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THIRD-GENERATION SYNCHROTRON RADIATION SOURCE AT THE JOINT INSTITUTE OF NUCLEAR RESEARCH

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An accelerator complex DÉLSI (Dubnen Electron Synchrotron) is planned for constuction as source of synchrotron radiation with high brightness in a wide spectral range – from far infrared (100 μm) up to high-energy x-ray (50 keV). This will make it possible to perform a wide range of research at the Joint Institute of Nuclear Research. The DÉLSI complex includes a linear electron accelerator up to energy 800 MeV and a storage ring with a 136 m perimeter at 1.2 GeV, in which a 10 T wiggler and an undulator (0.75 T, 150 periods) are built-in. The linear electron accelerator of the DÉLSI complex will be used for injection and for producing free-electron lasers. The parameters of synchrotron radiation from the bending magnets and built-in devices of the DÉLSI complex, the magnetic structure of the storage ring with the wiggler and undulator switched off, the effect of built-in devices on the ring optics, and the effect of errors on the closed orbit are examined; the synchrotron radiation parameters are briefly described.

Substantial results have been achieved in the last five years on the development of third-generation synchrotron radiation sources. Large storage rings have been put into operation – APS in the US and SPRING-8 in Japan – and the SLS storage ring in Switzerland is in the startup stage. In the ESRF storage ring (European Synchrotron Radiation Facility, Grenoble, France) the brightness of the synchrontron radiation was increased from 10^{18} to 10^{20} photons/(sec·mm^2·mrad^2·0.1% b.w.). Such a high brightness is achieved by using undulators built into the storage ring. At electron energies from 0.5 to 3 GeV the brightness of the synchrotron radiation emitted from the bending magnets is $2\cdot10^{12}$–$5\cdot10^{15}$ photons/(sec·mm^2·mrad^2·0.1% b.w.), the brightness of the radiation from the undulator is $3\cdot10^{18}$ photons/(sec·mm^2·mrad^2·0.1% b.w.), and the brightness of the radiation from the wiggler (for various sources) is $3\cdot10^{12}$–$1.5\cdot10^{16}$ photons/(sec·mm^2·mrad^2·0.1% b.w.). The size of the elec-

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tron beam in modern synchrotron-radiation sources is close to the diffraction limit, at which point further decreasing the size of the source no longer increases its brightness.

The DÉLSI (Dubnen Electron Synchrotron) accelerator complex is being built on the basis of the accelerator complex at the National Institute of Nuclear Physics and High-Energy Physics NIKHEF (Amsterdam, Holland), which by agreement between the two parties was disassembled in 1999 and transferred to Dubna [1]. The NIKHEF accelerator complex includes a MEA (medium energy accelerator) linear electron accelerator for electron energies 700 MeV and a AmPS storage ring (Amsterdam pulse stretcher) with maximum electron energy 900 MeV with accumulated-beam current 200 mA. The linear accelerator MEA in the DÉLSI design will be used in the electron storage mode, but in so doing the number of accelerating sections will be increased from 23 to 25 and the operating regime of the hf generators will be forced. This will make it possible to increase the electron energy up to 800 MeV.

The DÉLSI electron storage ring will be built using the components of the AmPS ring, altering its optics. The ring will also be an undulator with high brightness and a superconducting wiggler, generating high-energy x-rays. In DÉLSI the electron energy will be increased to 1.2 GeV by modifying the AmPS dipole magnets. Two hf stations will be installed in the storage ring: one will operate at 476 MHz and the other at the 2856 MHz frequency of the linear accelerator. This will make it possible to obtain short electron bunches (2.5 mm) for temporal modulation of the synchrotron radiation intensity in a wide time range. One possible direction of further elaboration of the complex could be using an MEA electron beam for free-electron lasers.

