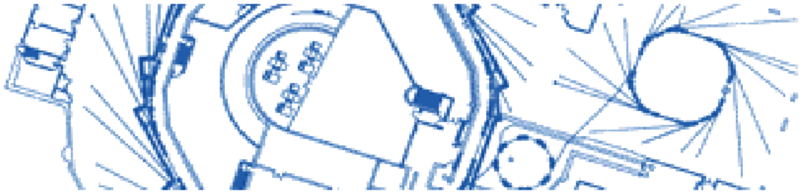
NSLS
NATIONAL SYNCHROTRON LIGHT SOURCE



Characteristics and Applications of High Intensity Coherent THz Pulses from Linear Accelerators

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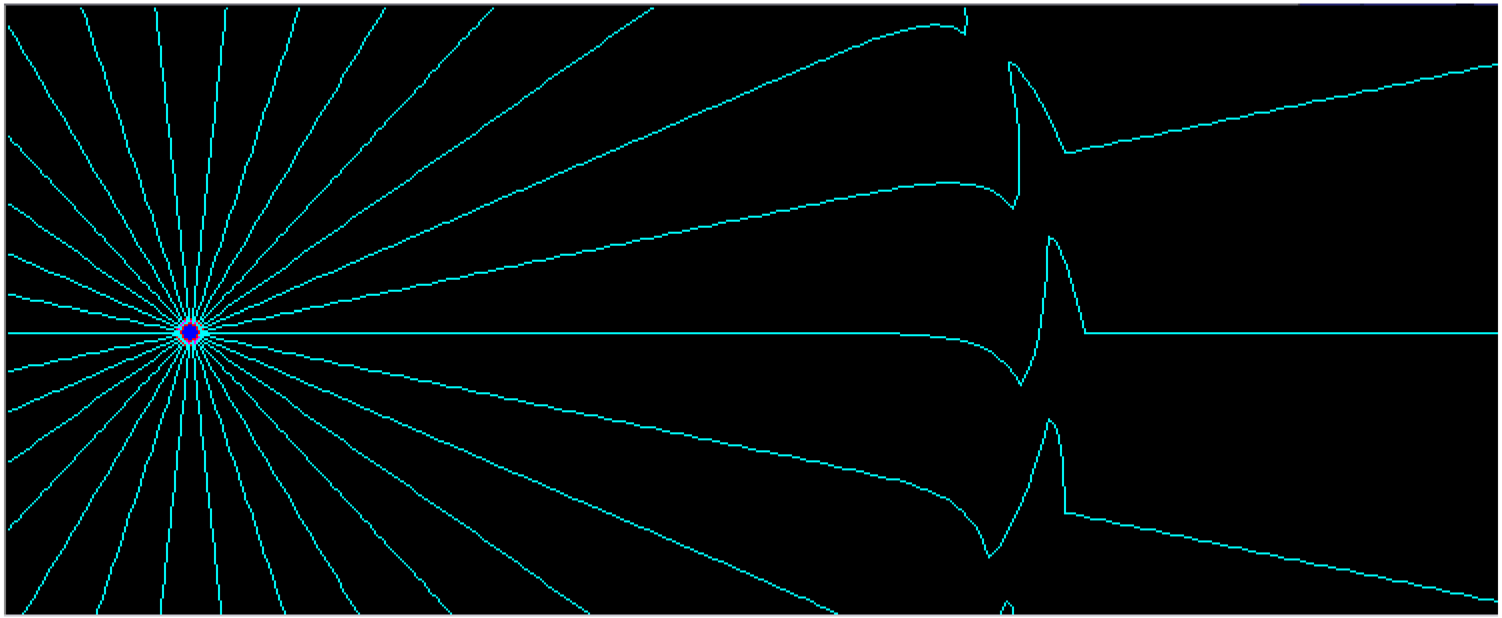
Outline

- Electromagnetic Radiation (in the far IR) from Relativistic Electrons
- Requirements for Coherent (THz) Radiation Emission: Short Electron Bunches
- High Energy Coherent THz Pulses from the NSLS / SDL Linac
- Electro-optic Detection: E-field Strengths Approaching 1 MV/cm
- Potential Application: Transient Supercurrents in Thin Film Superconductors
- Summary

Radiation from a Non-relativistic Electron

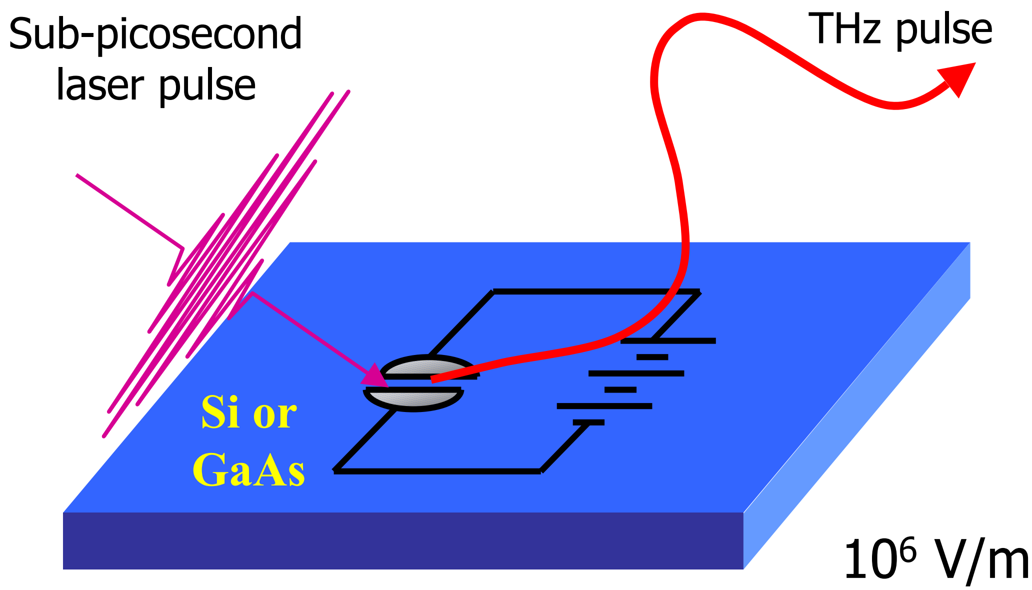
Radiated field for a brief lateral displacement



Modeled using Radiation2D code
Tsumoru Shintake *RIKEN / Spring-8*

Coherent THz Pulses: Photoconductive Switch Method

- Radiation from acceleration of photocarriers in a semiconductor.



D. Auston *et al*

D. Grischkowsky *et al*

$$P = \frac{2e^2a^2}{3c^3}\gamma^4 \qquad (1\ e)$$

γ=1 (non-relativistic)

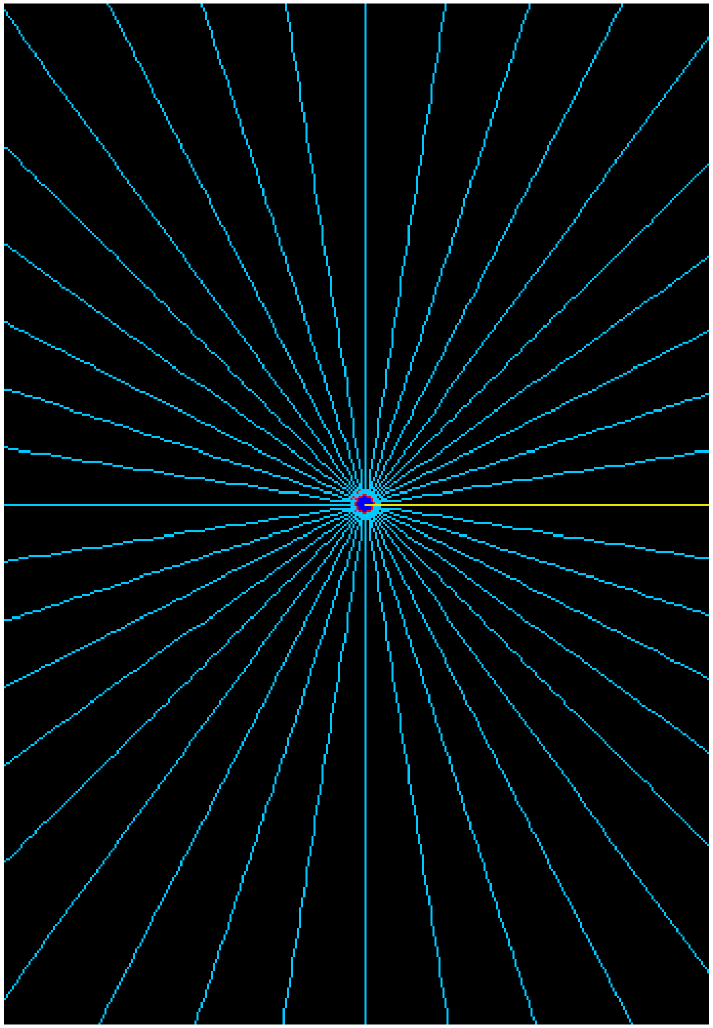
10^6 V/m => a ~ 10^{19} cm/s^2

Energy = 6x10^{-32} J per electron in 1 ps

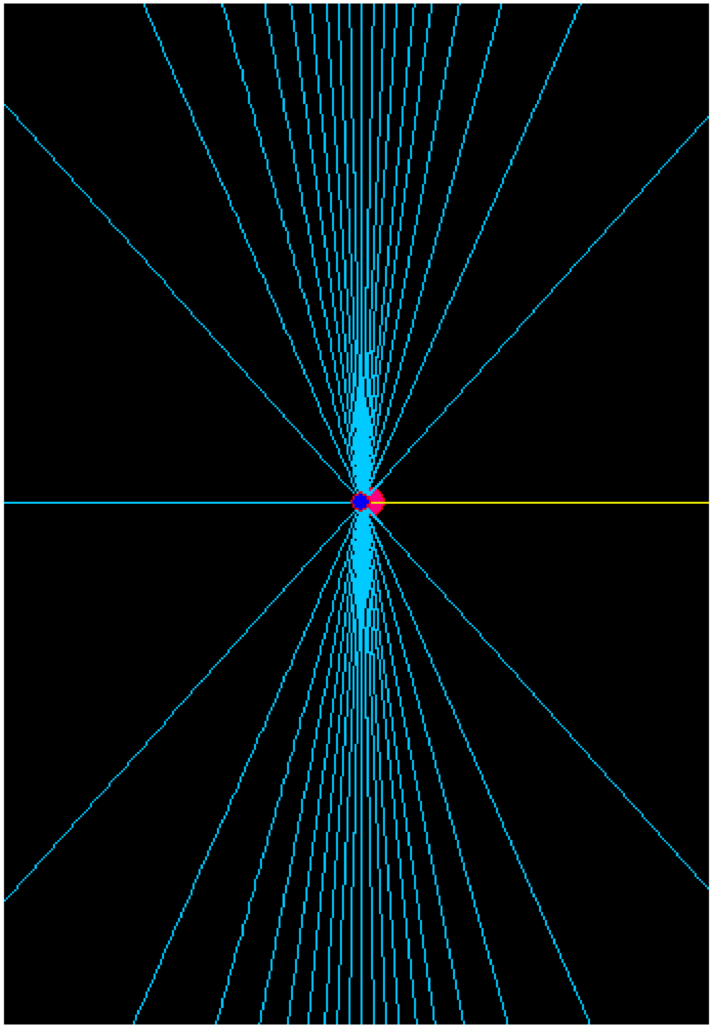
or *dE/dv* ~ 10^{-32} J/cm^{-1}/electron

