SYNCHROTRON RADIATION

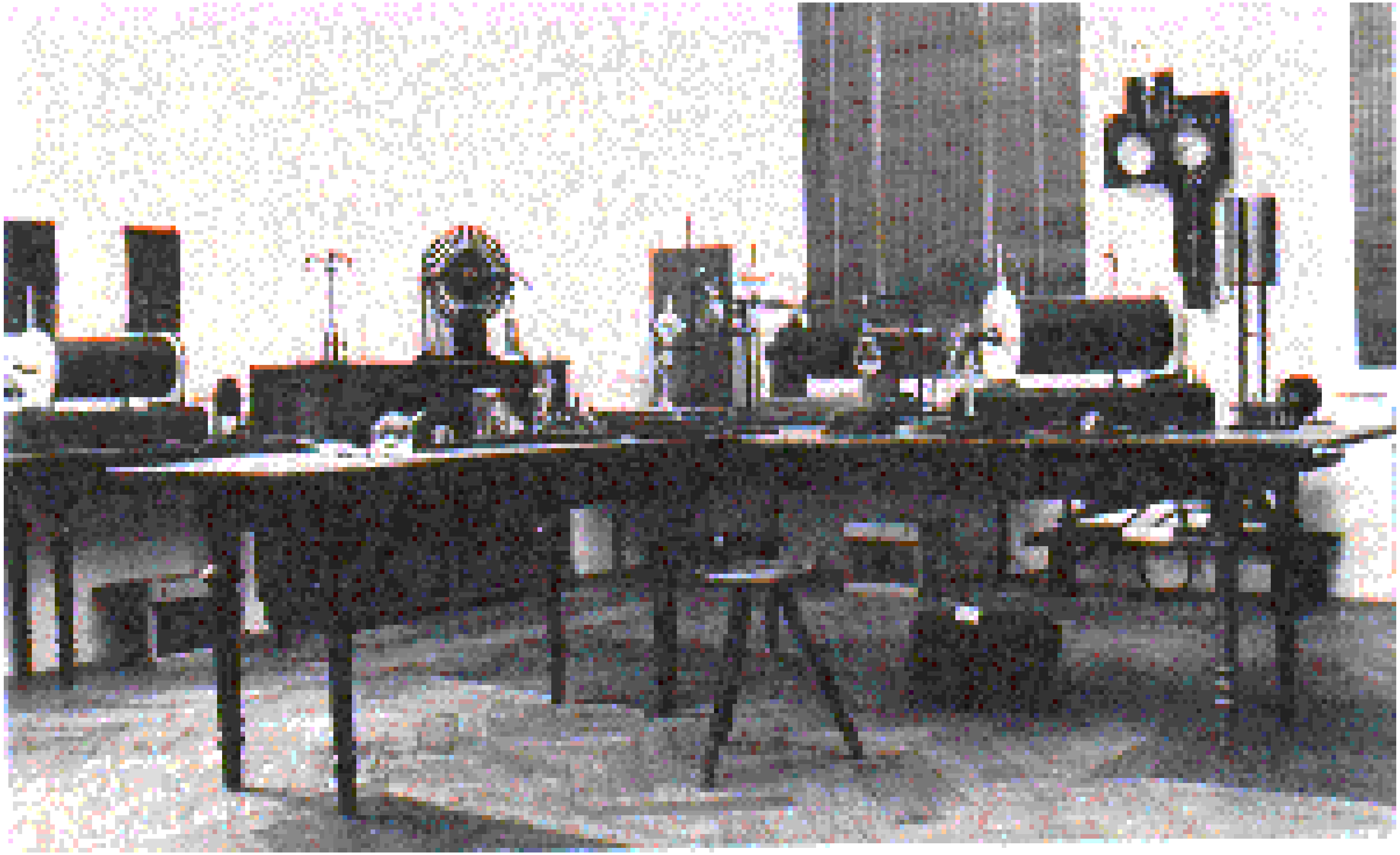
- **History and General Background**
- **Properties of Synchrotron Radiation**
- **Sources (bend magnets, wigglers, undulators)**
- **Research Facilities Around the World**
- **Future Sources**
- **Applications**

Presentation at JASS02 Seminar; Jordan – Oct. 19-28, 2002

Herman Winick, SSRL/SLAC, Stanford University

Wilhelm Roentgen 1845-1923
Discovered X-rays in 1995

Roentgen's Laboratory in Wurzburg, Germany - 1895



17 Nobel Prizes Based on X-ray Work

Physics:

1901: WILHELM RÖNTGEN

1914: MAX VON LAUE

1915: SIR WILLIAM HENRY BRAGG
and SIR WILLIAM LAWRENCE BRAGG

1917: CHARLES BARKLA

1924: KARL MANNE SIEGBAHN

1927: ARTHUR COMPTON

1981: KAI SIEGBAHN

Chemistry:

1936: PETER DEBYE

1962: MAX PERUTZ and SIR JOHN KENDREW

1964: DOROTHY HODGKIN

1976: WILLIAM LIPSCOMB

1985: HERBERT HAUPTMAN and JEROME KARLE

1988: JOHANN DEISENHOFER,
ROBERT HUBER and HARTMUT MICHEL

1997: PAUL D. BOYER and JOHN E. WALKER

Medicine:

1946: HERMANN JOSEPH MULLER

1962: FRANCIS CRICK, JAMES WATSON
and MAURICE WILKINS

1979: ALAN M. CORMACK and
SIR GODFREY N. HOUNSFIELD

Synchrotron Radiation - What is it?

- **First terrestrial sources were cyclic-electron synchrotrons developed for high-energy physics (HEP) research (1940-1970) and used parasitically as light sources with variable intensity and variable spectrum**
- **1960s began the development of storage rings – again for HEP – and used mostly parasitically as light sources, demonstrating the advantages of constant intensity and constant spectrum – the First Generation**

"The Crab Nebula, or Messier 1, is one of the most spectacular and intensively studied objects in the sky. It is the remnant of a supernova in AD 1054, observed as a "guest star" by the Chinese in today's constellation Taurus. It is among the brightest remnants across a broad wavelength spectrum. The Crab Nebula is probably the best-known synchrotron emission nebula. The synchrotron is what is primarily seen in the 2MASS image…. " http://www.ipac.caltech.edu/2mass/gallery/images_snrs.html

Early publication on radiation by accelerated particles

SSRL

L'Éclairage Électrique

REVUE HEBDOMADAIRE D'ÉLECTRICITÉ

CHAMP ÉLECTRIQUE ET MAGNÉTIQUE

PRODUIT PAR UNE CHARGE ÉLECTRIQUE CONCENTRÉE EN UN POINT ET ANIMÉE D'UN MOUVEMENT QUELCONQUE

Admettons qu'une masse électrique en mouvement de densité ρ et de vitesse u en chaque point produit le même champ qu'un courant de conduction d'intensité $u\rho$. En conservant les notations d'un précédent article (¹) nous obtiendrons pour déterminer le champ, les équations

$$\frac{1}{4\pi}\left(\frac{d\gamma}{dy} - \frac{d\beta}{dz}\right) = \rho u_x + \frac{df}{dt} \qquad (1)$$

$$V^2\left(\frac{dh}{dy} - \frac{dg}{dz}\right) = -\frac{1}{4\pi}\frac{d\alpha}{dt} \qquad (2)$$

avec les analogues déduites par permutation tournante et en outre les suivantes

$$\rho = \left(\frac{df}{dx} + \frac{dg}{dy} + \frac{dh}{dz}\right. \qquad (3)$$

$$\frac{d\alpha}{dx} + \frac{d\beta}{dy} + \frac{d\gamma}{dz} = 0. \qquad (4)$$

De ce système d'équations on déduit facilement les relations

$$\left(V^2\Delta - \frac{d^2}{dt^2}\right)f = V^2\frac{d\rho}{dx} + \frac{d}{dt}(\rho u_x) \qquad (5)$$

$$\left(V^2\Delta - \frac{d^2}{dt^2}\right)\alpha = 4\pi V^2\left[\frac{d}{dz}(\rho u_y) - \frac{d}{dy}(\rho u_z)\right] \qquad (6)$$

(¹) La théorie de Lorentz, *L'Éclairage Électrique*, t. XIV, p. 417. α, β, γ, sont les composantes de la force magnétique et f, g, h, celles du déplacement dans l'éther.

Soient maintenant quatre fonctions ψ, F, G, H définies par les conditions

$$\left(V^2\Delta - \frac{d^2}{dt^2}\right)\psi = -4\pi V^2\rho. \qquad (7)$$

$$\left.\begin{aligned}\left(V^2\Delta - \frac{d^2}{dt^2}\right)F &= -4\pi V^2\rho u_x\\ \left(V^2\Delta - \frac{d^2}{dt^2}\right)G &= -4\pi\rho u_y\\ \left(V^2\Delta - \frac{d^2}{dt^2}\right)H &= -4\pi V^2\rho u_z\end{aligned}\right\} \qquad (8)$$

On satisfera aux conditions (5) et (6) en prenant

$$4\pi f = -\frac{d\psi}{dx} - \frac{1}{V^2}\frac{dF}{dt} \qquad (9)$$

$$\alpha = \frac{dH}{dy} - \frac{dG}{dz}. \qquad (10)$$

Quant aux équations (1) à (4), pour qu'elles soient satisfaites, il faudra que, en plus de (7) et (8), on ait la condition

$$\frac{d\psi}{dt} + \frac{dF}{dx} + \frac{dG}{dy} + \frac{dH}{dz} = 0. \qquad (11)$$

Occupons-nous d'abord de l'équation (7). On sait que la solution la plus générale est la suivante :

$$\psi = \int \frac{\rho\left[x', y', z', t - \frac{r}{V}\right]}{r}\, d\omega' \qquad (12)$$

Liénard, A. (1898). L'Éclairage Électrique **16**, 5

A SHORT HISTORY OF SYNCHROTRON RAD. SOURCES

1945 First (indirect) observation of SR; J. Blewett, G.E. 100 MeV betatron
1947 1st visual observation; G.E. 70 MeV synchrotron

ZEROth GENERATION SOURCES
1950's-60's: ELECTRON SYNCHROTRONS (cyclic accelerators)

FIRST GENERATION SOURCES (storage rings)
1970's: *e+/e- COLLIDERS (Mostly Parasitic on High Energy Physics programs)*

