Filling the THz Gap

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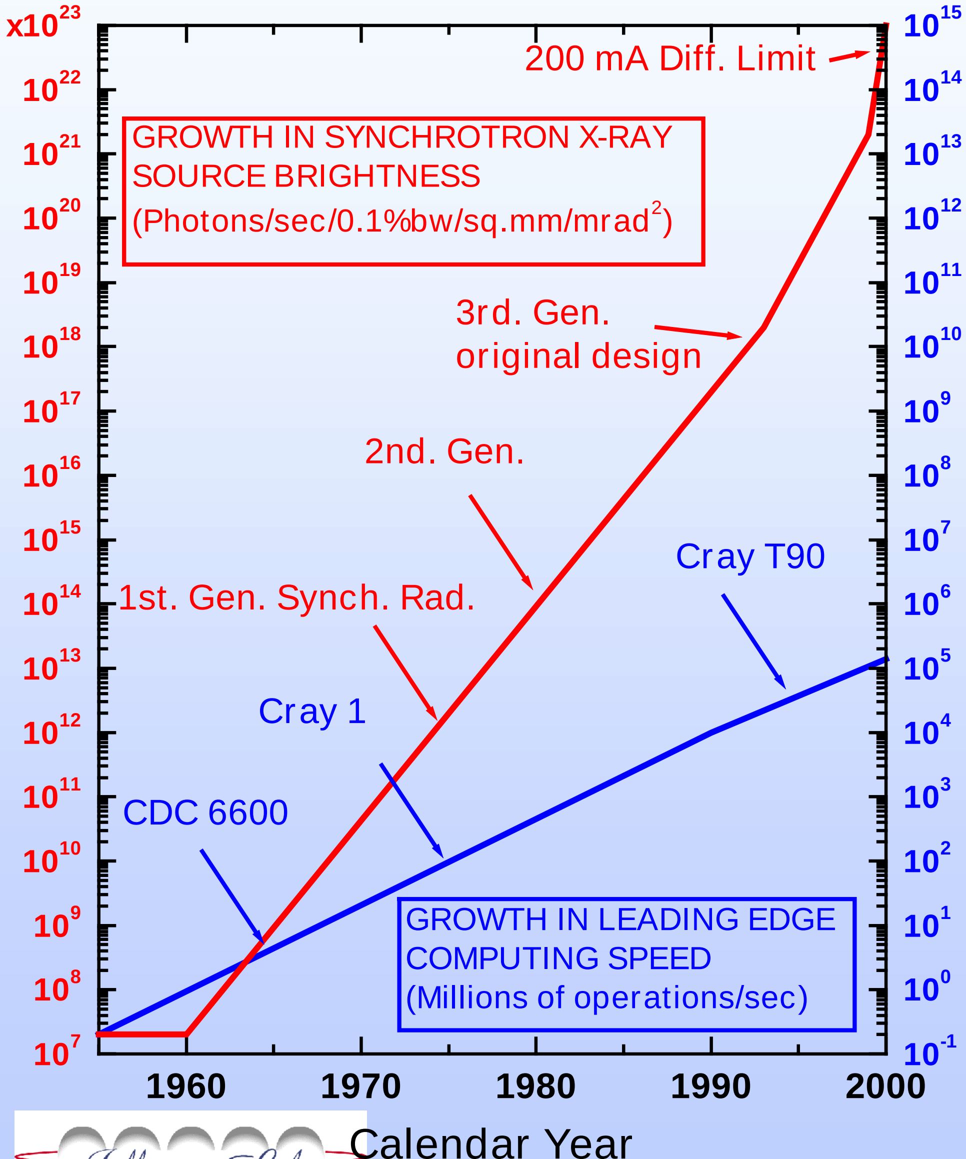
CASA Seminar, Novemer 14, 2003

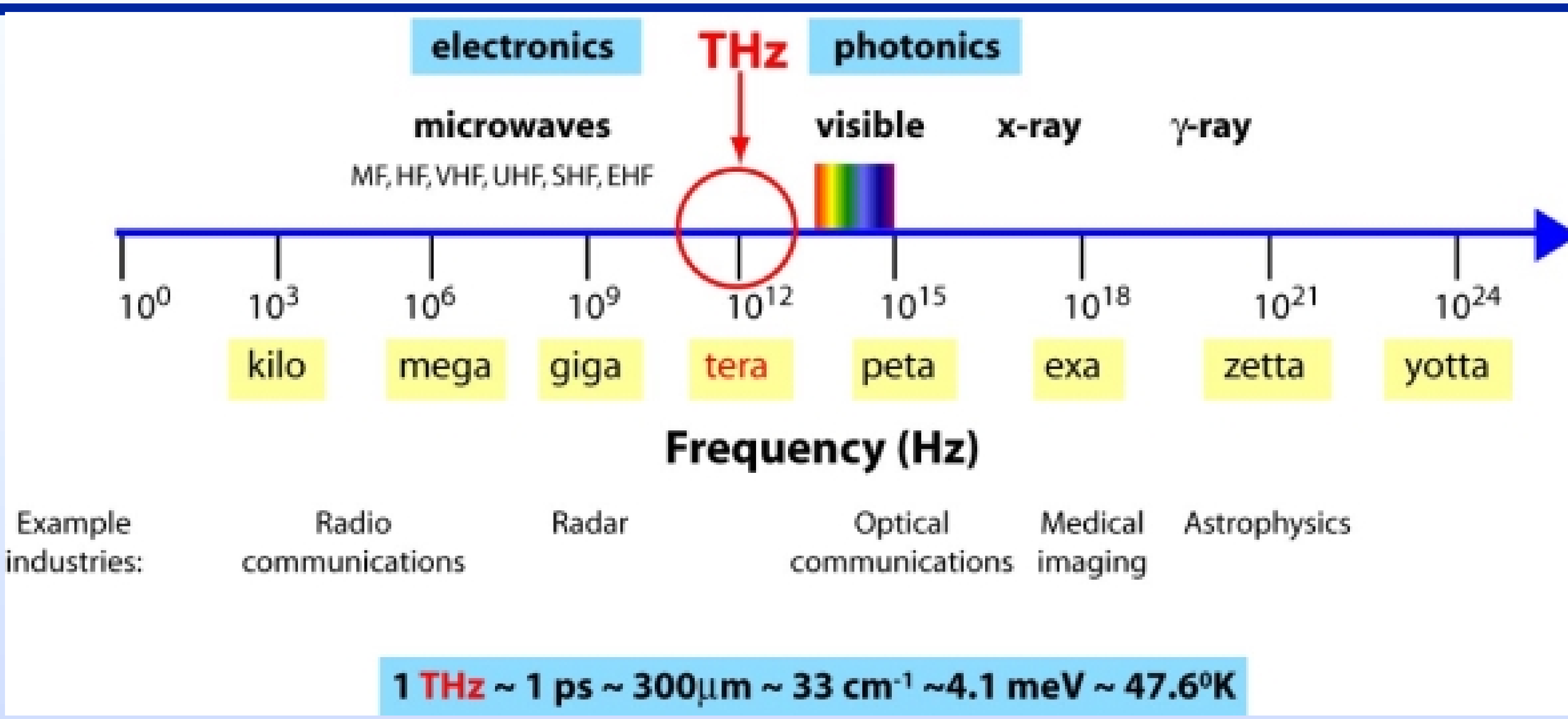


What's new?

Short pulses/
Multiparticle coherence

Near-field

The THz Gap



Many important dynamical processes occur in the THz region (5 meV). Superconducting band-gaps, protein conformational modes, phonons….

With high coherent power the key niche areas are non-linear dynamics and imaging.

THz – Brief History

Volume I. *July–August, 1893.* *Number 1.*

THE

PHYSICAL REVIEW.

A STUDY OF THE TRANSMISSION SPECTRA OF CERTAIN SUBSTANCES IN THE INFRA-RED.

By Ernest F. Nichols.

Within a few years the study of obscure radiation has been greatly advanced by systematic inquiry into the laws of dispersion of the infra-red rays by Langley,[1] Rubens,[2] Rubens and Snow,[3] and others. Along with this advancement has come

After Nichols left Berlin, Rubens continued the work, and in 1900 he isolated wavelengths of 6THz (50 microns) and made careful measurements which he gave to Max Planck who derived the Radiation Law. **Planck wrote in 1922 "Without the intervention of Rubens the formulation of the radiation law, and consequently the formulation of quantum theory would have taken place in a totally different manner, and perhaps even not at all in Germany".**

The Paper That Started it all.

Intense Coherent Submillimeter Radiation in Electron Storage Rings

F. Curtis Michel

Department of Space Physics and Astronomy and Department of Physics, Rice University, Houston, Texas 77001

(Received 23 November 1981)

Energetic electron bunches in storage rings produce pulsed bursts of *incoherent* synchrotron radiation. It is pointed out that they should also produce a roughly comparable power output of *coherent* radio-frequency radiation. Thus electron storage rings might additionally serve as pulsar simulators, producing a similar spectrum of coherent emission, the properties and modification of which could be studied in the laboratory. A spontaneous bunching of electrons (artificially bunched here) might be evidenced as "superbunching."

PACS numbers: 29.20.Dh, 41.70.+t, 97.60.Gb

1981

VOLUME 62, NUMBER 3 PHYSICAL REVIEW LETTERS 16 JANUARY 1989

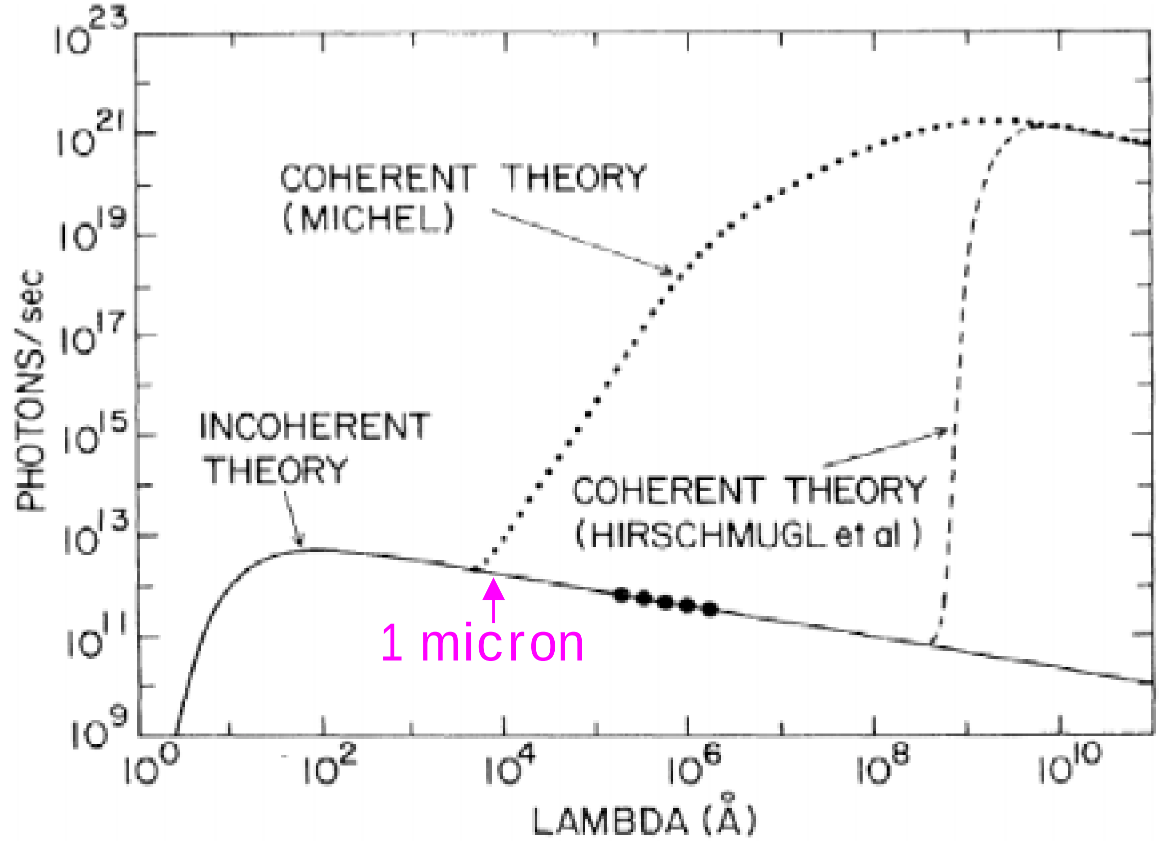
Coherence Effects in Long-Wavelength Infrared Synchrotron Radiation Emission

G. P. Williams, C. J. Hirschmugl, E. M. Kneedler, P. Z. Takacs, and M. Shleifer
National Synchrotron Light Source, Brookhaven National Laboratory, Upton, New York 11973

Y. J. Chabal
AT&T Bell Laboratories, Murray Hill, New Jersey 07974

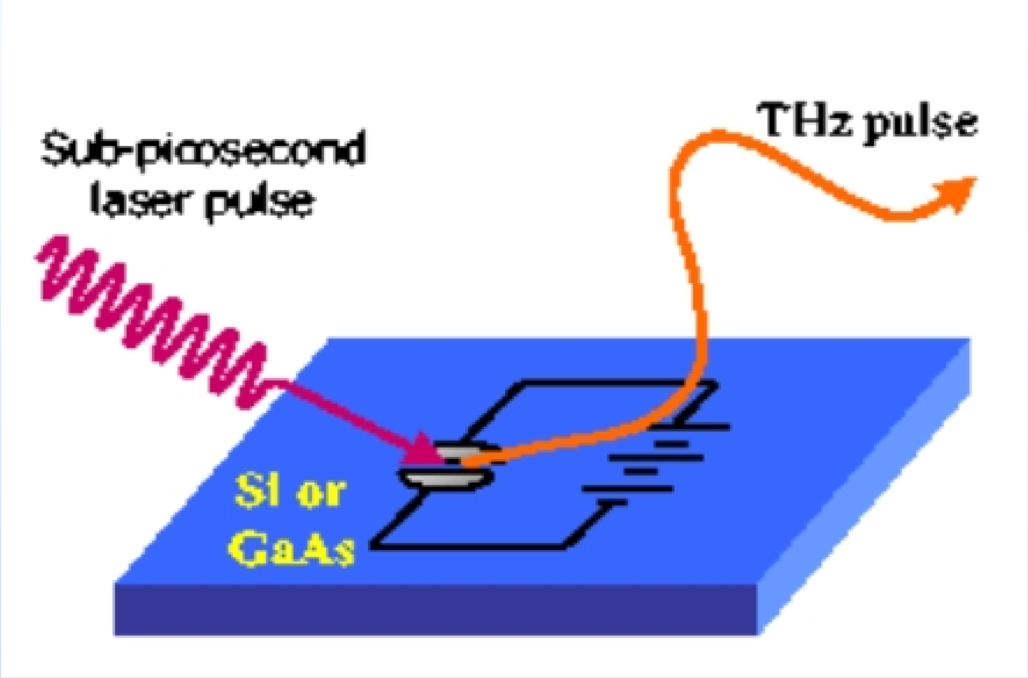
F. M. Hoffmann
Exxon Research and Engineering, Corporate Research Laboratories, Annandale, New Jersey 08801

(Received 26 August 1988)



Backing up….Auston Switch for producing THz light

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

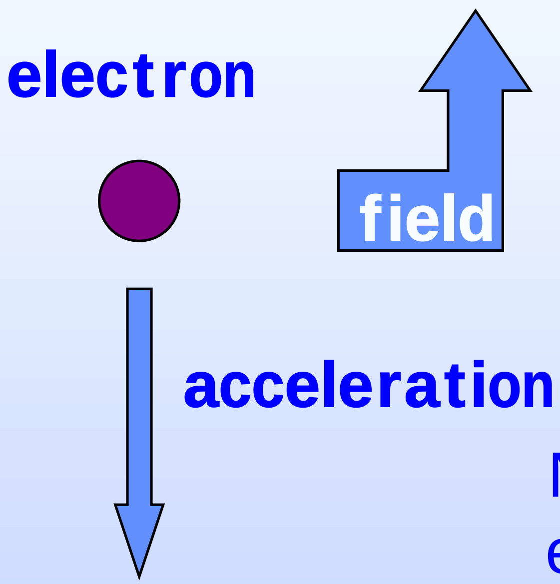


Auston, D.H., Cheung, K.P., Valdmanis, J.A. and Kleinman, D.A., *Phys. Rev.Letters* **53** 1555-1558 (1984).

