Accelerators-recuperators as 4th generation X-ray light sources

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Lecture 1

Introduction to accelerator based synchrotron radiation light sources

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Lecture 1. Introduction to accelerator based synchrotron radiation light sources.

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Lecture 3. Technical solutions for realization of the 4th generation SR sources based on accelerators-recuperators.

Lecture 4. Comparison of the one pass (ERL) and multi-pass (MARS) accelerators-recuperators.

Lecture 5. Status and future of light sources based on recirculating accelerators-recuperators.

Acknowledgement

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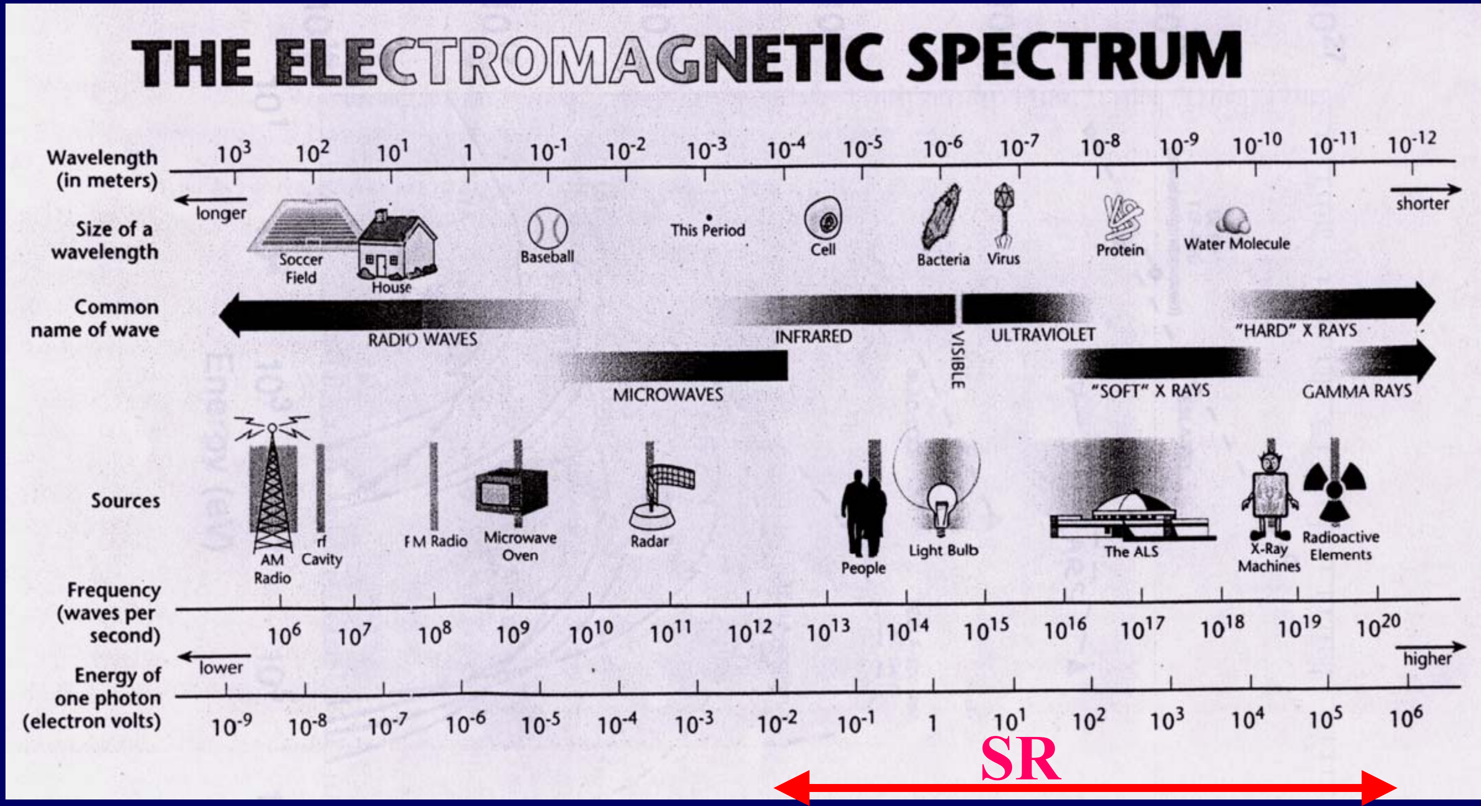
1. Position of synchrotron radiation in electromagnetic spectrum

Electromagnetic waves – the most important tool by which we know the world around us:

- our everyday experience;
- scientific exercise for an understanding of nature.



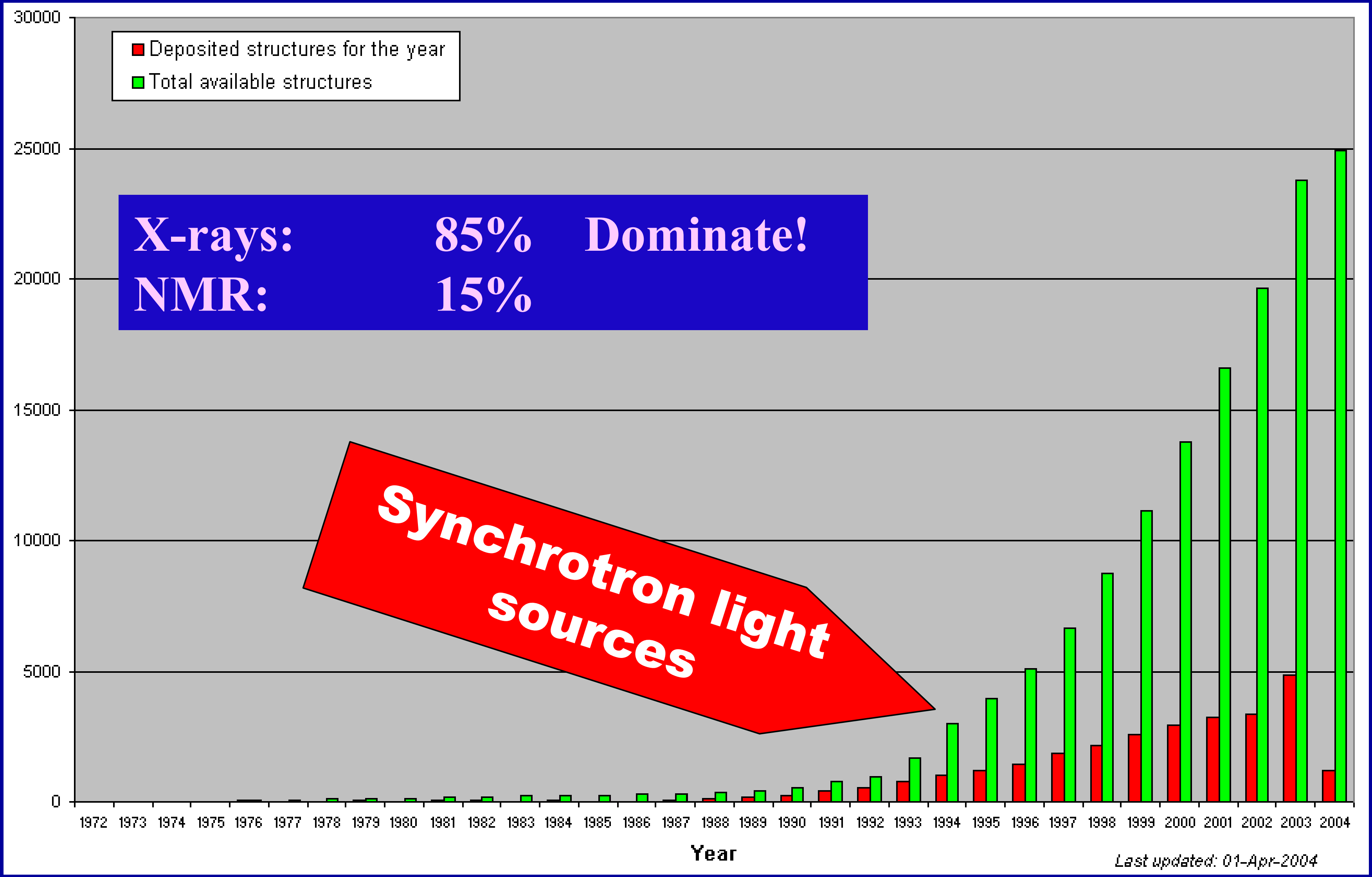
Using electromagnetic waves have played an important role in the development of modern science and technology.

- **X-ray diffraction: structure of crystals, helix structure of DNA, protein crystallography.**
- **Atomic and molecular spectroscopy: establishing the laws of quantum mechanics;**
- **Radio, TV, telecommunication.**

Now synchrotron radiation sources is more intensive in range are located within the electromagnetic spectrum between gamma rays (> 10^6 eV) and THz radiation (< 10^{-2} eV);

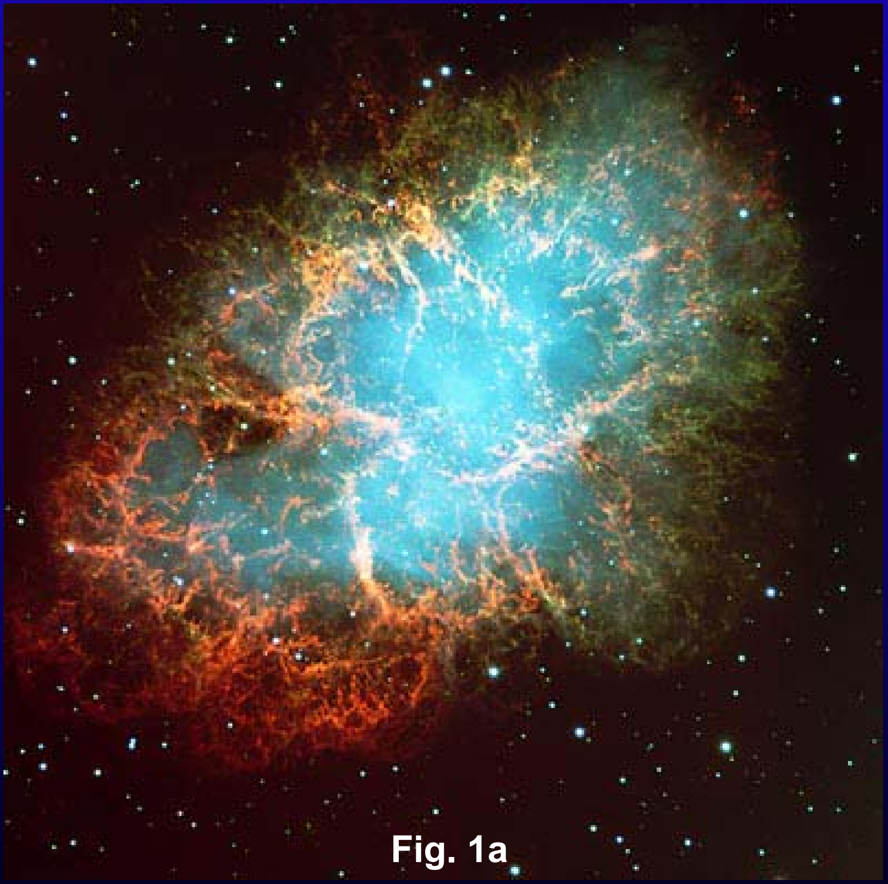
Synchrotron radiation facilities are important part of the infrastructure of a broad class of scientific studies, involved are solid state physics, surface physics, nanoscience, material science, biology.

Spectacular growth of structural biology



2. History of synchrotron radiation

Crab Nebula
6000 light years away



First light observed
1054 AD

The birth of the Crab Nebula is related to a supernova outburst in 1054, a fact documented in chronicles by Japanese and Chinese monks.

In the middle of the last century (after nine hundred years) hypothesis was put forward, and subsequently confirmed experimentally, that the radiation from the Crab Nebulae is actually the synchrotron radiation of ultrarelativistic electrons in interstellar magnetic fields.