Radiation from a Relativistic Electron

Non-relativistic Coulomb Field

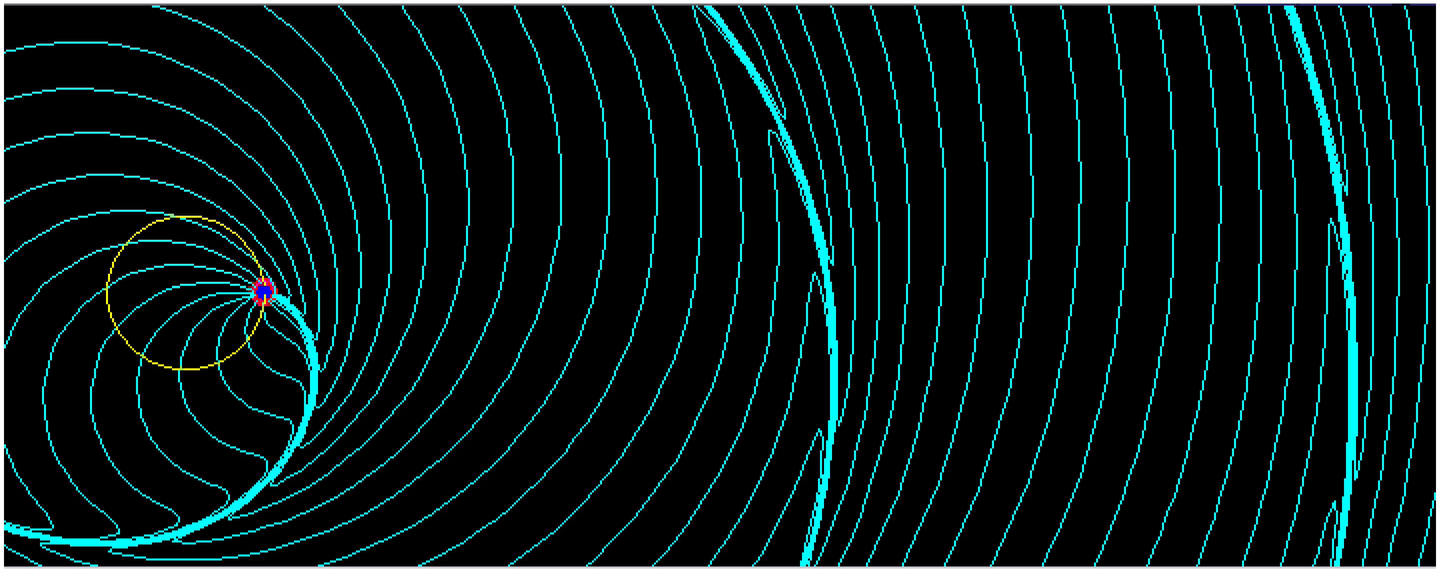


Relativistic (3 MeV) Coulomb Field

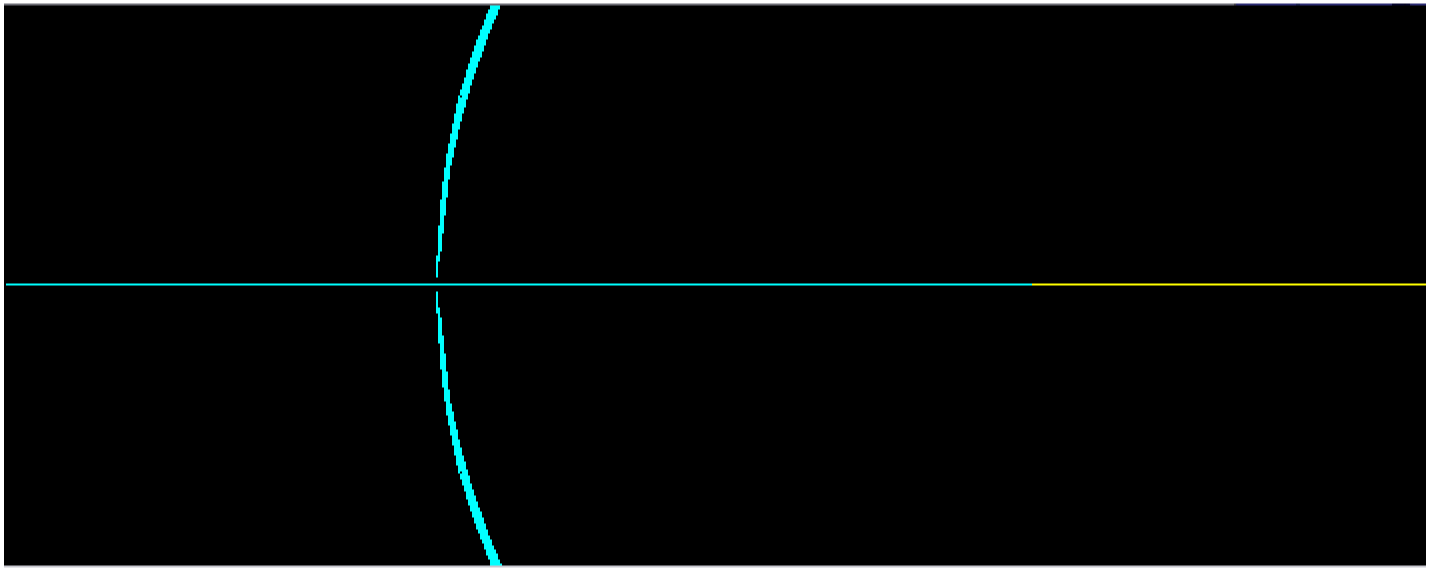


Radiation from a Relativistic Electron

Dipole bend
(linearly polarized)



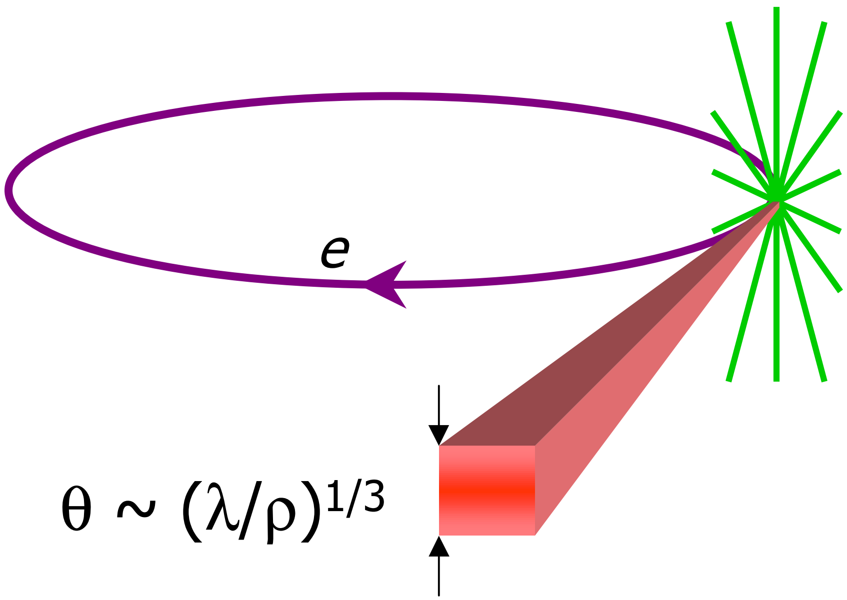
Transition
(radially polarized)



Calculated using
Radiation2D code
Tsumoru Shintake
RIKEN / Spring-8

Characteristics of (conventional) Synchrotron Radiation

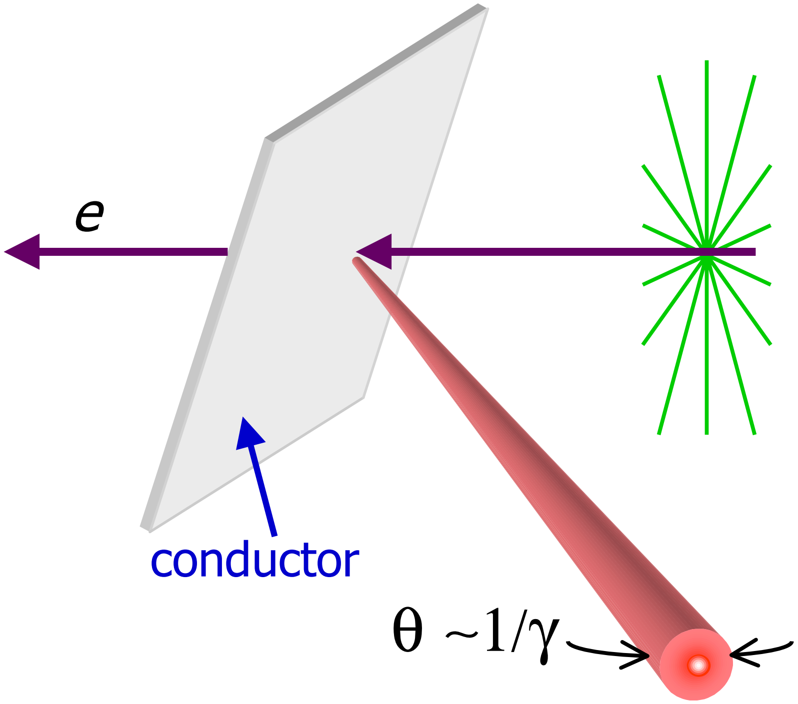
Bending magnet radiation



$$\frac{d^2 I}{d\omega\, d\Omega} = \frac{e^2\omega^2}{4\rho^2 c}\left(\int_{-\infty}^{\infty} \hat{n}\times\left(\vec{\beta}\times\hat{n}\right) e^{i\omega\left(t-\frac{\hat{n}\cdot\vec{r}(t)}{c}\right)} dt\right)^2$$

(Schwinger)

Transition radiation (edge)

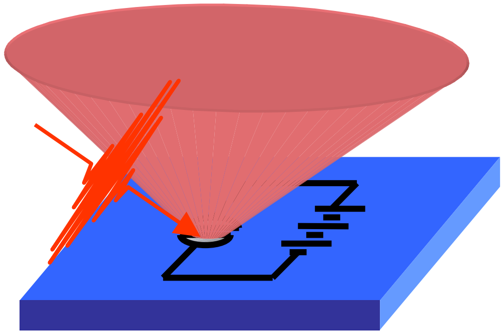


$$\frac{d^2 I}{d\omega\; d\Omega} = \frac{e^2}{\pi^2 c}\,\frac{\beta^2 \sin^2\theta}{\left(1-\beta^2\cos^2\theta\right)^2}$$

(Frank & Ginzberg)

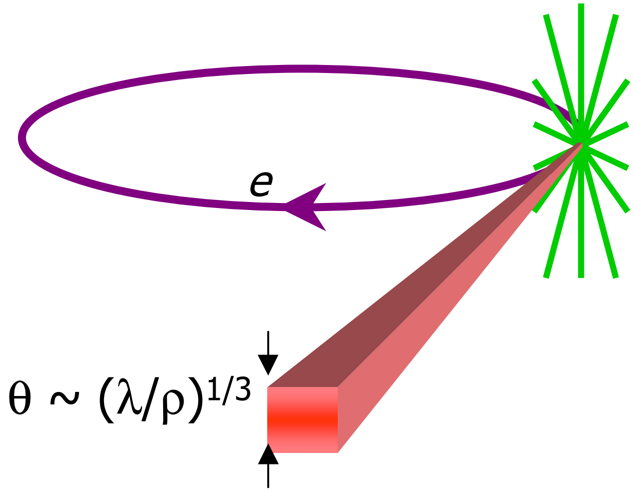
Approximate Source Comparison - Radiated Energy per Electron

Photoconductive switch



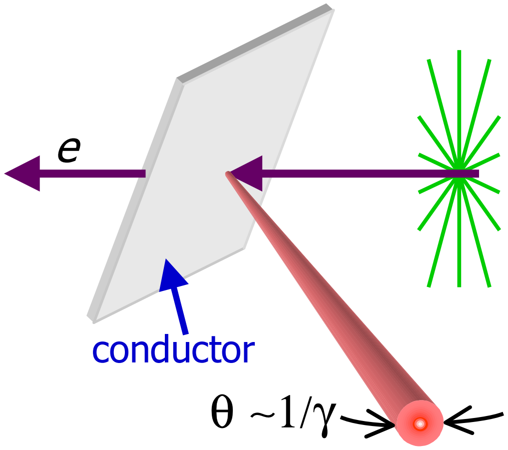
$$\frac{dE}{d\bar{\nu}} \approx 10^{-32}\ \mathrm{J/cm^{-1}/electron}$$

Bending magnet radiation



$$\frac{dE}{d\bar{\nu}} \approx 2\times10^{-25}\ \mathrm{J/cm^{-1}/electron}$$

Transition radiation

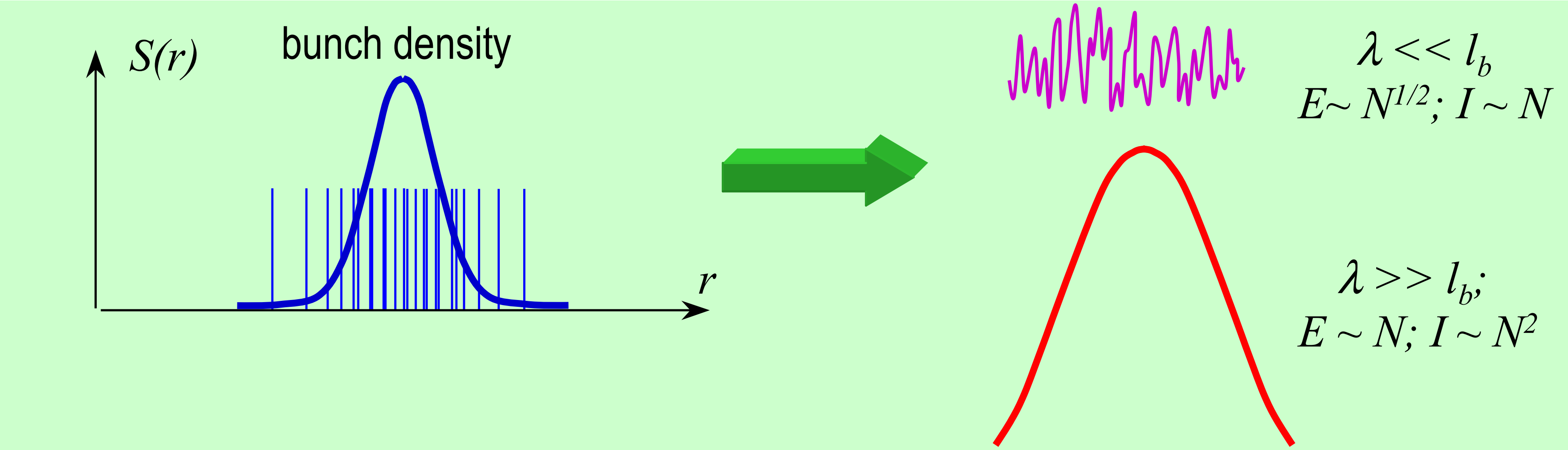


$$\frac{dE}{d\bar{\nu}} \approx 5\times10^{-25}\ \mathrm{J/cm^{-1}/electron}$$

NOTE: emitted energy, per electron, is 7 orders of magnitude greater than non-relativistic case.