Radiation from Accelerated Electron

Electric field goes linearly in the electric charge and the acceleration

- so intensity (power) goes like e^2a^2



But units of power are:

$$Power = \frac{Force \times Distance}{Time}$$

$$= \frac{MLT^{-2} \times L}{T} = ML^2T^{-3}$$

Now for an electric charge, force is e^2/L^2, so we can derive units for e thus:

$$\frac{e^2}{L^2} = MLT^{-2}$$

So e^2a^2 has units of : $ML^3\,T^{-2} \times L^2T^{-4} = ML^5T^{-6}$

And if we divide by c^3, or L^3T^{-3}, we get ML^2T^{-3}.

Radiation from Accelerated Electron

Also we note that radiation is emitted in only 2 out of 3 directions, so we have a 2/3 factor, yielding:

Larmor's Formula

$$Power = \frac{2e^2a^2}{3c^3}$$

Noting that the units of power are ML^2T^{-3}, and noting that M goes like gamma, L goes like 1/gamma and T goes like gamma in the moving frame, in the rest frame the relativistic version is :

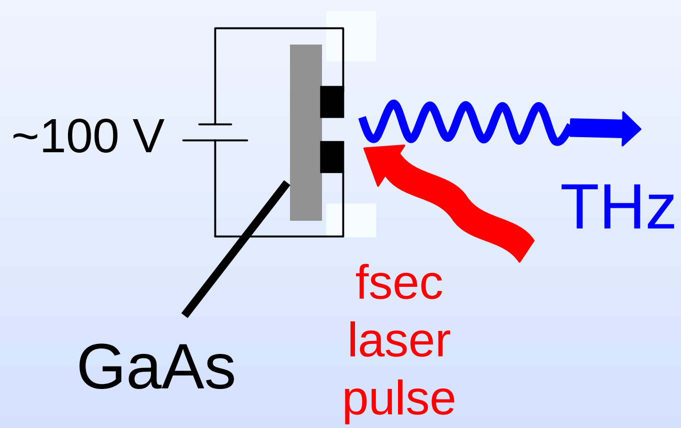
$$Power = \frac{2e^2a^2}{3c^3}\gamma^4$$

N.B. Radiated energy and elapsed time transform in the same manner under Lorentz transforms

Comparing Coherent THz Synchrotron and Conventional THz Sources

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

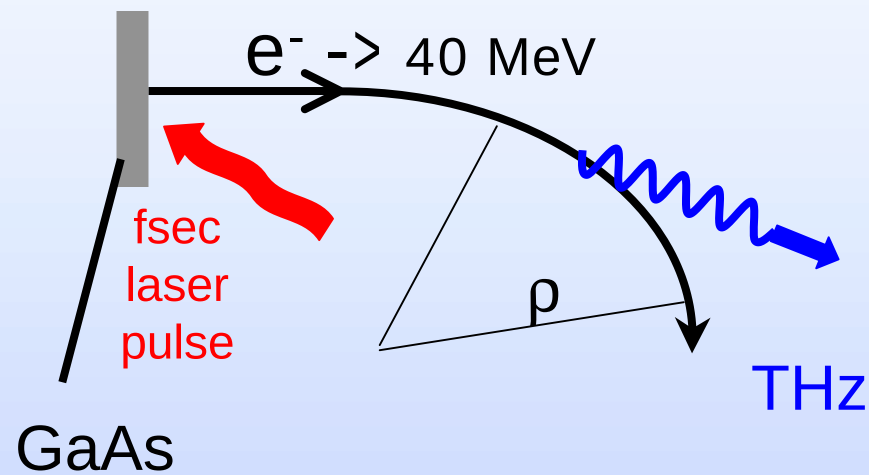
a=acceleration
c=vel. of light
γ=mass/rest mass



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

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

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

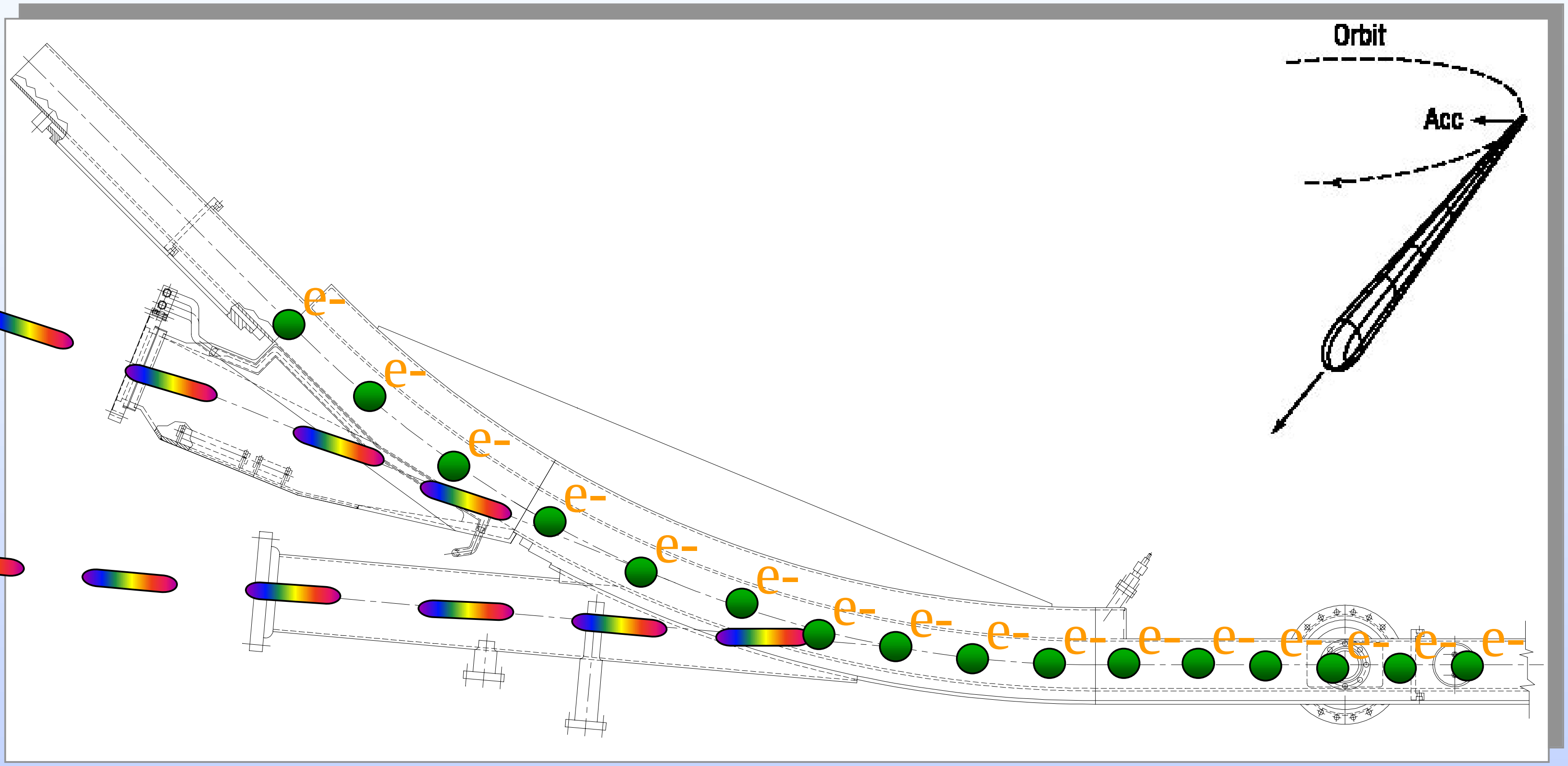


$$a = \frac{c^2}{\rho} = \frac{(3\times10^8)^2}{1} \cong 10^{17}\, m/sec^2$$

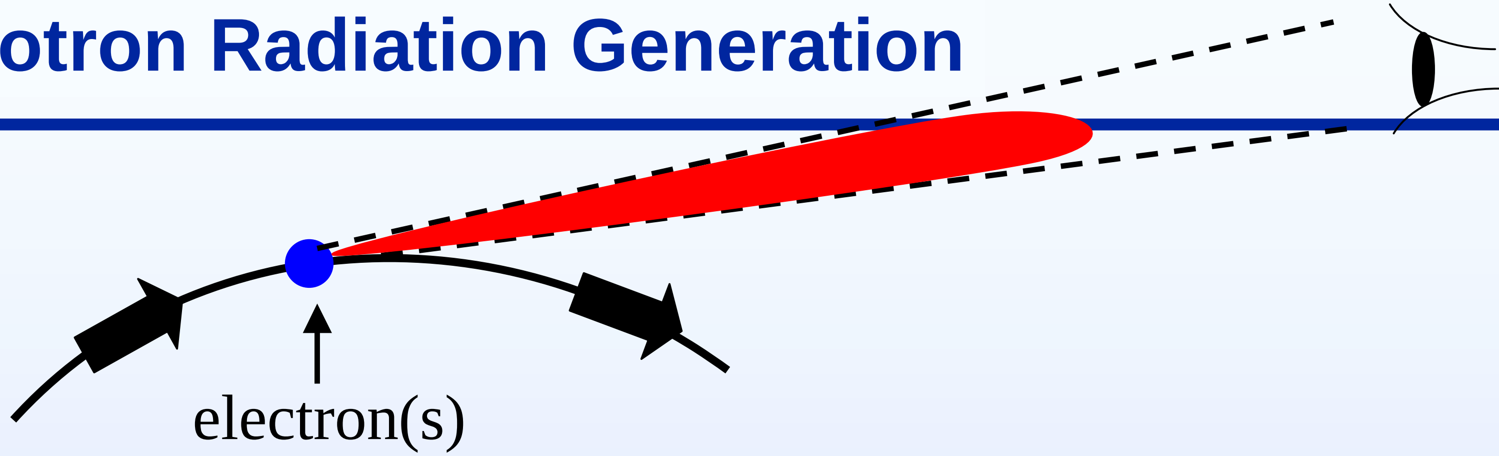
$$\text{if } \rho = 1\ m$$

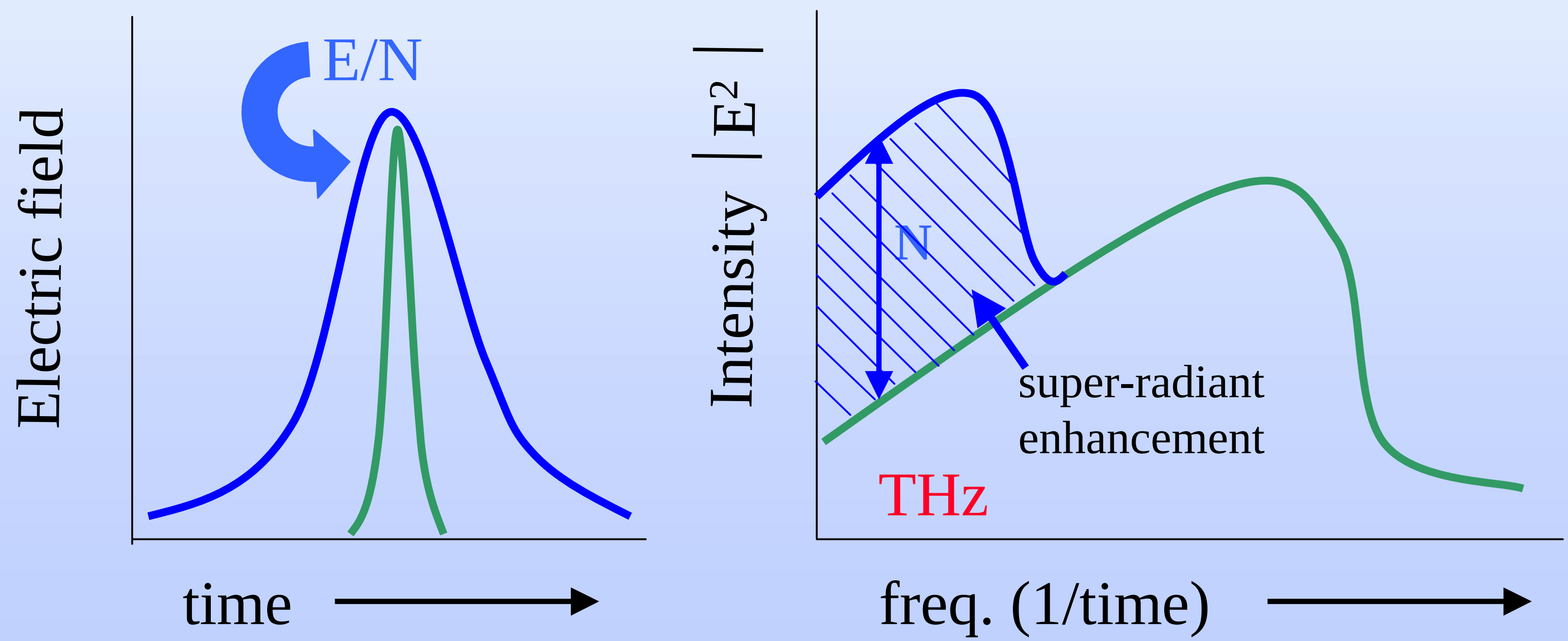
$$\gamma = 80 \ \ and \quad 80^4 = 10^7\ !!!!$$

Synchrotron Radiation Generation



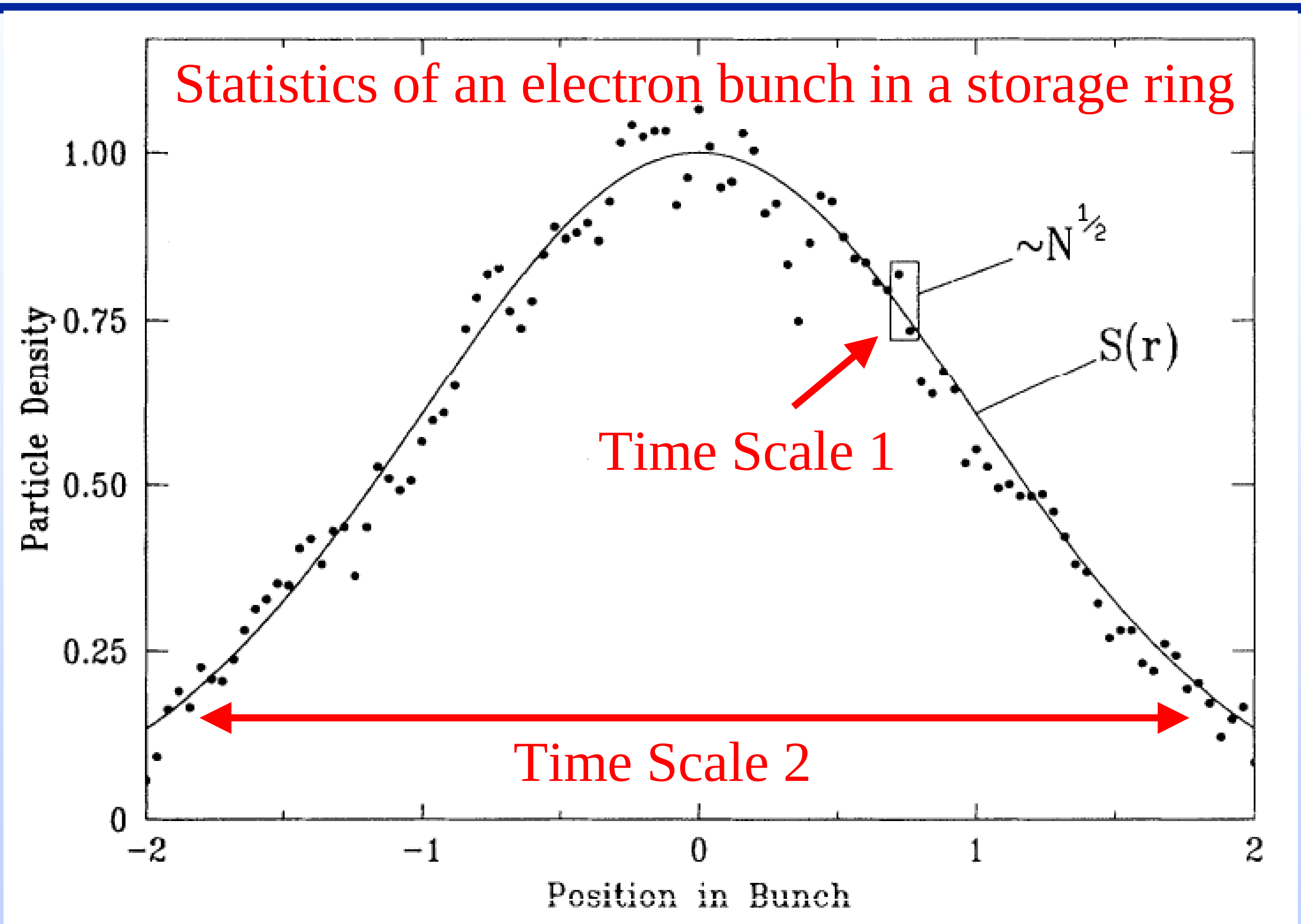
Synchrotron Radiation Generation





W.D. Duncan and G.P. Williams,"Infra-red Synchrotron Radiation From Electron Storage Rings", Applied Optics 22, 29l4 (1983).

