THz Radiation Diagnostic for Laser Plasma Accelerators

LOASIS Program Director:
W.P. Leemans

Nicholas Matlis

Scientist, LOASIS program

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Students & Staff

- G. R. Plateau
- J. Van Tilborg
- T. Gonsalves
- C. G. R. Geddes
- E. Esarey
- K. Nakamura
- Cs. Tóth
- C. Schroeder
- J. Osterhoff
- T. Sokollik
- C. Lin
- S. Shiraishi

http://loasis.lbl.gov/

Overview

- Brief introduction to laser-plasma acceleration

- Motivation for study of THz
  I. Noninvasive diagnostic for accelerator performance
  II. High-intensity source is good for applications

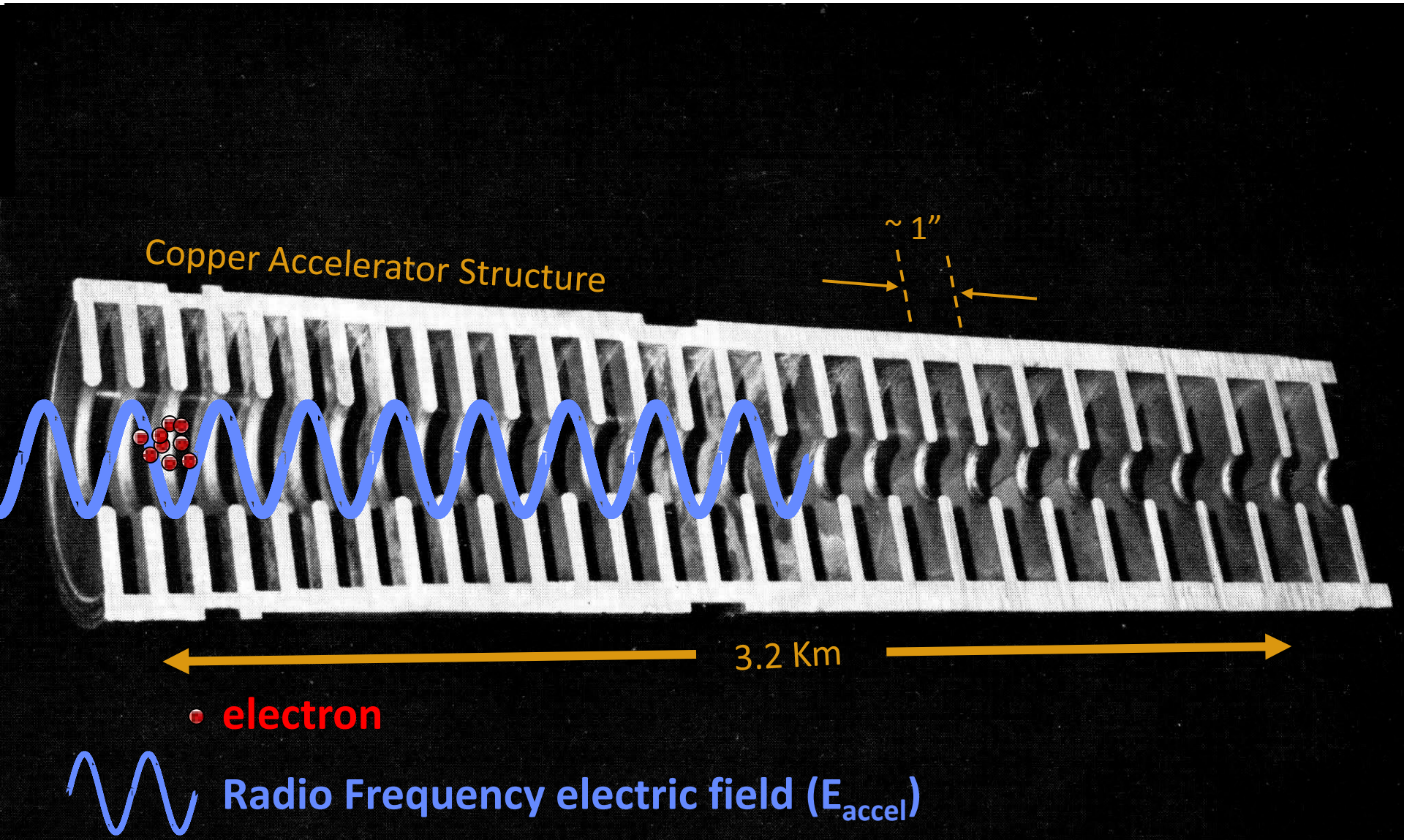
- THz generation and Characterization
  I. Coherent Transition Radiation (CTR)
  II. Electro-Optic Sampling
  III. Single-shot detection

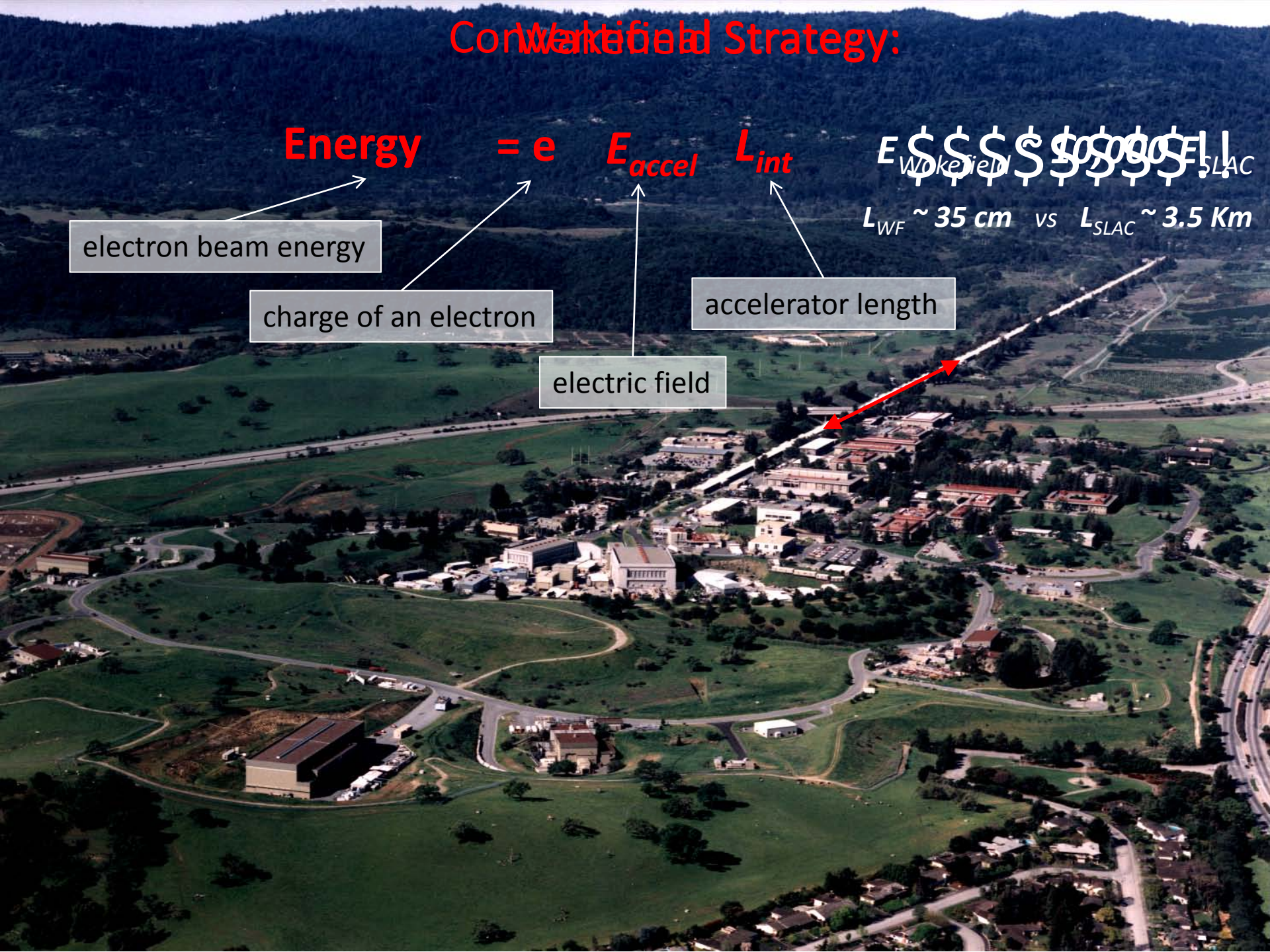
Motivation for Laser-Plasma Acceleration

