Applications of Intense CSR from a cw Linac at Jefferson Lab

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UVSOR Workshop on Terahertz Coherent Synchrotron Radiation September 23-25, 2007

Introduction to the Jefferson Lab CSR THz Source

Source Characteristics

- 1 microJoule per pulse, 75 MHz, 180 fs FWHM

  10 MW peak, 100 Watt average power

- Achieved using superconducting linac with cw rf

Overview of the CSR THz Programs at Jefferson Lab

- Tissue interactions and safety limits.
- Imaging.
- Spectroscopy development – signal to noise etc..
  - $\Rightarrow$ magnetism, dynamics of quasiparticles, spin
  - $\Rightarrow$ localization effects

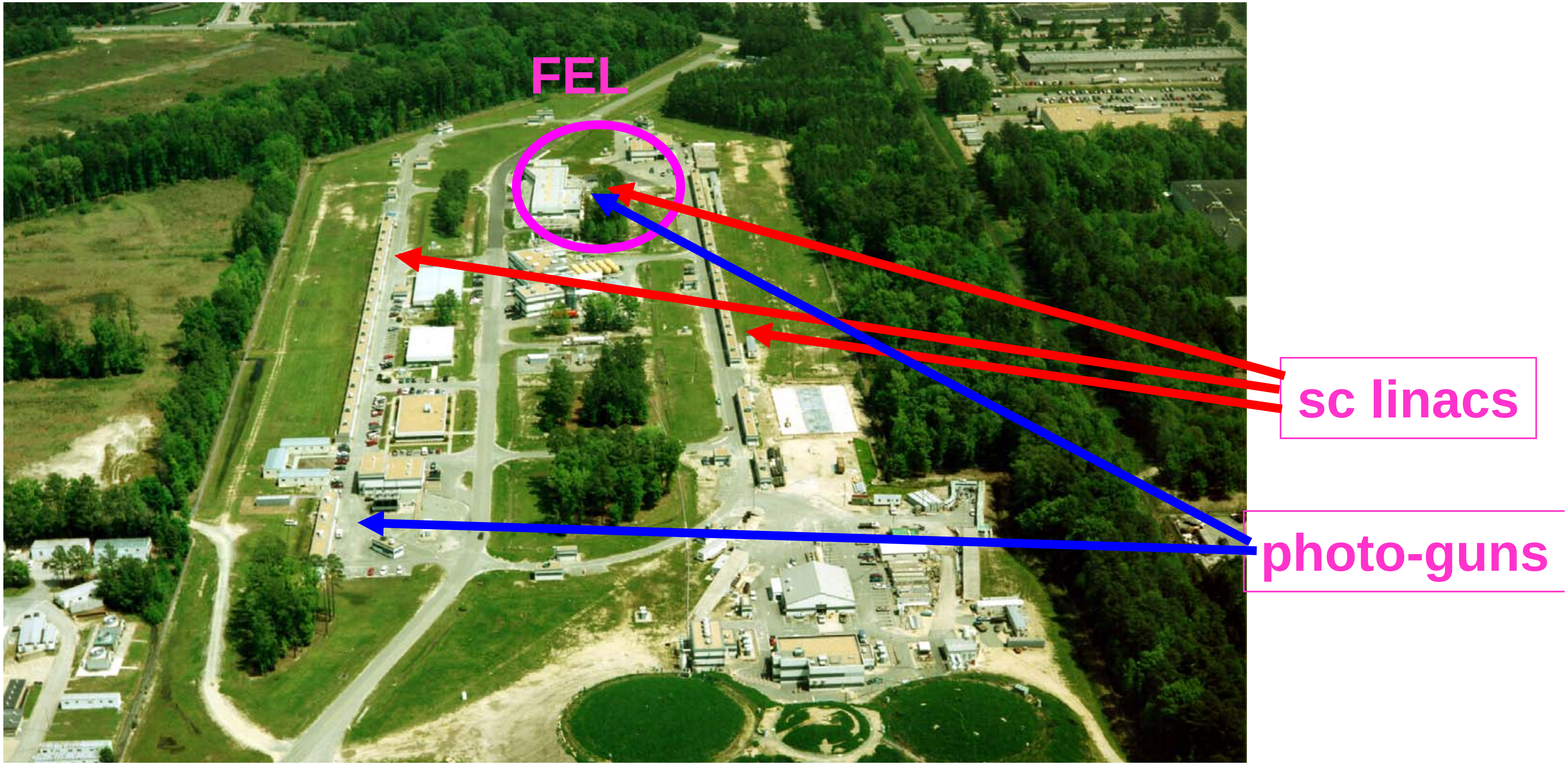
Future

- Electro-optical detection
- Quantum coherence and control.
- Coherent Half- and Few-Cycle Sources for Nonlinear and Non-Equilibrium Studies.

Jefferson Lab - where are we?

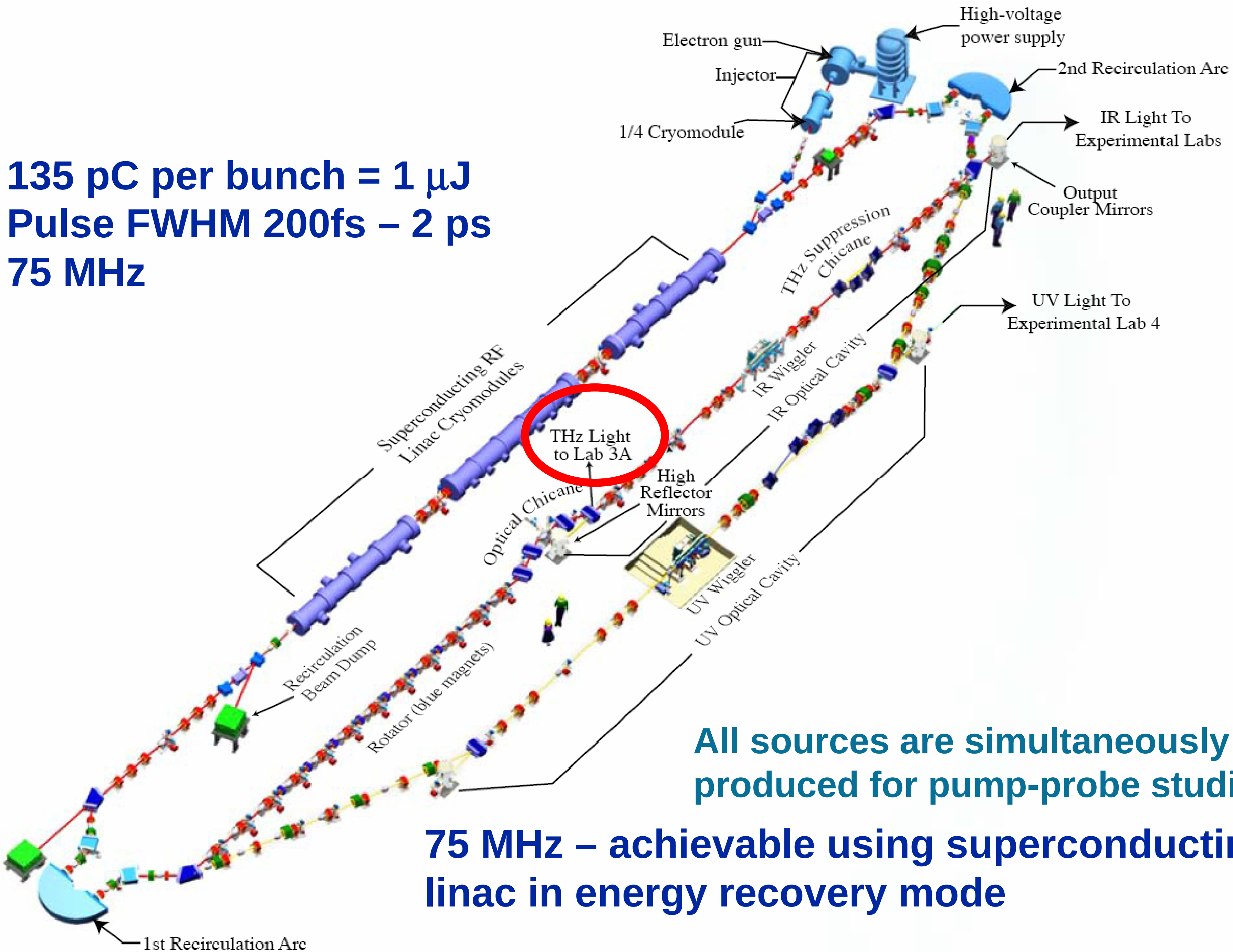
Jefferson Lab, Newport News, VA

Home of 2 accelerators: each with superconducting linacs, photo-cathode guns



JLab Free Electron Laser facility

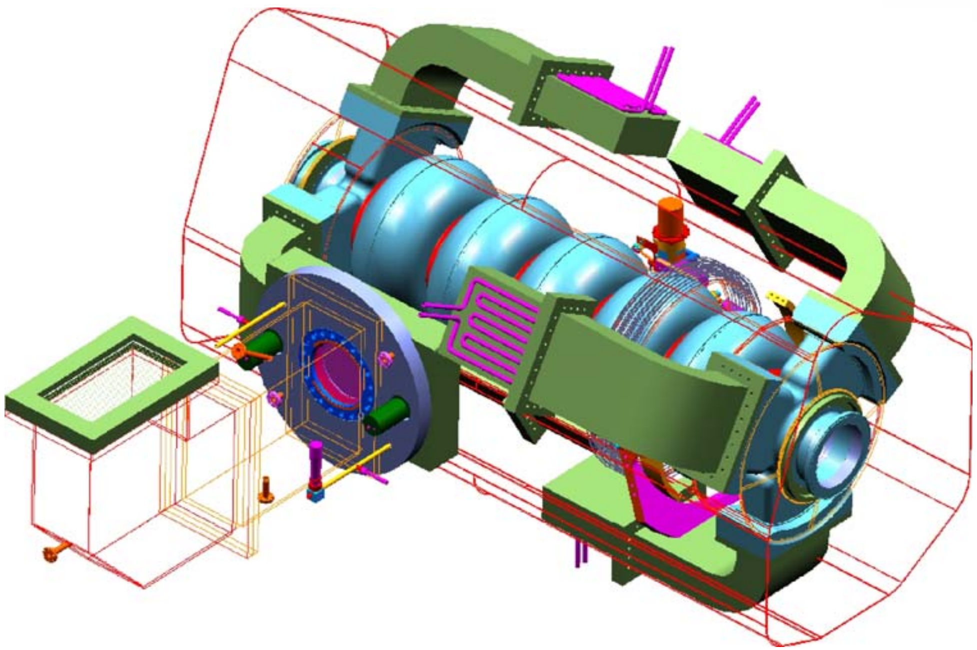
135 pC per bunch = 1 μJ
Pulse FWHM 200fs – 2 ps
75 MHz

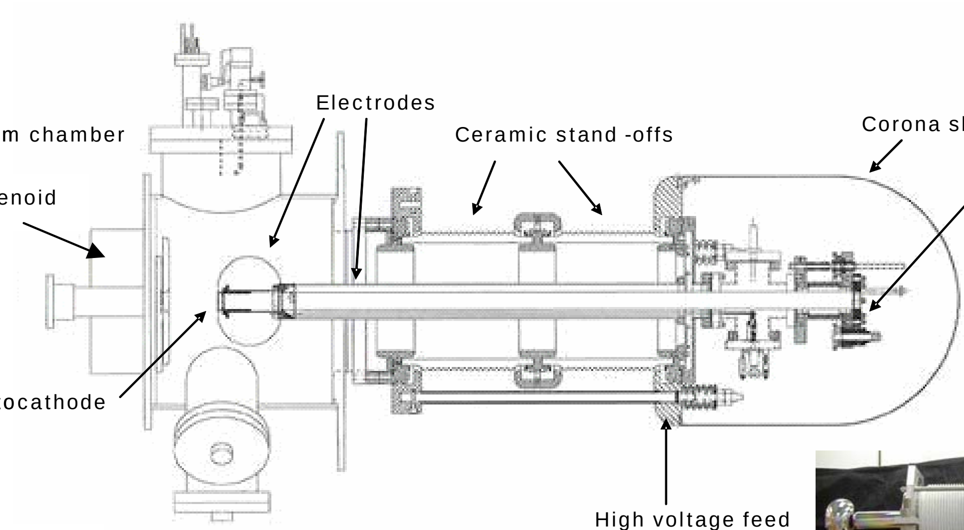


All sources are simultaneously produced for pump-probe studies

75 MHz – achievable using superconducting linac in energy recovery mode

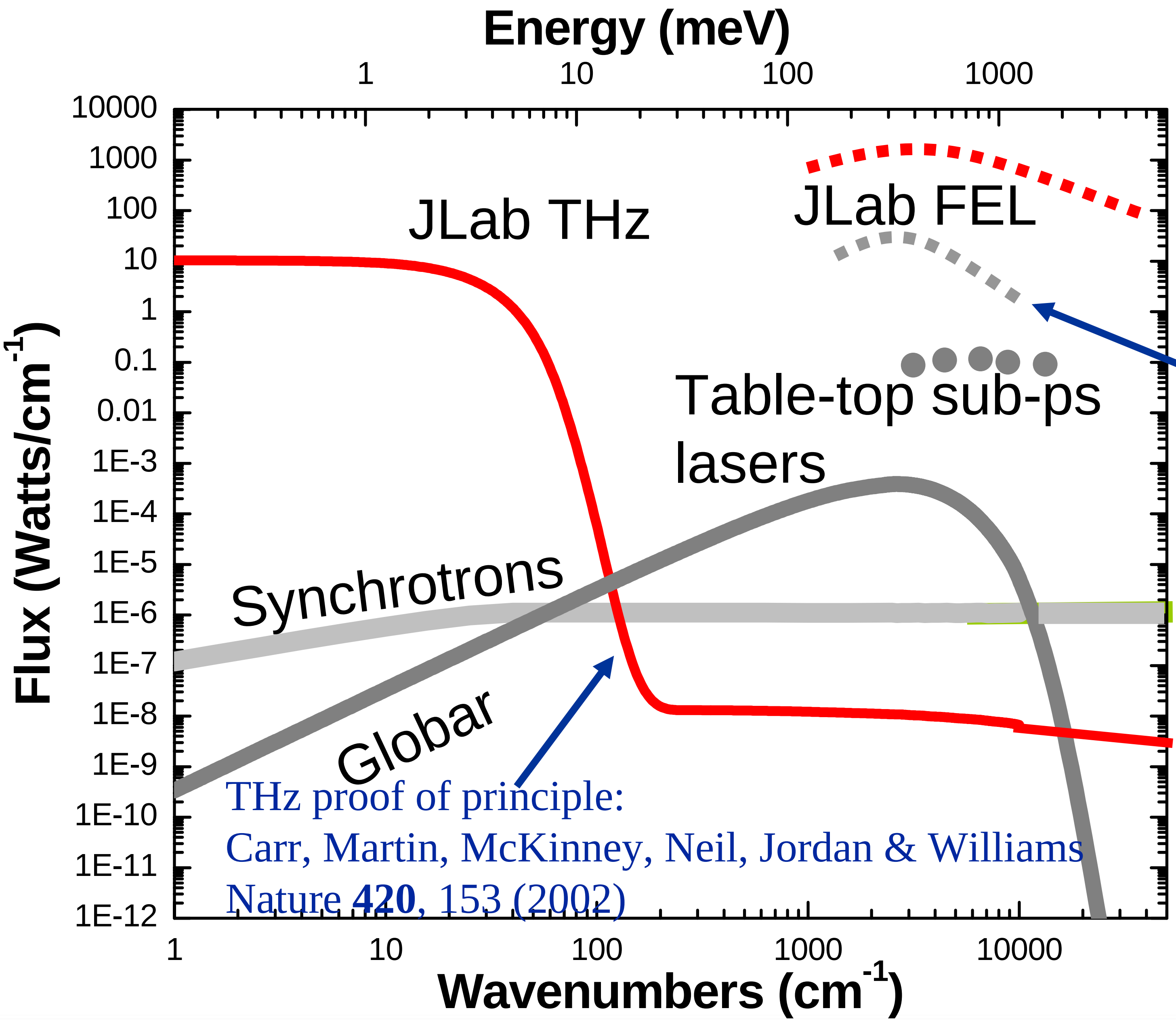
Superconducting linac cavity





Gun

Jefferson Lab Facility Spectroscopic Range and Power



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

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

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).

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

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

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

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

Larry Carr

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

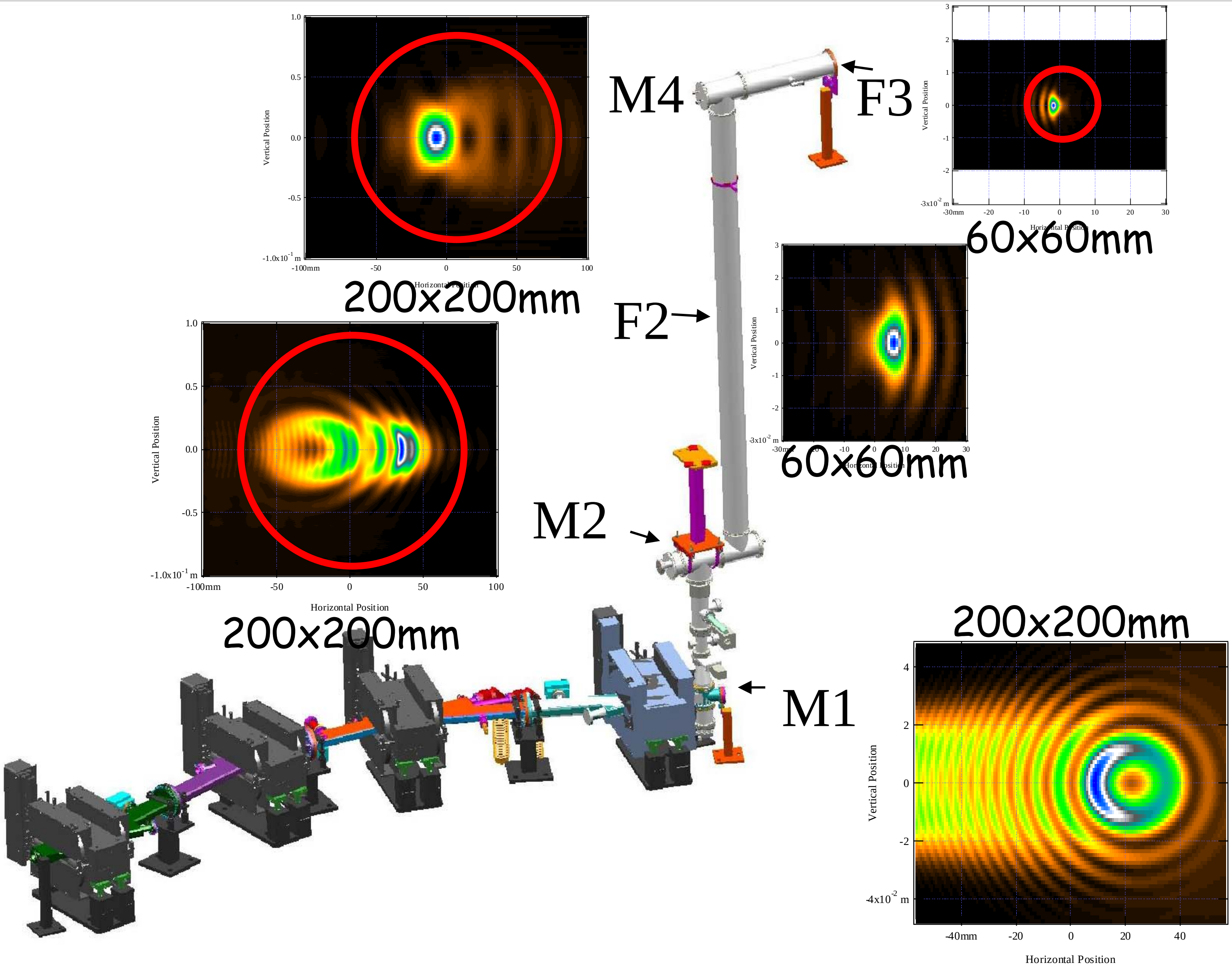
REFERENCES

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).

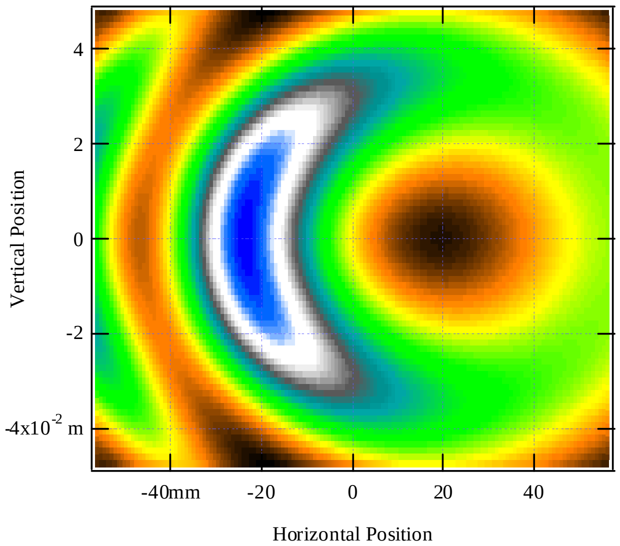
S. Nodvick and D.S. Saxon, Suppression of coherent radiation by electrons in a synchrotron. Physical Review **96**, 180-184 (1954).

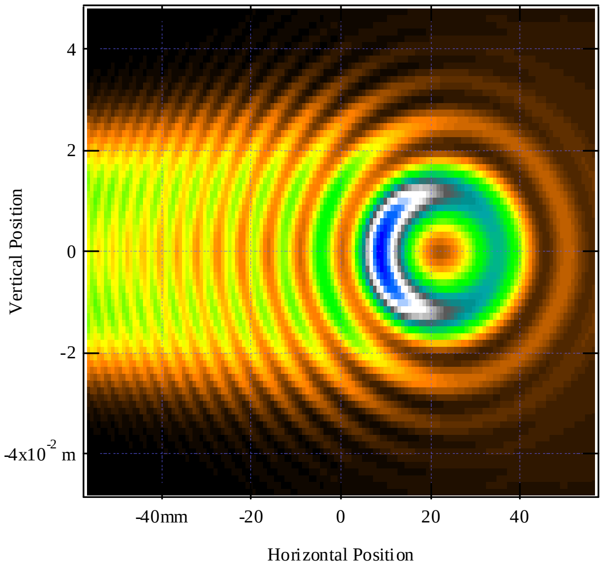
Carol J. Hirschmugl, Michael Sagurton and Gwyn P. Williams, Multiparticle Coherence Calculations for Synchrotron Radiation Emission, Physical Review **A44**, 1316, (1991).

