ELSEVIER

Nuclear Instruments and Methods in Physics Research A 407 (1998) 8–15

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

First UV/visible lasing with the OK-4/Duke storage ring FEL

V.N. Litvinenko[a,*], B. Burnham[a], S.H. Park[a], Y. Wu[a], R. Cataldo[a], M. Emamian[a], J. Faircloth[a], S. Goetz[a], N. Hower[a], J.M.J. Madey[a], J. Meyer[a], P. Morcombe[a], O. Oakeley[a], J. Patterson[a], G. Swift[a], P. Wang[a], I.V. Pinayev[b], M.G. Fedotov[b], N.G. Gavrilov[b], V.M. Popik[b], V.N. Repkov[b], L.G. Isaeva[b], G.N. Kulipanov[b], G.Ya. Kurkin[b], S.F. Mikhailov[b], A.N. Skrinsky[b], N.A. Vinokurov[b], P.D. Vobly[b], A. Lumpkin[c], B. Yang[c]

[a] *FEL Laboratory, Physics Department, Duke University, Durham, NC 27708, USA*
[b] *Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia*
[c] *APS, Argonne National Laboratory, Argonne, IL 60439, USA*

Abstract

In this paper, we report first lasing results in the near-UV and visible spectral ranges with the OK-4/Duke storage ring – the first storage ring FEL operating in the United States. The OK-4/Duke FEL was commissioned in November 1996 and demonstrated lasing in the 345–413 nm range with extracted power of 0.15 W. In addition to lasing, the OK-4/Duke FEL generated a nearly monochromatic (1% FWHM) γ-ray beams. In this paper, we describe initial performance of the OK-4/Duke storage ring FEL and γ-ray source in this demonstration experiment. We briefly discuss the present status of the project and its future user program.

1. Introduction

The Duke University Free Electron Laser Laboratory (DFELL) and the Budker Institute of Nuclear Physics (BINP) have collaborated on the OK-4/Duke storage ring XUV FEL project since 1992 [1]. The OK-4 FEL was built and operated in the 240–690 nm range using the VEPP-3 storage ring at Novosibirsk [2]. After commissioning the 1.1 GeV Duke storage ring in November 1994 [3], the OK-4 FEL made a trip around the globe and came to Duke in May 1995.

The OK-4/Duke FEL was prepared for the first demonstration experiment in November 1996. An UV streak-camera was brought to Duke from Argonne National Laboratory (APS) and has been used to measure electron bunch length, optical cavity length, and FEL pulse length [4].

After commissioning all critical OK-4/Duke FEL subsystems, the very first run on 13 November 1996, was successful. The OK-4/Duke storage ring FEL demonstrated operation in the near UV/visible range with a tunability of $\pm 18\%$ around the center wavelength of 380 nm. Two days later we demonstrated the generation of nearly monochromatic 3–15 MeV γ-rays [5] by tuning both the laser wavelength and the energy of the electron beam.

* Corresponding author. E-mail: vl@phy.duke.edu.

0168-9002/98/$19.00
PII S0168-9002(97)01357-0

The main problem for these experiments was the "blind-folded" alignment due to the absence of electronics for beam position monitors (BPM). The relatively high gain of the OK-4 FEL helped to overcome this problem. Experiments, dedicated mostly to the production and characterization of γ-ray beam, continued for about a month. In parallel with the γ-ray production, we had performed a number of measurements of the OK-4/Duke FEL parameters. In this paper, we focus on the first lasing with the OK-4/Duke storage ring FEL and its main parameters. The first unsuccessful attempts to lase with the OK-4/Duke FEL in August 1996 without several critical systems in place were presented at the previous FEL Conference and published elsewhere [6]. Initial performance and predictions for the OK-4/Duke monochromatic γ-ray source, a pleasant side-product of intracavity Compton scattering, are described in Refs. [5,7–9]. Details of the OK-4/Duke FEL micro-temporal structure are also discussed elsewhere [4,10].

Operation of the OK-4/Duke FEL was interrupted in the middle of December 1996 by an administrative decision of the DFEL laboratory to condition a klystron used to drive the last four sections of the linac-injector. This break continued for seven months. During this period of time, the Duke storage ring and the OK-4 FEL diagnostic systems were undergoing modifications.