GE Synchrotron New York State

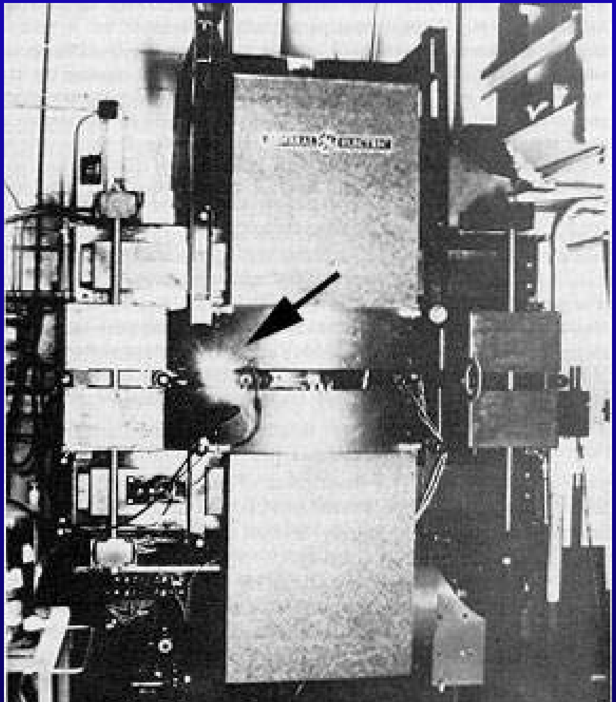
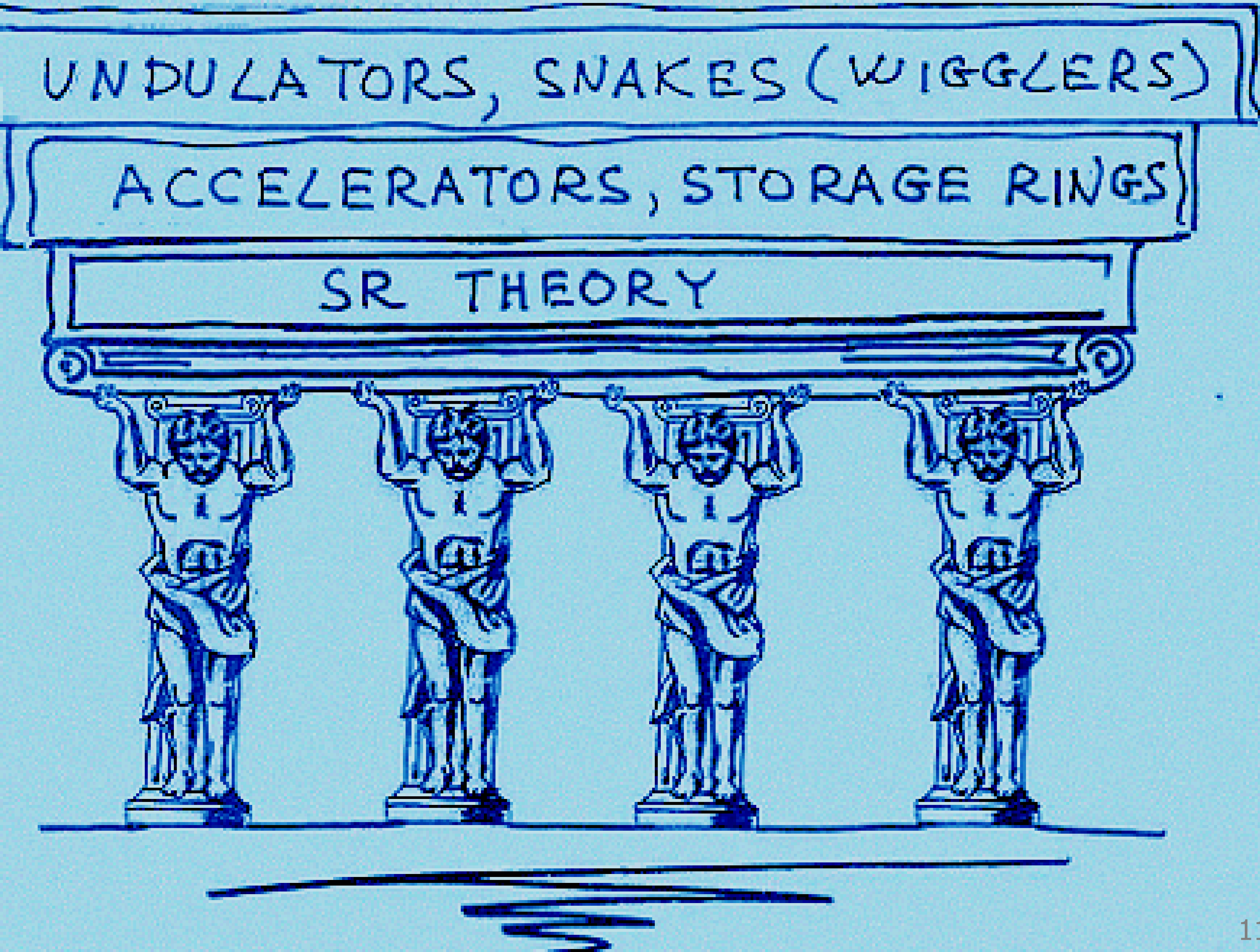


Fig. 1b

First light observed 1947

Figure 1b shows a photograph of artificial synchrotron radiation, first observed in 1947 at one of the first electron accelerators – a synchrotron made by the General Electric company in the USA.

The events illustrated by Figs 1a and 1b were separated by nine hundred years. Such was the period of time necessary for humankind to comprehend that the glow of the Crab Nebula is produced by synchrotron radiation, on the one hand, and, on the other, to devise modern physics, to elaborate the theory of synchrotron radiation, to establish principles and develop methods for accelerating charged particles and, then, to create charged particle storage rings and special generators of synchrotron radiation – undulators and wigglers.


UNDULATORS, SNAKES (WIGGLERS)
ACCELERATORS, STORAGE RINGS
SR THEORY

SR THEORY

1. Lienard (1898) Eclairage electrique V. 16 , p. 5-14

   - described the concept of retarded potentials in the calculation of electric and magnetic field, produced by electron traveling on a circular orbit, obtained formula for the rate of energy loss:

$$dE/dt=2/3\ (e^2 \cdot c \cdot \beta^4)/R^2 \cdot (E/m^2)^4$$

SR THEORY

2. G. A. Schott (1912) Electromagnetic Radiation, Cambridge University Press.

Developing of the theory of radiation of electrons, stimulated by study of various atom models, derived an expression describing the radiation spectrum of electron traveling in circular orbit, the angular distribution and the state of polarization of radiation.

1908, than 1912

G.A. Schott,
Cambridge, UK

ELECTROMAGNETIC RADIATION

AND THE MECHANICAL REACTIONS
ARISING FROM IT

BEING AN ADAMS PRIZE ESSAY IN THE
UNIVERSITY OF CAMBRIDGE

by

G. A. SCHOTT, B.A., D.Sc.
Professor of Applied Mathematics in the University College of Wales, Aberystwyth
Formerly Scholar of Trinity College, Cambridge

Cambridge:
at the University Press
1912

Title page of George Schott's Adams Prize Essay which covered the theory/of synchrotron radiation.

SR THEORY

3. I. Pomeranchuk (1939) JETP, V. 9, p. 915
- calculation of maximum energy of cosmic-ray electrons at the Earth due to energy loss of electron in earth's magnetic field

$$\Delta E \propto E^2 \cdot B^2 \cdot L$$

4. D. Iwanenko, I. Pomeranchuk (1944) Phys. Rev. 1944, V. 65, p.343
- calculation of maximum reachable energy in betatron due to radiation losses of higher energy electrons

$$\Delta W \propto E^4 / R$$

5. L. Artsimovich, I. Pomeranchuk (1945) Journal of Physics of USSR, V. IX, p. 267
- studied and obtained for the first time for relativistic electrons angular distribution of radiation ($\theta \propto 1/\gamma$), radiation spectrum ($\lambda \propto R/\gamma^3$), radiation of non-interacting system of electrons (and limits for such approach).

SR THEORY

Modern theory of synchrotron radiation:

6. D. Iwanenko, A. A. Sokolov (1948) DAN, V. 59, p. 1551-1554; J. Schwinger (1949) Phys. Rev. V. 75, p. 1912-1925

7. J. Schwinger (1949) “On Classical Radiation of Accelerated Electrons”

ELECTRON SYNCHROTRONS – FIRST SOURCES of SR

2. V. I. Veksler (1944) Comptes Rendus de l' Academic Sciences de l' URSS V. 43, 8, p.329
E. Mc. Millan (1945) Phys. Rev. V. 68, p. 144-145.
- independently discovered the principle of phase stability for RF acceleration of charged particles, moved in a circle of constant radius.

General Electric synchrotron (USA), FIAN synchrotron (USSR), Cornell synchrotron (USA), Frascati synchrotron (Italy)

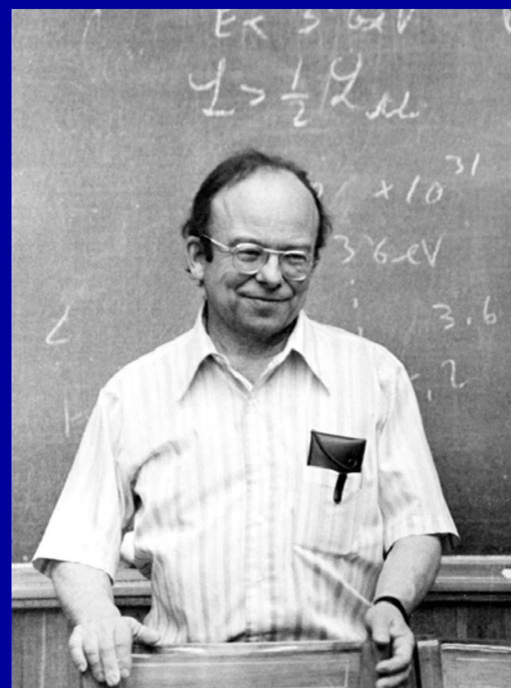
2. E. D. Courant, M. S. Livingston, M. S. Snyder (1952)
- invented strong focusing synchrotron

CEA (USA), NIA (UK), ARUS (USSR), DESY (Germany)

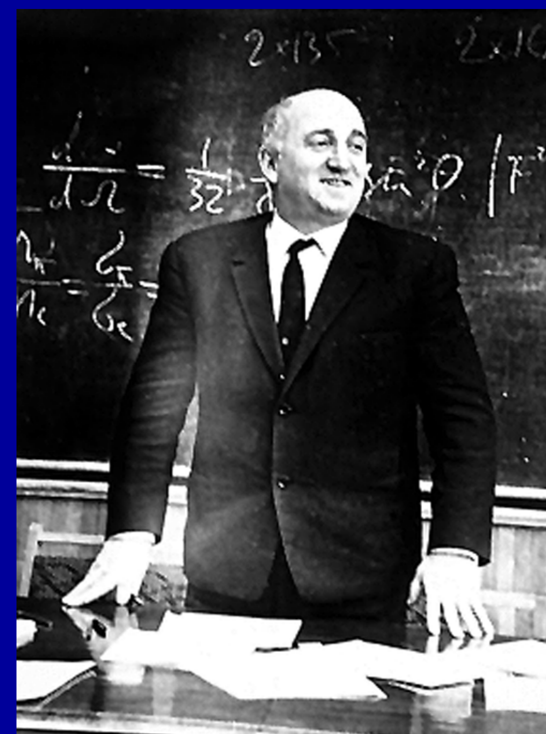
The further progress of SR sources is associated with development of storage rings for high energy physics colliders (AdA, VEP-1, PSSR)

B.Touschek (Frascati)

D.K.O’Neill (Princeton)

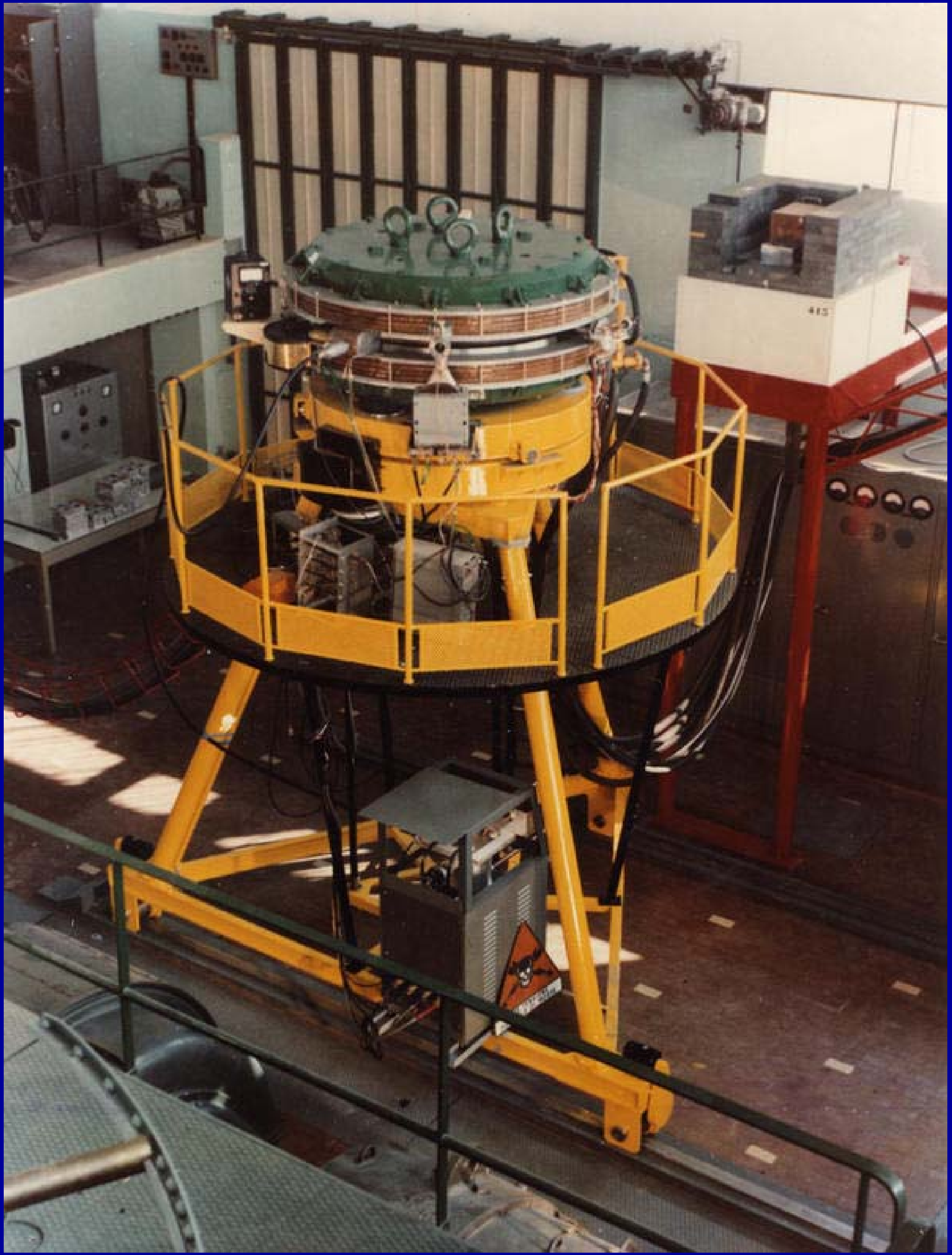


W.Panofsky (Stanford)

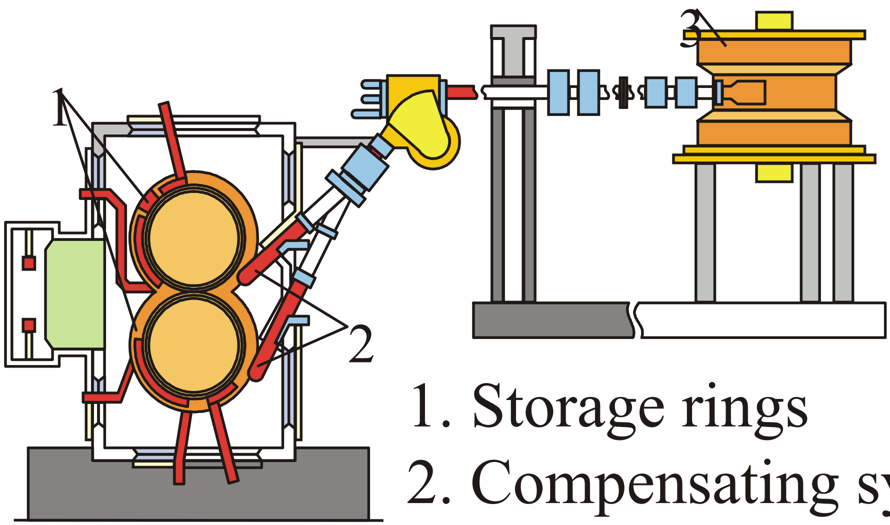


G.Budker (Novosibirsk)

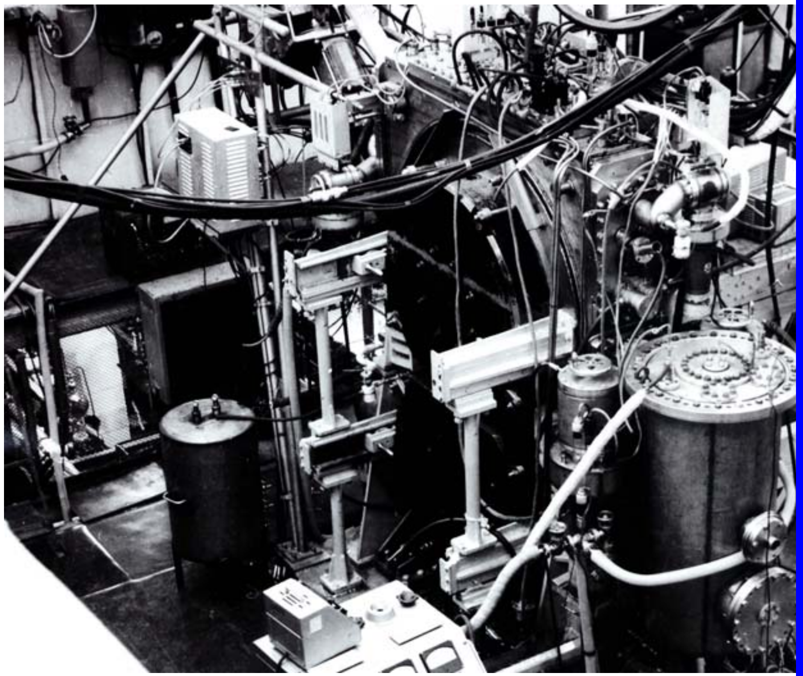
First Italy-France storage ring AdA



First Russian storage ring – electron-electron collider VEP-1 (1963, Novosibirsk).



