Terahertz Radiation:

Emerging Sources, Techniques & Applications

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BERKELEY LAB

ALS

Outline

Þ What is THz?

Þ Why use THz?

Þ THz Systems and application examples

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http://infrared.als.lbl.gov/

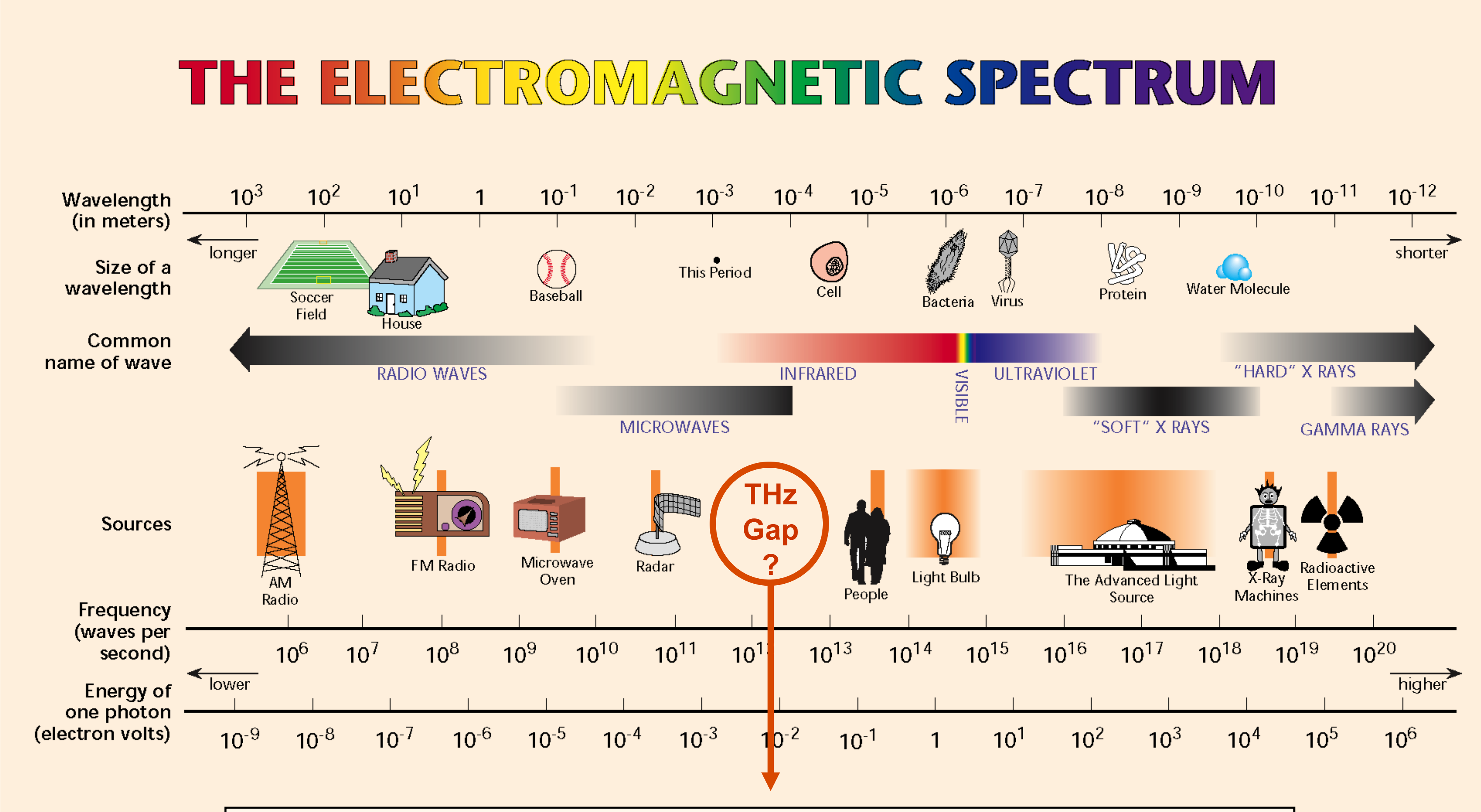
http://THzNetwork.net/

THz Science & Technology Network

Office of Science

U.S. DEPARTMENT OF ENERGY

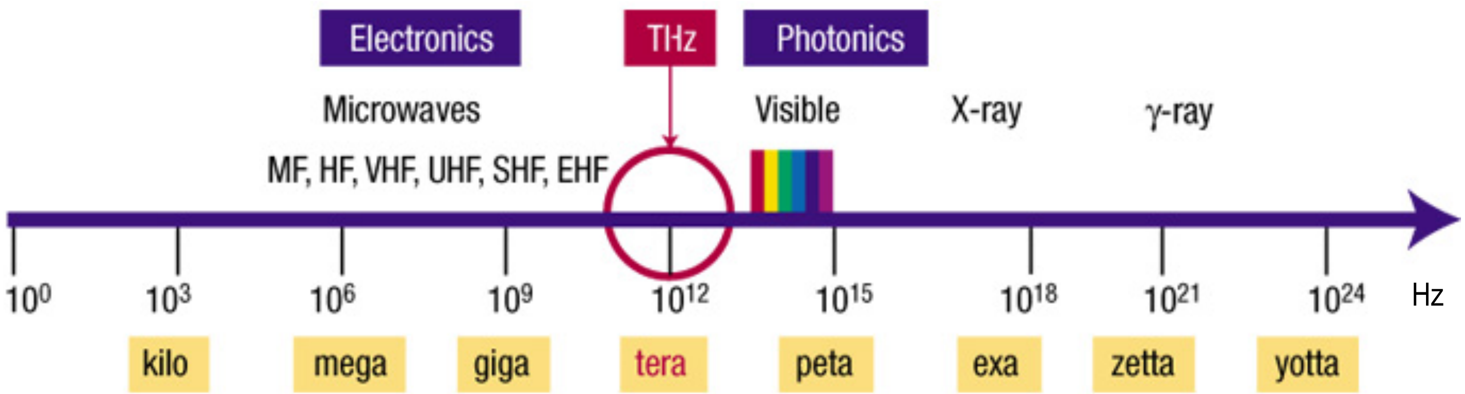
The EM Spectrum



1 THz ~ 1 ps ~ 300 μm ~ 33 cm^{-1} ~ 4.1 meV ~ 47.6 K

The Terahertz (THz) Gap

"The most scientifically rich, yet underutilized region of the EM spectrum" –Tom Crowe



1 THz
= 4.1 meV
= 33 cm^{-1}
= 300 mm

THz Science: collective excitations, protein motions & dynamics, superconductor gaps, magnetic resonances, terabit wireless, medical imaging, security screening, detecting explosives & bio agents …

"Much brighter terahertz beams are required for scientific and technological applications ... Large average and peak powers could be used to manipulate and alter materials, chemical reactions and biological processes."

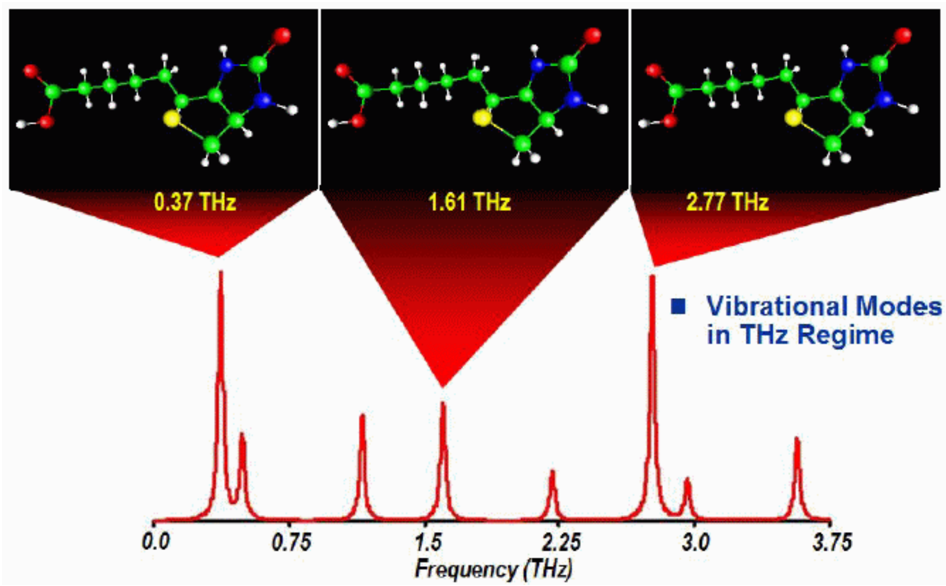
-Mark Sherwin, **Nature** *News & Views* **520**, 131 (2002).

Why THz?

Low-Frequency Vibrations; *ie* Torsions, Hydrogen-Bond Stretches and Bends } Large-amplitude motions

Biomolecules fold using large amplitude motions into the correct shape to function in biological systems.

This sensitivity can be used to monitor such motions, or to identify complex (biological) molecules.

