Coherent THz Pulses: Source and Science at the NSLS

H. Loos, B. Sheehy, D. Arena, J.B. Murphy, X.-J. Wang and G. L. Carr

National Synchrotron Light Source

Brookhaven National Laboratory

carr@bnl.gov

http://www.nsls.bnl.gov

http://infrared.nsls.bnl.gov

THz Workshop

Jefferson Lab, Sept 20, 2004

nsls

IR UV X

Funded under contract: DE-AC02-98CH10886

U.S. Department of Energy
Office of Basic Energy Sciences

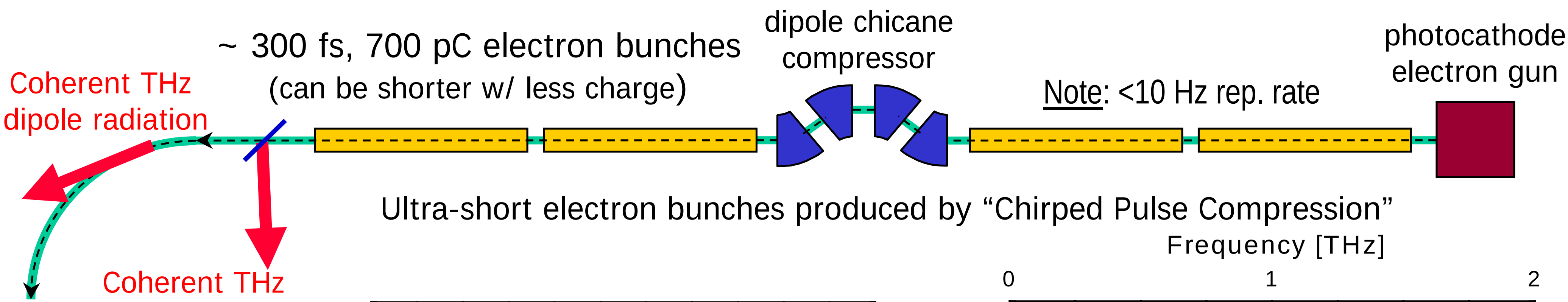
BROOKHAVEN NATIONAL LABORATORY

BROOKHAVEN SCIENCE ASSOCIATES

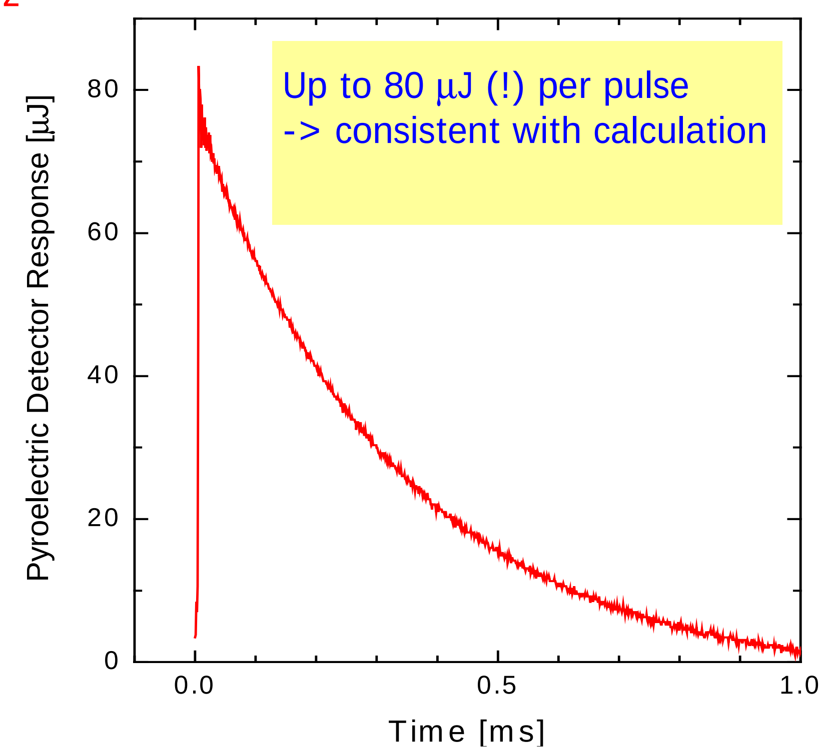
Coherent Synchrotron Radiation (CSR)

