Energy recovery linacs

(Recirculating accelerators-recuperators)
Multipass accelerator-recuperator

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Contents of the lecture:

1. Introduction to accelerator based synchrotron radiation light sources.
2. Why the 4th generation SR sources should use the accelerators-recuperators?
3. Technical solutions for realization of the 4th generation SR sources based on accelerators-recuperators.
4. Status and future of light sources based on recirculating accelerators-recuperators.

History of synchrotron radiation

Crab Nebula
6000 light years away

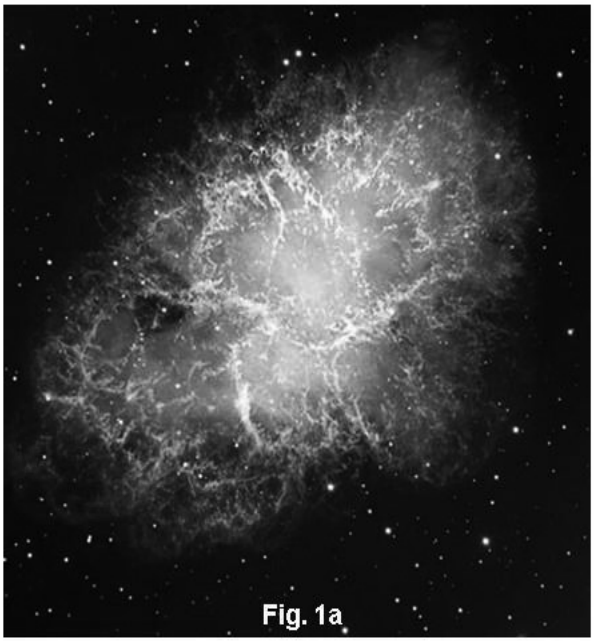


Fig. 1a

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

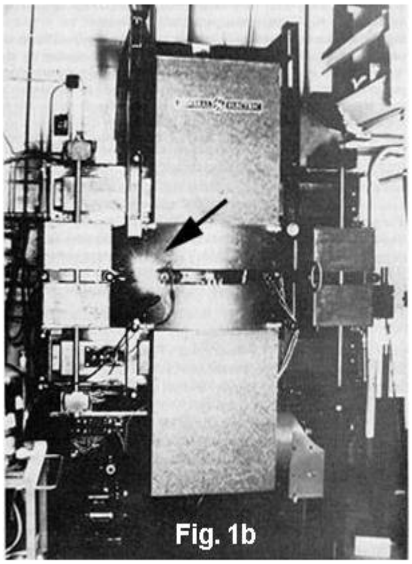
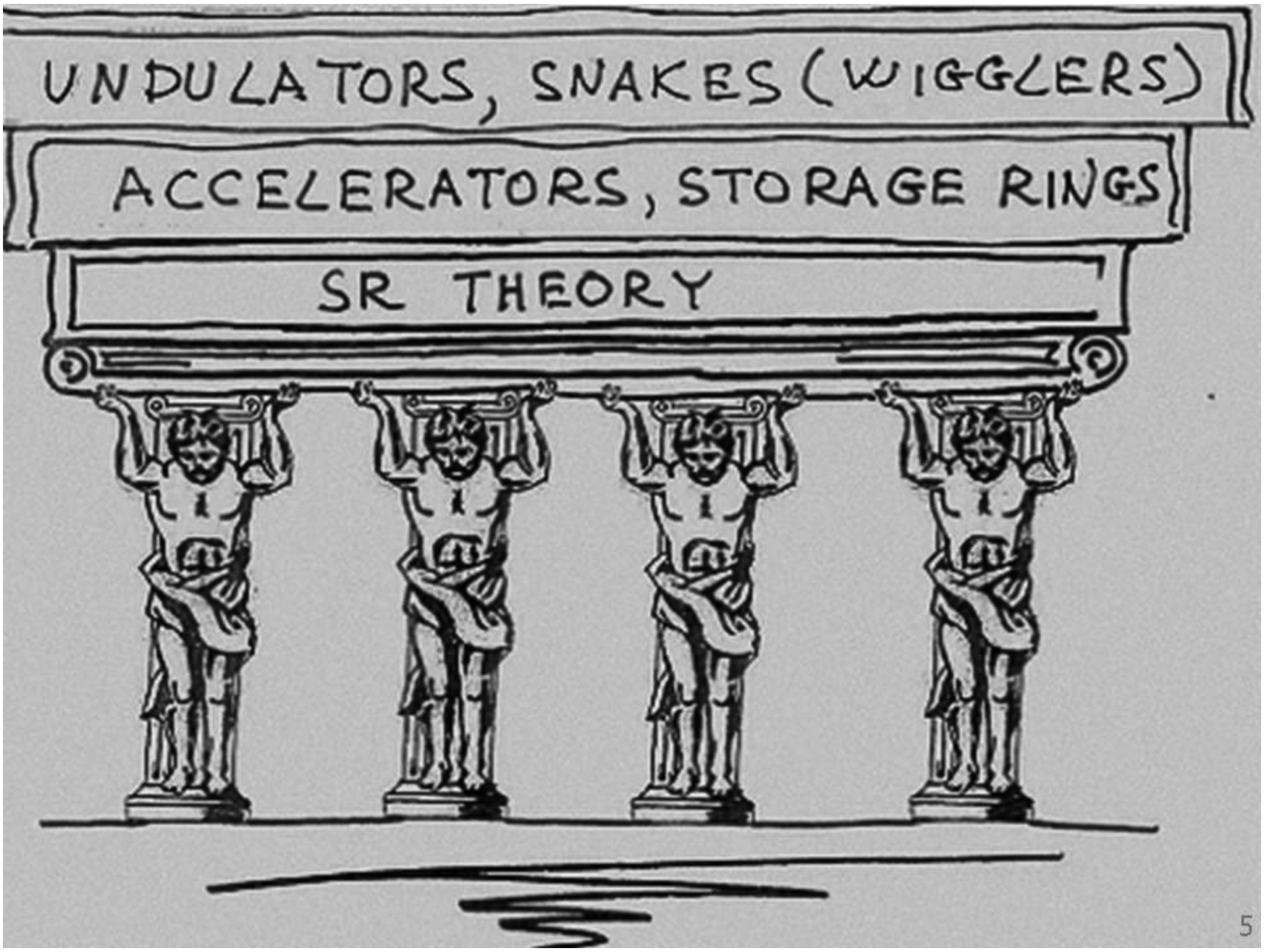


Fig. 1b

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.



ELECTRON SYNCHROTRONS – FIRST SOURCES of SR

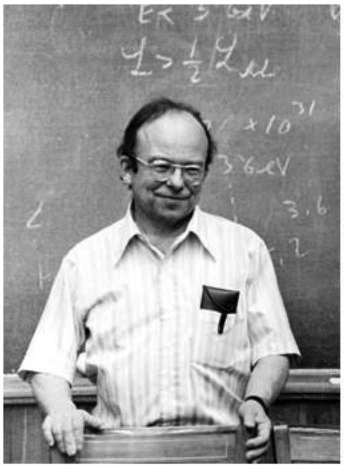
1. V. I. Veksler (1944) Comptes Rendus de
l' Academic Sciences de l' URSS V. 43, 8, p.329
E. Mc. Millan (1945) Phys. Rev. V. 68, p. 144-145.independently discovered the principle of phase stability for RF acceleration of charged particles, moved in a circle of constant radius.
General Electric synchrotron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

3. 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)

