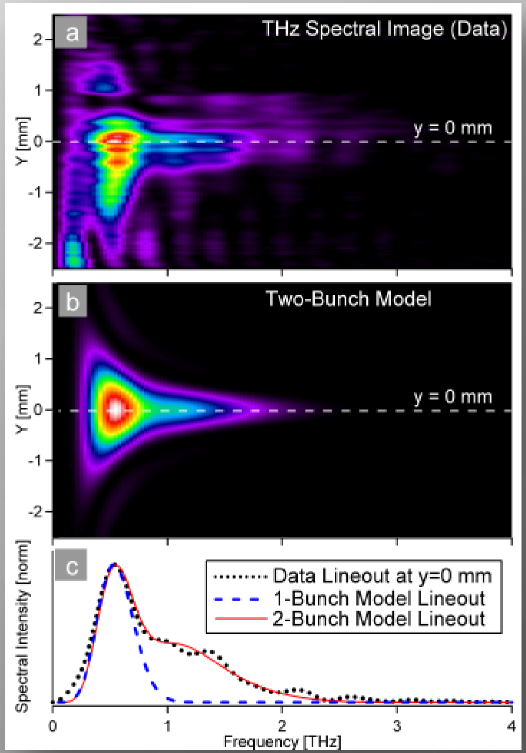
Focus on inside Gas Jet

**** 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)

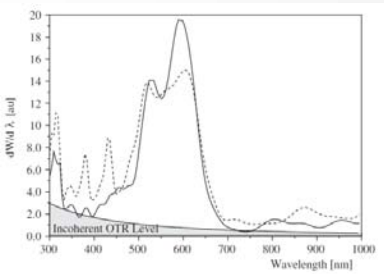
Matlis et al, submitted to JOSA B

OTR DIAGNOSTIC

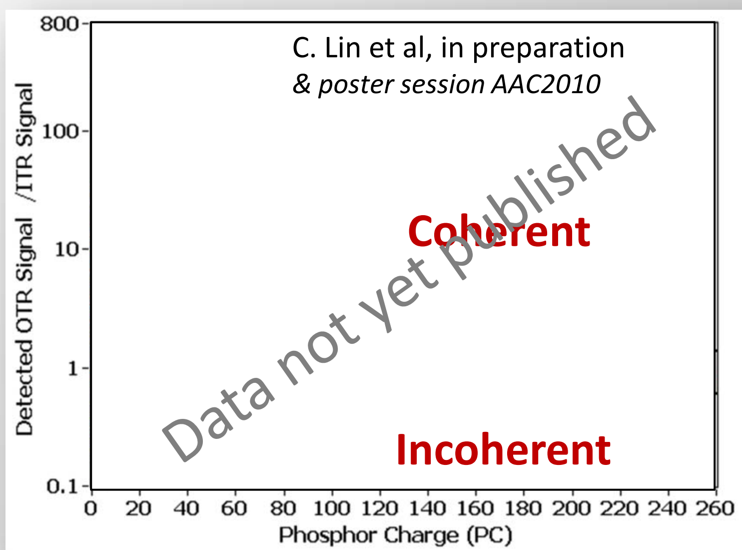
Measurement of electron bunch micro structure

Evidence for Coherent OTR at 3m

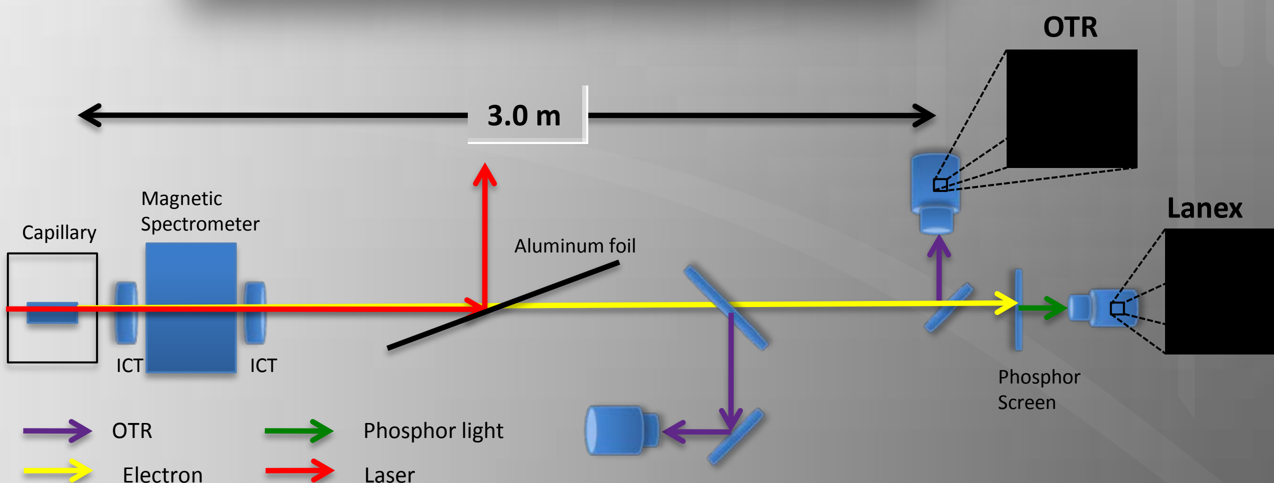
Glinec et al, PRL **98,** 194801 (2007)



Coherent OTR at
1.5 - 140 mm



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



LOASIS Experiment

Summary

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