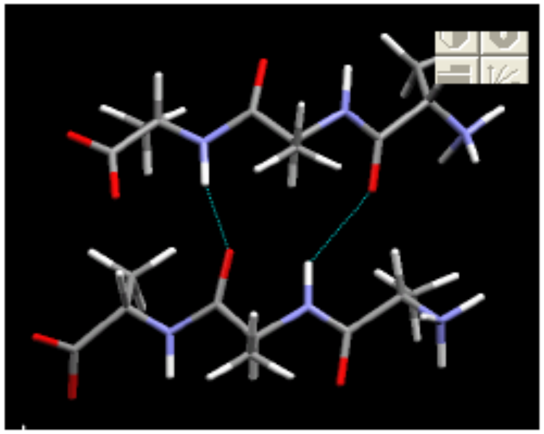


Chemical & Biological Warfare Agent Detection

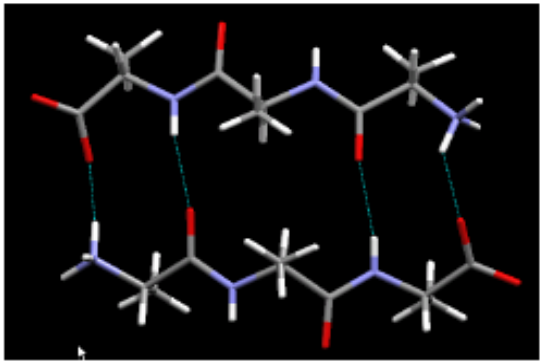
Why THz: High Specificity

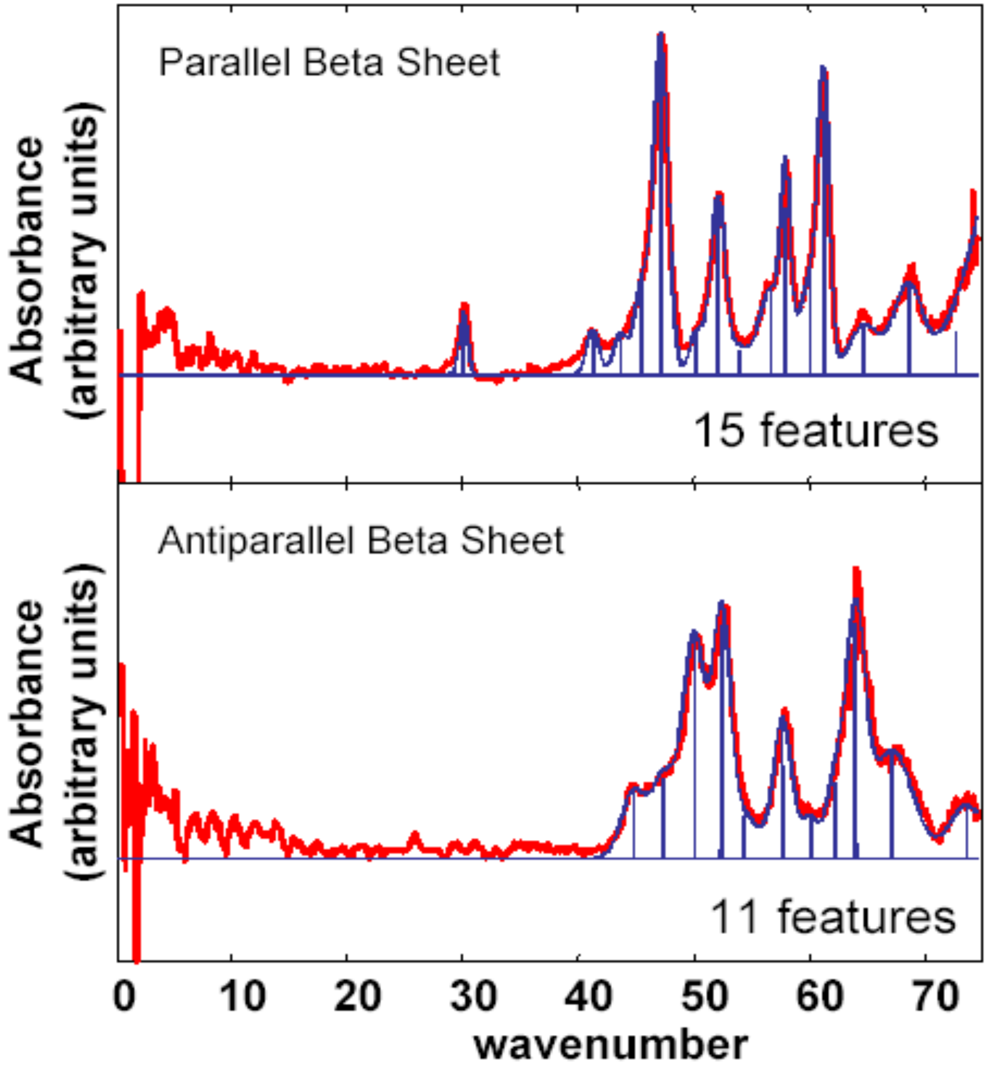
THz Spectra for parallel and antiparallel forms of trialanine show extreme sensitivity to the molecular environment.

Parallel Beta Sheet conformation

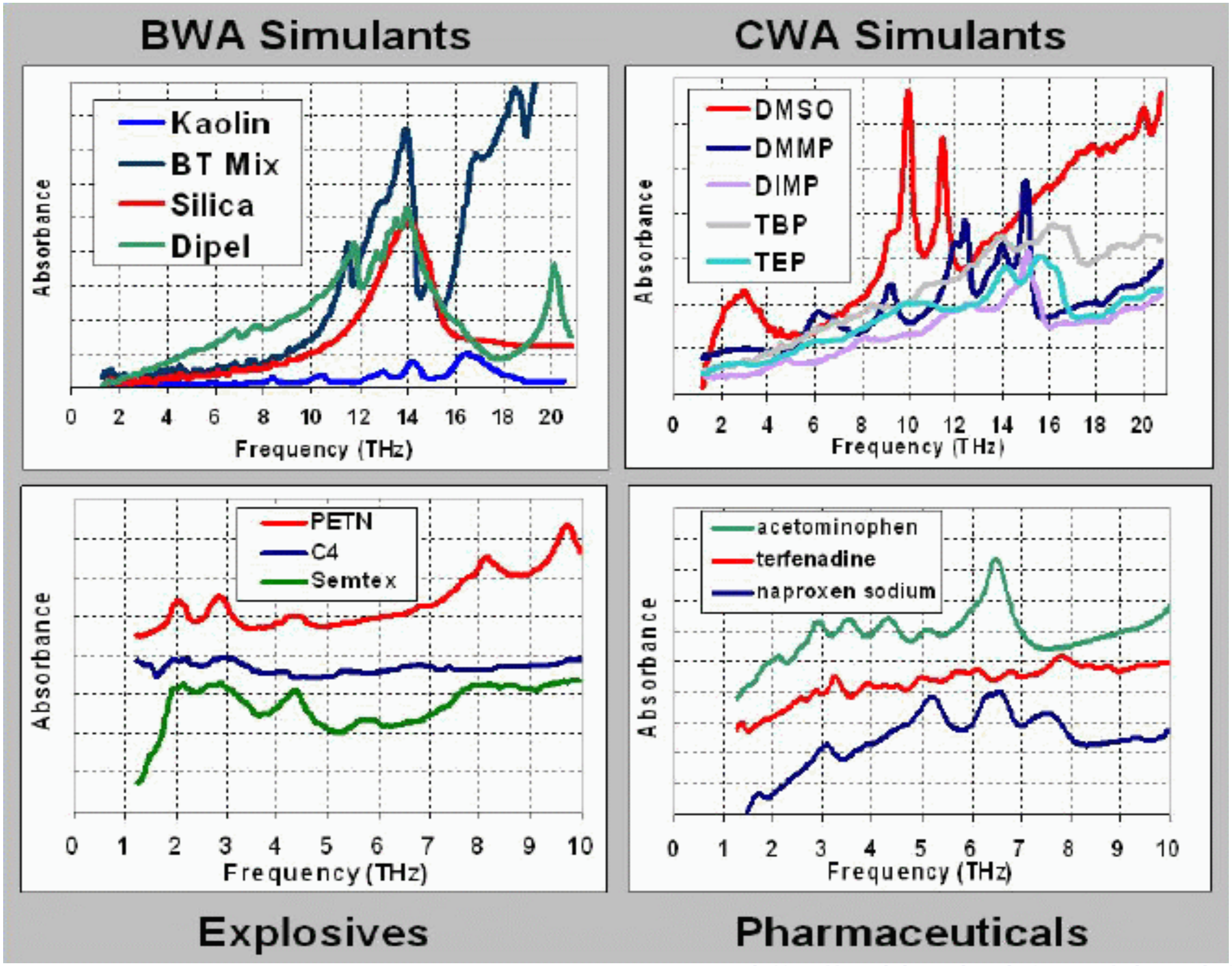


Antiparallel Beta Sheet conformation





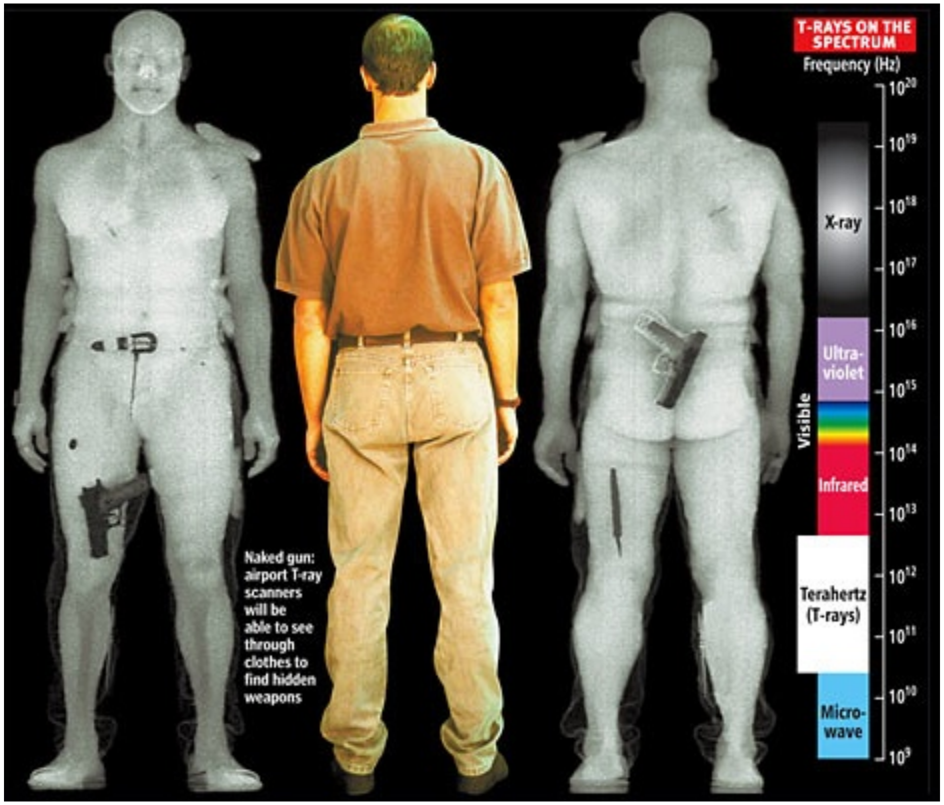
Why THz: Identify many agents

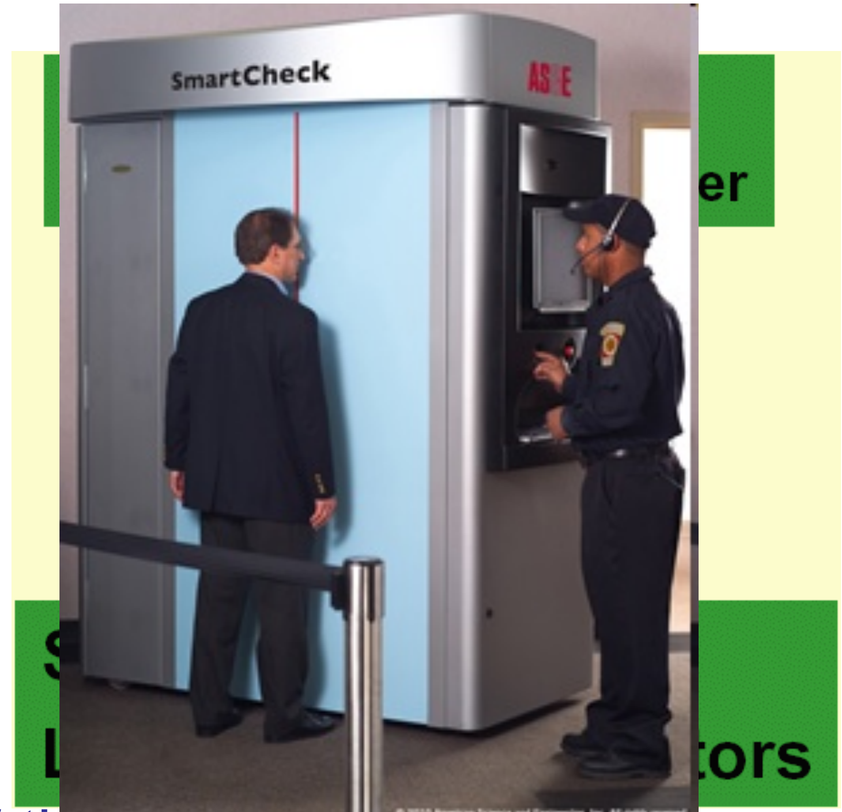


http://webbook.nist.gov/chemistry/thz-ir

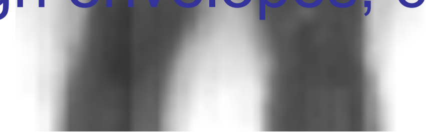
Why THz: Detection in the field

Terahertz transmits (at least partially) through many non-metal materials.





