PROJECT OF THE DUBNA ELECTRON SYNCHROTRON

E.I.Antokhin[2], N.I.Balalykin[1], P.F.Beloshitsky[1], V.G.Kadyshevsky[1], V.N.Kolobanov[3],
G.I.Kulipanov[2], E.B.Levichev[2], I.N.Meshkov[1], N.A.Mezentsev[2], V.V.Mikhaylin[3],
N.A.Morozov[1], A.N.Sissakian[1], G.I.Sidorov[1], A.N.Skrinsky[2], E.M.Syresin[1], I.V.Titkova[1],
M.V.Yurkov[1]

[1]*JINR, Dubna, Moscow region, Russia*
[2]*Budker INP, Novosibirsk, 630090, Rouusia*
[3]*MSU, Moscow, Russia*

1. Abstract

The DELSY (Dubna Electron Synchrotron) project [1] is intended to create a synchrotron radiation (SR) source at the Joint Institute for Nuclear Research. It allows one to extend ongoing investigations on condensed matter physics and atomic physics, biology and medicine, chemistry, geology and ecology problems (monitoring of the environment), and to develop new technologies based on SR applications those like micromechanics and lithography, technology of materials, metallurgy and others.

The decision to construct a new DELSY storage ring in Dubna was based on the following considerations:

- DELSY with its unique undulator and superconducting 10T wiggler will be the first 3rd generation synchrotron radiation source in Russia operational both in the VUV, soft X-ray and X-ray regions meeting the demands of various applications in increased brilliance.
- Infrastructure and expertise required to design, construct and run a new synchrotron radiation source are readily available in Dubna;
- In Dubna an operating high flux pulsed reactor IBR-2 is situated. Conveniently located synchrotron and neutron facilities exist already at several advanced research centres in the world. The complimentary use of synchrotron and neutron radiation opens up new horizons in many fields of condensed matter physics, biology, crystallography, chemistry, etc.
- Construction of a free electron laser which is a separate part of scientific program will make the DELSY accelerator complex the 4th generation synchrotron radiation source providing a new superior experimental level.

DELSY is being constructed on the base of the accelerator facility, which is dismounted and transferred to Dubna from the Netherlands National Institute for Nuclear Physics and High Energy Physics (NIKHEF) in compliance with the agreement between NIKHEF and JINR. The NIKHEF accelerator facility consists of a linear electron accelerator MEA [2] with energy of electrons of 700 MeV and the electron storage ring AmPS with the maximum energy of 900 MeV and beam current of 200 mA [3].

For DELSY the layout [4] with four straight sections was chosen. Every quadrant consists of MBA-structure, which provides emittance of 11 nm and two halves of straight sections. The circumference of the ring is 136 m. For the preliminary chosen working point $Q_x / Q_y = 9.44/3.42$ the dynamic aperture in the presence of the very strong wiggler (10 T) and undulator (0.75 T, 150 periods) is large enough for efficient injection, which is made at 0.8 GeV.

2. Introduction

The SR sources have made encouraging progress in the last five years when the sources of the so-called third generation were constructed and brought into operation. The first SR source of that class – the European Synchrotron Radiation Facility (ESRF, Grenoble, France) – increased its brilliance from 10^{18} up to 10^{20} photon/(s·mrad^2·mm^2·0.1% of the bandwidth). The large storage rings APS (USA) and SPRING-8 (Japan) have been brought into operation recently. Such a higher brilliance of SR was achieved owing to the application of undulators inserted into the ring structure. The SR brilliance from the dipole magnets varies from

$2 \cdot 10^{12}$ to $5 \cdot 10^{15}$ photon/(s·mm^2·mrad^2·0.1% of the bandwidth) when the electron energy lies in the range of 0.5 – 3 GeV. The wiggler SR brilliance varies from $3 \cdot 10^{12}$ to $1.5 \cdot 10^{16}$ photon/(s·mm^2·mrad^2·0.1% of the bandwidth) at the same energy range. The modern SR sources are closed to a so-called diffraction limit when the decrease of the source size does not increase its brilliance.

The DELSY facility is designed as the SR source at the electron energy of 1.2 GeV. It consists of an electron linac, transfer line, storage ring and 16 beamlines.

The electron beam from the linac is injected into the DELSY storage ring at the electron energy of 800 MeV and the beam current of 5-10 mA. The repetition frequency of the injection pulses is limited by the radiation damping of electron betatron oscillations in the ring and is of the order of 10 Hz. It is planned to obtain the stored beam of the circulating electrons with the current of 300 mA. The stored electrons are accelerated in the synchrotron mode from 0.8 GeV to 1.2 GeV. The life - time of the circulating electron beam at the energy of 1.2 GeV is from 5 to 10 hours depending on the beam parameters. The DELSY ring is used as the SR source in such a regime of operation. The cycle of the electron injection – acceleration repeats after a few hours of work to hold the circulating beam.

The magnet system of the DELSY ring (Table 1) is significantly changed in comparison with the AmPS ring. The mini-undulator installed in the DELSY ring will generate SR in the energy range from 150 eV to 3 keV at the brilliance of $2 \cdot 10^{19}$ photon/(s·mm^2·mrad^2·0.1% of the band-width). The superconducting wiggler with the magnetic field of 10T will provide hard X-ray radiation (the quanta energy of 20-50 keV).

Table 1. The main parameters of the DELSY storage ring without influence of the insertion devices.

