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RATED PARAMETERS OF THE JINR SYNCHROTRON RADIATION SOURCE FOR THE ELECTRON ENERGY 0.7 GeV

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The JINR compact synchrotron radiation source

The JINR compact SR source for the electron energy 0.7 GeV consists of an electron linac, storage ring and 5-6 channels for SR extraction (Fig.1). The linac injects electrons into storage ring with the energy 25 MeV. The electrons are stored and accelerated to the energy 0.7 GeV. Typical parameters of the electron ring are given in Table 1. The storage ring has 4 straight sections used for 2 superconducting wigglers, an undulator, RF station and an injection section.

The SR source is to satisfy the following requirements:

Generating SR in a wide energy range 0.1 eV-10keV;

High SR intensity from undulator in the energy range 150 eV-3 keV;

High power radiation of soft X-rays with the energy 100 eV-10 keV from the superconducting wiggler;

Low cost;

Compactness.

Discussing the rated maximum electron energy of the JINR SR source we remembered about the existing collaboration between JINR and the Russian Research Center Kurchatov Institute [1]. The SR source Siberia-2 [2-3] of Kurchatov Institute has maximum electron energy 2.5 GeV.

The realisation of the JINR SR source for the electron energy up to 0.7 GeV which incorporates superconducting wigglers and an undulator will make it possible to construct 3 channels for hard X-rays with the energy up to 10 keV.

Table 1. General parameters of the SR source

Circumference, m		24
Straight section length, m		2
Number of SR channels		5-6
Maximum electron beam energy, GeV		0.7
Injection energy, MeV		25
Beam current, A		0.1-0.2
Maximum number of stored electrons		$5*10^{10}-10^{11}$
Magnetic rigidity, Tm		1.75
Normalized acceptance	$\Delta p/p$	$5*10^{-3}$
	$\gamma\varepsilon$, $\pi\cdot mm\cdot mrad$	300
<u>RF parameters</u>		
Maximum RF voltage, kV		15
Maximum RF power, kW		5
<u>Undulator parameters</u>		
Number of undulators		1
Magnetic field, T		1
Length, m		1.5
<u>Wiggler parameters</u>		
Number of wigglers		2
Magnetic field, T		7
Length, m		1
Critical SR energy, keV		2.3
<u>Bending magnets parameters</u>		
Number of bending magnets		16
Bending radius, m		2.5
SR loss at 0.7 GeV due to bending magnets, keV/turn		8.5

First, the project for the construction of the JINR SR source is motivated by the purposes of X-ray lithography with a high resolution (Table 2). Second, another application of the wiggler and undulator radiation lies in the field of micromechanics, the so-called LIGA process. The energy spectrum of SR from the bending magnets in the source covers the energy range from infra-red to ultra-violet. SR from a bending magnet has the maximum intensity at 0.3 keV. This SR can be used at several stations for investigations in the field of condensed matter physics in the infra-red region, such as studies of impurities in semiconductors, measurements of the superconducting gap, radiometry in the vacuum ultra-violet region.

Use of SR source for the electron energy of 0.7 GeV permits us to obtain a low beam emittance, ε ($\varepsilon \propto \gamma^2$, γ is the Lorenz factor), and reduce the number of bending magnets. The choice of a scheme without a booster does not significantly change the quality of the beam in the ring at the electron energy 0.7 GeV and, at the same time, reduces the cost of the SR source approximately two times.

The choice of the electron beam parameters in the storage ring is determined by different requirements imposed on SR by bending magnets, an undulator and superconducting wigglers. For X-ray lithography the critical wavelength lies in the range $\lambda_c \approx 8\text{-}20\,\AA$ (E_c=1.5-0.6 keV) for the beam dimension of $\sigma_{x,y} \le 2$ mm and the horizontal divergence $\sigma_{x'} \le 1$ mrad to minimize image distortion (Table 2). The necessary radiation power is of the order of $P_\gamma = 3mW/mrad$ which corresponds to the stored current 100 mA. In the case of micromechanics, layers of several hundred microns thick are irradiated and therefore the optimum SR wavelength is in the range $\lambda_c \approx 2\text{-}3\,\AA$ (E_c=6-4 keV). The dimensions and divergence of the beam are not really very critical parameters. At a 10 m distance from the source the spectral power density $P = 50mW/nm \times cm^2$ should be available at $\lambda = \lambda_c$ (Table 2).

