From Röntgen to X-ray Free-electron Lasers

The Evolution of X-ray Sources & Science over 115 Years

Herman Winick – Part1

Stanford Synchrotron Radiation Lightsource (SSRL)
SLAC National Accelerator Laboratory
Stanford University, USA
winick@slac.stanford.edu

African School of Fundamental Physics
KNUST, Kumasi, Ghana; July-August, 2012

July 31, 2012; 11am

International Henry Moseley School and Workshop on X-ray Science

June 14 - 23, 2012

ITAP, Turunç, Marmaris, TURKEY

http://itap-tthv.org/moseley_2012/index.html

Outstanding lectures by eminent X-ray scientists, for example

http://itap-tthv.org/moseley_2012/pdf/day.09_june.22.2012_e.alp.pdf

http://itap-tthv.org/moseley_2012/pdf/day.01_june.14.2012_g.shenoy.pdf

Two pamphlets relevant to accelerators and a future African light source

1. ***Photon Science for Renewable Energy At Light-Source Facilities of Today and Tomorrow*****: Published by the Advanced Light Source at LBNL. Available at**

www.als.gov/als/publications/genpubs.html

2. *Accelerators and Beams*
Published by the American Physical Society Division of Physics of Beams (DPB). Available at:
www.aps.org/units/dpb

Note that Page 21 of this brochure, "Accelerators boost international cooperation" is about SESAME.

Selected References

Articles (compiled by Gopal Shenoy, Argonne, National Lab.)

M. L. Perlman, E. M. Rowe & R. E. Watson, "Synch Rad—Light Fantastic," Physics Today 27, No.7 (1974) 30.

G. C. Baldwin, "Origin of Synchrotron Radiation," Physics Today 28, No. 1 (1975) 9.

K. R. Lea, "Highlights of Synchrotron Radiation," Phys. Rep. (Phys. Lett. C) 43, No. 8 (1978) 337.

C. Kunz, "Introduction—Properties of Synchrotron Radiation," in Synchrotron Radiation Techniques and Applications, C. Kunz, ed., Springer-Verlag, Berlin, 1979, pp. 1-23.

H. Winick and S. Doniach, "An Overview of Synchrotron Radiation Research," in Synchrotron Radiation Research, H. Winick and S. Doniach, eds., Plenum Press, New York and London, 1980, pp. 1-10.

E. Rowe, "Synchrotron Radiation: Facilities in the United States, Physics Today 34, No. 5 (1981) 28.

H. Winick, G. Brown, K. Halbach, & J. Harris, "Synch Rad: Wiggler & Undulator Magnets," Physics Today 34, No. 5 (1981) 50.

H. C. Pollock, "The Discovery of Synchrotron Radiation," Am J. Phys. 51, No. 3 (1983) 278.

E.-E. Koch, D. E. Eastman, and Y. Farges, "Synchrotron Radiation—A Powerful Tool in Science," in Handbook on Synch Rad, Vol 1a, E.-E. Koch, ed., North-Holland Pub Co; Amsterdam, 1983, pp. 1-63.

G. N. Kulipanov and A. N. Skrinksy, "Early Work on Synch Rad," Synch Rad News 1, No. 3 (1988) 32.

P. L. Hartman, "Early Experimental Work on Synchrotron Radiation," Synch Rad News 1, No. 4 (1988) 28.

T. Sasaki, "A Prospect and Retrospect—the Japanese Case," J. Synch. Rad 4, Part 6 (1997) 359.

J. A. Clarke, The Science & Technology of Undulators & Wigglers, Oxford University Press, 2004

Books

H. Winick, ed; "Synchrotron Radiation Sources, A Primer", World Scientific 1994

D. Attwood; "Soft X-Rays & Extreme Ultraviolet Radiation", Cambridge Univ. Press, 1999

A. Hofmann; "The Physics of Synchrotron Radiation" Cambridge Univ. Press, 2004

Gopal Shenoy: 1st International Henry Moseley X-Ray Science Summer School and Workshop, June 14-23, 2012, Turunç, Marmaris, Turkey

References:

1. Classical Electrodynamics
Author: John David Jackson
Publisher: Wiley; 3rd Edition

2. Synchrotron Radiation Sources: A Primer
Editor: Herman Winick
Publisher: World Scientific Publishing Company

3. Elements of Modern X-ray Physics
Author: Jens Als-Nielson & Des McMorrow
Publisher: John Wiley and Sons, 2nd Edition, Apr 8, 2011 - 432 pages

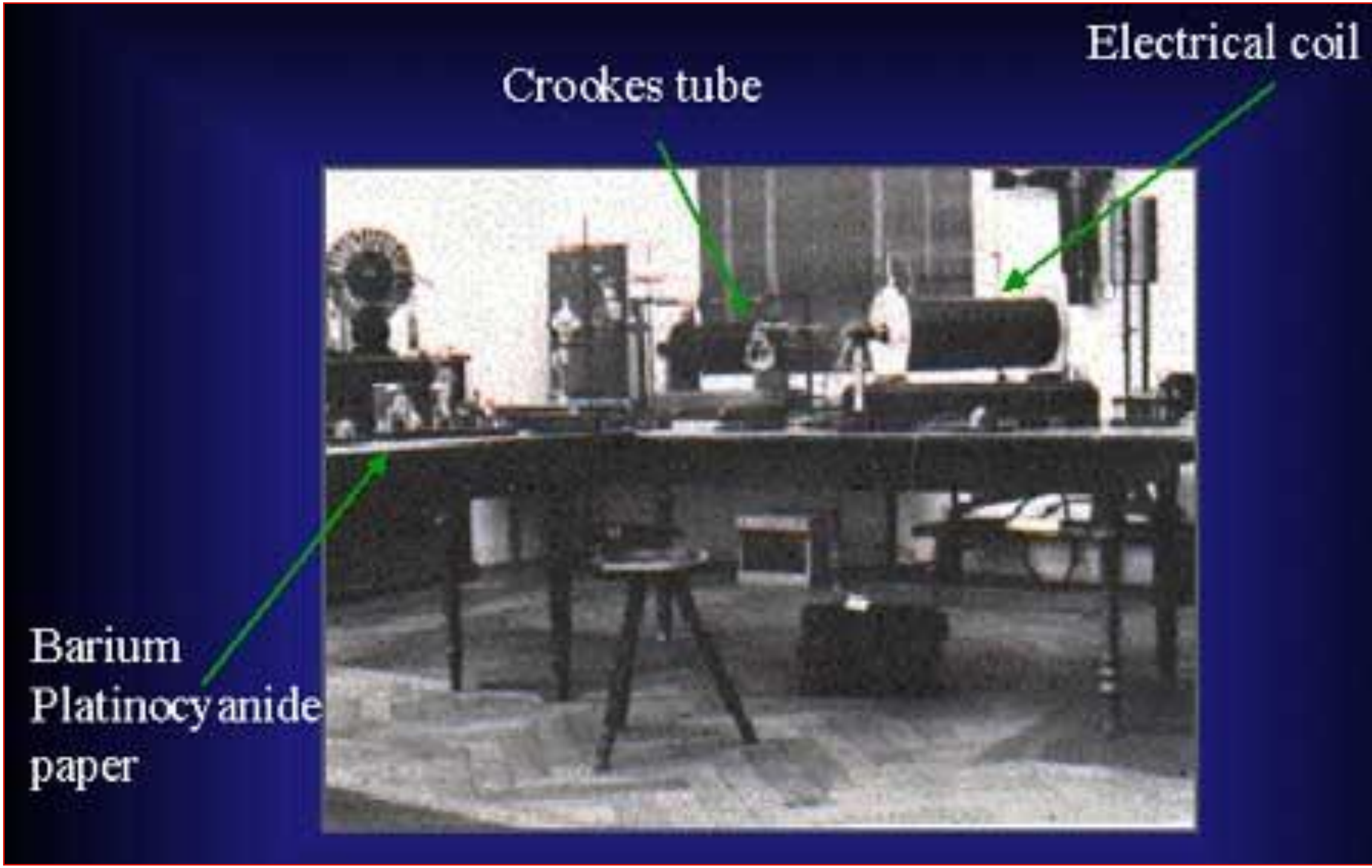
4. Insertion Devices For Synchrotron Radiation And Free Electron Laser
Authors: F Ciocci, G Dattoli, A Torre & A Renieri
Publisher: World Scientific Publishing Company

5. Soft X-Rays and Extreme Ultraviolet Radiation : Principles and Applications
Author: David Attwood
Publisher: Cambridge University Press

6. ***Synchrotron Radiation Sources and Their Applications (Scottish Universities Summer School in Physics)***
Author: N. Greaves
Publisher: Scottish Universities Gopal Shenoy 1st International Henry Moseley X-Ray Science Summer School and Workshop, June 14-23, 2012, Turunç, Marmaris, Turkey

Wilhelm Röntgen 1845-1923
Discovered X-rays in 1895

Curiosity Driven Research!!



Röntgen's Laboratory in Wurzburg, Germany - 1895

Wilhelm Röntgen
Universität Würzburg
Dec. 1895

Michael Pupin
Columbia University/New York
Feb. 1896

“This is of the hand of a gentleman resident in New York, who, while on a hunting trip in England a few months ago, was so unfortunate as to discharge his gun into his right hand, no less than forty shot lodging in the palm and fingers. The hand has since healed completely; but the shot remain in it, the doctors being unable to remove them, because unable to determine their exact location. The result is that the hand is almost useless, and often painful.” - Cleveland Moffett, McClure’s Magazine, April 1896

marresearch

High-performance X-ray data collection systems

mardtb/csc

- Advanced goniostat with integrated automatic cryogenic sample changer
- Easy manual or automatic sample mounting and centering
- Fully automated alignment to the X-ray beam
- Ideal laboratory screening station with mar345 or marccd
- Complete state-of-the-art high-throughput beamline endstation with marmosaic CCD detector

marmosaic

- Seamless multi-element CCD technology
- 225mm × 225mm or 325mm × 325mm active area
- Multichannel readout in 1 second
- Low noise, low dark current design for fully usable 16-bit dynamic range

marccd

- Largest available single chip design: 165mm diameter
- Based on 4k × 4k CCD with four parallel readouts
- Low noise, low dark current design for fully usable16-bit dynamic range
- Versatile detector for rotating anode and synchrotron beamlines

mar345

- Calibrated image plate
- Fast spiral readout
- Ultralarge 345mm diameter
- Perennial standard for accuracy and reliability

The marmosaic 225 with mardtb goniostat and cryogenic sample changer is a complete endstation for high-throughput crystallography.

marusa

www.mar-usa.com

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Evanston, IL 60201 USA
Toll-free: 1-877-MAR-XRAY (1-877-627-9729)
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Hans-Boeckler-Ring 17
22851 Norderstedt Germany
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E-mail: info@marresearch.com

WHY ARE X-RAYS SO IMPORTANT?

X-RAYS ARE A UBIQUITOUS TOOL FOR BASIC AND APPLIED RESEARCH, TECHNOLOGY AND MEDICAL APPLICATIONS

INTENSE X-RAYS FROM SYNCHROTRONS REVOLUTIONIZE OUR ABILITY TO UNDERSTAND THE PROPERTIES, STRUCTURE AND FUNCTION OF MATERIALS

X-RAYS ARE NOW BEING USED TO DEVELOP NEW MATERIALS WITH DESIRED PROPERTIES

SHORT PULSES OF X-RAYS ENABLE US TO FOLLOW CHEMICAL AND BIOLOGICAL PROCESS ON A TIME SCALE RANGING FROM MICROSECONDS TO FEMTOSECONDS.

X-rays Have Enabled Seminal Scientific Discoveries

20 Nobel Prizes Based on X-ray Work

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

2003: PETER AGRE and RODERICK MACKINNON

2006: ROGER KORNBERG

2009: VENTKATRAMAN RAMAKRISHNAN,
THOMAS STEITZ, ADA YONATH

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

Medicine

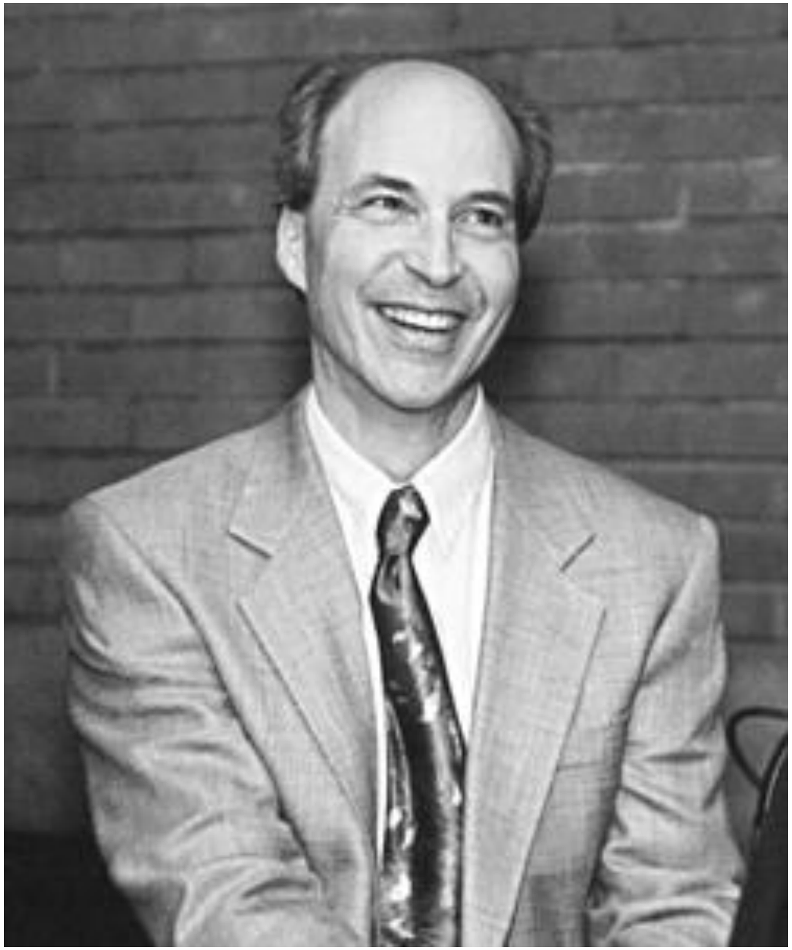
1946: **HERMANN JOSEPH MULLER**

1962: **FRANCIS CRICK, JAMES WATSON**
and **MAURICE WILKINS**

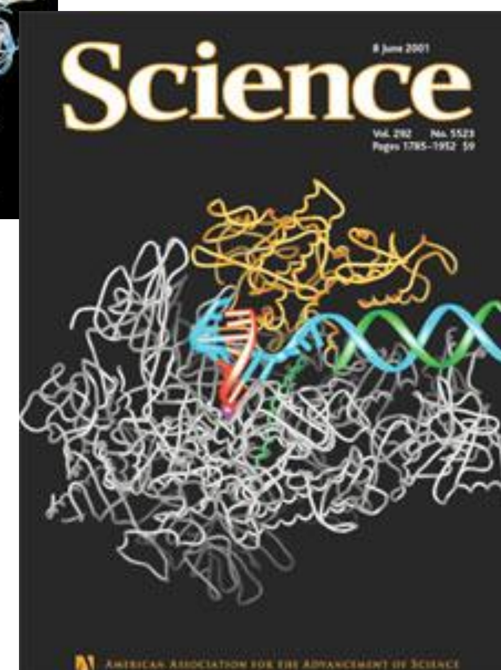
1979: **ALAN M. CORMACK** and
SIR GODFREY N. HOUNSFIELD

Roger Kornberg, Stanford University

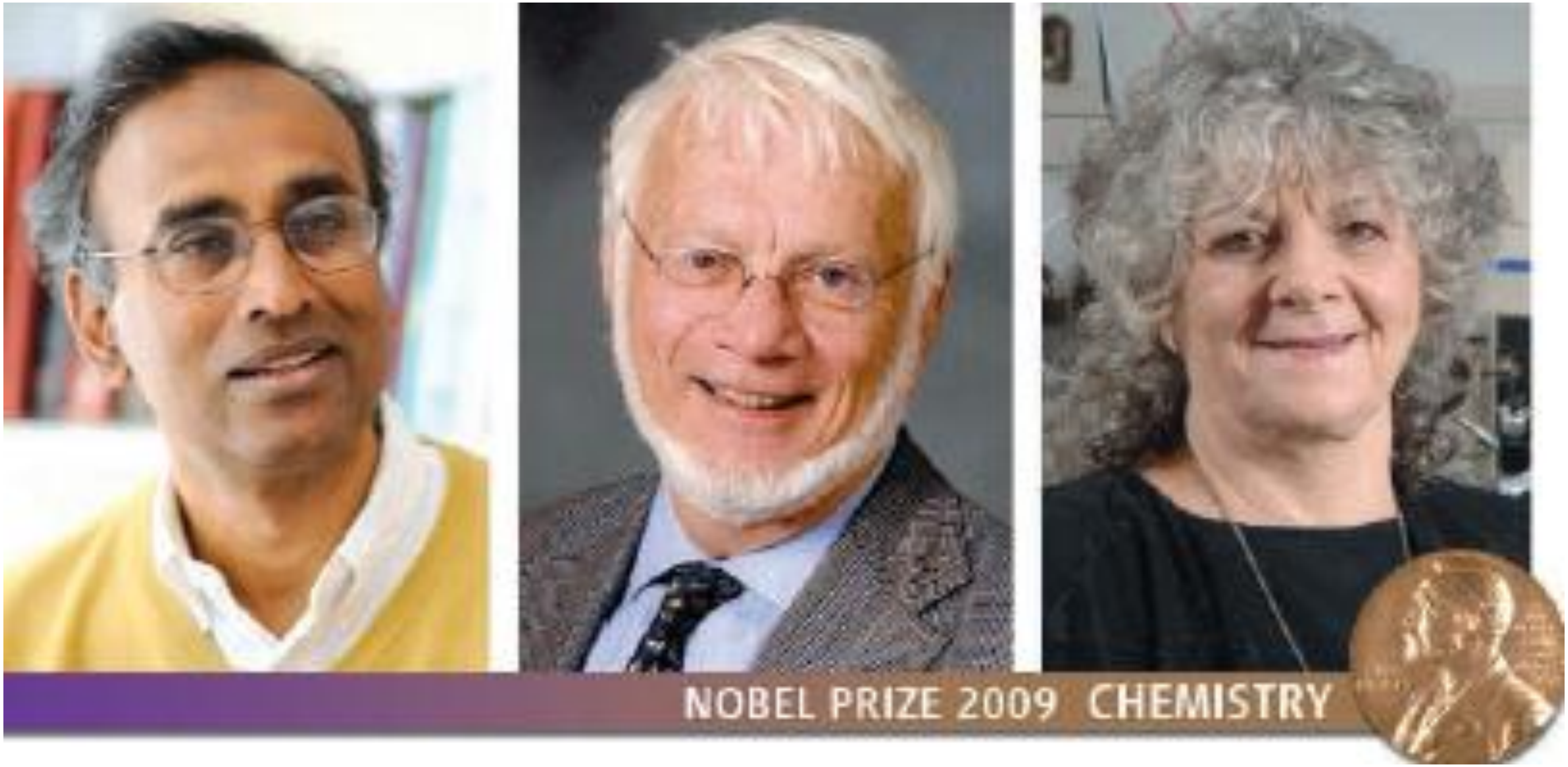
Nobel Prize in Chemistry, 2006



RNA
Polymerase

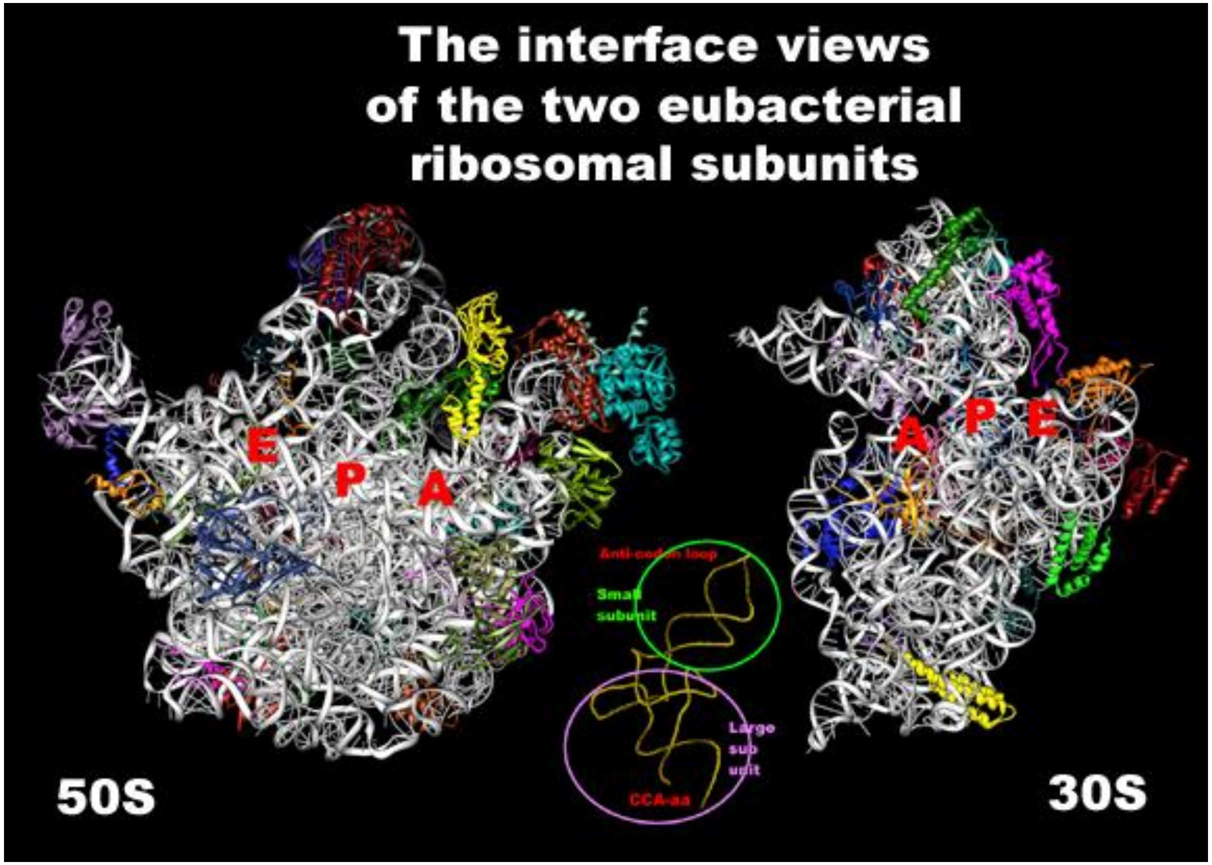


Required Synchrotron Radiation



Ventkatraman Ramakrishnan **Thomas Steitz** **Ada Yonath**

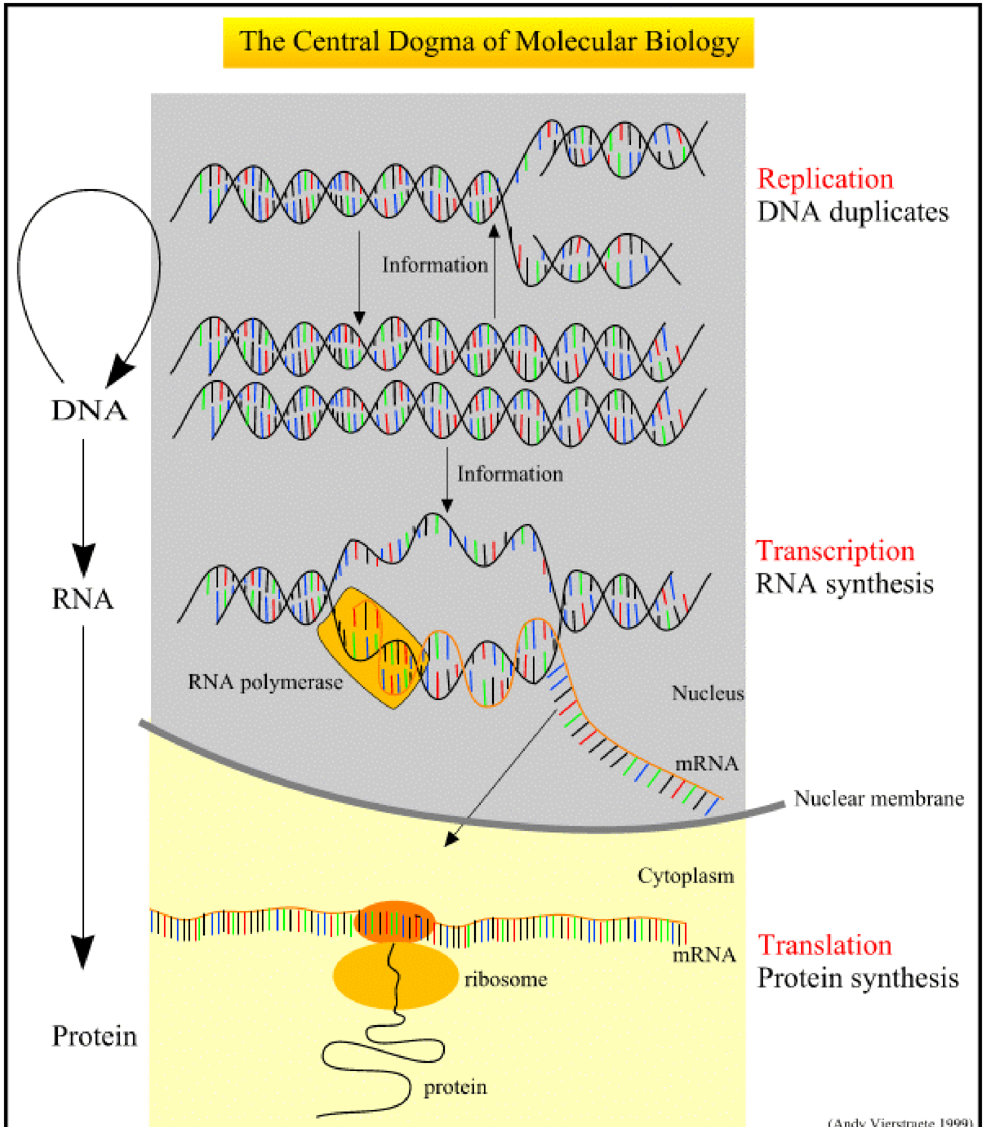
The 2009 Nobel Prize in Chemistry was shared by **Venkatraman Ramakrishnan**, **Thomas A. Steitz** and **Ada E. Yonath** for showing what the ribosome looks like and how it functions at the atomic level. They used ***synchrotron radiation*** X-rays to map the position for each and every one of the hundreds of thousands of atoms that make up the ribosome.

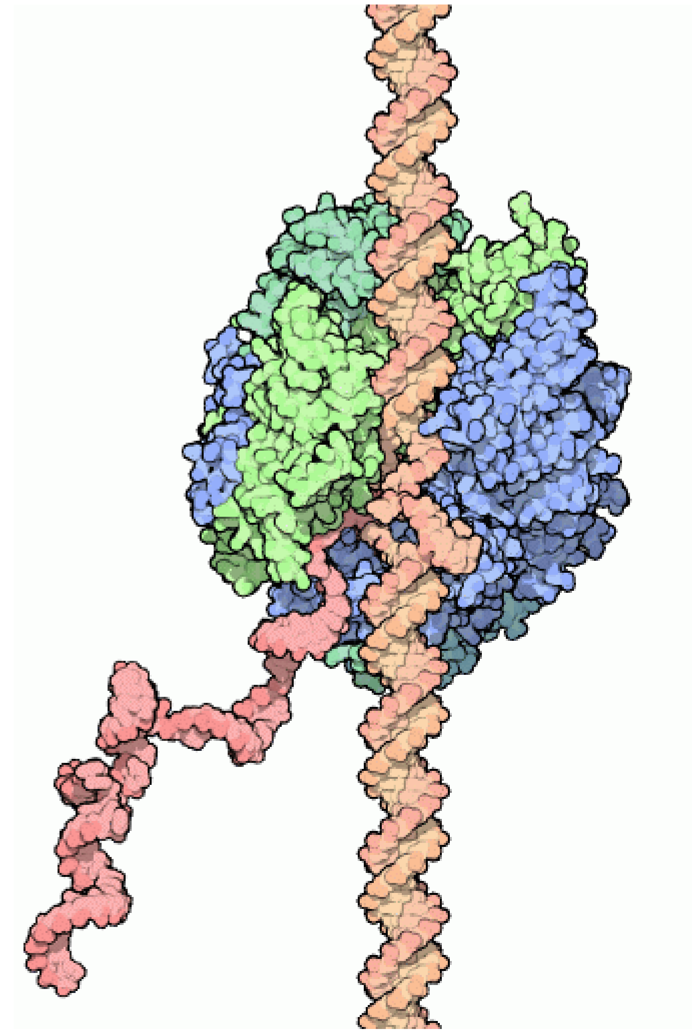


For detailed explanation, figures, movies see:

http://www.weizmann.ac.il/sb/faculty_pages/Yonath/home.html

Central Dogma of Life





Synchrotron radiation from Storage Rings is a very powerful tool for the study of material on the atomic and molecular scale

Although the pulses of light from storage rings, particularly from wigglers and undulators, are very intense, their pulse length is measured in tens of picoseconds.