Circumference, m	136.04
Bending radius, m	3.3
Betatrone tunes (h/v)	9.44/3.42
Orbit compaction factor	$5.03 \cdot 10^{-3}$
Chromaticity (h/v)	-22.2/-12.6
Storage electron current, mA	300
Horizontal emittance, nm	11.4
RF frequency, MHz	476
Bunch length, mm	8.67
Harmonics number	216
Electron energy loss per turn, keV	55.7

3. Synchrotron radiation from the bending magnets and insertion devices of the DELSY storage ring.

Synchrotron radiation from the dipole magnets of DELSY (Table 2, Fig.1) has rather high intensity in both ultraviolet and infrared regions. Numerous applications of this radiation can be used in photoelectron microscopy, time-resolved fluorescent studies of biological objects, in absorption spectroscopy, IR-spectroscopy, Soft X-ray reflection spectroscopy and scattering, photoelectron spectroscopy including angular resolved, in study of scintillators for nuclear physics and medical applications, in time-resolved VUV luminescence spectroscopy, metrology and photometry. Eight beam-lines will be constructed for the synchrotron radiation from the bending magnets.

Table 2. Parameters of synchrotron radiation from the DELSY bending magnets.

Electron energy, GeV	1.8	1.2	1	0.8
Current, mA	300			
Emittance (h/v), nm	25/0.250	11.43/0.114	7.72/0.078	4.94/0.049
Beta-functions in the point of radiation, m	1.618/8.288			
Photon critical energy, keV	6.46	1.16	0.80	0.51
Critical wave length, Å	1.92	10.68	15.38	24.03
Total power, kW	139.4	16.69	9.66	4.94
Linear power density, W/mrad	22.18	2.66	1.54	0.79
Photon flux, photon/(c·mrad·0.1% bw)	$8.65\cdot10^{12}$	$5.77\cdot10^{12}$	$4.81\cdot10^{12}$	$2.53\cdot10^{12}$
SR brilliance, photon/(s·mm^2·mrad^2·0.1% b.w.)	$3.9\cdot10^{14}$			

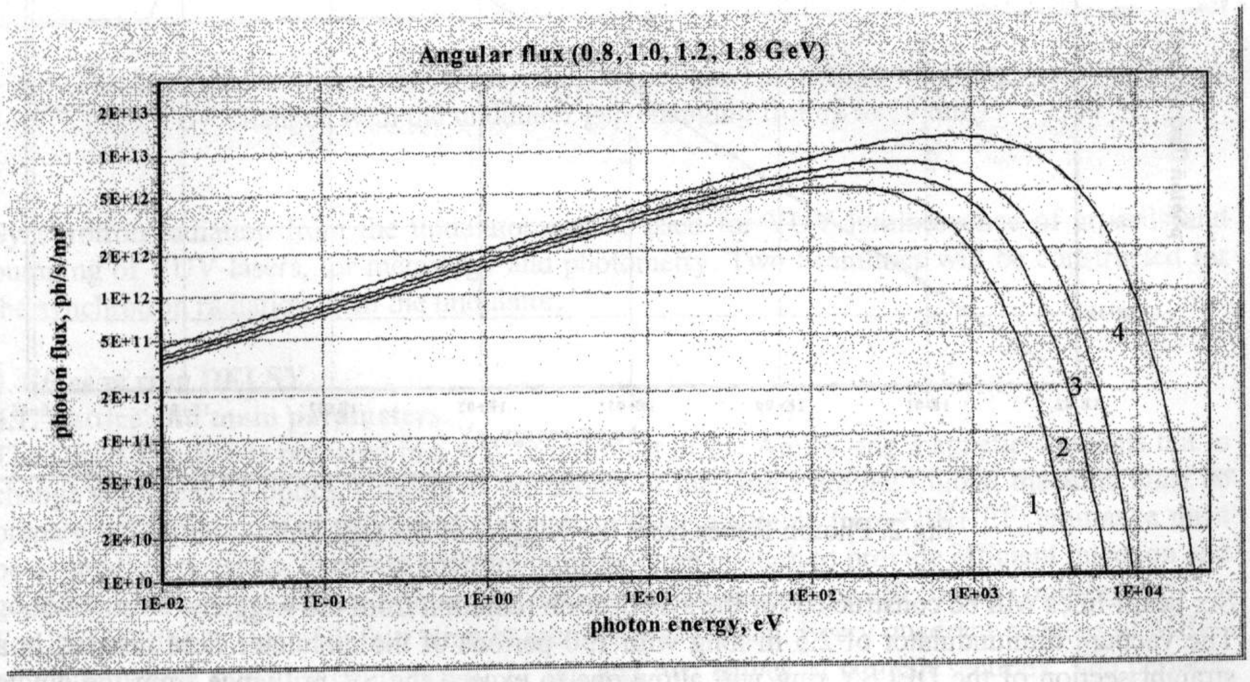

Fig.1. Photon flux from the DELSY bending magnets: 1 – electron energy 0.8 GeV, 2 – energy 1 GeV, 3 – energy 1.2 GeV, 4 – energy 1.8 GeV.

The application of the superconducting wiggler (the wavelength shifter) with the magnetic field of 10 T provides generation of the hard X-ray radiation of the photon energy of 20-50 keV. Hard X-ray radiation from the wiggler at the photon energy of 0.5-50 keV can be used for researching in VUV luminescence of crystals and pumping of VUV-lasers, time-resolved Moessbauer spectroscopy, EXAFS spectroscopy with soft and hard X-rays, DANES (Diffraction Anomalous Near Edge Structure), DAFS (Diffraction Anomalous Fine Structure), for macromolecular crystallography, time-resolved structural studies of biological objects, for X-ray microscopy based on multilayer optics (Table 3, Fig.2).