1. Storage rings
2. Compensating systems
3. Synchrotron B-2S



VEP-1
to-day as a monument

E = 90 MeV - 320 MeV (total); L= 5*10 ^{27} cm^{-2}s^{-1}

Exps 1965-1967 :

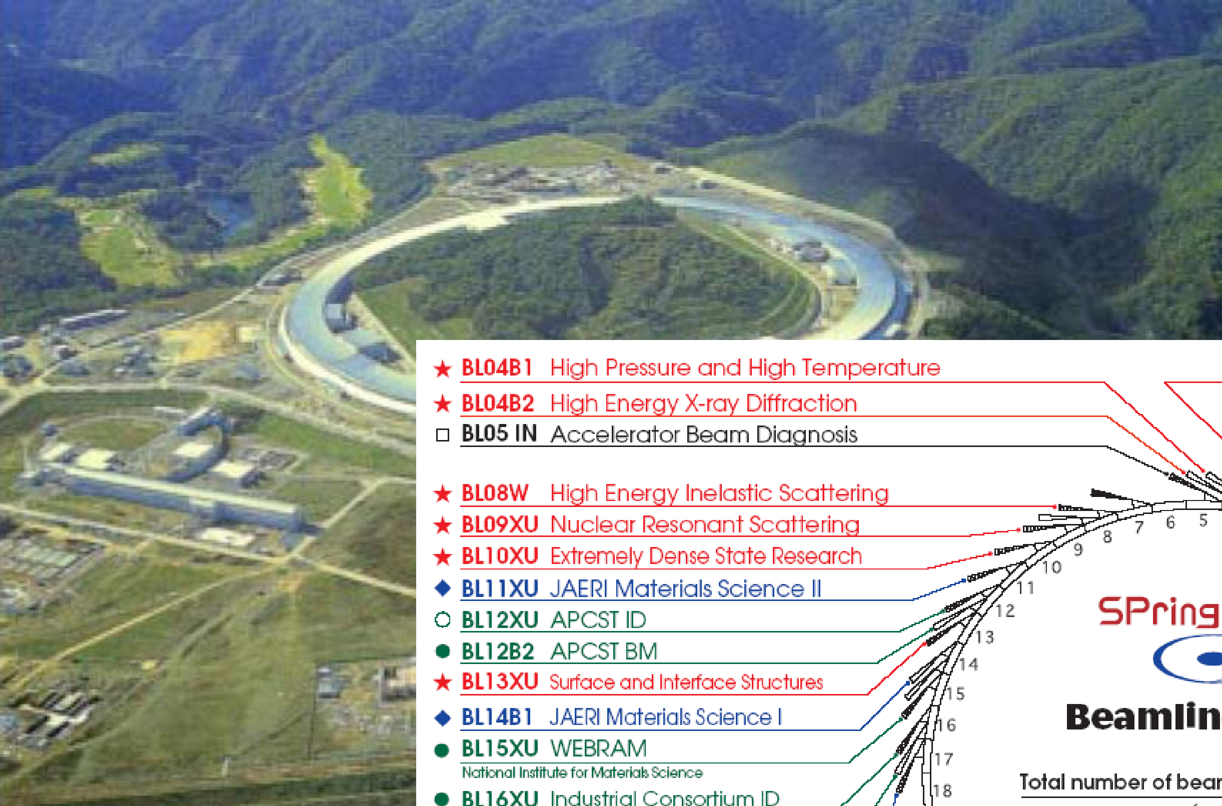
– **electron-electron elastic scattering (in parallel to Princeton-Stanford Rings);**

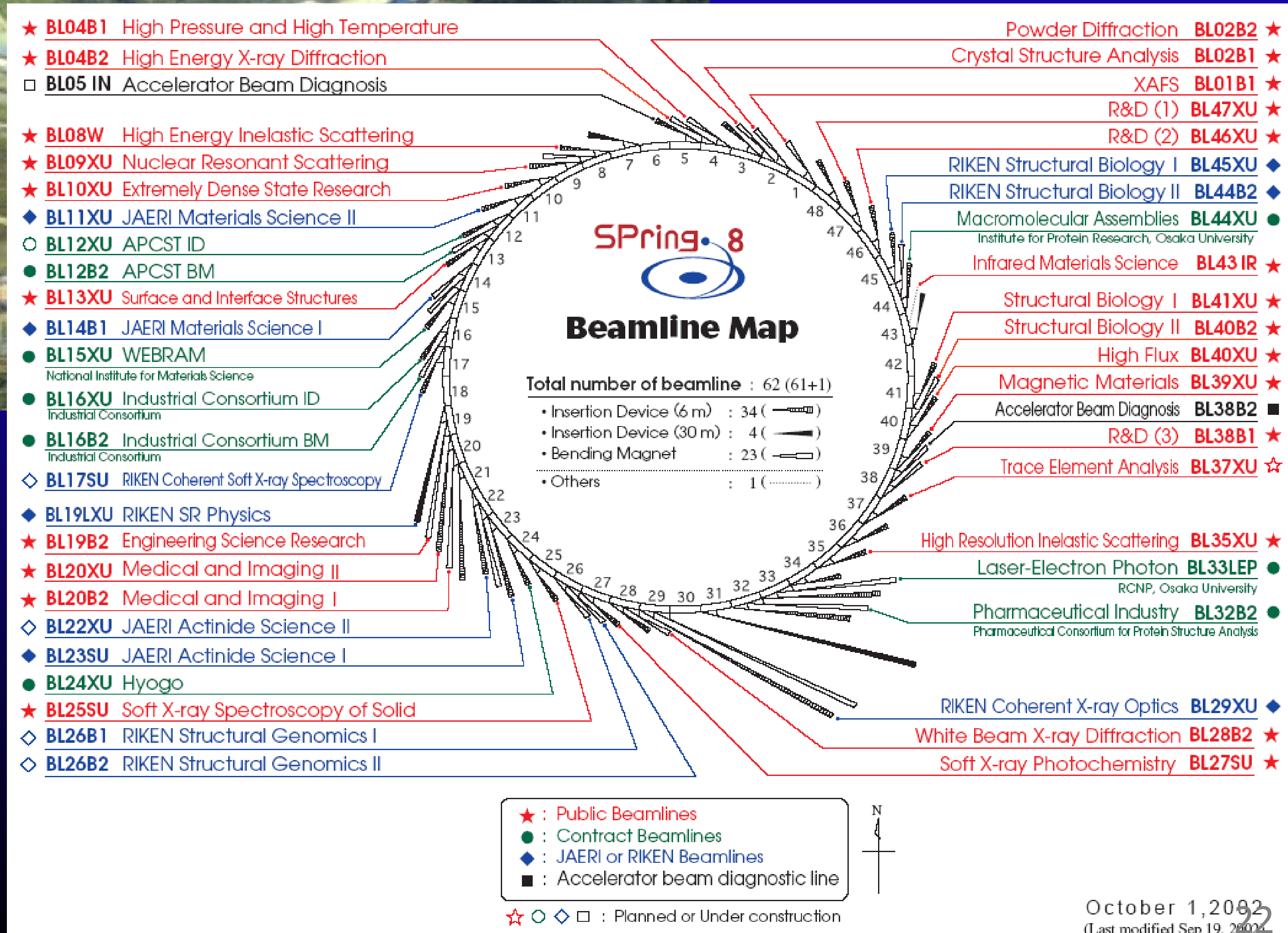
– **double bremsstrahlung (first observation and study)**

First electron-electron colliding beam experiments – 1965


APS

SPring8





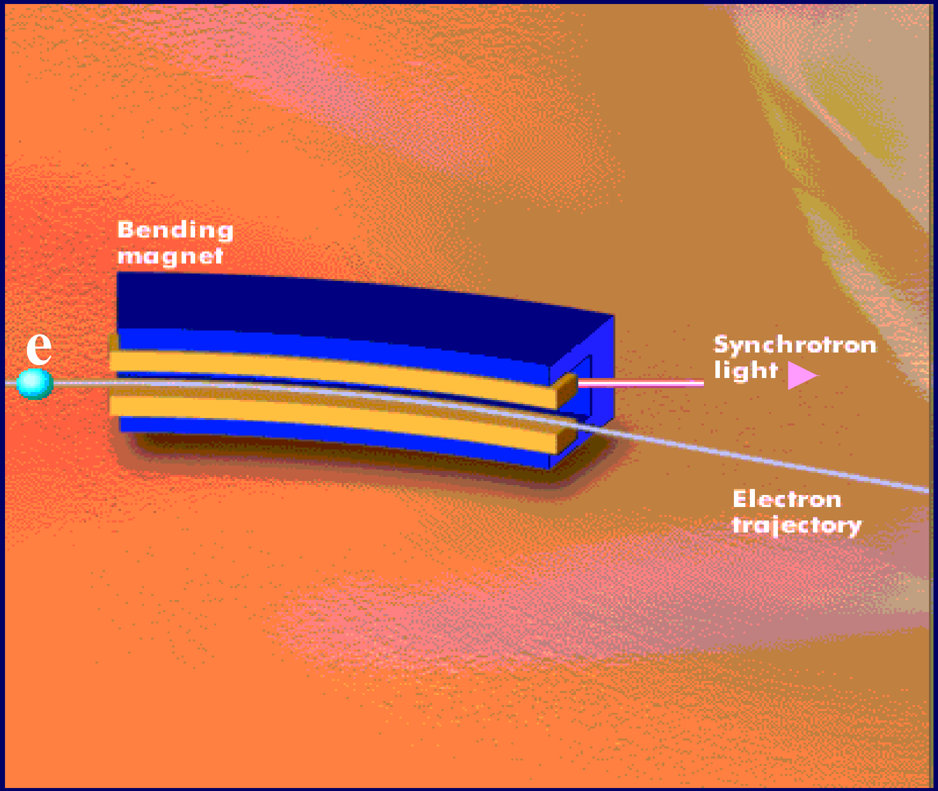
SPring-8
Beamline Map
Total number of beamline : 62 (61+1)
• Insertion Device (6 m) : 34
• Insertion Device (30 m) : 4
• Bending Magnet : 23
• Others : 1
★ BL04B1 High Pressure and High Temperature
★ BL04B2 High Energy X-ray Diffraction
□ BL05 IN Accelerator Beam Diagnosis
★ BL08W High Energy Inelastic Scattering
★ BL09XU Nuclear Resonant Scattering
★ BL10XU Extremely Dense State Research
◆ BL11XU JAERI Materials Science II
○ BL12XU APCST ID
● BL12B2 APCST BM
★ BL13XU Surface and Interface Structures
◆ BL14B1 JAERI Materials Science I
● BL15XU WEBRAM
National Institute for Materials Science
● BL16XU Industrial Consortium ID
Industrial Consortium
● BL16B2 Industrial Consortium BM
Industrial Consortium
◇ BL17SU RIKEN Coherent Soft X-ray Spectroscopy
◆ BL19LXU RIKEN SR Physics
★ BL19B2 Engineering Science Research
★ BL20XU Medical and Imaging II
★ BL20B2 Medical and Imaging I
◇ BL22XU JAERI Actinide Science II
◆ BL23SU JAERI Actinide Science I
● BL24XU Hyogo
★ BL25SU Soft X-ray Spectroscopy of Solid
◇ BL26B1 RIKEN Structural Genomics I
◇ BL26B2 RIKEN Structural Genomics II
Powder Diffraction BL02B2 ★
Crystal Structure Analysis BL02B1 ★
XAFS BL01B1 ★
R&D (1) BL47XU ★
R&D (2) BL46XU ★
RIKEN Structural Biology I BL45XU ◆
RIKEN Structural Biology II BL44B2 ◆
Macromolecular Assemblies BL44XU ●
Institute for Protein Research, Osaka University
Infrared Materials Science BL43 IR ★
Structural Biology I BL41XU ★
Structural Biology II BL40B2 ★
High Flux BL40XU ★
Magnetic Materials BL39XU ★
Accelerator Beam Diagnosis BL38B2 ■
R&D (3) BL38B1 ★
Trace Element Analysis BL37XU ☆
High Resolution Inelastic Scattering BL35XU ★
Laser-Electron Photon BL33LEP ●
RCNP, Osaka University
Pharmaceutical Industry BL32B2 ●
Pharmaceutical Consortium for Protein Structure Analysis
RIKEN Coherent X-ray Optics BL29XU ◆
White Beam X-ray Diffraction BL28B2 ★
Soft X-ray Photochemistry BL27SU ★
★ : Public Beamlines
● : Contract Beamlines
◆ : JAERI or RIKEN Beamlines
■ : Accelerator beam diagnostic line
☆ ○ ◇ □ : Planned or Under construction
N
October 1,2002
(Last modified Sep 19, 2002)