To study processes on a faster time scale, typical of atomic and molecular processes, an intense source with a shorter pulse duration is needed.

The Free-Electron Laser provides this.

Femtosecond pulses with >10^{12} photons per pulse

Looking back:

A brief history of synchrotron radiation

Early publication on radiation by accelerated particles

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 systèmè d'équations on déduit facilement les relations

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

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

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 :

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

(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.

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

A SHORT HISTORY OF SYNCHROTRON RADIATION 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 *DEDICATED USE OF e+/e- COLLIDERS,*
USE OF INSERTION DEVICES (IDs); WIGGLERS & UNDULATORS

THIRD GENERATION SOURCES
1990's: *RINGS OPTIMIZED FOR IDs; Low emittance, many straight sections*

FOURTH GENERATION SOURCES
2000's: **LINAC-BASED SOURCES**

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

2010's: *3rd & 4th Generations Sources & Ultimate Storage Rings reaching Diffraction limits at X-ray Wavelenghts.   NEW IDEAS*

FIRST GENERATION SOURCES

RINGS BUILT FOR HIGH ENERGY PHYSICS RESEARCH.

Synchrotron radiation programs usually started in a parasitic or partly dedicated mode.

Many have developed to become fully dedicated sources.

In several cases a low emittance optics has been developed, reducing the emittance to about 100 nm-radians.

Large *e+e*- colliders (PEP, PETRA, TRISTAN) are first generation rings which, operated at low energy, can reach extremely low emittance. Also, they have long straight sections for long insertion devices.

SECOND GENERATION SOURCES

RINGS BUILT FROM THE START AS FULLY DEDICATED LIGHT SOURCES

The primary sources on these rings are the bending magnets. Typically there is space for 2-6 wiggler and undulator insertion devices sources.

The emittance of these rings is typically in the *50*-200 nm-radian range.

NSLS and the Photon Factory each serve more than 2000 Users annually

THIRD GENERATION SOURCES

LOWER EMITTANCE RINGS WITH MANY STRAIGHT SECTIONS FOR INSERTION DEVICES

Typical emittance is 2-20 nm-radians. Latest ones go below 1nm.

2-3 orders of magnitude higher brightness and coherence than 1st and 2nd generation rings

1-2 GeV rings produce high brightness VUV/soft x-rays from ~10 eV to 2 keV. SC devices extend to higher energy

6-8 GeV rings extend high brightness to 20 keV and beyond

Advances in technology of IDs and accelerators now enable rings with E~2.5-3.5 GeV to produce hard x-rays with brightness approaching the higher energy, more expensive rings. Such an intermediate energy ring would be a good choice for Africa.

FOUNDATION GENERATION SOURCES

•Ultra-low emittance rings
- *higher brightness, coherence*

•Quasi-isochronous rings
- *picosecond bunches*

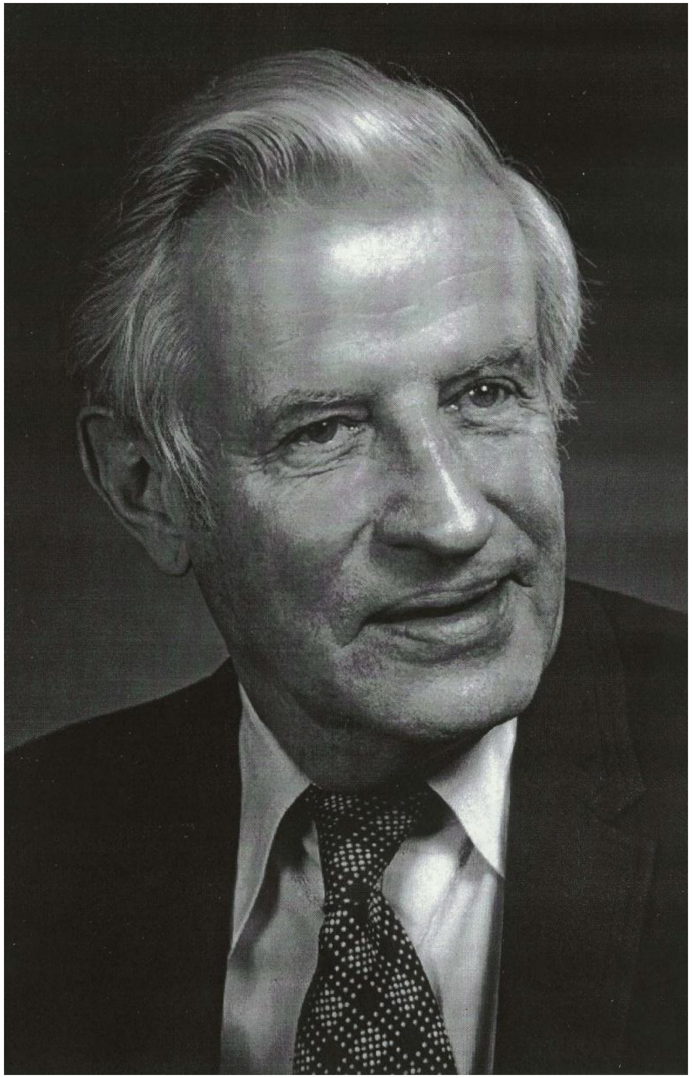
•FELs using rings and linacs
- *full coherence, high power, sub-picosecond bunches*

•Large e+/e- colliders
-*long straights, low emittance*

•Novel insertion devices

•New ideas

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

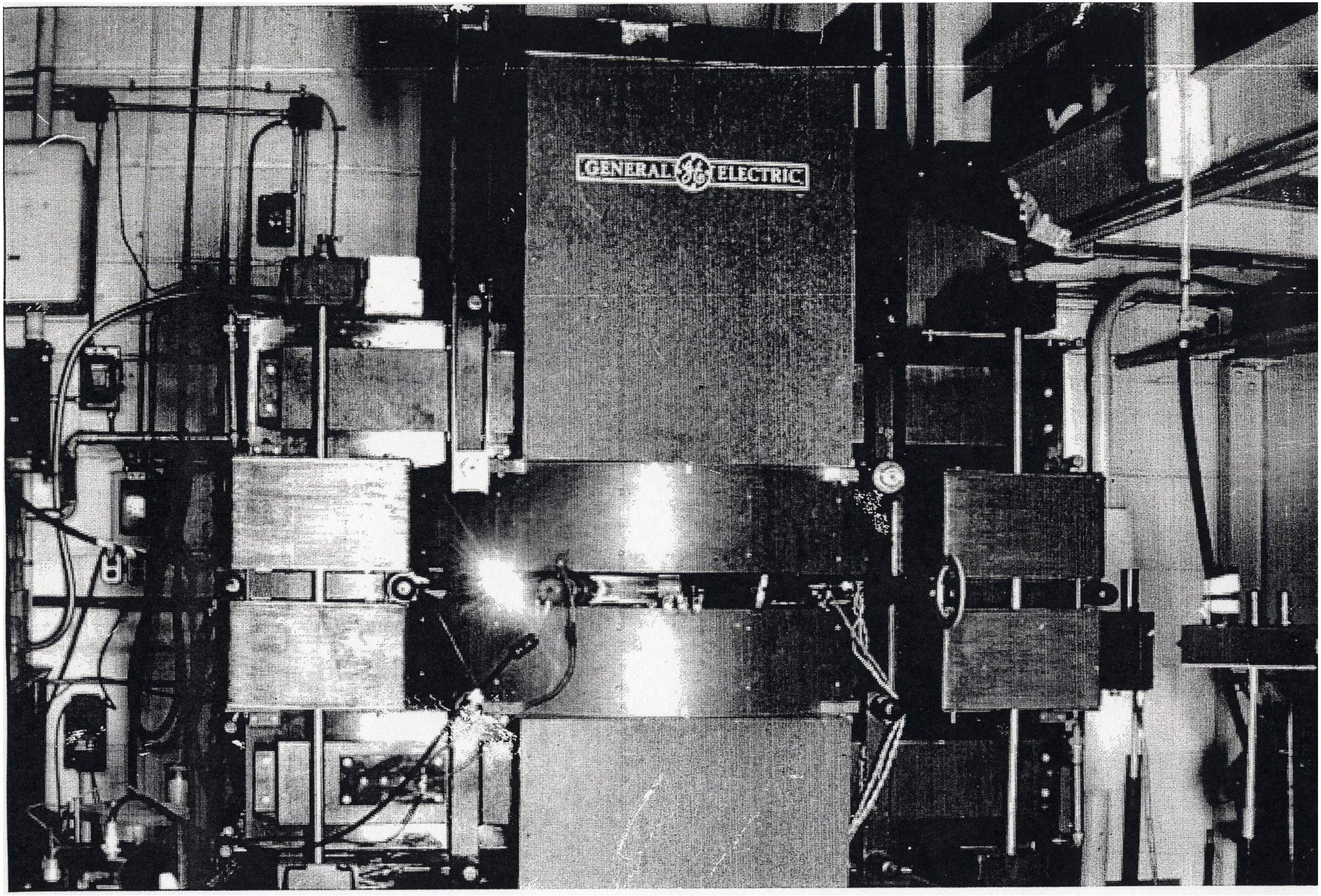
Radiation Losses in the Induction Electron Accelerator

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.

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



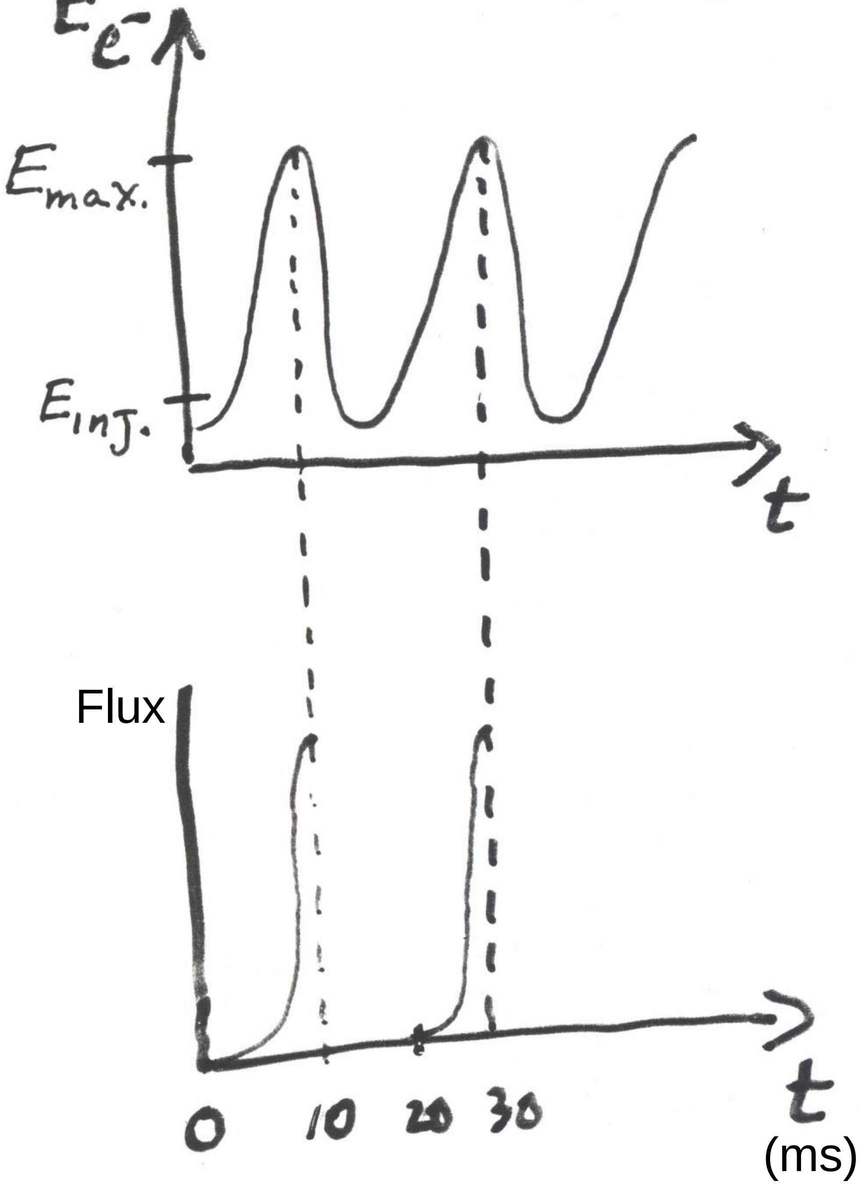
SYNCHROTRON RADIATION SOURCES – 1973

SYNCHROTRONS (Cyclic)	GeV
DESY – Hamburg	7.5
NINA – Daresbury	5.0
ARUS – Yerevan	4.5
BONN I	2.5
SIRIUS – Tomsk	1.36
INS-ES – Tokyo	1.3
PAKHRA – Moscow	1.3
LUSY – Lund	1.2
FIAN C-60 – Moscow	0.68
BONN II	0.5
NBS – Washington	0.18
STORAGE RINGS (Constant)	
CEA – Cambridge MA	3.5
VEPP2M – Novosibirsk	0.67
ACO – Orsay	0.54
TANTALUS – Wisconsin	0.24

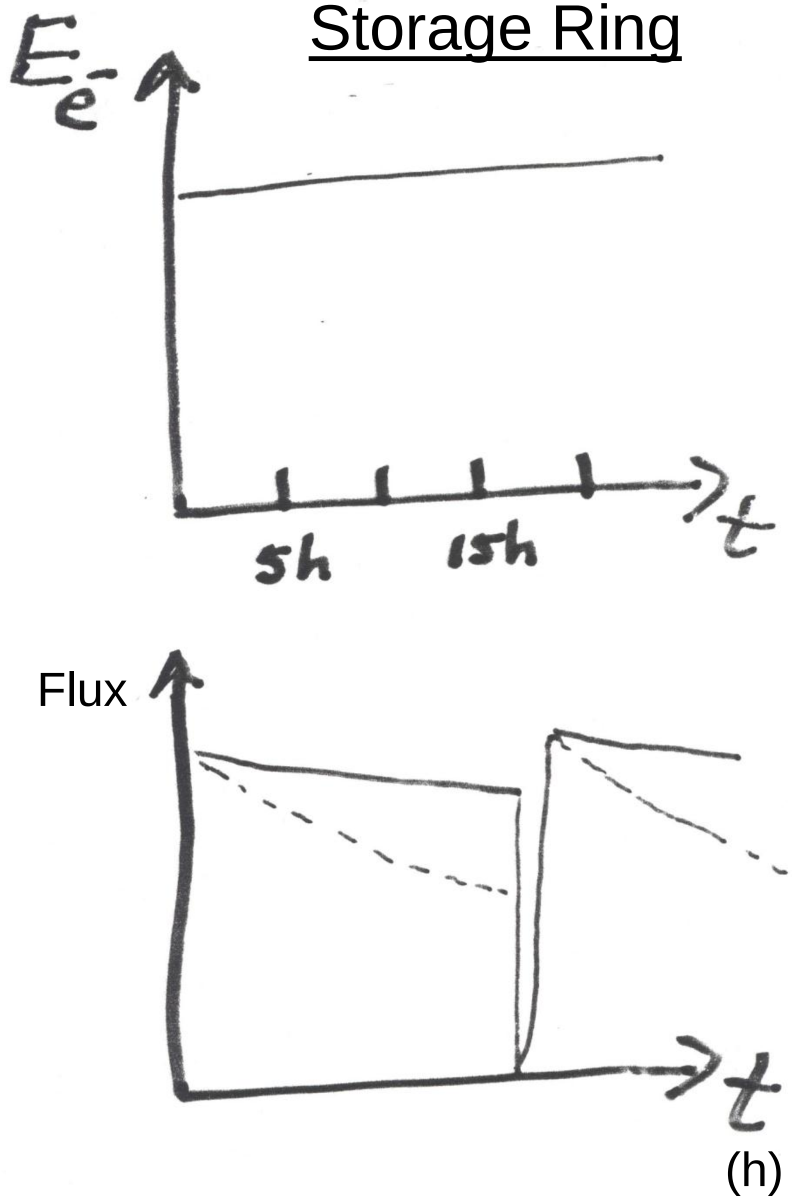
Comparison of Synchrotron Radiation from Synchrotrons and Storage Rings

	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 a few 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

Synchrotron



Storage Ring



Synchrotron Radiation Facilities Around the World

- **>60 in operation; 20 countries; >30,000 Users**

  In many technologically advanced countries plus

  Brazil, Korea, Taiwan, Thailand

- **Recently completed or in construction**

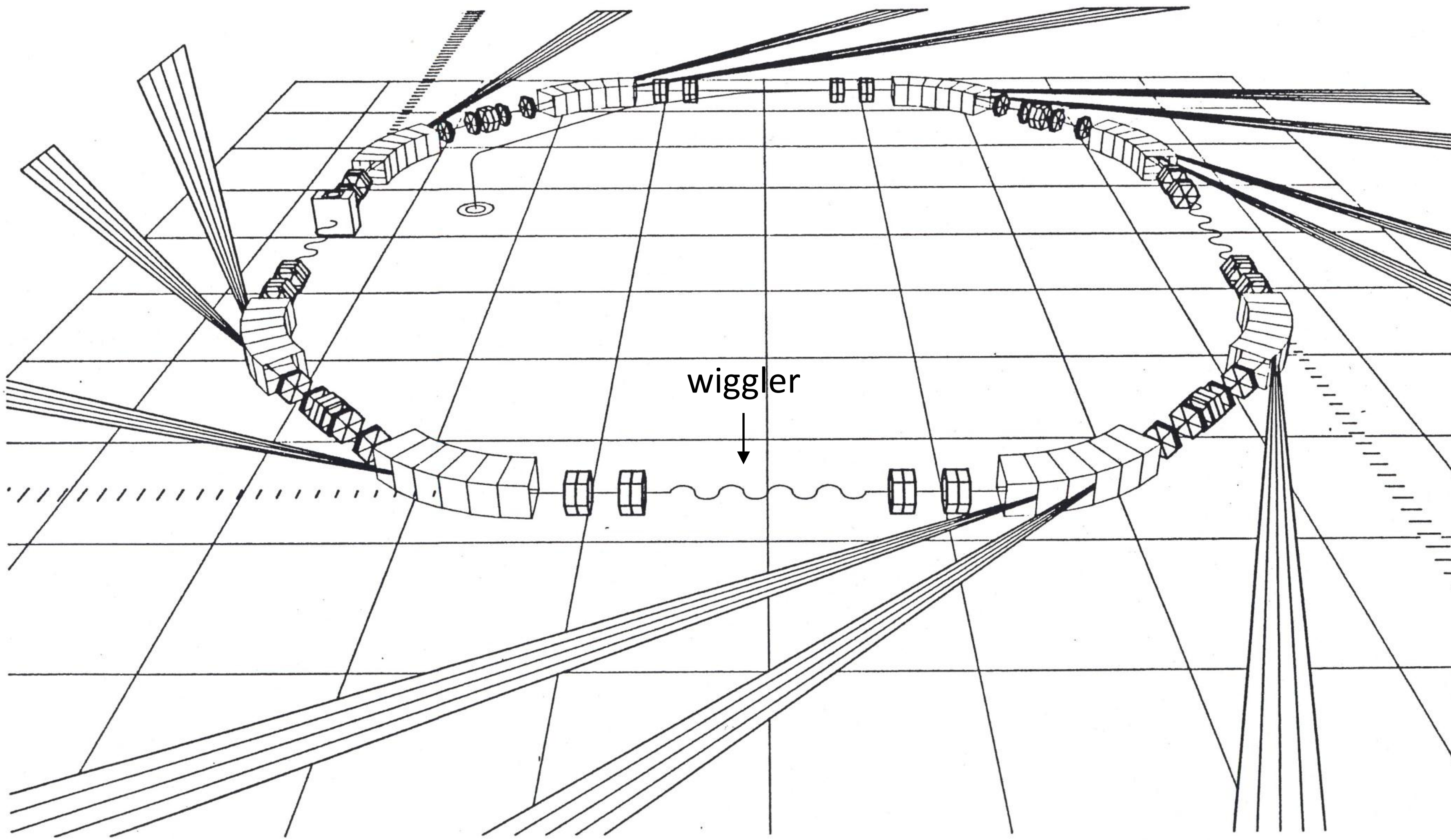
  Armenia, Australia, Brazil, China, France, Japan, Jordan, Korea, Poland, Russia, Spain, Taiwan, UK, US

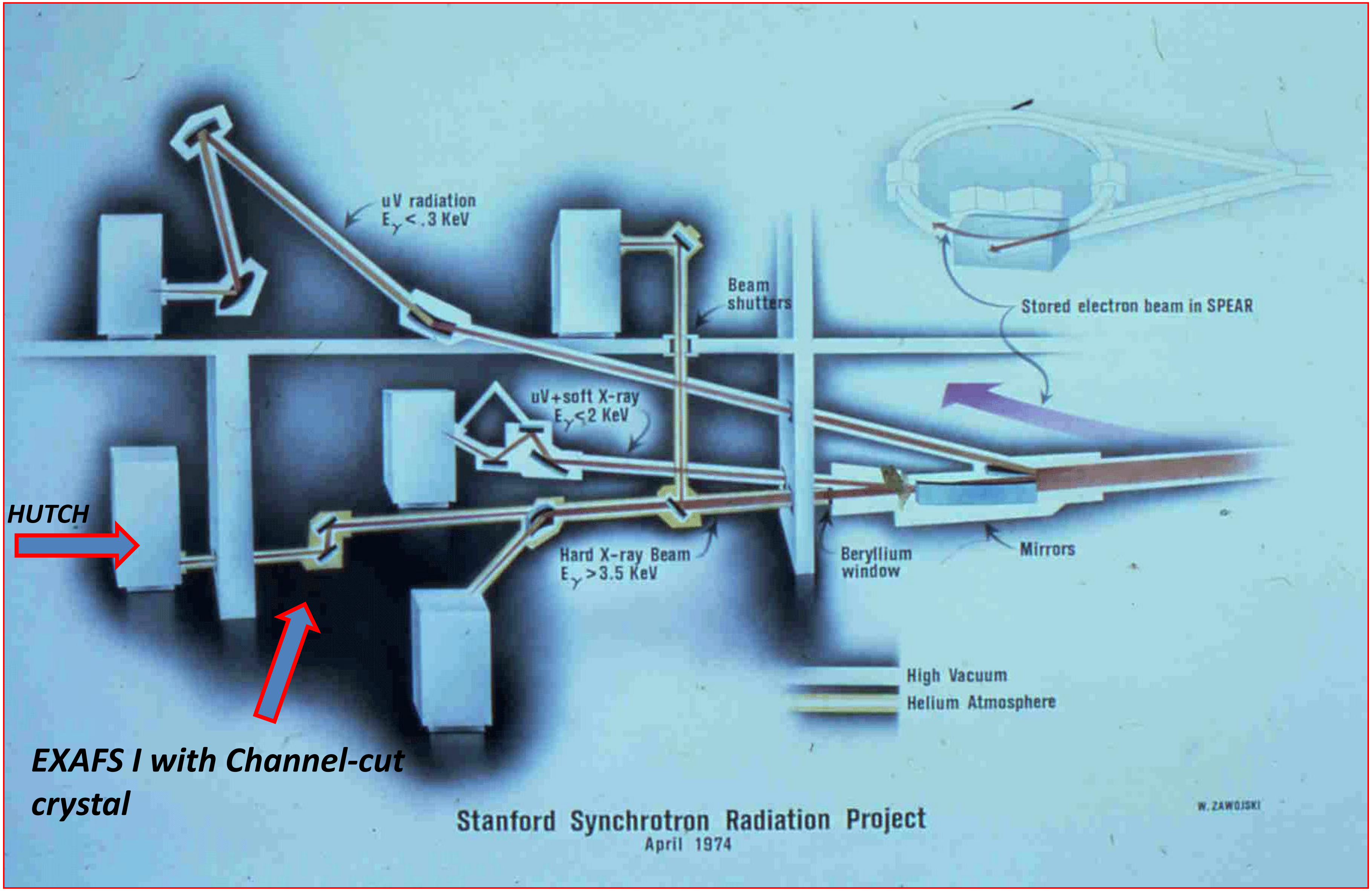
- **More in design/planning**

For a links to SR facilities around the world see

www.lightsources.org

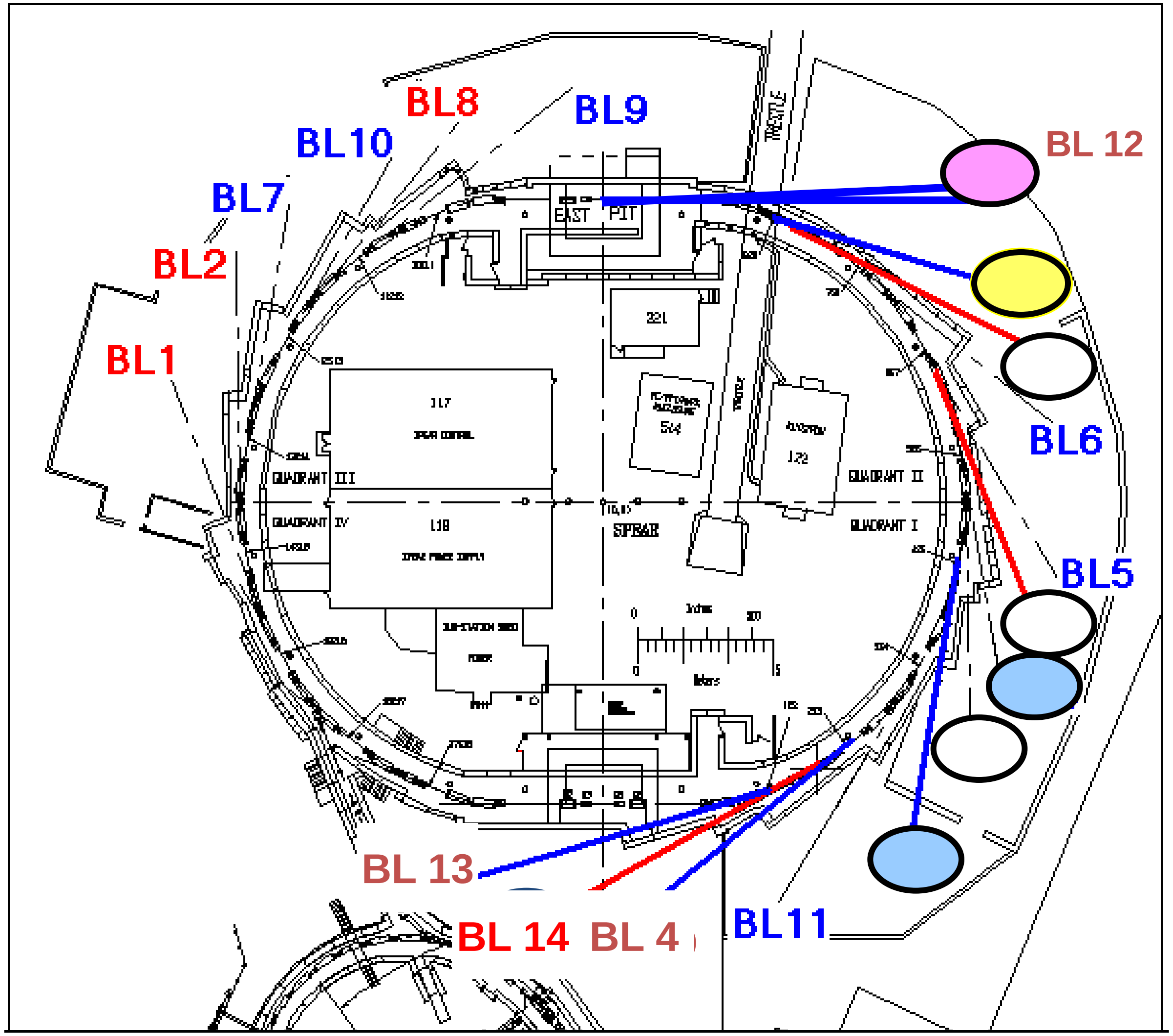
A small storage ring at Louisiana State University





SSRP in 1974; funded by $1.2M from NSF; Main beam line, 5 stations, controls, etc.