The basic parameters of the DÉLSI storage ring neglecting the built-in devices are as follows:

Perimeter, m	136.04
Radius of curvature of the trajectory in the bending magnets, m	3.3
Horizontal/vertical frequency of betatron oscillations	9.44/3.42
Orbit expansion ratio	$5.03 \cdot 10^{-3}$
Chromaticity (horizontal/vertical)	–22.2/–12.6
Stored electron current, mA	300
Horizontal emittance, nm	11.4
Accelerating voltage frequency, MHz	476
Equilibrium length of an electron bunch, mm	8.67
Harmonic number	216
Radiation losses per revolution in the bending magnets, keV	55.7

Synchrotron Radiation from the Bending magnets and Built-in Devices of the DÉLSI Storage Ring. The parameters of the synchrotron radiation from the bending magnets in DÉLSI (Fig. 1) make it possible to implement an extensive research program on atomic and photoelectronic spectroscopy, luminescence in the VUV region, x-ray luminophore and scintillator physics, and fluorescence spectroscopy of biological objects with high time resolution with low-energy x-rays. Eight synchrotron-radiation channels will be built for this. A metrological channel will be built for performing photometric measurements on detectors and dosimeters, which are used in many fields of science and technology, including in space studies. The parameters of the synchrotron radiation from the DÉLSI bending magnets are as follows:

Electron energy, GeV	1.8	1.2	1	0.8
Beam current, mA	300			
Horizontal/vertical emittance, nm	25/0.25	11.43/0.114	7.72/0.078	4.94/0.049
Ratio of the β functions at the emission point, m	1.618/8.288			
Critical photon energy, keV	6.46	1.16	0.80	0.51
Critical wavelength, nm	0.192	1.068	1.538	2.403
Total power, kW	139.4	16.69	9.66	4.94
Angular power density, W/mrad	22.18	2.66	1.54	0.79
Photon flux, photons/(sec·mrad·0.1% b.w.)	$8.65 \cdot 10^{12}$	$5.77 \cdot 10^{12}$	$4.81 \cdot 10^{12}$	$2.53 \cdot 10^{12}$
Maximum brightness, photons/(sec·mm^2·mrad^2·0.1% b.w.)	$3.3 \cdot 10^{14}$			

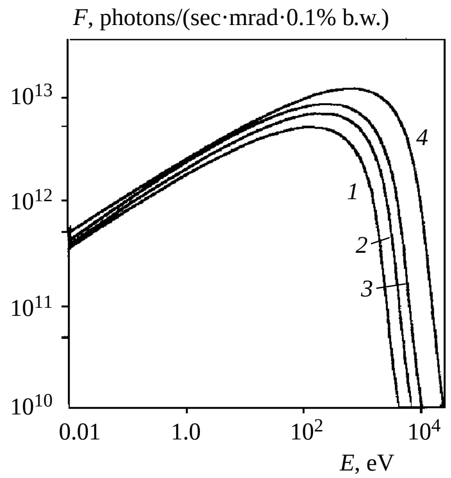

Fig. 1. Synchrotron photon flux from DÉLSI bending magnets: *1–4*) electron beam energy 0.8, 1, 1.2, and 1.8 GeV, respectively.

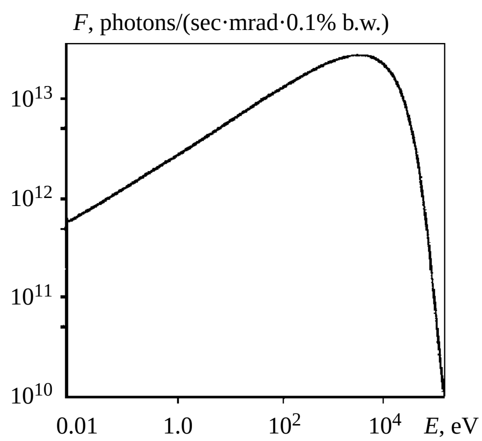

Fig. 2. Photon flux from the DÉLSI wiggler.

