Nuclear Instruments and Methods in Physics Research A 475 (2001) 407–416

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

The OK-5/Duke storage ring VUV FEL with variable polarization☆

V.N. Litvinenko[a,]*, S.F. Mikhailov[a], O.A. Shevchenko[a], N.A. Vinokurov[b], N.G. Gavrilov[b], G.N. Kulipanov[b], T.V. Shaftan[b], P.D. Vobly[b], Y. Wu[c]

[a] FEL Laboratory, Department of Physics, Duke University, P.O. Box 90319, Durham, NC 27708-0319, USA
[b] Budker Institute of Nuclear Physics, Novosibirsk, Russia
[c] ALS, Lawrence Berkeley National Laboratory, Berkeley, CA, USA

Abstract

The OK-5/Duke storage ring free electron laser (FEL) project was started in 1998. Presently, the components of the OK-5 FEL and the new South straight section are in the final stage of manufacturing. This paper describes the design and the main features of the OK-5/Duke storage ring FEL. The basic concepts and main compromises made in the design process are presented. Plans for the OK-5 FEL commissioning are discussed.

PACS: 41.60.Cr; 29.20D; 78.66; 52.75

Keywords: Free electron laser; Storage ring; Optical klystron; Deep ultraviolet; Coherence

1. Introduction

The initial concept of the distributed optical klystron (DOK) [1] for the Duke storage ring was developed in 1993 [2]. Its present realization, named the OK-5 "Blue Devil" FEL, is close to completion and will replace the OK-4 FEL at the Duke storage ring in the near future. The OK-5 FEL has the same origin as the series of optical klystrons named the OK-1, OK-2, OK-3 and OK-4, which were developed in the Budker Institute of Nuclear Physics (BINP), Novosibirsk [3]. Hence, the OK-5 has its natural "serial number" with "Blue Devil" sub-title indicating its future location[1] and the UV/VUV operation range. The OK-5 FEL is the first implementation of the distributed optical klystron with reasonably high gain in the UV and the VUV ranges of spectrum [4].

The schematic layout of the OK-5/Duke storage ring FEL system is shown in Fig. 1. The 24.2-meter long magnetic system of the OK-5 is comprised of four 4-m long electromagnetic

☆ Work supported Office of Naval Research Grant #N00014-94-1-0818, by the Duke University School of Arts and Sciences, by the Director, Office of Energy Research, Office of Basic Energy Sciences, Material Sciences Division, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

*Corresponding author. Tel.: +1-919-660-2568; fax: +1-919-660-2671.
E-mail address: vl@phy.duke.edu (V.N. Litvinenko).

[1] The "Blue Devil" basketball team and the deep blue color are popular symbols of the Duke University.

PII: S0168-9002(01)01548-0

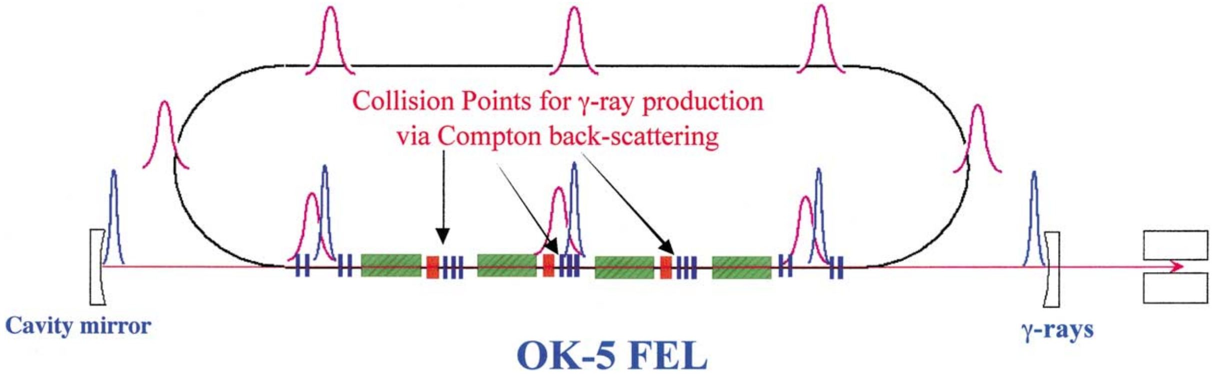

Fig. 1. Schematic layout of the OK-5/Duke storage ring FEL and γ-ray source. Four OK-5 wigglers (green) are separated by three midsections. Each midsection comprised of a triplet of quadrupoles, a buncher and eight dipole correctors. The length of the "OK-5 cell", i.e. the wiggler and midsection is equal to eight RF wavelength. With eight circulating electron bunches, this configuration provides three points where electrons and FEL photons collide head-on and generate a beam of γ-rays.

wigglers and three matching midsections between them. The design and the detailed description of the OK-5 electromagnetic wigglers are presented elsewhere [5]. These wigglers have the horizontal and vertical arrays of the poles shifted for a quarter of the period with respect to each other. The coils for the horizontal and vertical arrays are controlled independently. This feature provides the control of the polarization of the FEL light, which includes the left and the right circular polarization and the horizontal and the vertical linear polarization. The main mode of the OK-5 FEL will be based on the circular polarization. We plan to use the elliptical polarization of the wigglers for all OK-5 FEL operations. We will use the opposite helicity of the adjacent wigglers to lase with linear polarization in the OK-5 FEL. The use of the elliptical polarization will provide for strong reduction of the thermal load and the degradation of the downstream mirror compared with the straightforward use of plane wiggler field.