Table 3. Parameters of the synchrotron radiation from the wiggler (electron energy 1.2 GeV).

Photon critical energy, keV	9.58
Critical wave length, Å	1.30
Total power, kW	12.32
Power density, W/мм^2	639
Photon flux, photon/(c·mrad·0.1% bw)	$1.73\cdot10^{13}$
Photon flux density, photon/(c·mrad^2·0.1% bw)	$2.5\cdot10^{13}$
Brilliance, photon/(s·mm^2 .mrad^2·0.1% b.w.)	$1.6\cdot10^{15}$
K-parameter	280.3

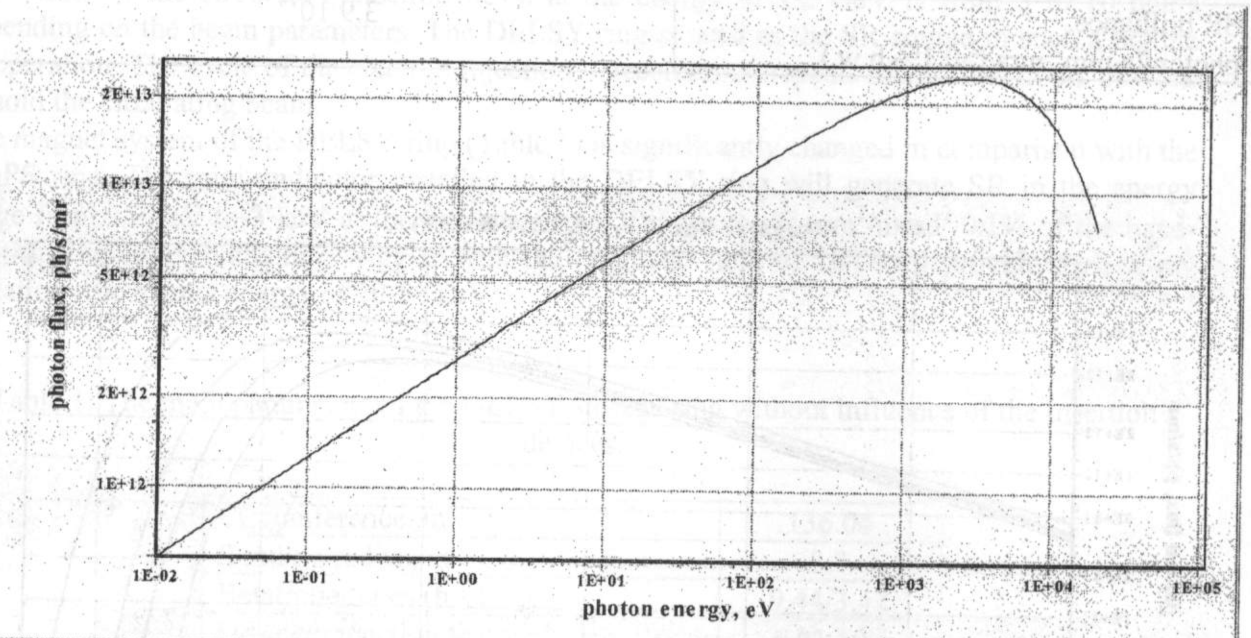

Fig.2. Photon fluxes from the wiggler of the DELSY.

Six beam-lines will be constructed for the synchrotron radiation from the wiggler.
The vacuum miniundulator of 2.5 m long with 150 periods of the undulator field inserted in a straight section of the DELSY ring will allow one to exceed the SR brilliance from the dipole magnets by 5 orders of magnitude. The application of miniundulators becomes more and more common nowadays. Such undulators installed, particularly, at ESRF and SPRING-8. They permit to reach the higher brilliance at a rather short straight section. The photon flux from the undulator can be changed by changing the K-parameter or the undulator gap (Table 4, Fig.3).

Table 4. Parameters of the synchrotron radiation from the undulator (electron energy 1.2 GeV).

Photon critical energy, keV	0.38
Critical wave length, Å	32.8
Photon flux, photon/(c·0.1% bw)	$5.2\cdot10^{15}$
Photon flux density, photon/(c·mm^2·0.1% bw)	$9.2\cdot10^{17}$
Brilliance, photon/(c·mm^2·mrad^2·0.1% bw)	$2.1\cdot10^{19}$