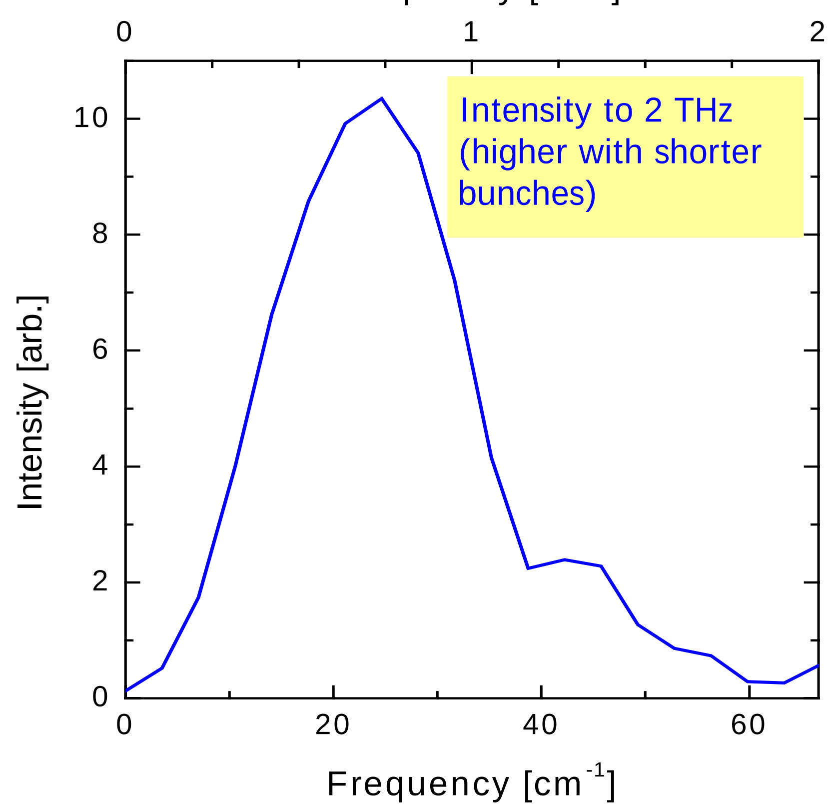
- 1st observations in linacs:
  - Nakazato et al (PRL ‘89), Happek et al (PRL ‘91)
- As a linac bunch diagnostic:
  - Shibata et al (PRE ‘94), Lai et al (PRE ‘94), Yan et al (PRL ‘00)
- As a THz source
  - Ishi et al (PRA ‘91), Takahashi et al (RSI ‘98), Carr et al., (Nature ‘02)
- CSR also from storage rings
  - Arpe et al, Carr et al, Anderson et al, Abo-Bakr et al. …
    - Instability in low RF frequency machines

Coherent Transition Radiation from the NSLS SDL Linac



Ultra-short electron bunches produced by “Chirped Pulse Compression”





Compare to ~ 1 nJ from a conventional photoconductive switch and an amplified, 250 kHz rep rate drive laser

Transition Radiation from Relativistic Electron

Transition radiation occurs when an electron crosses the boundary between two different media. For a relativistic electron ($\beta \equiv v/c \cong 1$) incident on a perfect conductor, the number of photons emitted per solid angle and wavelength range is:

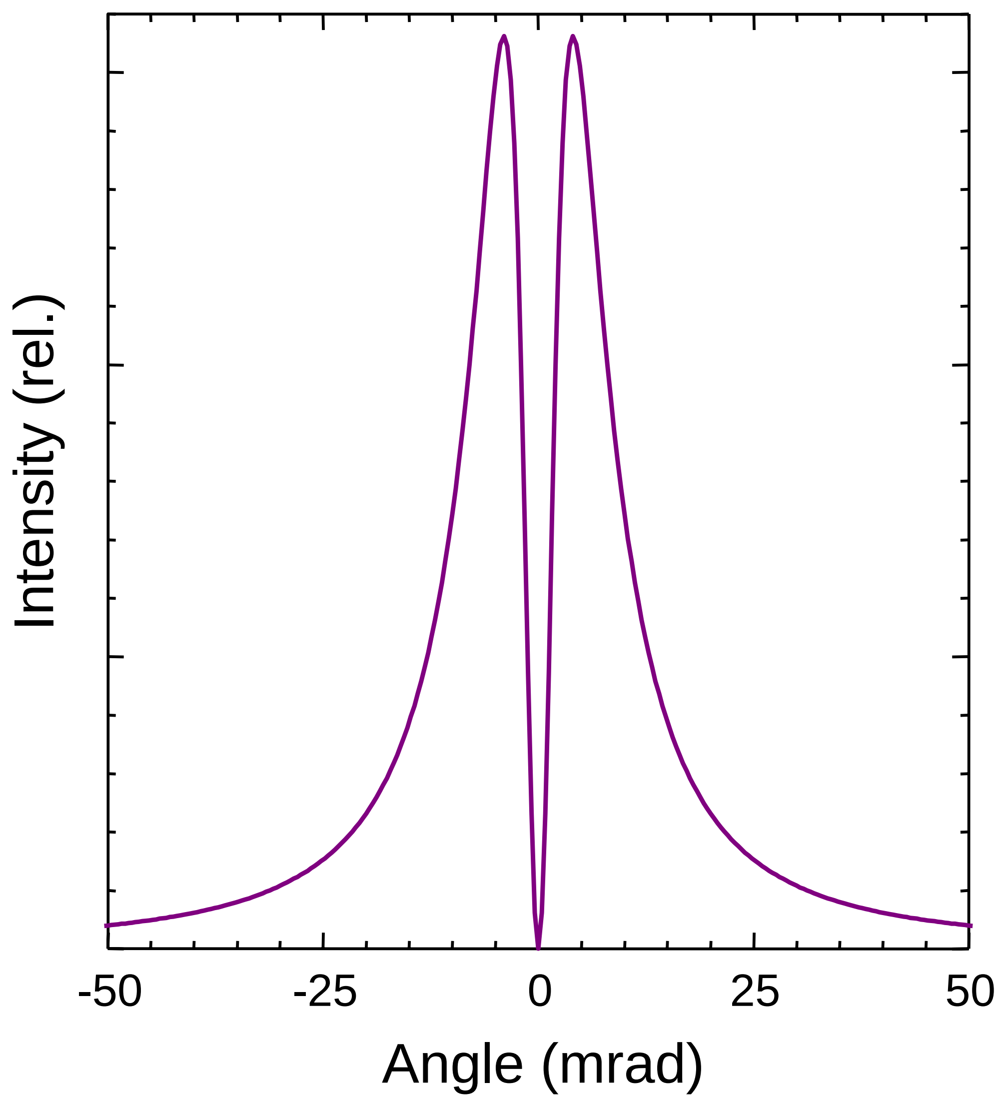
$$\frac{dN}{d\lambda d\Omega} = \frac{\alpha}{\pi^2 \lambda} \frac{\beta^2 \sin^2\theta \cos^2\theta}{\left(1-\beta^2\cos^2\theta\right)}$$

Intensity is 0 on axis, peaks at $\theta \sim 1/\gamma$.