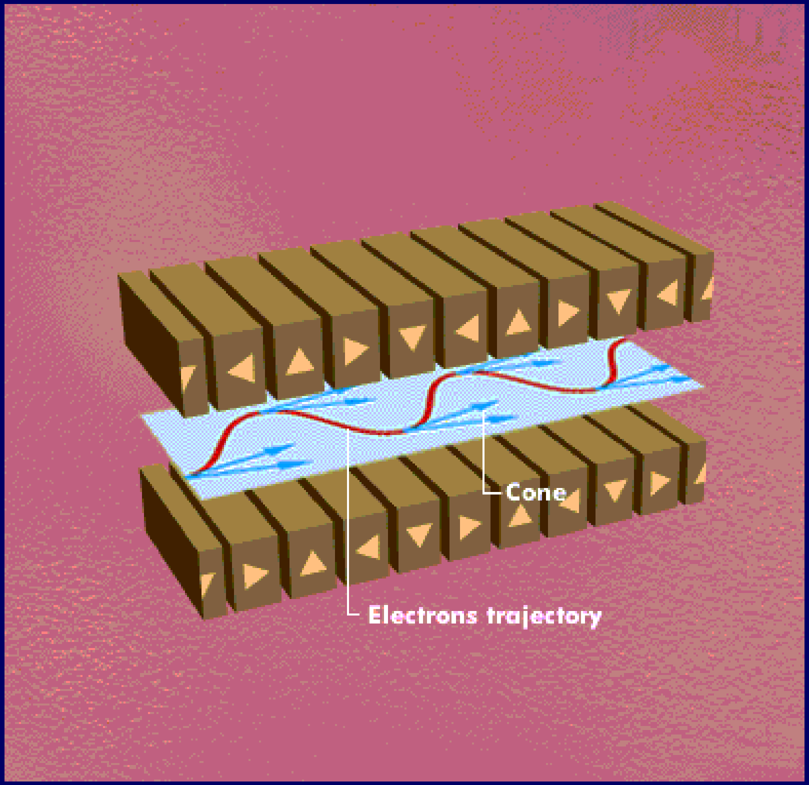
Location	SR Facility/ Storage Ring	Energy, GeV	Note*
NORTH AMERICA			
Canada, Saskatoon	CLS	2.5	DS
USA, Berkley, CA	ALS	1.5-1.9	DE
Argonne, IL	APS	7	DE
Baton Rouge, LA	CAMD	1.4	DE
Ithaca, NY	CHESS	5.5	PD
Stoughton, WI	SRC	0.8-1.0	DE
Stanford, CA	SSRL	3-3.5	DE
Gaithersburg, MD	SURF III	0.28	DE
Upton, NY	NSLS I	0.75	DE
	NSLS II	2.5-2.8	DE
Durham, NC	DFELL	1-1.3	DE/FE
SOUTH AMERICA			
Brazil, Campinas	LNLS-1	1.15	DE
	LNLS-2	2.0	DS/DE
EUROPE			
Germany, Karlsruhe	ANKA	2.5	DE
Berlin	BESSY I	0.8	DE
	BESSY II	1.7	DE
Dortmund	DELTA	1.5	DE/FE
Bonn	ELSA II	1.5-3.5	PD
Dresden	ROSY	3	DS/DE
Hamburg	HASYLAB/ PETRA II	7-14	PD
	DESY: DORIS III	4.5	DE
Denmark, Aarhus	ISA: ASTRID I	0.6	PD
	ASTRID II	1.4	PL/DE
Spain, Barcelona	LLC	2.5	DS/DE
France, Greboble	ESRF	6	DE
	DCI	1.8	DE
Orsay	LURE: super ACO	0.8	DE
	SOLEIL	2.5-2.75	PL/DE
Italy, Frascati	DAFNE	0.51	DE
Trieste	ELETTRA	1.5-2	DE
United Kingdom, Didcot	DIAMOND	3	PL/DE
Daresbury	SRS	2	DE
	SINBAD	3.0	DS/DE
Sweden, Lund	MAX: MAX I	0.55	DE
	MAX II	1.5	DE
Switzerland, Villingen	SLS	2.4	DE
Nitherlands, Amsterdam	AmPS	0.9	PL
Eindhoven	EUTERPE	0.4	PL
CIS COUNTRIES			
Russia, Moscow	KSRS: Sibir-1	0.45	DE
	Sibir-2	2.5	DE
Novosibirsk	BINP: SSRC	0.8	DE
	VEPP-2M	0.7	PD
	VEPP-3M	2.2	PD
	VEPP-4M	5-7	PD
Armenia, Yerevan	CANDLE	3	DS
ASIA			
South Korea, Pohang	PLS	2	DE
China, Beijing	BSRF	1.6-2.8	DE/PD
Hefei, Anhui	NSRL	0.8	DE
Shanghai	SSRF	2-2.5	DS/DE
India, Indore	INDUS I	0.45	DE
	INDUS II	2	DS/DE
Japan, Hiroshima	HISOR	0.7	DE
Ichihara	NANO-HANA	1.5-2	DS/DE
Tsukuba	PHOTON FACTORY	2.5	DE
Nishi Harima	SPRING 8	8	DE
Okazaki	UVSOR	0.75	DE
Tokyo	VSX	1-1.6	PD
	SOR-Ring	0.5	DE
Tsukuba	NIJI-II	0.6	DE
	NIJI-IV	0.5	DE/FE
	TERAS	0.8	DE
	NIJI-III	0.6	DE
Nishi-Harima	NewSubaru	1-1.5	DS/DE
Kusatsu	AURORA	0.6	DS/DE
Kashiwa	HBLS	2-2.5	DS/DE
Osaka	Kansai SR	1.8	DS/DE
Kyoto	KSR	0.3	DS/DE
Sendai	TLS	1.5	DS/DE
Singapore, Singapore	HELIOS 2 or SSLS	0.7	DE
Taiwan, Hsinchu	SRRC	1.3-1.5	DE
AUSTRALIA			
Australia, Viktoria	BOOMERANG	3 GeV	DS

* **DE** – dedicated (synchrotrons built solely to access the electromagnetic radiation emitted); **PD** – partly dedicated; **DS** – design; **PL** – planned use; **FE** – FEL (free electron lasers) use

More than 60 SR sources over the world

3. What is SR from bending magnet, undulator and wiggler?





Synchrotron radiation (SR) – electromagnetic radiation of relativistic charged particles in magnetic field.

The basic properties of synchrotron radiation

$$\theta \sim \frac{1}{\gamma} \sim \frac{m_0 c^2}{E} \quad \left(10^{-2} \div 10^{-4}\right) rad$$

$$\lambda_c \sim \frac{R}{\gamma^3} \quad \left(10^{-4} \div 10^{-12}\right) m$$

$$\varepsilon_c \sim E^2 B \quad \left(10^{-2} \div 10^{6}\right) eV$$

$$P \sim I_e E^2 B^2 L \quad \left(up\ to\ \ 100 kW\right)$$

Among the main elements of modern SR sources are undulators and wigglers - periodic magnetic structures, the use of which was first proposed in the work by V. Ginzburg in 1947; several years later, the first undulator was created and tested at the linear accelerator by Motz et al.,

first wiggler was created by K. Robinson in 1966.

Using straight sections of electron storage rings for housing wigglers and undulators (also called 'snakes'), which give rise to a periodic magnetic-field of alternatirig signs and of period λ_0 along a segment of length $L = N_u\lambda_0$ (where N_u is the number of periods) is a very effective method for enhancing the synchrotron radiation intensity. In the simplest case, the field in such structures has the form

$$B_y(z) = B_0 \sin\frac{2\pi z}{\lambda_0}$$

The total energy losses of electrons passing through such a periodic structure of length *L* are independent of the peculiarities of its construction:

$$\Delta W : r_e^2 \; \bar{B}_y^2 \gamma^2 L,$$

Where $r_e = \frac{e^2}{mc^2}$ is the classical electron

radius, and γ is the ratio of the electron energy to its rest energy mc^2.

However, the spectra1 and angular distributions of radiation from the snake depend significantly on how the condition for interference of the radiation is provided for and, correspondingly, on the geometric overlapping of electron radiation from all the poles of the undulator. This is why the operation mode of the snake is determined by the relation between the maximum turning angle of the electron in the magnetic field of the snake,

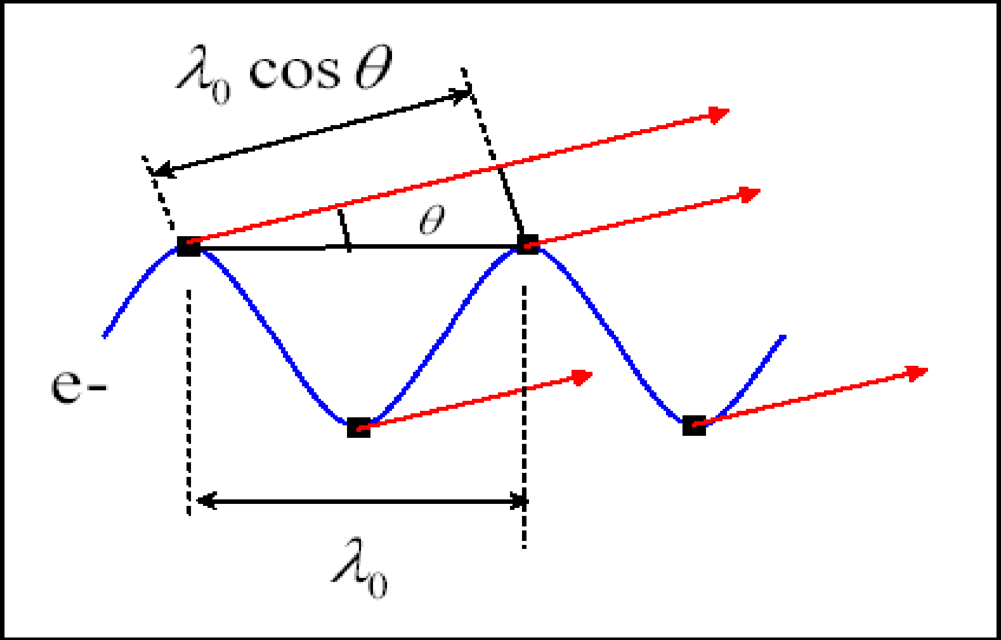
$\alpha_0 = \lambda_0/(2\pi R) = \lambda_0 e B_0/(2\pi\gamma mc)$ and by the characteristic angle of radiation divergence from each point of the electron's trajectory, $\psi_{x,z} \sim 1/\gamma$. The ratio of these quantities, $K = \alpha_0\gamma = \lambda_0 e B_0/2\pi mc$ is conventionally known as the undulator parameter.

Undulator mode ($K \ll 1$)

For relativistic electrons in the case of small fields $(K \ll 1)$, the transverse motion of electrons in the snake is nonrelativistic, and the longitudinal velocity modulation for an electron moving in the snake can be neglected. The electromagnetic wave emitted by an electron passing through the snake a single time (Fig. 3) arrives at the observation point on the axis of the snake in the form of a 'zug' of bursts of the electric and magnetic fields with a period

$$T_1 = \frac{\lambda_0}{\upsilon_P} - \frac{\lambda_0}{c}$$

where vII is the electron velocity along the axis of the snake.



$$\lambda = \frac{\lambda_u}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right)$$

Owing to the trajectory inside the snake being curved, the average longitudinal velocity of the electrons al0ng the z-axis is given by

$$\upsilon_P = \upsilon\left(1 - \frac{\alpha_0^2}{4}\right),$$

Whence follows

$$T_1 = \frac{\lambda_0}{\upsilon\left(1 - \alpha_0^2/4\right)} - \frac{\lambda_0}{c} = \frac{\lambda_0}{2\gamma^2 c}\left(1 + \frac{\alpha_0^2\gamma^2}{2}\right)$$

Correspondingly, radiation with a wavelength

$$\lambda_u = T_1 c = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{\alpha_0^2\gamma^2}{2}\right) = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2}\right)$$

will be registered at the observation point on the z-axis

The source of radiation approaches an observation point on a ray situated at a certain angle θ to the axis of the 'snake' with a velocity cosθ. At this point, the radiation is registered with the wavelength

$$\lambda_0 = \frac{\lambda_0}{2\gamma^2}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right).$$

The monochromaticity of undulator radiation at the zero angle is determined by the length of the 'zug' and, correspond-ingly, by the number of emitters (periods of the undulator):

$$\frac{\Delta\lambda}{\lambda_u} \sim \frac{1}{N_u}$$

The angular divergence of the undulator radiation by order of magnitude amounts to

$$\Delta\psi_{0z} \approx \Delta\psi_{0x} \approx \sqrt{\frac{\lambda_u}{L_u}} \approx \frac{\sqrt{1+K^2/2}}{\gamma\sqrt{2N_u}}$$

The 'effective' lateral dimension of the source, corresponding to this angular divergence, is equal to

$$\Delta_{1z} \sim \Delta_{1x} \sim \frac{1}{4\pi}\sqrt{\lambda_u L_u}$$

The total number of quanta emitted by a single electron passing through the undulator is evaluated as

$$N_{1u} = \frac{\Delta W_{sn} \lambda_u}{2\pi \mathrm{h} c} \approx \frac{1}{137} N_u \alpha_0 K^2 \gamma$$

The radiation from an undulator with a transverse magnetic field is linearly polarized, while the radiation from an undulator with a helical magnetic field, in which $B_y = B_o \sin(2\pi z/\lambda_0)$, and $B_x = B_o \cos(2\pi z/\lambda_0)$, is circularly polarized.

At present, the term 'undulator' is used for a ‘snake’ with a large number of poles, a weak magnetic field, and a small period, which deflects the trajectory of an electron by an angle $\alpha_0 \leq 1/\gamma$. The main requirement for the operation of a ‘snake’ in the undulator mode, which consists in providing conditions for constructive interference of the electron beam radiation from all the poles of the undulator, imposes severe restrictions on the angular divergence inside the electron beam. Thus, for example, modern projects of X-ray sources (λ_u ~Å) foresee the use of undulators ~ 100 m long, for which, according to the simple interference condition

$$\frac{1}{2} L_u \Theta^2_{x,z} < \frac{\lambda_u}{2\pi},$$

electron beams are required that exhibit angular divergences $\Theta_{x,z} < 10^{-6}$.