SPEAR3: 13 Existing and 7 Future Source points



7 future source points:

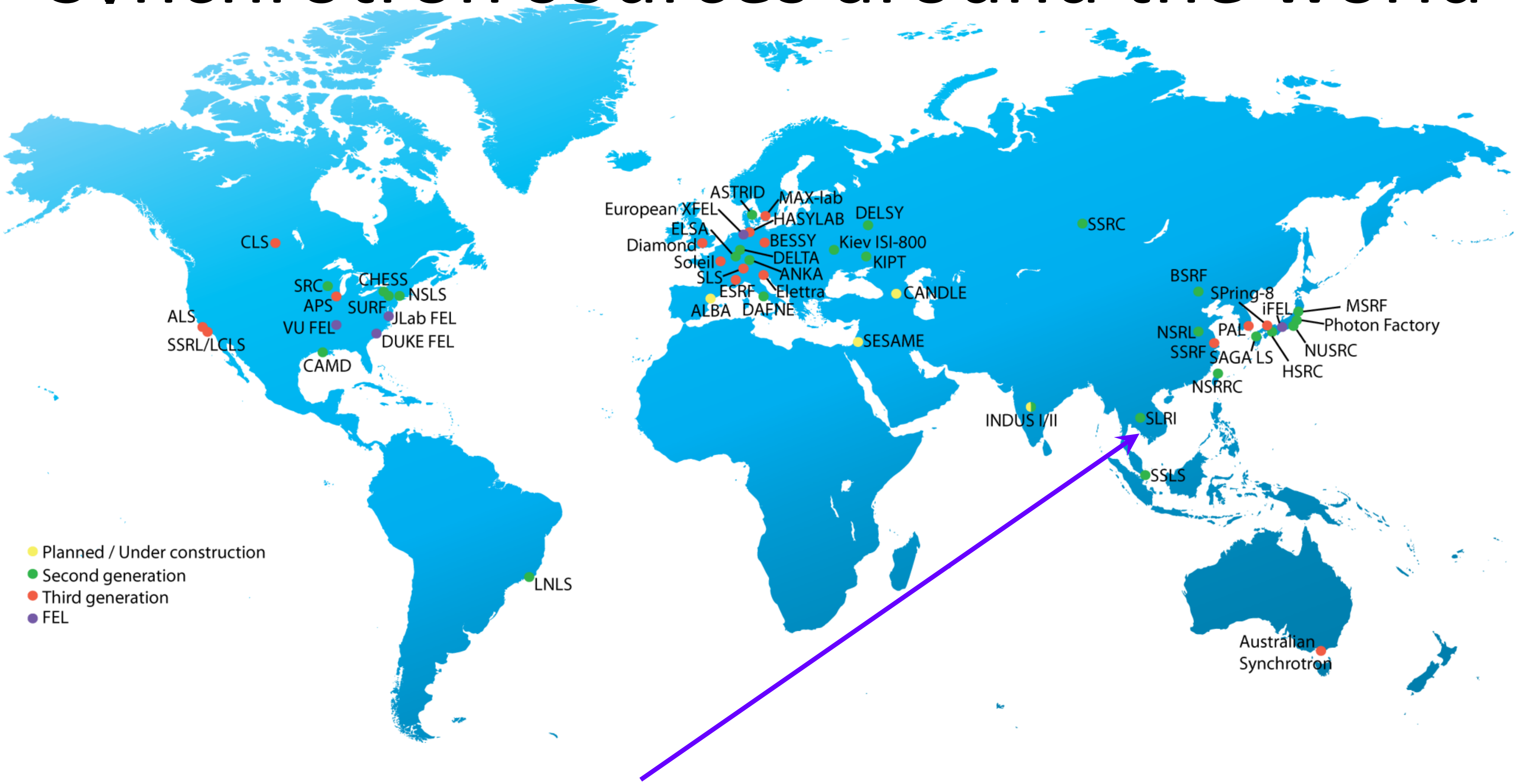
1x 1.5 m straight "East Pit"

1x 3.8m "matching straight"

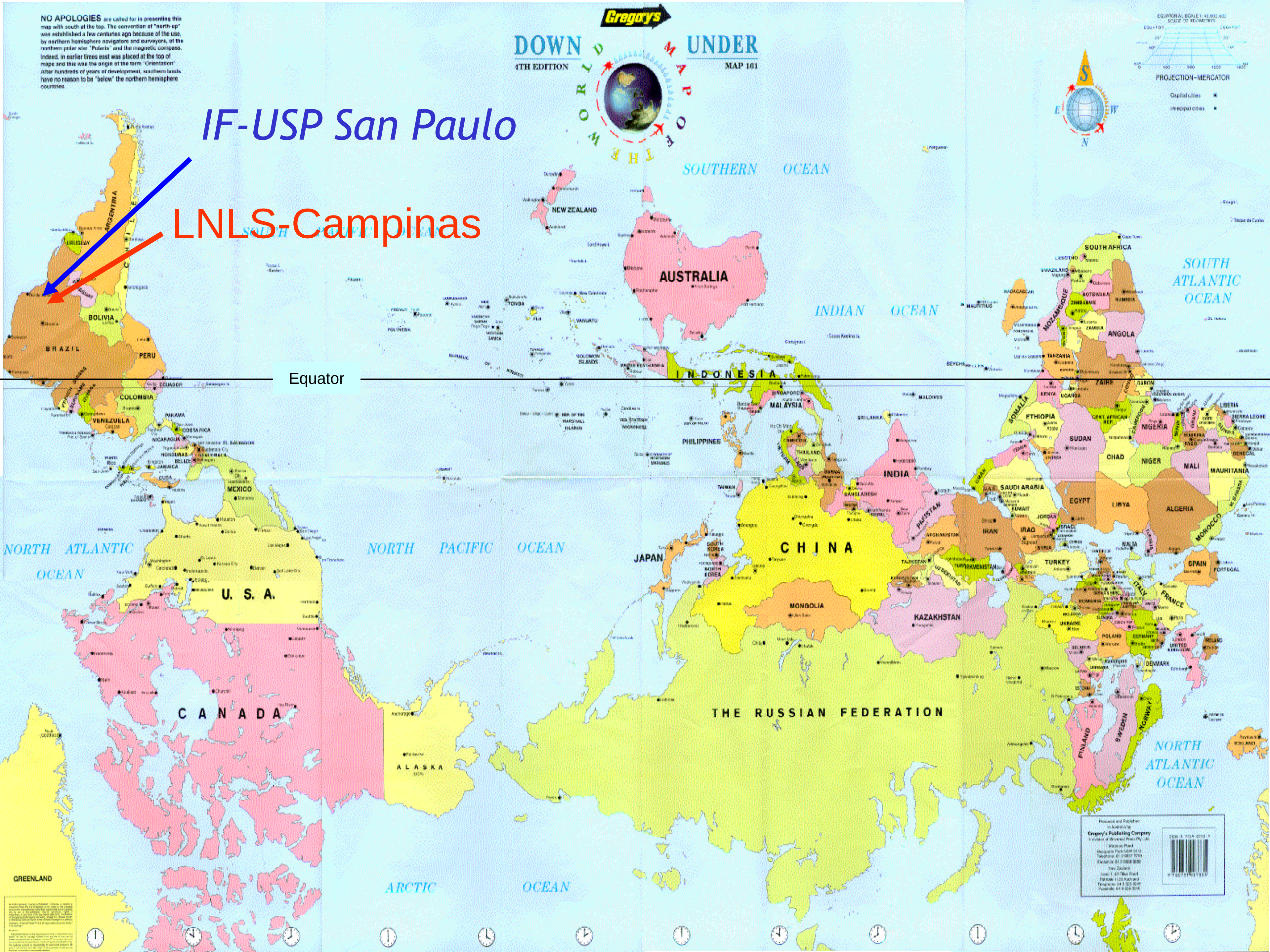
2x 2.3m "standard straight"

3x bend magnets

Synchrotron sources around the world

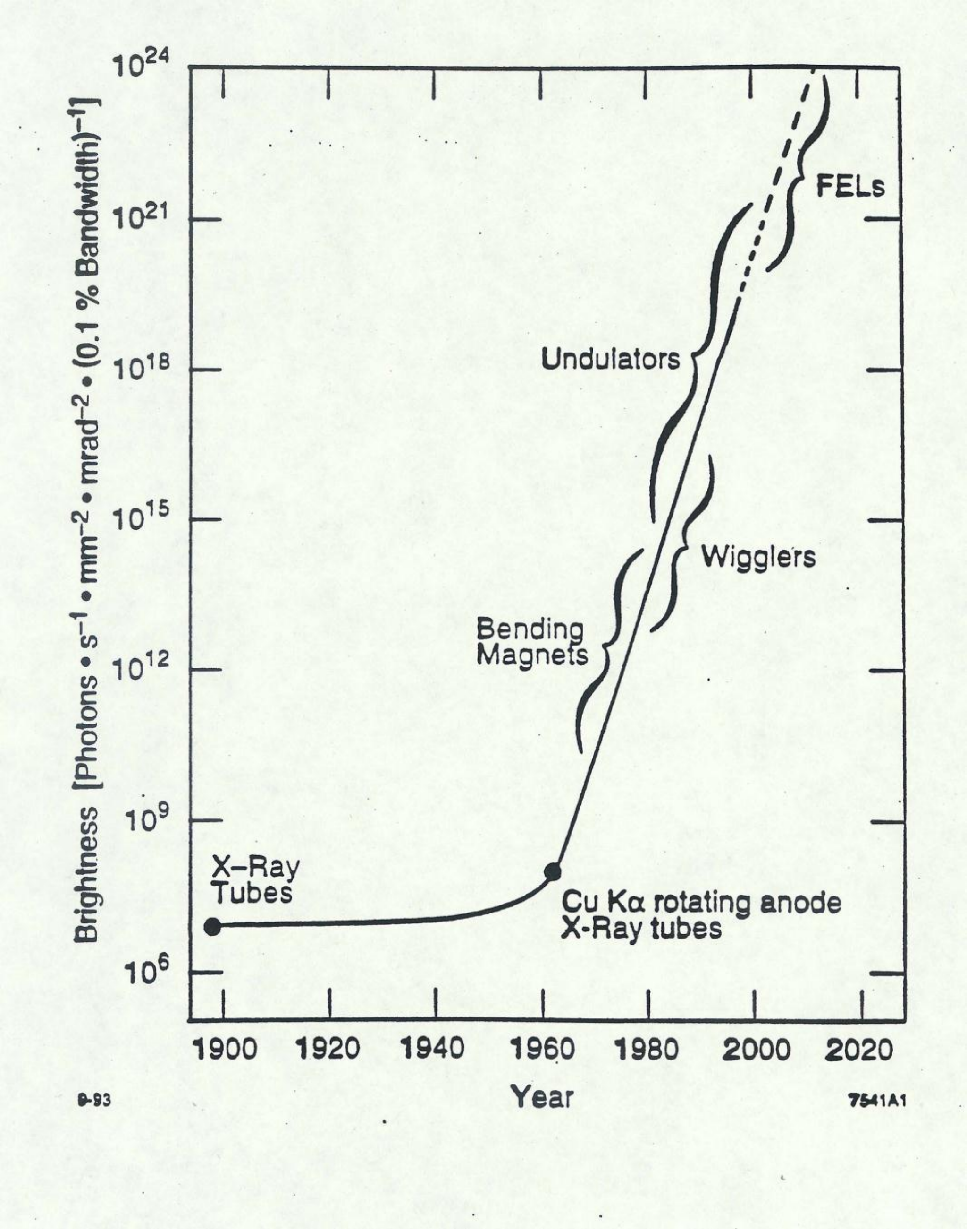


SLRI (Synchrotron Light Research Institute) is located in **Nakhon Ratchasima, Thailand**

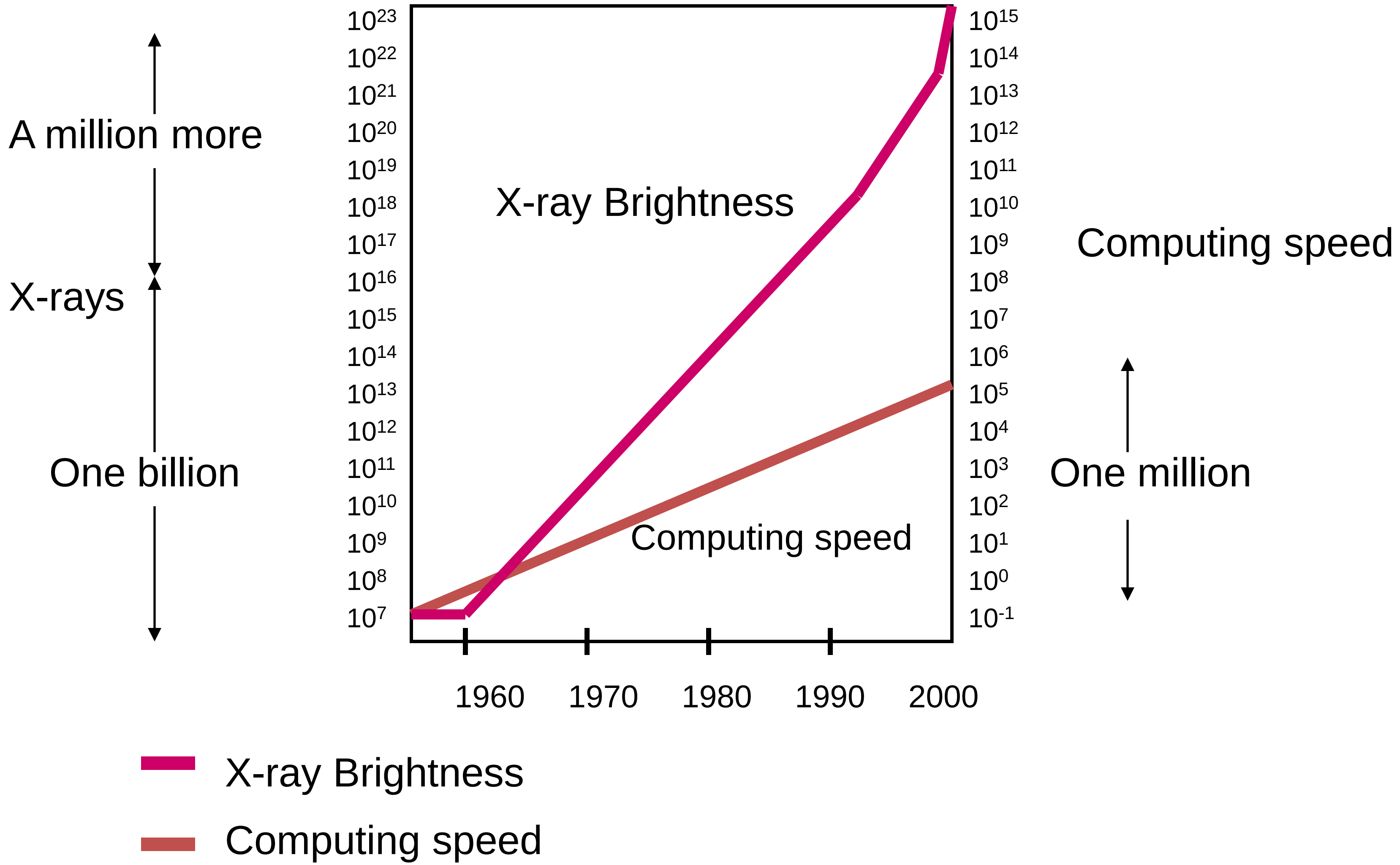


IF-USP San Paulo
LNLS-Campinas
Equator
Gregory's
DOWN UNDER
4TH EDITION
MAP 161
MAP OF THE WORLD
NO APOLOGIES are called for in presenting this map with south at the top. The convention of "north-up" was established a few centuries ago because of the use, by northern hemisphere navigators and surveyors, of the northern polar star "Polaris" and the magnetic compass. Indeed, in earlier times east was placed at the top of maps and this was the origin of the term "Orientation". After hundreds of years of development, southern lands have no reason to be "below" the northern hemisphere countries.
PROJECTION—MERCATOR
SOUTHERN OCEAN
SOUTH PACIFIC OCEAN
INDIAN OCEAN
SOUTH ATLANTIC OCEAN
NORTH PACIFIC OCEAN
NORTH ATLANTIC OCEAN
ARCTIC OCEAN
AUSTRALIA
NEW ZEALAND
INDONESIA
ARGENTINA
CHILE
URUGUAY
BOLIVIA
BRAZIL
PERU
COLOMBIA
VENEZUELA
MEXICO
U. S. A.
CANADA
ALASKA
GREENLAND
JAPAN
CHINA
MONGOLIA
KAZAKHSTAN
INDIA
THE RUSSIAN FEDERATION
SOUTH AFRICA
ANGOLA
ZAIRE
NIGERIA
SUDAN
CHAD
NIGER
MALI
ALGERIA
LIBYA
EGYPT
TURKEY
SPAIN
FRANCE
SWEDEN
NORWAY
FINLAND

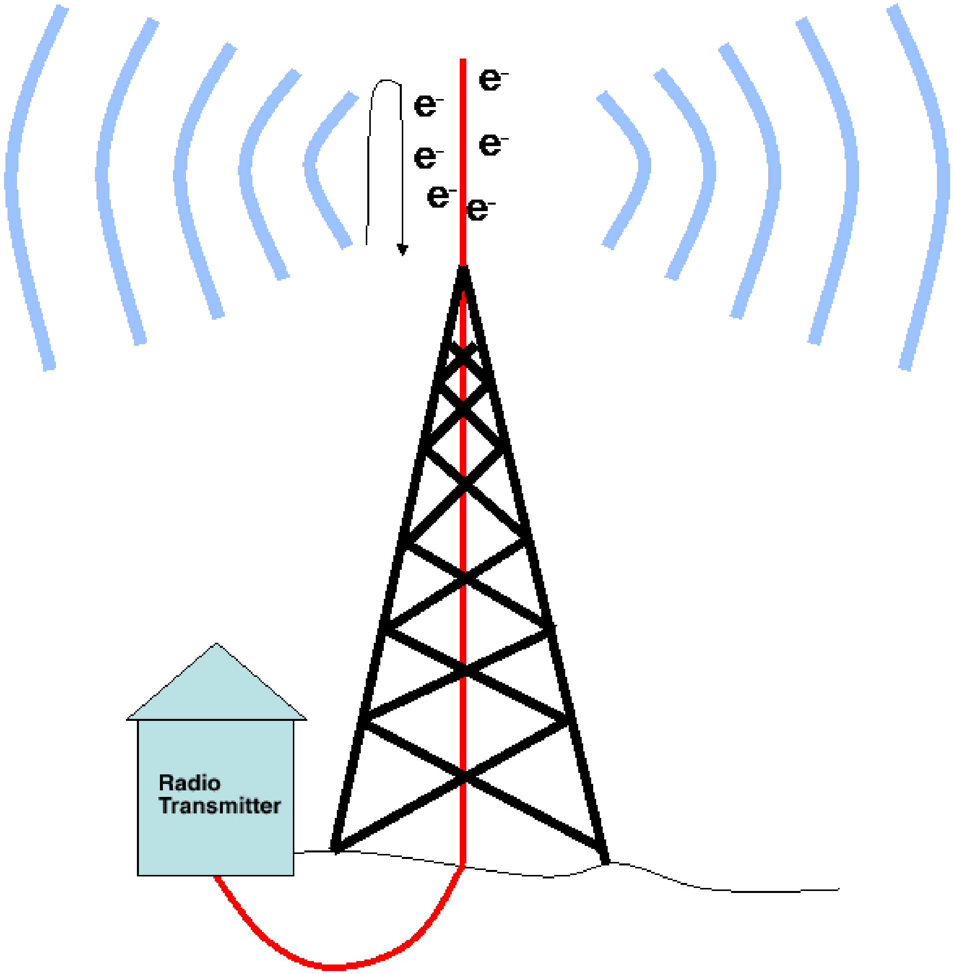
X-Ray Brightness vs. Time



Growth in X-ray Brightness compared to growth in computing speed



Electromagnetic Radiation

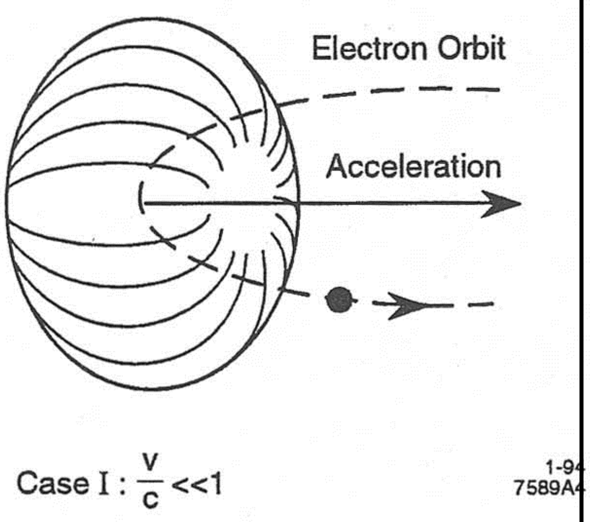


Electrons *accelerating* by running up and down in a radio antenna emit radio waves

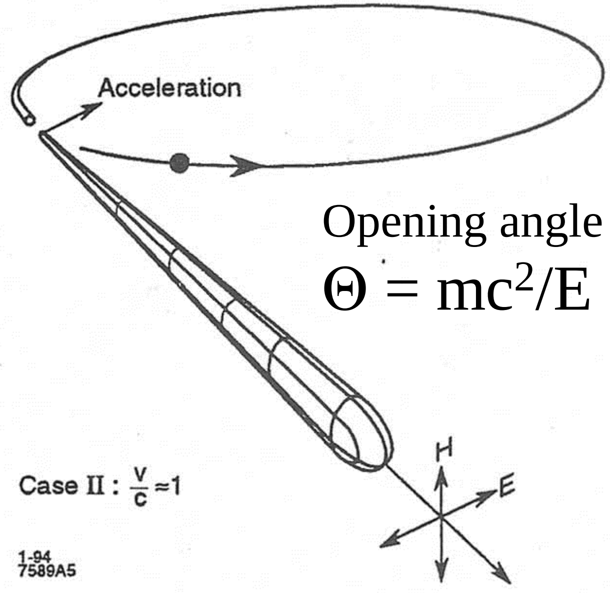
Radio waves are nothing more than Long Wavelength Light

Radiation Fundamentals

- When electrons are accelerated (*e.g*. linear acceleration in a radio transmitter antenna) they emit electromagnetic radiation (*i.e*., radio waves) in a rather non-directional pattern
- Electrons in circular motion are also undergoing acceleration (centripetal)



At low electron velocity (non-relativistic case) the radiation is emitted in a non-directional pattern



Opening angle

$$\Theta = mc^2/E = \gamma^{-1}$$

When the electron velocity approaches the velocity of light, the emission pattern is folded sharply forward. Also the radiated power goes up dramatically

SYNCHROTRON RADIATION

BASIC PROPERTIES

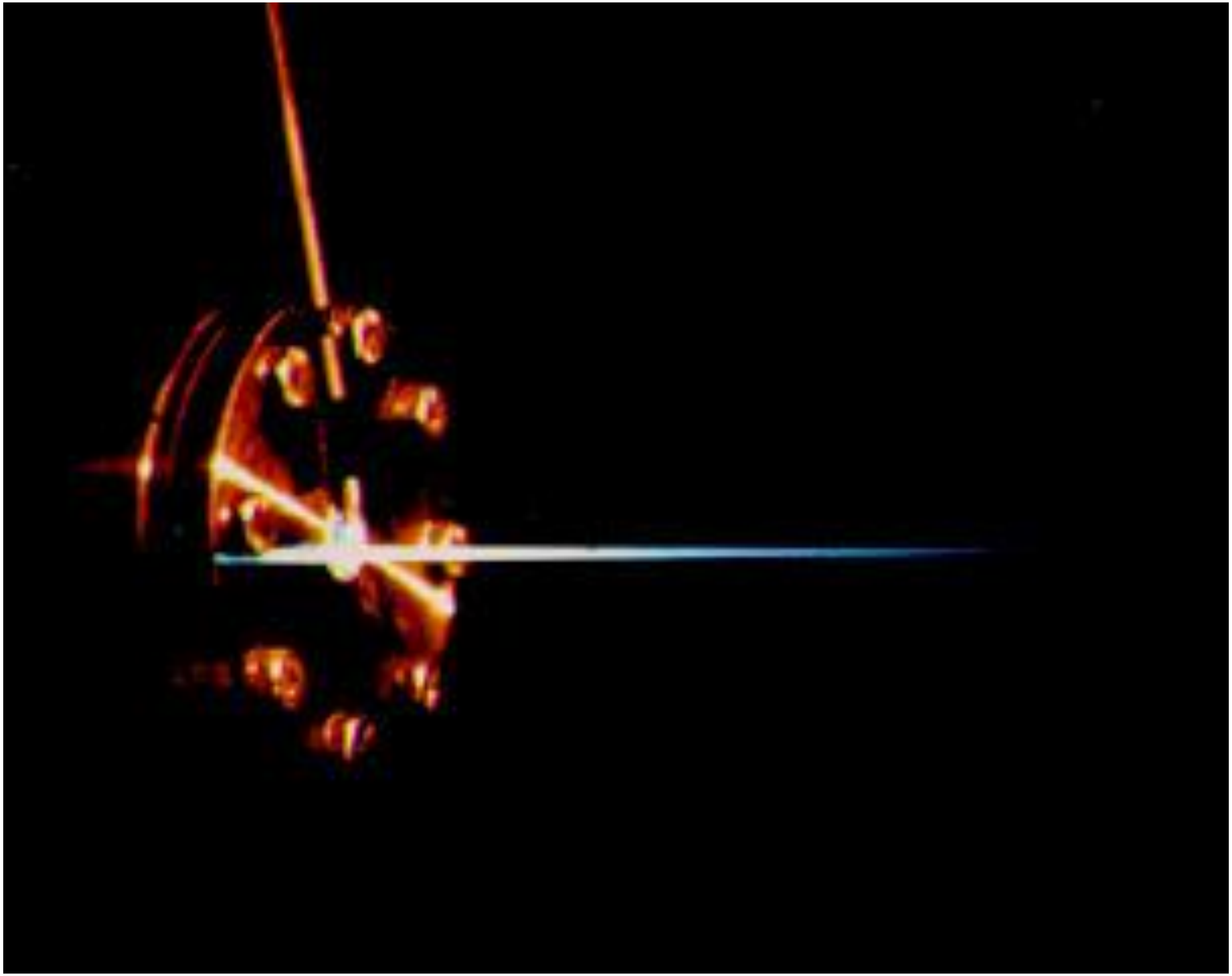
1. **<u>HIGH FLUX,</u> <u>BRIGHTNESS,</u> <u>STABILITY</u>**
2. **BROAD SPECTRAL RANGE - Tunability**
3. **POLARIZATION (linear, elliptical, circular)**
4. **PULSED TIME STRUCTURE (0.01 - 1 nsec)**
5. **SMALL SOURCE SIZE ($\leq$ mm)**
6. **PARTIAL COHERENCE**
7. **HIGH VACUUM ENVIRONMENT**