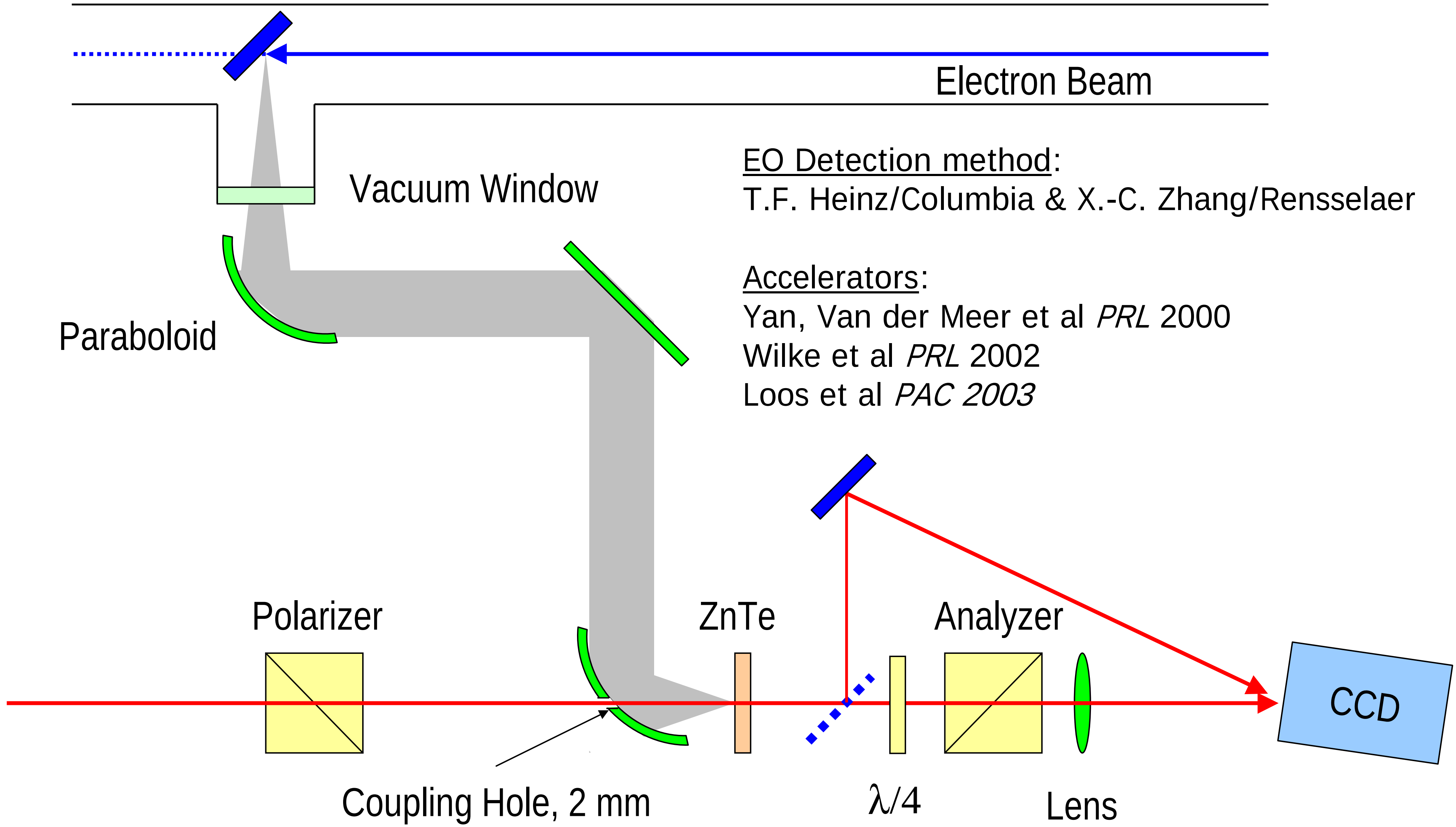
Polarization is radial

$$\frac{dP}{d\bar{\nu}} \approx 4.61\times 10^{-26} \underbrace{\left(\ln\frac{2}{1-\beta} - 1\right)}_{\substack{\text{11.4 for 130 MeV} \\ \text{20 for 9 GeV}}} \quad \text{J/cm}^{-1}\text{ per electron}$$