Generation of undulator radiation harmonics ($K \gtrsim 1$)

When the magnetic field in the ‘snake’ strengthens, the quantity *K* increases, the transverse motion of the electrons becomes relativistic, and modulation of the longitudinal electron velocity along the axis of the ‘snake’ becomes significant. In this case, harmonics of the undulator radia-tion (i = 1, 2, . . .) arise in the radiation spectrum:

$$\lambda_u = \frac{\lambda_0}{2i\gamma^2}\left(1 + \frac{K^2}{2} + \lambda^2\theta^2\right).$$

The parameter *K* determines the ratio of two character-istic times peculiar to radiation from the ‘snake’ in the case of a strong magnetic field. The first time corresponds to the duration of the burst of electric and magnetic, fields from the sole magnet, registered by the observer:

$$\Delta T_{SR} \sim \frac{m}{\gamma^2 eB}.$$

The second time is determined by the interval betwcen the bursts of electric and magnetic fields, emitted from adjacent periods:

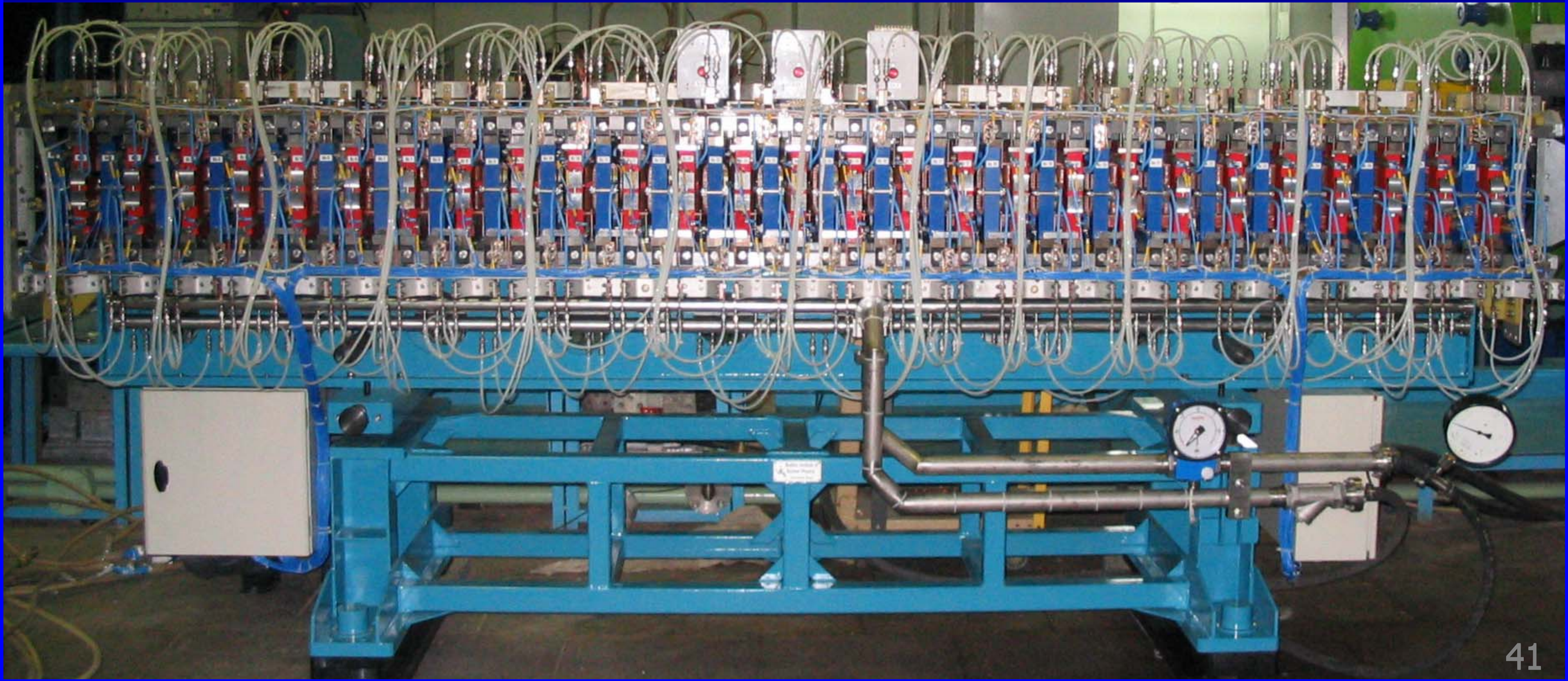
$$\Delta T_u = \frac{\lambda_0}{2\gamma^2 c}\left(1 + \frac{K^2}{2} + \gamma^2\theta^2\right).$$

It is the ratio $\Delta T_u / \Delta T_{SR} \sim K(1 + K^2/2)$ that determines the number of harmonics contributing significantly to the total radiation power of the ‘snake’,

Undulators HU256
For SR source Soleil (France)

designed and produced at the Budker INP
(Novosibirsk, Russia)

3 undulators + magn. meas. system
April 2004 – October 2005



Operation for the wiggler mode ($K \gg 1$)

In the case of a high magnetic field ($K \gg 1$), many harmonics appear in the radiation spectrum, which exhibit maximum intensity in the region of the synchrotron radiation wave-length determined by the local curvature of the trajectory) in a single magnet ($\lambda \sim R/\gamma^3$). Characteristics of the SR flux at the observation point are obtained by adding up the contributions from different segments of the trajectory.

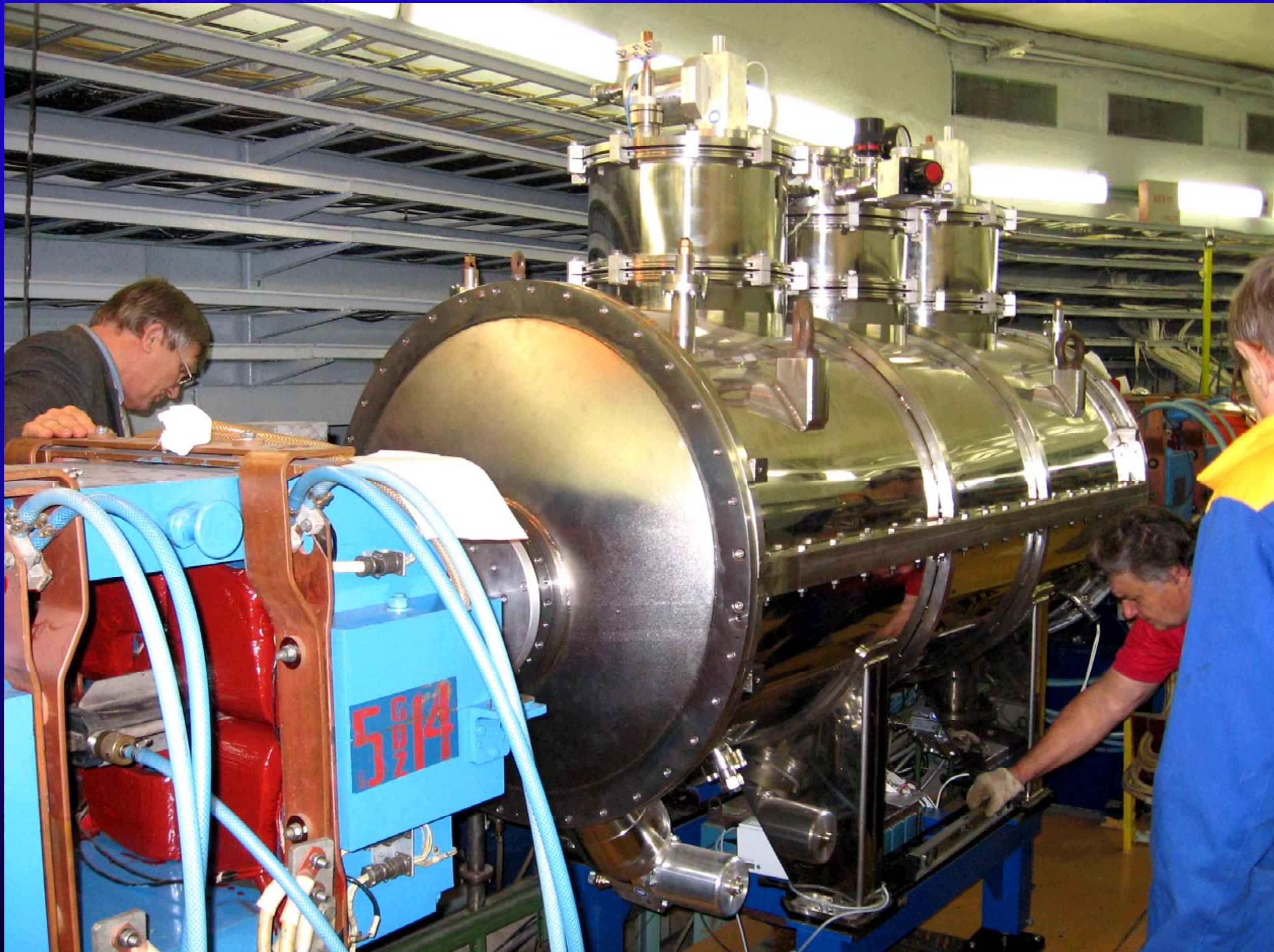
Integrating the intensity over a finite solid angle and averaging it over the parameters of electrons in the beam result in the higher harmonics (for $K \gg 1$) broadening and overlapping in the spectrum. The radiation angle in the long-wave region of the spectrum exceeds $\psi_{x,z} \sim 1/\gamma$, since $\psi_\lambda \sim (1/\gamma)(\lambda/\lambda_c)^{1/3}$, therefore interference in the long-wave part of the spectrum is also observed for $K \gg 1$.

Today, the word 'wiggler' is used in describing a 'snake' with a strong magnetic field and long period, which deflects electron trajectories at large angles $\alpha \gg 1/\gamma$, and is intended for generating radiation with a spectrum typical of SR. The use of wigglers permits:

(1) obtaining radiation with photons exhibiting higher energies, owing to the strong magnetic fields of a wiggler;

(2) enhancing the photon flux by a factor of $2N_u$ (N_u is the number of periods) as compared to the radiation from bending magnets, owing to the radiation from all the poles of the wiggler being added up;

(3) varying the spectrum independently at different experimental stations that make use of the radiation from different wigglers.



Superconductive 7.7 T 21-pole wiggler
at the second generation SR source “Siberia-2” (Moscow, Russia)

An analysis of the requirements to synchrotron radiation sources for various types of experiments [14] reveals that the main 'consumer' characteristic consists in the spectral bright-ness $B_\lambda = \acute{N}_{ph}/(S\Omega)$ determined by the number of photons emitted per unit time within a given spectral band$(\Delta\lambda/\lambda)$ from a unit area $(S \sim \Delta_x\Delta_z)$ to a unit solid angle $(\Omega \;\; \Delta_{x'}\Delta_{z'})$.

The spectral "brightness" of a light source:

Brightness = const $F/(S \cdot \Omega)$

To estimate the radiation brightness of undulators it is necessary to take into account the size of the source. So, the effective lateral dimensions of the radiation source are

$$\Delta_{x,z} = \sqrt{\sigma^2_{\mathrm{x,z}} + \left(\frac{\lambda L}{(4\pi)^2} + \Theta^2_{x,z} L_u^2 \right)},$$

while the effective angular divergence of the radiation is

$$\Delta_{x'z'} = \sqrt{\frac{\lambda}{L_u} + \Theta^2_{x,z}}$$

where $\sigma_{x,z}$ is the electron beam cross section, and $\Theta_{x,z}$ is the angular divergence of the electron beam.

Since

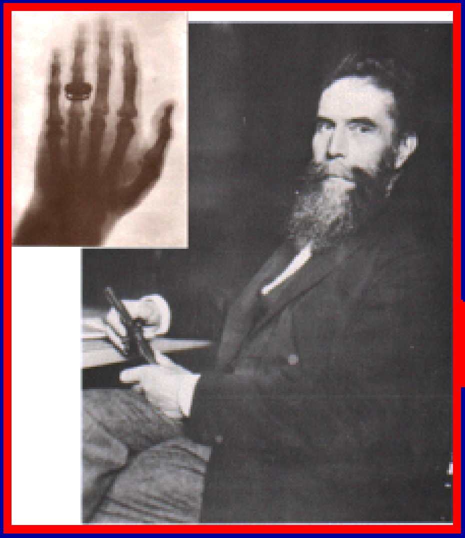
$$\sigma_{x,z} \cdot \Theta_{x,z} = \varepsilon_{x,z}\ ; \qquad \sigma_{x,z} = \sqrt{\varepsilon_{x,z}\beta_{x,z}}\ ; \qquad \Theta_{x,z} = \sqrt{\frac{\varepsilon_{x,z}}{\beta_{x,z}}}$$