The control of the polarization in the OK-5 FEL is critical for a number of experiments under consideration. First, we plan to use the OK-5/Duke SR FEL for effective generation of mono-energetic polarized γ-ray beams in the scheme similar to that used with the OK-4 FEL [6]. The nuclear physics experiments with polarized targets require switchable, circular and linear polarization of γ-rays [7]. Second, we plan to use left-and-right circular polarization in the 150–250 nm range for studies of the dichroizm of biological objects. The use of the polarization increases the contrast of the images. Third, we plan to conduct the experiment on the parity violation in atomic transitions 1S–2S in hydrogen [8]. We also plan to use the OK-5 FEL as the research tool to develop an effective scheme for coherent harmonics generation in the soft-X-ray range. The variety of anticipated applications and the requirements to support "top-off" injection, are reflected in the complexity of the OK-5/Duke storage ring FEL design. We designed the lattice for the OK-5 FEL to be flexible for a wide spectrum of applications [9] as well as with a potential for low emittance operations [10]. In both cases, the lattices provide sufficient dynamic aperture for the effective "top-off" injection and a reasonably long beam lifetime [9,10]. This paper is focused on the global aspects of the OK-5/Duke storage ring system while the details can be found in Refs. [4,5,9,10].

In Section 2 we describe the design of the OK-5/Duke storage ring FEL. Section 3 presents issues related to the optical cavity with emphasis on the downstream mirror heat-load and degradation. In Section 4 we discuss the spectrum and polarization of spontaneous radiation, and the features of the OK-5 FEL gain. We conclude with the summary of the main parameters and discussions of our plans.

2. Design of the OK-5/Duke storage ring FEL system

The 24.2-m long magnetic system of the OK-5 comprises four electromagnetic wigglers with controllable polarization and three midsections between them. Each mid-section has a buncher and a triplet of qudrupoles. The OK-5 magnetic system fits into the center of the 34.2-m long, dispersion free South straight section of the Duke storage ring. Two 5-m long bilaterally symmetric sections with four quadrupoles provide the matching between the arcs and the OK-5 system [9].

The design of the complete OK-5/Duke storage ring FEL system went through a number of iterations bringing together a set of contradicting requirements. The main compromise in the OK-5 FEL performance was imposed by the need for efficient generation of γ-ray beams. A Compton γ-ray source with good energy resolution requires a field-free collision point with low angular e-beam spread [11]. These points could not be located in the wigglers or between the quadrupoles, where $\alpha_{x,y}$ are large. Collision points are located in the triplet centers, where $\alpha_{x,y}=0$ [9]. It was the natural choice to space them by the OK-5 FEL super-period (SP), i.e. the wiggler + the mid-section. The SP length must satisfy the collider-condition, i.e. must be equal to an integer number of the RF half-wavelengths, λ_{RF}. The Duke ring RF system operates on 64th harmonic with $\lambda_{RF} = 1.68$ meters. Given lengths of the OK-5 wigglers, the buncher and the quadrupoles reduce our choices of SP length the either to 7/2 λ_{RF} or 4 λ_{RF}. The "7/2 λ_{RF}" option provided for 15% higher OK-5 FEL gain but would reduce the effectiveness of the γ-ray production by a factor of ~3. The oddness of the numbers, 7 and 64, contradicts to the effective use of three collision points. The "4 λ_{RF}" with 2.68-m long SP option is a natural match with evenly spaced 8 bunches and provides 3×8 of collisions per turn. We decided that improved performance of the γ-ray source is worthy of the 15% reduction in the OK-5 FEL gain.

The final design of the OK-5 FEL midsection is shown in Fig. 2. The lattice of the midsection has bilateral symmetry with the triplet in the middle. The symmetry of the midsection is slightly violated by the buncher, which provides a weak vertical focusing. A small variation in the triplet setting compensates this asymmetry. Four x- and four y-dipole correctors provide the independent, local control of the "$x-y$" positions and angles in triplet center, i.e. in the collision point. A beam-position monitor (BPM) is located next to the collision point. These features are essential for attainment of the high γ-ray flux and low energy spread of the collimated γ-ray beam. When desired, the correctors will completely "turn-off" the γ-ray production by shifting the e-beam for ~5 mm away from the optical axis in the collision points, where RMS radius of FEL beam is less than 0.5 mm. In addition, we plan to use these dipole correctors for testing of the "e-beam" outcoupling technique [12] for harmonic generation.

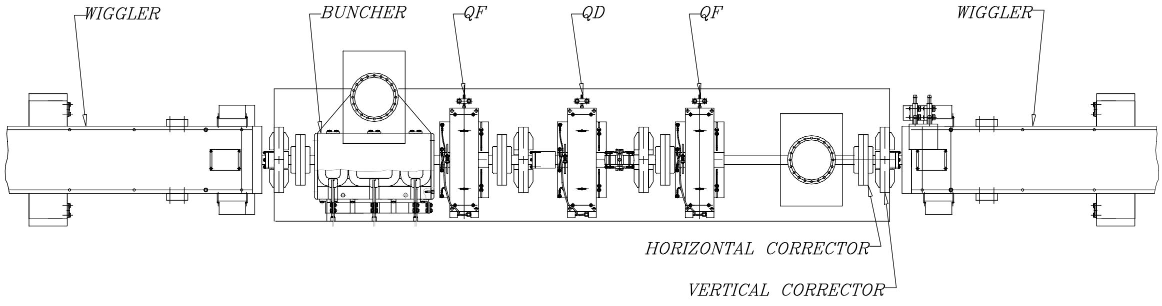

Fig. 2. The layout drawing of the OK-5 midsection (top-view). The main component are a buncher, three quadrupoles, a beam-position monitor of APS type (adjacent to the center quadrupole), two ion pumps (equipped with sublimation pumps) and eight dipole correctors.