Far field distribution for γ = 200



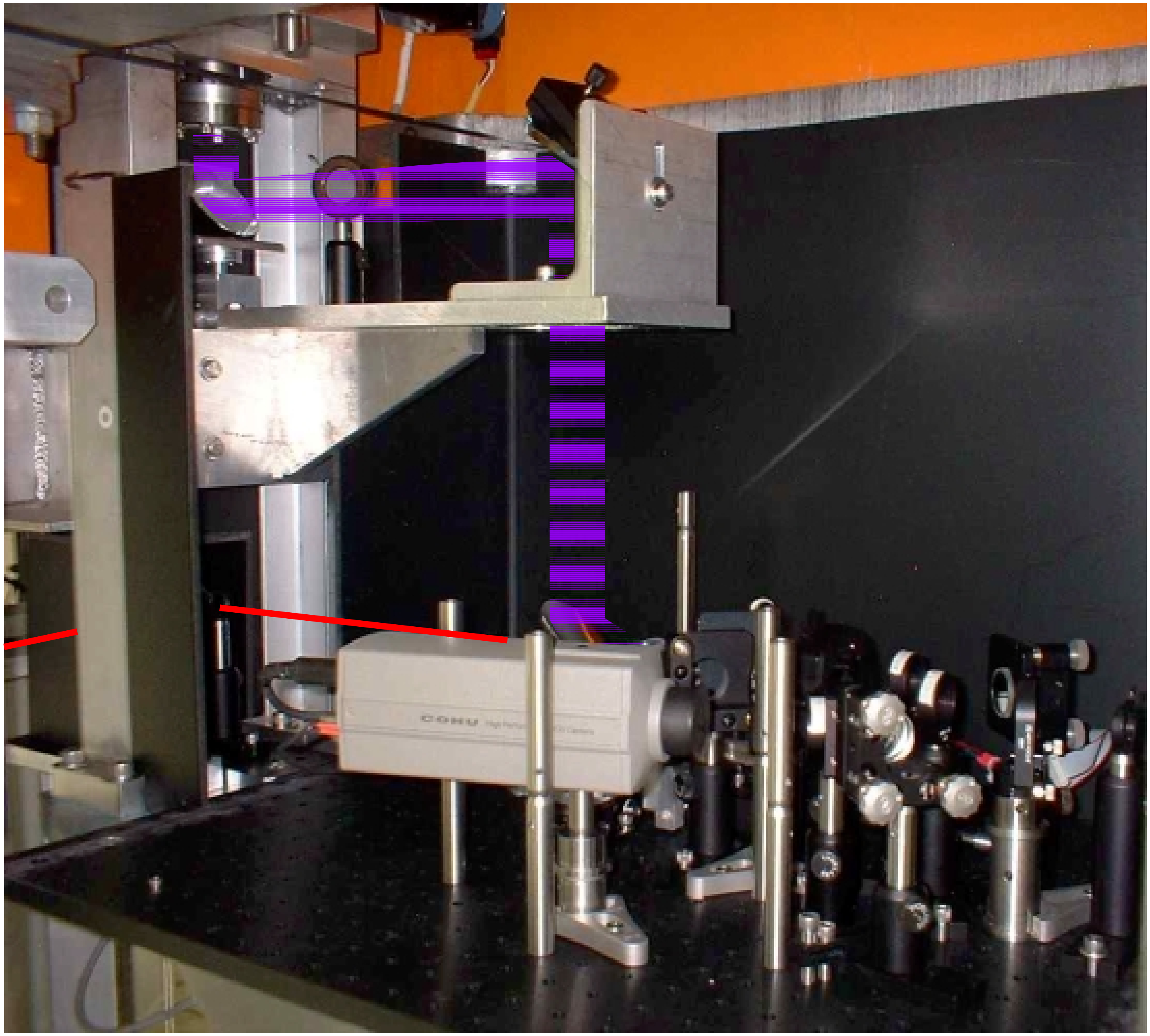
Electro-Optic THz Detection



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

Accelerators:
Yan, Van der Meer et al *PRL* 2000
Wilke et al *PRL* 2002
Loos et al *PAC 2003*

THz and Sampling Laser Beam Path



EO Detection of SDL Linac Coherent THz Pulses

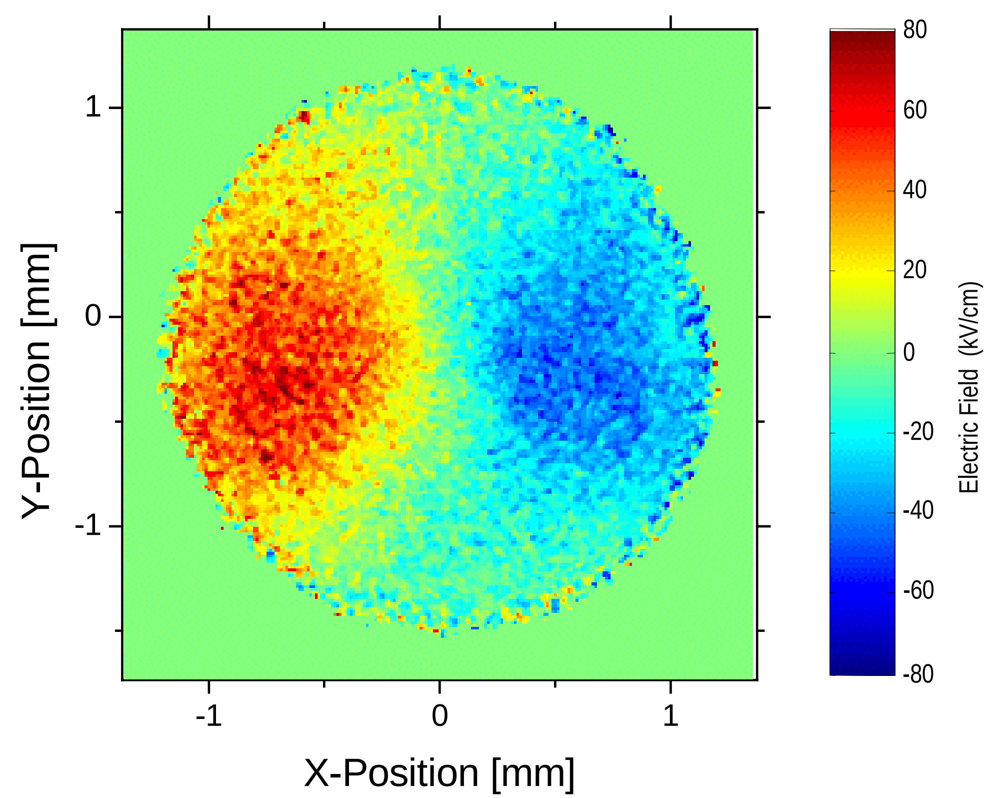
Focusing a 100 μJ pulse, 1 THz (nominal) pulse into a 1 mm^3 volume yields an energy density of 10^5J/m^3 , so that $E = [2D_E/\varepsilon_0]^{1/2}$ **~ 10^8 V/m (~ MV/cm)**.