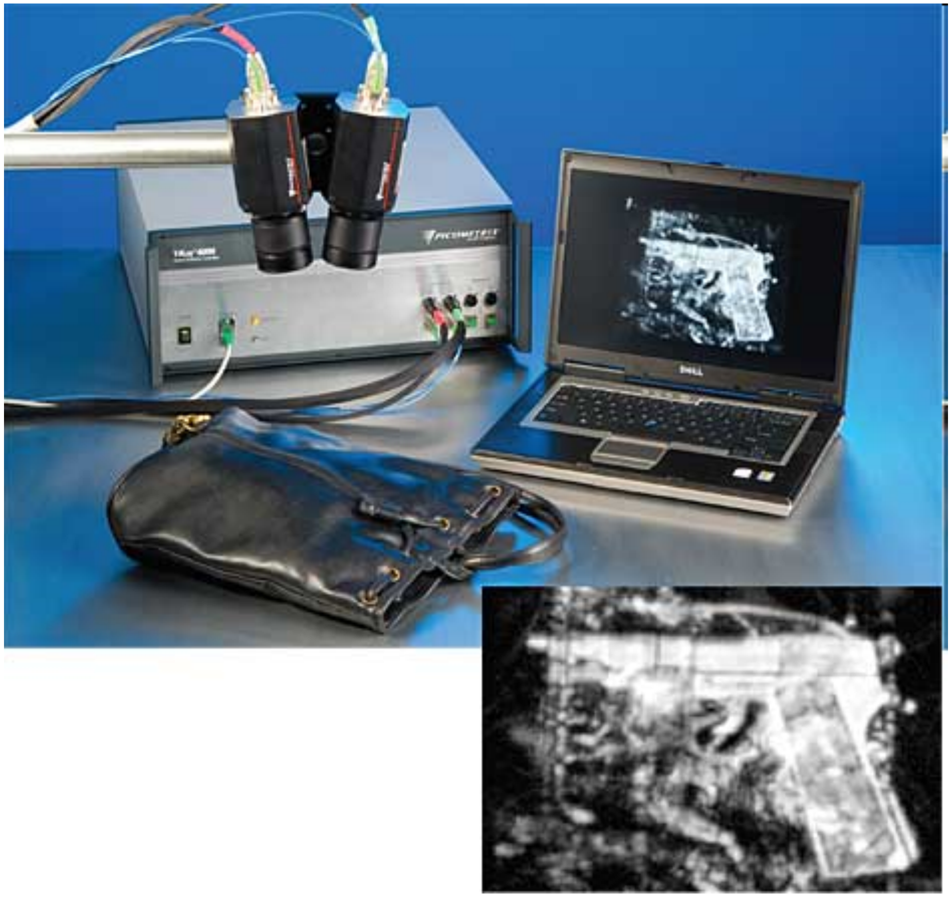
- Detection of bombs, BW & CW through envelopes, clothes, suitcases, soil …

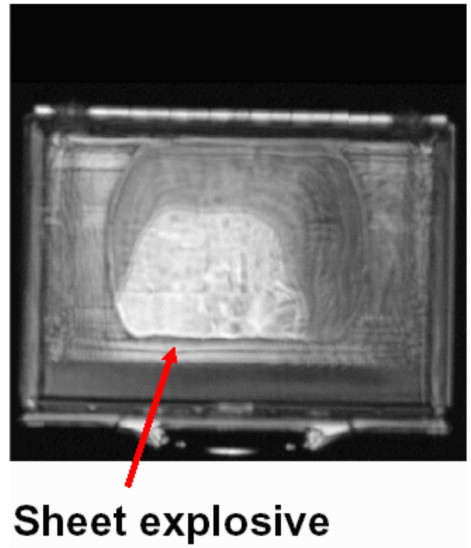


- Stand-off imaging & threat detection
- Security & military applications beginning to be deployed.

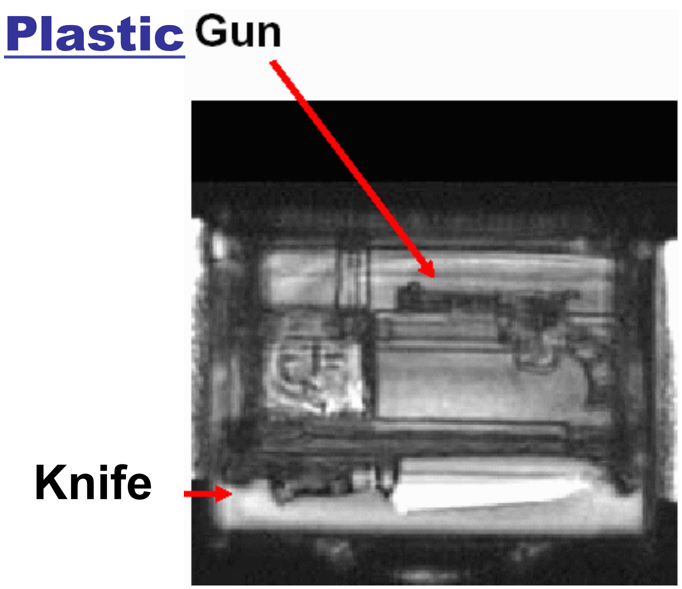
Why THz: Detection through objects

Security screening demonstrations





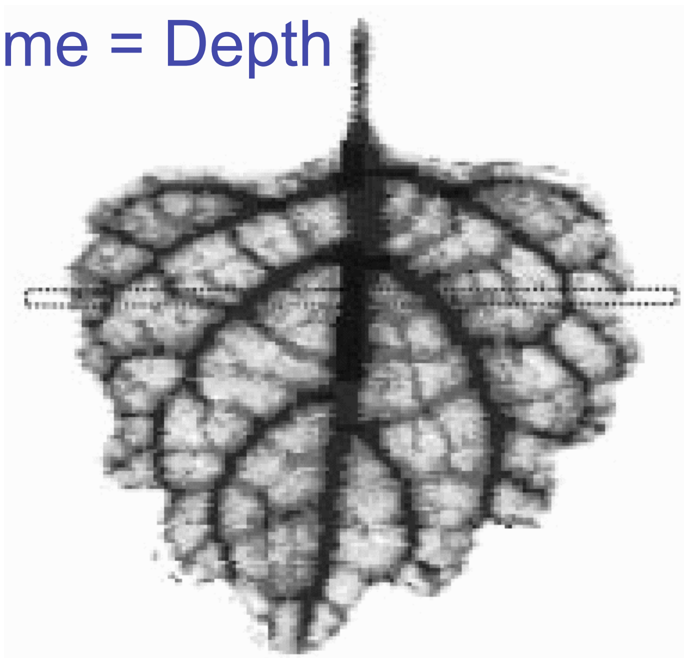
THz image through briefcase captures all depths at once.

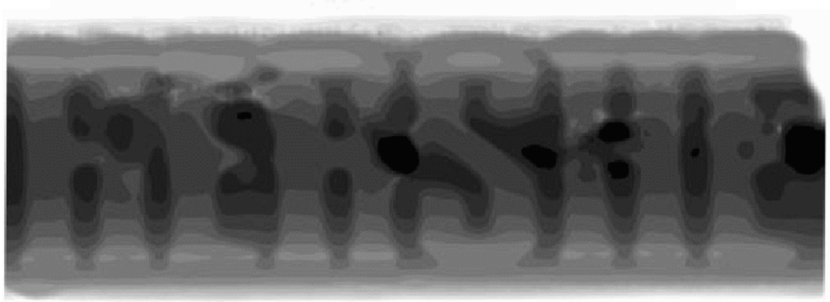


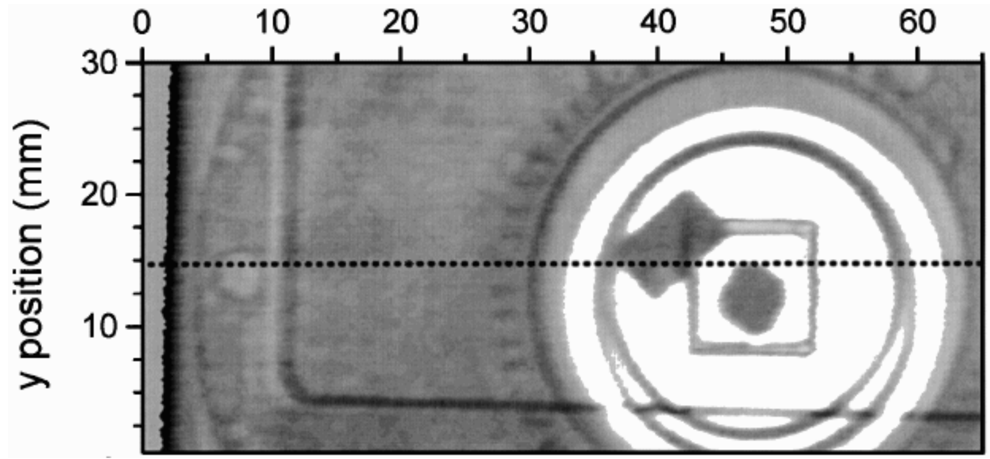
Why THz: Imaging

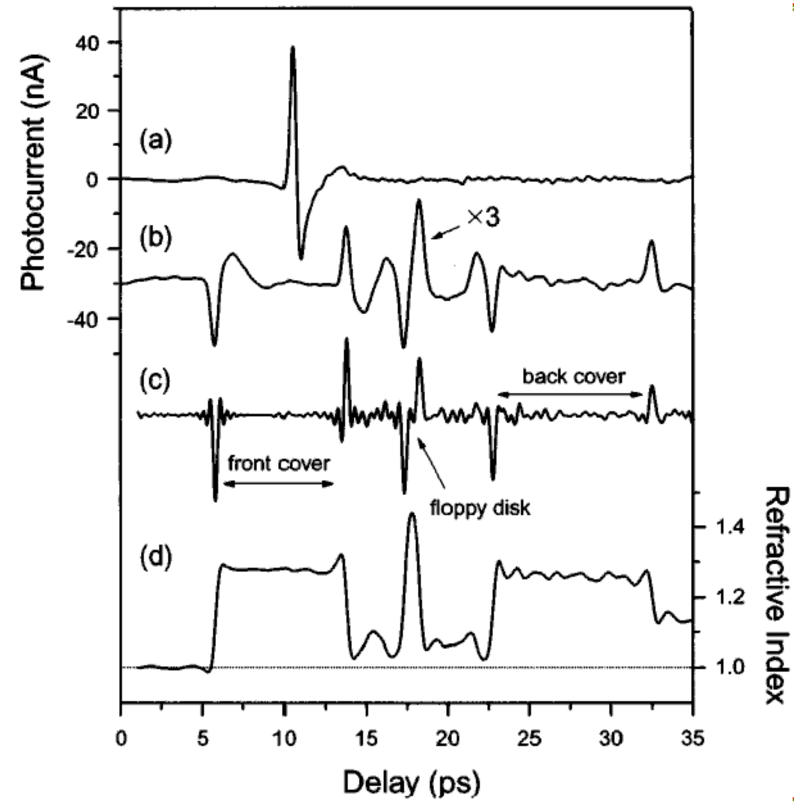
Imaging Applications:

- THz is non-ionizing, and non-destructive
- Time = Depth







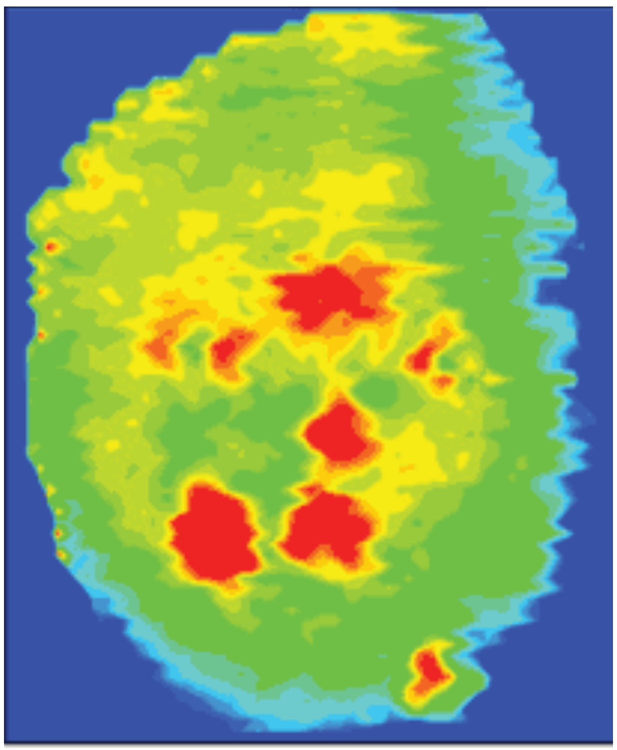


from Dan Mittleman

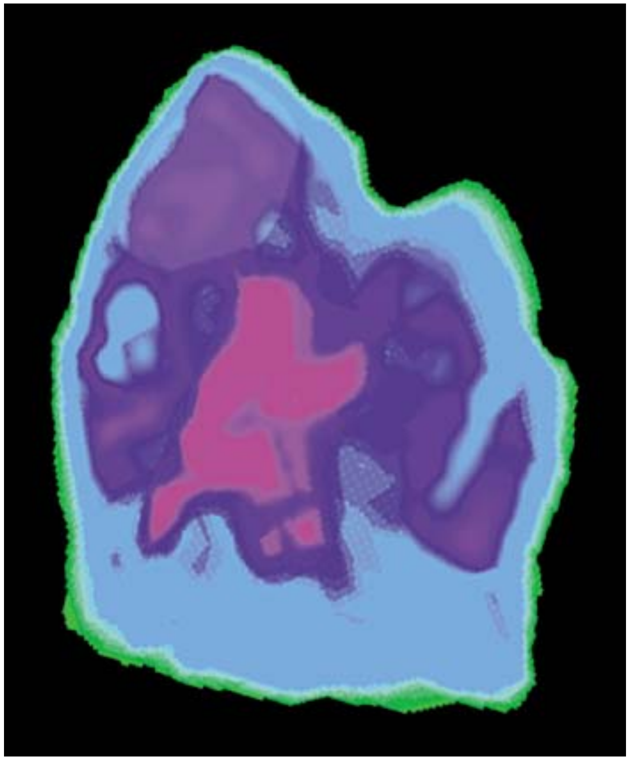
Why THz: New medical imaging tool

Medical Imaging Applications:

- THz is non-ionizing
- Can probe to some depth
- Some specific spectral signatures



Skin cancer (basal cell carcinoma) image just under the skin (from TeraView)



Transmission of a human tooth. Pink shows location of buried decay.

High-power 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).

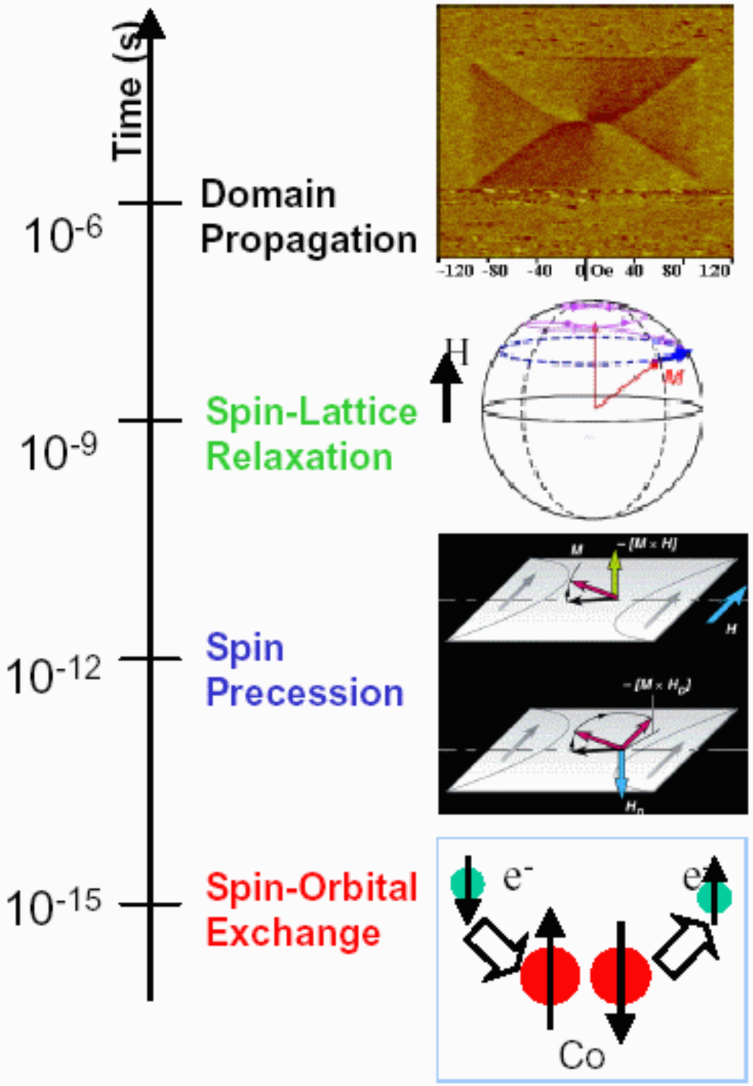
Or, some other shape pulse?

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

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

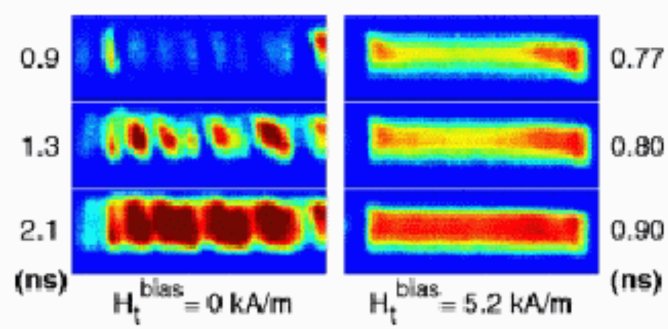
High-power THz Driven Magnetic Dynamics

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



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.

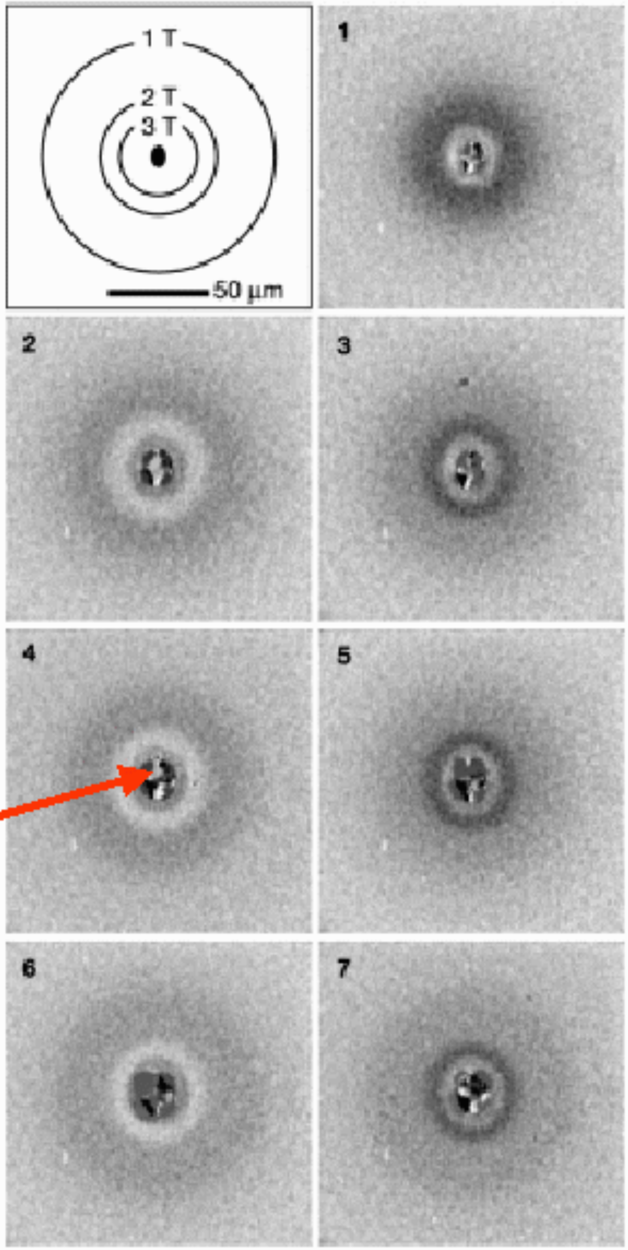
Transient Magnetization at SPPS/SLAC

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

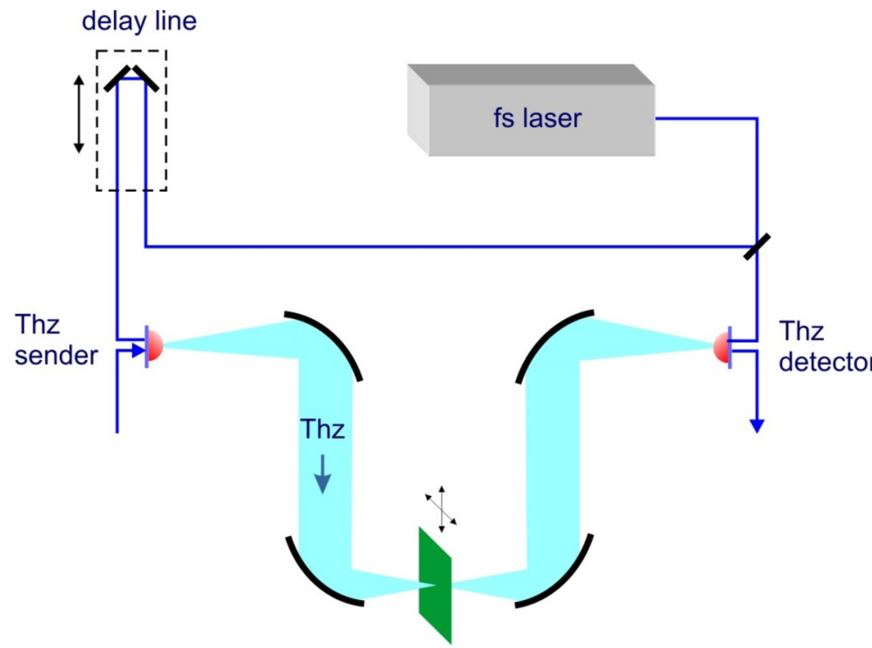
28 GeV electrons (SLAC), 2.3 ps duration.

