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

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Lecture 2

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

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1. Requirements for 4th generation of the X-ray sources.

2. Comparison of storage rings, linacs and recirculating accelerators-recuperators.

3. Description of proposals of 4th generation light sources, based on recirculating accelerators-recuperators.

4. Summary.

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.

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.

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.

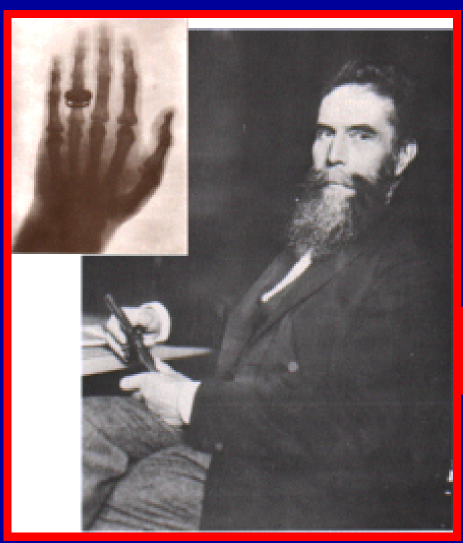
List of requirements for future generation of the X-ray sources:

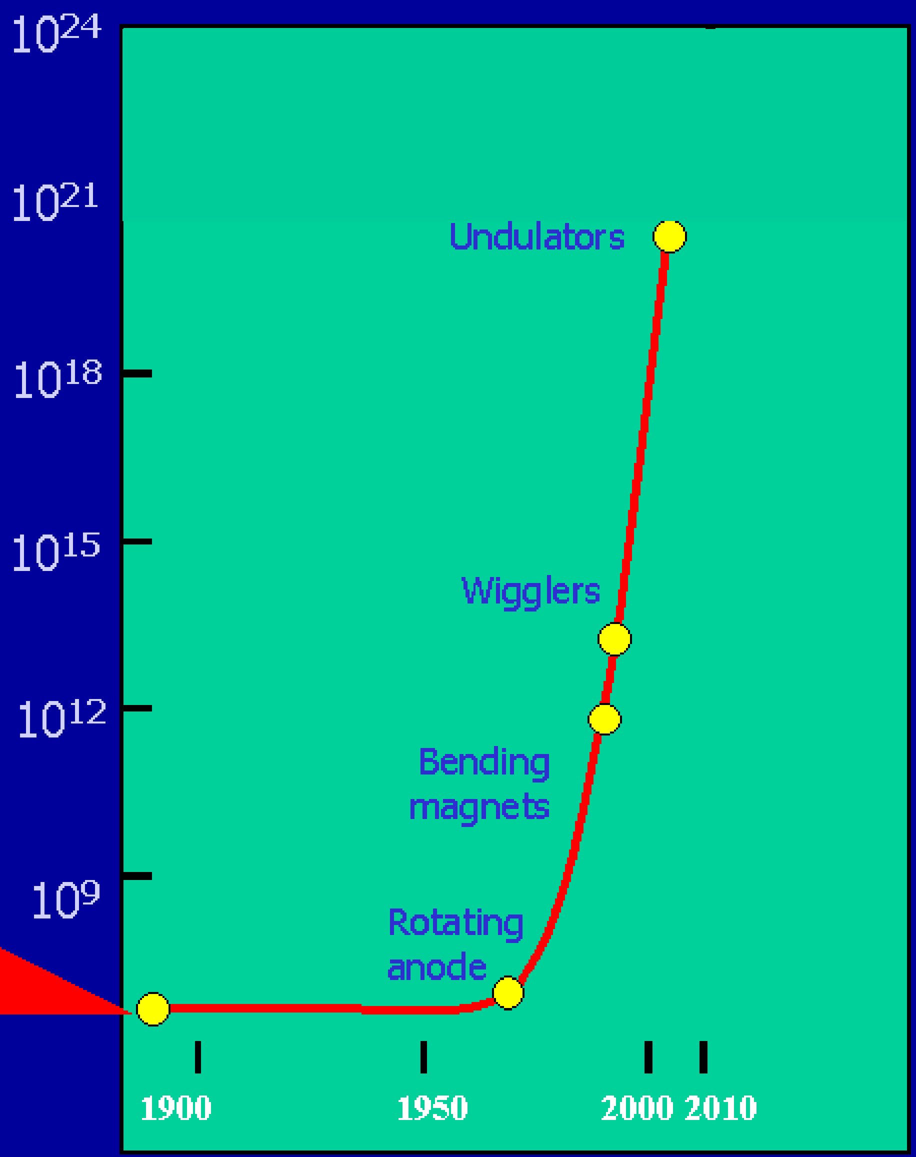
- full spatial coherence;
- as high as possible temporal coherence ($\Delta\lambda/\lambda < 10^{-4}$ without additional monochromatization;
- the averaged brightness of the sources has to exceed 10^{23}-10^{24} photons $s^{-1}mm^{-2}mrad^{-2}(0.1\%\ bandwidh)^{-1}$;
- the full photon flux for the 4th 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.

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 based on storage rings has been increased by the factor of a billion.

Steep rise in brightness/brilliance

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





Spring-8

Siberia-2

VEPP-3

- 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}.

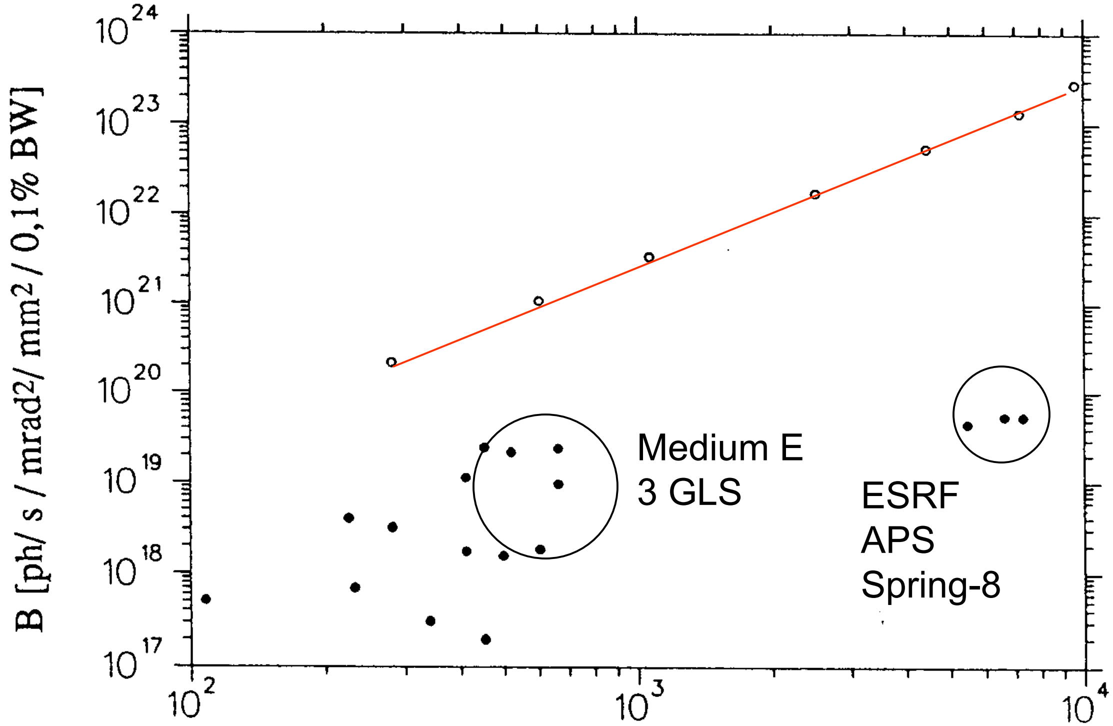
- Nevertheless, at the modern sources, the flux of the coherent quanta is only 10^{-3} of the total flux. Therefore, in spite of the successful demonstration of the X-ray holography, it did not become the efficient technique for structural studies of the real objects having mostly noncrystalline structures.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

PERFORMANCE OF 3th GENERATION LIGHT SOURCES

BRIGHTNESS:



PHOTON ENERGY [eV]

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)

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

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 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

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

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

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

Long undulator with 10^4 periods provides the radiation with narrow-peak spectrum and large length of the temporal coherence without additional monochromatization. This radiation can be successfully used for X-ray holography, X-ray microprobe and other experiments without using of monochromator.

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.

Thus it is seen that advantage is taken of four factors in order to increase the brightness of SR sources based on storage rings:

increase in the current, ensuring a proportional increase of the flux of SR quanta;

decrease in the electron beam emittance which causes a proportional decrease of both the area of the source and the angular spread in the beam; the later circumstance is of the value in the case of undulators;

increase in the energy of the electron beam, which proportionally increases the quantum flux, decreases the solid angle of radiation, and offers the possibility of employing the undulators to generate the short-wave radiation;

undulators allow a N_u-fold increase of the quantum flux as compared with radiation emitted from the magnets (N_u – is the number of poles) and the additional N_u-fold reduction of the solid angle of radiation.

In reality, these factors are interconnected, although each of them has specific feature of its own. Therefore, taking all of them into account can give a consistent solution of the brightness increase problem. The maximum current in storage rings has remained, practically, constant ($I_{max} \leq 1A$) for a long time. Increasing the current, in particular accompanied by the growth in energy, introduces many physical (transverse and longitudinal instabilities, increasing the emittance and energy spread), technological (the necessity to absorb high-power SR beams inside the vacuum chamber, with the super high vacuum conserved), technical (the creation of high-power RF generators whose averaged power is tens of Megawatts), and economical difficulties.

Decreasing the beam emittance with a simultaneous increase of its energy, allowing the undulators to be used as generators of short-wave radiation, is the main way of increasing the SR brightness.

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.

Radiation damping.