<u>Flux</u> = $\dfrac{\text{No. of Photons at given } \lambda \text{ within a given } \Delta\lambda/\lambda}{\text{s, mrad } \Theta}$

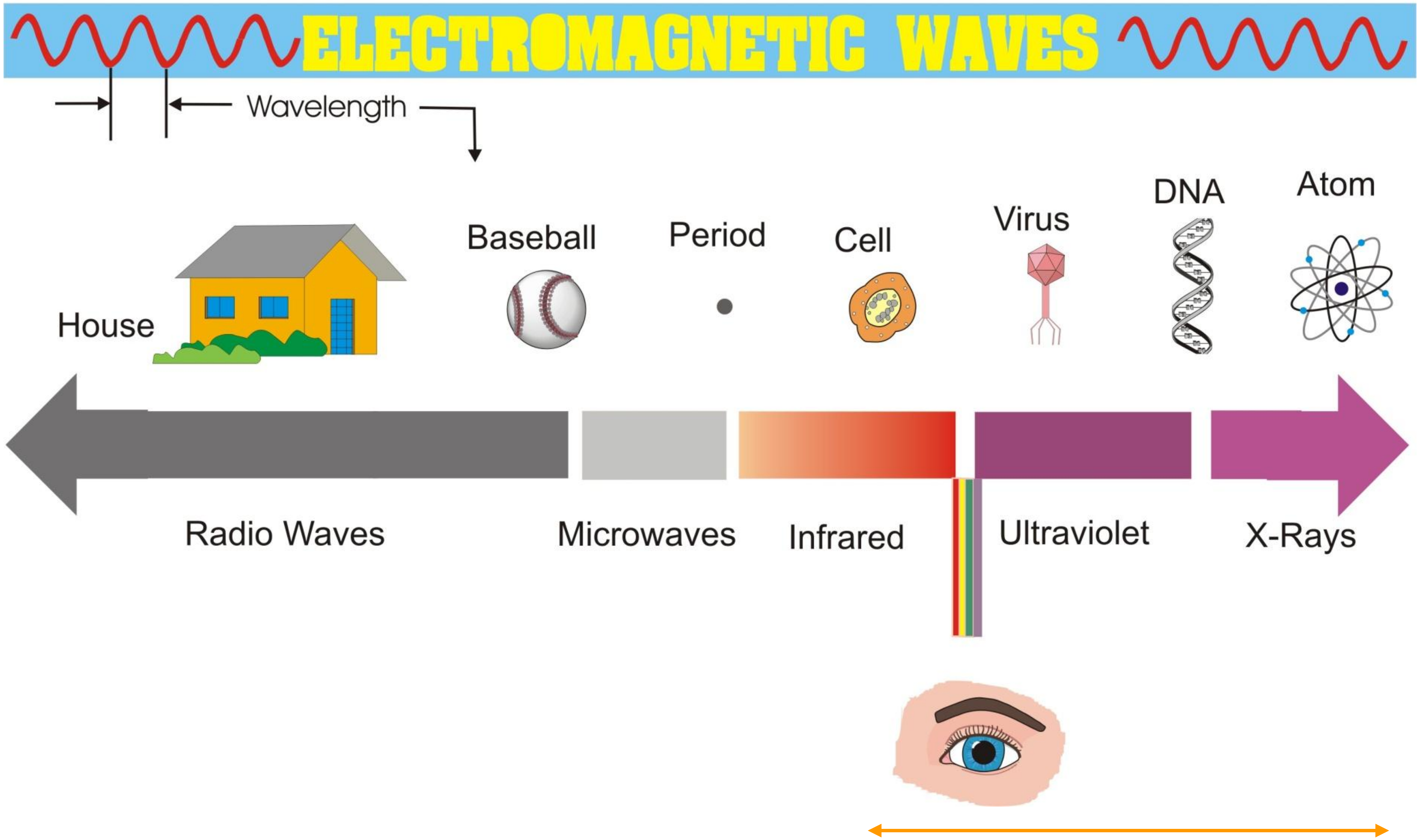
<u>Brightness</u> = $\dfrac{\text{No. of Photons at given } \lambda \text{ within a given } \Delta\lambda/\lambda}{\text{s, mrad } \Theta\text{, mrad } \varphi\text{, mm}^2}$

(a measure of the concentration of the radiation)

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



Electromagnetic Radiation - How It Relates to the World We Know



Synchrotron radiation is used for experiments typically over this region

Approaches to Reducing Emittance in Storage Rings

1. Reduce emission of radiation in bending magnets → lower electron energy and weaker field → ***larger circumference*** (PetraIII) for a given energy. Radiated Energy ~ E^2B^2

2. Reduce length of bending magnet to reduce separation of orbits of electrons with different energies.

⇒ Above considerations lead to designs with small angular deflections in each bending magnet. Quadrupoles between bends refocus the beam before it gets too large.

Emittance $\varepsilon \sim E^2\Theta^3$

E = electron energy

Θ = angular deflection in each bending magnet

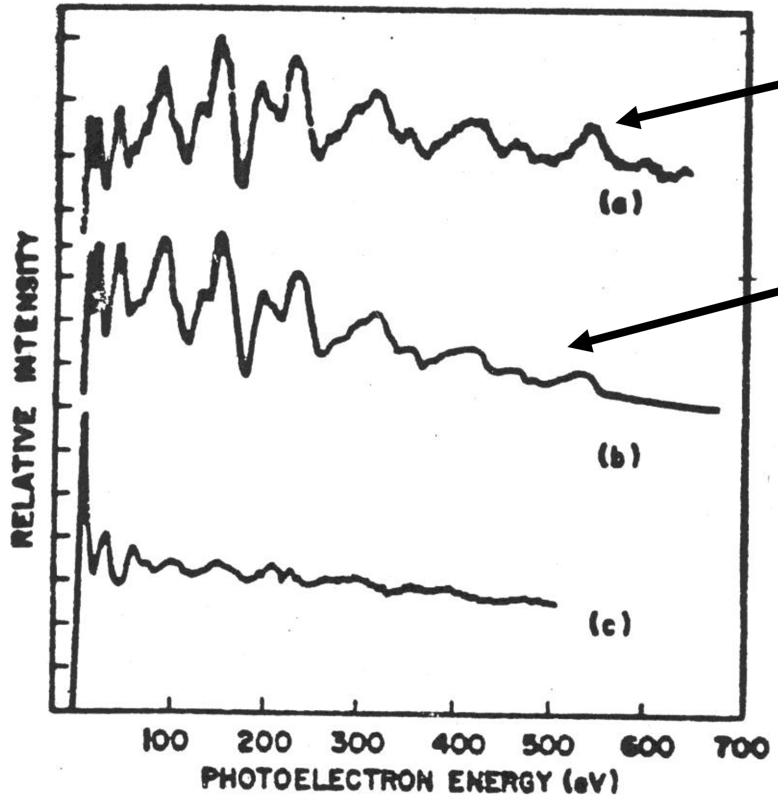
Emittance in rings can also be reduced using strong wiggler magnets, so called ***"Damping Wigglers"***

Importance of low emittance in a light source first emphasized by R. Chasman and K. Green at BNL in 1976.

Large circumference required for low electron beam emittance

- *ESRF, APS, SPring-8;* **0.8-1.5 km**
- *PEP, PETRA, TRISTAN;* **2-3 km**
- *LEP (now LHC);* **27 km**

EXAFS 1974 – Parasitic Operation on a First Generation Ring



~ 10 days using rotating anode X-Ray tube

Cu EXAFS

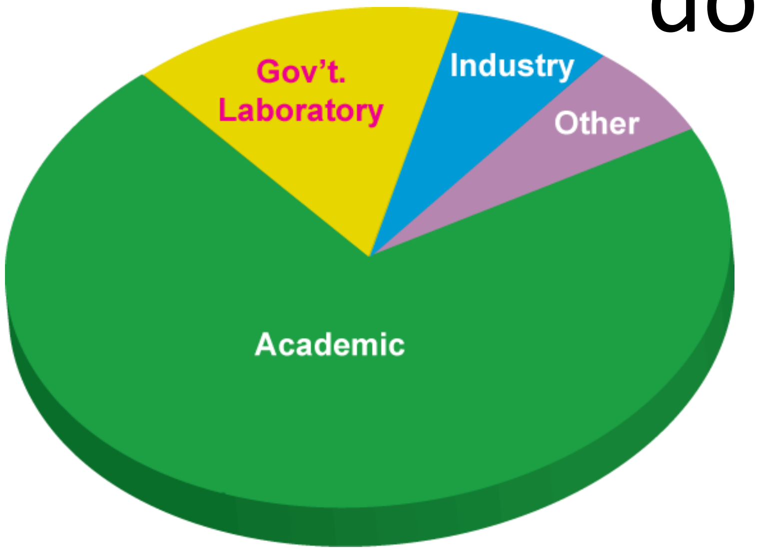
~ 20 minutes using synch. rad. from SPEAR bending magnet

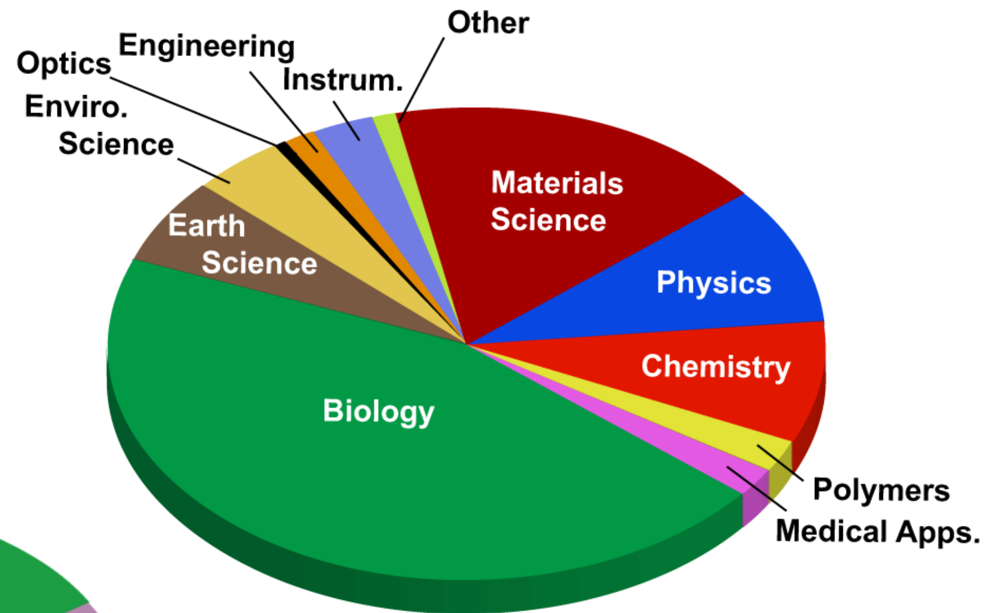
Ratio of intensity; SR/X-Ray Tube ~100,000

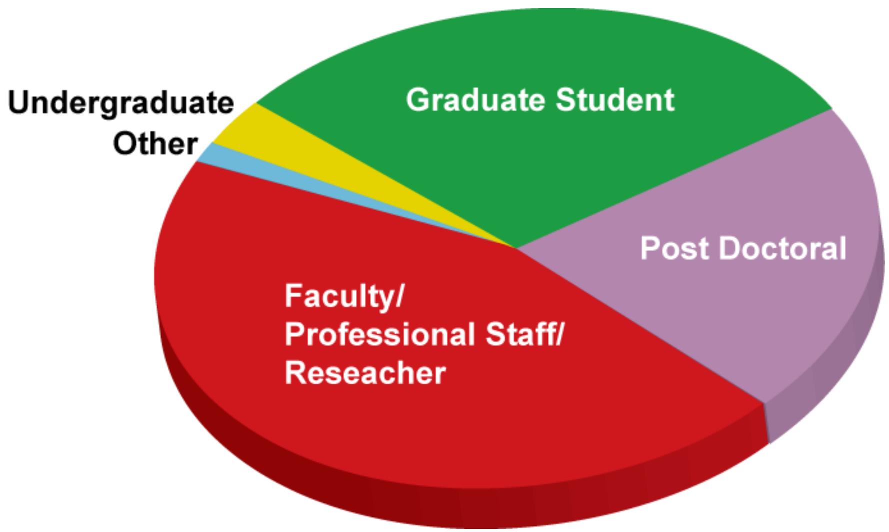
X-ray absorption spectra: (a) Cu spectrum using conventional sources; (b) Cu spectrum using synchrotron radiation; (c) thin superconducting Nb_3Ge film spectrum using synchrotron radiation.

P. Eisenberger, B. Kincaid

APS users – who are they and what do they do?







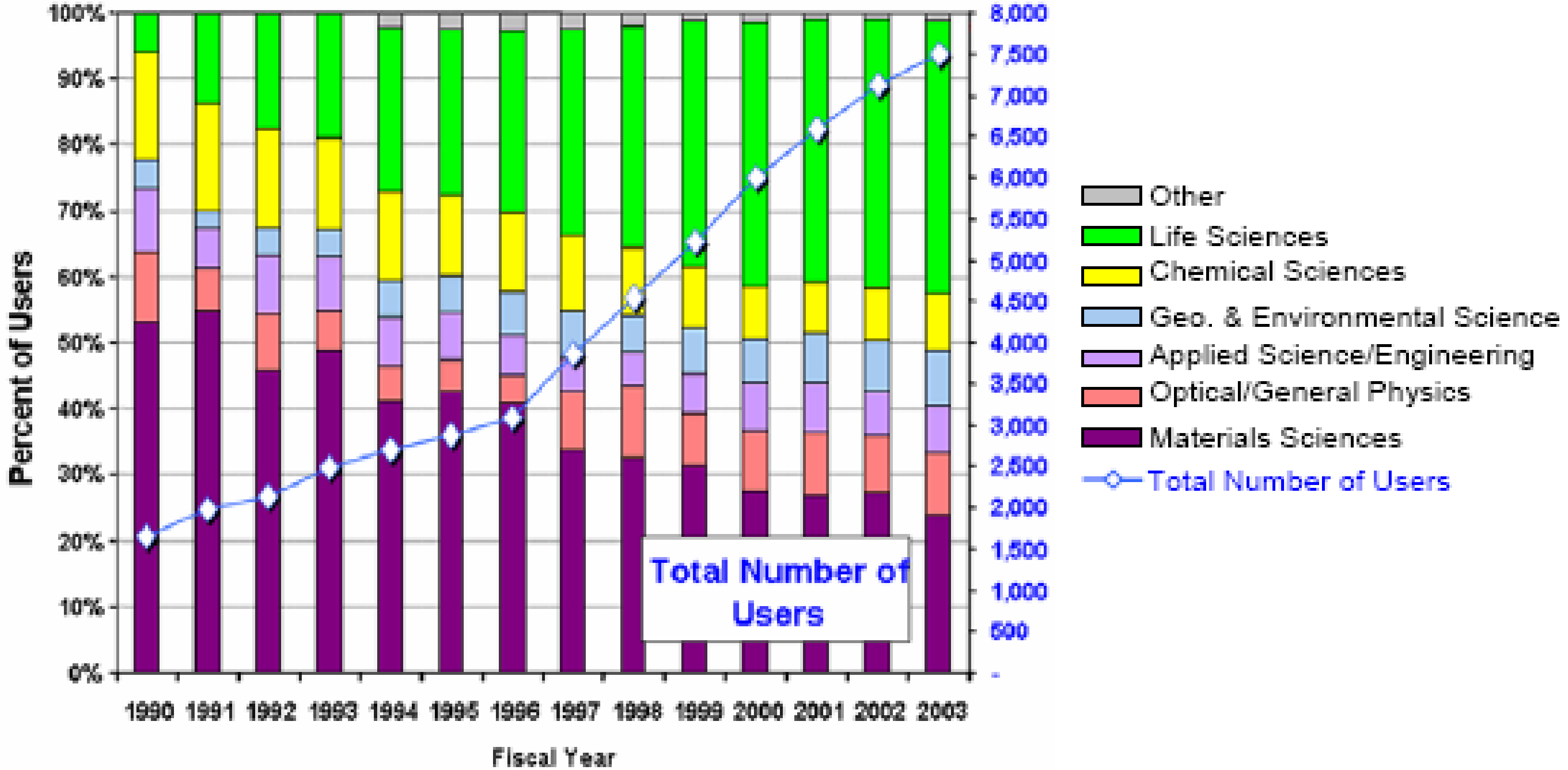


Figure 1.3.1 *User profile by discipline of experiments and total number of users for the four DOE synchrotrons (ALS, APS, NSLS, SSRL). This shows the strong increase in the percentage of users in the life sciences as well as the dramatic growth in total number of users. Current projections are that the total number of users will grow to ~ 11,000 annually in coming years.*

Report of the Synch. Rad. Light Source Working Group of the Basic Energy Sciences Advisory Comm. of the US Department of Energy- Oct. 8-9, 1998

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."

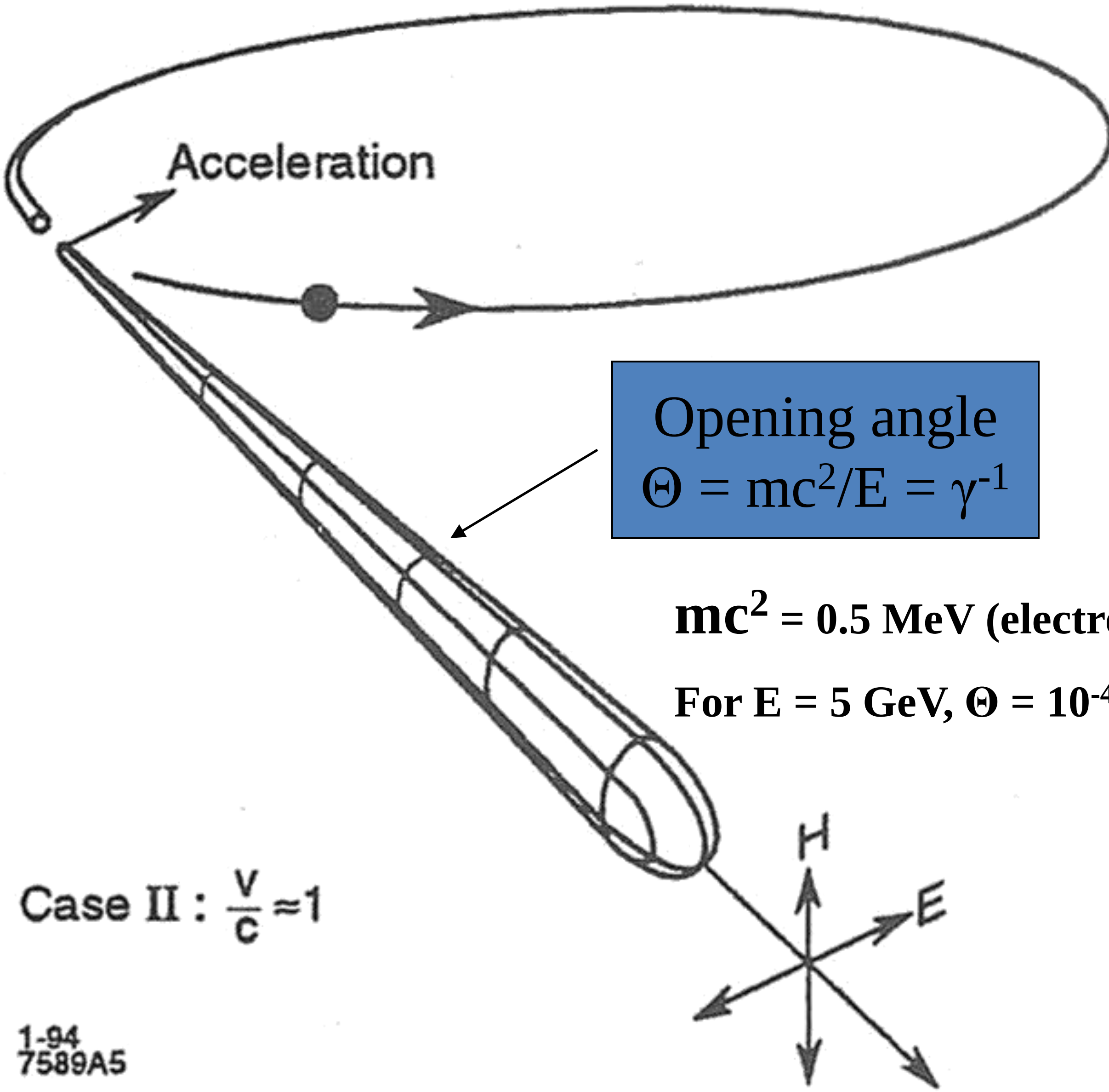
Sources of Synchrotron Radiation

- Bending magnets
- Wigglers
- Undulators

INSERTION DEVICES (WIGGLERS & UNDULATORS)

Extending performance of photon sources beyond bending magnets

- ***Higher flux***
- ***Higher brightness***
- ***Higher coherence***
- ***Flexible polarization***
- ***Extended spectral range (e.g. SC wigglers)***
- ***Quasi-monochromatic beams (undulators)***

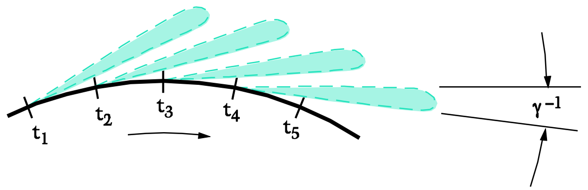


Opening angle
$\Theta = mc^2/E = \gamma^{-1}$

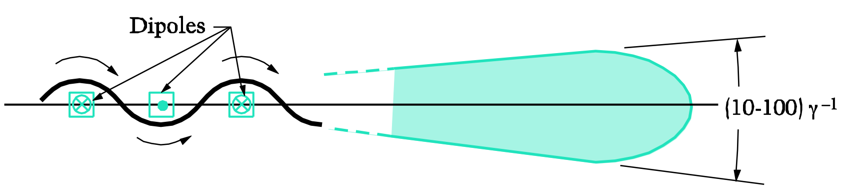
mc^2 = 0.5 MeV (electron rest mass)

For E = 5 GeV, $\Theta = 10^{-4}$ radians = .006^{o}

Bending Magnets & Insertion Devices on Storage Rings



bending magnet - a "sweeping searchlight"



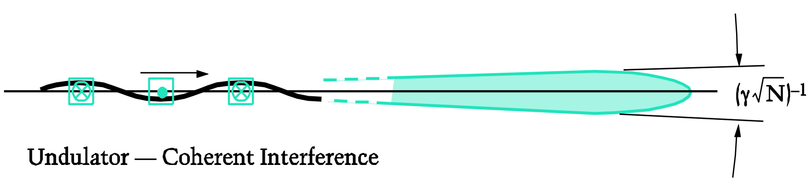
wiggler - incoherent superposition

Continuous spectrum characterized by ε_c = critical energy

ε_c(keV) = 0.665 B(T)E^2(GeV)

eg: for B = 2T E = 3GeV ε_c = 12keV

(bending magnet fields are usually lower ~ 1 – 1.5T)



undulator - coherent interference

$\gamma = E/mc^2 = 6{,}000$ @ 3 GeV

Quasi-monochromatic spectrum with peaks at lower energy than a wiggler

$$\lambda_1 = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2}\right) \sim \frac{\lambda_u}{\gamma^2} \quad \text{(fundamental)}$$

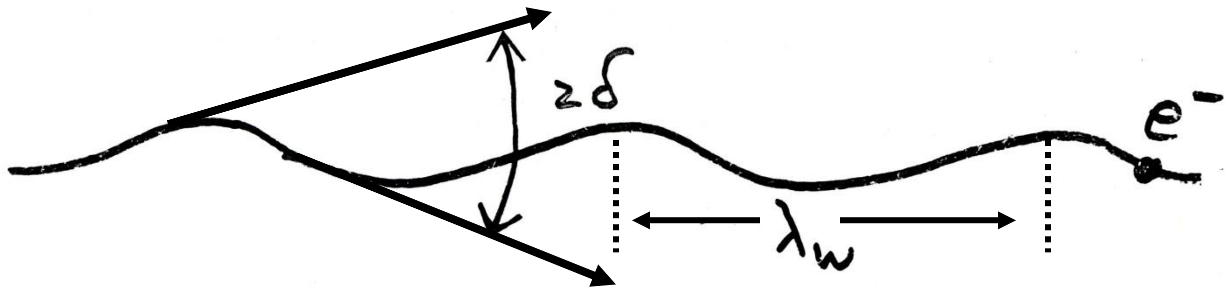
+ harmonics at higher energy

$$\varepsilon_1 \text{ (keV)} = \frac{0.95\, E^2 \text{ (GeV)}}{\lambda_u^{\text{(cm)}} \left(1 + \frac{K^2}{2}\right)}$$

$K = \gamma\theta$ θ=angular deflection in each pole

Wigglers & Undulators

$$B_0 \cos\left[\frac{2\pi}{\lambda_w} z\right] \qquad\qquad y_0 \cos\left[\frac{2\pi}{\lambda_w} z\right]$$

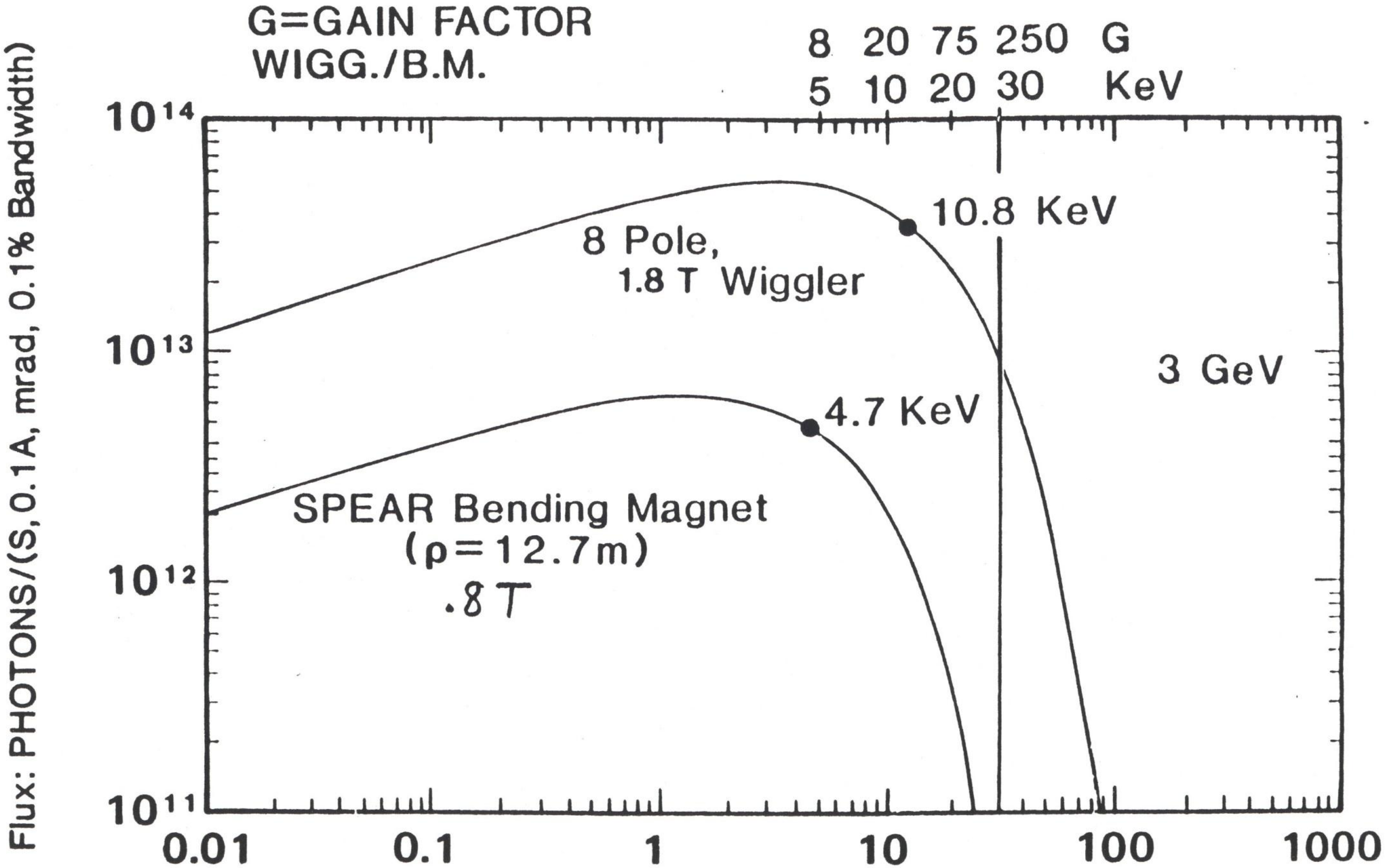


$$K = \gamma\delta = .934\, B_0(T)\, \lambda_w(cm) \qquad \gamma = \frac{E}{mc^2}$$

