MULTITURN ERL X-RAY SOURCE (MARS) FEASIBILITY STUDY

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Abstract

Multiturn energy recovery linacs (ERL) looks very promising for making ERLs less expensive and more flexible, but have serious intrinsic problems. At this time only one multiturn ERL exists. This Novosibirsk ERL operates with two orbits and two free electron lasers 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 two-linac ERL (D. Douglas, 2001) makes multiturn operation much easier. 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 have accepted a program of building one of the six mega-science projects, and one of them can be a new 4-th generation x-ray light source based on accelerator-recuperator.

At the last 30 years development of the synchrotron radiation (SR) sources have been aiming to different purposes. The main ones are the increasing of spectral brightness and energy of generated quanta, using of specific properties of SR radiation (coherence, polarization, time structure, etc.). Also, it is very important that each SR source has been used by a large number of users groups (up to 60) from different areas of science and has worked for 7000 hours a year.

Today, the SR sources of the 3rd generation available and those under construction (APS, ESRF, Spring-8, SLS, ELETTRA, DIAMOND, SOLEIL, PETRA-III, ALBA …) are the efficient factories for generation of the new knowledge, new technologies and new materials.

REQUIREMENTS TO SR SOURCES

In the last two decades, 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 [1]:

- 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 $s^{-1}mm^{-2}mrad^{-2}(0.1\%\ bandwidth)^{-1}$;
- 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% bandwidth)$^{-1}$ 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 sources is the most important from all the requirements to SR sources of the 4th generation. 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, is also of great importance.

It is impossible to satisfy all requrements for the 4-th 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 hight pulse current (I_p > 1 kA). The first XFEL - LCLS is in operation since 2009 with 10 fs x-ray pulses at 1 Å wavelengh and the second one, SPring-8, has started operation in 2011. In the next years x-ray FELs will start to work in Europe and Korea.

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

To generate full spatially coherent undulator radiation with wavelength λ = 0.1nm it is necessary to decrease emittance of electron beam at E = 5÷6 GeV to diffraction limit $\varepsilon_{x,z} < \lambda/4\pi \approx 10^{-11}$. Therefore, the charge in one bunch should be no more than 10^{-11} C. For the RF frequency 1.3 GHz that corresponds to the average current 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

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the current value compared with that of the 3rd generation SR sources, we shall use radiation only from three types of undulators with number of periods N_{u1}=100, N_{u2}=1000, N_{u3}=10000, not from bending magnets. In this case, 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.

ACCELERATOR SCHEME

A conception of accelerators-recirculators with one accelerating structure was proposed for realization a fully spatially coherent X-ray source in 1997 [2,3]. The main disadvantage of this scheme is that two electron bunches (accelerating and decelerating) are circulated simultaneously at every magnetic arc except the last one. Due to this, in undulators of the lower-energy orbits radiation is generated by both accelerating and decelerating electrons. Therefore the precise aligment of both beams is required. Moreover, this complicates the control of electron beams. 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]).

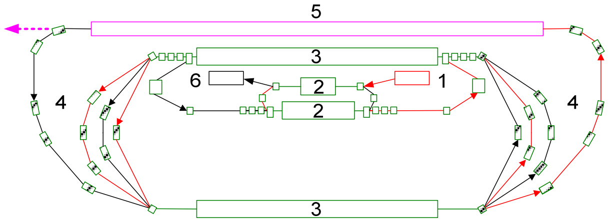

Figure 1: The simplest scheme of accelerator with 2 separated accelerating structures: 1 – injector, 2 – two preliminary accelerating structures, 3 – two separated linacs, 4 – magnetic arcs, 5 – undulator, 6 – dump.

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 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.

The main features of facility are the following.

Injection. Cascade injection system consists of two preliminary acceleration sections, which accelerate electrons to energies 50 MeV and 400 MeV. This relatively high injection energy simplifies focusing of particles with different energies traveling simultaneously in the accelerating structure. Moreover, it increases the threshold current of the transverse beam breakup (BBU). For the same reasons, we use two asymmetrical main accelerating structures (0.7 and 1.9 GeV). The using of the cascade injection and energy recovery decreases radiation hazard and eliminates the induced radioactivity due to the low energy of electrons at the dump (5-8 MeV). It leads to reduction in the cost of building and RF power supply for the injector.

