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Synchrotron Light Sources and Recent Developments of Accelerator Technology

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The main aim of the next-generation synchrotron radiation sources is to provide diffraction-limited undulator radiation in the 0.1–4 nm range with an average power of 10–1000 W and monochromaticity of 10^{-3}–10^{-4}. A review of new accelerator technologies that could be used for the construction of such types of synchrotron radiation sources is given.

Keywords: accelerators; new accelerator technology.

1. Introduction

Over the three years since the SRI94 meeting, the synchrotron radiation community has achieved several outstanding results in the development of third-generation synchrotron radiation sources. The large storage rings APS (USA) and SPring-8 (Japan) have been commissioned successfully. At the first storage ring of this class, ESRF (Europe), the brightness was increased to the record value of 10^{20} photons s^{-1} mm^{-2} $mrad^{-2}$ (0.1% bandwidth)$^{-1}$ by optimization of the lattice and other improvements. Hopefully, the brightness at these storage rings may be increased further, up to 10^{21}, in the near future.

Projects for the fourth-generation X-ray sources have being discussed intensively over the past few years. These discussions are reflected in a large number of publications in the proceedings of accelerator conferences and dedicated workshops (*Workshop on Fourth Generation Light Sources*, 1992; *Tenth ICFA Beam Dynamics Panel Workshop on Fourth-Generation Light Sources*, 1996). Summarizing their findings, one can list the following requirements for fourth-generation X-ray sources.

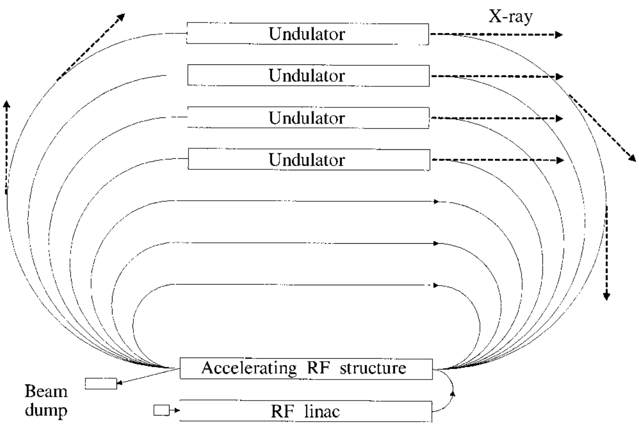

Figure 1
Schematic diagram of the experimental set-up

(i) The average brightness of the source in the 0.01–4 nm wavelength range has to exceed 10^{22}–10^{23} photons s^{-1} mm^{-2} $mrad^{-2}$ (0.1% bandwidth)$^{-1}$.

(ii) The increase of brightness must not be accompanied by an increase of the full photon flux, *i.e.* the total average power of the undulator radiation must not exceed 1 kW.

(iii) The use of long undulators with number of periods of the order of 10^4 is preferable as they provide radiation with narrow on-axis spectra (bandwidth $< 10^{-4}$) and correspondingly large coherence length ($>10^{-6}$ m); such radiation may be useful for performing X-ray holography, X-ray microprobe *etc.* experiments without monochromators.

(iv) Short pulses of radiation with a subpicosecond duration are interesting for several experiments.

(v) High peak brightness of the order of 10^{30} photons s^{-1} mm^{-2} $mrad^{-2}$ (0.1% bandwidth)$^{-1}$ is important for some experiments.

A single radiation source will hardly satisfy all of these requirements. Two approaches to the problem are now considered. The first approach uses long undulators installed on advanced storage rings. The second approach is the X-ray free-electron laser, which also uses a long undulator, but also a linac as the source of the electron beam. Both approaches require an 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 (tenths of milliamperes), but the peak current is relatively low (less than 1 A). On the contrary, the second case requires high (multikiloampere) peak current, but uses low (less than 10^{-7} A) average current. Both approaches present some technical problems which are currently unsolved.

The physical phenomena that determine the brightness for the storage-ring-based sources have been well investigated: they are the quantum fluctuation of the synchrotron radiation and the intrabeam scattering. The third-generation synchrotron radiation sources are optimized to suppress their influence on the brightness. The fourth-generation storage-ring projects utilize further attempts in this direction. However, the further increase of the lattice focusing strength is limited by the decrease of dynamic aperture, and there are no solutions to this problem as yet. 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. At high peak current, however, which is necessary for the superradiant free-electron laser, space charge fields lead to the growth of emittance.

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

2. Set-up

The general scheme of the multi-turn accelerator–recuperator source (MARS) of X-rays is shown in Fig. 1.

The electron beam from the gun is accelerated in the RF linac. The electrons then 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.

3. Undulator

Because the undulator gap will be limited mainly by the radiation losses in the walls of the vacuum chamber, a 5 mm gap seems reasonable. Then, choosing the undulator deflection parameter, K, equal to unity, one can obtain a 1.5 cm period, λ_w, from the Halbach equation (Halbach, 1983) for the planar hybrid permanent-magnet undulator.† A wavelength $\lambda = 0.1$ nm corresponds to an electron energy of 5.42 GeV.