2. The OK-4/Duke XUV storage FEL

Schematic layout of the 1.1 GeV Duke storage ring and the OK-4 XUV FEL facility is shown in Fig. 1. The OK-4 FEL is installed in the south straight section dedicated for FEL operation. The present lattice is optimized for maximum OK-4 FEL gain and has both transverse β-functions of 4 m at the center of the OK-4. The 11 m long vacuum chamber for the OK-4 magnetic system has 8 m of constant cross-section and two 1.4 m long smooth transitions from the 2.2 cm $\times$ 7.5 cm flat shape to the 10 cm round pipe. Three ion pumps are located at the center and two ends of the OK-4 system, providing vacuum in the 10^{-10} Torr range. For installation on the Duke storage ring, the magnetic system of the OK-4 FEL was slightly modified. The gap in the OK-4 was increased to 2.25 cm to accommodate a new vacuum chamber. The buncher was shifted from the center of the OK-4 to provide a magnetic-field-free collision point for the Compton γ-ray production.

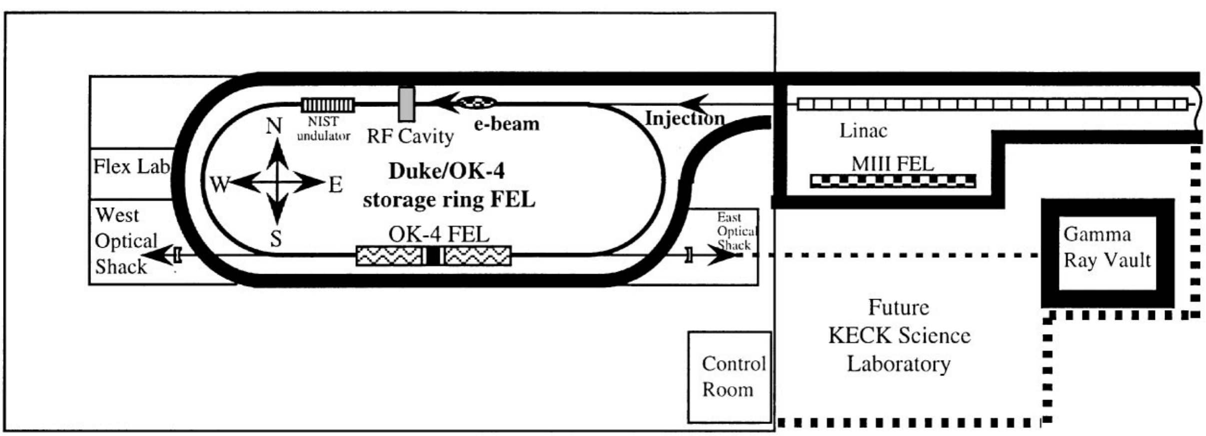

Fig. 1. Layout of the Duke/OK-4 storage ring FEL facility. The 1.1 GeV Duke storage ring is surrounded by 2′ concrete shielding. Two mirrors of the 53.73 m long OK-4 optical cavity and its diagnostics are located outside of the shielding in the optical shacks. These shacks and a flex-lab will be used for pilot OK-4 FEL user experiments prior to the completion of the construction of the dedicated Keck Science Laboratory by 1999.

Table 1
Duke storage ring electron beam parameters

Operational Energy (GeV)	0.25 − 1.1
Circumference (m)	107.46
Impedance of the ring, Z/n, (Ω)	2.75 ± 0.25
Stored current (mA)[a]	
Multibunch	155
Single bunch	20[b]/8[c]
Bunch length, σs (ps)[d]	
Natural (low current)	15
With 5 mA in single bunch	60
Relative energy spread, $\sigma E/E$[d]	
Natural (low current)	2.9×10^{-4}
At 5 mA in single bunch	1.1×10^{-3}
Peak current (A)[d]	
With 5 mA in single bunch	12
With 20 mA in single bunch[e]	31
Horizontal emittance (nm × rad)	
5 mA/bunch @ 700 MeV	< 10[f]
3 mA/bunch @ 500 MeV	< 8[f]

[a]Maximum current at 1 GeV is limited to 2–3 mA before crotch-chambers with absorbers are installed;
[b]Per bunch using standard thermionic gun;
[c]In single bunch mode with photocathode gun;
[d]At 500 MeV, $V_{RF} = 500$ kV; measured by the streak-camera [4] and dissector;
[e]Expected from the broad band impedance model with $Z/n = 2.75\,\Omega$;
[f]Extracted as the top limit from the OK-4 spontaneous radiation spectra.