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

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



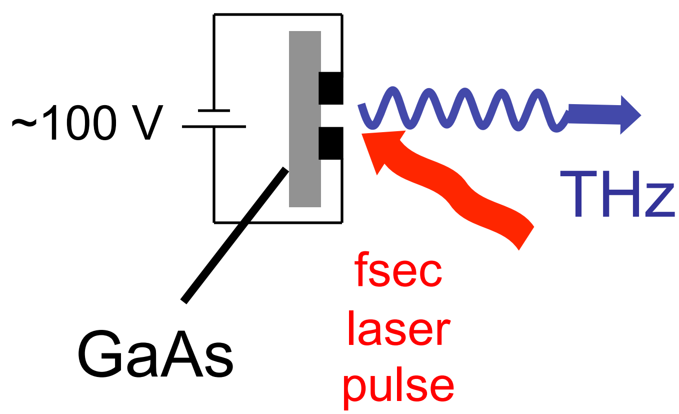
THz Spectroscopy Techniques

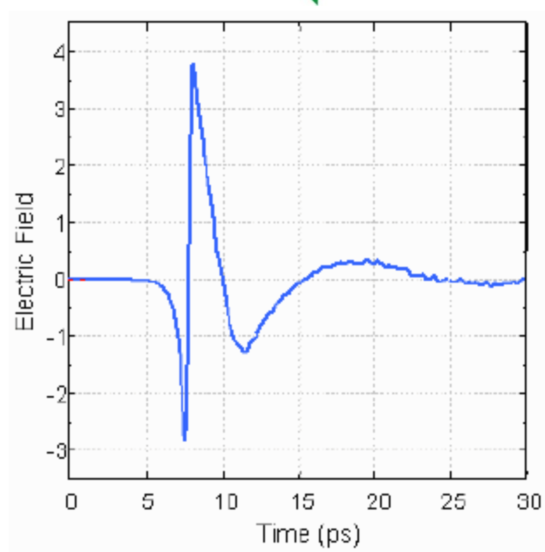


Time-domain and Scanning Techniques

- **Based on time domain spectroscopy (TDS)**
- **Uses recent advances in fs-laser technology.**
- **Measures intensity and phase of E-field vs time of a single cycle THz pulse**
- **Typically 0.2 – 2.5 THz, depending on fs laser**

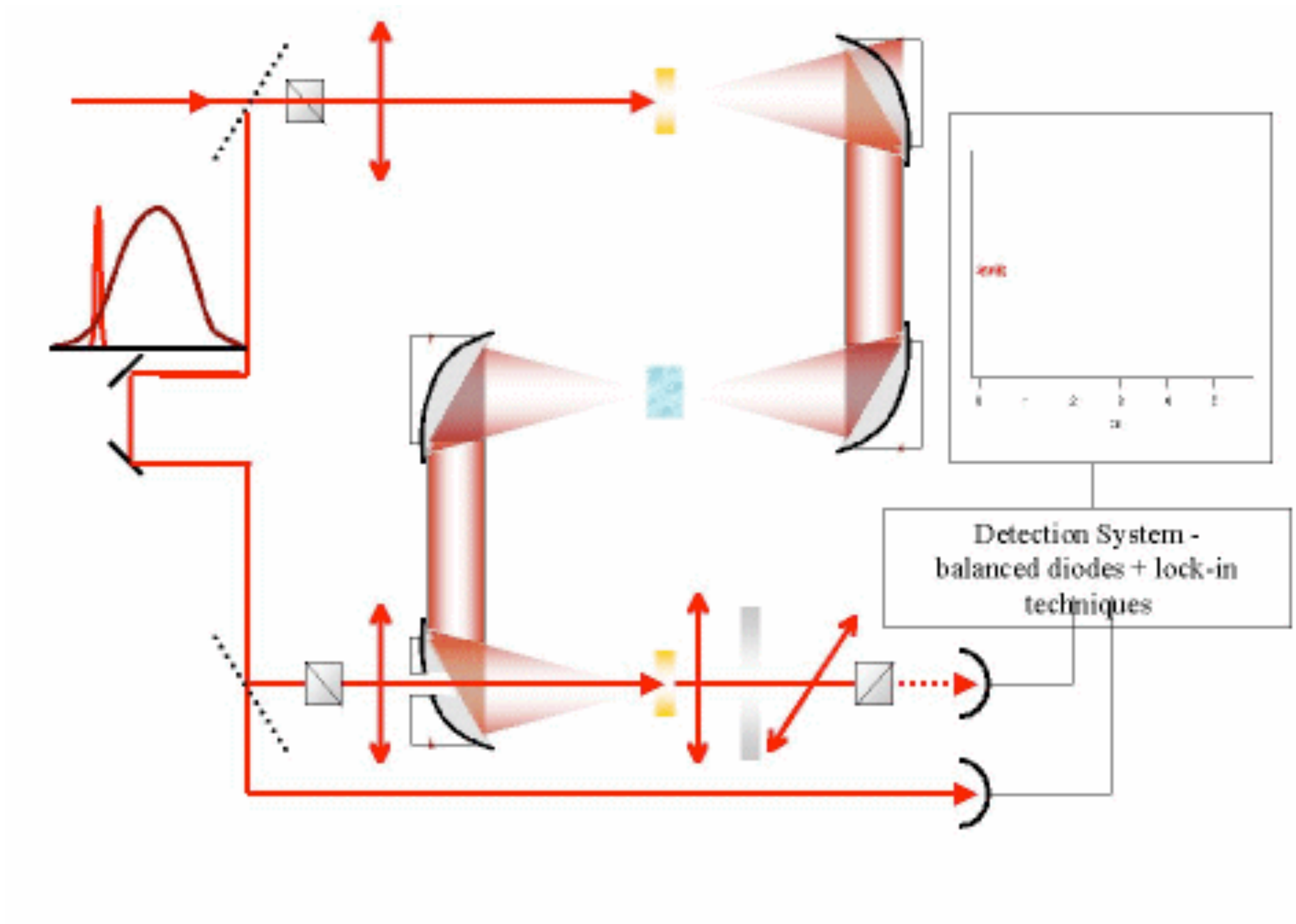
Auston switch





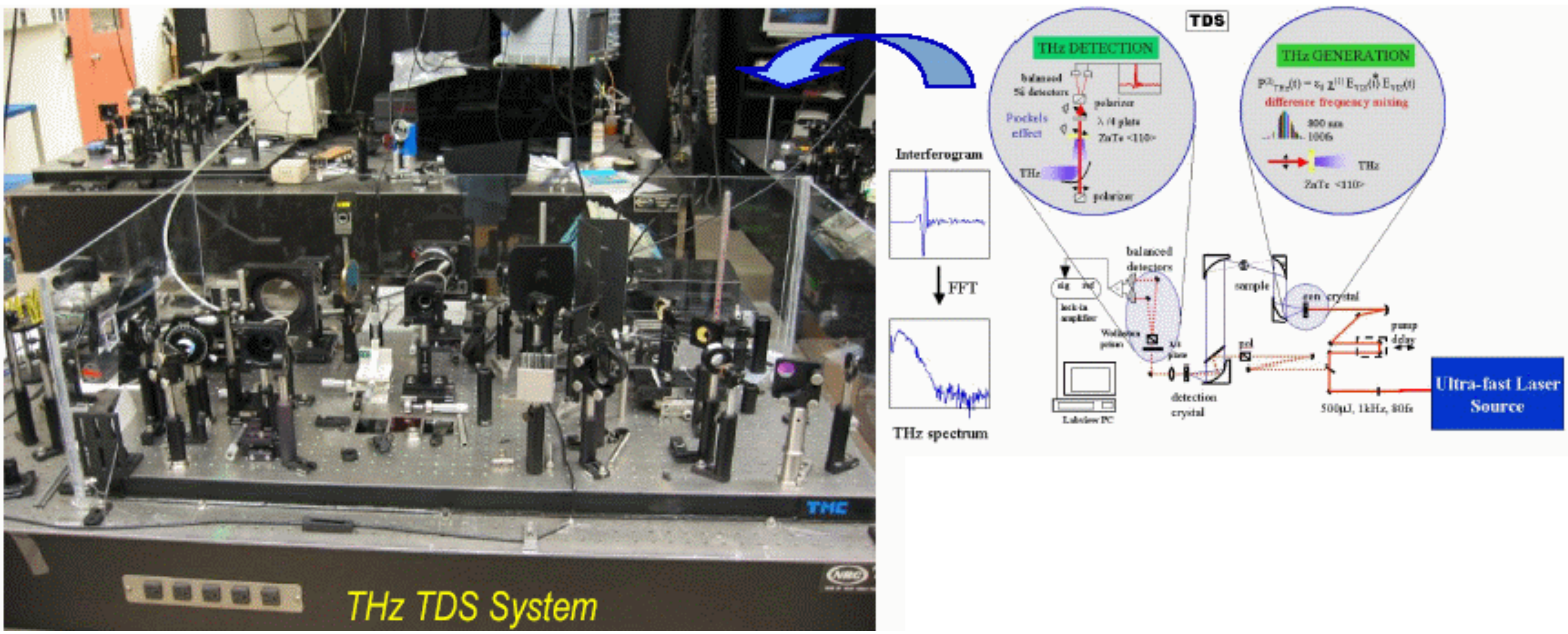
Time-domain THz

Electro-optic detection: EO crystal rotates polarization when E-field (THz) is applied.