This E-field is too large for 500 μm ZnTe (E > 170 kV/cm yields > λ/4 phase shift)

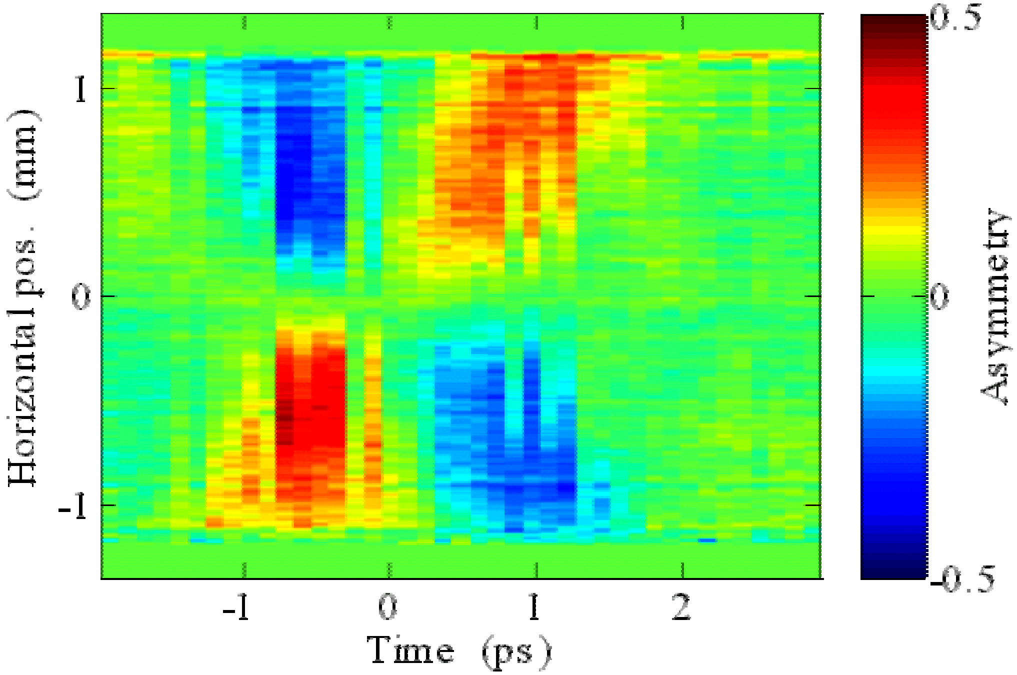
=> Reduce compression, lower charge to get "on-scale"