LHC: $8 Billion, 27 Km!

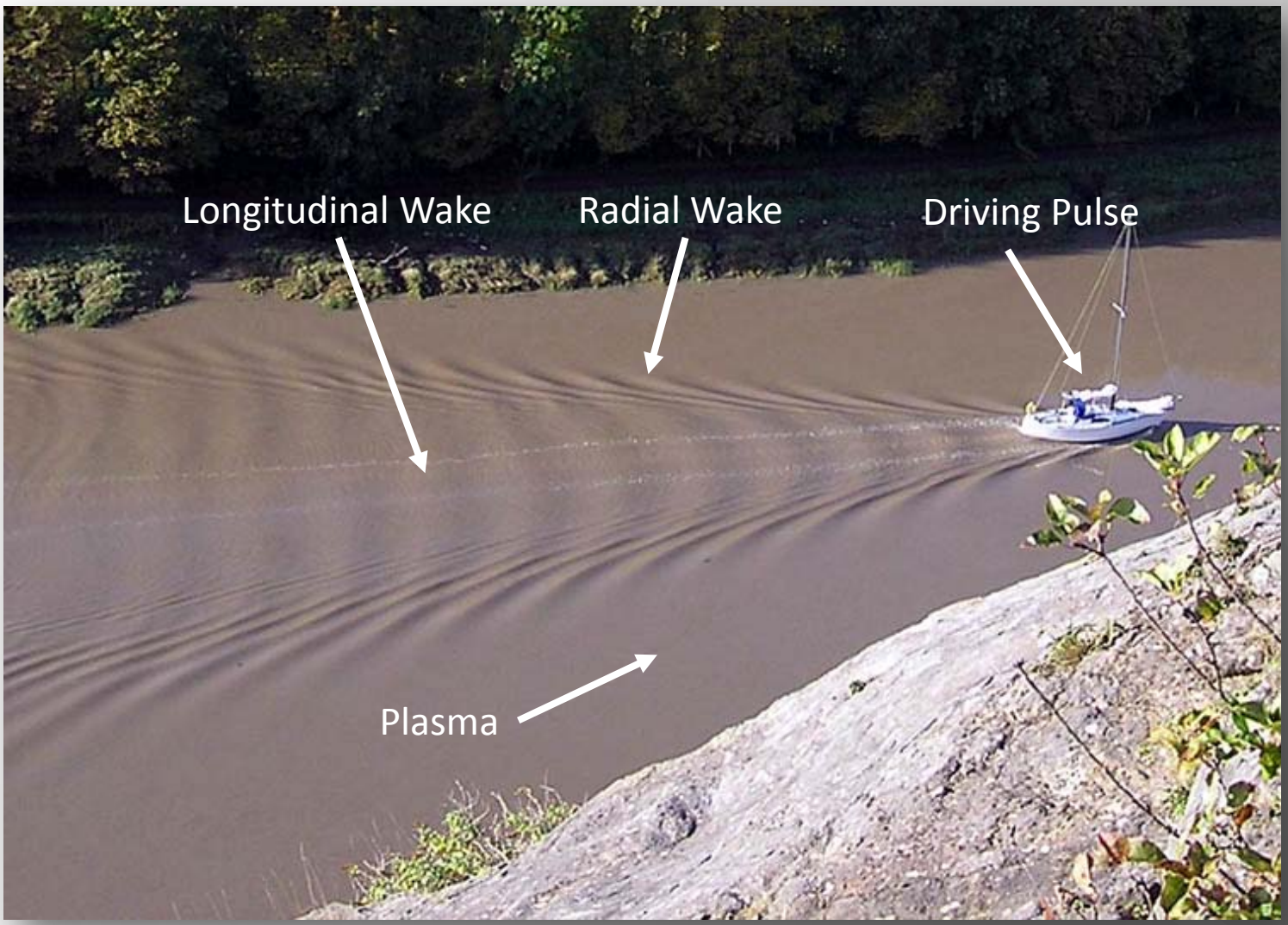
We need a technology to make high energy physics accessible!