Multi-particle Coherent Synchrotron Radiation (CSR)

Accelerators typically have many electrons traveling in a "bunch". Can emission be coherent?
Yes -- if bunch (or some portion of it) has length that is short compared to wavelength.



$$\left.\frac{dI(\omega)}{d\omega}\right|_{\text{multiparti cle}} = [N + N(N-1)f(\omega)]\frac{dI(\omega)}{d\omega}$$

where $$f(\omega) = \left| \int_{\infty}^{\infty} e^{i\omega\hat{n}\cdot\vec{r}/c} S(r)dr \right|^2$$ *(Nodvick & Saxon)*

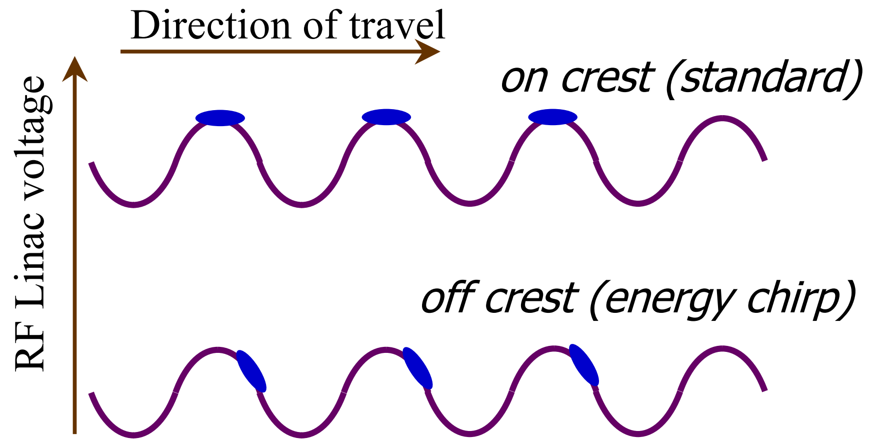
In some accelerators, bunch lengths are 100s of fs (=>THz), and N can be large e.g. ~ 10^{10}

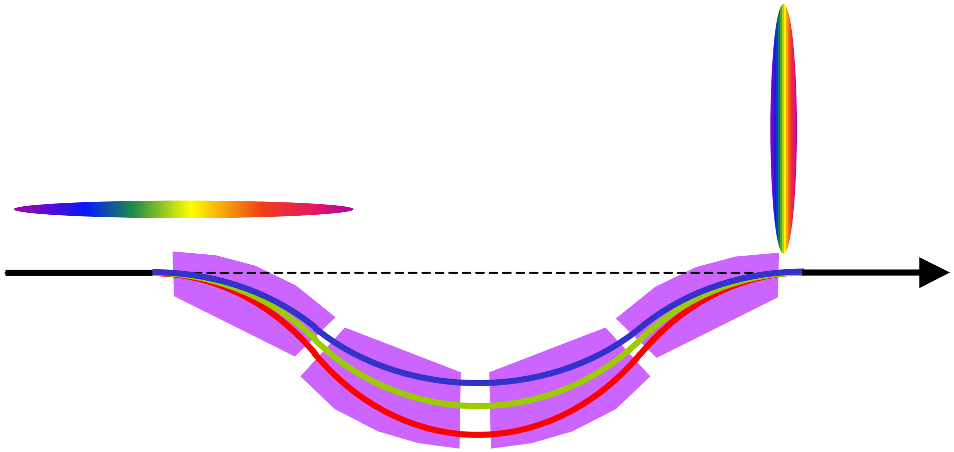
Making Short Bunches

- Electrons have charge(!) => Coulomb repulsion
  - Coulomb interaction causes spread in the energy distribution of a bunch.
  - For a non-relativistic electron, energy spread => velocity spread => distance spread.
  - BUT: For highly relativistic electrons, velocity spread remains small (*mass* varies).

=> Start with long bunch, accelerate to high energy, <u>then</u> compress.

Compression method analogous to light, magnets serve as dispersive electron optics.





Dipole chicane to compress chirped bunch

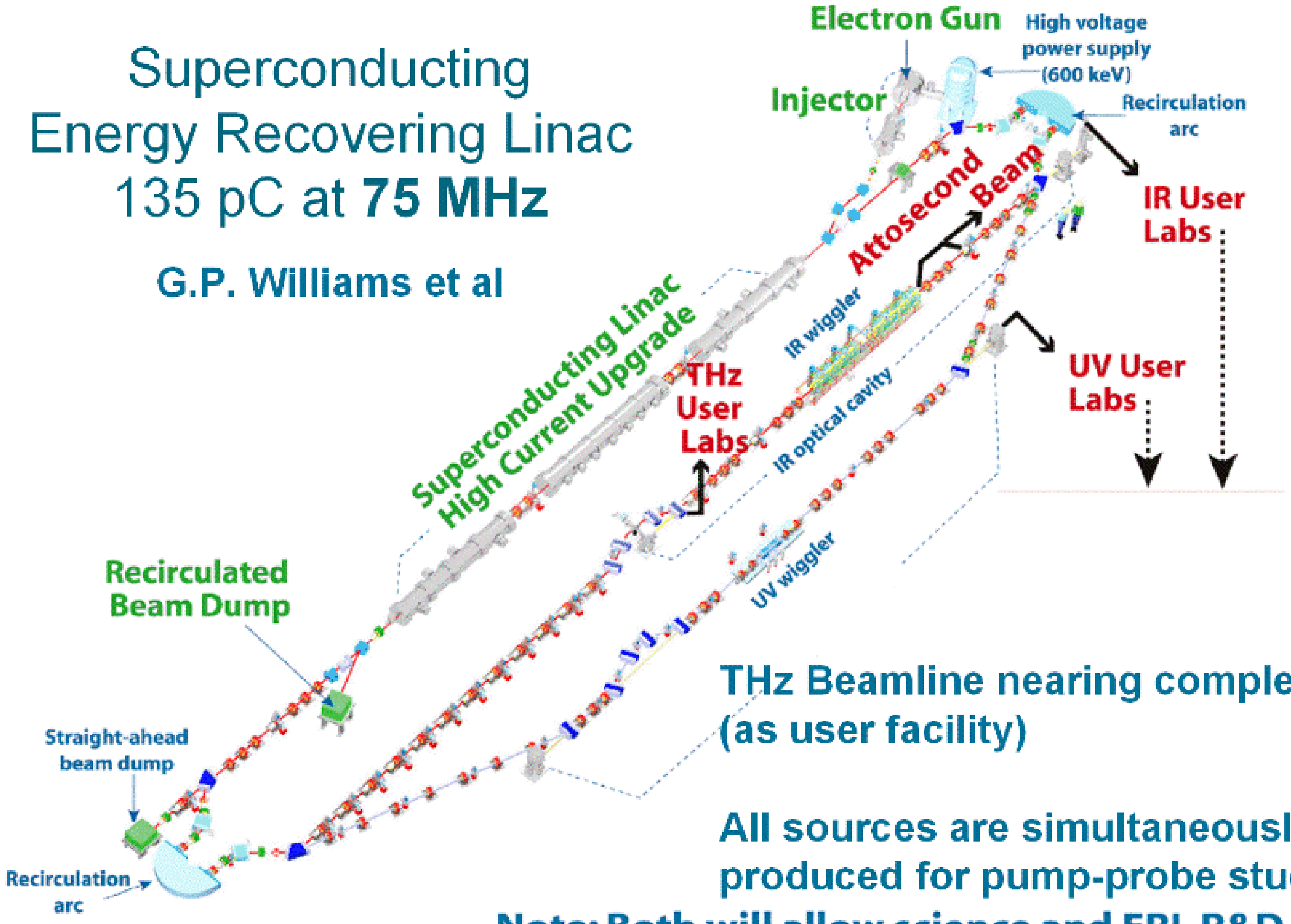
Aside: Other Coherent THz Sources

- Jefferson Lab Energy Recovery Linac (high repetition rate)
- Storage Ring Coherent Synchrotron Radiation

JLab FEL & THz facility (Newport News, VA)

Superconducting
Energy Recovering Linac
135 pC at **75 MHz**

G.P. Williams et al

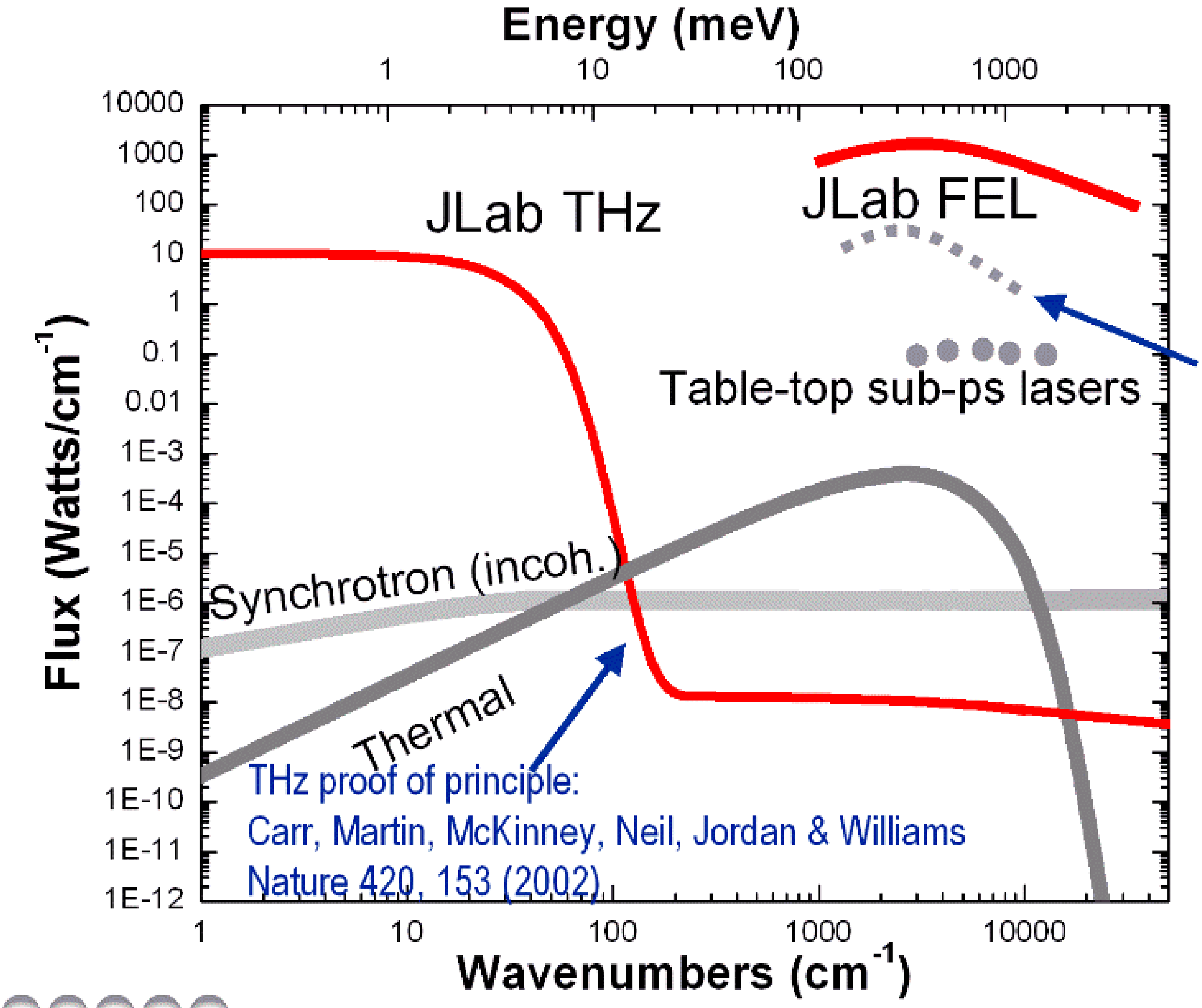


THz Beamline nearing completion (as user facility)