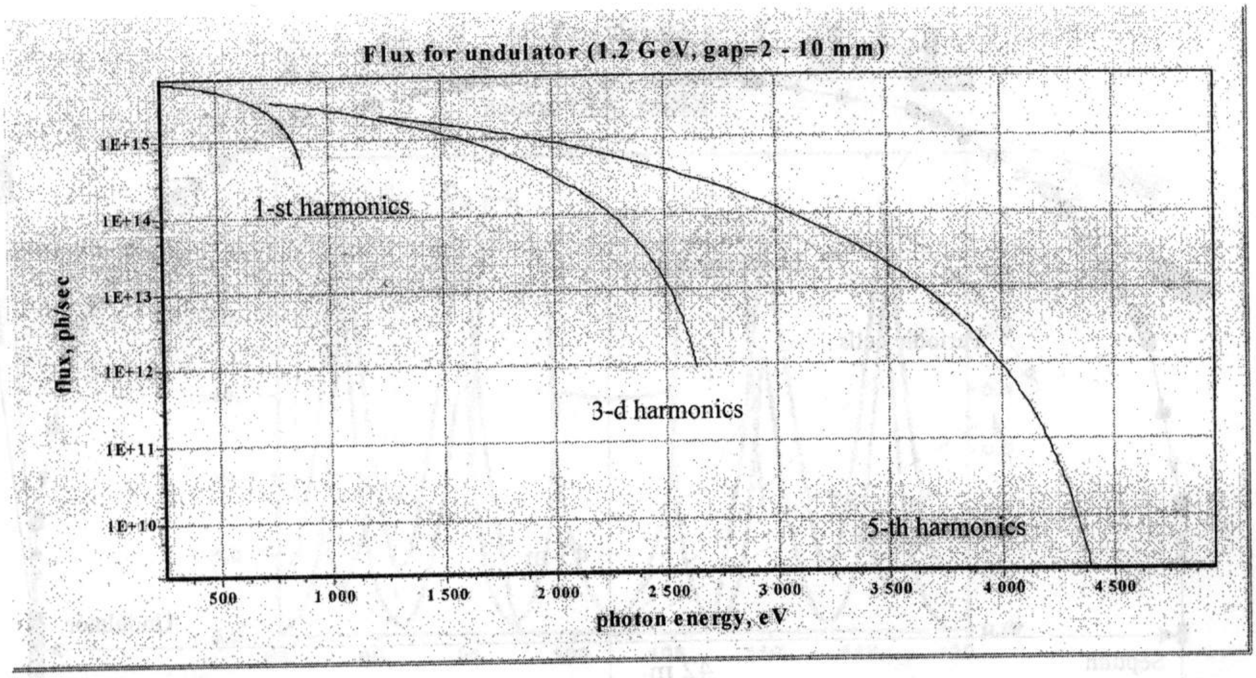

Fig.3. The dependence of the photon flux (1,3,5 harmonics) on the photon energy (photon flux is changed with the undulator gap changing from 2 to 10 mm)

Synchrotron radiation from the undulator can be used for VUV luminescence of crystals and pumping of VUV-lasers, for metrology and photometry. Two beamlines will be constructed for the synchrotron radiation from the undulator.

4. Storage ring DELSY.

4.1. Lattice and main parameters.

The DELSY lattice is prepared in a way to use most of the AmPS ring magnetic elements but to change significantly optics. Criteria of the choice of the lattice are the follow: machine must be prepare with minimum of additional elements to those available from NIKHEF, emittance must be as small as possible, dynamic aperture must be large enough to provide efficient injection and good lifetime, adverse effects of insertion devices on lattice must be effectively compensated.

For DELSY the layout with four straight sections was chosen. Every quadrant consists of MBA-structure, which provides emittance of 11 nm and two halves of straight sections. The periodic cell (Fig.5) consists of two dipoles and three quadrupoles. The phase advance in the periodic cell is equal to $\mu_x = 0.43 \cdot 2\pi$, $\mu_y = 0.15 \cdot 2\pi$. The horizontal phase advance is determined by the condition of the horizontal emittance minimisation, yet maintaining reasonable natural chromaticity.

The matching cell contains two dipoles and provides zero dispersion in the straight section. The particular values of the beta functions in straight sections are adjusted by use of doublet.

