The High Power* Broadband THz Facility at Jefferson Lab

Gwyn P. Williams, Mike Klopf & FEL Team

* 100 watts av ; >10 MW pk

Talk Outline

- Description of JLab THz facility – design philosophy
- Implementation
- Applications – diagnostics
  - – real-time imaging
  - – matter under extreme conditions
  - – pump-probe dynamics

Jefferson Lab – Newport News, VA USA

Thomas Jefferson National Accelerator Facility

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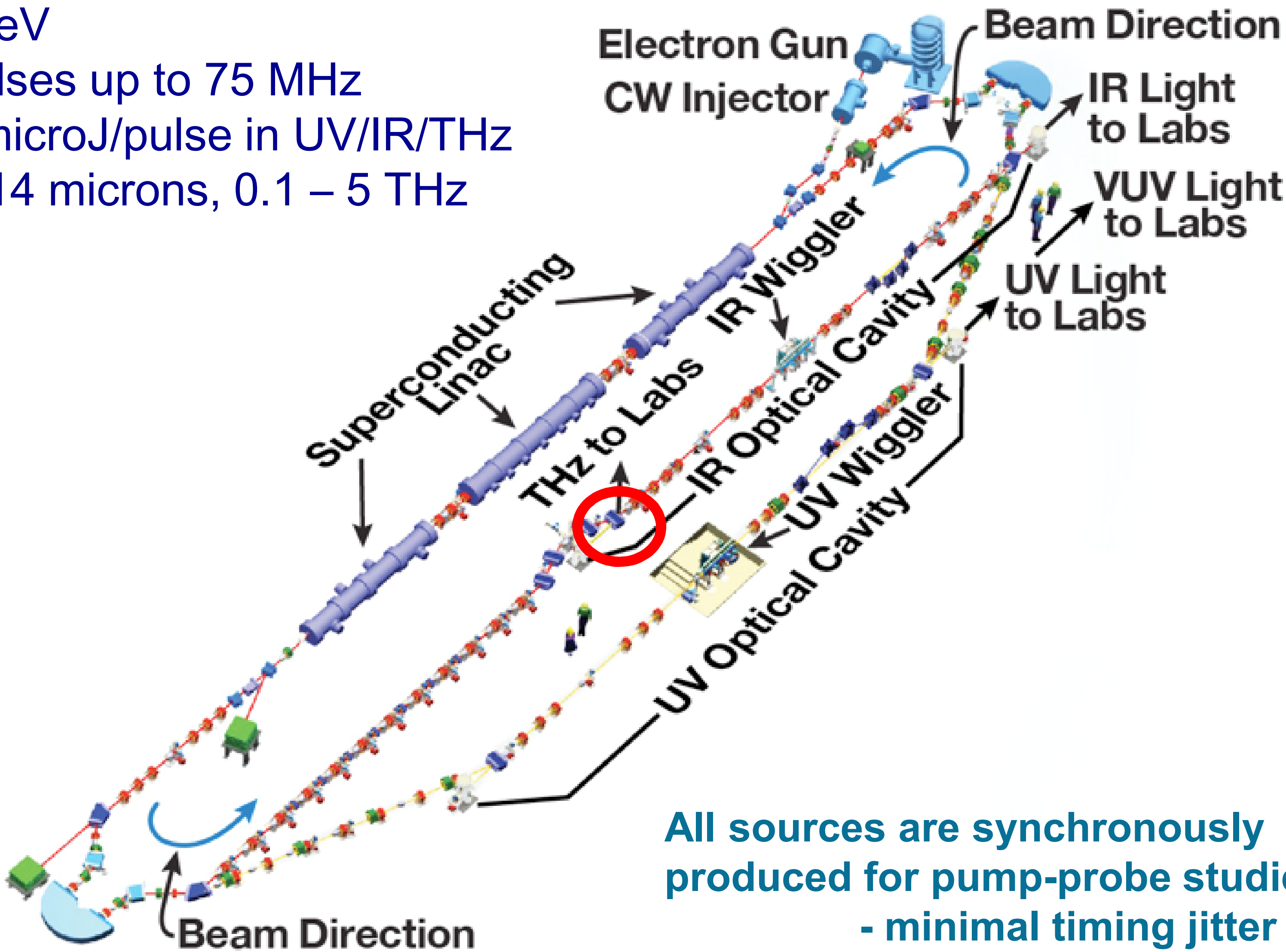
JLab Energy Recovered Linac (4GLS) facility schematic

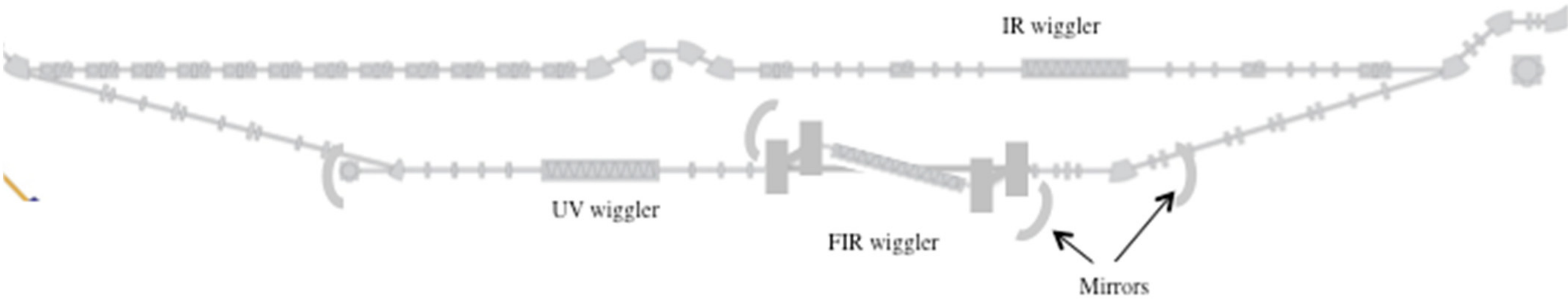
E = 150 MeV
135 pC pulses up to 75 MHz
20/120/1 microJ/pulse in UV/IR/THz
250 nm – 14 microns, 0.1 – 5 THz



All sources are synchronously produced for pump-probe studies - minimal timing jitter

A SYNCHRONIZED VUV/FIR LIGHT SOURCE AT JEFFERSON LAB

S. Benson#, D. Douglas, G. Neil, M. Shinn, and G. Williams



presented at IPAC-12, New Orleans, LA May 20-25 2012

Coherent Synchrotron Radiation Generation - theory

Jackson, Classical Electrodynamics, Wiley, NY 1975

Near-field term not normally considered for synchrotron calculations

Electric field for single particle:-

$$\vec{E}_\omega = ec^{-1}\int_{-\infty}^{+\infty} \frac{\vec{n}\times[(\vec{n}-\vec{\beta}_e)\times\dot{\vec{\beta}}_e] + cR^{-1}\gamma^{-2}(\vec{n}-\vec{\beta}_e)}{(1-\vec{n}\vec{\beta}_e)^2 R} \exp[i\omega(\tau + R/c)]d\tau$$

REFERENCES

R.A. Bosch, Nuclear Instr. & Methods **A431** 320 (1999).

M. Buess, G.L. Carr, O. Chubar, J.B. Murphy, I. Schmid & G. P. Williams “Exploring New Limits in Understanding The Emission of Light from Relativistic Electrons” presented at the SRI conference, Stanford, 1999.

O. Chubar, P. Elleaume, "Accurate And Efficient Computation Of Synchrotron Radiation In The Near Field Region", proc. of the EPAC98 Conference, 22-26 June 1998, p.1177-1179.

Coherent Synchrotron Radiation Generation - theory

$$\frac{d^2 I}{d\omega \;\; d\Omega} = \left[N[1 - f(\omega)] + N^2 f(\omega) \right] \times \left[single \;\; particle \;\; intensity \right]$$

f(ω) is the form factor – the Fourier transform of the normalized longitudinal particle distribution within the bunch, S(z)

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

$$\frac{dE}{d\bar{\nu}} \approx 2 \times 10^{-25} \text{ J/cm}^{-1}\text{/electron}$$

S.L. Hulbert and G.P. Williams, Handbook of Optics: Classical, Vision, and X-Ray Optics, 2nd ed., vol. III. Bass, Michael, Enoch, Jay M., Van Stryland, Eric W. and Wolfe William L. (eds.). New York: McGraw-Hill, 32.1-32.20 (2001).

S. Nodvick and D.S. Saxon, Suppression of coherent radiation by electrons in a synchrotron. Physical Review **96**, 180-184 (1954).

Carol J. Hirschmugl, Michael Sagurton and Gwyn P. Williams, Multiparticle Coherence Calculations for Synchrotron Radiation Emission, Physical Review **A44**, 1316, (1991).

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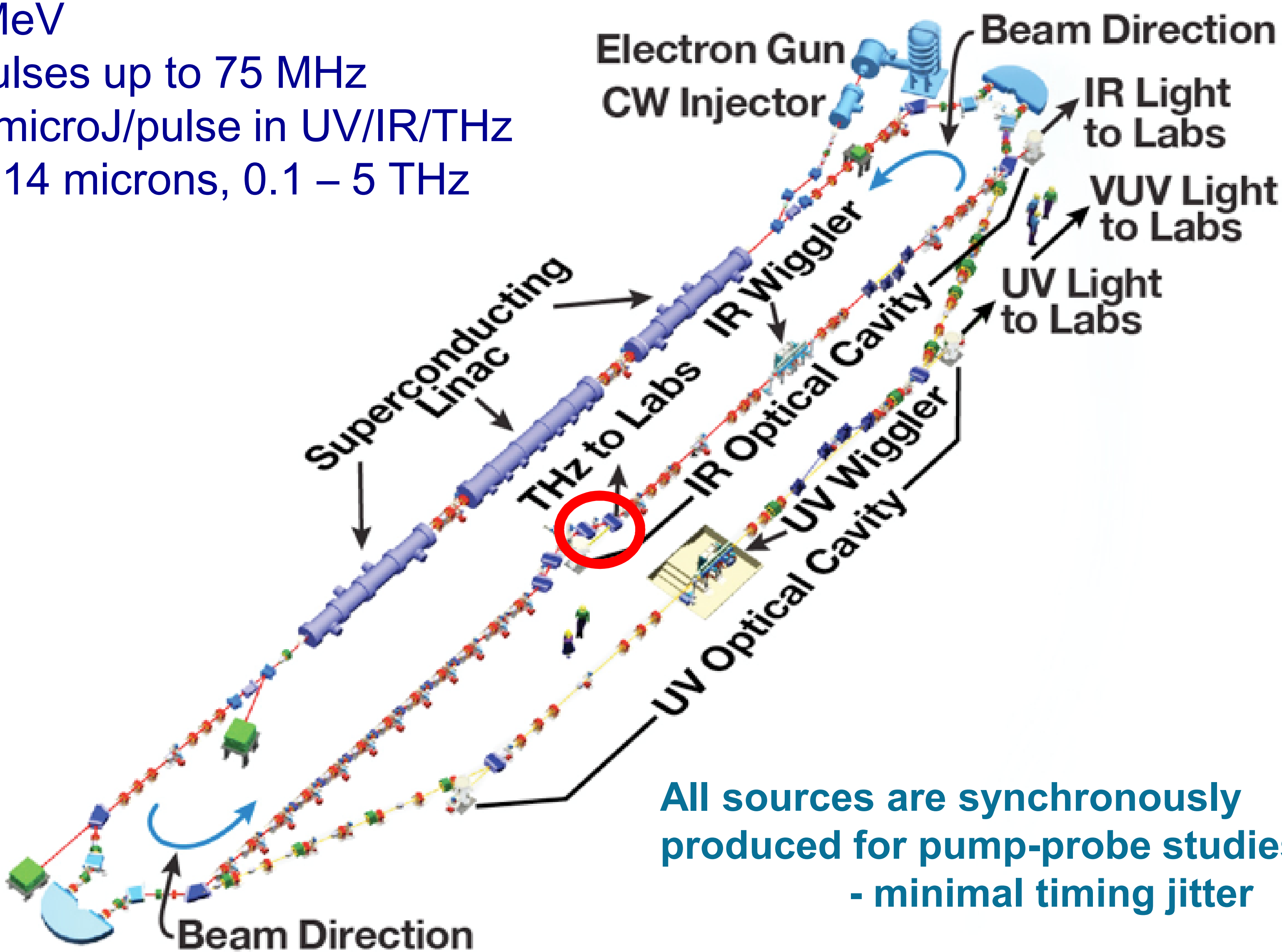
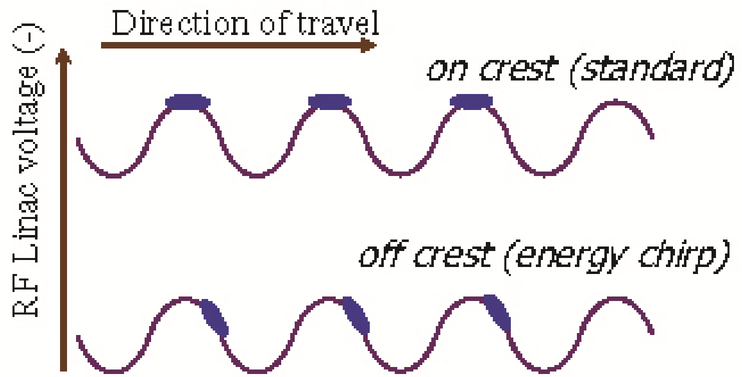


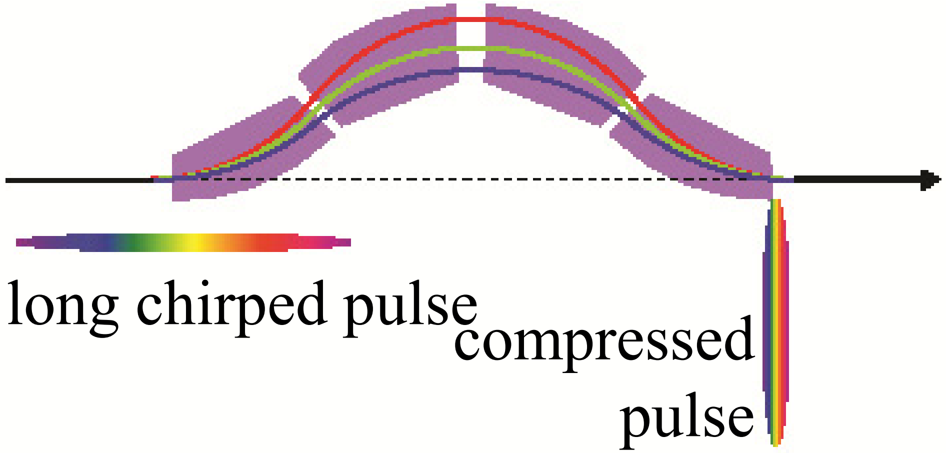
All sources are synchronously produced for pump-probe studies - minimal timing jitter

Coherent THz Radiation From Short Electron Bunches

- **acceleration of e- bunches off-crest produces an energy spread or chirp**



- **Magnetic chicane provides dispersion and path geometry to compress the chirped pulses**



G. Larry Carr, BNL

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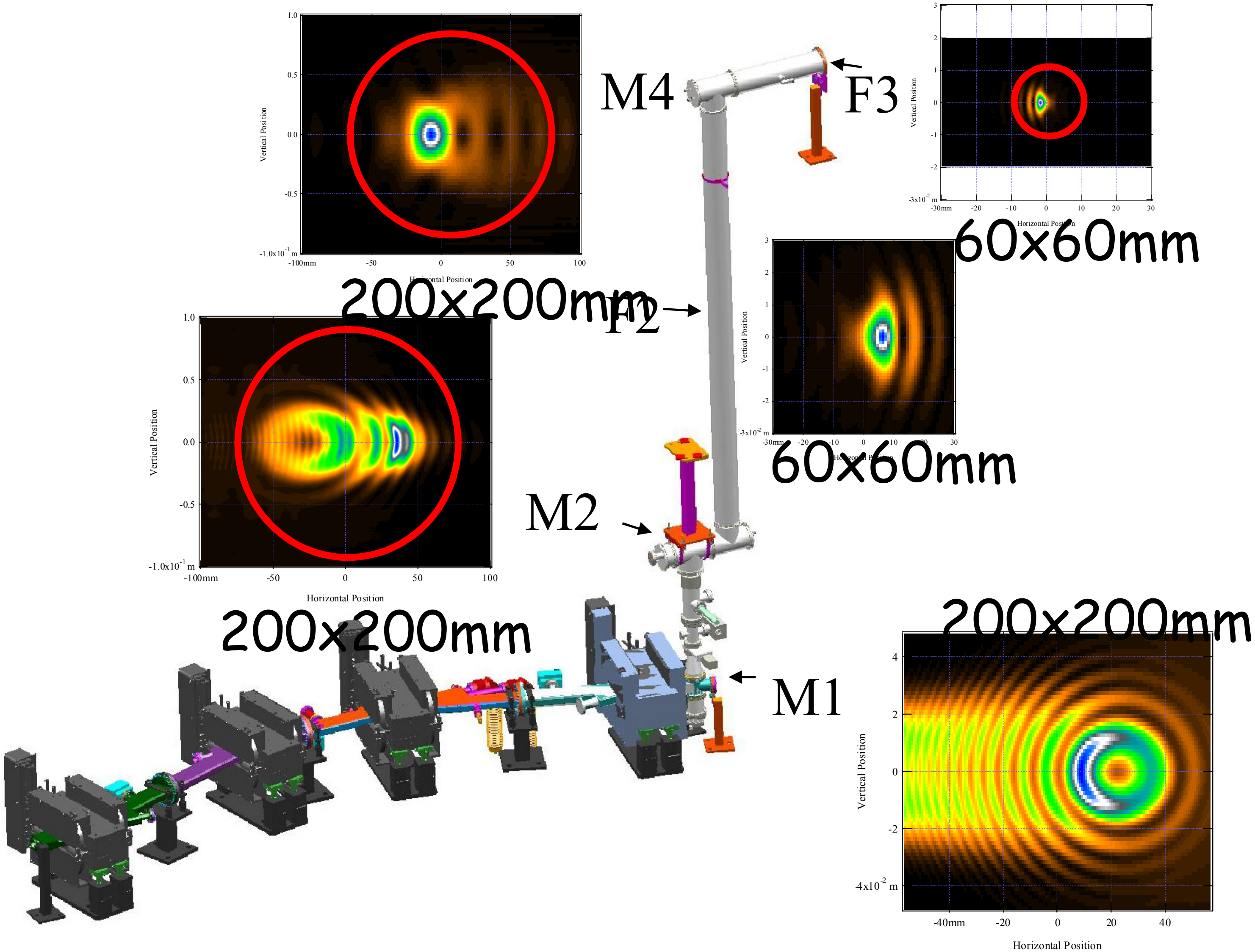
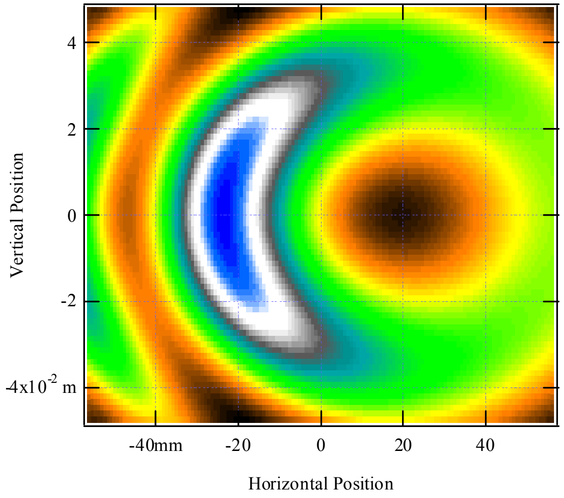
JLab THz Beam Schematic with Optical Beam Ray-tracing