Define 2 regimes

a) $\underline{K \lesssim 1}$; $\delta \lesssim \gamma^{-1}$ (Undulator)

b) $\underline{K \gg 1}$; $\delta \gg \gamma^{-1}$ (Wiggler)



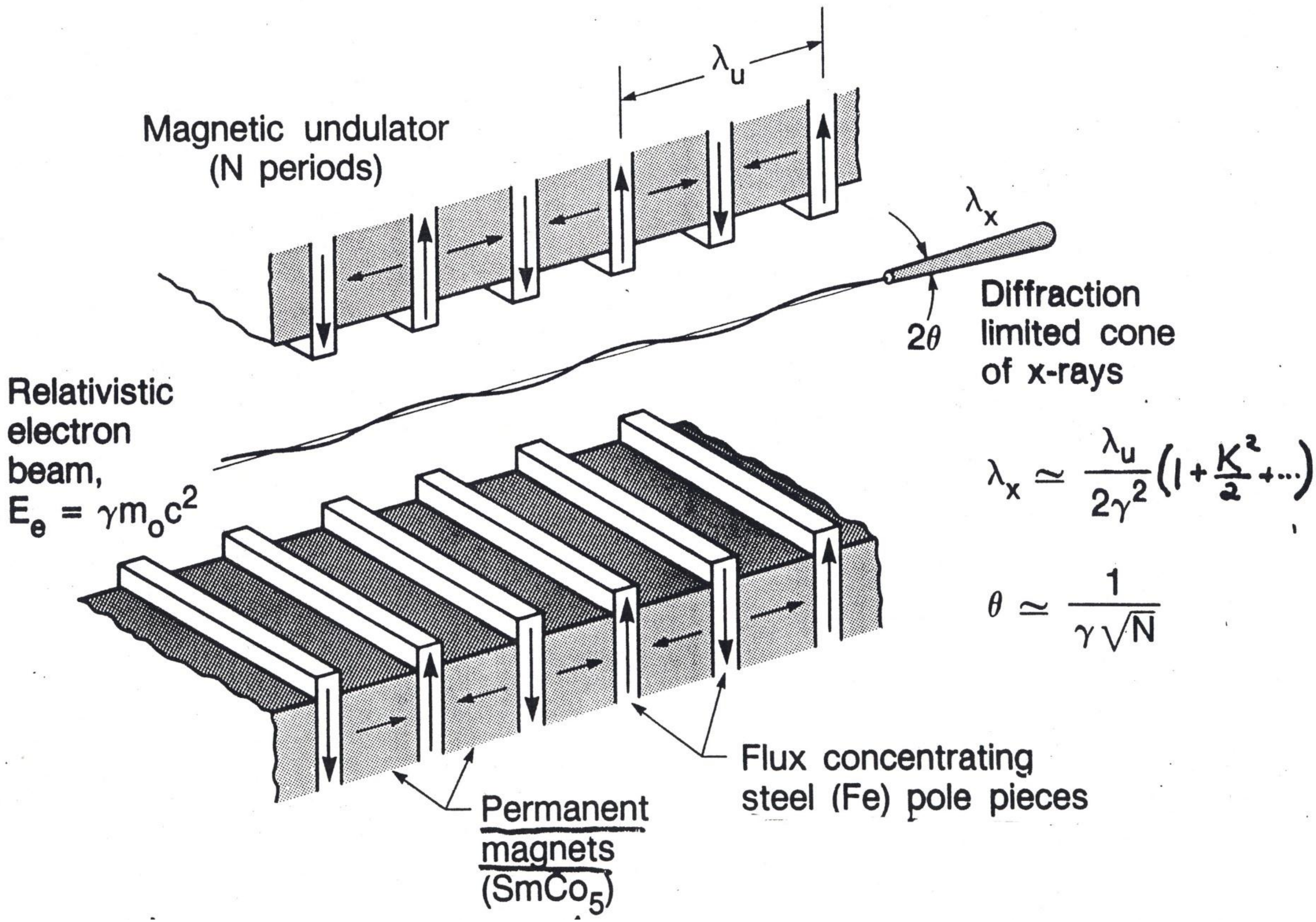
PHOTON ENERGY (KeV)

ε_c(keV) = 0.665 B(T)E^2(GeV)

for B = 0.8T E = 3GeV ε_c = 4.7keV

for B = 1.8T E = 3GeV ε_c = 10.8 keV

Coherent X-Rays, Tuneable Across A Broad Spectral Region, are Generated.



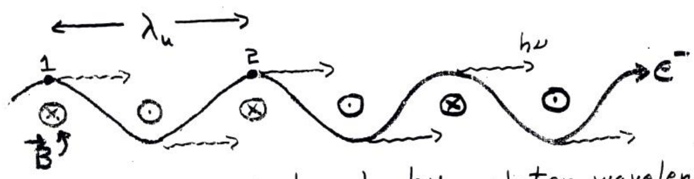
Hybrid Design; K. Halbach & N. Vinokurov

Undulator Radiation

Interference effects in the radiation by an electron in a periodic field

Simple case to illustrate basis Physics

Weak field approximation & radiation on axis only



λ_u = undulator period $\quad \lambda = \frac{h\nu}{c}$ = photon wavelength

Electron takes longer than photon to go from 1-2 because electron travels at BC rather than C.

$$t_{e^-} - t_{h\nu} = \Delta t = \lambda / c \quad \text{for } \underline{\text{constructive interference}}$$

$$t_{e^-} - t_{h\nu} = \frac{\lambda_u}{\beta c} - \frac{\lambda_u}{c} = \frac{\lambda_u}{c}\left[\frac{1-\beta}{\beta}\right] \approx \frac{\lambda_u}{c}\left[\frac{1}{2\gamma^2}\right] = \frac{\lambda}{c}$$

$$\boxed{\lambda = \frac{\lambda_u}{2\gamma^2}}$$

All the radiation occurs at this wavelength in the weak field approximation

$$\gamma = \frac{1}{(1-\beta^2)^{1/2}} = E/mc^2$$

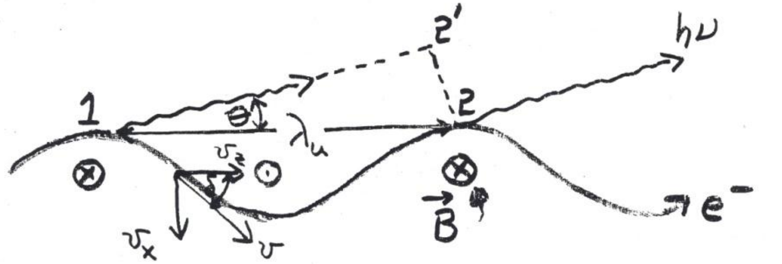
If we take into account the extra distance traveled by the electron & also the angle of emission of the radiation (0) we get

$$\lambda = \frac{\lambda_u}{2\gamma^2}\left[1 + \frac{K^2}{2} + \gamma^2\theta^2\right] \qquad K = .934\, B_{max}(T)\, \lambda_u(cm)$$

Correlation between photon wavelength and emission angle

Undulator Radiation

More realistic treatment: Take into account sinusoidal electron motion & off axis radiation



$$v^2 = v_x^2 + v_z^2 \qquad v_x \ll v_z \approx v \qquad \delta \ll 1 \qquad \theta \ll 1$$

Electron flight time from 1 to 2: $t_{e^-} = \lambda_u / \langle v_z \rangle$

Photon flight time from 1 to 2: $t_{h\nu} = \dfrac{\lambda_u \cos\theta}{c} \approx \dfrac{\lambda_u}{c}\left[1 - \dfrac{\theta^2}{2}\right]$

$t_{e^-} - t_{h\nu} = \Delta t = \lambda / c$ for constructive interference

$$\Delta t = \frac{\lambda_u}{\langle v_z \rangle} - \frac{\lambda_u}{c}\left(1 - \frac{\theta^2}{2}\right) = \frac{\lambda}{c}$$

$$\lambda = \lambda_u\left[\frac{c}{\langle v_z \rangle} - 1 + \frac{\theta^2}{2}\right] \qquad \langle v_z \rangle = \left[v^2 - \langle v_x^2 \rangle\right]^{1/2} \approx v\left[1 - \frac{\langle v_x^2 \rangle}{2v^2}\right]$$

$$\lambda = \lambda_u\left[\frac{c - v\left(1 - \frac{\langle v_x^2 \rangle}{2v^2}\right)}{v} + \frac{\theta^2}{2}\right] = \lambda_u\left[\frac{1-\beta}{\beta} + \frac{\langle v_x^2 \rangle}{2v^2} + \frac{\theta^2}{2}\right]$$

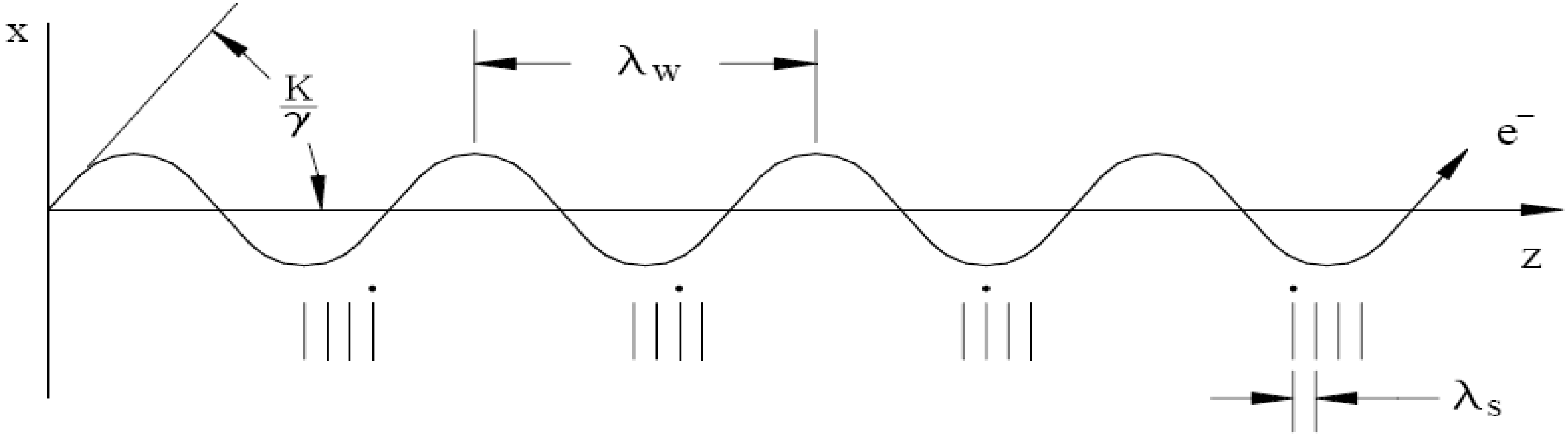
$$\frac{1-\beta}{\beta} = \frac{1}{2\gamma^2}; \quad \frac{\langle v_x^2 \rangle}{v^2} = \frac{v_{x\,max}^2}{2v^2} = \frac{\delta^2}{2}$$

$$\lambda = \lambda_u\left[\frac{1}{2\gamma^2} + \frac{\delta^2}{4} + \frac{\theta^2}{2}\right] = \frac{\lambda_u}{2\gamma^2}\left[1 + \frac{\gamma^2\delta^2}{2} + \gamma^2\theta^2\right] = \frac{\lambda_u}{2\gamma^2}\left[1 + \frac{K^2}{2} + \gamma^2\theta^2\right]$$

Correlation between wavelength & viewing angle

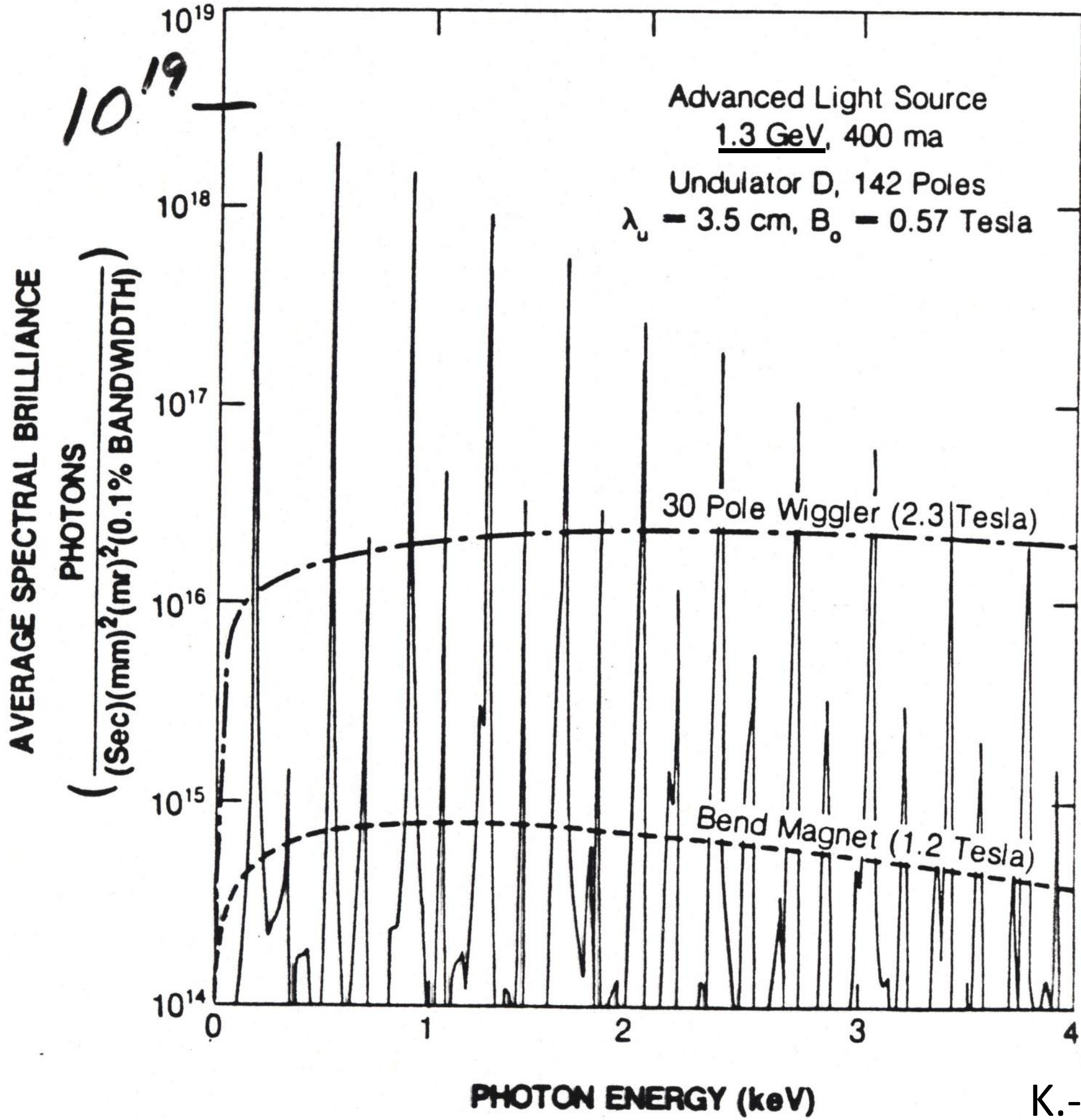
$K = \gamma\delta = .934\, B(T)\, \lambda_u(cm) \lesssim$ 1 or 2

Resonance Condition



Resonance: In the time it takes an electron to travel the length of one undulator period, the light wavefront travels one *light wavelength further.*

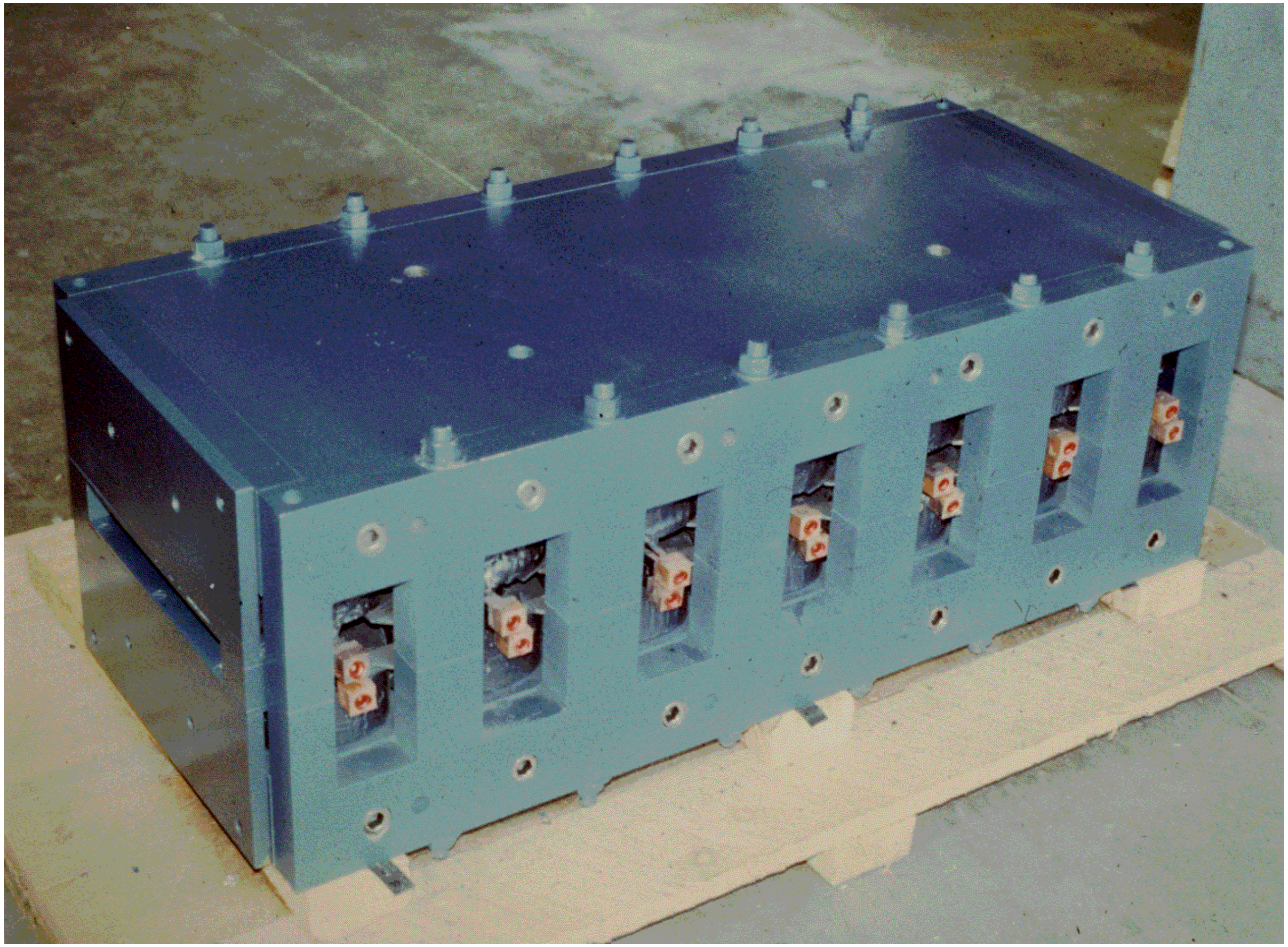
This gives constructive interference, enhances the probability of emission of light at that wavelength.



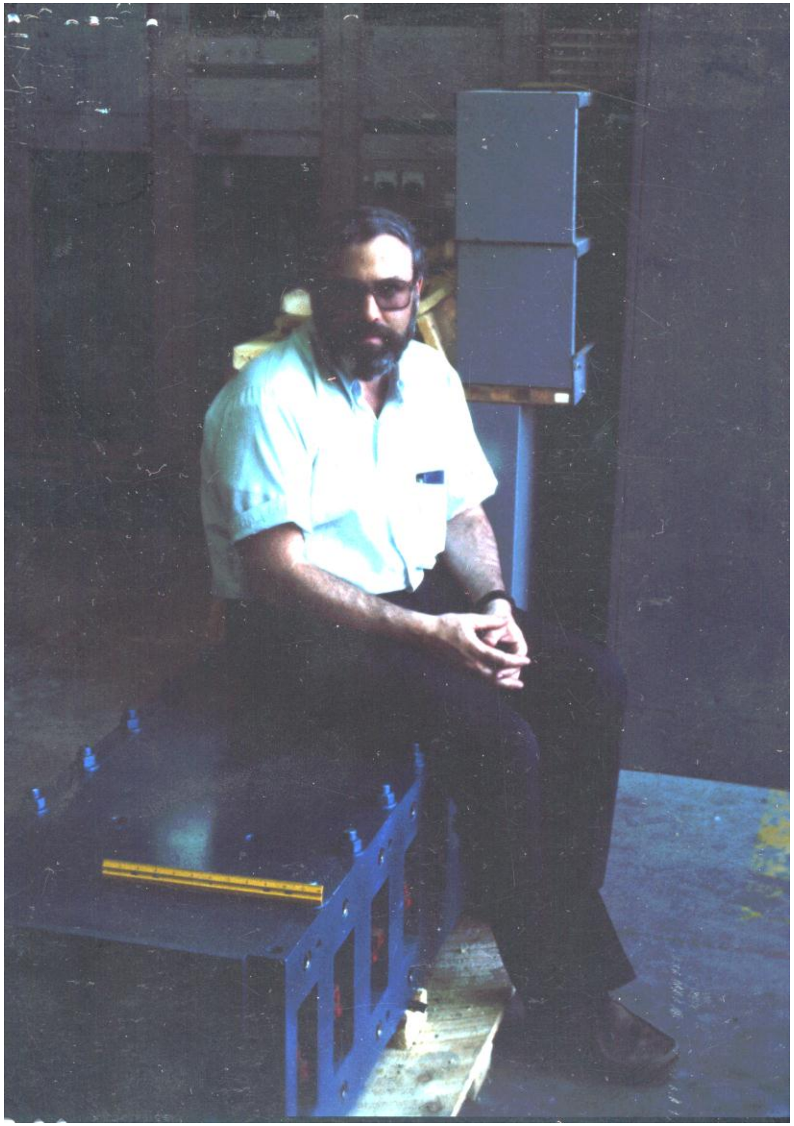
10^19
10^19
10^18
10^17
10^16
10^15
10^14
Advanced Light Source
1.3 GeV, 400 ma
Undulator D, 142 Poles
λu = 3.5 cm, Bo = 0.57 Tesla
30 Pole Wiggler (2.3 Tesla)
Bend Magnet (1.2 Tesla)
AVERAGE SPECTRAL BRILLIANCE
(PHOTONS / (Sec)(mm)^2(mr)^2(0.1% BANDWIDTH))
0
1
2
3
4
PHOTON ENERGY (keV)