For ultrarelativistic electrons synchrotron radiation is directed into a narrow forward radiation cone of angle $Q \sim \frac{1}{\gamma}$

Due to full energy (transverse and longitudinal) loss into synchrotron radiation while RF cavity compensates only the longitudinal energy,

and transverse oscillation amplitudes are damped with damping time

$$\tau_{x,z} \sim \frac{E}{W_0} T_0$$

E – energy of electrons, $W_{0[keV]} \sim \frac{90 E_{GeV}^4}{Rm}$ - energy loss per revolution,

T_0 – period of revolution.

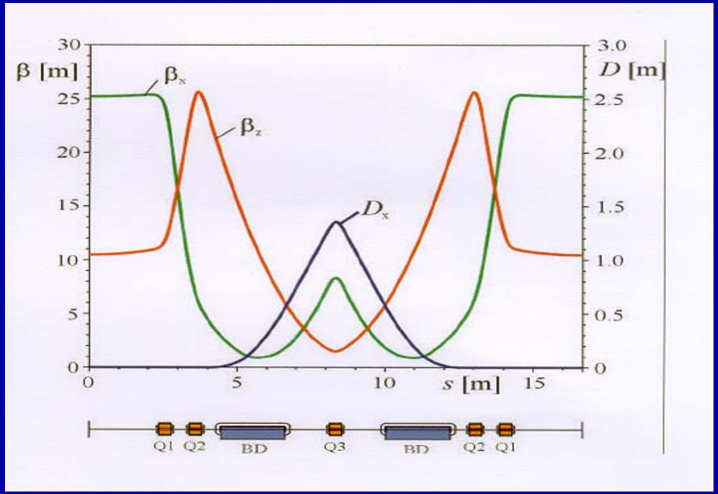
Damping for energy deviation and bunch length derives from energy dependence of radiation.

It is clear from a qualitative point of view (M. Sands) that emittance should depend on the number of quanta emitted for the damping time $\left(N = \frac{E}{\varepsilon_c}\right)$ the squared energy of a characteristic quantum which is normalized over the electron energy $\left(\frac{\varepsilon_c^2}{E^2}\right)$ and on a certain quantity <H>mag, determined by behavior of the betatron and dispersion function $\left(\beta_x, \beta'_x, \eta_x, \eta'_x\right)$ in bendung magnets

$$\varepsilon_x = \frac{E}{\varepsilon_c} \cdot \frac{\varepsilon_c^2}{E^2} \langle H \rangle_{mag}$$

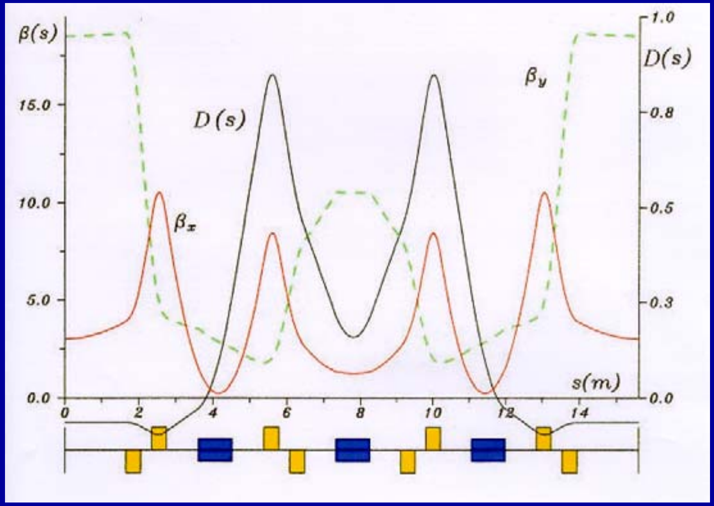
SMALL EMITTANCE LATTICES: ACHROMAT STRUCTURES

$$\varepsilon_x = \frac{c_q \gamma^2}{J_x} \cdot K \cdot \theta_B^3$$



DBA / Double Bend Achromat

$$K = \frac{1}{4\sqrt{15}} \approx 6{,}5 \cdot 10^{-2}$$



TBA / Triple Bend Achromat

$$K = \frac{7}{36\sqrt{15}} \approx 5 \cdot 10^{-2}$$

Last twenty years the basic way of decreasing the emittance is to optimize the magnetic lattices, that lead to increasing the hardness of focusing ν_x. However, such method has physical restrictions which are due to the fact that an increase of ν_x requires a great numbers of strong quadrupole lenses and, as a consequence, there appears strong chromaticity. The compensation of the latter requires, in turn, a large number of strong sextupoles.

In addition, sextupoles also give rise to a strong dependence of the frequencies of betatron oscillations on the amplitude and, as a consequence, to the reduction of the dynamic aperture because of strong third-order resonance.

There are several methods for increasing the dynamic aperture. There can only contribute to an improvement of the situation to a certain extent, not changing it in a radical way. In view of this, increasing the dynamic apertureis a acceleration problem, which is very important for further advance of SR sources.

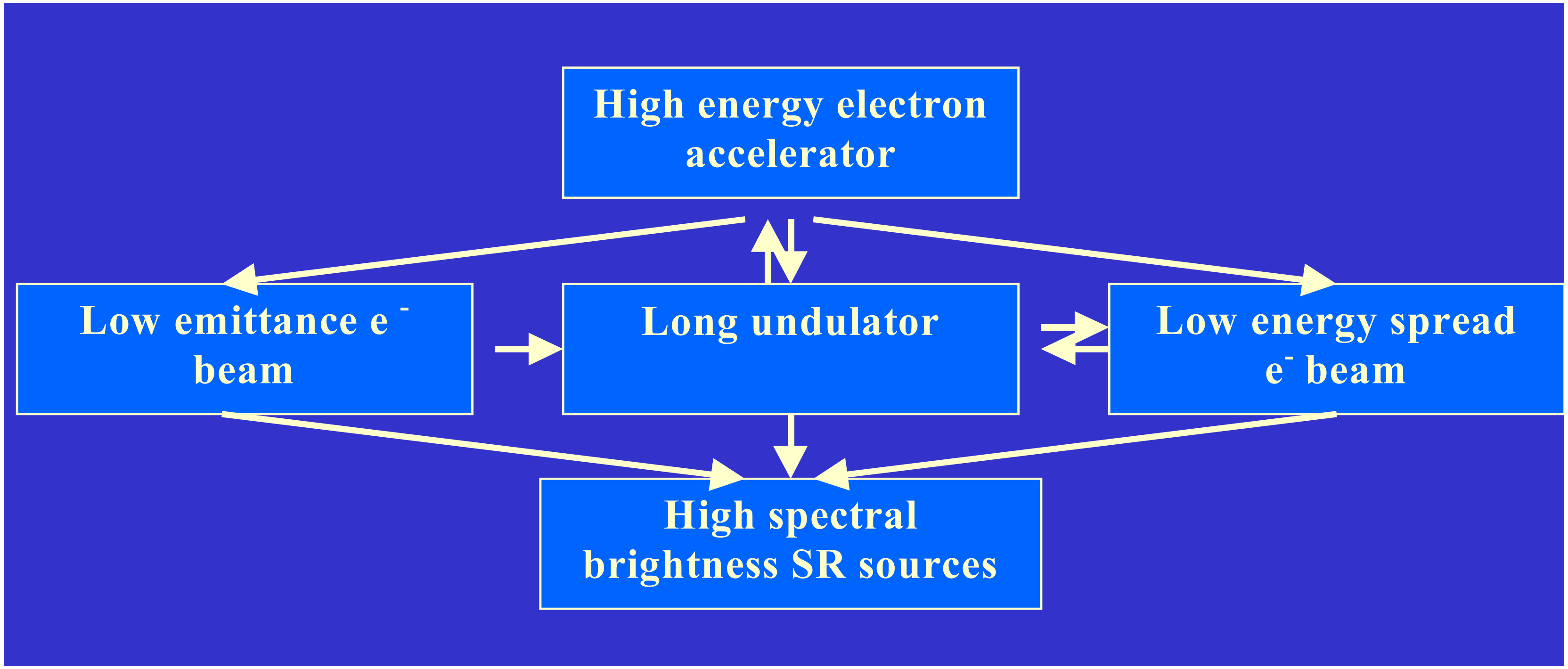
There appear other possibilities of obtaining low emittance if special long damping wigglers are in use. These devices are able to make the radiation damping time several times lower. If in the wiggler site $\eta=\eta'=0$ at low wiggler fields, the additional radiation damping results in decreasing the emittance. Nevertheless, if the field grows the wiggler excites, similar to conventional dipole magnets, the natural dispersion functions, thereby causing an additional quantum excitation.

This method is rather effective for the modernization of PETRA because, at first, PETRA have long straight sections and, second, the rather high RF power supply necessary to compensate additional energy losses in wigglers. In addition to evident problems associated with the extraction of the high-power SR beams from wigglers, this method is also limited by large cubic nonlinearity caused by such wigglers. The still longer wigglers will lead to an increased $\partial\nu/\partial\alpha^2$ and reduced dynamic aperture.

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).



Storage rings:

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

- 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 $\varepsilon_{x,z} \sim 10^{-11}$ mrad 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*).