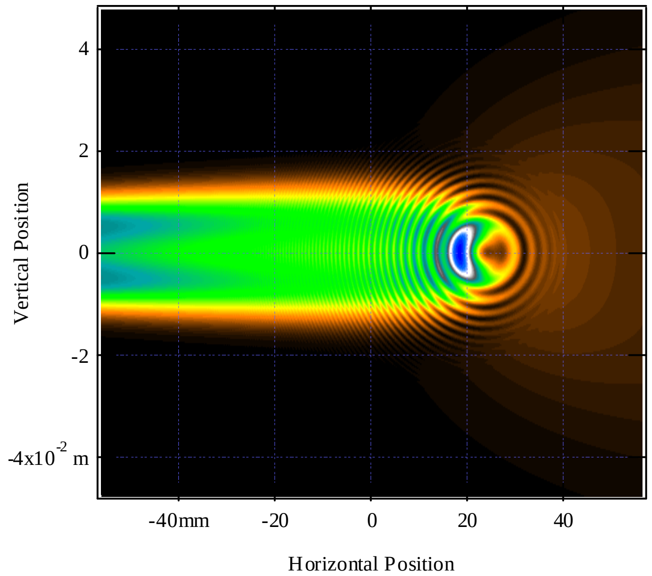
JLab THz Beam Schematic with Optical Beam Ray-tracing



JLab THz Beam Pattern on Mirror 1



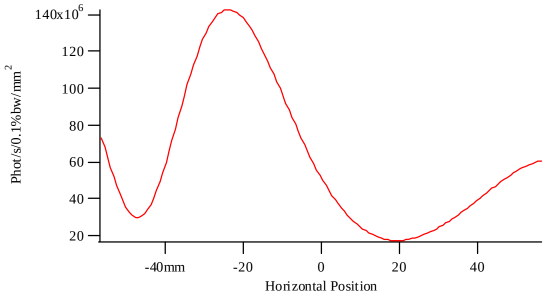


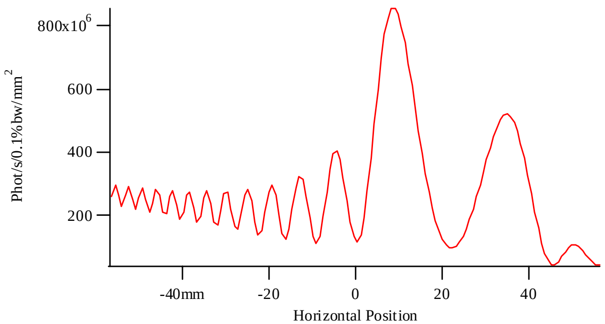


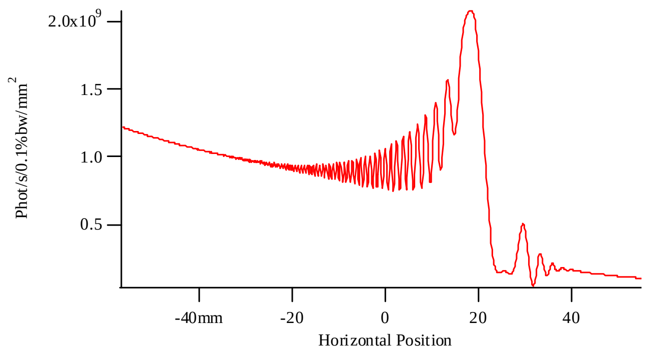
0.1 THz
$3.3\ cm^{-1}$

1 THz
$33\ cm^{-1}$

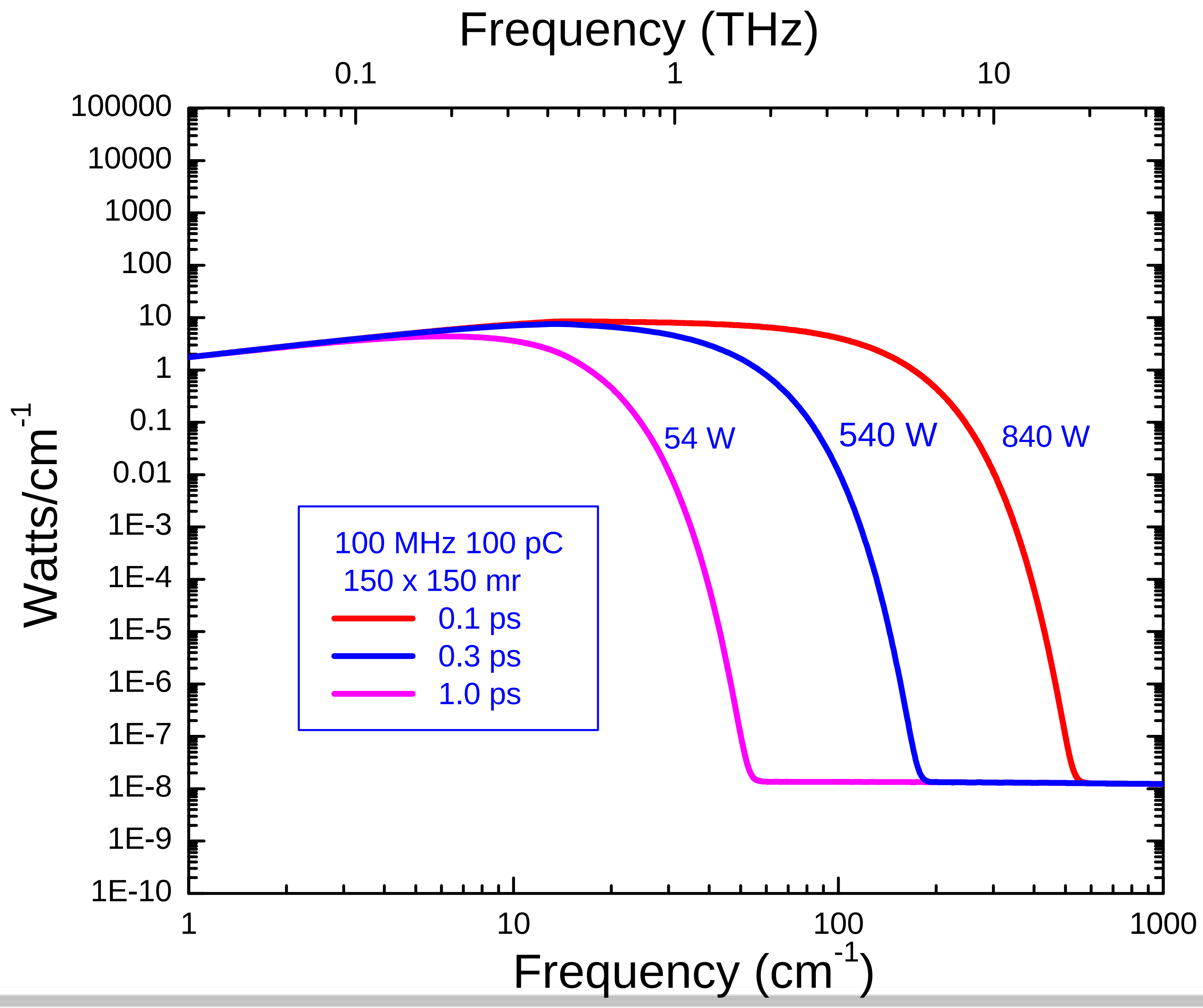
10 THz
$330\ cm^{-1}$







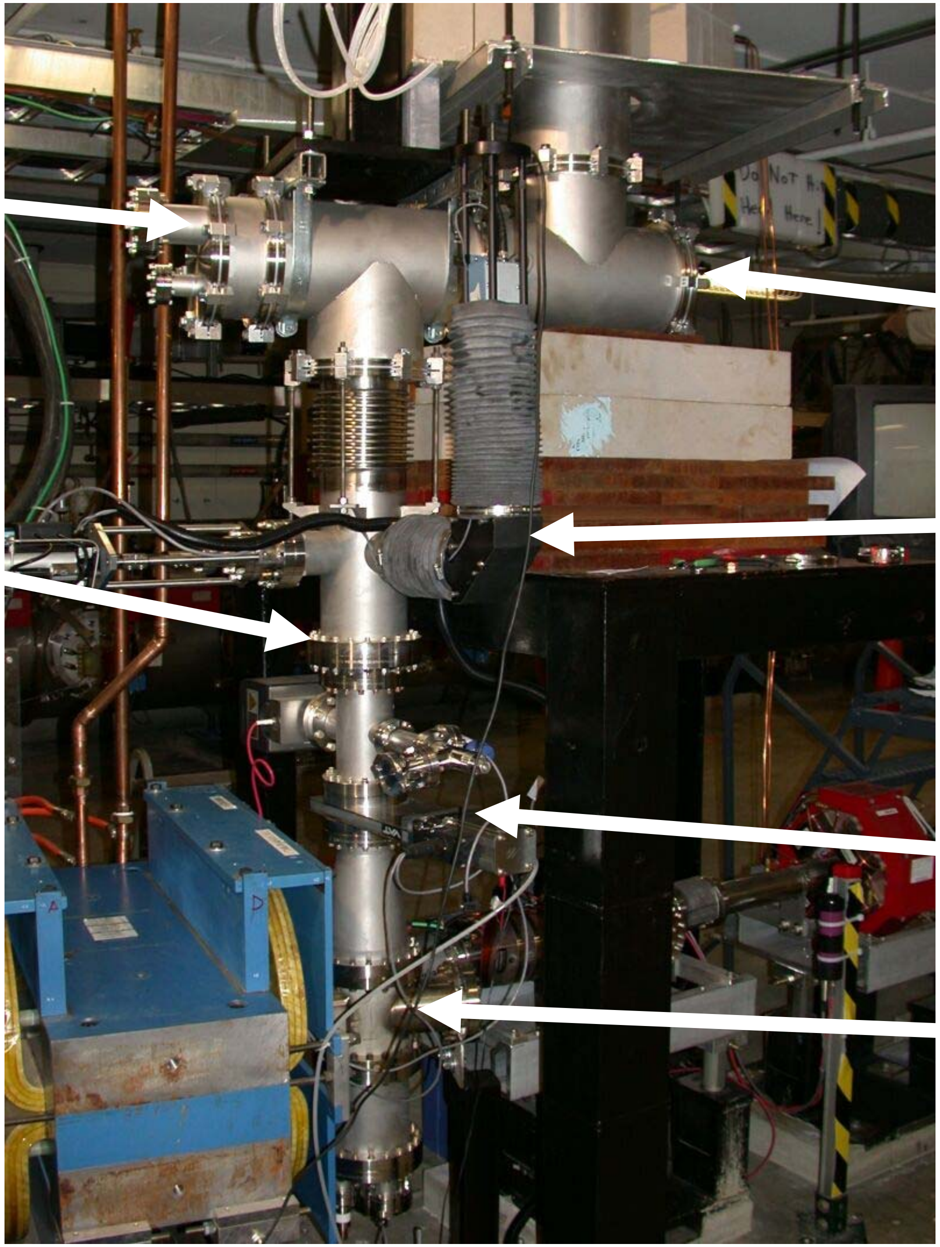
Jefferson Lab THz spectra and total power



JLab Terahertz Beam Extraction and Transport

M2

diamond window



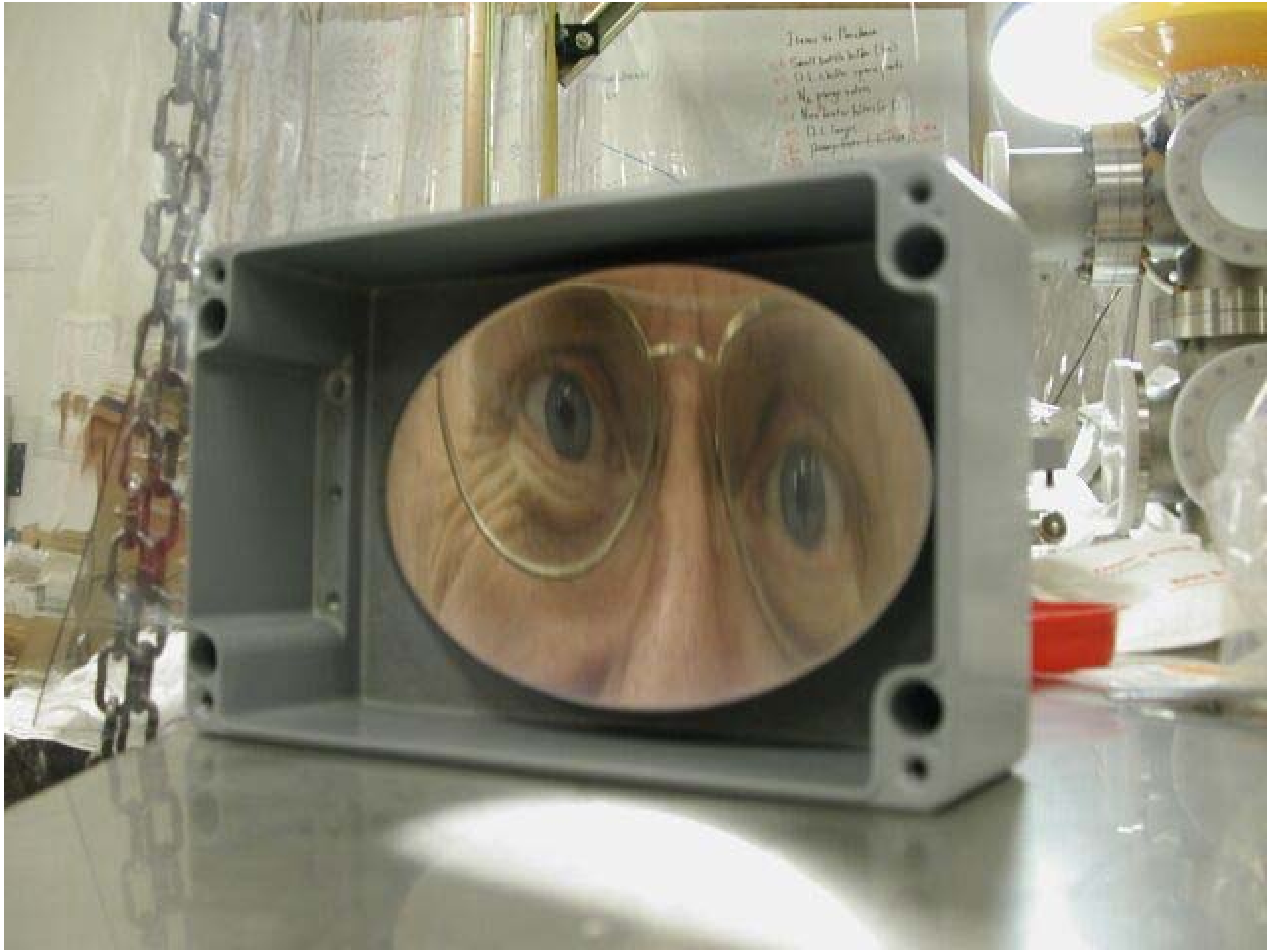
M3

Shutter/viewer & camera

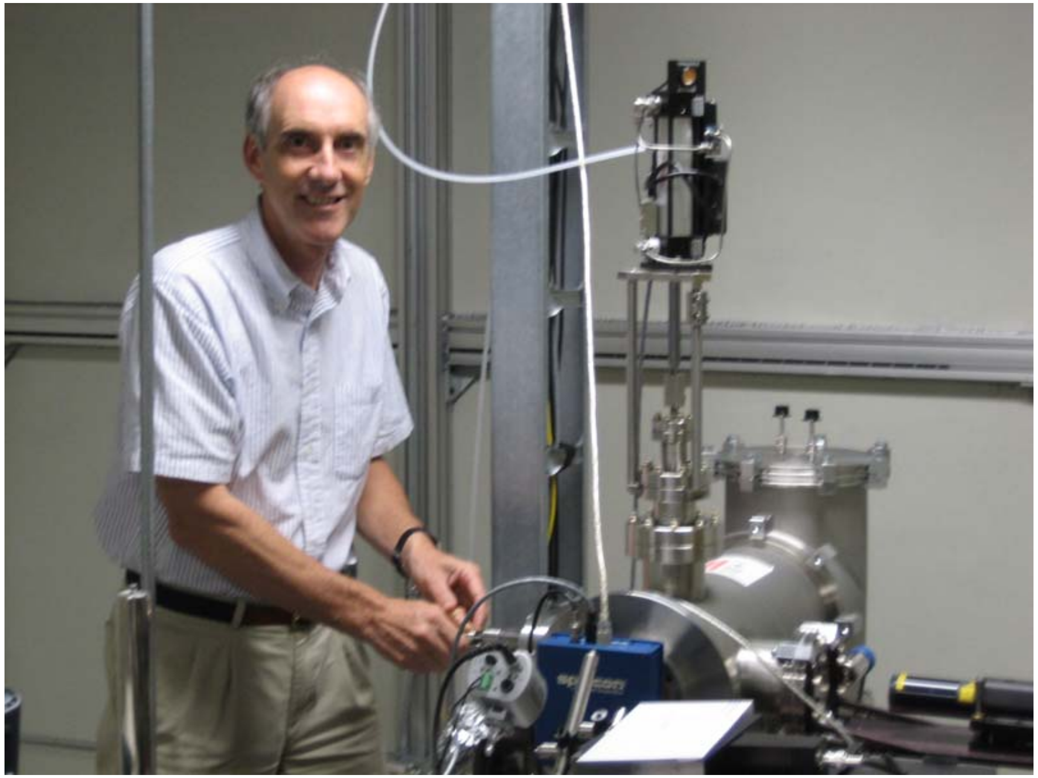
V1

M1

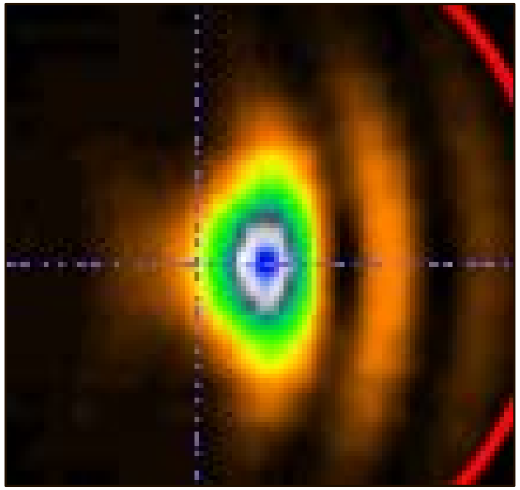
Mirror 1 - courtesy of Richard Wylde, (Thomas Keating)



JLab power permits large area imaging ~ m^2

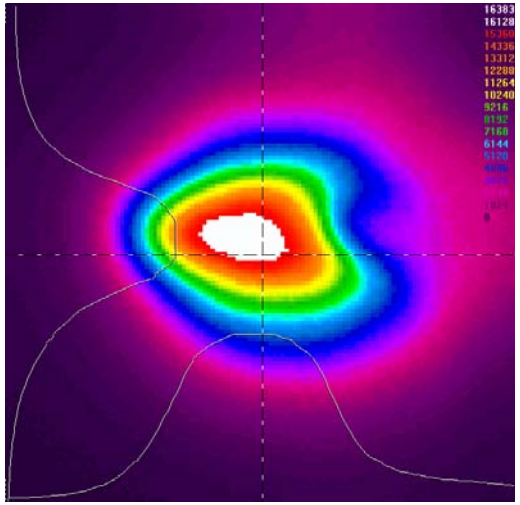


Optical transport output in User Lab



Ray trace

10mm^2



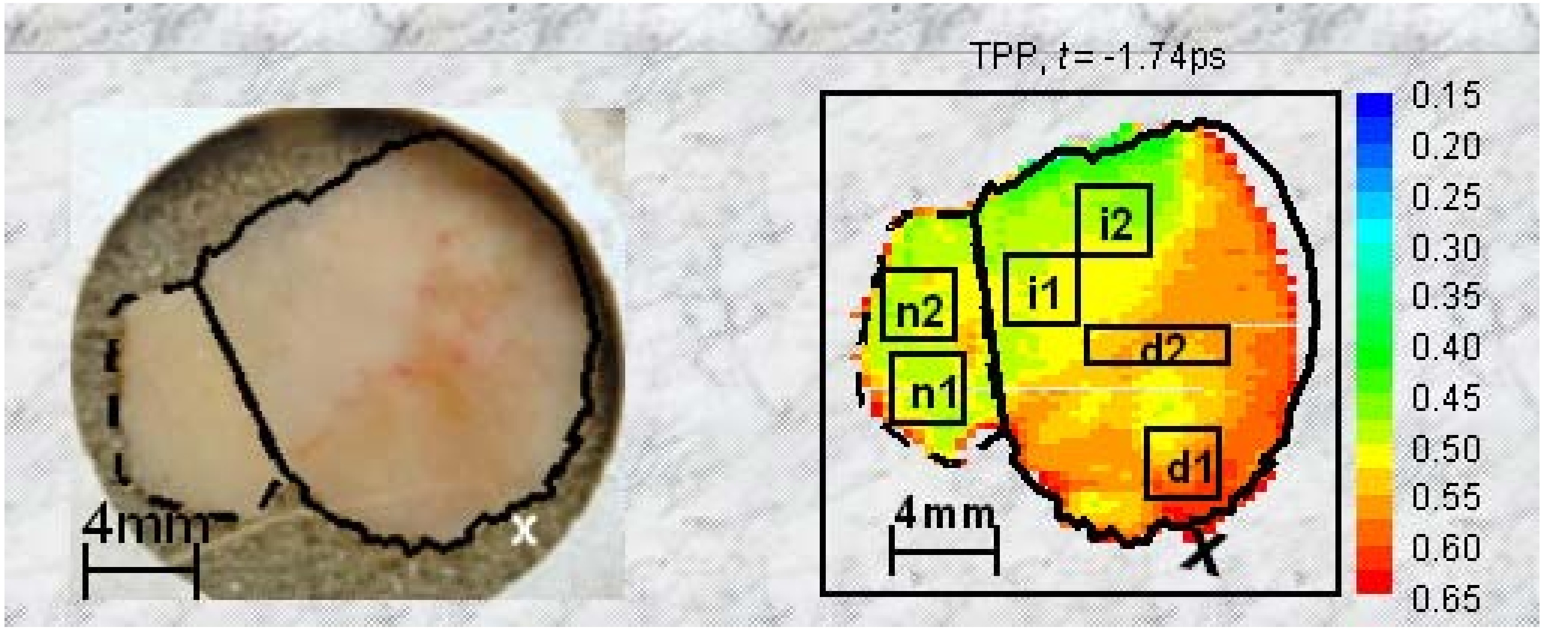
Real time image

Thomas Jefferson National Accelerator Facility

Challenges of Stand-off THz Imaging

- Providing sufficient THz power to illuminate a large field of view and to image in real time
- Properly collecting the scattered 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

Imaging / bio-medical cancer screening



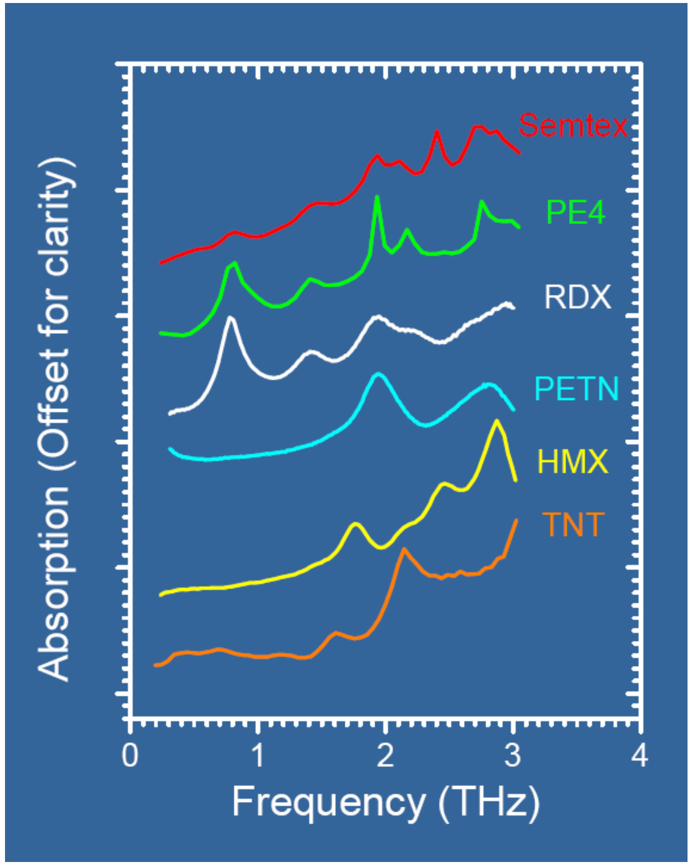
Basal cell carcinoma shows malignancy in red. Teraview Ltd.