The radiation spectrum from the wiggler is similar to that of the bending magnet, but here the photon energy is much higher (proportional to the magnetic field). The use of a superconducting three-pole wiggler ("shifter") with a 10 T magnetic field will make it possible to generate high-energy x-rays (Fig. 2). The parameters of the synchrotron radiation from the DÉLSI wiggler are as follows:

Electron energy, GeV	1.2
Critical photon energy, keV	9.58
Critical wavelength, nm	0.13
Total power, kW	12.32
Power density, W/mm^2	639
Photon flux, photons/(sec·mrad·0.1% b.w.)	$1.73 \cdot 10^{13}$
Flux density, photons/(sec·$mrad^2$·0.1% b.w.)	$2.5 \cdot 10^{13}$
Maximum brightness, photons/(sec·mm^2·$mrad^2$·0.1% b.w.)	$5.3 \cdot 10^{14}$
Undularity parameter	280.3

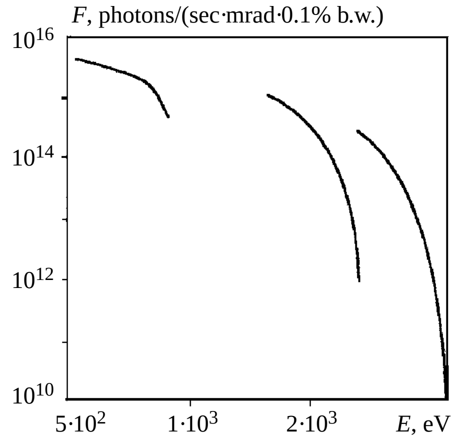

Fig. 3. Photon flux (first, third, and fifth harmonics) versus the photon energy (varied by changing the undulator gap from 4 to 10 mm).

Six channels will be built for operating with high-energy x-ray radiation from the DÉLSI wiggler. It will be used for time-resolved structural investigations of biological objects, x-ray microscopy, investigation of the luminescence of crystals and for solid-state lasers pumped by synchrotron radiation in the VUV range, research in time-resolved Mossbauer spectroscopy, EXAFS spectroscopy, and crystallography.

A special feature of undulator radiation is linear polarization at a fixed radiation frequency. The maximum radiation power is obtained at the first harmonic, and all even harmonics are suppressed. The synchrotron radiation flux can be varied by varying the gap in the undulator or the undularity parameter (Fig. 3). The perimeters of synchrotron radiation from the DÉLSI undulator are as follows:

Electron energy, GeV	1.2
Undulator gap, mm	5
Critical photon energy, keV	0.64
Critical wavelength, nm	0.19
Photon flux, photons/(sec·mrad·0.1% b.w.)	$3.2 \cdot 10^{15}$
Flux density, photons/(sec·mrad^2·0.1% b.w.)	$6.3 \cdot 10^{17}$
Maximum brightness, photons/(sec·mm^2·mrad^2·0.1% b.w.)	$1.97 \cdot 10^{19}$

At the first stage two channels will be built to work with radiation from the DÉLSI undulator. The radiation can be used for studies in metrology and photometry, crystallography, x-ray holography, and for pumping solid-state lasers in the VUV range.

Structure and Basic Parameters of the DÉLSI Storage Ring. The magnetic structure of DÉLSI was developed on the basis of the following general requirements:

– use of magnetic components of the AmPS storage ring;

– achieving minimum emittance with a dynamical aperture giving effective injection and long lifetime of stored electrons;

– maximum brightness with built-in systems.

A symmetric structure consisting of four quadrants was chosen for DÉLSI [2]. A variant where a quadrant consists of a periodicity component, a matching cell, a rectilinear gap for built-in systems, a matching cell, and periodicity element, was chosen as the basic variant. A quadrant is an achromatic lens. The phase increments of the betatron oscillations in the periodicity component are $\mu_x = 0.43 \cdot 2\pi$ and $\mu_y = 0.15 \cdot 2\pi$. The phase increments in the horizontal direction are determined by the condition for minimum emittance. The phase increment in the vertical direction must be comparatively small to ensure low chromaticity. Two families of sextapole lenses are used to correct the chromaticity.