SECOND GENERATION SOURCES
1980's: *NEW RINGS* and *FULLY DEDICATED USE OF e+/e- COLLIDERS, USE OF WIGGLERS & UNDULATORS*

THIRD GENERATION SOURCES
1990's: *LOW EMITTANCE RINGS WITH MANY STRAIGHT SECTIONS*

FOURTH GENERATION SOURCES
2000's: LINAC-BASED SOURCES

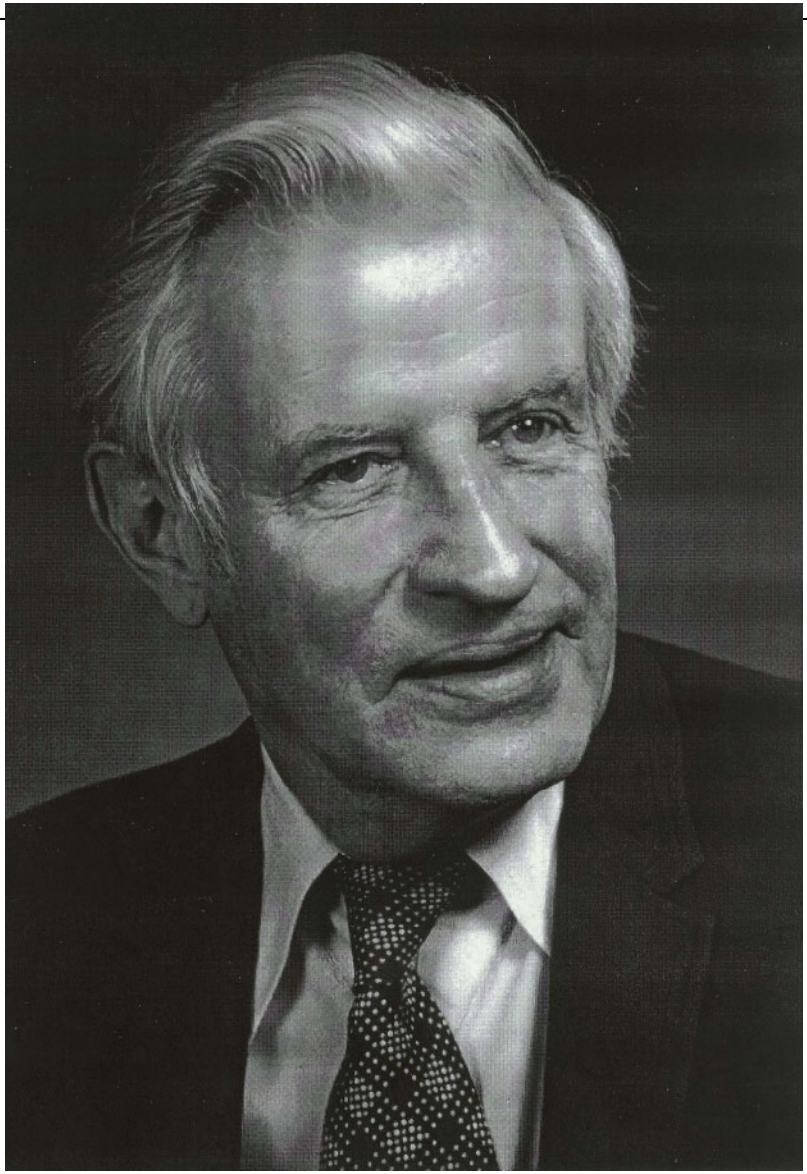
- Free-electron laser (FEL)
- Energy Recovery Linac (ERL)

DIFFRACTION-LIMITED RINGS; ULTRA-SHORT BUNCHES; NEW IDEAS

Comparison of Synchrotron Radiation from Synchrotrons and Storage Rings

	Synchrotron	*Storage Ring*
Spectrum	Varies as e^- energy changes during each cycle	Constant
Intensity	Varies as e^- energy changes during each cycle. also cycle to cycle variations	Decays slowly over many hours
Source Position	Varies during the acceleration cycle	Constant within 1-50 microns
High Energy Radiation Background (Bremsstrahlung + e^-)	High – due to loss of all particles on each cycle	Low – same particles are stored for many hours

John Blewett; Observed Effects of Synchrotron Radiation in General Electric 100 MeV Betatron - 1945



PHYSICAL REVIEW VOLUME 69, NUMBERS 3 AND 4 FEBRUARY 1 AND 15, 1946

Radiation Losses in the Induction Electron Accelerator

JOHN P. BLEWETT
Research Laboratory, General Electric Company, Schenectady, New York

(Received September 13, 1945)

This paper discusses the possibility that radiation losses because of the high radial accelerations experienced by the electrons in an induction electron accelerator may introduce limitations in the design of accelerators for energies above 100 million electron volts. The effects of radiation losses on the electron orbits are calculated, and it is shown that not only should the orbit shift pulse necessary to bring electrons to a target inside the equilibrium orbit fall below the value expected in the absence of radiation, but also electrons should eventually arrive at the target with no orbit shift pulse whatever, at a phase of the field wave predictable from the theory. Both effects have been observed in the General Electric 100-Mev unit in a manner consistent with the predictions of the theory. The radiation itself has not yet been detected.

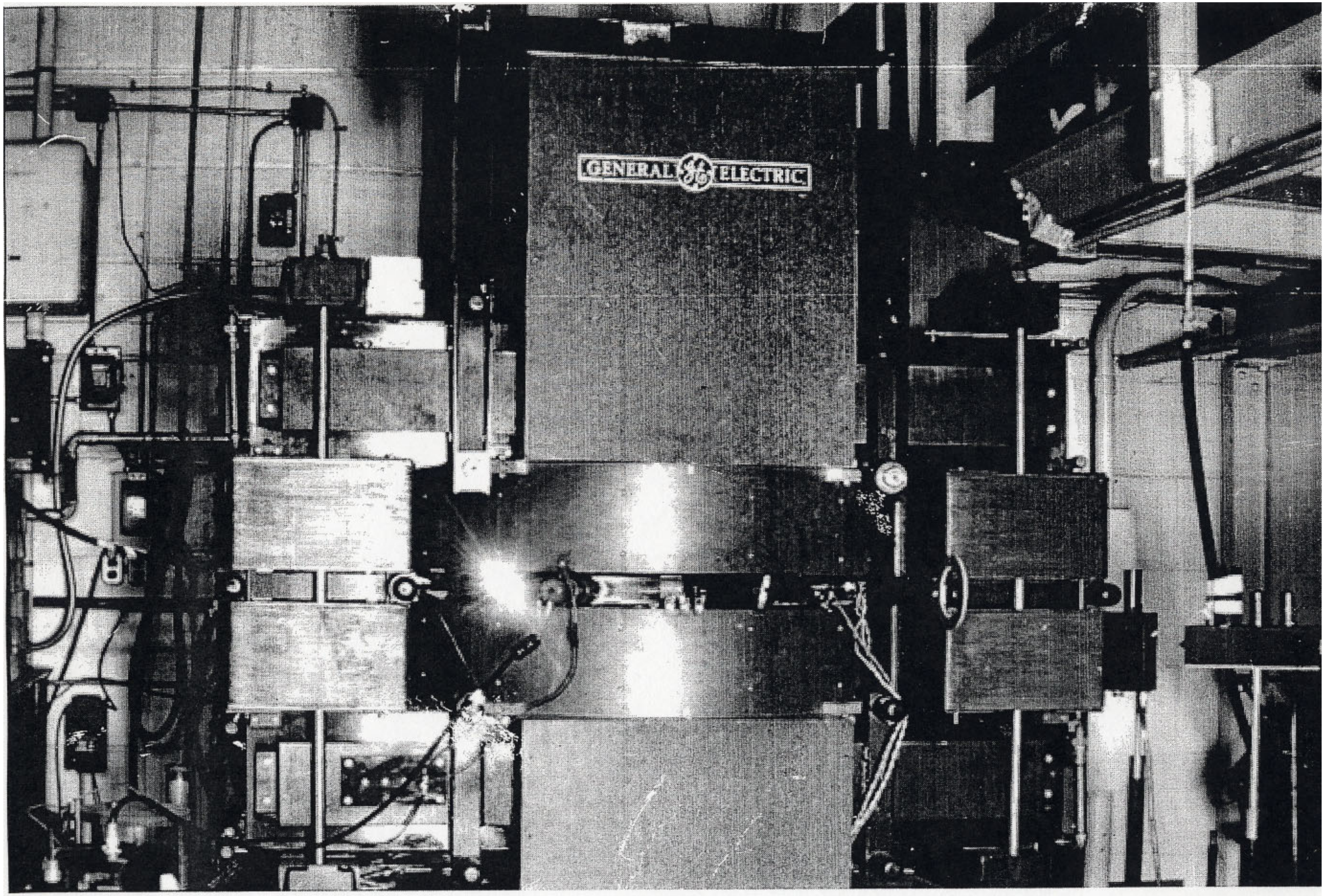
1. INTRODUCTION*

In the induction electron accelerator, the electrons are subjected continually to radial accelerations of the order of 10^{17} meters per second per second. It has been pointed out by

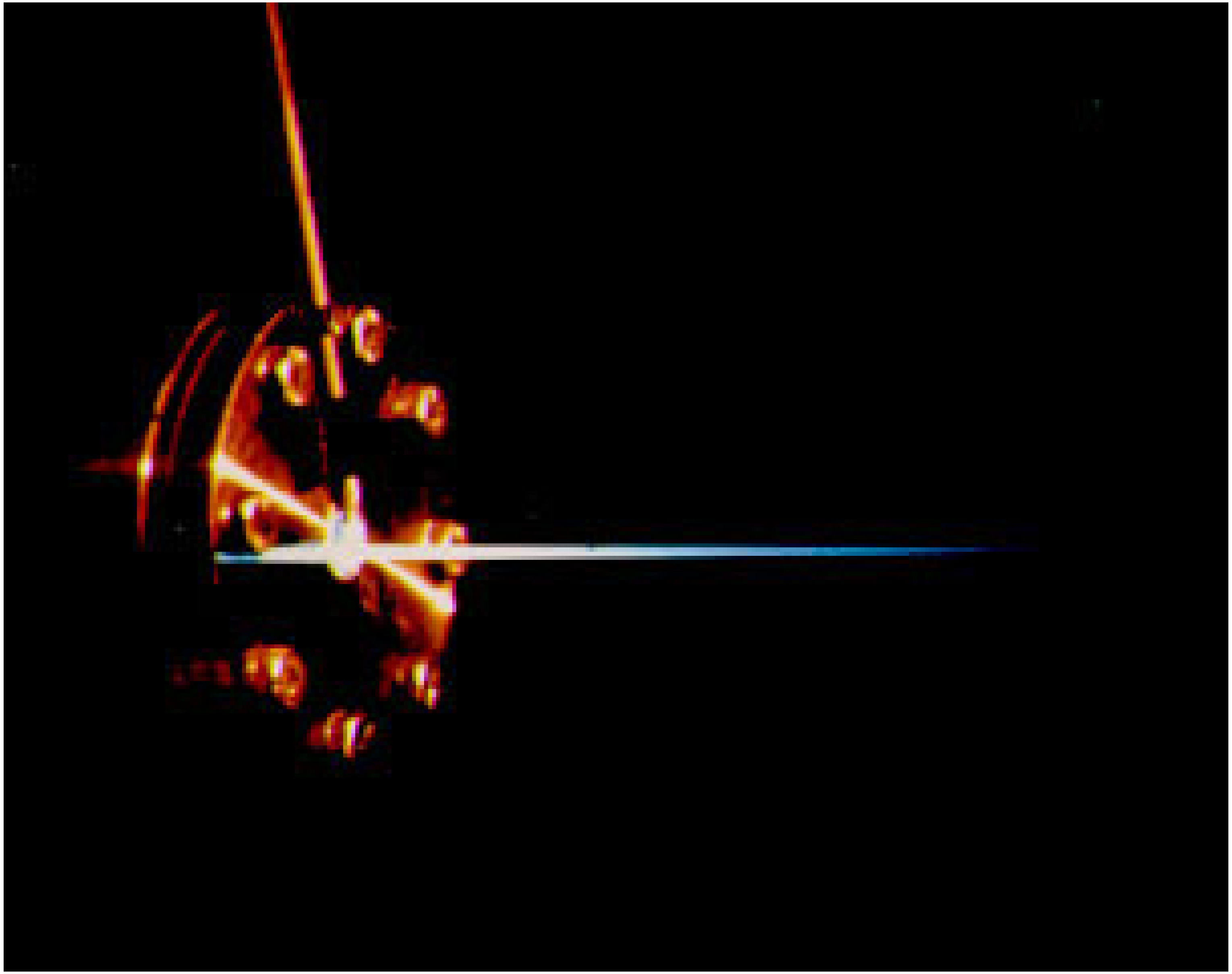
* *Symbols:*—Unrationalized m.k.s. units will be used throughout: The following symbols will be employed:

A = peak value of applied magnetic flux density at the equilibrium orbit (webers per sq. m)
A' = peak value of magnetic flux in orbit shrinking pulse at the equilibrium orbit (webers per sq. m)
B_0 = applied magnetic flux density at the equilibrium orbit (webers per sq. m)
B_r and B_z are components of magnetic flux density (webers per sq. m)
c = velocity of light = 3.00×10^8 m per sec.
e = charge on the electron = 1.602×10^{-19} Coulomb
E_r and E_z are components of electric field (volts per m)
f_n and f_t are normal and tangential components of the acceleration vector f (m per sec. per sec.)
$F(\omega t) = (\omega t/\sin \omega t) - \cos \omega t - (2/3)\sin^2 \omega t \cos \omega t$
h = Planck's constant = 6.624×10^{-34} joule sec.
H_r and H_z are components of magnetic field
I = beam current (amperes)
m_0 = rest mass of the electron = 9.107×10^{-31} kg

First visual observation of synchrotron light at the General Electric 70 MeV synchrotron in 1947

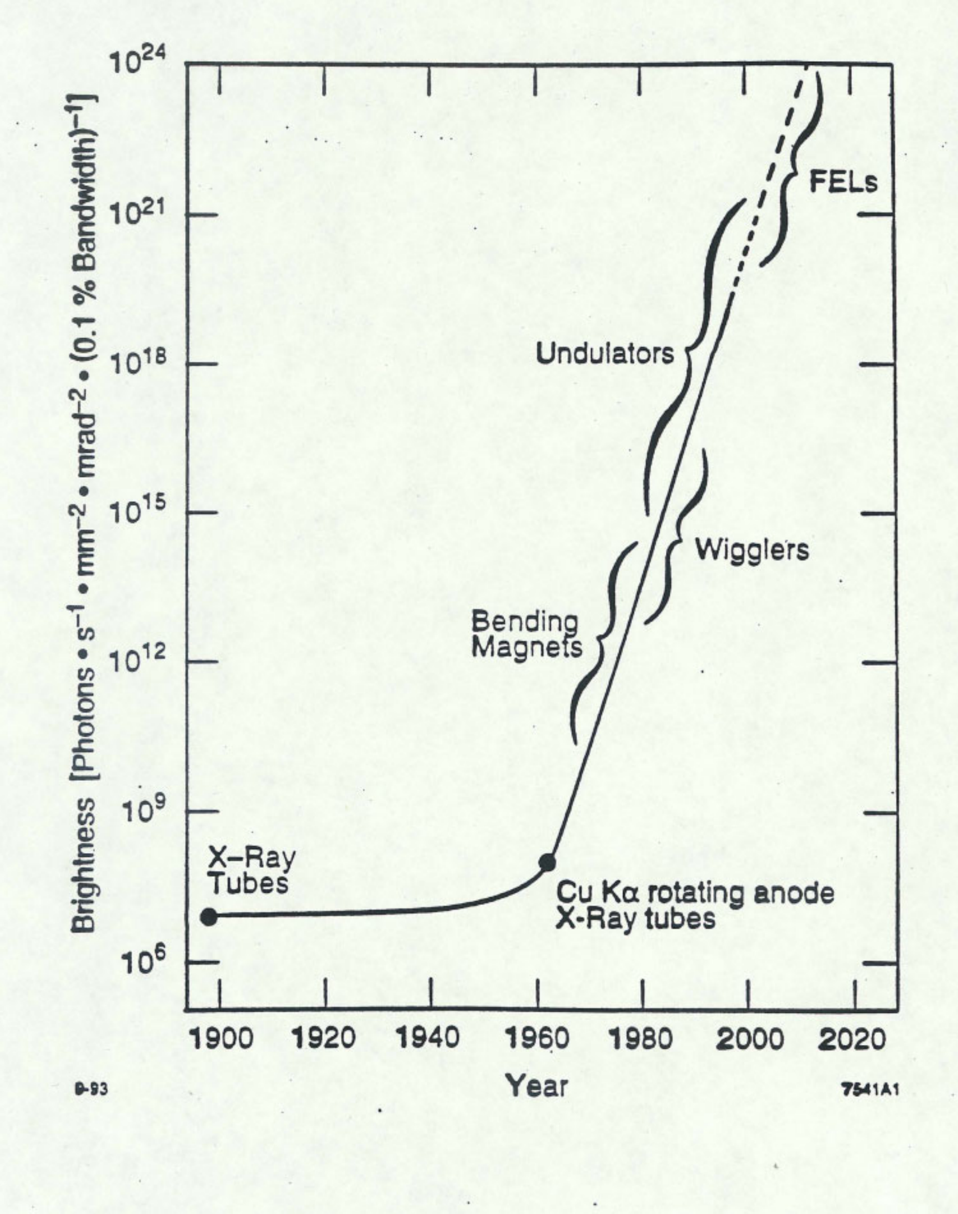


Focused x-ray beam from the Cambridge Electron Accelerator – 1972 (Paul Horowitz, Harvard University)

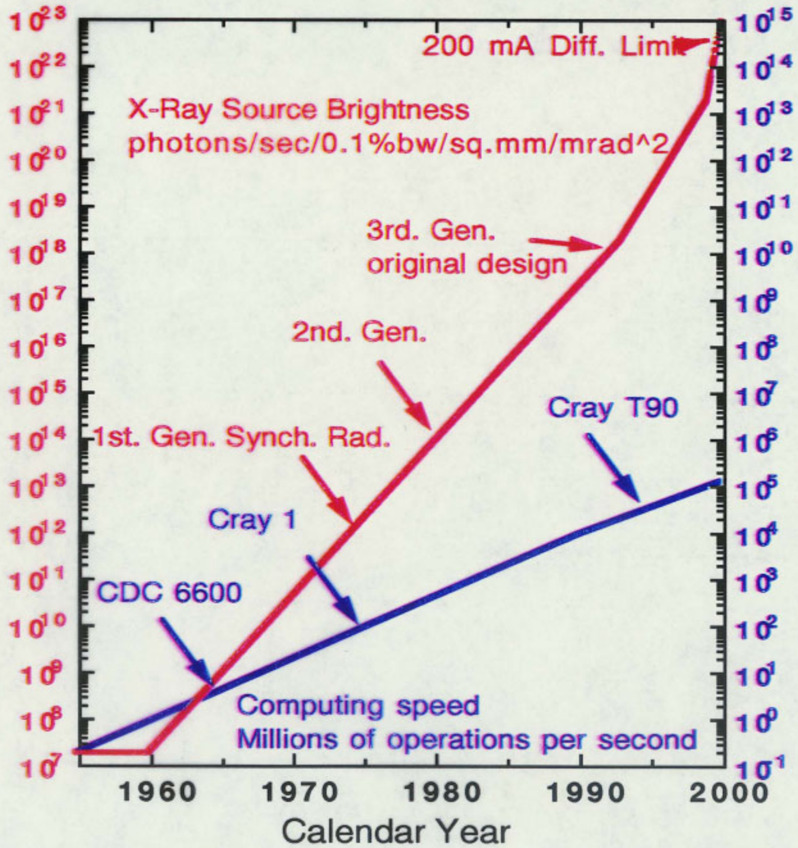


X-Ray Brightness vs. Time

SSRL



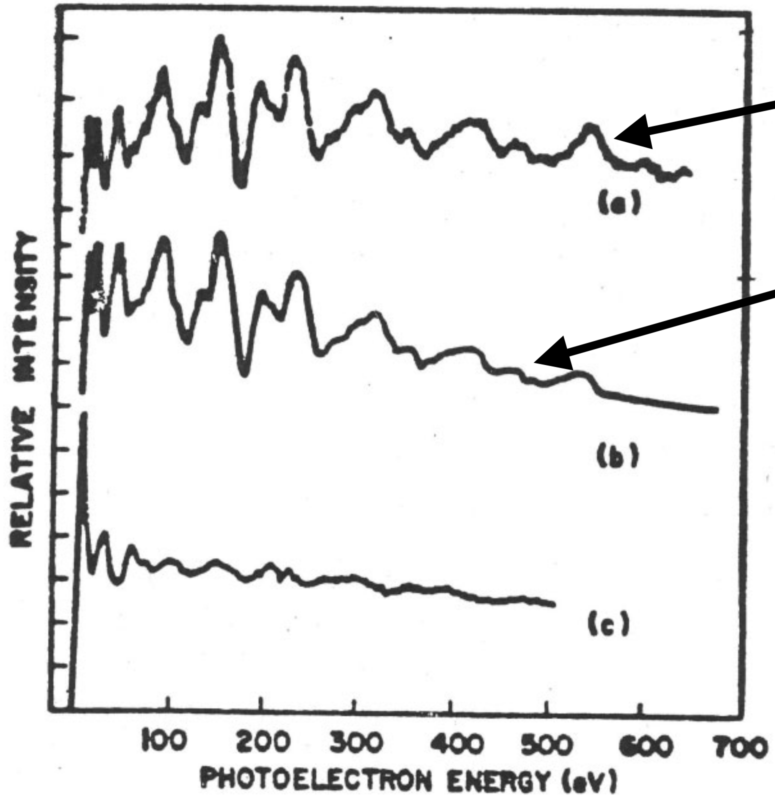
Growth in X-Ray Brightness compared to growth in computing power