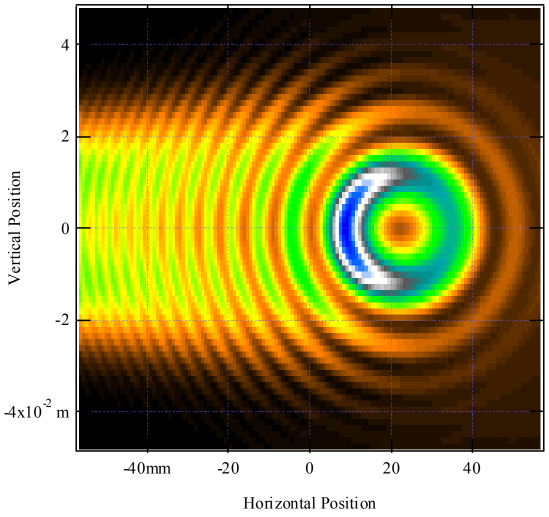


JLab THz Beam Pattern on Mirror 1



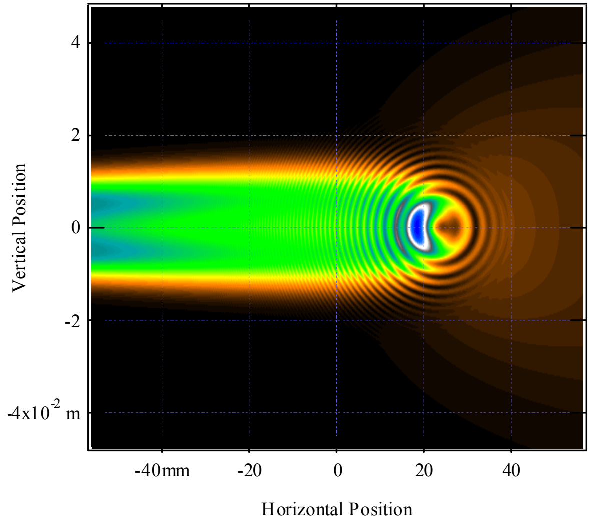
0.1 THz

3.3 cm^{-1}



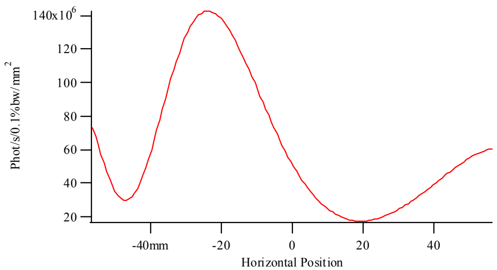
1 THz

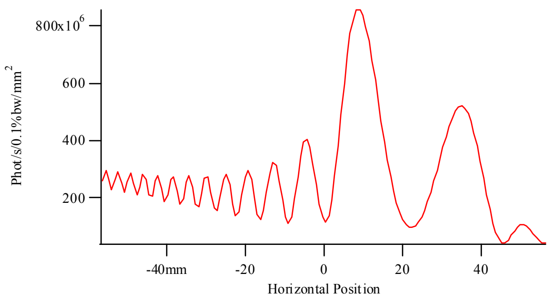
33 cm^{-1}

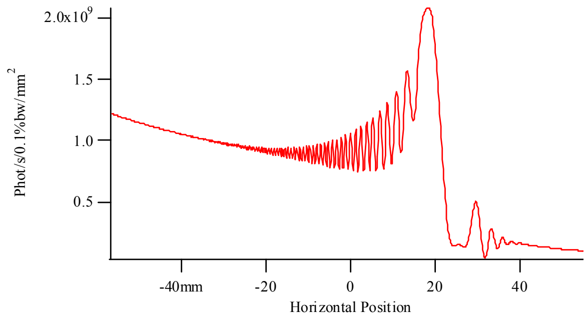


10 THz

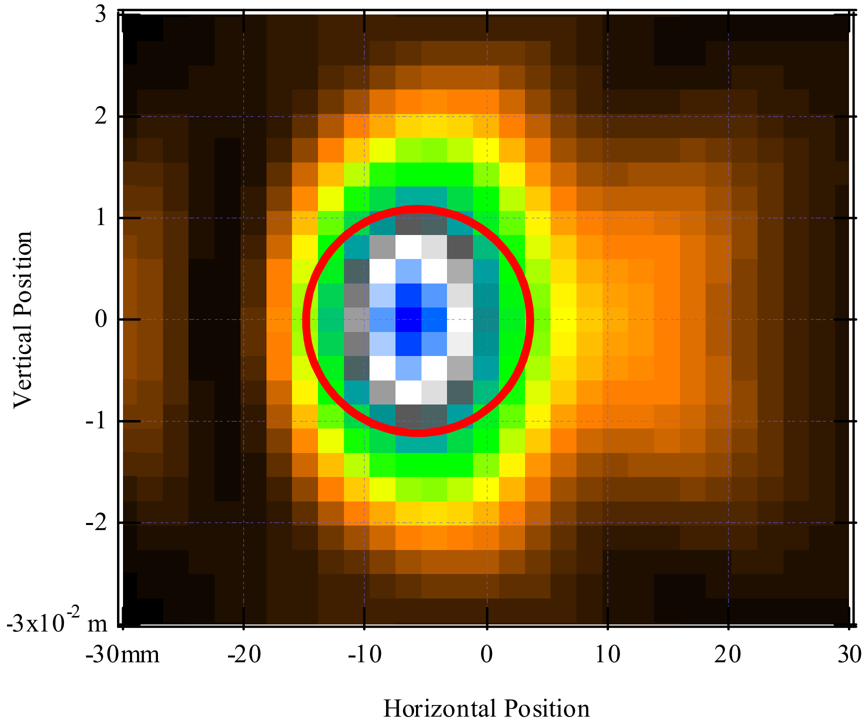
330 cm^{-1}







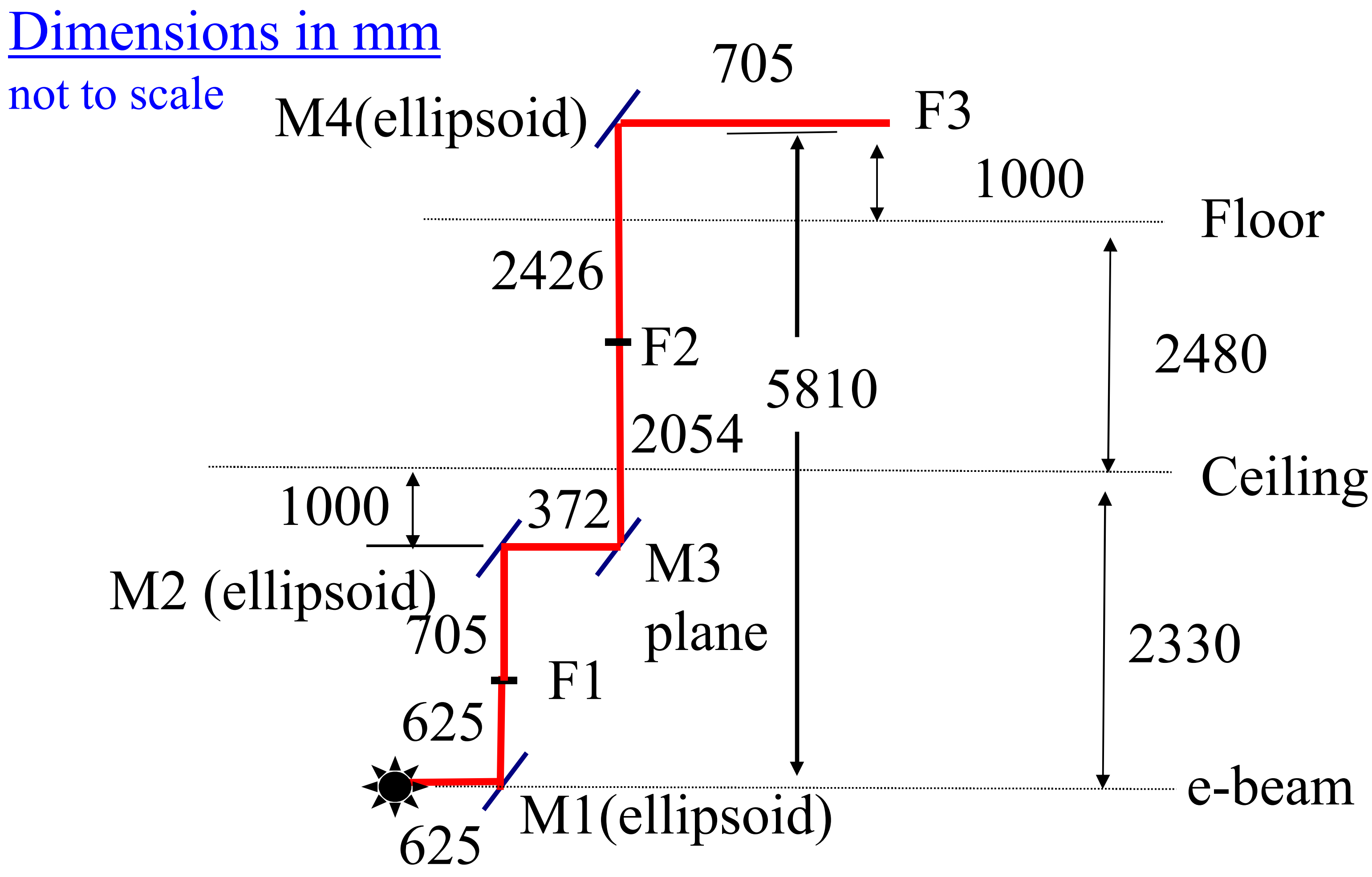
JFEL THz Port at 0.1 THz (3.3 mm, 3 cm^{-1})



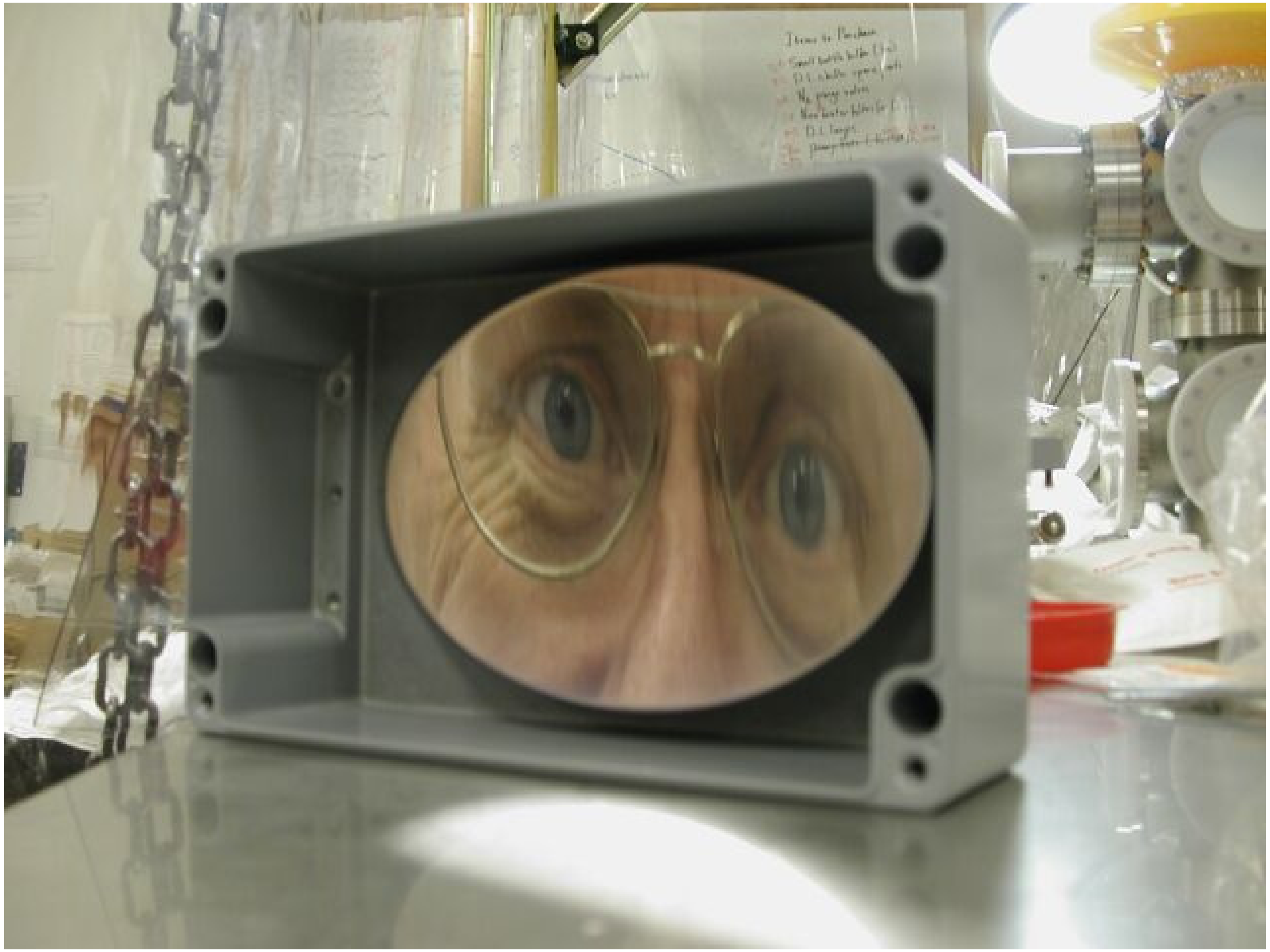
67.5% of light passes aperture

F1 for 3mm light with 20mm aperture

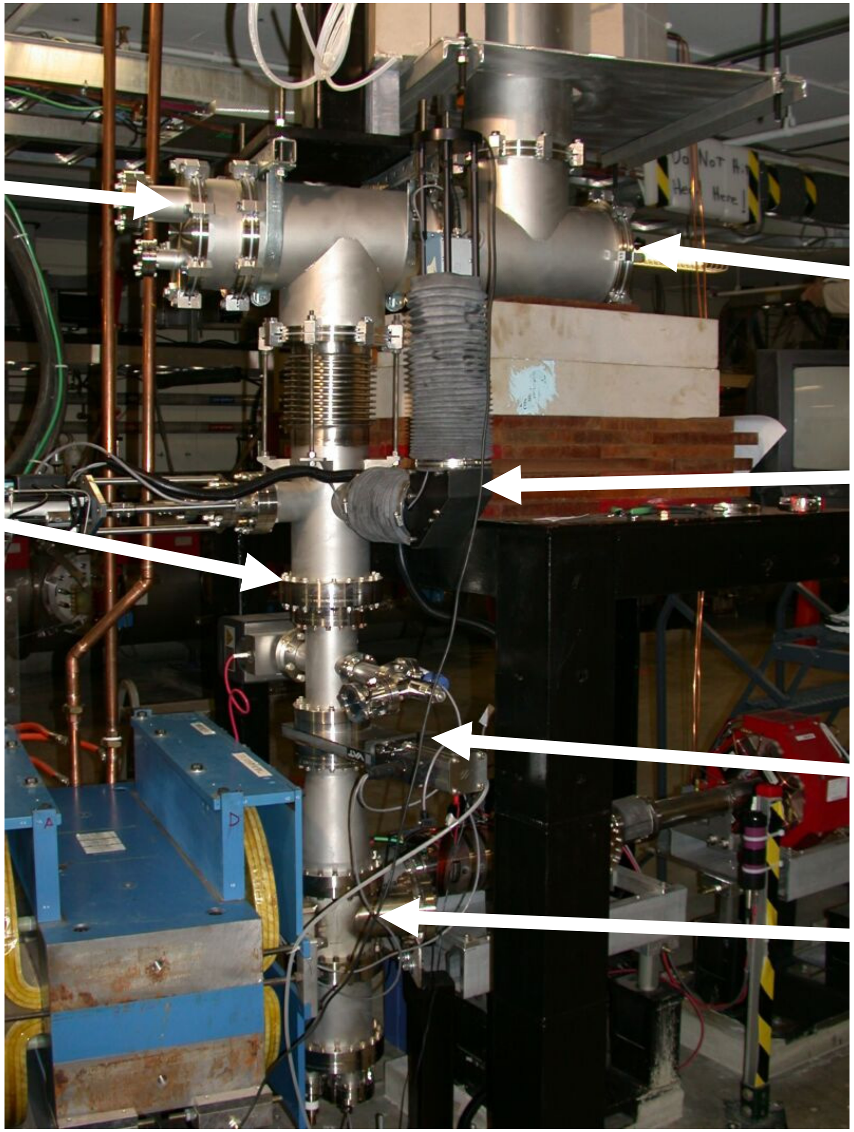
JFEL THz Beamline Schematic



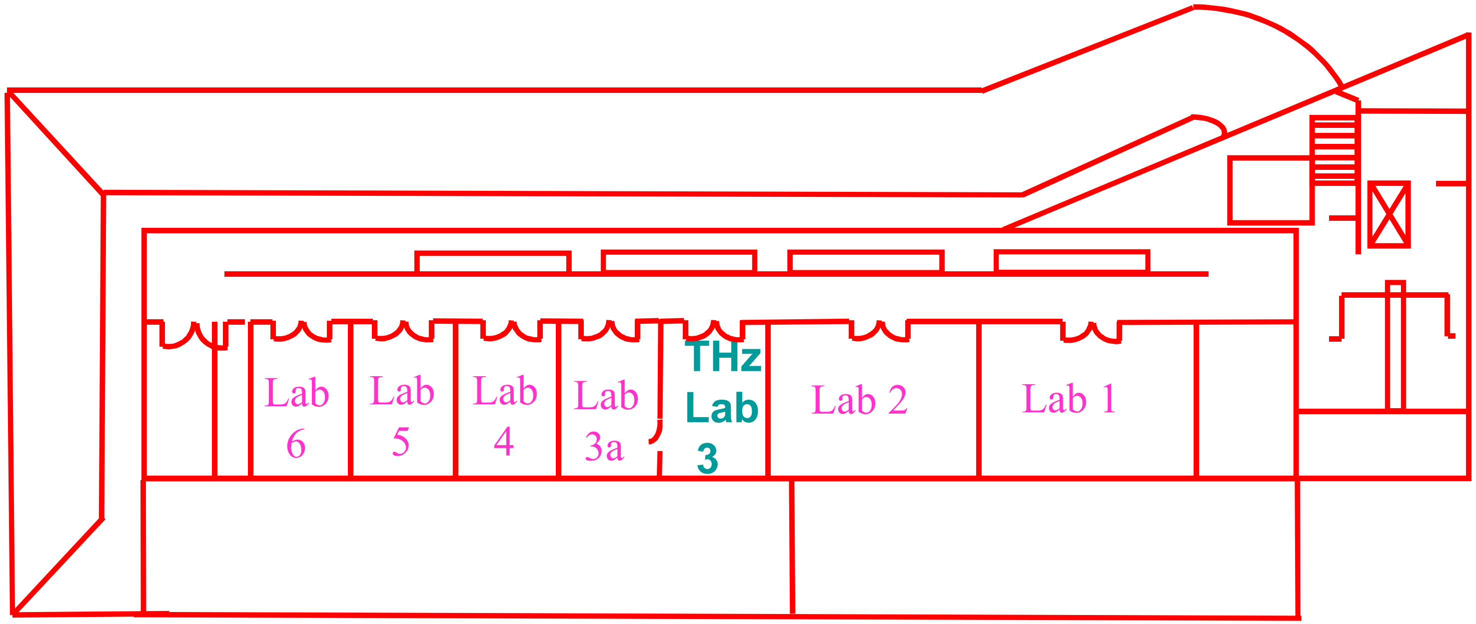
Mirror 1 - courtesy of Richard Wylde, (Thomas Keating)



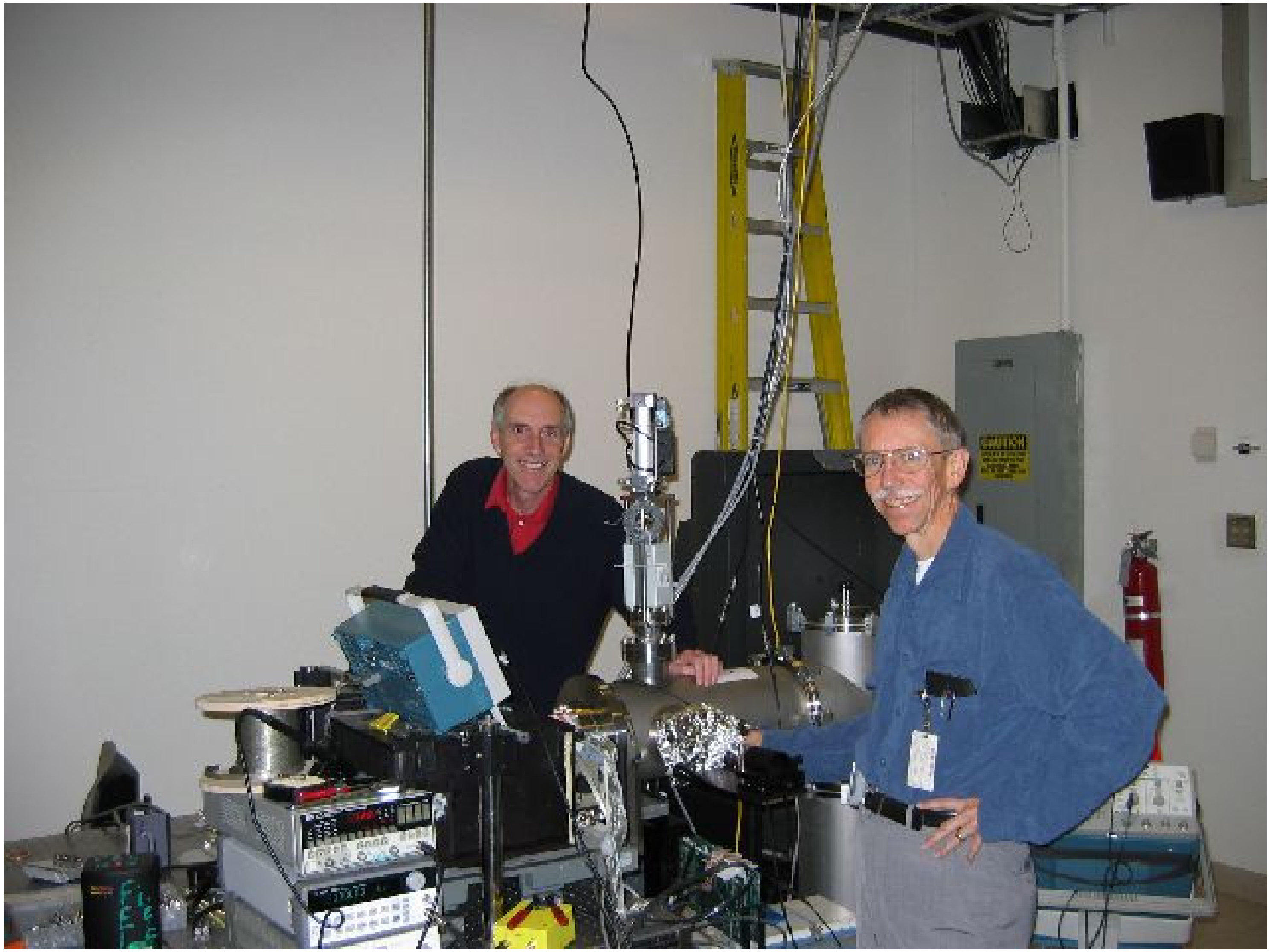
JLab Terahertz Beam Extraction and Transport