K.-J. Kim

SSRL 6 pole Electromagnet Wiggler 1978

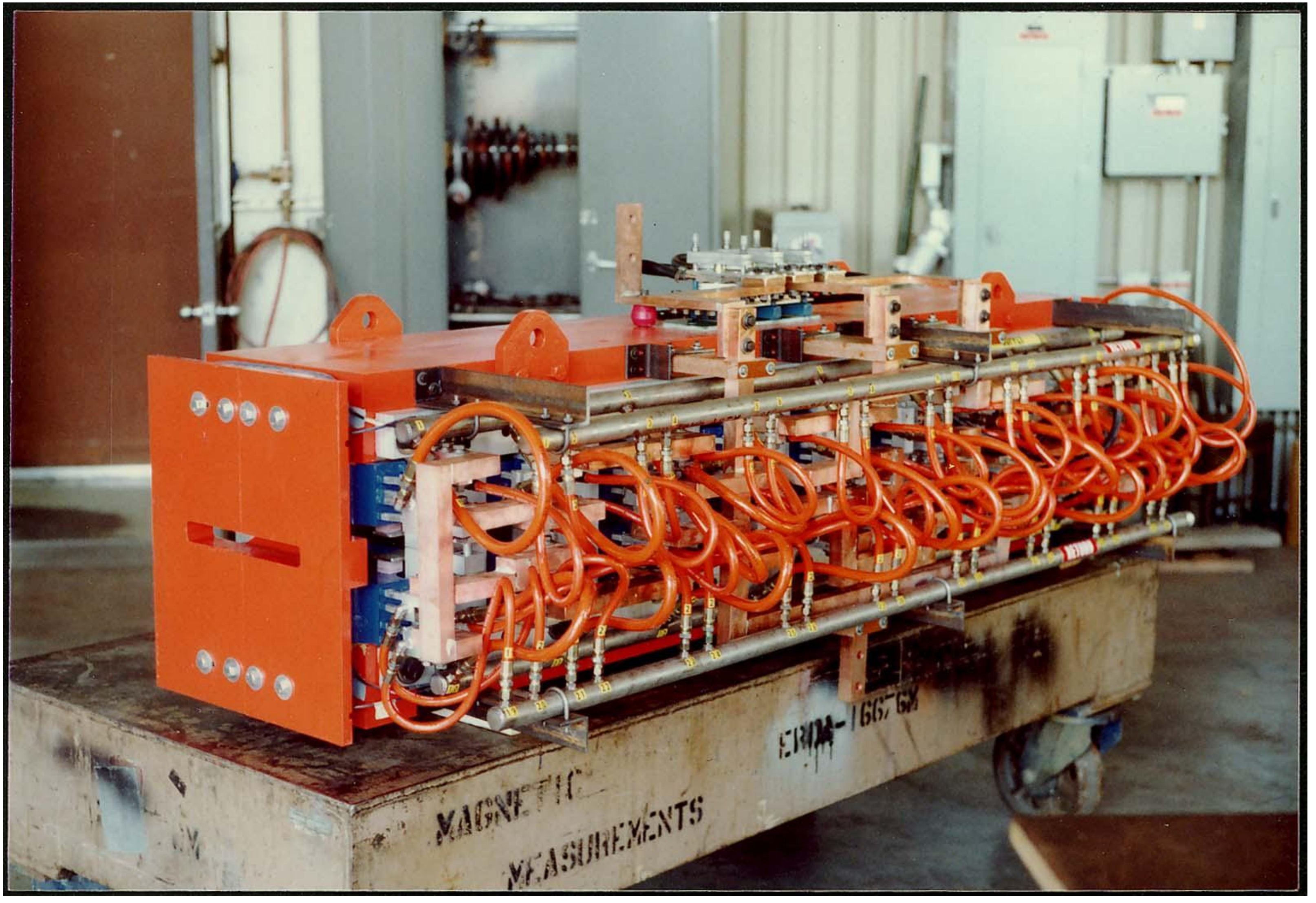


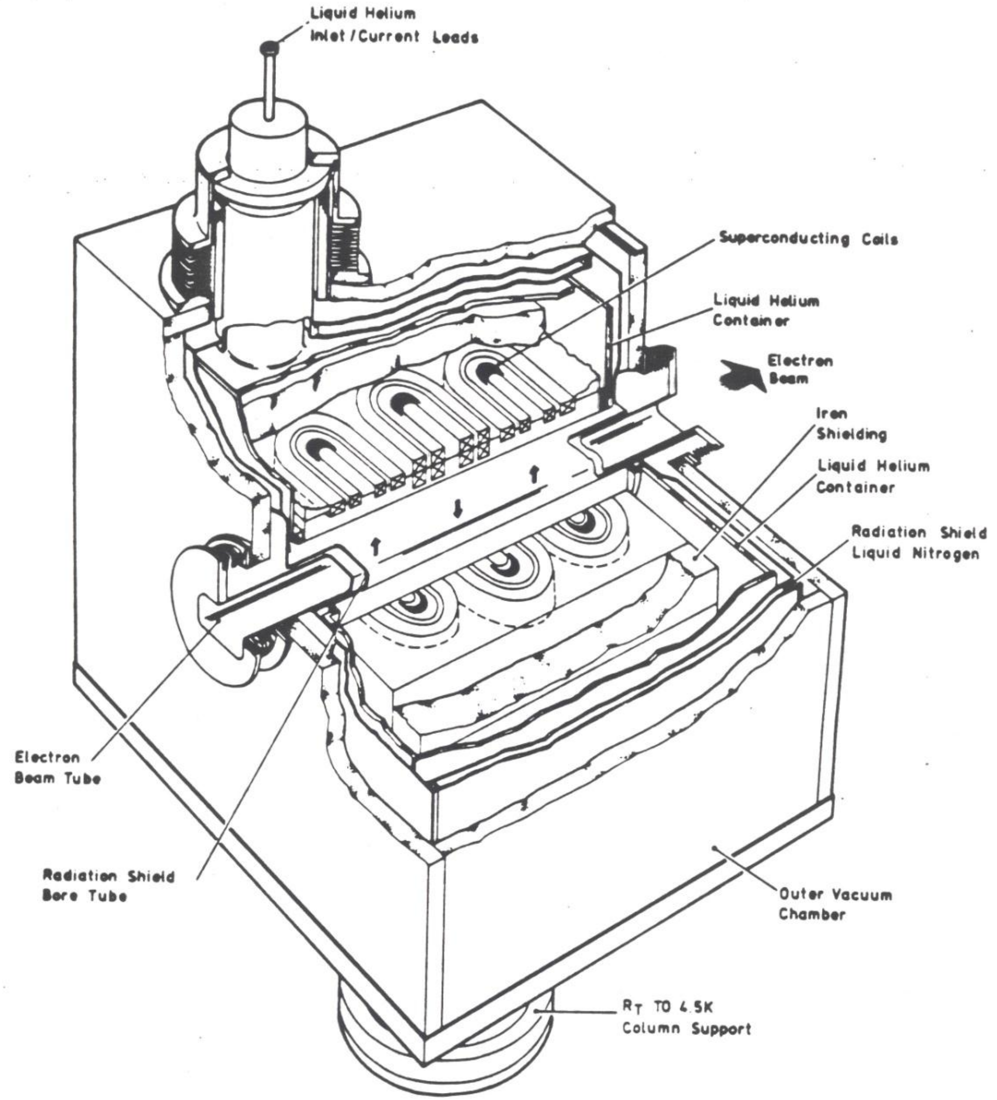
First SSRL Wiggler - 1978



Display of 1st Wiggler at SSRL/SLAC

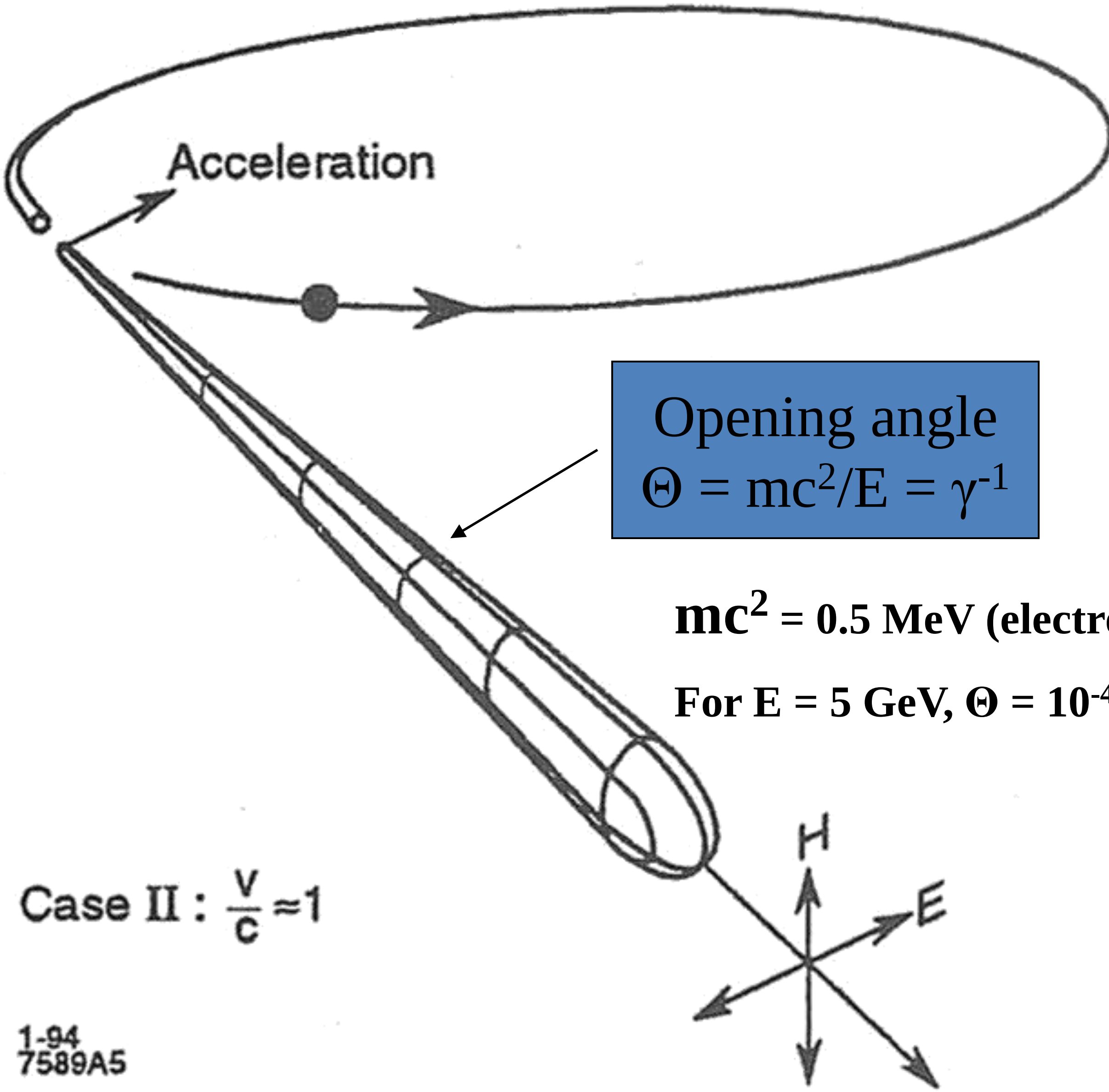
SSRL 9-Pole Electromagnet Wiggler - 1980





Daresbury SRS Superconducting Wiggler – Wavelength Shifter

Wide fan – Served 7 experimental stations

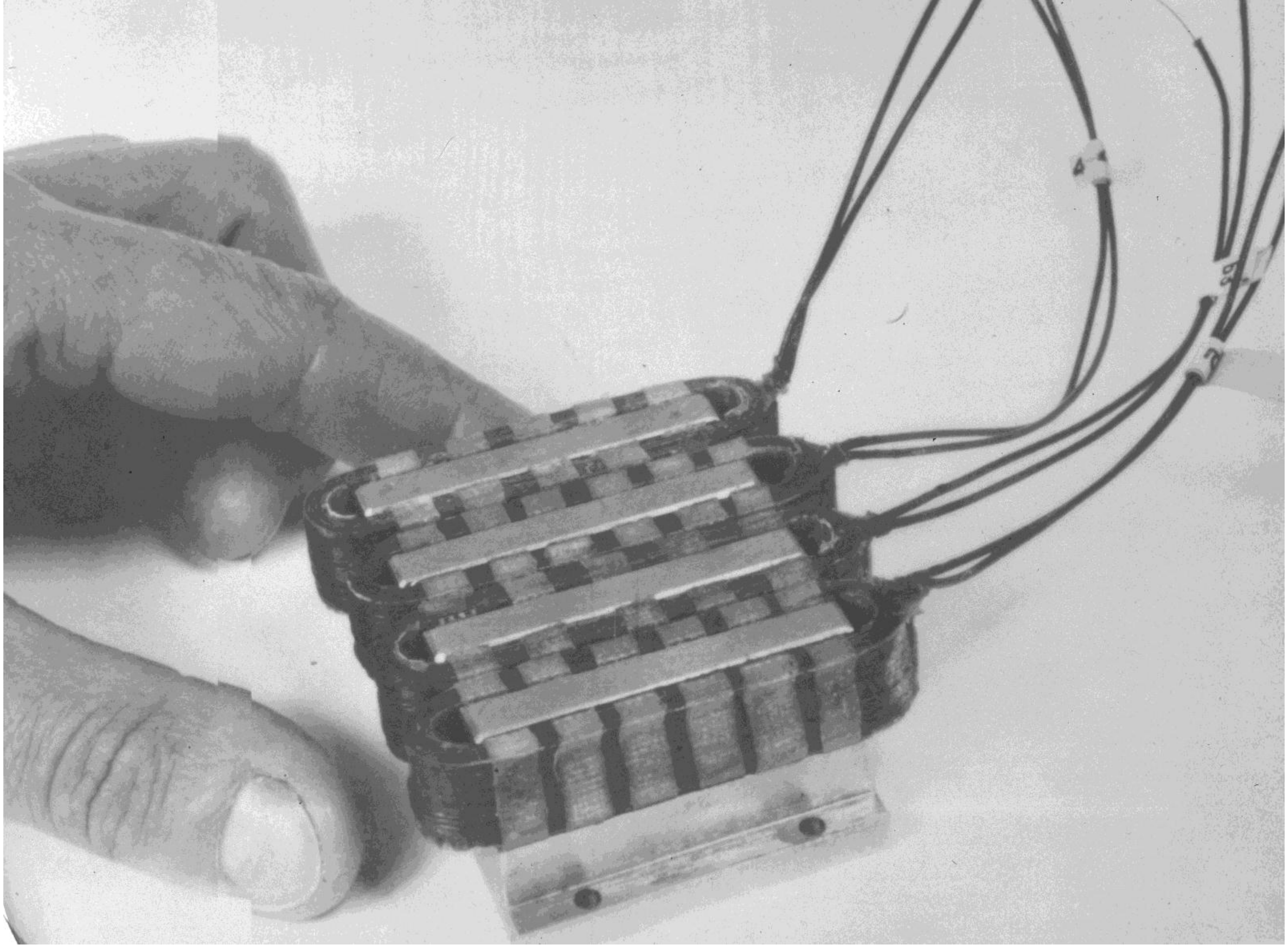


Opening angle

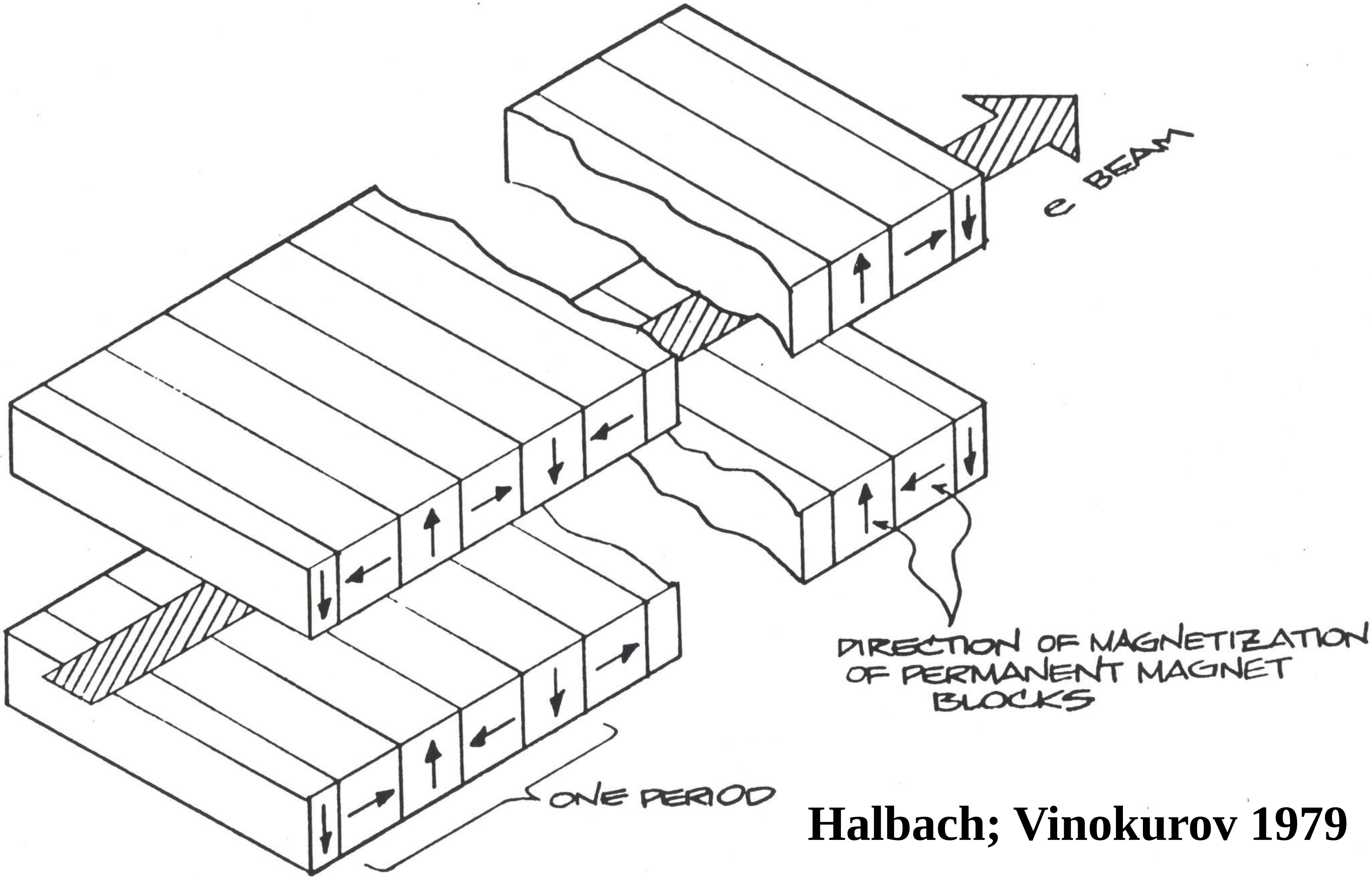
$\Theta = mc^2/E = \gamma^{-1}$

mc^2 = 0.5 MeV (electron rest mass)

For E = 5 GeV, $\Theta = 10^{-4}$ radians = .006^o

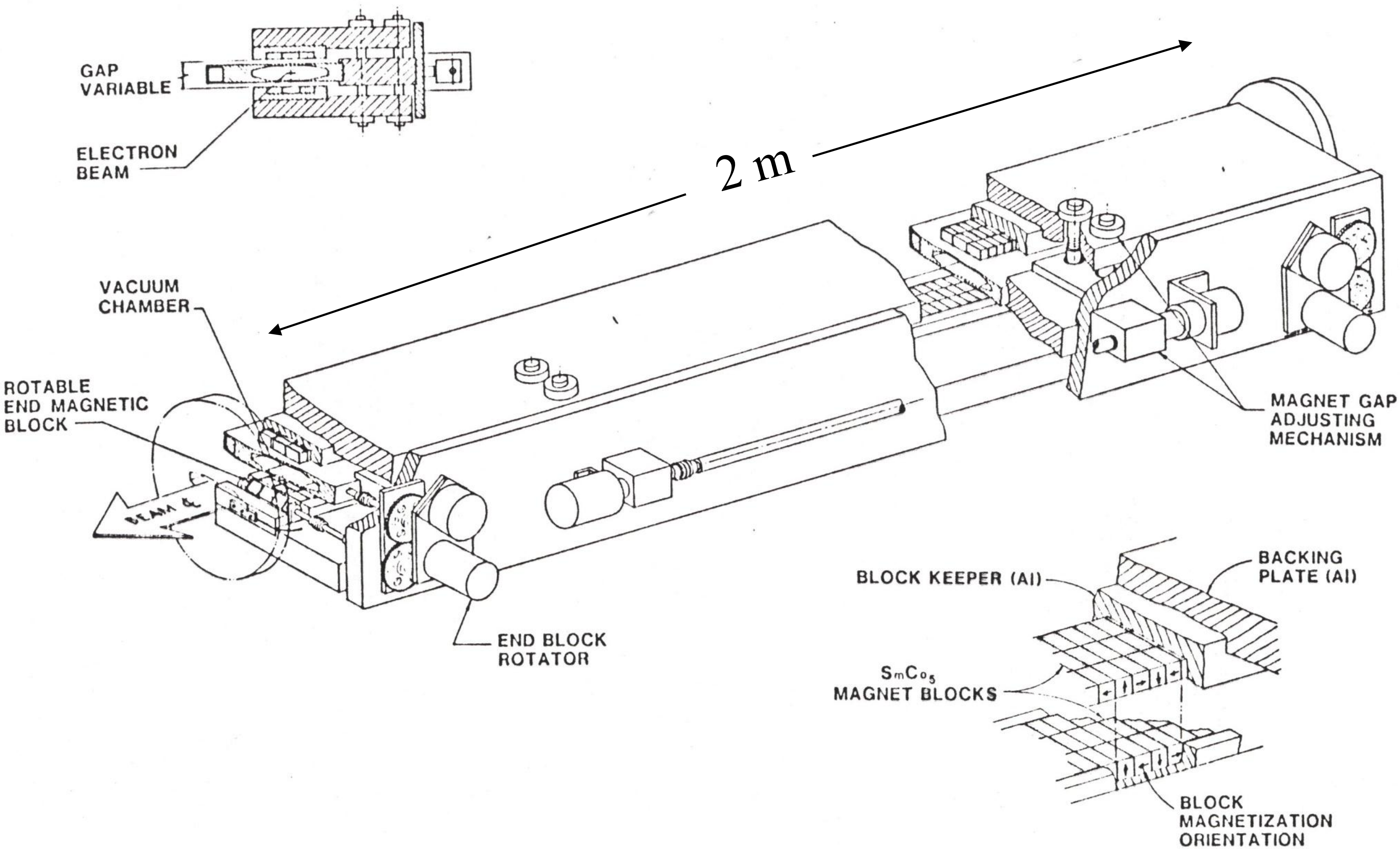


Coils for a superconducting undulator in Orsay; ~1980



Halbach; Vinokurov 1979

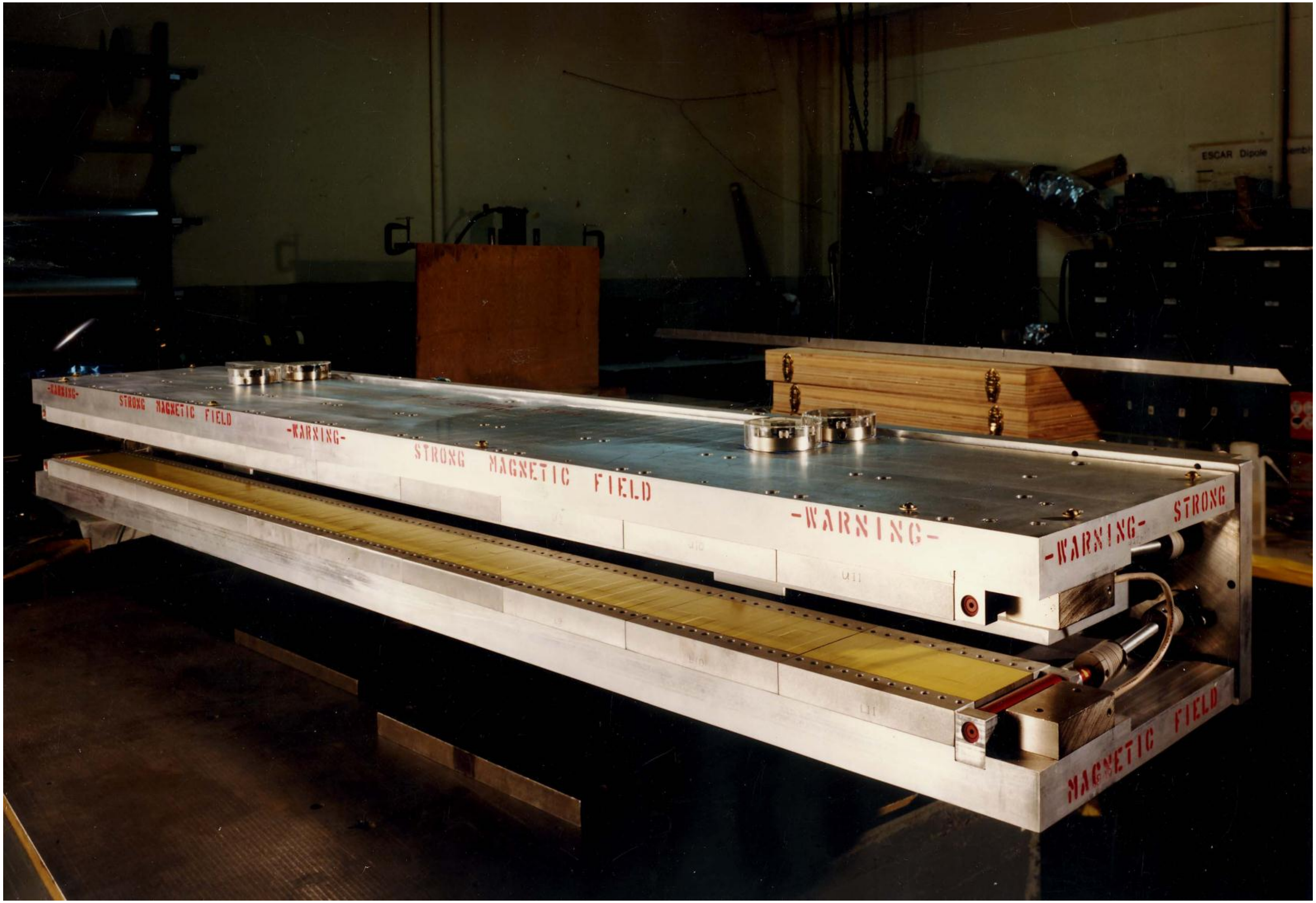
PERMANENT MAGNET UNDULATOR
CONCEPTUAL DRAWING



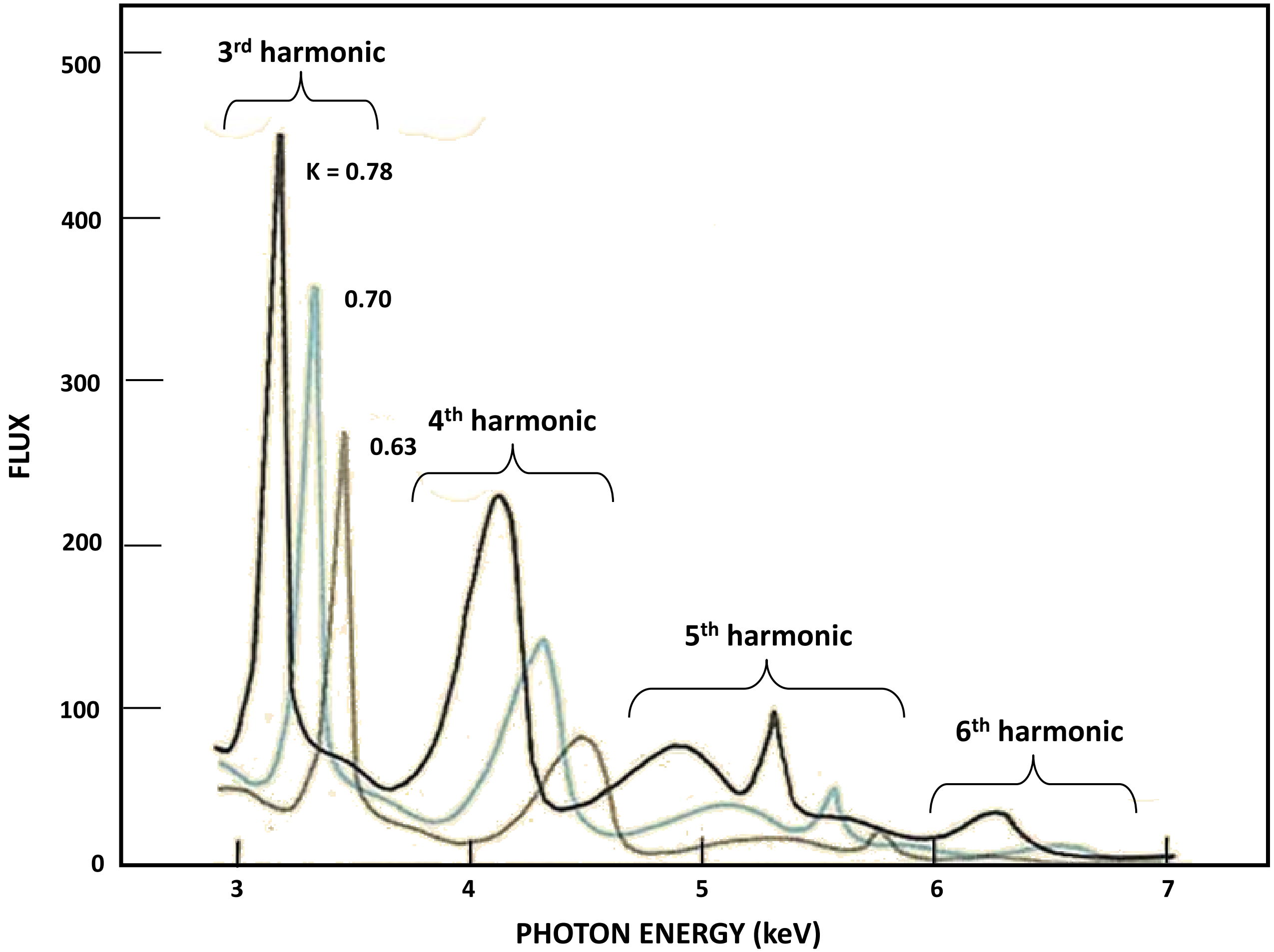
LBL - SSRL UNDULATOR

1980

LBL/SSRL 30 Period Permanent Magnet Undulator -1980



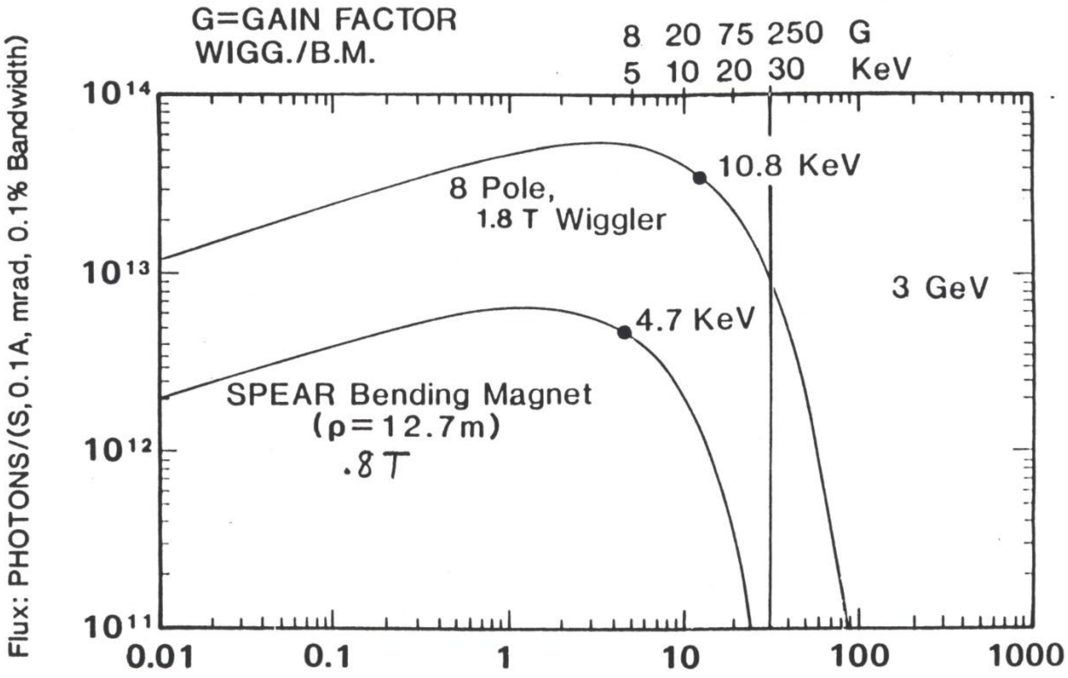
First X-ray Undulator Spectrum; SSRL, 1980

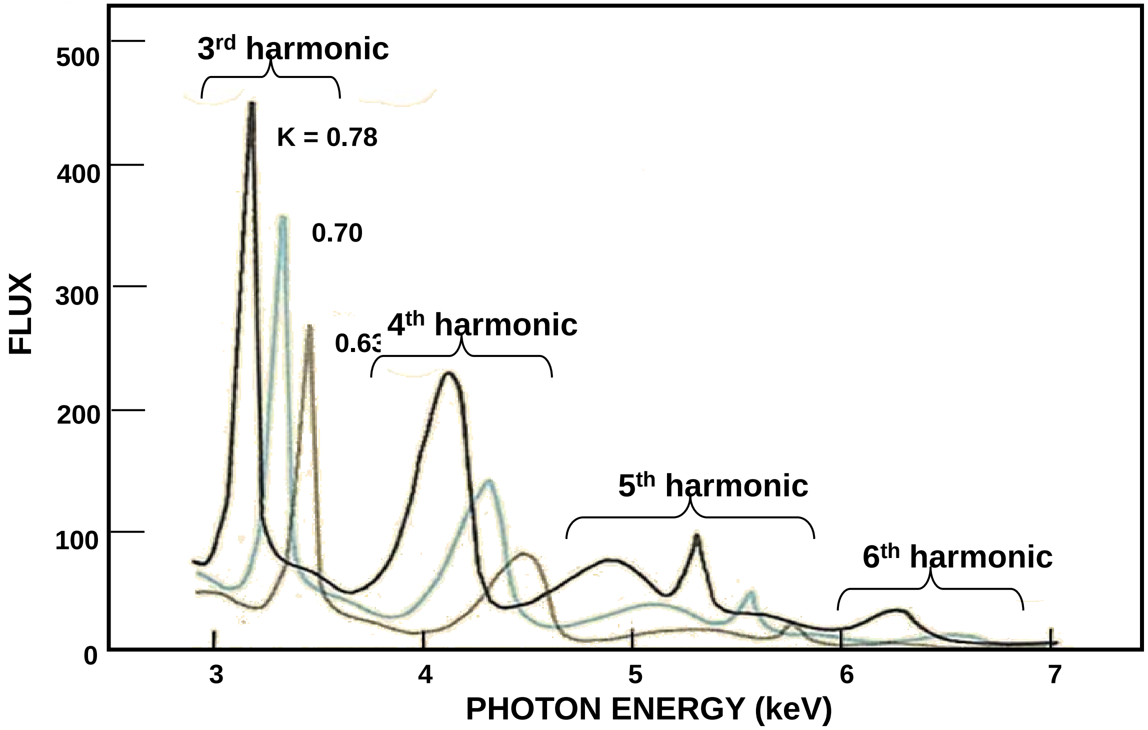


Peaks tuned by varying the magnet gap

Higher-harmonic spectrum produced by 3-GeV electrons in the LBL-SSRL 30-period permanent-magnet undulator. Slits were used to define a very small angular acceptance (18×10^{-6} radians horiz, 8.8×10^{-6} radians vertical).