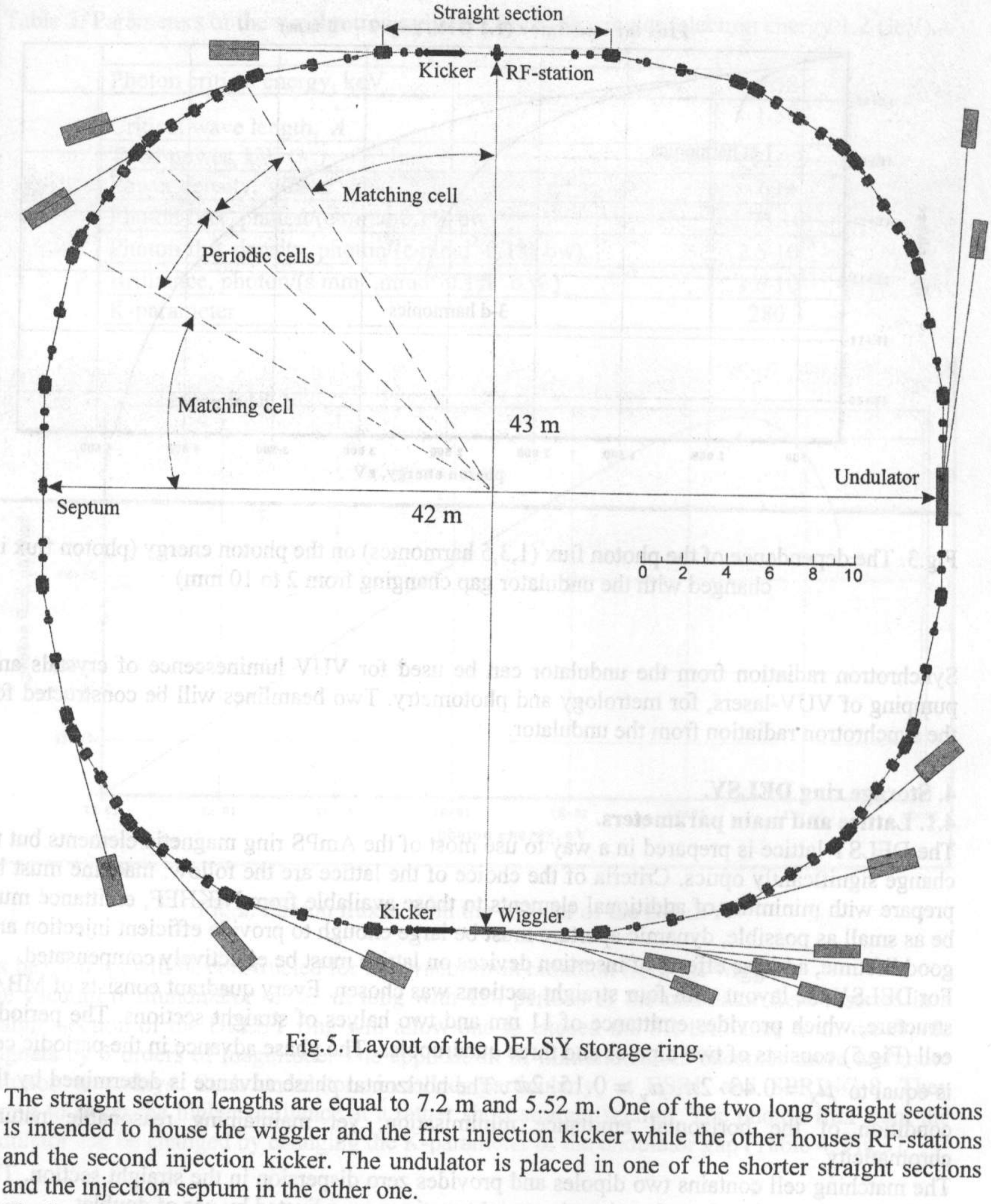

Fig.5. Layout of the DELSY storage ring.

The straight section lengths are equal to 7.2 m and 5.52 m. One of the two long straight sections is intended to house the wiggler and the first injection kicker while the other houses RF-stations and the second injection kicker. The undulator is placed in one of the shorter straight sections and the injection septum in the other one.

The beta functions in a very strong wiggler must be small enough to avoid emittance increase and to minimise optics distortion with wiggler on. In our case β_x=1.05 м и β_y=2.80 м (Fig.6).

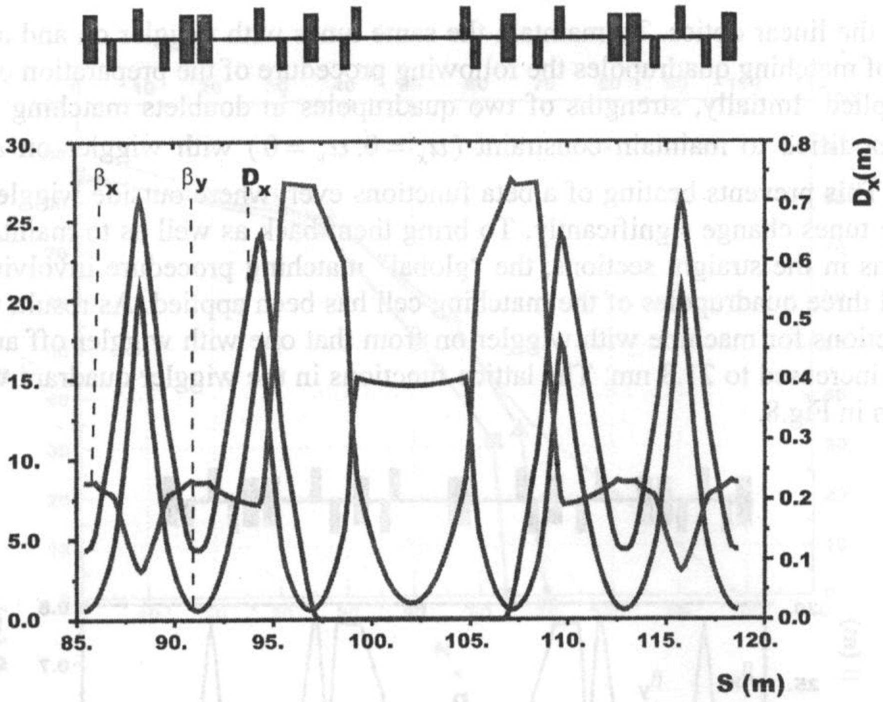

Fig.6. Lattice functions in the matching cell and the straight section for undulator.

The vertical beta function in the centre of the undulator must be small still keeping tolerable lifetime limited by the residual gas scattering. It was accepted β_x=14.55 m и β_y=0.98 m. Lattice functions for the undulator quadrant are showed in Fig.7

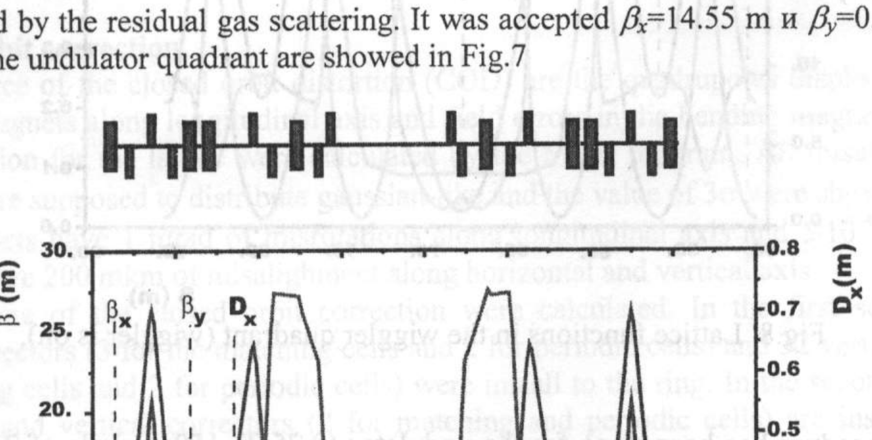

Fig.7. Lattice functions in the matching cell and the straight section for wiggler.