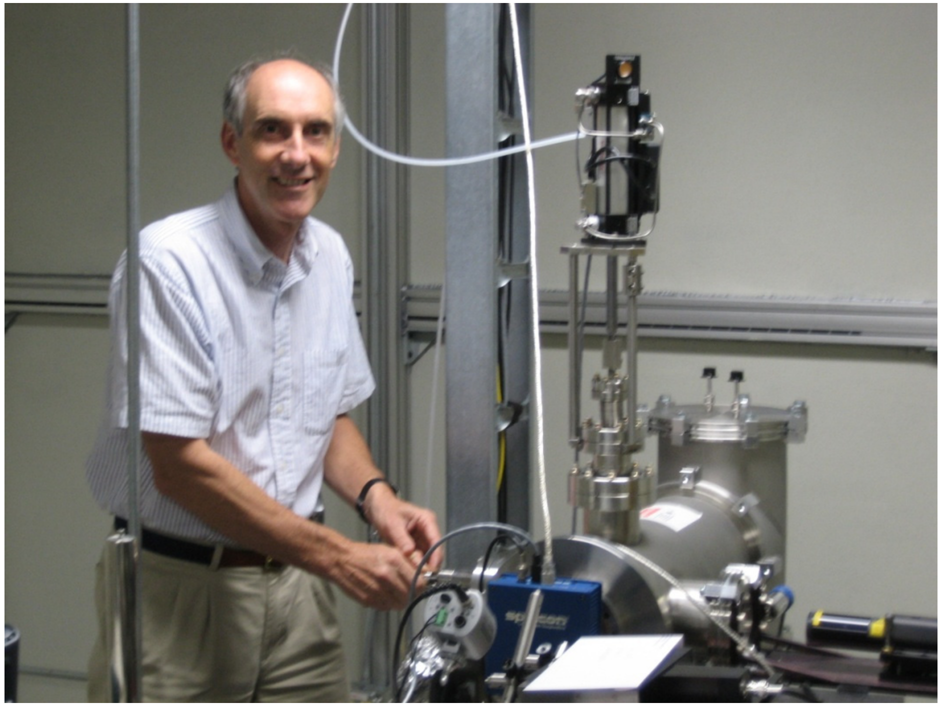
JLab FEL User Lab Layout



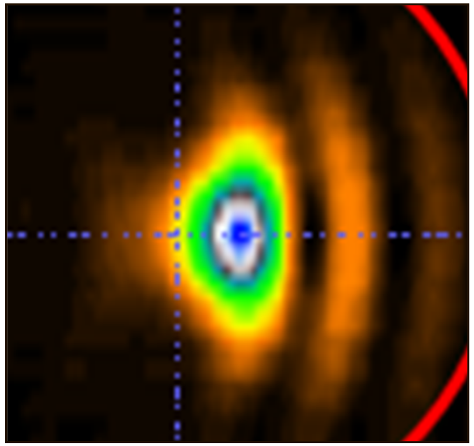
JLab High Power THz User Lab 3



THz Lab and image of beam

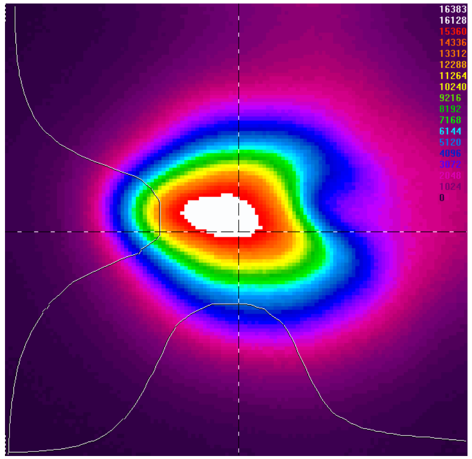


Optical transport output in User Lab



Ray trace

10mm^2



Real time image

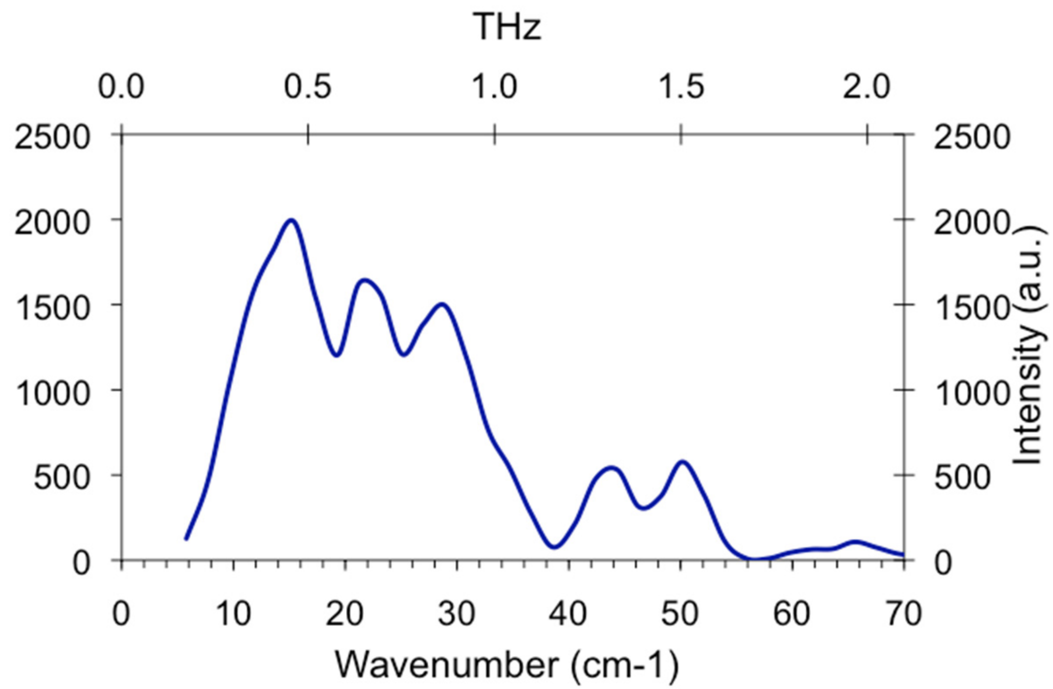
Measured spectrum at Jefferson Lab

<u>Jlab THz Source</u>

•broadband

•ultrashort pulse
($\tau_p \sim 300$ fs FWHM)

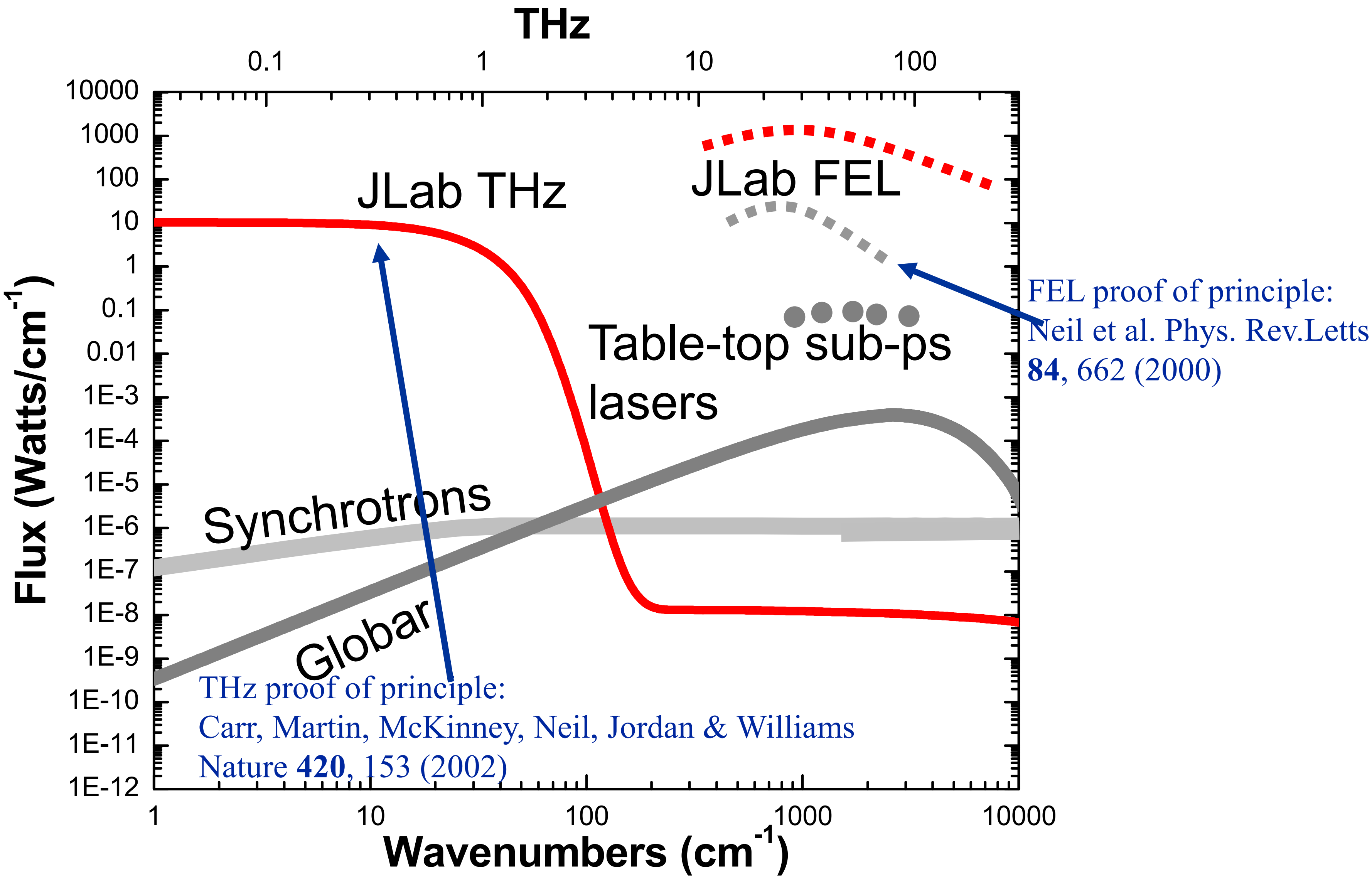
•polarization
(3:1 linear:radial)



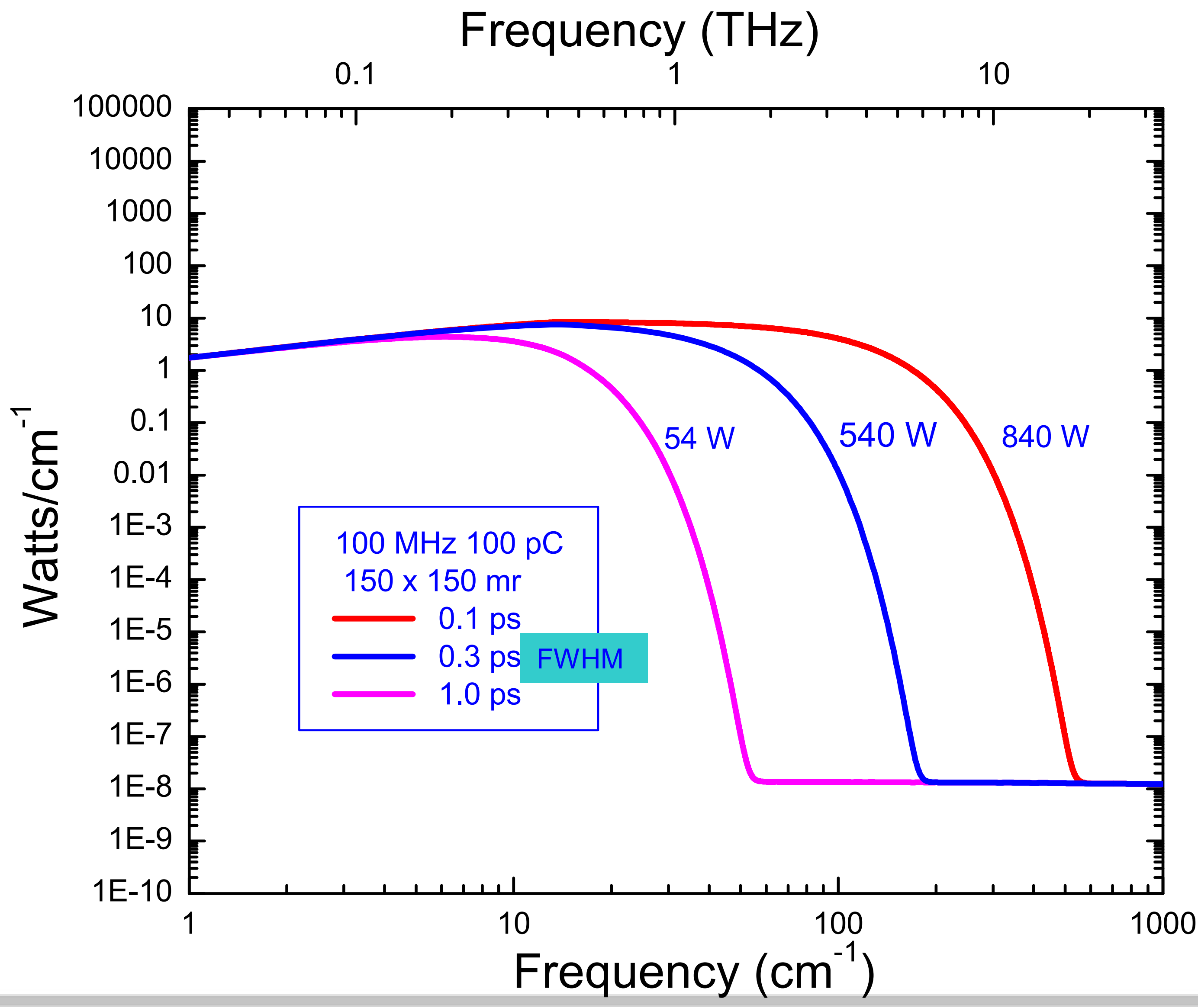
•high average power - CW (> 1 W typical, up to 10's W)

•Pulse structure highly variable
- single-shot up to 75 MHz
- macropulse width variable (5 μs to several ms)

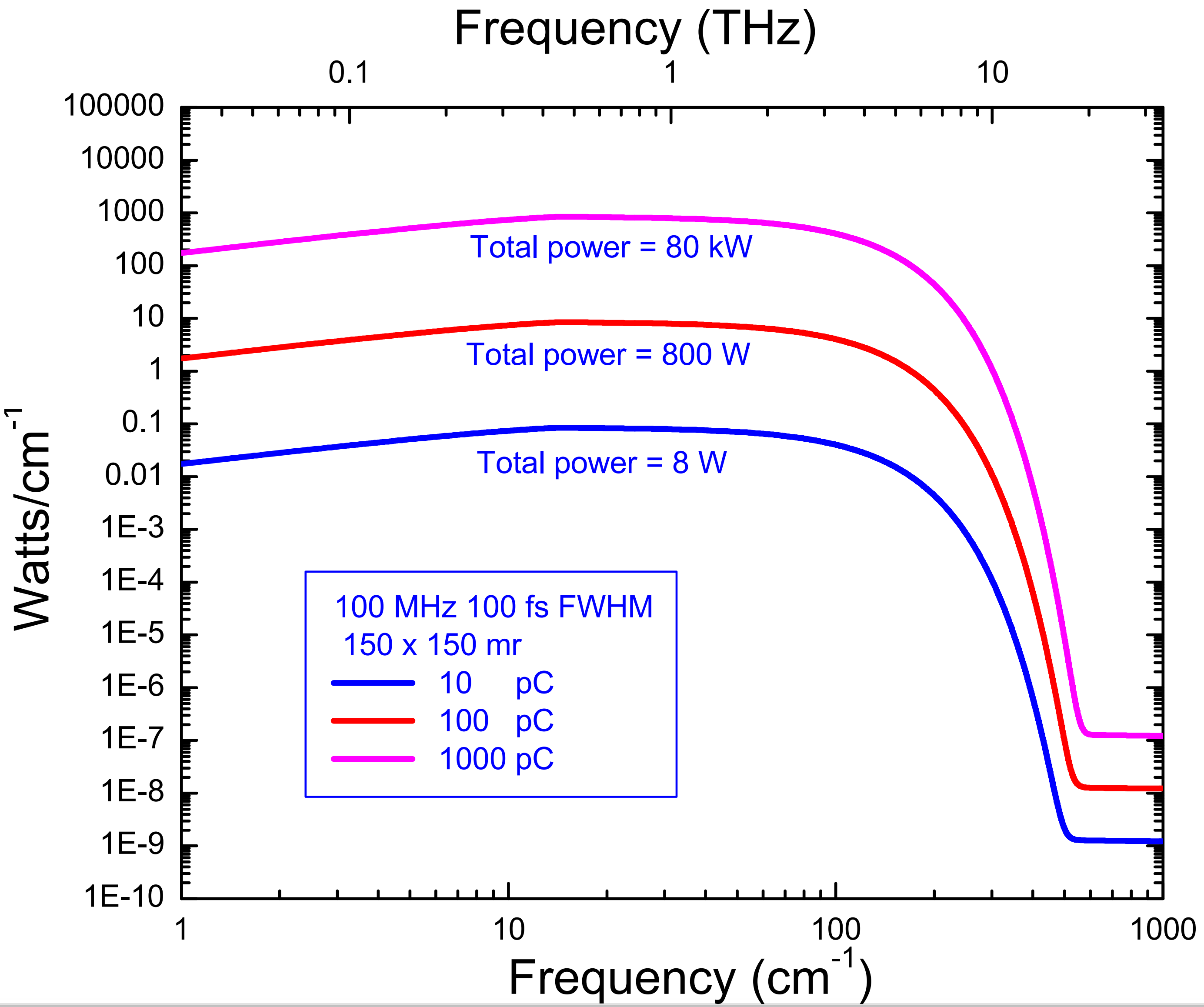
Jefferson Lab facility unique spectroscopic range