G.P. Williams

01/02/97

EXAFS 1974 – Parasitic Operation on SPEAR



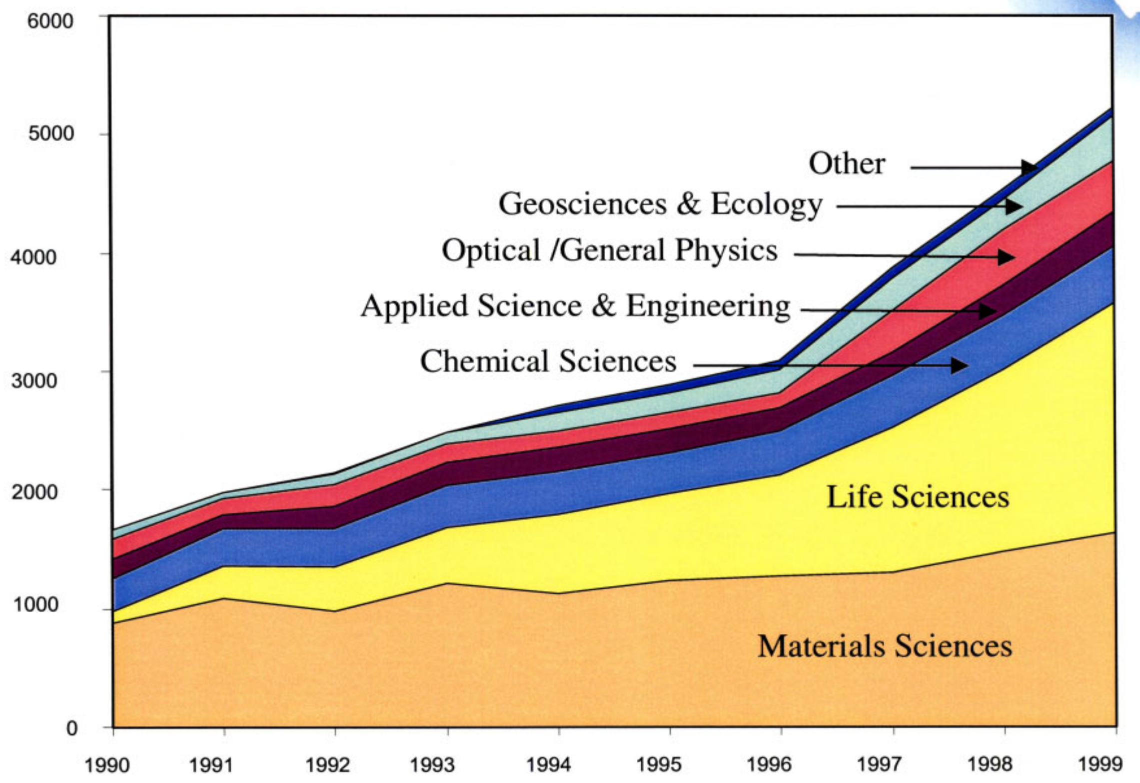
~ 10 days using rotating anode. X-Ray tube

~ 20 minutes using synch. rad. from bending magnet

X-ray absorption spectra: (a) Cu spectrum using conventional sources; (b) Cu spectrum using synchrotron radiation; (c) thin superconducting Nb_3Ge film spectrum using synchrotron radiation.

P. Eisenberger, B. Kincaid

Numbers of Light Source Users (ALS, APS, NSLS and SSRL) by Discipline



R. Birgeneau (MIT) - Chairman
Z.-X. Shen (Stanford) - Vice-Chairman

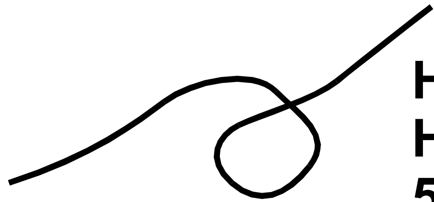
from the Executive Summary:

"The most straightforward and most important conclusion of this study is that over the past 20 years in the United States synchrotron radiation research has evolved from an esoteric endeavor practiced by a small number of scientists primarily from the fields of solid state physics and surface science to a mainstream activity which provides essential information in the materials and chemical sciences, the life sciences, molecular environmental science, the geosciences, nascent technology and defense-related research among other fields."

Seeing the Invisible

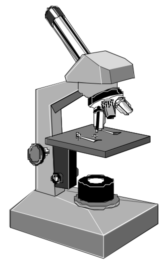
Magnifying Glass

10X

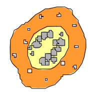


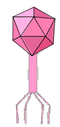
Human Hair 50 μm

Light Microscope



1000X



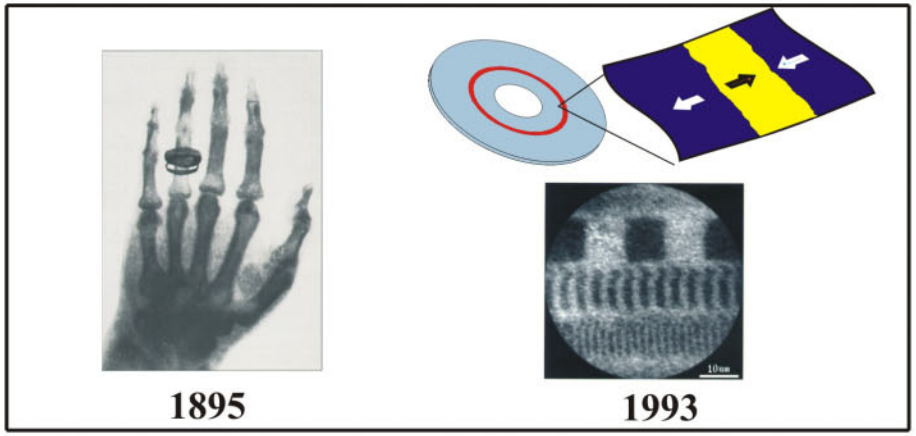


Cell 30μm **Virus 0.2μm**

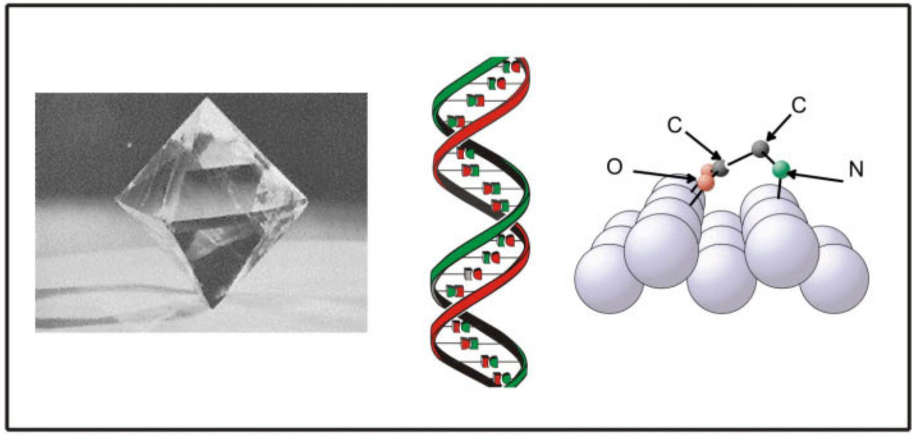
X-rays can "see" smaller things - down to the size of molecules and individual atoms

These Techniques Provide Very Valuable Information

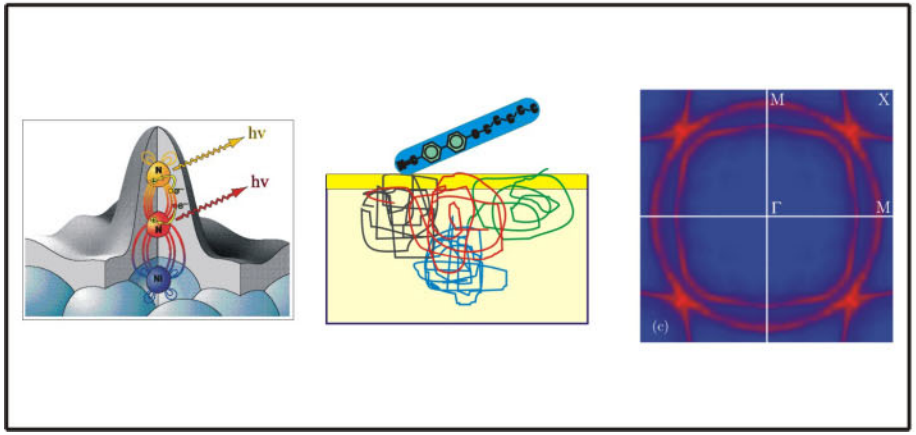
Imaging - Seeing the Invisible



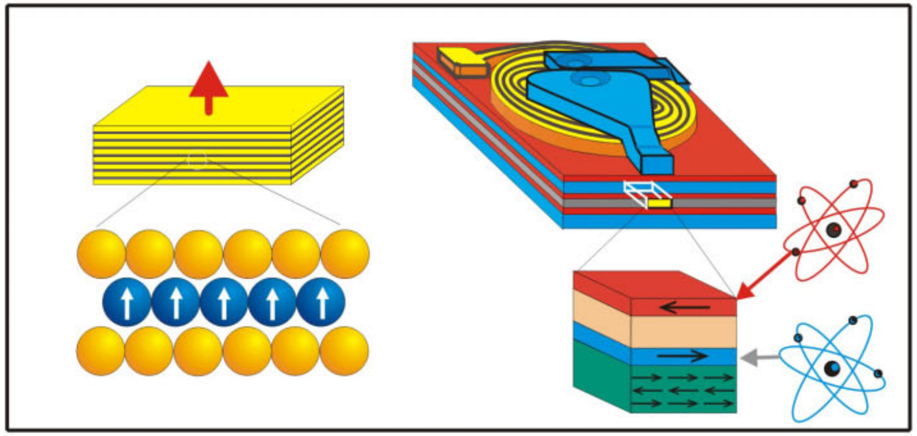
Atomic and Molecular Structure
- where are the atoms -



Electronic Structure and Bonding
- where are the electrons -

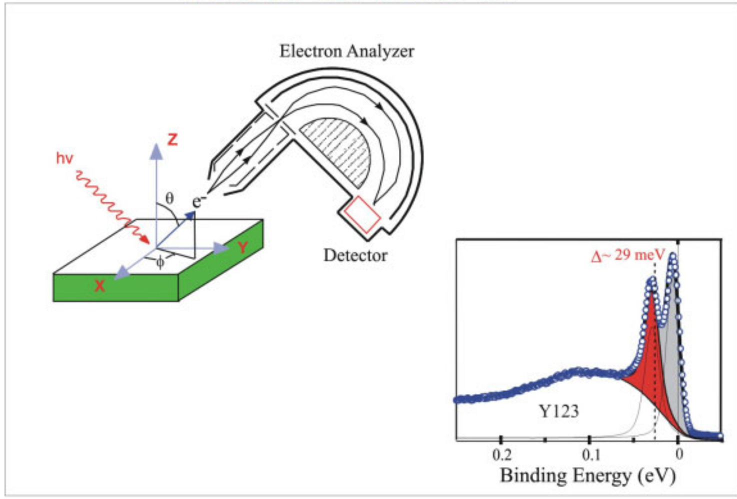


Magnetic Structure and Properties
- where are the spins-

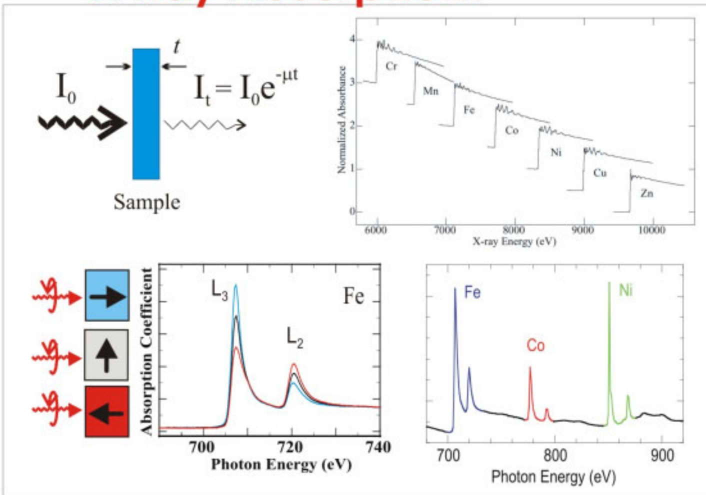


For Example, Modern X-ray Based Techniques Include

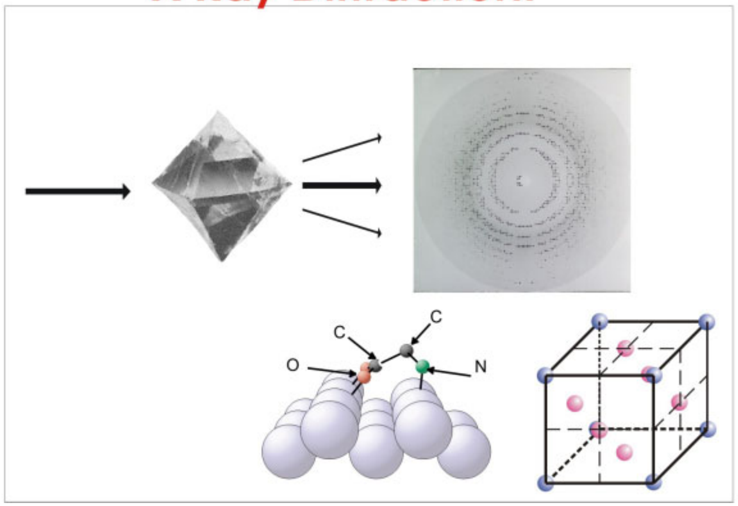
Photoemission:



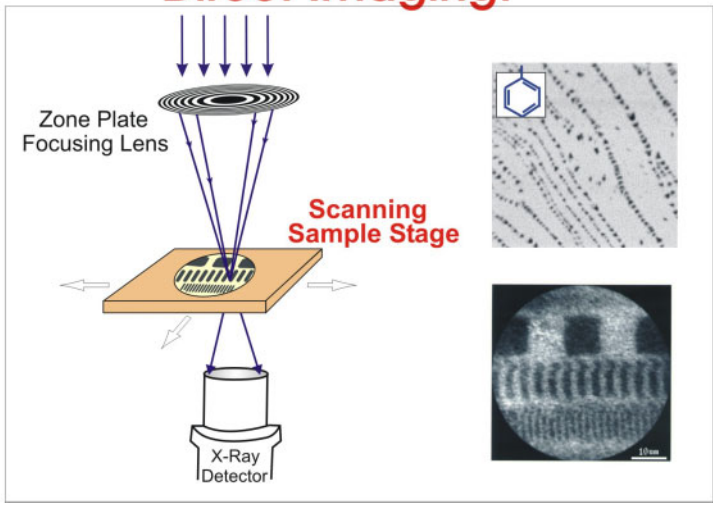
X-Ray Absorption:



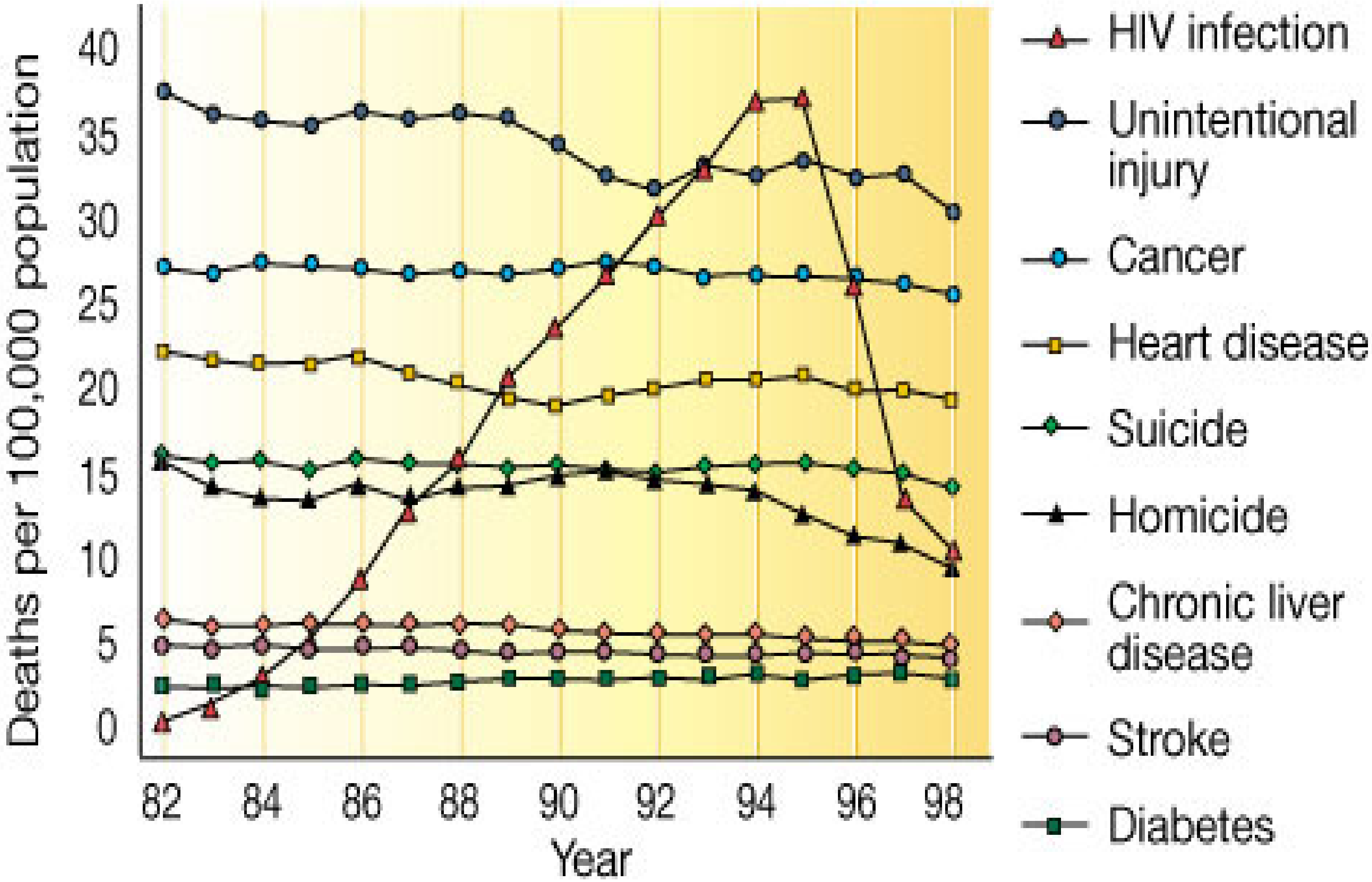
X-Ray Diffraction:



Direct Imaging:



Studies with SR contribute to decline in HIV infection

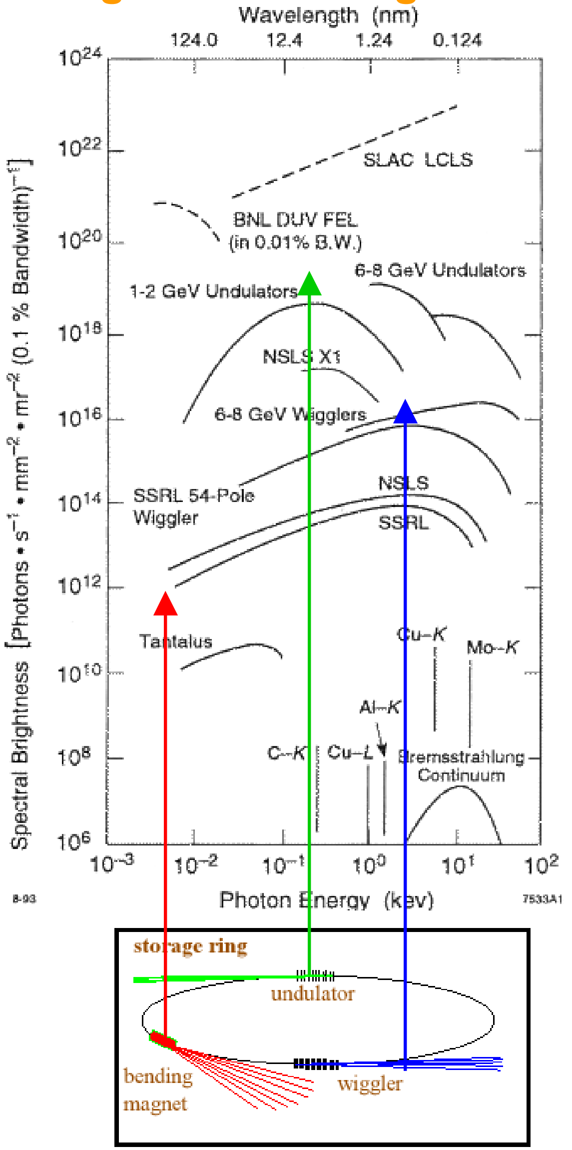


Nature **410**, 963-7, (2001)

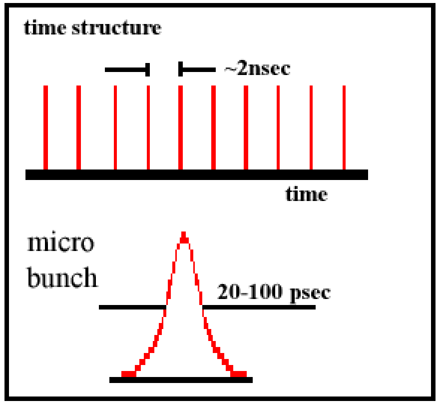
Figure 3; Trends in annual rates of leading causes of death among adults aged 25–44 years in USA over the period 1982–1998. The data from 1998 are preliminary. (Source: Centers for Disease Control and Prevention.)