In another undulator quadrant injection septum is placed. The phase advance between two kickers is 9π.

4.2. The influence of the insertion devices to the linear optics.

For the linear optics and dynamic aperture calculations with wiggler on the measured multipole components of the 10 T wiggler have been used [5]. The very strong wiggler produces great distortion of the linear optics. To maintain the same tunes with wiggler on and avoid increasing the number of matching quadrupoles the following procedure of the preparation of a linear optics has been applied. Initially, strengths of two quadrupoles in doublets matching wiggler section have been modified to maintain constraint ($\alpha_x = 0, \alpha_y = 0$) with wiggler on as well as with wiggler off. This prevents beating of a beta functions everywhere outside wiggler section. After this machine tunes change significantly. To bring them back as well as to maintain the required beta functions in the straight sections, the "global" matching procedure involving all matching doublets and three quadrupoles of the matching cell has been applied. As result, the deviation of the beta functions for machine with wiggler on from that one with wiggler off are less than 7%, emittance is increased to 21.3 nm. The lattice functions in the wiggler quadrant with the wiggler on are shown in Fig.8.

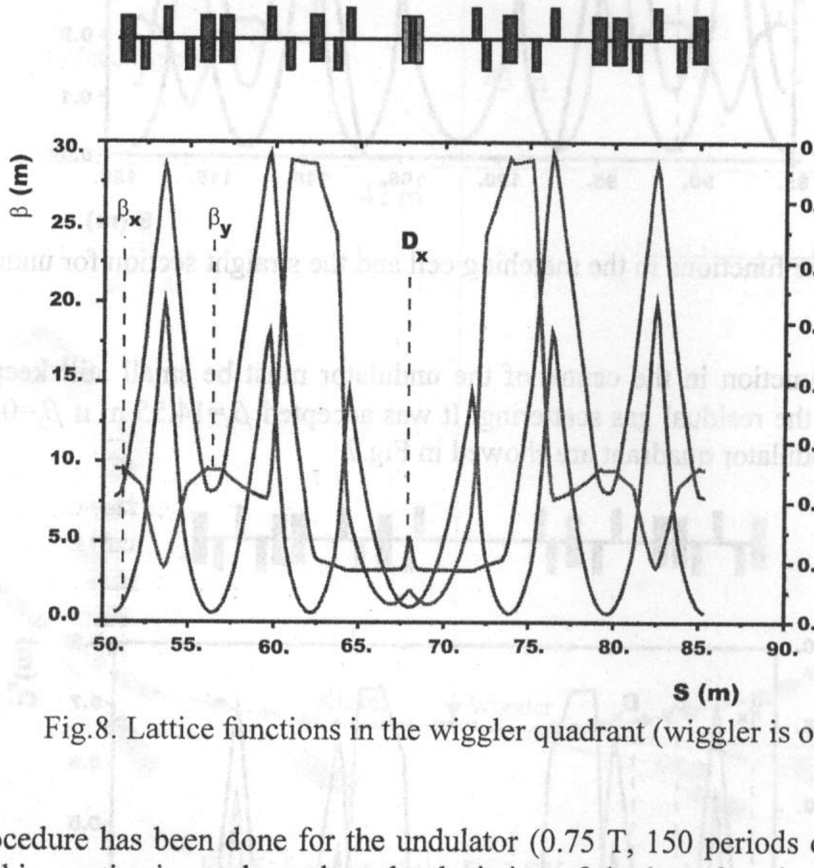

Fig.8. Lattice functions in the wiggler quadrant (wiggler is on).

The same procedure has been done for the undulator (0.75 T, 150 periods of 2.25 cm), but its effect on machine optics is much weaker: the deviation of the beta functions for machine with undulator on are less than 1%, emittance is decreased to 11.14 nm.

4.3. Dynamic aperture.

The injection energy for DELSY is 0.8 GeV, while operation is at 1.2 GeV. This put strong requirements to the dynamic aperture. The required dynamic aperture in the horizontal plane, expressed in the number N of standard deviation σ with the emittance of the injected beam 18.3 nm and the emittance of the circulated beam 4.9 nm at 0.8 GeV must fulfil $31\sigma_x$. For the energy 1.2 GeV without errors and with zero momentum deviation the dynamic aperture must fulfil $21\sigma_x$. Dynamic aperture is calculated with MAD computer code [6] (Lie3 method, 400 stable particle revolutions) and equal to $99\sigma_x$ and $87\sigma_y$ respectively (without influence of the insertion devices) (Fig.9). For the particles with momentum deviation $\Delta p=+1\%$ the dynamic aperture is decreased to $71\sigma_x$ and $81\sigma_y$, for the particles with $\Delta p=-1\%$ $70\sigma_x$ and $79\sigma_y$ respectively.
When the wiggler is on, the dynamic aperture is decrease to $64\sigma_x$ and $86\sigma_y$, with undulator on – to $70\sigma_x$ and $78\sigma_y$ (Fig.9). In both cases this dynamic aperture is enough to good lifetime. One of the ways to improve dynamic aperture is use of additional sextupole families.