Synchrotron Radiation Generation - actual situation



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

Coherent Synchrotron Radiation Generation - theory

$$\frac{d^2I}{d\omega\, d\Omega} = \left[N[1-f(\omega)] + N^2 f(\omega)\right] \times \frac{e^2\omega^2}{4\pi^2 c}\left|\int_{-\infty}^{\infty} \hat{n}\times\left(\vec{\beta}\times\hat{n}\right)\, e^{i\omega\left(t-\frac{\hat{n}\cdot\vec{r}(t)}{c}\right)}dt\right|^2$$

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

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

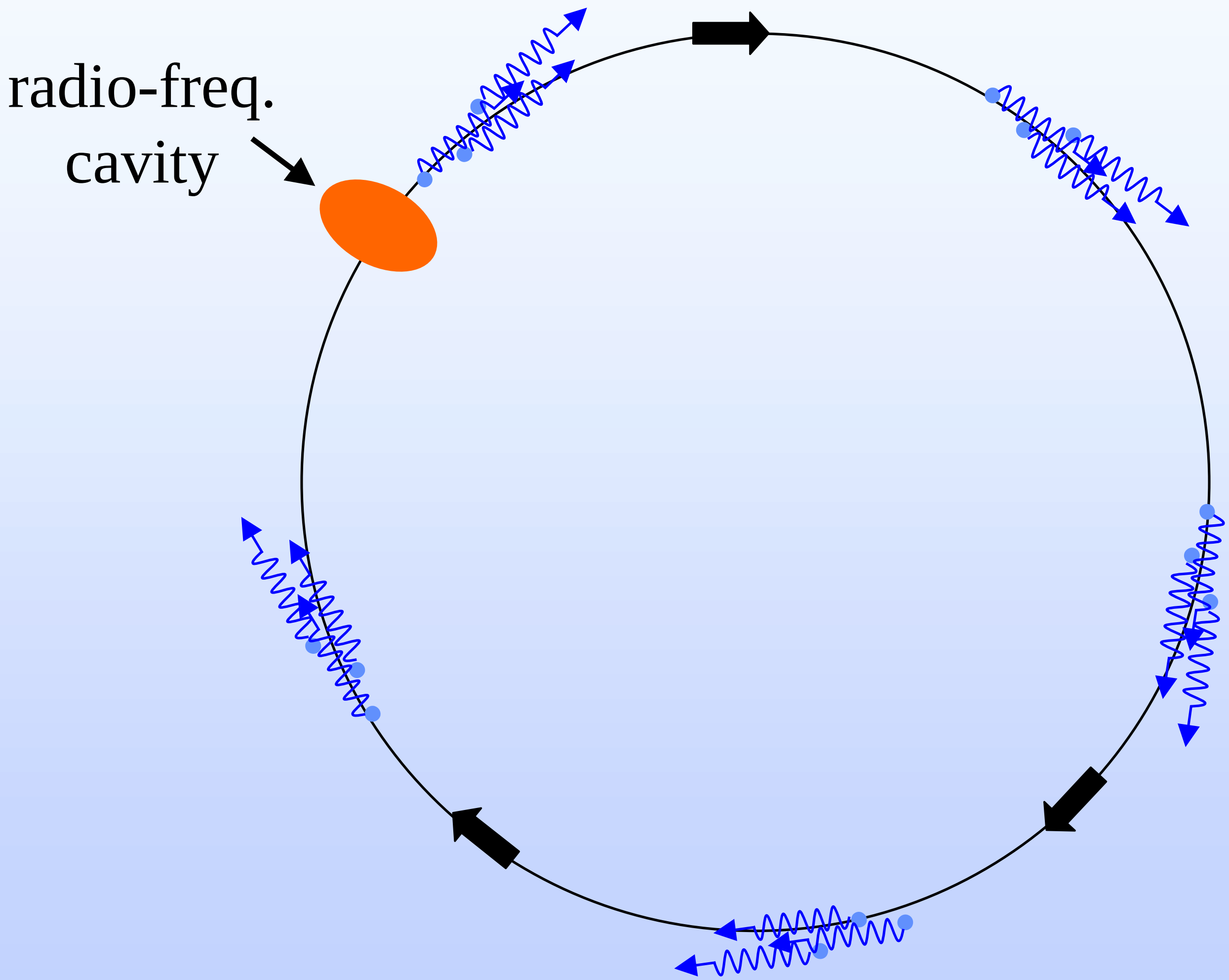
REFERENCES

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).

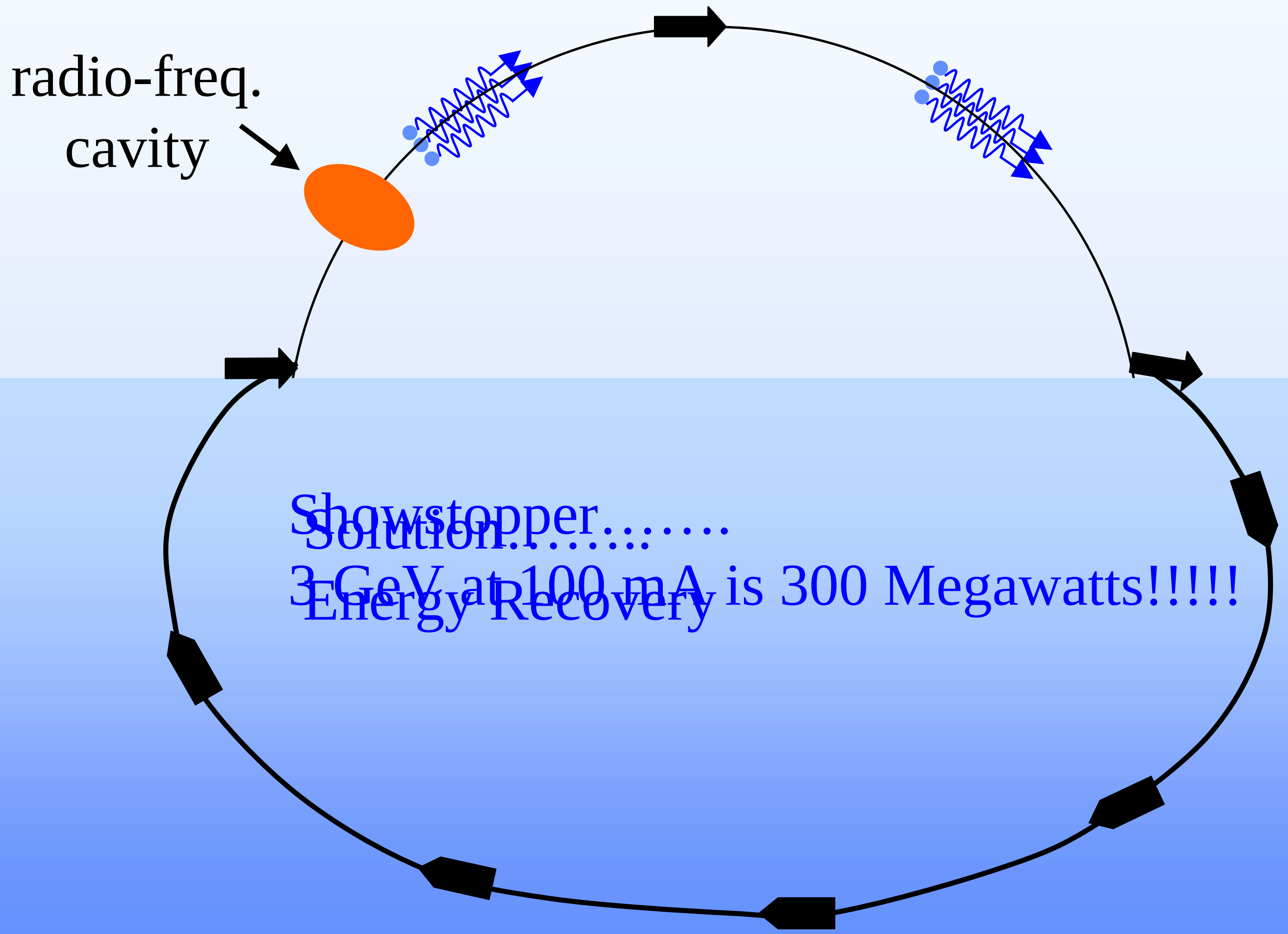
S. Nodvick and D.S. Saxon, Suppression of coherent radiation by electrons in a synchrotron. Physical Review **96**, 180-184 (1954).

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

Synchrotron Radiation - so what's new here?



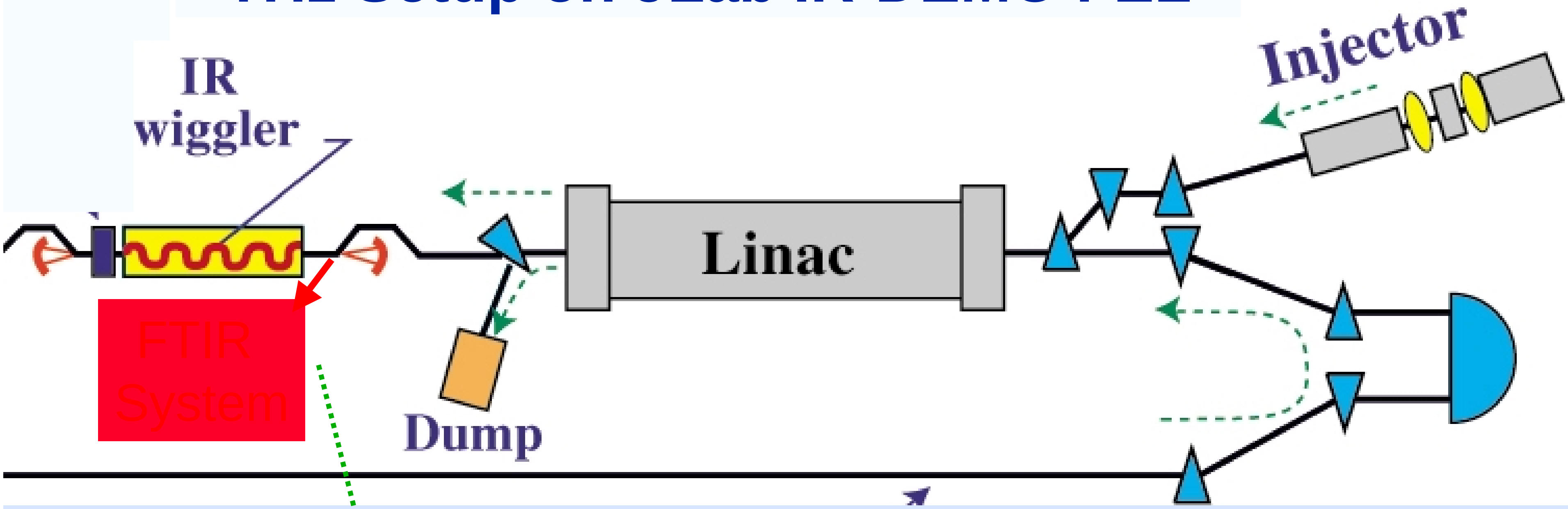
Synchrotron Radiation - so what’s new here?

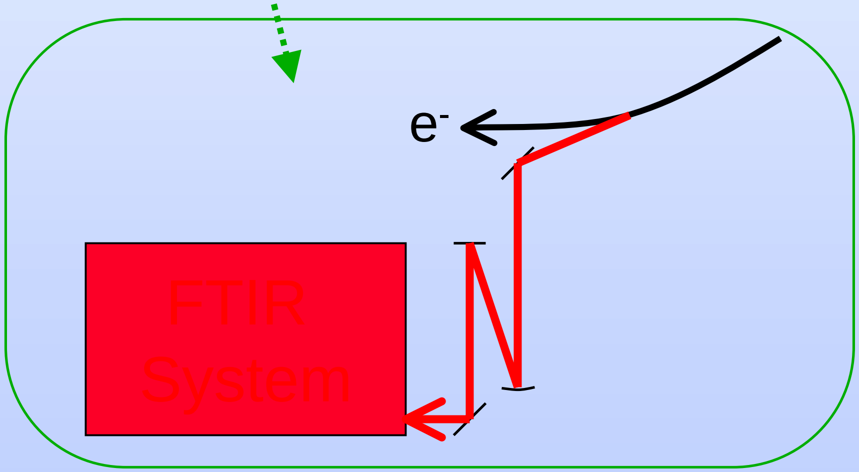


Showstopper…….
3 GeV at 100 mA is 300 Megawatts!!!!!

Solution…….
Energy Recovery

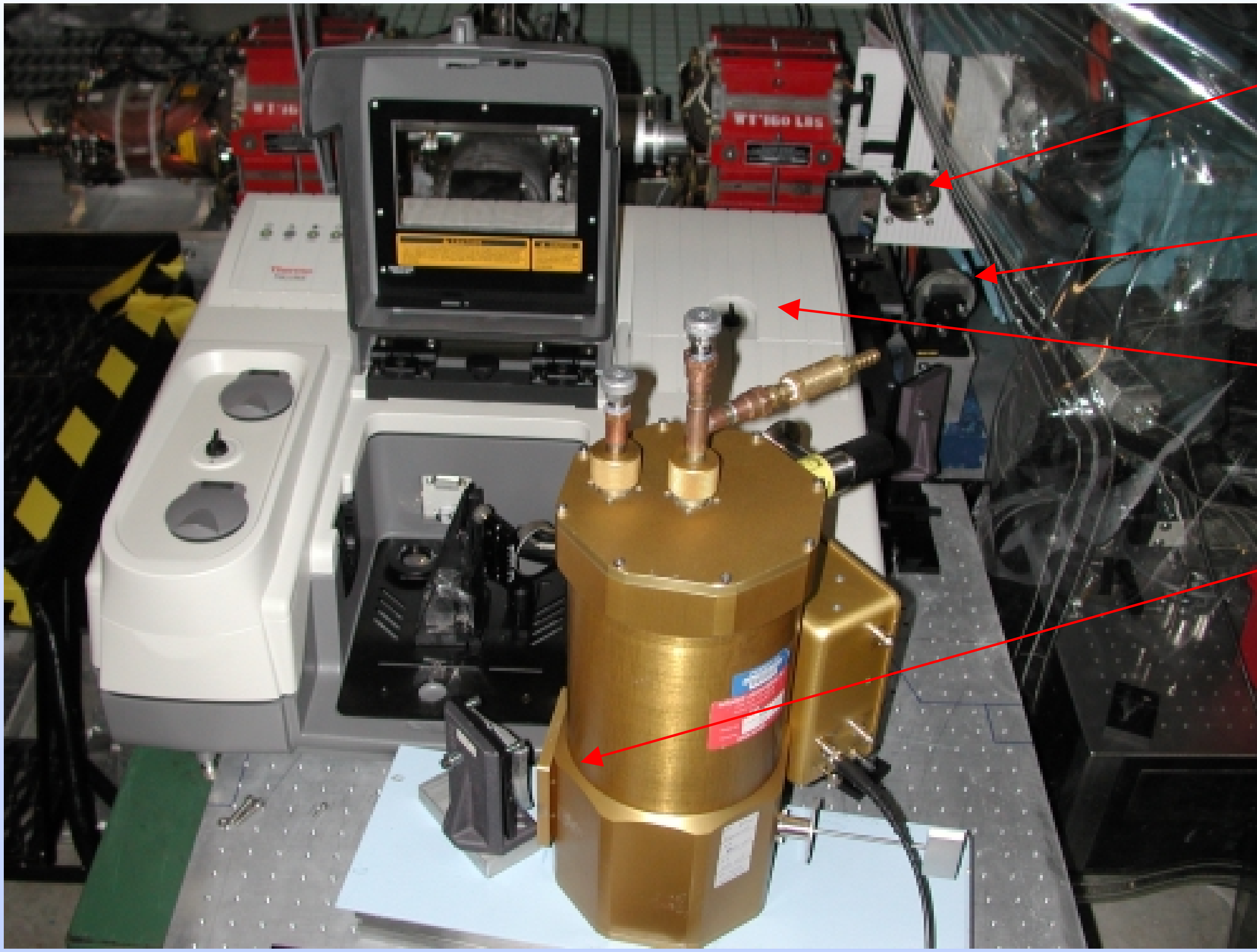
THz Setup on JLab IR-DEMO FEL





We measured the bend-magnet synchrotron radiation right before the FEL, when the beam is maximally compressed.

THz Setup on JLab IR-DEMO FEL



Crystal quartz window

Collimating optic

Nicolet Nexus 670 FTIR bench

LHe cooled Si bolometer detector

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Terahertz waves penetrate the world of imaging

Foiling terrorists, detecting cancer and designing new drugs are just some of the potential applications for equipment that exploits the unique properties of terahertz waves. Oliver Graydon looks behind the scenes at one of the hottest sectors in photonics research today.