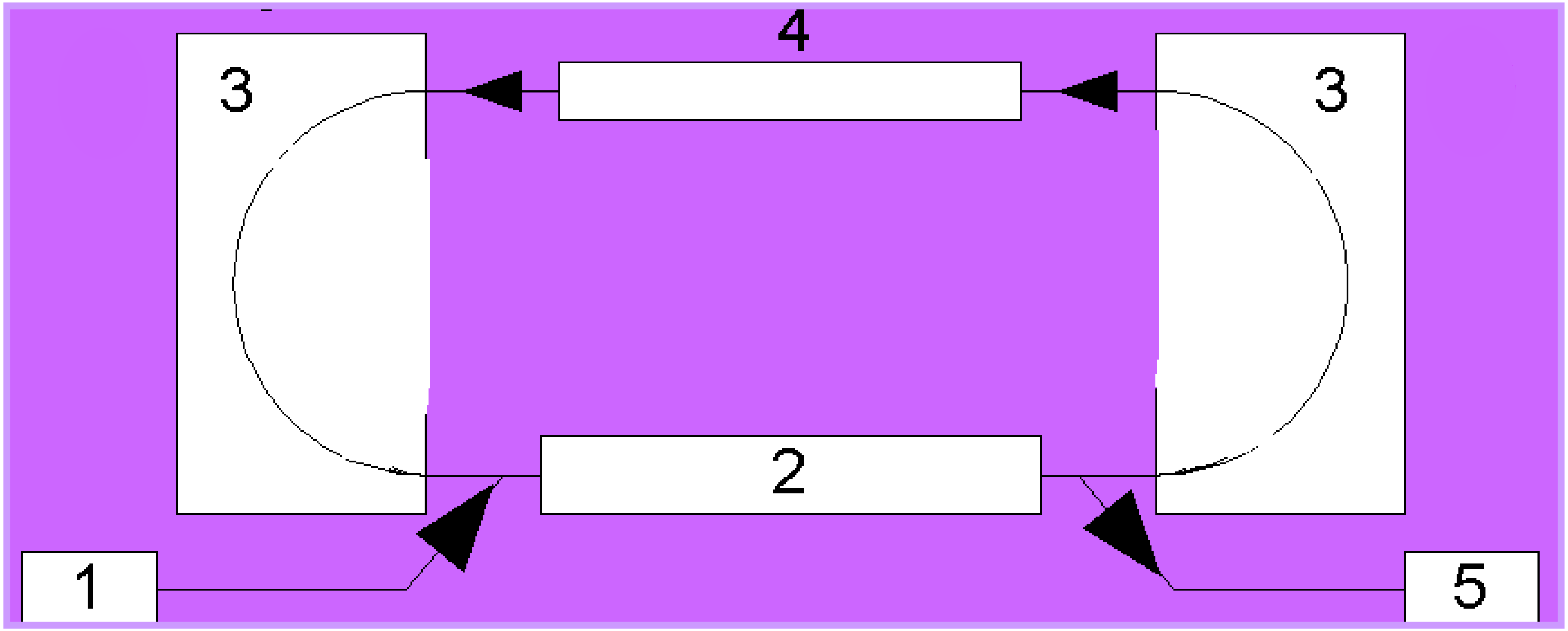
- Presentation of MARS - recuperator based diffraction-limited X-ray source was made on ICFA workshop on future light sources (ANL, USA, July 1999).

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

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

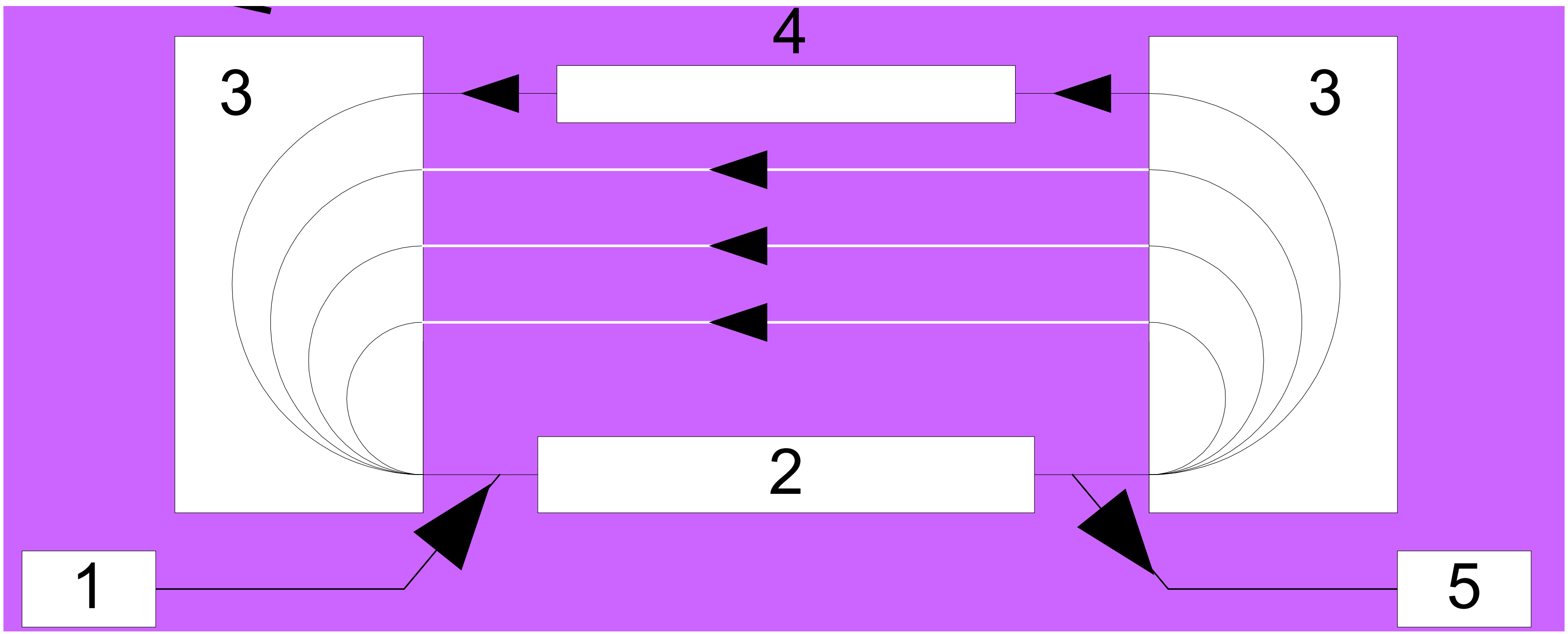
All the requirements to X-ray radiation sources of the 4th generation cannot be satisfied with the use of only one kind of a source. The high peak brightness and femtosecond duration of radiation pulses can be attained at the linac based X-ray SASE FEL with a high pulse current (I_p >1 kA). All the remaining 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

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.

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.

- In the linacs and recirculating accelerators-recuperators 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.

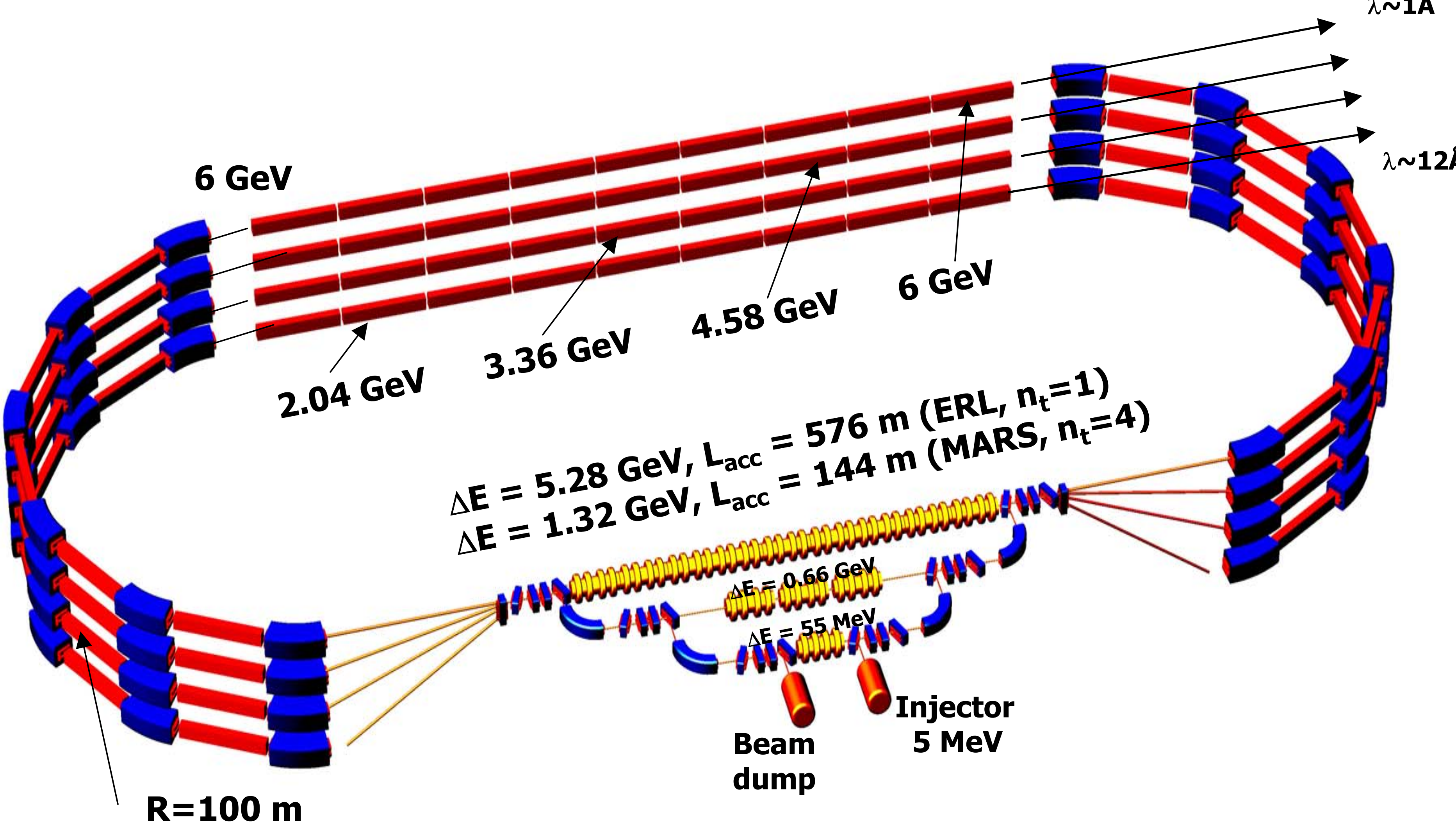
- In the recirculating accelerators-recuperators, time of the acceleration is shorter compared to the time of radiation damping in the storage rings ($10^3 \div 10^4$ times) and because of this fact, the diffusion processes cannot spoil the electron beam emittance and its energy spread.