We will use a simple design of the buncher. The 0.7-m long buncher is a compensated 3-pole EM wiggler with 40 mm gap and $K_{max} \sim 30$, similar to that of the OK-4 FEL [3] but twice longer. Longer buncher length lowers the peak value of magnetic field to 5.5 kGs at its maximal setting. Lower fields in the buncher reduces the power of synchrotron radiation and, therefore, the potential mirror damage. The downstream mirror is naturally exposed to the synchrotron radiation from the end-of-the arcs bending magnets, whose magnetic field is $\sim$19 kGs at 1.2 GeV. The power density at the downstream mirror from the bending magnets exceeds that of three bunchers at least four folds. We are convinced that the use of helical bunchers for reducing mirror damage is not justified in our case.

The vacuum chamber in the OK-5 FEL has a uniform round pipe with an internal diameter of 37 mm. There are two water-cooled copper-masks at the entrance and at the middle of each midsection. The masks have an internal diameter of 35 mm and intercept only a small part of the radiation from the wigglers. The main goal of these masks is to protect fragile BPM buttons and bellows while having sufficient aperture for an effective injection. The masks also shield a part of the vacuum chamber in the wigglers. In most of the practical settings, a substantial part of the up-stream wiggler radiation will reach the walls of the vacuum chamber in the downstream wiggler. The vacuum chambers of the end-matching sections have 60-mm external and 58-mm internal diameters. These sections are connected with other vacuum chambers via smooth transitions. The main absorber combined with a smooth transition is located at the downstream end of the straight section. Other local masks protect fragile parts of the system.

The 4.04-m length of the OK-5 wigglers was determined by the manufacturing capability of the high precision and computer controlled milling machine at BINP. The wiggler period of 12 cm was chosen [13] to provide the desirable tunability range with rather large, 4 cm $\times$ 4 cm, gap required for effective injection [4,5,9]. A round stainless-steel vacuum chamber for the OK-5 wigglers has external diameter of 40 mm. The inside wall of the vacuum pipes is electrochemically polished to reduce the out-gassing. Four cooling channels are attached to vacuum pipe with special thermo-conducting glue. This design provides sufficient cooling capacity to evacuate the heat generated by radiation in the vacuum chamber. We anticipate an initial period of operation with mediocre vacuum before the vacuum chamber will be cleaned by the radiation. The details of the OK-5 wiggler design and its magnetic field are published in a separate paper [5].

3. The optical cavity for the OK-5/Duke storage ring FEL system

We will use an improved version of the 53.73-m long OK-4 optical cavity system [14] with the feedback and the computer control incorporated into the Duke storage ring EPICS control system. For the future operations, we plan to design and to build a new optical cavity system with a vacuum loading dock for new mirrors and the capability for the in-vacuum change of mirrors.

The OK-5 FEL has maximum gain with Rayleigh range $\beta_0 \sim 4.5$ m, which requires mirror radii to be 27.62 m. Variation of the β_0 within the range of 3–6 m changes the relative value of the OK-5 gain by less than 10%. It means that initially we can use existing OK-4 mirrors with 22.27-m radii of curvature and $\beta_0 = 3.3$ m. It also means, that we can use $\beta_0 \sim 5.5$ m with mirror radii of 28 m with improved stability of the optical cavity with marginal loss in the OK-5 gain. The use of 28-m radii will reduce sensitivity to the angular misalignments of the mirrors by a factor of 2.7 compared with the OK-4 FEL system. It also will allow us to reduce the diameter of the mirror substrates from the present 5 to 3 cm for long wavelength and to 2-cm for short wavelengths. Even at $\lambda = 1$ μm the RMS FEL beam radius at the mirror will be $\sim$3.4 mm ($\beta_0 = 5.5$ m) and the use of 1.5-cm radius (3-cm diameter) mirror substrates provide for very low diffraction losses. In the UV and the VUV, a 2-cm diameter mirrors will be sufficient. Presently, the vertical aperture for the OK-4 FEL beam is limited to the 2-cm in the end-of-the-arc bending magnets. This aperture translates into 3.1 cm at the mirrors. This limitation did not create any adverse effects for the OK-4 FEL operating at wavelengths from 193.7 to 730 nm. This experience made us confident and committed to the reduction of the mirror diameter in the near future.

Small mirrors have serious advantages when used in FEL with high-K helical or elliptical wigglers. These wigglers have very low intensity of the radiation on the axis while the most intense radiation is directed into the K/γ cone around the axis [15]. Fig. 3 shows the power of spontaneous radiation absorbed in a downstream mirror from 100 mA, 1 GeV e-beam and the OK-5 FEL wigglers. The 3 cm or 2 cm mirrors will absorb 5.1 W or 1.0 W, respectively, compared with 27.7 W for a 5 cm mirror.

In addition to the lower power load, the smaller mirrors are more rigid and allow effective cooling using indium brazing. We are testing this concept with the existing 5 cm mirrors. Mirrors with 28-m radii also provide wider range of the stability that currently used, and allow larger stresses. We are inclined to chose $\beta_0 \sim 5.5$ m for the OK-5 FEL optical cavity.