1 mW source images 1 cm^2 in 1 minute

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

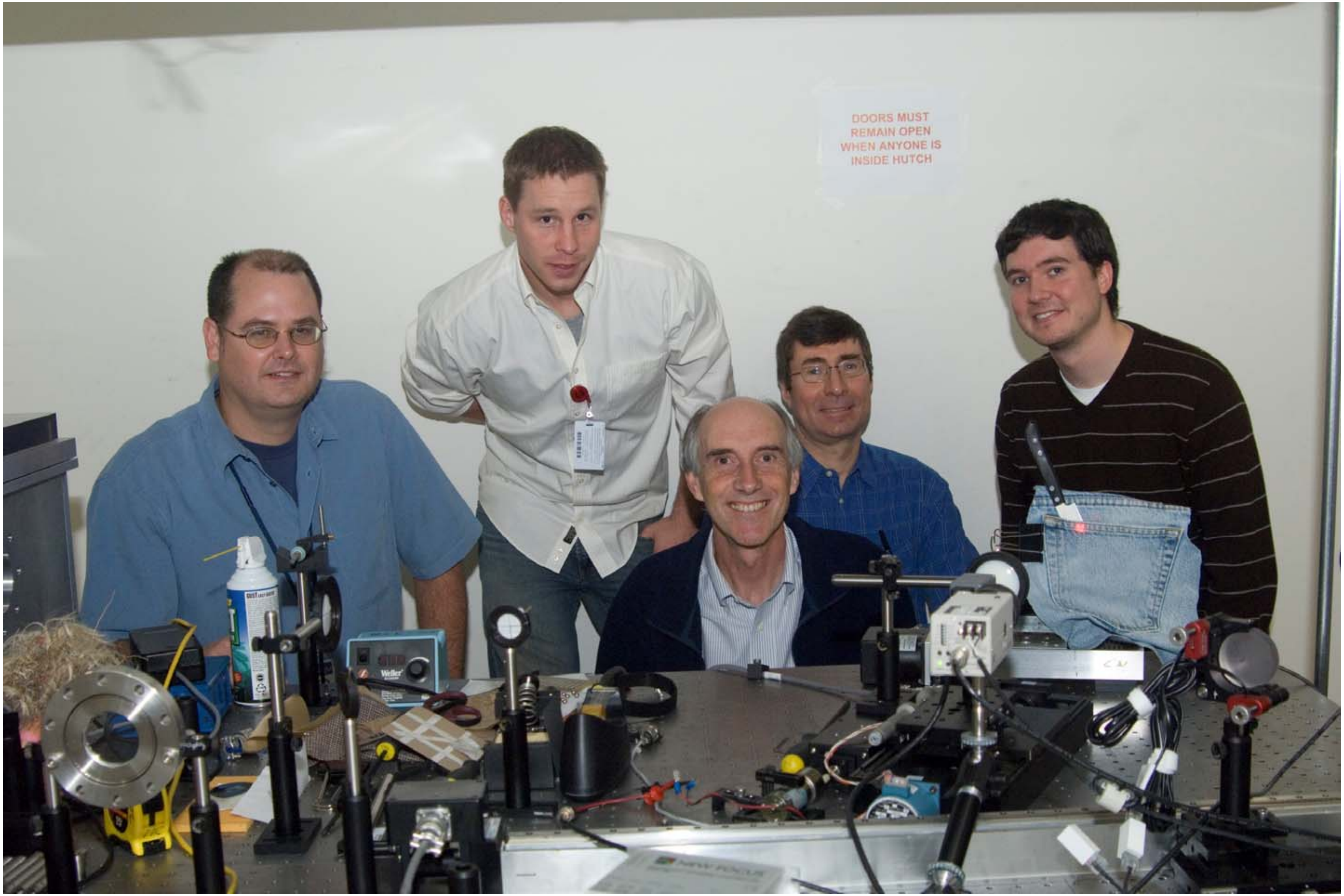
Imaging / security screening at portals

Clery, Science **297** 763 (2002)

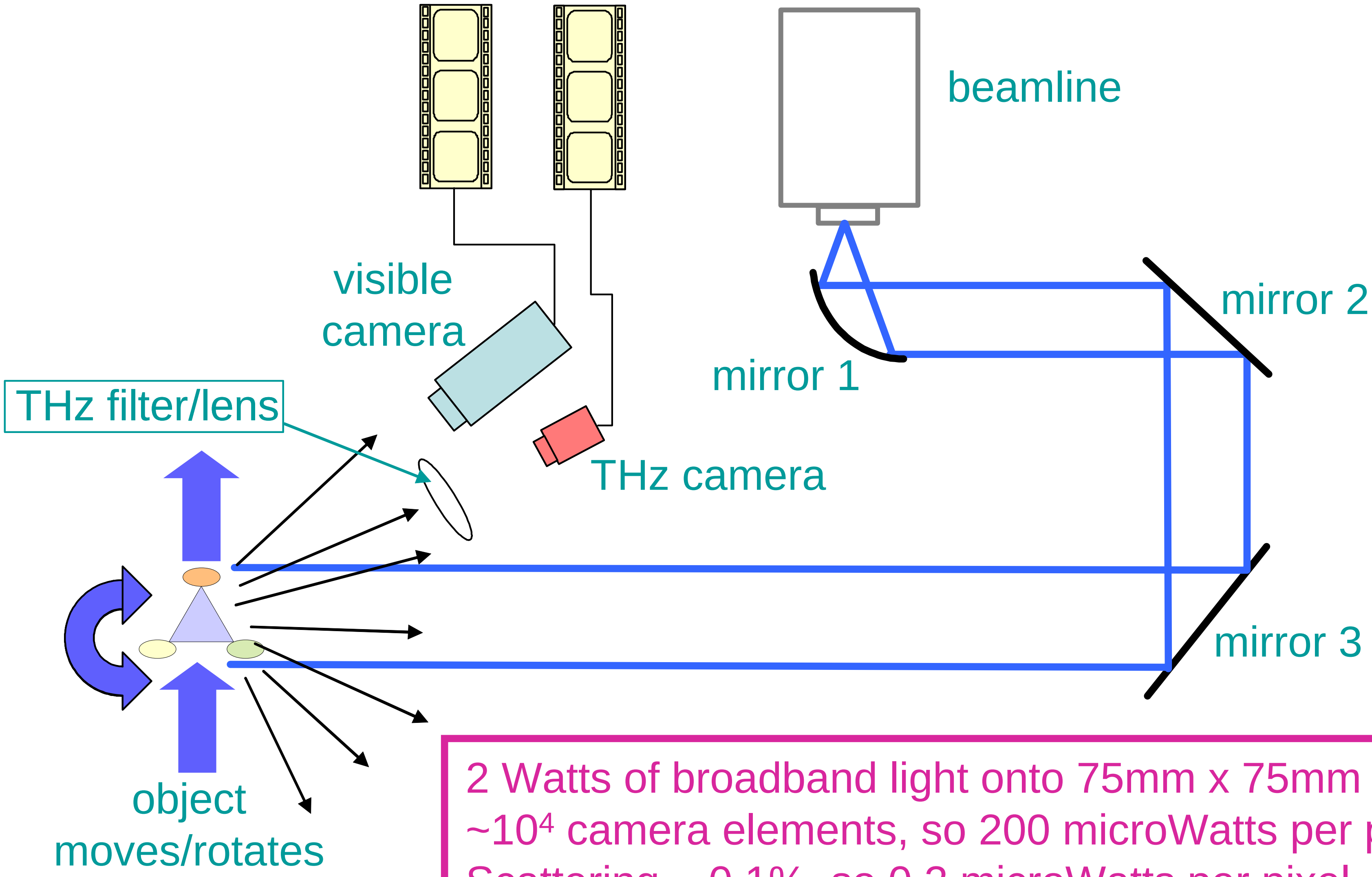


Spectra of explosives courtesy of Teraview

Jefferson Lab & U. of Delaware Team



THz Imaging Schematic



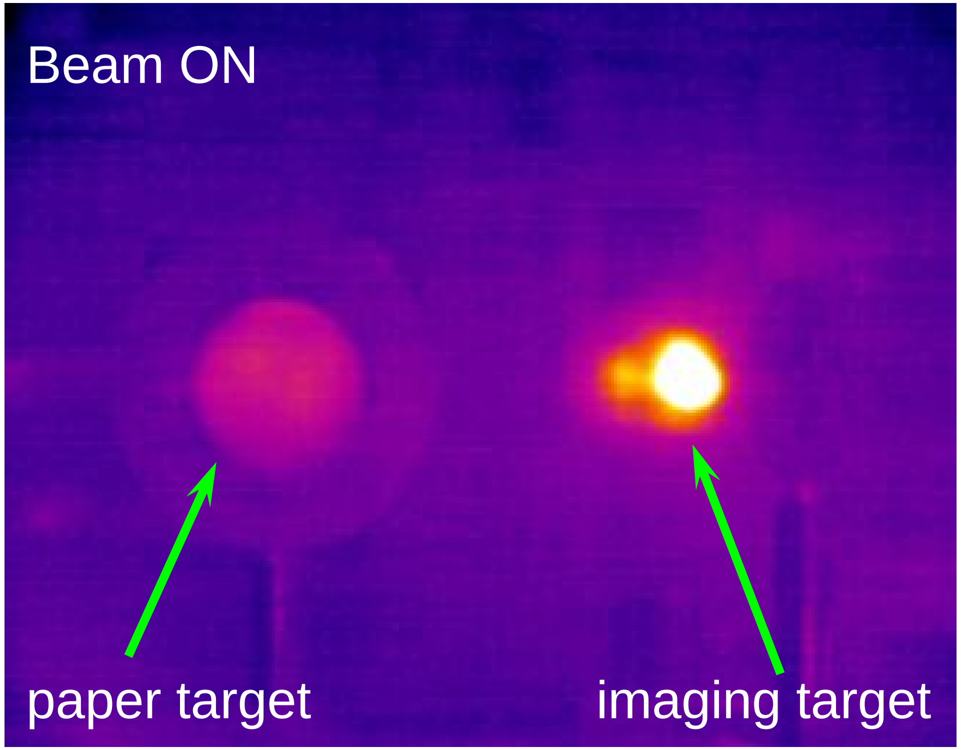
2 Watts of broadband light onto 75mm x 75mm field.
~10^4 camera elements, so 200 microWatts per pixel.
Scattering ~ 0.1%, so 0.2 microWatts per pixel.
Noise level, 1 nanoWatt, so S/N is ~200.

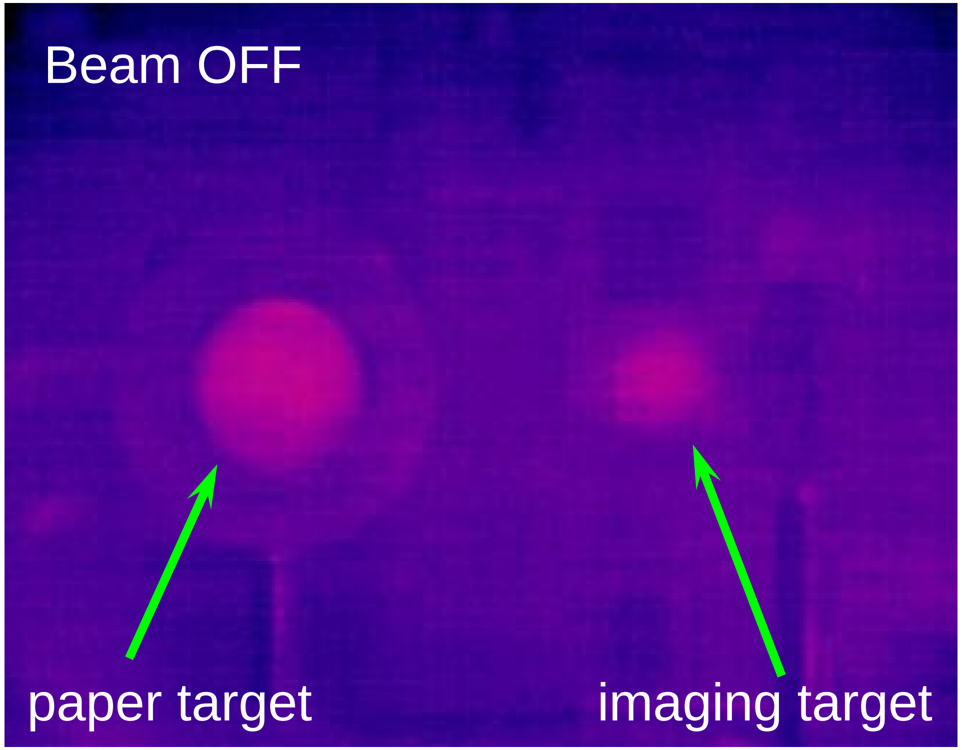
The Camera

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

THz Imaging Layout

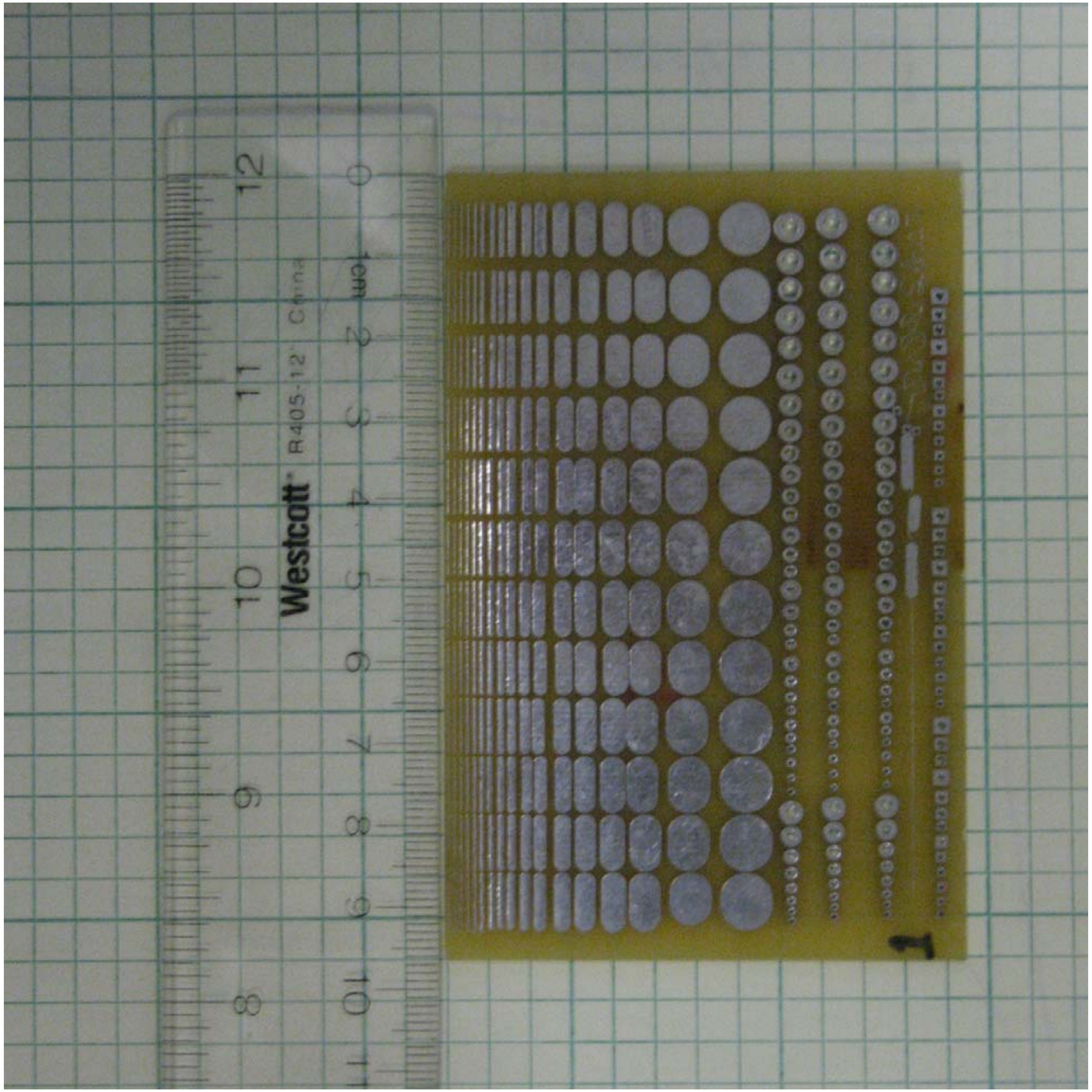
THz Induced Thermal IR



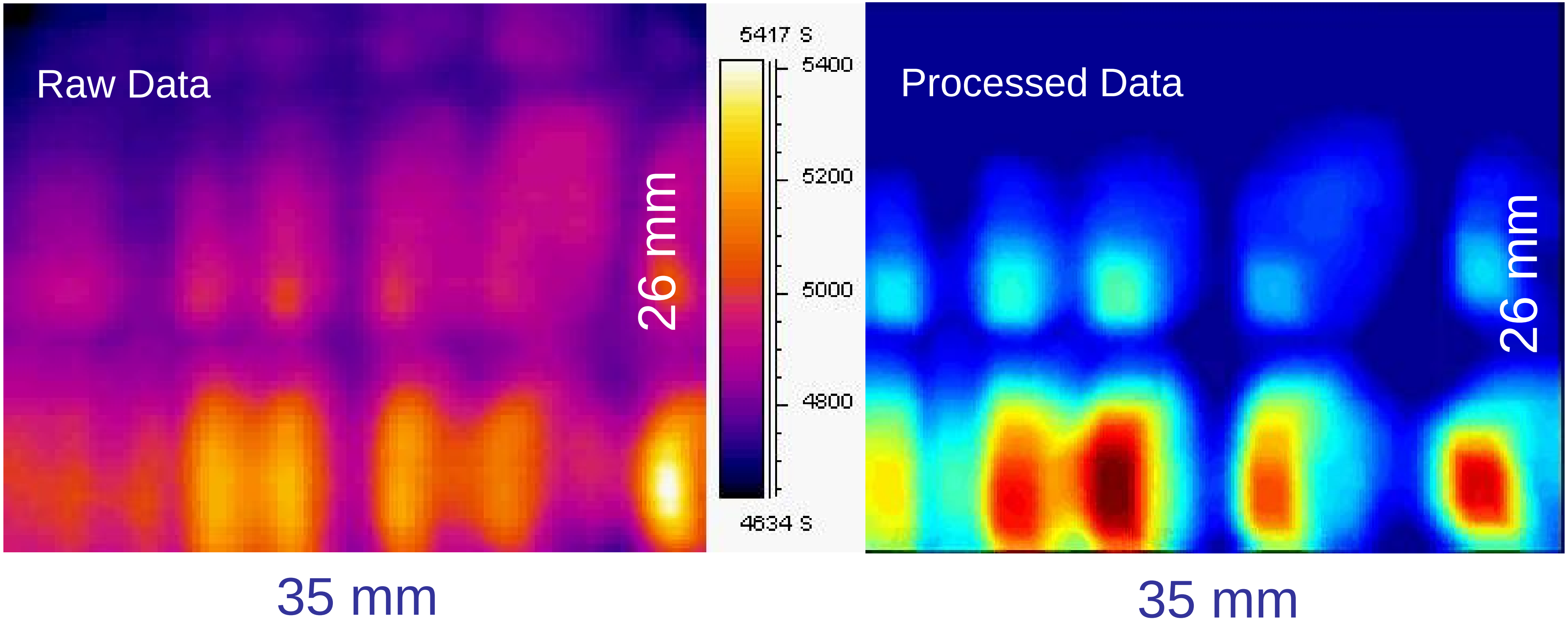


- Images taken using the stock Ge lens
- THz passes through paper target and is reflected off of the imaging target
- Heating due to absorption of THz heats the paper and the imaging target, producing the thermal IR seen above

Test Pattern Imaging Target

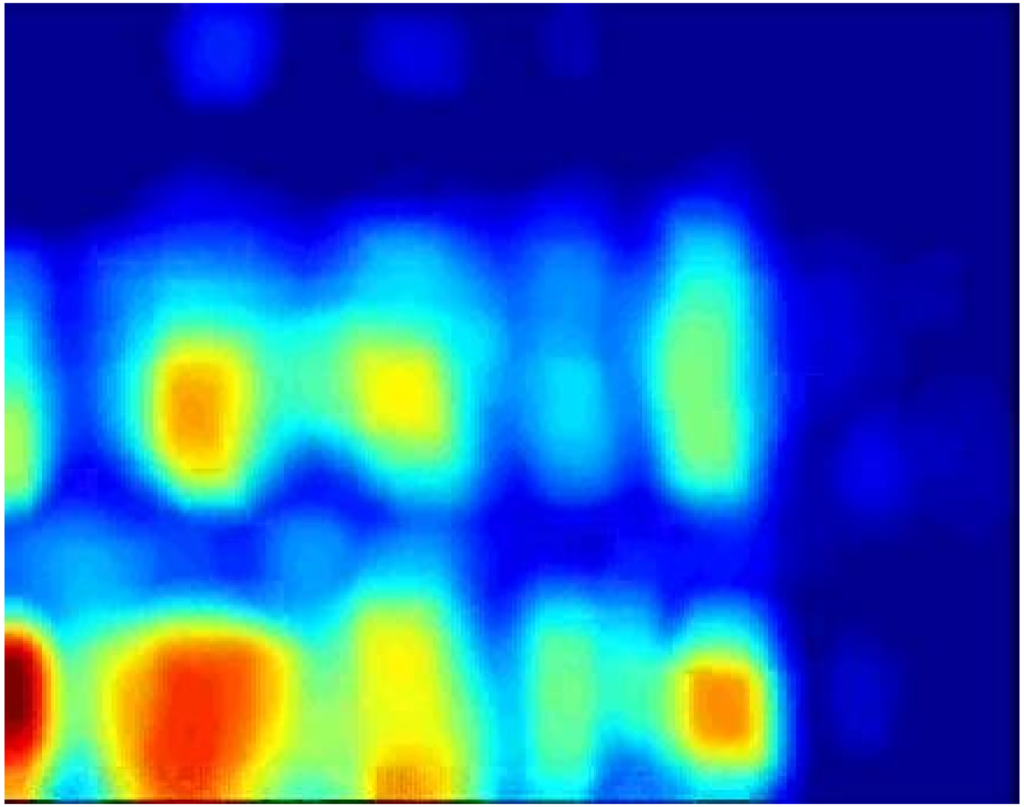


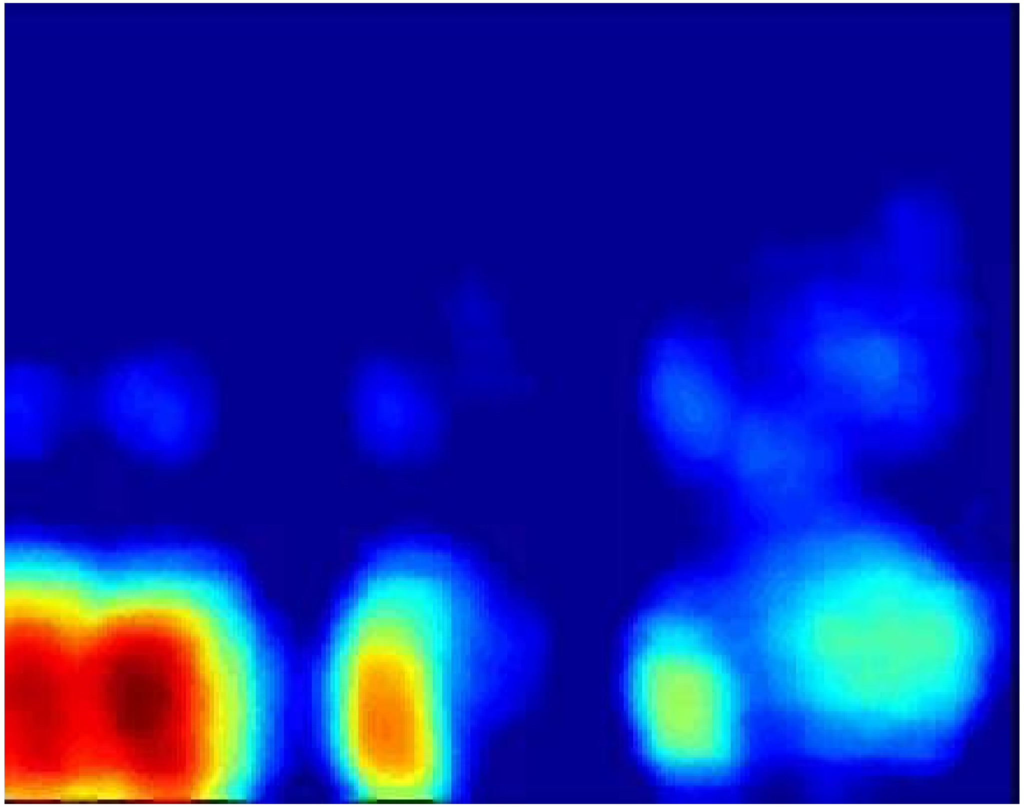
Test of Imaging Resolution



- 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

THz Imaging Covered Target


CD mailer covering


cloth covering

THE AIR FORCE RESEARCH LABORATORY
LEAD | DISCOVER | DEVELOP | DELIVER

THEORETICAL AND EXPERIMENTAL BIOEFFECTS RESEARCH FOR HIGH-POWER TERAHERTZ ELECTROMAGNETIC ENERGY

23 Jan 07

Jill McQuade, PhD
Research Physiologist
Human Effectiveness Directorate
Air Force Research Laboratory

