Synchrotron Radiation:
Generation and Applications

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Contents:

1. Introduction. History of synchrotron radiation activity.

2. Three generations of SR sources.

3. Ways of increasing of brightness of SR sources.

4. Why the 4^{th} generation SR sources should use the accelerators-recuperators?

5. MARS – diffraction limited coherent X-ray source for national or international SR centers.

6. X-ray SASE Free electron lasers (XFEL)

7. Conclusion.

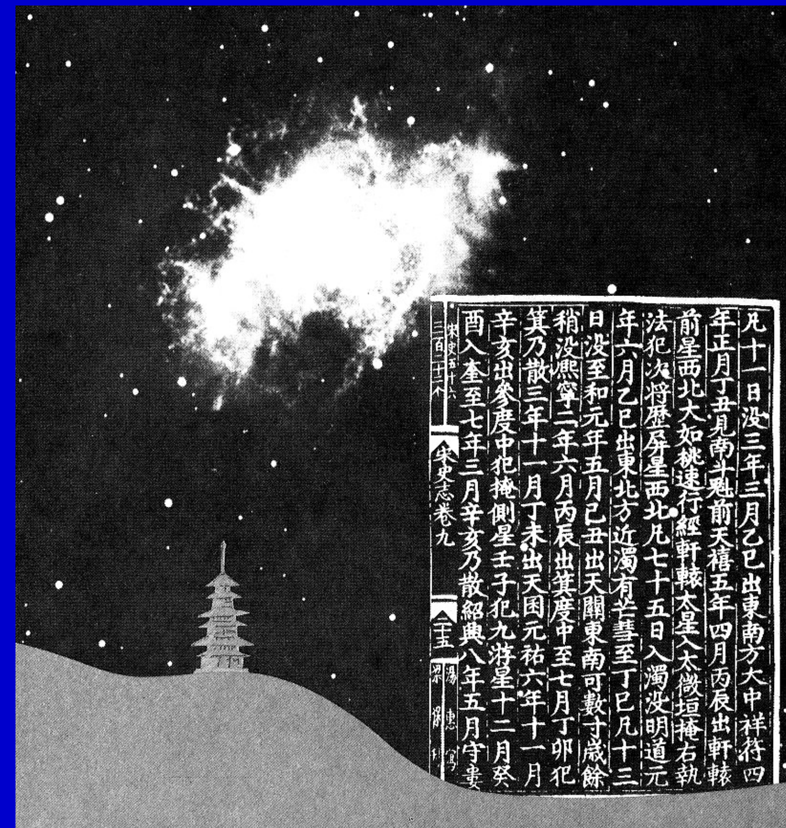
1. Introduction.

History of synchrotron radiation activity

First observation of synchrotron radiation

Crab Nebula
6000 light years away

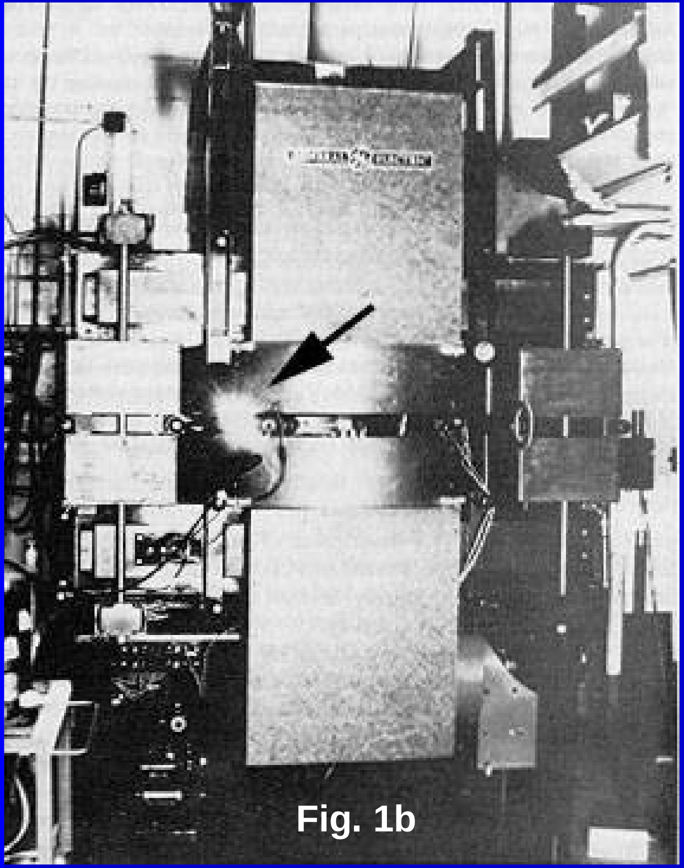
First light observed
1054 AD



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 Nebula is actually the synchrotron radiation of ultrarelativistic electrons in interstellar magnetic fields.

GE Synchrotron New York State



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. Two years later SR light from synchrotron had been observed in FIAN USSR.

The events illustrated by Figs 1a and 1b were separated by nine hundred years. It was the period of time necessary for mankind to comprehend that the glow of the Crab Nebula is produced by synchrotron radiation, on the one hand, and, on the other, to create the 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.

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:

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

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.

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

$$\Delta E \propto \mathbf{E}^{2}\cdot \mathbf{B}^{2}\cdot L$$

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

$$\Delta W \propto \mathbf{E}^{4}/R$$

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 ($\propto R/\gamma^3$), radiation of non-interacting system of electrons (and limits for such approach).

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 SR SOURCES

1. **V. I. Veksler (1944)** Comptes Rendus de ' 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)

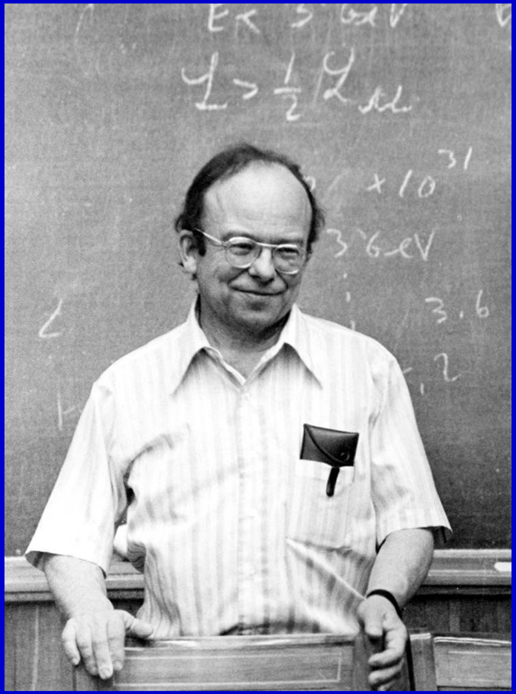
- invented strong focusing synchrotron

CEA (USA), NINA (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)

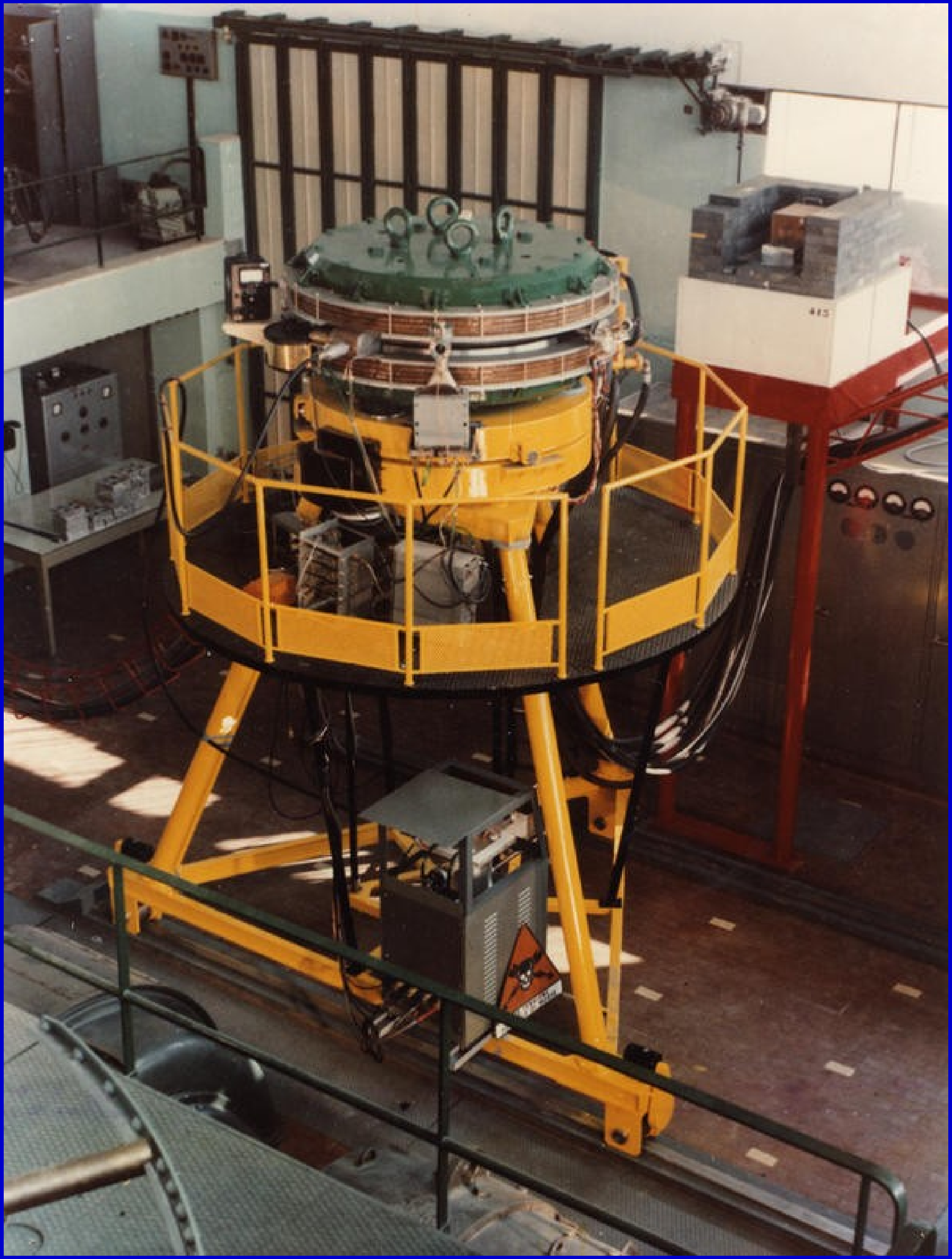
D.K.O'Neill
(Princeton)



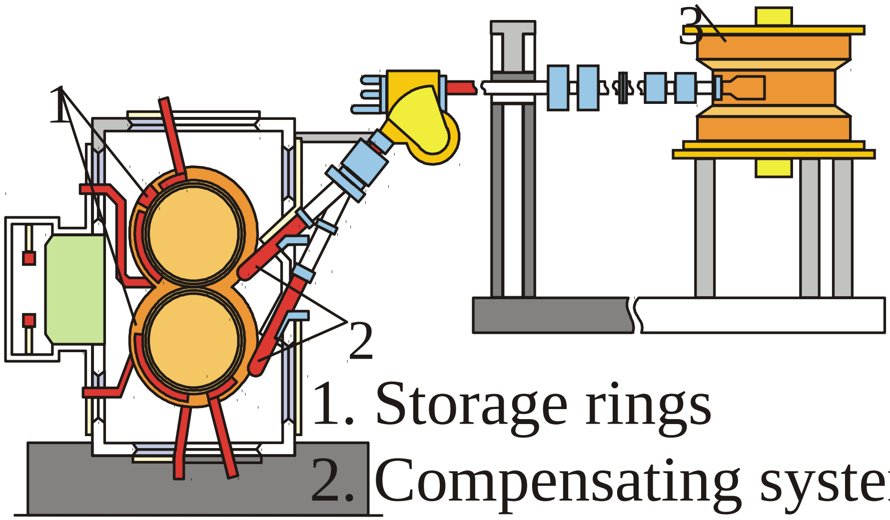
W.Panofsky
(Stanford)

G.Budker
(Moscow-Novosibirsk)

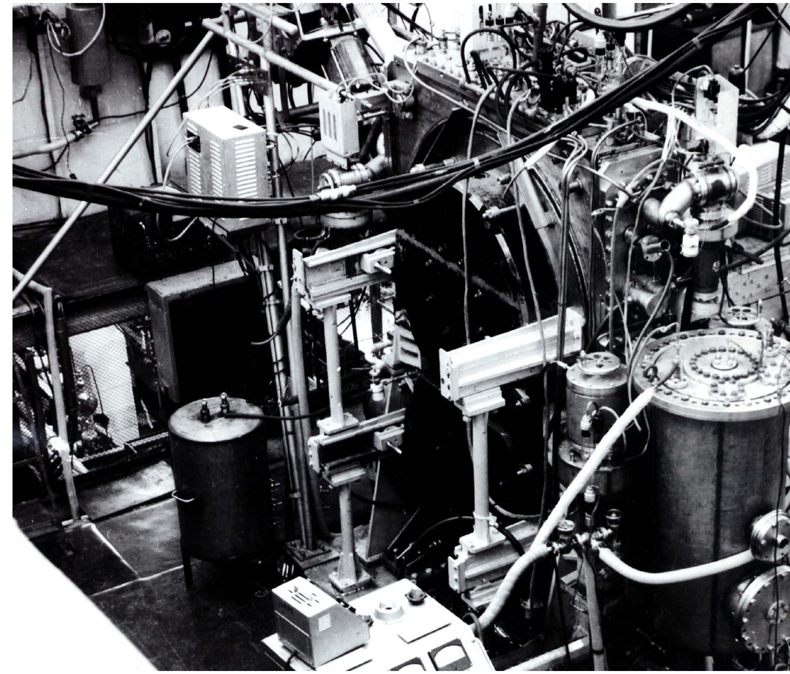
First Italy-France storage ring AdA



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



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



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

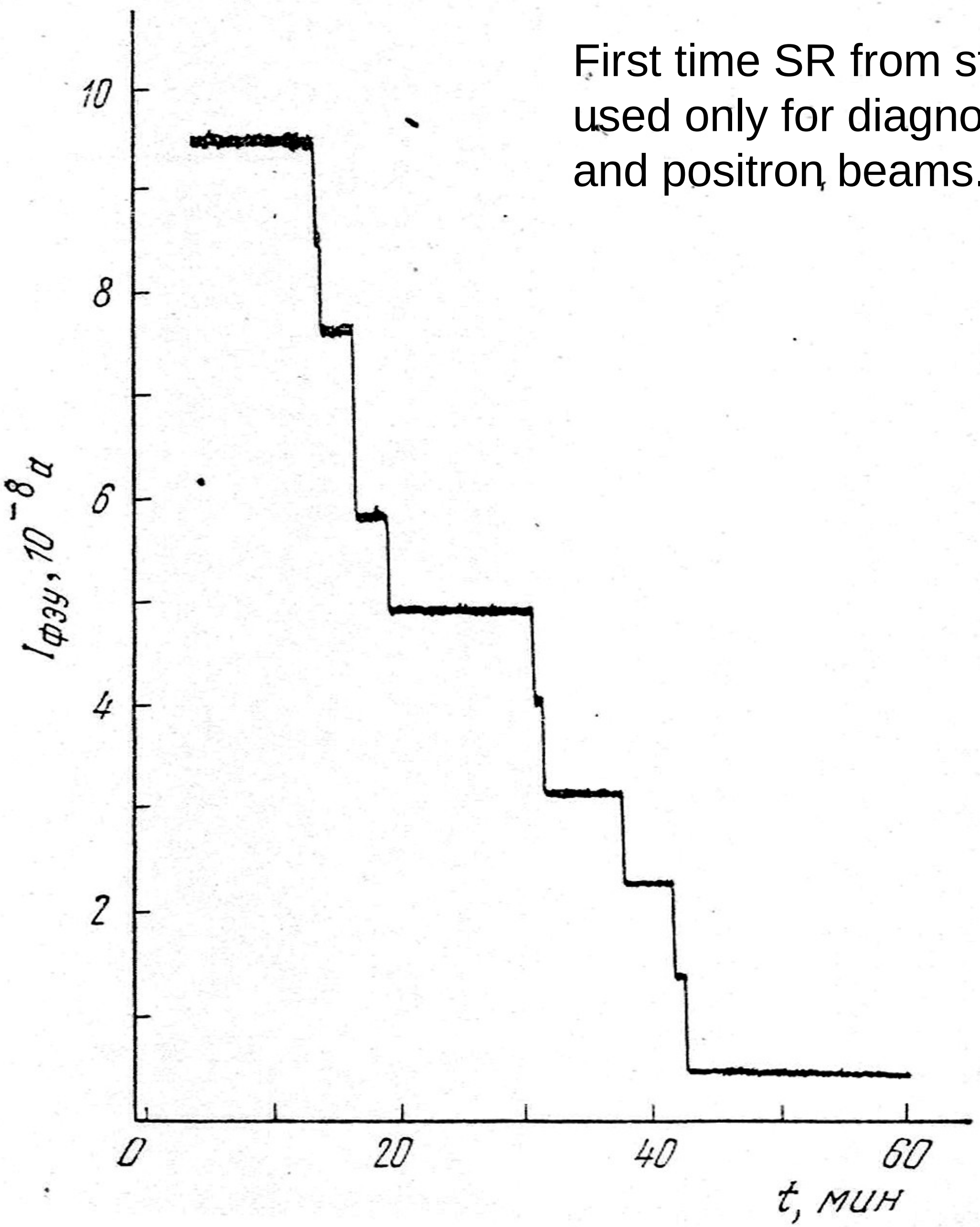
Exps 1965-1967 **:**

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

— double bremsstrahlung (first observation and study)