Acceleration in a conventional RF Accelerator

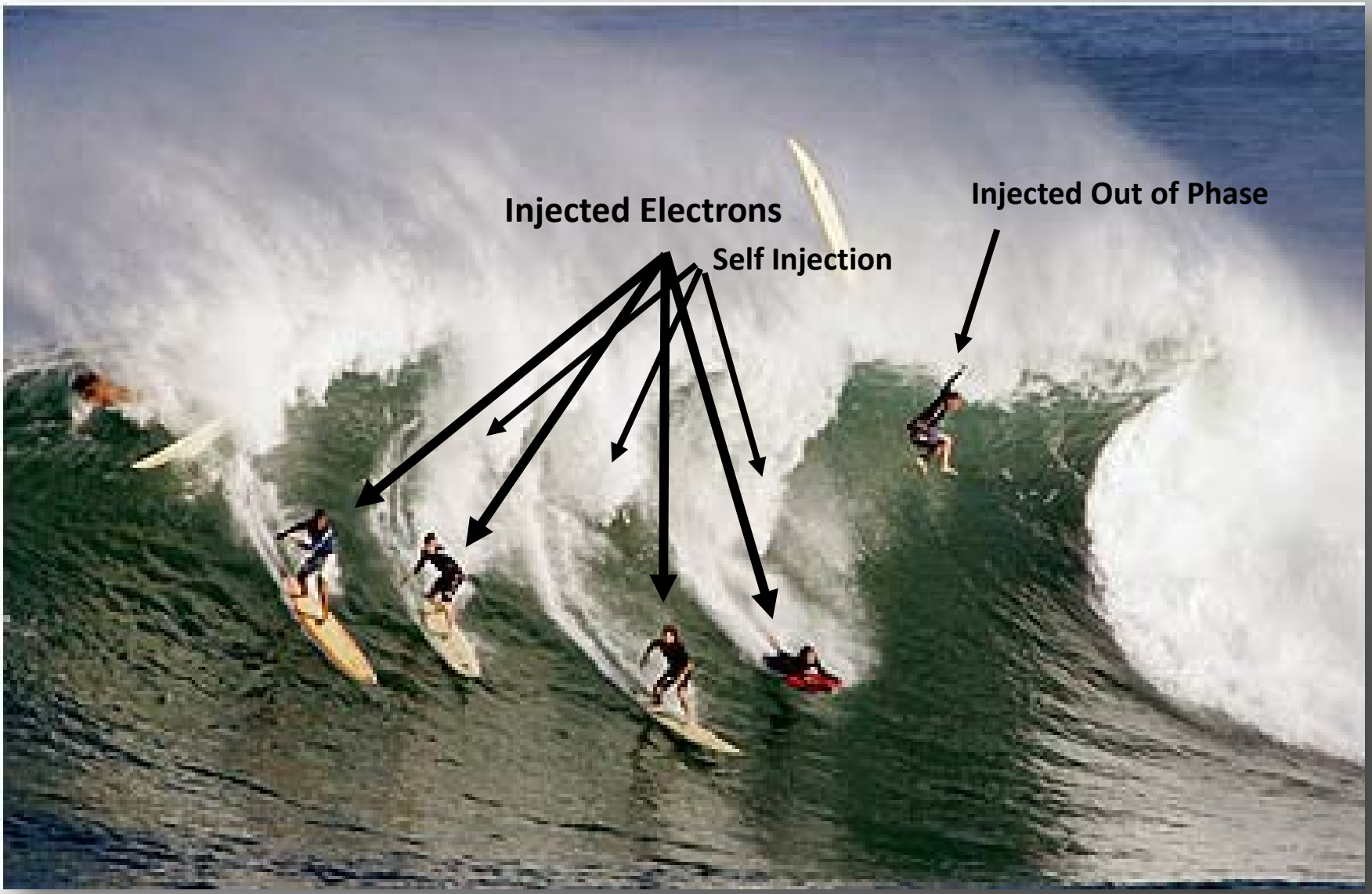



Conventional Strategy:
Wakefield
Energy = e E_{accel} L_{int}
$E_{Wakefield}$ = E_{SLAC}
L_{WF} ~ 35 cm vs L_{SLAC} ~ 3.5 Km
electron beam energy
charge of an electron
electric field
accelerator length

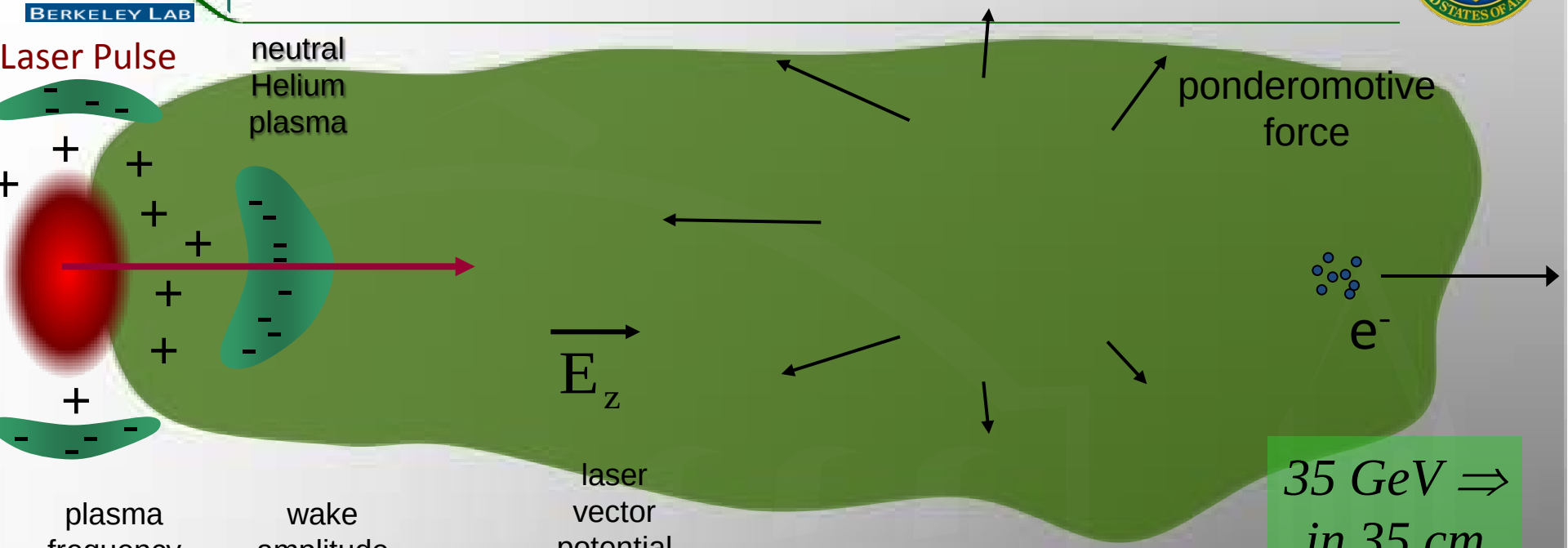
Marine Wakefield



Electrons surf on a plasma wave



Laser Wakefield Generation:



35 GeV ⇒ in 35 cm

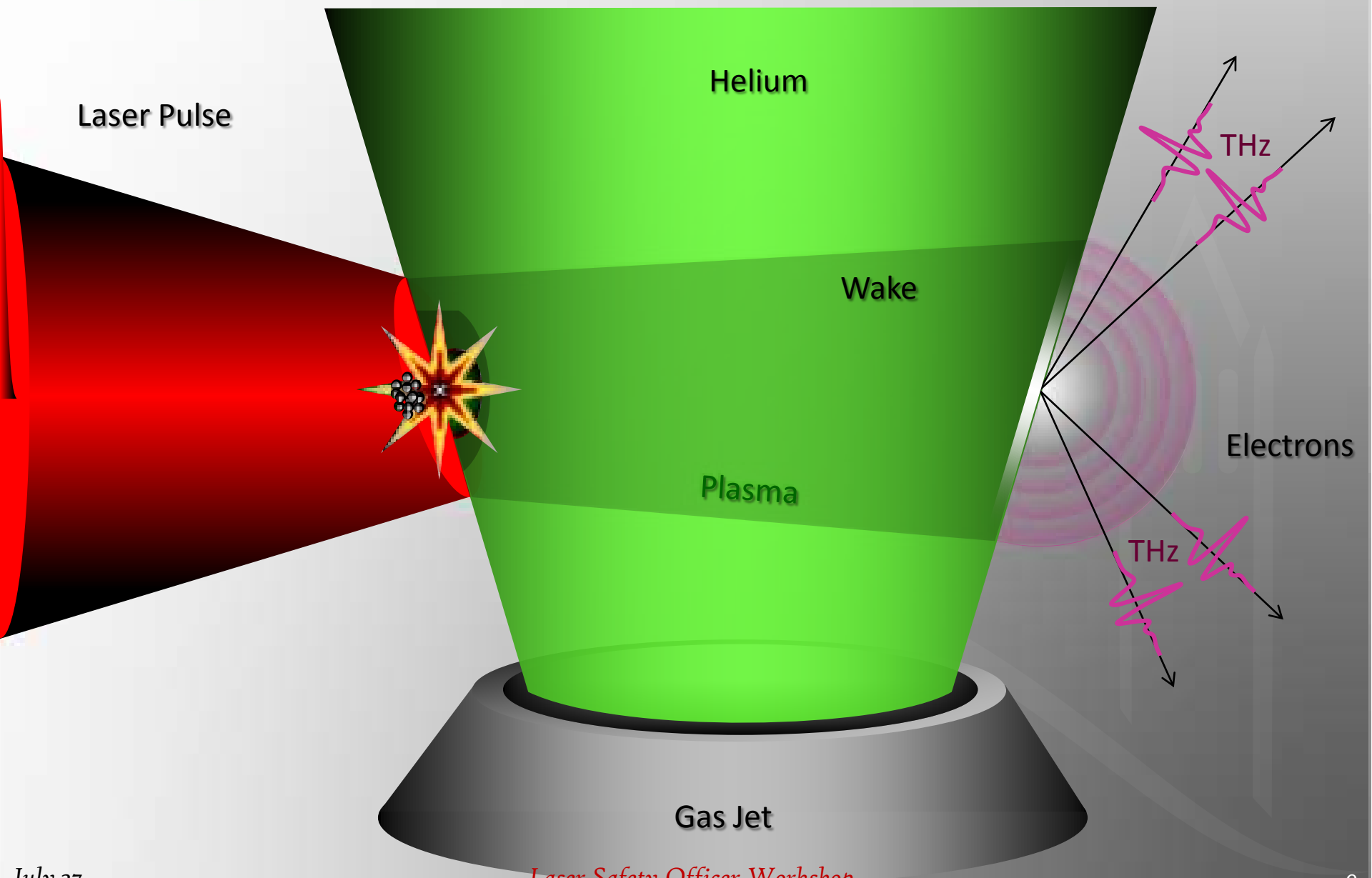
plasma frequency — wake amplitude — laser vector potential

$$\left(\frac{d^2}{dt^2}+\omega_p^2\right)\frac{\delta n}{n_0}=\frac{c^2}{2}\nabla^2 a(r,z,t)$$

30 TW
$I_0 = 1 \times 10^{19}$ W/cm^2
$\tau_p = 30$ fs

E ~ 100 GV/m

Using Wakefields to Accelerate Electrons

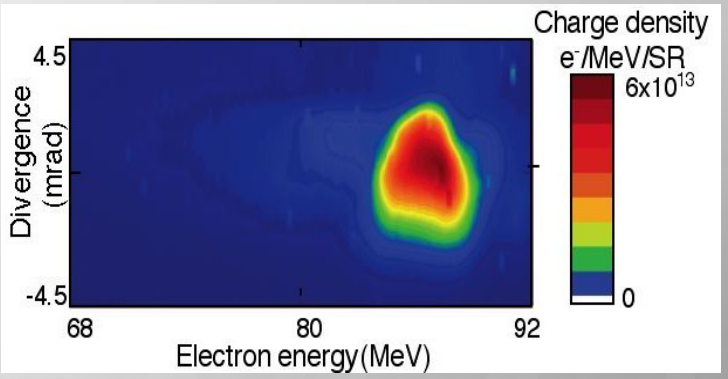


Recent Progress in Laser Plasma Acceleration

*Geddes et al., Nature **431**, 538 (2004)*

9 TW: 86 MeV/c
Δp = 4 MeV/c FWHM*

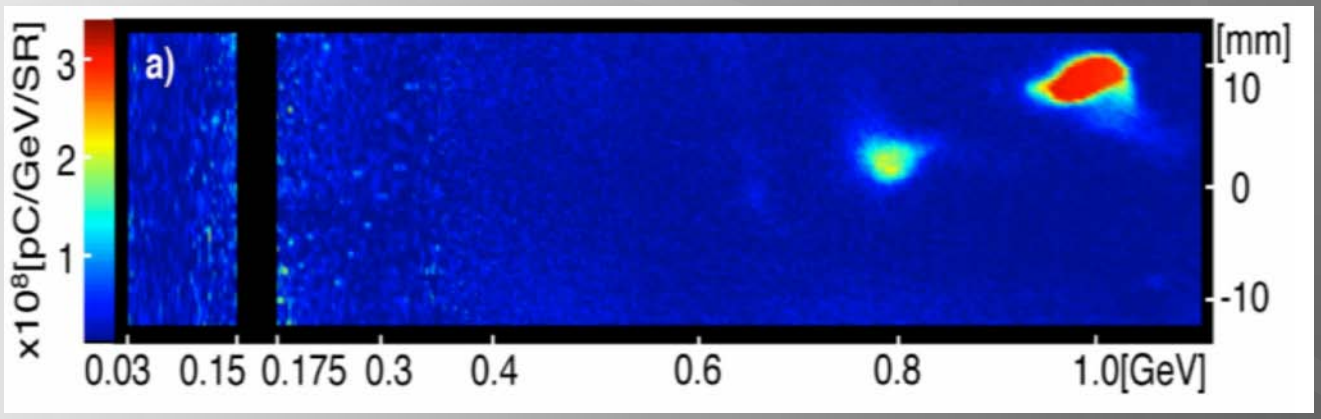
2004



*Leemans et al., Nature Physics **2**, 696 (2006)*

40 TW, 1 GeV/c,
Δp = 25 MeV/c rms**

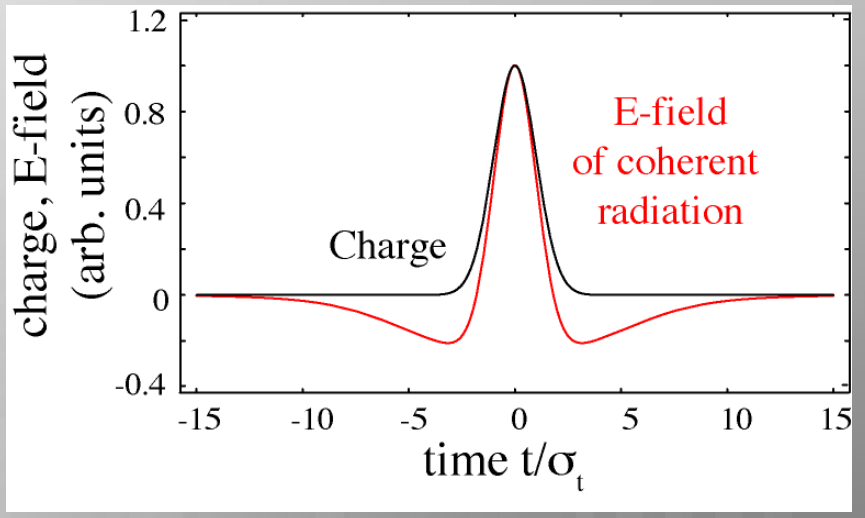
2006



Motivation for studying THz

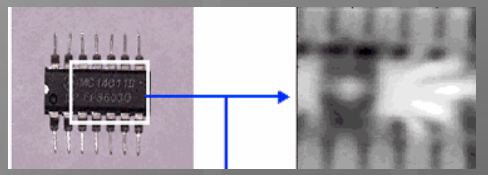
1. THz as a bunch diagnostic:

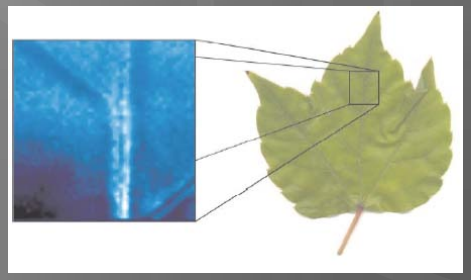
Measurements of THz waveform allow characterization of accelerated e^- bunch



2. THz as a unique source:

- **Remote Sensing**
- **Rapid 2D Imaging** of biological and semiconductor samples
- **Pump-Probe Experiments**
  - **E_{THz} ~ 0.01-10 MV/cm** (traditional sources: E_{THz} ~ 0.1 MV/cm)
  - intrinsic synchronization with laser, electrons, x-rays, etc.