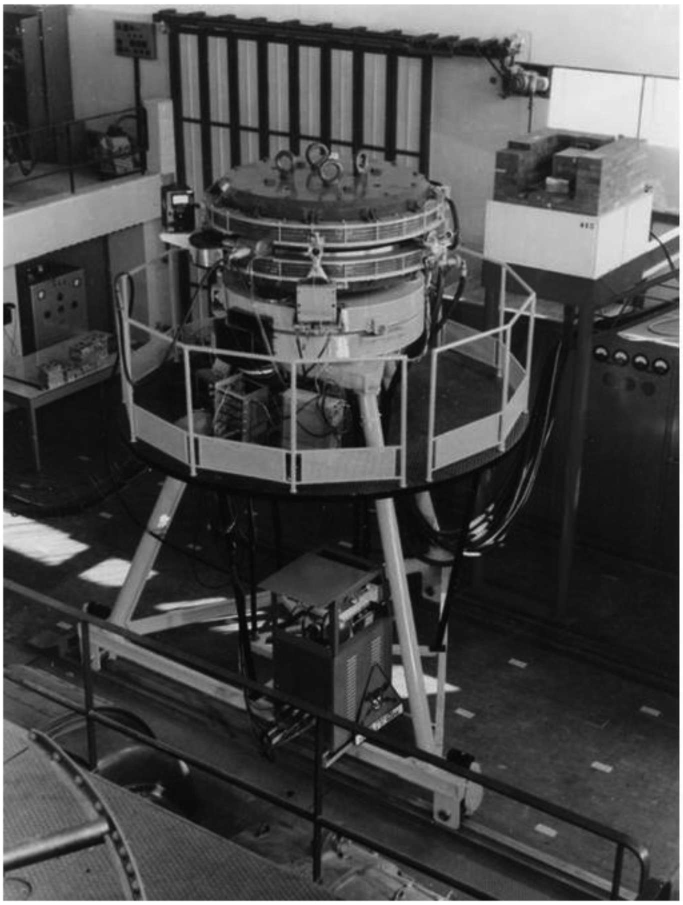
D.K.O'Neill
(Princeton)



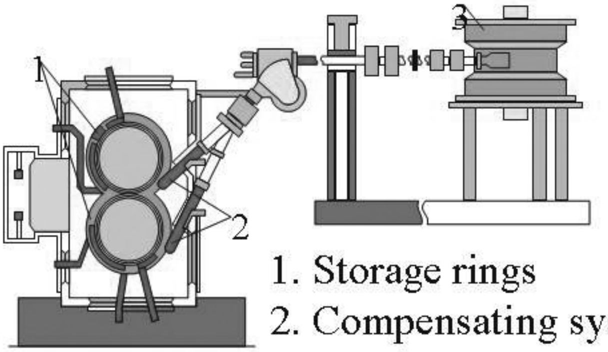
W.Panofsky
(Stanford)

G.Budker
(Novosibirsk)

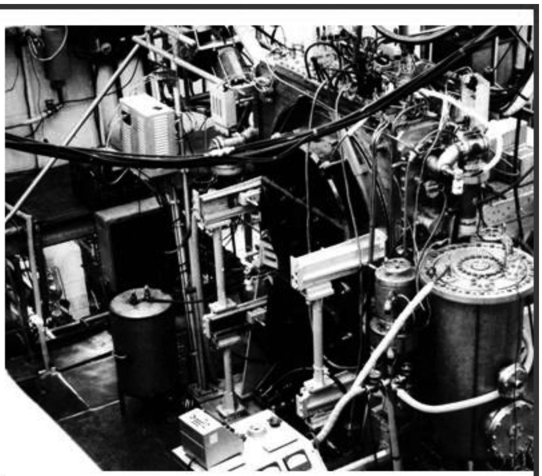
First Italy-France storage ring AdA



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}

Experiments 1965-1967 **:**

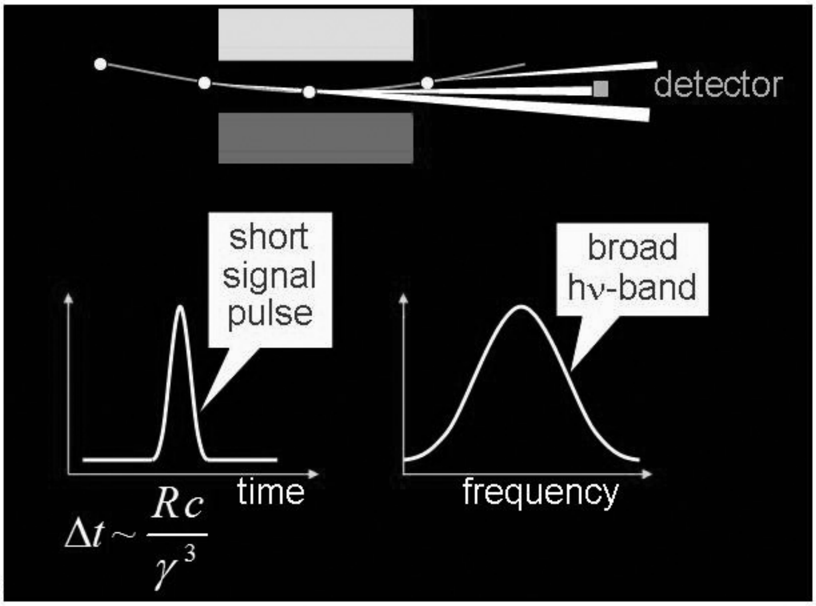
— electron-electron elastic scattering (in parallel to Princeton-Stanford Rings);

— double bremsstrahlung (first observation and study)

First electron-electron colliding beam experiments – 1965

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

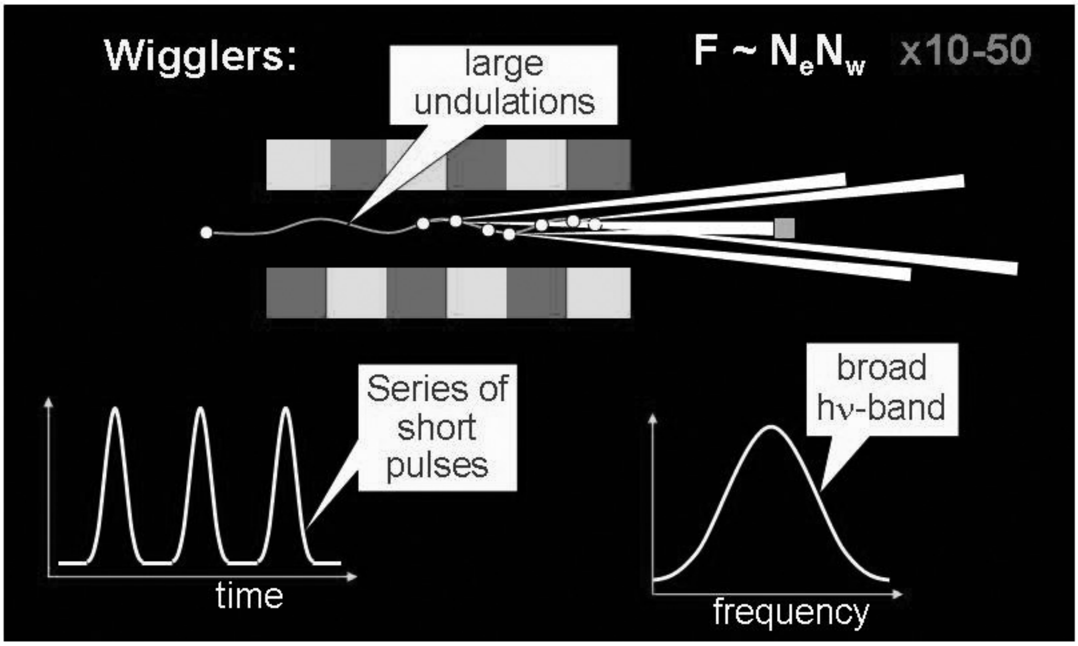
Bending magnets: **$F \sim N_e$**



after G. Margaritondo

Second generation SR sources – dedicated storage ring - synchrotron radiation sources

