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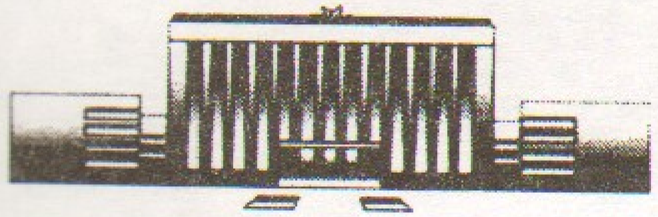

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Abstract

The main aim of the next generation synchrotron radiation (SR) sources is to provide diffraction limited undulator radiation in the 0.1 - 4 nm range with average power of 10 - 10^3 W and monochromaticity of 10^{-3} - 10^{-4}. The review of new accelerator technologies that could be used for the construction of such kind of SR sources is given.

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Introduction

For three years, passing from the SRI - 94, the SR community achieved several outstanding results in the development of the third generation SR sources. Large storage rings APS (USA) and SPRING-8 (Japan) were commissioned successfully. At the first storage ring of this class, ESRF (Europe) the brightness was increased to the record value of 10^{20} ph./s/mm^2/mrad^2/.1% b.w. by the optimization of lattice and other improvements. Hopefully, the brightness at these storage rings may be increased further, up to 10^{21} in the near future.

The projects of the fourth generation X-ray sources are being discussed intensively for the last few years. These discussions are reflected in a large number of publications in the proceedings of the accelerator conferences and dedicated workshops (Workshop, 1992; 10-th ICFA.... 1996). Summarizing the findings of them one can list the following requirements for the fourth generation X-ray sources:

- Average brightness of the source in the 0.01 - 4 nm wavelength range have to exceed 10^{22} - 10^{23} ph./s/mm^2/mrad^2/.1% b.w.;
- The increase of brightness must not be accompanied by the increase of the full photon flux, i.e. the total average power of the undulator radiation must not exceed 1 kW;
- The use of long undulators with the number of periods of the order of 10^4 is preferable as they provide radiation with narrow on-axis spectrum (the bandwidth less than 10^{-4}) and correspondingly large coherence length (more than 10^{-6} m); such radiation may be useful to perform some experiments in the X-ray holography, X-ray microprobe, etc. without monochromators;

- Short pulses of radiation with a subpicosecond duration are interesting for several experiments;
- High peak brightness of the order of 10^{30} ph./s/mm^2/mrad^2/.1% b.w. is important for some experiments.

A single radiation source will hardly satisfy all of these requirements. Two approaches to the problem are considered now. First one uses the long undulators, installed on the advanced storage rings. The second is the X-ray free electron laser, which also uses a long undulator, but also a linac as the source of electron beam. Both approaches needs the electron beam with energy higher than 5 GeV and emittance smaller than 10^{-11} m×rad. The average current for the first case is typically rather high (tenth of milliamperes), but the peak current is relatively low (less than one ampere). In contrary, the second case require high (multikiloampere) peak current, but use low (less than 10^{-7} A) average current. Both approaches have some technical problems unsolved yet.

The physical phenomena, which determine the brightness for the storage ring based sources, are investigated well now. They are the quantum fluctuation of the SR and the intrabeam scattering. The third generation SR sources are optimized to suppress their influence on the brightness. The fourth generation storage ring projects utilize further attempts in this directions. But the further increase of the lattice focusing strength is limited by the decrease of dynamic aperture, and there are no solution of this problem up to now. Moreover, even with low emittance the energy spread will limit the brightness.

In the linear accelerators the normalized emittance can be conserved during the acceleration process. But at high peak current, which is necessary for the superradiant free electron laser, the space charge fields leads to the emittance growth.

The third possible approach, which is described in this paper, combines the features of the first and the second. The high quality electron beam with significant (milliamperes) average current and long undulator are used for the source of spontaneous undulator radiation. The accelerator, which is capable of providing such electron beam is recirculating radiofrequency (RF) accelerator-recuperator (see e. g. Rand, 1984). The key component for this accelerator, the RF system, is very similar to the RF systems of large electron storage rings (LEP, PEP, PETRA, TRISTAN). The energy recovery is necessary for the reduction of both the RF system power and radiation hazard. The similar, but lower energy (100 MeV) accelerator-recuperator for the high power infrared free electron laser is under construction in Novosibirsk now (Vinokurov et al., 1996).

The setup

The general scheme of the multiturn accelerator-recuperator source (MARS) of X-ray is shown in Fig. 1.