The diffraction-limited brightness increases linearly with the undulator length, L (inversely proportional to the line width $\delta\omega/\omega = 0.4/N$, $N = L/\lambda_w$). However, at some length this growth becomes slower due to the longitudinal velocity spread and the corresponding spectral line broadening. The energy spread, σ_γ/γ (γ is the relativistic factor), does not cause any broadening if

$$\sigma_\gamma/\gamma < \delta\omega/2\omega = 0.2/N. \quad (1)$$

We can satisfy condition (1) with a 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),

$$(\sigma_\gamma/\gamma)^2 \simeq 180 r_0 \lambda_C \gamma^2 (K/\lambda_w)^3 z, \quad (2)$$

where r_0 and λ_C are the classical radius and the Compton wavelength of an electron, and z is the distance from the undulator entrance. The combination of (1) and (2) at $z = L/2$ gives the limitation of the undulator length,

$$L < (9 \times 10^7\ \mathrm{m}^{-2/3})\lambda_w^{5/3}/\gamma^{2/3}K. \quad (3)$$

For our parameters the right-hand side of inequality (3) gives 170 m, so we choose L = 150 m. Then $\delta\omega/\omega = 4 \times 10^{-5}$ and, according to inequality (1), the energy spread σ_γ/γ 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 a magnetic system is $\sim 3^{1/2}\varepsilon/\beta$ (Vinokurov *et al.*, 1997). Then the corresponding contribution to the line broadening is

$$(\delta\omega/\omega)_\varepsilon = 2(3^{1/2})\gamma^2\varepsilon/\beta(1 + K^2/2) \quad (4)$$

and therefore the requirement for the emittance is given by

$$\varepsilon < 2(2^{1/2})\lambda\beta/4\pi L. \quad (5)$$

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

$$(\varepsilon\beta)^{1/2} < (\lambda L)^{1/2}/4\pi, \quad (6)$$

and may be written in the form

$$\varepsilon < (\lambda/4\pi)(L/4\pi\beta). \quad (7)$$

In the optimal case the right-hand sides of the inequalities (5) and (7) are equal (at $\beta \simeq L/6$ = 25 m for our example) and they give

$$\varepsilon < \lambda/8\pi. \quad (8)$$

Therefore, the desirable normalized emittance is less than 0.04 mm mrad. Modern electron gun technology demonstrated 1 mm mrad normalized emittance at 100 A peak current (Palmer *et al.*, 1997; Schmerge *et al.*, 1997). At lower current it is possible to achieve the lower values (that were obtained in the electron microscopes and the

† Theoretically, helical undulators are better, as they provide 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 gap and deflection parameter values.

Table 1
Comparison of the parameters of sample X-ray sources.

	ESRF storage ring	LCLS† 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) 0.025 (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^{-1})	6×10^{12}	6×10^{14}	7×10^{13}
Bandwidth	10^{-2}	10^{-3}	10^{-4}
Average brightness [photons s^{-1} mm^{-2} $mrad^{-2}$ (0.1% bandwidth)$^{-1}$]	10^{20}	6×10^{22}	3×10^{23}
Peak brightness [photons s^{-1} mm^{-2} $mrad^{-2}$ (0.1% bandwidth)$^{-1}$]		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

† Stanford Linear Collider Light Source (*Workshop on Fourth Generation Light Sources*, 1992; *Tenth ICFA Beam Dynamics Panel Workshop on Fourth-Generation Light Sources*, 1996).

electron lithography installations), so our emittance requirements seem reasonable.

The diffraction-limited brightness may be approximated by the expression

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

where α is the fine-structure constant, J_0 and J_1 are the Bessel functions, I is the beam current, e is the electron charge and $\Delta\omega/\omega$ is the standard bandwidth, which conventionally is equal to 10^{-3}. To be a fourth-generation source, the installation has to provide a brightness of 10^{23} photons s^{-1} mm^{-2} $mrad^{-2}$ (0.1% bandwidth)$^{-1}$. Substituting the earlier-defined parameters one can conclude that this value corresponds to a beam current of 0.3 mA.

4. 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° 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

$$R > \big[r_0/(\sigma_\gamma/\gamma)\big]\big[55\pi\gamma^5/24(3^{1/2})\alpha\big]^{1/2}. \qquad (10)$$

Assuming $\sigma_\gamma/\gamma = 1 \times 10^{-5}$, one finds 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. 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 Fig. 1 and have to be defined in further studies (for example, all orbits may have the same length and be placed inside the single tunnel). Options of installing undulators at other orbits and using synchrotron radiation from bending magnets have also to be inspected.

The transverse regenerative beam break-up caused by excitation of the higher-order modes in the RF resonators limits the average current. Therefore, the RF system has to be either non-superconducting or superconducting with the asymmetric high-order modes suppression. For the non-superconducting 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 sufficient for the lengths of the straight line sections to be about 300 m.

Table 1 compares the parameters of the sample X-ray sources.

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

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