Synchrotron Radiation - Basic Properties

High flux and brightness



Pulsed time structure



Broad spectral range

Polarized (linear, elliptical, circular)

Small source size

Partial coherence

High stability

Flux = $\frac{\text{\# of photons in given } \Delta\lambda/\lambda}{\text{sec, mrad } \theta}$

Brightness = $\frac{\text{\# of photons in given } \Delta\lambda/\lambda}{\text{sec, mrad } \theta\text{, mrad } \varphi\text{, mm}^2}$

(a measure of concentration of the radiation)

SYNCHROTRON RADIATION

BASIC PROPERTIES

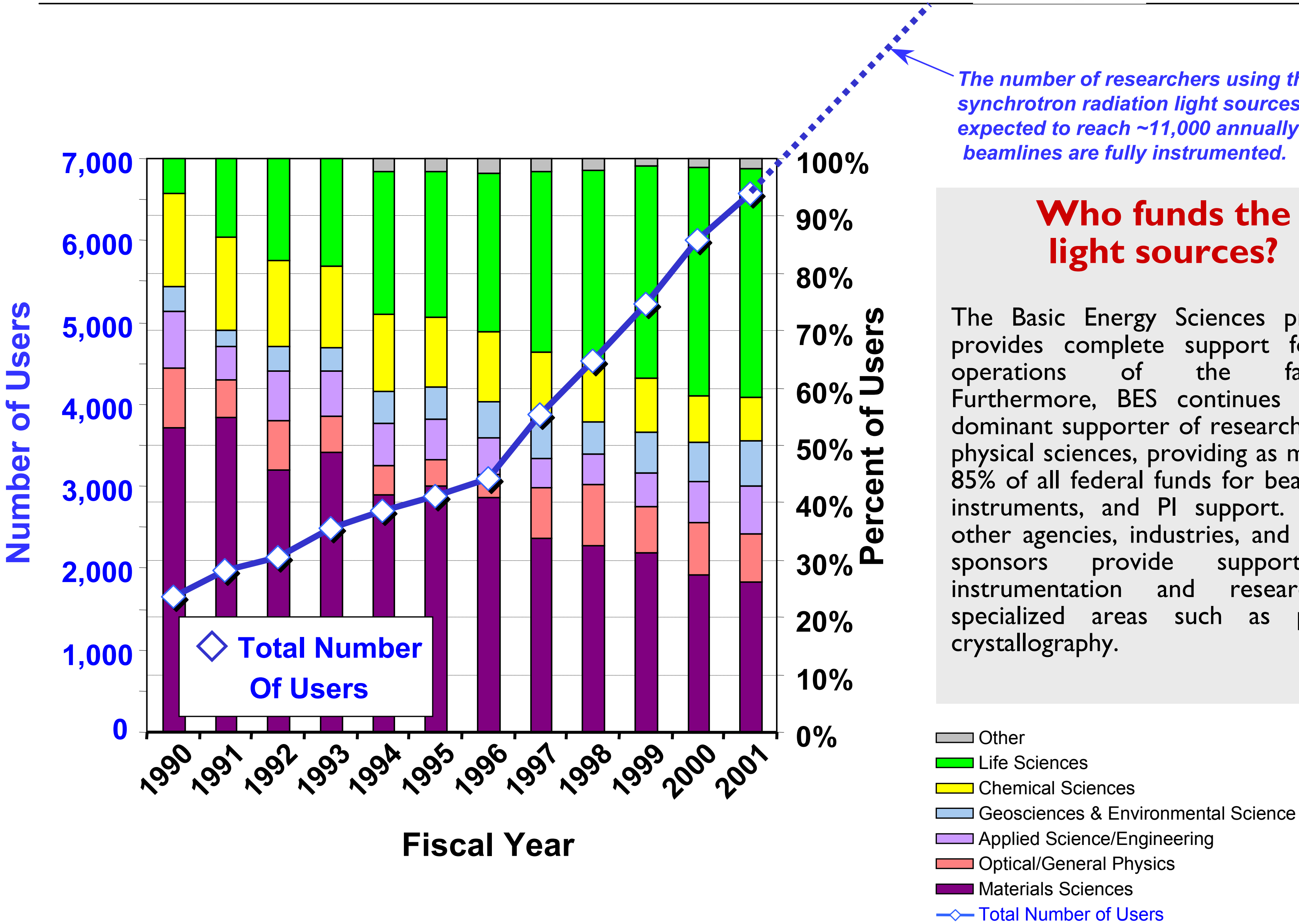
1. HIGH FLUX, BRIGHTNESS, STABILITY
2. BROAD SPECTRAL RANGE - Tunability
3. POLARIZATION (linear, elliptical, circular)
4. PULSED TIME STRUCTURE (0.01 - 1 nsec)
5. SMALL SOURCE SIZE ($\leq$ mm)
6. PARTIAL COHERENCE
7. HIGH VACUUM ENVIRONMENT

$$\textbf{Flux} = \frac{\text{No. of Photons at given } \lambda \text{ within a given } \Delta\lambda/\lambda}{\text{s, mrad } \Theta}$$

$$\textbf{Brightness} = \frac{\text{No. of Photons at given } \lambda \text{ within a given } \Delta\lambda/\lambda}{\text{s, mrad } \Theta\text{, mrad } \varphi\text{, mm}^2}$$

(a measure of the concentration of the radiation)

Numbers of Light Source Users (ALS, APS, NSLS and SSRL) by Discipline

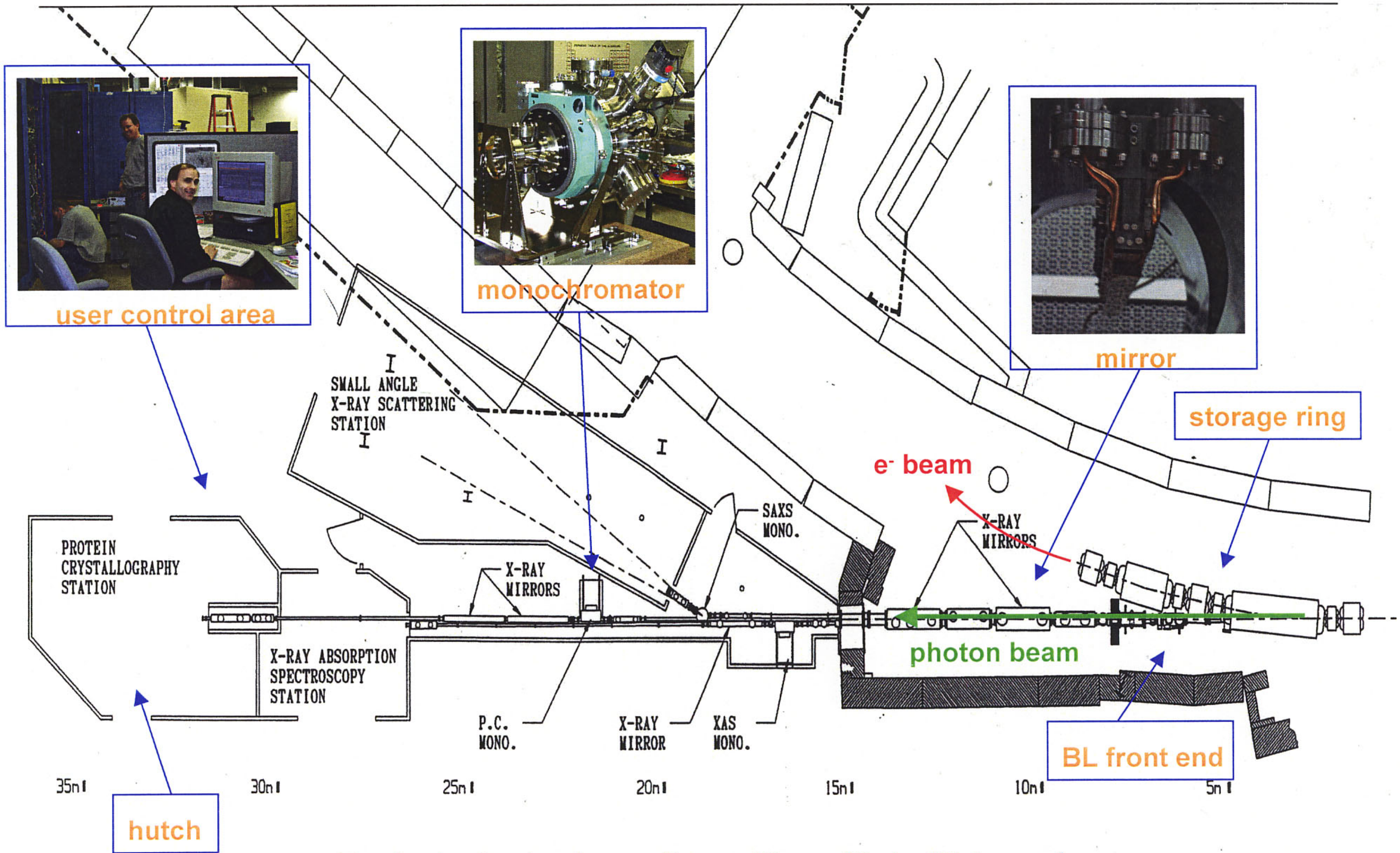


The number of researchers using these synchrotron radiation light sources is expected to reach ~11,000 annually when beamlines are fully instrumented.

Who funds the light sources?

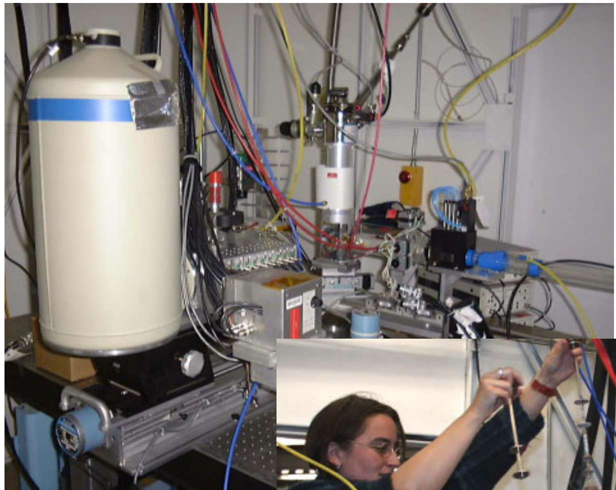
The Basic Energy Sciences program provides complete support for the operations of the facilities. Furthermore, BES continues as the dominant supporter of research in the physical sciences, providing as much as 85% of all federal funds for beamlines, instruments, and PI support. Many other agencies, industries, and private sponsors provide support for instrumentation and research in specialized areas such as protein crystallography.

Beam Lines - Delivering the Photons to the Experimenters
- What are they?

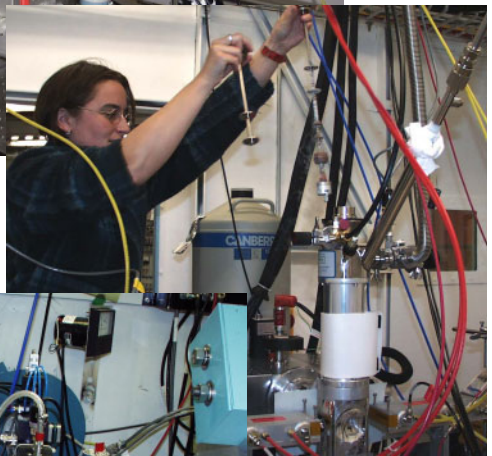


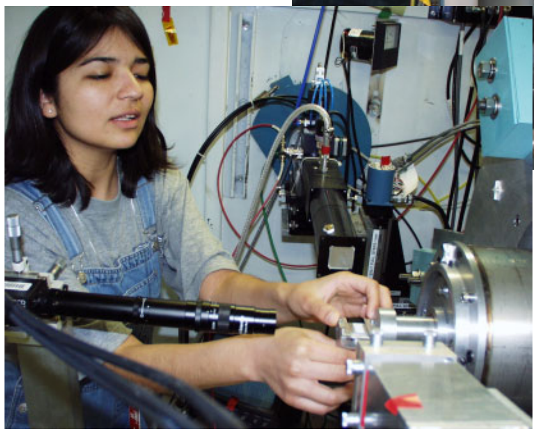
Typical wiggler beam line with multiple (3) branches

Beam Lines - Delivering the Photons to the Experimenters - Instrumentation and Control Systems