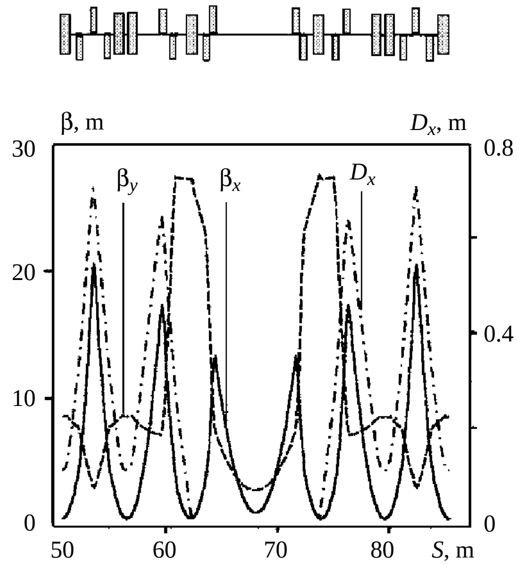

Fig. 4. Structure functions of a quadrant of the storage ring with a rectilinear gap for the wiggler.

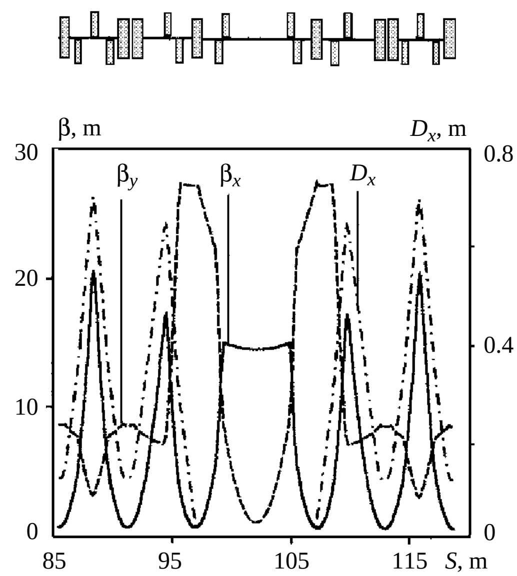

Fig. 5. Structure functions of a quadrant of the ring with a rectilinear gap for the undulator.

One of two "long" rectilinear gaps (7.2 m long) will be used for the wiggler and the injection kicker, and the other will be used for the hf resonators and a second kicker. The undulator will be placed in one of the "short" rectilinear gaps (5.52 m long) and a septum magnet will be placed in the other. The horizontal and vertical β functions at the center of the rectilinear gap for the wiggler were chosen to be small – β_x = 1.05 m and β_y = 2.8 m (Fig. 4) – in order to optimize the synchrotron radiation from the wiggler and minimize the perturbations introduced with the wiggler switched on.

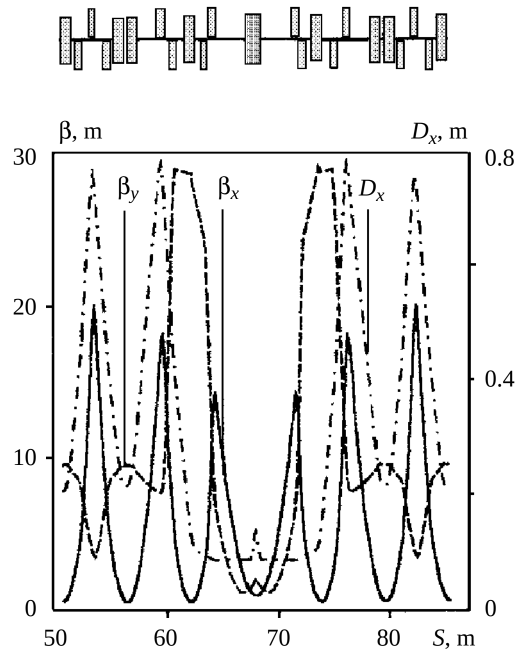

Fig. 6. Structure functions of a quadrant of the storage ring with the wiggler switched on.