From Opto & Laser Europe October 2002

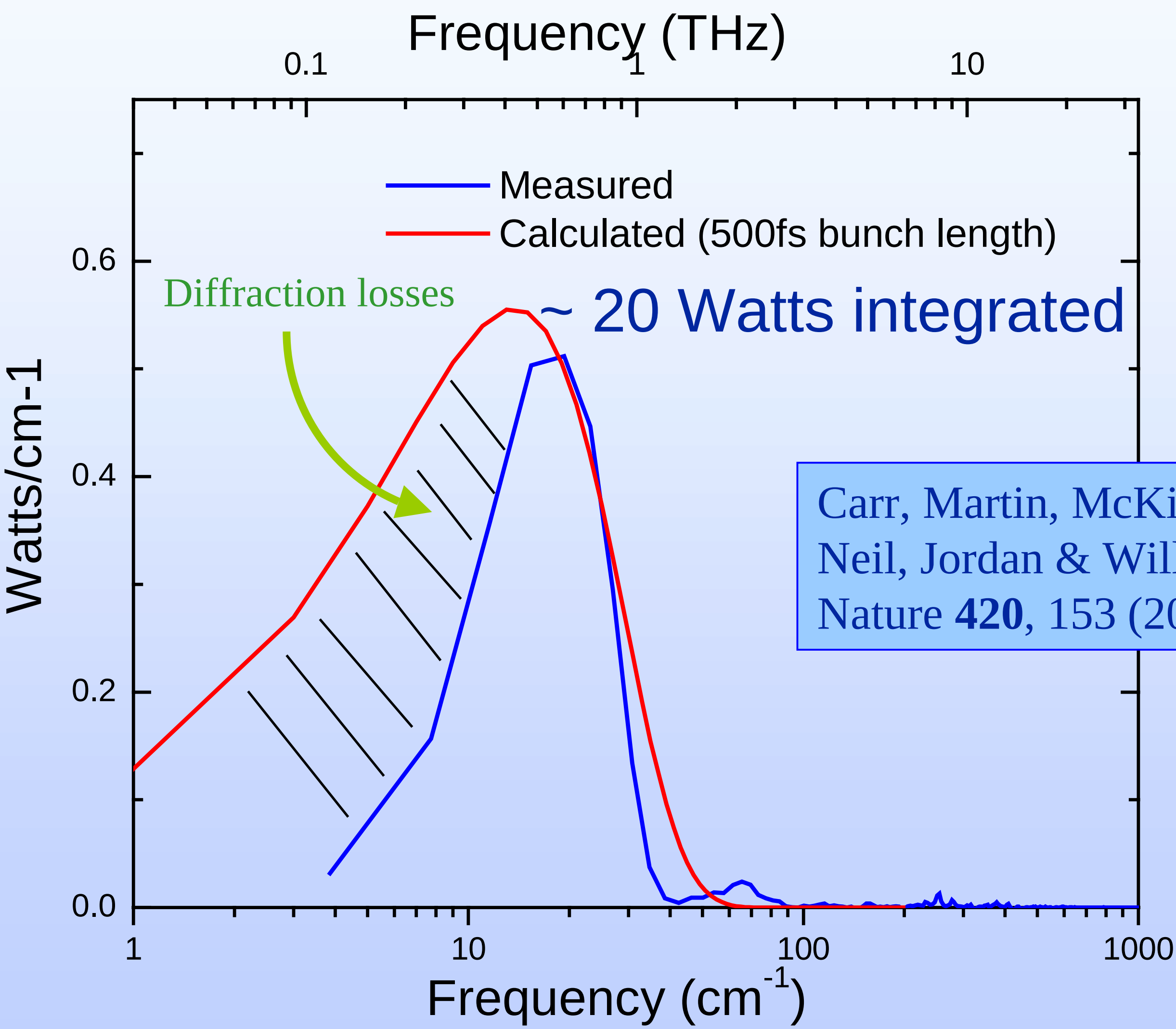
October 2002

Quantum leap

The development of such emitters has recently taken a leap forward, thanks to the invention at Bell Labs, US, of the quantum-cascade laser, which emits in the mid-infrared at around 4 µm. Semiconductor scientists are now adapting the technology to design lasers that are operational in the far-infrared and terahertz regions.

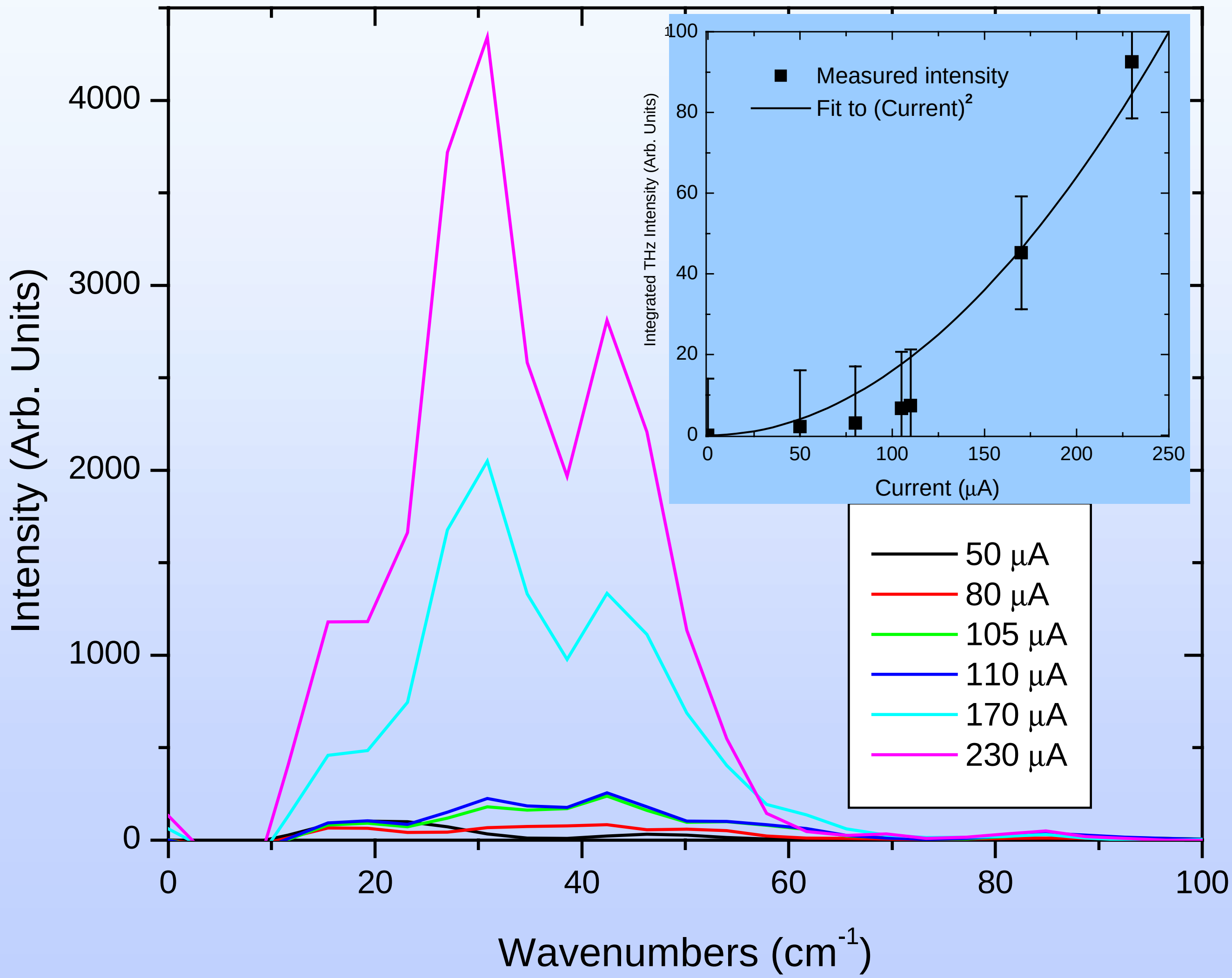
Earlier this year, researchers from Teraview, the University of Cambridge, and the National Institute for the Physics of Matter (INFM) in Italy made a series of quantum cascade lasers that operate in pulsed and continuous-wave mode at 4.4 THz (wavelength 68 µm). Although the lasers can only currently work at low temperatures of up to 50 K, they emit up to 2 mW of singlemode terahertz radiation. The challenge now is to raise the operational temperature, which, although it may take several years, is definitely feasible.

THz Expt and Calculation

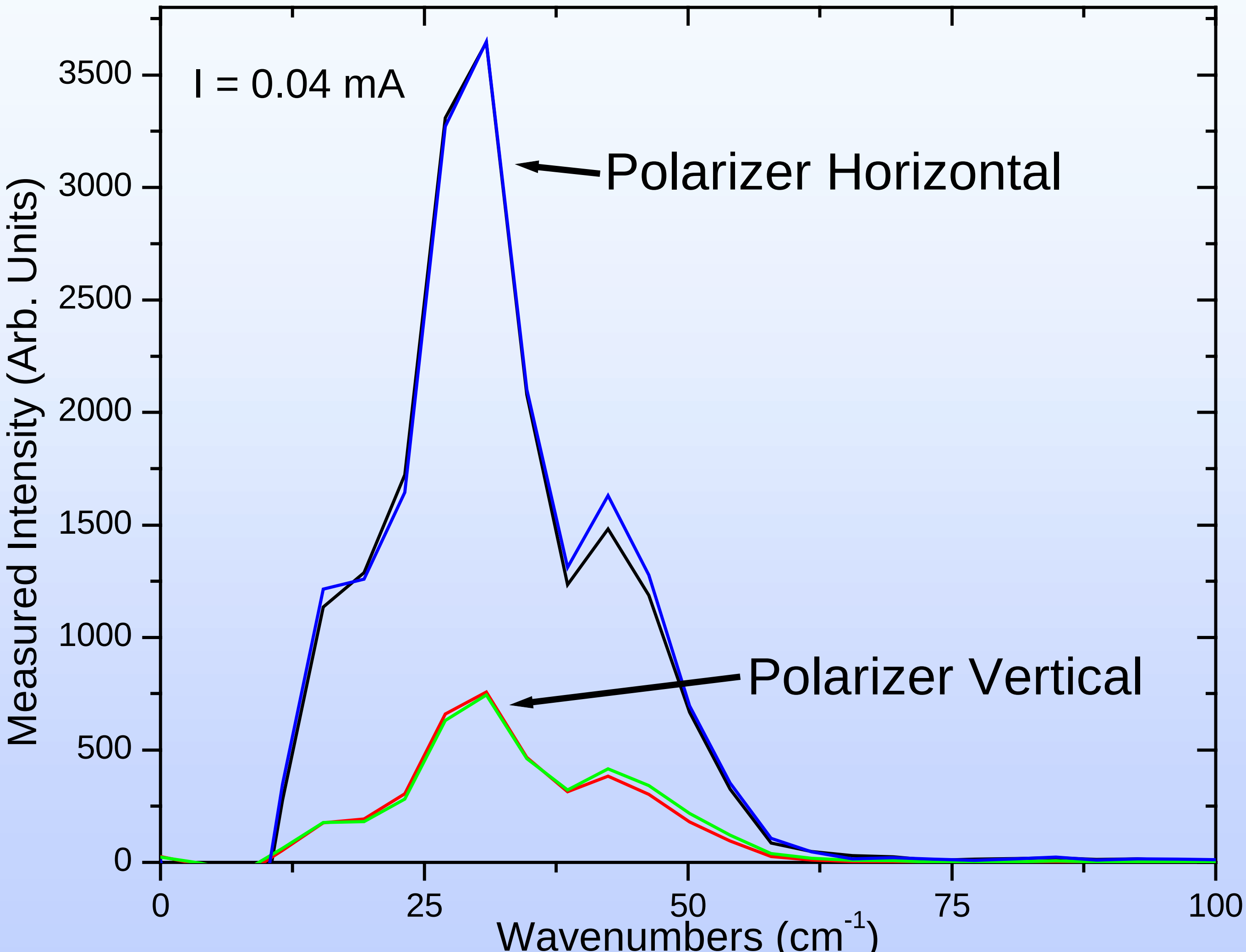


Carr, Martin, McKinney, Neil, Jordan & Williams Nature **420**, 153 (2002)

Coherent THz vs. Current



Polarization of Coherent THz



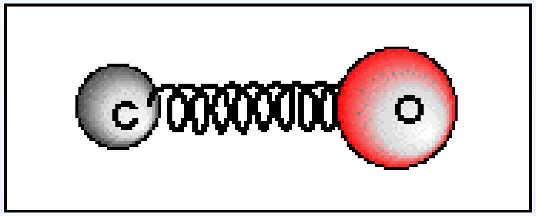
Expected polarization ratio for 60 mrad port at 30 cm^{-1} is 6:1.

We observed 5:1. Good agreement.

Why do this? Terahertz Imaging

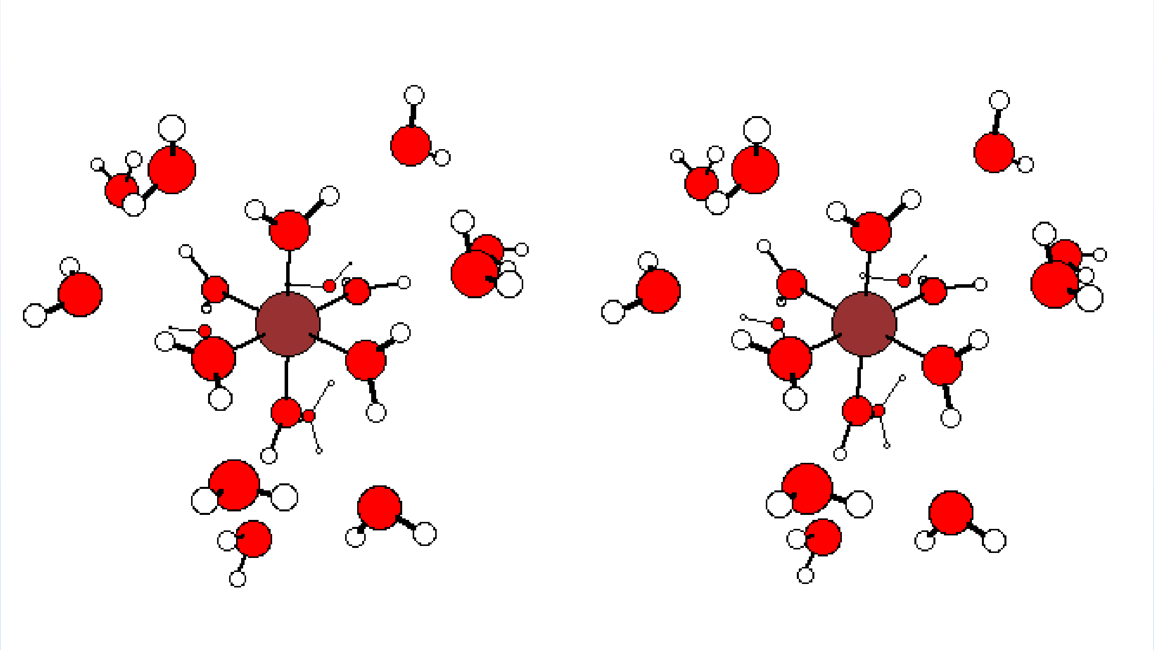
Clery, Science **297** 763 (2002)