Human Effects, contd. - Jill McQuade

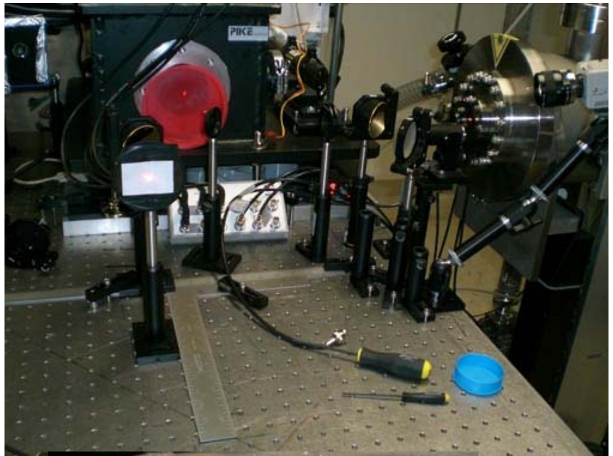
- Many applications for THz sources
- High-power sources and detectors are being developed
- Bioeffects need to be understood for the health and safety of personnel
- Bioeffects efforts need to catch up to or even lead technology development
- Bioeffects data pertaining to the health effects of high-powered THz exposure are non-existent

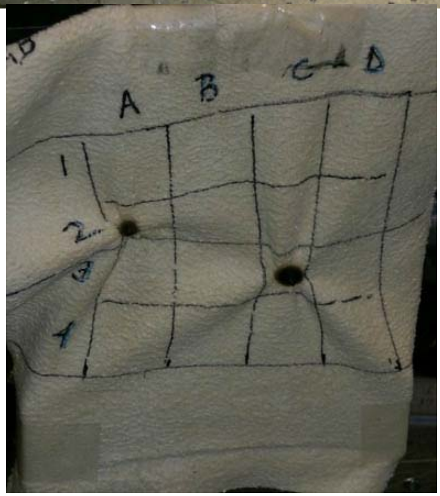
Brooks Air Force Base – Human Effects Division, Terahertz Team

Dr. Jill McQuade	HEDR	Physiologist: Project Lead
Dr. Bob Thomas	HEDO	Physicist: Modeling
Mr. Jason Payne	HEDR	Biomedical Scientist: Modeling
Ms. Nichole Jindra	HEDO	Biologist: Expt, pilot lead
Dr. Semih Kumru	HEDO	Physicist: Expt
Mr. Victor Villavicencio	HEDO-NG Cont	Physicist: Expt
Dr. Ron Seaman	HEDR–GD-AIES Cont	Physiologist: Expt, protocol
Mr. Alex Salazar	HEDR–GD-AIES Cont	Physiologist: Expt
Dr. Walter Hubert	HEDR	Molecular Biologist: Biotechnology

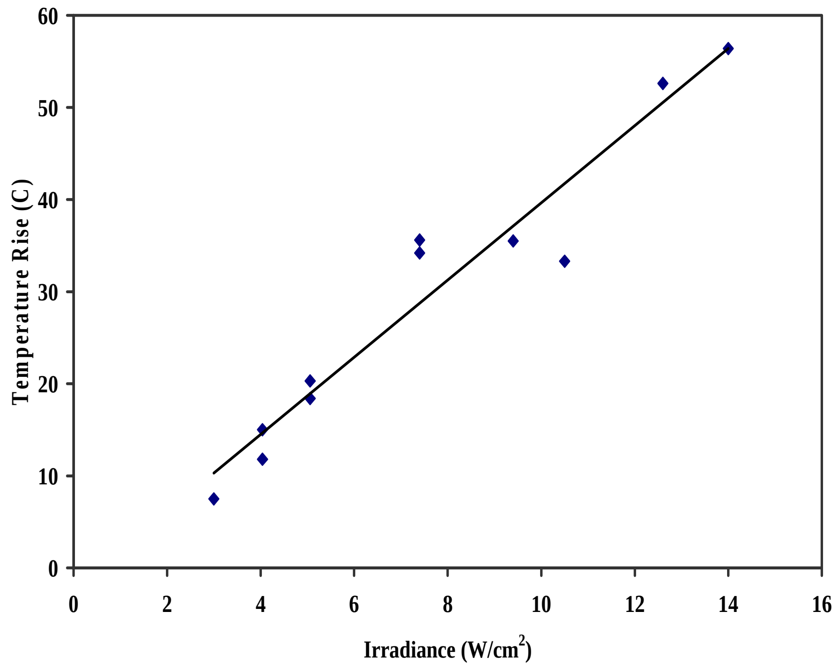
Brooks Terahertz Experiments & Modeling

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

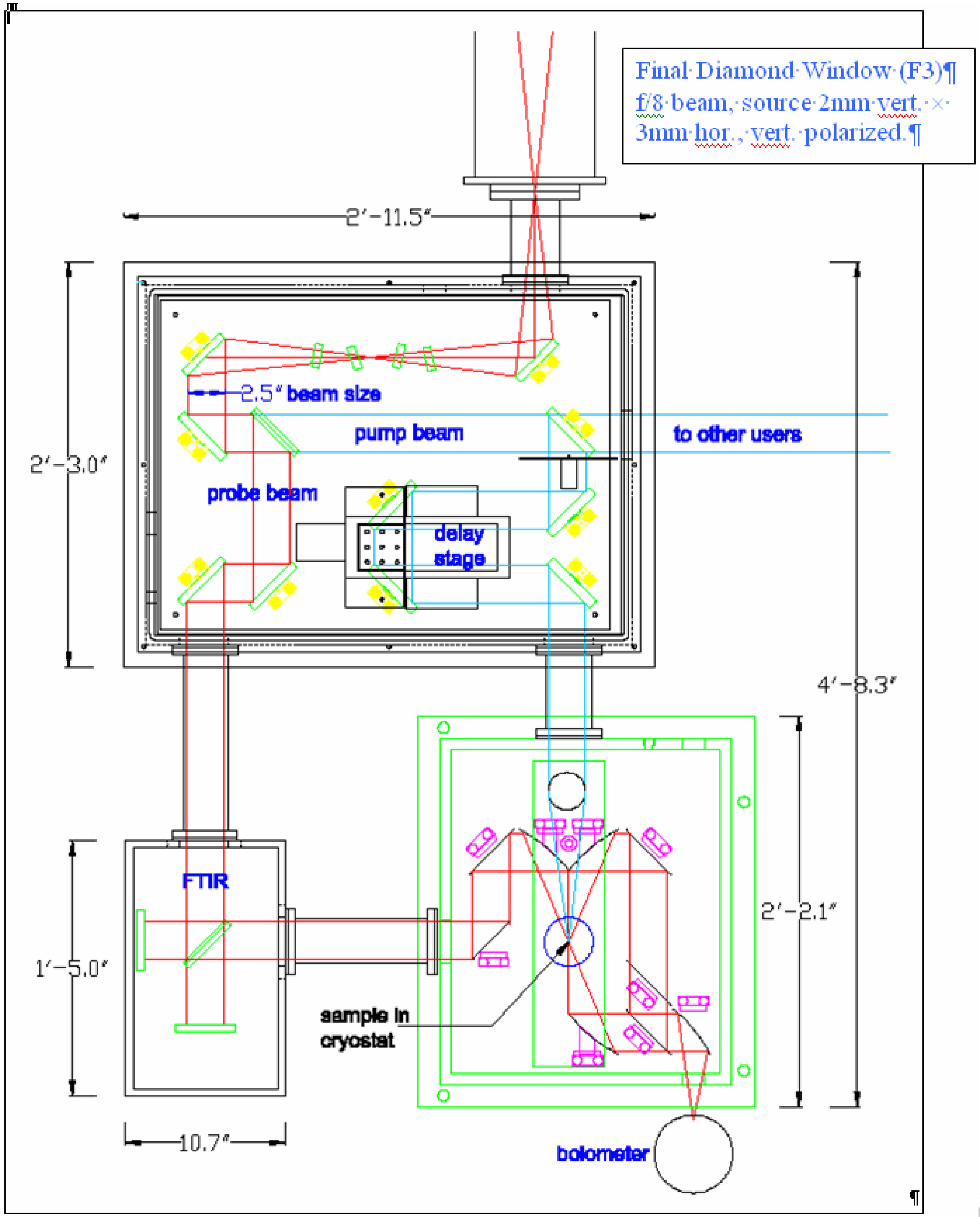




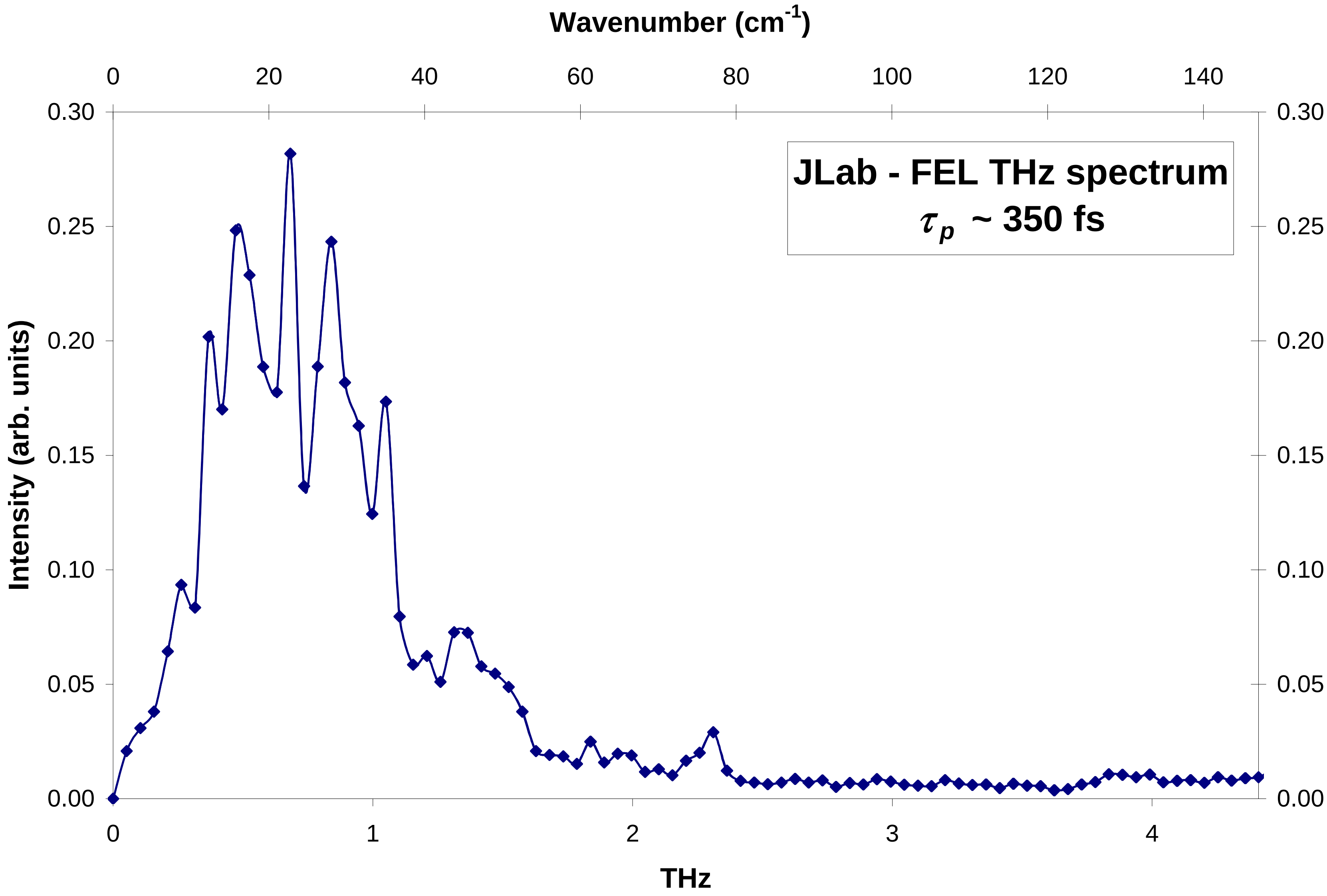
- ED_{50} (2 s exposure) chamois = 7.14 W/cm^2
- Model predicted 4-5 W/cm^2



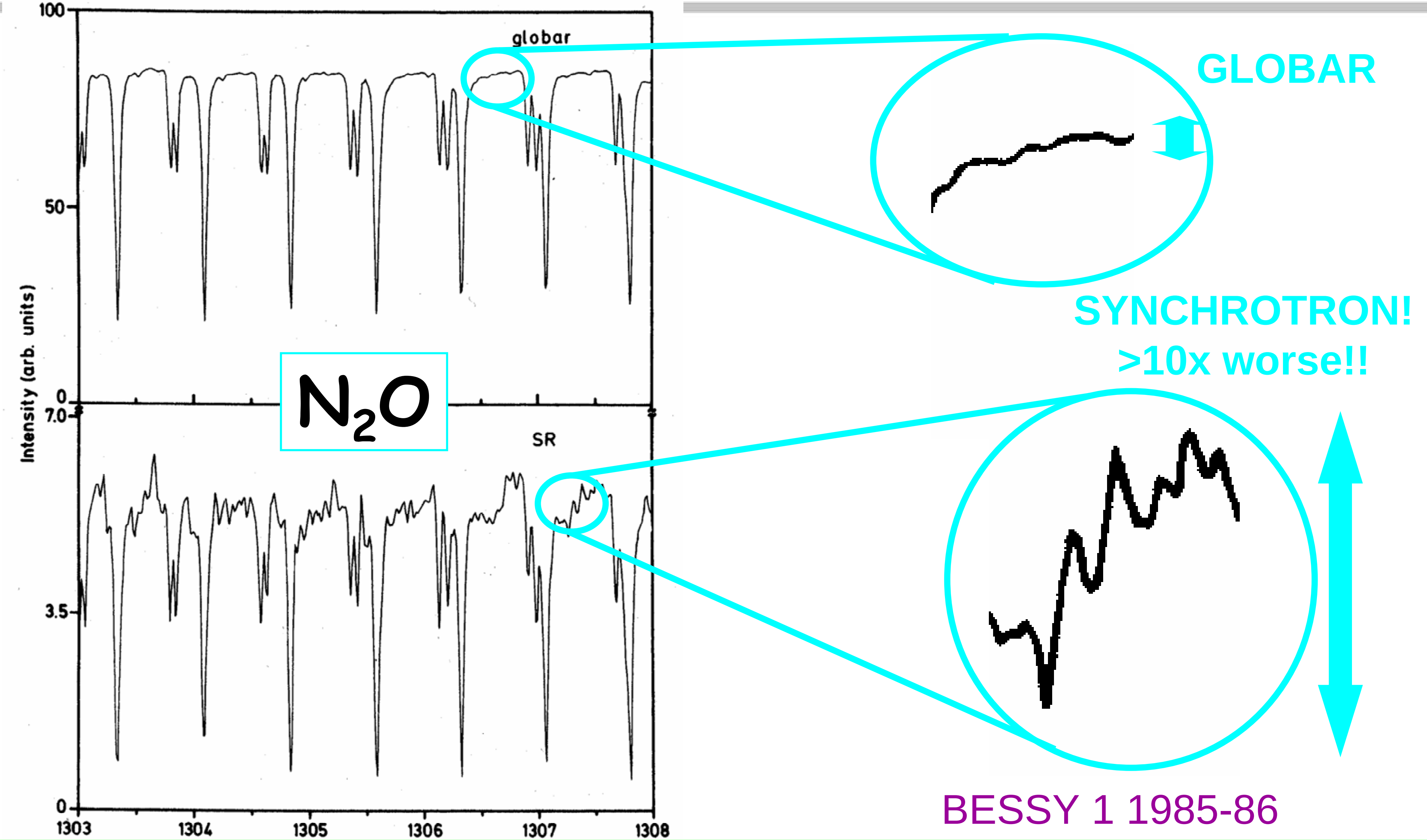
Laboratory layout for spectroscopy & pump-probe



Measured JLab – FEL THz Spectrum in Air



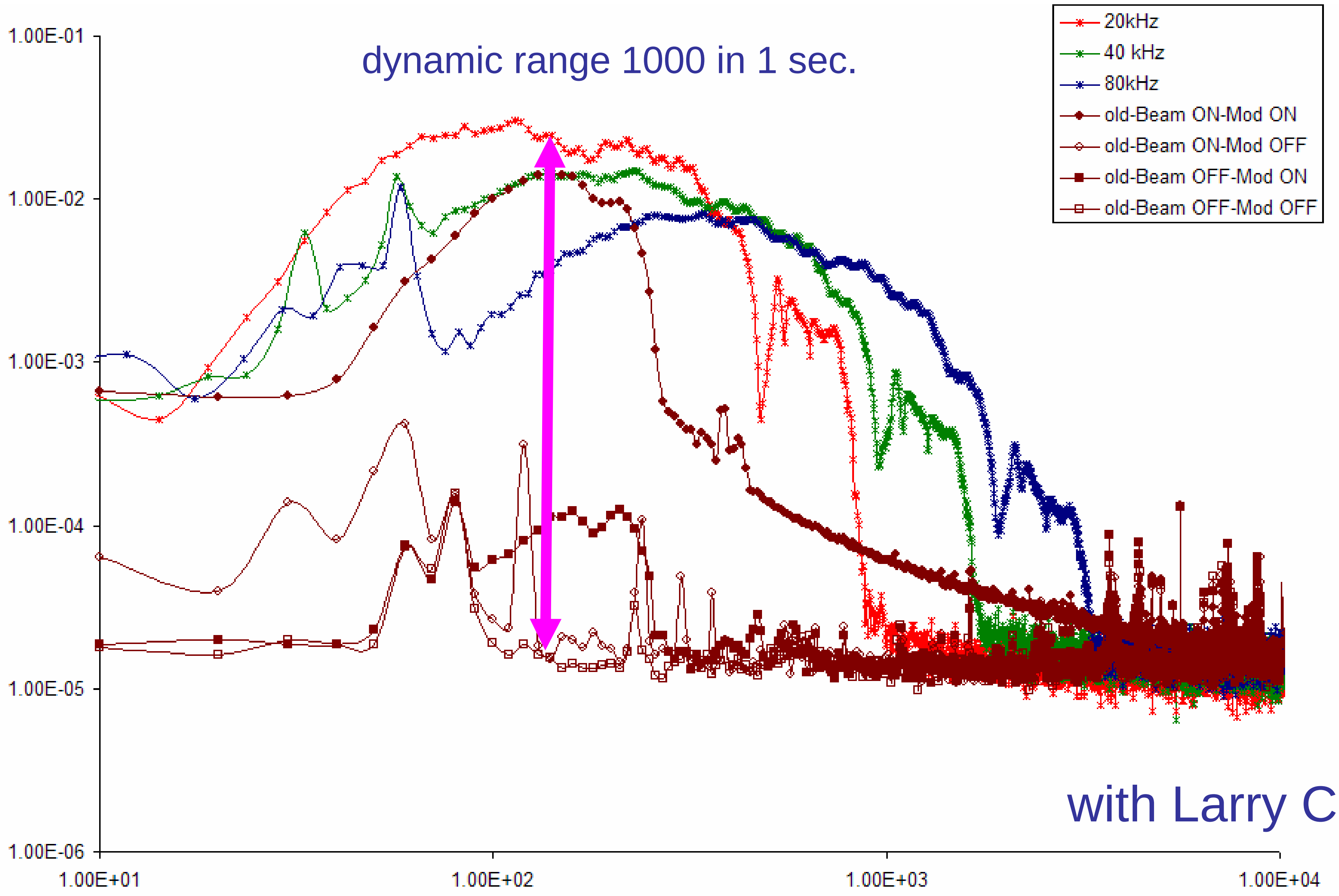
Early IRSR experiments



BESSY 1 1985-86

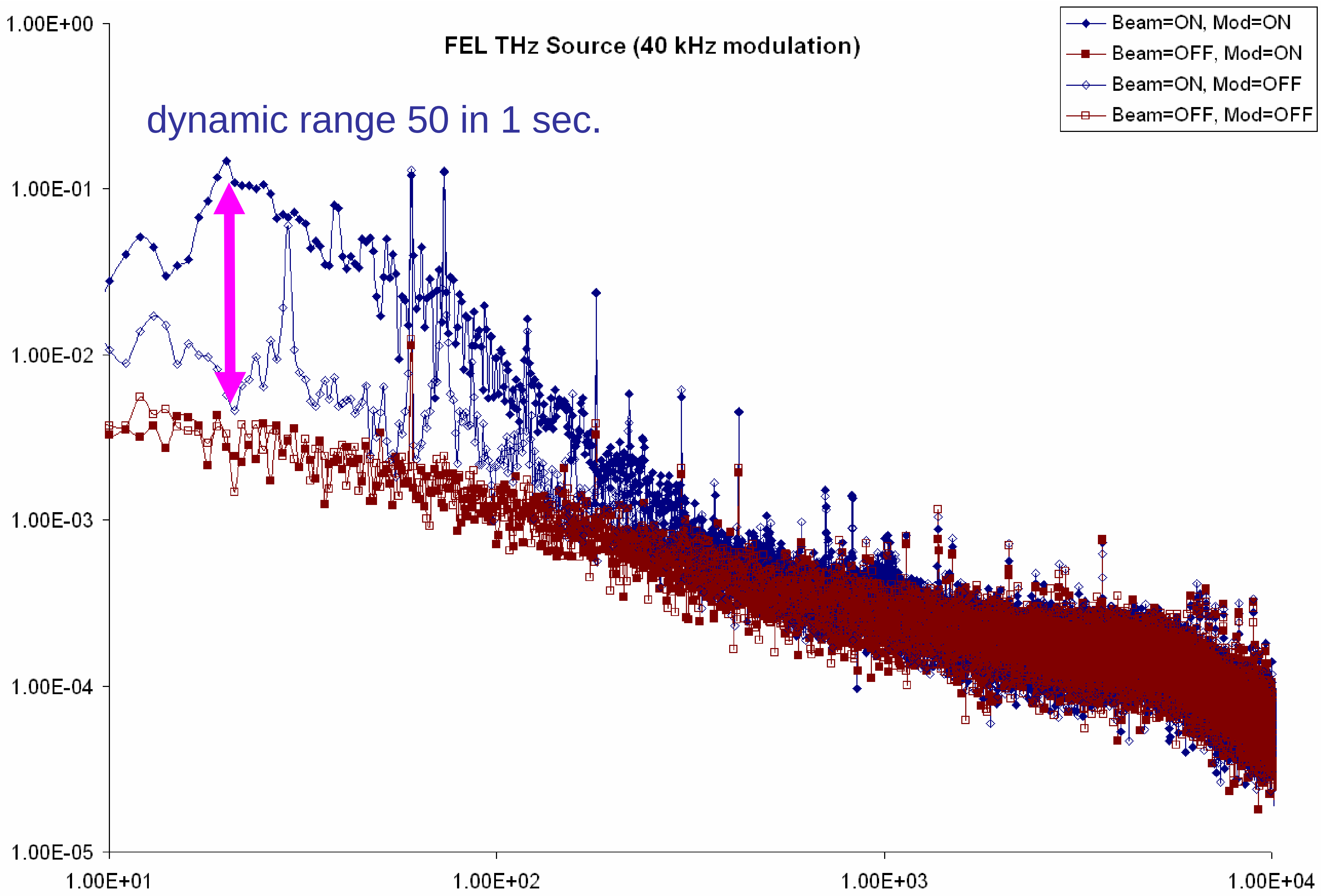
Schweitzer, Nagel, Brain, Lippert and Bradshaw Nucl. Instr. & Methods A246 163 (1986)