All sources are simultaneously produced for pump-probe studies

Note: Both will allow science and ERL R&D

Jefferson Lab facility actual spectroscopic range



THz proof of principle:
Carr, Martin, McKinney, Neil, Jordan & Williams
Nature 420, 153 (2002)

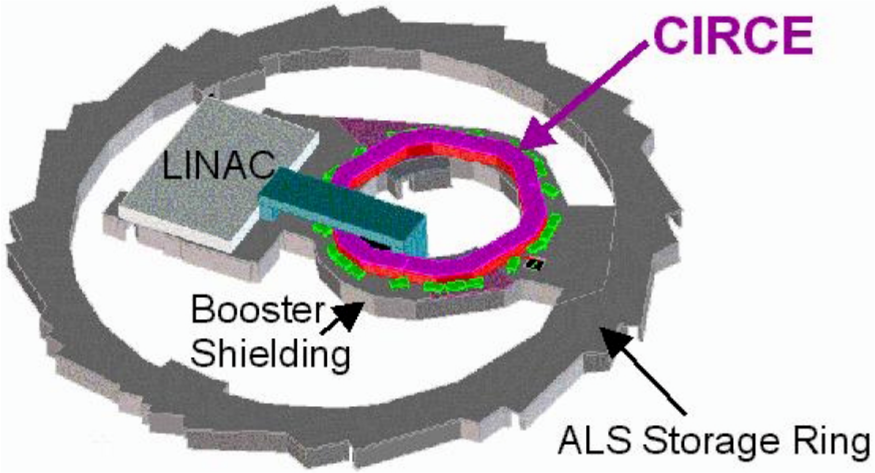
FEL proof of principle:
Neil et al. PRL **84**, 662 (2000)

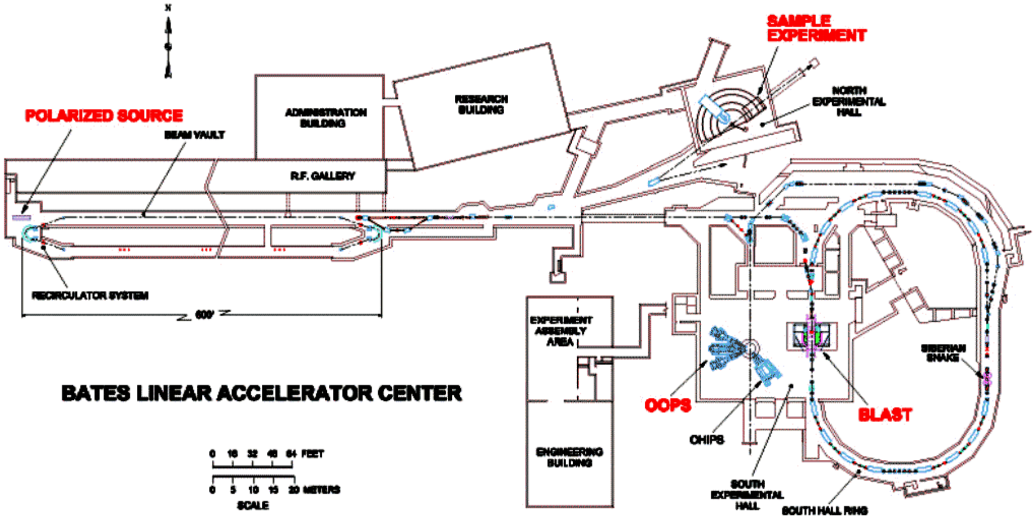
“Self” Compression in a Synchrotron Storage Ring

- An initially short electron bunch emitting Synchrotron Radiation develops a small energy chirp (electrons at front re-absorb SR emitted from the electrons behind).
- Adjust storage ring dispersion so that bunch slowly compresses over many orbits.
- New equilibrium bunch shape with “sharp” structure => Coherent THz Radiation

  Requires ring with high RF frequency to develop stable output

  - Unstable/bursting: NSLS VUV (53 MHz), NIST, MAX, ….
  - Stable: BESSY II (500 MHz), ANKA (500 MHz) (detailed analysis: Byrd, Sannibale et al - Berkeley)
  - CIRCE (proposed at Berkeley) (500 MHz to 1.5 GHz)
  - MIT Bates (3 GHz, not yet tested)

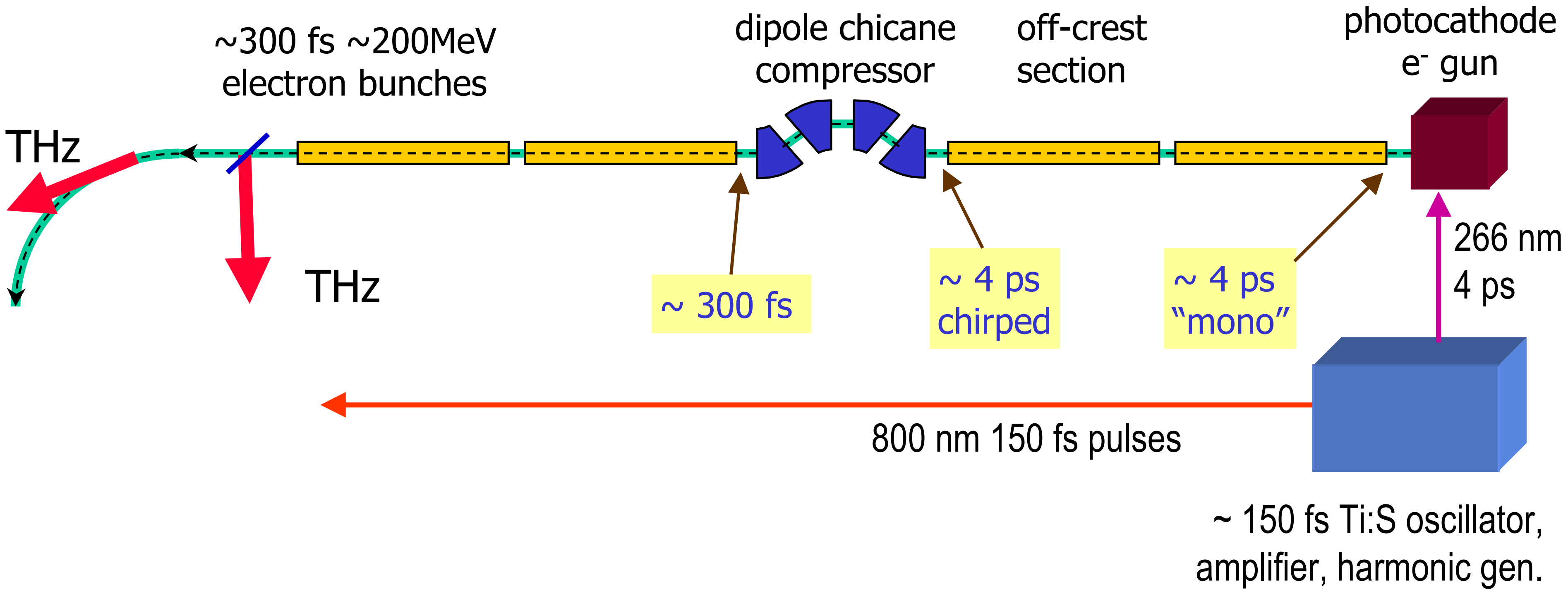




The NSLS Source Development Lab Linac

X.-J. Wang et al

- Photocathode gun produces ~ 0.7nC (4.4x10^9 electrons) per "shot"



THz

~300 fs ~200MeV electron bunches

dipole chicane compressor

off-crest section

photocathode e^- gun

THz

~ 300 fs

~ 4 ps chirped

~ 4 ps "mono"

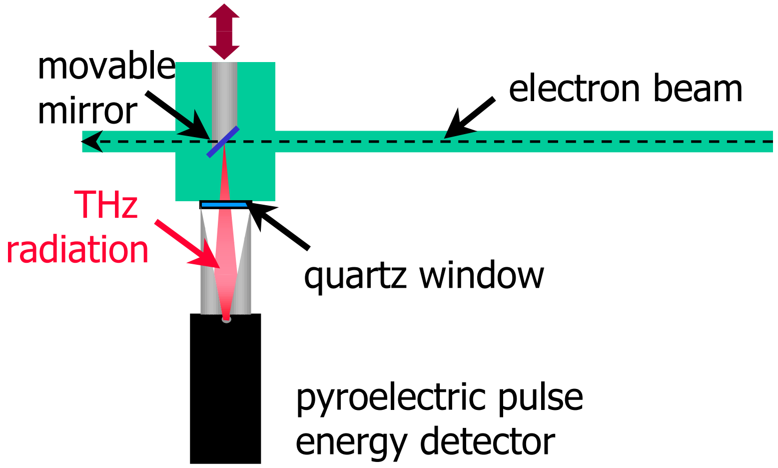
266 nm 4 ps

800 nm 150 fs pulses

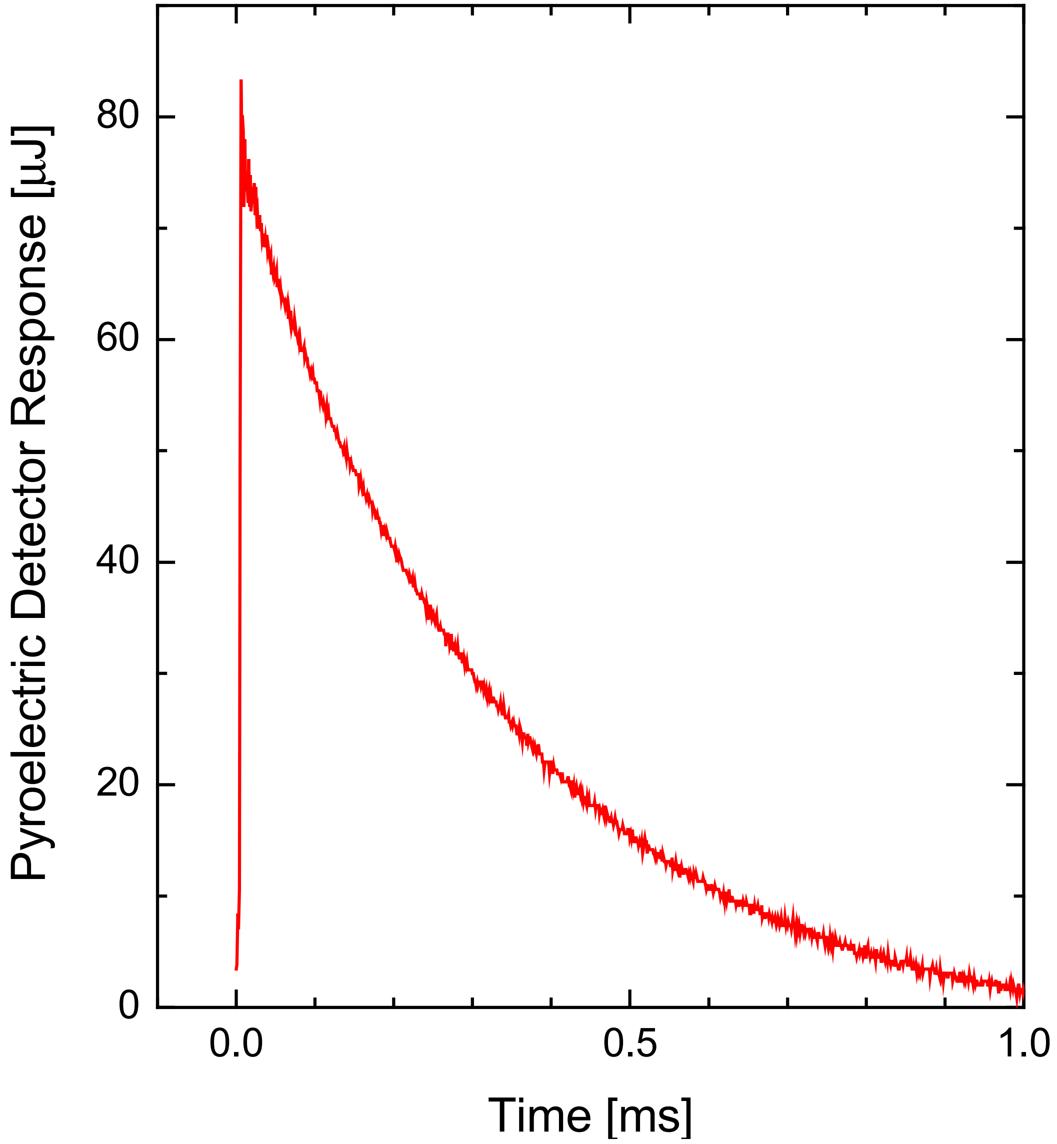
~ 150 fs Ti:S oscillator, amplifier, harmonic gen.