VEP-1 to-day as a monument

First electron-electron colliding beam experiments –

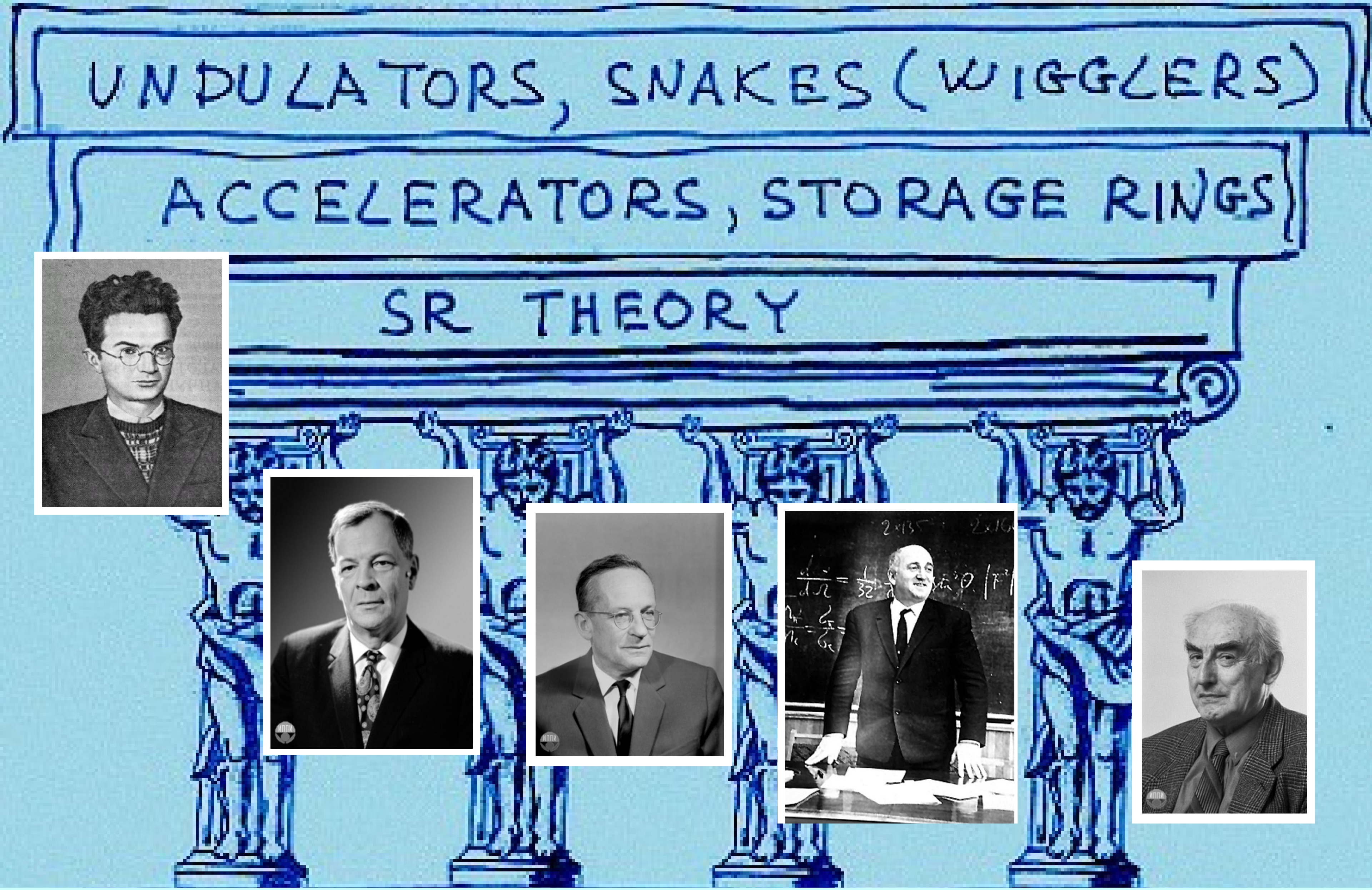


First time SR from storage rings was used only for diagnostics of electron and positron beams.

- 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 for solution of accelerator tasks at CEA (Cambridge, USA);

- first superconducting 20-pole 3.3 T wiggler for experiments with X-ray SR was created at Novosibirsk Budker INP in 1979.



In spite of the international character of science, Russian scientists have practically always happened to be among the first to resolve the aforementioned problems. Figure presents the photographs of outstanding Russian scientists who laid the physical foundations for the creation of SR sources:
I.Ya. Pomeranchuk, L.A. Artsimovich, V.I. Veksler, G.I. Budker, and V.L. Ginzburg.

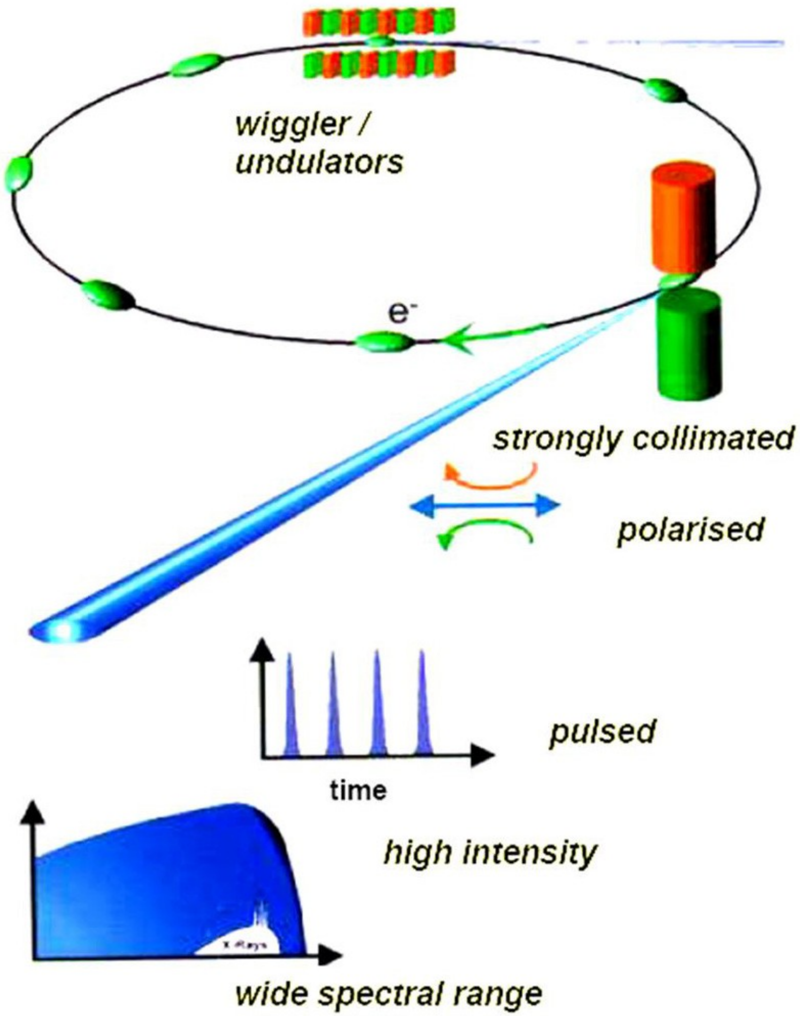


Схема электронного накопителя с источниками СИ (поворотным магнитом и вигглером/ондулятором) и основные свойства излучения (оно узко направленное, поляризованное, импульсное, имеет высокую яркость, интенсивность и широкий спектральный диапазон).

Диапазон излучения:
•от терагерцовой области до жесткого рентгена
Основные методы:
• спектроскопия
• дифракция/рассеяние
•визуализация
Области применения:
•физика твердого тела
•кристаллография
•структурная биология
•химия/катализ
•науки о Земле и экология
•материаловедение, нанотехнологии
•медицина
•атомы, молекулы и кластеры
•магнетизм
•технические науки

Основные параметры пучка синхротронного излучения:

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

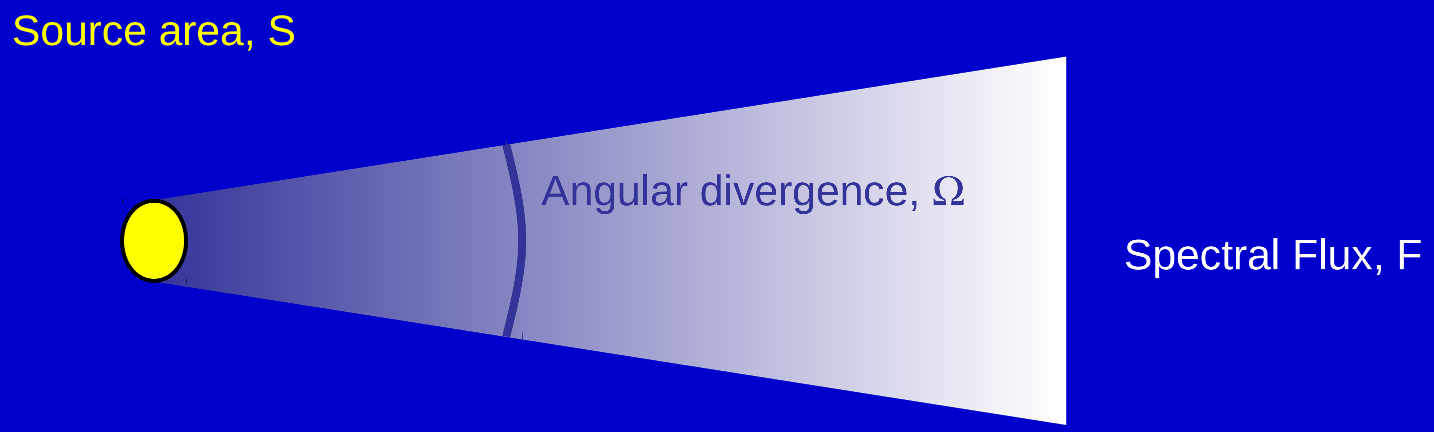
Характеристическая длина волны $\lambda_c \sim \dfrac{R}{\gamma^3}$ $\left(10^{-4} \div 10^{-12}\right) m$

Характеристическая (критическая) энергия кванта $\varepsilon_c \sim E^2 B$ $\left(10^{-2} \div 10^{6}\right) eV$

Мощность $P \sim I_e E^2 B^2 L$ $\left(up\ to\ \ 1000 kW\right)$

Спектральная яркость $\dfrac{\text{Photons}}{\text{sec}\cdot\text{mm}^2\cdot\text{mrad}^2\,(0.1\%\Delta\lambda/\lambda)}$ $(up\ to\ 10^{21})$

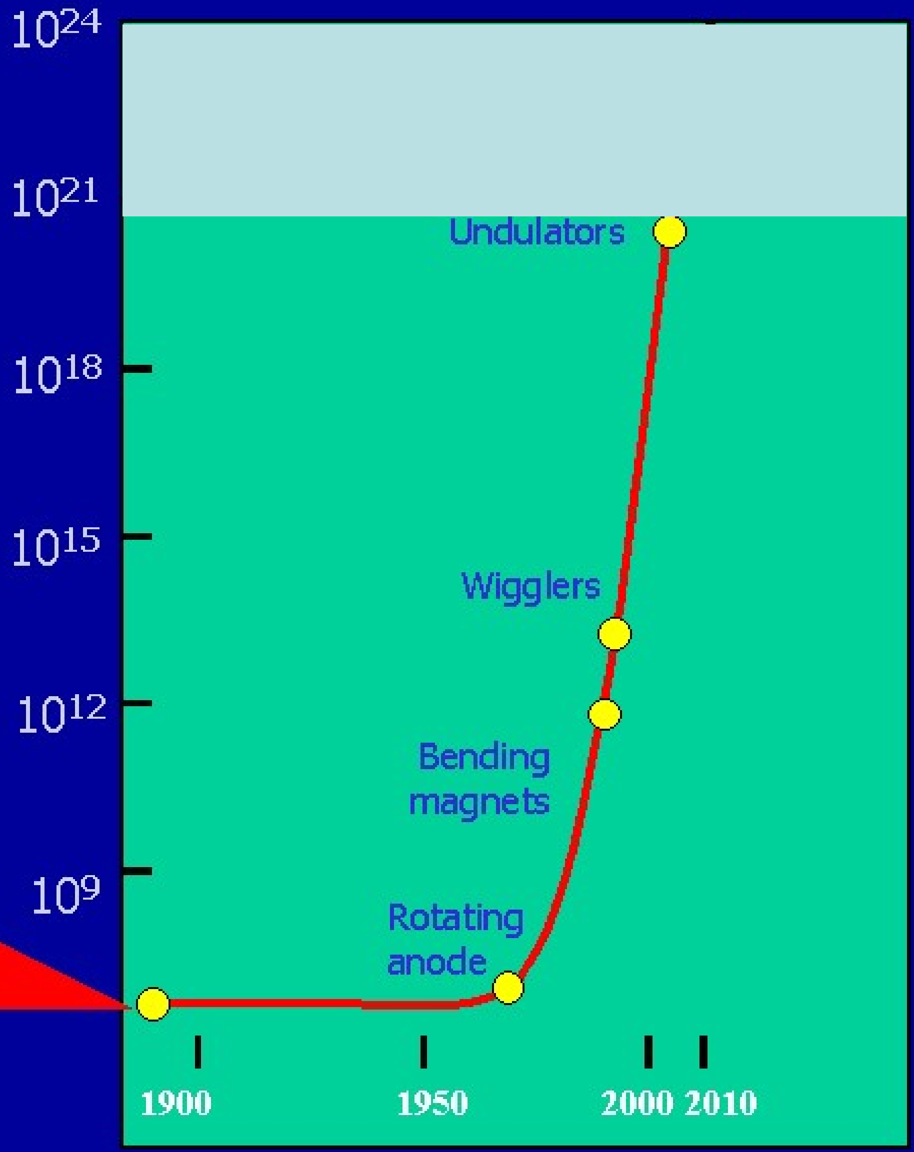
The spectral "brightness" - main user's characteristic of a light source

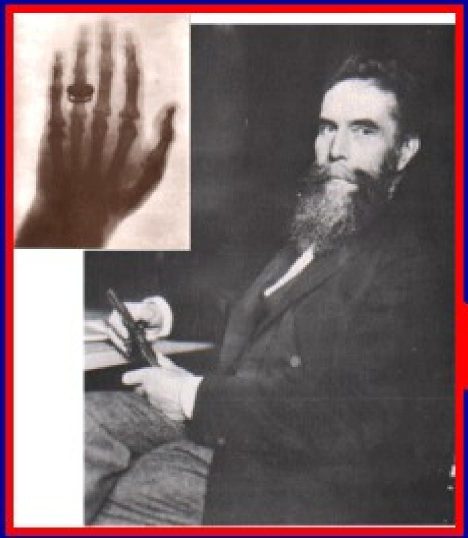


Brightness = const $F/(S \cdot \Omega)$

Steep rise in brightness/brilliance

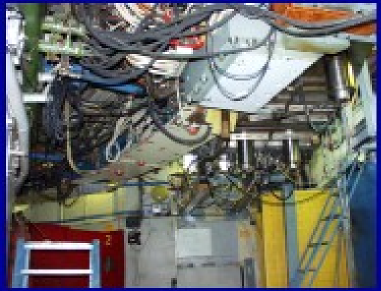
(units: photons/mm²/s/mrad², 0.1% bandwidth)





Spring-8

Siberia-2



VEPP-3

Development of the sources of synchrotron radiation always was aimed at solution of different tasks such as:

1 - increase of spectral brightness;

2 - increase of hardness of the radiation;

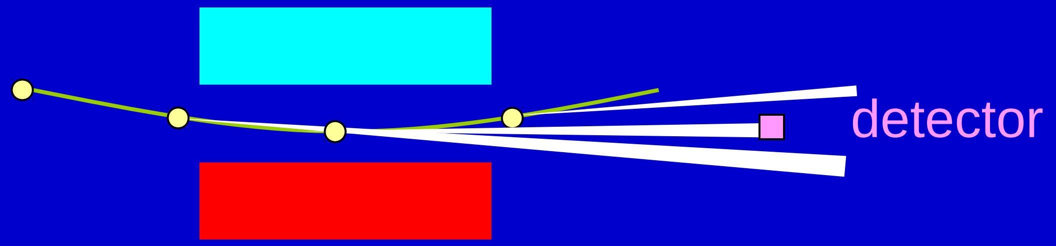
3 - application of the specific SR features (polarization, time structure, coherence and so on).