For digital subtraction angiography it is necessary to have monochromatic radiation with $\lambda_c \approx 2\text{-}3\,\AA$ (E_c=6-4 keV) and the flux-density 10^{11} photons/mm²/sec.

Table 2. Channels of extracted SR from bending magnets, wigglers and an undulator

Method	Applications	Peculiarities	Energy range, Energy resolution $\Delta E/E$	Size of SR beam in focus plane, mm²	Intensity
X-ray lithography	Plate lithography, Creation of masks		(1-4) keV	150×10	
Deep X-ray lithography	Micromechanics (LIGA)		(3-8) keV	120×8	40 W
Photoelectron microscopy with high spatial resolution	Analysis of surfaces with high resolution		(0.09-1.4) keV 2×10^{-4} (400 eV)	1.5×1.5	10^{11} photon/sec (400 eV)
Infrared spectroscopy	High spatial resolution for chem. Analyses, Investigation of phonons		1 cm^{-1}-10^4cm^{-1}	0.02	10^{12} photon/sec
Fluorescent topography	Track chem. analyses, control of internal strains	Large SR beam cross section		20×20	3×10^{13} photon/sec
EXAFS	Analysis of short range order in alloys and nanostructures of different origin	High resolution	(2-20) keV 2×10^{-4}	2×2	2×10^{11} photon/sec
Small angle scattering (SAXS)	Investigation of large –scale structure	High intensity	(5-15) keV 5×10^{-4}	0.5×0.5	10^{12} photon/sec
Crystallography	Structure of organic molecules	High intensity, small divergence	(5-15) keV 5×10^{-4}	0.5×1	10^{12} photon/sec
X-ray imaging	Internal strains, high spatial resolution	High intensity, small divergence	(5-30) keV 5×10^{-4}	0.5×10	10^{12} photon/sec

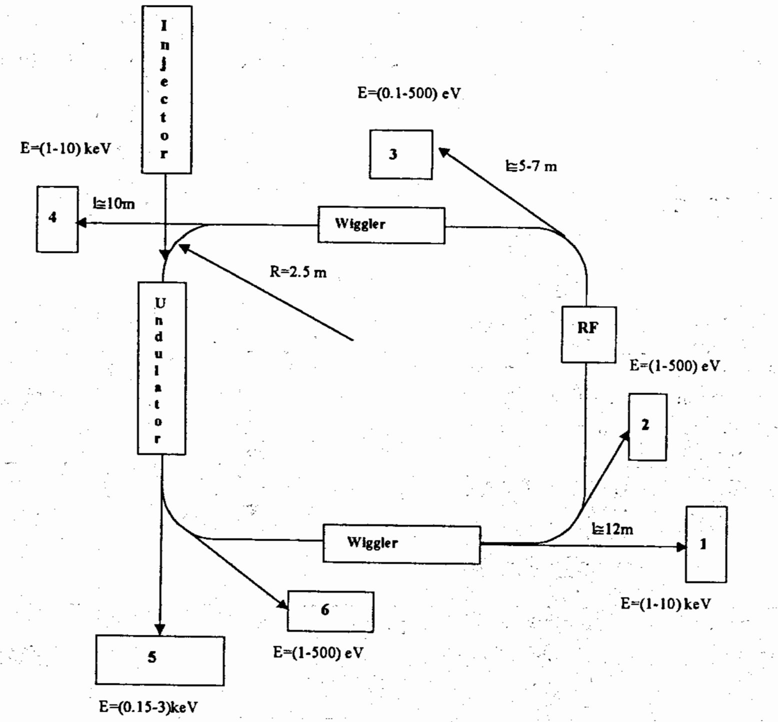


Fig.1.The block scheme of the JINR compact SR source. 1-Wiggler SR station for EXAFS, SAXS, fluorescent analysis, protein diffraction, 2- SR station for radiometry in VUV , 3-SR station in infrared region, 4- Wiggler SR station for deep lithography, micromechanics, x-ray imaging, diffraction, 5 – Undulator SR station for photoelectron spectroscopy with high resolution, 6-SR radiation station.

Synchrotron radiation parameters from bending magnets

SR from bending magnets can be used for radiometry in the ultra-violet region, photoelectron spectroscopy and infra-red spectroscopy. The parameters of SR from bending magnets are given in Table 3 and in Fig.2 The SR maximum lies at E=0.3 keV. The SR spectrum in the infra-red region is from λ=1 μm ($\nu=10^4$ cm^{-1}, E=1.2 eV) to

λ=100 μm (($\nu=10^2$ cm^{-1}, E=0.012 eV). The resolution is $\Delta\nu \approx 10^{-2}$ cm^{-1} . It focusing optics is used. The size of the SR beam on the sample is d<20 μm. The scheme of experiment including SR extracted from bending magnet is shown in Fig.3. Possible applications of SR from bending magnets are summarized in Table 4.

