MARS: FOURTH GENERATION X-RAY LIGHT SOURCE BASED ON MULTITURN ENERGY-RECOVERY LINAC

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Abstract

In the recent years, Russian government and scientific society have been coming gradually to an understanding the way of development science in Russia. Government have accepted a program of building six mega-science projects, and one of them can be a new fourth generation x-ray light source based on accelerator-recuperator. Multiturn energy recovery linacs (ERL) looks very promising for making modern synchrotron radiation sources, being less expensive and more flexible. At this time only one multiturn ERL exists. This Novosibirsk ERL operates with two orbits and two free electron lasers based on one linac now. The conception of Multiturn Accelerator-recuperator Radiation Source (MARS) was proposed in 1997 by G.N. Kulipanov, A.N. Skrinsky and N.A. Vinokurov. The use of the ERL with two separated accelerating structures allows to exclude main disadvantages of scheme with one linac, such as the pass of electron bunches with different energies through the same magnetic arcs. The feasibility study for such ERL-based high brightness x-ray source is presented.

INTRODUCTION

In the recent years, Russian government and scientific society have been coming gradually to an understanding the way of development science in Russia. Government has accepted a program of building one of the six mega-science projects, and one of them can be a new fourth generation x-ray light source. At the last 30 years the development of the synchrotron radiation (SR) sources has been aiming to different purposes. The main ones are the increase of spectral brightness and energy of generated quanta, using specific properties of SR radiation (coherence, polarization, time structure, etc.). Also, it is very important that each SR source is used by a large number of research groups (up to 60) from different areas of science and is worked for 7000 hours a year. Today, the SR sources of the third generation became the efficient factories for generating new knowledge, new technologies and new materials.

REQUIREMENTS TO FOURTH GENERATION SYNCHROTRON RADIATION SOURCES

For the last two decades, the development of SR sources of the fourth generation has been actively

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discussed. The world's physical community has worked out the following requirements to these sources. Full spatial coherence; the highest temporal coherence ($\Delta\lambda/\lambda < 10^{-4}$) without additional monochromatization; the averaged brightness of the sources has to exceed 10^{23}-10^{24} photon$\cdot$s^{-1}mm^{-2}mrad^{-2}(0.1% bandwidth)$^{-1}$; the full photon flux for the fourth generation sources must be at the level of the third generation SR sources; high peak brightness of the order of 10^{33} photon$\cdot$s^{-1}mm^{-2}mrad^{-2}(0.1% bandwidth)$^{-1}$ is important for some experiments; electron bunch length shorter, than 1 ps; high long-term stability; generation of linear and 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 [1].

During the last 30 years, the brightness of the x-ray SR sources based on storage rings has been 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 non-crystalline structure. Even for crystalline structures it is very important to use the speckle spectroscopy, which is accessible only in coherent light. Accordingly, the most important from all the requirements are: - the obtaining a fully spatially coherent flux of quanta with full photon flux at the level of the third generation SR sources, - a possibility of obtaining undulator radiation with a monochromaticity of 10^{-3} - 10^{-4} without using monochromators, which as a rule spoil the beam spatial coherence.

It is impossible to satisfy all requirements for the fourth generation SR sources using only one type of sources. High peak brightness and femtosecond length of light pulses can be achieved by using x-ray free electron lasers based on linacs with high (more than 1 kA) peak current.

Other requirements can be implemented easier and cheaper by using radiation from long undulators installed on the accelerator-recuperator.