Table 2
Some of the OK-4 FEL parameters

Optical cavity	
Optical cavity length (m)	53.73
Radius of the mirrors, measured (m)	27.27
Rayleigh range in OK-4 center (m)	3.3
Angular control accuracy (rad)	better than 10^{-7}
OK-4 wiggler [1,14]	
Period (cm)	10
Number of periods	2×33.5
Gap (cm)	2.25
Kw/I (1/kA)	1.804
Kw	0–5.4[a]

[a]At the time of November 1996 experiment Kw was limited to 3.8. At present time, Kw is limited to 4.5 by the power supply.

The main parameters of the low emittance Duke storage ring are published elsewhere [3,11] and briefly summarized in Table 1. For experiments reported in this paper we have operated the Duke storage ring in energy range from 270 MeV (injection energy) to 550 MeV. We were not able to operate at wavelength of 380 nm above 550 MeV due to the limitation of wigglers power supply (see the note attached to Table 2).

The existing injection system limited the maximum stored current to 8 mA/bunch. In future, we plan to improve efficiency of injection and increase the current to 20–40 mA/bunch.

The storage ring RF system [12] operates at 178.5 MHz which is the 64th harmonic of the revolution frequency. The RF frequency is generated by a SAW master oscillator which is controlled by a 16-bit DAC via the Duke storage ring control system [13]. Typical OK-4 FEL operation mode used RF voltage of 500–550 kV. A short list of up-to-date OK-4 FEL parameters is summarized in Table 2. Other parameters and expected performance of the OK-4 FEL are described in previous publications [2,14].

Two Trans-Rex power supplies, donated by Fermi Lab, have been repaired, equipped with external LC filters and are presently used to drive the OK-4 wigglers and buncher. Overall performance of the power supplies is close to specifications (with about 100 ppm stability) and will be improved in the near future by using a second stage of regulation and an active feedback from the OK-4 FEL diagnostics. We also plan to extend the operation range of the wiggler power supply from the present limit of 2.5 kA to 3 kA required for full range OK-4 FEL tunability.

The controls of the OK-4 FEL systems are part of the Duke storage ring control system [13]. The control system provides flexible operation of the OK-4 and the possibility to ramp the energy of the storage ring without changing the OK-4 wavelength. A number of lattices (snapshots in control system terminology) were created to operate the OK-4 FEL. Once created, the snapshots can be used to re-establish lasing. In addition, we have demonstrated continuous lasing in the OK-4 FEL during the ramping from the injection energy to 500 MeV.

The RF-smooth crotch chambers providing passage of the optical beam have been designed but are still in the process of manufacturing. In order to facilitate commissioning of the OK-4 system, we have installed temporary crotches *without absorbers*. A rather large vacuum chamber impedance due to the non-smooth transitions of the temporary crotch-chambers causes microwave bunch-lengthening to begin at ~ 0.1 mA per bunch at 500 MeV. This is the main factor limiting the OK-4 FEL gain. We have used the APS streak-camera [4], a dissector with 15 ps resolution, and spontaneous radiation spectra from the OK-4 to determine the parameters of the electron beam in the single bunch mode (Table 1). According to the bunch-length and the OK-4 FEL gain measurements, the impedance of the vacuum chamber is about 2.75 Ω.

One of the main challenges for the OK-4/Duke storage ring FEL was a 57 m long optical cavity which required mirrors with extremely high precision radii and a sophisticated mirror control and stabilization system. Description of the mirror control and feed-back system as well as brief description of the OK-diagnostics can be found elsewhere [6]. A 30-m-long mirror radii measurement system similar to that described in Ref. [15] has been used to measure 27.26 m radii of the custom made mirrors (by Lumonics Optics Group, Canada) with an accuracy of a few cm. We found that the original clamping scheme of the mirrors had reduced their radii below stability limit for the OK-4 optical cavity. At the present time we are using a different clamping technique.

3. Commissioning of OK-4 FEL

During the preparation for the OK-4 operation, we have established three main storage ring modes at energies of 270 (injection), 500, and 700 MeV and a number of supplementary modes (at 350, 400, 550, 600, 650, and 750 MeV). In addition, we have measured the β-functions in the OK-4 FEL and created computer tools to vary OK-4 wiggler current while keeping betatron tunes stable. The main problem was the absence of electron beam position measurement electronics which could have provided us with information about electron beam orbit. We were forced to use labor intensive and inaccurate ways to find approximate position of the electron beam.