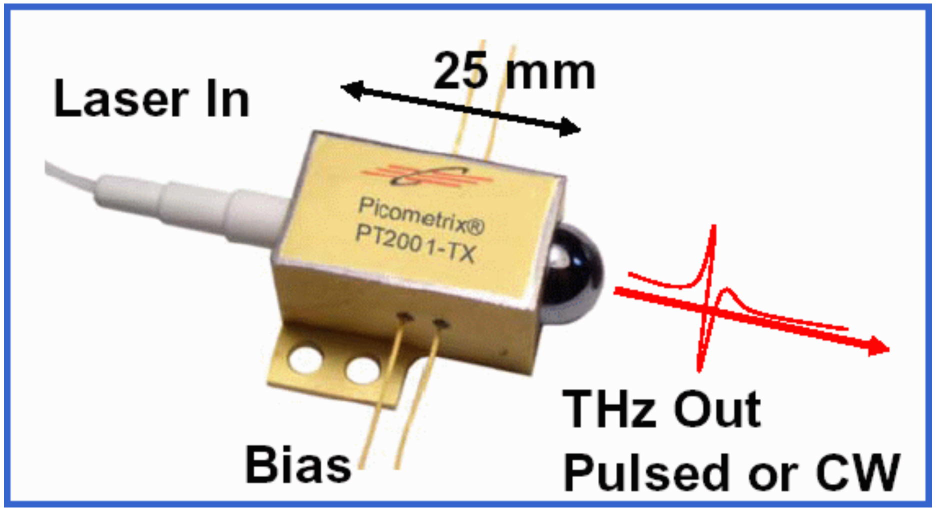
Time-domain THz Setup

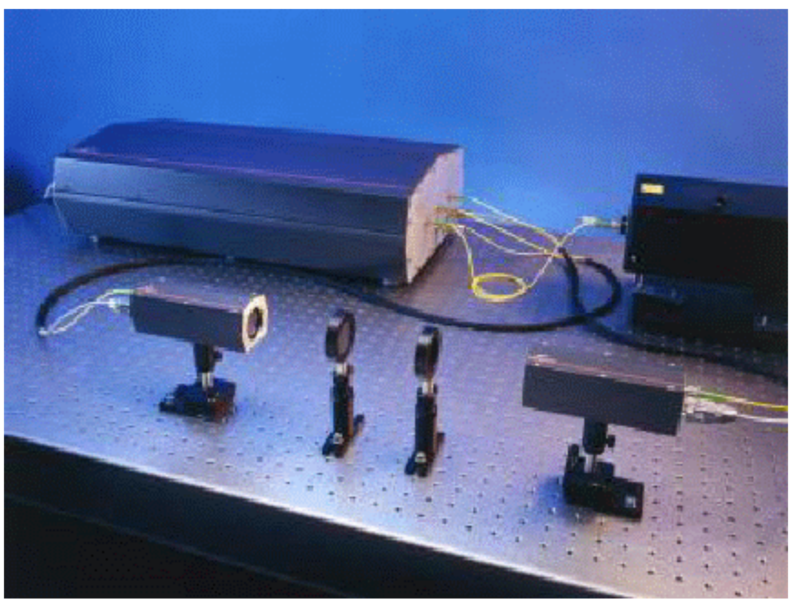
A typical research time-domain THz spectroscopy setup