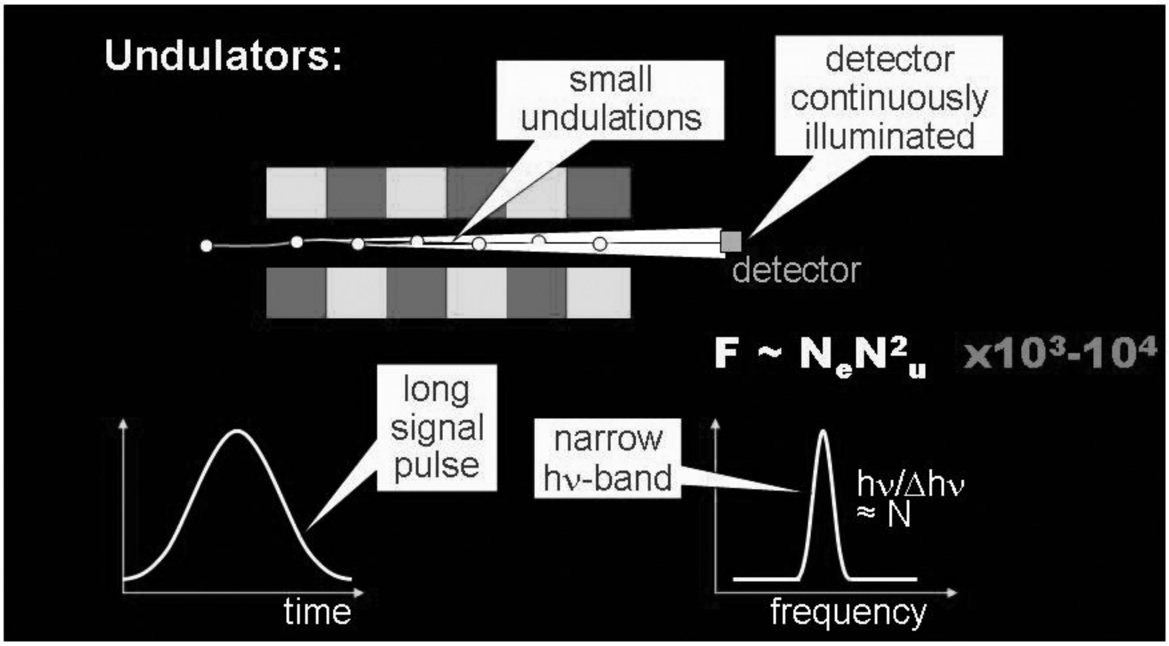
(low emittance $\varepsilon \sim 30$ nm, set of straight sections for wigglers)



after G. Margaritondo

Third generation SR sources – storage rings optimized for installation of undulators

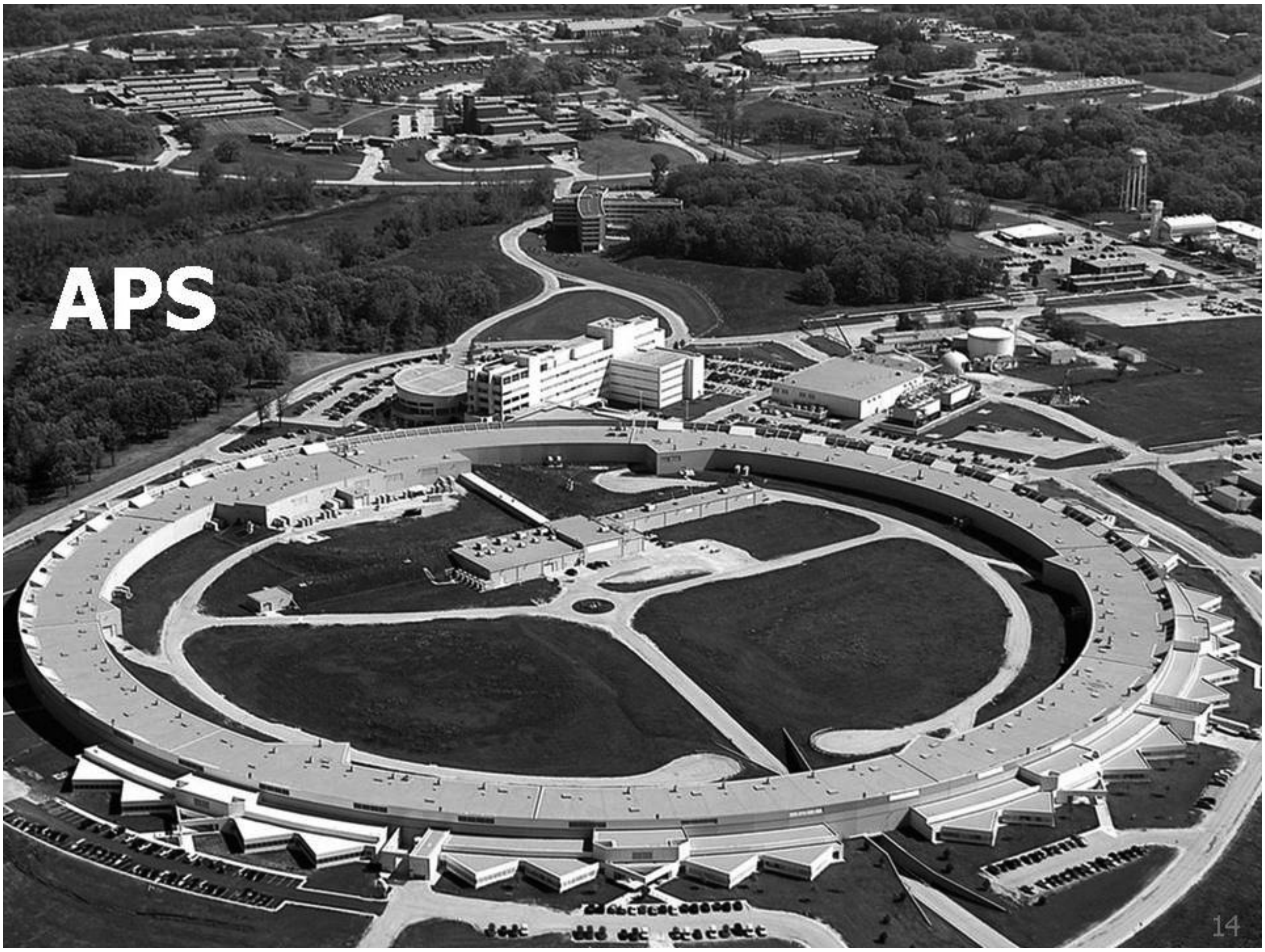
(low emittance $\varepsilon \sim 3$ nm, set of long straight sections for long undulators)