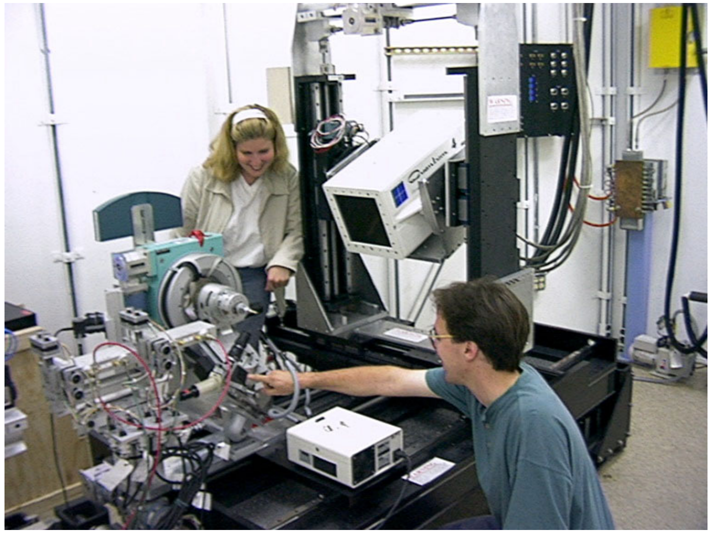
High energy resolution multi-element fluorescence detector (left)

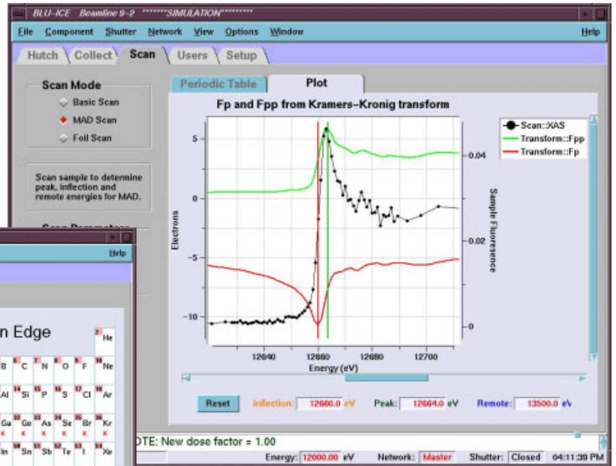


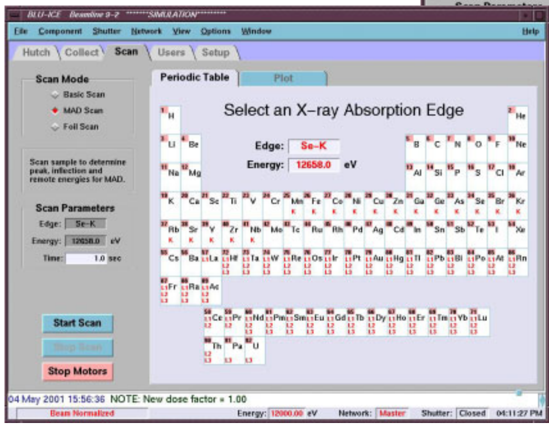


Sample handling systems - e.g. cryostats

X-ray array CCD detector (right)







Control and data acquisition hardware and software

Brightness and Pulse Length in Electron-based X-ray generation

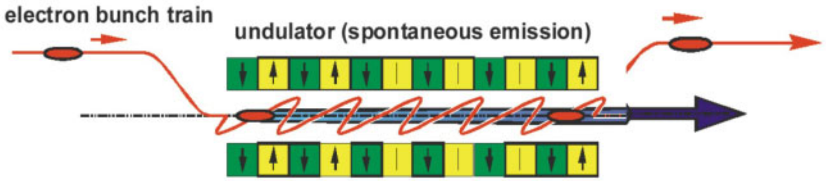
- X-ray brightness determined by electron beam brightness
- X-ray pulse length determined by electron beam pulse length

Storage ring ("conventional synchrotron radiation")
Emittance and bunch length are result of an equilibrium
Typical numbers: 5-100 nm-rad, 50 psec

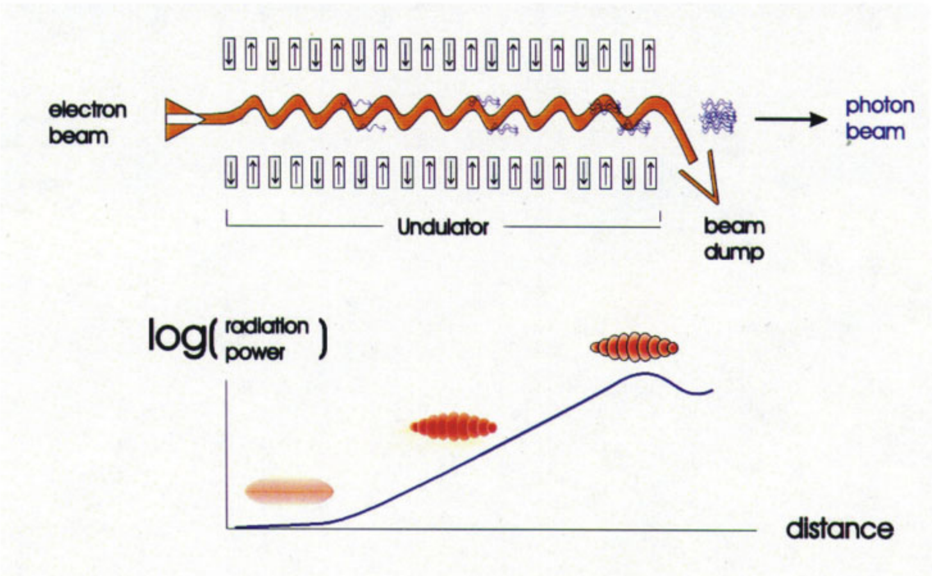
Linac (source for x-ray FEL or ERL)
Normalized emittance is determined by electron gun
Bunch length is determined by electron compression
Typical numbers: 0.03 nm rad, 100 fs or shorter

Linac beam can be much brighter and pulses much shorter!
– at cost of "jitter"- and provides necessary characteristics for ERLs or x-ray FEL generation

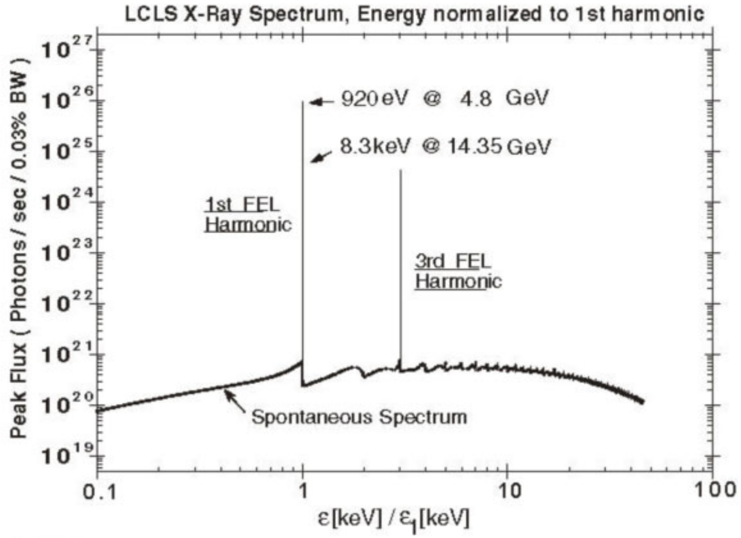
Conventional Undulator - Spontaneous Emission



Long Undulator - Self Amplified Spontaneous Emission (SASE)