Fortunately, the OK-4 FEL has a rather high gain and demonstration of lasing in the near UV was a relatively easy task. It took about 2 h of e-beam and optical cavity alignment to obtain first lasing at 380 nm. Knowledge of the optical cavity length obtained with the use of the streak-camera [4] proved to be very useful. Lasing at 400 and 500 MeV was demonstrated during the same shift. Later we achieved lasing at 550 MeV using the maximum current available (at that time 2.1 kA) in the OK-4 wigglers.

Two days after first lasing, the monochromatic γ-rays (with 1% FWHM resolution, monochromatized by a lead collimator) were produced by operating the OK-4/Duke storage ring FEL with two equally separated electron bunches. This mode provides for head-on collisions of the optical and electron beams at the center of the optical cavity, and the generation of γ-rays via Compton backscattering [8,9]. Most of our shifts were dedicated to the study and characterization of the γ-ray beam, and the results are published elsewhere [5,7]. Most of the OK-4 FEL parameters reported here were measured in parallel with the γ-ray experiments. Tuning within the reflectivity bandwidth of the optical cavity was straightforward by variation of the wigglers current. A typical tuning wavelength range and one of many measured lasing spectrum are shown in Fig. 2. Optical cavity losses were determined by a measurement of the optical cavity ring down time. Lasing was reasonably easy because the OK-4 gain was at least 10–20 times higher than losses at 380 nm. The start-up current for lasing was 0.3 mA, and with 3 mA/bunch we were able to lase in both optical klystron (buncher on) and conventional FEL mode (buncher off). In all cases the use of the buncher increased the FEL gain and allowed us to lase with one or, if desired, two lasing lines.

FEL power reaches maximum electron beam and optical pulse when the round-trip times are equal, i.e. at perfect synchronism. We measured dependencies of the OK-4 FEL power on detuning $\delta = C_o/\beta - 2L_c$ (where C_o is circumference of the ring, L_c is the optical cavity length and $\beta = v_e/c$) from exact synchronism by varying the RF

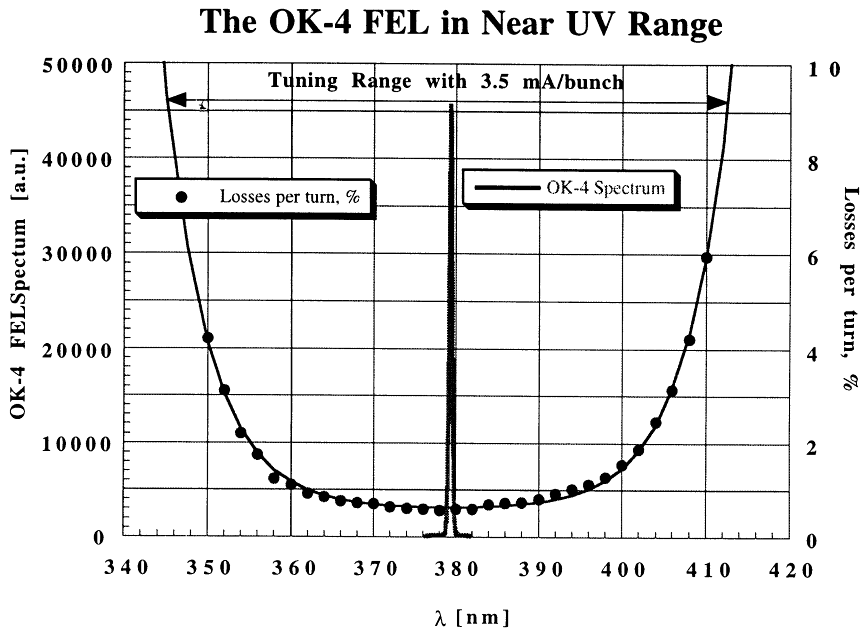

Fig. 2. The tuning range of the OK-4 FEL (with a 3.5 mA/bunch at 500 MeV with 500 kV RF voltage) using 380 nm mirrors. The line in the center is a measured time-averaged lasing line. This line was tuned $\pm$ 18% from 345 to 413 nm by changing the current in the OK-4 wigglers. The dots were measured round trip cavity losses and the smooth curve is a fit. Round-trip losses at the edges of the tuning range give the value of the FEL gain at a given current: gain $>$ 9% at 345 nm with 3.5 mA/bunch, at 500 MeV and a RF voltage of 500 kV.