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.

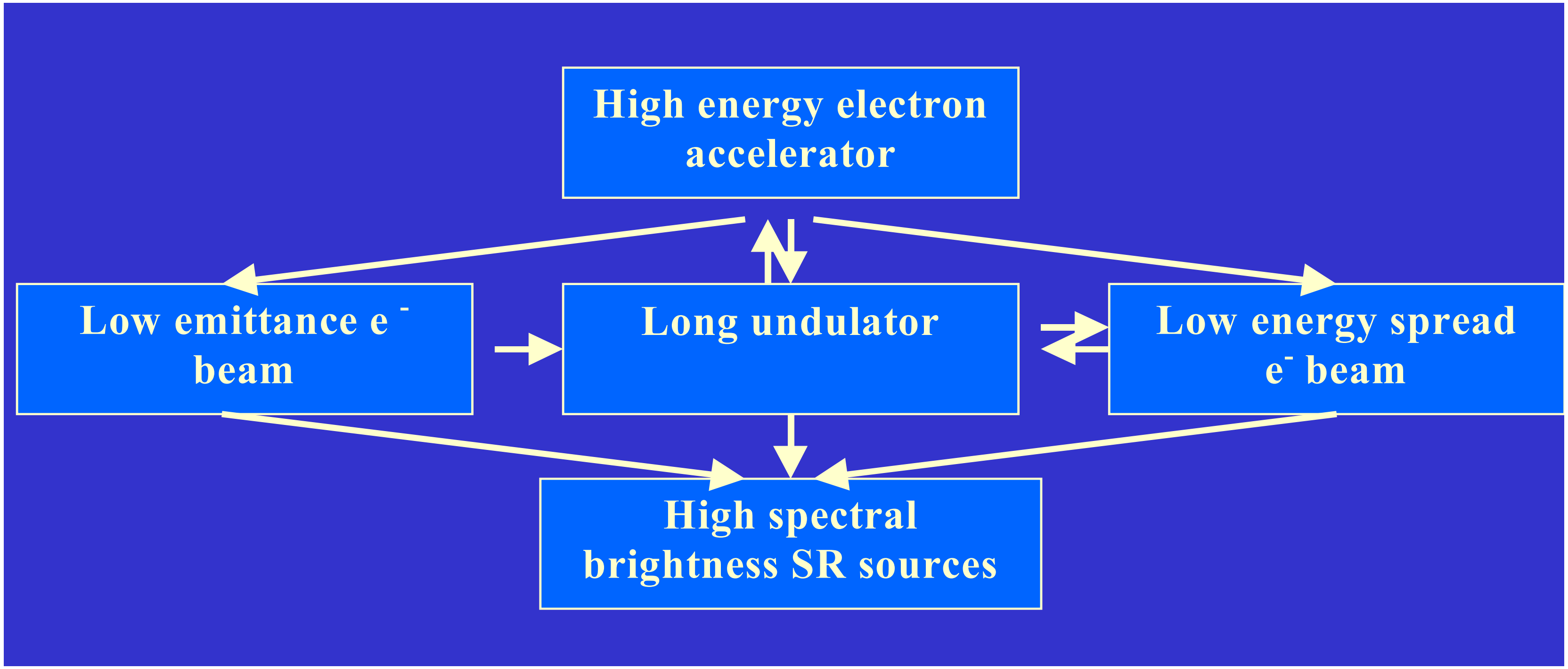
Basic overall dimensions of ERL and MARS (E_{max} = 6 GeV)

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 ε_{min} ~ 10^{-2} nm rad and energy spread σ_E/E ~ 10^{-4}. For MARS project, four undulators 150 – 200 m long (N ~ 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.

As in MARS the time of the acceleration is small in comparison with the radiation damping time in storage ring (factor 10^3) main diffusion processes (quantum fluctuation of the SR in arc and intrabeam scattering) cannot "spoil" emittance and energy spread.



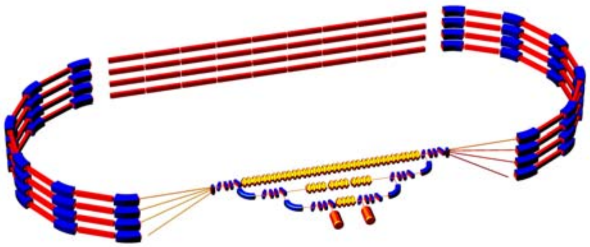
1980	$\varepsilon \sim 10^{3}$ nmrad	$N_u \sim 10$	$\sigma_E/E \sim 10^{-3}$
1990	$\varepsilon \sim 10^{2}$ nmrad	$N_u \sim 10^{2}$	$\sigma_E/E \sim 10^{-3}$
2000	$\varepsilon \sim 1$ nmrad	$N_u \sim 10^{3}$	$\sigma_E/E \sim 10^{-3}$
2015	$\varepsilon \sim 10^{-2}$ nmrad	$N_u \sim 10^{4}$	$\sigma_E/E \sim 10^{-4}$

Storage rings (1980–2000)

MARS (2015)

Comparision of parameters of SR sources

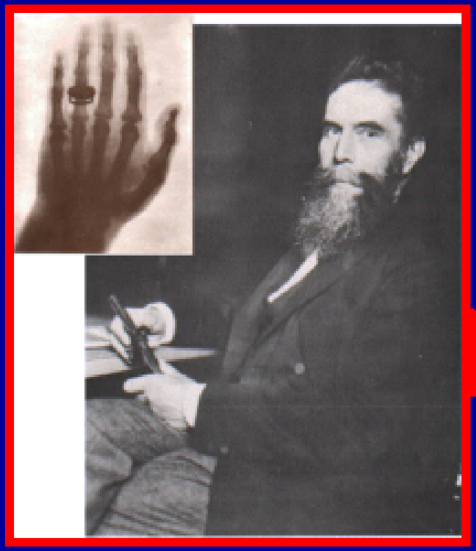
MARS (I_e=2.5 mA) and Spring-8 (I_e=100mA)

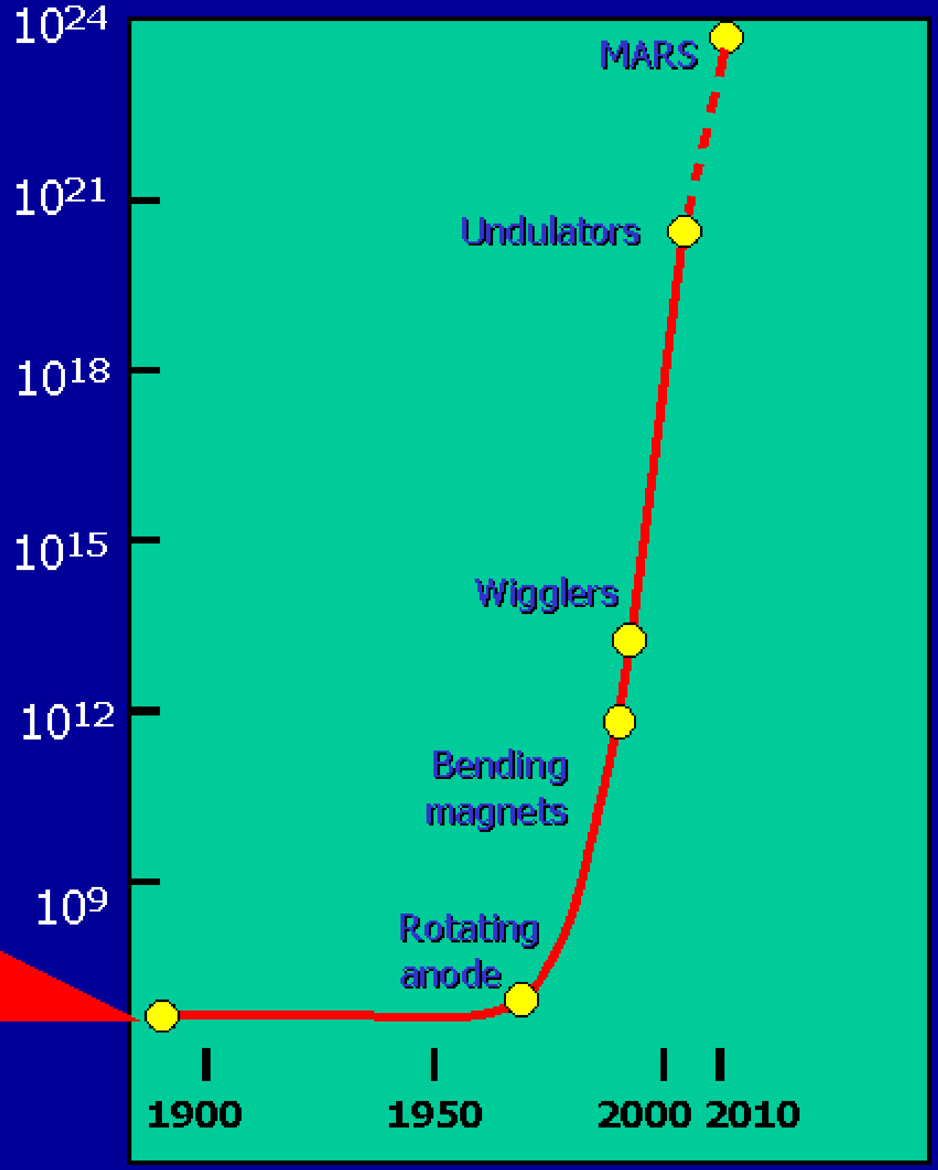


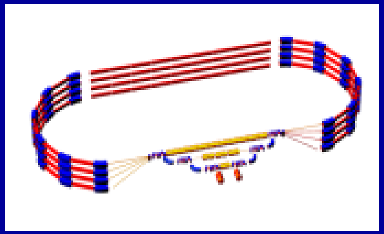
		Number of beamlines	**B**, ph•sec^{-1}•mm^{-2}•mrad^{-2} ($\delta\lambda/\lambda=10^{-3}$)	**F**, ph/sec ($\delta\lambda/\lambda=10^{-3}$)
MARS	Undulator $N_u \sim 10^2$	32	10^{22}	$4.6 \cdot 10^{13}$
	Undulator $N_u \sim 10^3$	12	10^{23}	$4.6 \cdot 10^{14}$
	Undulator $N_u \sim 10^4$	4	10^{24}	$4.6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

