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KURCHATOV SYNCHROTRON RADIATION SOURCE – FROM THE 2ND TO THE 4TH GENERATION*

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Abstract

The inauguration of the only dedicated synchrotron radiation source in Russia was held at NRC "Kurchatov Institute" in 1999. At present according to its main parameters it is a "2+" generation synchrotron radiation facility. In this article we consider the possibility of the Kurchatov synchrotron radiation source upgrade up to compact 3rd generation facility with keeping of all experimental stations at the same places. Also we present the conceptual design of the new diffraction limited synchrotron radiation source (4th generation facility) for NRC "Kurchatov Institute".

INTRODUCTION

Kurchatov synchrotron radiation source is dedicated synchrotron light facility and works for the experiments in the range of synchrotron radiation from VUV up to hard X-ray. It consists of 80 MeV linac, 450 MeV booster synchrotron and 2.5 GeV main storage ring. Synchrotron radiation from bending magnets of the main storage ring overlapping the spectral range of 0.1-2000 Å.

The lattice of the main storage ring consists of 6 superperiods with two types of 3 m straight sections [1]. Dispersion free straight sections are used for installation of wigglers and RF cavities. And straight sections with nonzero dispersion function are used for injection, for installation of diagnostic, feedback systems and undulators.

The main storage ring has only one user operation mode with 98 nm·rad electron beam emittance. Its main parameters are given in Table 1, lattice functions of one of superperiods – in Fig. 1 and dynamic aperture in the centre of dispersion straight section – in Fig. 2.

Table 1: The Main Parameters of the Main Storage Ring

Parameter	Value
Energy	2.5 GeV
Circumference	124.13 m
Number of superperiods	6
Beam current	100 – 150 mA
Beam lifetime	15-20 h
Horizontal emittance	98 nm·rad
Horizontal/vertical tune	7.775 / 6.695
Horizontal/vertical chromaticity	-16.9 / -12.9

According to its main parameters Kurchatov synchrotron radiation source is a "2+" generation facility. But due the facility was initially designed to have some space for improvement in the future now it is possible to upgrade it up to a compact 3rd generation synchrotron light source.

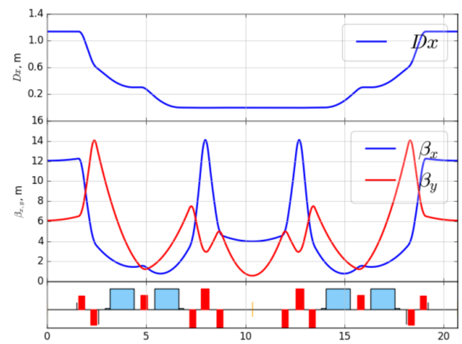

Figure 1: Lattice functions in user operation mode.

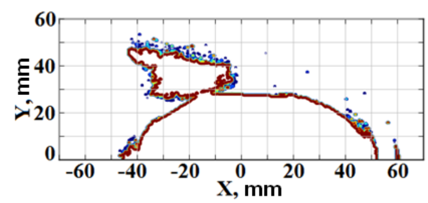

Figure 2: Dynamic aperture.

TO THE 3RD GENERATION LIGHT SOURCE

Currently a lot of work is carried out to improve facility performance and extend its experimental capabilities. Namely new photon beamlines are comissionning, next year two superconducting wiggers will be installed at the main storage ring, many facility systems are under upgrade and so on.

The research carried out in ref. [2, 3] show that it is possible to reduce electron beam emittance by varying excitation currents into quadrupoles and, most importantly, without any changings of geometric sizes or positions of all magnetic elements. So if the beam current and lifetime will remain at the same level then the intensity and brightness of synchrotron radiation will be increased.

If the size of the dynamic aperture is kept sufficient for an electron beam injection from the existing booster synchrotron, storing and acceleration up to working energy then there are two options with completely different main storage ring lattices. The first option is the lattice with 60-65 nm·rad emittance and dispersion free into one of two straight sections. Lattice functions and dynamic aperture of lattice tuning to achieve 67 nm·rad emittance are shown in Fig. 3 and Fig. 4. The second option is the lattice with 15-20 nm·rad emittance and nonzero dispersion into both two straight sections. Lattice

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functions and dynamic aperture of lattice tuning to achieve 17 nm·rad emittance are shown in Fig. 5 and Fig. 6.

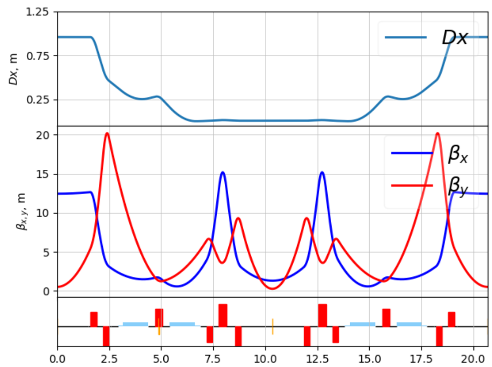

Figure 3: Lattice functions in 67 nm·rad operation mode.