Radiation. It was already mentioned, that to achieve full spatial coherence with conservation of photon flux on the level of the third generation sources it is necessary to use long undulators. Thus, another advantage of split accelerating structure is a possibility of servicing the multi-user community. A scheme with one undulator (Fig.1) can be extended by installations of the long undulators into bending arcs 4 (see Fig. 2). There are 7 undulators for 5.6 GeV, and 4 undulators for 3.7 GeV, 3 GeV and 1.1 GeV. To simplify the radiation output the magnetic arcs are separated both horizontally and vertically.

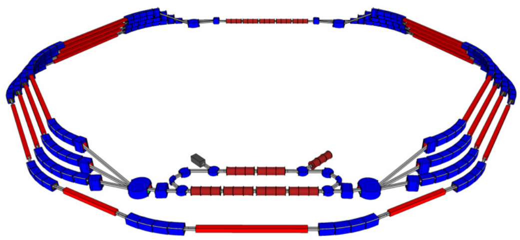

Figure 2: Scheme of MARS with main features: cascade injection, two accelerating structures, separated bending arcs, vertical separation of radiation beamlines.

The radiation parameters comparison of MARS (I=10 mA) and the best of existing third generation SR sources SPring-8 (100 mA) is presented In the table 1

Table 1: Comparison of SR Sources MARS and SPring-8

facility	Number of undulator periods	Number of channels	Brightness	Flux
MARS	10^2	48	10^{22}	$7.7\cdot10^{13}$
	10^3	12	10^{23}	$7.7\cdot10^{14}$
	10^4	4	10^{24}	$7.7\cdot10^{15}$
SPring-8	Bending magnets	23	10^{16}	10^{13}
	130	34	$3\cdot10^{20}$	$2\cdot10^{15}$
	780	4	10^{21}	$1.2\cdot10^{16}$

Magnetic structure of the each orbit (4 at Fig.1) consists of six 60-degrees achromatic bending arcs with 26 magnets in each. Quantum fluctuations of SR practically do not increase energy spread and transverse emittances. For this, at the last turn bending radius should be more than 60m. To simplify the vacuum chamber elements, the same radius is used at all orbits. At the maximum energy (last orbit) the growth of the horizontal emittance limits «invariant» of the dispersion function: $\gamma_T\eta^2 + 2\alpha_T\eta\eta' + \beta\eta'^2 < 3\,\text{cm}$, where $\gamma_T, \beta, \alpha_T$ are the Twiss parameters, and η is the horizontal dispersion function.

To control the longitudinal motion bending arcs are not isochronous. Longitudinal motion should provide low energy spread ($2\cdot10^{-5}$) and low bunch length (<0.1ps). This requires longitudinal emittance less than 5 keV·ps. Furthermore, longitudinal focusing should provide low bunch length at the last arcs. Limit of «invariant» of horizontal dispersion function also limits the longitudinal dispersion $R_{56} = \pi\bar{\eta}/3$ (0.18m for the 60-degree arcs of the last turn). For the energy spread $2\cdot10^{-5}$ this corresponds to bunch lengthening 11fs only. It means that two last turns cannot be used for bunching. At the two first turns the growth of emittance due to quantum fluctuations is less; therefore it is possible to increase the transverse and so the longitudinal dispersion.

RF structure. To achieve the energy 5.6 GeV electrons it is planned to use two main accelerating superconducting RF structures with energy gain 0.7 GeV and 1.9 GeV and two preliminary ones for 42 MeV and 350 MeV. There are four electron beams (two accelerating and two decelerating) with average current 10 mA in each main linac simultaneously. Consequently, the main goal is not to get high acceleration rate, but a stability of the bunch.

Since the magnetic structure of accelerator is not an isochronous, all three types of beam-cavity interaction instabilities are exited (beam-loading, HOM transverse and longitudinal BBU). In the simplest case of single-cavity model, threshold current of transverse BBU can be estimated as [6]

$$I_{th} \approx 0.14 I_A \frac{\lambda\sqrt{\gamma_1\gamma_2}}{Q\sqrt{\beta_1\beta_2}},$$

where I_A = 17 кА, γ_1 and γ_2 are the Lorentz factors of electrons at the first and the second passes through the cavity, β_1 and β_2 are the corresponding beta-functions of the beams. Therefore, for the current 10 mA, $\lambda_{RF} = 0.23m$ and $Q_{load} = 10^6$ it is enough to have $\sqrt{\beta_1\beta_2}/\sqrt{\gamma_1\gamma_2} < 0.06$ m. So, for energies at the entrance of the first main accelerating structure 400 MeV and 3 GeV this gives $\sqrt{\beta_1\beta_2} < 120$ m, which is easily achievable.