Steep rise in brightness/brilliance

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



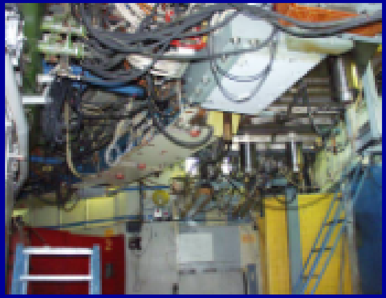




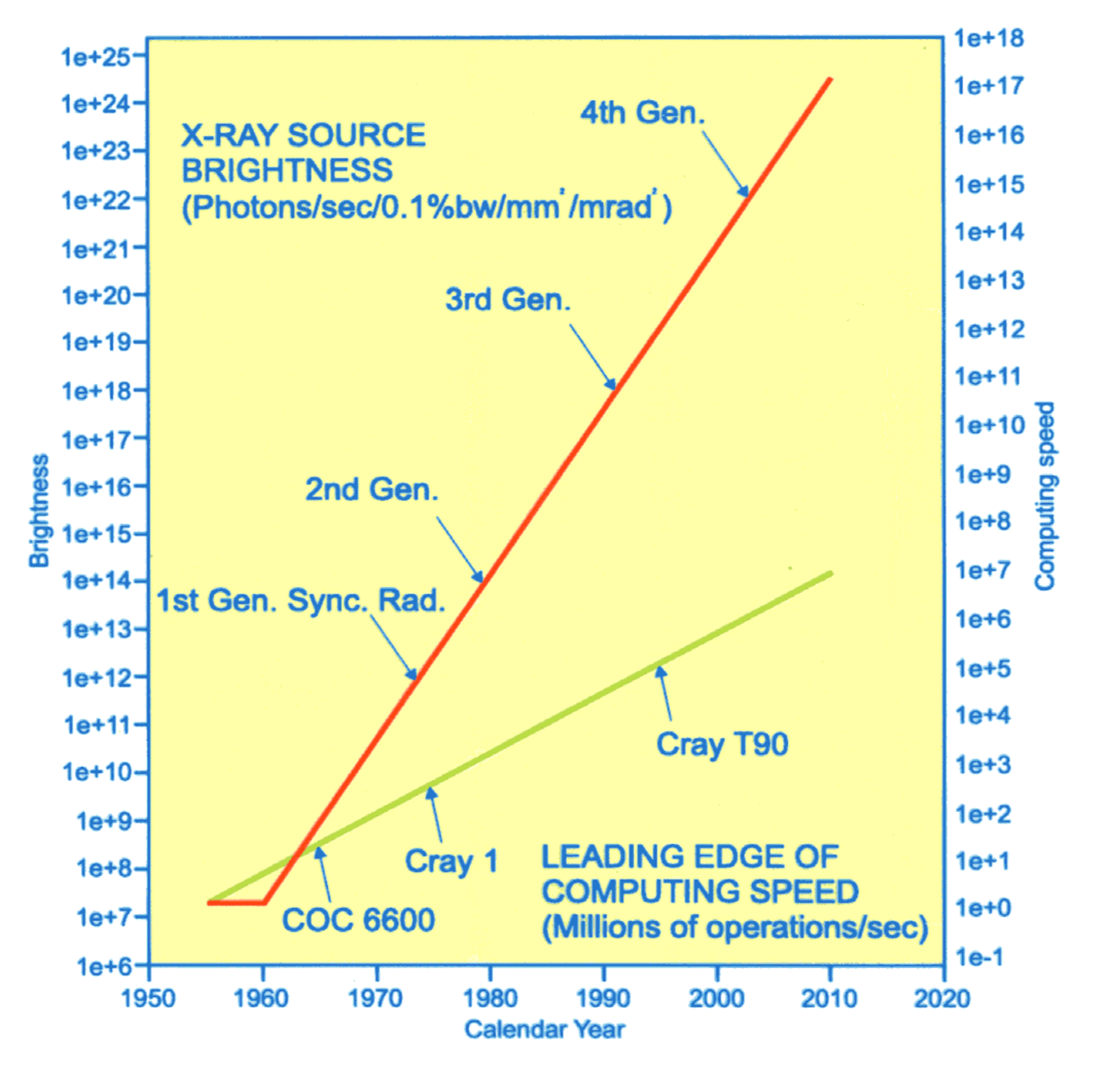
4 MARS

3 Spring-8

2 Siberia-2



1 VEPP-3


X-RAY SOURCE
BRIGHTNESS
(Photons/sec/0.1%bw/mm²/mrad²)
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
Computing speed
Calendar Year
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
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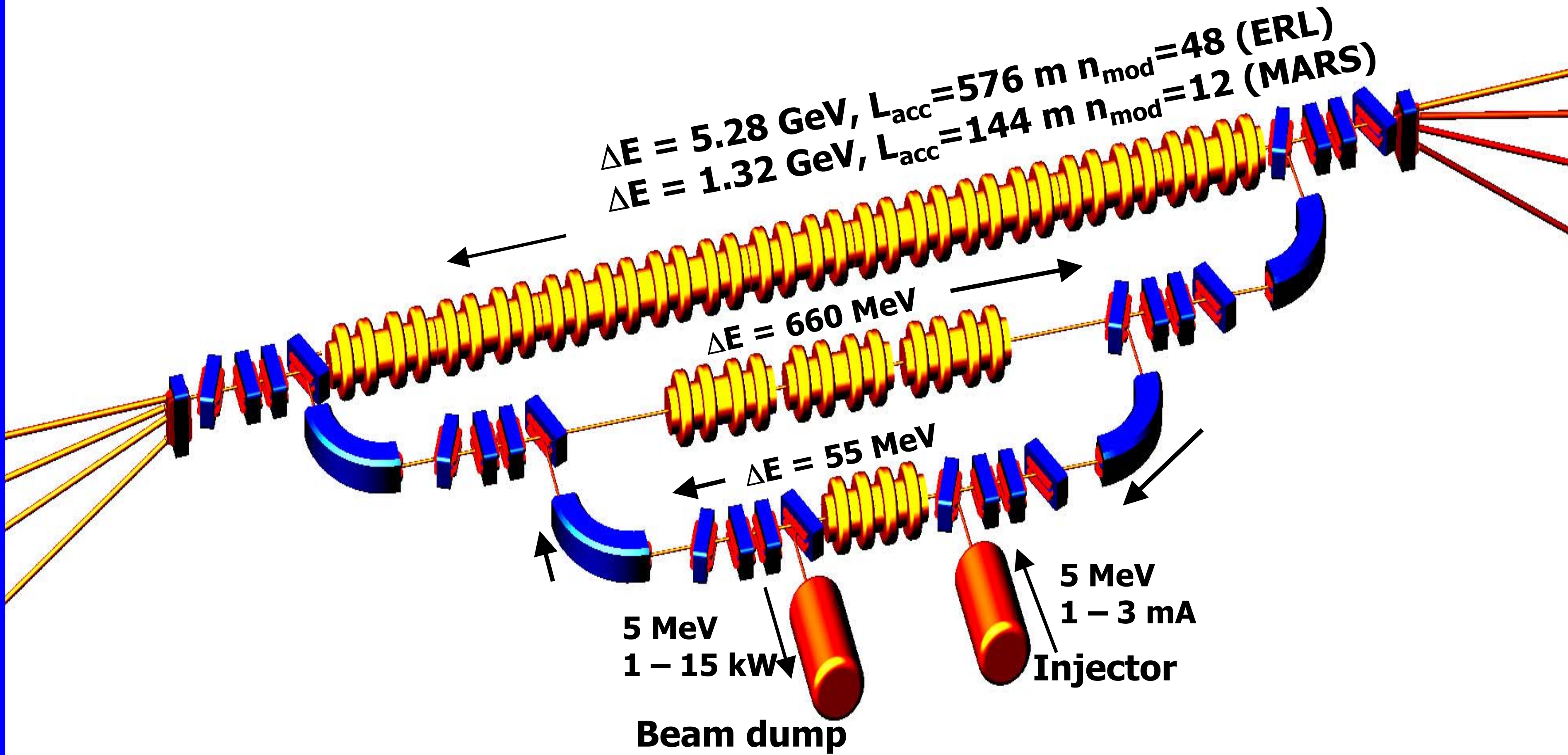
1e+11
1e+10
1e+9
1e+8
1e+7
1e+6
1e+5
1e+4
1e+3
1e+2
1e+1
1e+0
1e-1
1950
1960
1970
1980
1990
2000
2010
2020

Cascade scheme of injection

First linac has 5-10 MeV energy and does not use energy recovery.