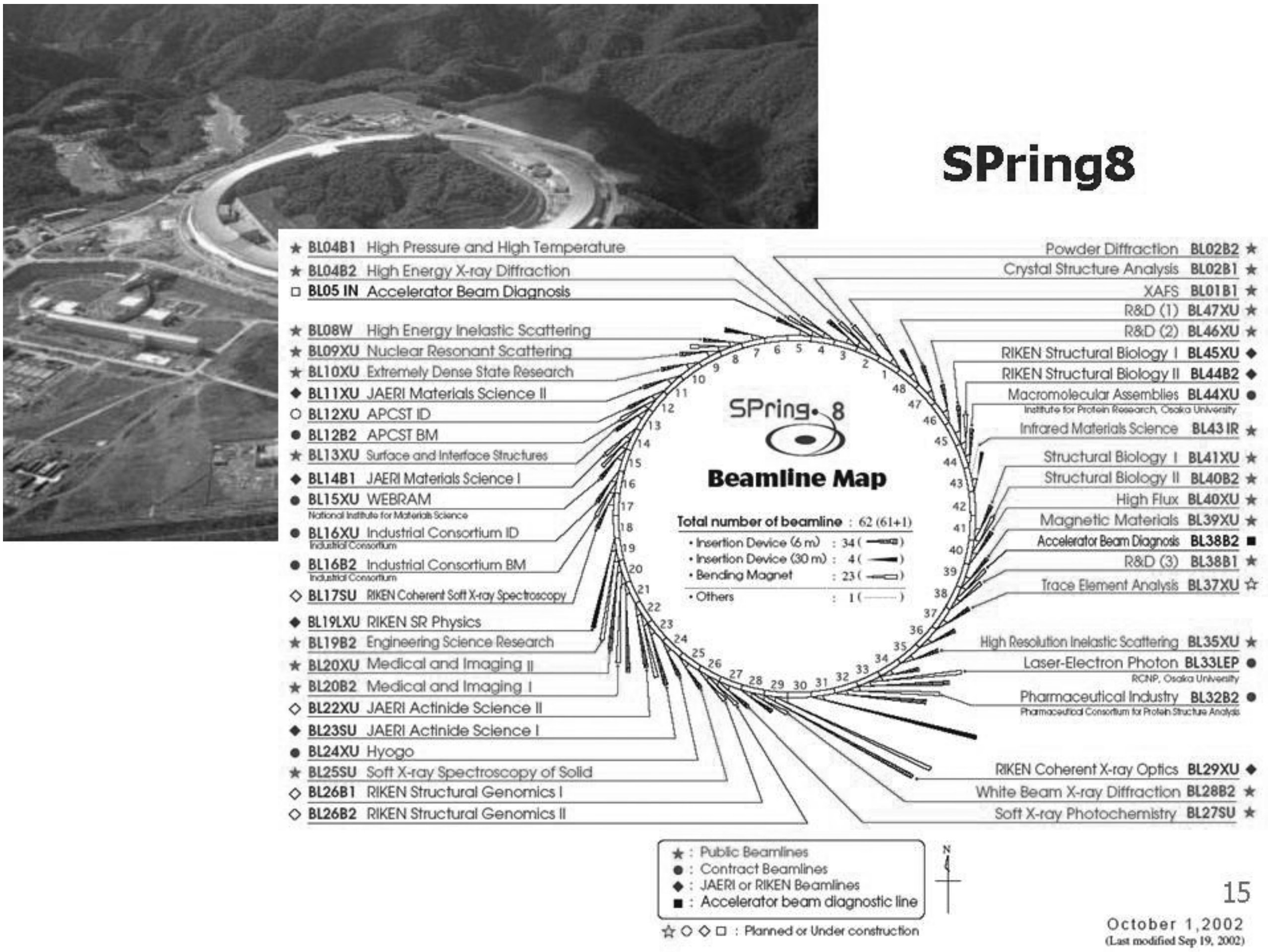
after G. Margaritondo

- 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.

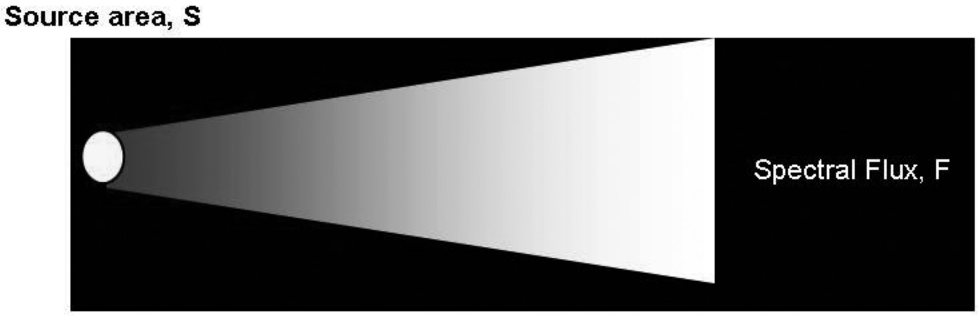


SPring8

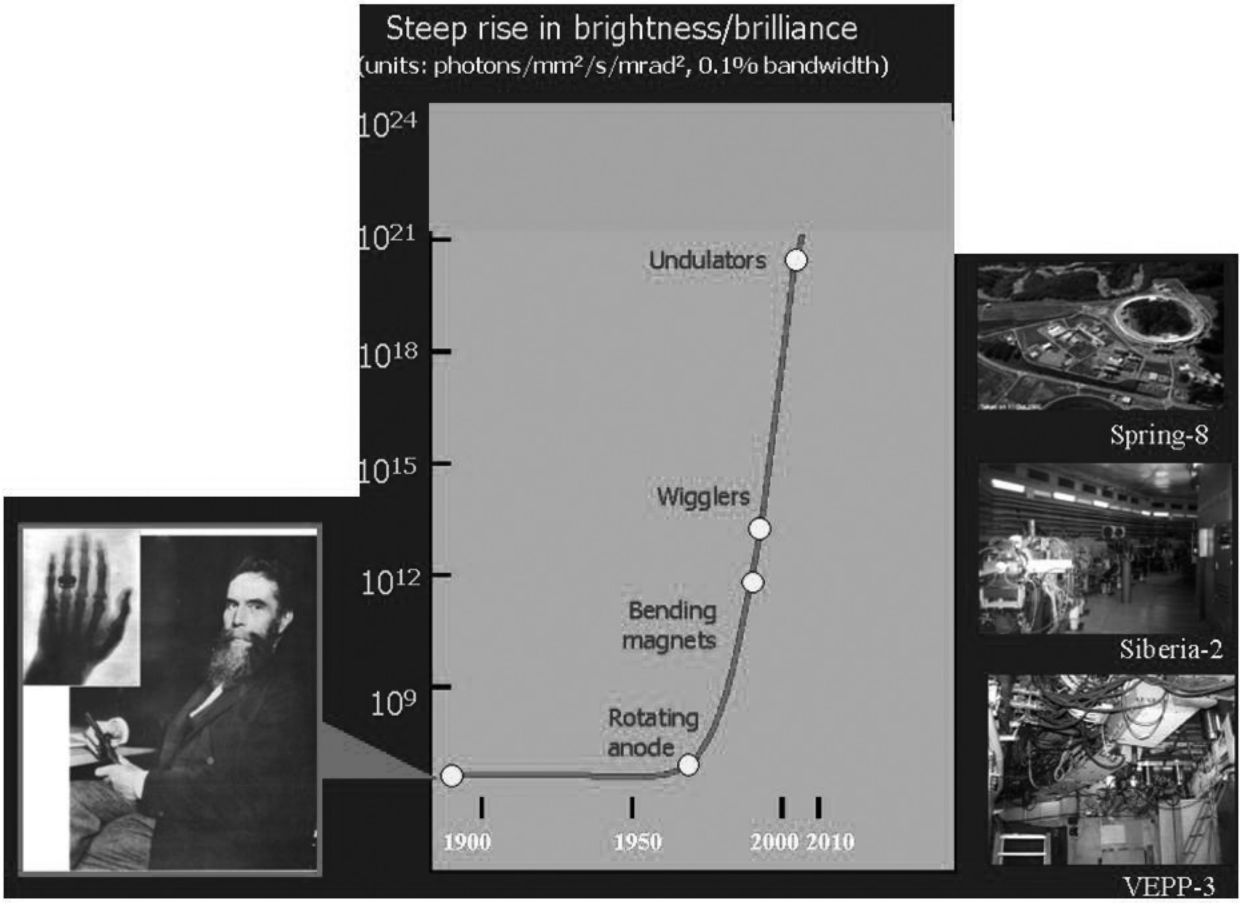


October 1,2002
(Last modified Sep 19, 2002)

The spectral “brightness” of a light source:



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



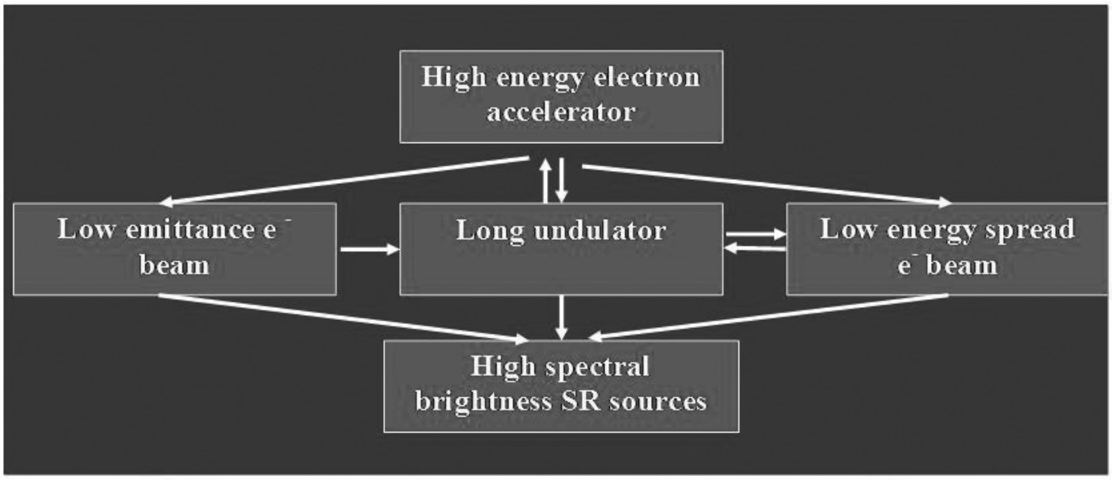
Steep rise in brightness/brilliance

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

Spring-8

Siberia-2

VEPP-3



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

- 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.

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

☐ full spatial coherence;

☐ the highest temporal coherence ($\Delta\lambda/\lambda<10^{-4}$) without additional monochromatization;

☐ the averaged brightness of the sources is 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 at the level of the 3rd generation SR sources;

☐ high peak brightness of the order of 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 if a specialized technique is used, the X-ray pulses become smaller than 100 fs;

☐ high long-term stability; generation of linear left-right circular polarized radiation with fast switching of the polarization type and sign; constant heat load on chambers and optics, etc.

☐ servicing the multi-user community.

- During the last 30 years, the brightness of the X-ray SR sources based on storage rings increased by a factor of 10^9.

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

- Therefore, obtaining a fully spatially coherent flux of quanta with full photon flux at the level of the 3rd generation SR sourcesis is the most important from all the requirements to SR sources of the 4th generation.

- A possibility of using undulator radiation with a monochromaticity of $10^{-3} \div 10^{-4}$ with no need in monochromators, which as a rule spoil the beam spatial coherence, is also of great importance.

An important task for the future generation of X-ray sources is to provide:

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

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

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

In this case, the source provides 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

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

- The linewidth of undulator radiation is determined by the number of undulator periods and energy spread of electron beam

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

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

$$\left(\frac{\sigma_E}{E}\right)^2\sim180\cdot r_0\cdot\lambda_c\cdot\gamma^2\cdot\left(\frac{K}{\lambda_u}\right)^3 Z ,$$

r_0,λ_c are the classical radius and Compton wavelength of electron, K is the undulator parameter, Z is the distance from the undulator entrance

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

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

3. Using a long undulator with a 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 have been considered recent years:

- **long undulators installed on advanced storage rings;**
- **long undulators installed on linear electron accelerators;**
- **long undulators installed on recirculating accelerator-recuperator sources.**

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, low radiation background and absence of induced radioactivity;

c) a lot of SR beam lines in simultaneous operation (up to 50 on a storage ring) – service the 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 SR and by intrabeam scattering in case of high-density beams.

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

Advantages and disadvantages of linacs:

- Advantages of linacs: the normalized emittance ε_n can be conserved during the acceleration process. With a good injector with $\varepsilon_n < 10^{-7}$ m·rad, adiabatic damping at energy E > 5 GeV allows emittance $\varepsilon_{x,z} \sim 10^{-11}$ mrad and energy spread $\delta_E /E \sim 10^{-4}$.

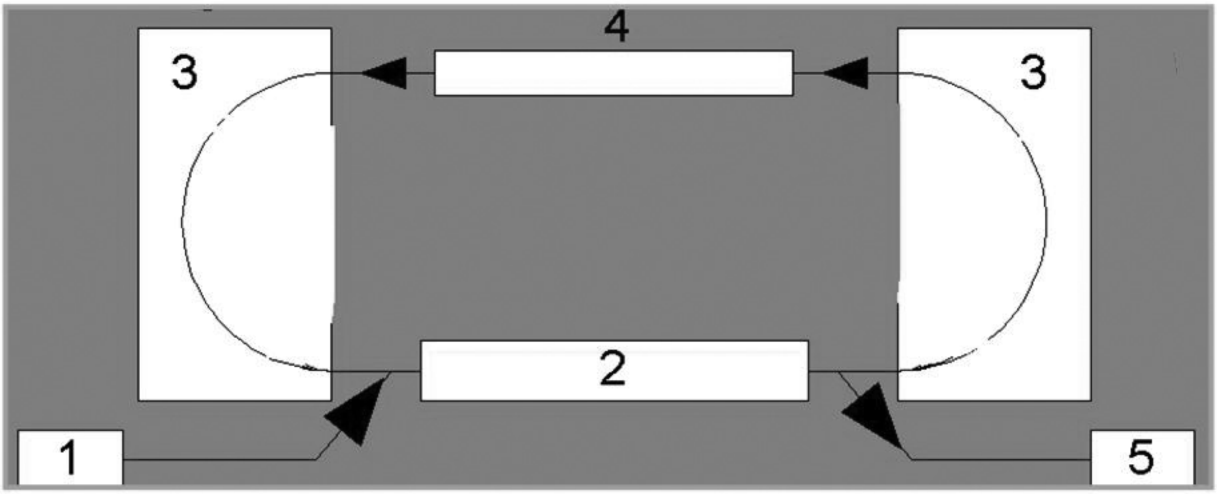
- Main disadvantages of linacs: low average current (10^{-7}A) in case of pulsed normal-conductance linacs.

- If current is increased in case of superconducting linacs, radiation hazard is a very serious problem.

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

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.