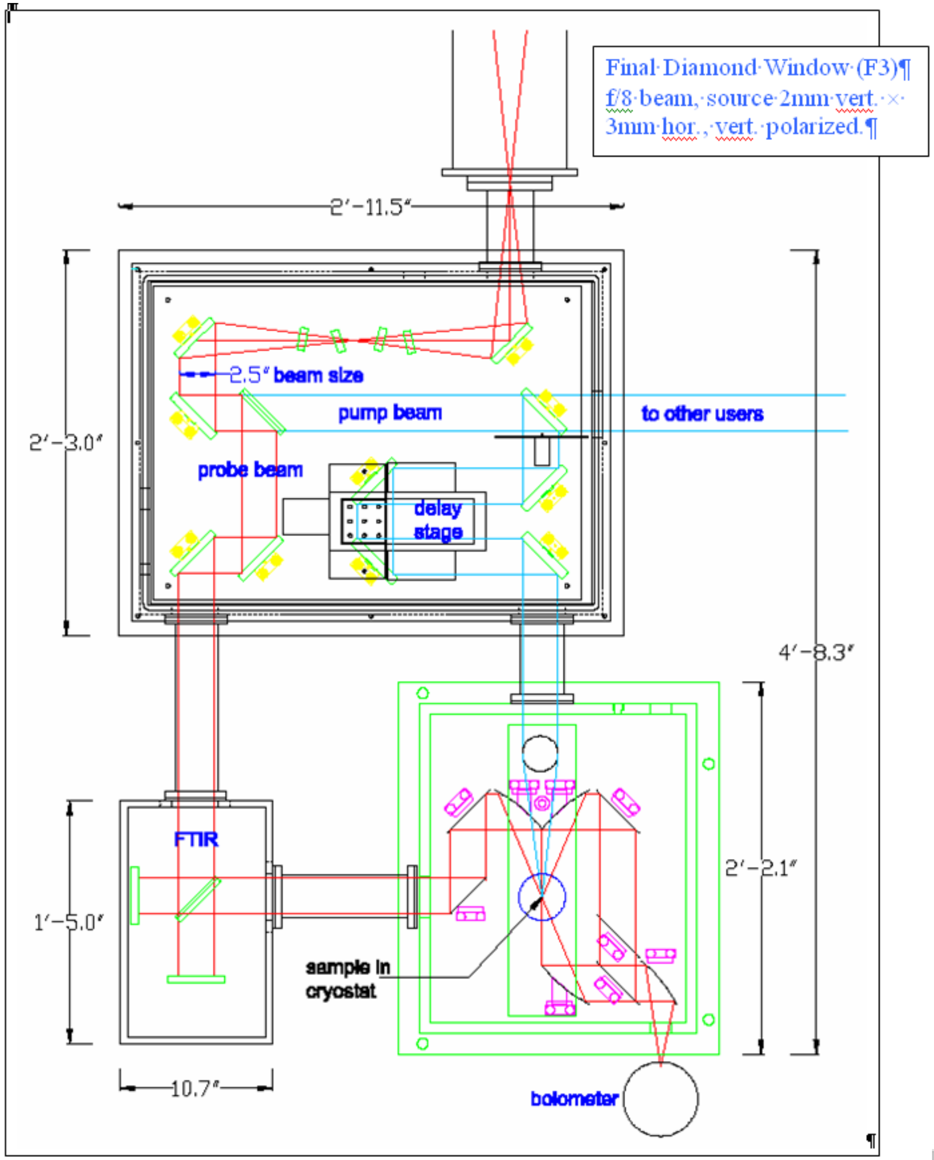
High Power THz - Effect of Pulse Length



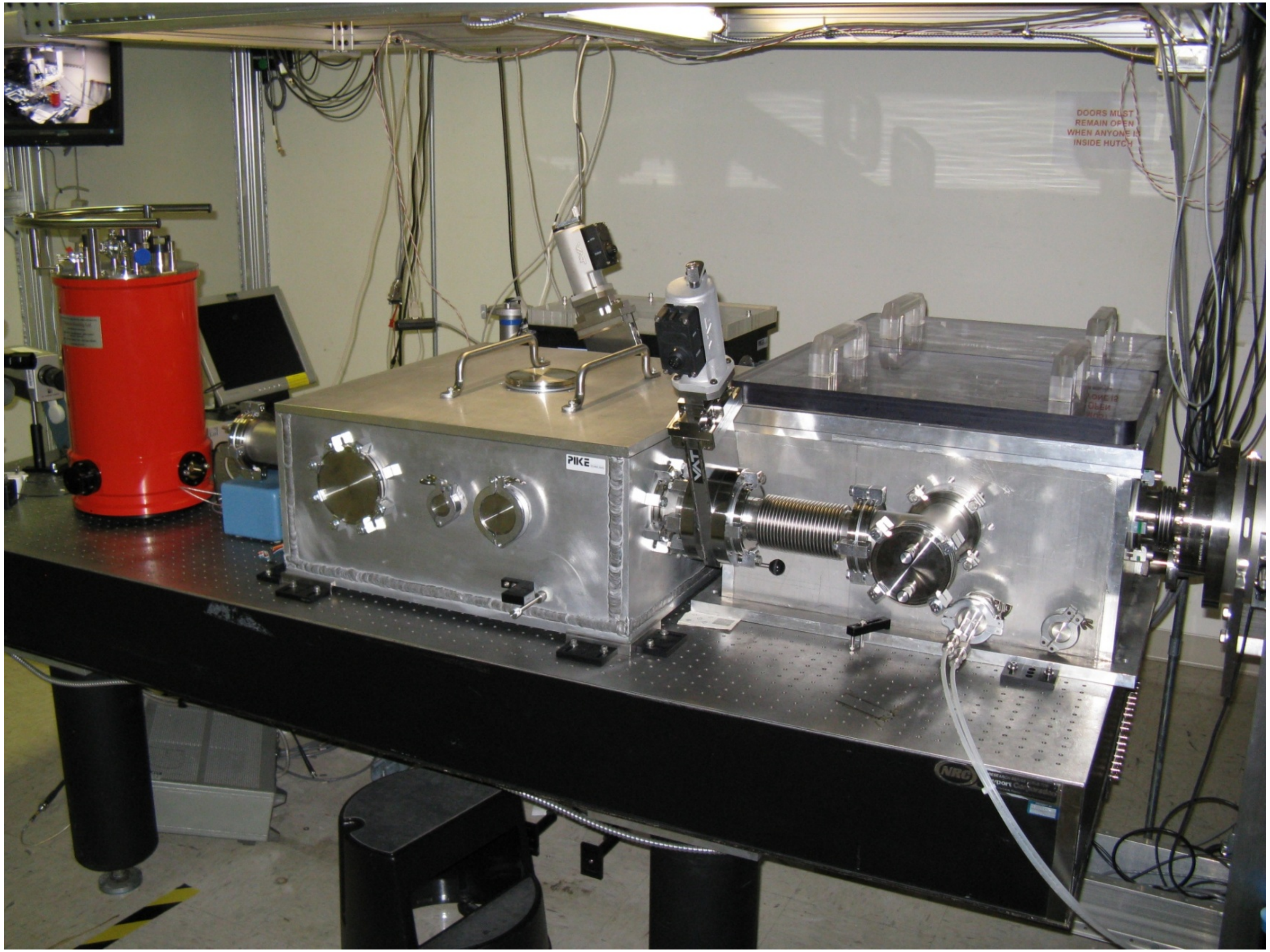
High Power THz - Effect of Pulse Charge



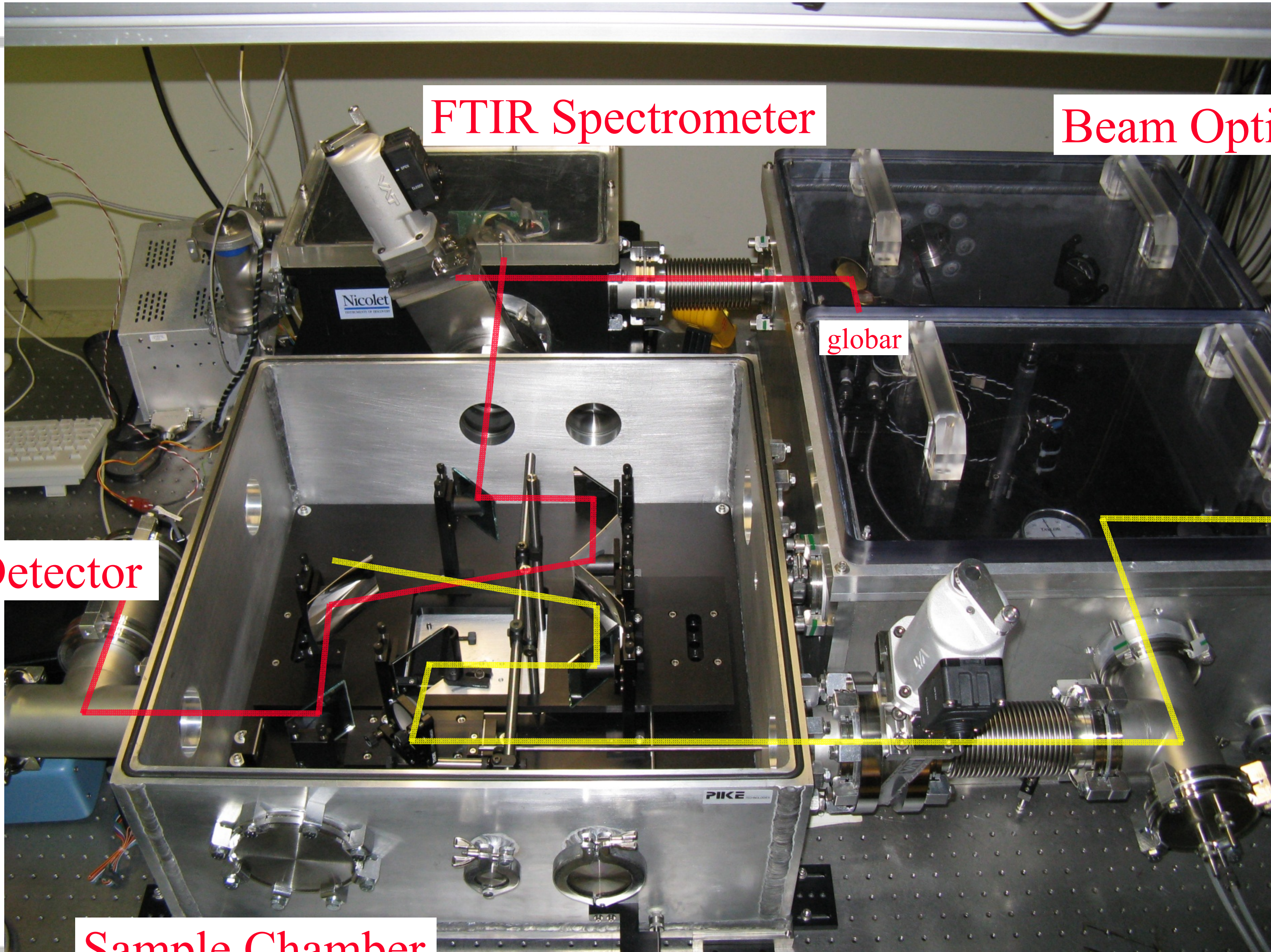
Laboratory layout for spectroscopy & pump-probe



THz Spectroscopy Vacuum System



THz Spectroscopy Vacuum System



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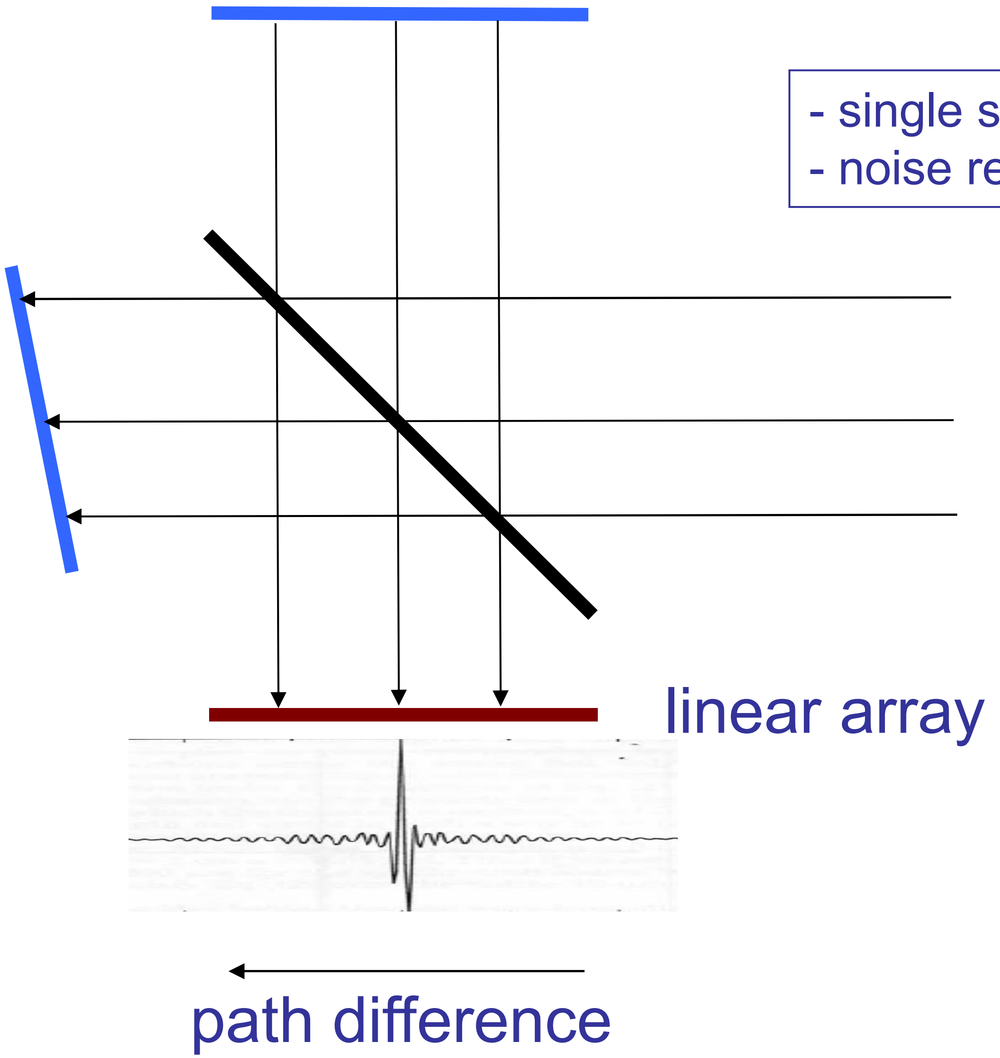
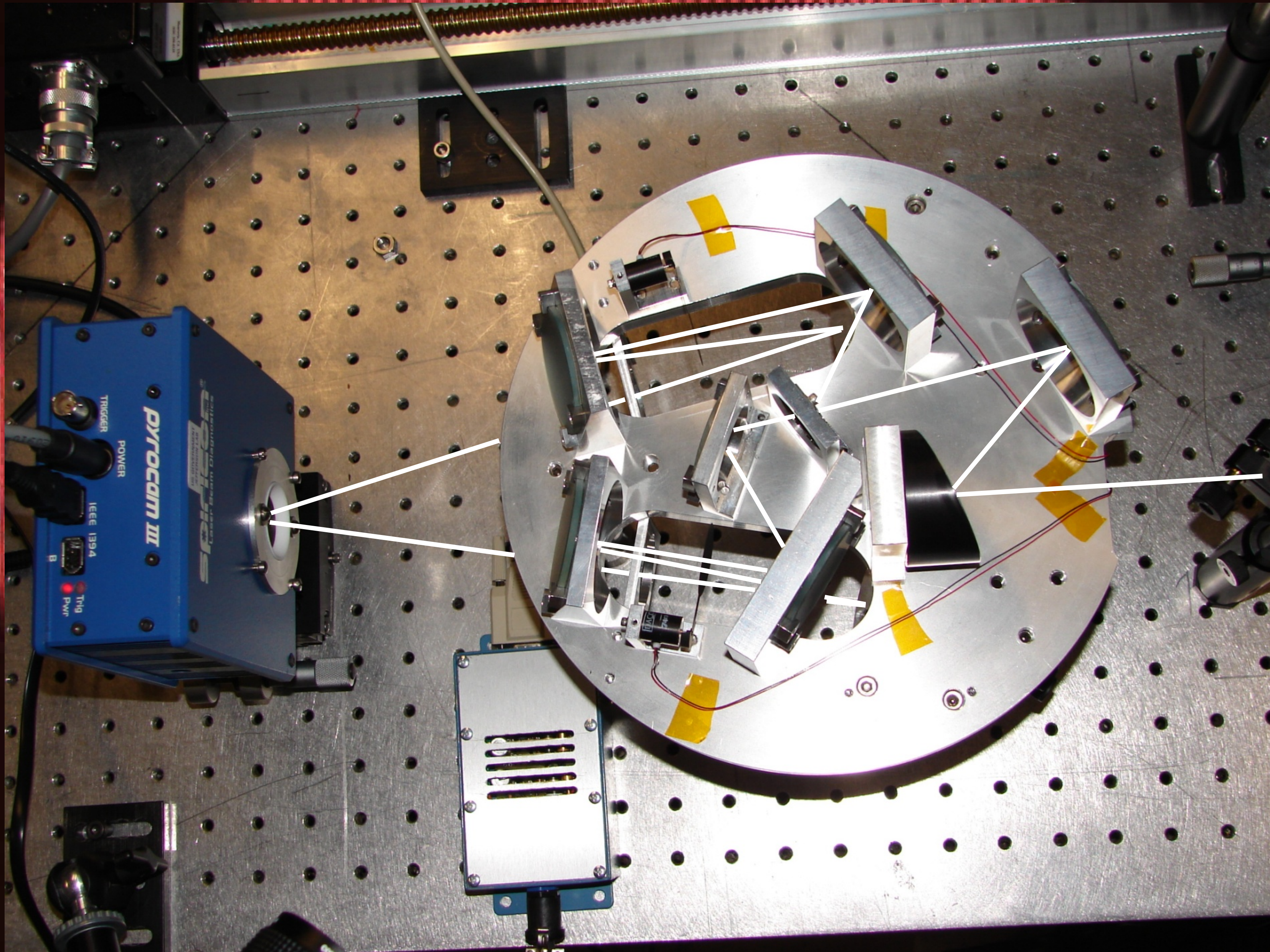
Shear Interferometer – Sievers and Agladze, Cornell

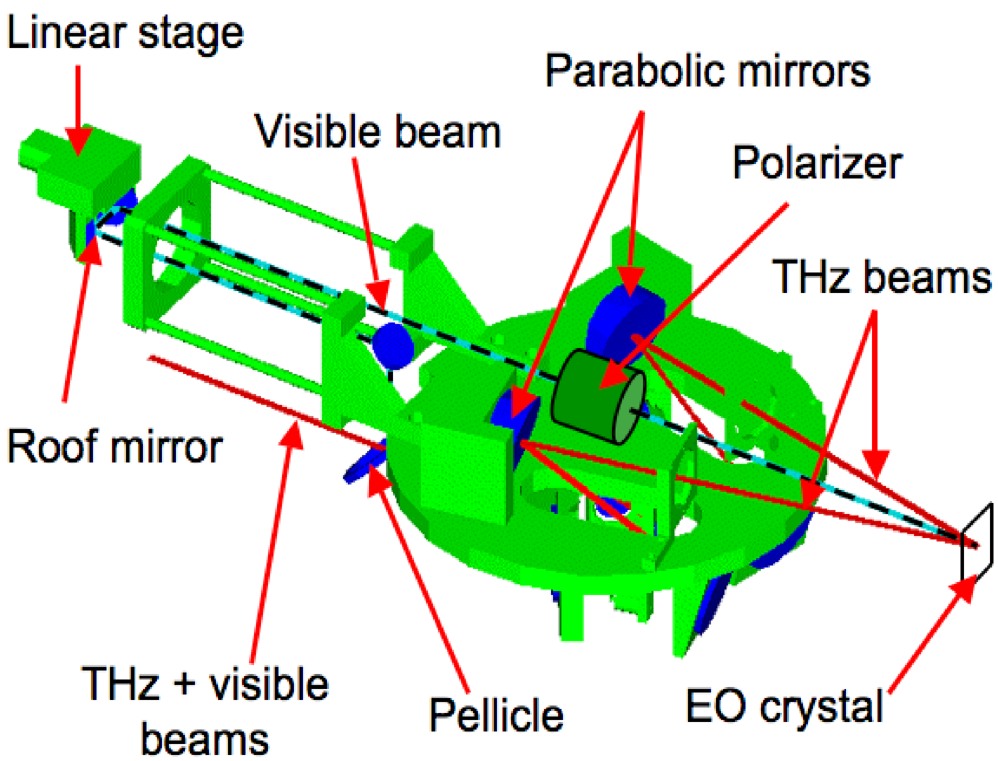
- single shot spectrum
- noise reduction

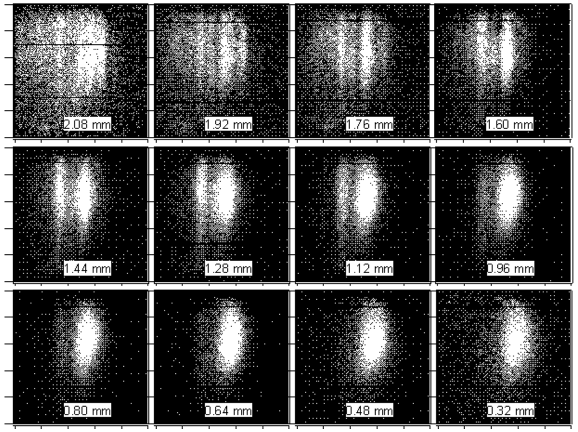


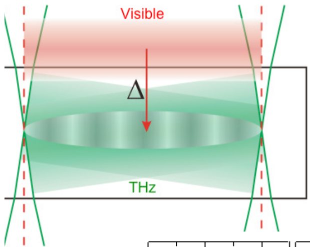
THz HFTS during experiments at Jefferson Lab FEL

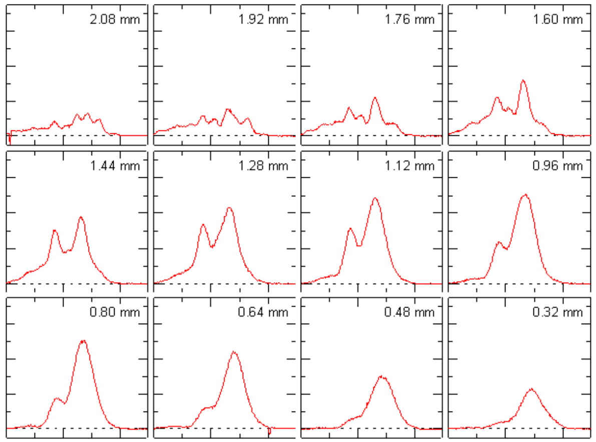


Shear Interferometer in autocorrelation mode









N. I. Agladze, J. M. Klopf, G. P. Williams and A. J. Sievers, "Terahertz spectroscopy with a holographic Fourier transform spectrometer plus array detector using coherent synchrotron radiation ", Appl. Optics **49,** 3239-3244 (2010).

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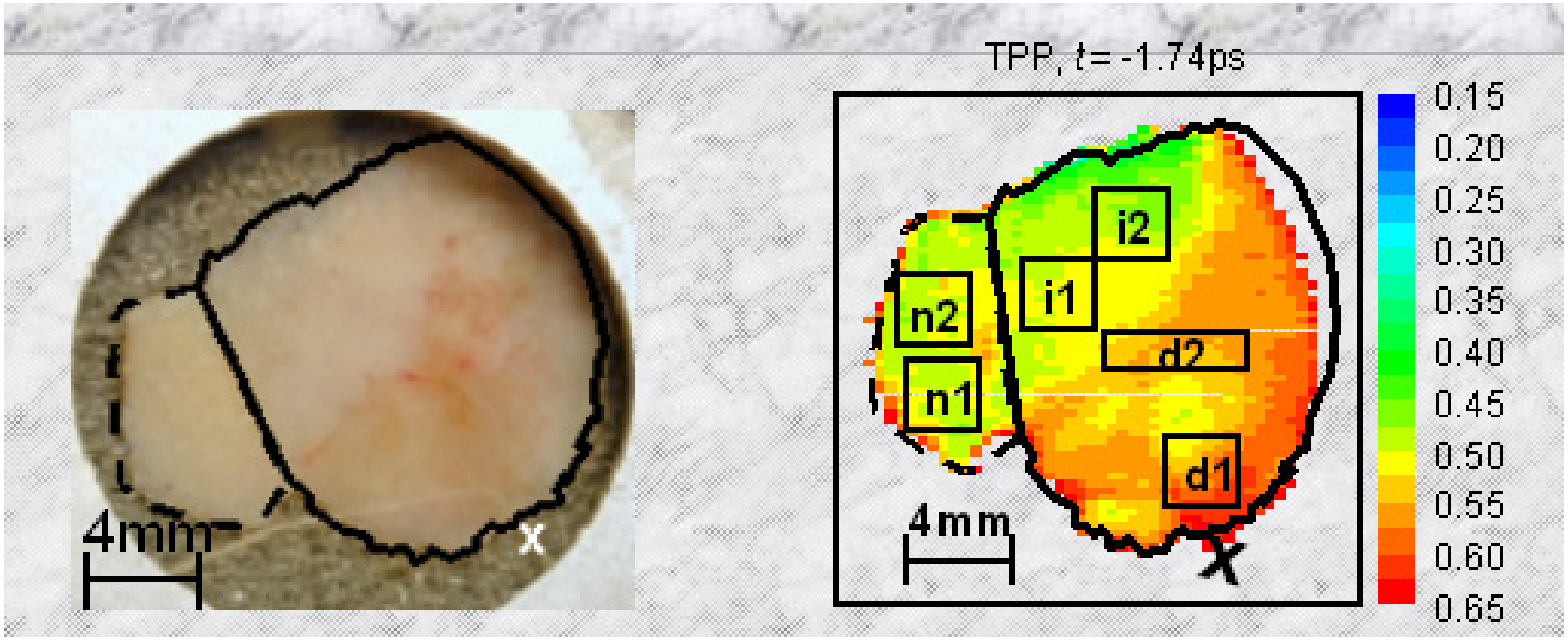
Medical – cancer screening