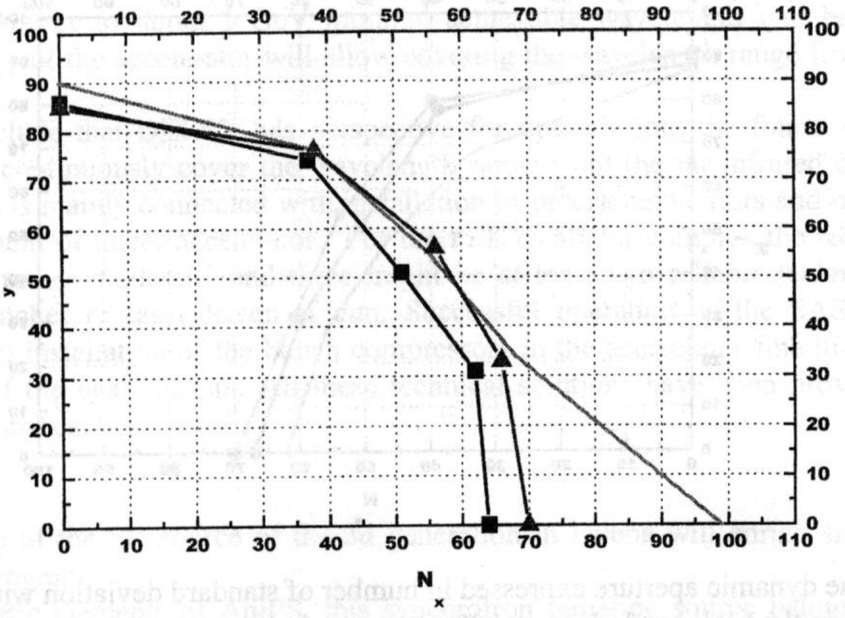

Fig.9. The dynamic aperture expressed in number of standard deviation (without errors): solid line – for the structure without insertion devices, square – wiggler is on, triangle – undulator is on.

4.4. Closed orbit correction.

The main source of the closed orbit distortion (COD) are the quadrupoles displacement, tilt of the bending magnets along longitudinal axis and field errors in the bending magnets. The COD and its correction for the lattice were calculated by the MAD program. All misalighments and field errors were supposed to distribute gaussian-like and the value of 3σ were shown as below. Bending magnets have 1 mrad of misrotations along longitudinal axis and $5\cdot10^{-4}$ error fields, quadrupoles have 200 mkm of misalighment along horizontal and vertical axis.

The two scheme of the closed orbit correction were calculated. In the first scheme the 40 horizontal correctors (3 for the matching cells and 2 for periodic cells) and 32 vertical correctors (2 for matching cells and 2 for periodic cells) were install to the ring. In the second scheme the 32 horizontal and vertical correctors (2 for matching and periodic cells) are install. For both schemes the 48 vertical and horizontal monitors are used (3 for matching and periodic cells).

The 50 variants of the errors are calculated. Maximum horizontal and vertical CODs were 15 mm and 26 mm for the horizontal and vertical plane respectively. In one variant from 50 the synchrotron is unstable because of sum resonance of couple.

After the correction for the structure without insertion devices the maximum horizontal COD was 1.8 mm for the first scheme of correction and 3 mm for the second scheme of correction, the vertical COD was 0.99 for both schemes. It was found that maximum 0.84 mrad of horizontal corrector force in the first scheme of the correction and 0.74 mrad for the second scheme were required. Calculations show not significant reduction in the emittance.

The dynamic aperture was calculated for the two variants of the errors: one for the variant with maximum COD, another – for the variant with typical COD. For the first scheme of the correction (40 correctors for the horizontal plane and 32 for the vertical plane) the dynamic aperture was $67\sigma_x$, $91\sigma_y$ for the variant with maximum COD and $70\sigma_x$, $88\sigma_y$ for the variant with the typical COD. For the second scheme of the correction (32 correctors for the horizontal and vertical planes) the dynamic aperture was $58\sigma_x$, $100\sigma_y$ and $64\sigma_x$, $95\sigma_y$ respectively. Thus the dynamic aperture in the septum is 24 mm that enough for the effective injection.

When the wiggler is on the dynamic aperture is $62\sigma_x$, $87\sigma_y$ for the variant of errors with maximum COD (Fig.10).

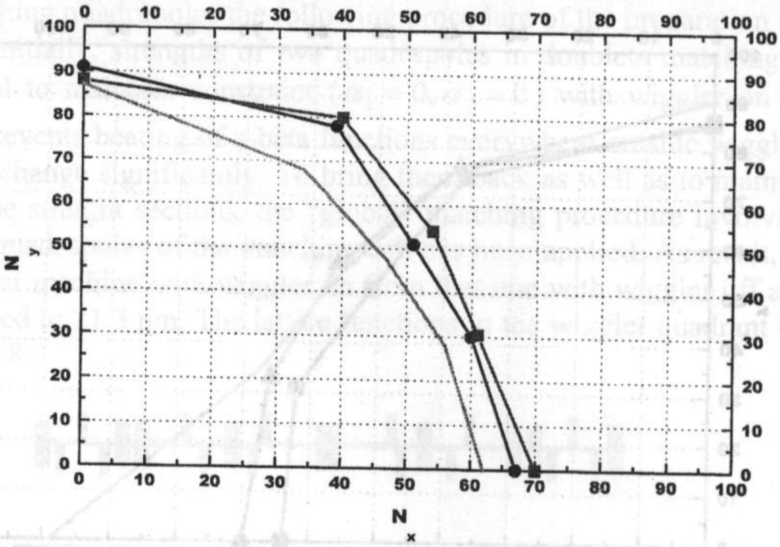

Fig.10. The dynamic aperture expressed in number of standard deviation with the errors (40 correctors in the horizontal plane and 32 correctors inthe vertical plane): solid line – for the structure with maximum COD and wiggler is on, square – structure with the typical COD, circle – structure with the maximum COD.