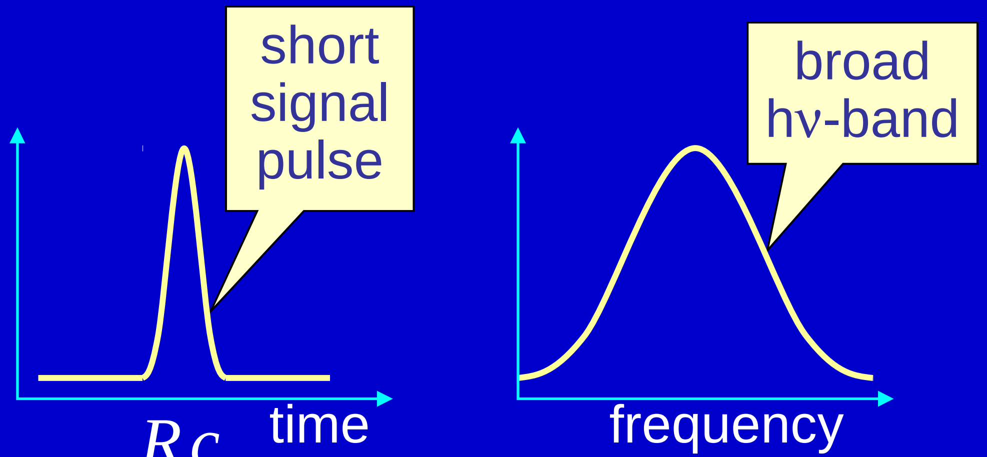
4 – serving multi-user SR community.

2. Three generations of SR sources.

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

Bending magnets: $B \sim N_e$





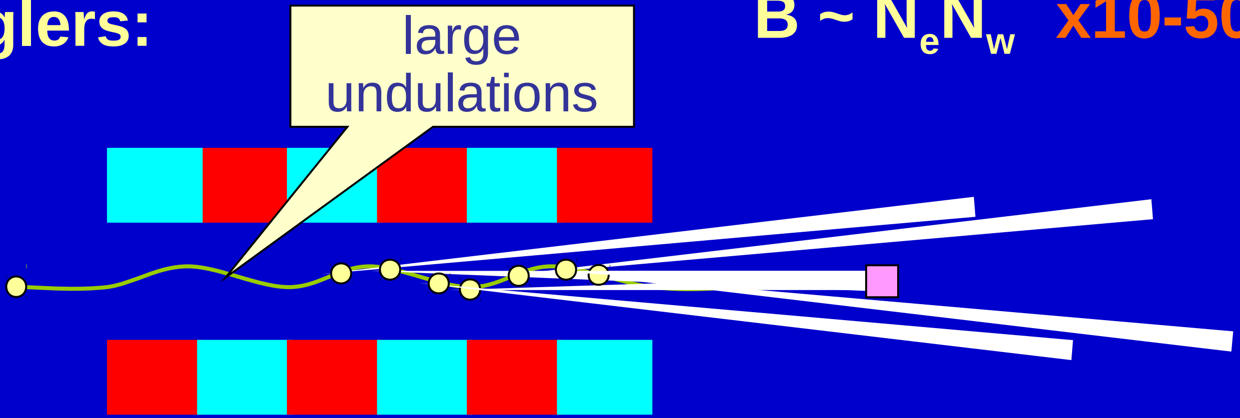
$$\Delta t \sim \frac{Rc}{\gamma^3}$$

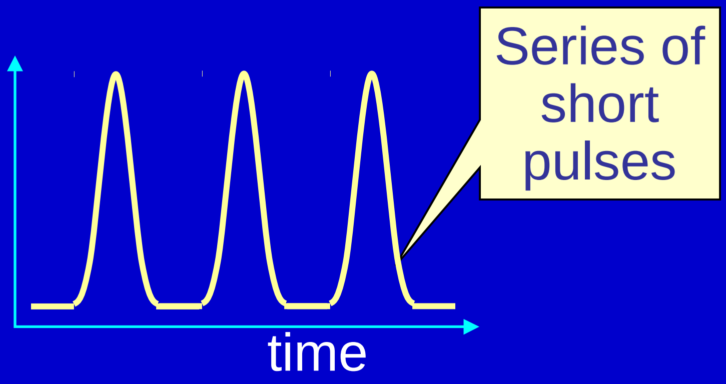
after G. Margaritondo

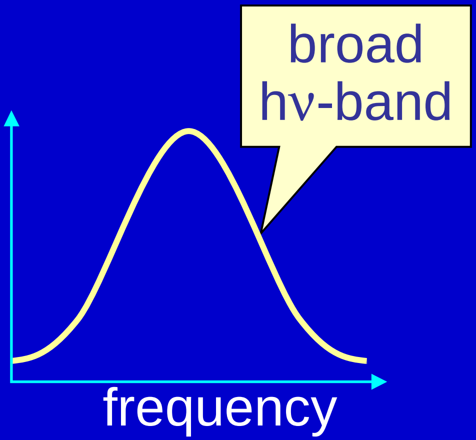
Second generation SR sources – dedicated storage ring - synchrotron radiation sources (low emittance ε ~ 30 nm, set of straight sections for wigglers)

Wigglers:

$B \sim N_e N_w$ x10-50

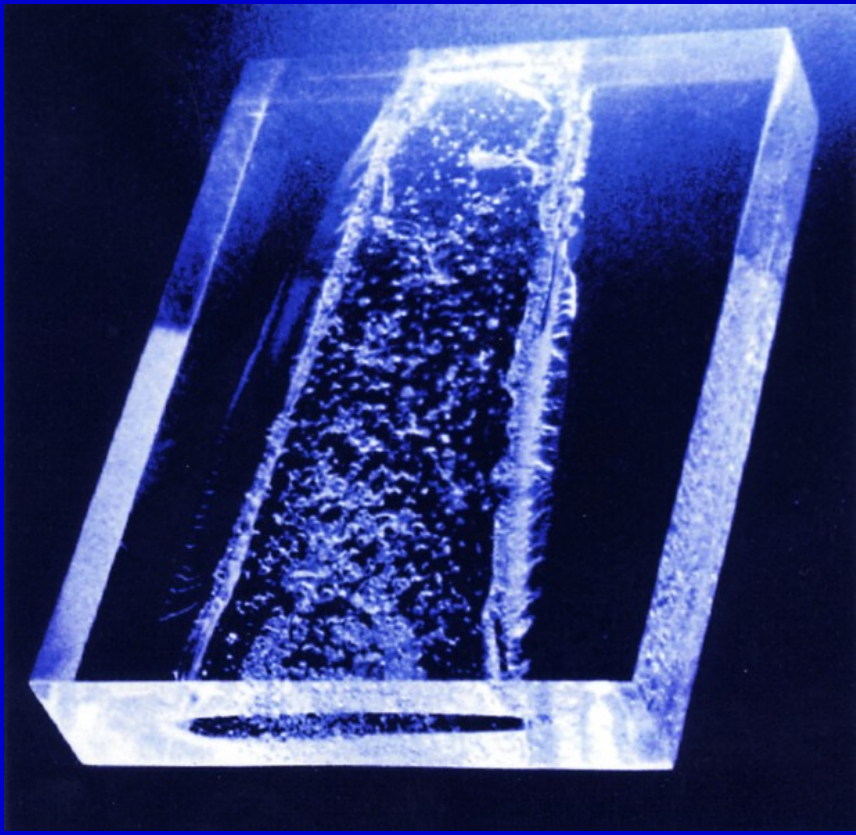






after G. Margaritondo

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



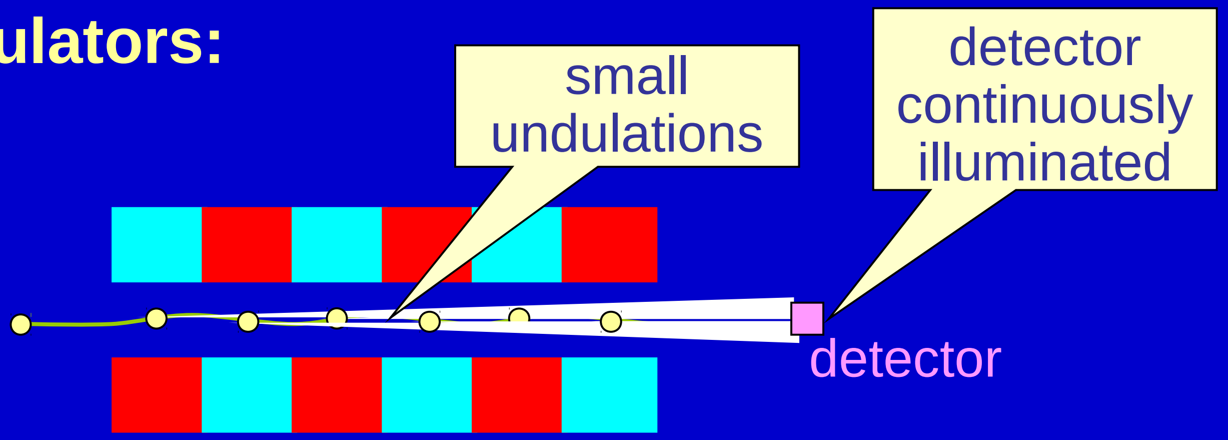
3.3 T, 20 poles, period = 9 cm
ε_c ~ 8 KeV, Pw max ~ 1.2 KW

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

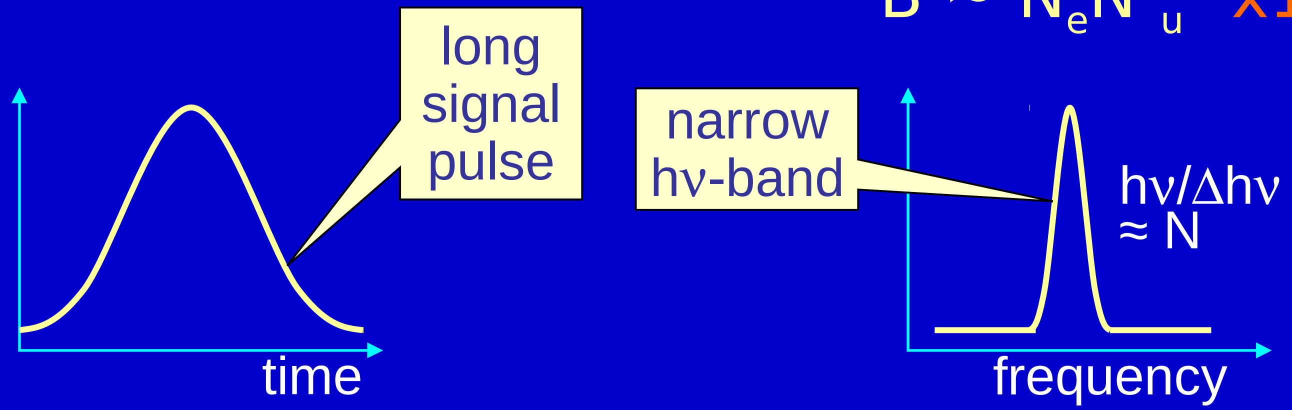
Superconductive 2.2 T 63-pole wiggler
designed and produced at the Budker INP (Novosibirsk, Russia)
at the third generation Canadian Light Source
(CLS, University of Saskatchevan, Canada, 2005)

Third generation SR sources – storage rings optimized for installation of undulators (low emittance ε ~ 3 nm, set of long straight sections for long undulators)

Undulators:



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



after G. Margaritondo

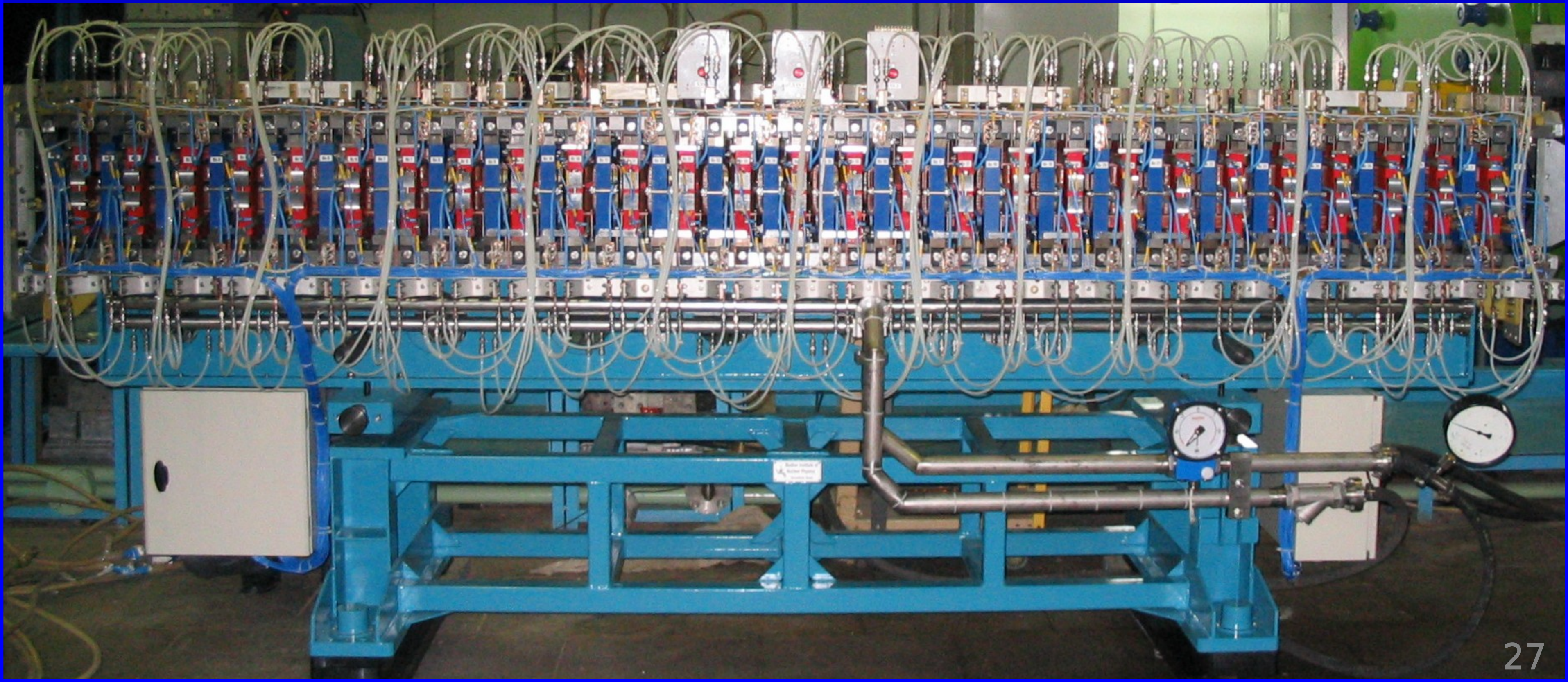
In-vacuum undulator U-24 (Spring-8 / SLS)