- Coherent output to over 1 THz. Potential for shorter bunches with less charge.
- Low rep. rate (1 to 10 Hz)

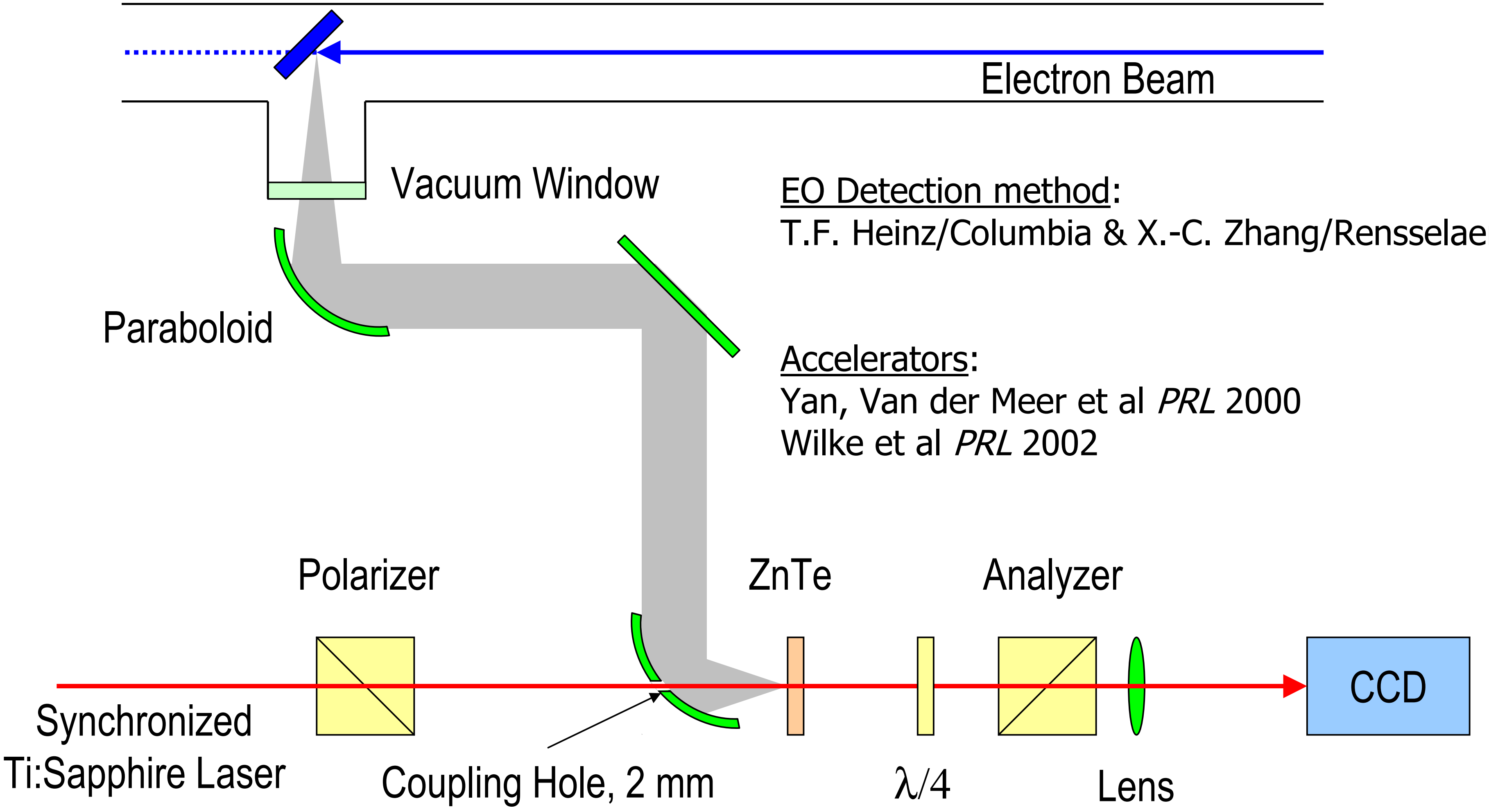
Basic Pulse Characteristics



- 80 μJ in a single pulse
- Consistent with prediction based on coherent transition radiation



Electro-Optic THz Radiation Setup



<u>EO Detection method</u>:
T.F. Heinz/Columbia & X.-C. Zhang/Rensselaer

<u>Accelerators</u>:
Yan, Van der Meer et al *PRL* 2000
Wilke et al *PRL* 2002

Signal and Reference

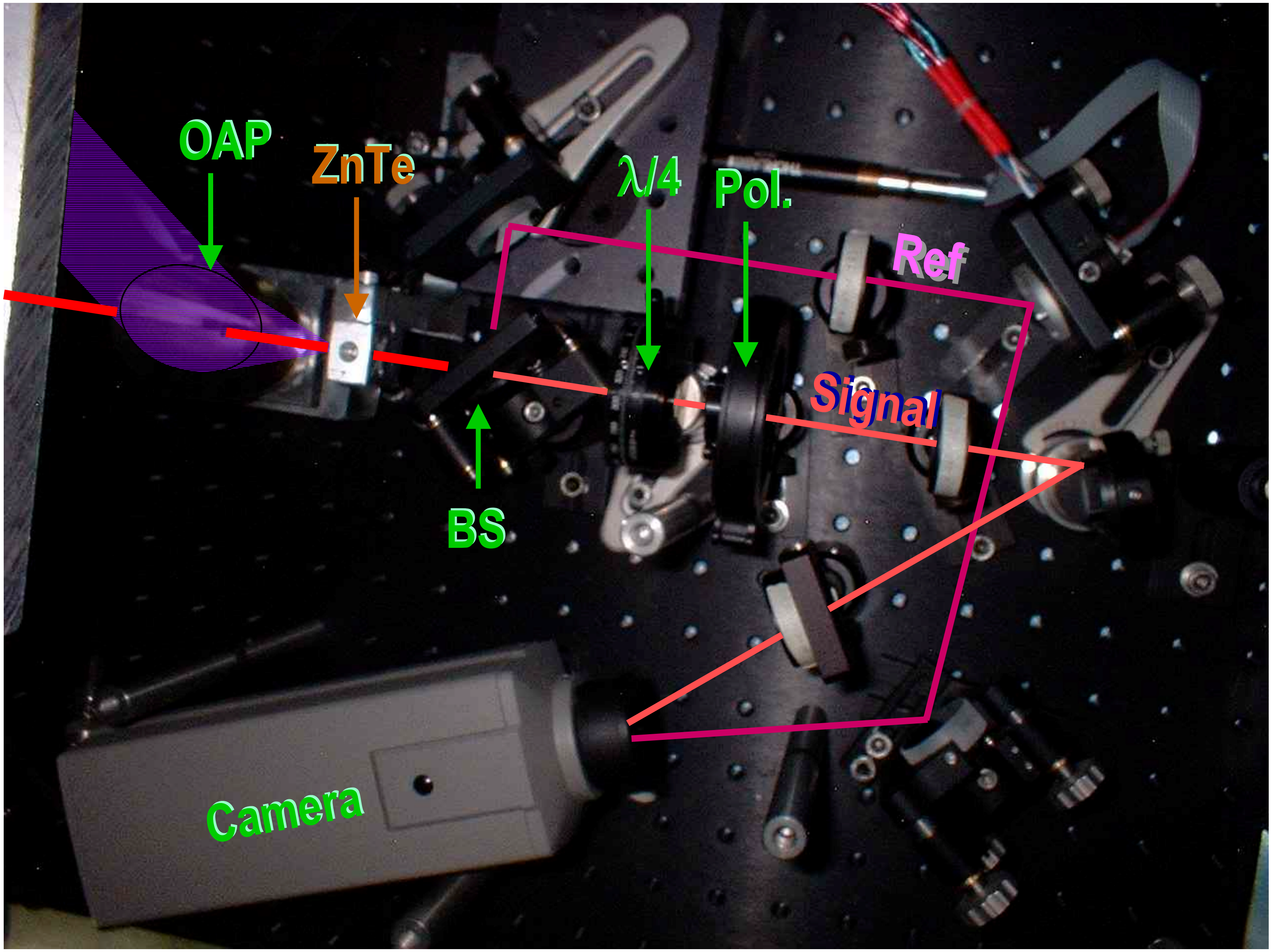
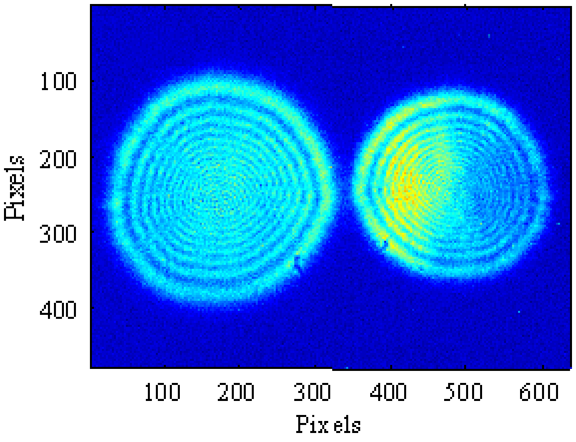
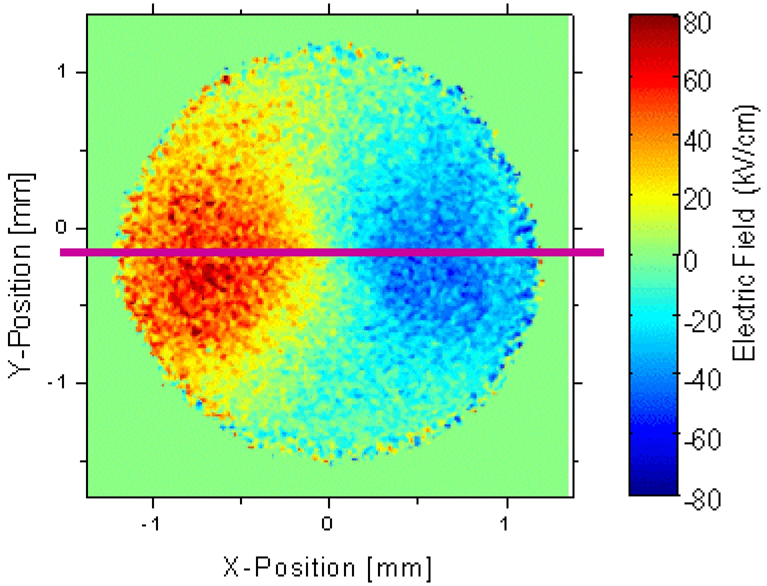