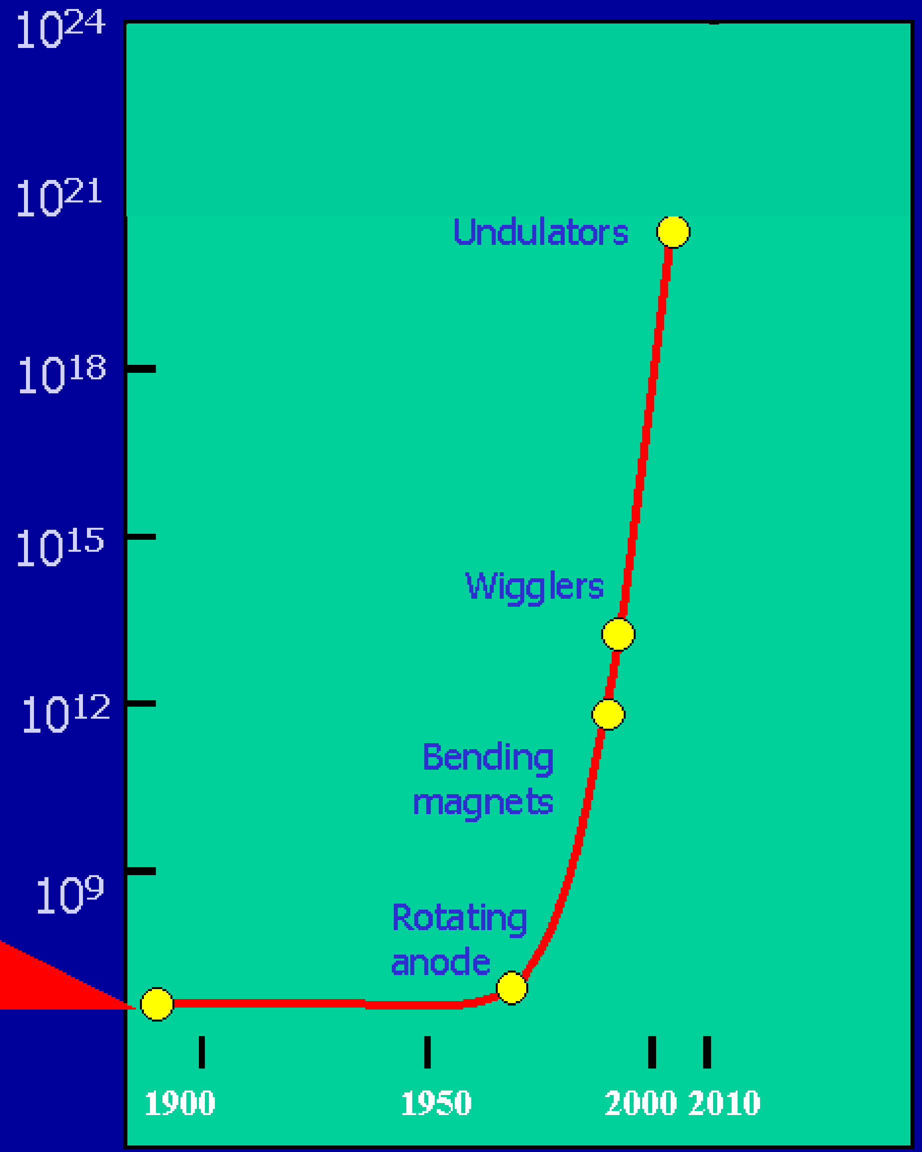
where $\varepsilon_{x,z}$ is the emittance (phase volume) of the electron beam, $\beta_{x,z}$ is the local effective focal distance of the magnetic system ($\beta_{x,z} \sim L$, when the undulator has been placed in an optimal manner), the most important condition for enhance-ment of the brightness consists in the reduction of the emittance of the electron beam together with a simultaneous increase in its energy, which permits applying long undulators for generating short-wave radiation

The next diagram outlines the history, the present-day state of affairs, and the plans for enhancing the brightness of X-ray sources. Everything, of course , started with the discovery by W C Roentgen in 1895 of the rays that bear his name, after which the first X-ray tubes were created with a brightness $B_\lambda \sim 10^6$ photons per 1 s per mm^2 $mrad^2$ (0.1 % $\Delta\lambda/\lambda$). After about 60 years, their brightness was increased via evolutionary development approximately by two orders of magnitude owing to enhancement of the electron beam power due to the use of a rotating anode and of micro focus X--ray tubes which allowed reducing the dimension of the electron beam at the anode.

Steep rise in brightness/brilliance

(units: photons/mm^2/s/mrad^2, 0.1% bandwidth)





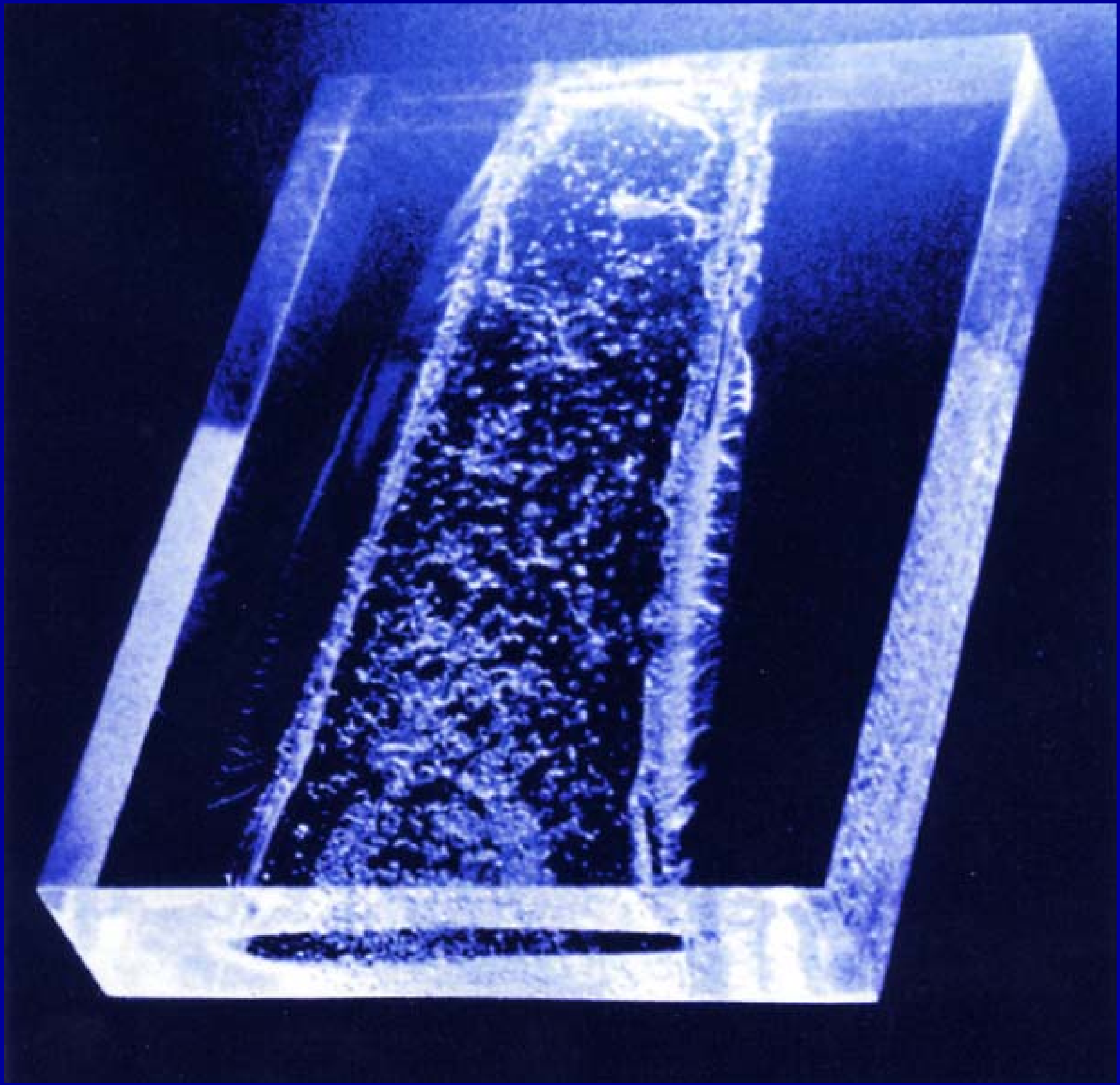
Spring-8

Siberia-2

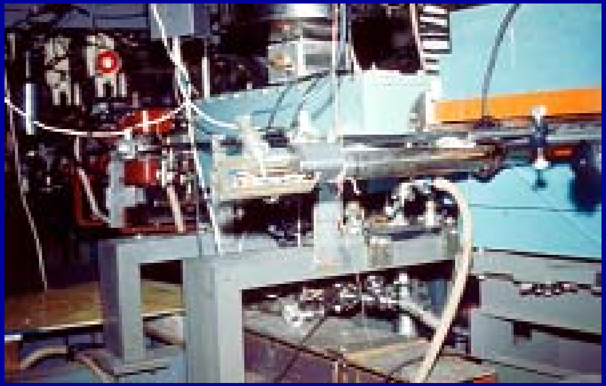
VEPP-3

The use of electron synchrotrons, and subsequently of electron storage rings, as sources of X-ray synchrotron radiation permitted the accelerator community, starting from the 1980s, to perform purposeful work aimed at achieving a revolutionary increase in the brightness of X-ray sources. Passage from synchrotrons to storage rings in the 1970s resulted in an increase in the brightness approximately by a factor of 10^2 - 10^3 owing to the average current in storage rings being higher and the emittance and, subsequently, the electron beam lateral dimensions being smaller (ε_x ~ 300 nm rad) due to radiation damping.

Further enhancement of the brightness (approximately by a factor of 10 – 100) was implemented by making use of multipole wigglers. The creation in the 1980s of specialized storage devices - SR sources of the second generation - permitted reducing the emittance of electron beams to $\varepsilon_x \sim 30$ nm rad and, thus, decreasing the area of the radiation source and enhancing the brightness by approximately one more order of magnitude.



Ablation of PMMA (organic glass) due to treatment of SR beam from superconductive wiggler Installed on VEPP-3 storage ring (Novosibirsk, 1979)



“Zmeyka” – first in the world multi-pole superconductive wiggler – SR source installed on storage ring (VEPP-3, Novosibirsk, 1979-1982)

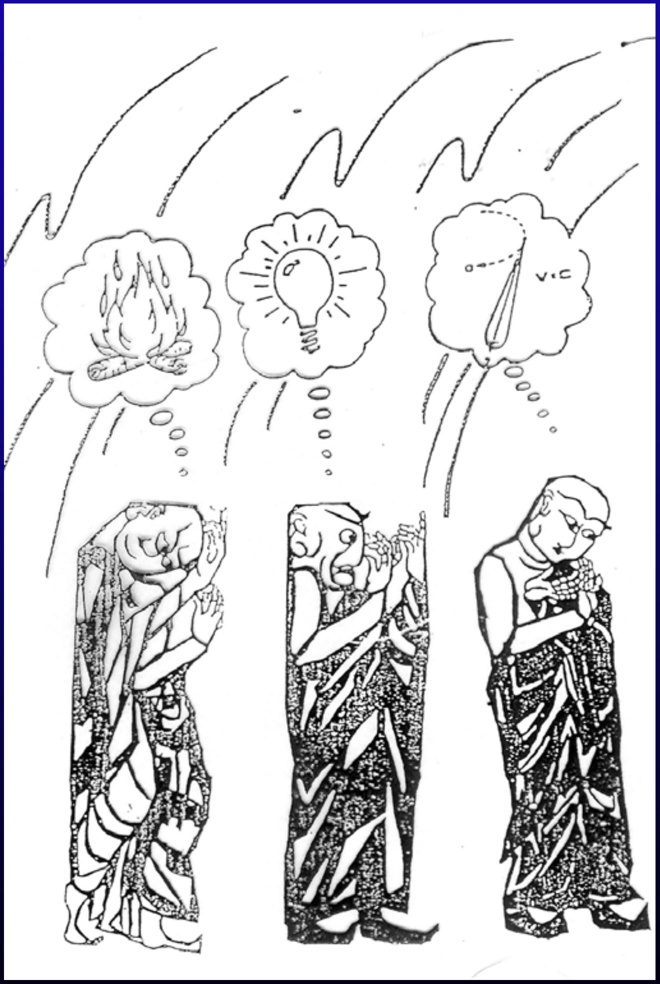
3.3 T, 20 poles, period = 9 cm

ε_c ~ 8 KeV, Pw max ~ 1.2 KW

The SR sources of the third generation, created in the 1990s and having even smaller emittances (ε_x ~ 3 nm rad) and higher energies (*E* ~ 6- – 8 GeV), make use of long undulators with N_u ~ 10^2 – 10^3 as X-ray sources. This enabled increasing the flux of quanta as compared to the case of beam-bending magnets by a factor of N_u and, also, owing to interference of the radiation from all poles of the undulator, additionally decreasing the solid angle by N_u times, as a result of which the brightness of the undulator increased by a factor of N_u (~ 10^4 – 10^6)!

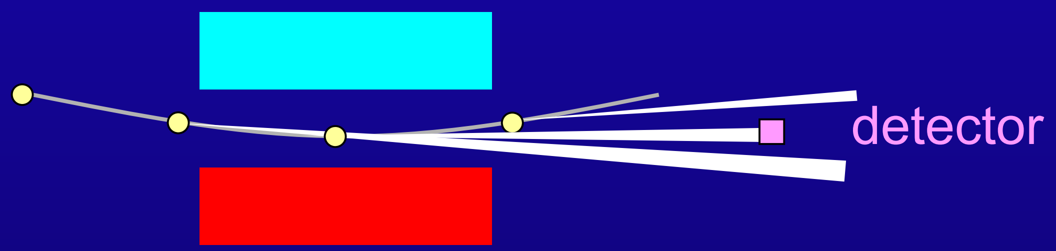
Due to the purposeful work of accelerator physicists the brightness of new sources of X-ray synchrotron radiation increased by three orders of magnitude every decade, which has permitted increasing the brightness of X-ray sources by a factor of 10^9 during the past thirty years.