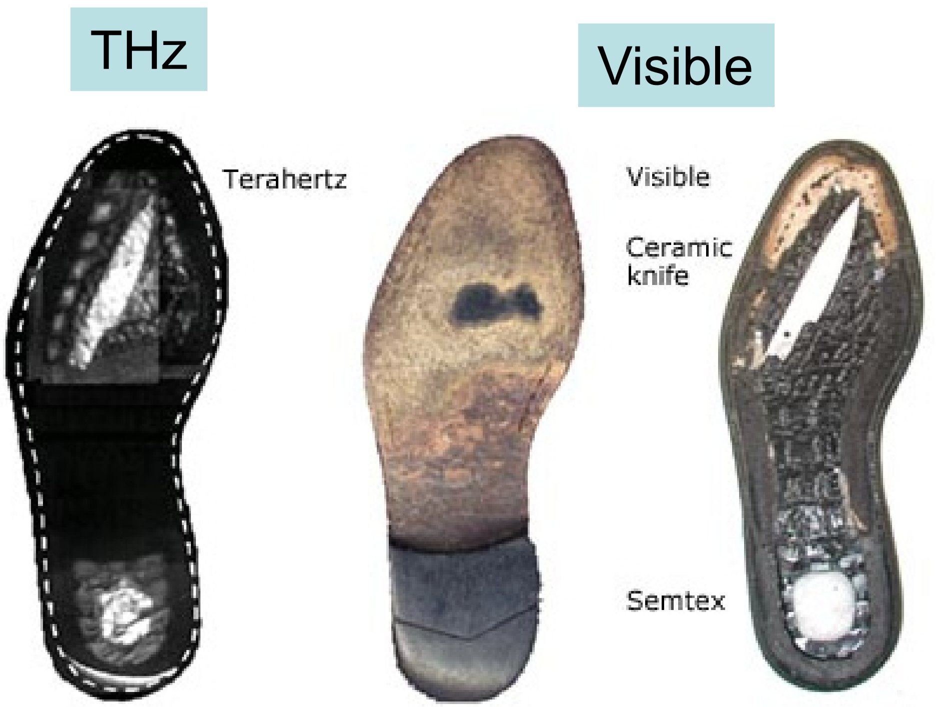


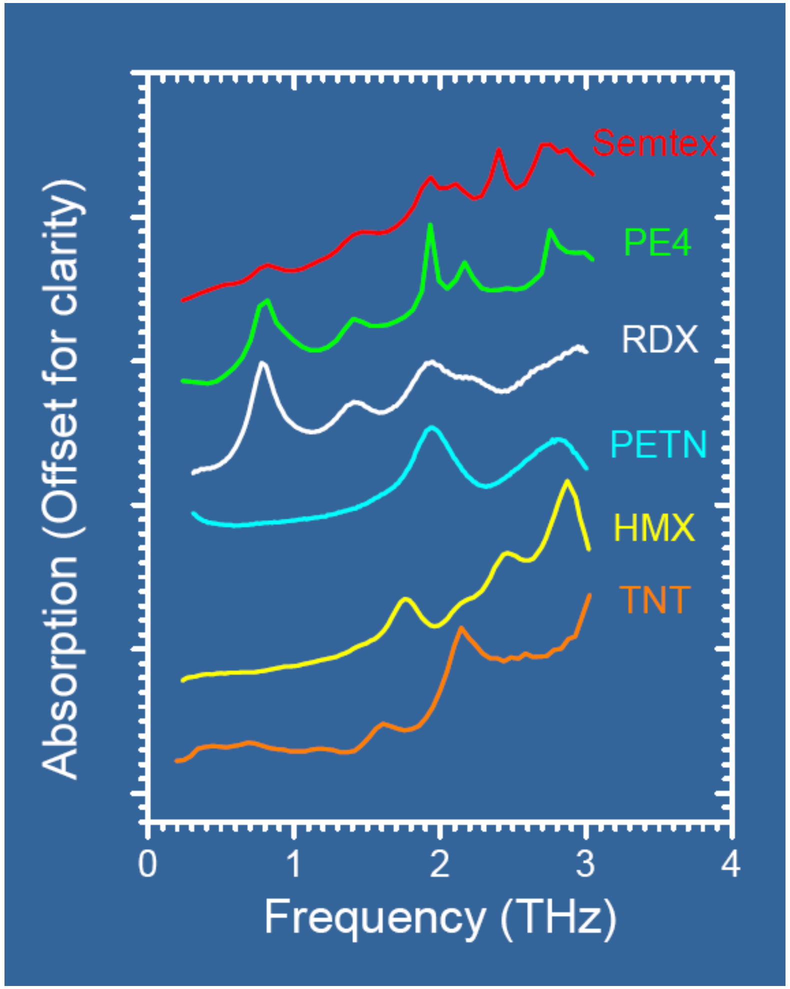
Basal cell carcinoma shows malignancy in red. Teraview Ltd.

1 mW source images 1 cm^2 in 1 minute

100 W source images whole body (50 x 200cm) in few seconds

Security – hidden weapons, explosives





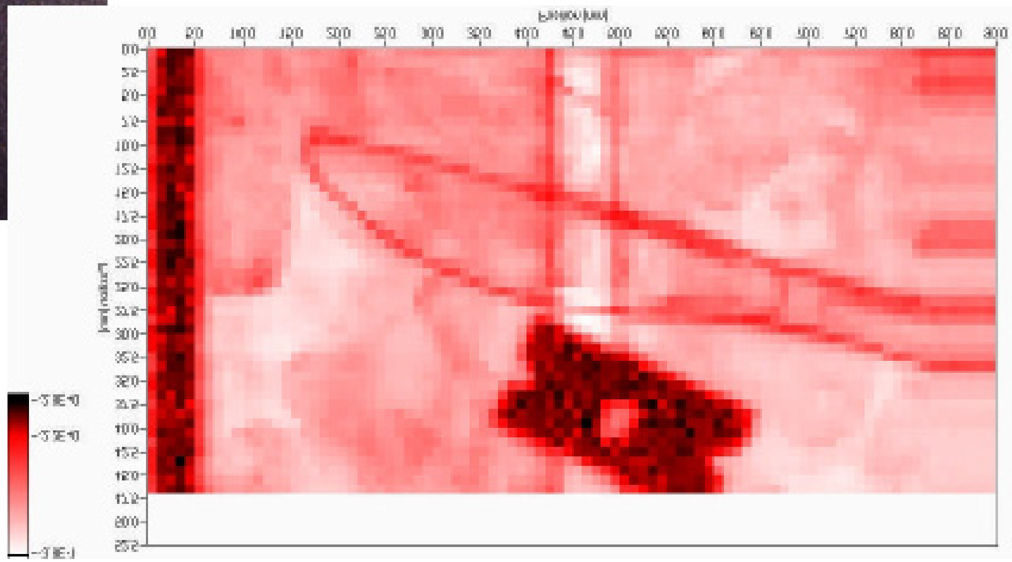
Explosive "fingerprints"

Security – hidden non-metallic weapons

Sealed Package

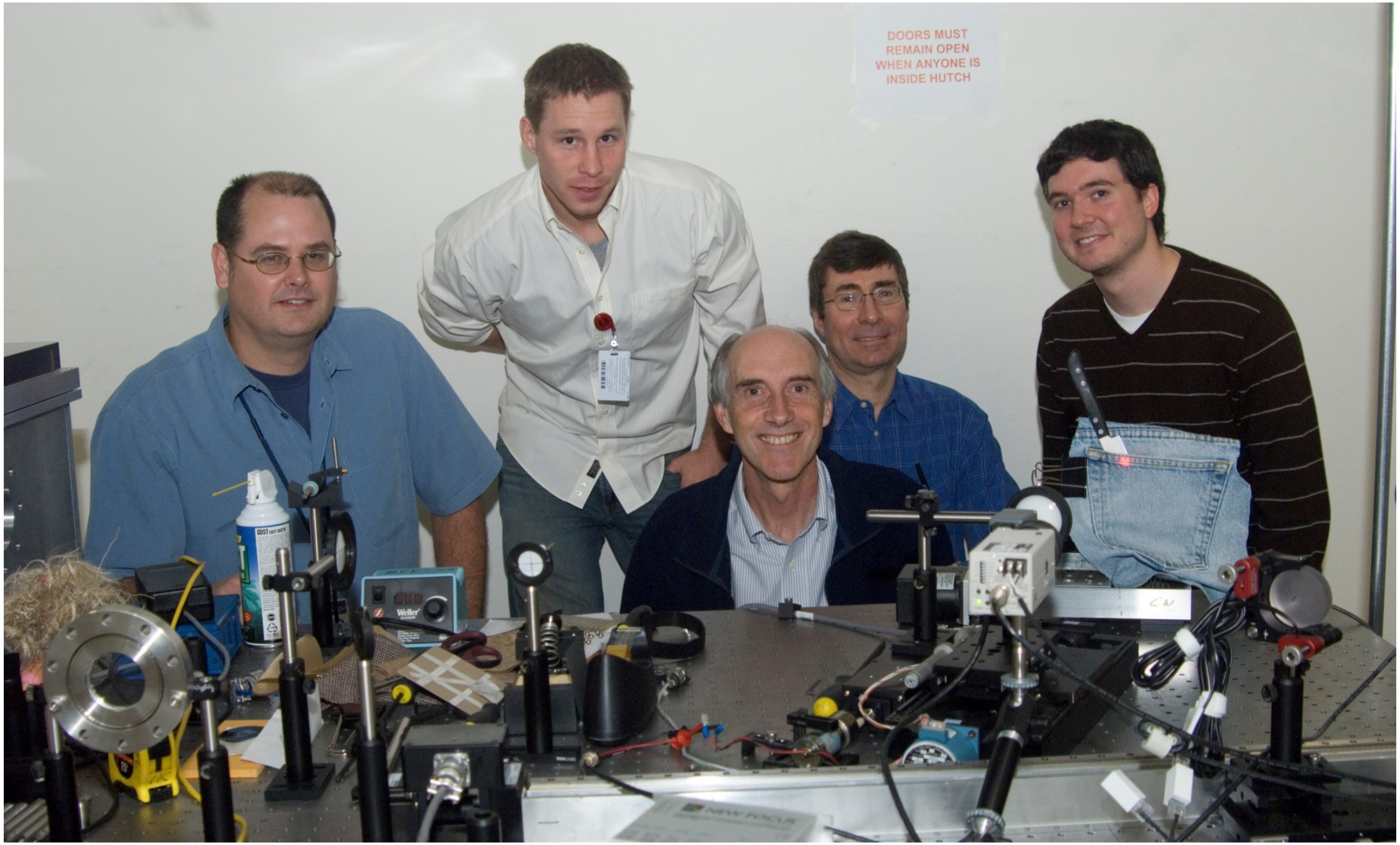
PICOMETRIX®

Non-metallic Weapons Easily Detected



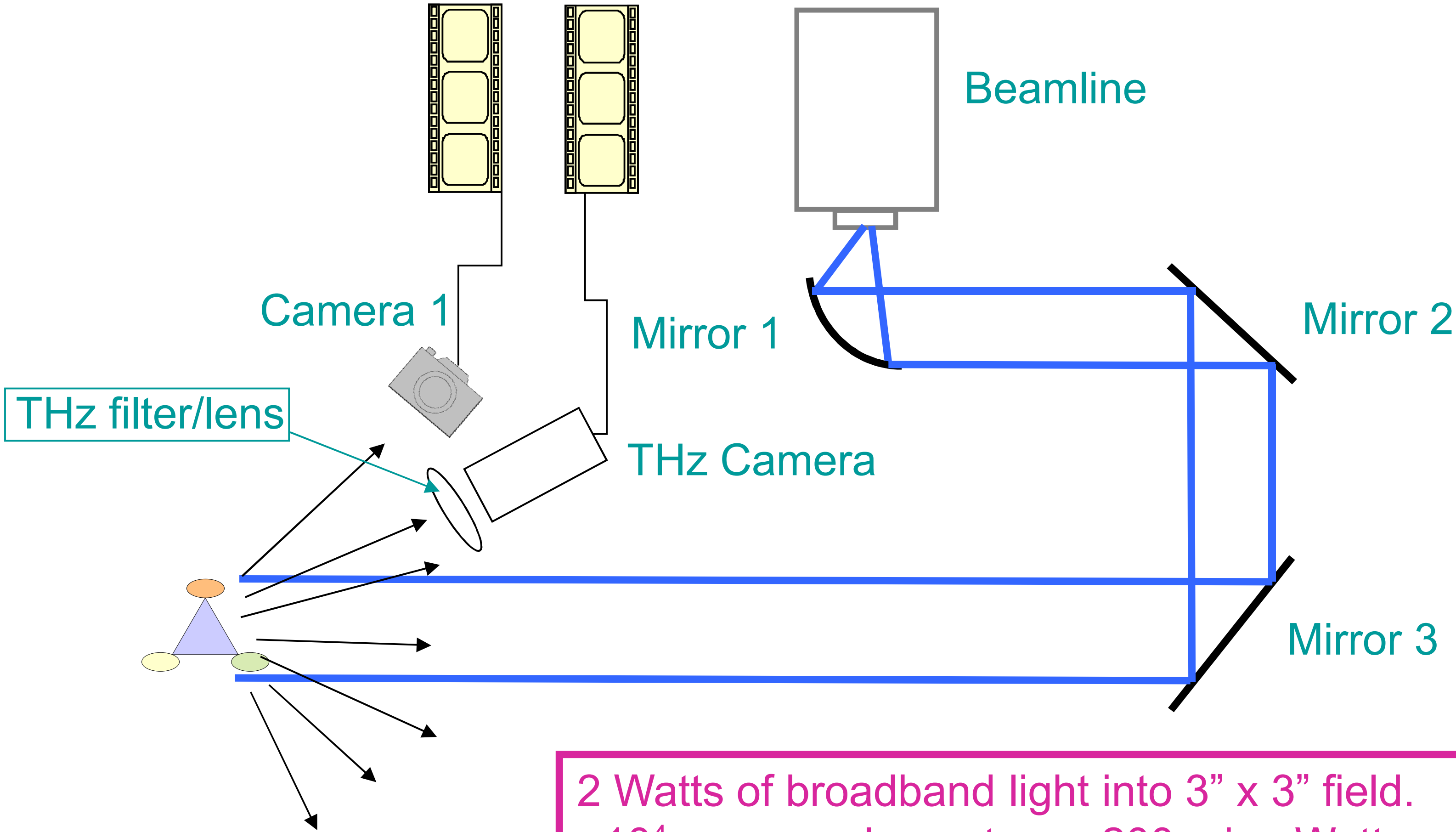
David Zimdars SPIE 5070 (2003)

Jefferson Lab & U. of Delaware Team



Mike Klopf, Matthew Coppinger, GPW, James Kolodzey, Nathan Sustersic

THz Imaging Schematic

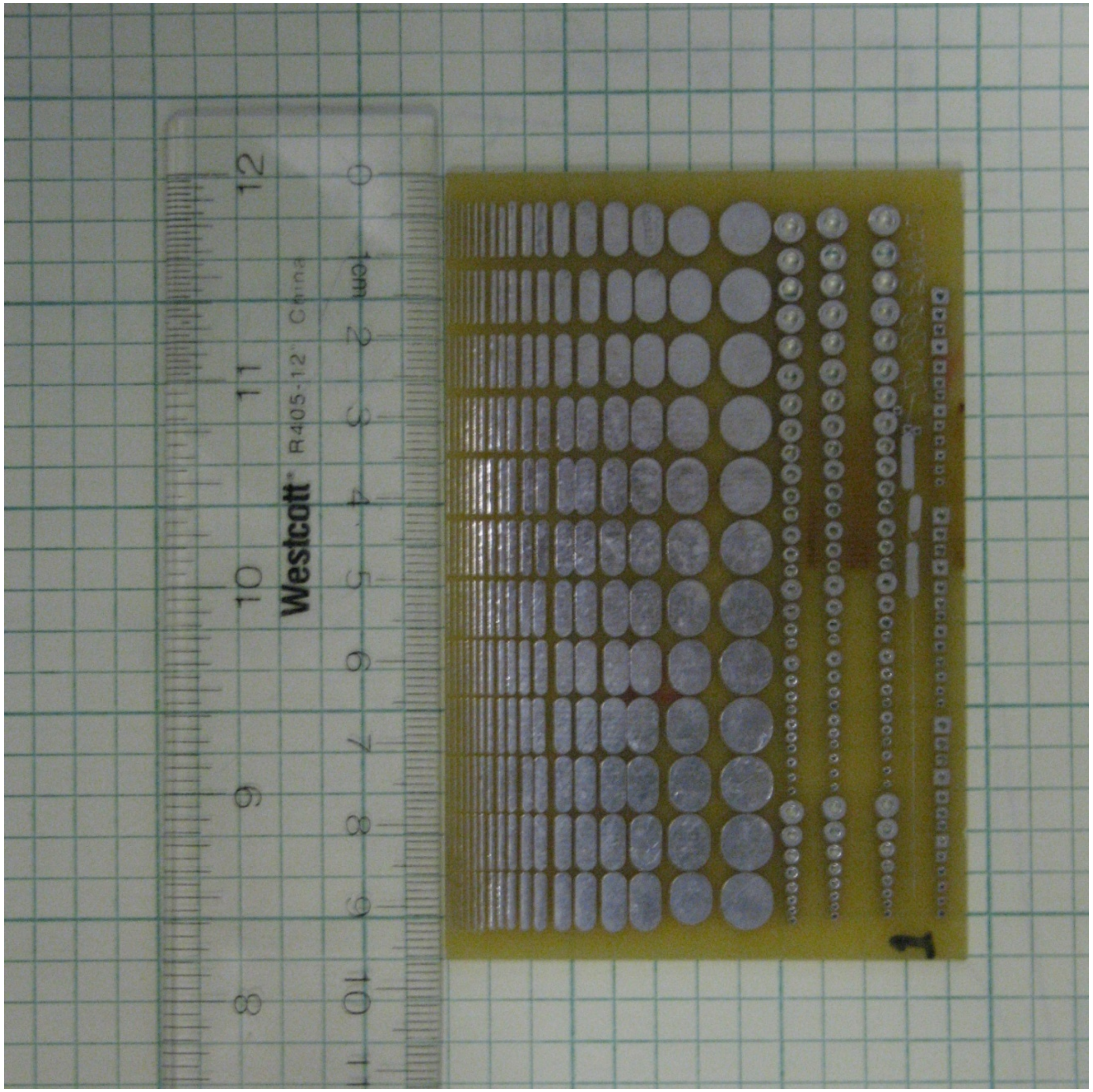


2 Watts of broadband light into 3” x 3” field.
~10^4 camera elements, so 200 microWatts per pixel.
Scattering ~ 0.1%, so 0.2 microWatts per pixel.
Noise level, 1 nanoWatt, so S/N is 200 in real time.

The Camera

http://www.corebyindigo.com/PDF/TVMicron.pdf

Test Pattern Imaging Target



THz Imaging Layout

Parameters

2 Watts source

Camera (FLIR)

160x128 pixels

(50x50 microns)

20,480 pixels

100 microW/pixel

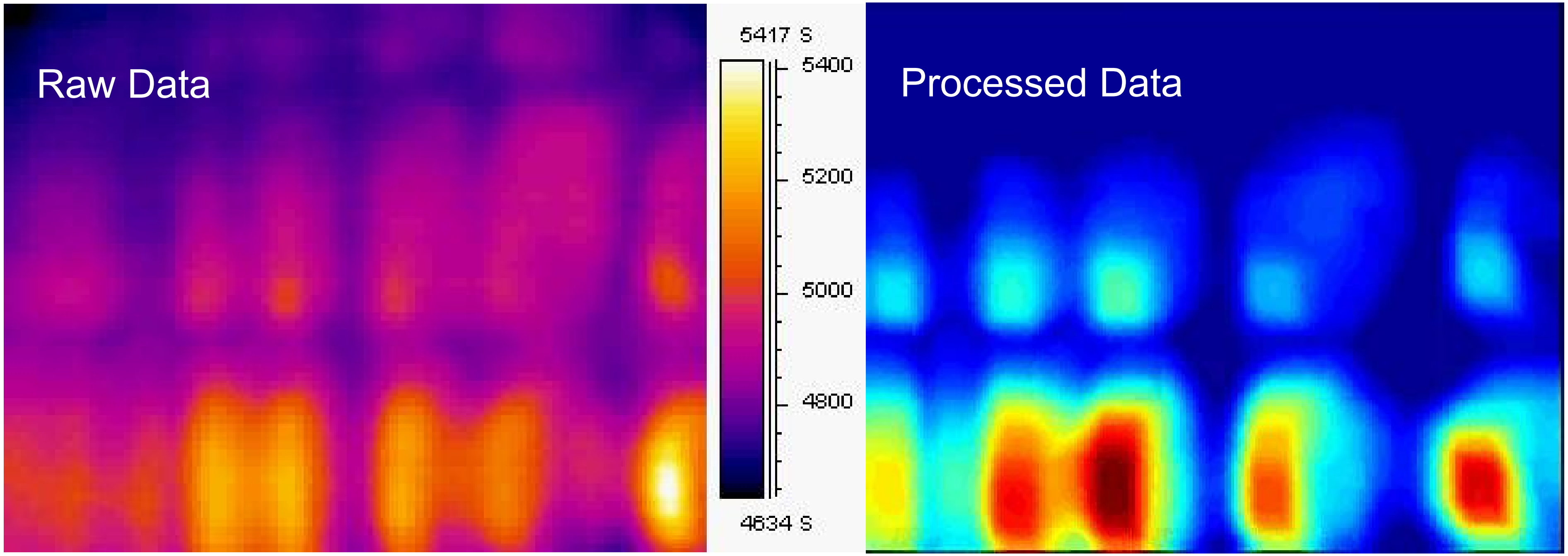
Incident

Backscattered

10^{-3}, so 100nW

S/N ~ 100

Test of Imaging Resolution



- Raw THz images are processed to reduce the background and improve contrast
- Current configuration resolved down to the 1mm wide contact pads
- Polyethylene lens filtered the thermal IR, but does not image well