To obtain a long beam lifetime the scattering by residue-gas atoms must be minimized. For this the vertical β function at the center of the rectilinear gap, containing the undulator, must be small. In the DÉLSI storage ring the β functions at the center of the rectilinear gap with the undulator are chosen to be $\beta_x = 14.55$ m and $\beta_y = 0.98$ m (Fig. 5).

The "short" rectilinear gap, which is identical to that of the undulator, contains the injection devices. Two kickers, placed in the opposite rectilinear gaps and separated according to the phase of the betatron oscillations by 9π, are used to bring a closed orbit with a circulating beam up to the septum.

Effect of Built-In Devices on the Linear Optics; Dynamical Aperture and Closed-Orbit Correction. The magnetic measurements of the field of a three-pole wiggler with a 10 T field in the central part, developed at the G. I. Budker Institute of Nuclear Physics at the Siberian Branch of the Russian Academy of Sciences, were used to calculate the effect of the wiggler on the optics of the storage ring. The "reconstruction" of the optics was performed in two steps in order to decrease the influence of the wiggler on the magnetic structure. First, the conditions $\alpha_x = \alpha_y = 0$ at the center of the wiggler were satisfied by varying the forces in the doublet of the gap with the wiggler. In the rest of the ring the β functions were kept the same as with the wiggler switched off, but the frequencies of the betatron oscillations Q_x and Q_y were varied by varying the β functions in the gap with the wiggler. Next, the frequencies of the betatron oscillations were corrected and the separation of the β functions over the entire accelerator was minimized at the same time. The forces of all quadrupole families were varied at the same time. As a result, the change in the β functions for the structure with the wiggler switched on was 7%, and the emittance of the electron beam increased from 11.4 to 21.3 nm. The final form of the structure functions of the quadrant with the wiggler switched on is presented in Fig. 6. The same procedure was used to calculate the effect of the undulator on the accumulator optics (0.75 T, 150 periods, period length 2.25 cm). Its effect was much weaker: the separation of the β functions is less than 1% and the beam emittance decreased to 11.14 nm.

Effective injection at 0.8 GeV requires a dynamical aperture in the horizontal direction greater than $31\sigma_x$, since the AmPS septum knife thickness is to be 3 mm. At 1.2 GeV the dynamical aperture must be greater than $21\sigma_x$ for particles with zero momentum deviation. MAD calculations [3] have shown that for structures with the wiggler and undulator switched off, neglecting errors, and with zero momentum deviation the dynamical apertures are $99\sigma_x$ and $87\sigma_y$ at 1.2 GeV (Fig. 7). For particles with momentum deviation $\Delta p = +1\%$ the computed dynamical aperture decreases to $71\sigma_x$ and $81\sigma_y$; for particles

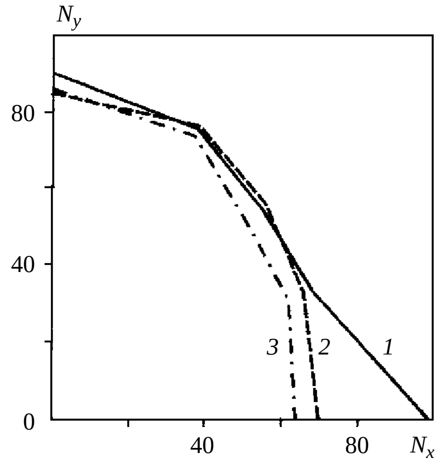

Fig. 7. Dynamical aperture (expressed in standard deviations) neglecting the errors for a structure without builtin devices (*1*), for a structure with the undulator switched on (*2*) and the wiggler switched on (*3*), respectively.

with momentum deviation Δp – 1% the aperture decreases to $70\sigma_x$ and $79\sigma_y$, respectively. When the wiggler is switched on the dynamical aperture decreases to $64\sigma_x$ and $86\sigma_y$, and with the undulator switched on it decreases to $70\sigma_x$ and $78\sigma_y$. In both cases the dynamical aperture is sufficient for a satisfactory lifetime. A possible way to increase the dynamical aperture is to install additional families of sextupoles in the gaps with zero dispersion.