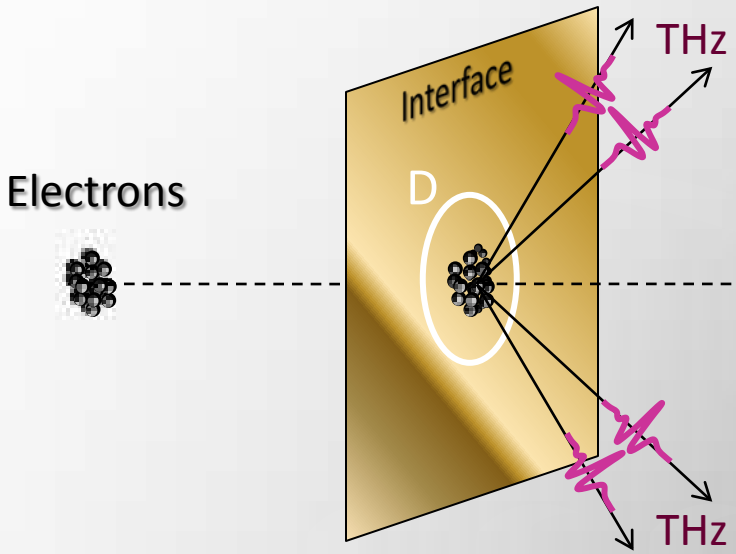




THz Radiation as an Electron Bunch Diagnostic

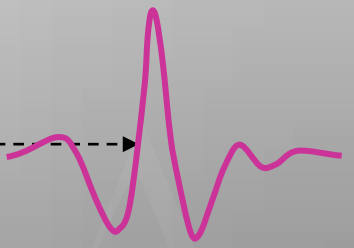
Measurement of electron bunch temporal structure

Transition Radiation is Emitted by electrons passing an Interface



Coherence Condition
(high cutoff)