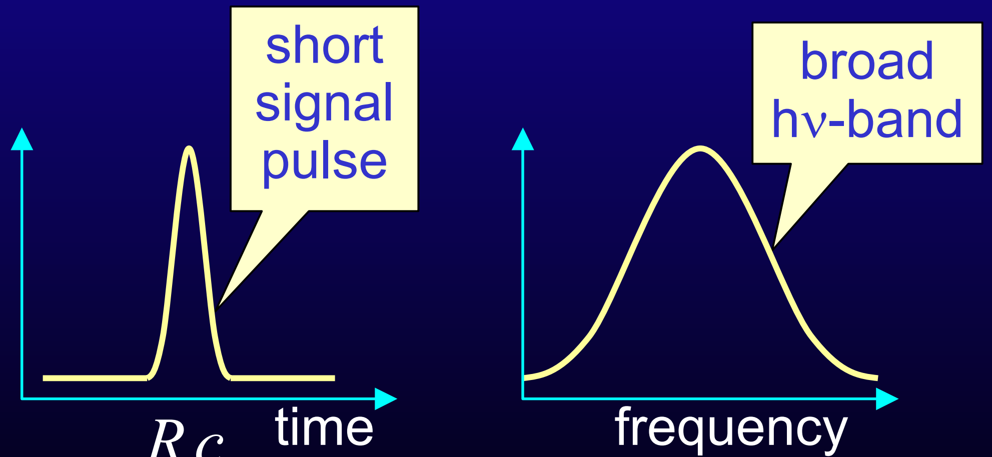
3. Three generations of light sources



First generation SR sources – using of cyclic electron synchrotrons and electron-positron storage rings with emittance $\varepsilon \sim 300$ nm in parasitic mode during high energy experiments

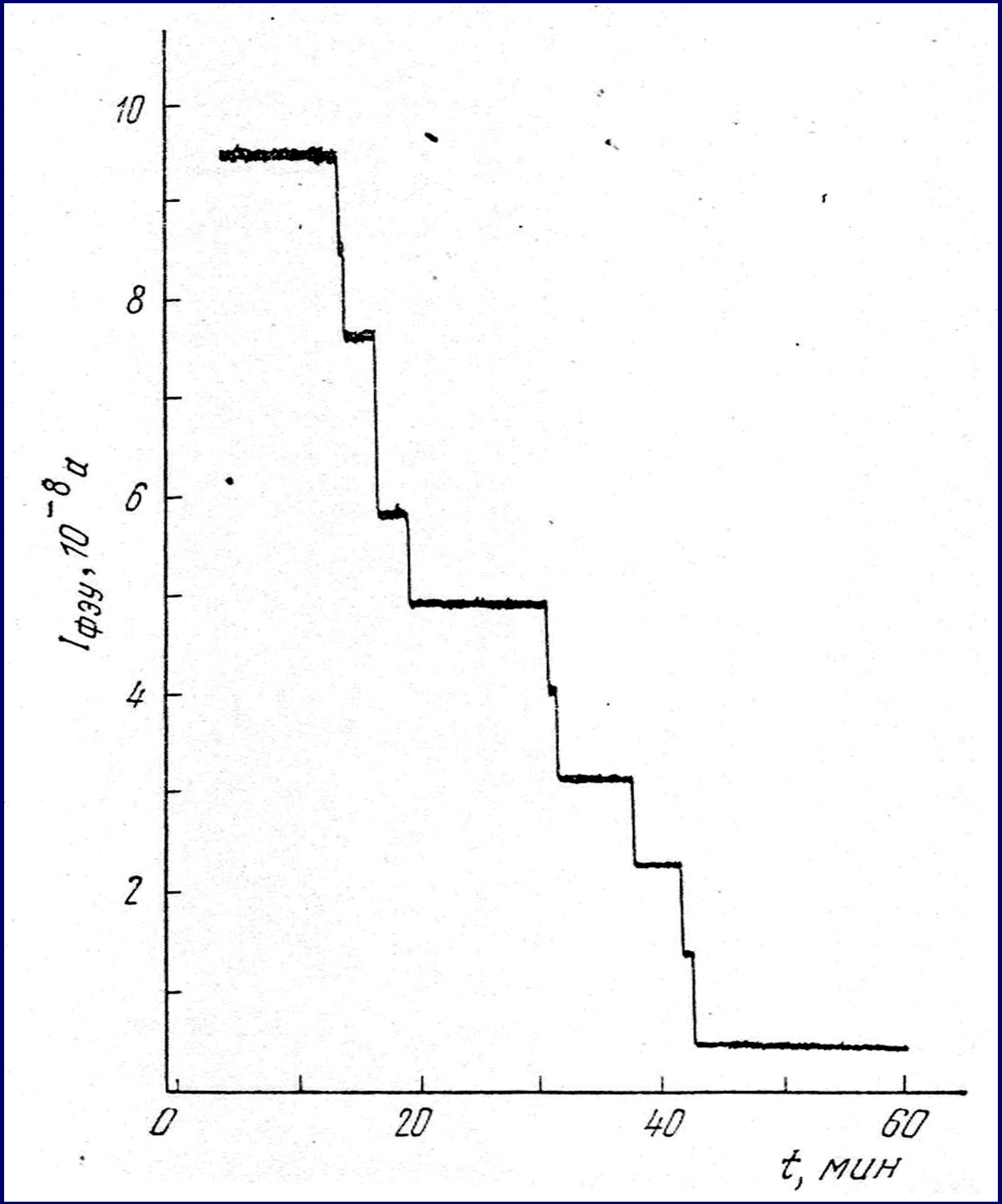
Bending magnets: $F \sim N_e$



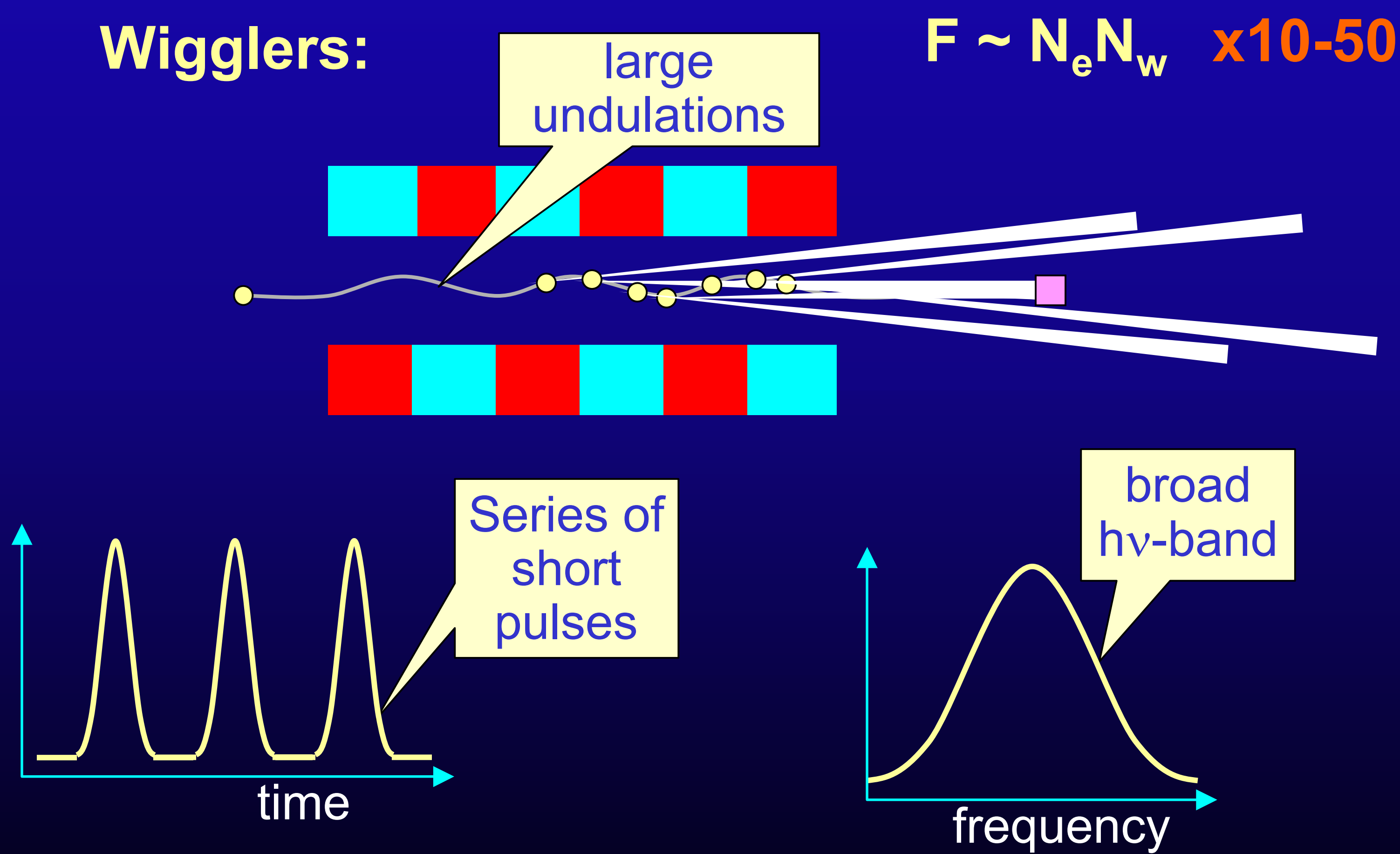


$$\Delta t \sim \frac{Rc}{\gamma^3}$$

after G. Margaritondo


10
8
6
4
2
$I_{фэу}, 10^{-8} a$
0
20
40
60
t, мин

Second generation SR sources –
dedicated storage ring - synchrotron radiation sources
(low emittance ε ~ 30 nm, set of straight sections for wigglers)

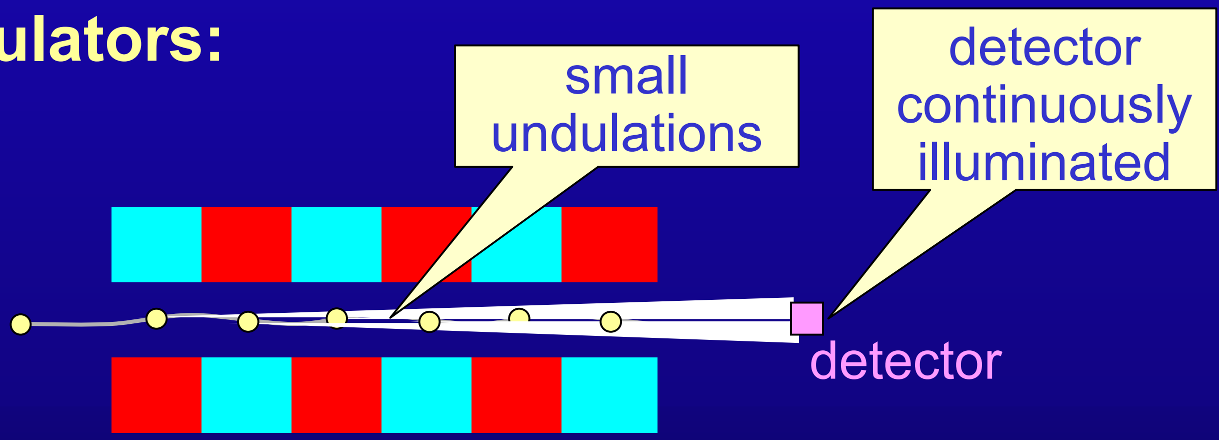


after G. Margaritondo

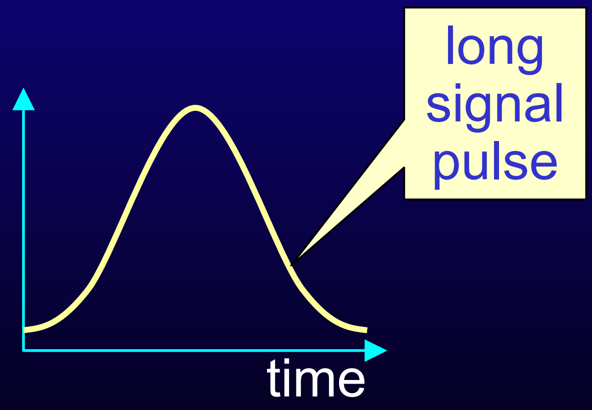
Superconductive 2.2 T 63-pole wiggler
designed and produced at the Budker INP (Novosibirsk, Russia)
at the third generation Canadian Light Source
(CLS, University of Saskatchevan, Canada, 2005)

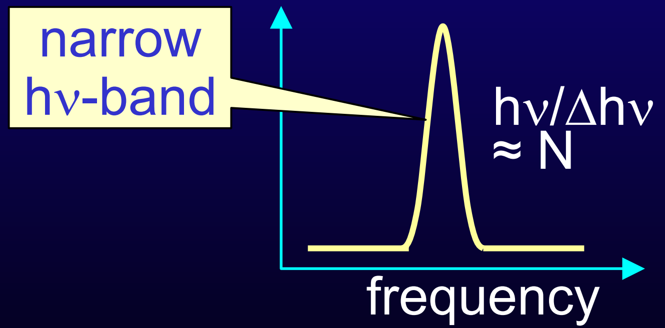
Third generation SR sources – storage rings optimized for installation of undulators (low emittance $\varepsilon \sim 3$ nm, set of long straight sections for long undulators)

Undulators:



$F \sim N_e N^2_u$ x10^3-10^4





after G. Margaritondo

In-vacuum undulator U-24 (Spring-8 / SLS)

G. Ingold
T. Schmidt

SUMMARY II

- **The SR sources of the 3rd generation available and those under construction (APS, ESRF, Spring-8, SLS, DIAMOND, SOLEIL …) are the efficient factories for generation of the new knowledge, new technologies and new materials.**

- **In the last decade, there were active discussions on the development of SR sources of the 4th generation. The world's physical community worked out the requirements to these sources and suggested several ways for the development of such sources.**

- ***SR sources of the 4th generation is a subject of our next lecture.***

THANK YOU FOR ATTENTION

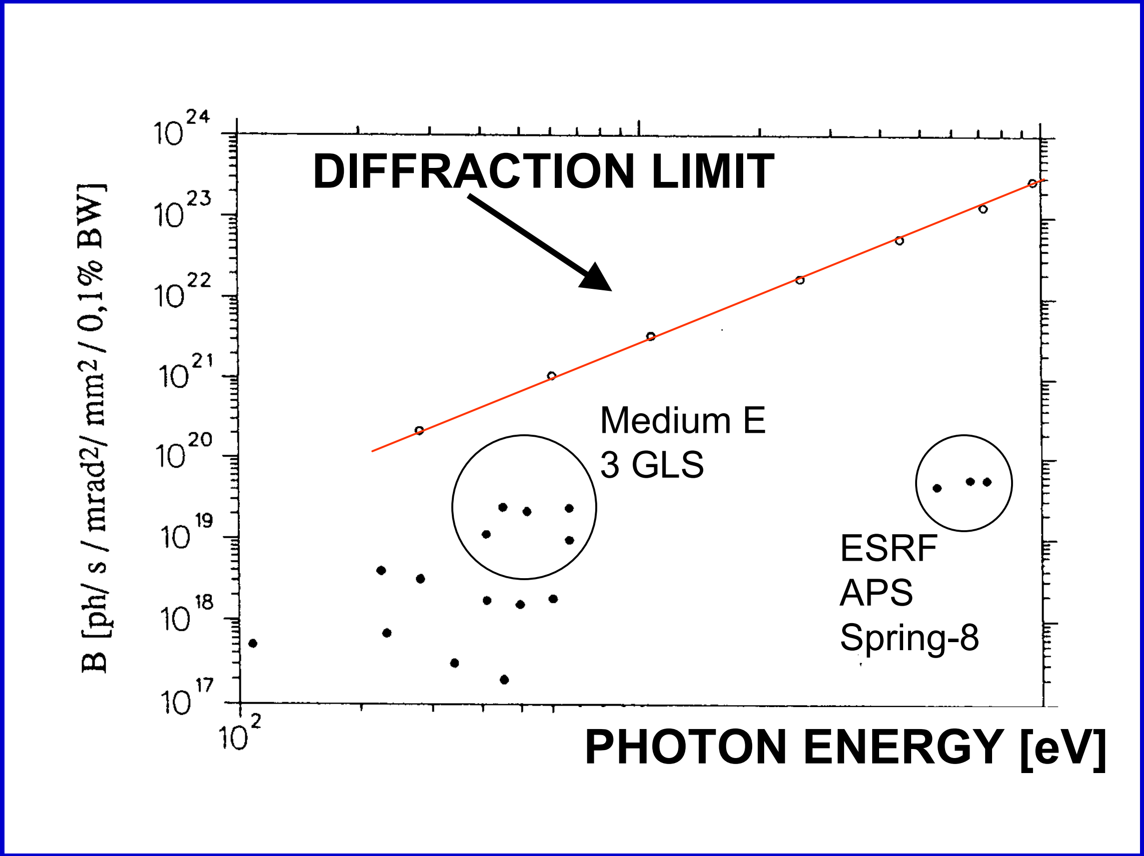
The flux of spatially coherent quanta increased in proportion to the brightness enhancement, since one has

$$\dot{N}_{\text{coh}} : B_{\lambda} \cdot \lambda^{2}.$$

Nevertheless, in the most modern sources, APS (Advanced Photon Source) (USA) and SPring-8 (Super Photon ring) (Japan), the flux of coherent quanta only amounts to 10^{-3} of the total flux. Therefore, in spite of successful experiments on X-ray holography, this method has not become effective for structure studies of real objects (the structures of most of which are not crystalline). Even in studies of crystalline structures, the speckle spectroscopy, for which spatially coherent irradiation is also necessary, rather often happens to be very important.