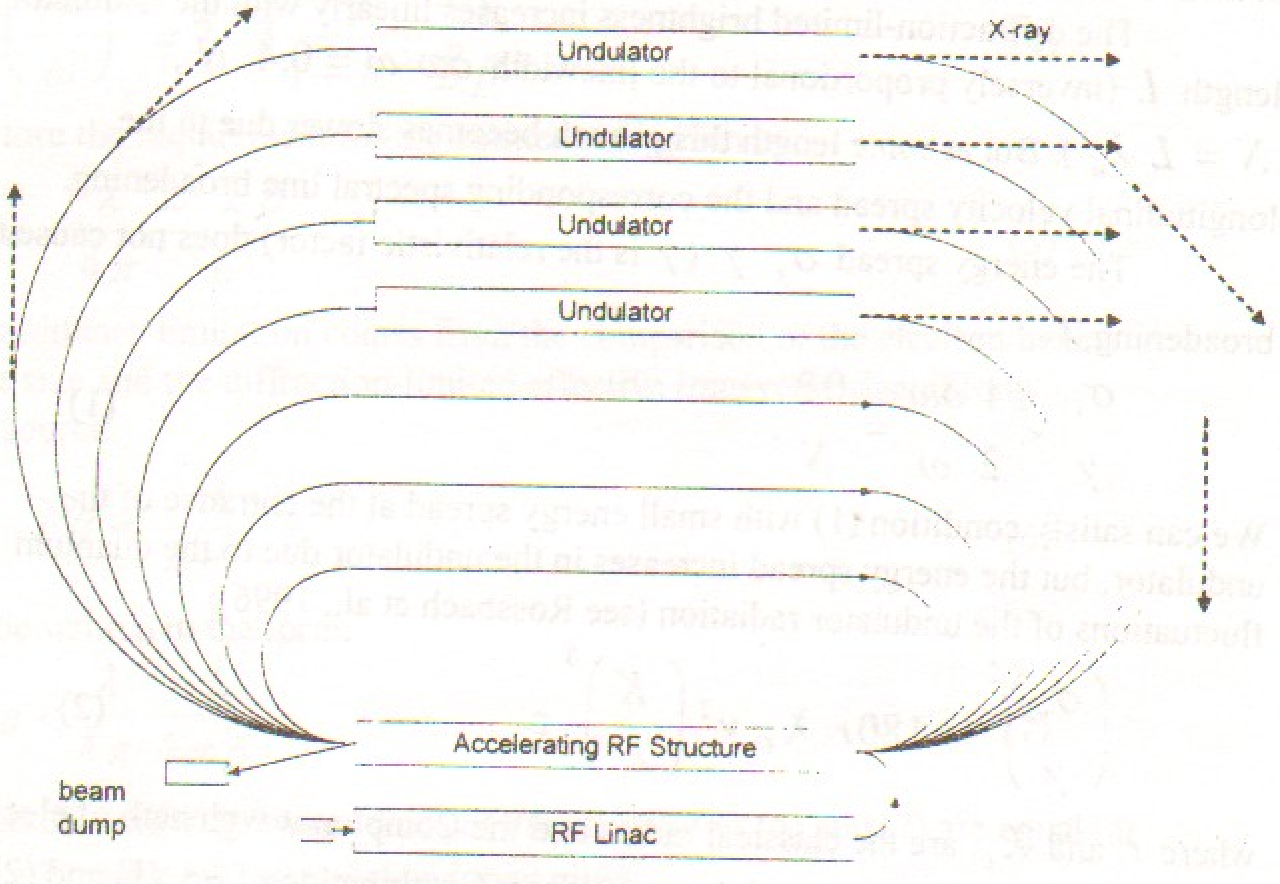

Fig. 1 Schematic of setup

Electron beam from the gun is accelerated in the RF linac. After that the electrons pass through the accelerating RF resonators of the recirculator several times. The accelerated beam passes through the long undulator. The «exhaust» beam is decelerated in the recirculator, giving the power back to the RF resonators, and is absorbed into the beam dump.

The undulator

Because the undulator gap will be limited mainly by the radiation losses in the walls of vacuum chamber, the 5 mm gap seems reasonable. Then, choosing the undulator deflection parameter K equal to one, one can obtain the 1.5 cm period λ_w from the Halbach equation (Halbach, 1983) for the planar hybrid permanent magnet undulator[1]. For the wavelength λ =.1 nm it corresponds to the 5.42 GeV electron energy.