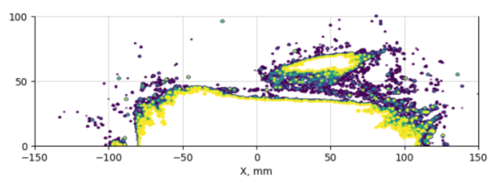

Figure 4: Dynamic aperture.

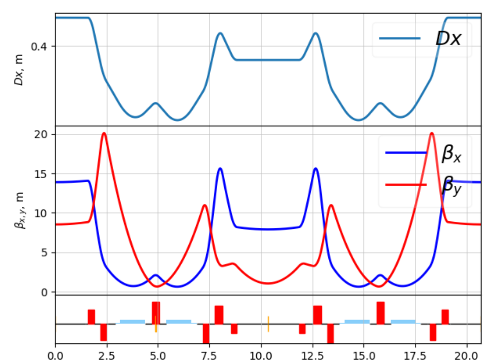

Figure 5: Lattice functions in 17 nm·rad operation mode.

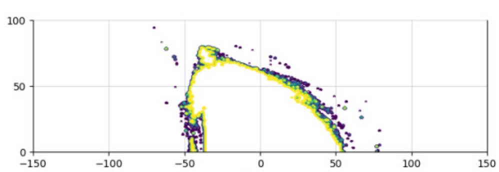

Figure 6: Dynamic aperture.

However, we note that the facility operation in the mode with nonzero dispersion function for experiments with synchrotron radiation from insertion devises must be performed with care. In this mode the operation of some insertion devices can lead to a significant increase in the electron beam emittance and, accordingly, to a decrease in the brightness of synchrotron radiation.

Emittance values of 67 and 17 nm·rad mentioned above are compromise between small of emittance and good dynamic aperture. Further decrease of emittance is possible for both cases. But the size of the dynamic aperture will also decrease. In the existing injection scheme this will lead to a decrease in the injection efficiency large electron beam emittance (800 nm·rad) in booster synchrotron. So electron beam storing in the main storage ring will have problems and under certain conditions it will be impossible at all. All of this will lead to a decrease in the beam current and lifetime in any user operation mode.

Most problems associated with an electron beam storing in the main storage ring, longtime electron and photon beams stabilization, electron beam emittance minimization as much as possible can be solved by injection system upgrade and full energy booster synchrotron construction.

There are two options for the full energy booster synchrotron with minimal changings of facility systems and construction work. The first option is a full-scale booster synchrotron located in one tunnel with the main storage ring [4, 5]. The second option is a compact booster synchrotron located in one area with the linac [11]. The existing small booster must be dismantled in the second case.

The main advantage of a full-scale booster synchrotron is a simple lattice with compact and not strong magnetic elements. In a lattice of compact booster synchrotron combined functions magnets with superconducting excitation coils are used. However the maximum magnetic field in these magnetic elements will not exceed 2.2 T. And this will significant simplify the design of magnets. The main advantage of a compact booster synchrotron is that minimal construction work is required in the tunnel of the main storage ring when installing a booster synchrotron. And the installation itself will take a minimum time due to the ability to perform a lot of work outside the facility.

After full upgrade of the injection system and switch to new brighter lattices Kurchatov synchrotron radiation source will approach the sources of the 3rd generation in intensity and brightness of synchrotron radiation in some operation modes.

In order to stay competitive in future further improvement in intensity and brightness of synchrotron radiation is required. To realize this it is necessary to change of Kurchatov synchrotron radiation source lattice to completely new one. Experience of 3rd generation sources (such as ESRF, SLS, APS, Spring-8) shows that with the help of full facility upgrade it is possible to reduce electron beam emittance of the main storage ring by 10-20 times with keeping all user beamline stations and also the beam current and lifetime [6, 7]. First of all such a significant decrease in the electron beam emittance was made possible by the progress in the technology of magnetic and vacuum systems. Due to this progress it became possible to build facilities with more complicated lattices (such as MBA) instead of DBA (standard lattices of 2nd and 3rd generation synchrotron radiation sources).