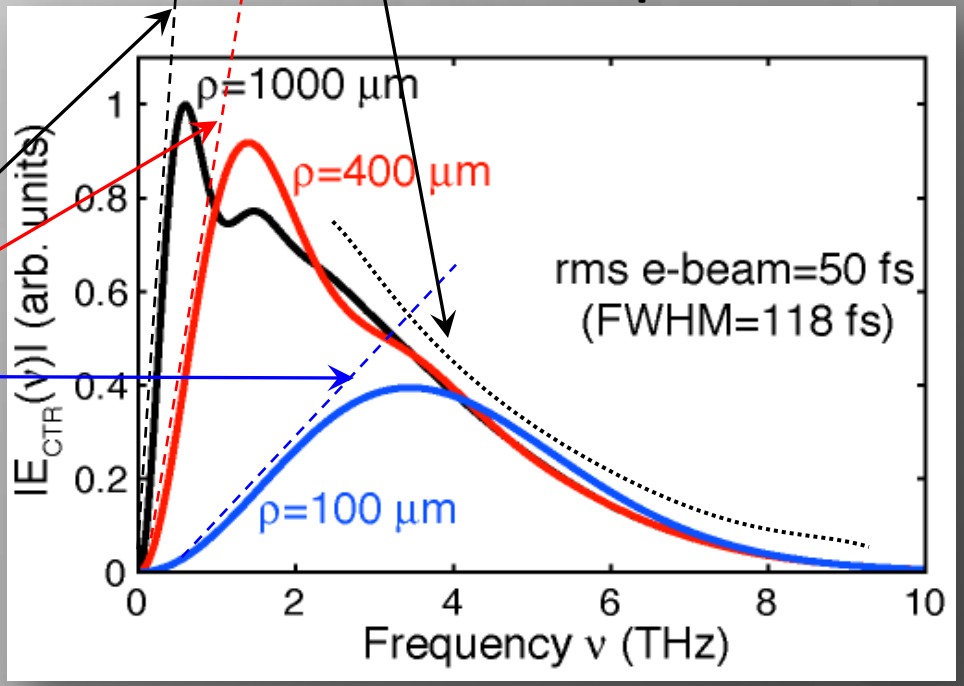
$\lambda_{THz} > \tau_{e\text{-}bunch}$



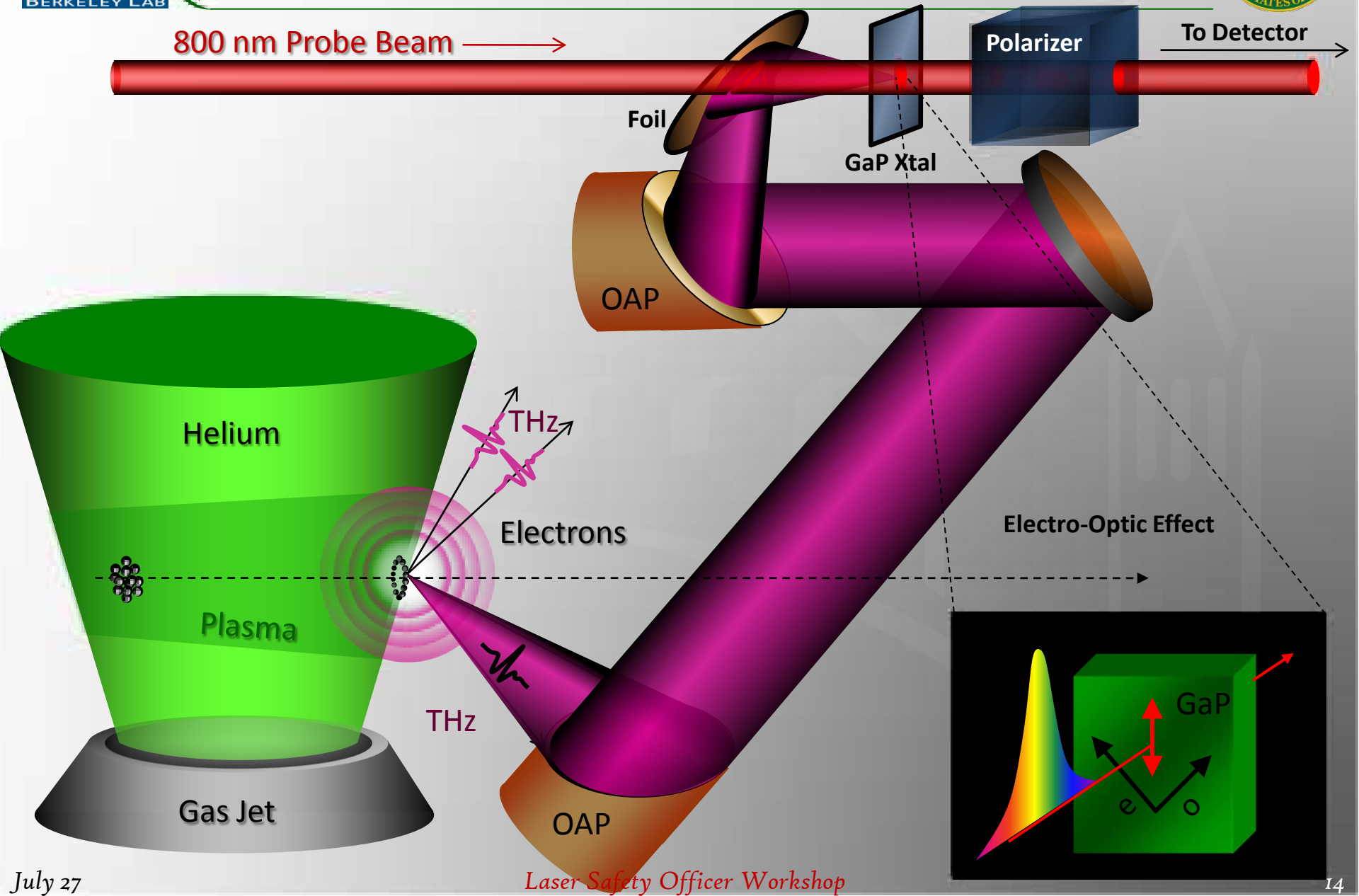
THz Spectrum

Diffraction Condition
(low cutoff)

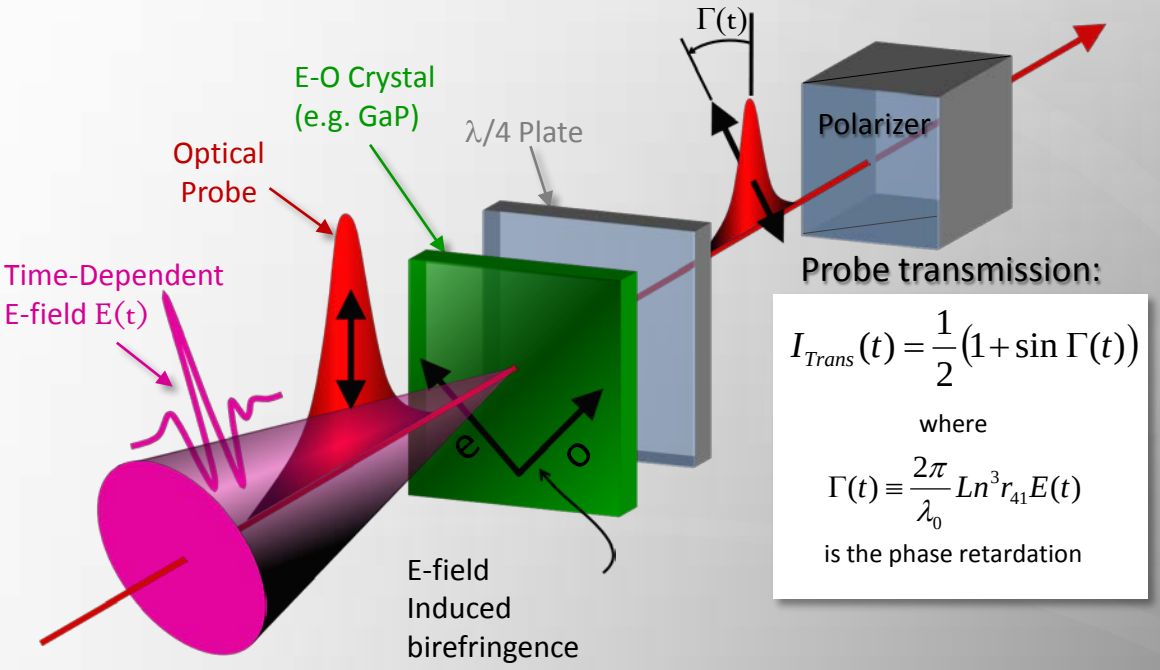
$D_{source} > \lambda_{THz}$



THz Collection Geometry



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

Electro-Optic Sampling:

1. High electric field of THz polarizes crystal atoms, inducing birefringence

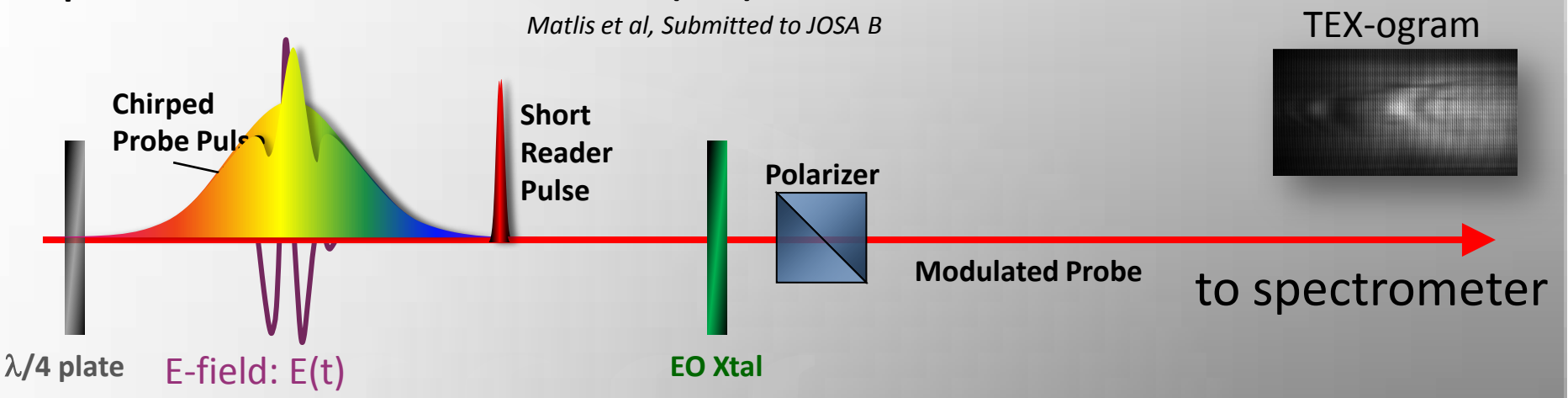
2. Optical probe (laser pulse) "samples" the birefringence.