Layout of the SR source based on one-pass accelerator-recuperator



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

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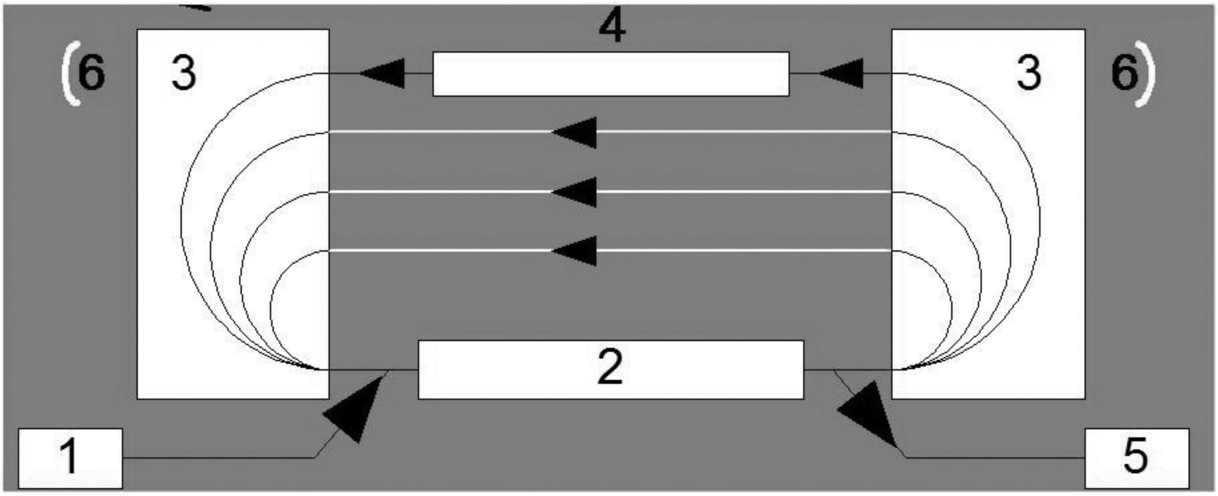
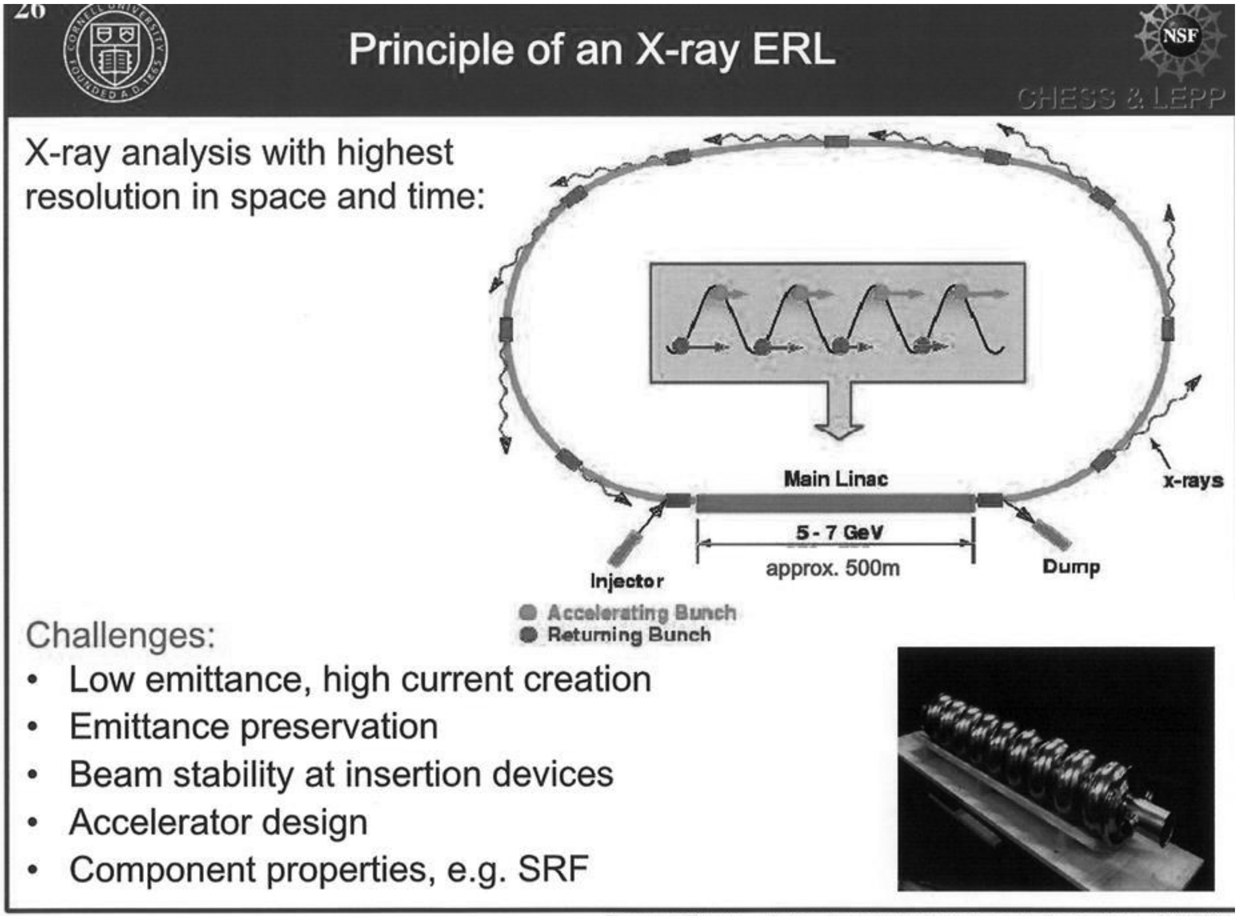
Layout of the SR source based on four-passes accelerator-recuperator



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



Principle of an X-ray ERL

CHESS & LEPP

X-ray analysis with highest resolution in space and time:

Challenges:

- Low emittance, high current creation
- Emittance preservation
- Beam stability at insertion devices
- Accelerator design
- Component properties, e.g. SRF

Georg H. Hoffstaetter Argonne National Laboratory general physics colloquium 03/23/2007

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

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

Main motivation for multipass accelerator-recuperator:

☐ Combination of the advantages of storage ring (high reactive power in beam and low radiation hazard) and linac (normalized emittance and energy spread can be conserved during the acceleration process);

☐ radiation hazard can be eliminated owing to energy recovery and the cost of construction will be reduced;

☐ the cost of the accelerating RF system can be reduced owing to multipass acceleration.

History of physical proposals based on using of accelerator – recuperator:

- M. Tigner (1965) for realization of linear e^-e^- collider using SRF linacs with energy recovery; (not realized) (M. Tigner, Nuovo Cimento, **37,** (1965).)
- G. Budker (1968) for creation electron coolers using DC electron accelerators; first demonstration of energy recovery cooler was made in Novosibirsk (1974); now all electron coolers (more 10) use energy recuperation.
- A. Skrinsky, N. Vinokurov (1976) for increasing efficiency and power of FEL; first demonstration of energy recovery SRF linac was made at Stanford University (1986); (T. Smith e. a., NIMA, **259** (1987). Now in operation ERL-FELs in Jefferson Laboratory FEL (USA), Budker Institute of Nuclear Physics FEL (Russia), JAERI FEL (Japan).

- Realization of a fully spatially 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: [1] *Kulipanov G., Skrinsky A., Vinokurov N. MARS - recirculator-based diffraction limited X-ray source. // Budker INP preprint No 97-103 (1997);*

  [2] *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*).

- MARS, a recuperator-based diffraction-limited X-ray source, was presented and discussed at the ICFA workshop on future light sources (ANL, USA, July 1999) and SRI-2000 (Berlin), "ERLSYN-2002" (Erlangen, Germany, 2002), "SR-2004" (Novosibirsk, Russia, 2004); "RUPAC-2005" (Dubna, Russia, 2005); "Nano-Beam 2005" (Kyoto, Japan, 2005).

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

- Recirculating accelerators with multipass crossing accelerating sections and independent magnetic transport system for each pass – basis of the projects MARS and ERL light sources.

- Creation of microtrons, racetrack microtrons, cascaded race-track microtrons been very important steps for understanding problems of recirculating accelerators.

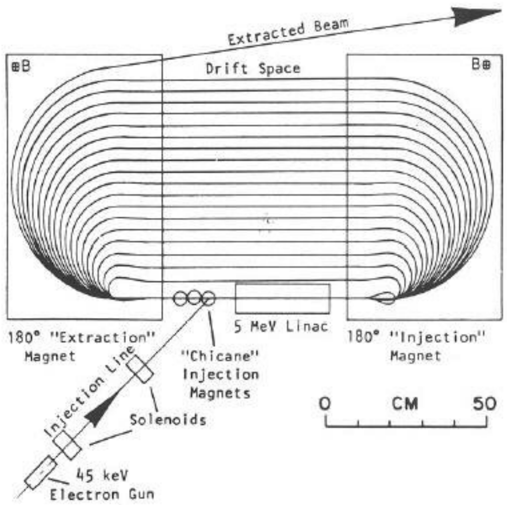


Figure 5.8 Schematic layout of the race-track microtron injector for the storage ring Aladdin at the Synchrotron Radiation Center of the University of Wisconsin (Green *et al.*, 1981; © 1981 IEEE)