The main sources of the closed-orbit error for a horizontal plane of the DÉLSI storage ring are the errors of the field in dipole magnets (instability of the power supplies) and displacement of the quadrupole lenses in the horizontal direction, and for the vertical plane the sources are the shift of the quadrupole lenses in the vertical direction and rotation of the dipole magnets around the longitudinal axis. The errors in the components of the structure were set randomly, the rms deviations being as follows: the shift of the quadrupole lenses 200 μm, rotation of the dipole magnets around the longitudinal axis 1 mrad, and magnetic field tolerance in the dipole magnets $5 \cdot 10^{-4}$.

Two schemes were proposed to correct the closed orbit. The first scheme used 40 correcting magnets for the horizontal plane (three for matching cells and two for periodic cells) and 32 correcting magnets for the vertical plane (two each in the matching and periodic cells). The second correction scheme employed 24 correcting magnets for the horizontal plane (two for the matching cells and one for the periodic cells) and 32 correcting magnets for the vertical plane (two each in the matching and periodic cells). In both correction schemes there are 48 beam-position sensors (three each in the matching and periodic cells).

The orbit was calculated with the correction system switched on and off with electron beam energy 1.2 GeV. Fifty error-accumulation variants were calculated. The maximum deviation of the orbit with the correction system switched off was 15 mm in one variant for the horizontal plane and 26 mm for the vertical plane. In one of the 50 variants the synchrotron was unstable because of sum resonance coupling.

With the correction system switched on the maximum deviation of the orbit was 1.8 mm for the horizontal plane in the first correction scheme (40 correcting magnets) and 3 mm in the second scheme (24 correcting magnets); for the vertical plane the deviation was 0.99 mm. The maximum force of the correctors was 0.84 mrad in the first correction scheme and 0.74 mrad in the second scheme; this corresponds to the force of the correcting magnets. The change in the beam emittance is negligible.

The dynamical aperture with the correction system switched on was calculated for two sets of errors. The maximum orbit deviation for all 50 variants arises in the first set, and the typical deviation (average over all variants) arises in the second set. The dynamical apertures for these two sets were $67\sigma_x$, $91\sigma_y$ and $70\sigma_x$, $88\sigma_y$, respectively, in the first correction scheme (40 correctors for the horizontal plane and 32 for the vertical plane) and $58\sigma_x$, $100\sigma_y$ and $64\sigma_x$, $95\sigma_y$ in the second

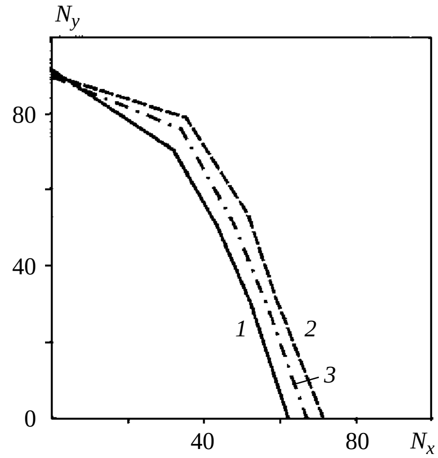

Fig. 8. Dynamical aperture taking account of the errors, expressed in standard deviations (40 correctors for the horizontal plane, 32 for the vertical plane), for a structure with maximum orbit deviation and the wiggler switched on (*1*), with average (*2*) and maximum (*3*) orbit deviation, respectively.

correction scheme (24 correctors for the horizontal plane and 32 for the vertical plane). Thus, the minimum dynamical aperture at the location of the septum magnet is 24 mm, which is sufficient for organizing effective injection. With the wiggler switched on the dynamical aperture was $62\sigma_x$ and $87\sigma_y$ for a structure with a set of errors giving the maximum orbit deviation over all 50 variants (Fig. 8).