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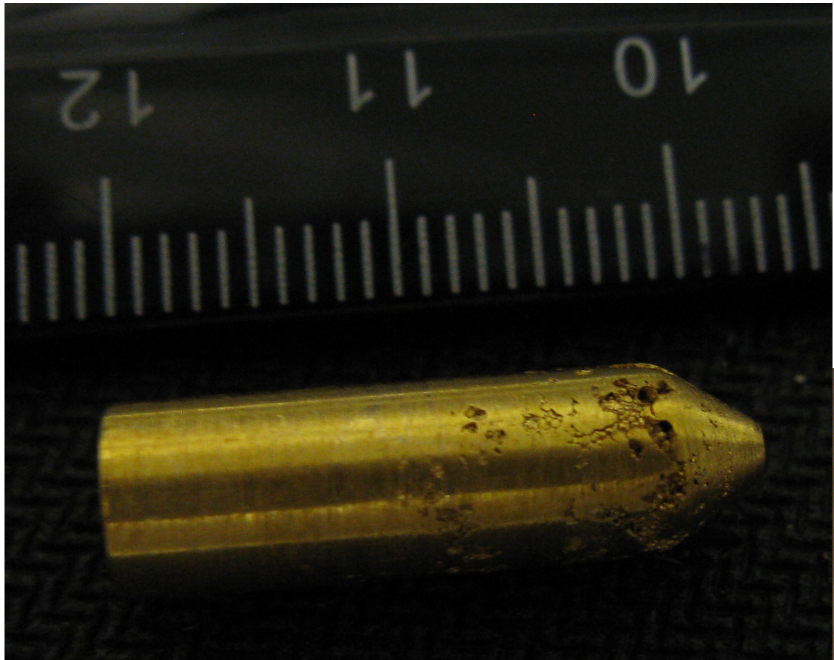
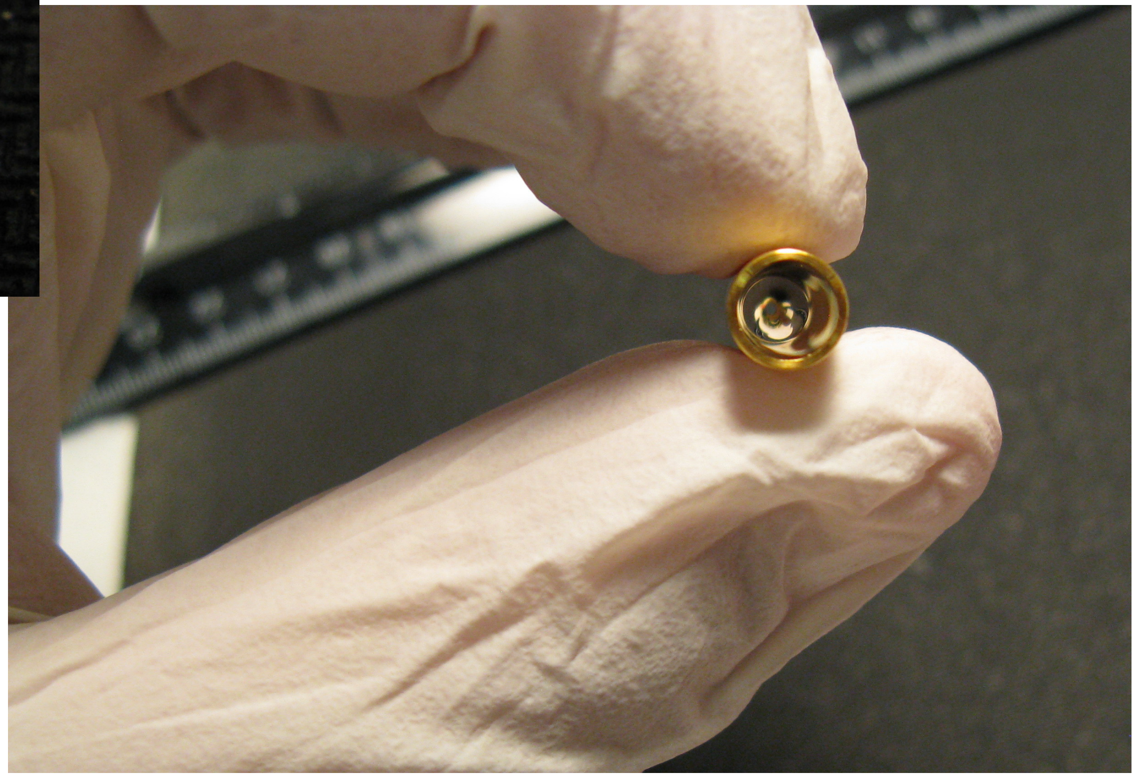
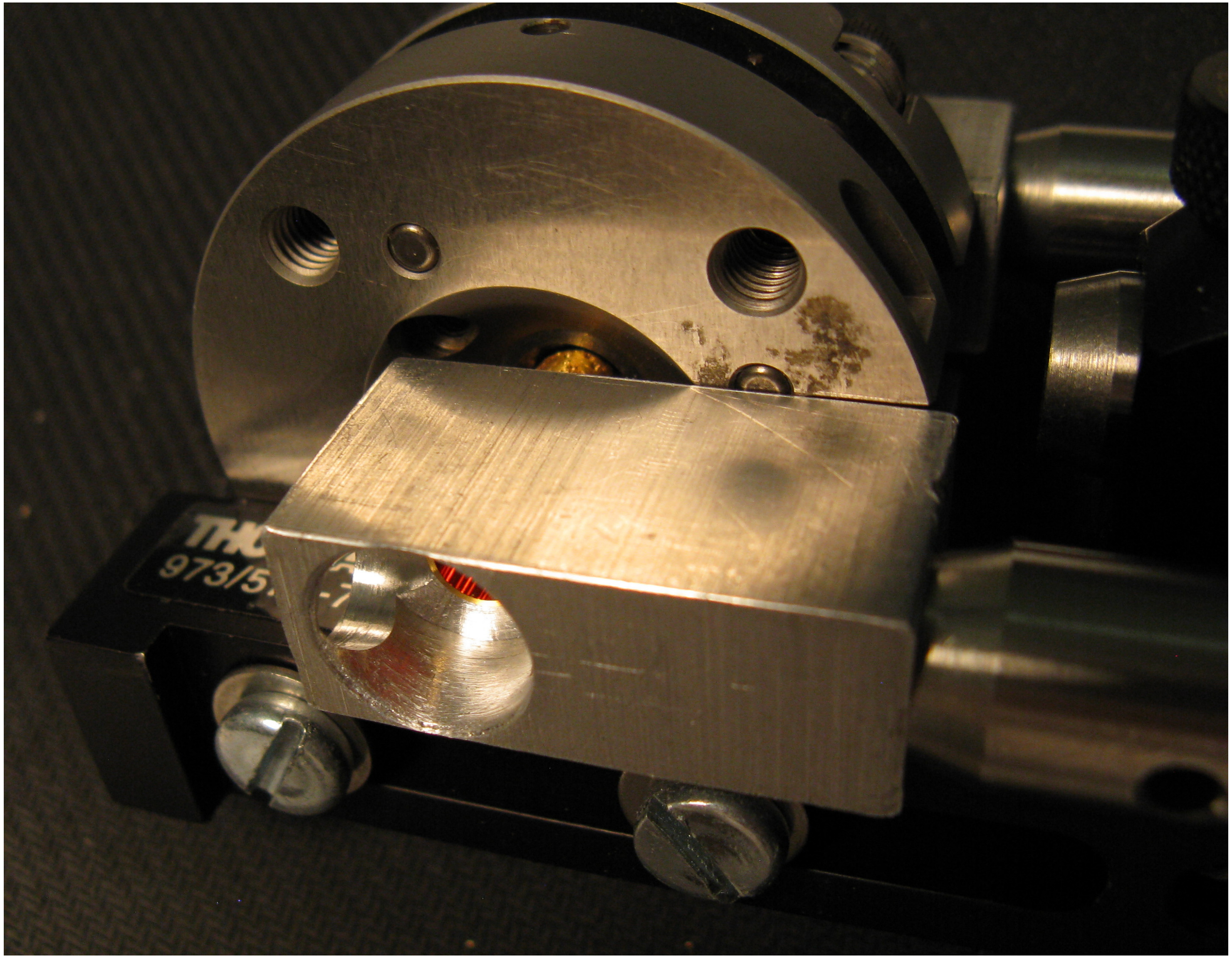
Custom Winston Cones for Diamond Anvil Cell



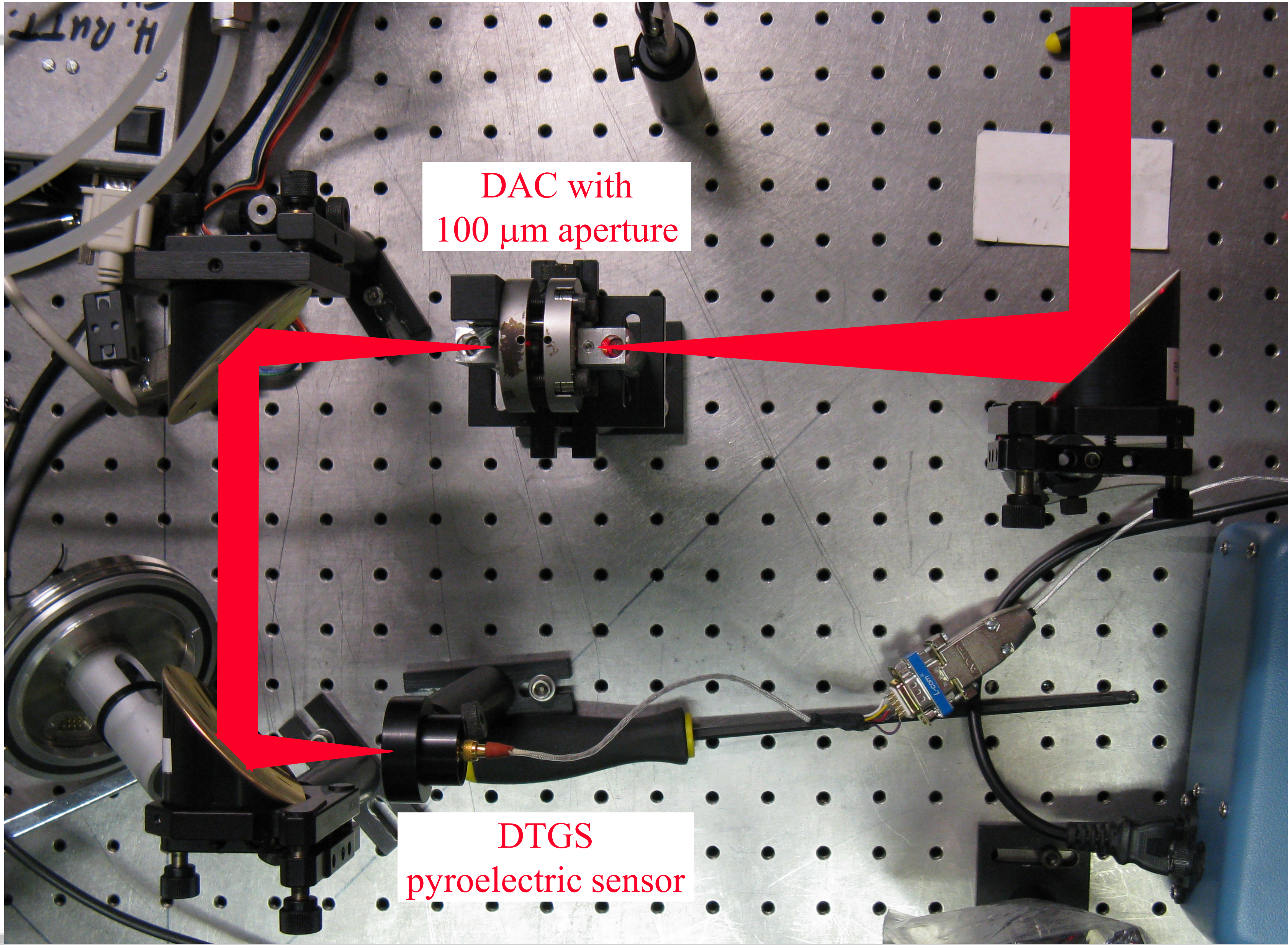
- Winston Cones were formed in Copper, then gold plated for improved reflectivity
- pitting does not impinge on inner reflective surface



DAC-Winston Cone Assembly



First THz Transmission Test Layout



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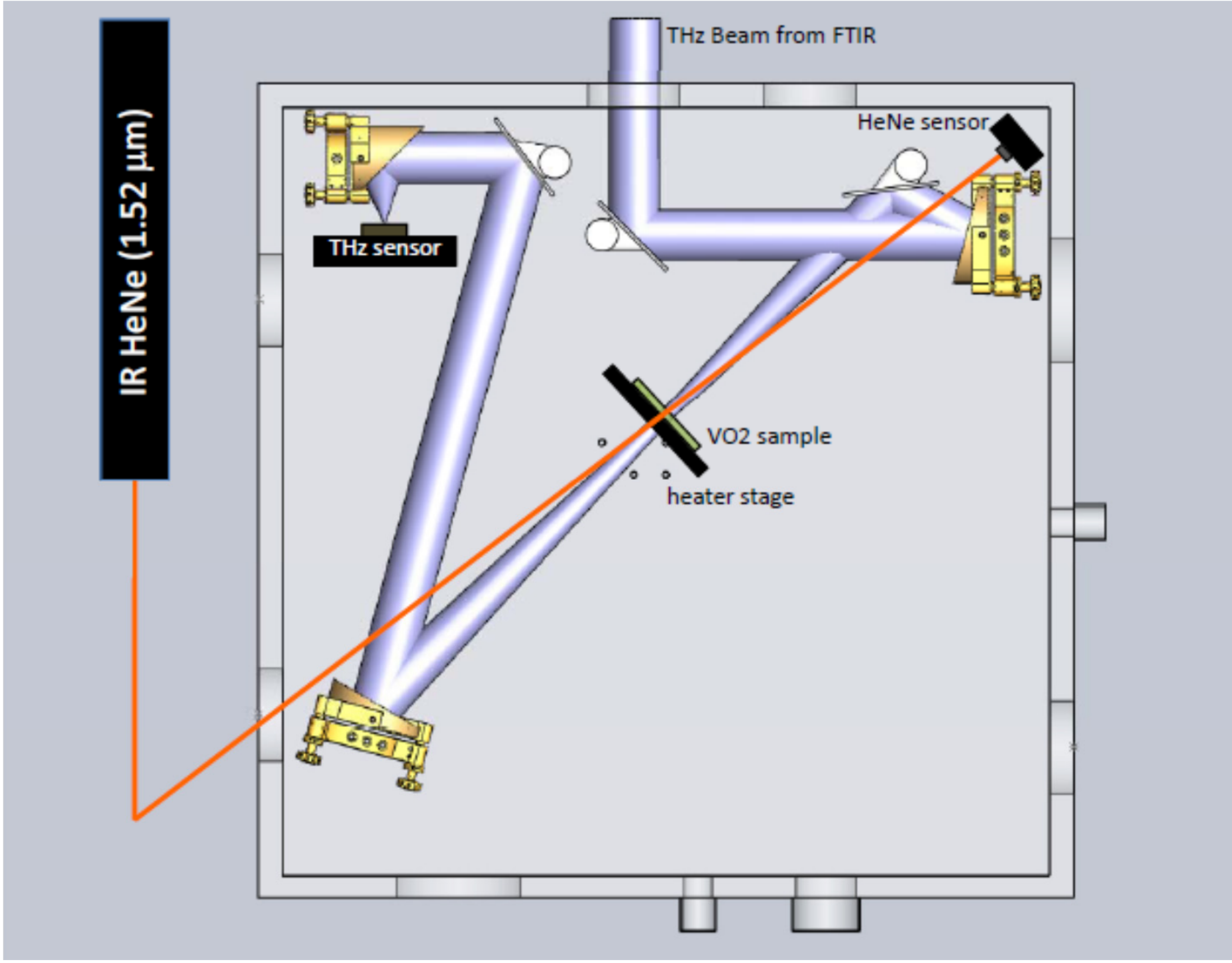
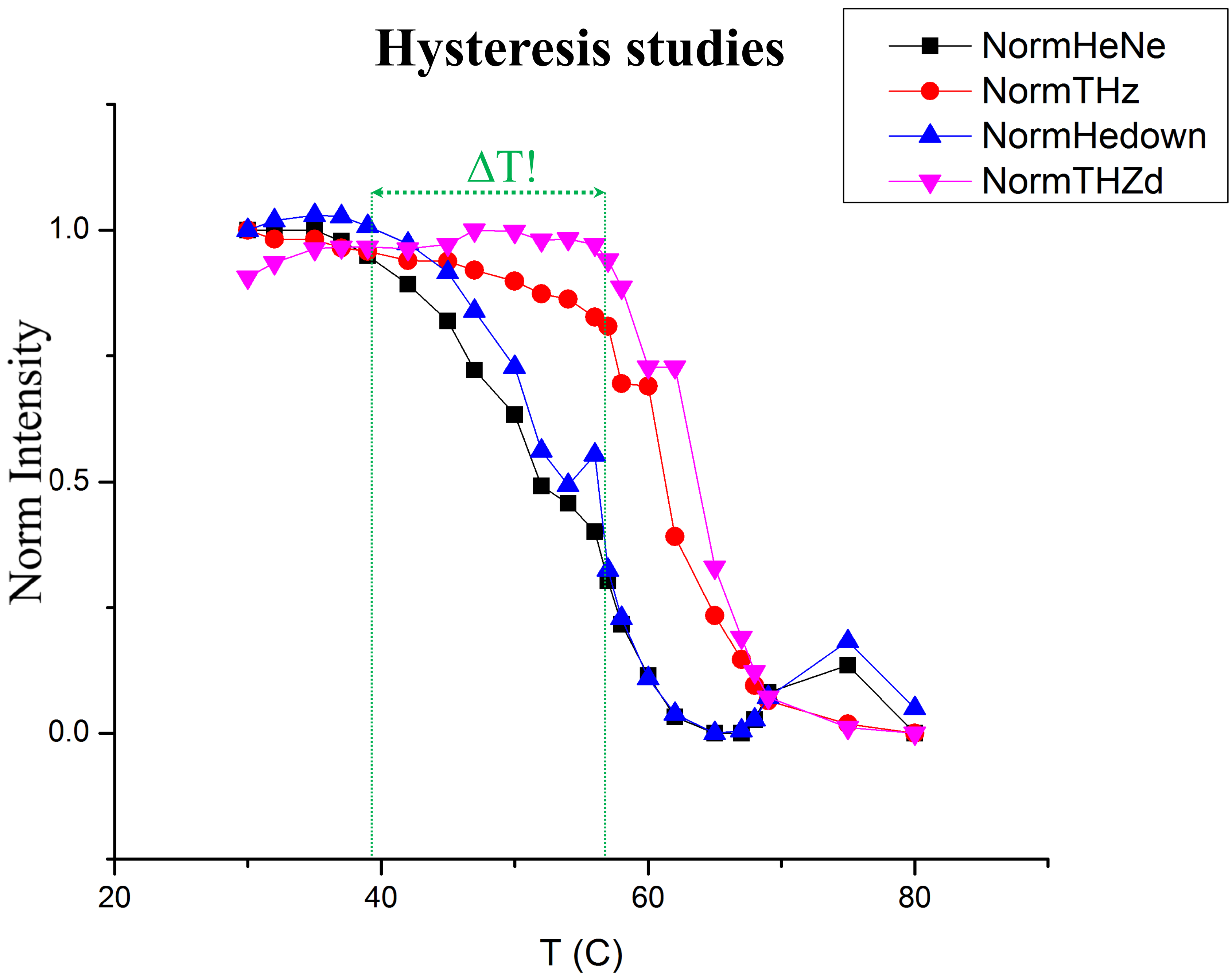
Metal-insulator phase transition in VO_2



R. A. Lukaszew, College of William and Mary
G. Scarel, James Madison University



Hysteresis studies
NormHeNe
NormTHz
NormHedown
NormTHZd
ΔT!
Norm Intensity
1.0
0.5
0.0
20
40
60
80
T (C)

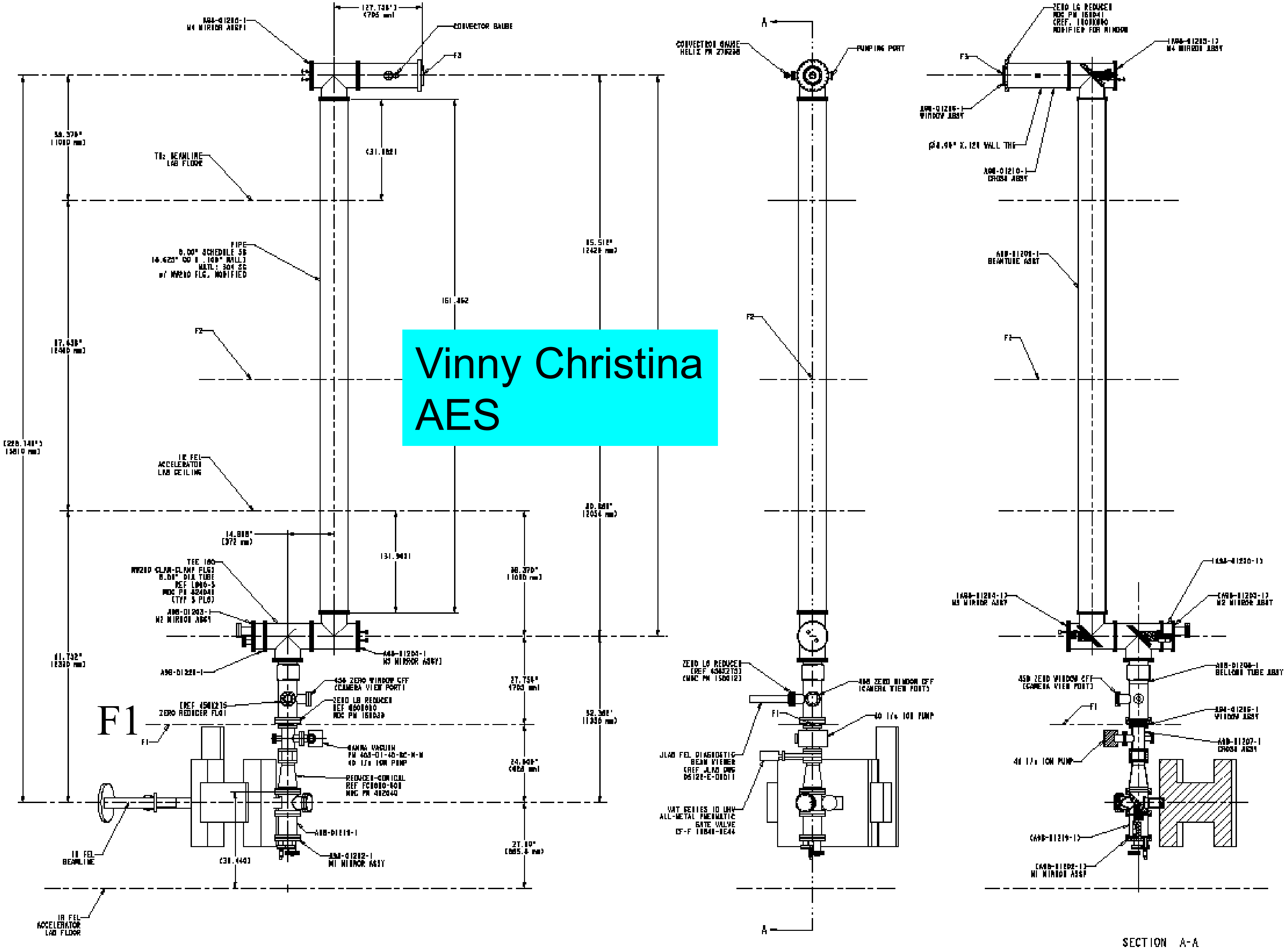
Summary

- We have built a high power, high brightness THz source
- Many opportunities from basic science, to security to medical imaging