3. Amplitude modulation is recorded

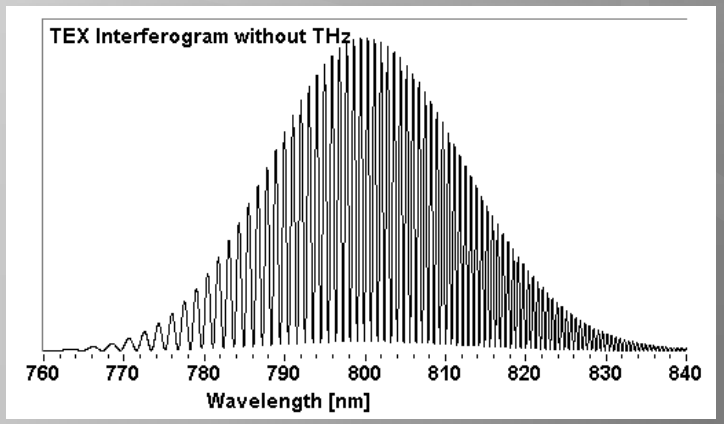
TEX Detection Method

Temporal Electric-field Cross-correlation (TEX)

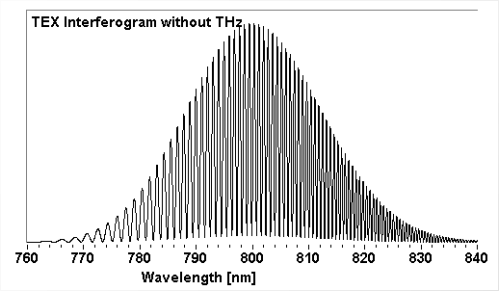
Matlis et al, Submitted to JOSA B

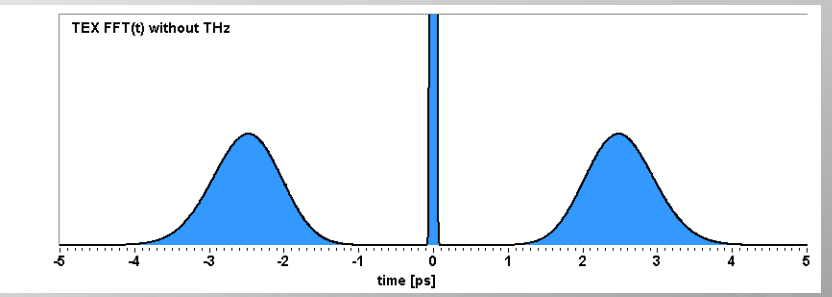


1. Variation of THz E-field in space and time is mapped onto probe
2. Spectral interference of probe and reader pulses allow waveform recovery:

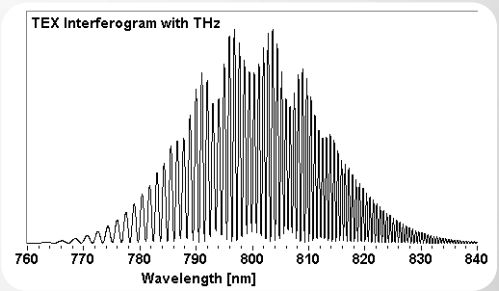


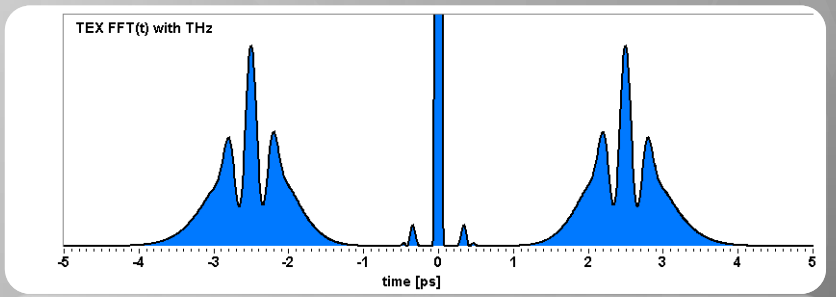
How TEX works





FFT





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

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

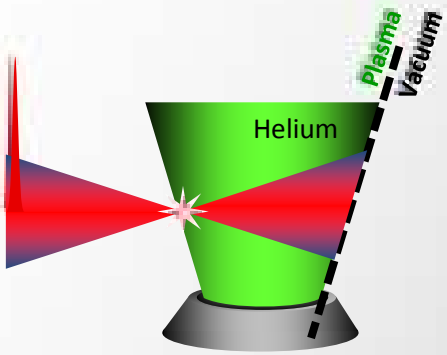
FFT

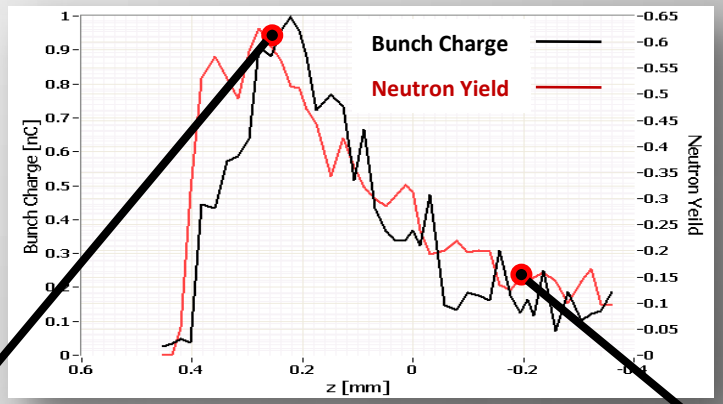
TEX Recovers temporal amplitude and phase information!

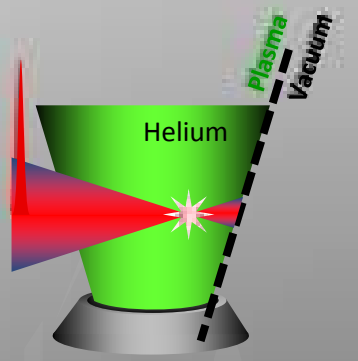
THz resolves variation in accelerator performance during parameter scans

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***

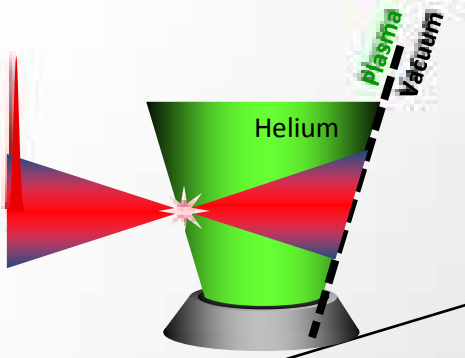
- higher n,γ production
- less Coulombic expansion
- *expect* higher THz frequencies