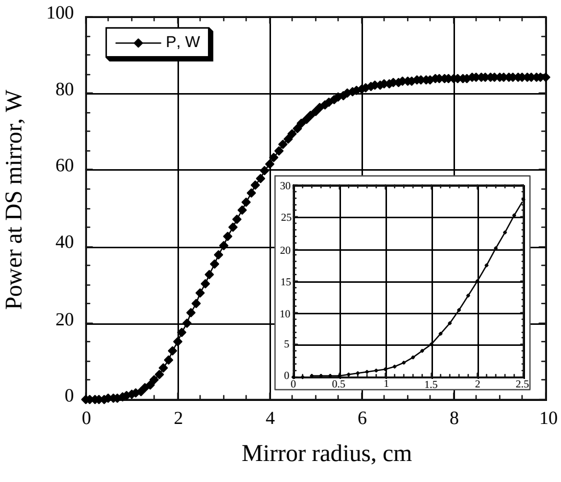

Fig. 3. The power of spontaneous radiation from OK-5 FEL wigglers deposited onto the downstream mirror as the function of its radius. The distance from the downstream mirror to end of the fourth wiggler is 14.81 m. The furthest distance to the beginning of the first wiggler is 38.92 m. $E = 1$ GeV, $I_b = 100$ mA, $\lambda = 100$ nm. Details for the center cone of radiation are shown in the right-down corner.

4. Spectrum and polarization of the OK-5 FEL spontaneous radiation

We intend to use spectral and polarization features of spontaneous radiation from the OK-5 FEL system for selected user applications [16], as well as for the FEL diagnostic. The flexibility of the OK-5 FEL system provides features which can be very unique. For example, in configuration in which adjacent wigglers have opposite helicity, we can generate the beam combining horizontally polarized photons at wavelength λ_1 and vertically polarized photons at wavelength λ_2. By adjusting the OK-5 bunchers, we can control the difference in the wavelength $\lambda_1 - \lambda_2$.

In the OK-5 wigglers, the horizontal and the vertical fields are controlled independently by their coil currents. This configuration allows controlling both the wavelength and polarization of radiation. The wavelength is determined by the values of the wiggler field $B_{x,y}$, the wiggler period λ_w and the e-beam relativistic factor $\gamma = E/mc^2$:

$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + a_x^2 + a_y^2\right), \qquad a_{x,y} = \frac{e\lambda_w\sqrt{\langle B_{y,x}^2 \rangle}}{2\pi mc^2} \quad (1)$$

where e and m are the charge and the mass of electron, c is the speed of the light. It means that RMS values of the fields determine the wavelength:

$$\lambda = \frac{\lambda_w}{2\gamma^2}\left(1 + K_w^2\right), \qquad K_w \equiv \sqrt{a_x^2 + a_y^2}. \quad (2)$$

The spectrum of spontaneous radiation from the OK-5 FEL differs from that of a conventional FEL and a conventional OK. For identical setting of the bunchers and a single electron with relativistic factor of γ_0, the spectrum at zero angle is a result of interference of radiation from four wigglers:

$$I_{DOK}(k) = I_0\left(\frac{\sin \pi N_w(1-X)}{\pi N_w(1-X)}\right)^2 \times \left(\frac{\sin(4\pi(N_w + N_d)X)}{\sin(\pi(N_w + N_d)X)}\right)^2, \quad X = \frac{k}{k_0} \quad (3)$$

where $k_0 = 2\pi/\lambda_0$, N_w is the number of periods per wiggler, $N_d = \Delta s(\gamma_0)/\lambda_0$ is the dimensionless slippage in the bunching straight section. The first term in Eq. (3) is the well-known spectrum of the radiation from one wiggler. The second term is the interference term. Fig. 4(a) shows this spectrum for ideal electron beam for $N_{\mathrm{d}} = 25$ and its envelope. The well-developed fringe pattern and clearly separated peaks are distinguishable features of DOK spectra. Finite energy spread and emittance of electron beam smooth those features making them less pronounceable. Formulae (3) can be easily integrated with the e-beam distribution with finite energy spread and emittance using, for example, Mathematica [17]. Figs. 4(b) and (c) show the effect on the spectra by finite energy spread and emittance of the electron beam. As expected, the DOK is very susceptible to the energy spread, which reduces the depth of the fringes and smoothes other fine features. Similar to the standard OK, the measured depth of modulation can be used for measuring the e-beam energy spread and for tuning bunchers to maximize the FEL gain [18]. The finite angular spread shifts spectra towards longer wavelength and makes it asymmetric. At low level, the DOK gain is proportional to the negative derivative on the e-beam energy of the spontaneous radiation intensity into $\mathrm{TEM}_{\mathrm{oo}}$ mode [19]. Even though the on-axis, i.e. zero-angle, spectra do not reflect all 3-D effect, they are practically useful for optimization of the FEL performance. Specifically, optimal buncher strengths (see [4] for specific examples) do not depend strongly on the beam emittance. Therefore, the maximization of the sharpness of