Transition Radiation is Radially Polarized

single shot image of E_H



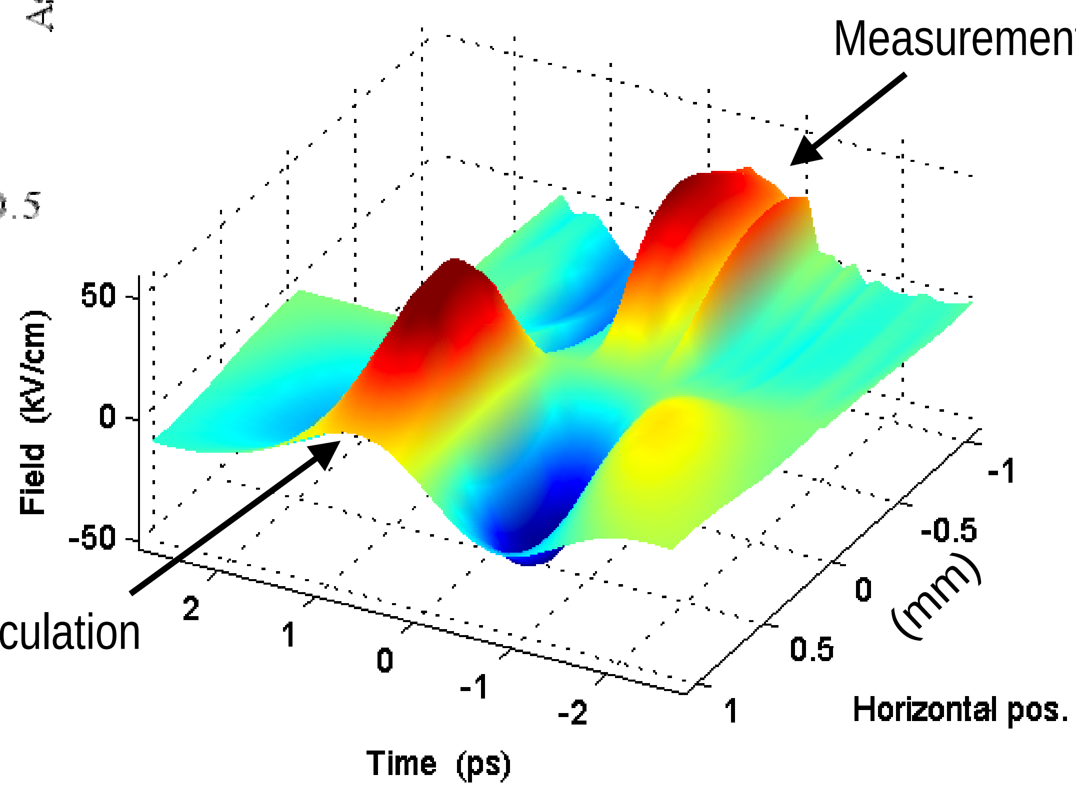
Temporal E-Field Cross Section at Focus



E-field along horizontal plane

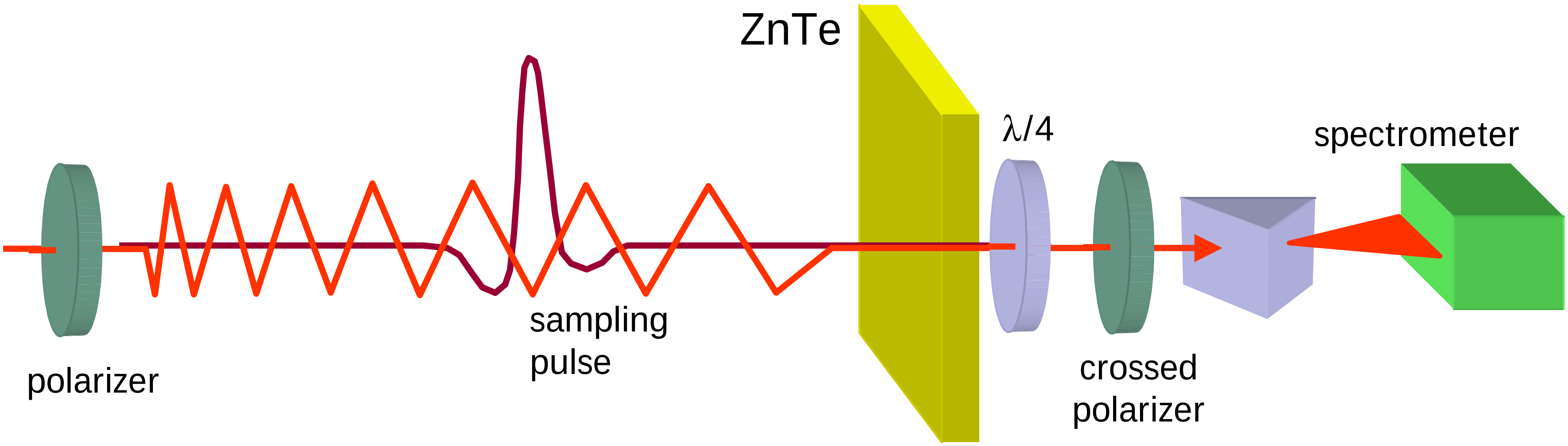
Temporal-spatial E-field profile of coherent transition radiation pulse at ~ f/1.5 focus

Note: opposite sides are <u>asymmetric</u>, as shown (radial polarization)



Electro-Optic Spectroscopy Method

- DUV-FEL laser for photocathode (linac) provides synchronized sampling pulse for EO detection.



- Laser pulse is “chirped” and can be used for EO sampling of THz fields in single-shot mode. [Jiang and Zhang, *APL* (1998), also Wilke et al *PRL* 2002].

Studies using High-Field, Half-Cycle THz Pulses

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

- **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, ...)
- **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?

$$\left.\frac{dI(\omega)}{d\omega}\right|_{multiparticle} = [N + N(N-1) f(\omega)] \frac{dI(\omega)}{d\omega} \qquad f(\omega) = \left| \int_{-\infty}^{\infty} e^{i\omega \hat{n}\cdot\vec{r}/c} S(r)\, dr \right|^2$$

=> shape electron bunch profile to control E-field shape (coll. W/J. Neuman, U. Md.)

NSLS / SDL Measurement Plans

- “In Situ” (or “in vaulto”) Experiments
  - complete study of through-focus THz waveform and 1/2-cycle character.
  - transient magnetization of thin magnetic films.

- Beam transport to external optical table.
  - THz and sampling laser pulses.
  - Transient currents in superconductors (easier at JLab?)