G. Ingold
T. Schmidt

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



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

Over ~ 60 years after GE Synchrotron *(1947-2009)*

42 operational + 13 under construction SR sources over the

Japan – 15 SR sources in operation, including 2 first-rate user's facilities: Spring-8 and Photon Factory
Europe – 13 in operation and 3 under construction
USA – more than 10 SR sources in operation
…………..
Russia – 2 SR Centers (4 SR sources) in operation and 1 under construction

~ 50 000 SR users worldwide

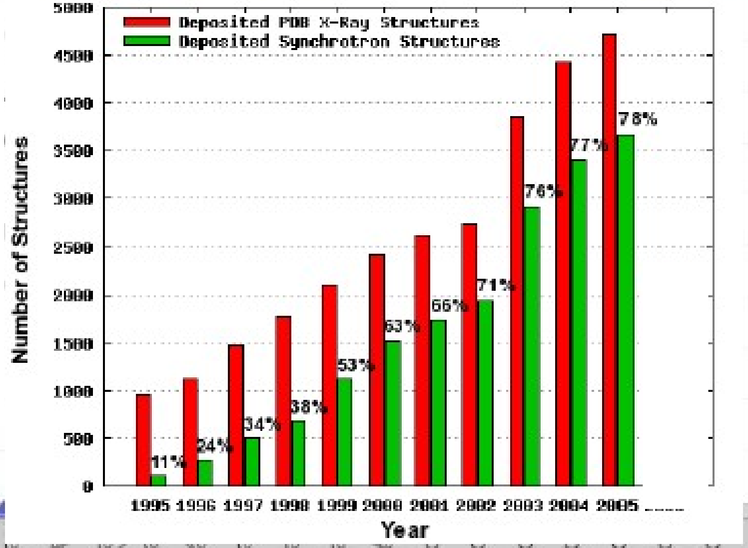

APS

Phenomenal success of Macromolecular Crystallography

Number of X-ray structures solved per year from 1976 - 2006

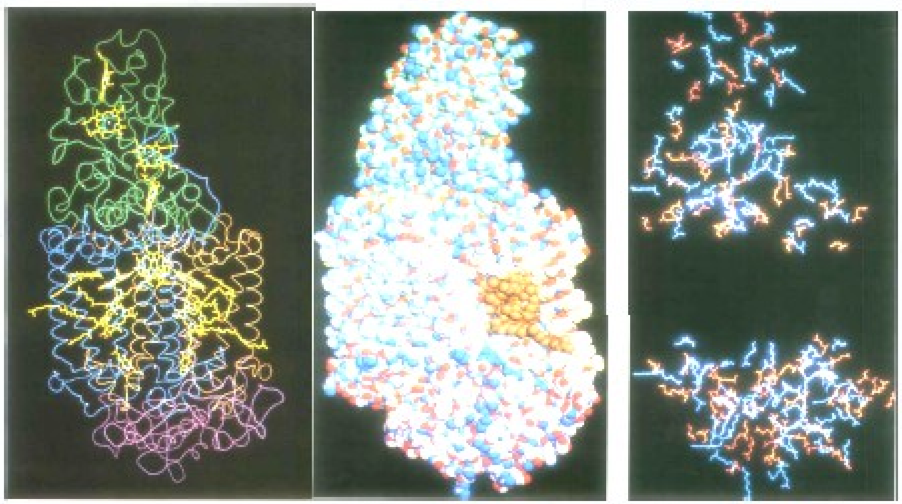
- **Bright non-divergent beam**: hence able to work with small samples (> 10 μm);
- improved precision of the data; improved resolution

- **Tunable wavelength**: ability to optimise anomalous scattering and hence
- exploit for phase determination.

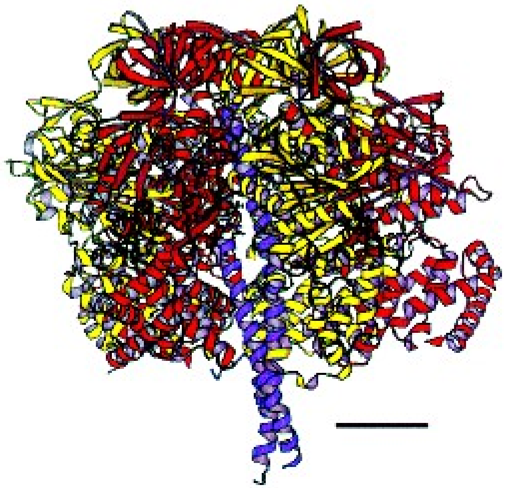


SRS 1981, Elettra 1993, APS 1994, ESRF 1994, Spring 8 1997, Diamond 2007

Nobel prizes in synchrotron structural biology

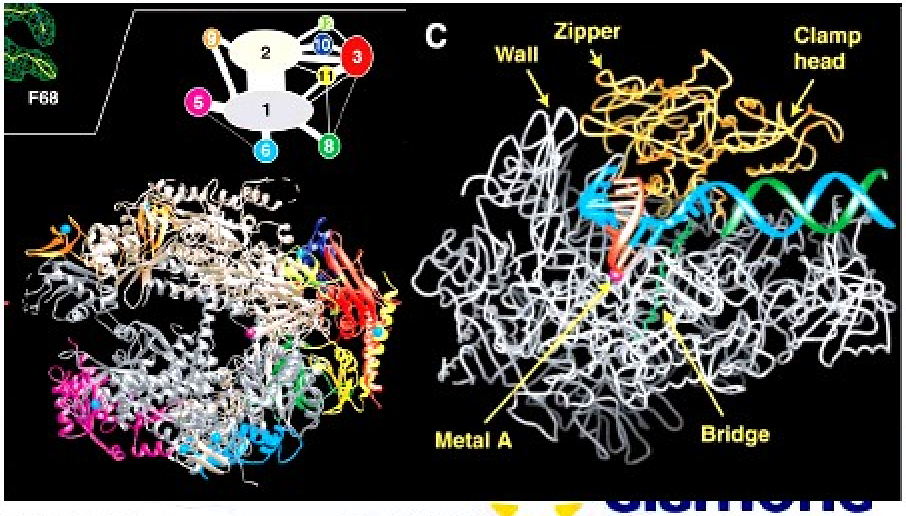


Bacterial photoreaction centre (1985)
J. Deisenhofer, R. Huber & H. Michel (Nobel 1989)



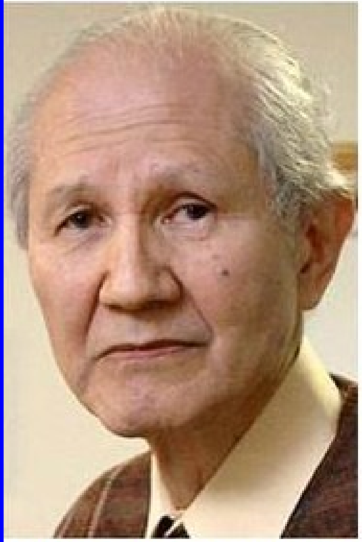
F1-ATPase (1993)
J. Walker (Nobel 1997)

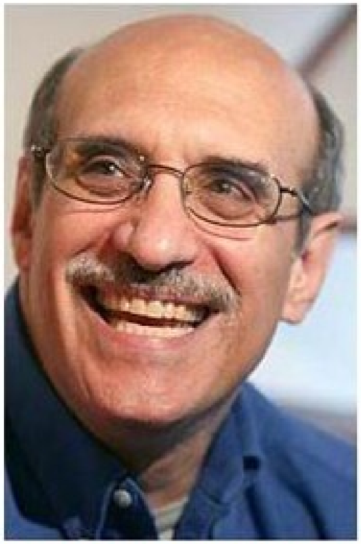
KcsA potassium channel (1998)
R. MacKinnon (Nobel 2004)

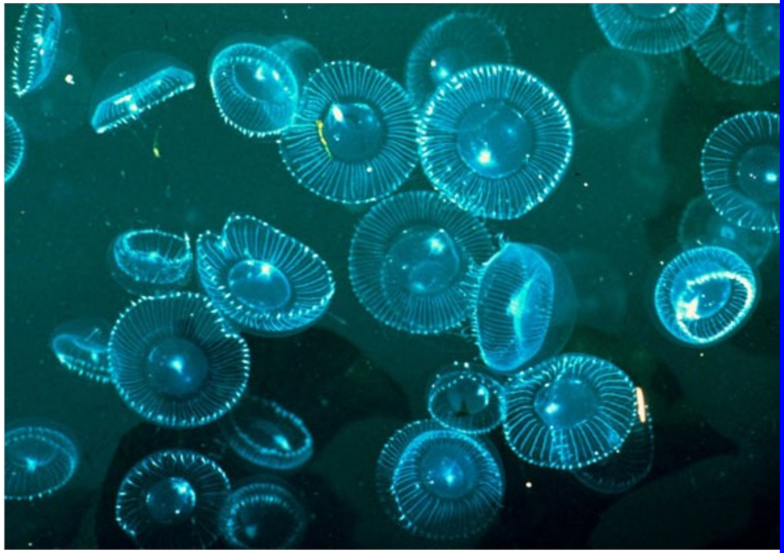


RNA Polymerase II (2001)
R. Kornberg (Nobel 2006)

The Nobel Prize in chemistry in 2008 was awarded to Osamu Shimomura, Martin Chalfie, and Roger Tsien for their discovery and development of methods of utilization of green fluorescent protein, which has been widely applied all over the world to investigation into physiological processes at the cell and organism level as well as gene expression.







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The Nobel Prize in Chemistry 2009

"for studies of the structure and function of the ribosome"

Photo: MRC Laboratory of Molecular Biology

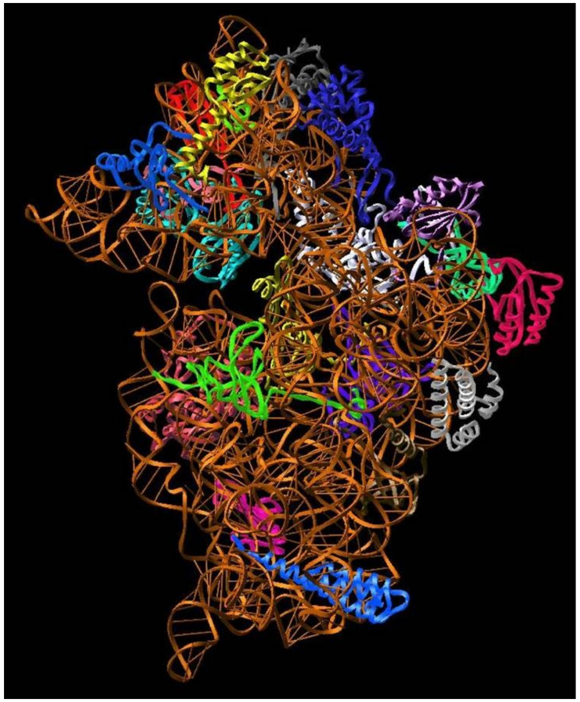
Venkatraman Ramakrishnan

Credits: Michael Marsland/Yale University

Thomas A. Steitz

Credits: Micheline Pelletier/Corbis

Ada E. Yonath



3. Ways of increasing of brightness of SR sources.

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.

List of requirements for future generation of the X-ray sources:

- full spatial coherence;
- as high as possible temporal coherence ($\Delta\lambda/\lambda < 10^{-4}$ without additional monochromatization;
- the averaged brightness of the sources has to exceed 10^{23}-10^{24} photons $s^{-1}mm^{-2}mrad^{-2}(0.1\%$ bandwidh$)^{-1}$;
- the full photon flux for the 4th generation sources must be on level of 3rd generation SR sources;
- the high peak brightness of order 10^{33} photons $s^{-1}mm^{-2}mrad^{-2}(0.1\%$ bandwidh$)^{-1}$ is important for some experiments;
- electron bunch length up to 1 ps and using a specialized technique X-ray pulses smaller than 100 fs;
- high long-term stability; generation linear, left-right circular polarized radiation with fast switching tipe and sign polarization; constant heat load on chambers and optics; etc.
- serving multi-user community.

- For the last 30 years the brightness of the X-ray SR sources based on storage rings has been increased by the factor of 10^{9}.

- Nevertheless, at the modern sources, the flux of the coherent quanta is only 10^{-3} of the total flux. Therefore, in spite of the successful demonstration of the X-ray holography, it did not become the efficient technique for structural studies of the real objects having mostly noncrystalline structures. Even for the crystalline structures, the speckle-spectroscopy is very important and it is accessible only in coherent light.

- Therefore, of all the requirements to SR sources of the 4th generation, obtaining of the fully spatially coherent flux of quanta, keeping the same flux of quanta provided with a sources of the 3rd generation, is most important.

- Also, a possibility of using the undulator radiation with a monochromaticity of $10^{-3} \div 10^{-4}$ without using a monochromators, which, as a rule, spoil the beam spatial coherence, is of great importance.

Important task for the future generation of the X-ray source is providing:

- full spatial coherence;
- as high as possible temporal coherence.

In this case the increase of spectral brightness take place without increasing of the total photon flux for minimization of the problems with X-ray optics and the sample degradation.

$$B_\lambda = \frac{N_{ph}}{\Delta t} \cdot \frac{1}{\Delta S \cdot \Delta\Omega} \cdot \frac{1}{\Delta\lambda/\lambda}$$

Diffraction limit of optical source phase volume ("mode" volume)

$$(\Delta S \cdot \Delta\Omega)_{\min} = \frac{\lambda^2}{4}$$ - Gaussian beam.

The emittance of electron beam must be small enough.

$$\varepsilon_x = \sigma_x \cdot \sigma_{x'} \leq \frac{\lambda}{4\pi}$$

In this case the source provide full spatial coherence of radiation:

$$\overset{\circ}{N}_{coh} = B_\lambda \cdot \lambda^2 \cdot \frac{\Delta\lambda}{\lambda} = \frac{N_{ph}}{\Delta t}$$

- The temporal coherence of source is determined by the radiation bandwidth

$$l_{coh} = \frac{\lambda^2}{2\Delta\lambda}$$

- Linewidth of undulator radiation is determined by number of undulator periods and energy spread of electron beam

$$\frac{\Delta\lambda}{\lambda} \sim \frac{1}{N_u} \quad \text{for} \quad N_u < \frac{1}{2\pi}\left(\frac{\sigma_E}{E}\right)^{-1}$$

- Fundamental limit of energy spread is determined by quantum fluctuation of undulator radiation

$$\left(\frac{\sigma_E}{E}\right)^2 \sim 180 \cdot r_0 \cdot \lambda_c \cdot \gamma^2 \cdot \left(\frac{K}{\lambda_u}\right)^3 Z \quad ,$$

r_0, λ_c - classical radius and Compton wavelength of electron

K - undulator parameter , Z - distance from the undulator entrance

Main way of increasing the brightness of 4th generation X-ray source:

1. Decreasing the electron beam emittance down to diffraction limit

$$\varepsilon_x < \frac{\lambda}{4\pi} \sim 10^{-11} mrad \left(\lambda \sim 1 \mathring{A} \right)$$

2. Decreasing the electron beam energy spread down to fundamental limit due to quantum fluctuation of undulator radiation ($\sigma_E/E<10^{-4}$);

3. Using of long undulator with number of periods, determined by the fundamental limit due to quantum fluctuation of undulator radiation ($N_u \sim 10^4$).