5.Future development of DELSY.

5.1. Increase of the magnetic rigidity.

The first way of the DELSY development is the increasing of the magnetic rigidity. For this purpose the bending magnets of the storage ring will be substitute for the special magnets that worked out in Budker INP (Novosibirsk). Those magnets have got a concentrator of the magnetic field, as a result the magnetic field in the gap will be increased to 3-4 T. The electron energy will be increased to 1.8 GeV, the photon critical energy will be 6 keV (Table 2, Fig.1). The other possibility of the DELSY future development is a free electron laser creation.

5.2.Perspectives of the DELSY as a fourth generation facility.

Linear rf accelerator of DELSY has potential to reach the energy up to 1 GeV and average power of few tens of kilowatts. It seems be very attractive to use this accelerator for driving the complex of free electron lasers (Fig.11) [7]. FEL oscillators can cover the wavelength range from the far infrared down to ultraviolet, 0.2 - 100 mkm. The setup is similar to that operating at FELI Research Institute in Osaka [8].

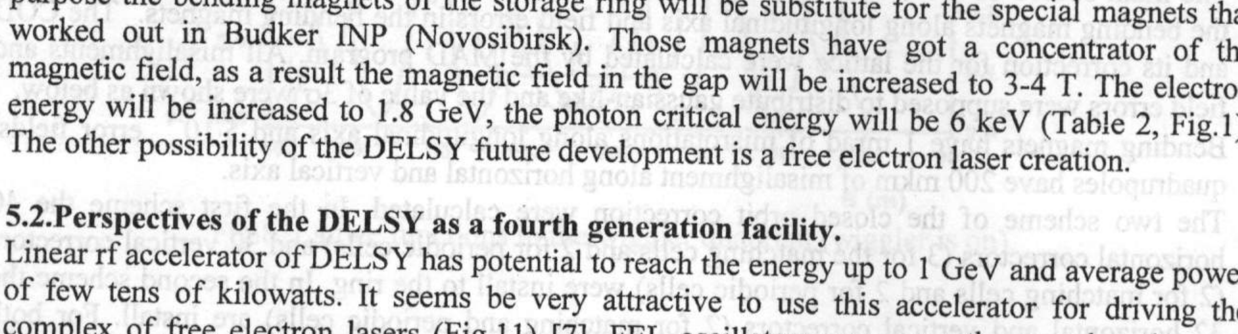

Fig.11. FEL on the DELSY facility.

Also, it is possible to produce shorter-wavelength radiation with single-pass SASE (self amplified spontaneous emission) scheme, similar to the Tesla Test Facility (TTF) FEL at DESY [9, 10]. At the energy of about 1 GeV minimal achievable wavelength will be about 5 nm. Tuning the energy of the accelerator will allow covering the wavelength range from 5 up to 200 nm.

So, we can conclude that DELSY has perspective for upgrade into the fourth generation SR facility that can continuously cover the wavelength range from the far infrared down to 5 nm. Such an upgrade is mainly connected with installation of precise undulators and modification of the injection system of linear accelerator. For the FEL oscillator complex the requirements for the injector are rather moderate, and there might be at least two reliable technical solutions, subharmonic buncher or laser-driven rf gun. Successful operation of the SASE option will require additional installation of the bunch compressors in the accelerator line in order to reach required value of the peak current. All these technical solutions have been proven recently in different accelerator centres.

6. Conclusions.

The construction of the SR source of the 3d generation in Dubna will enrich significantly the JINR research program.

Based on magnetic elements of AmPS, this synchrotron radiation source belongs to the third generation. Machine optics is designed in a way to install at least one very strong wiggler with magnetic filed about 10 T and one undulator. The scheme of the closed orbit correction is allowed to use the correctors from AmPS.

DELSY complex has unique capability to be upgraded in perspective synchrotron radiation source of fourth generation.

References

[1] I.V.Titkova, V.A.Arkhipov, V.K.Antropov, et al. Project of the Dubna Electron Synchrotron. – Proc.of EPAC'2000, 25-30 June, 2000, Vienna, Austria, p.702-705.

[2] Kroes F.B., Electron Linac MEA Linacs. – LINAC'96 Conference, Geneva, 22-29 August 1996.

[3] Maas R., Wu Y. New layout of Amsterdam Pulse Strecher. – NIKHEF-K/APS/88-01, 1988.

[4] I.V.Titkova, P.F.Beloshitsky, I.N.Meshkov, et all. Magnet Lattice of the Synchrotron Radiation Source DELSY. – Proc. of EPAC'2000, 25-30 June, 2000, Vienna, Austria, p.708-710.

[5] E.B.Levichev. Private communication.

[6] The MAD Program, Version 8.19, CERN/SL/90-13(AP) (Rev.5).

[7] I.N. Meshkov, E.M. Syresin, M.V. Yurkov et al. Perspective of DELSY for the fourth generation SR facility. – Proc.of EPAC'2000, 25-30 June, 2000, Vienna, Austria, p.660-662.

[8] T. Tomimasu, K.Saeki, Y.Miyauchi et al. «the FELI FEL facilities – challenges at simultaneous FEL beam sharing systems and UV-range FELs», NIM A375 (1996) 626.

[9] «A VUV Free Electron Laser at the TESLA Test Facility: Conceptual Design Report», DESY Print TESLA-FEL 95-03, Hamburg, DESY, 1995.

[10] J.Rossbach, «A VUV free electron laser at the TESLA test facility at DESY», NIM A375 (1996) 269.