Experimentation Issues – NSLS Signal to Noise

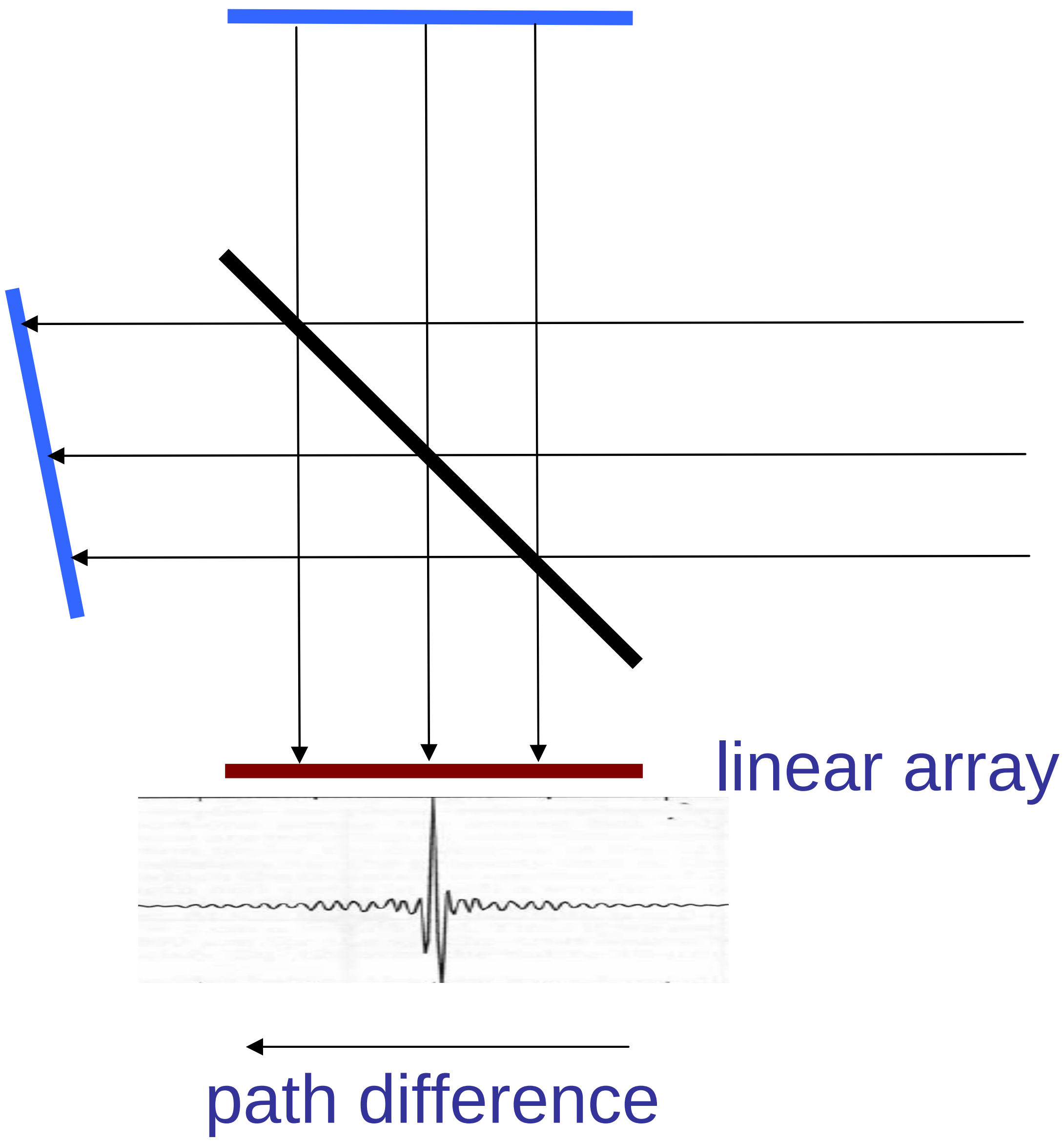


with Larry Carr

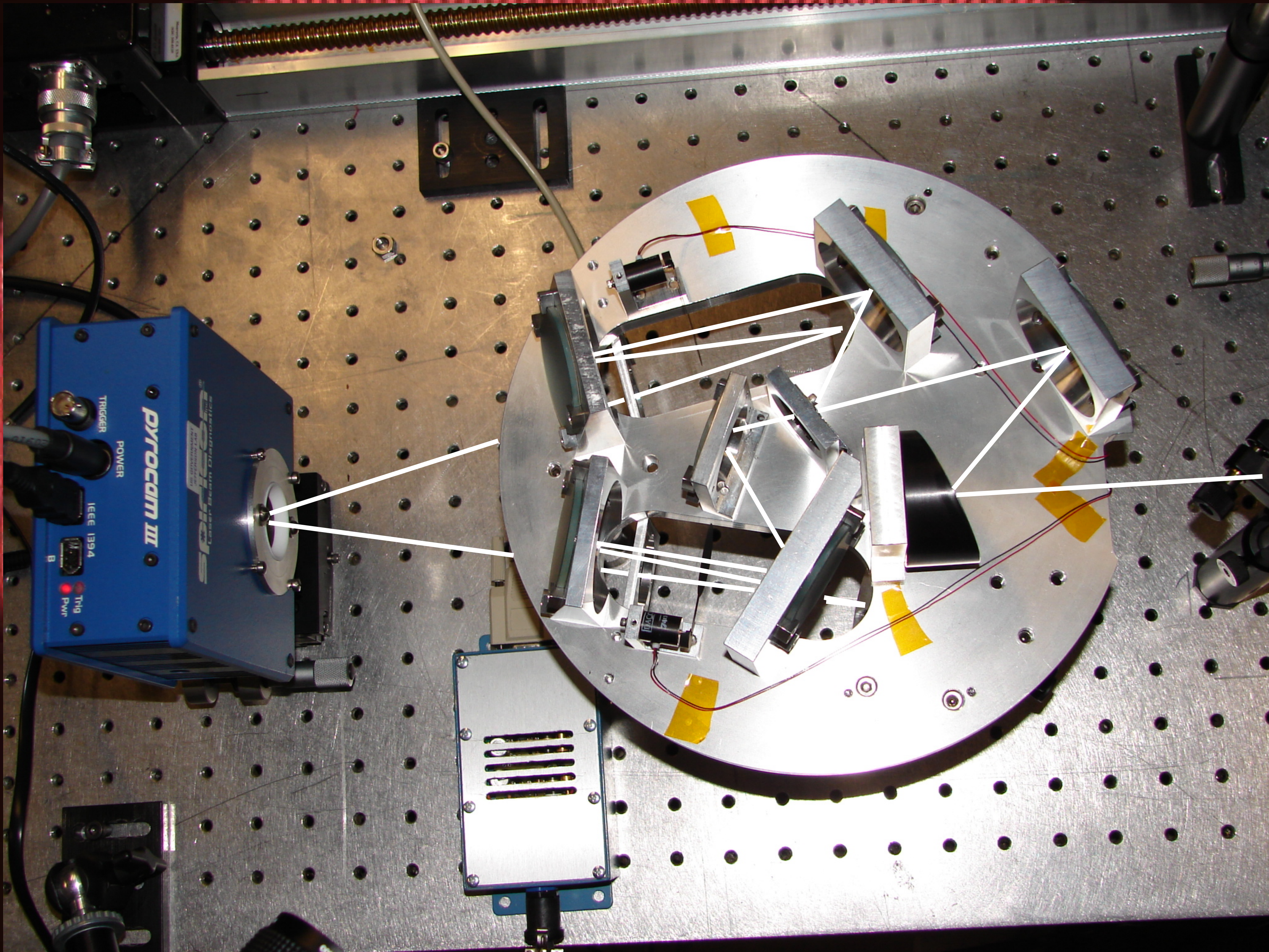
Experimentation Issues – FEL Signal to Noise



Shear Interferometer – Sievers and Agladze, Cornell

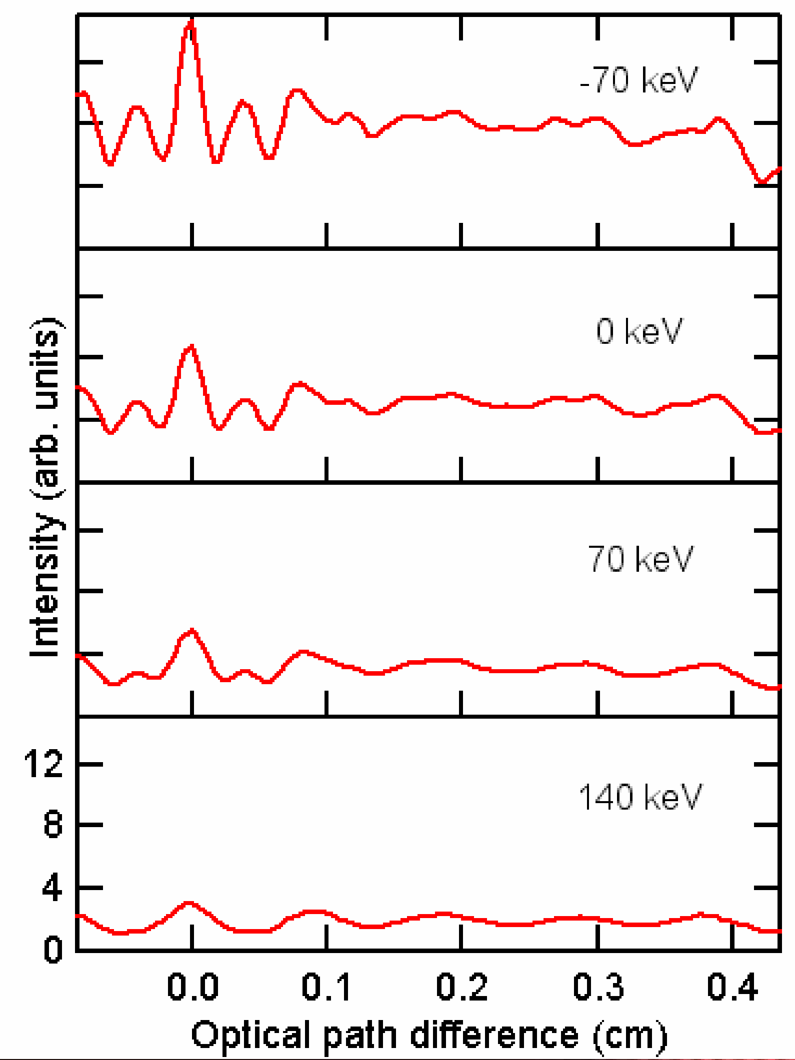


THz HFTS during experiments at Jefferson Lab FEL

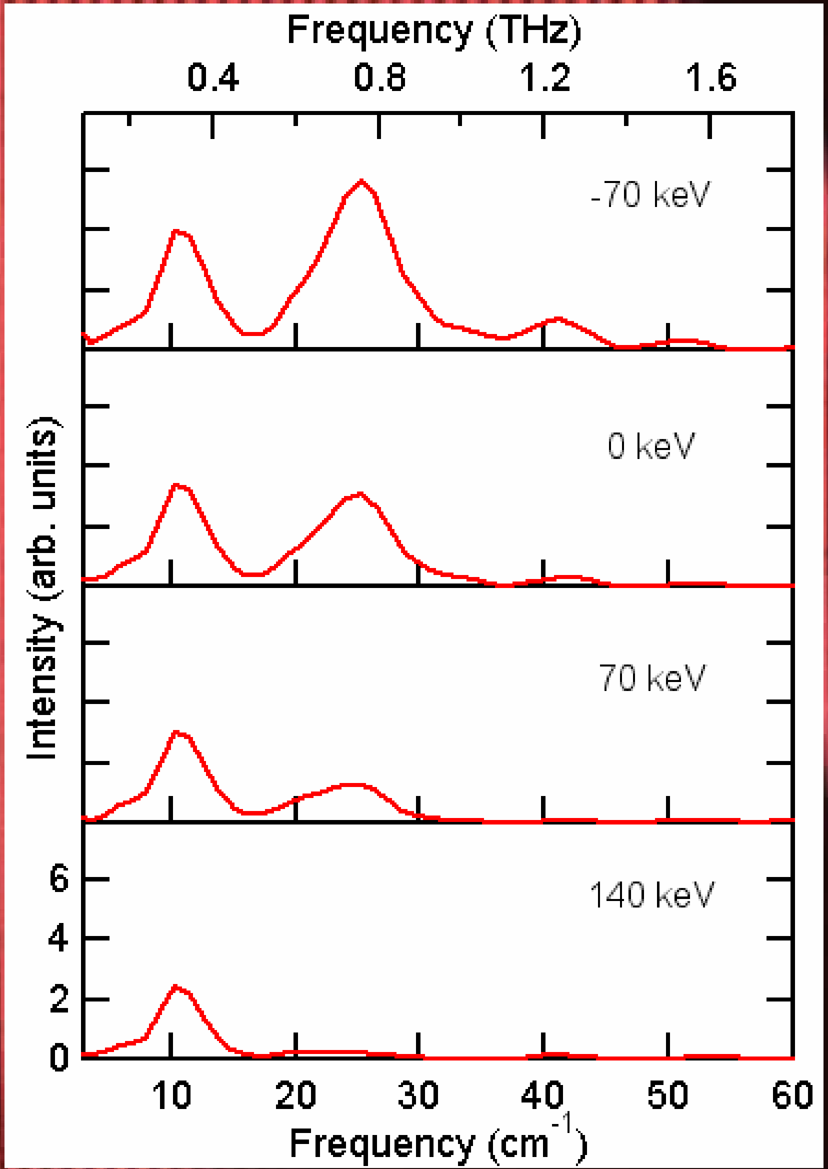


Coherent synchrotron radiation measurements

Interferograms



Calculated spectra

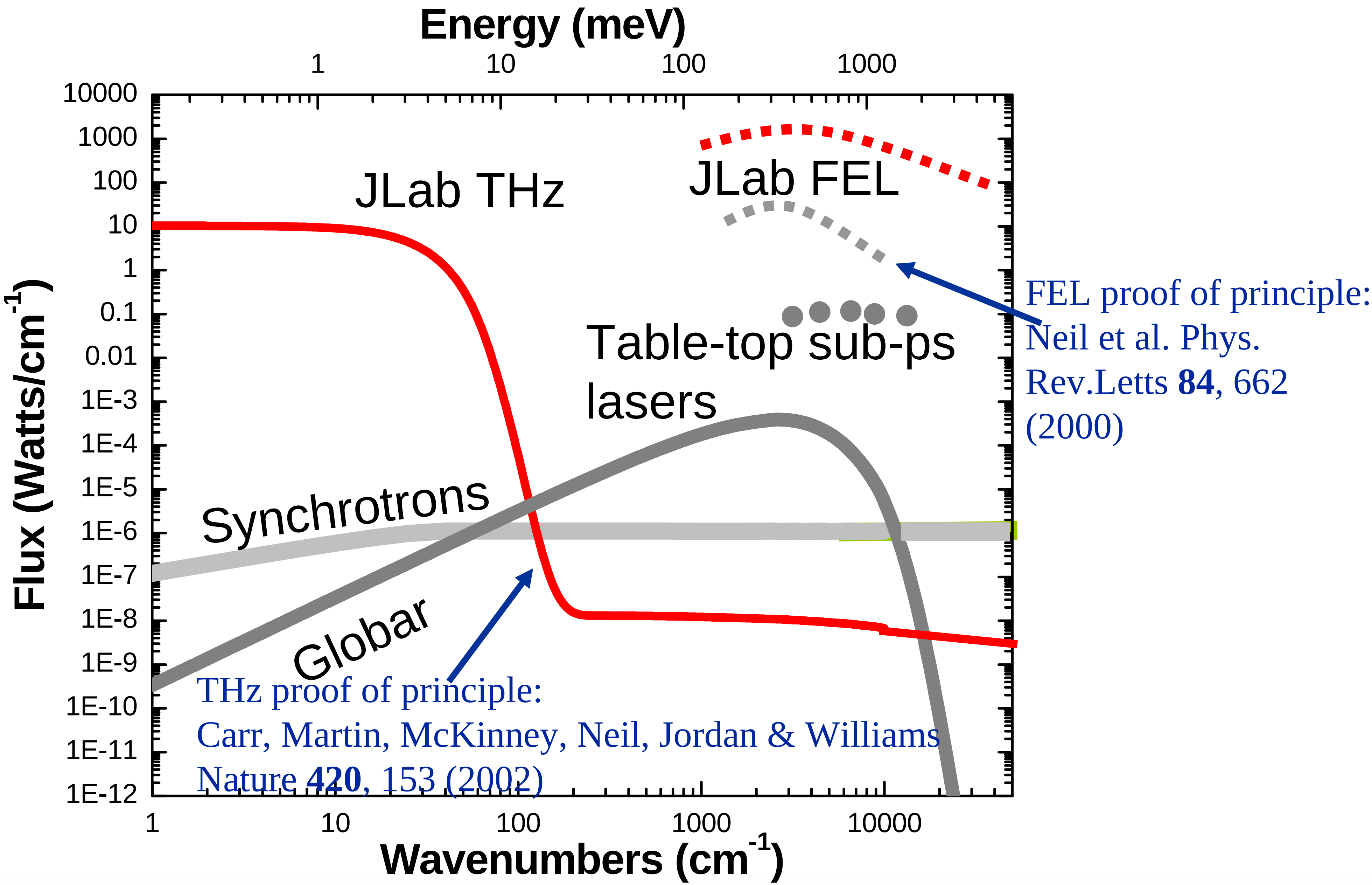


Some of the JLab Team

Photo taken Jan 16, 2007

This work supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the Air Force Research Laboratory, The US Army Night Vision Lab, and by DOE under contract DE-AC05-060R23177.

Jefferson Lab Facility Spectroscopic Range and Power



Conclusions

- We have a high power CSR THz source capable of illuminating a large field of view which can be imaged at full video rates
- Initial results have resolved features down to 1mm
- Filtering of the thermal IR is necessary to utilize the important properties of THz radiation
- Development of compact high power THz source will enable deployed systems (Advanced Energy Systems)
- We have a user program in place to look at biological effects
- We have just started our spectroscopy programs

Some of the JLab Team

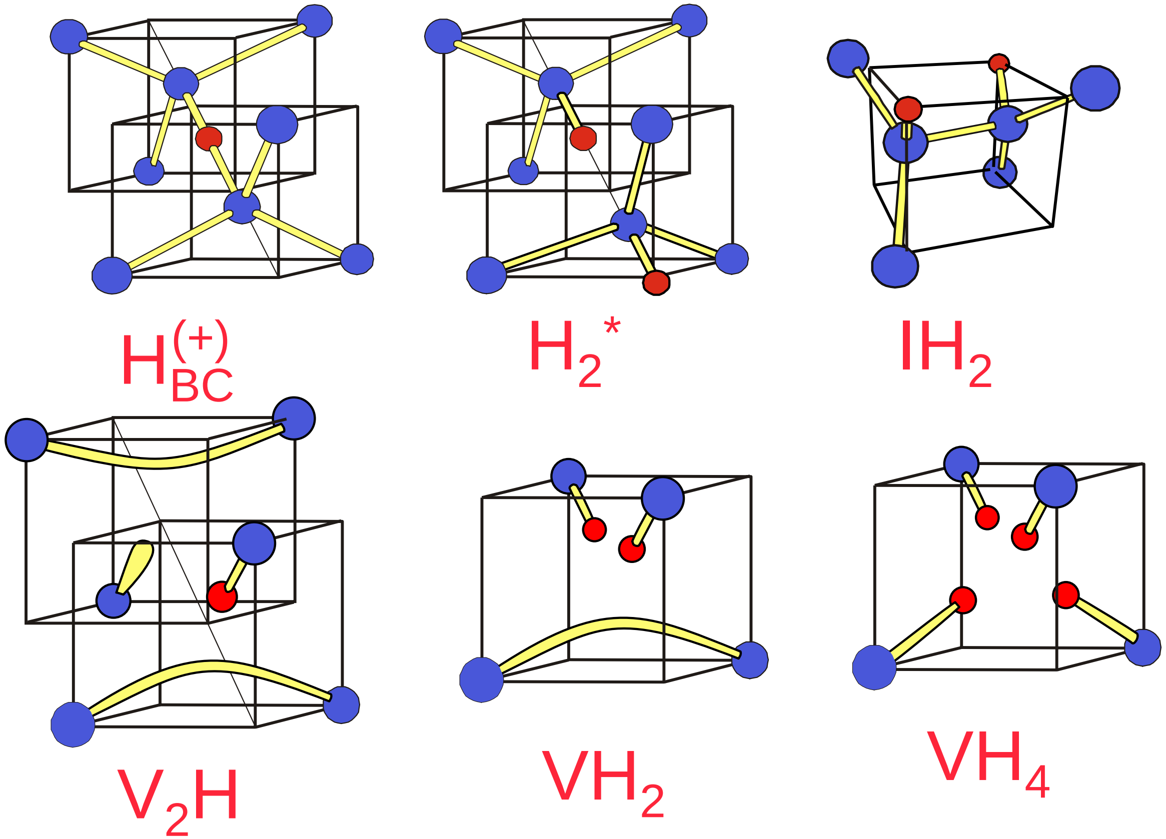
Photo taken Jan 16, 2007

This work supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the Air Force Research Laboratory, The US Army Night Vision Lab, and by DOE under contract DE-AC05-060R23177.