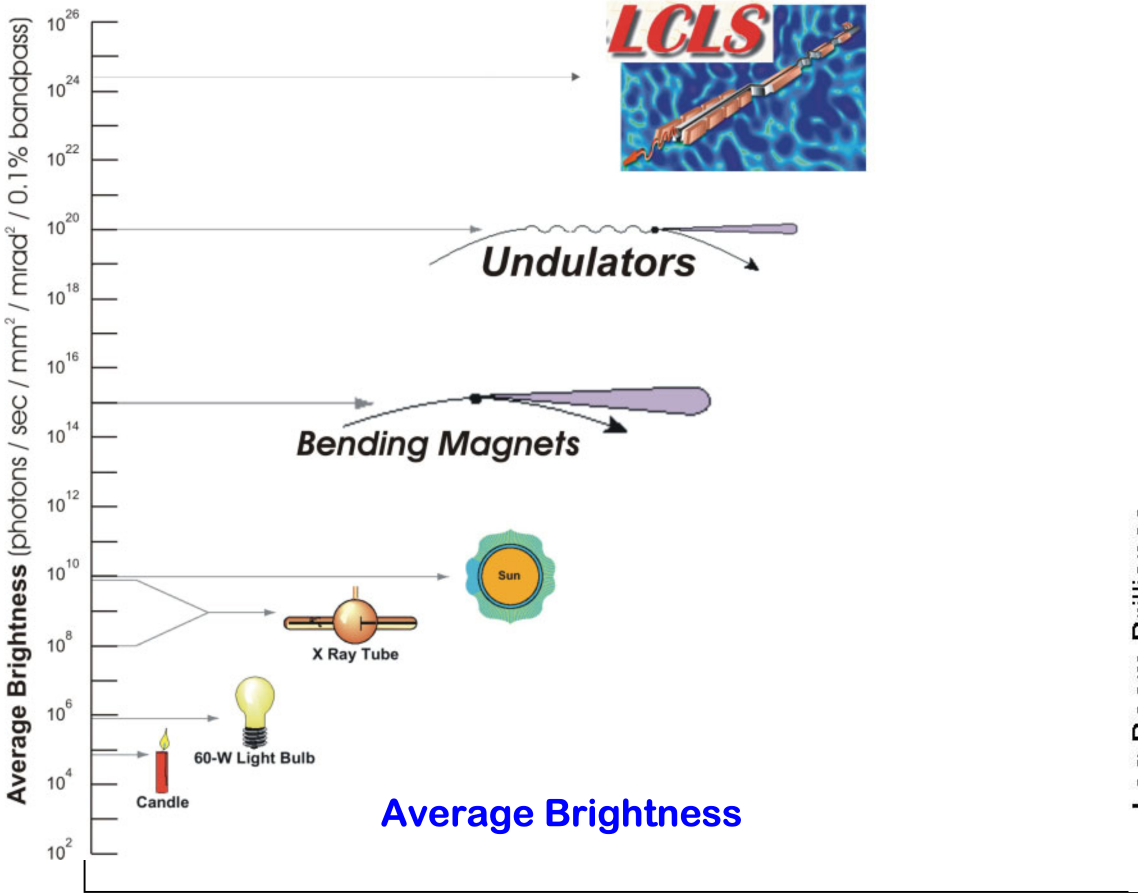
LCLS Performance

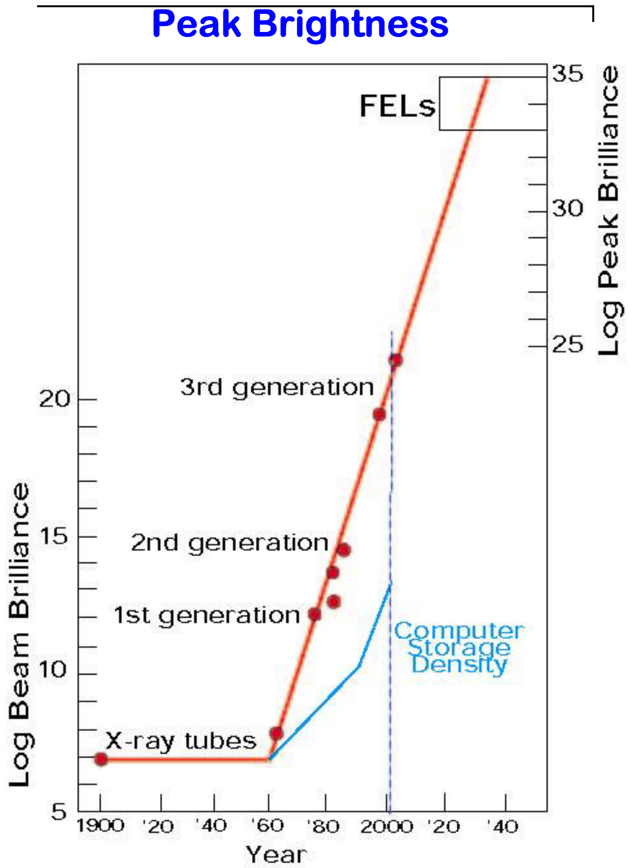


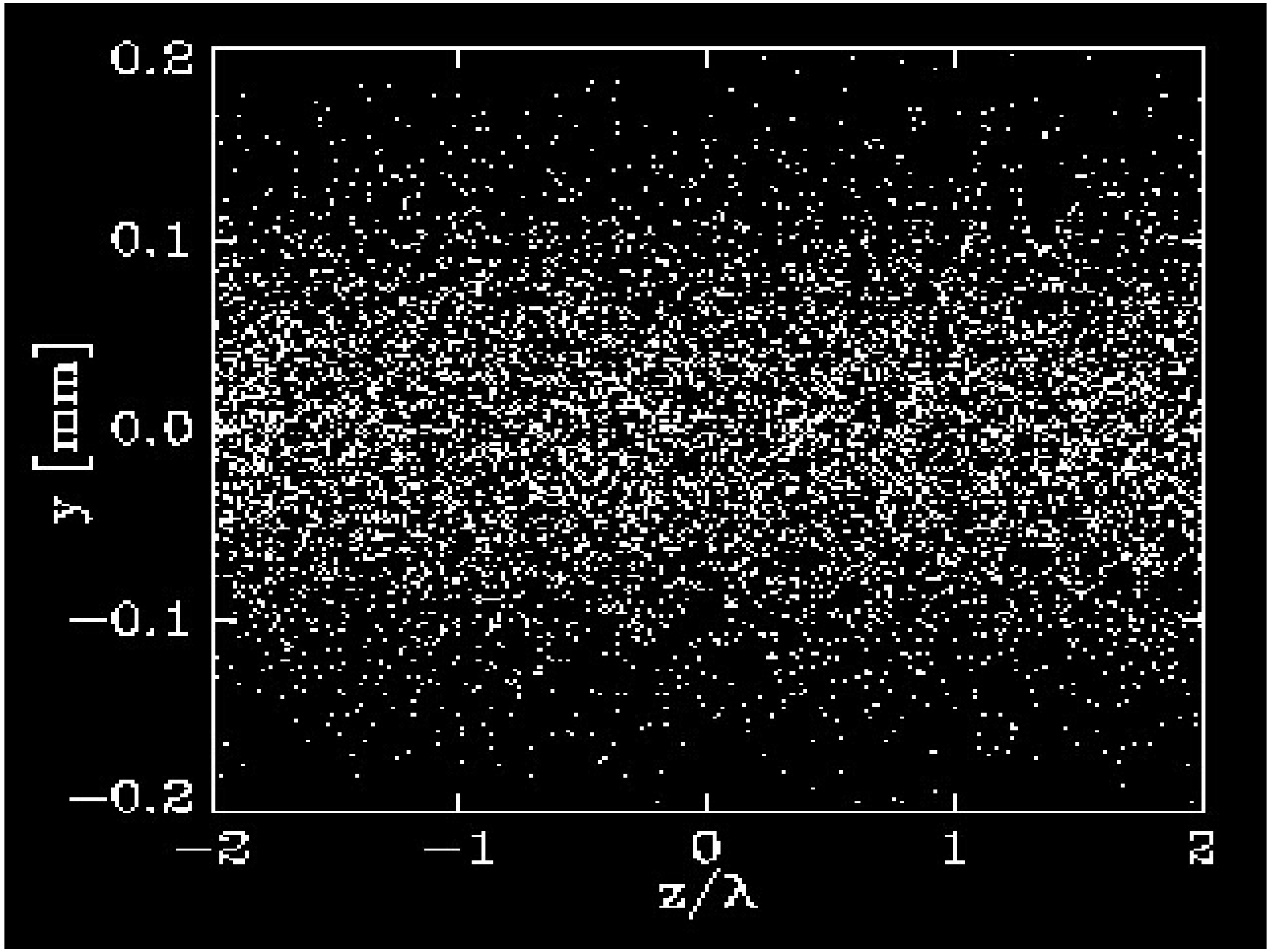
- SASE gives 10^6 intensity gain over spontaneous emission
- FELs and ERLs can produce ultrafast pulses (of order 100 fs or less)

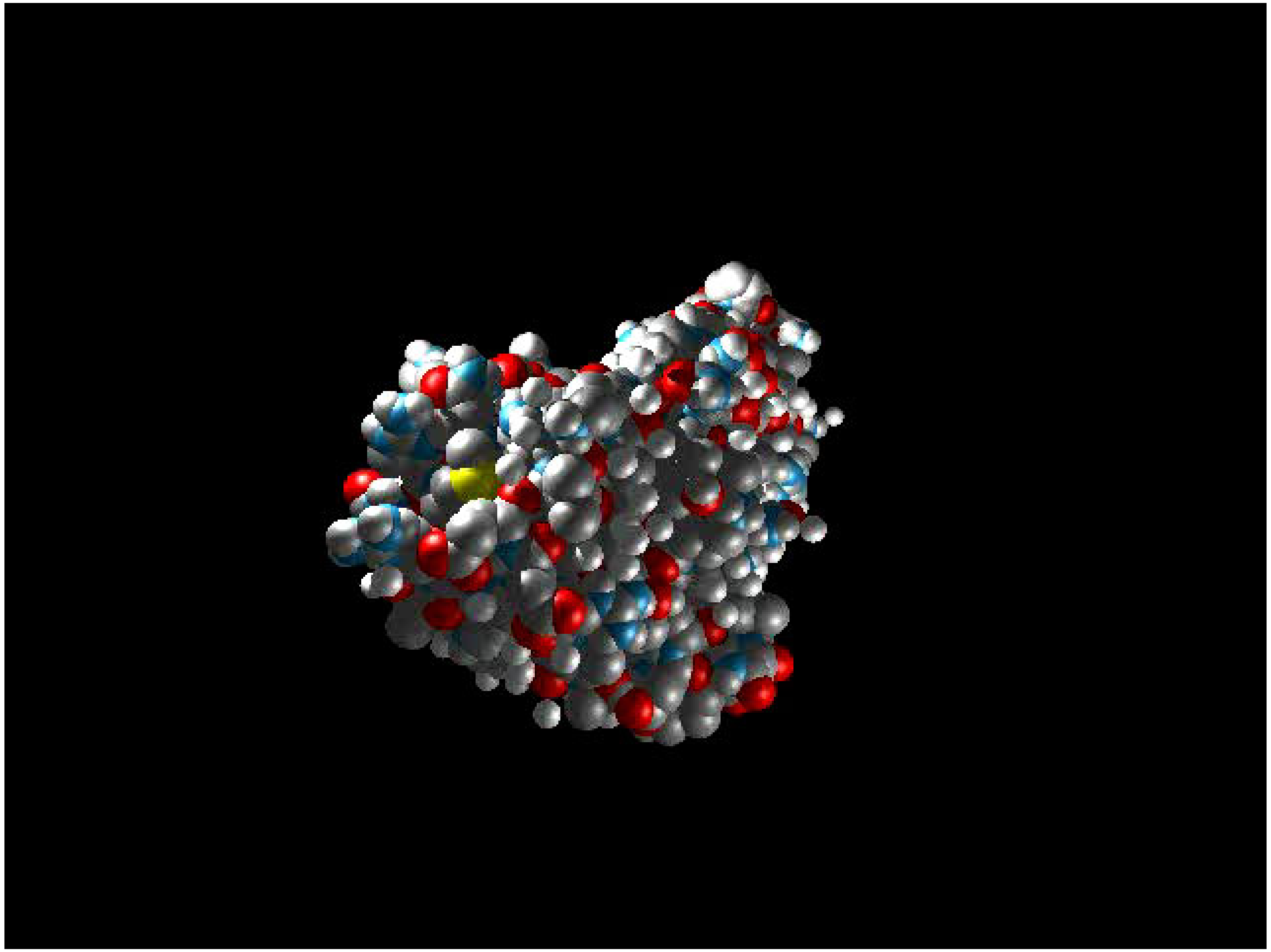
XFEL Properties Enable Unique New Science

How bright are different light sources ?





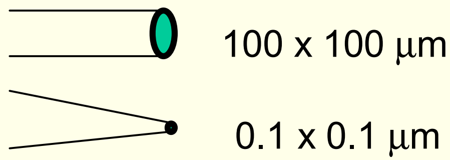

0.2
0.1
0.0
−0.1
−0.2
y [mm]
−2
−1
0
1
2
z/λ



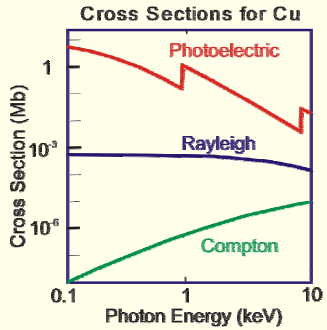
XFEL Properties Enable Unique New Science

XFEL Beams can Probe or Manipulate Matter

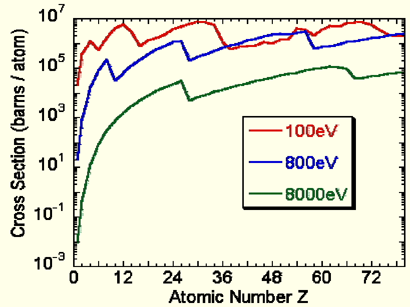
- *Flux density can be varied by focussing: factor 10^6*



- *X-ray absorption can be varied by tuning energy: factor 10 - 10^2*



- *X-ray absorption depends on atomic number: factor 10^5*



WHY WE BUILD RESEARCH FACILITIES

SSRL

Testimony by Robert Wilson, first Director of Fermilab, in a hearing before the Joint Energy Committee of the US Congress on April 17, 1969

Senator Pastore: **Is there anything connected with the hopes of this accelerator that in any way involves the security of this country?**
Wilson: **No sir, I don't believe so.**
Pastore: **Nothing at all?**
Wilson: **Nothing at all.**
Pastore: **It has no value in that respect?**
Wilson: **It has only to do with the respect with which we regard one another, the dignity of men, our love of culture. It has to do with whether we are good painters, good sculptors, great poets. I mean all the things we really venerate in our country and are patriotic about.**
It has nothing to do directly with defending the country except to make it worth defending.

End of this part of presentation