Three different kinds of SR sources are considered for last years:

- long undulators installed on the advanced storage rings;
- long undulators installed on the electron linear accelerators;
- long undulators installed on the recirculating accelerator-recuperator source).

Advantages of storage rings:

a) high average reactive power in beam (E = 8 GeV; I = 1,5 A,

$P_{reactive}$ = 12 GW)

b) long life time (~ 10 - 100 h), small losses of high-energy particles per unit time, and, correspondingly, a low radiation background and the absence of induced radioactivity;

c) simultaneously lot of SR beam lines in operation (up to 50 on storage ring) – serving multi-user community.

Disadvantages of storage rings:

Emittance and energy spread of electron beam depends on the equilibrium between radiation damping and diffusion, caused by quantum fluctuations of the SR and by intra beam scattering in the case of high-density beams.

There is no a solution to decrease the emittance in storage ring $\varepsilon_x < 10^{-10}$ mrad and energy spread $\sigma_e/E < 10^{-3}$
(quantum fluctuation of the SR, the intrabeam scattering).

High energy electron accelerator

Low emittance e^- beam

Long undulator

Low energy spread e^- beam

High spectral brightness SR sources

1980	$\varepsilon \sim 300$ nmrad	$N_u \sim 10$	$\sigma_E/E \sim 10^{-3}$
1990	$\varepsilon \sim 30$ nmrad	$N_u \sim 10^2$	$\sigma_E/E \sim 10^{-3}$
2000	$\varepsilon \sim 3$ nmrad	$N_u \sim 10^3$	$\sigma_E/E \sim 10^{-3}$
2010	$\varepsilon \sim 1$ nmrad	$N_u \sim 10^3$	$\sigma_E/E \sim 10^{-3}$

Storage rings

- Advantages of linacs: normalized emittance ε_n can be conserved during the acceleration process. Having a good injector with $\varepsilon_n < 10^{-7}$ m·rad, due to the adiabatic damping on energy E > 5 GeV emittance $\varepsilon_{x,z} \sim 10^{-11}$ m•rad and energy spread δ_E /E~10^{-4} is possible.

- Main disadvantages of linacs: low average current

(10^{-7}A) in case of pulsed normal conducting linacs.
If you increase current in a case of superconducting linacs the radiation hazard is a very serious problem.

- Realization of a fully spatial coherent source is possible in case of a shift from electron storage rings to accelerators with energy recuperation, which was first discussed at SRI-97 (see: *Kulipanov G., Skrinsky A., Vinokurov N. Synchorton light sources and recent development of accelerator technology. // J. of Synchrotron Radiation –1998 V.5 pt.3 P.176*).

- Presentation of MARS - recuperator based diffraction-limited X-ray source was made on ICFA workshop on future light sources (ANL, USA, July 1999).

- After that, the idea of using the accelerators-recuperators was actively discussed at Jefferson Lab, Cornell Uni., BNL, LBL, Erlangen Uni., Daresbury Lab., KEK.

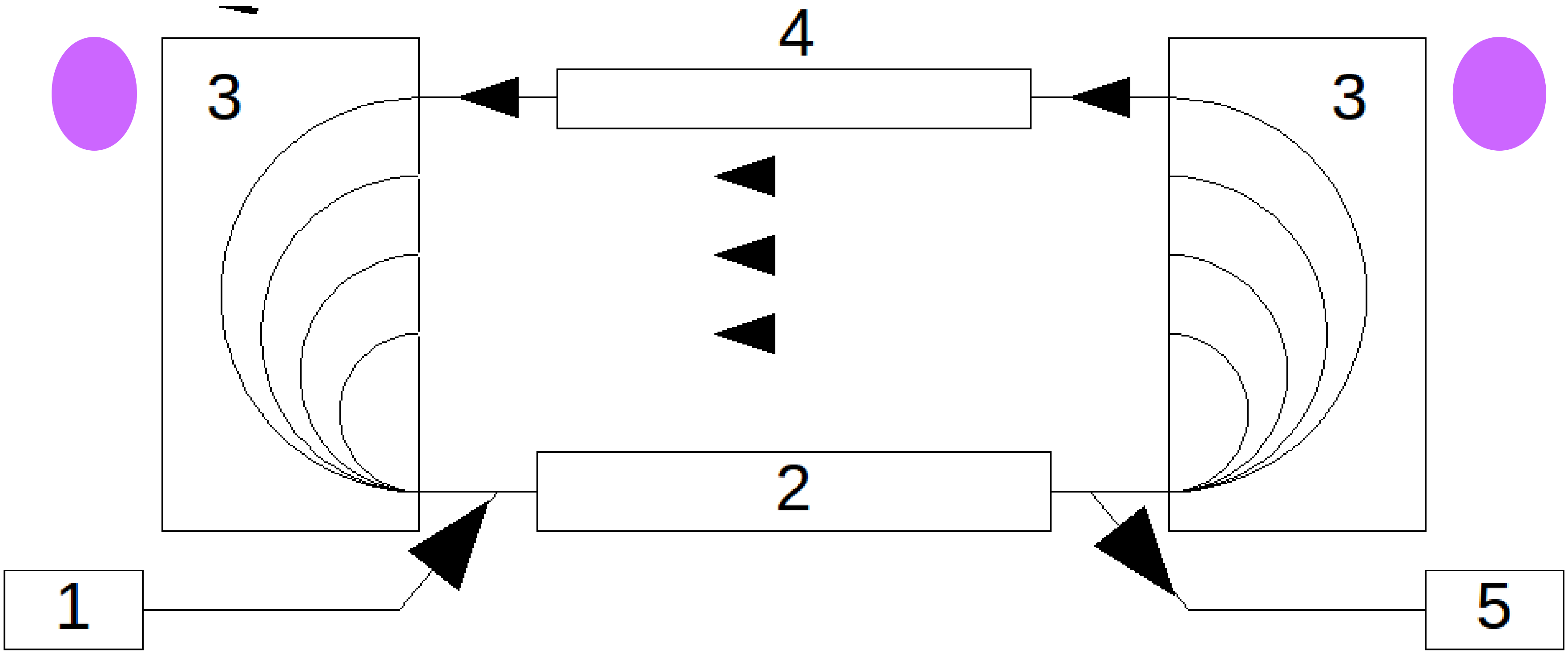
All the requirements to X-ray radiation sources of the 4th generation cannot be satisfied with the use of only one kind of a source.

The high peak brightness and femtosecond duration of radiation pulses can be attained at the linac based X-ray SASE FEL with a high pulse current (I_p >1 kA).

All the remaining requirements are easier and cheaper realized with the use of radiation from the long undulators installed at the accelerator-recuperator.

4. Why the 4th generation SR sources should use the accelerators-recuperators?

Layout of the SR source based on four-passes accelerator-recuperator



1 - injector, 2 - RF accelerating structure, 3- 180-degree bends, 4 – undulator, 5- beam dump.

- In the linacs and accelerators-recirculators normalized emittance ε_n can be conserved during the acceleration process. Having a good injector with $\varepsilon_n < 10^{-7}$ m·rad, due to the adiabatic damping on energy E > 5 GeV emittance $\varepsilon_{x,z} \sim 10^{-11}$ mrad and energy spread $\delta_E / E \sim 10^{-4}$ is possible.

- In the accelerators-recirculators, time of the acceleration is shorter compared to the time of radiation damping in the storage rings ($10^3 \div 10^4$ times) and because of this fact, the diffusion processes cannot spoil the electron beam emittance and its energy spread.

Main motivation for multipass accelerator-recuperator:

- to combine the advantages of storage ring (high reactive power in beam, low radiation hazard) and linac (normalized emittance and energy spread can be conserved during the acceleration process);
- due to energy recovery radiation hazard can be eliminated and the cost of the building will be reduced;
- due to multipass acceleration the cost of the accelerating RF system can be reduced.

High energy electron accelerator

Low emittance e^- beam

Long undulator

Low energy spread e^- beam

High spectral brightness SR sources

1980	$\varepsilon \sim 300$ nmrad	$N_u \sim 10$	$\sigma_E/E \sim 10^{-3}$
1990	$\varepsilon \sim 30$ nmrad	$N_u \sim 10^2$	$\sigma_E/E \sim 10^{-3}$
2000	$\varepsilon \sim 3$ nmrad	$N_u \sim 10^3$	$\sigma_E/E \sim 10^{-3}$
2010	$\varepsilon \sim 1$ nmrad	$N_u \sim 10^3$	$\sigma_E/E \sim 10^{-3}$
2020	$\varepsilon \sim 0.01$ nmrad	$N_u \sim 10^4$	$\sigma_E/E \sim 10^{-4}$

Storage rings

MARS

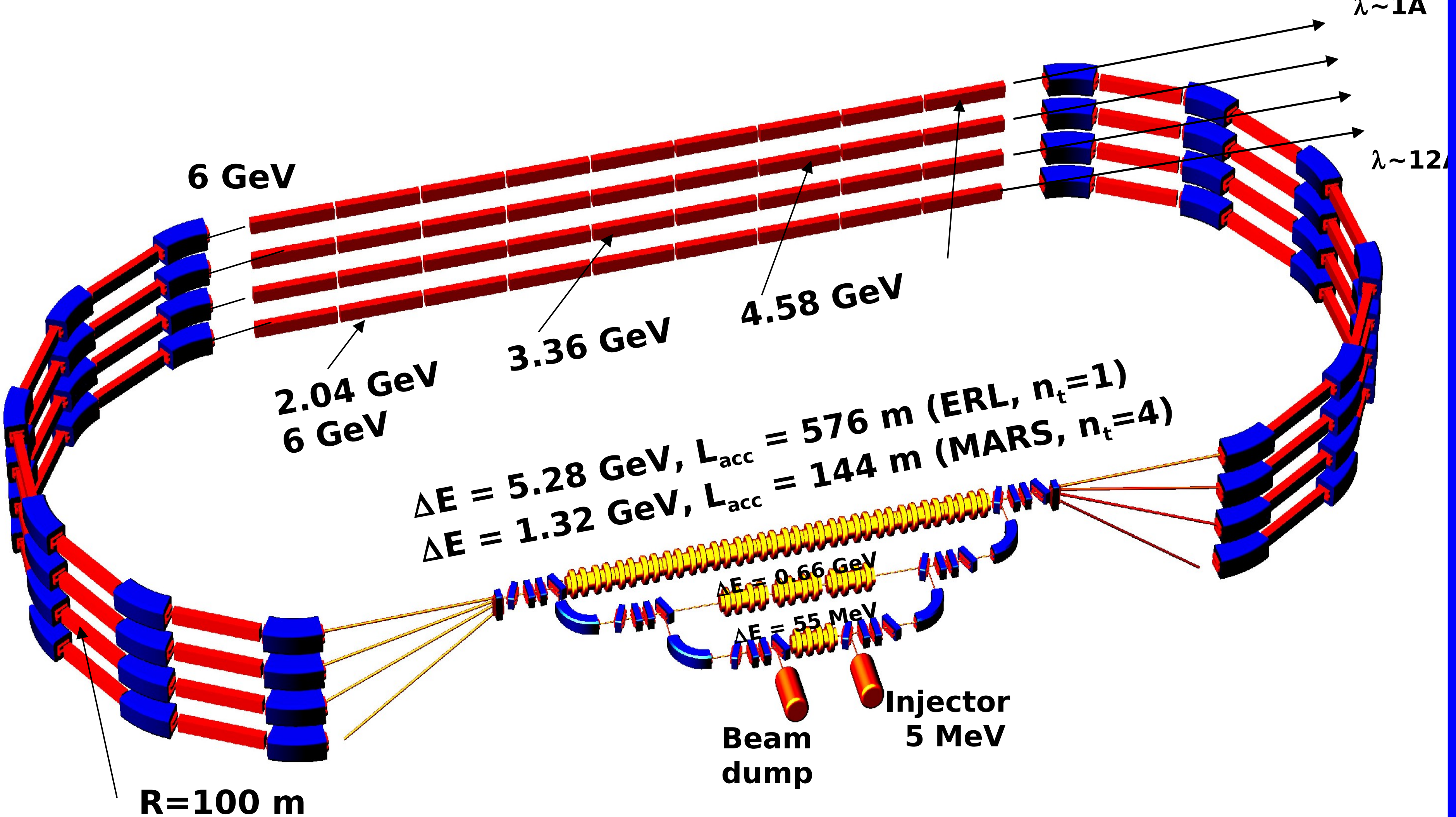
MARS – diffraction limited coherent X-ray source for national or international SR centers.

The next figure presents the layout of the four-turn recirculating 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 MARS, electrons undergoing acceleration and deceleration travel simultaneously along four tracks.

Basic overall dimensions of ERL and MARS (E_{max} = 6

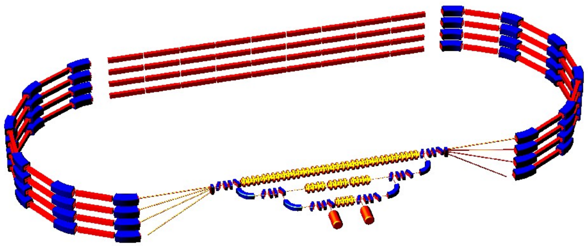
MARS: 3D view



- 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.

Comparision of parameters of SR sources

MARS (I_e=2.5 mA) and Spring-8 (I_e=100mA)

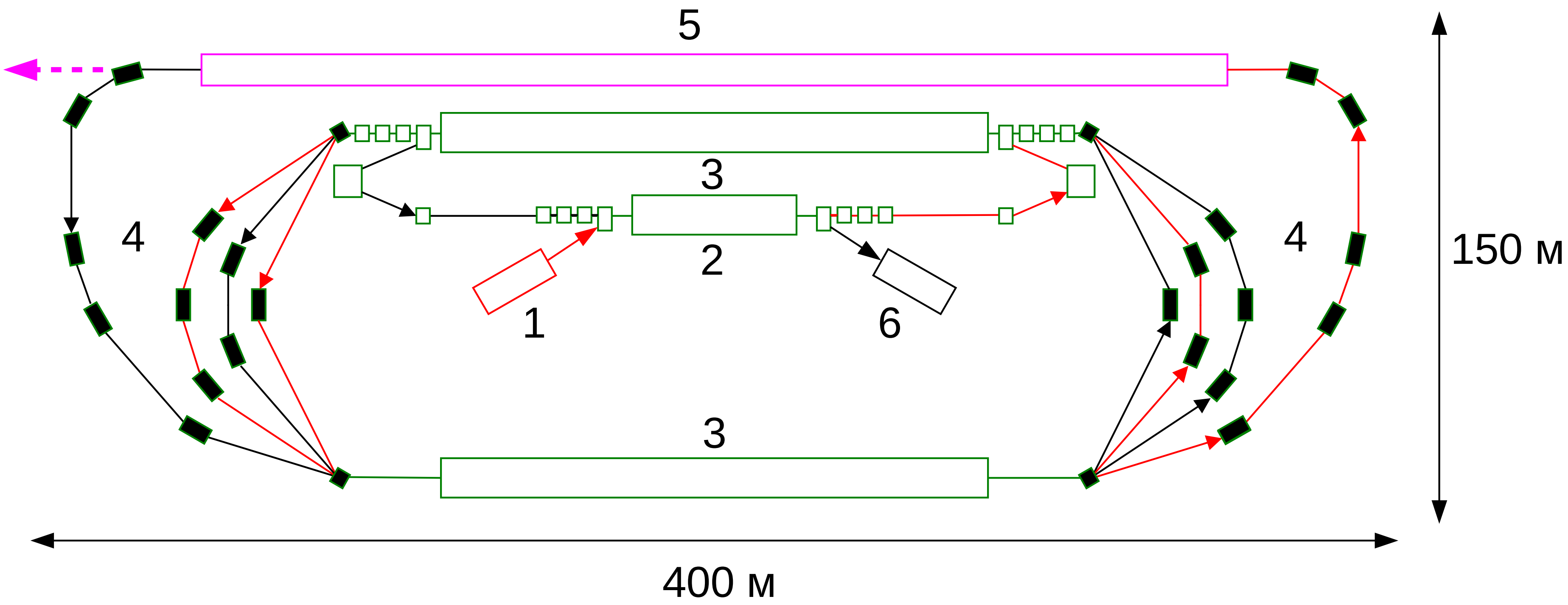


		Number of beamlines	**B**, ph•sec^{-1}•mm^{-2}•mrad^{-2} ($\delta\lambda/\lambda=10^{-3}$)	**F**, ph/sec ($\delta\lambda/\lambda=10^{-3}$)
MARS	Undulator $N_u \sim 10^2$	32	10^{22}	$4.6 \cdot 10^{13}$
	Undulator $N_u \sim 10^3$	12	10^{23}	$4.6 \cdot 10^{14}$
	Undulator $N_u \sim 10^4$	4	10^{24}	$4.6 \cdot 10^{15}$
SPring-8	Bending magnet	23	10^{16}	10^{13}
	Undulator N_u=130	34	$3 \cdot 10^{20}$	$2 \cdot 10^{15}$
	Undulator N_u=780	4	10^{21}	$1.2 \cdot 10^{16}$

The initial scheme of the accelerator-recuperator MARS suffers from a number of shortcomings. The main one is that two beams – under acceleration and deceleration – are circulating simultaneously on all the tracks, which creates two sources of radiation from undulators on those tracks.