IR Spectroscopy & Dynamics is based on Vibrations



Simple molecule

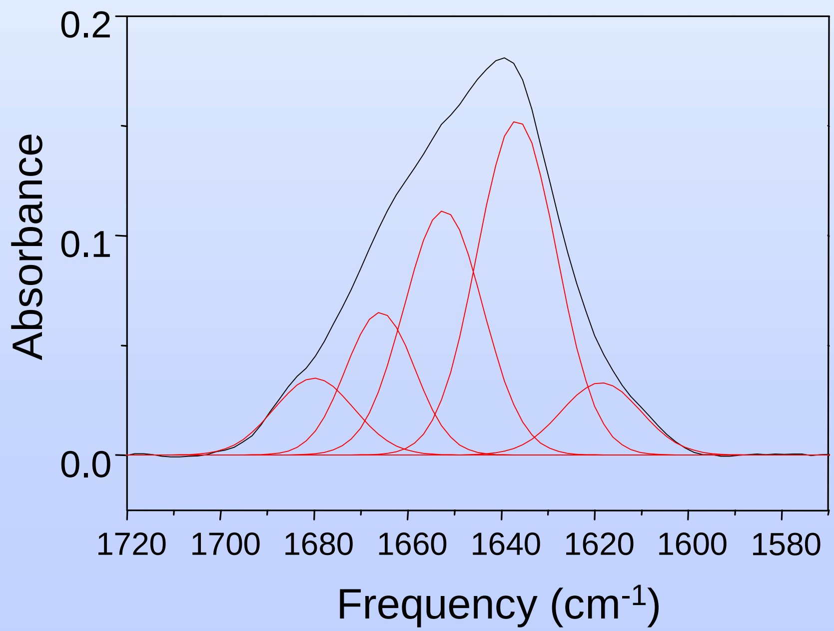
More complicated molecule - protein



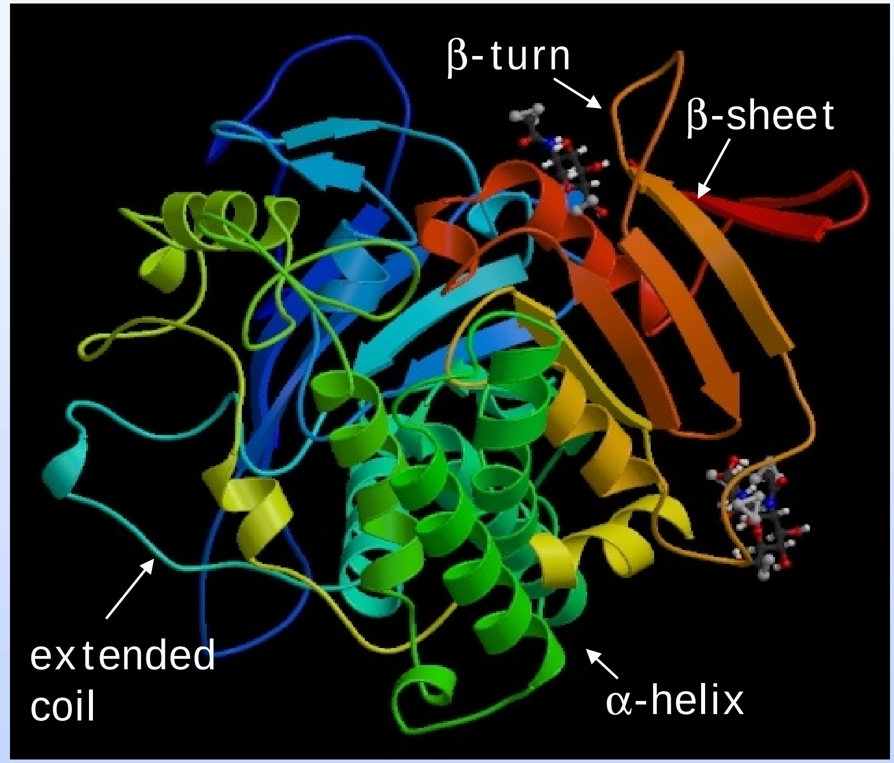
Slide courtesy Paul Dumas, LURE, Orsay, France

Protein Structure / Folding Dynamics

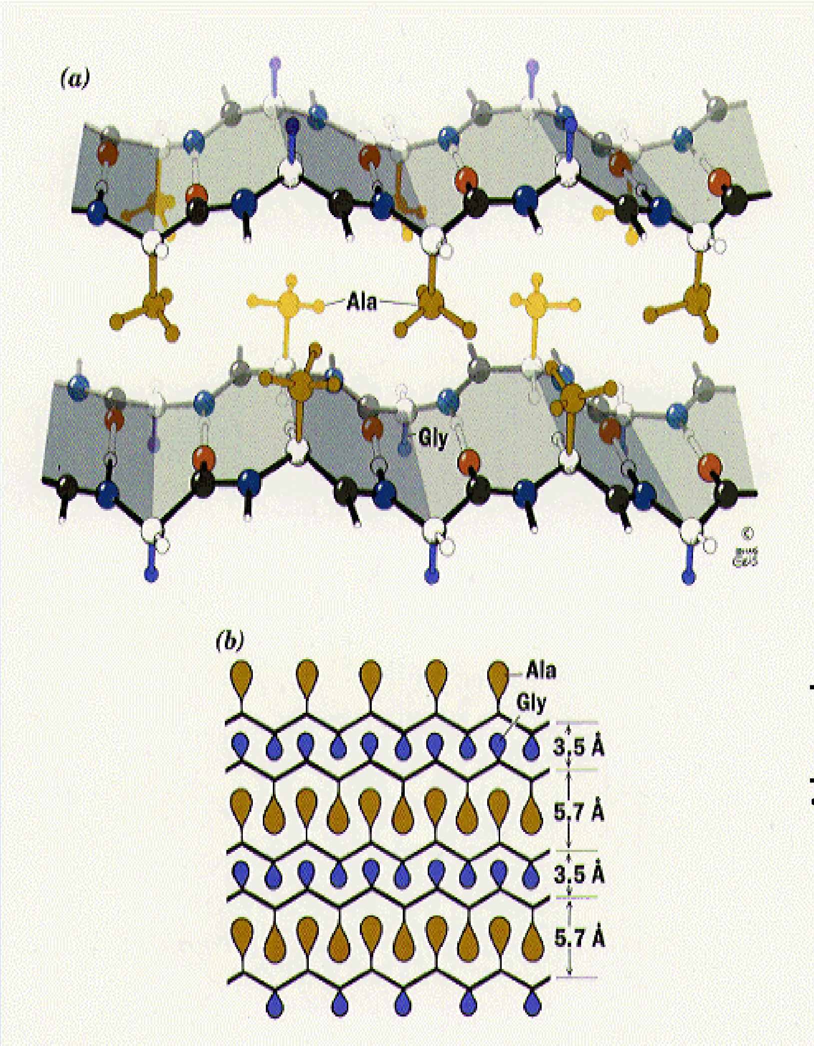
Amide I Secondary Structure Assignments:	
1620 - 1640	β-sheet
1644	extended coil (D_2O)
1648 - 1657	α-helix
1665	3_{10} helix
1670 - 1695	anti-parallel β-sheet, β-turn



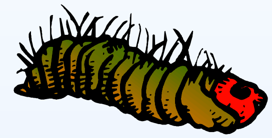
Carboxypeptidase



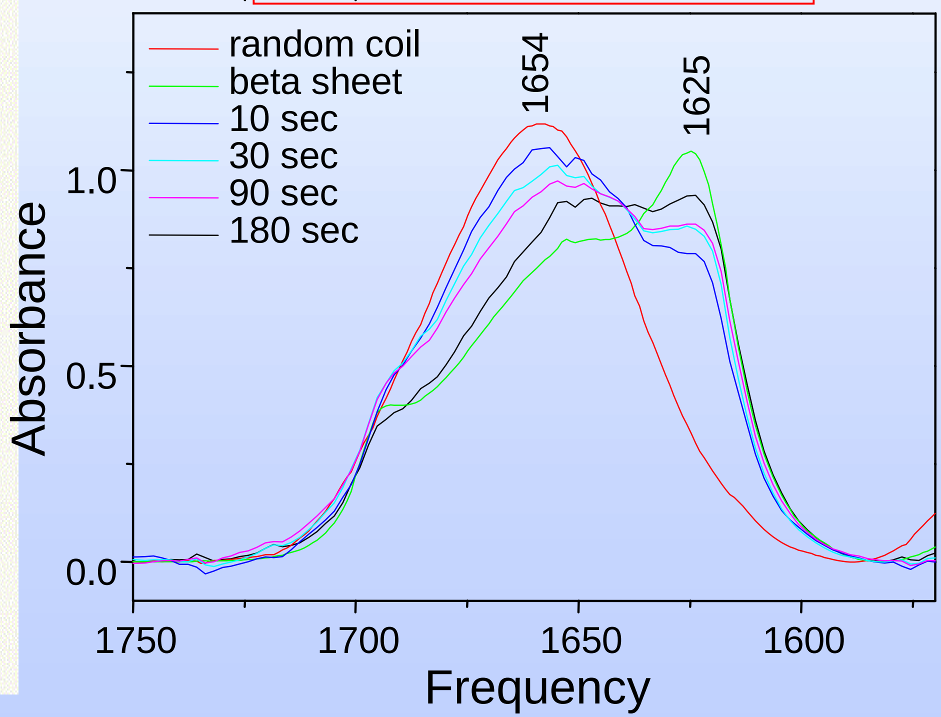
Protein Folding Dynamics - Silk Fiber Formation



SCAN PARAMETERS:

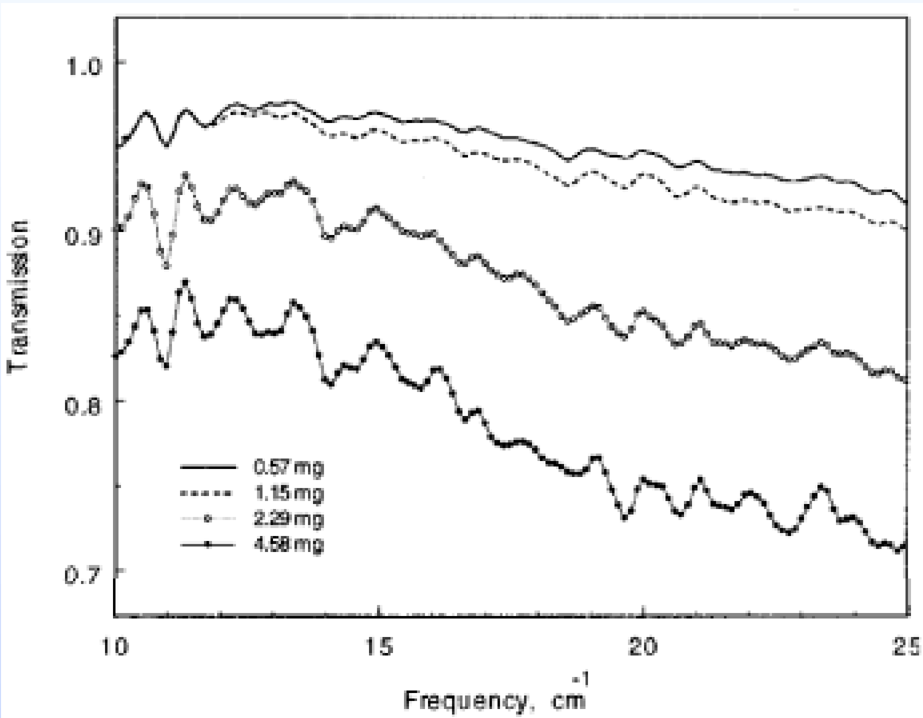


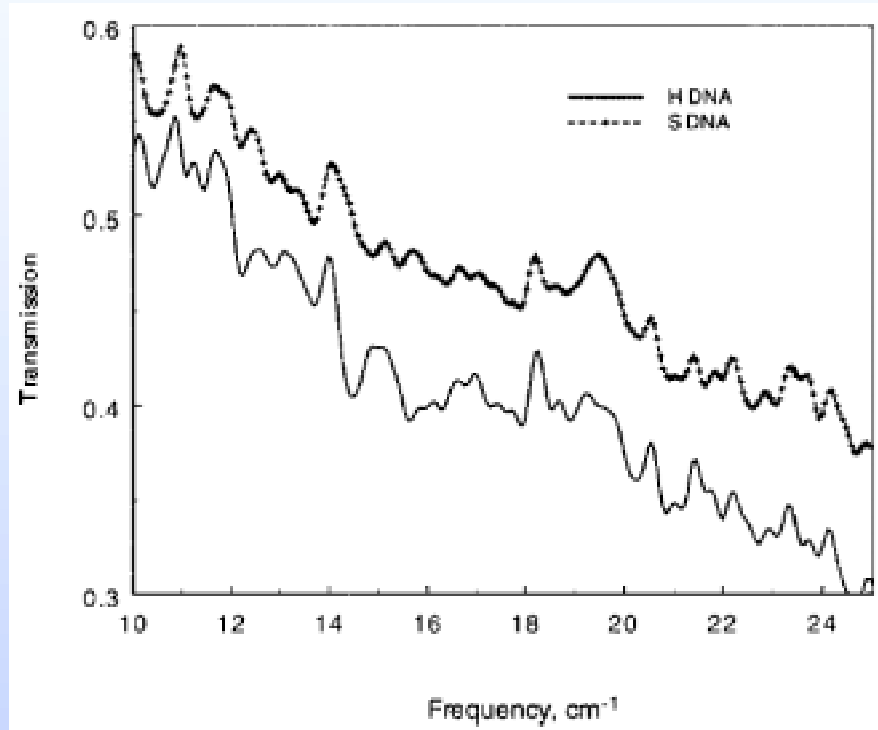
- %T: silk fibroin on BaF_2 disk
- 32 scans at 200 KHz (2.3 sec)
- 4 cm^{-1} resolution
- MCT detector



Lisa Miller, Mark Chance et al.

THz Spectroscopy

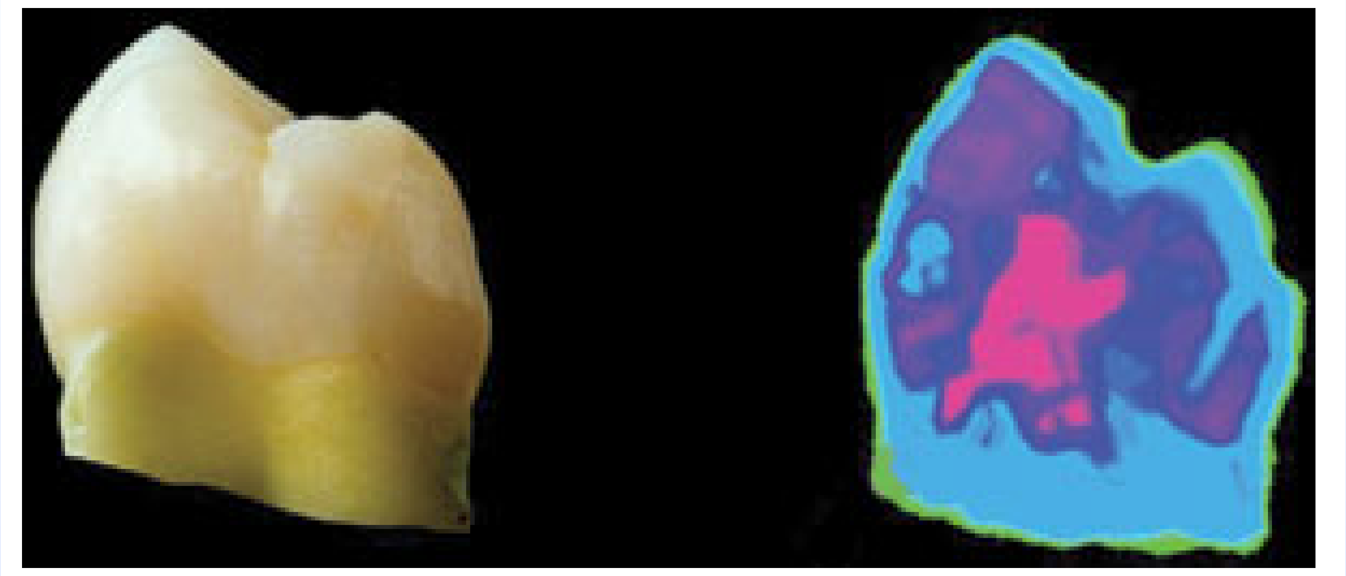




Anthrax proxy **DNA**

Globus et al. University of Virginia J. App. Phys. 91 6105 (2002)

THz Imaging



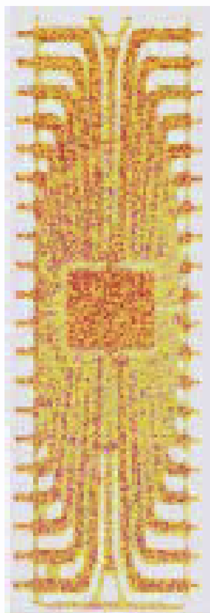
A tooth cavity shows up clearly in red. Teraview Ltd.