Table 3.The parameters of SR from bending magnets.

Electron energy, GeV	0.7
Beam current, A	0.2
Bending radius, m	2.5
Magnetic field, T	0.94
Critical energy of synchrotron radiation, keV	0.3
Maximum of photon flux, Photons/s/0.1% bandwidth/mrad horiz.	$1.5*10^{12}$
Power of radiation, kW	1.4
Power density on axis, W/$mrad^2$	0.5
Linear power density, W/mrad (horizontal)	0.27

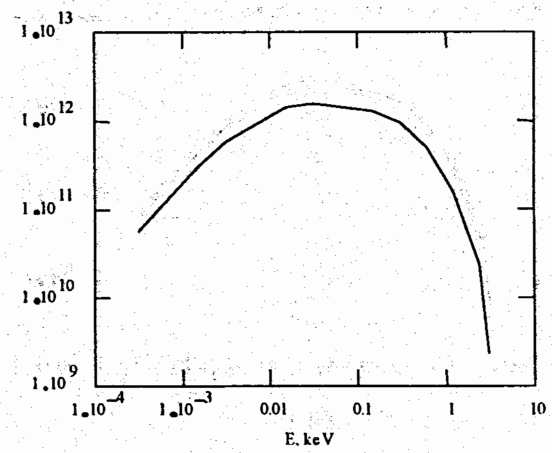


Fig.2.The dependence of the SR flux, (Photons/s/0.1% bandwidth/mrad horiz.) on the photon energy.

Table 4. Applications of SR from bending magnets

Applications	Wavelength, μm
Condensed matter physics : linear and non-linear spectroscopy	1-100
Semiconductors: impurities, excitations of quantum wells, optical modulation, recombination dynamics	1-100
Superconductors: band-gaps, impurities, low-dimensional structures, low-energy excitations	1-100
Communication and electronics: opto – modulation, lithography	10^{-3}
Molecular dynamics: surface physics, reflection/absorption spectroscopy of vibration modes	1-20
Surface chemistry: catalysis, crystal growth, optical damage	$10^{-2} - 1$
Photochemistry, isotope separation, powder synthesis	1
Biophysics: synthesis of nucleic acid, dynamics of proteins, biopolimer spectroscopy	10^{-2}
Biomedicine: microsurgery, phototherapy	0.5-3
Radiometry in VUV: calibration of devices for different applications, Raman spectroscopy	10^{-3}-0.1

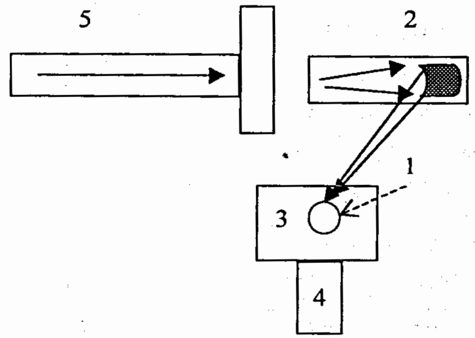


Fig.3.The registration scheme of infra-red SR extracted from the bending magnets. 1-sample, 2- SR focusing system, 3- Fourier interferometer, 4-detector, 5 - SR channel

The parameters of SR from the undulator

The undulator inserted in the storage ring is designed for EXAFS spectroscopy, X-ray imaging, protein crystallography and other applications. The undulator covers the X-ray energy range 150 eV-3 keV using the tunability of the *K* number and electron beam energy (Table 5). The achieved photon flux density is $3*10^{16}$ Photons/s/0.1% bandwidth/mrad horiz.

The quality of the electron beam is important to make a high brightness undulator. The SR parameters of from undulator especially depend on the electron beam emittance. The lattice of the ring has been adopted to produce the low emittance of the electron beam. Other important parameters of the electron beam for using the undulator are as follows. A small cross section and zero dispersion in the undulator section. The variation in the beam size should be as small as possible over the undulator length. The size of the electron beam in the undulator section is estimated to be about $\sigma_x / \sigma_y = 500/50$ μm at the electron energy 0.7 GeV. The electron angular spread at this energy is $\sigma_{x'} / \sigma_{y'} \approx$ 0.5/0.05 mrad.