Prospects for Elaboration of the DÉSLI Complex. The magnet structure chosen has the advantage that the storage ring can be further modified in order to increase the energy and the hardness of the synchrotron radiation. For this, it is proposed that in each variant eight regular bending magnets be replaced by special magnets which are constructed using a technology developed at the G. I. Budker Institute of Nuclear Physics of the Siberian Branch of the Russian Academy of Sciences. These magnets possess field concentrators based on permanent magnets, making it possible to increase the magnetic field in the gap up to 3–4 T without using superconductivity. Using these magnets will make it possible to increase the accelerator energy to 1.8 GeV and will shift the maximum of the synchrotron radiation spectrum from the bending magnets to proton energies ~6 keV.

Another possibility for elaboration of the system is to develop a family of free-electron lasers. The DÉLSI linear accelerator can accelerate electrons up to 800 MeV with average beam power of tens of kilowatts; this makes it possible to develop a unique system of free-electron lasers, covering the wavelength range from the far infrared up to low-energy x-ray. Free-electron lasers placed directly into the accelerator tunnel will generate 0.2–100 μm radiation. Three FEL generators, whose peak output radiation power will be several megawatts with an average power of several watts [4], will cover the indicated range. The technical characteristics of the equipment are close to those of a FEL complex constructed at the FELI Research Center (Osaka, Japan) [15]. It is important to note that using the existing enclosures of the linear accelerator building will make it possible to bring the radiation users online in the laboratory very quickly.

It will be possible to generate short-wave length coherent radiation with a single pass of the electron beam of the DÉLSI linear accelerator through a long undulator. The absence of mirrors will make it possible to obtain radiation with any wavelength up to x-ray [6]. This scheme is called SASE FEL (Self Amplified Spontaneous Emission Free Electron Laser). A system with close parameters is now being constructed at DESY (Hamburg, Germany) [7, 8]. Estimates show that for a 1 GeV electron beam the minimum wavelength in the DÉLSI system will be about 5 nm. Adjusting the energy of the linear accelerator will make it possible to cover smoothly the wavelength range from 5 to 200 nm. Peak radiation power is 2–3 GW with an average power of several watts. Compared with the third-generation synchrotron radiation source, the peak radiation power is 10^7 times higher. In the future the energy of the DÉLSI linear accelerator can be increased to 2 GeV by appropriately modifying the microwave power supply system. As a result, the minimum wavelength can be reduced to 1 nm [4].

Estimates show that the DÉLSI equipment can be modified to expand its possibilities as a fourth-generation source of synchrotron radiation for wavelengths ranging from far infrared to 1–5 nm. The modification will largely be due to installation of undulators and high-current injectors of the linear accelerator. For the system of FEL generators the requirements for the beam parameters are comparatively easy: the peak current in a bunch will be several tens of amperes with normalized emittance 20–30 mm·rad. Such an injector can be built either using the technology for subharmonic microwave bunchers or using a microwave beam with a photocathode. A high peak current is required to generate short wavelengths in a single-pass FEL amplifier; this is achieved by additionally installing dispersion sections (bunch compressors) in the accelerator channel.

It should be noted that the examples mentioned above, showing an increase in the peak current, have been successfully implemented in practice.

Conclusions. It is now possible to produce at the Joint Institute of Nuclear Research a third-generation source of synchrotron radiation DÉLSI, based on components of the NIKHEF accelerator system, as a high-brightness source of synchrotron radiation in a wide spectral range – from far-infrared (100 μm) up to high-energy x-ray (50 keV). This will greatly expand the program of scientific research performed at the institute.

The magnetic structure developed for the DÉLSI storage ring based on AmPS components will make it possible to install a 10 T wiggler and an undulator. The dynamical aperture sufficient for effective injection and for attaining the required lifetime. Existing dipole correctors can be used for the system for correcting a closed orbit.

Building free-electron lasers will make it possible to produce a universal laser center with no analogs in the world with respect to the range of smooth tuning of the radiation wavelength, from far-infrared up to low-energy x-ray. The use of FEL radiation synchronized with synchrotron radiation pulses from the DÉLSI storage ring will greatly expand synchrotron-radiation research.

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