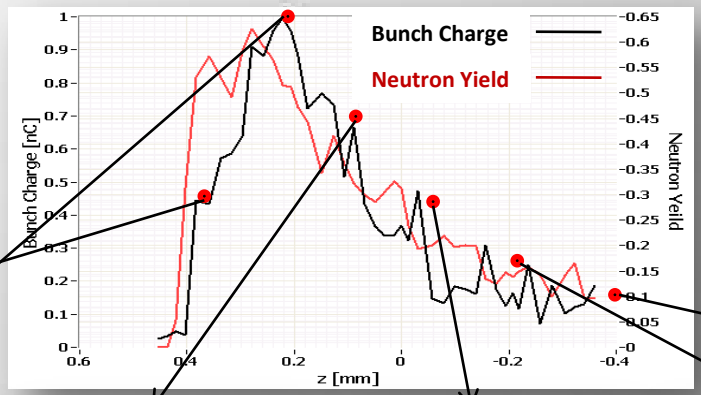
Focus on inside Gas Jet

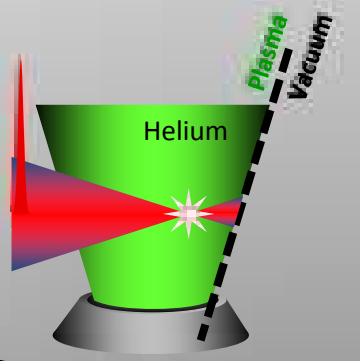
**** lower energy e-bunches***

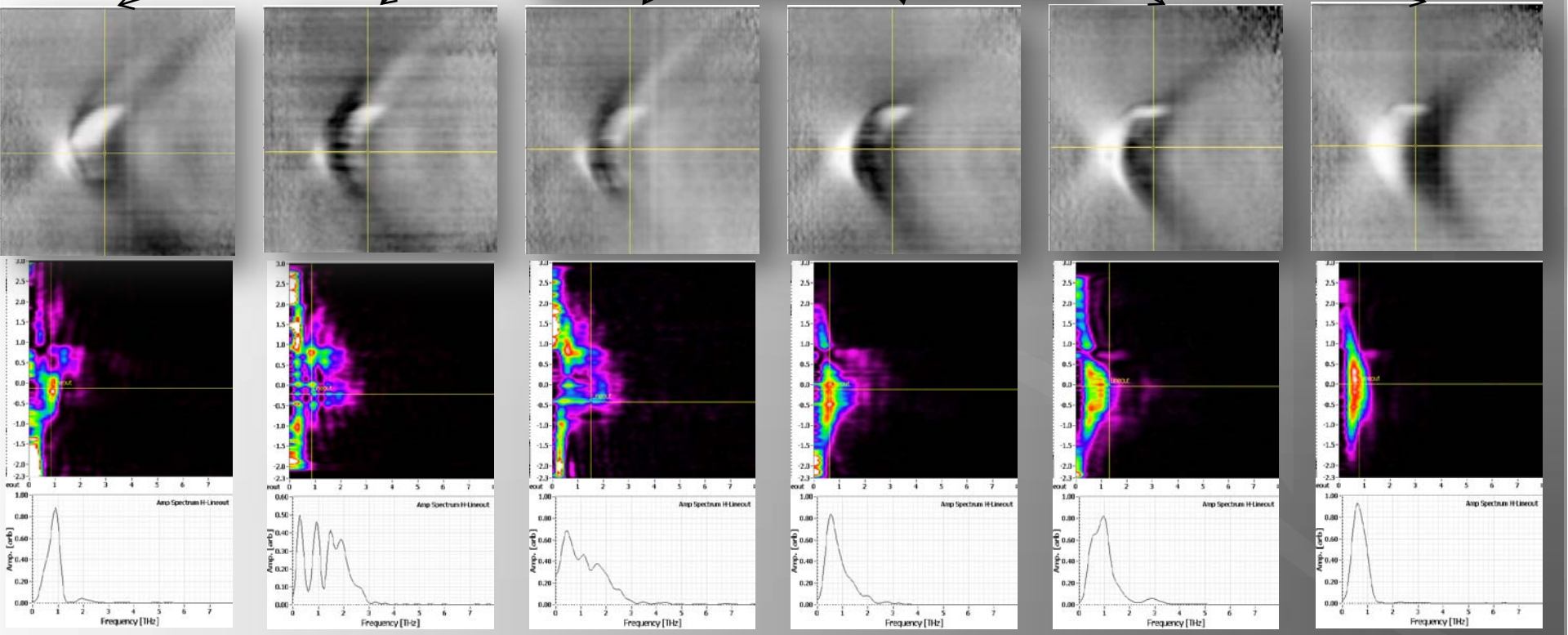
- lower n,γ production
- more Coulombic expansion
- *expect* lower THz frequencies

THz spectrum correlates with accelerator performance

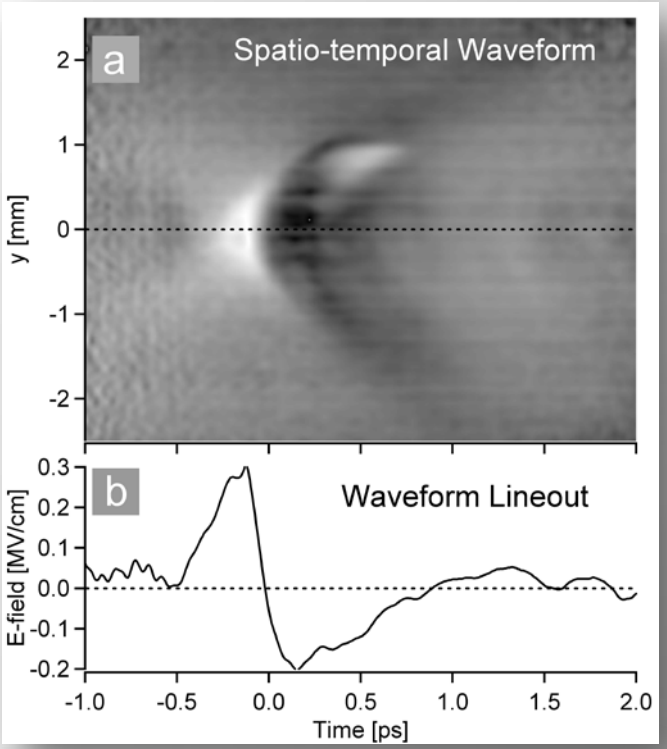


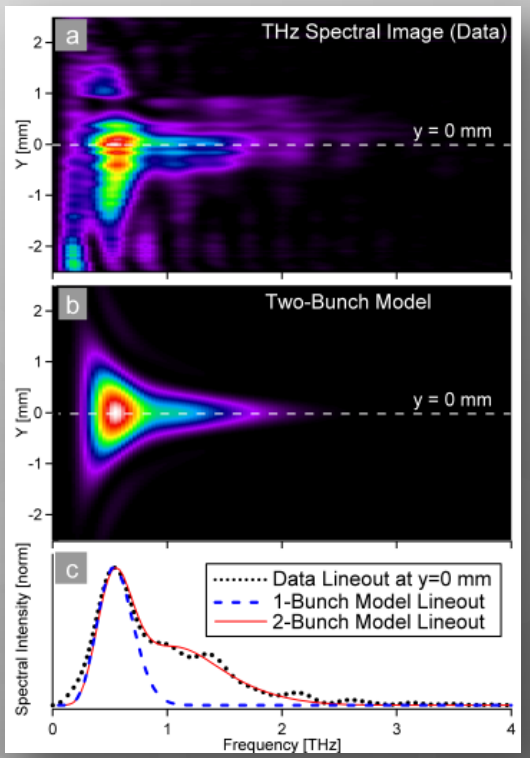






Bunch properties can be inferred from spatio-temporal model





- 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)

Summary

1. Laser Plasma Accelerators offer potential for a low-cost alternative for electron acceleration

2. Coherent THz Transition Radiation is generated at plasma boundary
   - Source of high-field THz pulses for applications
   - THz emission provides a non-invasive bunch diagnostic

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

THE END