The undulator has been designed taking into consideration the X-ray energy and available insertion space. As result, the undulator length is 1.5 m.

Table 5. The parameters of SR from the undulator

Electron energy, GeV	0.7
Beam current, A	0.2
Magnetic field, T	1
Period of undulator, cm	1.5
Number of periods, N	100
Maximum SR flux, Photons/s/0.1% bandwidth/mrad horiz.	$3.1*10^{16}$
Power of SR, kW	0.1
Power density along axis, W/mrad^2	50

The maximum photon flux density along the electron beam axis for n_{th}-harmonic is

$$\frac{d^3N}{dtd\lambda d\Omega}=\frac{4.5*10^4\gamma^2N_pF_n(K)}{\sqrt{\left(1+\left(\frac{\sigma_{x'}}{\sigma_U}\right)^2\right)\left(1+\left(\frac{\sigma_{y'}}{\sigma_U}\right)^2\right)}},$$

where γ is the Lorenz factor, N_p is number of periods, σ_u is natural angular spread of X-rays, $\sigma_{x',y'}$ are the angular spreads of the electron beam in the x and y directions, $F_n(K)$ is expressed using the Bessell functions $J_n(\xi)$ as

$$F_n(K)=\frac{nK^2}{\left(1+\frac{K^2}{2}\right)}\left[J_{(n-1)/2}(\xi)-J_{(n+1)/2}(\xi)\right]^2,$$

$$\xi=\frac{nK^2/4}{1+K^2/2},$$

where the factor K is equal to

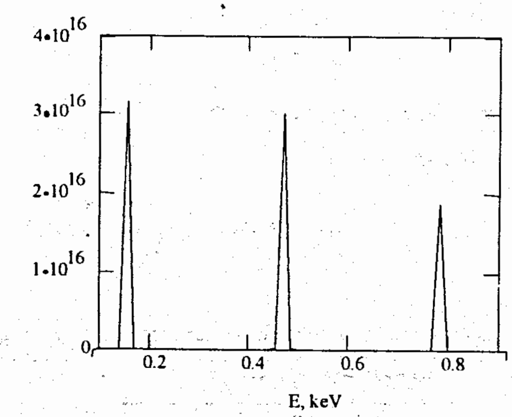
$$K=0.934B(T)\lambda_0(cm),$$

λ_0 is the length of one undulator period. The relation between the K number and the wavelength λ of X-rays for the first harmonic radiation is

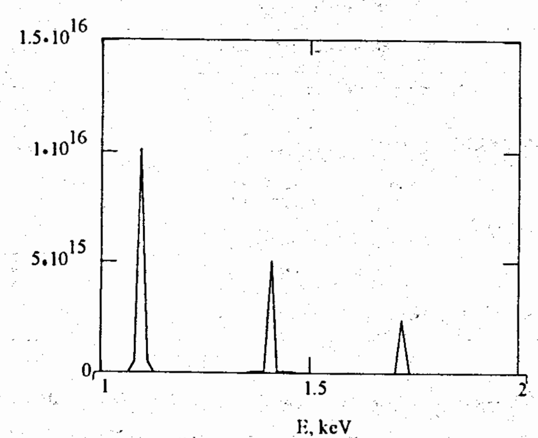
$$\lambda=\frac{\lambda_0}{2\gamma^2}\left(1+\frac{K^2}{2}+\gamma^2\left(\theta^2+\psi^2\right)\right),$$

where θ is the horizontal angle, ψ is the vertical angle.

The photon density flux from the undulator is shown in Fig.4. The distance between the peaks and the peak amplitudes are determined by the parameters of electron beam and the undulator.



a)



b)

Fig. 4. The dependence of the SR flux (Photons/s/0.1% bandwidth/mrad horiz.) on the X-ray energy; a) for 1,3, 5 harmonics, b) for 7, 9, 11 harmonics.