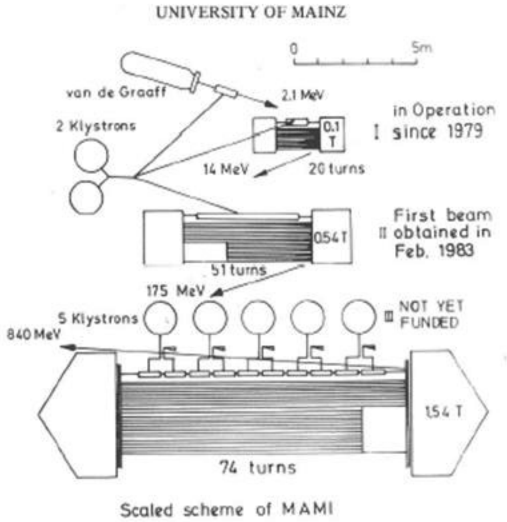
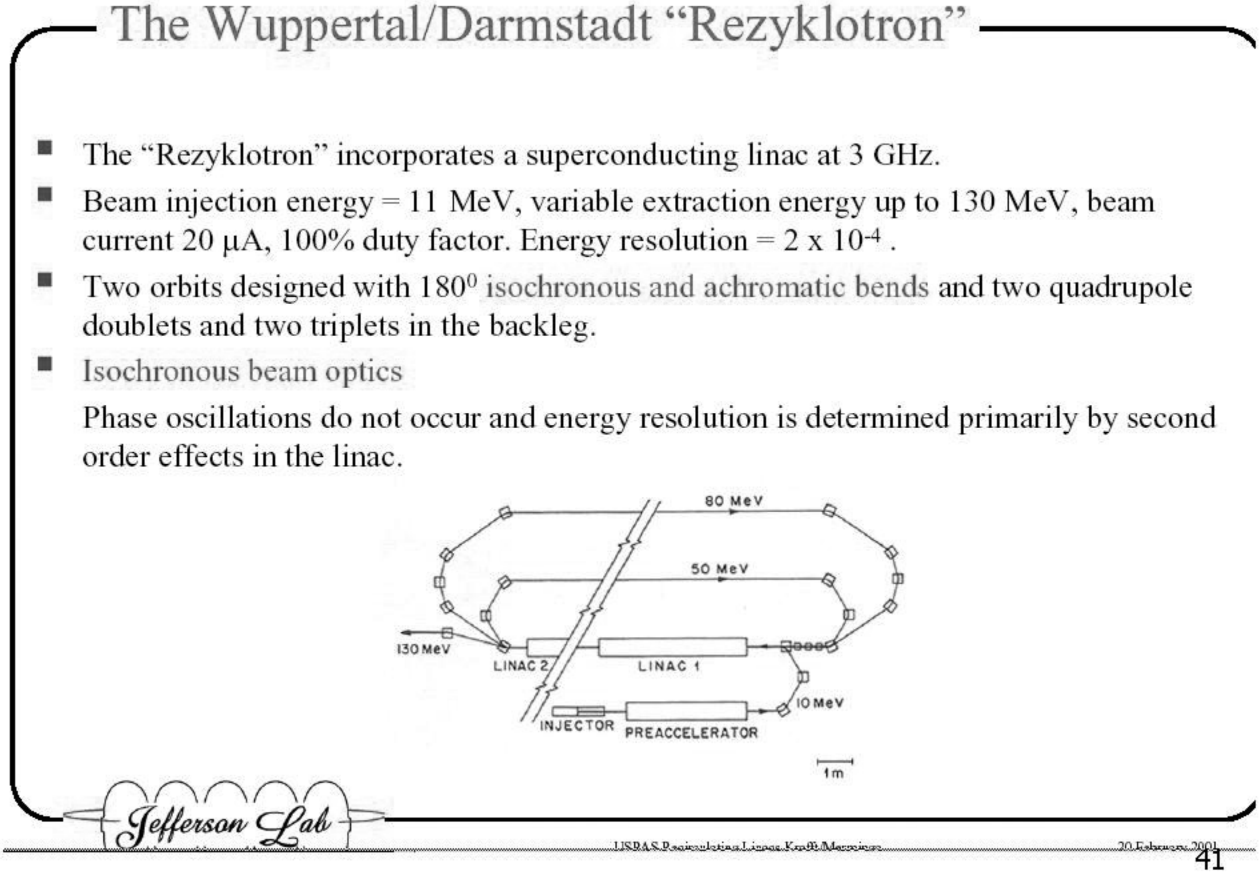


Figure 5.5 Schematic layout of the University of Mainz three-stage cascaded race-track microtron, MAMI (Herminghaus *et al.*, 1983; © 1983 IEEE)



The Wuppertal/Darmstadt "Rezyklotron"

- The "Rezyklotron" incorporates a superconducting linac at 3 GHz.
- Beam injection energy = 11 MeV, variable extraction energy up to 130 MeV, beam current 20 μA, 100% duty factor. Energy resolution = 2 x 10^{-4} .
- Two orbits designed with 180^0 isochronous and achromatic bends and two quadrupole doublets and two triplets in the backleg.
- Isochronous beam optics

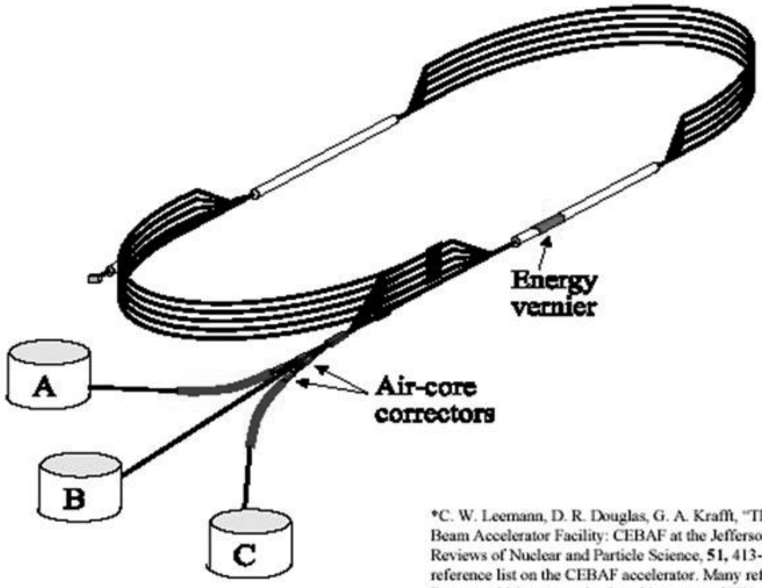
  Phase oscillations do not occur and energy resolution is determined primarily by second order effects in the linac.

Jefferson Lab

USPAS Recirculating Linacs Krafft/Merminga 20 February 2001

- Superconducting RF technology was developed by Cornell University, KEK, CERN, Jefferson Laboratory, DESY.
- The CEBAF at Jefferson Laboratory was first in world large scale implementation SRF technology and using multipass beam recirculation.
- The CEBAF accelerator is a 5-pass recirculating SRF linac with CW beams of up to 200 μA, full energy is nearly 6 GeV, geometric emittance ε < 10^{-9} m·rad and relative energy spread of a few 10^{-5}.