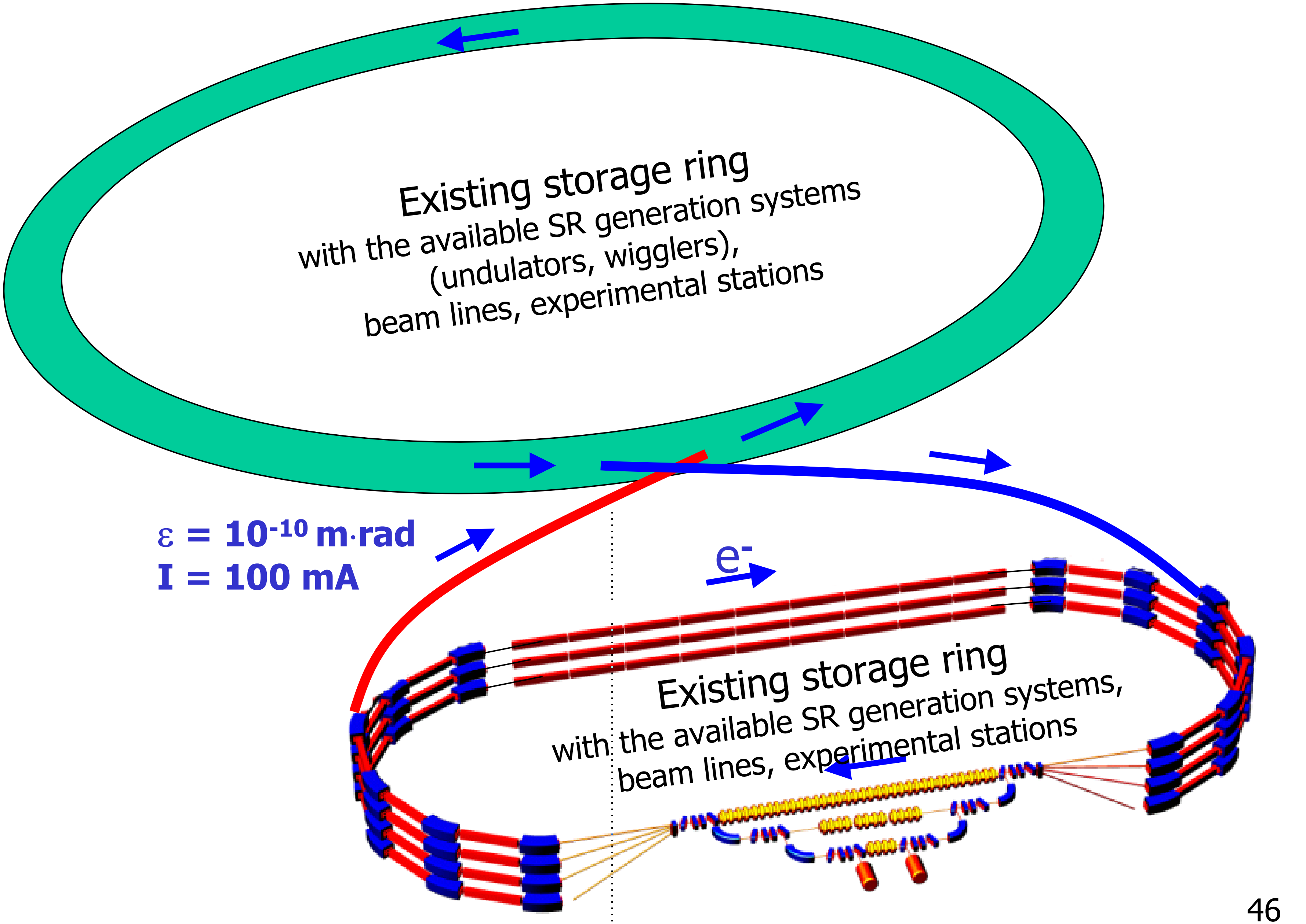
To booster linacs (55 MeV and 660 MeV energy gain) energy recovery used.



Cascade scheme of injection is provided effective and economical solution of the next problems:

- Decreasing of radiation hazard and limitation of induced radioactivity;
- Reduction of the cost of building and the cost of the RF power system for injector;
- Simplifying the problem of focusing particles of different energies, which are traveling simultaneously in the accelerating structure, because cascade scheme enables injection of electrons into all the accelerating structures with energies of no less than $E_{max}/10$ (E_{max} is the maximum energy of electrons traveling in the accelerating structure).

- It is quite probable that in some cases, a multi-turn accelerator-recuperator can be used for improving the brightness and for obtaining the fully spatially coherent source at the upgrade of the available SR sources of the 2nd and 3rd generations. In this case, the existing storage ring with the available generation systems, beam lines, etc., can be used as the last track (I. Koop, ERL Syn-2002, Erlangen).

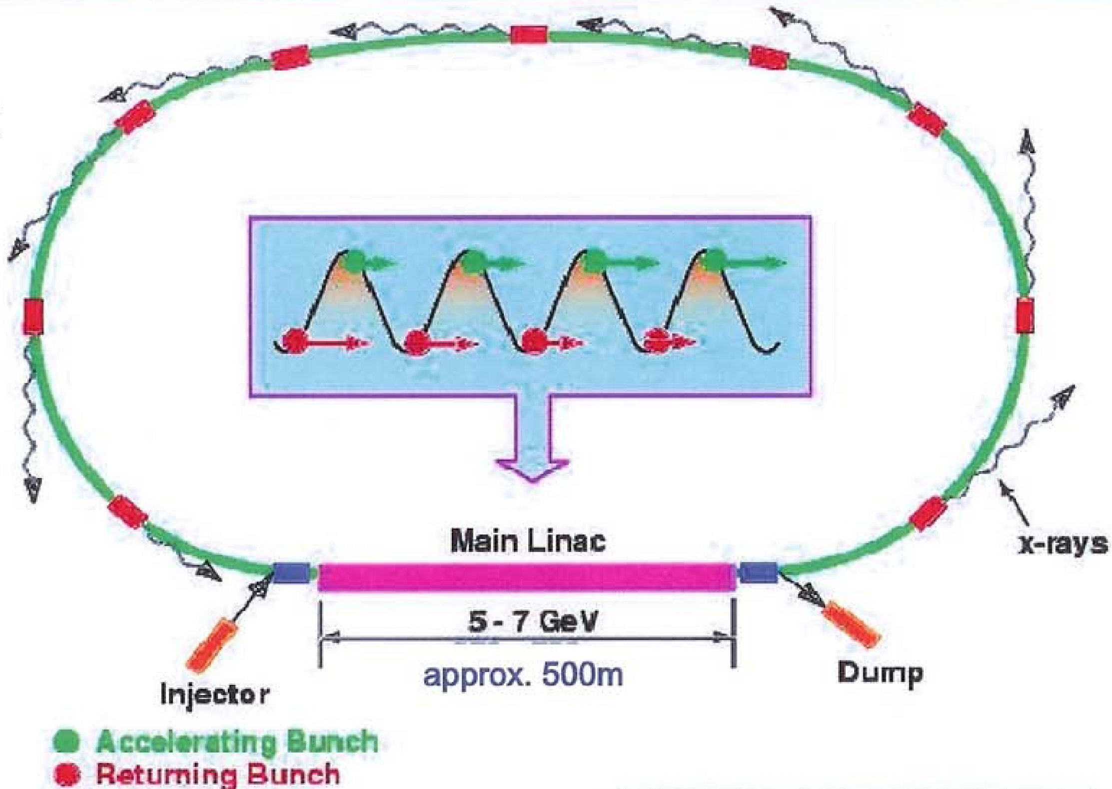


Existing storage ring
with the available SR generation systems
(undulators, wigglers),
beam lines, experimental stations
ε = 10^-10 m·rad
I = 100 mA
e-
Existing storage ring
with the available SR generation systems,
beam lines, experimental stations

Principle of an X-ray ERL

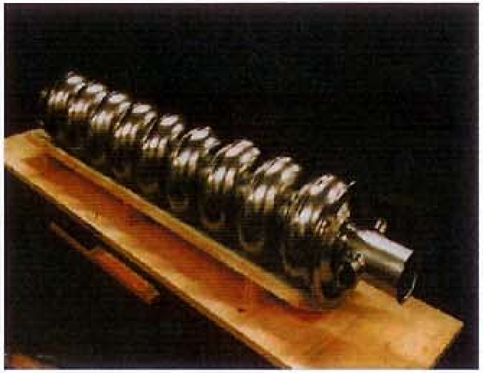
CHESS & LEPP

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



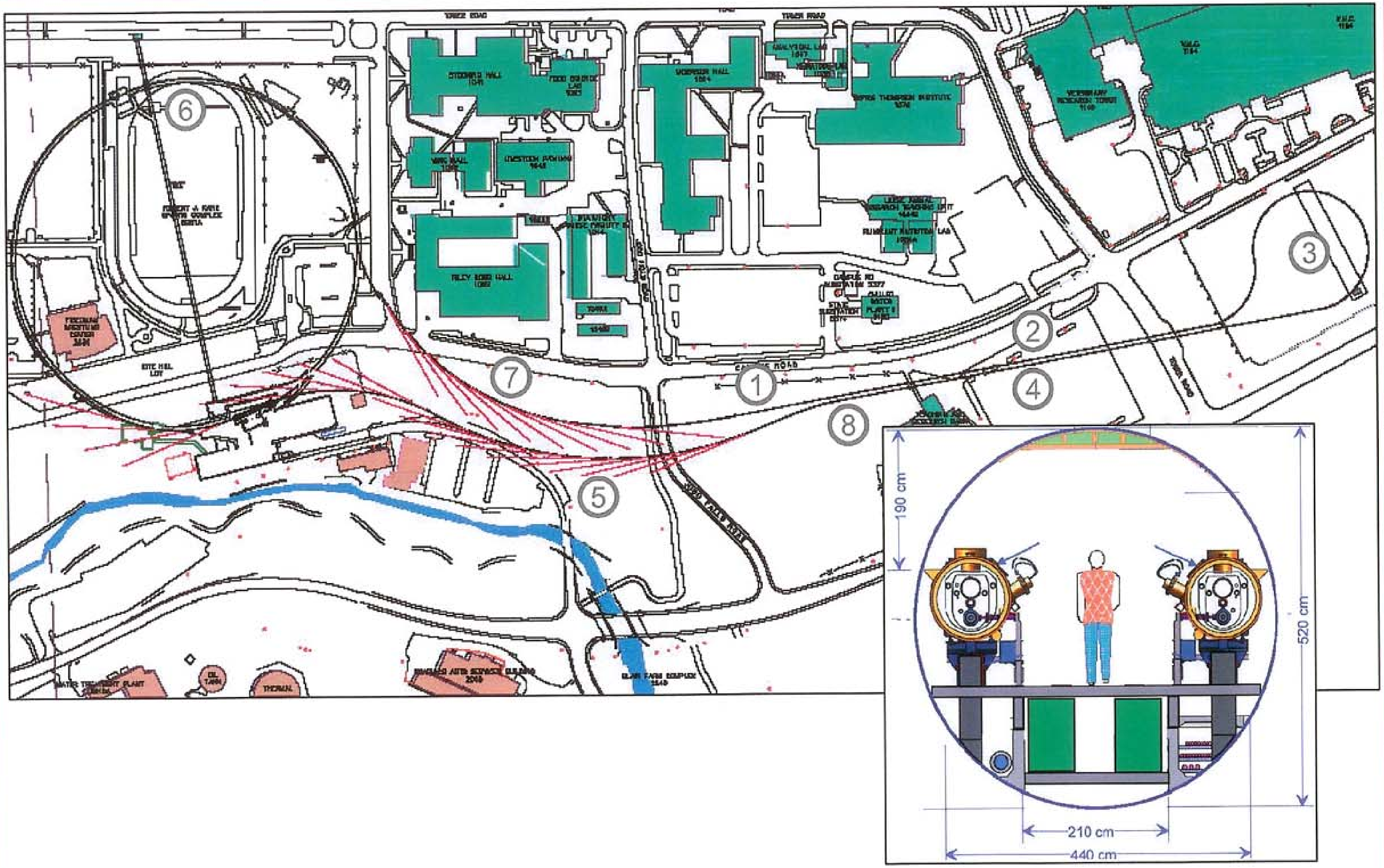
Challenges:

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

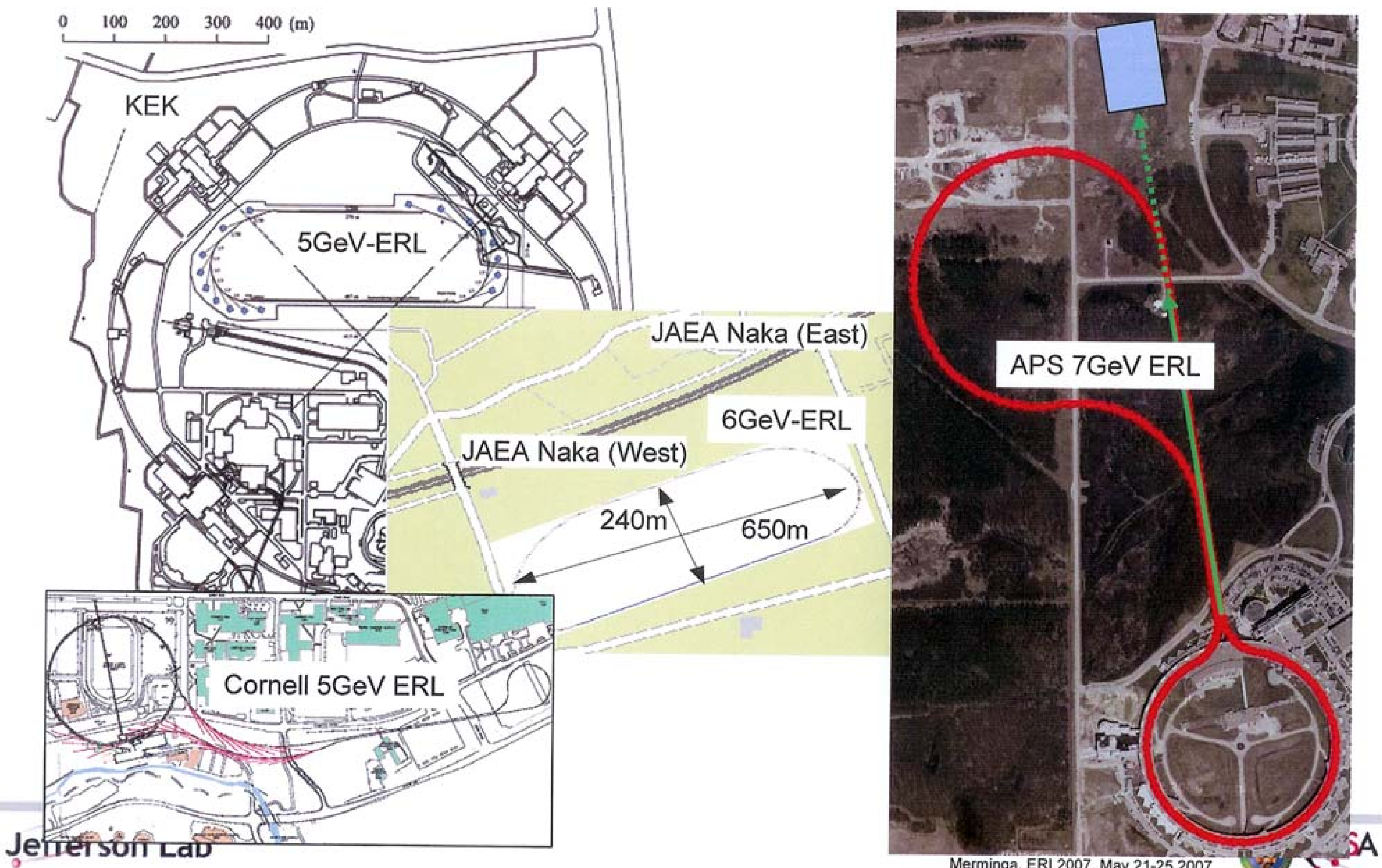


ERL@CESR design version 1.3

CHESS & LEPP



Cornell / KEK / JAEA / APS ERLs



APS Upgrade Review

CHESS & LEPP

An "Outfield" ERL Option (G. Decker[1])

- Advantages
  - Linac points away from APS[2] to give straight-ahead FEL hall[3]
  - Beam goes first into new, emittance-preserving turn-around arc[4]
  - Avoids wetlands etc. by using narrow corridor for linac and return line
- Issues
  - Big and expensive
  - Turn-around should be *bigger* than shown
  - Beam goes wrong way around the APS in this sketch (readily fixed)
  - No space for really long undulators.

[1]G. Decker, "APS Upgrade External ERL Option," 9/27/06.
[2]M. Borland, "ERL Upgrade Options and Possible Performance," 9/18/06.
[3]M. Borland, "Can APS Compete with the Next Generation?", May 2002.
[4]M. Borland, OAG-TN-2006-031, 8/16/06.

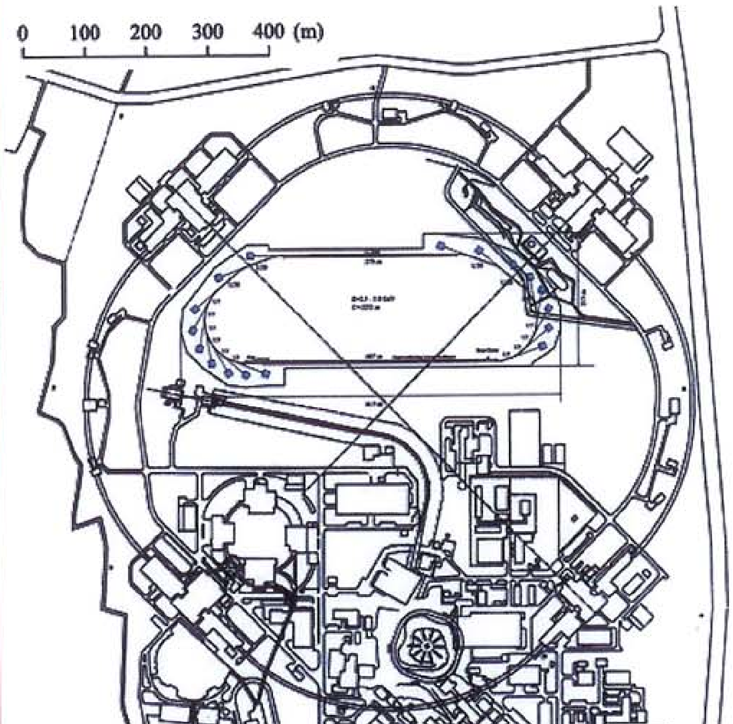
ERL Colleagues: KEK

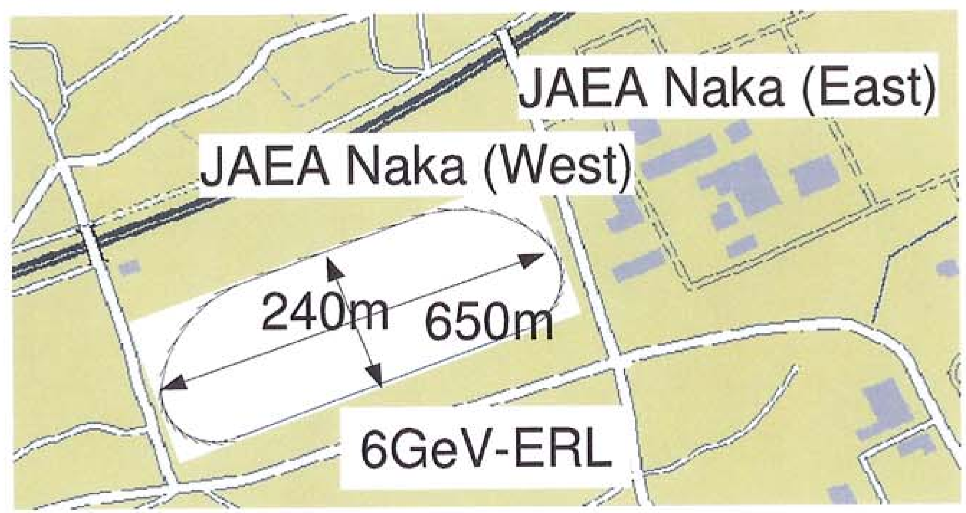
CHESS & LEPP

Two Japanese institutes, KEK and JAEA, proposed each own ERL-based synchrotron light source.