ACCELERATOR SCHEME

A concept of accelerators-recuperators with one accelerating structure was proposed for realization a fully spatially coherent x-ray source in 1997 [2, 3]. Today, there is only one multiturn ERL in the world. It is

Novosibirsk ERL [4], which operates routinely with two orbits and two free electron lasers now. And, at this spring, four pass ERL was commissioned. But, the scheme of acceleration has serious intrinsic problems. The main disadvantage is that two electron beams (accelerating and decelerating) pass simultaneously through every magnetic arc, except the last one. It means, in particular, that variation of any element of this arc (steering coil or quadrupole gradient) changes the motion of accelerating particles, but after that, changes their motion again, when they pass this element during deceleration. Moreover, accelerating and decelerating beams have, in general, different initial conditions (average angles and transverse coordinates, and envelopes). It causes many constrains during the optimization of focusing and orbit correction, and therefore complicates the control of electron beams. Due to this, it is useless to install undulators into the lower-energy arcs. Indeed, since two beams in such undulator have different angles and coordinates, and it is impossible to correct them for both beams, the radiation quality will be poor. Therefore, it has been proposed to use scheme with two accelerating sections (see Fig. 1) and separated magnetic arcs for accelerating and decelerating beams [4, 5].
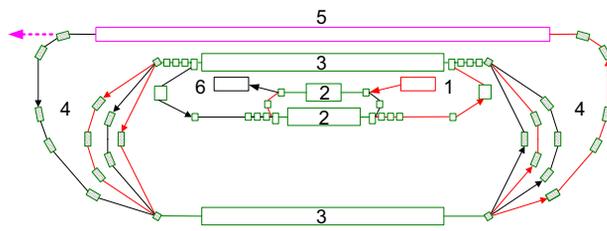

Figure 1: ERL with two separated linacs.

Principle of operation is the following: electrons with energy 8 MeV from injector 1 pass two preliminary accelerating RF sections 2 (42 MeV and 350 MeV) and come to first main accelerating structure 3 (0.7 GeV). Then, magnetic structure 4 bends electrons to the second main RF structure 3 (1.9 GeV). After 2 passes through each accelerating structure 3, electrons gain the final energy 5.6 GeV and pass to the undulator 5. Used electrons are decelerated at the same RF structures. In this case, accelerating and decelerating bunches pass through different magnetic arcs. Decelerated particles drop to the dump 6.

To generate fully spatially coherent undulator radiation with wavelength 0.1 nm it is necessary to decrease emittance of electron beam at the final energy to diffraction limit $\varepsilon_{x,z} < \lambda/4\pi \approx 10^{-11}$ m. It corresponds to the normalized emittance 10^{-7} m. Such slice emittance was already demonstrated for single bunches with the 0.1 nC charge. Therefore we suppose that it is also possible for 10 pC in CW mode. For the RF frequency 1.3 GHz that corresponds to the average current about 10 mA. The version suggested for some single-turn ERL projects - using current up to 100 mA for keeping the photon flux - seems to be far from optimum, since with such an increase in current the brightness does not increase and even decreases sometimes. To compensate the decrease in the current value compared with that of the third generation SR sources, we shall use radiation from long undulators. For the planar undulator with $N = 10^4$ periods the diffraction-limited average brightness is about 10^{24} photon s^{-1}mm^{-2}mrad^{-2} (0.1% bandwidth)$^{-1}$. This way we solve the problem of full spatial coherence and at the same time keep the photon flux at the level of the 3rd generation sources. It worth noting, that, since electron energy deviation ΔE leads to the shift of the undulator radiation spectrum by $\Delta\lambda/\lambda = -2\Delta E/E$, and the "natural" undulator radiation spectral width is $1/N$, the spectral brightness is not reduced for low enough energy spread [$\sigma_E/E < 1/(4N)$] only. Another advantage of split accelerating structure is a possibility to provide radiation with different wavelength ranges at different beamlinrs. A scheme with one undulator (Fig.1) can be extended by installations of long undulators into bending arcs 4 (see Fig. 2).
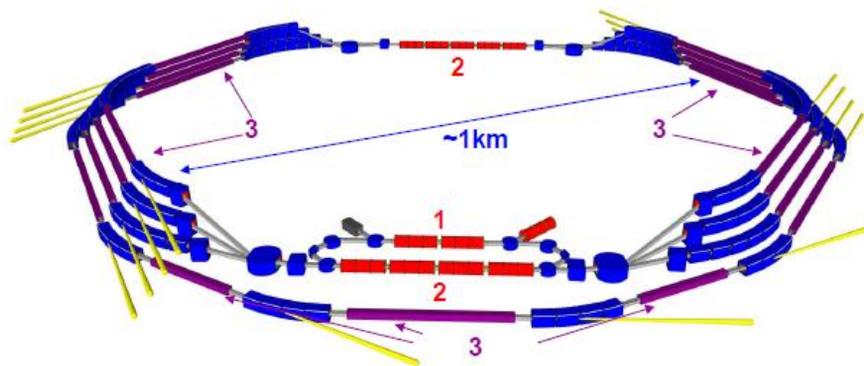