For this reason it was suggested recently to turn to an accelerator-recuperator scheme with two acceleration sections, similar to the scheme of the US accelerator CEBAF. Such schemes are considered below.

The simplest scheme of ERL with separated channels



Scheme of ERL with one undulator:

1 – injector, 2 – preliminary accelerating system, 3 – main accelerating RF structure, 4 – magnets, 5 – undulator, 6 – dump.

red arrows – accelerating bunch

black arrows – used decelerating bunch

Multy-pass Accelerator-Recuperator with two linacs

MARS

Scheme of MARS

1-injector, 2-1-st linac, 3 -2-d linac, 4 – spreders & recombiners, 5 – undulators, 6 – user stations

Supposed parameters

Energy range *5.6, 3.8, 3, 1.2 GeV*

Emittance: $\xi_n < 10^{-7} m \cdot rad$

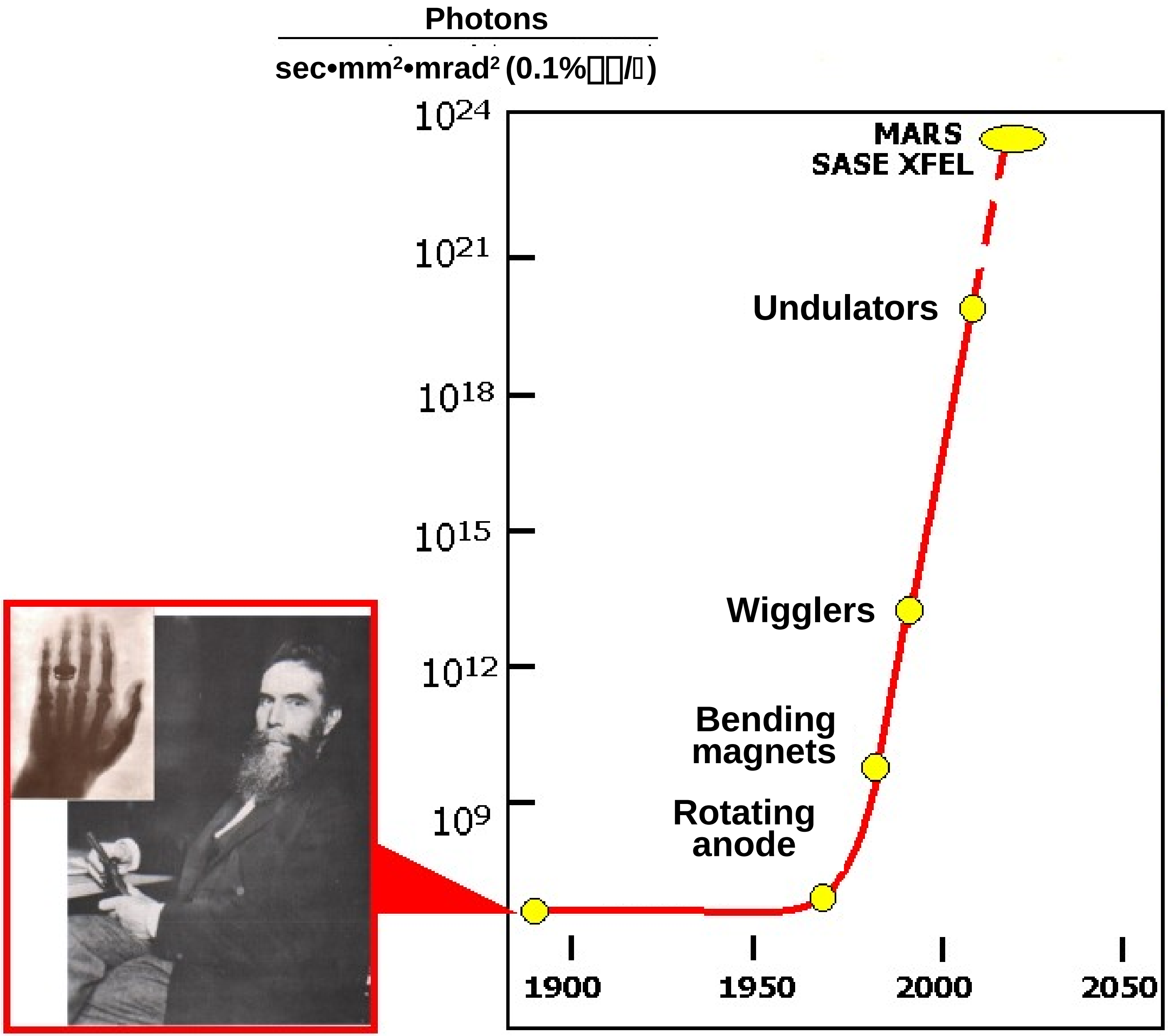
Bunch Charge: $Q \leq 10^{-11} Cl$

Pulse duration $\tau_n \sim 14 ps$

Users stations:

- 5 undulators for 5.6 GeV
- 4 undulators for 3.8 GeV
- 4 undulators for 3 GeV
- 4 undulators for 1.2 GeV

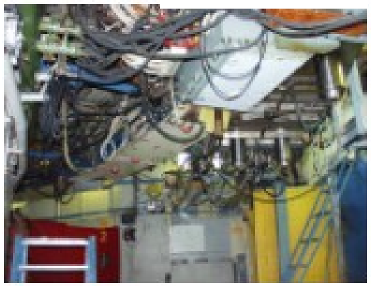
Step rise in average brightness



MARS

SPring-8

Siberia-2



VEPP-3

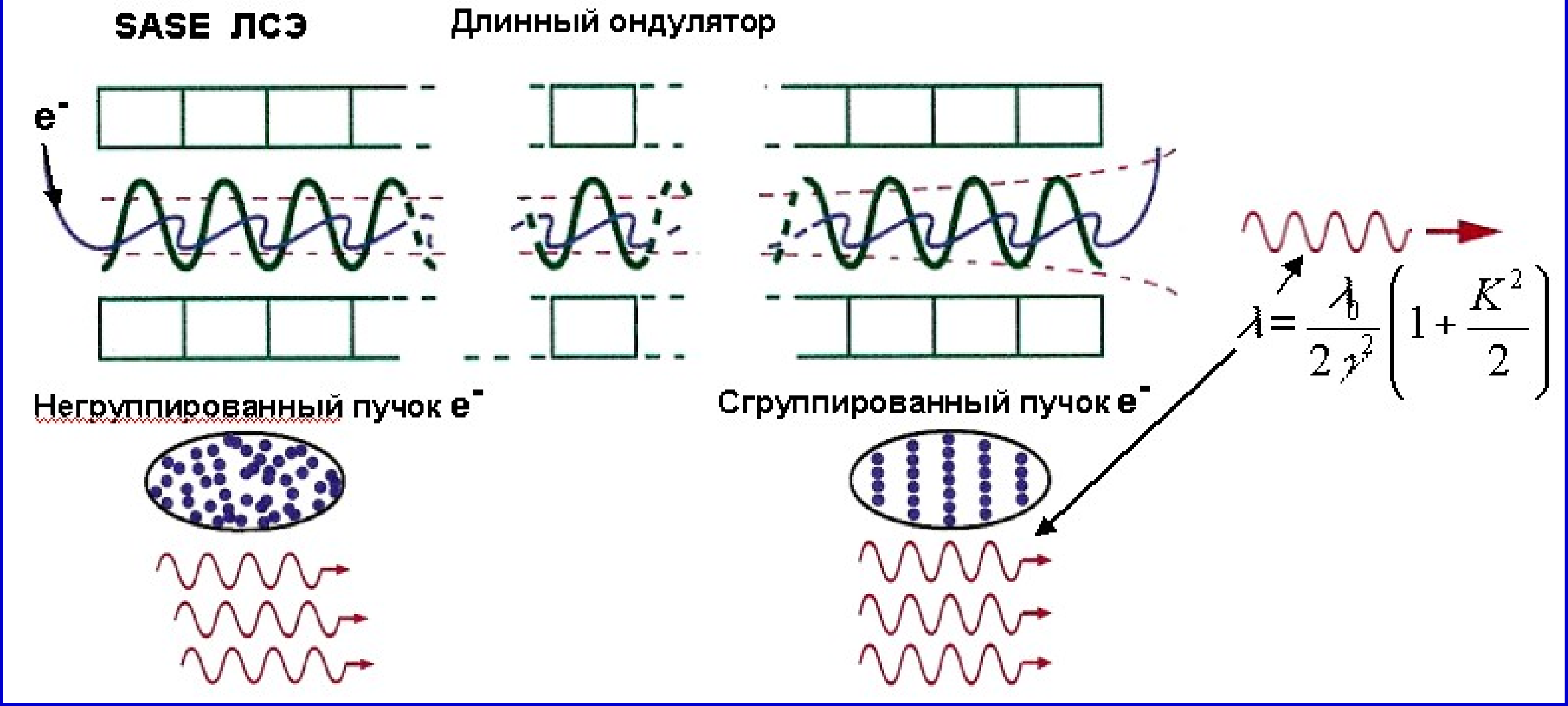
- At present, the projects of the 4th generation SR sources on the basis of accelerators-recuperators are considered at Budker INP, Daresbury Laboratory, Jefferson Laboratory, Cornell University, LBL, KEK, Erlangen University, Brookhaven National Laboratory.

- The accelerating schemes and most of the systems , which make the basis of the projects, have already been tested in many laboratories (Jefferson Laboratory, DESY, MAMI, LEP, Budker INP, KEK, MAX).

6. X-ray SASE Free electron lasers (XFEL)

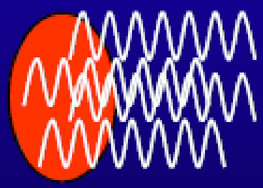
Scheme of SASE (Self Amplified Spontaneous Emission) FEL

(E. Saldin, A. Kondratenko, 1979)