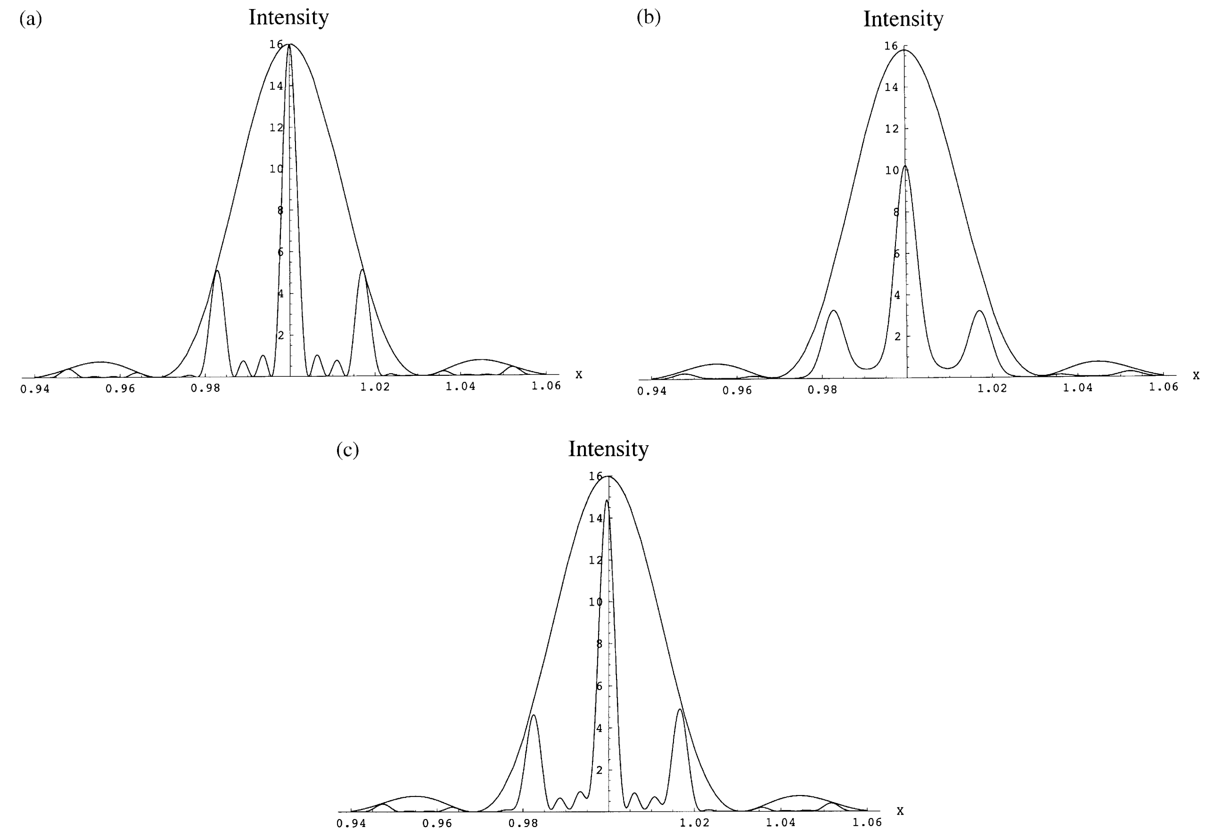

Fig. 4. On-axis spontaneous radiation spectra from the OK-5 FEL system with $N_{\mathrm{d}} = 25$. The envelope is the spontaneous radiation spectrum from one wiggler scaled up by 16-fold. Vertical scale is in units of the radiation from one wiggler, horizontal scale, $X = k/k_0$, is the relative detuning from the FEL resonance. (a) for ideal e-beam; (b) for e-beam with 0.1% RMS energy spread; (c) for e-beam with 10 nm rad emittance at $E = 700$ MeV, $\lambda = 200$ nm. .

the fringes provides a tool for optimizing DOK gain. Fig. 5 shows typical dependence of the DOK spectra on N_d which clearly indicates the best range for the gain around $N_d \sim 55$. The OK-5 FEL gain has fast oscillating dependencies on a number of parameters, including the relative strengths of three bunchers. The detailed studies are published separately [4]. The gain dependence for OK-5 FEL

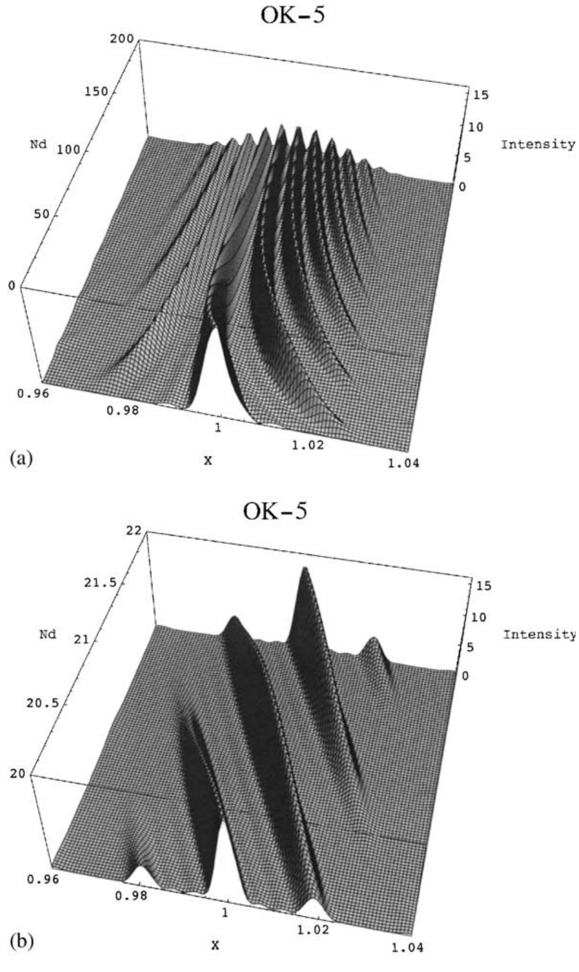

Fig. 5. The spectrum of spontaneous radiation from OK-5 FEL as the function of the detuning $X = k/k_0$ and the strength of the bunchers N_d for e-beam with the RMS energy spread of 0.05%. Vertical axis is the spectral intensity in the units of the radiation from one wiggler at $X = 0$. The horizontal axis is X, the third axis is N_d: (a) N_d in the range from 0 to 200 with an integer step of 2 for avoiding the fast oscillating features; (b) N_d in the range from 20 to 22 with a fractional step of 0.02 to show the fast oscillating features.