The Jefferson Lab FEL Team

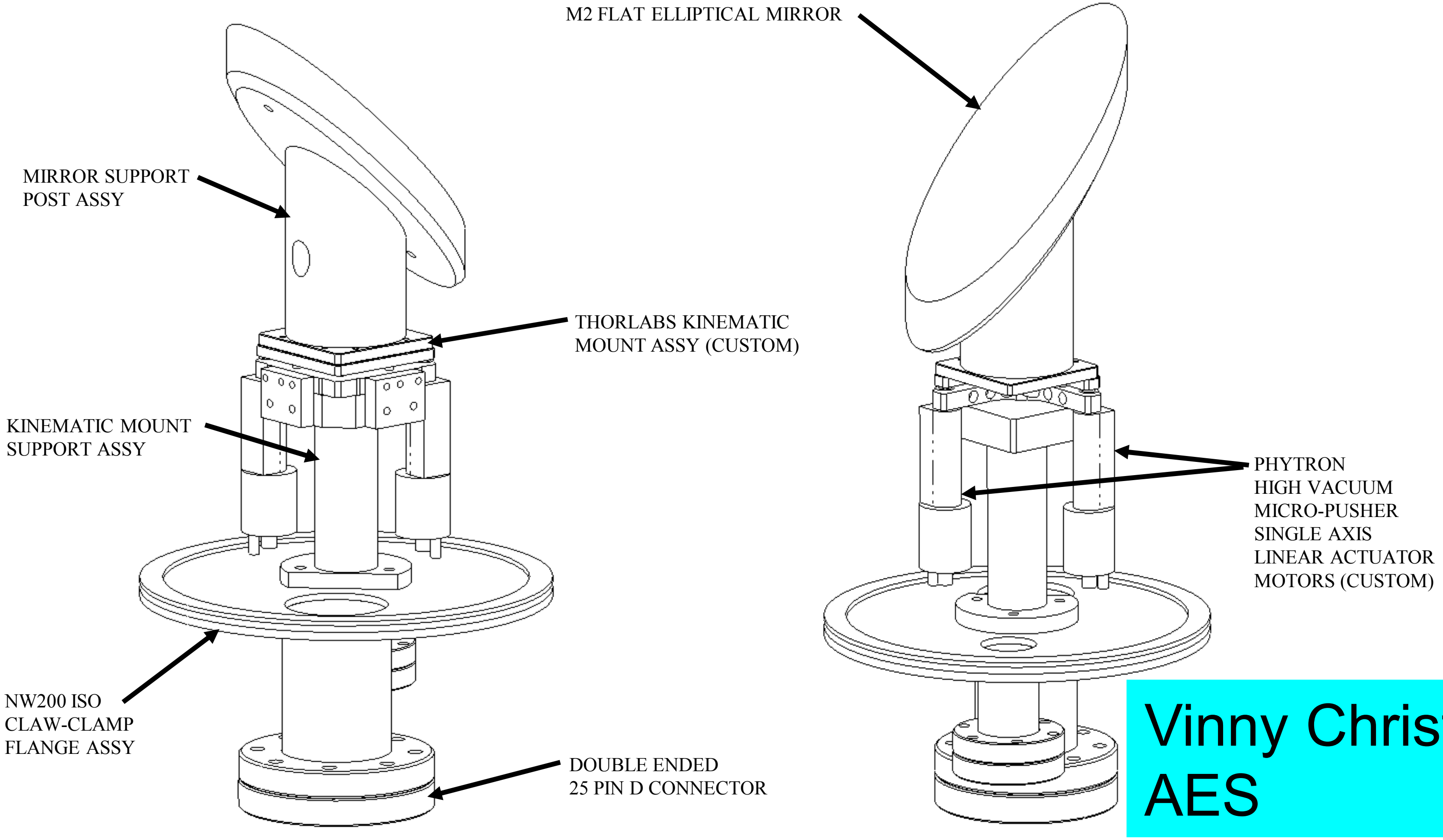
This work supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the DOE Air Force Research Laboratory, The US Army Night Vision Lab, and by DOE Basic Energy & Nuclear Sciences under contract DE-AC05-

EXTRA SLIDES



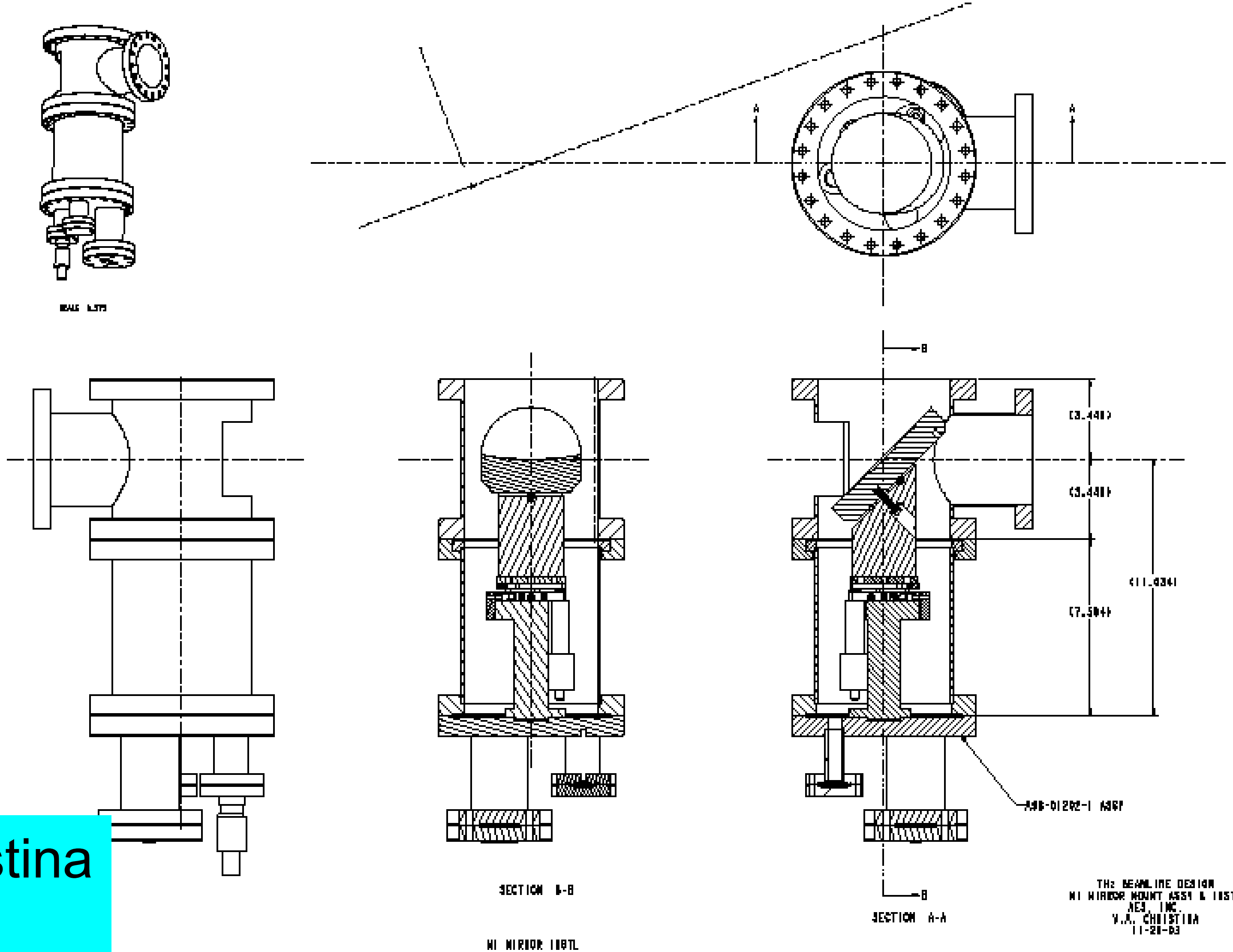
Vinny Christina
AES
CONVECTOR GAUGE
PUMPING PORT
F1
F2
F3
40 l/s ION PUMP
IR FEL BEAMLINE
IR FEL ACCELERATOR LAB FLOOR
SECTION A-A

M2 Mirror Mount Assembly



Vinny Christina
AES

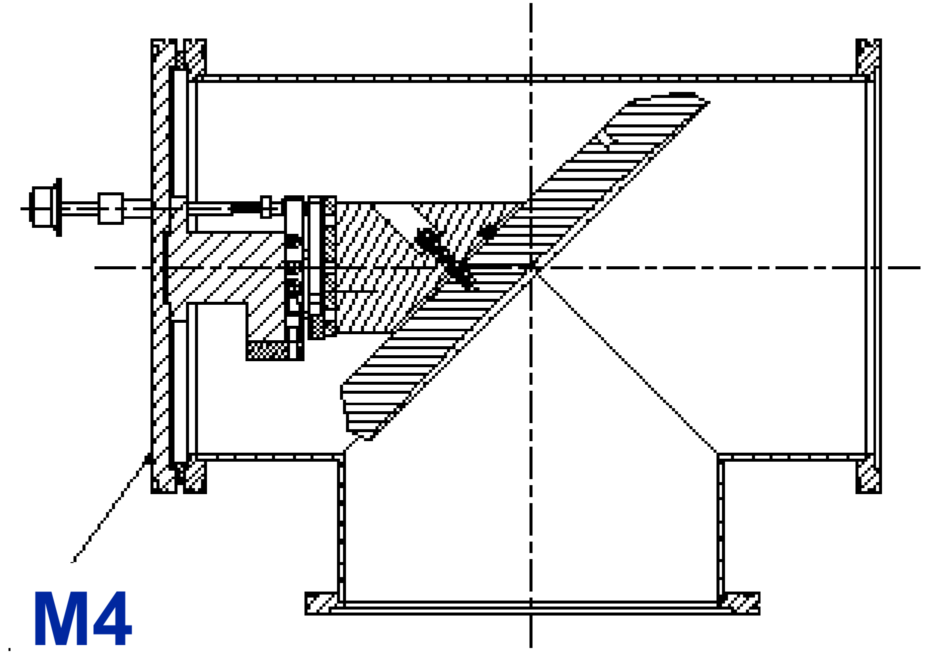
Mirror M1

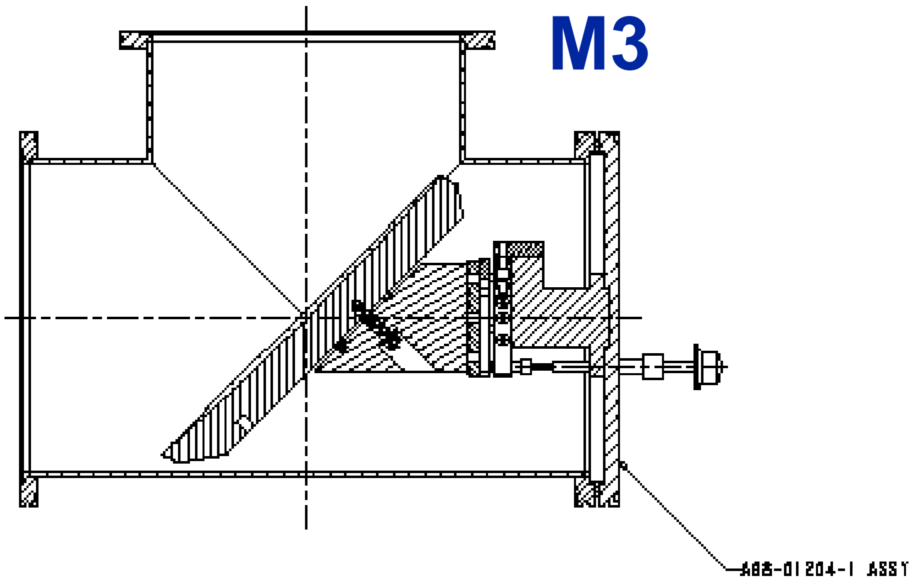


Vinny Christina
AES

Mirrors M3 & M4

Manual adjustment





Vinny Christina
AES

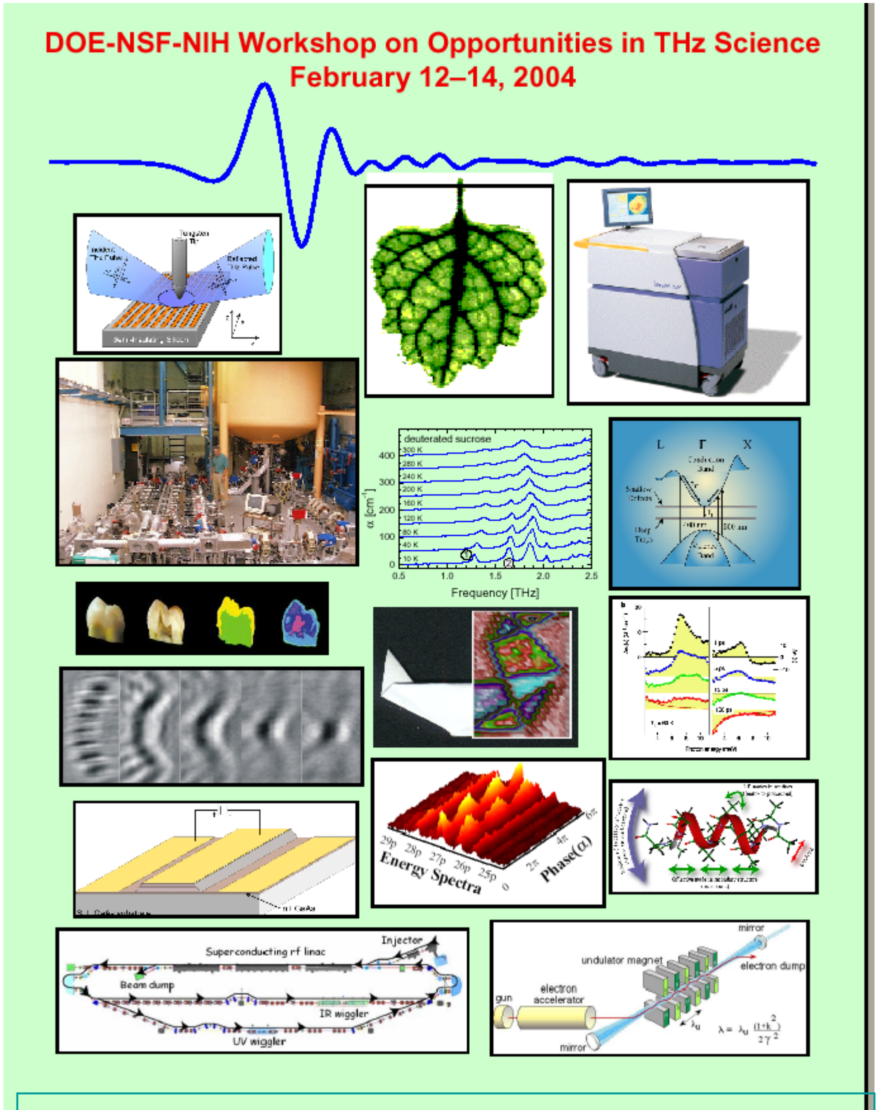
Applications of THz light

High power niche

- Small samples
- Real-time imaging

Ultra-fast niche

- Dynamics

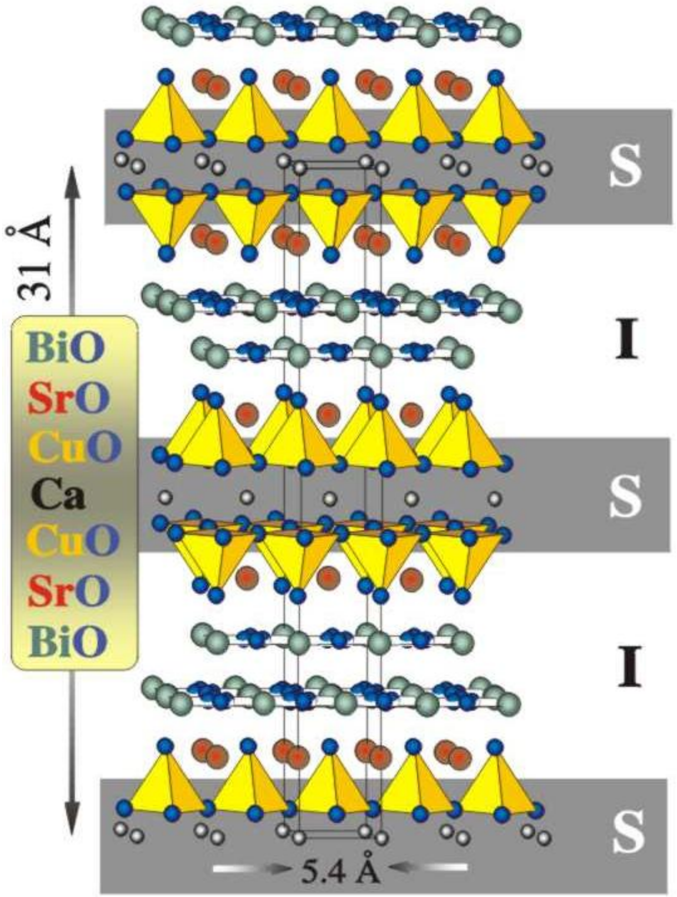


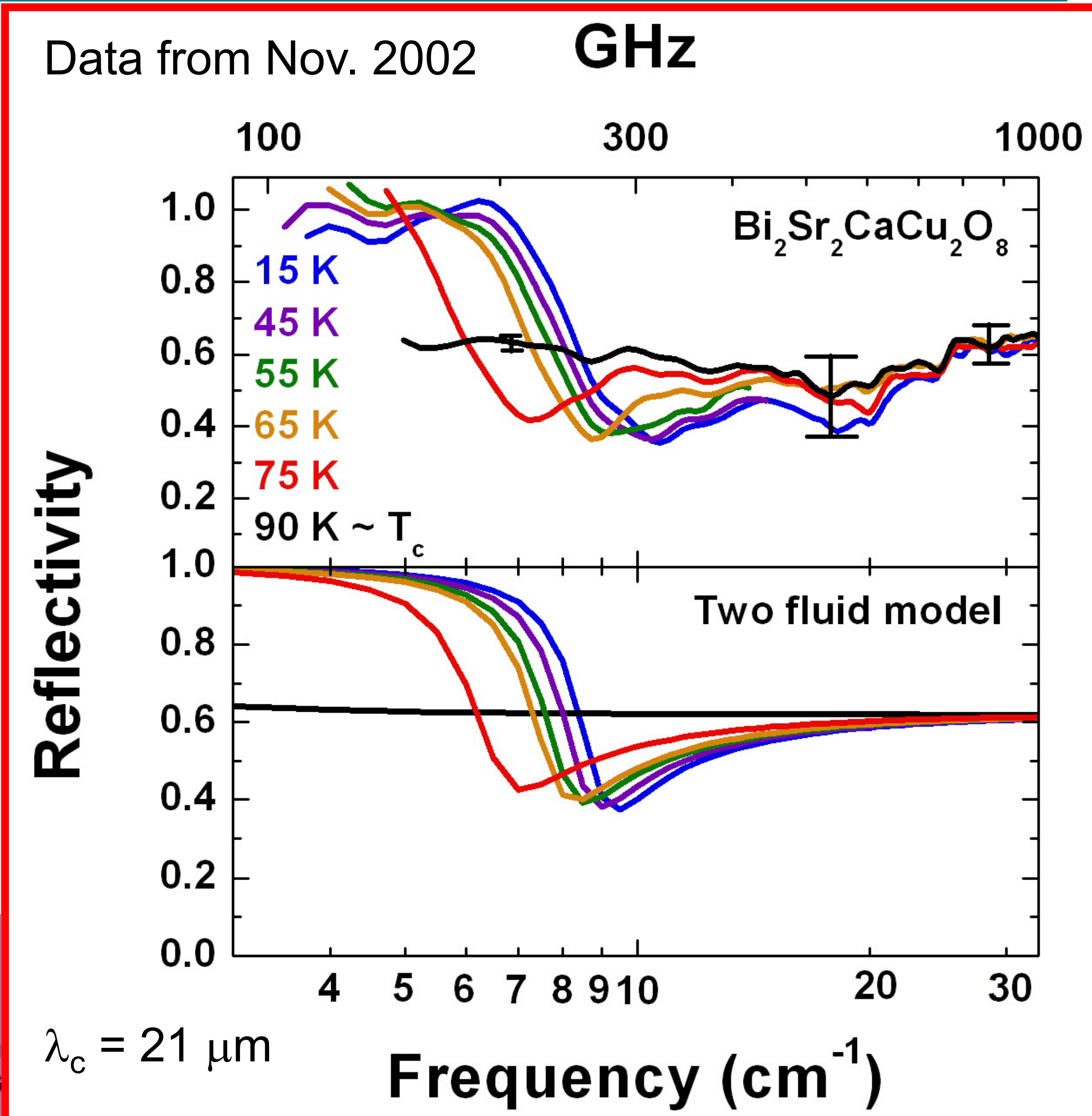
http://www.er.doe.gov/production/bes/reports/list.html