CEBAF Accelerator Layout*



*C. W. Leemann, D. R. Douglas, G. A. Krafft, "The Continuous Electron Beam Accelerator Facility: CEBAF at the Jefferson Laboratory", Annual Reviews of Nuclear and Particle Science, **51,** 413-50 (2001) has a long reference list on the CEBAF accelerator. Many references on Energy Recovered Linacs may be found in a recent ICFA Beam Dynamics Newsletter, #26, Dec. 2001: http://icfa-usa/archive/newsletter/icfa_bd_nl_26.pdf

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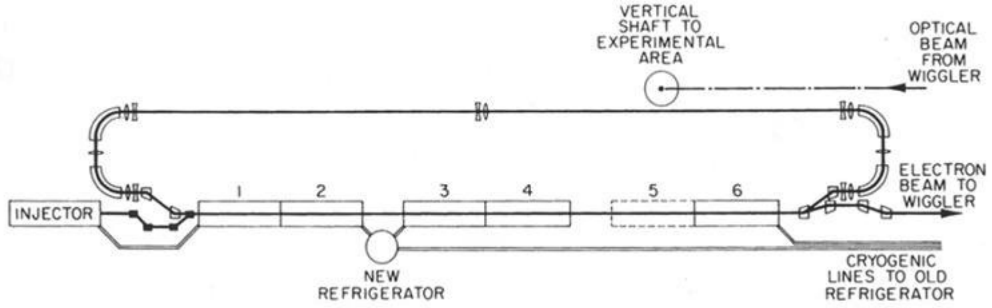
CEBAF Beam Parameters

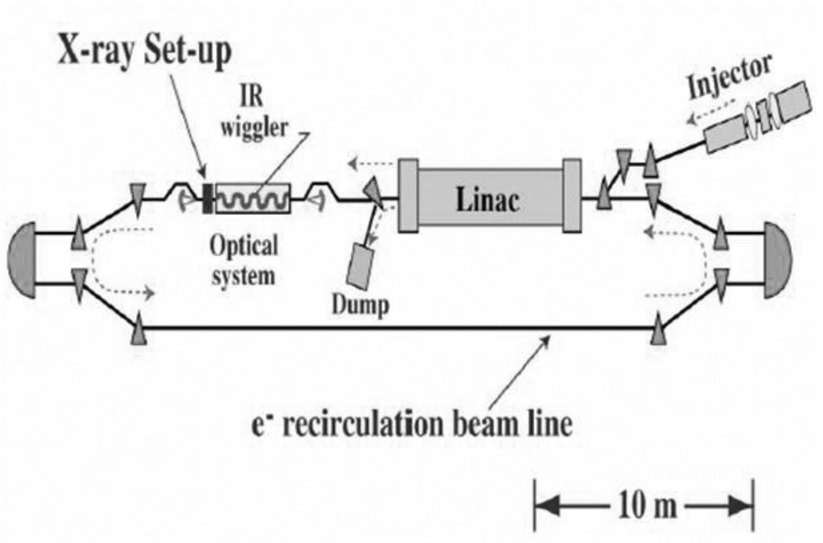
Beam energy	6 GeV
Beam current	A 100 μ A, B 10-200 nA, C 100 μ A
Normalized rms emittance	1 mm mrad
Repetition rate	500 MHz/Hall
Charge per bunch	< 0.2 pC
Extracted energy spread	$< 10^{-4}$
Beam sizes (transverse)	< 100 microns
Beam size (longitudinal)	100 microns (330 fsec)
Beam angle spread	$< 0.1/\gamma$

The SCA/FEL Energy Recovery Experiment

- Same-cell energy recovery was first demonstrated in the SCA/FEL in July 1986
- Beam was injected at 5 MeV into a ~50 MeV linac (up to 95 MeV in 2 passes), 150 μA average current (12.5 pC per bunch at 11.8 MHz)
- The previous recirculation system (SCR, 1982) was unsuccessful in preserving the peak current required for lasing and was replaced by a doubly achromatic single-turn recirculation line.
- All energy was recovered. FEL was not in place.

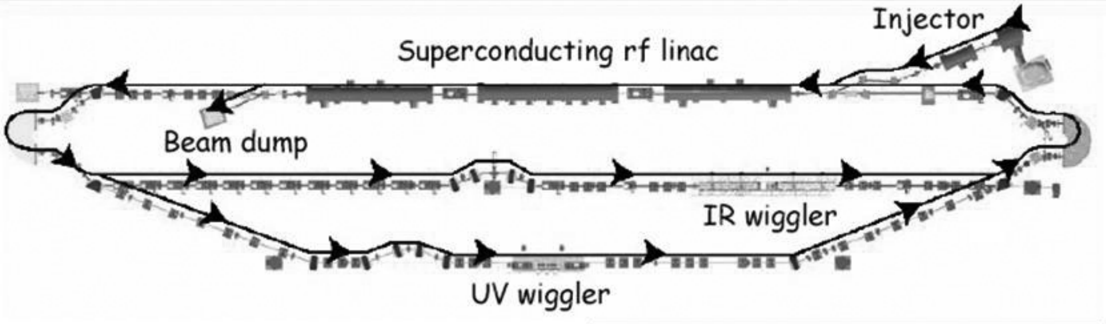


Jefferson Lab FEL



Neil, G. R., *et. al*, *Physical Review Letters*, **84**, 622 (2000)

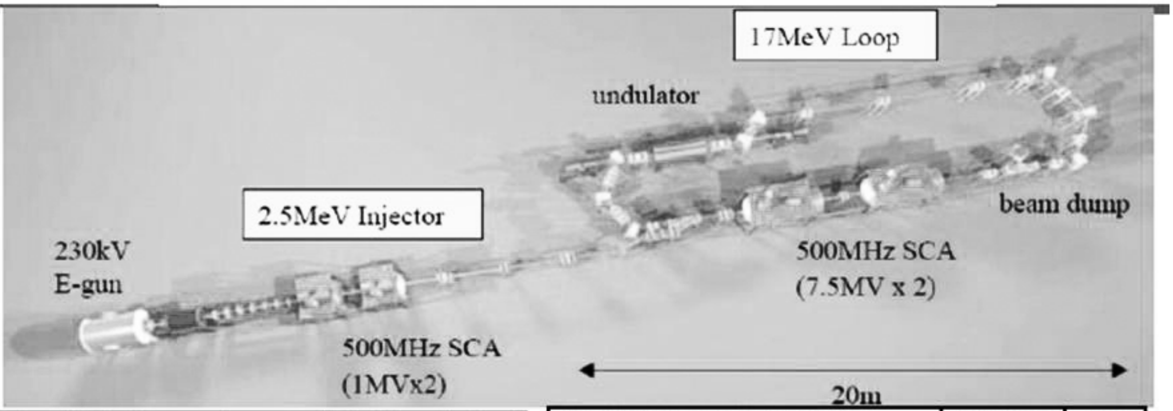
JLab 10kW IR FEL and 1 kW UV FEL



Output Light Parameters	IR	UV
Wavelength range (microns)	1.5 - 14	0.25 - 1
Bunch Length (FWHM psec)	0.2 - 2	0.2 - 2
Laser power / pulse (microJoules)	100 - 300	25
Laser power (kW)	>10	> 1
Rep. Rate (cw operation, MHz)	4.7 – 75	4.7 – 75

Electron Beam Parameters	IR	UV
Energy (MeV)	80-200	200
Accelerator frequency (MHz)	1500	1500
Charge per bunch (pC)	135	135
Average current (mA)	10	5
Peak Current (A)	270	270
Beam Power (kW)	2000	1000
Energy Spread (%)	0.50	0.13
Normalized emittance (mm-mrad)	<30	<11
Induced energy spread (full)	10%	5%

JAERI ERL-FEL



Output Light Parameters	Achieved	Goal
Wavelength range (microns)	22	22
Bunch Length (FWHM psec)	15	6
Laser power / pulse (microJoules)	10	120
Laser power (kW)	0.1	10
Rep. Rate (MHz)	10.4	83.2
Macropulse format	10ms 10Hz	CW

Electron Beam Parameters	Achieved	Goal
Energy (MeV)	17	16.4
Accelerator frequency (MHz)	500	500
Charge per bunch (pC)	500	500
Average current (mA)	5	40
Peak Current (A)	33	83
Beam Power (kW)	85	656
Energy Spread (%)	~0.5	~0.5
Normalized emittance (mm-mrad)	~40	~40
Induced energy spread (full)	~3%	~3%