on the buncher strength differs from that of an FEL or conventional OK. Fig. 6 illustrates this difference. The conventional OK has the cos-like gain dependence with the maximum very close to N_d = integer −0.25, i.e. exactly as it was predicted by OK inventors [20]. The OK-5 FEL gain has two closely space positive and negative peaks, separated by a "no-gain" flat zone. The maximum of the OK-5 gain is located at $N_d \approx$ integer −0.13. This tendency for DOK peak gain to shift towards $N_d \approx$ integer was also expected [1]. This feature is the direct consequence of the DOK spontaneous radiation spectrum and the Einstein relations between induced and spontaneous radiation.

Another interesting feature of the OK-5 is its flexible polarization determined by the geometry of the wiggler and the relative strength of horizontal and vertical fields. On the axis of the wiggler the polarization is

$$\rho_{xy} = \frac{1}{2}\begin{bmatrix} 1+\xi_3 & \xi_1 - i\xi_2 \\ \xi_1 + i\xi_2 & 1-\xi_3 \end{bmatrix} = \frac{1}{a_x^2 JJ_+^2 + a_y^2 JJ_-^2} \times \begin{bmatrix} a_x^2 JJ_+^2 & -ia_x a_y JJ_+ JJ_- \\ ia_x a_y JJ_+ JJ_- & a_y^2 JJ_-^2 \end{bmatrix}$$

$$JJ_\pm = J_0(\xi) \pm J_1(\xi), \qquad \xi = \frac{a_y^2 - a_x^2}{2(1 + a_y^2 + a_x^2)}$$

$$\xi_2 = \frac{2a_x a_y JJ_+ JJ_-}{a_x^2 JJ_+^2 + a_y^2 JJ_-^2}; \qquad \xi_3 = \frac{a_x^2 JJ_+^2 - a_y^2 JJ_-^2}{a_x^2 JJ_+^2 + a_y^2 JJ_-^2} \tag{4}$$

where J_0 and J_1 are Bessel functions of the first kind and ξ_2 and ξ_3 are degrees of circular and linear polarization, respectively [21]. The OK-5 wiggler geometry defines the absence of linear polarization at 45° ($\xi_1 = 0$) in contrast with permanent magnet devices, where polarization is changed by lateral shift of the horizontal and vertical array with respect to each other [15,22]. The OK-5 light is generally 100% elliptically polarized with $\xi_2^2 + \xi_3^2 = 1$. When field amplitudes are equal ($|a_x| = |a_y|$), the polarization is circular with helicity defined by the sign of the product $a_x a_y$: $\xi_2 = 1$ for right, and $\xi_3 = -1$ for left circular polarization. Therefore, it is very straightforward to set the OK-5 FEL for circular polarization.

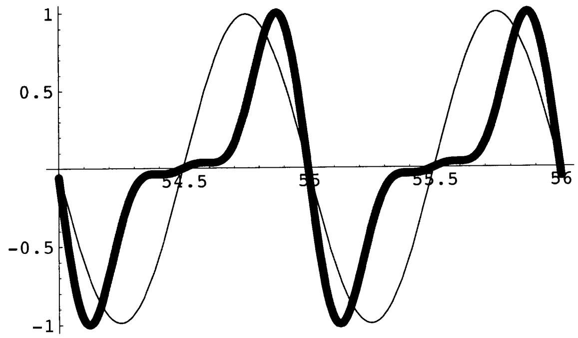

Fig. 6. Detailed dependence of the OK-5 (DOK) FEL and a conventional OK (COK) gains on the buncher(s) strength N_d (horizontal axis) in the range from 54 to 56. The gains (vertical axis) are calculated at the resonant wavelength ($X = 1$) and normalized to their maximal value in the range. The COK is a reduced OK-5 with two wigglers and one buncher. The e-beam RMS energy spread is 0.05%. The thick line is the OK-5 gain, the thin line is the COK gain. The OK-5 gain reaches maximum at $N_d = 54.8694$ and the COK gain has the peak gain at $N_d = 54.7758$.

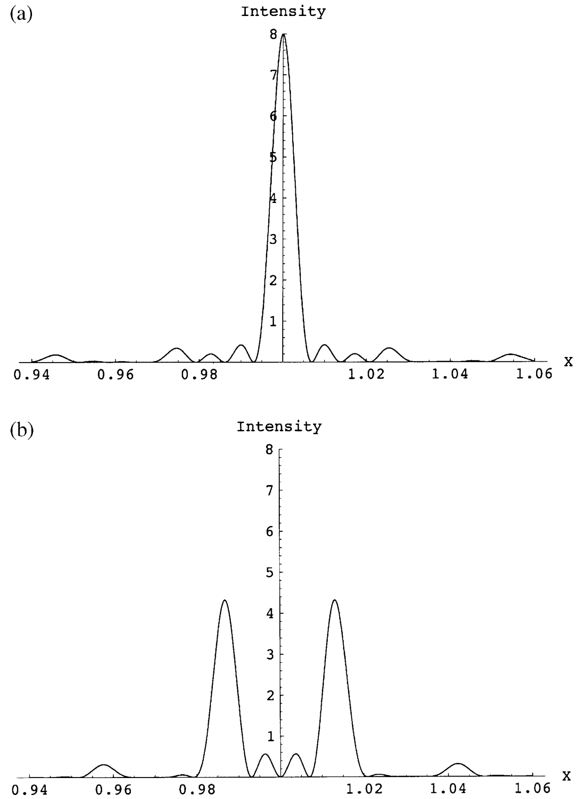

Fig. 7. Typical example of spectra for linearly polarized light with alternating helicity in the OK-5 wigglers by changing sign of the horizontal filed in adjacent wigglers. $N_d = 5$, (a) spectrum of horizontally polarized light; (b) spectrum of vertically polarized light.