The Promise of THz – novel imaging

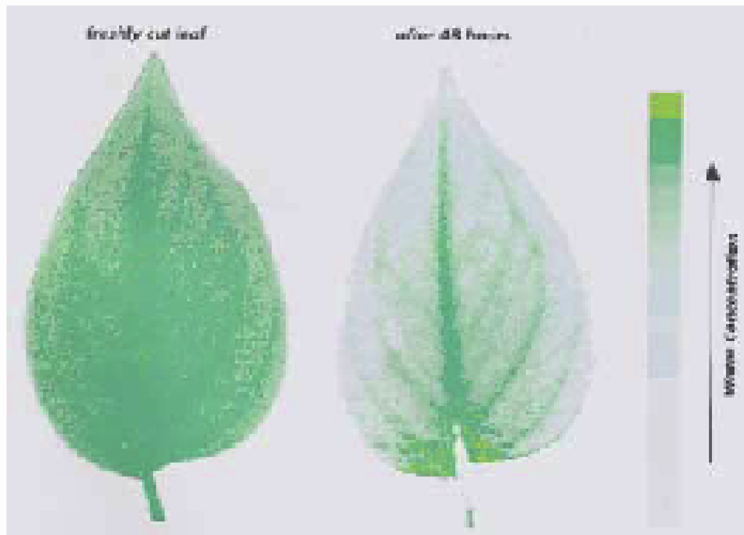
Opt. Lett. 20, 1716 (1995)

Imaging with terahertz waves

B. B. Hu and M. C. Nuss



THz image of an IC chip

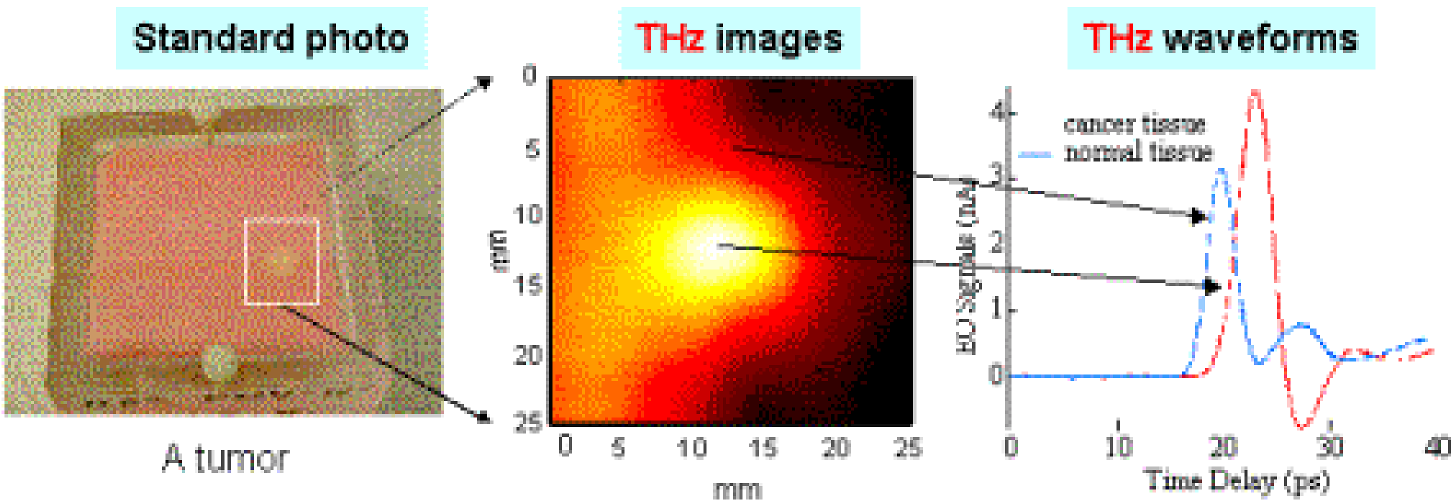


THz images of a fresh leaf and of the same leaf after 48 hrs

http://www.rpi.edu/~zhangxc

The Promise of THz – novel imaging

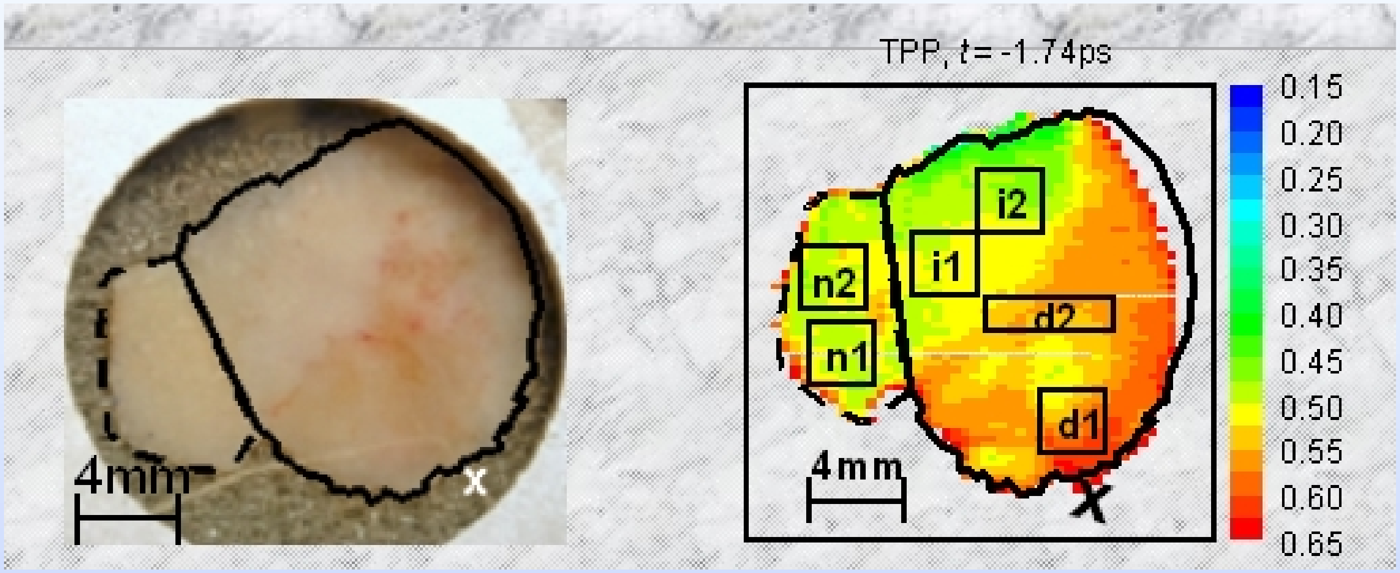
THz Imaging of a Breast Tumor (Phantom)



Amplitude, timing and shape of the waveforms change between normal and cancerous tissues. It should give the density and signature of the tumors.

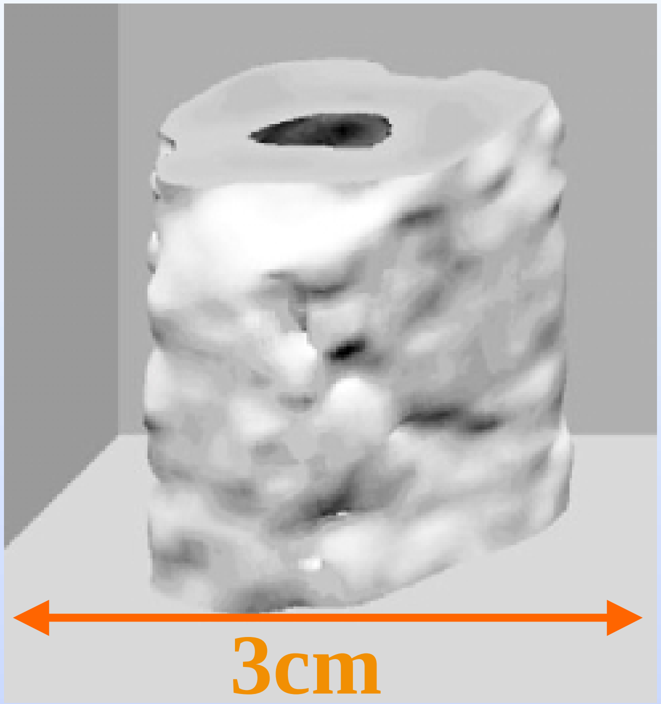
http://www.rpi.edu/~zhangxc

THz Imaging

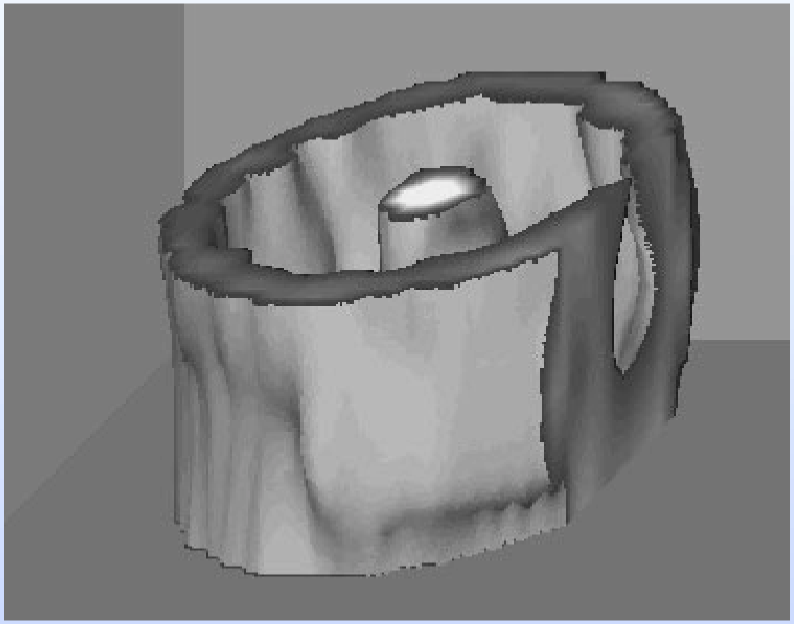


Basal cell carcinoma shows malignancy in red. Teraview Ltd.

Terahertz computerized tomography



Turkey Bone

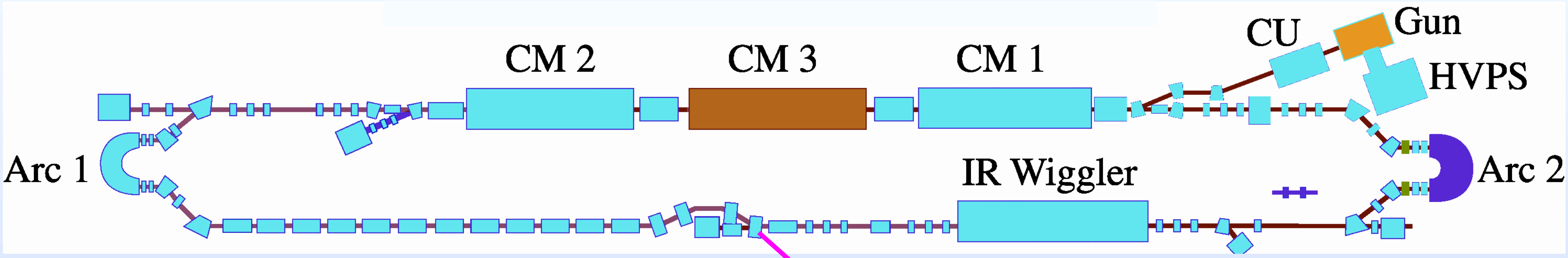


Test Object

Ferguson et. al. Phys. Med. Biol. 47 3735 (2002)

So – where are we going at JLab with THz?

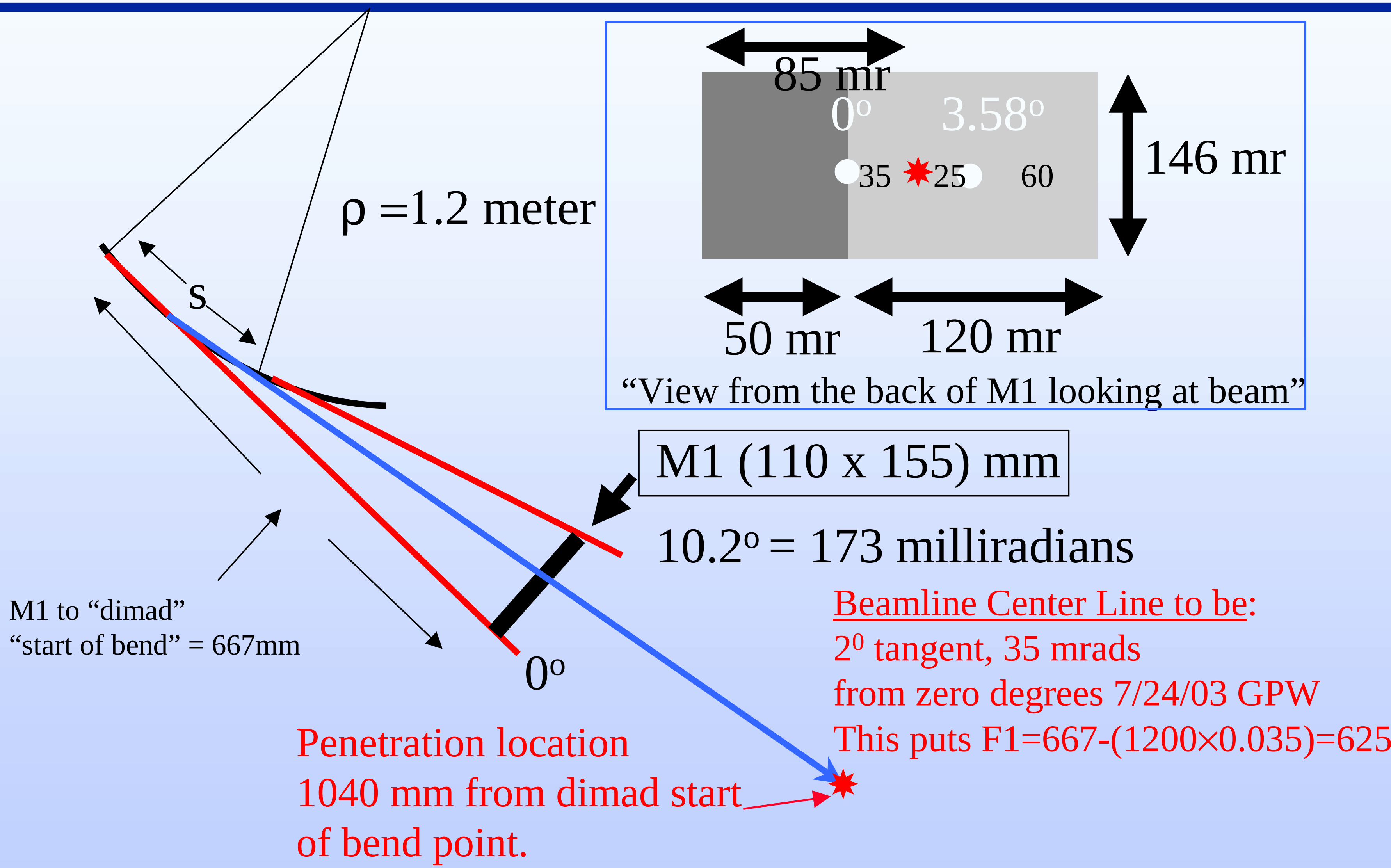
FEL upgrade, phase 1



THz light port

Jefferson Lab's new ERL/FEL/THz source
Turned-on June 2003!!