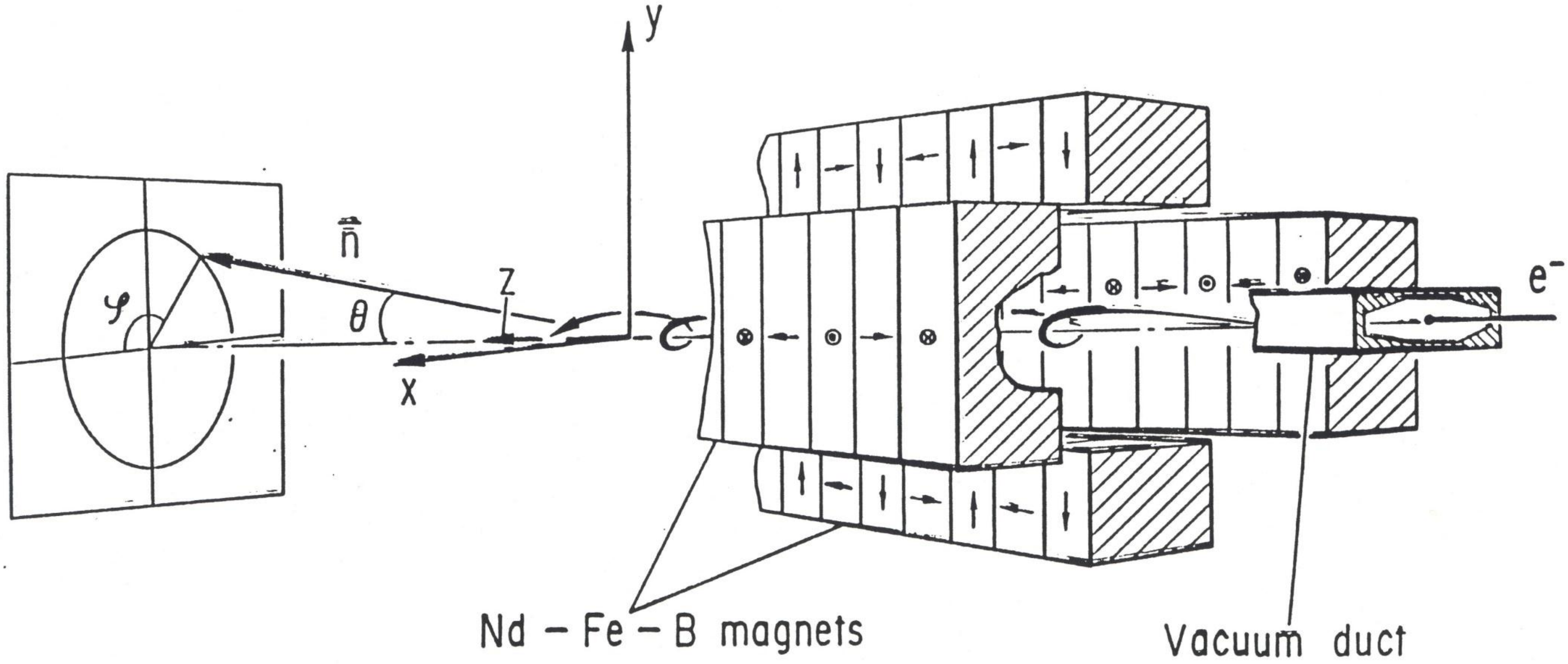
Changing the direction for synchrotron radiation sources; 1978-80



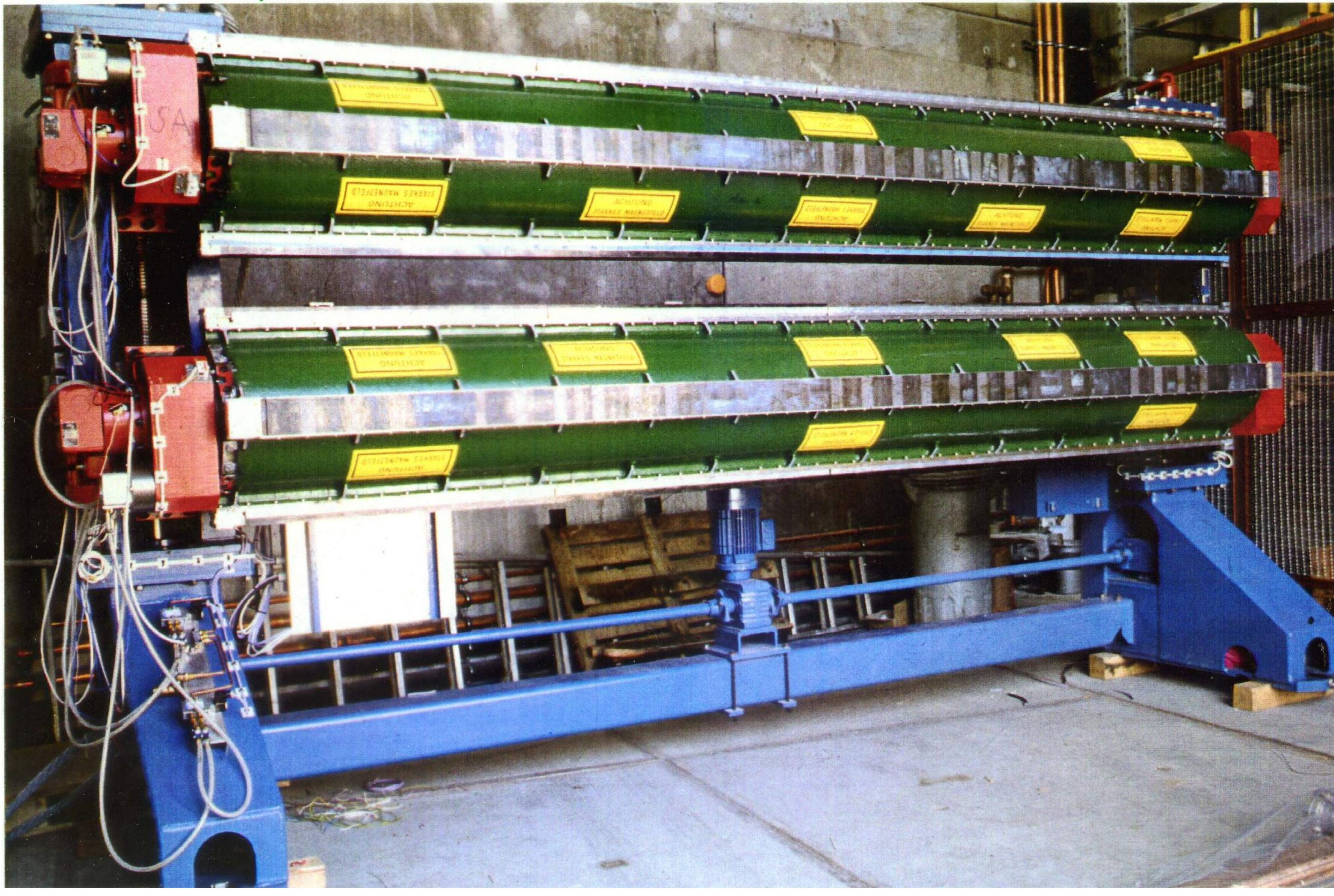


Elliptical Undulator, Photon Factory, Japan

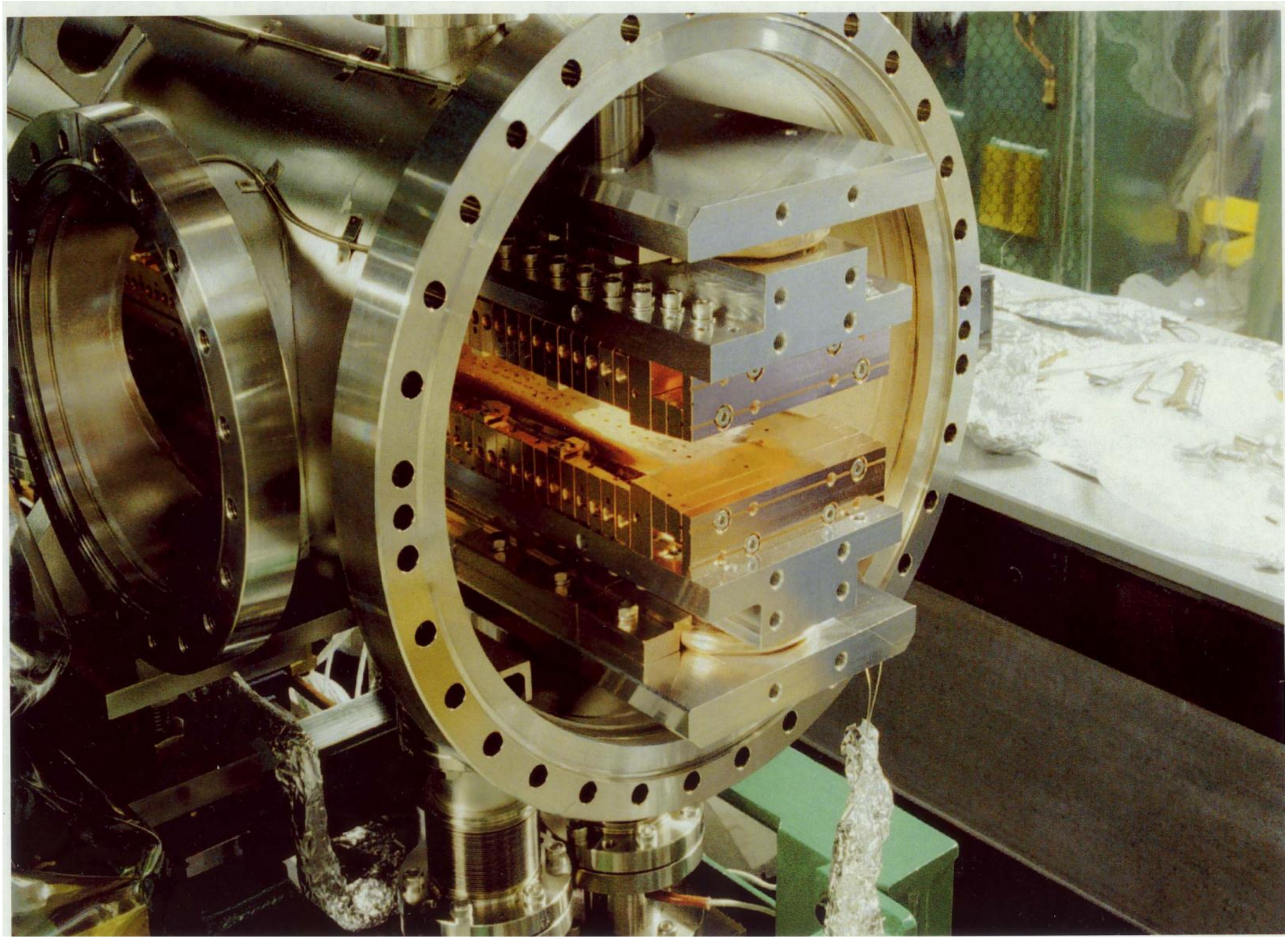
H. Kitamura, S. Yamamoto



Quadruple Undulator - DORIS Bypass-HASYLAB

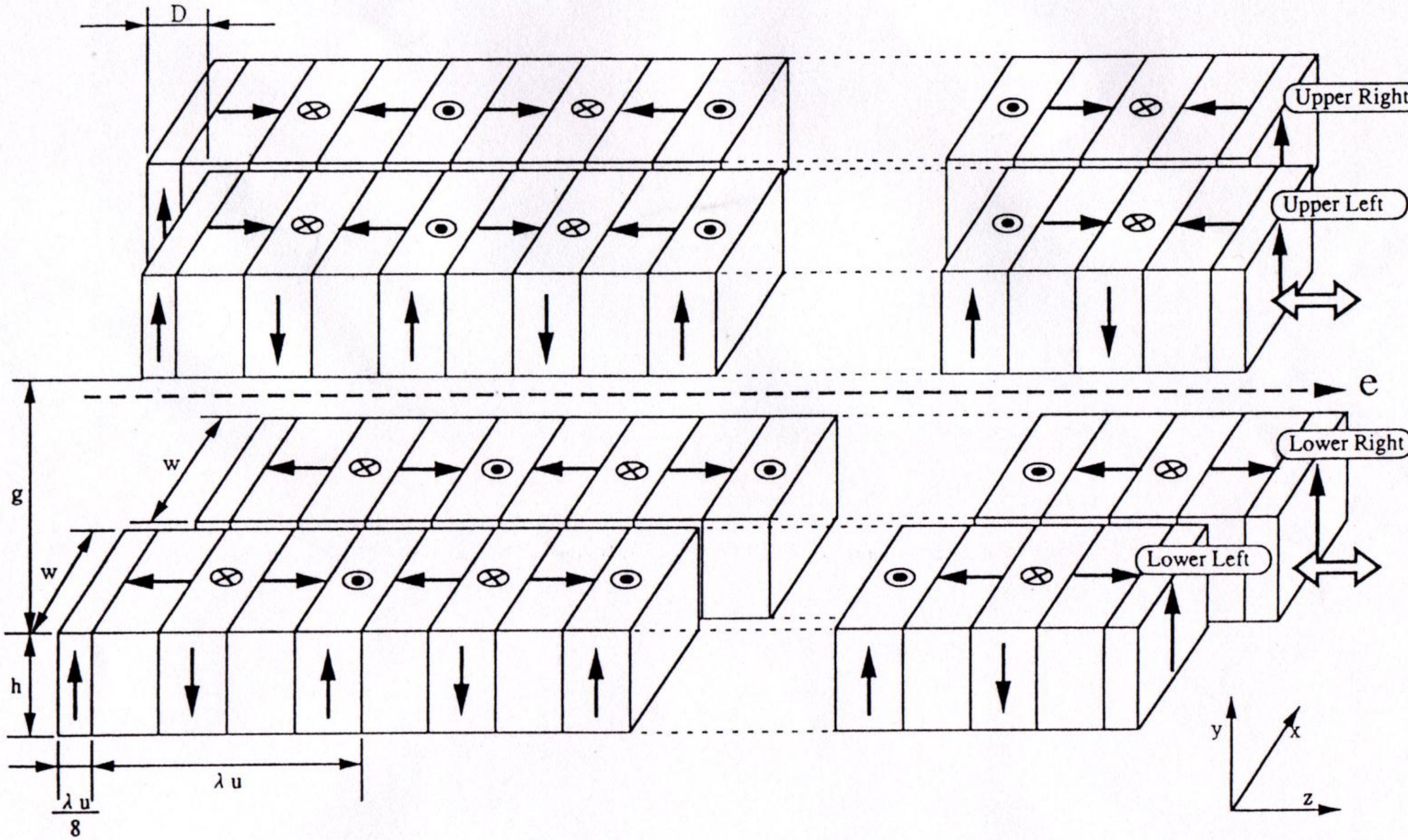


In-Vacuum Permanent Magnet Undulator in SPring-8 – H. Kitamura



APPLE Undulator Magnetic Structure

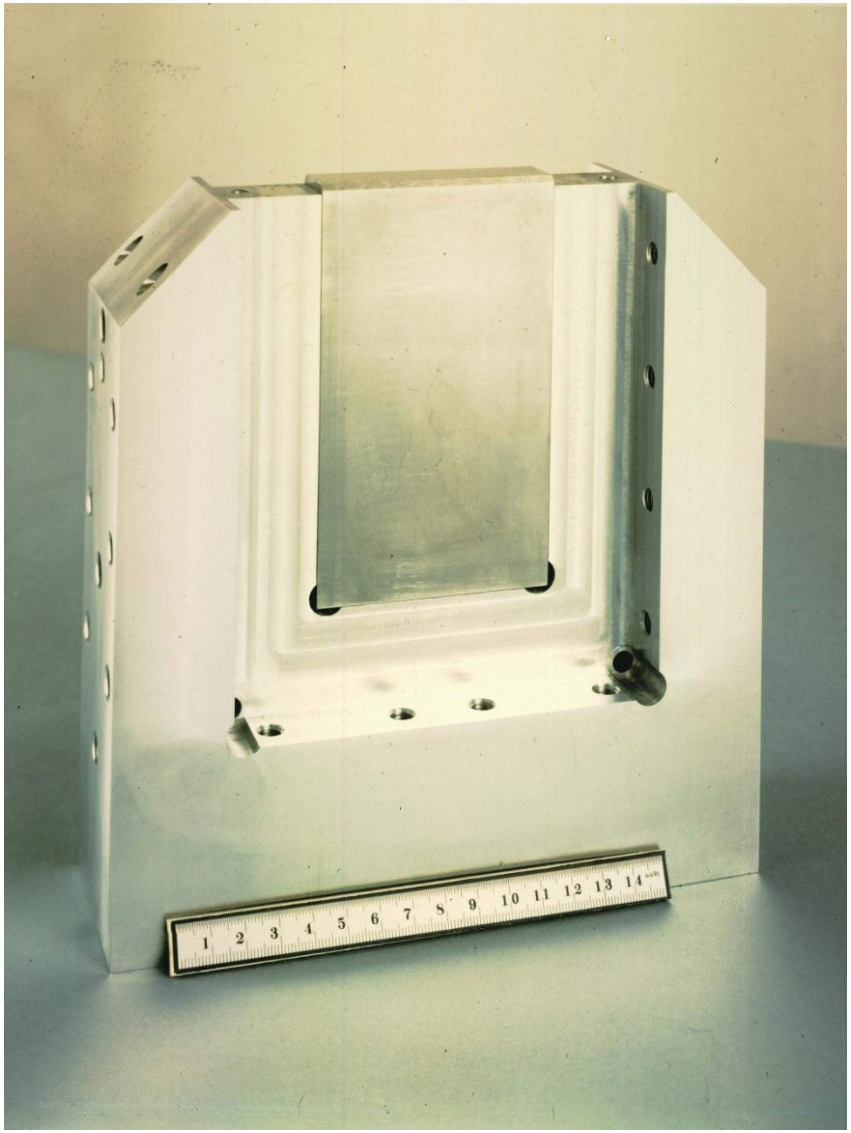
S. Sasaki



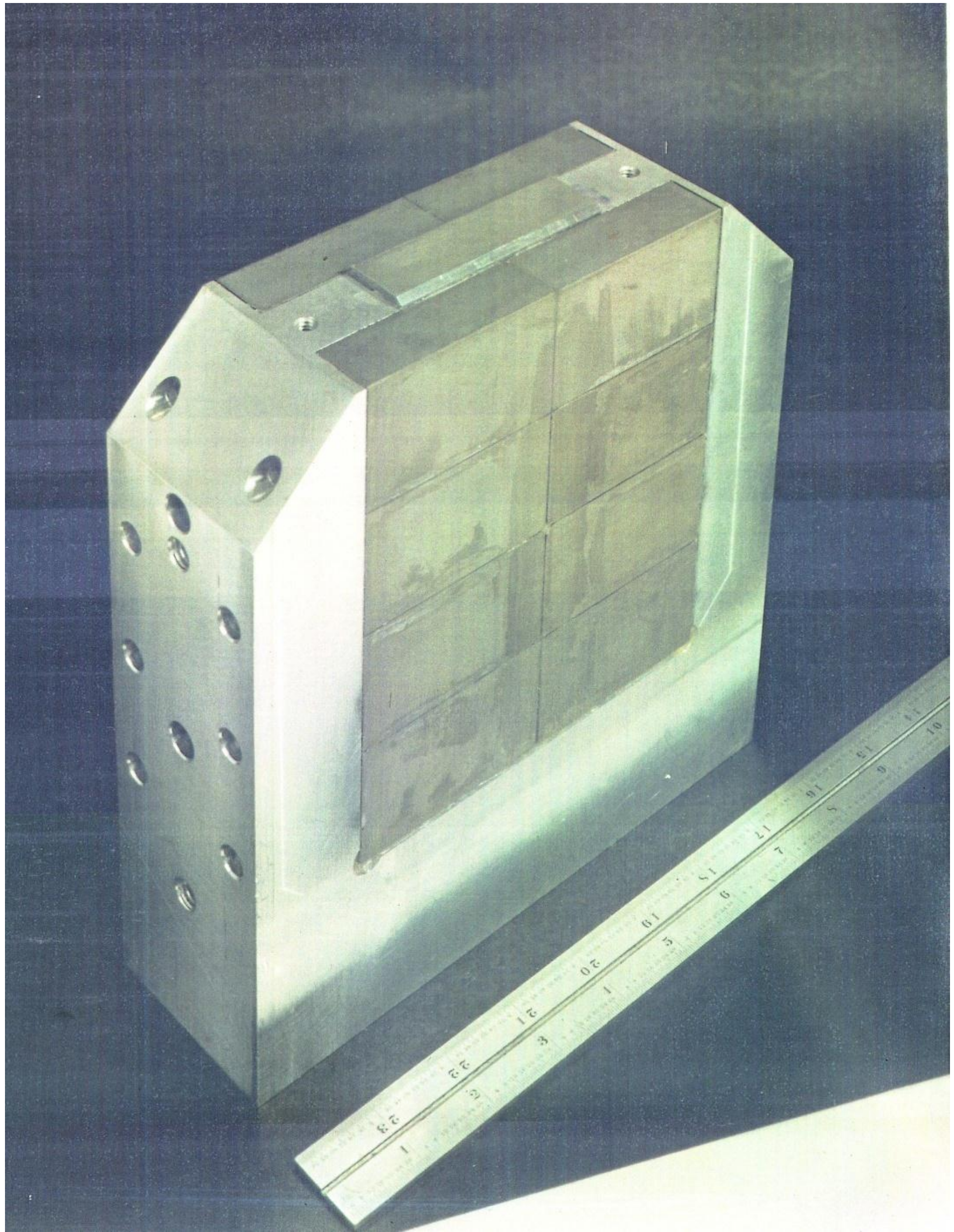
Schematic view of the magnetic structure for generating variably polarized undulator radiation. $D=\lambda_u/4$.