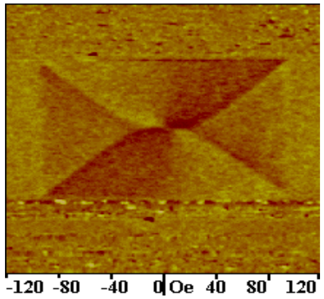
- Beam shaping (for 2nd color)
  - All THz pump-probe (spectroscopy of probe and pump)
  - Superconductors with complex gap structure (cuprates, MgB_2)

THz Driven Magnetic Dynamics

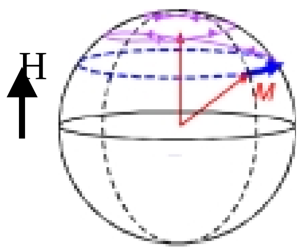
*Use ultra-short magnetic field pulses to induce spin excitations (**D. Arena / NSLS**)*

Time (s)

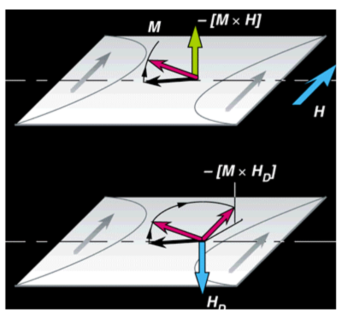
10^{-6} **Domain Propagation**



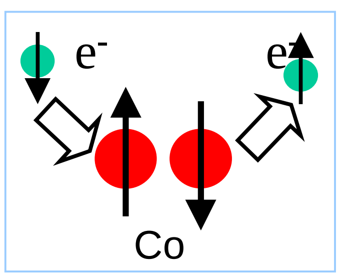
10^{-9} **Spin-Lattice Relaxation**



10^{-12} **Spin Precession**

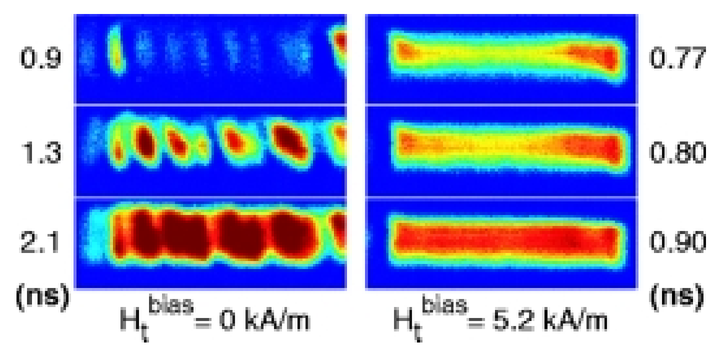


10^{-15} **Spin-Orbital Exchange**



Excitation / Interaction	Timescale (sec)
Exchange interaction	10^{-15}
Stoner excitations	10^{-15} - 10^{-14}
Spin waves	10^{-12} (low q limit)
Spin – lattice relaxation	10^{-12} - 10^{-11} (in manganites)
Precessional motion	10^{-10} - 10^{-9}
Spin injection	TBD
Spin diffusion	TBD
Spin coherence	TBD

Soft Ferromagnet Dynamics Time-resolved MOKE on permalloy strip. B.C. Choi *et al.*,PRL **86**, 728, (2001)



Other systems of interest: Dilute Mag. Semiconductors, Manganites.

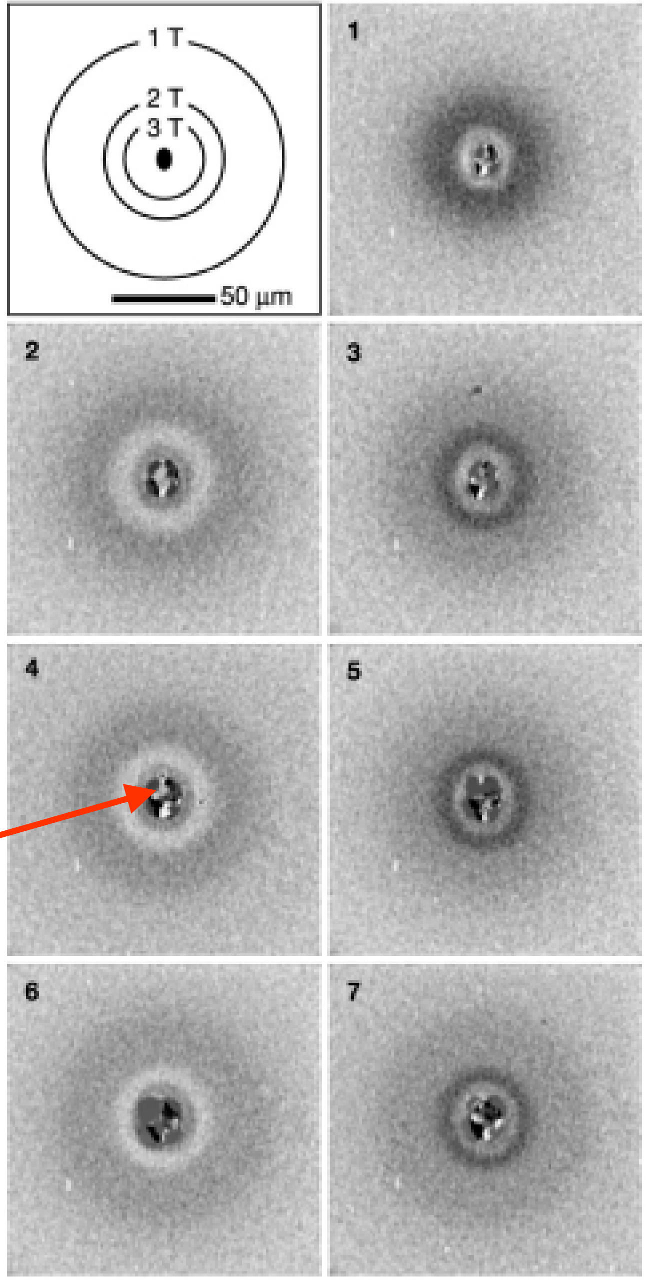
Transient Magnetization Study at SLAC/SPPS