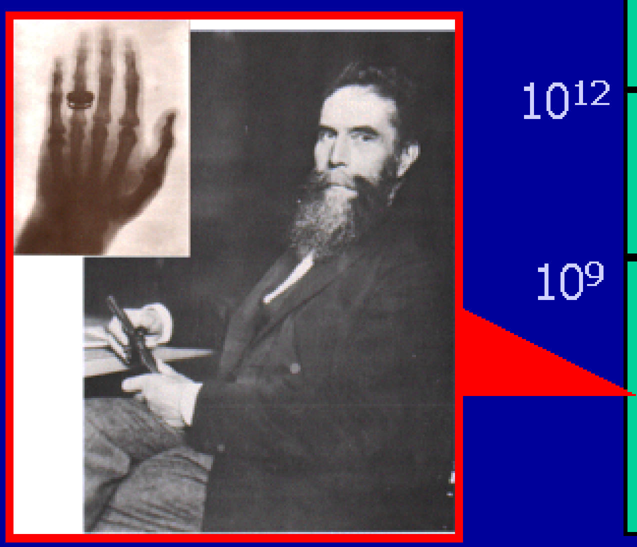
PERFORMANCE OF 3th GENERATION LIGHT SOURCES

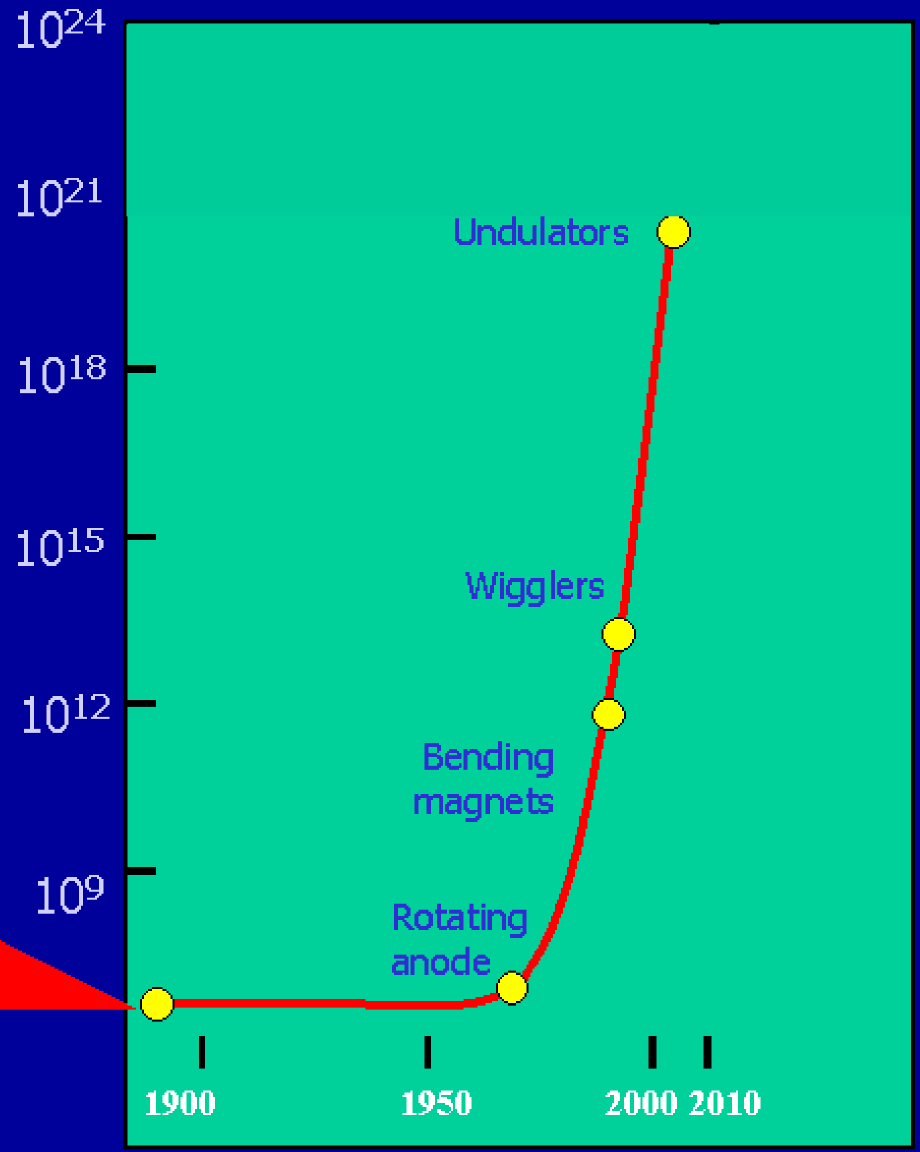
BRIGHTNESS:



Steep rise in brightness/brilliance

(units: photons/mm²/s/mrad², 0.1% bandwidth)





Spring-8

Siberia-2

VEPP-3

The realization of a totally spatially coherent source will become possible if the phase volume of the optical source becomes smaller than the diffraction limit:

$$\Delta_{x,z} \cdot \Delta_{x',z'} \leq \frac{\lambda}{4\pi}$$

To this end, the emittance of the electron beam must be sufficiently small, so that

$$\varepsilon_{x,z} = \sigma_{x,z} \cdot \Theta_{x,z} < \frac{\lambda}{4\pi}$$

(which for X-ray radiation means $\varepsilon_{x,z} < 10^{-2}$ nm rad).

The emittance and energy spread of an electron beam in an electron storage ring depends on the equilibrium between radiation damping and diffusion, caused by quantum fluctuations in the synchrotron radiation and by scattering inside the beam in the case of high-density beams. Additional analysis has shown that in a storage ring it is impossible to obtain an emittance of the electron beam inferior to 10^{-1} nm rad and an energy spread less than 10^{-3}, therefore realization of a totally spatially coherent X-ray source is possible in the case of passage from electron storage rings to energy recovery accelerator.

This proposal, first put forward by our team in 1997 at the conference SRI-97 (6th International Conference on Synchrotron Radiation Instrumentation) has now been adopted and is being actively developed at many world centers.

Energy recovery accelerators combine the advantages of electron storage rings (high reactive power of the beam; small losses of high-energy particles per unit time, and, correspondingly, a low radiation background and the absence of induced radioactivity) and linear accelerators (the normalized emittance ε_n of the electron beam and energy spread can be kept during acceleration).

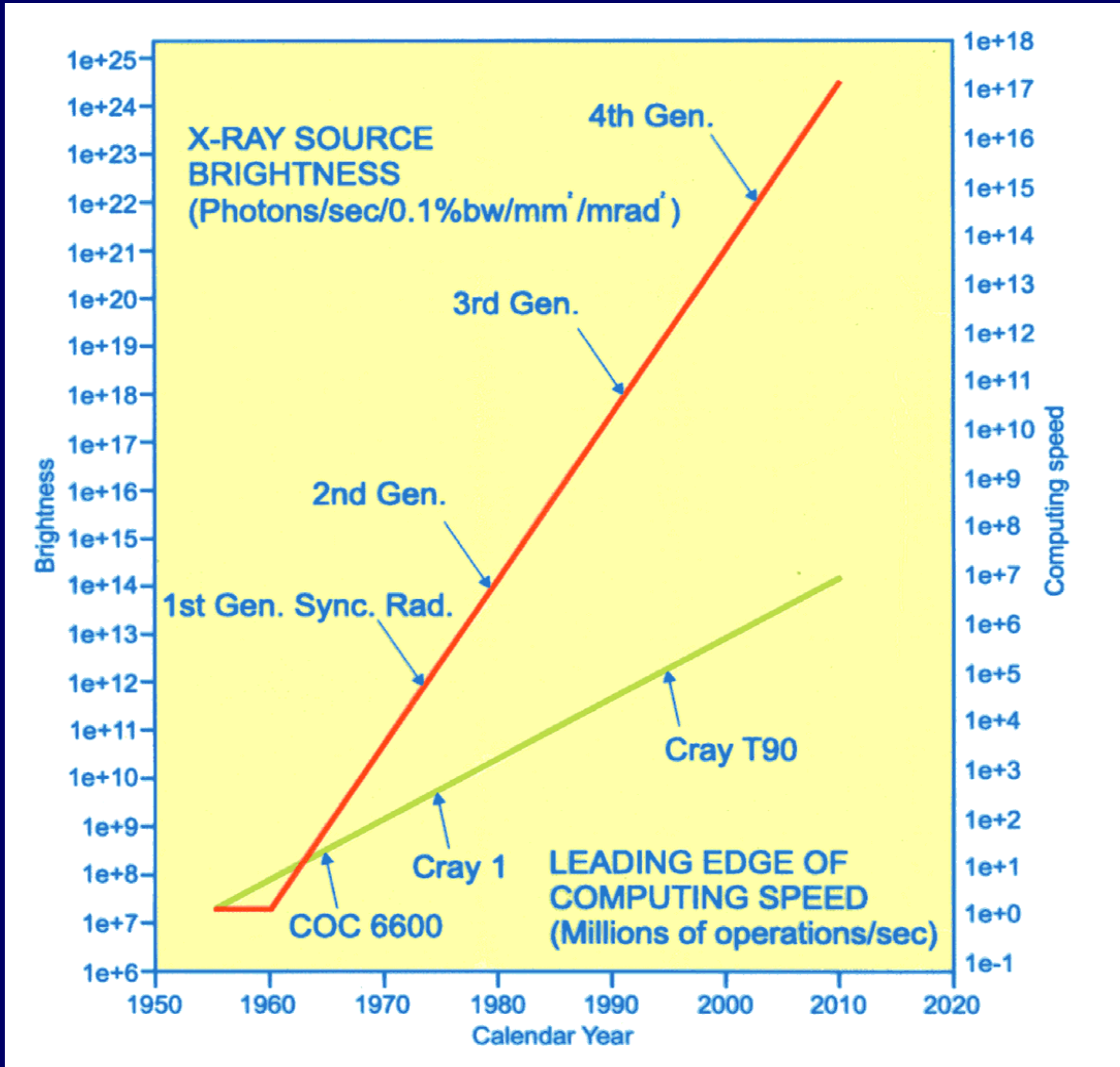
Therefore, if a good injector with ε_n < 100 nm rad is available, then, owing to adiabatic damping during acceleration up to high energies (E > 5 GeV, $\gamma > 10^4$), it is possible to obtain an emittance $\varepsilon_{x,z}$ = $\varepsilon_n/\gamma \sim 10^{-2}$ nm rad and an energy spread $\sigma_E/E \sim 10^{-4}$.

In accelerator-recuperators, the acceleration time ($\tau_{acc} \sim 1 - 10\mu s$) is significantly shorter (by 3 – 4 orders of magnitude) than the characteristic time of radiative damping in storage rings ($\tau_{rad} \sim 10$ ms), therefore diffusion processes cannot have a negative influence on the emittance and the energy spread of the electron beam

The next figure presents the layout of the four-turn re-circulating accelerator-recuperator MARS (Multi-turn Accelerator-Recuperator Source), which is at present being developed by our team. In MARS, the electrons obtained in the injector with an energy of ~ 5 MeV are then accelerated in an additional two-cascade injector, after which they pass through the main accelerating high-frequency structure four times, thus increasing their energy up to 6 GeV.

After acceleration, the electrons again travel in the same direction through the same high-frequency structures, but in a deceleration phase, decrease their energy to 5 MeV, and then land in the dump. In the ERL, electrons undergoing acceleration and deceleration travel simulta-neously along four tracks.

The users of synchrotron radiation will perceive the radiation from the MARS undulators like radiation from a storage ring, with the only difference that each time new ('fresh') electrons are used with a small emittance $\varepsilon_{min} \sim 10^{-2}$ nm rad and energy spread $\sigma_E/E \sim 10^{-4}$. For MARS project, four undulators 150 – 200 m long ($N \sim 10^4$) are placed in the four tracks, as well as several dozen undulators 5 – 20 m long ($N = 10^2 – 10^3$) into the arcs.


X-RAY SOURCE
BRIGHTNESS
(Photons/sec/0.1%bw/mm^2/mrad^2)
4th Gen.
3rd Gen.
2nd Gen.
1st Gen. Sync. Rad.
Cray T90
Cray 1
COC 6600
LEADING EDGE OF
COMPUTING SPEED
(Millions of operations/sec)
Brightness
1e+25
1e+24
1e+23
1e+22
1e+21
1e+20
1e+19
1e+18
1e+17
1e+16
1e+15
1e+14
1e+13
1e+12
1e+11
1e+10
1e+9
1e+8
1e+7
1e+6
Computing speed
1e+18
1e+17
1e+16
1e+15
1e+14
1e+13
1e+12
1e+11
1e+10
1e+9
1e+8
1e+7
1e+6
1e+5
1e+4
1e+3
1e+2
1e+1
1e+0
1e-1
1950
1960
1970
1980
1990
2000
2010
2020
Calendar Year

It is worth mentioning that due to the purposeful work of the accelerator physicists the brightness of new SR sources was improved by three orders of magnitude each decade. Therefore, for the last 30 years the brightness of X-ray SR sources has been increased by the factor of a billion.

Thank you for your attention