KEK 5GeV ERL at Tsukuba site

JAEA 6GeV ERL at Naka site





A few on SASE FEL

SASE FEL

- **UNBEATABLE BRILLIANCE**

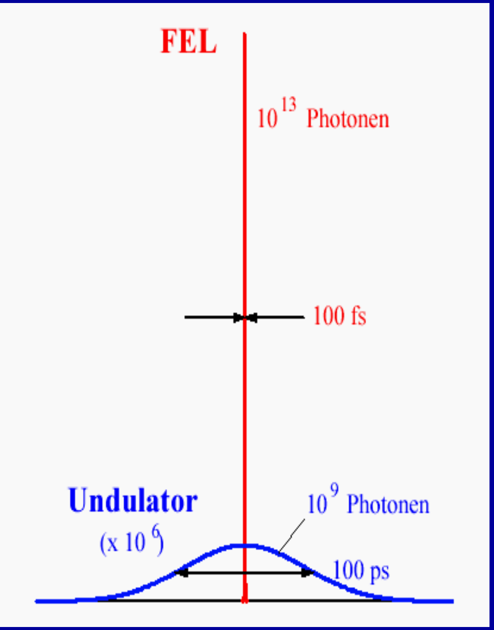
  (10^{30} - 10^{33})

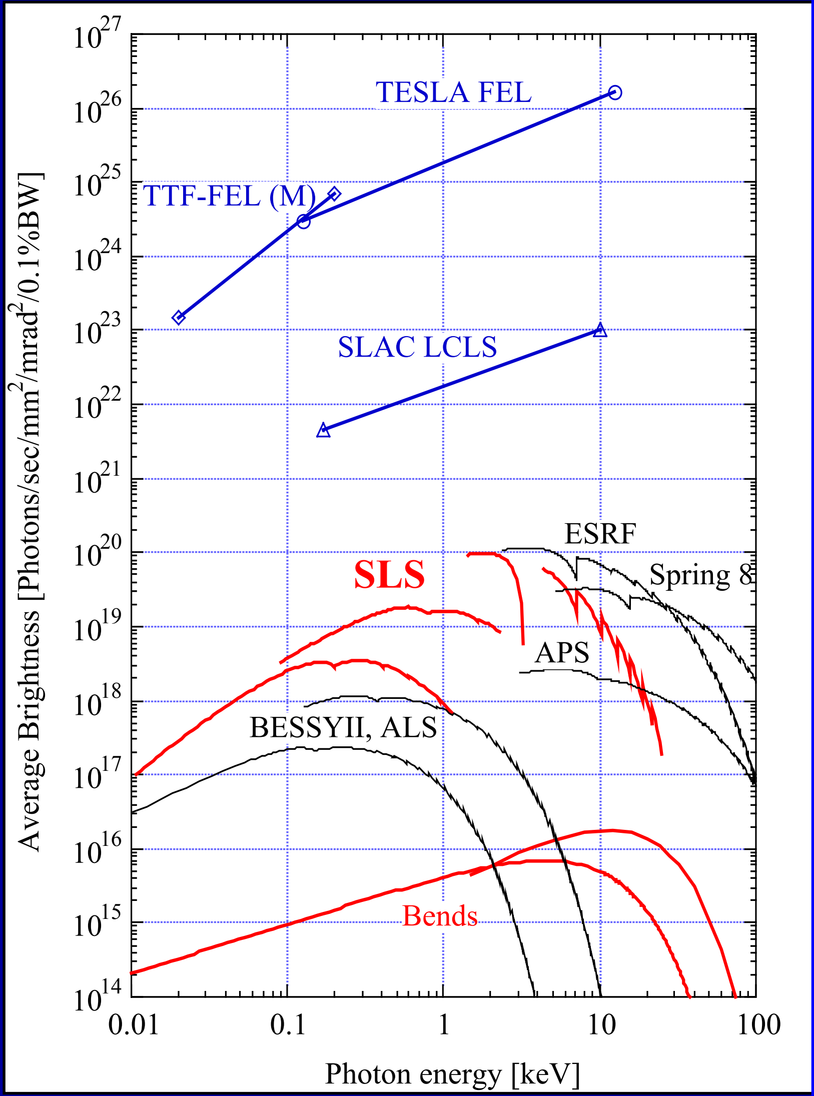
- **HIGH AVERAGE BRILLIANCE**

  (10^{22} - 10^{25})

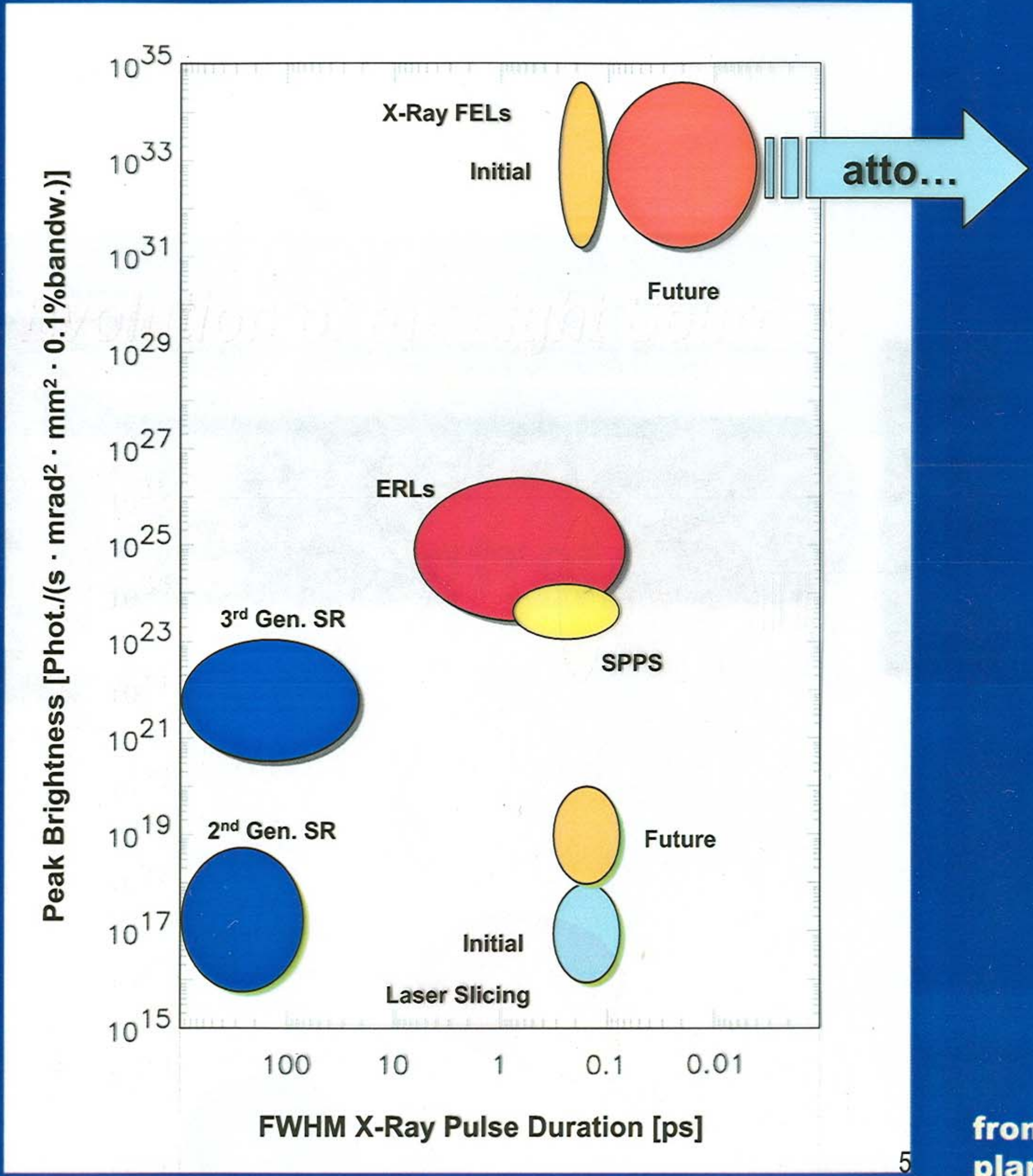
- **SHORT PULSES**

  (1 ps – 50 fs)





Evolution of the Light Sources



from DOE long term planning discussions

Summary

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.

Thank you for your attention

Comparison of various types of the coherent X-ray sources:

	ESRF storage ring	LCLS linac	MARS
Wavelength, nm	.1	.15	.1
Electron energy, GeV	6	14	5.4
Average current, A	.2	$3x10^{-8}$	10^{-3}
Peak current, A		$3.4x10^{3}$	1
Relative energy spread		$2x10^{-4}$	$1x10^{-5}$
Emittance, nm εx εz	4 $2.5x10^{-2}$	$5x10^{-2}$	$3x10^{-3}$
Undulator period, cm	4.2	3	1.5
Undulator length, m	5	120	150
Coherent flux, photon/s	$6x10^{12}$	$2x10^{14}$	$7x10^{13}$
Bandwidth	10^{-2}	10^{-3}	10^{-4}
Average brightness, $ph/s/mm^2/mrad^2/0.1$ %BW	10^{20}	$4x10^{22}$	$3x10^{23}$
Peak brightness, —//—		$1x10^{33}$	$3x10^{26}$
Transverse size of source (standard deviation),μm	σ_x 350 σ_y 8	15	10
Radiation transverse divergence (standard deviation), μrad	$\sigma_{x'}$ 13 $\sigma_{y'}$ 3	1	1