Image Processing for Field Measurement

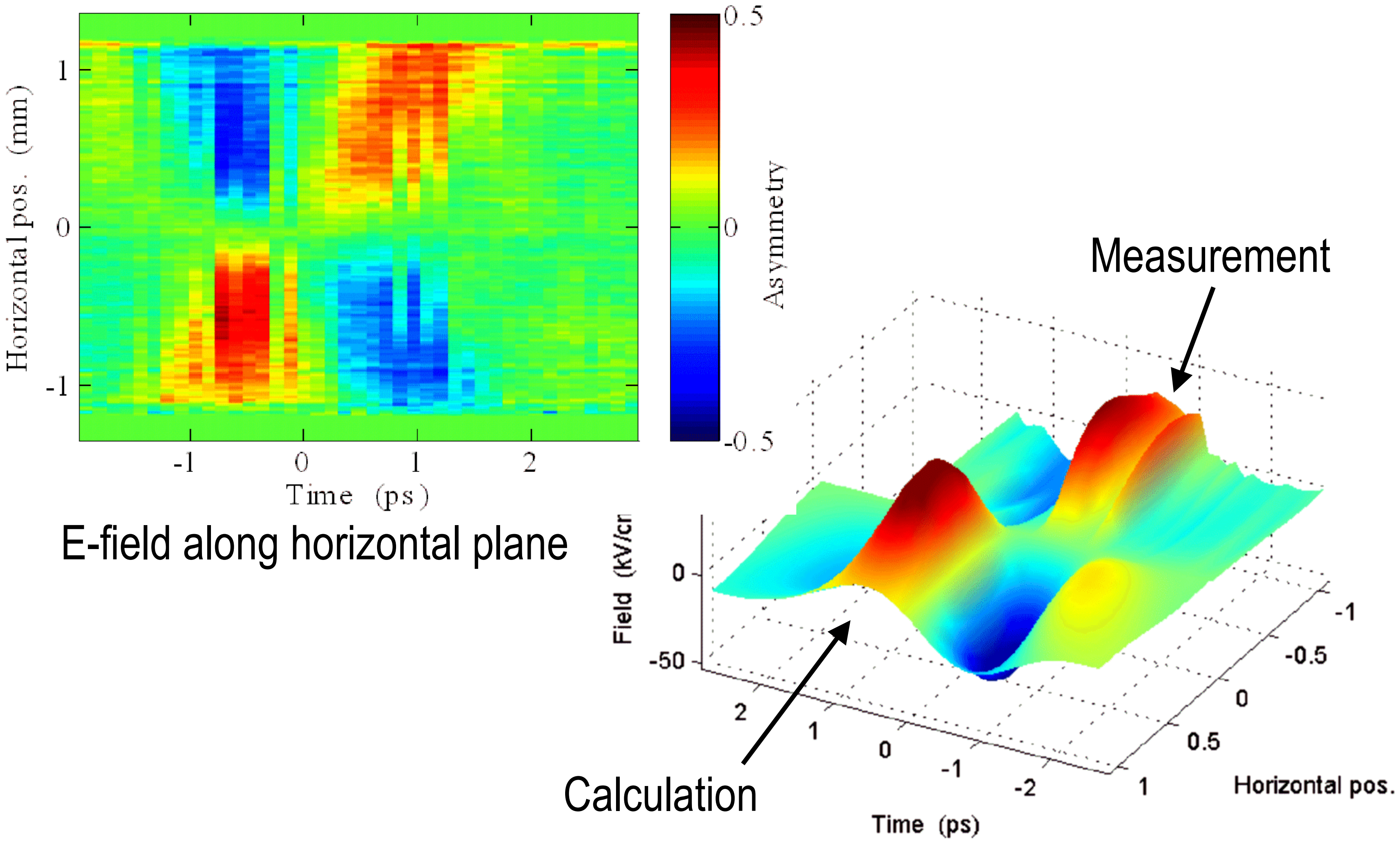
- First, turn down intensity to get “on-scale” for 500 μm thick ZnTe (reduce charge, less compression)
- Reference I_R (left image) and Signal I_S (right image) obtained simultaneously (for each linac pulse).
- Images scaled to match and normalize both.
- Calculate asymmetry *A* of Signal, subtract pattern w/o THz.



$$A = 2I_S/I_R - 1$$



Temporal E-Field Cross Section at Focus



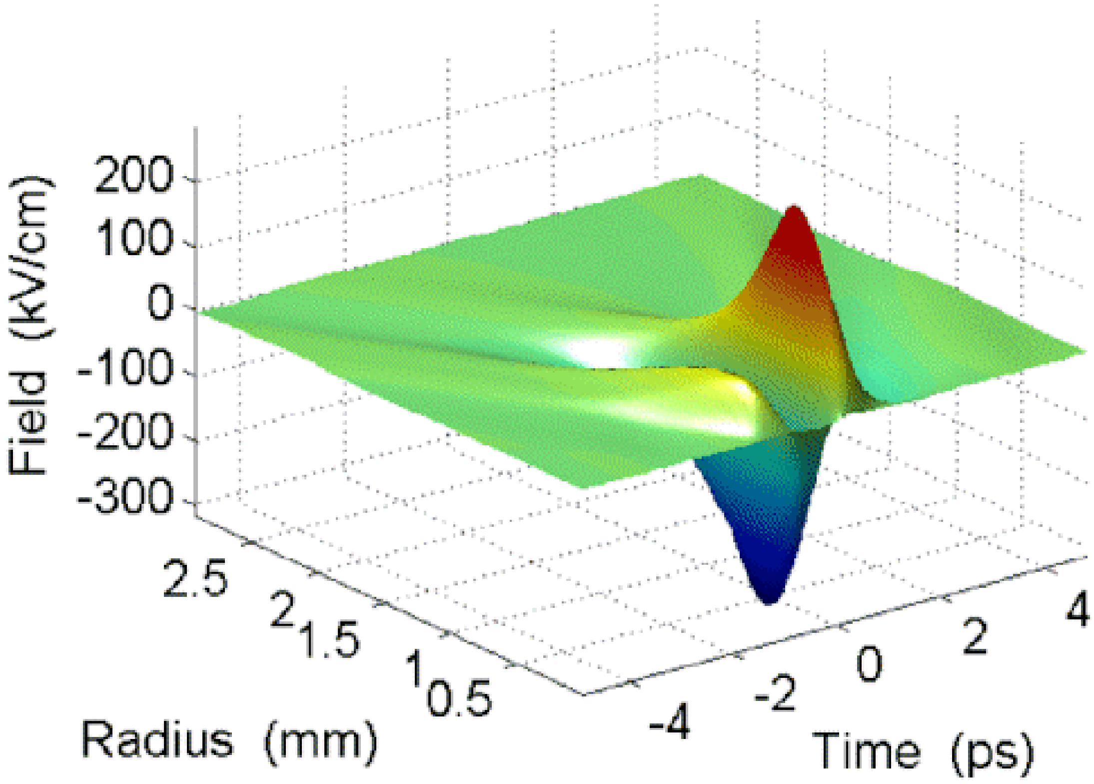
E-field along horizontal plane

Measurement

Calculation

Calculated Focus Distribution of THz

- Expand in Gauss-Laguerre modes and propagate to focus.
- Focus spot size 3 mm diameter.
- Single period oscillation.
- 300 fs rms length
- Electric field strength ~ 300 kV/cm at 300 pC charge.



Studies using High-Field, Half-Cycle THz Pulses

A 100 μJ, half-cycle THz pulse, focused into a volume of 1 mm^3.

- **E-field** = $[2D_E/\varepsilon_0]^{1/2}$ **~ 10^8 V/m (~ 1 MV/cm)**.
- => Use large electric field to displace atoms in polar solids (structural phase transitions, soft modes, ferroelectricity, …), induce large transient currents.
- **H-field = E/c ~ 0.3 T**
- => Use transient magnetic field to create magnetic/spin excitations and follow dynamics on ps time scale (e.g., time-resolved MOKE).

Or some other shape pulse? (R&D activity to control density modulation)

$$\left.\frac{dI(\omega)}{d\omega}\right|_{multiparti\ cle} = [N + N(N-1)f(\omega)]\frac{dI(\omega)}{d\omega}$$

$$f(\omega) = \left|\int_{-\infty}^{\infty} e^{i\omega\hat{n}\cdot\vec{r}/c} S(r)\,dr\right|^2$$

How would a superconductor respond to one of these intense pulses?

THz Transmission through a Superconducting Film

Transmission through thin conducting film (thickness d on substrate with refractive index n)

$$T = \frac{4n}{\left(n+1+377\sigma_1 d\right)^2 + \left(377\sigma_2 d\right)^2}$$

where $\sigma(\omega) = \sigma_1 + i\sigma_2$

Drude model for optical response

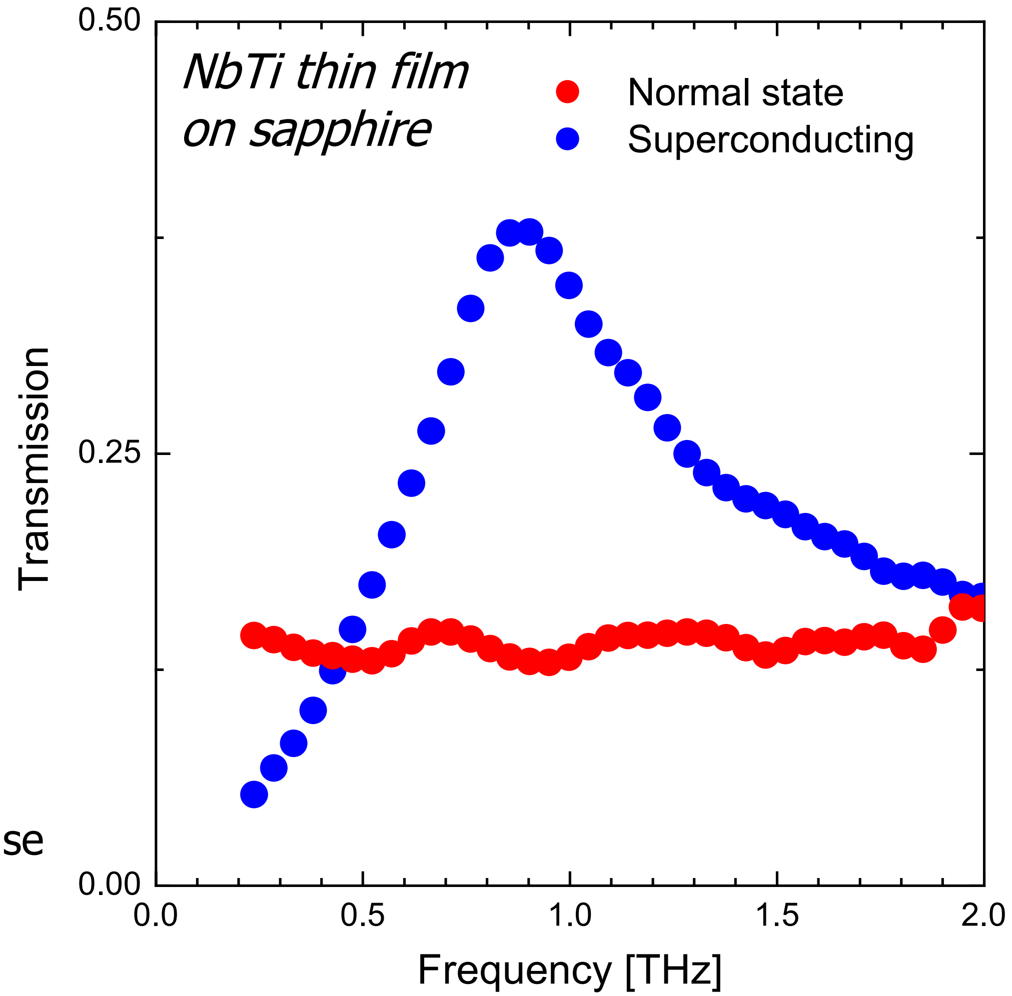
$$\sigma(\omega) = \frac{\omega_p^2 \tau \varepsilon_0}{\left(1 - i\omega\tau\right)}$$

… assume in dirty limit for Normal state

$$\sigma(\omega << 1/\tau) = \omega_p^2 \tau \varepsilon_0 \sim const.$$

Superconductor has energy gap, but below gap frequency, have only superfluid response

$$\sigma(\omega >> 1/\tau) = i\frac{\omega_p^2 \varepsilon_0}{\omega} \sim {}^{i}\!/_{\omega}$$