Figure 2: MARS scheme: 1 –cascade injection, 2 – linacs, 3 – long undulators.

There are 7 undulators for 5.6 GeV, and 4 undulators for 3.7 GeV, 3 GeV and 1.1 GeV in this scheme. To simplify the radiation output the magnetic arcs are separated both horizontally and vertically. The

radiation parameters comparison of MARS (with average current $I = 10$ mA) and one of the best of existing third generation SR sources SPring-8 (with the average current $I = 100$ mA) is presented in the table 1.

Table 1: Comparison of MARS (I=10 mA) and SPring-8 (I=100 mA)

Facility	Number of undulator periods	Number of beamlines	Brightness, photon·s^{-1}mm^{-2}mrad^{-2} (0.1% bandwidth)$^{-1}$	Flux, photon·s^{-1}(0.1% bandwidth)$^{-1}$
MARS	10^3	3	10^{23}	10^{15}
	10^4	16	10^{24}	10^{16}
SPring-8	Bending magnets	23	10^{16}	10^{13}
	130	34	$3\cdot10^{20}$	$2\cdot10^{15}$
	780	4	10^{21}	$1.2\cdot10^{16}$

CONCLUSION

The main ideas of MARS design allow to reduce significantly the cost of the facility and energy consumption, providing the servicing of many users simultaneously. These ideas are simple and clear:

1). Using energy-recovery scheme.

2) Emittance of the electron beam is less than 10^{-11} m, which corresponding to the normalized emittance 10^{-7} m·rad.

3) Bunch charge should not exceed 10 pC. That corresponds to a 10 mA beam current.

4) Photon flux is proportional to the average current I and number of undulator periods N. To compensate the 10-50 times current decrease, it is necessary to use the radiation from undulators and wigglers with large ($N > 1000$) number of periods.

5) To provide a low level of radiation hazard and eliminate induced radioactivity, electron energy at the beam dump should not exceed 10 MeV.

6) To provide proper focusing for electrons with different energies in accelerating (decelerating) RF structures, it is necessary to use cascade scheme of injection.

7) For simultaneous multi-users servicing a scheme with two separated accelerating structures can be used. This eliminates the main disadvantage of the scheme with single linac, where accelerating and decelerating bunches create two radiation sources in each undulator, and simplifies the control of the beam.

8) Magnetic structure should contain long interspaces ($L \sim 200$ m) for mounting a large number of undulators with $N \sim 10^2$ - 10^4 periods.

9). Energy spread of electrons at low energy should not exceed $1/N \sim 10^{-4}$.

10). A bending radius in magnetic arcs should exceed 60 m to decrease energy spread and emittance growth due to quantum fluctuations of the synchrotron radiation.

The use of long undulators with the high-quality electron beam of ERL is the solution for the fourth-generation x-ray sources. There are no any essential physical problems in the development of the fourth generation x-ray sources on the base of accelerators-recuperators with the average current about 10 mA. The main problem is the cost of such source and its further maintenance.

After successful commissioning of the third stage of the NovoFEL ERL (four-pass), the next step of MARS development should be a building of its lower energy prototype – ERL for extreme ultraviolet lithography (wavelength 13.5 nm) free electron laser [6].

ACKNOWLEDGMENTS

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