First CSR Science: Josephson Plasma Resonance in $Bi_2Sr_2CaCu_2O_8$

ERNEST ORLANDO LAWRENCE BERKELEY NATIONAL LABORATORY

BESSY

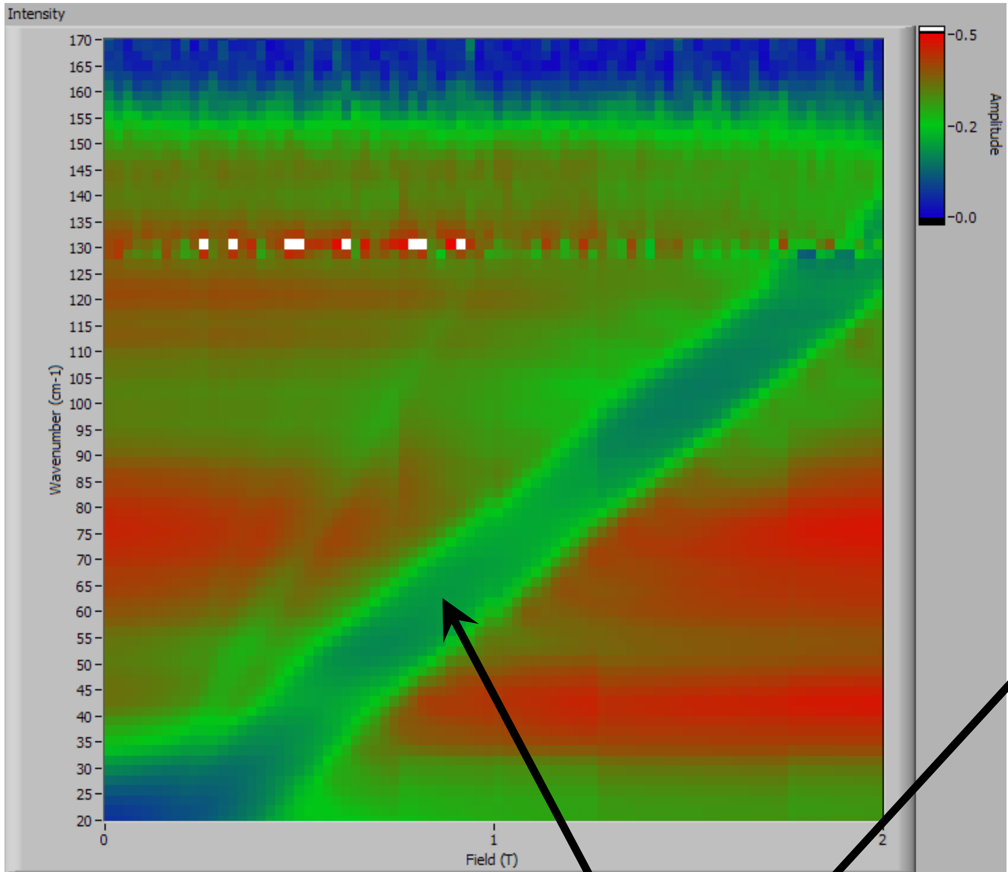




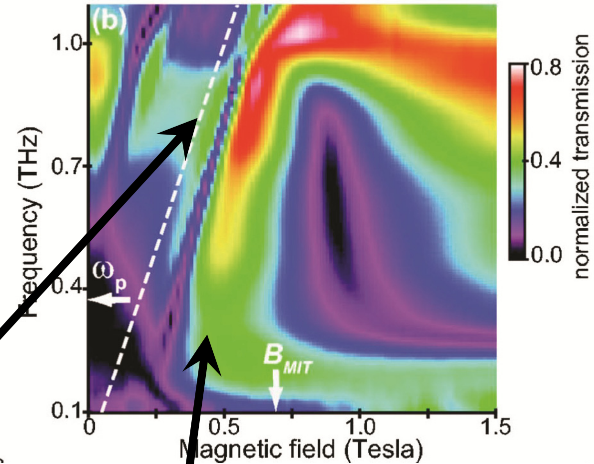
+ Indications for inhomogeneous superfluid

M. Abo-Bakr et al. Phys. Rev. B **69** (9), 092512 (2004).

THz Magneto-Optical Spectroscopy (LANL/JLab/BNL)



NSLS U4IR beamline/10T s.c. magnet (BNL/CCNY)



X.P.A. Gao, J.Y. Sohn, and S.A. Crooker, Appl. Phys. Lett **89**, 122108 (2006).

cyclotron resonance feature (slope matches fairly well)

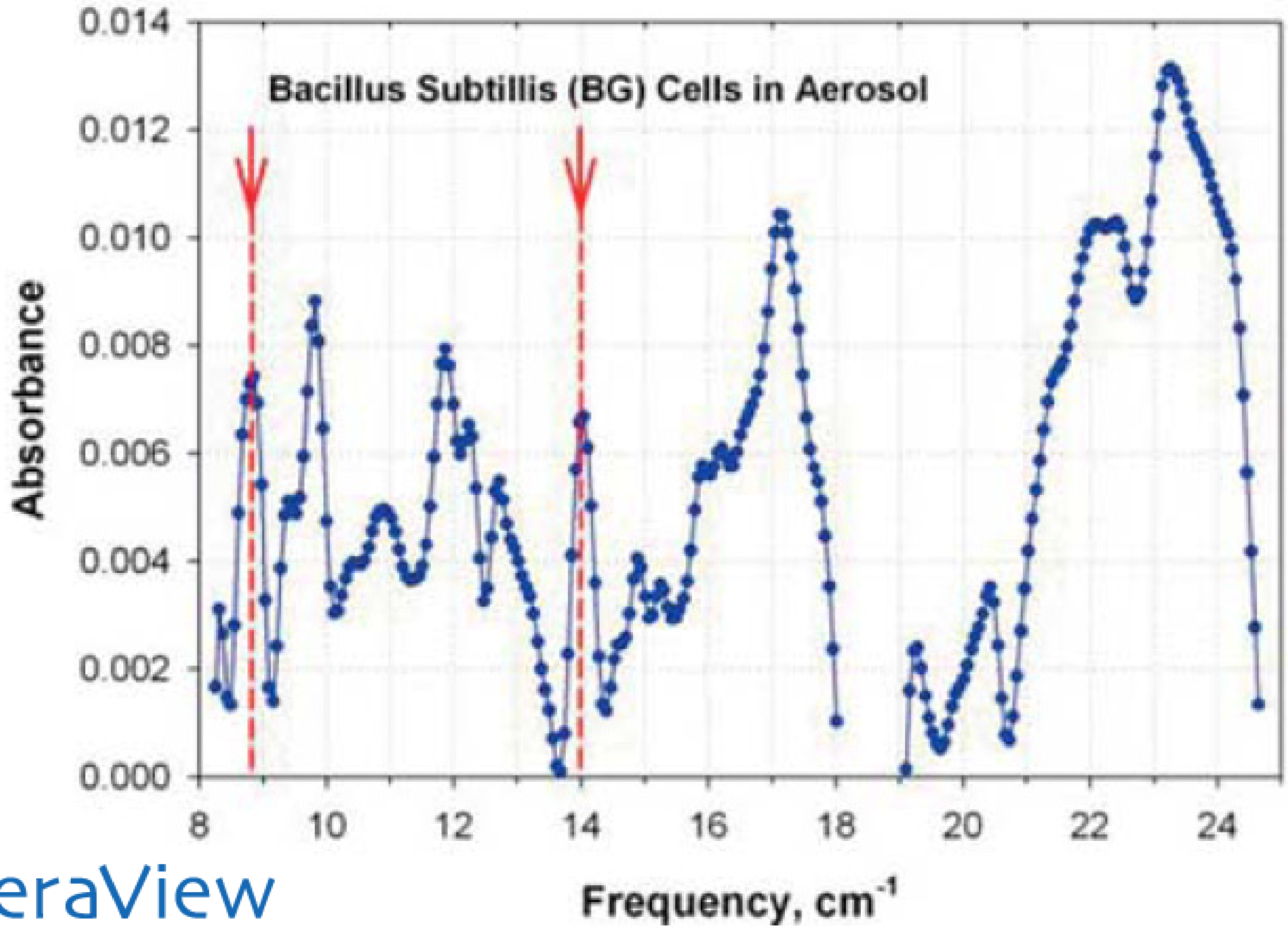
features near metal-insulator transition not seen in our data

Imaging with Terahertz Light

Applications……………………..

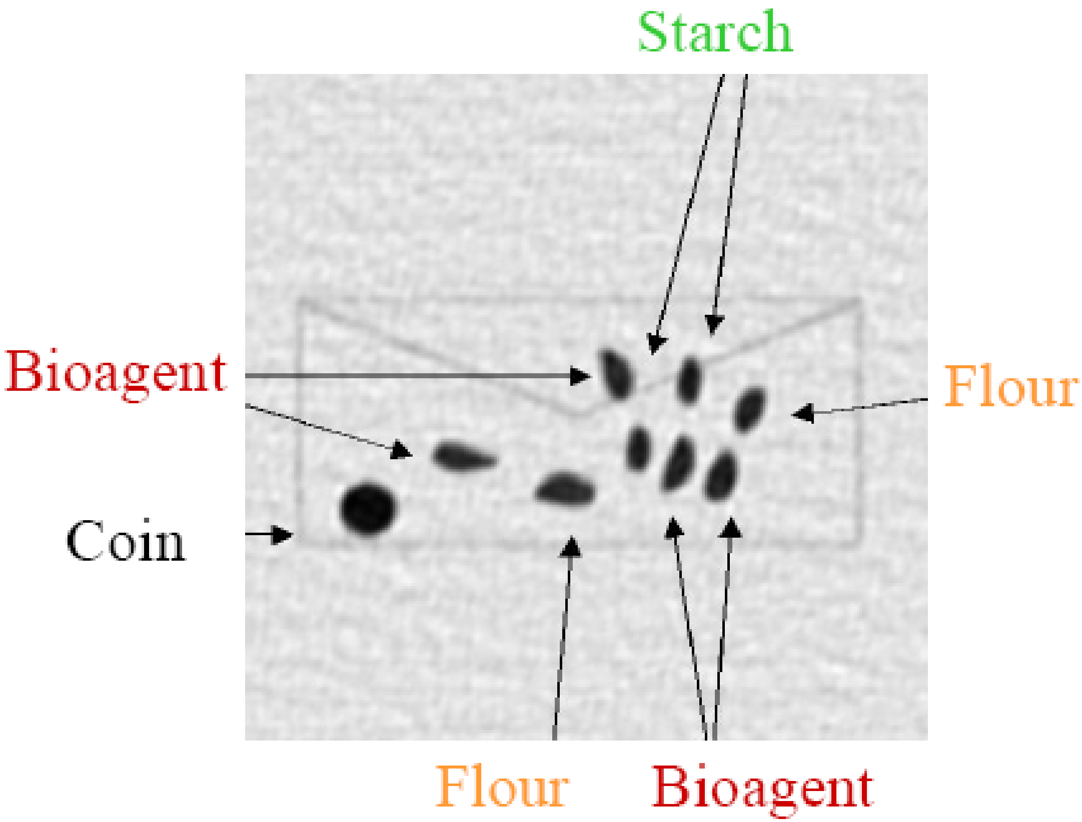
- Security
- Medical screening (skin cancer)
- Pharmaceuticals (drug verification and testing)
- Non-destructive evaluation
- Environmental monitoring
- High speed communication

Security – fingerprint of anthrax proxy

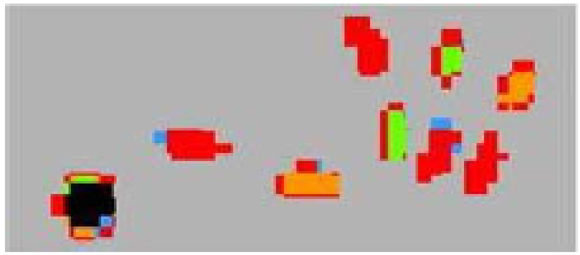


TeraView

Security – hidden bio-agents, explosives



NN Analysis



GREY=backgrnd
BLUE=unknown

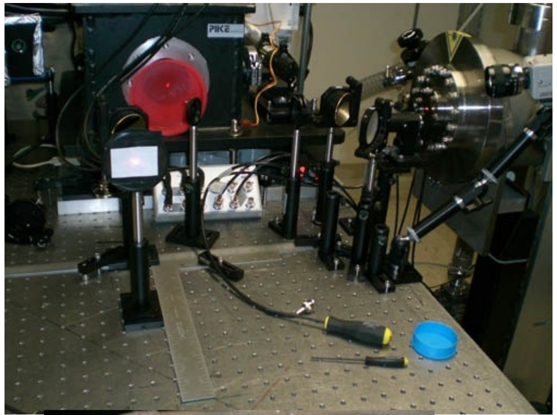
PICOMETRIX

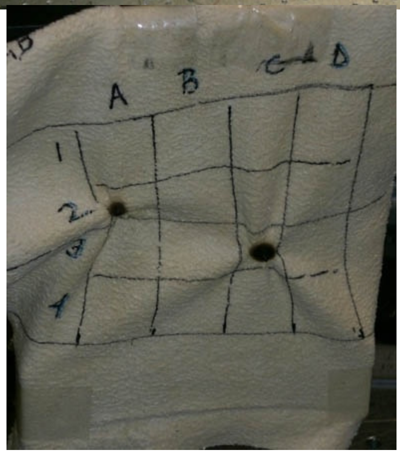
NJIT Department of Physics

David Zimdars, John Federici

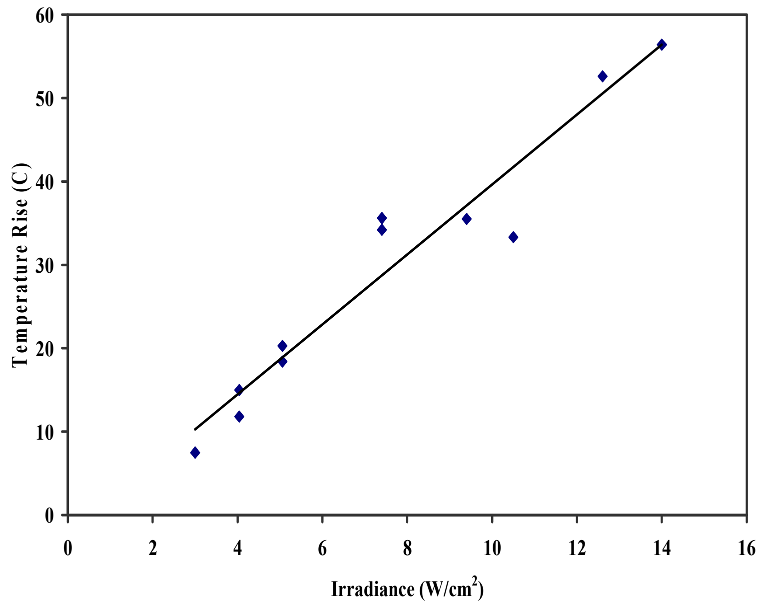
Brooks AFB Terahertz Skin Experiments & Modeling

- Performed at Jefferson Laboratory
- Experimental Validation of models
  - characterization of the beam
  - exposures of wet chamois, 2 phantoms





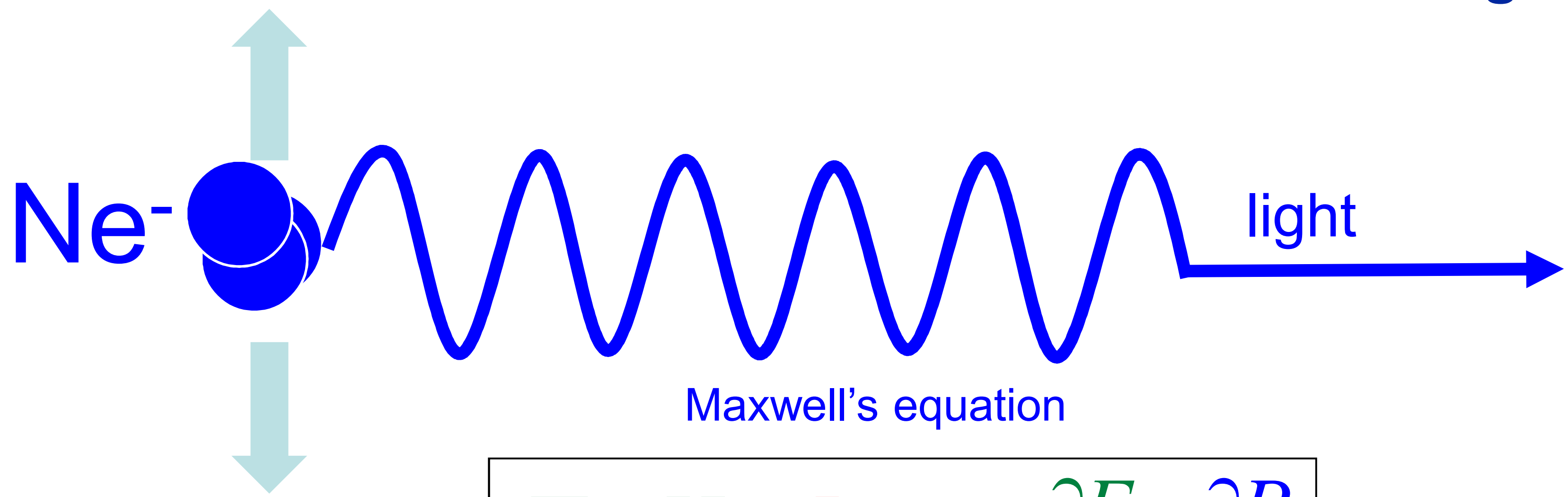
- ED_{50} (2 s exposure) chamois = 7.14 W/cm^2
- Model predicted 4-5 W/cm^2



- Jill McQuade et al.

How do we make light – why are accelerators so spectacular?

N electrons make N^2 as much light.



Maxwell's equation

$$\nabla \times H = J_{"Free"} + \varepsilon_o \frac{\partial E}{\partial t} + \frac{\partial P}{\partial t}$$

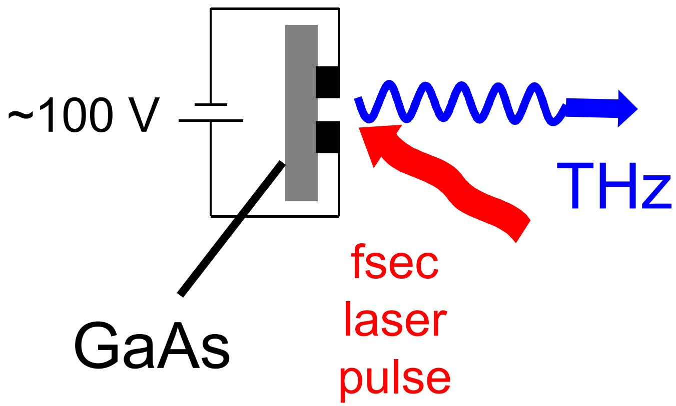
$$\frac{dE}{d\bar{\nu}} \approx 2 \times 10^{-25} \text{J/cm}^{-1}\text{/electron}$$

$$\text{Larmor's Formula: Power} = \frac{2(Ne)^2 a^2 \gamma^4}{3c^3} \text{ (cgs units)}$$

Comparing Conventional and Accelerator THz Sources

Larmor's Formula: $\text{Power} = \dfrac{2e^2a^2}{3c^3}\gamma^4$ (cgs units)

a=acceleration
c=vel. of light
γ=mass/rest mass

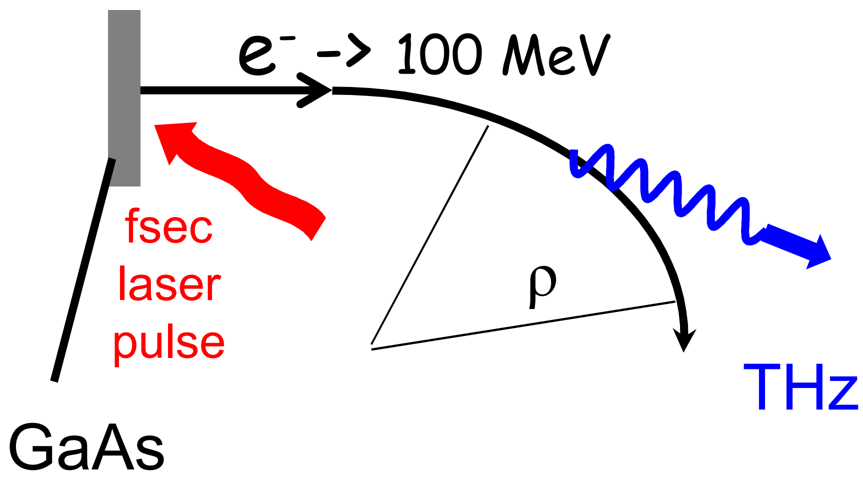


$$E = \frac{100V}{10^{-4}m} = 10^6\, V/m$$

$$a = \frac{F}{m} = \frac{10^6 V}{.5MeV/c^2} = \frac{10^6(3\times10^8)^2}{0.5\times10^6}$$

$$\cong 10^{17}\, m/sec^2$$

Carr et al Nature **420**, 153 (2002)



$$a = \frac{c^2}{\rho} = \frac{(3\times10^8)^2}{1} \cong 10^{17}\ m/sec^2$$

$$if\ \ \rho = 1\,meter$$

$$\gamma \approx 200\ \ and\ \ \ 200^4 = 10^9\ !!!!$$

Challenges of THz Imaging

- Providing sufficient THz power to illuminate a large field of view
- Properly collecting the reflected THz radiation from the target region (transmission mode generally not useful)
- Filtering of the THz induced thermal IR
- Properly imaging onto a detector array
- Creating imaging arrays designed specifically for THz imaging
- Defining and satisfying safe exposure limits