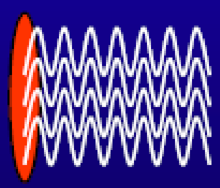
COHERENT EMISSION BY THE ELECTRONS

Intensity $\propto N$



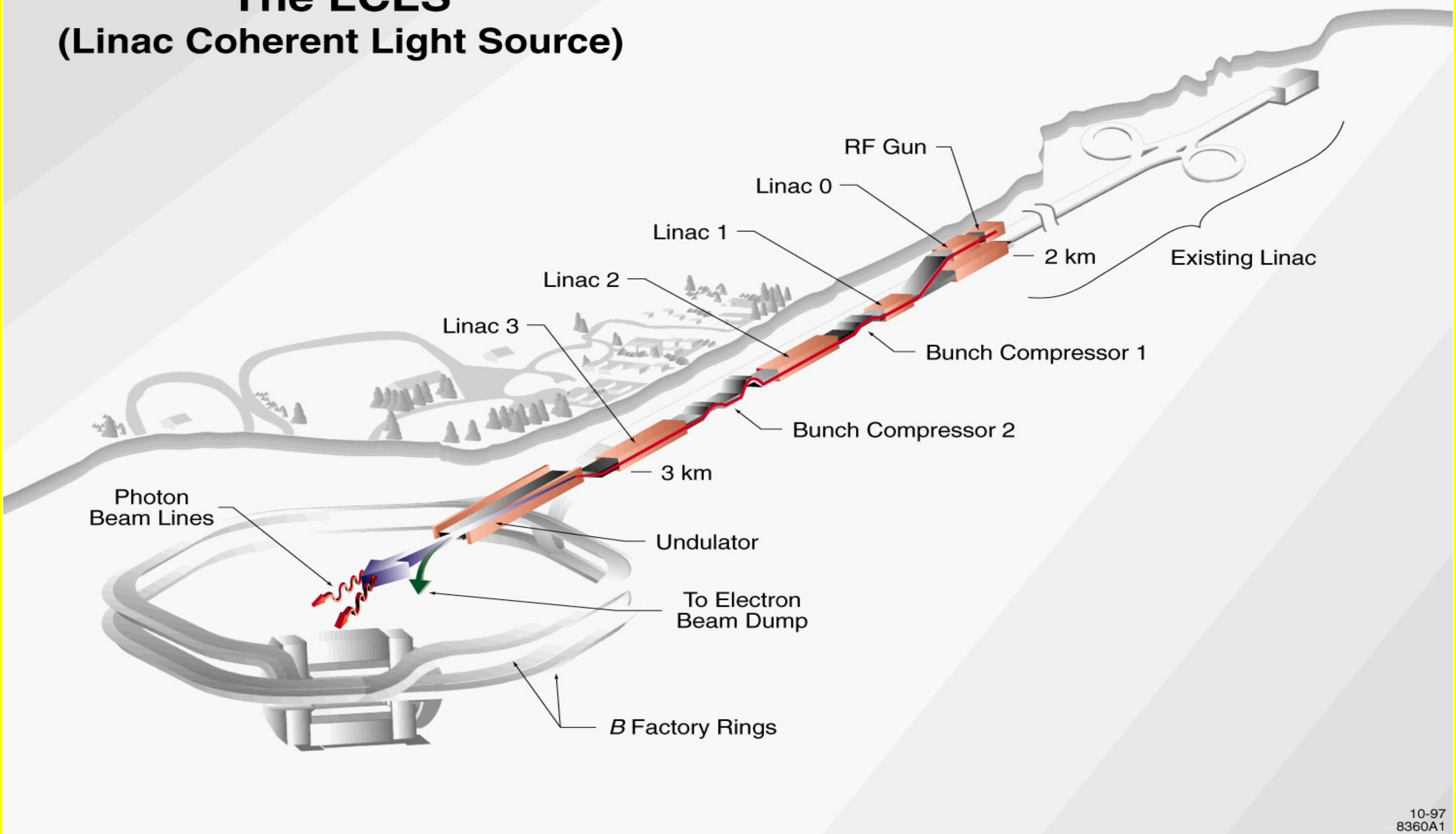
INCOHERENT EMISSION

Intensity $\propto N^2$



COHERENT EMISSION

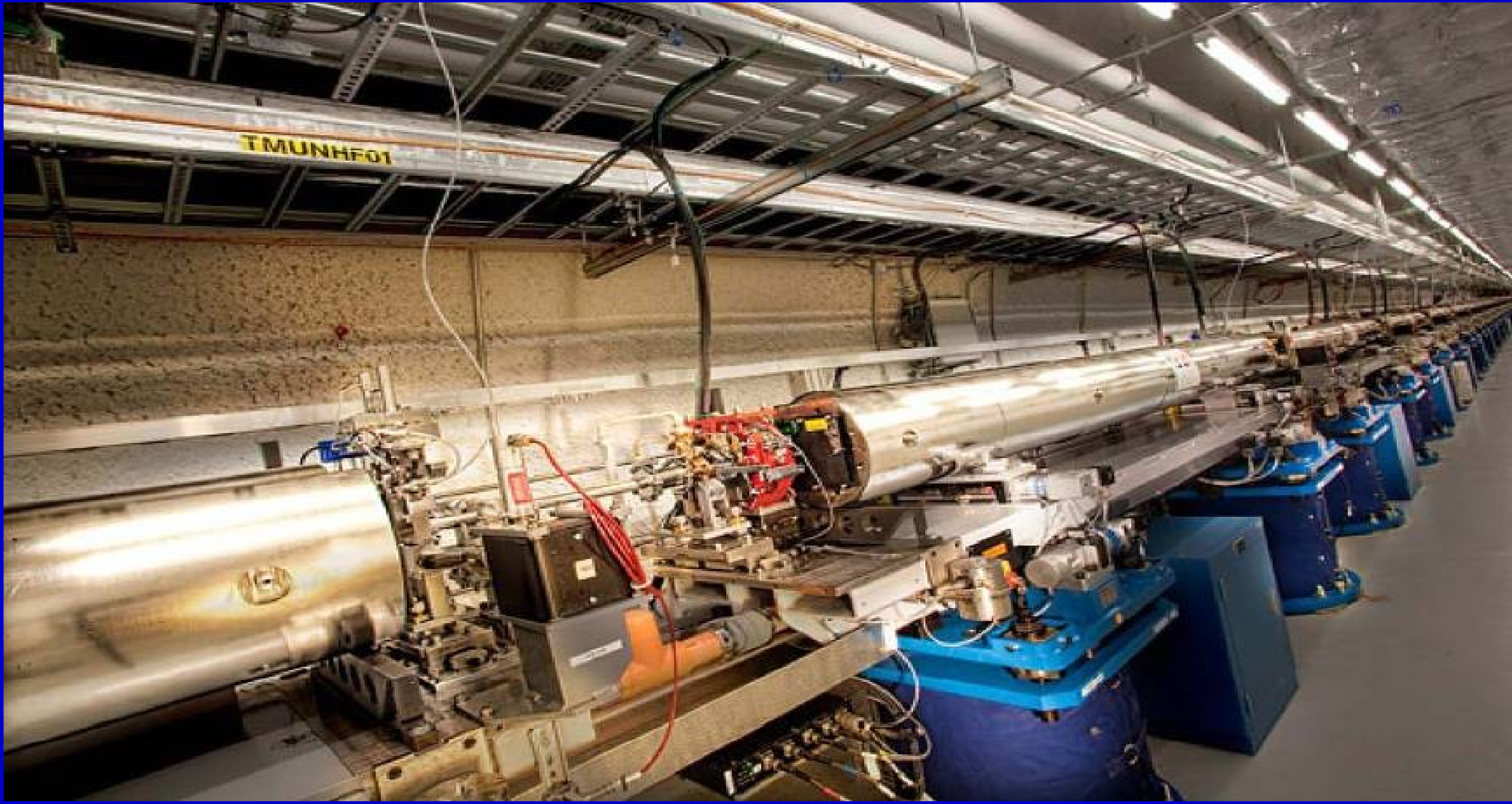
The LCLS
(Linac Coherent Light Source)



Parameters of Stanford XFEL (LCLS)

	SASE XFEL (LCLS)
Wavelength : λ	**1.5 Å**
Electron energy	**15 GeV**
# Photons/ pulse : $N\gamma$	**10^{12}**
Pulse length (FWHM): $\Delta\tau$	**160 fs**
Bandwidth : $\Delta\omega/\omega$	**0.3 x10^{-3}**
Temporal coherence	***partially coherent***
$[0.5\lambda]$ / $[c\Delta\tau\,\Delta\omega/\omega]$	**5.1x10^{-3}**
Intensity fluctuation	**7% (classical)**
Trans. coherence	***fully coherent***
Rep rate : f_{rep}	**60 - 120 Hz**
$B_p = N\gamma / [\Delta\tau\,\Delta\omega/\omega(\Delta x\,\Delta\phi)^2]$	**1.5x10^{33}**
$B_{average} = B_p\,\Delta\tau\,f_{rep}$	**2.9x10^{22}**
Angular divergence, microradian	**1.0**

Undulator of Stanford XFEL (L = 150 m)

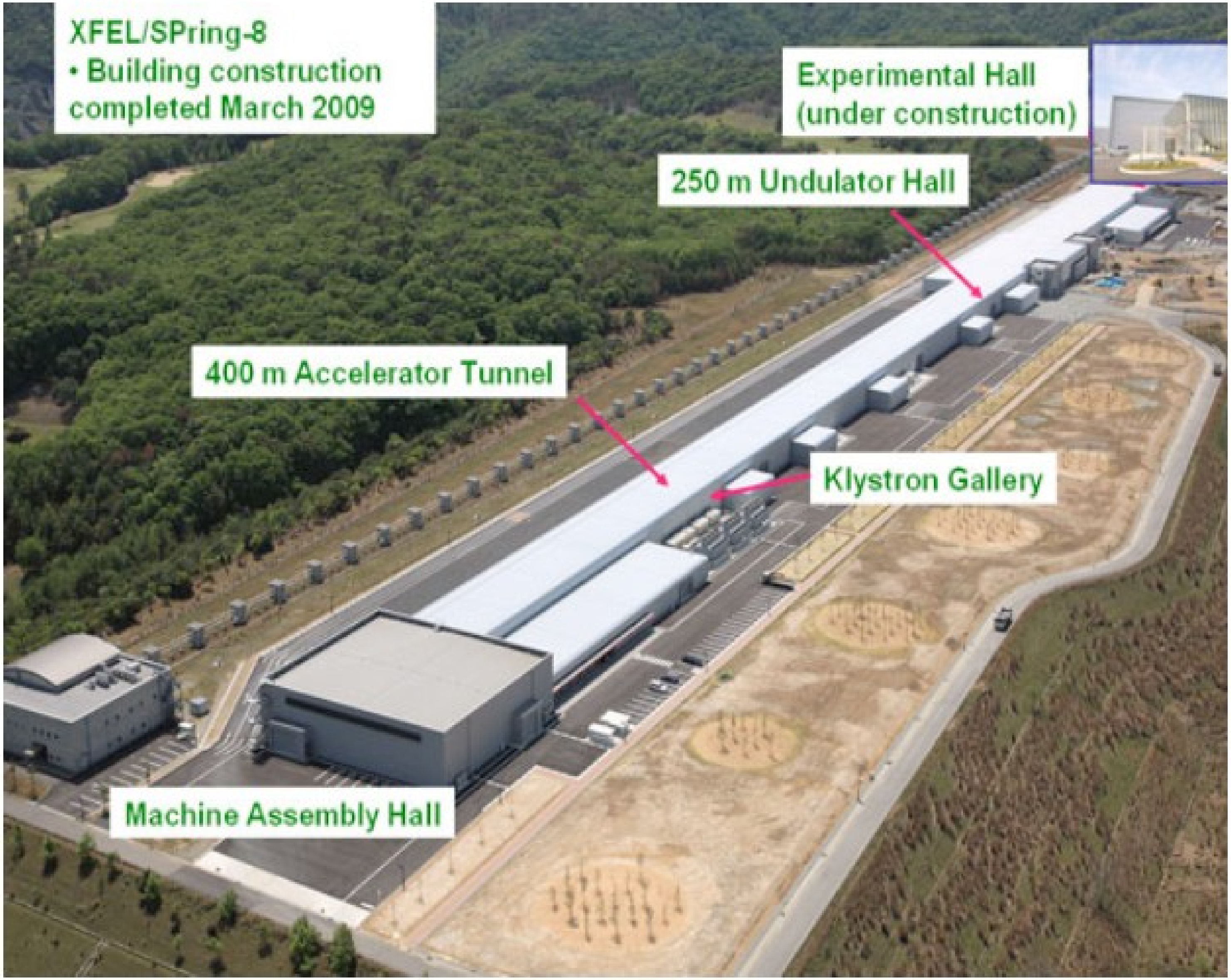


SPring8
(Japan)

X-FEL (In operation from 2011)

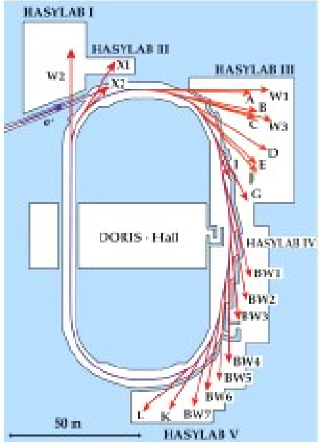
EUV-FEL
(in operation)

SPring-8


XFEL/SPring-8
• Building construction
completed March 2009
Experimental Hall
(under construction)
250 m Undulator Hall
400 m Accelerator Tunnel
Klystron Gallery
Machine Assembly Hall

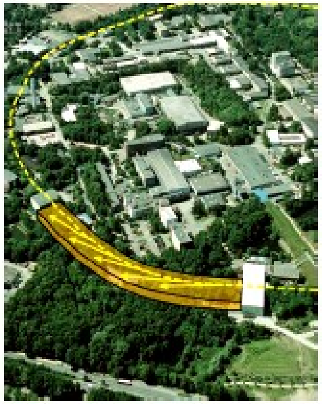
Photon Facilities at DESY

DORIS III

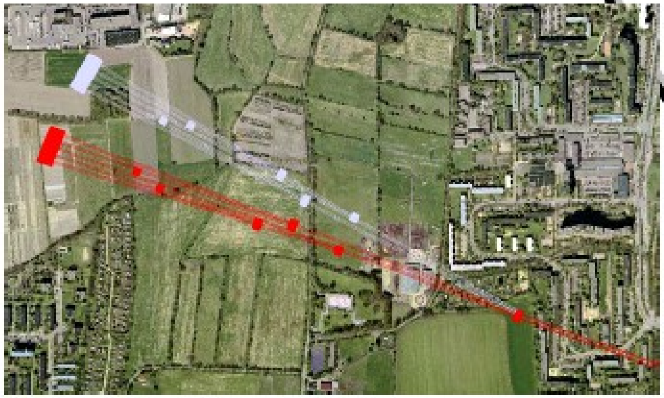


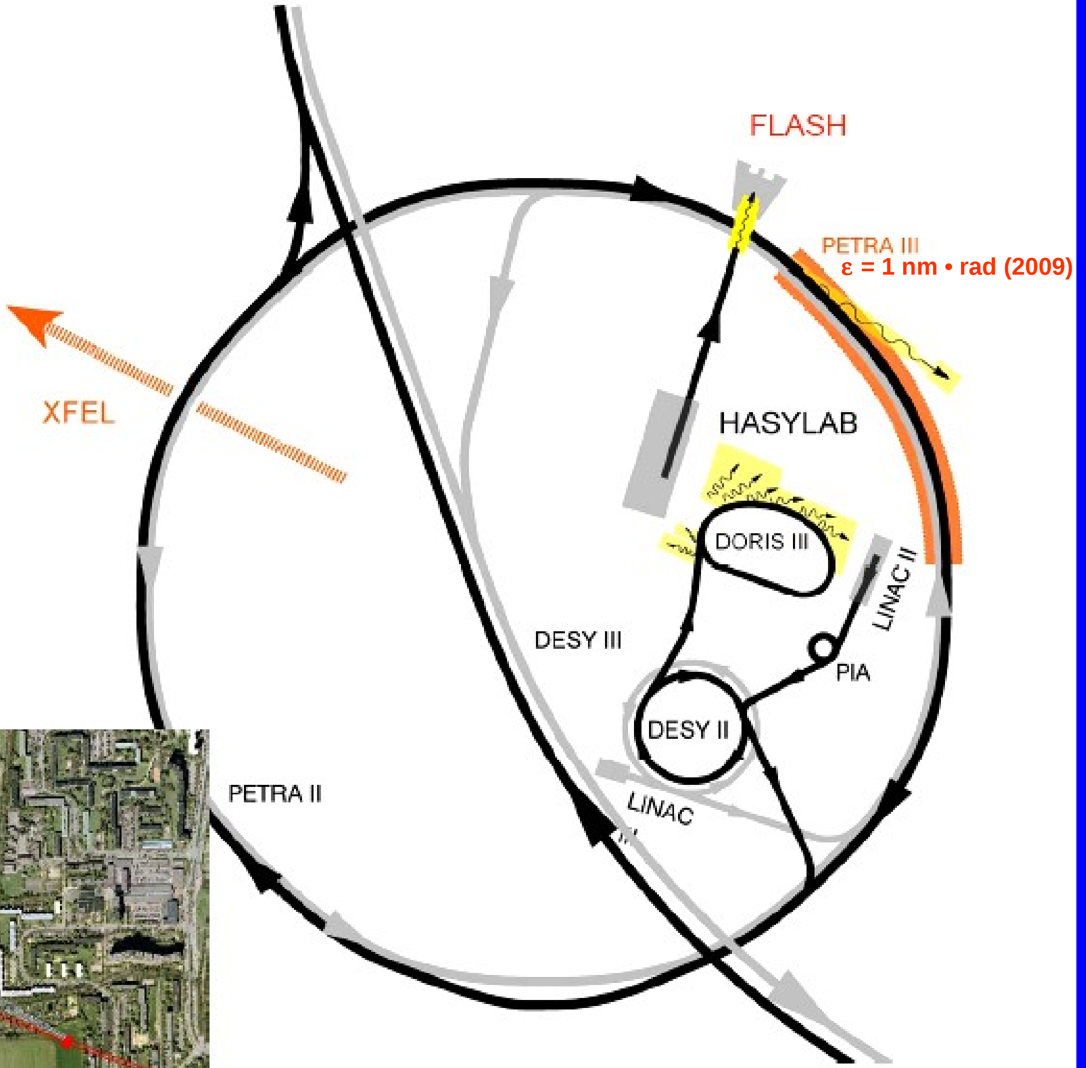
FLASH

PETRA II/III



XFEL

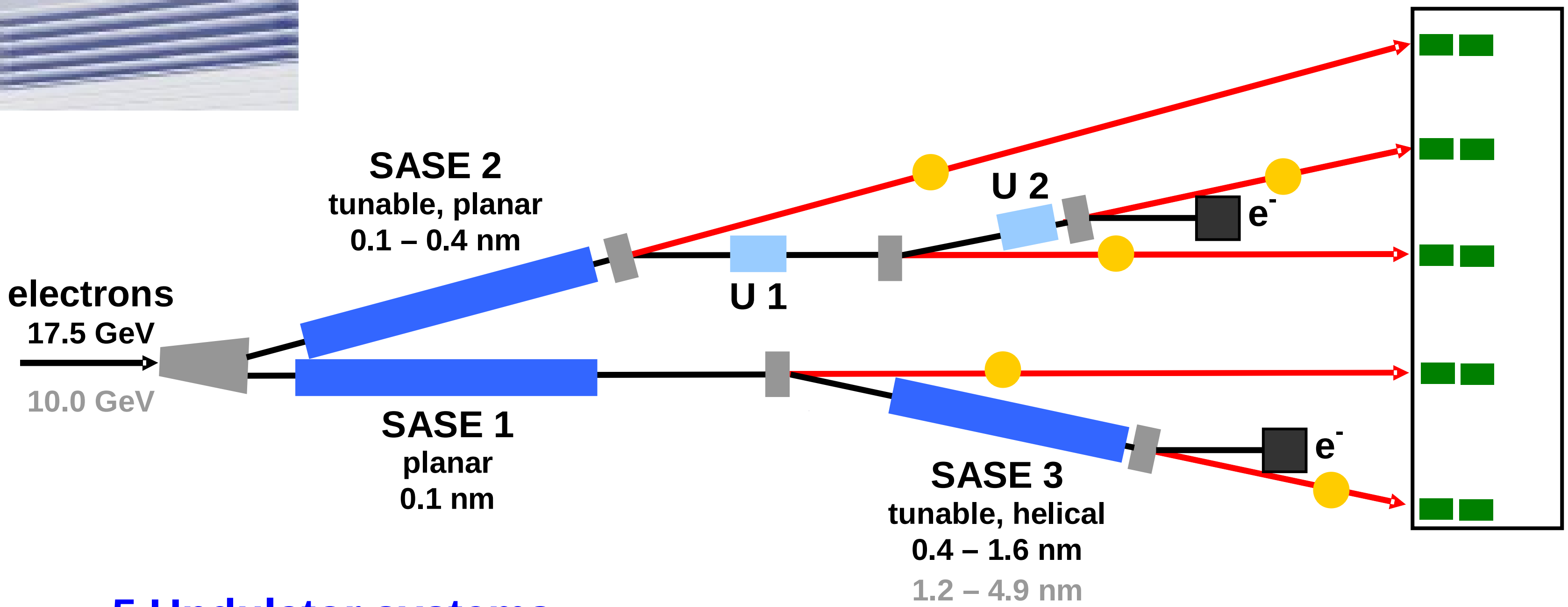




Production and assembly of superconducting cavities for FLASH

Scheme of EuroXFEL (Hamburg, Germany)