The diffraction-limited brightness increases linearly with the undulator length L (inversely proportional to the linewidth $\delta\omega\ \ \omega = 0.4\ \ N$, $N = L\ \ \lambda_w$). But at some length this growth becomes slower due to the longitudinal velocity spread and the corresponding spectral line broadening.

The energy spread $\sigma_\gamma\ \ \gamma$ (γ is the relativistic factor) does not cause the broadening if

$$\frac{\sigma_\gamma}{\gamma} < \frac{1}{2}\frac{\delta\omega}{\omega} = \frac{0.2}{N}. \qquad (1)$$

We can satisfy condition (1) with small energy spread at the entrance of the undulator. but the energy spread increases in the undulator due to the quantum fluctuations of the undulator radiation (see Rossbach et al., 1996):

$$\left(\frac{\sigma_\gamma}{\gamma}\right)^2 \approx 180 r_0 ƛ_C \gamma^2 \left(\frac{K}{\lambda_w}\right)^3 z, \qquad (2)$$

where r_0 and $ƛ_C$ are the classical radius and the Compton wavelength of electron . z is the distance from the undulator entrance. Combination of Eq. (1) and (2) at $z = L\ \ 2$ gives the limitation of the undulator length:

$$L < 9\cdot 10\ m^{-\frac{2}{3}} \frac{\lambda_w^{\frac{5}{3}}}{\gamma^{\frac{2}{3}} K}. \qquad (3)$$

For our parameters the right hand side of the inequality (3) gives 170 m, so we choose L=150 m. Then $\delta\omega\ \ \omega$ =4×10^{-5} and according to the inequality (1) the energy spread $\sigma_\gamma\ \ \gamma$ must be less than 2×10^{-5}.

Suppose we use the triplets between the undulator sections, which provide the equal and almost constant (inside undulators) beta-functions $\beta_x = \beta_y = \beta$. and both emittances are equal to ε. The emittance contribution to the spread of the longitudinal velocities in such magnetic system is about $\overline{3\varepsilon\ \beta}$ (Vinokurov et al., 1997). Then the corresponding contribution to the line broadening is

$$\left(\frac{\delta\omega}{\omega}\right)_\varepsilon = 2\ \ \overline{3}\,\frac{\gamma^2}{1+K^2\ \ 2}\frac{\varepsilon}{\beta}, \qquad (4)$$

and therefore the requirement for the emittance is given by:

$$\varepsilon < \frac{\lambda}{4\pi}\frac{2\cdot\overline{2\beta}}{L}. \qquad (5)$$

Another emittance limitation comes from the comparison of the electron beam transverse size and the diffraction-limited effective transverse size of long radiation source

$$\overline{\varepsilon\beta} < \frac{\overline{\lambda L}}{4\pi}, \qquad (6)$$

and may be written in the form:

$$\varepsilon < \frac{\lambda}{4\pi}\frac{L}{4\pi\beta}. \qquad (7)$$

In the «optimal» case right hand sides of the inequalities (5) and (7) are equal (at $\beta \cong L\ \ 6$=25 m for our example) and they gives

$$\varepsilon < \frac{\lambda}{8\pi}. \qquad (8)$$

Therefore the desirable normalized emittance is less than .04 mm×mrad. The modern electron gun technology demonstrated the 1 mm×mrad normalized emittance at hundred-ampere peak current (Palmer, 1997; Schmerge, 1997). At lower current it is possible to achieve the lower values (that was obtained in the electron microscopes and the electron lithography installations), so our emittance requirements seems reasonable.

The diffraction-limited brightness may be approximated by the expression:

$$B \cong \frac{4\pi\alpha N}{\lambda^2}\frac{K^2}{1+K^2\ \ 2}\left[J_0\left(\frac{K^2}{4+2K^2}\right) - J_1\left(\frac{K^2}{4+2K^2}\right)\right]^2 \frac{I}{e}\frac{\Delta\omega}{\omega}, \qquad (9)$$

where α is the fine structure constant, J_0 and J_1 are the Bessel functions, I is the beam current, e is the charge of electron and $\Delta\omega\ \ \omega$ is «the standard

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[1] Theoretically, the helical undulators are better, as they provides higher brightness and suppress harmonics. but there are many unsolved technical problems concerning them. For the planar undulators the permanent magnet hybrid design gives the shortest period at these values of the gap and the deflection parameter.

bandwidth», which conventionally is equal to 10^{-3}. To be «the fourth generation source» the installation has to provide the brightness of 10^{23} ph./s/mm^2/mrad^2/0.1%b.w. Substituting the earlier defined parameters one can conclude, that this value corresponds to the 0.3 mA beam current.