When one of the field components is zero, the polarization is linear: $\xi_3 = 1$ for horizontal, and $\xi_3 = -1$ for vertical linear polarization. Nevertheless, this simple-minded approach of turning off one of the arrays has three major drawbacks. First, the radiation for the planar wiggler has strong harmonics on the axis, which can be harmful for the OK-5 mirrors. Second, in planar configuration the OK-5 wigglers will have reduced tunability range by a factor ~ 2. Third, some of our spontaneous radiation users need a clean narrow-band fundamental line in the VUV. The harmonics of the fundamental wavelength could be harmful for experiments. The use of a monochromator or a filter in the VUV means a big loss in the beam intensity and, often, makes experiment impossible. We plan to use helical (or almost circular) configuration of the wiggles with opposite the helicity in the adjacent wigglers. The spectra for this configuration for the horizontal and the vertical polarization are shown in Fig. 7. One of the low N_d settings (Fig. 7) provides the narrow line horizontally polarized light for user application, while vertically polarized light is shifted to the wings.

To lase in the OK-5 FEL with horizontal polarization, we will use higher N_d and will shift the spectra of the desirable linear polarization to the position of the maximum gain. Fig. 8 shows the relative values of gain for horizontally and vertically polarized light. The net difference in the gain of $\sim 8\%$ is sufficient for complete domination of the horizontal linear polarization in the lasing mode. The other choice of the N_d or/and other alternation scheme would give preference for the vertical polarization. We can also use a slight elliptical polarization with a few percents difference in the x or y coils to increase the gain difference. The OK-5 FEL operating with the linear polarization will have $\frac{1}{2}$ gain compared to that for the circular polarization. The OK-5 FEL

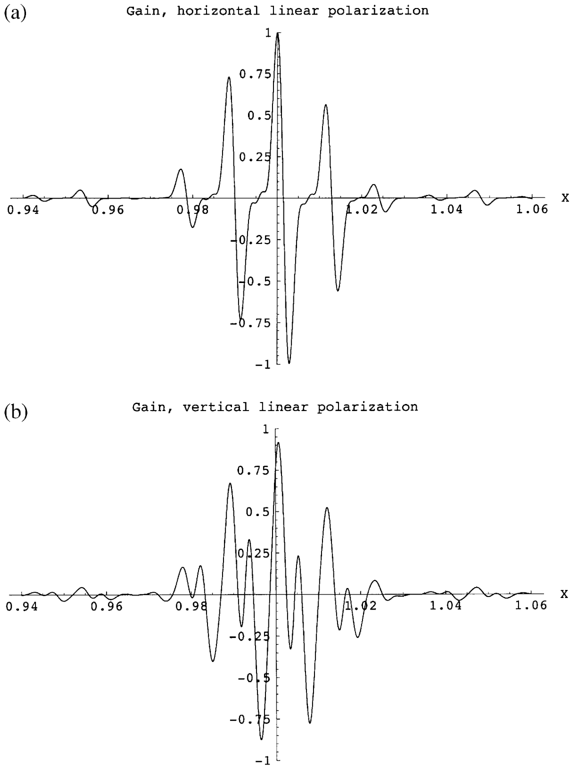

Fig. 8. Gain vs. detuning parameter X. The OK-5 has alternating helicity of the wigglers and the bunchers set at $N_d = 54.8694$. The gain is normalized to its maximum value for horizontally polarization. (a) gain for horizontally polarized light; (b) gain for vertically polarized light.

gain with planar wiggler and with alternating helical configurations will be at the same level.

In conclusion, the OK-5 can be tuned in the way that the horizontal and vertical polarization have the same level of gain, but at different wavelength. This unusual lasing mode will provide two-color FEL beam easily separable by polarizers.

5. Conclusions and acknowledgements

The OK-5 FEL/Duke storage ring FEL promises further advanced of FEL-oscillators into the UV and VUV range. It has substantial gain to operate below 200 nm. It will provide remarkable features for the users of spontaneous and coherent radiation in the UV and the VUV ranges of spectra. A pleasant side-product of the OK-5 FEL, the Compton back-scattered monochromatic, polarized γ-ray beams, will be used for nuclear physics experiments [4].

The real potential of the OK-5 FEL will be realized after modification of the Duke storage ring with lower emittance and low impedance vacuum chamber [10]. Gain $\sim$1000% per pass [4] will allow the OK-5 to lase below 100 nm and to generate coherent soft-X-ray harmonics.

The final design of all components of the OK-5 FEL and 34 m straight sections was completed by mid-2000. Four OK-5 wigglers have been manufactured and are undergoing magnetic measurements, fine tuning and minor modification of the pole-tips. The quality of the wigglers seems to be excellent. The rest of the system is in the production stage and should be finished in the summer of 2001. The OK-5 FEL system will go through additional tests at Duke University prior to installation onto the Duke storage ring. We hope to report the first results attained with the OK-5/Duke storage ring in 2002.