(scheduled operation from 2014)

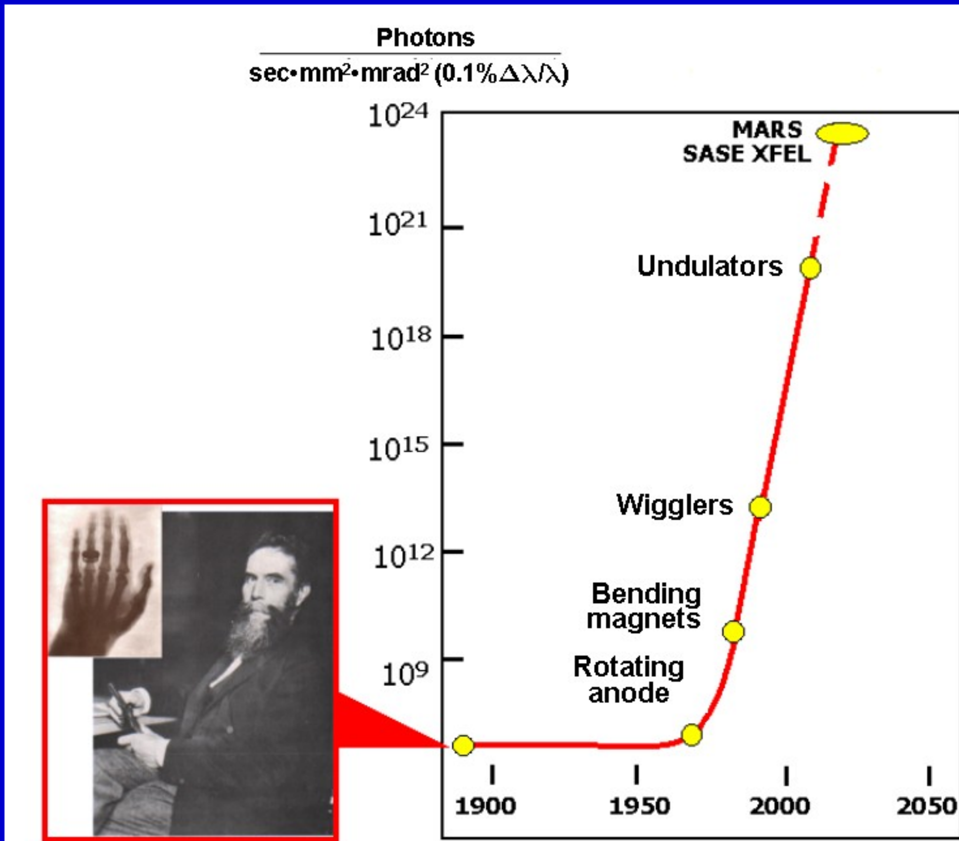


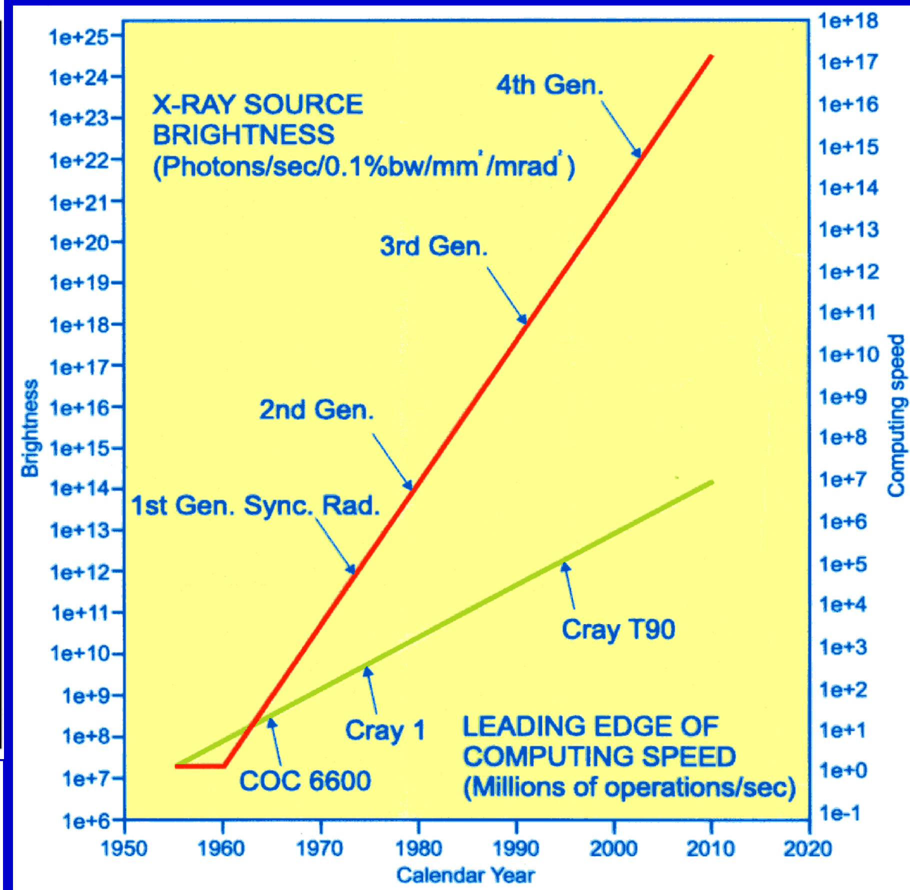
5 Undulator systems
5 Photon diagnostics
5 Photon beamline
10 Instruments

Infrastructure for scientific instruments

- **3 2D area detectors**
- **optical laser systems**
- **sample environment R&D**
- **special instruments**
- **preparation & characterization labs.**

Comparison:



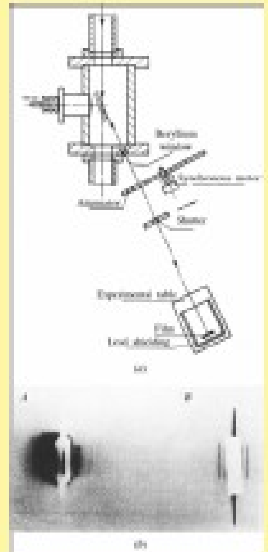


1980	$\varepsilon \sim 300$ nmrad	$N_u \sim 10$	$\sigma_E/E \sim 10^{-3}$	Storage rings
1990	$\varepsilon \sim 30$ nmrad	$N_u \sim 10^2$	$\sigma_E/E \sim 10^{-3}$	
2000	$\varepsilon \sim$ 1-3 nmrad	$N_u \sim 10^3$	$\sigma_E/E \sim 10^{-3}$	
2015	$\varepsilon \sim 10^{-2}$ nmrad	$N_u \sim 10^4$	$\sigma_E/E \sim 10^{-4}$	MARS XFEL

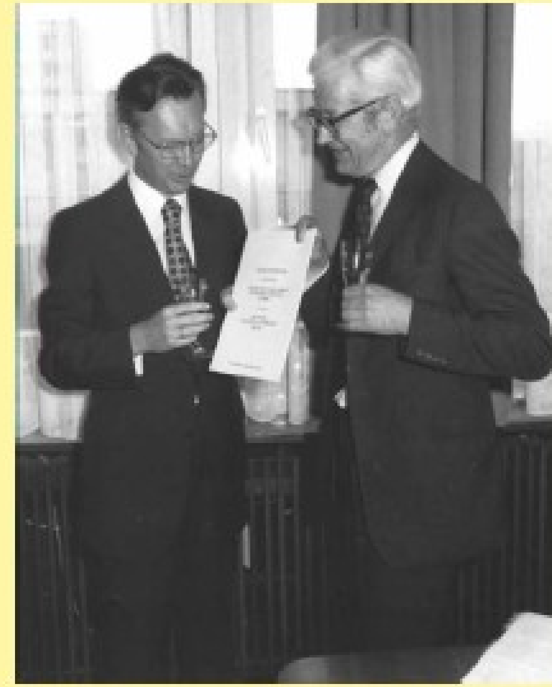
Conclusion

- In the 1970s and 1980s works on the generation and application of synchrotron radiation in Russia were up to the world standards and defined the level of research in the world;

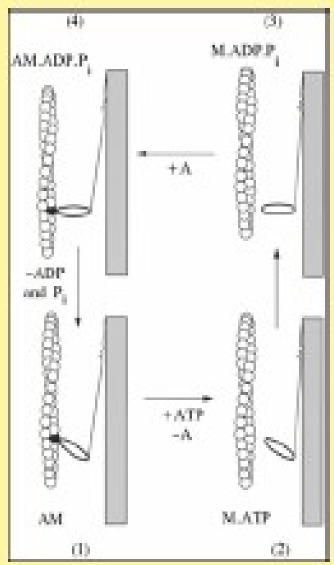
1971 First biological experiment at DESY, Hamburg (G. Rosenbaum, K. C. Holmes & J. Witz Nature 230, 434-437).



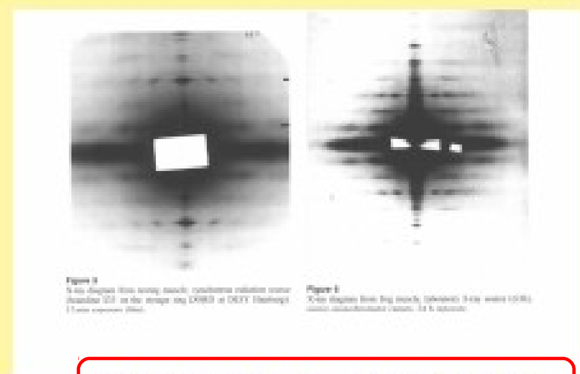
First synchrotron photo of muscle (1971)



H. Schopper & J. C. Kendrew agree the EMBL outstation at DESY 1975



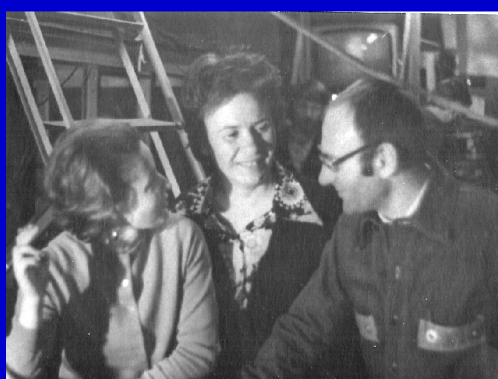
Muscle



12 min SR   24 h Lab !

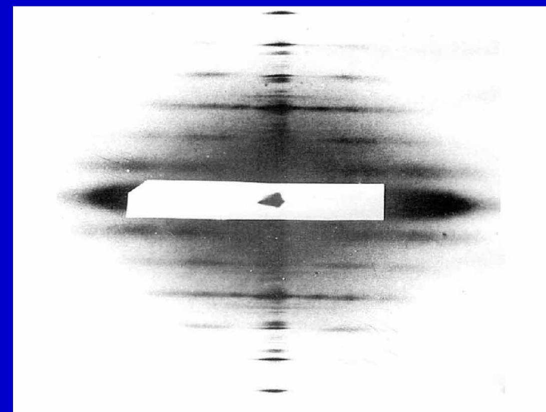
The experiments with using of SR beams at the Novosibirsk Institute of Nuclear Physics had been started at VEPP-3 SR source on July, 1973.

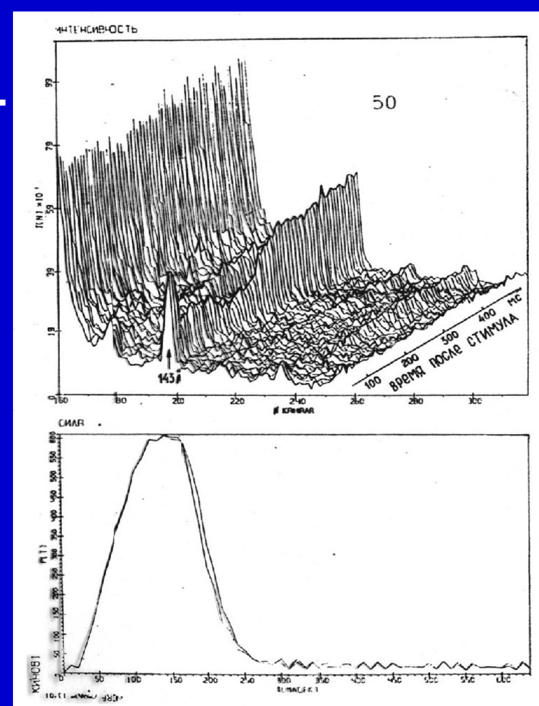
In 1973 the team of Prof. Mark Mokulsky from the Moscow Institute of Molecular Genetics obtained first SR diffractograms for structure determining of heavy Cs - DNA.

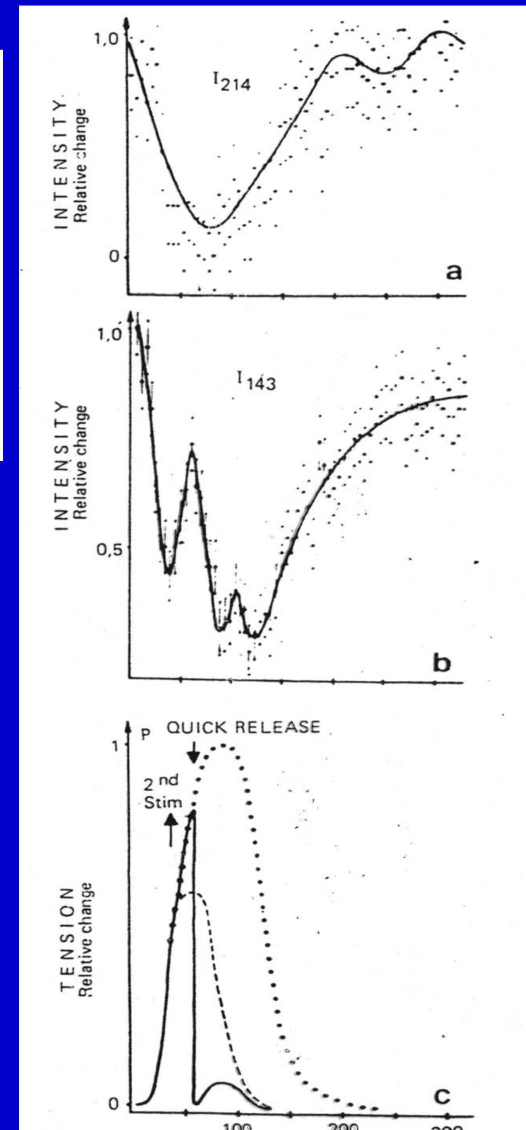


Next, 1974 year, Alvina Vazina from the Institute of Biophysics (Puschino) started a study of structure of biopolymers with large periods, in particular, musle structure

1 frame per 10 second







Time resolution – 2 ms !

- A significant lag behind other countries have been observed recent years, which is caused by the absence of modern sources of synchrotron radiation in Russia;

- Development of science and technology in Russia (biology, chemistry, physics, materials science, nanotechnology, etc) necessitates creation of a number of modern sources of synchrotron radiation throughout the country (Novosibirsk, Ekaterinburg, Saint Petersburg) on the basis of the suggested synchrotron radiation source using an electron storage ring with superconductive magnets;

- Construction of the synchrotron radiation source on the basis of the accelerator-recuperator MARS at Kurchatov Institute will allow Russia to offer the Russian and world-wide scientific community an

Thank you for your attention