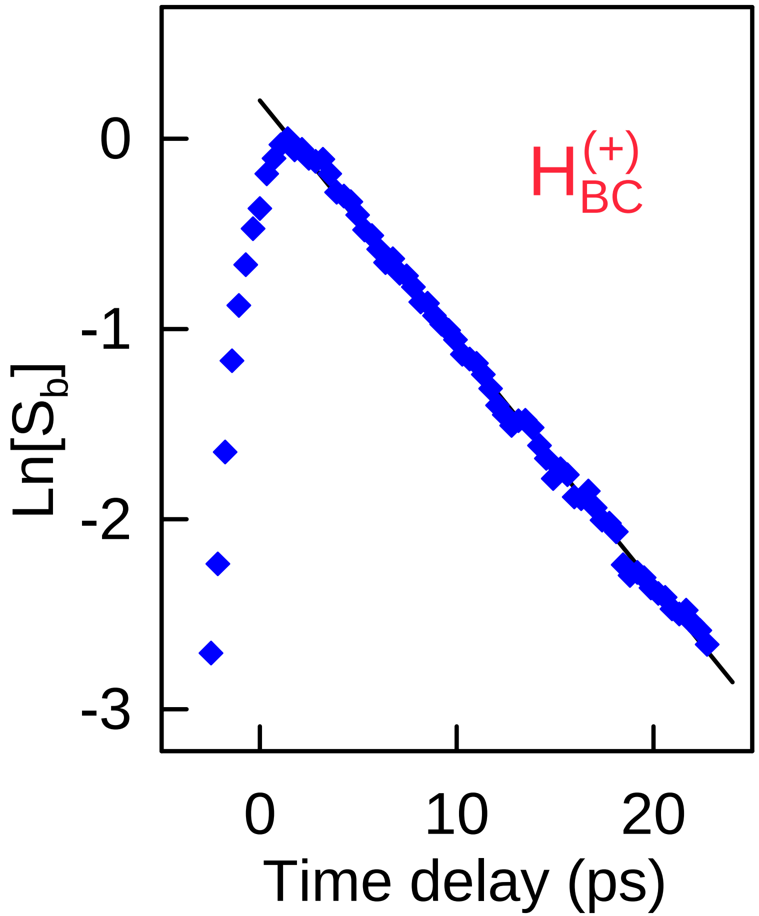
EXTRA SLIDES

Example of niche of 4th. Generation → Si:H

Defect Dynamics



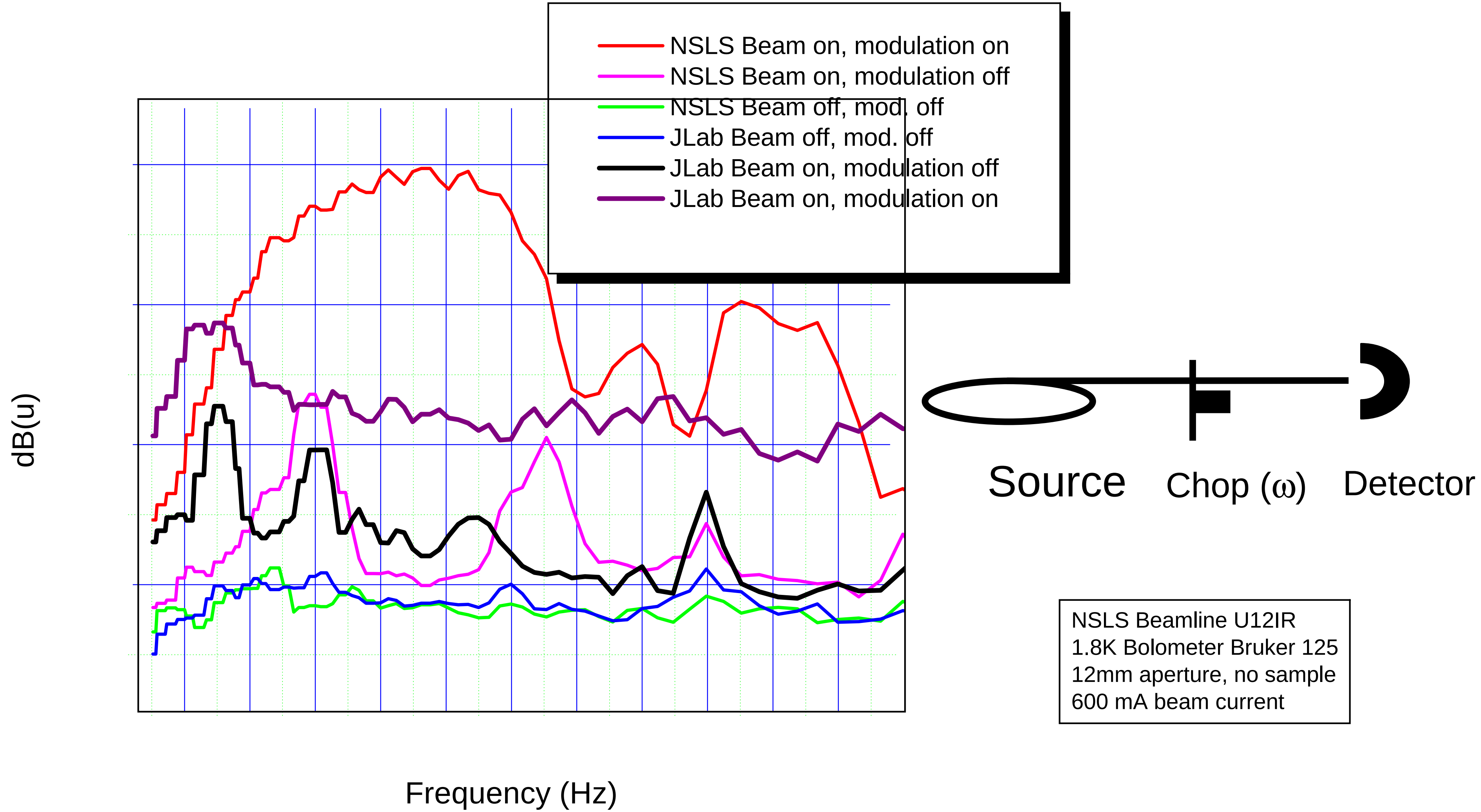
Luepke et al. CWM/Vanderbilt



Luepke et al. Phys. Rev. Letts **85**, 1452 2000
Wm. & Mary Phys. Rev. Letts **88**, 135501, 2002
Vanderbilt Phys. Rev. Letts **87**, 145501, 2001
Phys. Rev. **B63** 195203 2001
J. Appl. Phys. **93** 2316, 2003

$T_1 = 7.8 \pm 0.2$ ps

Experimentation Issues



NSLS Beamline U12IR
1.8K Bolometer Bruker 125
12mm aperture, no sample
600 mA beam current

Concluding Remarks

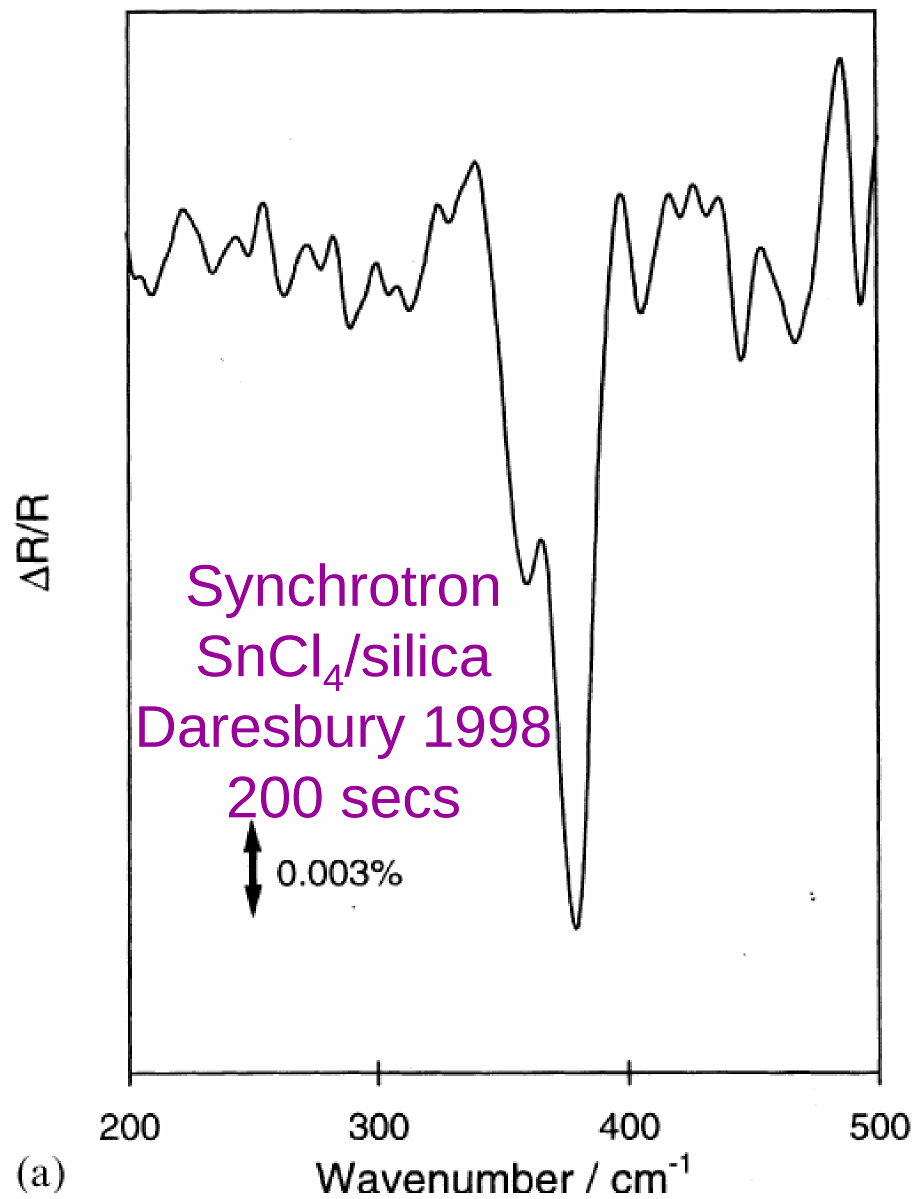
- **Over the past 10 years Jefferson Lab has constructed and commissioned a next generation light source based on an Energy Recovered Linac.**
- **Our experience with generating ultrafast electron beams and diagnostics, can help implementation of Cornell ERL.**
- **This ERL, or an x-ray ERL yielding THz light could have a huge impact on high pressure research.**

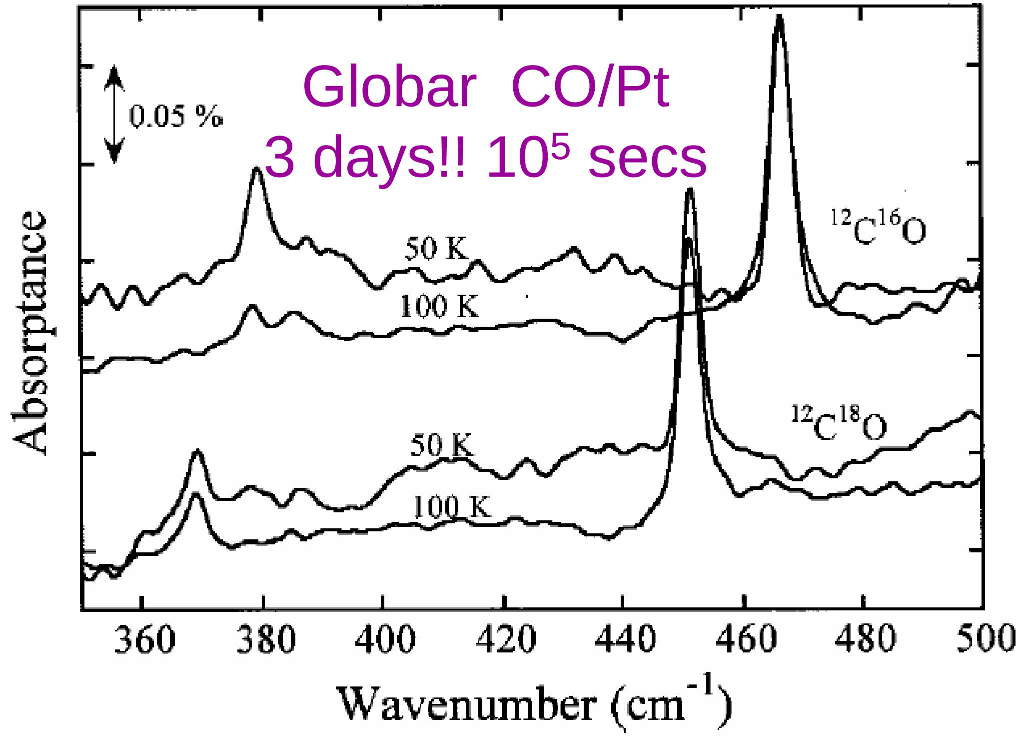
Summary

- Tremendous opportunities
- In class of our own
- Must stay at scientific frontiers
- Great local university teams
- Helping Florida State, Cornell, Daresbury and other 4th. generation light source facilities

This work supported by the Office of Naval Research, the Joint Technology Office, the Commonwealth of Virginia, the Air Force Research Laboratory, The US Army Night Vision Lab, and by DOE under contract DE-AC05-060R23177.

Daresbury data holds world record!!



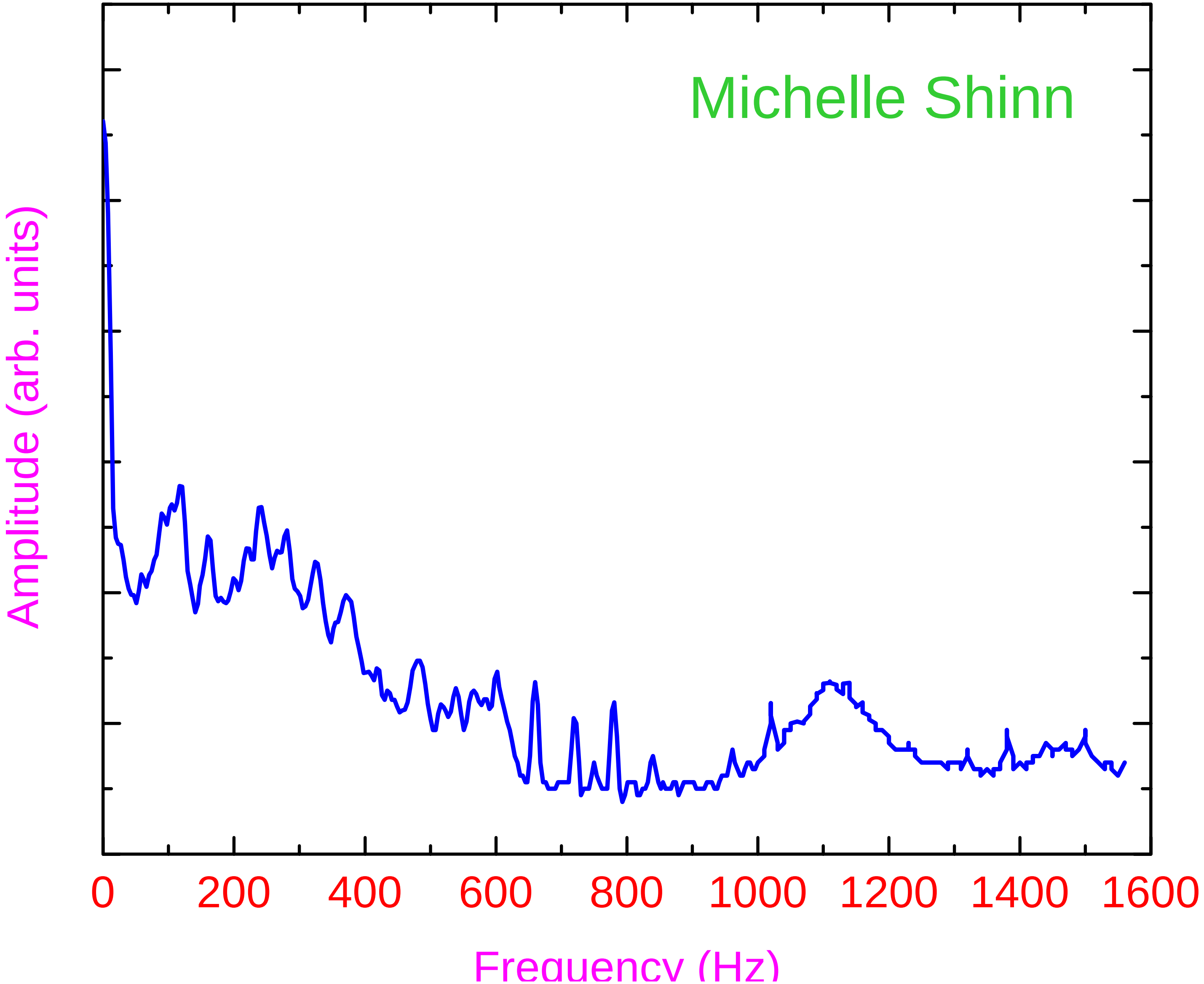


Engstrom and Ryberg,
J. Chem. Phys. **115** 519 (2001)

Paul Dumas and collaborators
- many papers

Pilling, Gardner, Pemble and Surman, Surf. Sci. **418** L1 (1998)

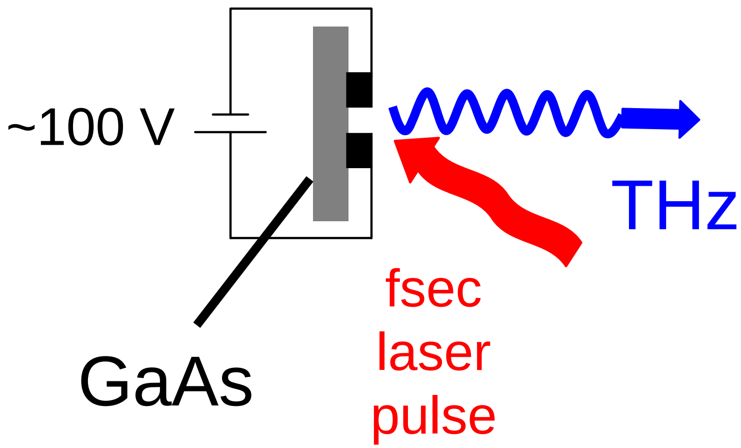
JLab FEL Drive Laser Noise



Comparing Conventional THz Sources and Coherent THz Synchrotron

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

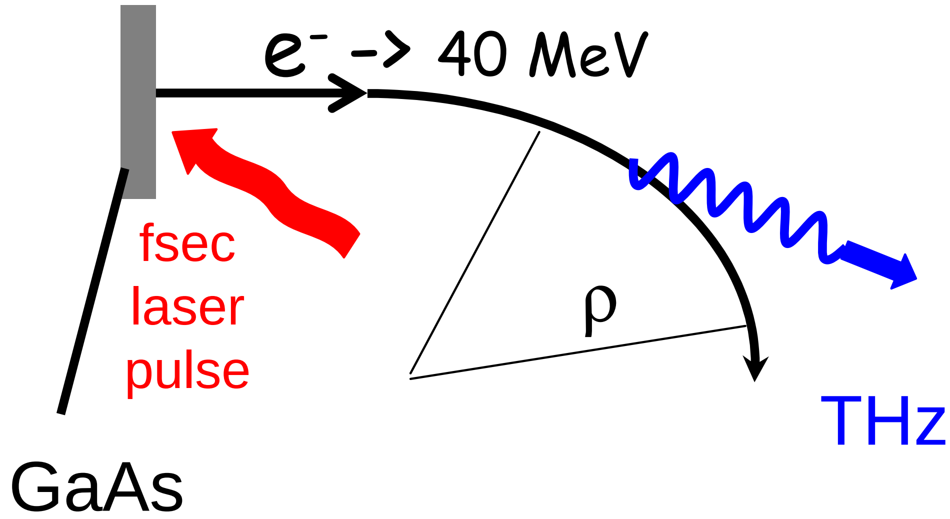
a=acceleration
c=vel. of light
γ=mass/rest mass



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

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

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

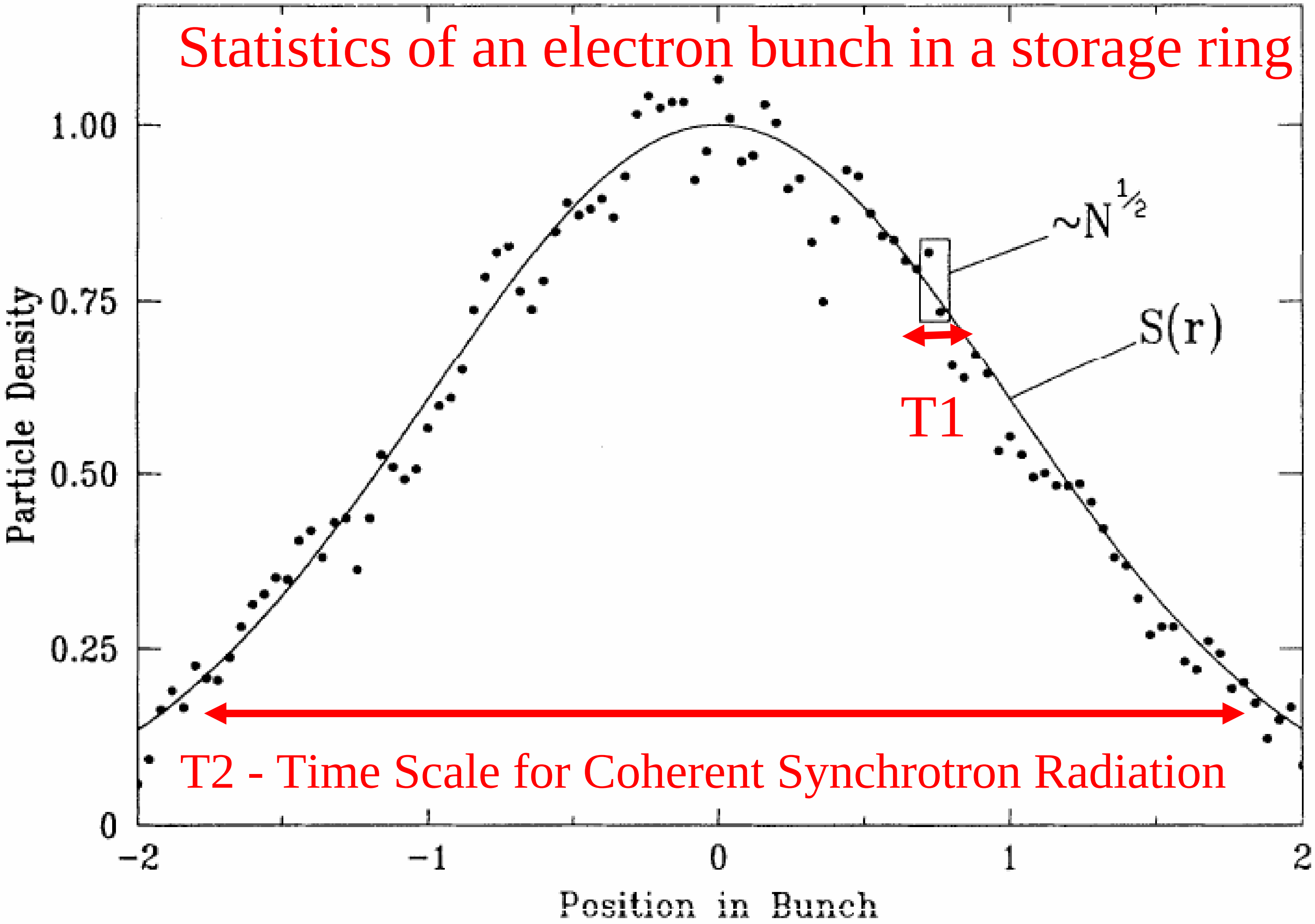


$$a = \frac{c^2}{\rho} = \frac{(3\times10^8)^2}{1} \cong 10^{17}\, m/sec^2$$

$$if\ \rho = 1\ m$$

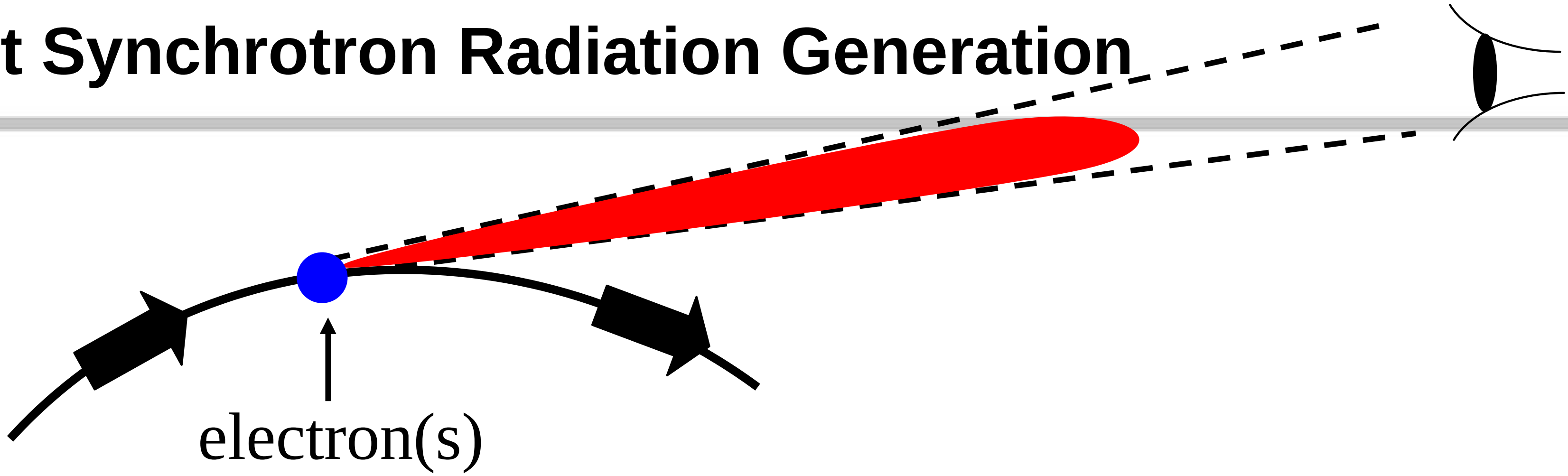
$$\gamma = 200\ \ and\ \ 200^4 = 10^9\ !!!!$$