The accelerator

The preparation of the electron beam with the above-mentioned parameters is also a challenge.

The quantum fluctuation induced growth of energy spread in the 180-degree bend must be smaller, than the acceptable energy spread, therefore the bending radius R of the last arc must be larger than a quantity, namely

$$R > \frac{r_0}{\sigma_\gamma \ \gamma}\sqrt{\frac{55\pi}{24\sqrt{3}\,\alpha}}\,\gamma^5 . \tag{10}$$

Assuming $\sigma_\gamma \ \gamma = 1\times10^{-5}$, one can find that $R > 100$ m and, correspondingly, the field in the bending magnets must not exceed 0.2 T. The emittance growth can be reduced to an acceptable value by the focusing lattice optimization. It is probably necessary to provide the second order achromaticity of these arcs. The similar problems concerning the bend of the low emittance and high energy beam were solved successfully at the Stanford Linear Collider. The actual shapes and sizes of the orbits may be very different from the Fig. 1 and have to be defined at further studies (for example, all orbits may have the same length and be placed inside the single tunnel). The options to install undulators at other orbits and to use the synchrotron radiation from the bending magnets have also to be inspected.

The transverse regenerative beam breakup caused by excitation of the higher order modes in the RF resonators limits the average current. Therefore the RF system have to be either nonsuperconducting or superconducting with the asymmetric high order modes suppression. For the nonsuperconducting RF the number of orbits tends to be larger. For example, for 20 orbits energy gain per pass will be about 260 MeV. Then it is enough to have the length of straight line sections about 300 m.

The table, comparing the parameters of sample X-ray sources, is shown below.

	ESRF storage ring	LCLS[2] linac	MARS
Wavelength, nm	0.1	0.15	0.1
Electron energy, GeV	6	14	5.4
Average current, A	0.2	3×10^{-8}	10^{-3}
Peak current, A		3.4×10^{3}	1
Relative energy spread		2×10^{-4}	1×10^{-5}
Emittance, nm	4 (horizontal) .025 (vertical)	3×10^{-2}	3×10^{-3}
Undulator period, cm	4.2	3	1.5
Undulator length, m	5	100	150
Coherent flux, photon/s	6×10^{12}	6×10^{14}	7×10^{13}
Bandwidth	10^{-2}	10^{-3}	10^{-4}
Average brightness, photon/s/0.1%b.w./mm^2/mrad^2	10^{20}	6×10^{22}	3×10^{23}
Peak brightness, photon/s/0.1%b.w./mm^2/mrad^2		5×10^{33}	3×10^{26}
Transverse size of source (standard deviation), μm	350 (horizontal) 8 (vertical)	9	10
Radiation transverse divergence (standard deviation), μrad	13 (horizontal) 3 (vertical)	2	1

In the conclusion we would like to give some remarks on the feasibility of the MARS. Our estimations are certainly very preliminary, but up to now we have not found any clear physical obstacles to this approach. The most key systems used here were already tested at other facilities. So, it seems, the obtaining of high brightness in this way is mainly the issue of funding. The very rough and preliminary cost estimations indicates, that the scale of the cost is the same as for the existing big third generation facilities (APS, ESRF, etc.).

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[2] The Stanford Linear Collider Light Source (Workshop, 1992; 10-th ICFA…, 1996).

References

10-th ICFA Beam Dynamics Panel Workshop on 4-th Generation Light Sources. Grenoble, January 1996.

Workshop on Fourth Generation Light Sources. Stanford, February 1992, SSRL 92-02.

K. Halbach, J. Phys. Colloq. 44 (1983) C1-211.

D. T. Palmer et al., Proc. of SPIE v.2988, p. 78, 1997.

R. E. Rand, Recirculating Electron Accelerators, Harwood Academic Publishers, 1984.

J. Rossbach et al., Nucl. Instr. and Meth. A374 (1996) 401.

G. S. Schmerge et al., Proc. of SPIE v.2988, p. 90, 1997.

N. A. Vinokurov et al., Nucl. Instr. and Meth. A375 (1996) 403.

N. A. Vinokurov et al., Proc. of SPIE v.2988, p. 64, 1997.

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