Steps in producing an insertion device

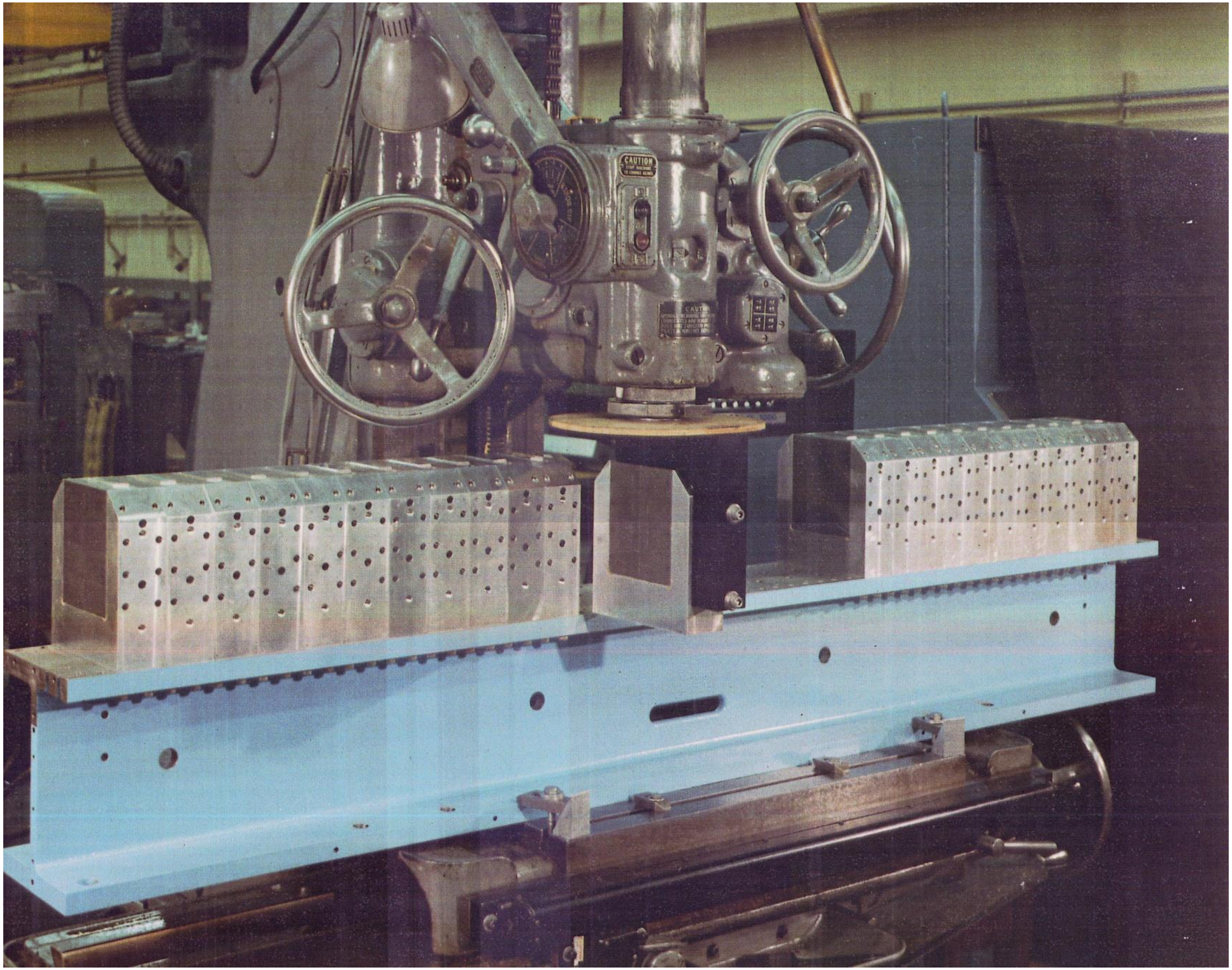
Al keeper + high permeability steel pole



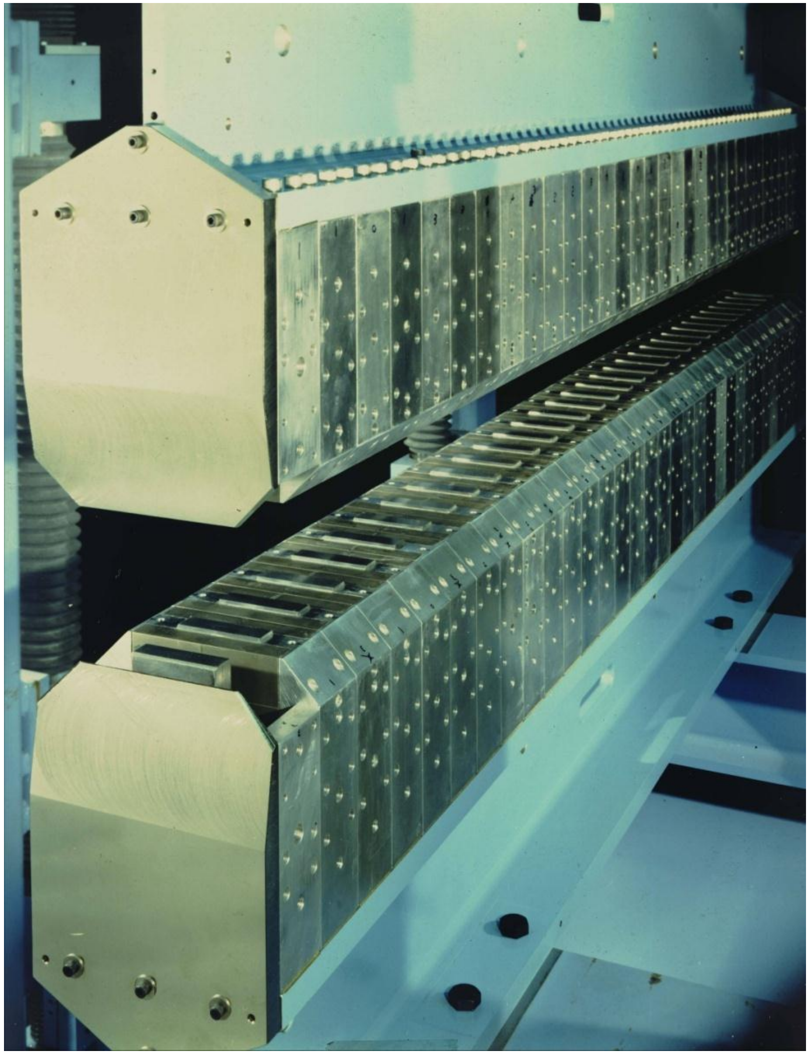
Adding magnetic material to each unit



Assembling the individual units on a strongback



LBL/SSRL 54 Pole Permanent Magnet Hybrid Wiggler ~1985

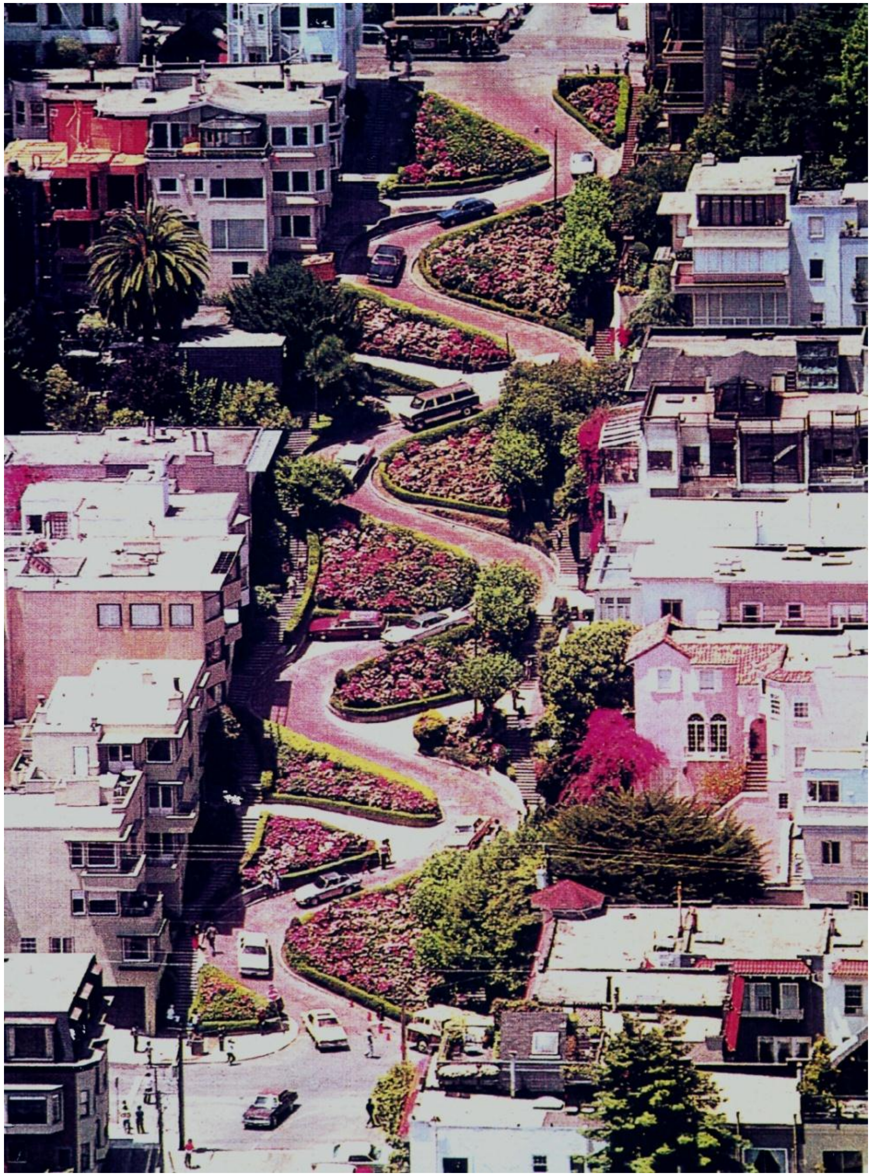


Completed wiggler in support frame; ready for installation of the vacuum chamber

Nicolai Vinokurov & Klaus Halbach receiving the first Compton Award at APS; October, 1995

Pioneers in permanent magnet technology for insertion devices

An Inspirational Wiggler

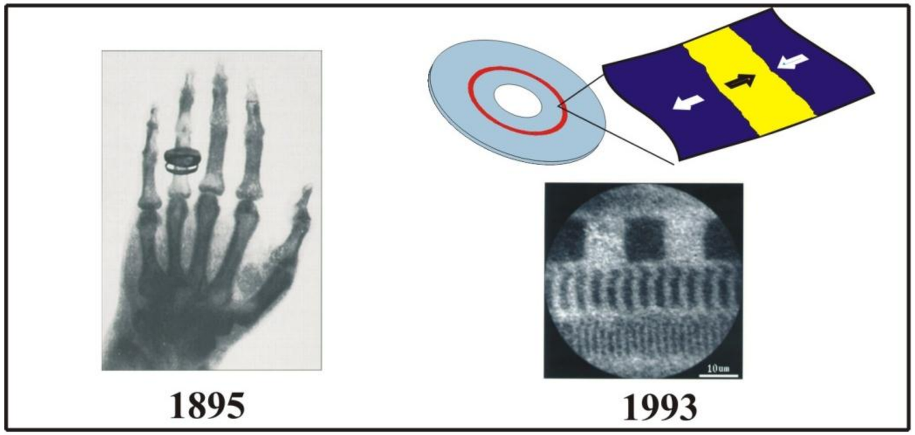


Using X-rays

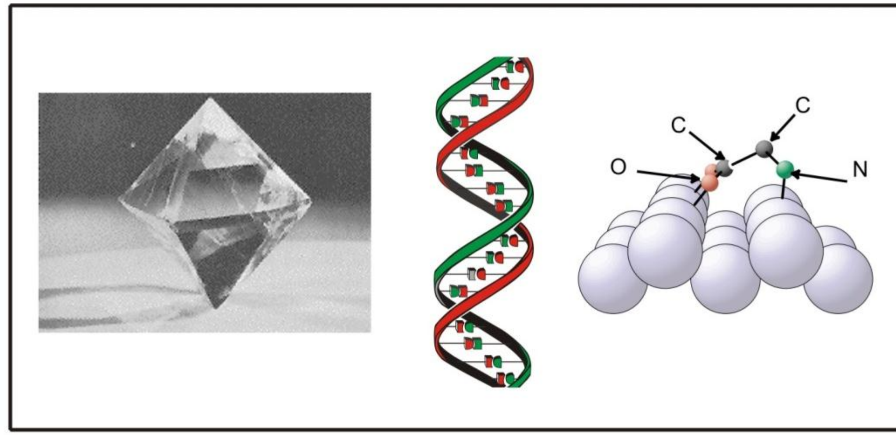
Techniques, Applications, etc.

These Techniques Provide Very Valuable Information

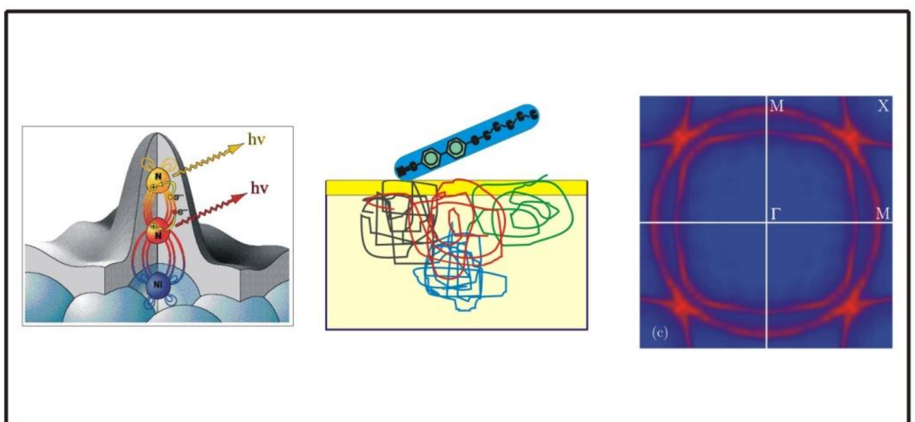
Imaging - Seeing the Invisible



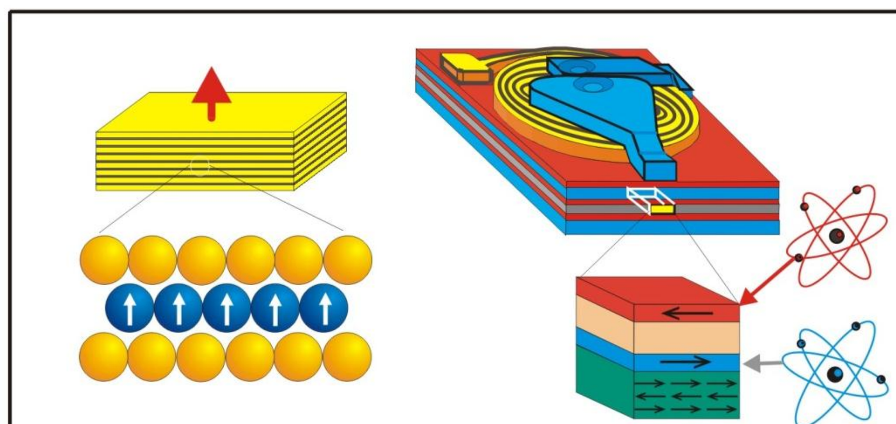
Atomic and Molecular Structure
- where are the atoms -



Electronic Structure and Bonding
- where are the electrons -



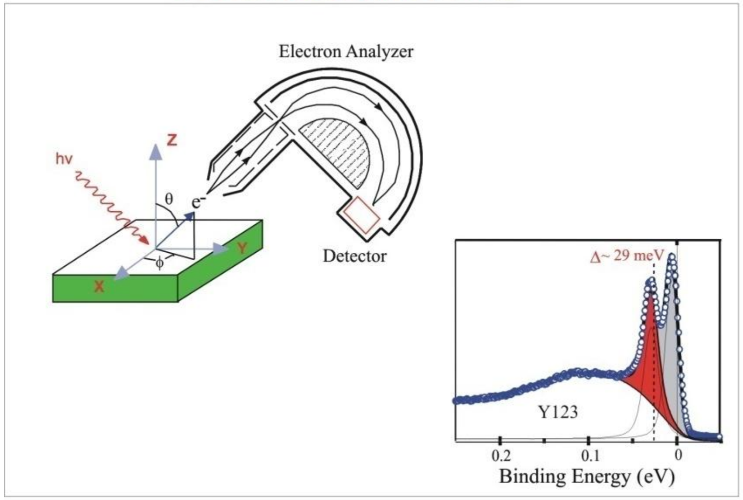
Magnetic Structure and Properties
- where are the spins-



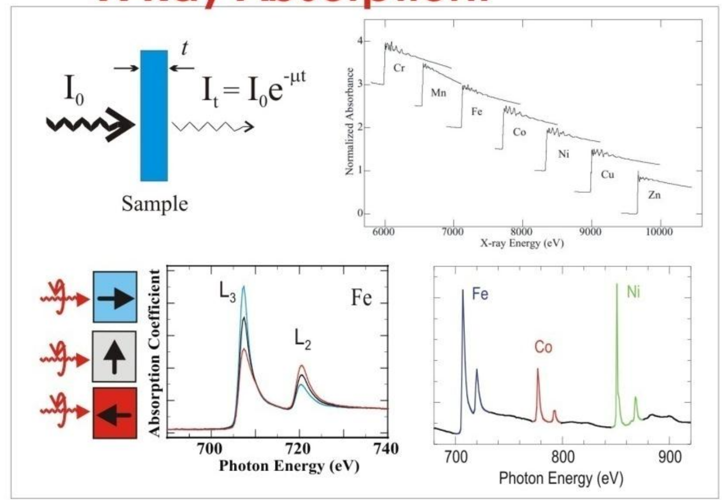
Photons Enable a Range of Modern Techniques to Study Matter

For Example, Modern X-ray Based Techniques Include

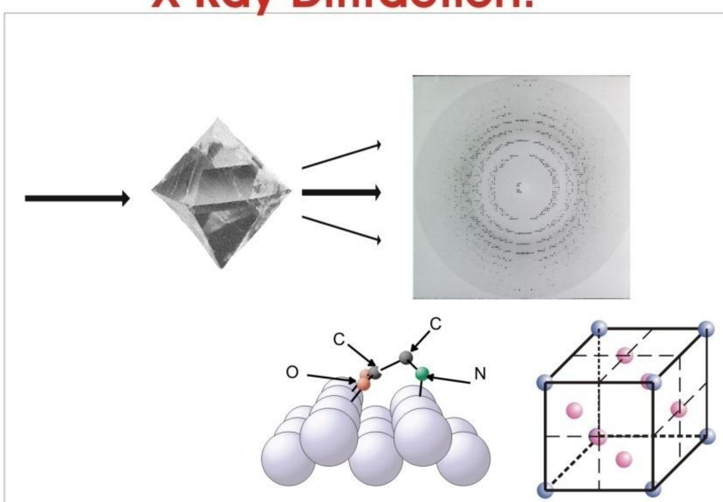
Photoemission:



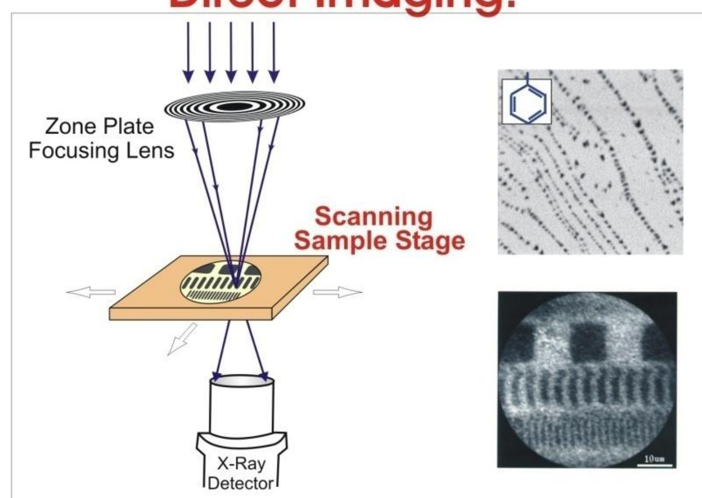
X-Ray Absorption:



X-Ray Diffraction:



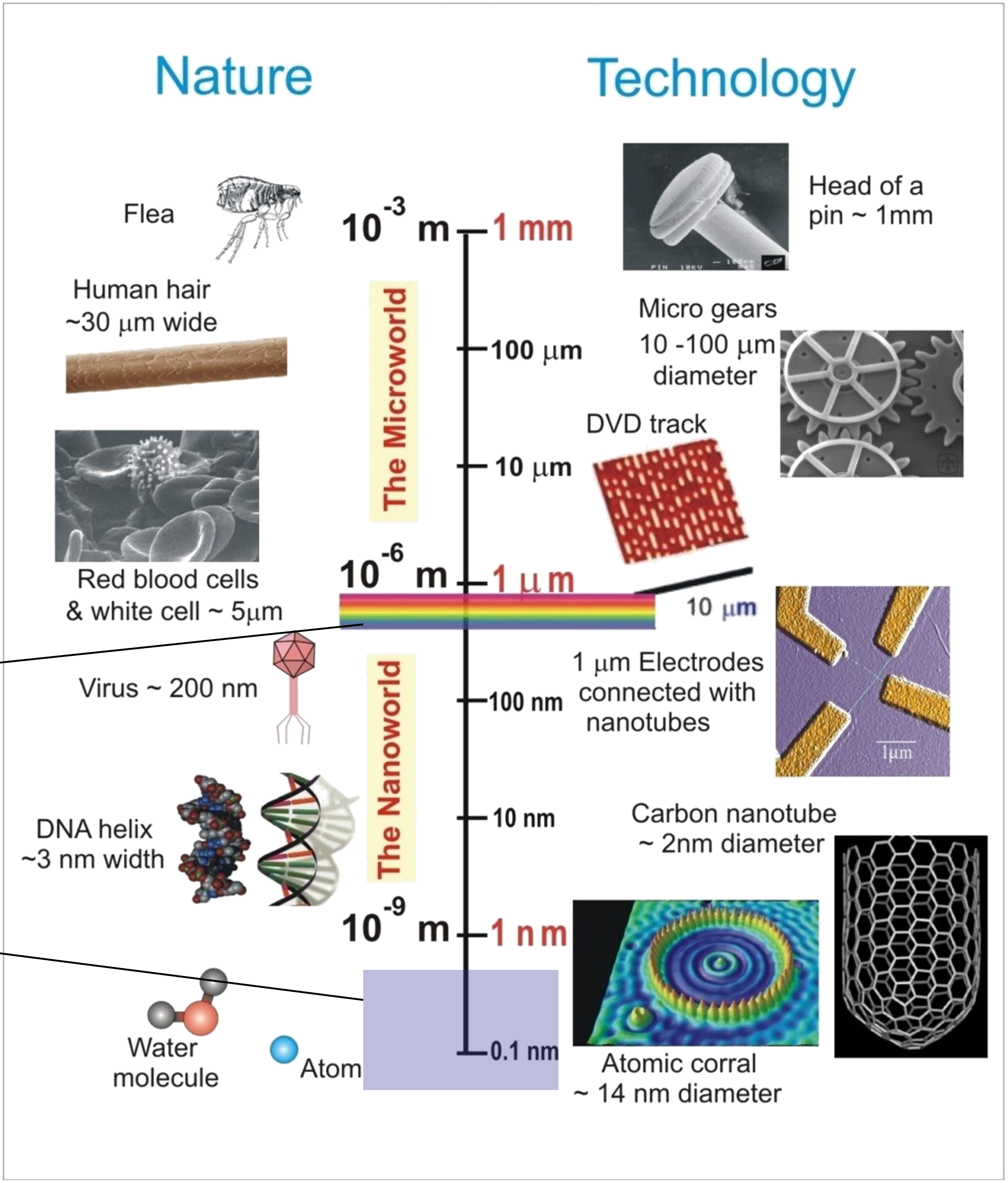
Direct Imaging:



X-rays have opened the ultra-small world

visible

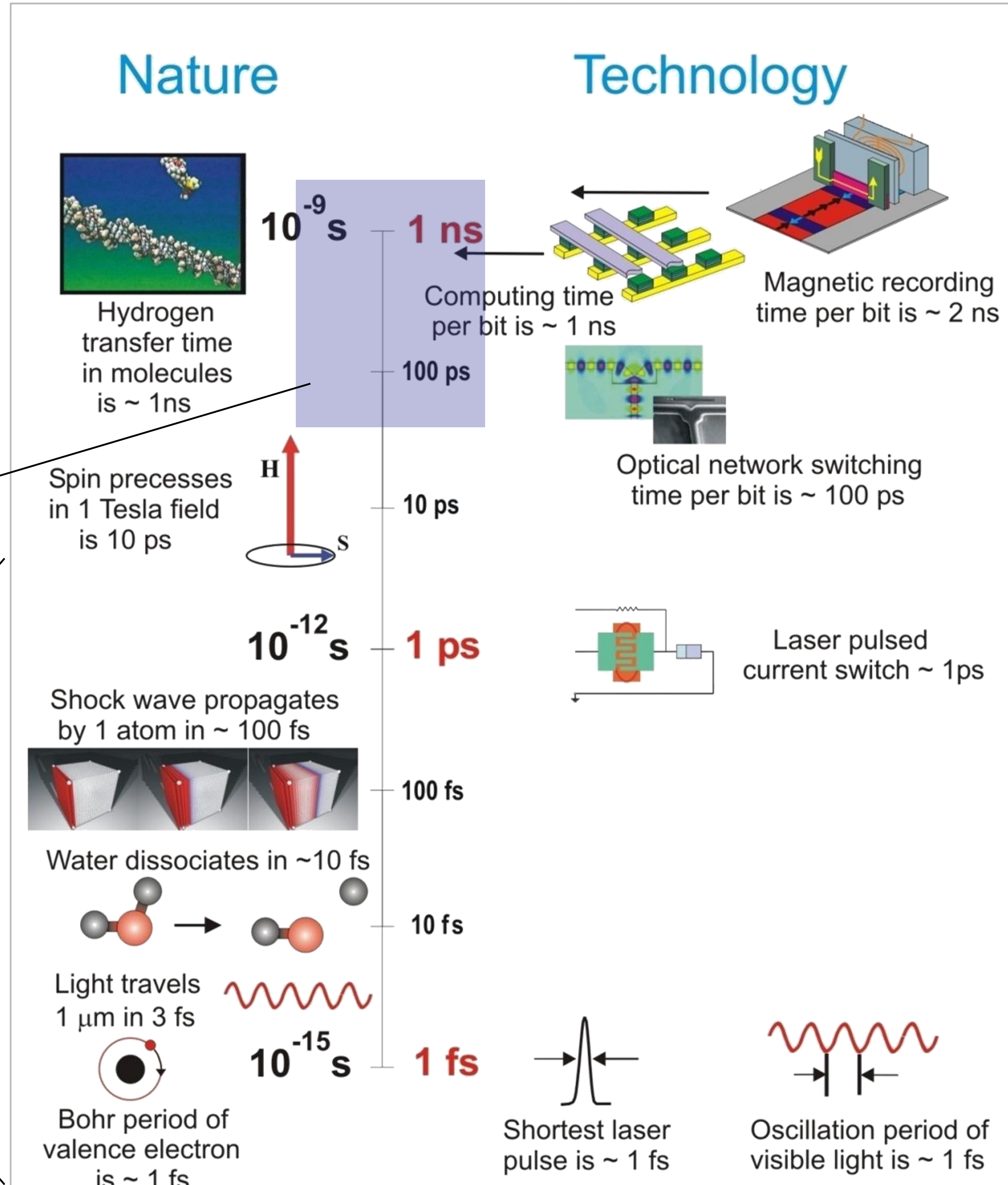
x-ray



In addition to the Ultra-Small world, we'd like to explore the ***Ultra-Fast***

synchrotron source

new territory



To explore the ultra-fast regime, one needs an ultra-fast, pulsed x-ray source. Ideally, it would produce a lot of x-rays in each fast pulse.

To go much beyond what today's synchrotron source can provide, one needs a new type of source. The best candidate is the *Free-Electron Laser*

Examples of Synchrotron Science:

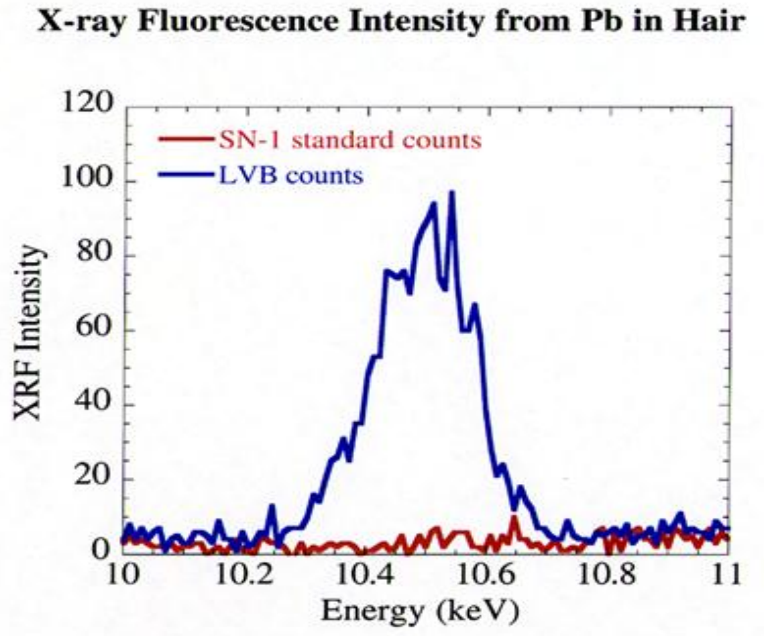
X-Rays Illuminate Ancient Secrets

Archimedes' exceptionally advanced ideas have been lost and found several times throughout the ages. Now scientists are employing modern technology, including x-ray fluorescence, to completely read the Archimedes Palimpsest, the only source for at least two previously unknown treatises.

(Images provided by Will Noel, The Walters Art Museum)

A photograph of one page of the Archimedes Palimpsest. Visible and UV light cannot see Archimedes' text under the gold painting done by a 20th Century forger.

X-ray fluorescence imaging revealed the hidden text. This x-ray image shows the lower left corner of the page.



Intensity of Pb x-ray fluorescence from a standard hair (SN-1) with 6 ppm of lead compared to that of a hair from Beethoven (LVB) as determined at APS.

Synchrotron studies at the Advanced Photon Source reveal massive amounts of lead in bone fragments from skull of Beethoven.

These findings confirm studies of Beethoven hair samples.

Researchers believe this confirms lead poisoning as cause of composer's chronic illness.