Example:
14 nm thick films of granular CoCrPt
(magnetic recording media)

28 GeV electrons (SLAC), 2.3 ps duration.

I. Tudosa et al, *Nature* **428** 831 (2004).

Sample placed ***in*** the 28 GeV SLAC beam



"Low" Energy Electrodynamics in a Superconductor

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

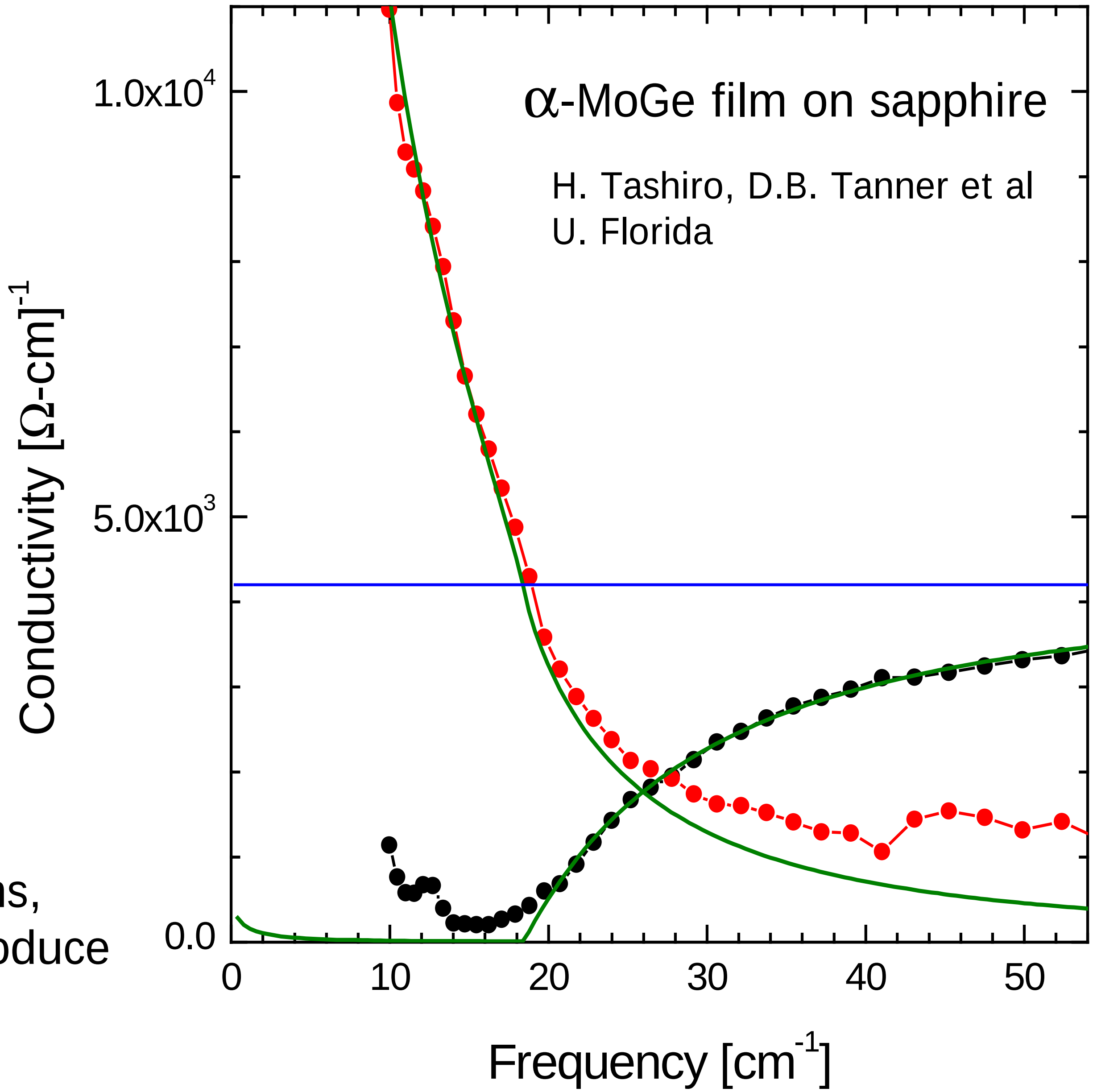
Estimate induced current density

$J = \sigma E \sim 10^{10} A/cm^2$

Typical $J_C \sim 10^8\ A/cm^2$

=> "over twist" the local SC phase, spin off vortices?

<u>Experiment</u>:
THz-driven supercurrent excitations, study gap as J_C is approached, produce novel non-equilibrium state.



Summary

Accelerator-based THz Sources should be able to create novel excitations:

- *High pulse energy (80 μJ per pulse)*
- *1/2 or single cycle pulses, ~ 1 ps or less*
- *E-field ~ 1 MV/cm, H-field ~ 3kG*

Potential experiments will depend on other source / facility aspects

- *repetition frequency (<u>big</u> JLab advantage)*
- *availability of synchronized sampling pulses (coherent EO detection)*
- *2nd color pulse (for pump or probe)*
  - *THz, IR, UV, x-ray?*