The lattice of Kurchatov synchrotron radiation source can be also upgraded from DBA type to MBA with keeping all user beamline stations. The main difficulty in the development of a new MBA type lattice is the fact that at present long 1.2 m bending magnets with a field of 1.7

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T are used. It will require strict restrictions on the magnetic system parameters if all user beamline stations must be kept. Nevertheless, to achieve a significant decrease in emittance (at least 10 times) is possible. This can be achieved by using superbend magnets with a longitudinal field gradient (also maybe with superconducting coils) and combined functions magnets. As a result, it is possible to expect the electron beam emittance in the main storage ring at a level of 1-5 nm·rad at 2.5 GeV. Also the installing Robinson wigglers into 2-4 straight sections can provide additional reduction of the electron beam emittance. A slight decrease the energy of an electron beam, for example, up to 2 GeV can be also compromise between simplification of the magnetic system and reduction of the emittance. In this case, the brightness of the synchrotron radiation will still be higher due to a significant decrease in the emittance.

So, after full upgrade of Kurchatov synchrotron radiation source, it will become a compact 3rd generation synchrotron radiation source.

USSR – 4TH GENERATION KURCHATOV SYNCHROTRON RADIATION SOURCE

For the 4th generation synchrotron radiation source, the world scientific community compiled a list of basic requirements [8]:

- The achievement of a diffraction-limited source at a wavelength of 1 Å.
- Full spatial coherence.
- Maximum achievable time coherence.
- Average source brightness higher than 10^{23-24} photons·s^{-1}·mm^{-2}·mrad^{-2}·(Δλ/ λ=0.1%)$^{-1}$.
- Peak source brightness higher than 10^{33} photons·s^{-1}·mm^{-2}·mrad^{-2}·(Δλ/ λ=0.1%)$^{-1}$.
- High long-term stability.
- Simultaneous work of a large number of user beamline stations.

However in the electron storage ring, the emittance has a fundamental limit that does not satisfy the requirement of full spatial coherence of the radiation [9]. Nevertheless, due to the progress in the accelerator physics and technologies, the development of effective algorithms for the simulation of magnetic fields and particle dynamics, increase the accuracy of measuring beam parameters, the development of new technologies to achieve a high vacuum synchrotron radiation sources based on storage rings become the optimal candidates for the 4th generation sources.

USSR – Ultimate source of synchrotron radiation – the new project of NRC “Kurchatov Institute” of 4th generation synchrotron radiation source based on 6 GeV electron storage ring.

The main feature of the USSR lattice is the achievement of a diffraction-limited source at a wavelength of 1 Å. This requires that the electron beam emittance of the storage ring must be less than 8 pm·rad.

At present, modern synchrotron radiation sources operate mainly in two energy ranges of the electron beam – 3 GeV (for example, MAX-IV, Sirius, NSLS) and 6 GeV (for example, ESRF, PETRA-II, APS).

Due to the characteristics of physical processes taking place in the electron beam in the storage rings the operation at higher energies will allow achieving smaller emittances. Although in this case, the size of the facility itself will be much larger.

DBA lattice was developed in the 1970s and made the basis of 2nd generation synchrotron radiation sources. Already in the 1980-90s the development and construction of 3rd generation synchrotron radiation sources are carried out. The results of the researches showed that it is possible to achieve smaller the electron beam emittance with the help of using more complicated lattices such of MBA. However, the technologies level of the time did not allow achieving impressive results from the use of new structures. Therefore, in order to minimize the risks during new 3rd synchrotron radiation sources commissioning, the sources themselves were still based on the DBA lattice.

For the first time the MBA lattice was realised in MAX-IV [10]. In this project the use of height precision magnetic elements with small aperture allowed to increase the gradients of magnetic fields, to make shorter magnetic elements and, thereby, to achieve a significant decrease in the electron beam emittance.

Further improvement of the MBA lattice was realized in the ESRF upgrade project [6]. Here different types of bending magnets in the superperiod lattice are used to minimize the electron beam emittance, to keep all user beamline stations and also to satisfy other additional requirements. To make zero dispersion function in straight sections used for insertion devices the pair of special bending magnets with longitudinal magnetic field gradient are used at both ends of the lattice. Also, these bending magnets provide a dispersion function bump in the places for weak chromatic sextupoles installing.

One of the latest MBA lattice improvements was realized in the SLS upgrade project [7]. In this project much less the electron beam emittance can be achieved than in the previous two projects due to the simultaneously using of superbend and antibend magnets. A magnet of the first type has a high magnetic field value at the centre which rapidly decreases to the edges. A magnet of the second type has opposite direction of a magnetic field.

As a prototype for the USSR lattice the upgraded SLS-2 lattice was chosen. To achieve an electron beam emittance of 8-10 pm·rad, obtaining a dynamic aperture sufficient for injection and an acceptable lifetime the number of superperiods was chosen of 48.

Recalling basic principles, quantum excitation is minimized if dispersion is suppressed in regions of high bending field. In the longitudinal gradient bend dispersion is focused to virtually zero at a peak of highest field. In the regions before and after the focus, where the dispersion is larger, the field strength is reduced correspondingly. Since the magnetic field is the source of dispersion, both quantities are connected, and the

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longitudinal field variation providing minimum emittance for given initial conditions (e.g. beta-function at focus) and constraints (e.g. maximum peak field, magnet length) was obtained from numerical optimization.