Synchrotron Radiation Generation - 2 time-scales

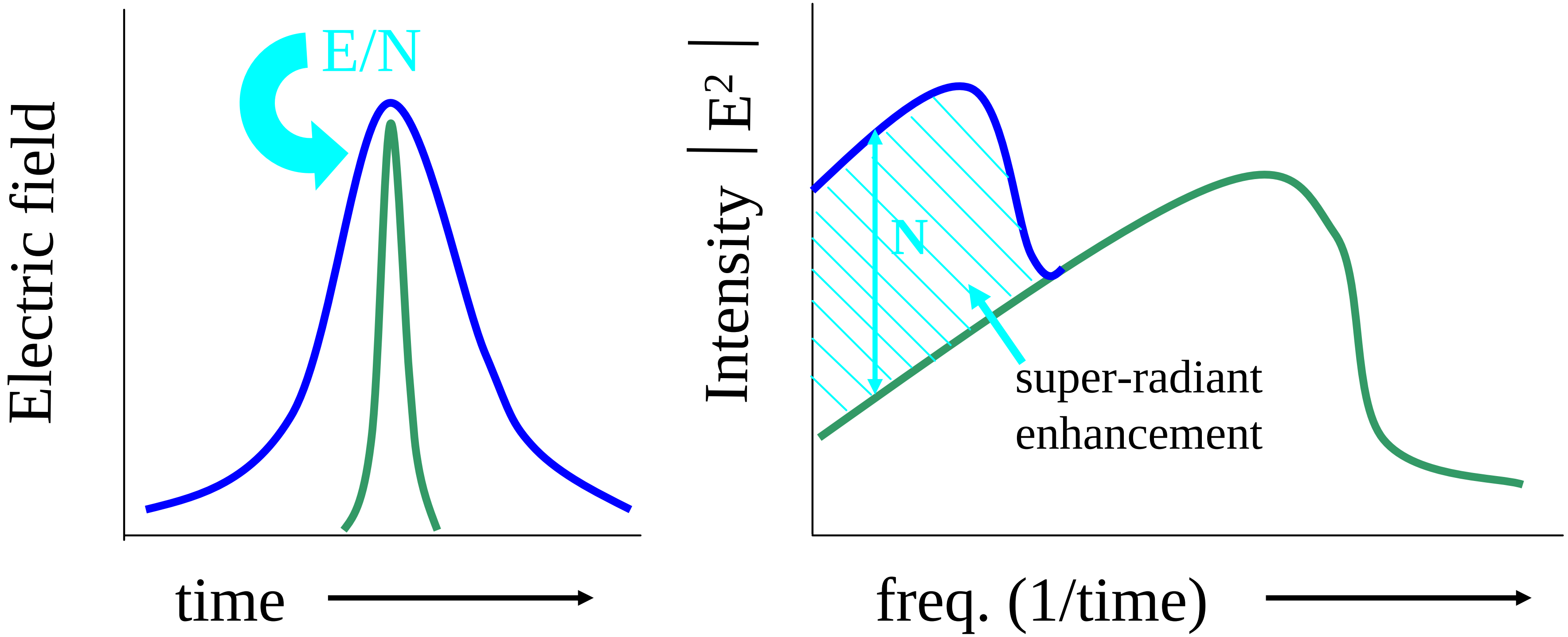


Hirschmugl, Sagurton and Williams, Physical Review **A44**, 1316, (1991).

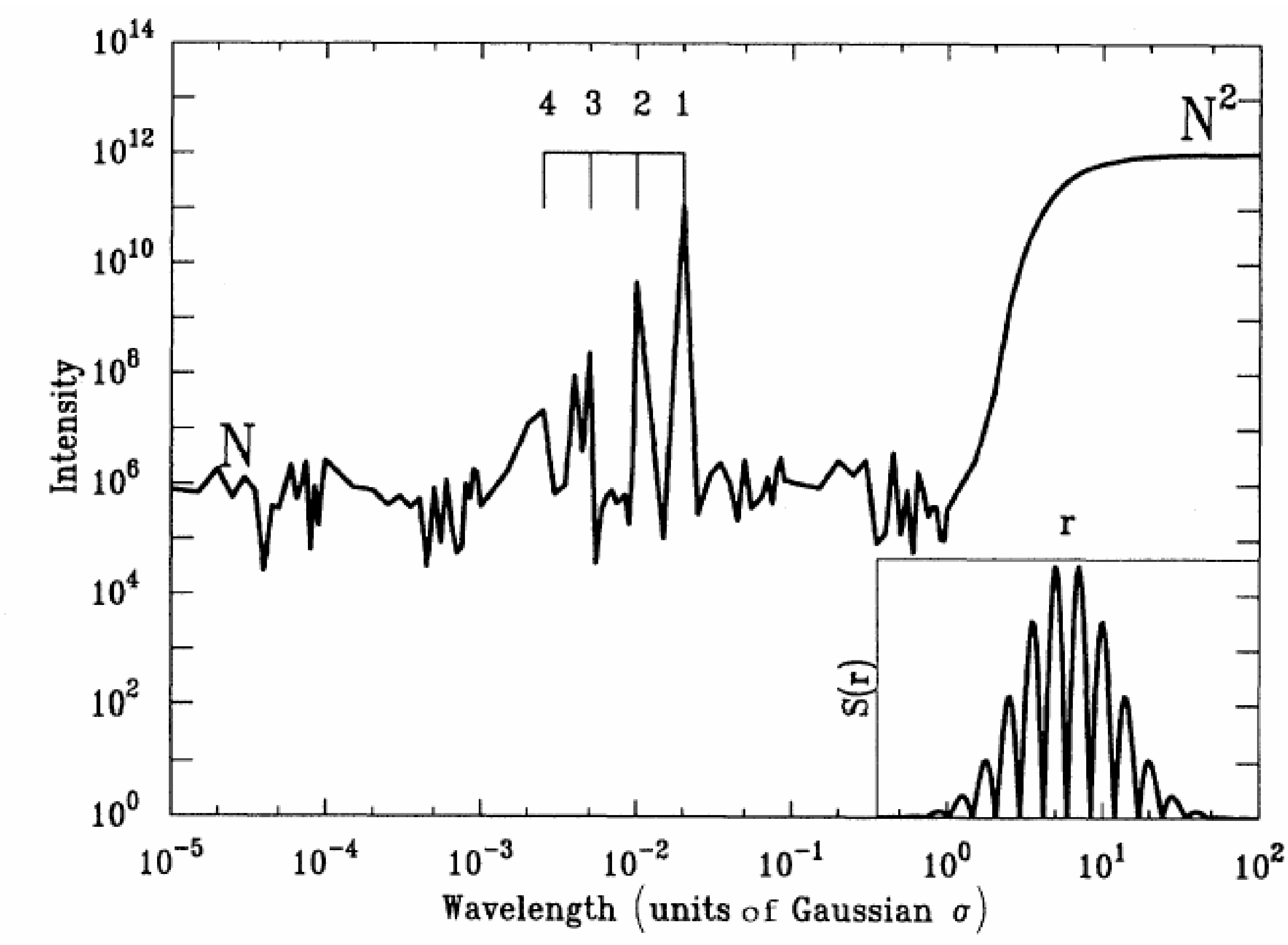
Coherent Synchrotron Radiation Generation



$$\Delta t = \frac{1}{\gamma^2}\frac{\rho}{c\gamma} = \frac{5}{4000^3 \times 3 \times 10^8} \approx 0.25\ Attoseconds$$



Multiparticle coherence – Free Electron Laser



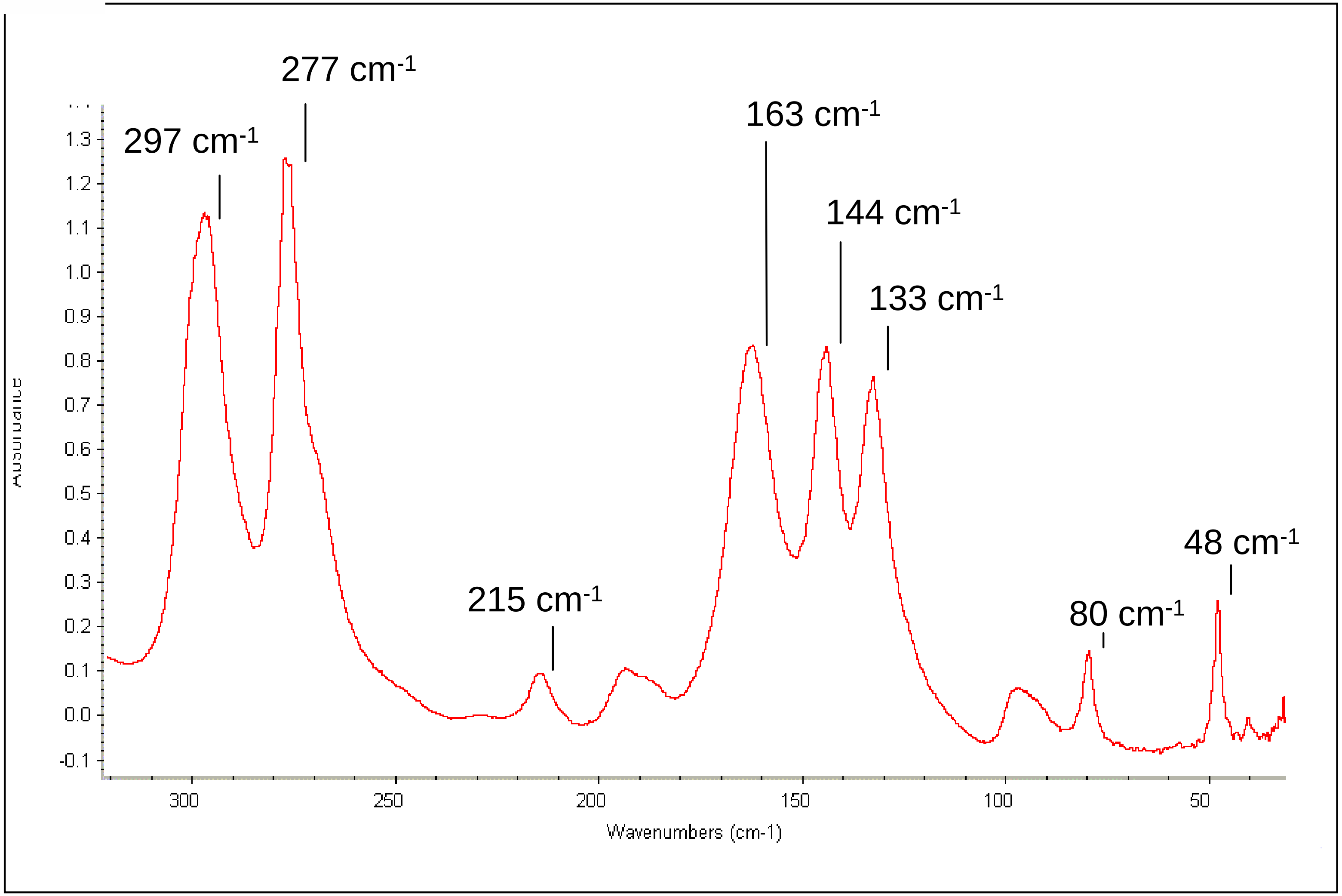
Hirschmugl, Sagurton and Williams, Physical Review **A44**, 1316, (1991).

MANCHESTER 1824

The University of Manchester

Spectrum of uric acid

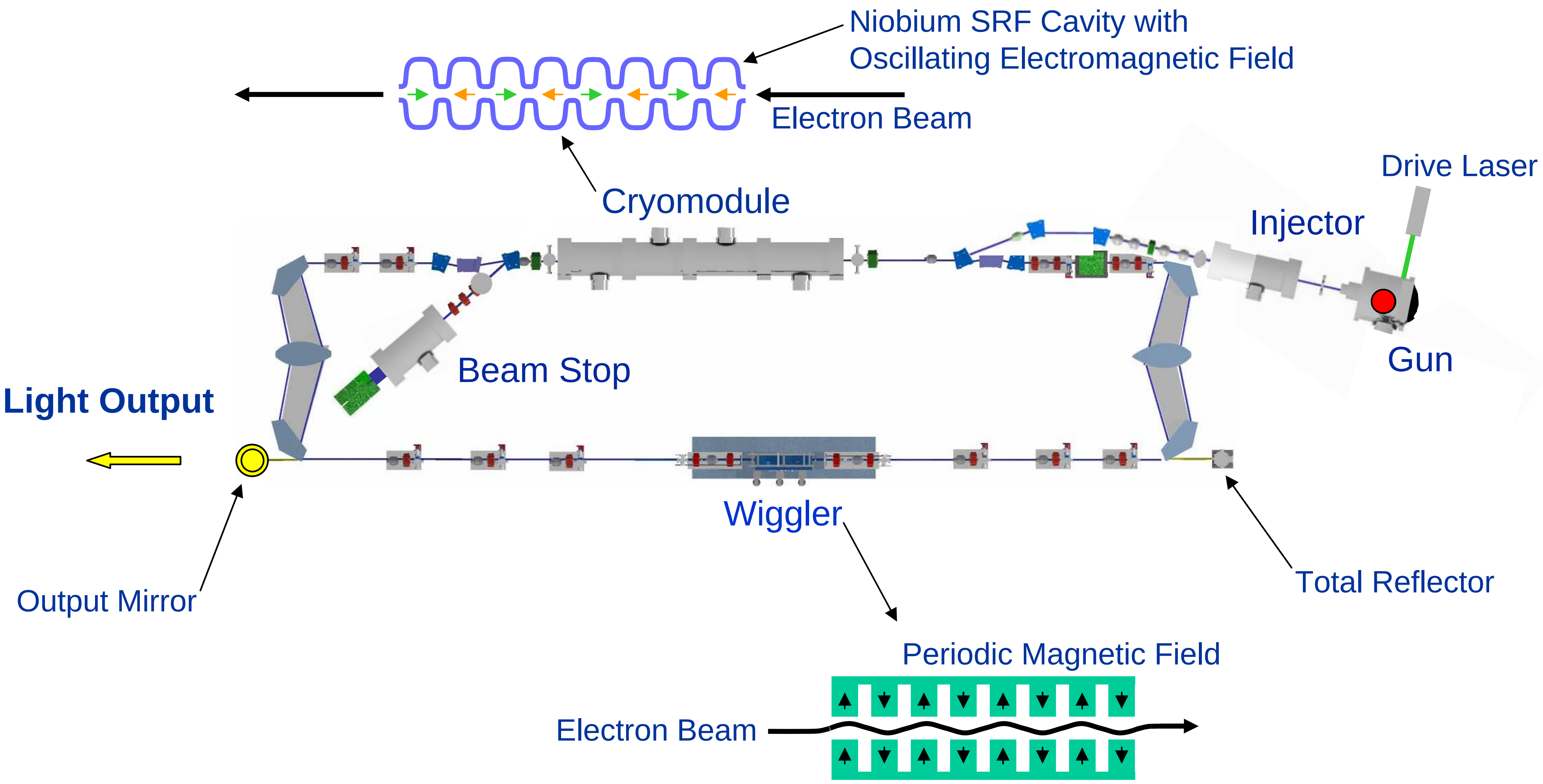
cm^{-1} spectral resolution Recorded at SFTC Daresbury



Jeff

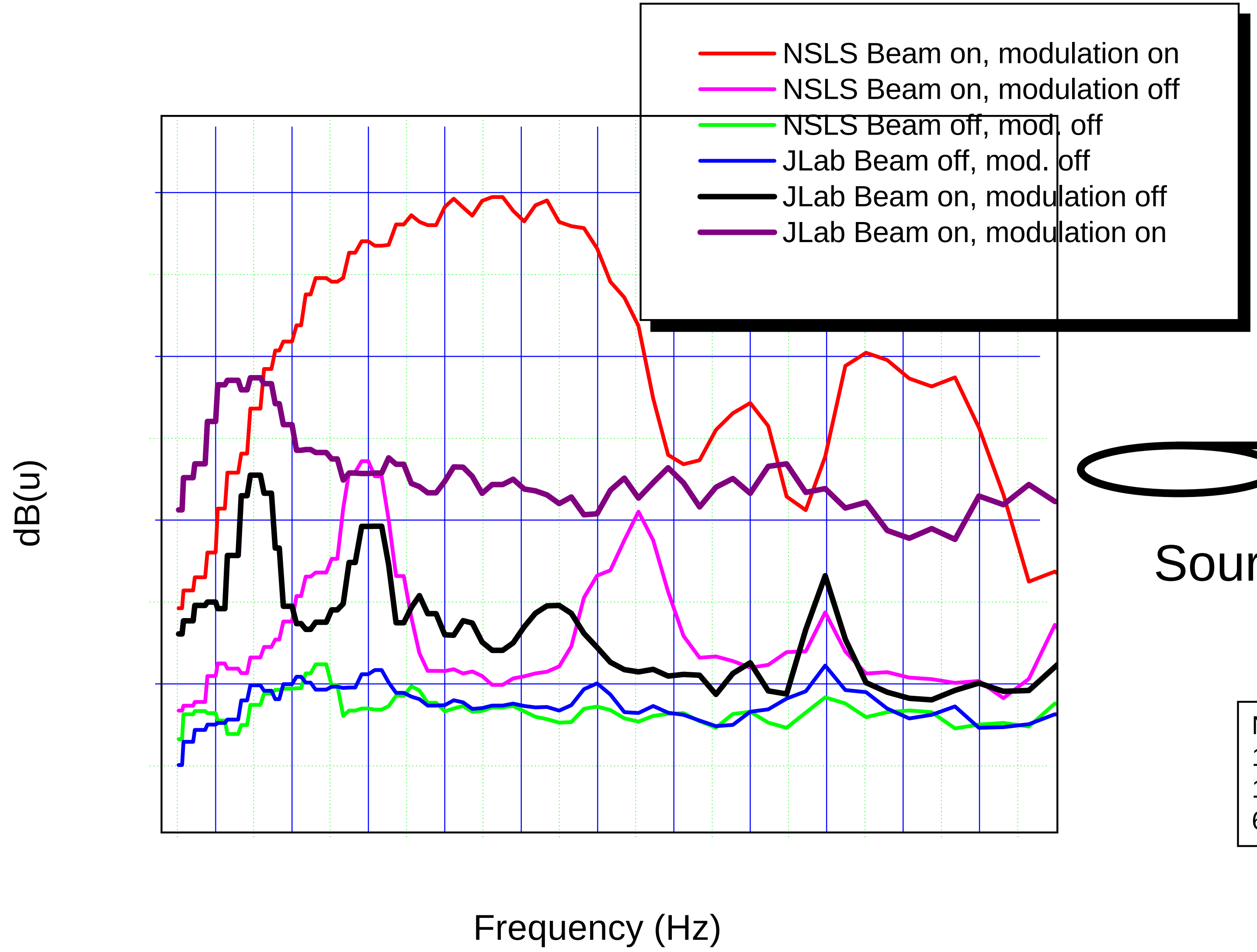
JSA

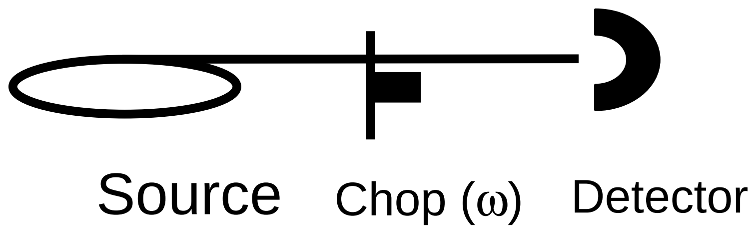
Schematic of JLab 4th. Gen. Light Source Operation