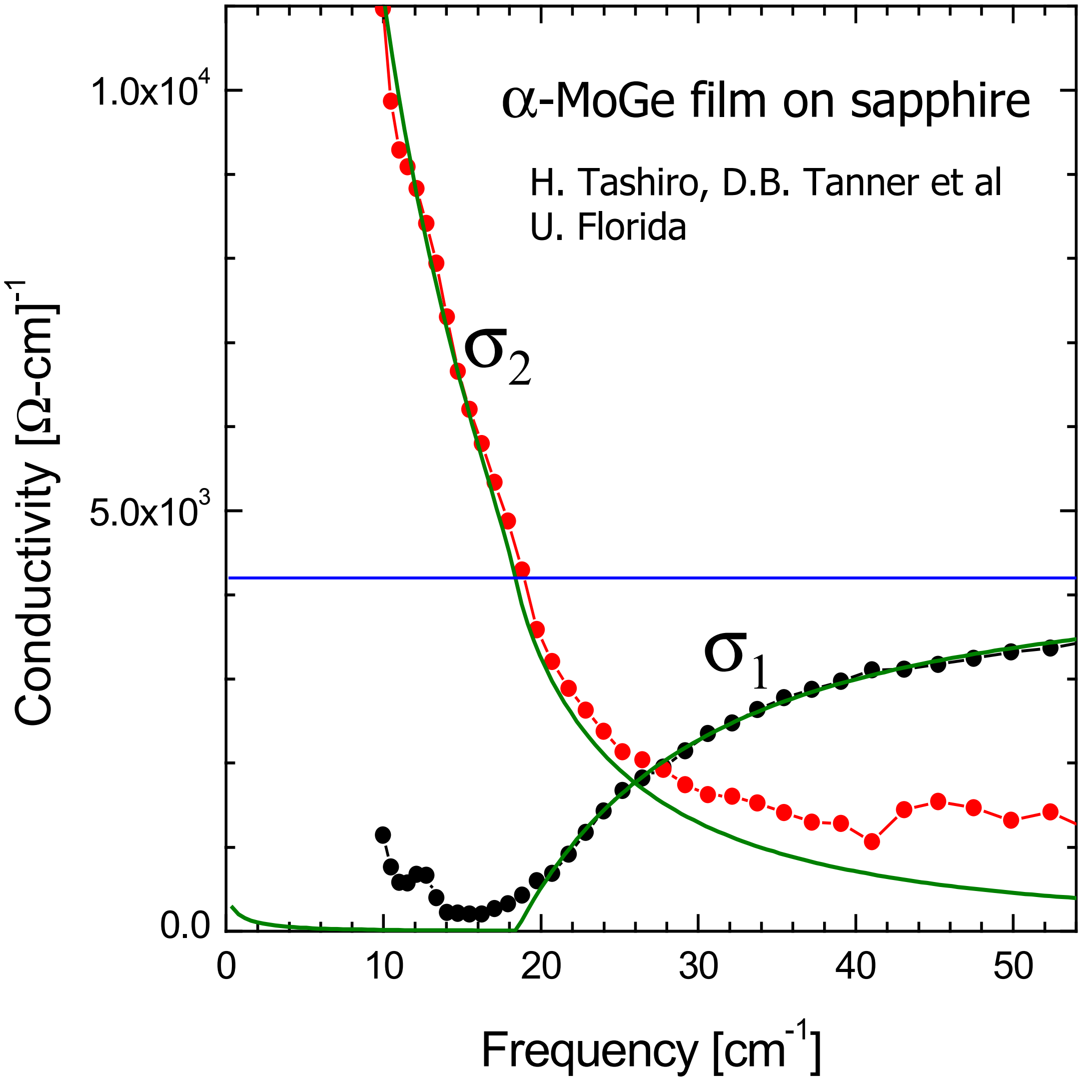
"Low" Energy Electrodynamics in a Superconductor

What is supercurrent response to ~ 1ps intense E-field transient? ($T << T_C$, $\omega < \omega_g$)

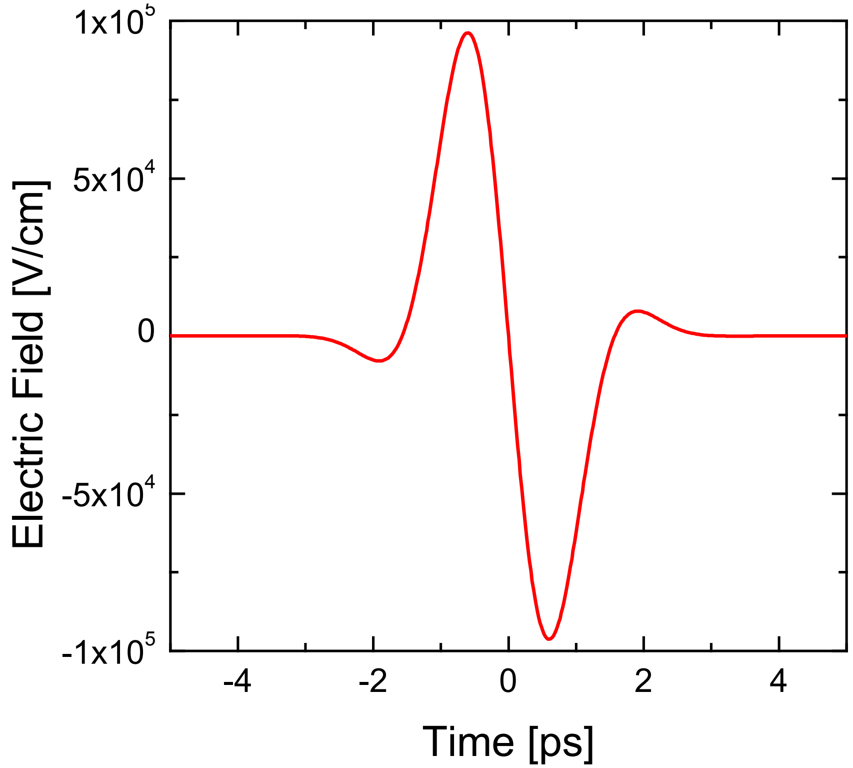
- Low frequency response is dominated by imaginary part of conductivity $\sigma_2 \cong A/\omega$; $A \cong \sigma_n \omega_g$ (purely inductive).

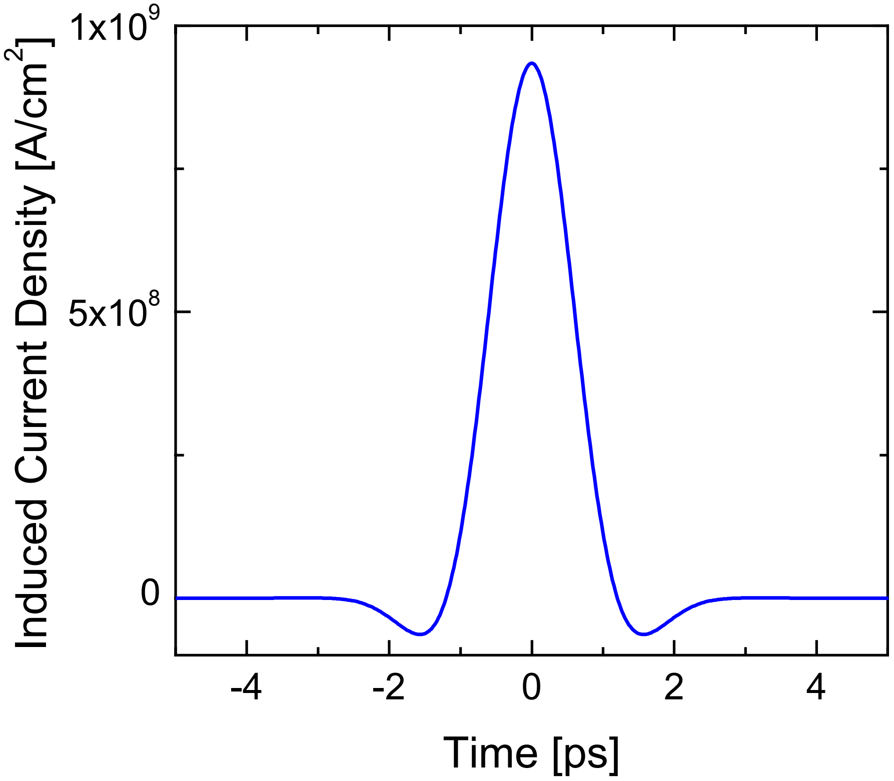
$$L\frac{dI}{dt} = V \qquad I(t) = \frac{1}{L}\int_{-\infty}^{t} V(t')dt'$$

- $J \cong \sigma_n \omega_g \int_{-\infty}^{t} E(t')dt'$



Proposed Experiment: Time-dependent Supercurrent





Typical superconductor has $J_C \sim 10^8$ A/cm^2. What happens if J_c is exceeded?
=> "over twist" the local superconducting phase, spin off vortices?
How quickly can a vortex be created? How does dissipation initially appear?

Need an analytical method for <u>time-dependent</u> propagation through film.

Model Calculation: FDTD Technique

- FDTD starts with discrete formulation of Maxwell's equations. *(K. Yee - '66)*

$$\nabla\times\vec{H}=\frac{\partial\vec{D}}{\partial t}\qquad\qquad\nabla\times\vec{E}=\frac{\partial\vec{B}}{\partial t}$$

- Dielectric response included through displacement in normal fashion

$$\vec{D}(t)=\varepsilon_\infty\varepsilon_0\vec{E}(t)+\varepsilon_0\int_0^t\vec{E}(t-\tau)\,\chi(\tau)d\tau$$

- Solve numerically
  - Provides accurate description of THz propagation across dielectric boundaries.
  - Recursive convolution method for materials where loss is described by exponential damping (e.g., Lorentzian) *(Luebbers, Hunsberger and Kunz - '91)*.

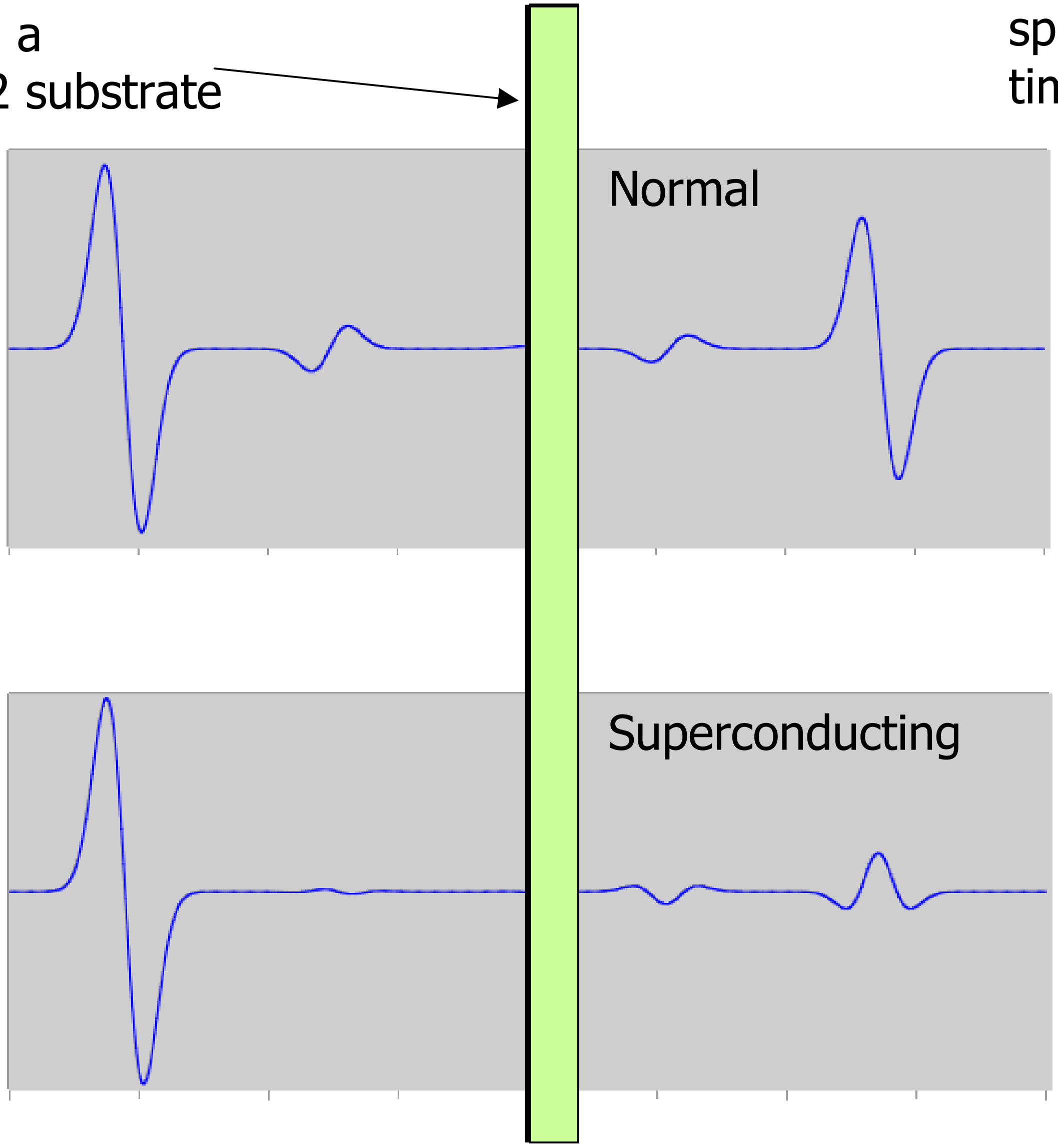
$$\sigma(\omega)=\frac{\omega_p^2\tau\varepsilon_0}{(1-i\omega\tau)}\quad\longrightarrow\quad\chi(t)=\omega_p^2\tau\left[1-e^{-t/\tau}\right]\theta(\tau)$$

  - Successfully used for time-resolved spectroscopy (where ω_p and/or τ are themselves time-dependent). *(Beard and Schmuttenmaer - '01)*