JFEL THz Port Description Final Rev. 1 Dated 8-13-2003

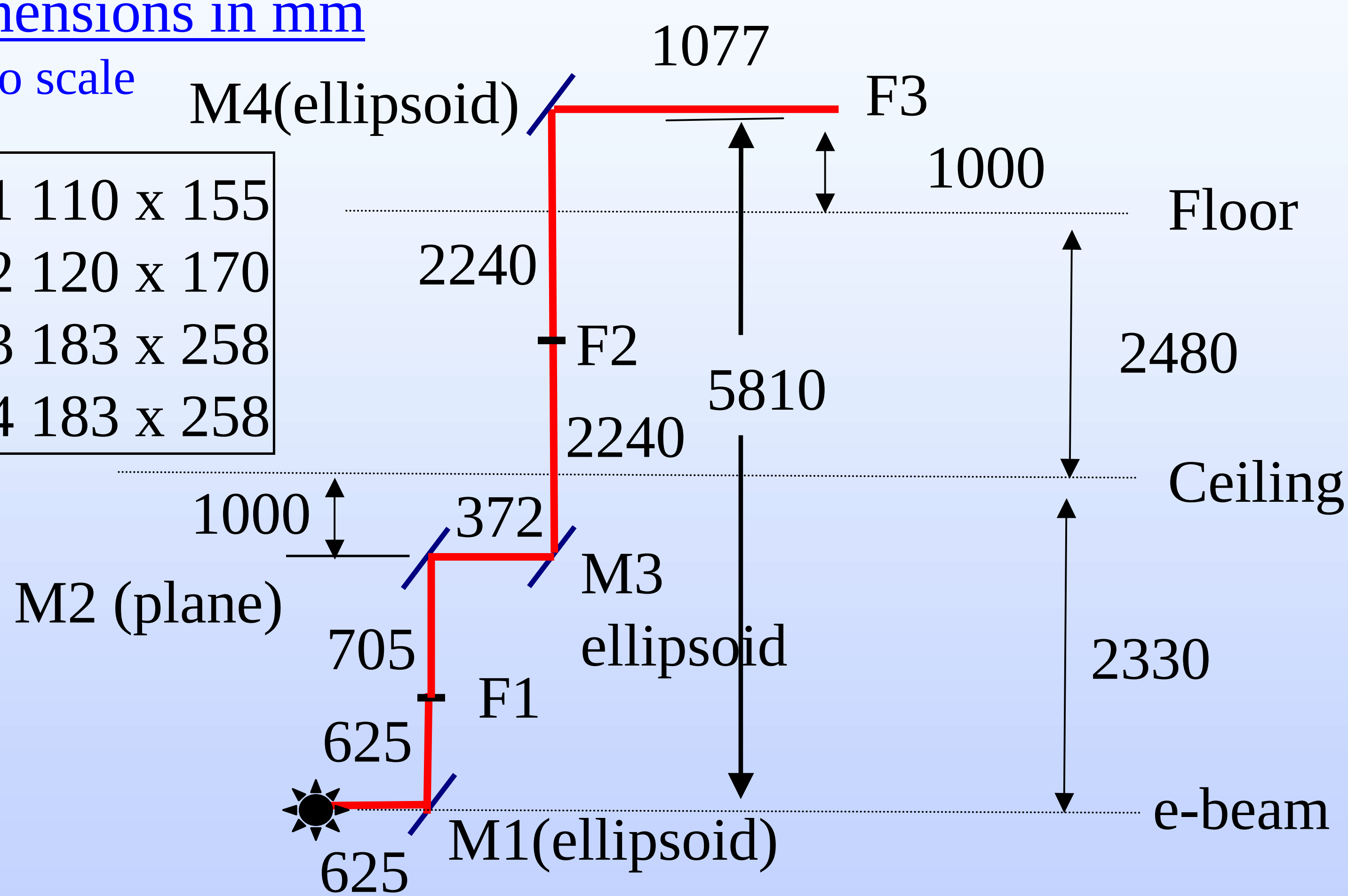


JFEL THz Port Description Final Rev. 1 Dated 8-13-2003

Dimensions in mm

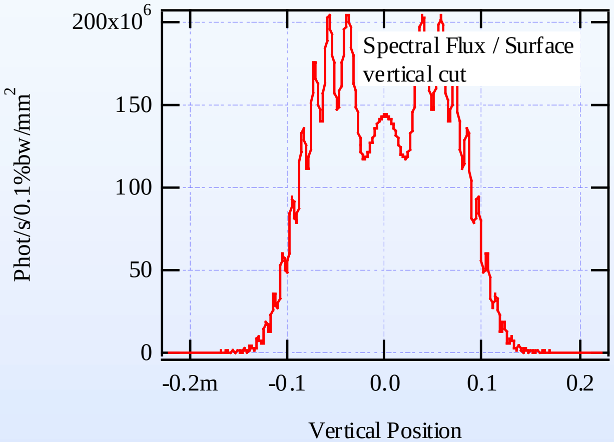
not to scale

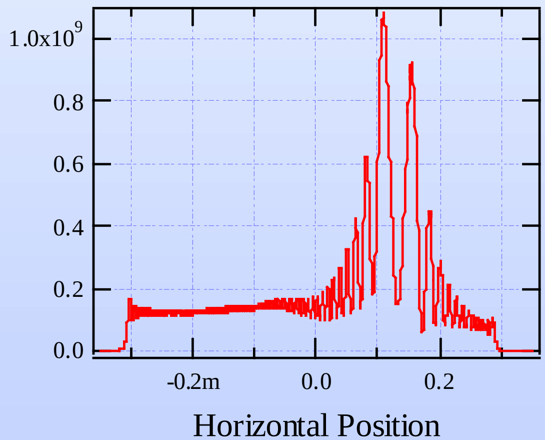
M1	110 x 155
M2	120 x 170
M3	183 x 258
M4	183 x 258

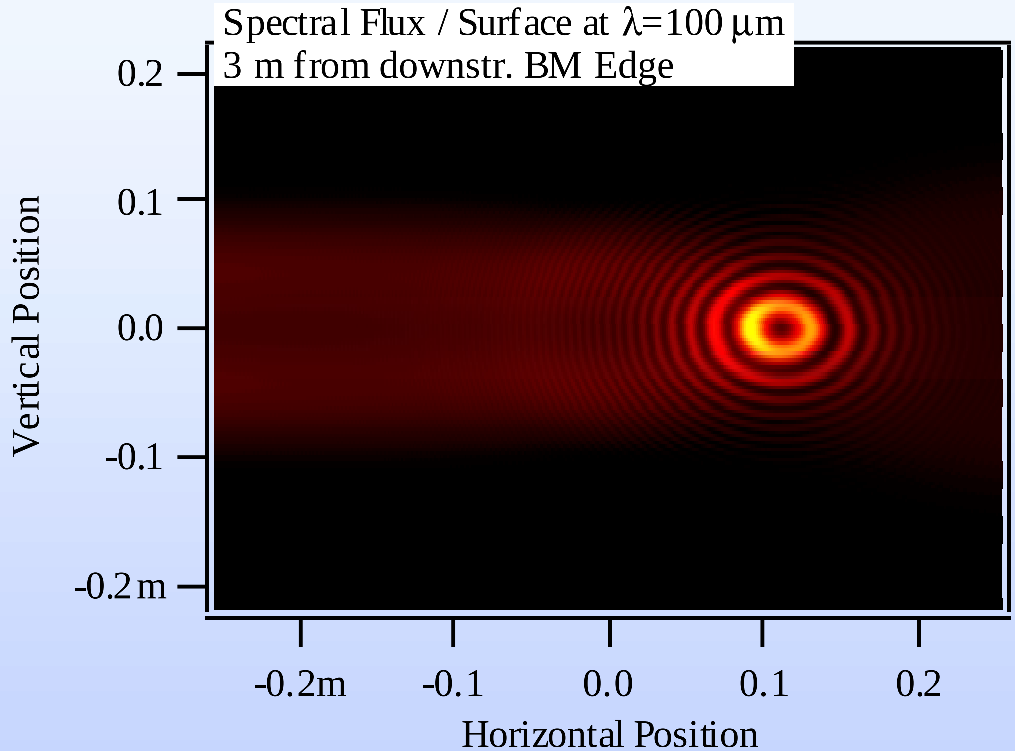


Neil/GPW

SRW Calculation of light on screen 3.0 m from source by Paul Dumas

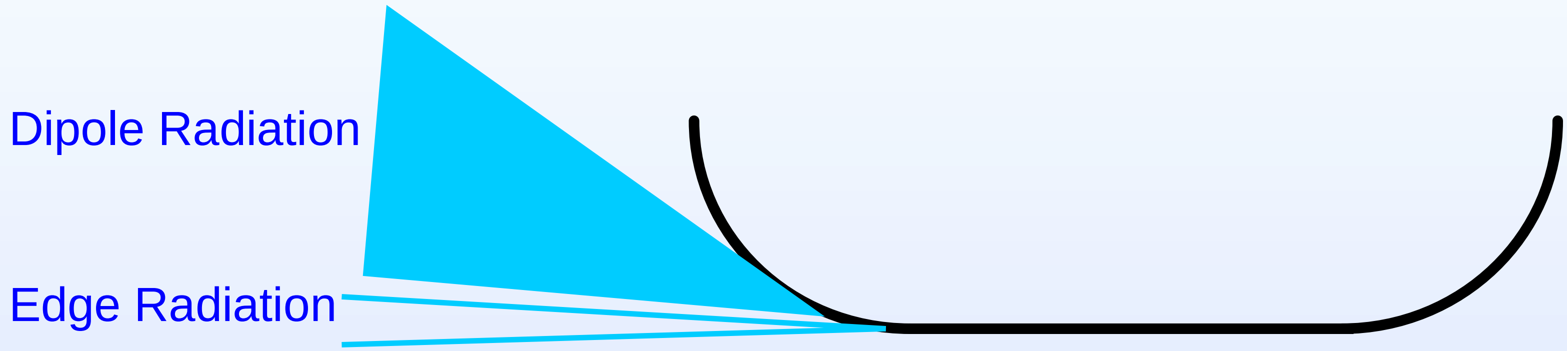






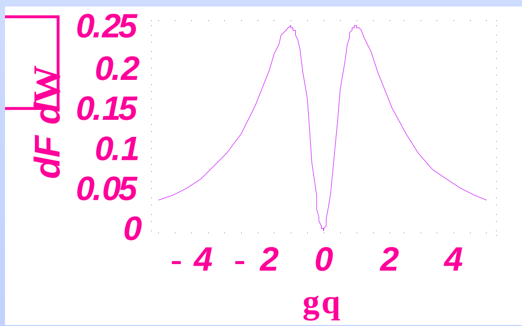
Flux after 1-st Aperture: 2.0479e+13 Photons/s/.1%bw

What is Edge Radiation?

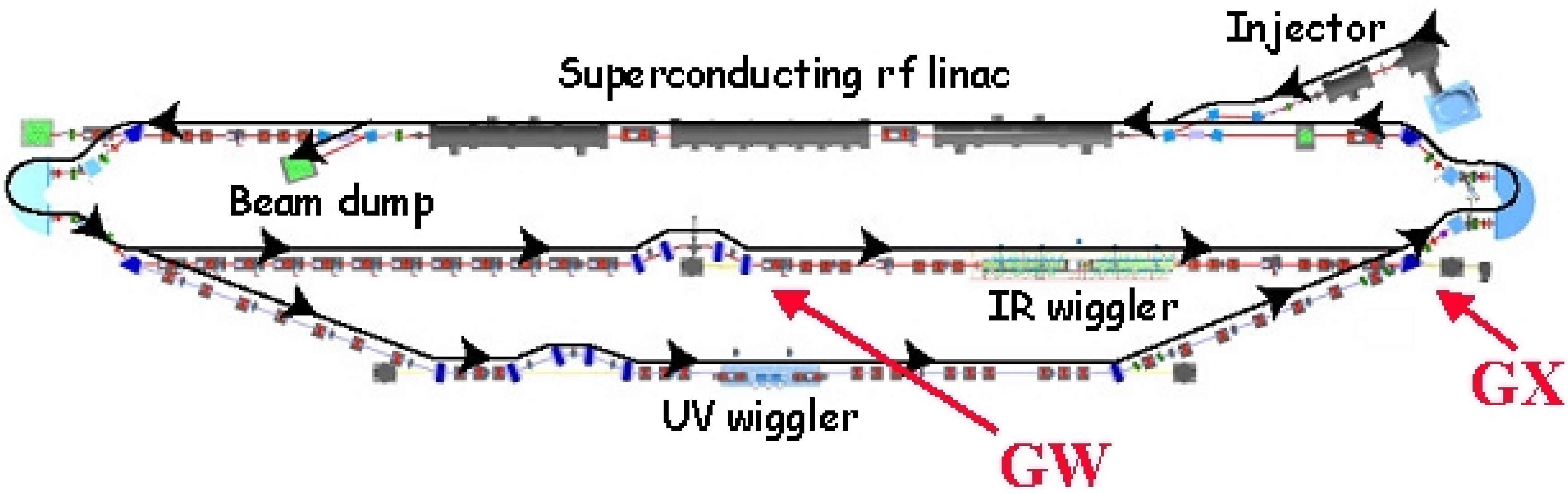


Edge Radiation is light emitted as the electrons enter the fringe field of a dipole magnet. For long wavelengths the fringe field maybe treated as an impulse acceleration. Thus edge radiation has characteristics similar to transition radiation. In the far field approximation for a single edge the angular spectral flux is "white" up to a cutoff determined by the details of the fringe and is given by,

$$\frac{dF}{d\Omega} = \alpha \frac{\Delta\omega}{\omega} \frac{I}{e\pi^2} \frac{\gamma^4\theta^2}{\left(1+\gamma^2\theta^2\right)^2}$$



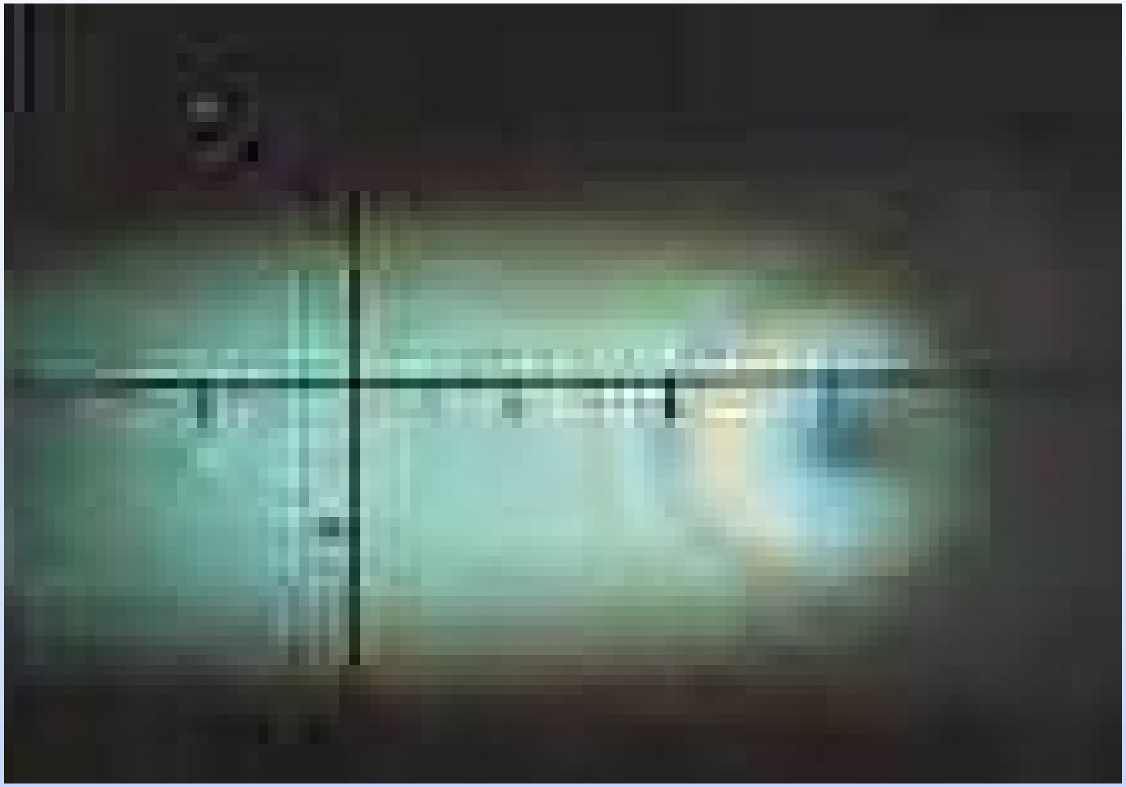
Reference: R.A. Bosch, Nuclear Instr. & Methods **A431** 320 (1999).



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

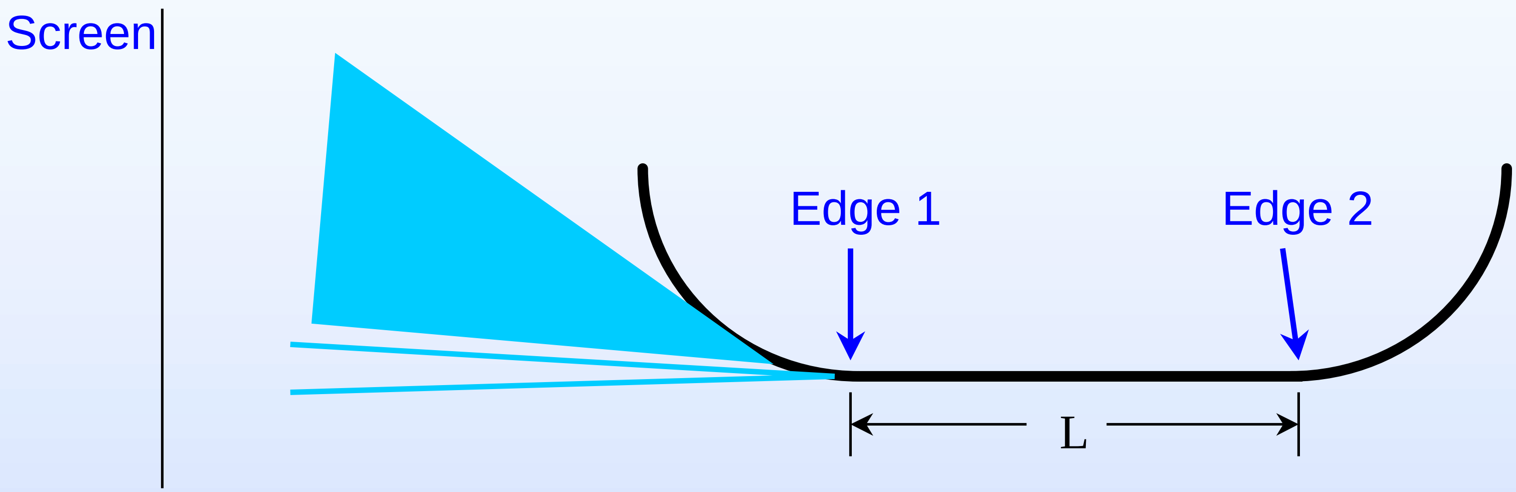
Full formula

What does edge Radiation look like?