Authors would like to acknowledge the financial support for this project by the Office of Naval Research and Duke University. Authors are grateful to Prof. Berndt Müller, the Dean of the Natural Sciences, Duke University for continuous financial and moral support of the project. Authors would like to thank colleagues from the Duke Free Electron Laser Laboratory, especially Mark Emamian and Gary Swift, for their thoughtful contributions into this project, and Prof. Glenn Edwards, the Director of FEL laboratory for his support of the project.

References

[1] V.N. Litvinenko, Nucl. Instr. and Meth. A 304 (1991) 463;. N.A. Vinokurov, Nucl. Instr. and Meth. A 375 (1996) 264.
[2] DFELL booklet, Duke University, 1993.
[3] A.S. Artamonov, et al., Nucl. Instr. and Meth. 177 (1980) 247;
G.A. Kornyukhin, G.N. Kulipanov, V.N. Litvinenko, N.A. Mezentsev, A.N. Skrinsky, N.A. Vinokurov, P.D. Vobly, Nucl. Instr. and Meth. A 237 (1985) 281;
I.B. Drobyazko, et al., Nucl. Instr. and Meth. A 282 (1989) 424.

[4] V.N. Litvinenko, N.A. Vinokurov, O.A. Shevchenko, Predictions and Expected Performance for the VUV OK-5/Duke Storage Ring FEL with Variable Polarization, Nucl. Instr. and Meth. A 475 (2001) 97, these proceedings.
[5] V.N. Litvinenko, S.F. Mikhailov, N.A. Vinokurov, N.G. Gavrilov, G.N. Kulipanov, O.A. Shevchenko, P.D. Vobly, Helical wigglers for the OK-5 storage ring VUV FEL at Duke, Nucl. Instr. and Meth. A 475 (2001) 247, these proceedings.
[6] V.N. Litvinenko, et al., Phys. Rev. Lett. 78 (24) (1997) 4569.
[7] W. Tornow, V.N. Litvinenko, H. Weller, High Intensity γ-Ray Source for nuclear physics, Proposal to the US Department of Energy, August 2000;
E.C. Schrieber, et al., Phys. Rev. C 61 (Rapid Comm.) (2000) 061604.
[8] T. Burt, V.N. Litvinenko, Feasibility studies of the parity violation experiment in ^1S–^2S transitions in atomic hydrogen using the OK-5/Duke storage ring FEL, unpublished.
[9] Y. Wu, V.N. Litvinenko, S.F. Mikhailov, N.A. Vinokurov, N.G. Gavrilov, O.A. Shevchenko, T.V. Shaftan, D.A. Kairan, Lattice Modification and Nonlinear Dynamics for Elliptically Polarized VUV OK-5 FEL Source at Duke Storage Ring, Nucl. Instr. and Meth. A 475 (2001) 253, these proceedings.
[10] S.F. Mikhailov, V.N. Litvinenko, Y. Wu, Low Emittance Lattice for the Duke Storage Ring soft-X-Ray FEL, Nucl. Instr. and Meth. A 475 (2001) 417, these proceedings.
[11] V.N. Litvinenko, J.M.J. Madey, SPIE 2521 (1995) 55;
V.N. Litvinenko, J.M.J. Madey, Nucl. Instr. and Meth. A 375 (1996) 580.
[12] N.A. Vinokurov, Concept of the e-beam outcoupling, BINP, 1985.
[13] N.A. Vinokurov, Magnetic design of the helical undulators for the Duke FEL, Design Report, Novosibirsk, 1998.
[14] I.V. Pinayev, M. Emamian, V.N. Litvinenko, S.H. Park, Y. Wu, CP451, Beam Instrumentation Workshop, in: R.O. Hettel, S.R. Smith, J.D. Masek (Eds.), The American Institute of Physics, 1998, p. 545.
[15] H. Hama, K. Kimura, M. Hosaka, J. Yamazaki, T. Kinoshita, Nucl. Instr. and Meth. A 393 (1997) 23.
[16] H. Ade, Y. Wang, S.L. English, J. Hartman, R.F. Davis, R.J. Nemanic, V.N. Litvinenko, I.V. Pinayev, Y. Wu, J.M.J. Madey, Surf. Rev. and Lett. 5 (6) (1998) 1257.
[17] Mathematica 4, © Copyright 1988–1999 Wolfram Research, Inc.
[18] G.A. Kornyukhin, G.N. Kulipanov, V.N. Litvinenko, N.A. Mezentsev, A.N. Skrinsky, N.A. Vinokurov, P.D. Vobly, Nucl. Instr. and Meth. A 237 (1985) 281;.
N.A. Vinokurov, A.N. Skrinsky, Theory of the Optical Klystron, MW Relativistic Electronics, Gorky, 1981, p. 204.
[19] N.A. Vinokurov, Classical analog of Einstein relations, Preprint 81-02, BINP, Novosibirsk, 1981;
V.N. Litvinenko, N.A. Vinokurov, Nucl. Instr. and Meth. A 331 (1993) 440.
[20] N.A. Vinokurov, A.N. Skrinsky, Optical klystron, Preprint 77–59, BINP, Novosibirsk, 1977.
[21] L.D. Landau, E.M. Lifshitz, The Classical Theory of Fields, 4th Revised Edition, Pergamon Press, Oxford, 1975, p. 123.
[22] R. Walker, et al., Initial Performance of the European UV/VUV Storage Ring FEL at ELETTRA, Nucl. Instr. and Meth. A 475 (2001) 20, these proceedings.