As a result of optimization USSR regular lattice it consists of 5 periodic cells and 2 suppressors. One superbend magnet with 2.2 T magnetic field in the center and combined function part at edges with 2 combined antibend magnets and 4 sextupoles (used for chromaticity correction) are composed into periodic cell. Suppressor part consists of half of a periodic cell and triplet with 3 harmonic sextupoles. Also to increase the size of dynamic aperture at the injection point there are 2 special injection cells with high horizontal beta function.

USSR main parameters are shown in Table 2. Lattice functions one of the regular cells are shown in Fig 7 and dynamic aperture at injection point – in Fig. 8.

Table 2: USSR Main Parameters

Parameter	Value
Energy	6.0 GeV
Circumference	2218 m
Number of superperiods	48
Horizontal emittance	10.42 nm·rad
Horizontal/vertical tune	159.913 / 44.146
Horizontal/vertical chromaticity	-424 / -154

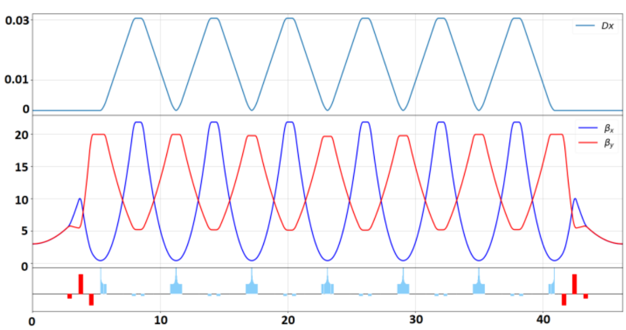

Figure 7: USSR regular lattice functions.

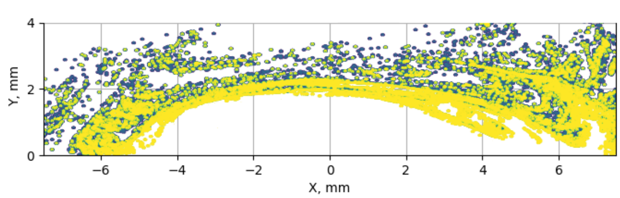

Figure 8: Dynamic aperture.

Despite the fact that the size of the dynamic aperture is only a few millimetres the ratio between sizes of dynamic aperture and electron beam is much larger than one in the 2nd and 3rd generation synchrotron radiation sources. Full energy linac or booster synchrotron can be used as injector. In both cases, the electron beam emittance of 1-10 nm·rad is already acceptable for injection.

The obtained USSR lattice is a good approximation for the further more detail lattice research and optimization to find the best compromise between the minimum achievable electron beam emittance, dynamic aperture, circumference end other parameters taking into account also different effects such as longitudinal motion, impact of insertion devices, intrabeam scattering, electron beam instabilities, magnet field errors and misalignments, instability of power supplies and so on.

CONCLUSION

The upgrade of Kurchatov synchrotron radiation source to 3rd generation source and a new 4th generation source creation will require the innovations and evolution in the domestic technologies of magnetic and vacuum systems, the solution of new problems in materials science and instrument engineering. As a result, this new facilities will become one of the biggest world scientific centers conducted researches in a variety of disciplines spanning physics, chemistry, materials science, biology and nanotechnology.

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REFERENCES

[1] V. Anashin et al. // Nucl. Instr. and Meth. A282 (1989) 369.
[2] Ye. Fomin et al., The use of multi-objective genetic algorithms for accelerator and light source optimization // Proceedings of RuPAC2016.
[3] Ye. Fomin et al., Multiobjective optimization of the synchrotron radiation source Siberia-2 lattice using a genetic algorithm // Physics of Particles and Nuclei Letters, 2018.
[4] M. Kovalchuk, V. Korchuganov et al., Modernization project of synchrotron source in Kurchatov Institute: booster synchrotron // Proceedings of RuPAC2006.
[5] V. Korchuganov et al., A new injection system for Kurchatov source of SR // Proceedings of RuPAC2008.
[6] ESRF upgrade programme phase II (2015 - 2022) Technical Design Study // ESRF, 2014.
[7] SLS-2 Conceptual Design Report // PSI-Bericht, 2017.
[8] Falcone R. et al., Scientific Needs for Future X-Ray Sources in the U.S // Lawrence Berkeley National Laboratory, SLAC, 2008.
[9] Hofmann A., The physics of Synchrotron Radiation. // Cambridge University Press, 2004.
[10] MAX-IV Concenpual Design Report // MAX-lab.
[11] M. Kovalchuk, V. Korchuganov et al., Kurchatov synchrotron radiation source facilities modernization // Proceedings of RuPAC2012.