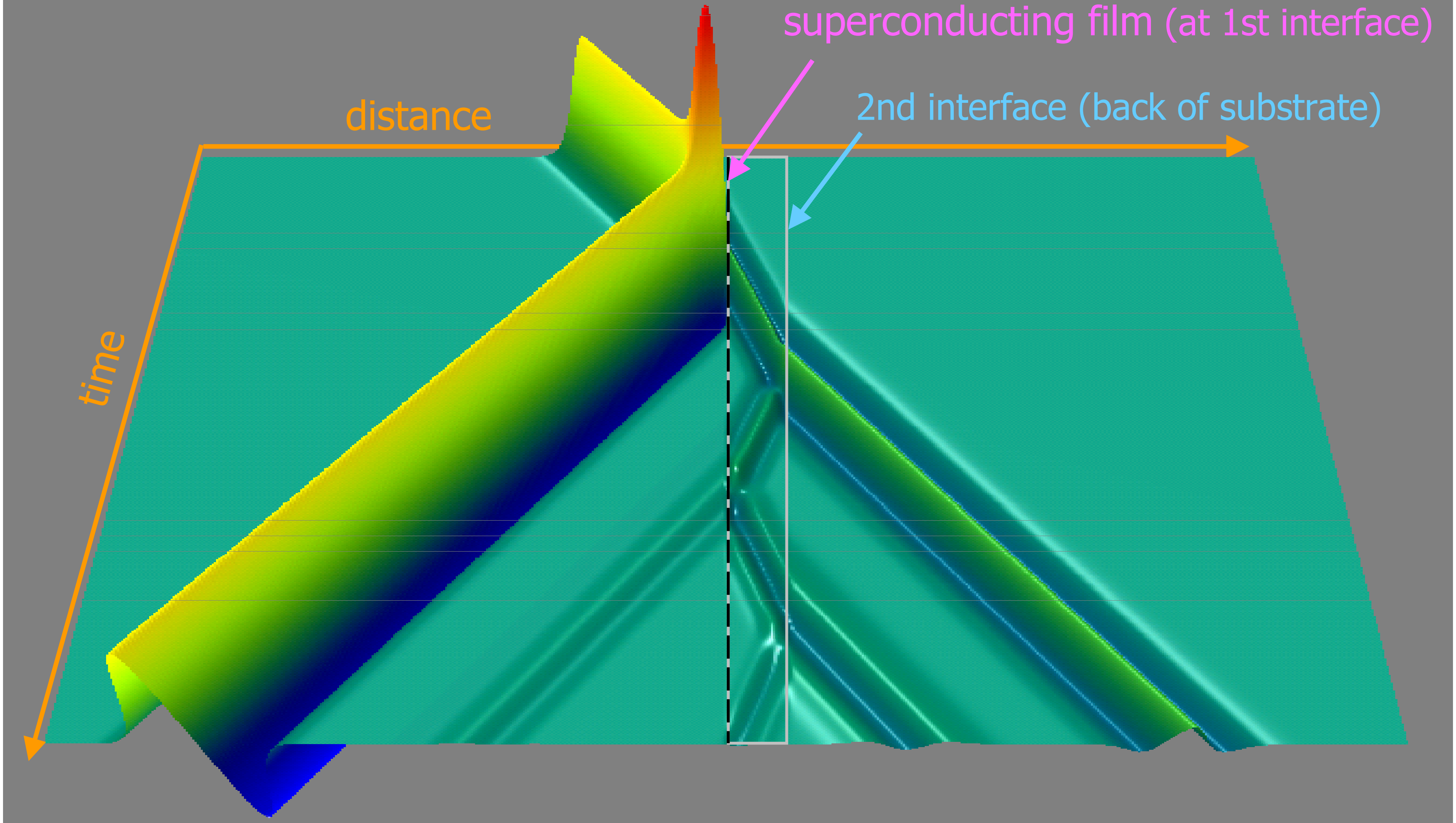
FDTD Test / Demonstration

Thin metal film on a
100 μm thick, n=2 substrate

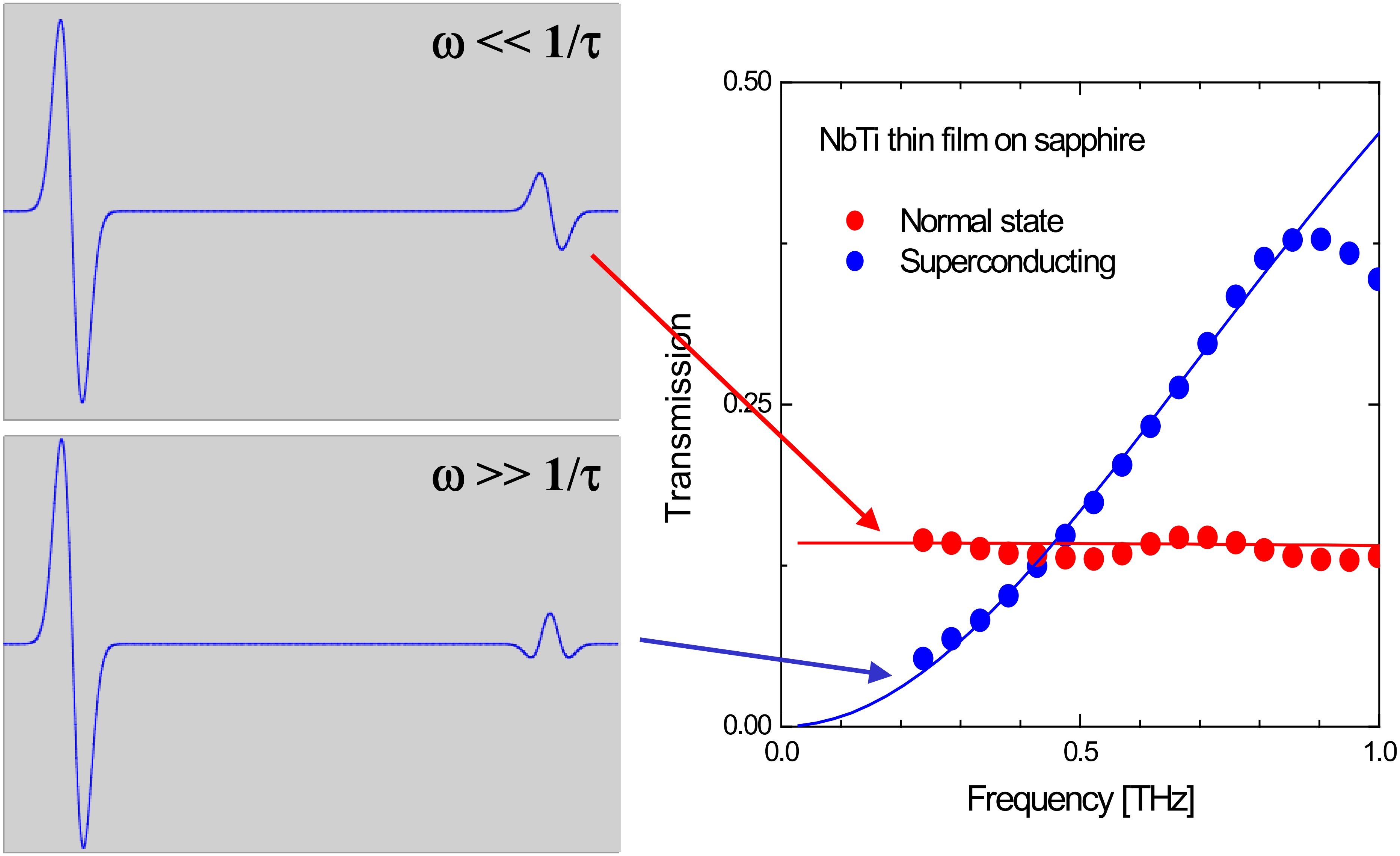
space inc. = 10 μm
time inc. = 16.8 fs



FDTD demonstration



FDTD Calculation for Transmission



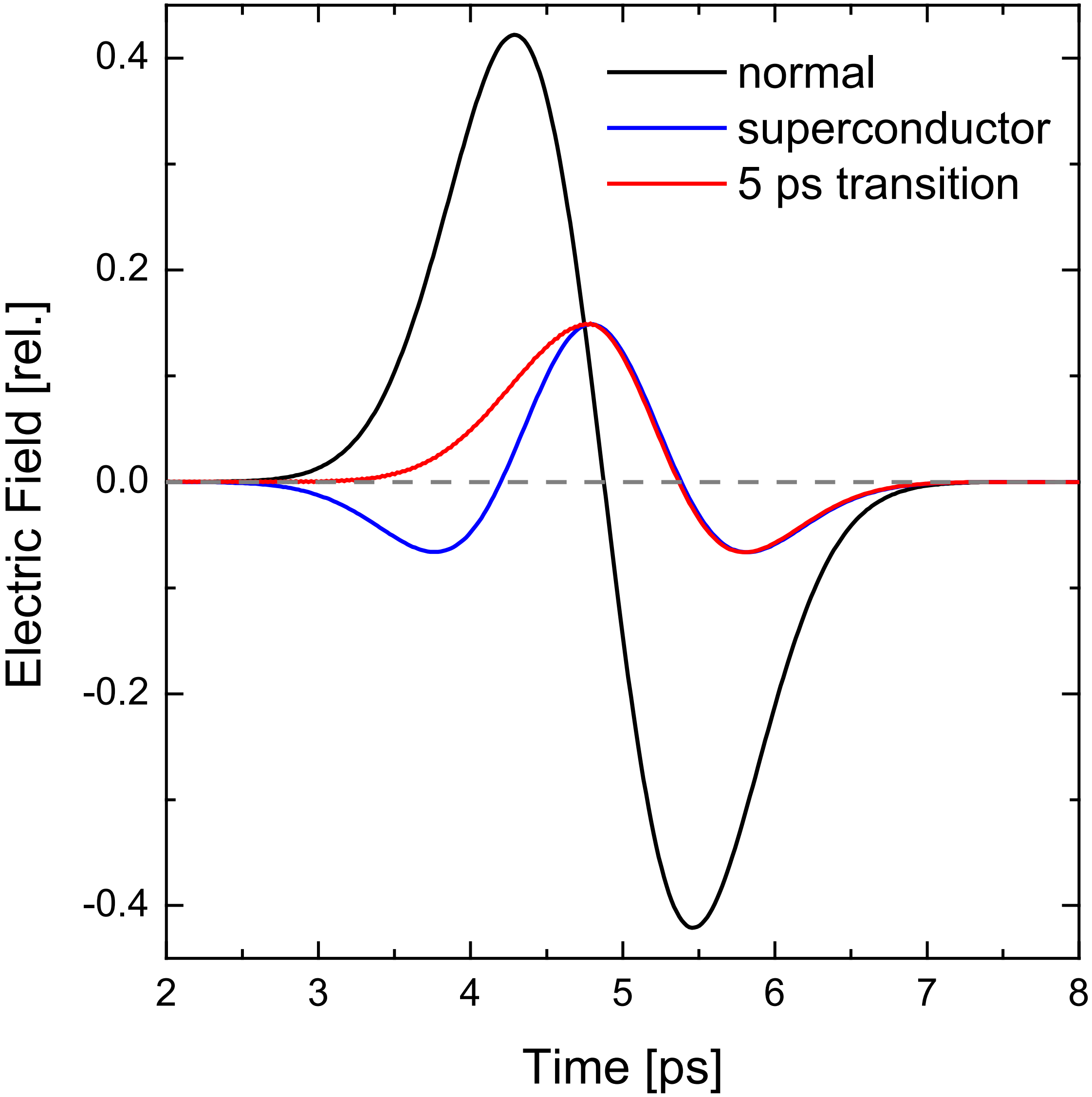
Model for Exceeding Critical Current

If induced J exceeds J_C, changeover to state with dissipation. How quickly?

Model as linear change (with time) of $1/\tau$, increasing from $1/\tau$ = 0 THz and increasing to a final value of 2 THz.

Assume process takes 5 ps to complete

=> Expect non-linear effects.



Summary

Accelerator-based THz Sources produce Coherent Pulses:

- *High pulse energy*
- *1/2 or single cycle pulses, ~ 1 ps or less*
- *E-field ~ 1 MV/cm, H-field ~ 3kG*
  - *should be sufficient to drive supercurrents in excess of critical value.*
- *high repetition rate from SC linac* (JLab energy recovery linac)
  or storage ring (less charge per bunch and control of shape, but more stable?)

NSLS Source Development Lab (SDL):

- *80 μJ pulse energy demonstrated*
- *spectral content to 2 THz (anticipate even higher)*
- *demonstrated coherent EO detection*
- *transition radiation: radial polarization*
  (suitable for coupling to wires or other cylindrical modes)
- *Potential for 2nd color (pump or probe)*
- *Not presently a "User Facility", but potential exists with sufficient interest.*