Daresbury Lab
Ann Rep 1984/5

Two Edges Interfere



Interference of Two Edges in Far Field

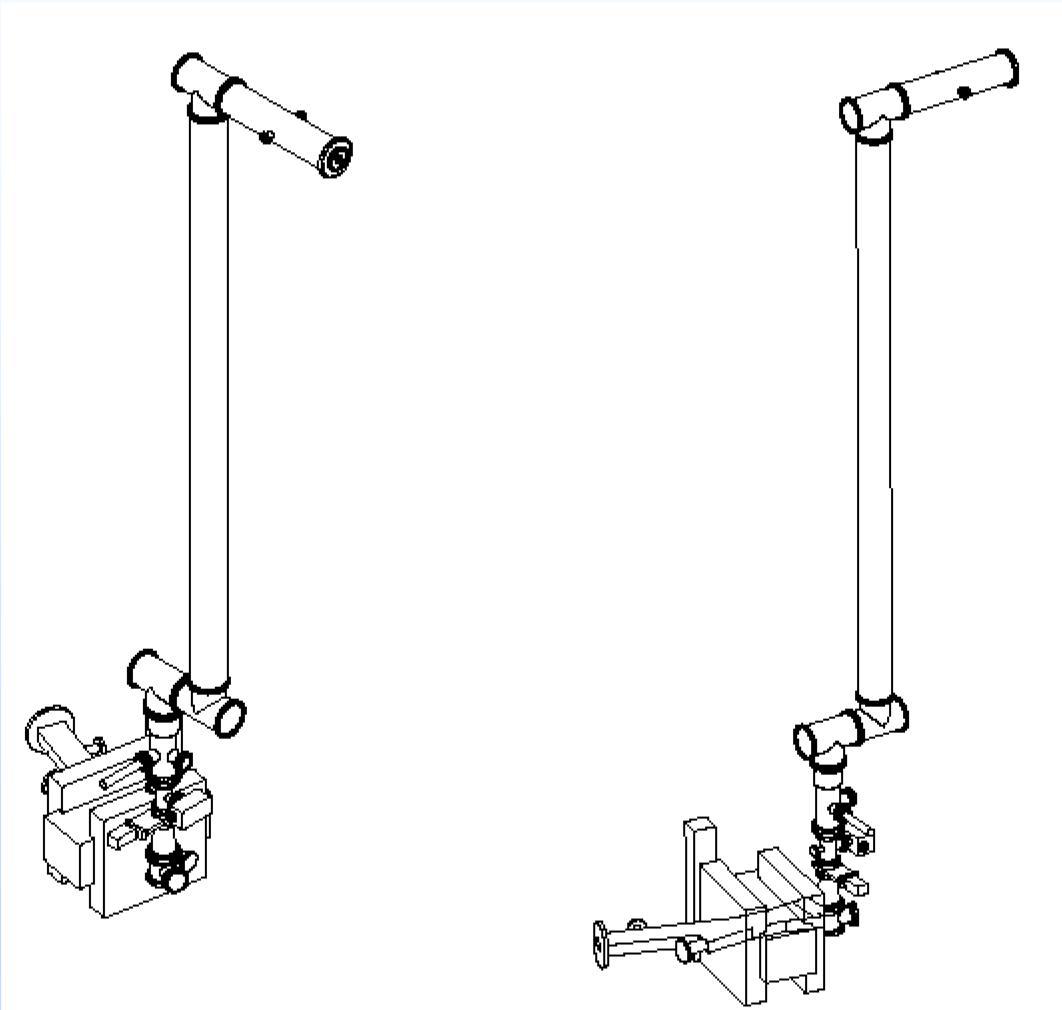
Near Field Calculation of Two Edges using SRW (Chubar& Elleaume, ESRF)

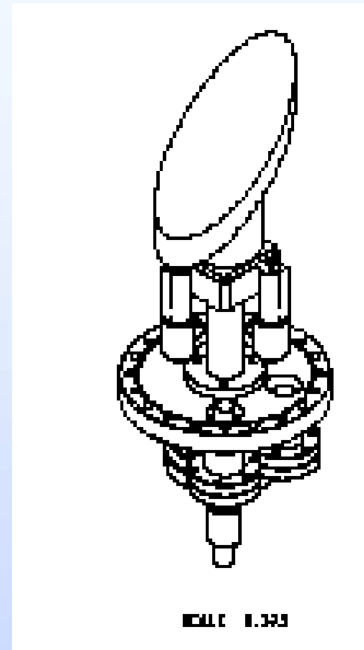
$$\left.\frac{dF}{d\Omega}\right|_2 \approx \left.\frac{dF}{d\Omega}\right|_1 \left|1 - \mathrm{Exp}\left[\frac{\pi L}{\lambda\gamma^2}\left(1+\gamma^2\theta^2\right)\right]\right|^2$$

$$\approx 4\left.\frac{dF}{d\Omega}\right|_1 \mathrm{Sin}^2\left[\frac{\pi L}{2\lambda\gamma^2}\left(1+\gamma^2\theta^2\right)\right]$$

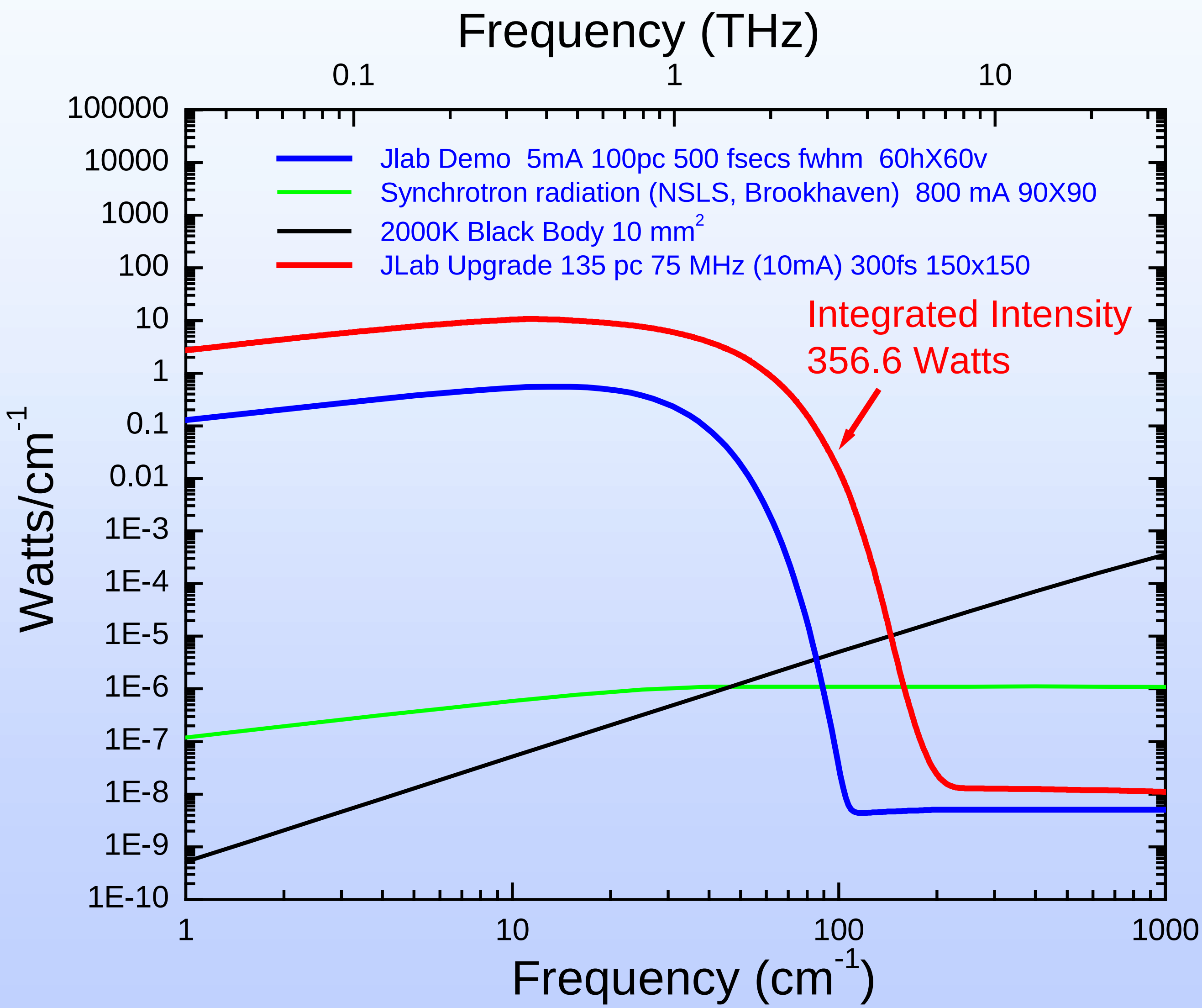
- Spectrum is no longer white
- Opening angle depends on λ

JLab’s new THz Beamline

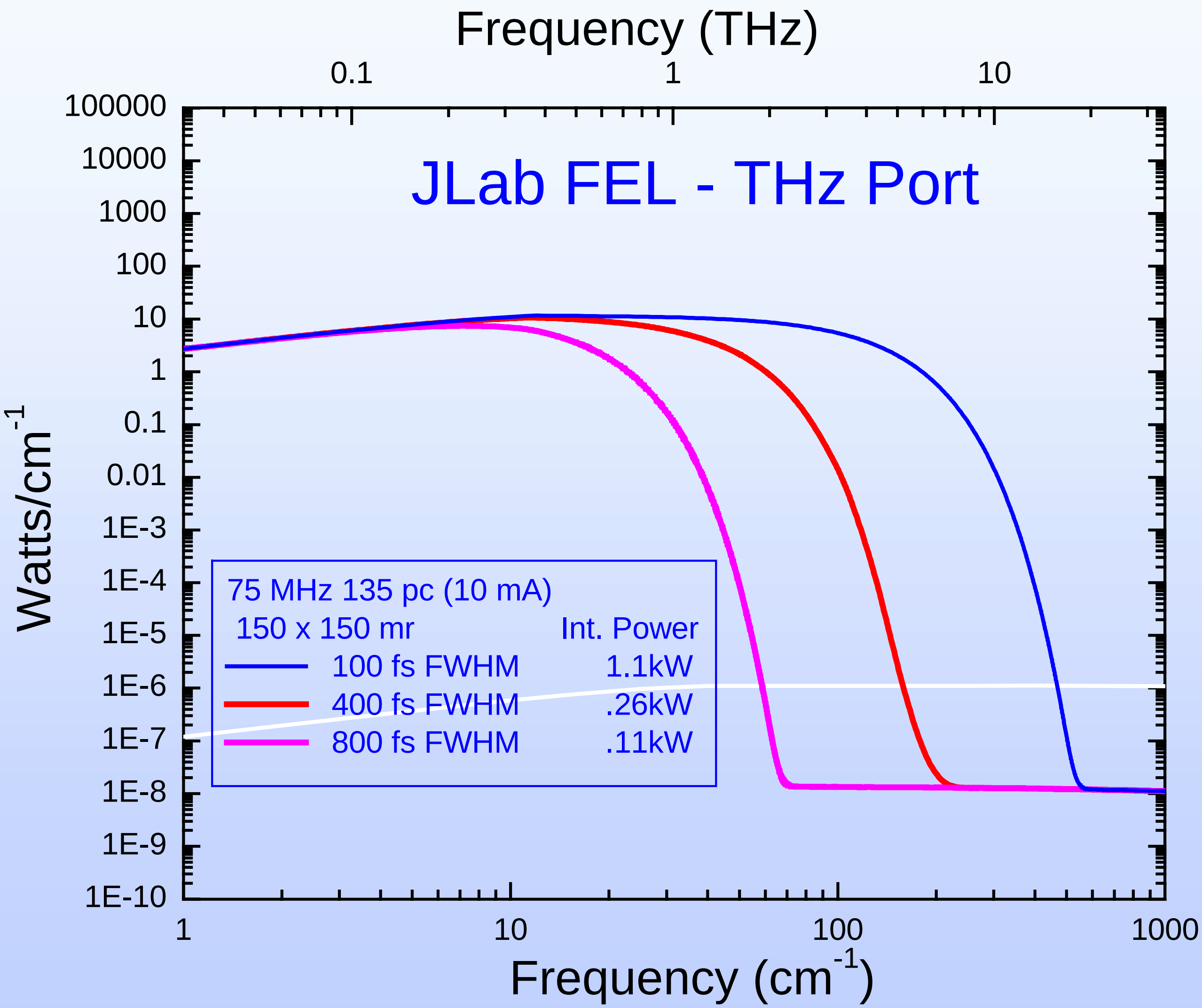




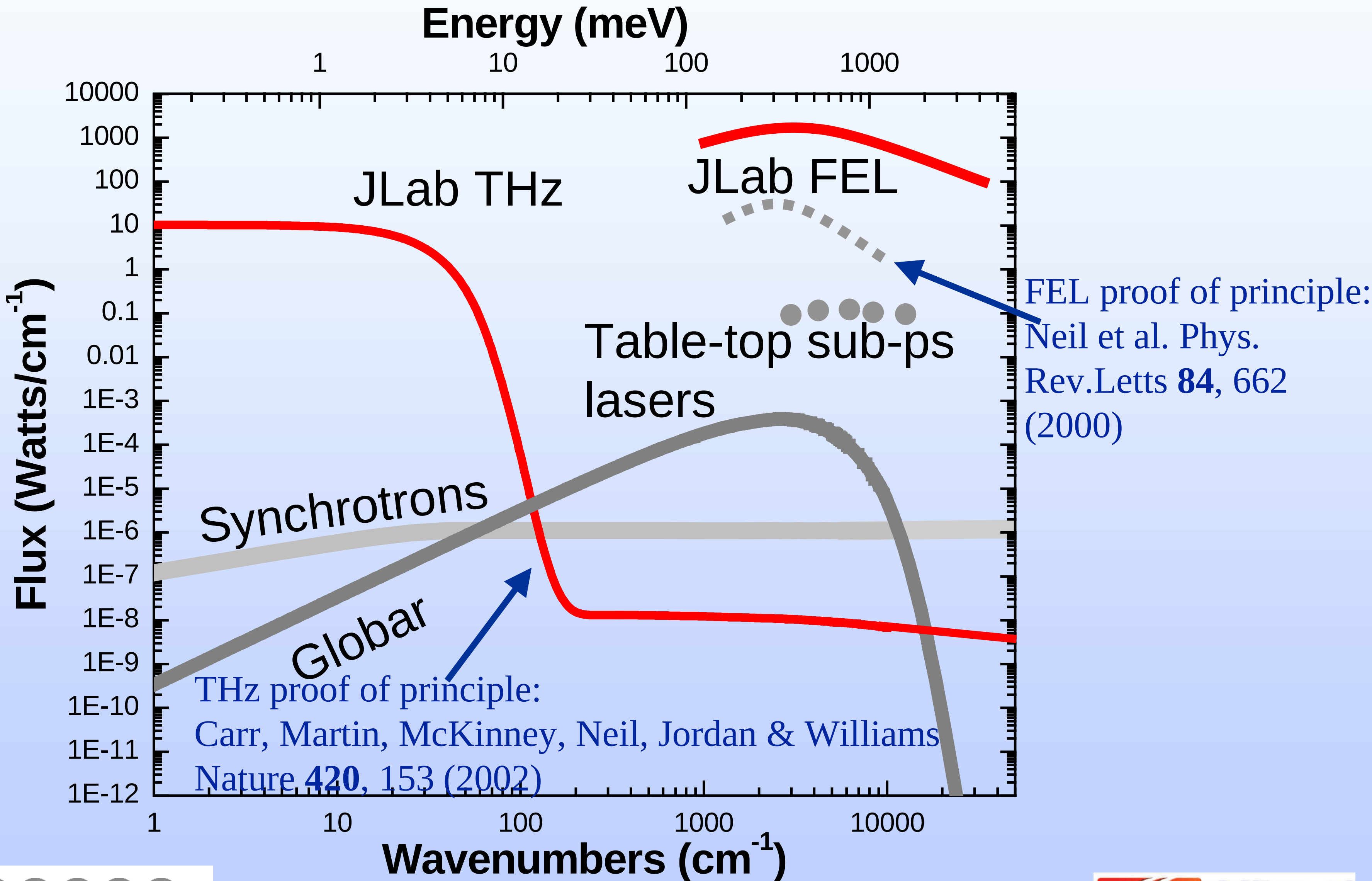
JLab's new THz Beamline



JLab's new THz Beamline



Brightness of IR Sources



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