Beam-loading instability may take place, as the R_{56} elements of transport matrices between accelerating structures are not zero. There are four electron beams in each linac simultaneously. So, in the single cavity model, the necessary condition for the longitudinal stability is [7]

$$e\rho_1 I \sin(2\Phi_1)\sum_{n=0}^{N-1}\sum_{k=0}^{N-1} S_{4N-2n-1,2k} + $$
$$+ e\rho_2 I \sin(2\Phi_2)\sum_{n=0}^{N-1}\sum_{k=0}^{N-1} S_{4N-2n-2,2k+1} < \frac{1}{Q_1} + \frac{1}{Q_2}.$$

Here I is the beam current, S_{nk} is the R_{56} transport matrix element between k-th and n-th passage through the accelerating structures, ρ and Q are the characteristic impedances and loaded qualities for the fundamental mode (TM_{010}), and $\Phi_{1,2}$ are phases of the acceleration in the first and the second accelerating structures. Of course, threshold current depends on phases of acceleration $\Phi_{1,2}$, which are also determined by requirements of the bunch longitudinal focusing. Simulations show that there are areas of the stable accelerating phases (left part of the stability condition is negative).

The main parameters of the ERL are listed in Table 2.

Table 2: The Accelerator Parameters

Energy	5.6 GeV
Average current	10 mA
Peak current	10 A
Normalized emittance	0.1 mkm
Relative energy spread	$2.2\cdot10^{-5}$
SR sources	19 Undulators (N_u~10^2, N_u~10^3, N_u~10^4)
Geometrical sizes	1x1 km

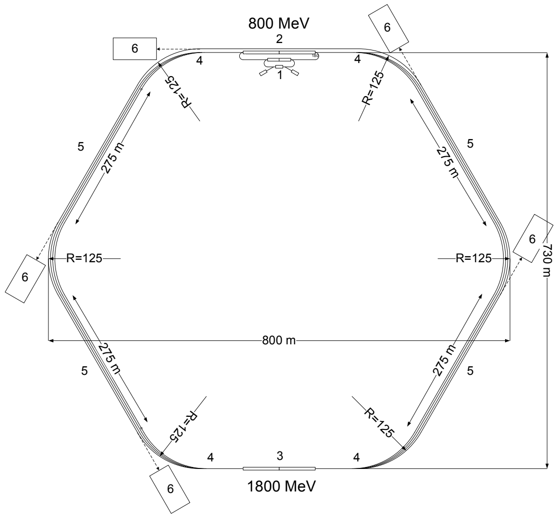

Figure 3: Scheme of MARS in scale: 1-injector and preliminary accelerating sections, 2,3– two separated linacs, 4 – magnetic arcs, 5 – undulator, 6 – user stations.

CONCLUSION

The use of long undulators with the high-quality electron beam of ERL is the solution for the fourth-generation x-ray sources. The accelerating schemes and most of the systems, which make the basis of the projects, have already been tested in many laboratories (Jefferson Laboratory, DESY, MAMI, LEP, Budker INP, KEK, MAX). There are no any essential physical problems in the development of the 4th generation SR sources on the base of accelerators-recuperators with average current 10 mA. The main problem is the cost of such SR source and its further maintenance.

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

1) Emittance of the electron bunch with energy $E = 5 \div 6$ GeV is less, than 10^{-11} m · rad , which corresponding to the normalized emittance $\varepsilon_n < 10^{-7}$ m · rad .

2) Bunch charge should not exceed $Q = 7.7 \cdot 10^{-12}$ C . That corresponds to a current value of 10 mA.

3) Photon flux from source proportional to the average current I of accelerator $\Phi \sim I \cdot N$, N is a number of emitters in the source. To compensate the current decreasing in 10-50 times, it is necessary to use the radiation from undulators and wigglers with number of periods $N_u>100$.

4) To provide a low level of radiation hazard and eliminate induced radioactivity, the bunch energy should not exceed 5-8 MeV in the beam dump.

5) To provide easily achievable conditions for simultaneous movement of the electron bunches with different energies in accelerating (decelerating) RF structures, it is necessary to use cascade scheme of injection.

6) 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.

7) Magnetic structure should contain long interspaces (L~200 m) for mounting a large number of undulators with number of periods $N_u = 10^2 \div 10^4$.

8). Energy spread of electron bunch at low energy should not exceed $\Delta E/E = 10^{-4}$.

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