Laser Wavelength ~ Wiggler wavelength/(2Energy)^2

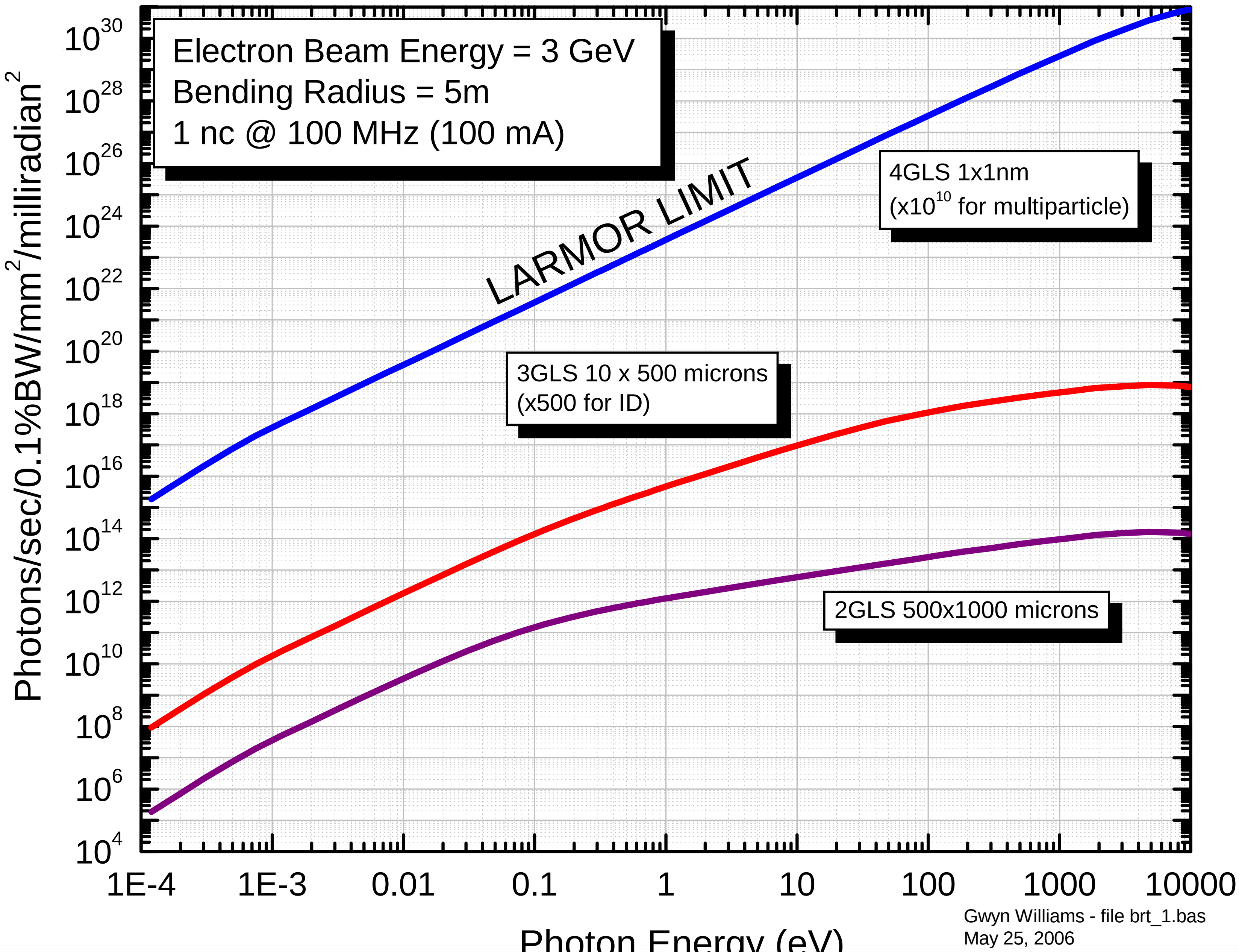
Experimentation Issues





NSLS Beamline U12IR
1.8K Bolometer Bruker 125
12mm aperture, no sample
600 mA beam current

Generic Light Source Landscape – Average Brightness



General Landscape – Light Source "Generations"

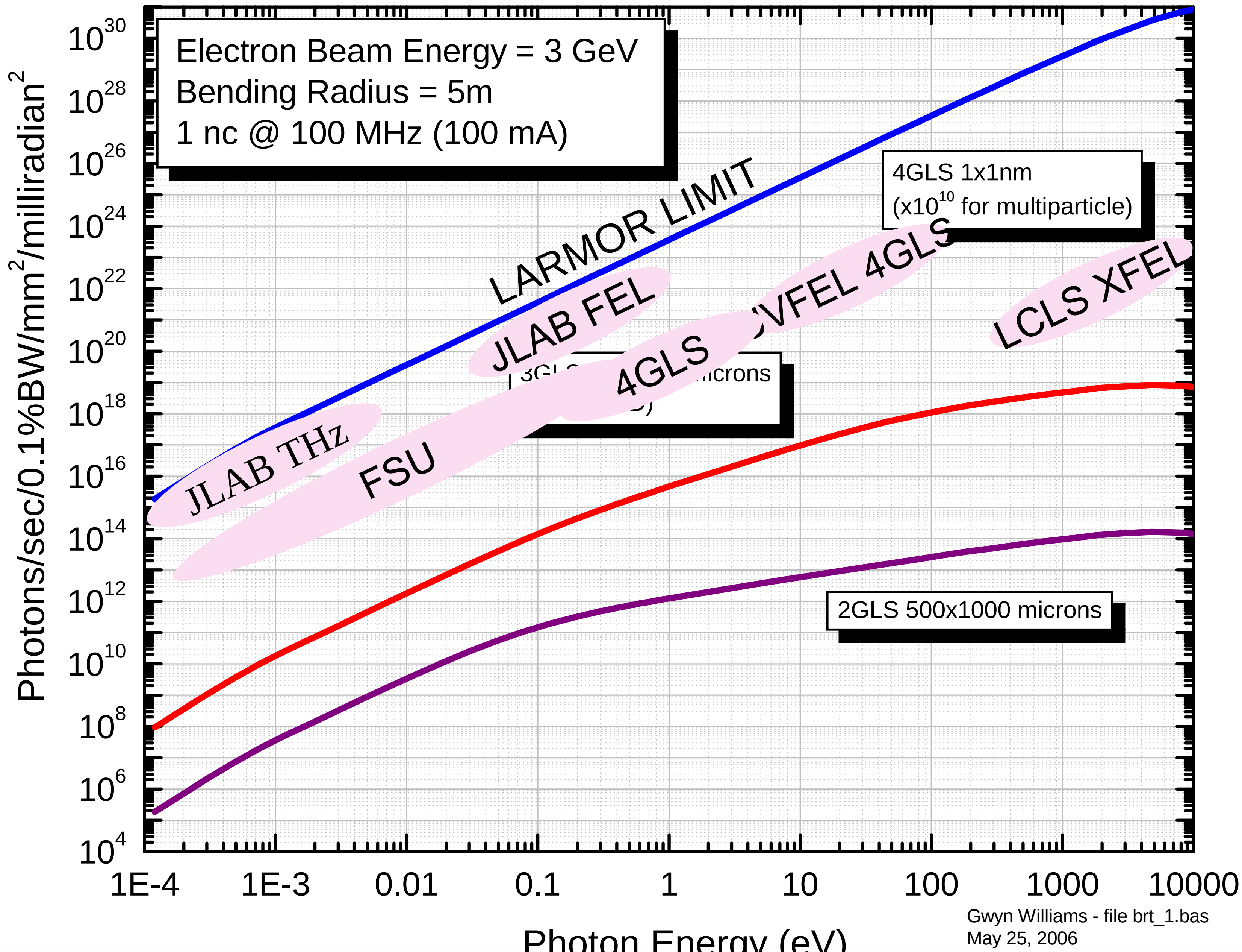
1st. Generation – parasitic use of nuclear and high energy physics machines

2nd. Generation – dedicated storage rings – higher current, lower emittance

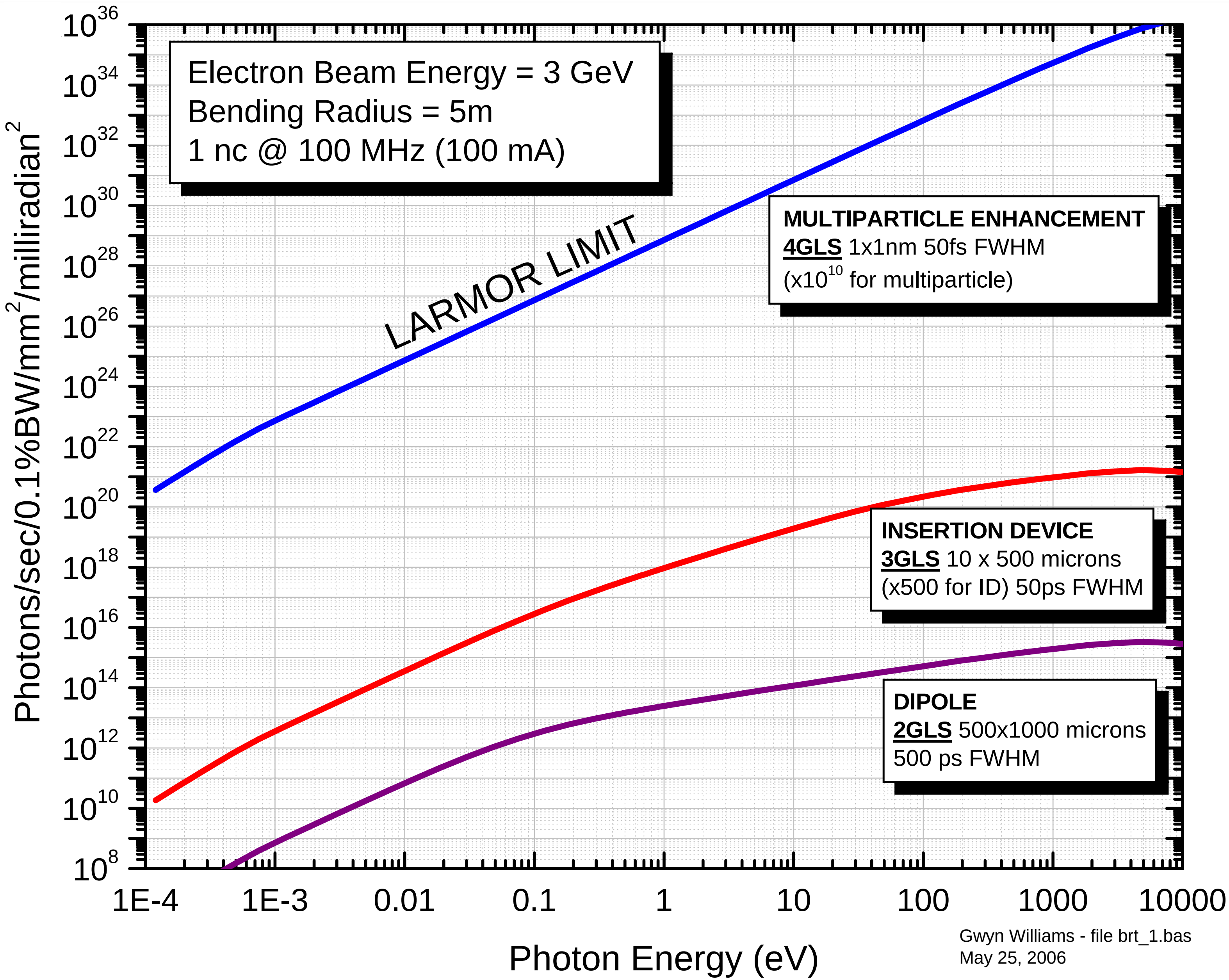
3rd. Generation – storage rings with insertion devices (wigglers), lower emittance

4th. Generation – typically linac based, lower emittance, multiparticle coherence

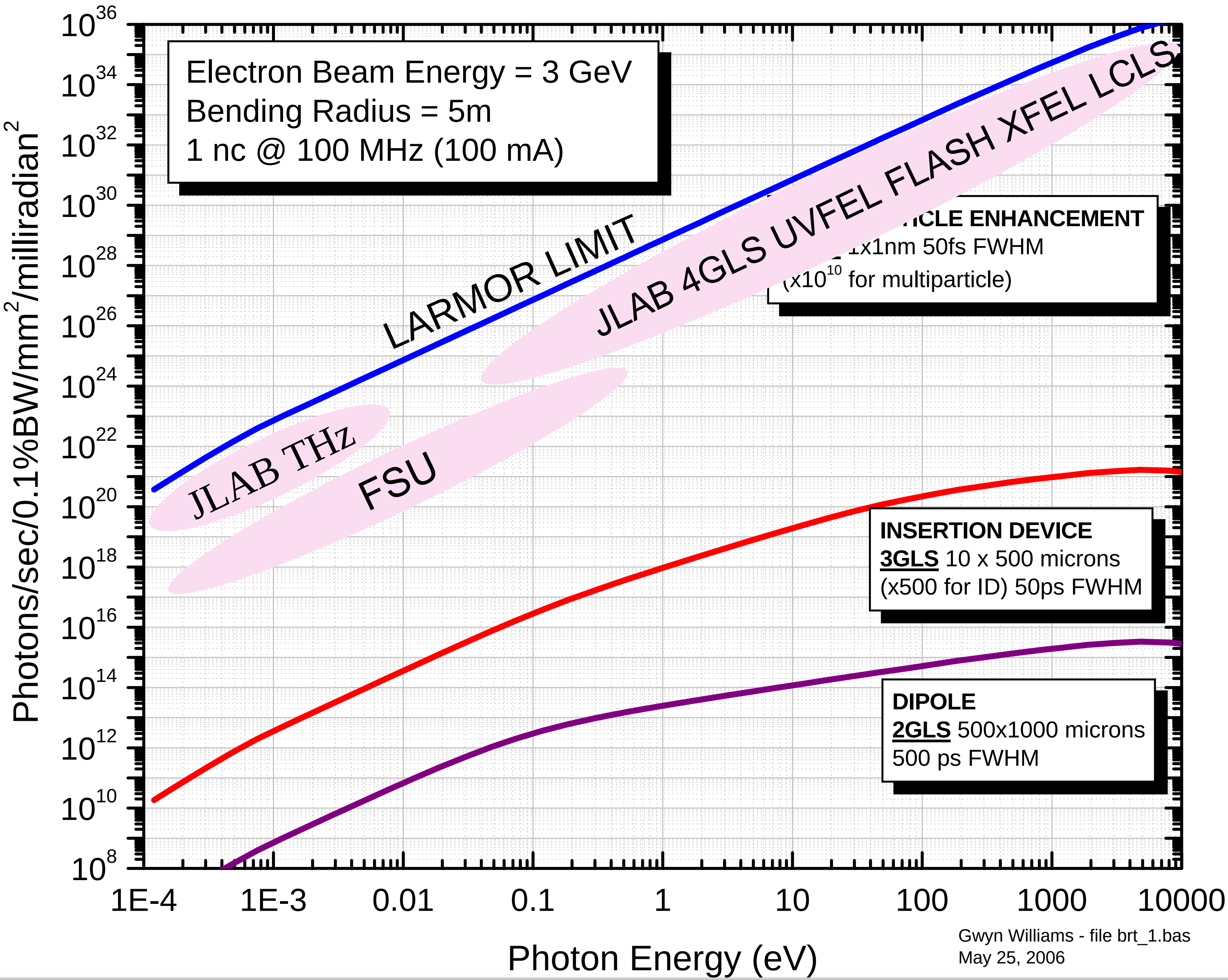
Generic Light Source Landscape – Average Brightness



Generic Light Source Landscape – Peak Brightness

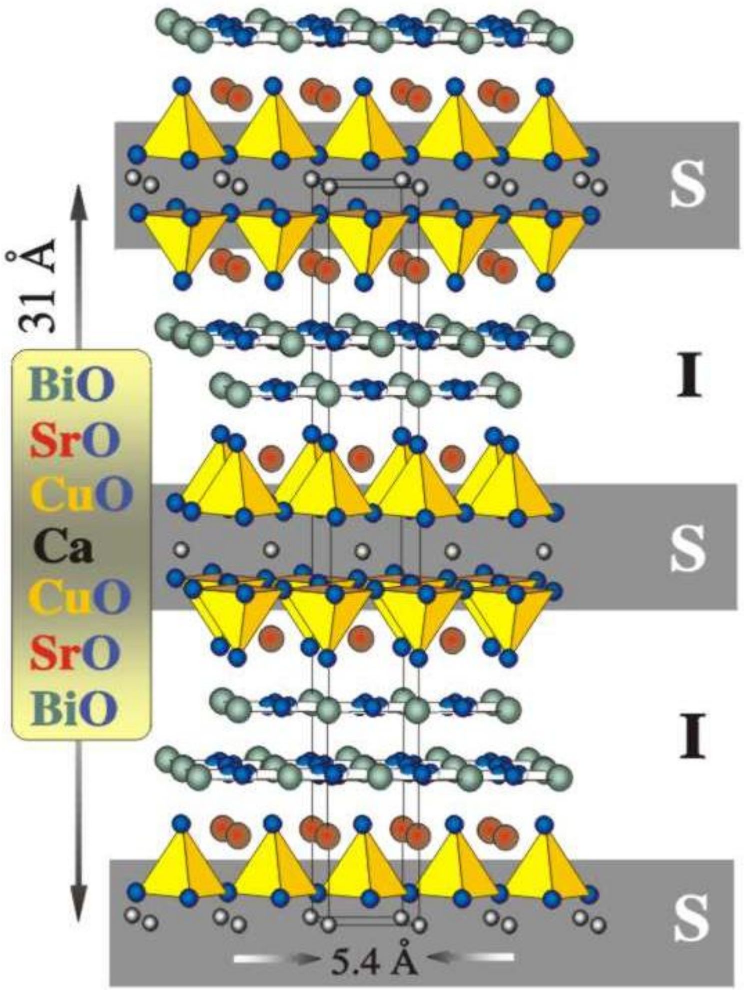


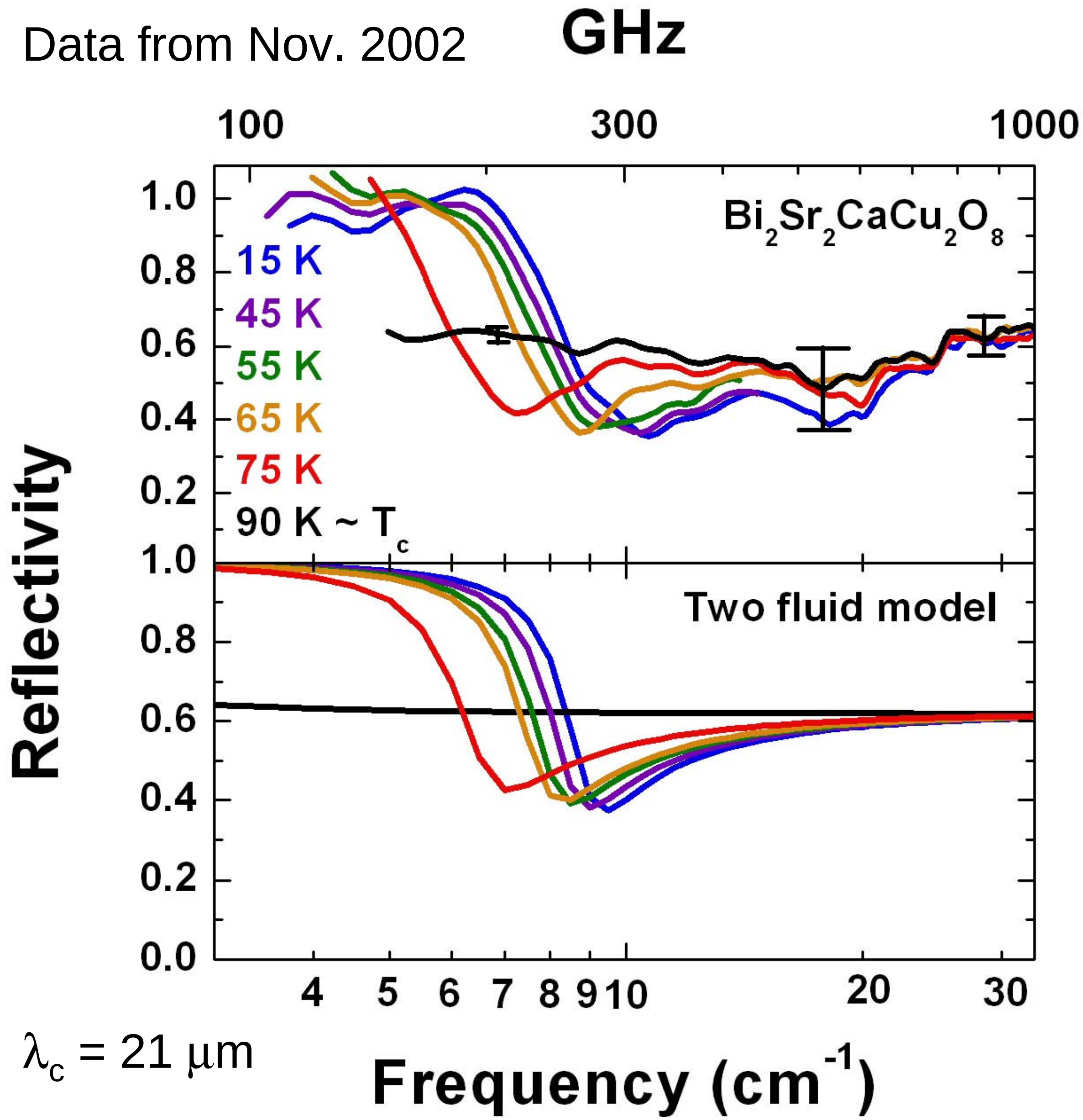
Generic Light Source Landscape – Peak Brightness



Gwyn Williams - file brt_1.bas
May 25, 2006

First CSR Science: Josephson Plasma Resonance in $Bi_2Sr_2CaCu_2O_8$



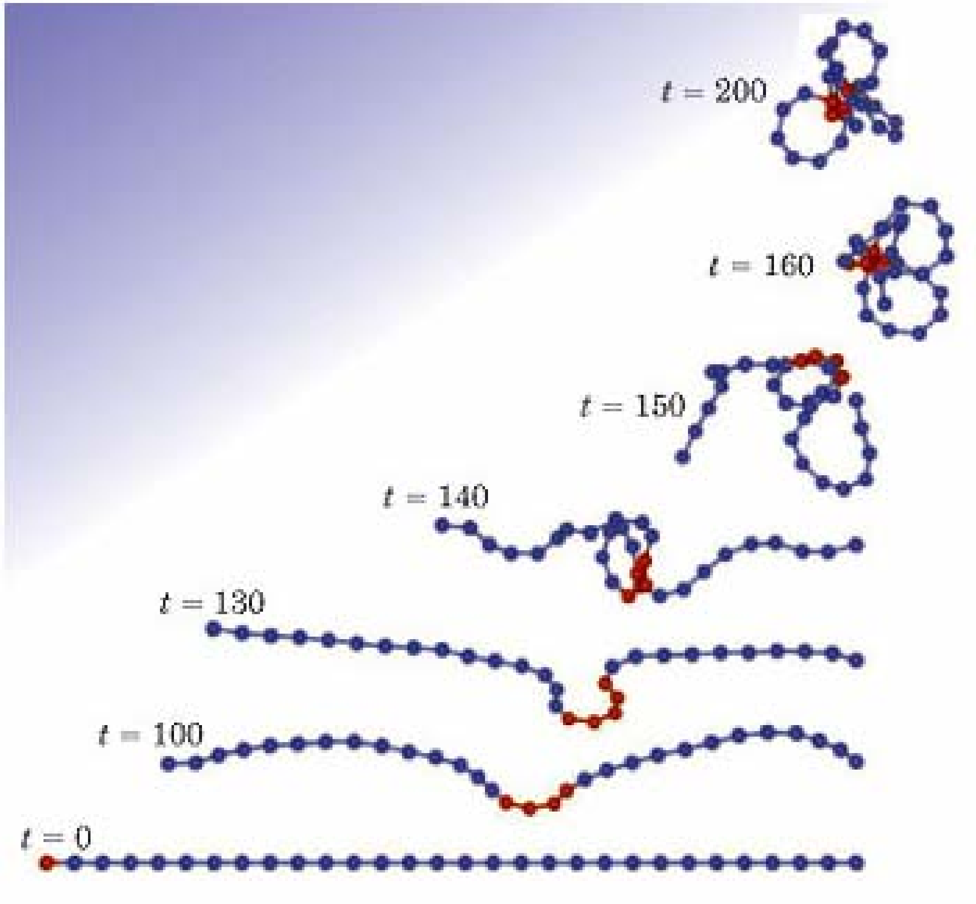


+ Indications for inhomogeneous superfluid

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

Non-linear dynamical effects using high field THz light

High electric fields are predicted to generate localized modes!



A biopolymer chain buckles and folds on itself due to an instability produced by a <u>nonlinear localized mode</u> – Physics Today Jan. 2004 p43.
Mingaleev et al Europhys. Lett. **59** 403 (2002)

JLab collaboration with Al Sievers, Cornell U.