Commercial Time-domain THz

A commercialized time-domain THz spectroscopy setup

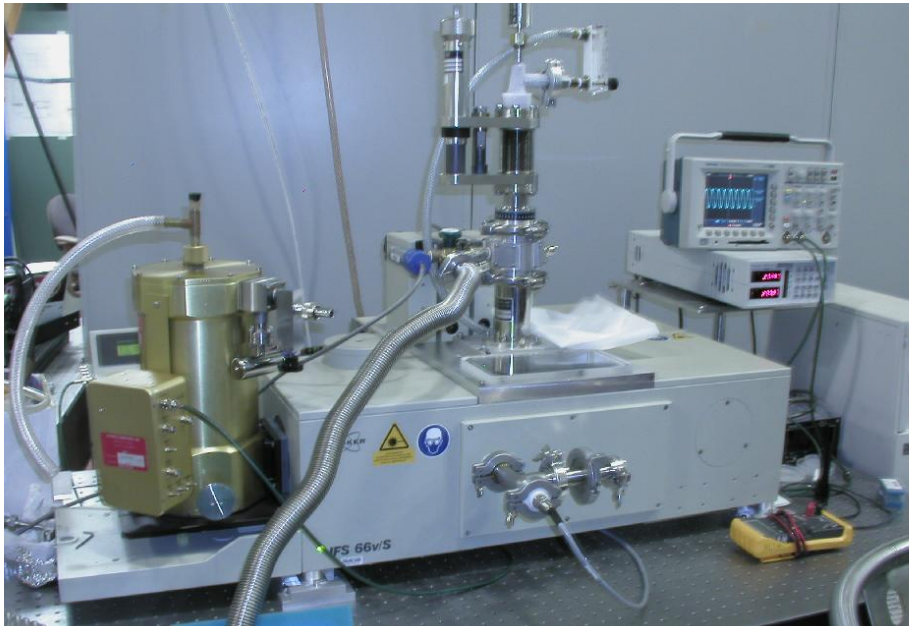


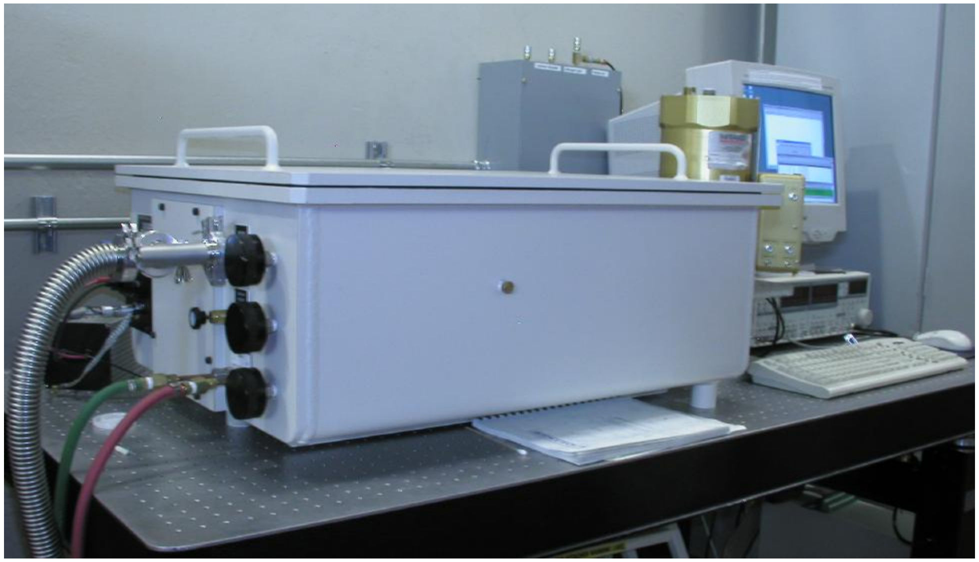


PICOMETRIX®
an API company

THz FTIR

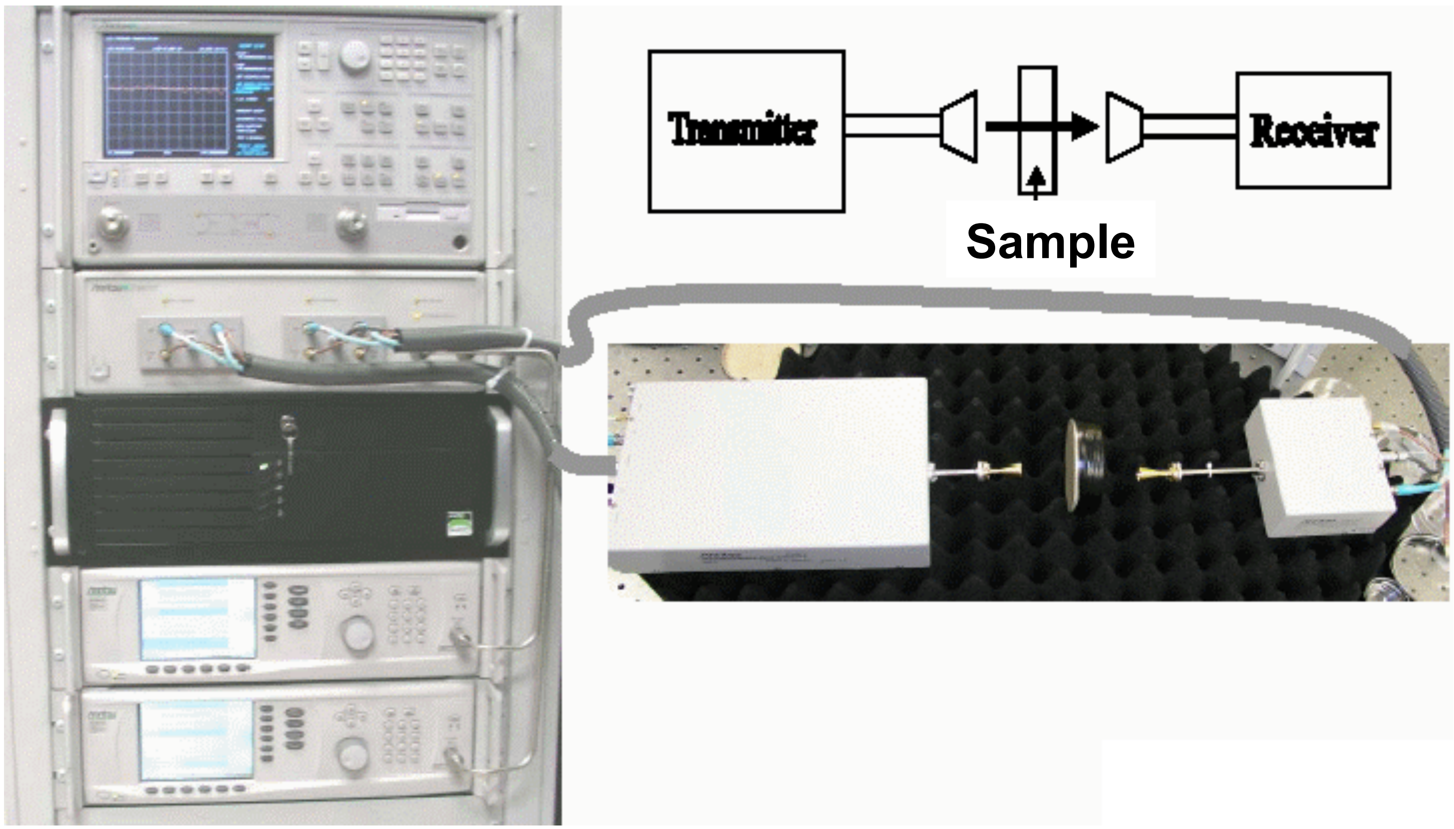
Typical THz FTIR systems



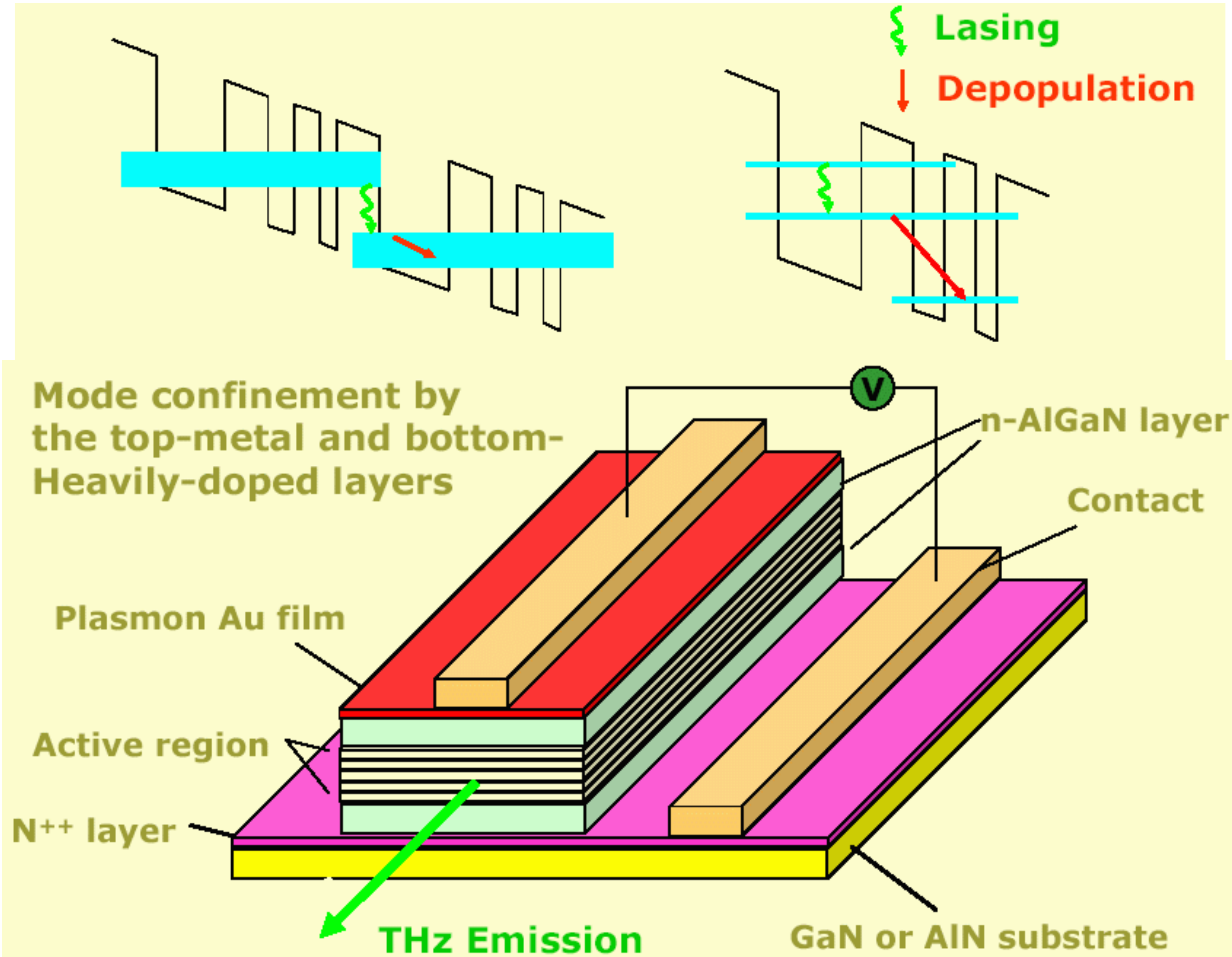


THz Measurement Techniques

Microwave transmitter / receiver / mixer / network analyzers at high microwave frequencies approaching THz



Quantum Cascade Lasers in the THz



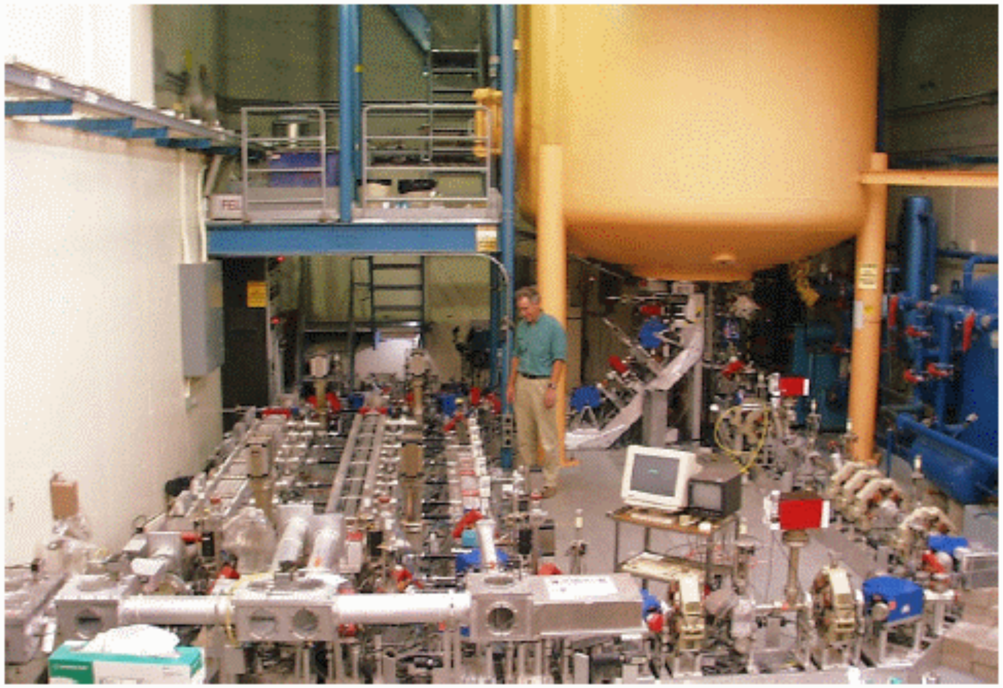
Free-Electron Lasers in the THz

UCSB FREE-ELECTRON LASER

Kilowatts, 500 W - 5 kW

Tunable terahertz radiation
  120 GHz to 4.8 THz
  2.5 mm to 60 μm

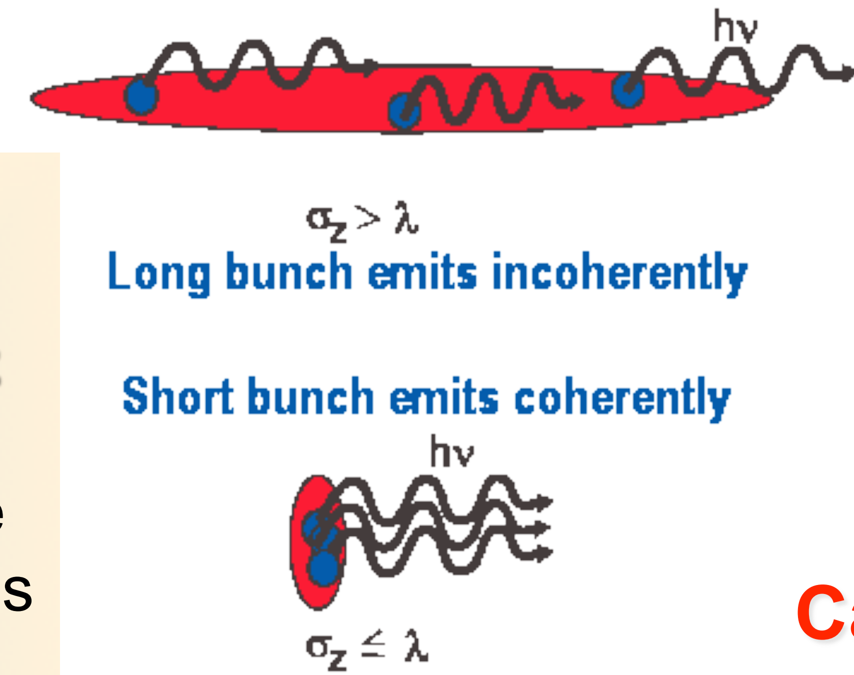
1- 20 μsecs, 1 Hz rep rate ("Quasi - CW")
  ~1 picosec to 4 nanosecond Pulse Slicer



- THz Electro-Optics
- THz Coherent Quantum Control
- Superconductivity
- THz Photon Assisted Transport
- Non-linear THz Dynamics
- THz Materials Physics
- THz Non-equilibrium dynamics
- THz Device Physics

Courtesy of J.Allen

Coherent THz Synchrotron Light



A source optimized for **Coherent THz** will have **10^6 - 10^{10}** more flux & brightness than other broadband sources

Light is emitted coherently when bunch length is shorter than the wavelength.

$P \quad N^2$

Can be huge!

Nodvick & Saxon, Phys. Rev. **96**, 180 (1954).
Nakazato et al., PRL (1989), Hirschmugl et al., Phys. Rev. A (1991).
Murphy & Krinsky, NIM A **346**, 571 (1994).