The parameters of radiation from superconducting wigglers

The intensity of SR radiation from superconducting wiggler with $K>>1$ is proportional to the number of wiggler periods N_p. If the parameter $K>>1$, the spectrum from wiggler looks very similar to the one generated by a bending magnet with strong magnetic field. As a result, the wiggler produces soft X-rays comparing with SR from the bending magnets (Table 6, Fig.5). The critical energy of SR from wiggler is

$$E_c(eV) = 0.665E^2(GeV)B(T).$$

In the direction of observation which forms the angle θ with wiggler axis the critical energy is roughly given by

$$E_c(\theta) = E_c(\theta = 0)\sqrt{1 - \left(\frac{\theta\gamma}{K}\right)^2}.$$

Table 6. The parameters of SR from a superconducting wiggler

Electron energy, GeV	0.7
Beam current, A	0.2
Magnetic field, T	7
Period of wiggler, cm	30
Number of periods, N_p	3
Critical energy of wiggler radiation, keV	2.3
Maximum SR flux, Photons/s/0.1% bandwidth/mrad horiz.	$4.7*10^{12}$
Power of SR, kW	2,85
Power density along axis, $W/mrad^2$	11

Two SR channels from the wigglers are planed to be constructed at the SR source (Fig.1). They will make it possible to conduct EXAFS spectroscopy, small angle scattering (SAXS), fluorescence topography, microfluorescent analysis, protein crystallography investigations on them (see Table 2).

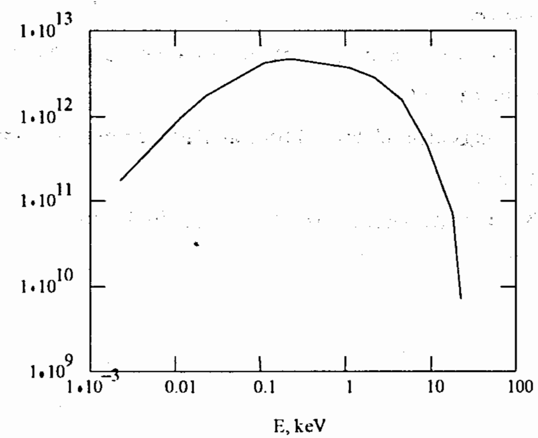


Fig.5.The dependence of the SR flux (Photons/s/0.1% bandwidth/mrad horizont.) on the X-ray energy .

The total power (integrated over the phase space and the photon energy) generated by wiggler is simply estimated as

$$P(kW) = 0.63E^2(GeV)B^2(T)L(m)I(A),$$

where L is the wiggler length, I is the electron beam current. At $K>>1$ the power density of SR from wiggler along the axis is

$$\frac{dP}{d\theta d\psi}(W/mrad^2) = 10.8B(T)E^4(GeV)I(A)N_p.$$

The estimates of the basic parameters of SR from the wiggler are given in Table 6 and Fig.5.

Conclusion

The proposed JINR compact SR source for the electron energy up to 0.7 GeV will allow the member-states of JINR to perform investigations in X-ray lithography, micromechanics-LIGA process, condensed matter physics, infra-red spectroscopy, photoelectron microscopy and other applications. Use of an undulator and superconducting wigglers extends essentially the possibilities of this SR source. Moreover the estimated cost of realization is 1M$, which is quite realistic in the present difficult financial situation at JINR.

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Проектные параметры источника синхротронного излучения ОИЯИ с энергией электронов до 0,7 ГэВ

Приведены первые оценочные параметры источника синхротронного излучения ОИЯИ с энергией электронов до 0,7 ГэВ. Для генерации синхротронного излучения (СИ) с энергией γ-квантов до 10 кэВ в накопительном кольце планируется разместить два сверхпроводящих виглера и ондулятор. Жесткое СИ из виглеров и ондулятора планируется использовать в проекте для исследований в микромеханике и литографии. Энергетический спектр СИ, выведенного из поворотных магнитов, располагается в инфракрасной — ультрафиолетовой областях. Проект СИ источника направлен на реализацию исследований в области физики конденсированных сред, полупроводников, биофизики, радиометрии и в другух направлениях.

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Rated Parameters of the JINR Synchrotron Radiation Source for the Electron Energy 0.7 GeV

This paper gives the first estimates of the rated parameters of the JINR compact synchrotron radiation (SR) source for the electron energy 0.7 GeV. The realization of the JINR SR source which incorporates superconducting wigglers and an undulator will make it possible to construct few channels for hard X-rays with the energy up to 10 keV. The project for the construction of the SR source is motivated by the purposes of X-ray lithography and micromechanics, the so-called LIGA process. The energy spectrum of SR from the bending magnets in the source covers the energy range from infra-red to ultra-violet. This SR can be used at several stations for investigations in the field of condensed matter physics in the infra-red region, such as studies of impurities in semiconductors, measurements of the superconducting gap, radiometry in the vacuum ultra-violet region.

The investigation has been performed at the Frank Laboratory of Neutron Physics, JINR.

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