$$P(\omega) = p(\omega)\left[N + N(N-1)g(\sigma_l)\right]$$

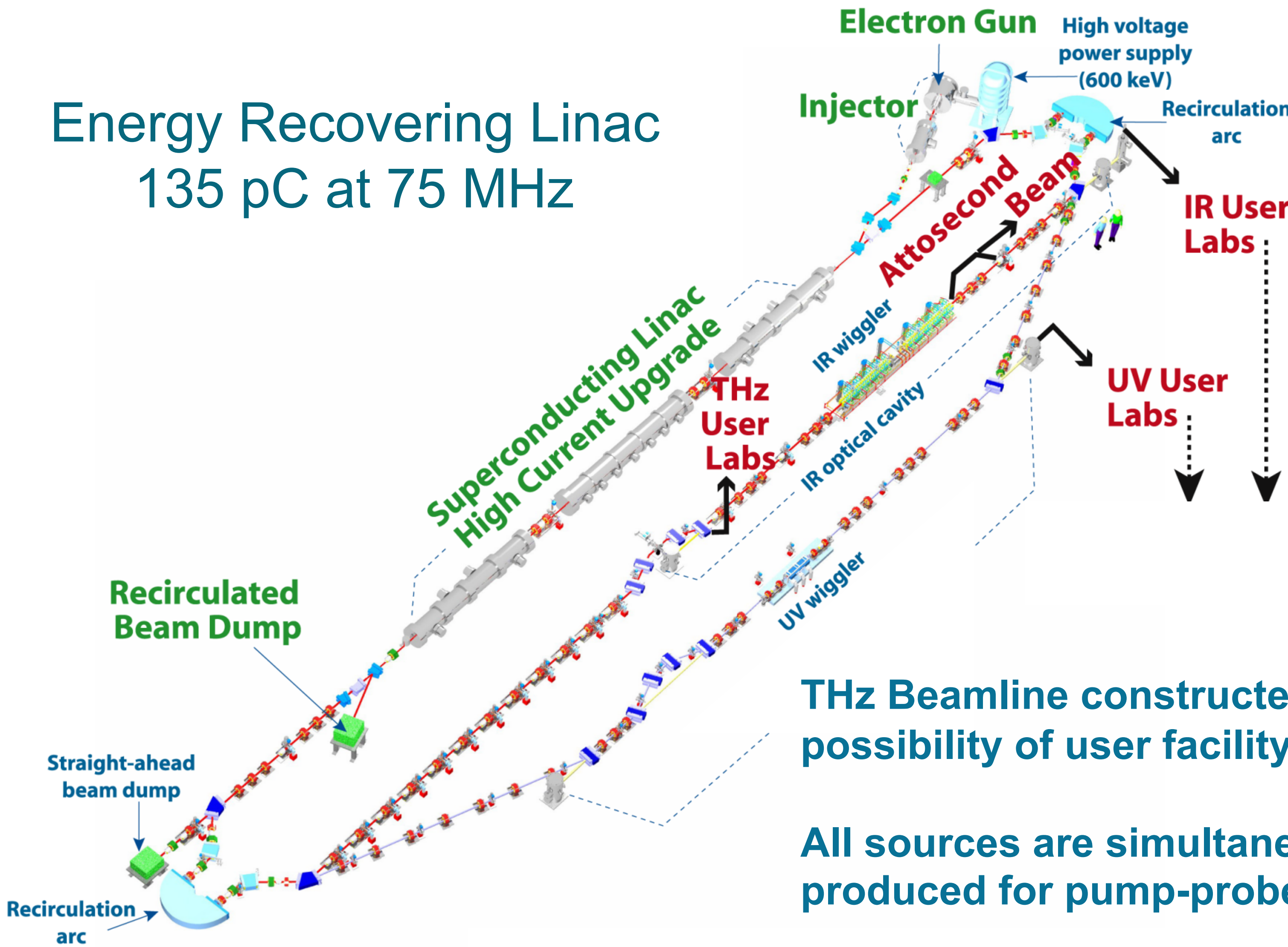
INCOHERENT   COHERENT

Nature **420,** 153 (2002), Phys. Rev. Lett. **89**, 224801 (2002)
Phys. Rev. Lett. **88**, 254801 (2002), Phys. Rev. Lett. **90**, 094801 (2003), Phys. Rev. Lett. **91**, 074802 (2003),
Phys. Rev. Lett. **93**, 094801 (2004), Phys. Rev. B **69**, 092512 (2004)
Phys. Rev. ST Accel. Beams 8, 014202 (2005), and more …

Michael C. Martin

JLab FEL & THz facility

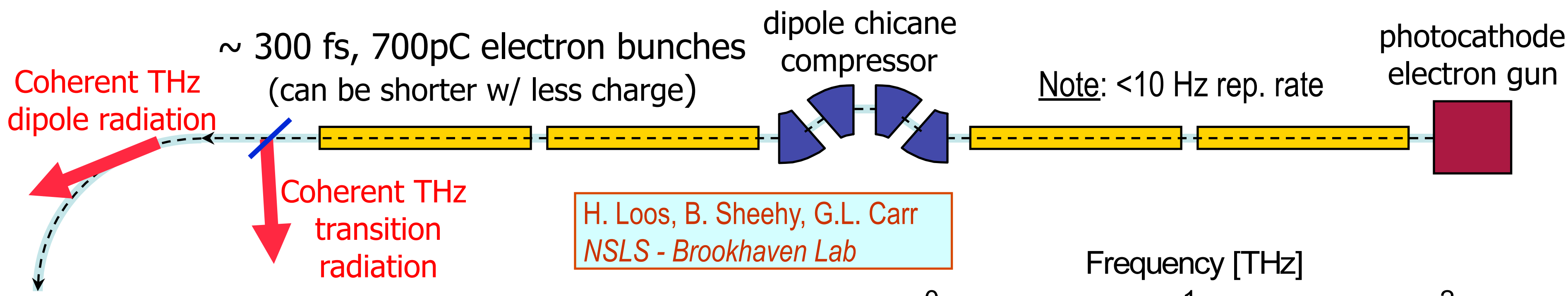
Energy Recovering Linac
135 pC at 75 MHz



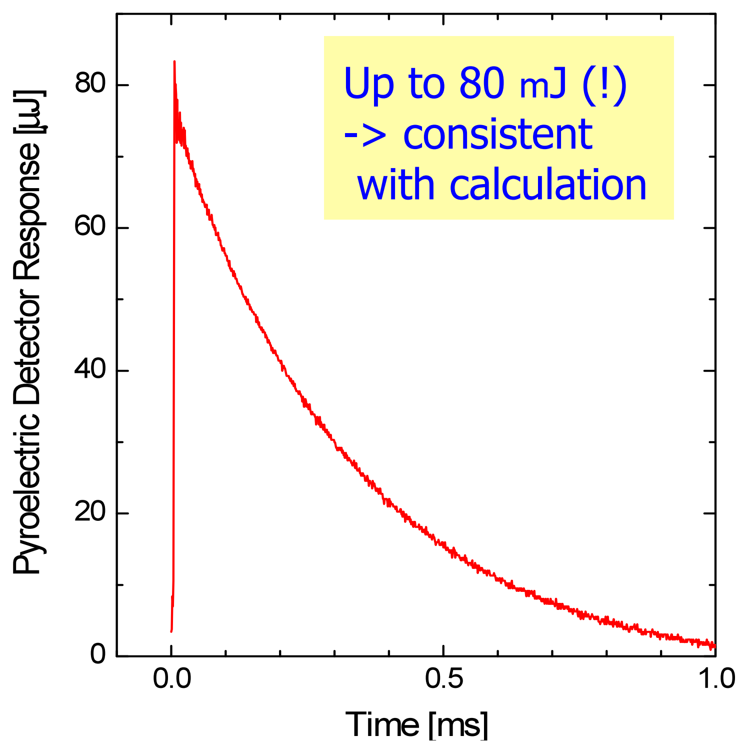
THz Beamline constructed and offers possibility of user facility

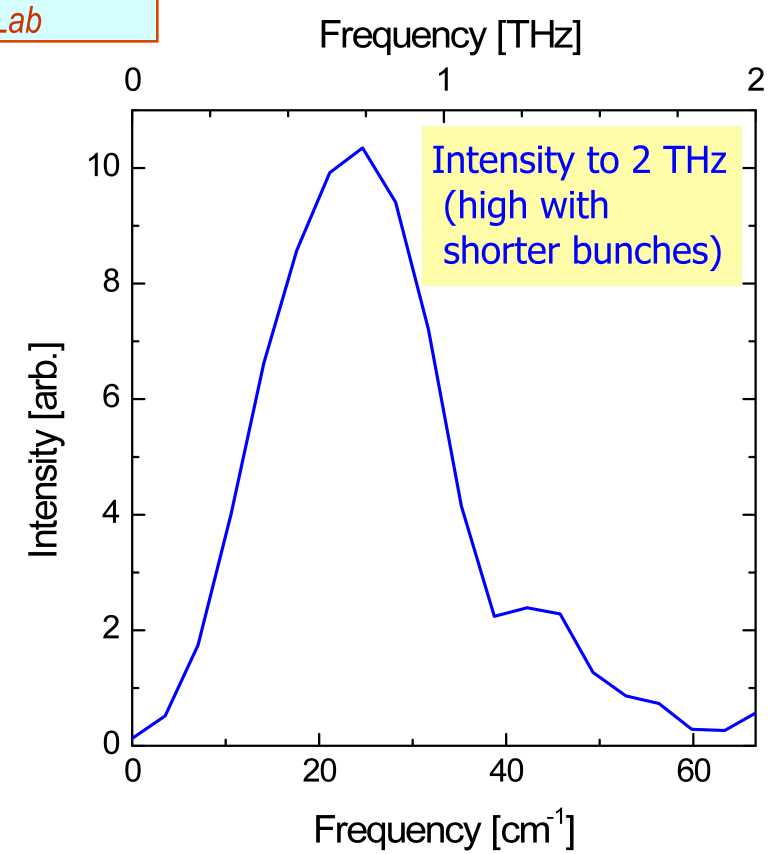
All sources are simultaneously produced for pump-probe studies

Intense Coherent THz Pulses from the NSLS SDL Linac



H. Loos, B. Sheehy, G.L. Carr
NSLS - Brookhaven Lab





Synchronous THz ultrafast excitations are needed at all next generation FEL's

We are only beginning to explore the effects of high power THz fields on matter.

Only recently have THz pulses with E-field strengths rivaling bonding fields in materials (~ V/atom) possible.

With such strong transient electric and magnetic fields, ask:

- Can one switch, or modulate, the collective magnetic state of a complex oxide at THz frequencies?
- Can one photo-induce a quantum coherent state and, indeed, superconductivity?
- Can one control magnetic systems (and frustration) on the ultrafast timescale?

FLASH. Free-electron laser FLASH

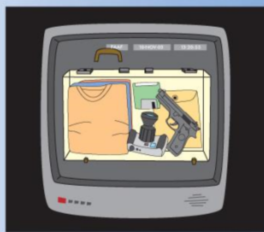
DESY

SwissFEL

NGLS

Security

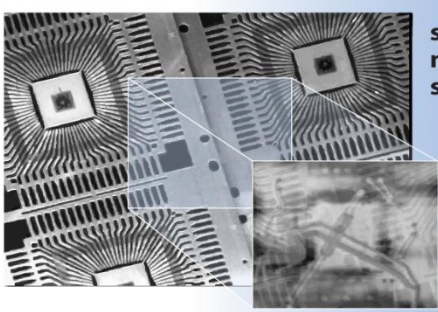
fingerprint chemical and biological terror materials in packages, envelopes or air



find concealed weapons

locate hidden explosives and land mines

Communications



see buried metal layers in semiconductors

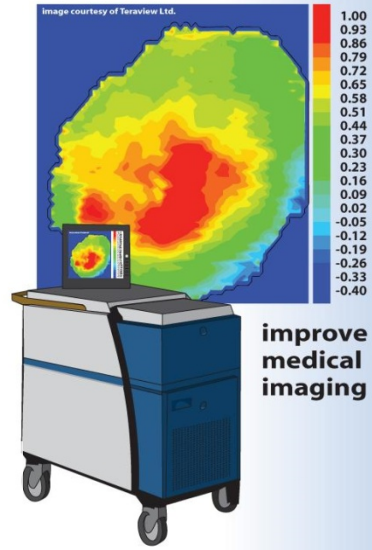
widen frequency bands for wireless communi-cation

Many basic science and novel applications

A fast-growing field filling the "THz Gap"

Most need high power ultrafast lasers

Medical Imaging

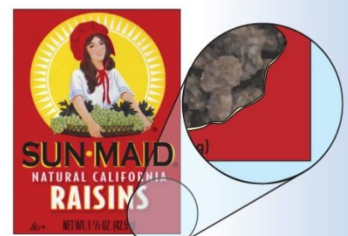


improve medical imaging

diagnose skin cancer

spot tooth erosion earlier than x-rays

Quality Assurance



count items in packages

control quality of pharmaceuticals

help airline pilots navigate through fog

detect dangerous flaws in space shuttle components