frequency and as a result the revolution frequency of the electrons. A typical dependence of out-coupled power on detuning with 0.3 mm FWHM is shown in Fig. 3. We have studied the microtemporal structure as a function of detuning and bunchlength of the electron beam [10]. Typical RMS values of the FEL pulse were 5–10 times shorter than the electron bunch length. Using very precise tuning of the revolution frequency, we have registered FEL micropulses as short as 2.5 ps RMS with the APS streak-camera. The duration of these pulses is consistent with the super-modes predicted in [16]. We report these results in a separate paper [10].

Fig. 4 shows a comparison of the measured and predicted extracted power from the OK-4 FEL in the near UV. We have used our self-consistent storage ring FEL code [17,18] and measured broadband (Z/n = 2.75 Ω) impedance model to predict the OK-4 performance. The agreement between the measured and predicted values at two different bunch currents is very reasonable.

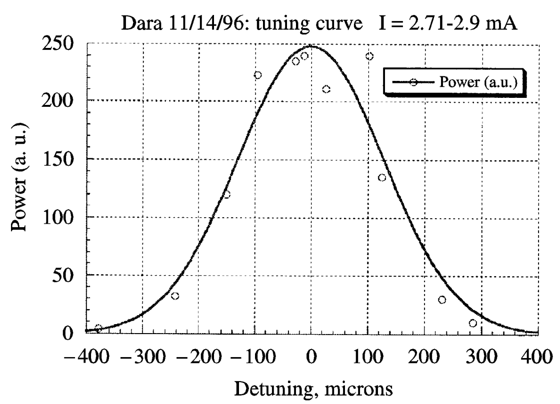

Fig. 3. Measured dependence of the outcoupled power versus detuning from exact synchronism δ.

Therefore, we expect that our predictions of the OK-4/Duke FEL gain at 193 nm will be reasonable. With expected cavity losses about 3% [1], the OK-4 should lase at 193 nm with a beam current of a few mA/bunch. With 10 mA per bunch and

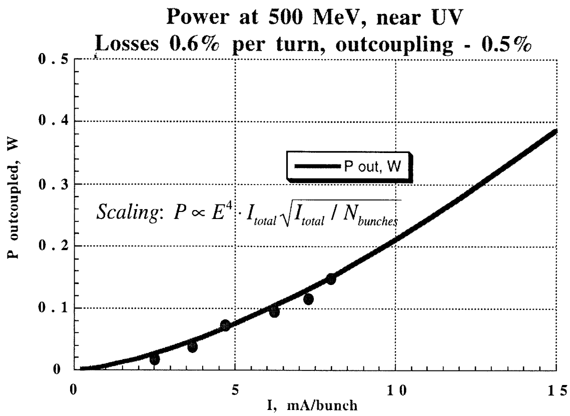

Fig. 4. Measured and predicted extracted lasing power from the OK-4 FEL. About 80% of the power was extracted.

existing set of mirrors, we expect to lase within the 188–197 nm range. Table 3 gives a summary of the measured OK-4/Duke storage ring parameters.

Lasing power depends on the electron beam current, the setting of the OK-4 buncher and detuning from exact synchronism. Data presented in Fig. 5 were measured at a fixed wavelength. We optimized the current in the OK-4 buncher, i.e. the OK-4 dispersion, in order to reach maximum power. We have observed the increase of the energy spread and bunch length by a factor of 2–5 induced by the lasing. Typical electron beam energy spread induced by lasing in the OK-4 FEL was 0.2–0.6% RMS while operating with 2–8 mA currents. The optimized gain of an optical klystron is proportional to the peak current $\hat{I} = I_b(C/\sqrt{2\pi}\sigma_s)$ (where I_b is a current per bunch, C is the ring circumference and σ_s is RMS bunchlength) and inversely proportional to the energy spread of electron beam [19] within some resonable limits of parameters. At fixed energy and RF voltage, the bunch length is proportional to the energy spread σ_E. It means that the optimized optical klystron (OK) gain is inversely proportional to the square of the energy spread:

$$G_{OK} = c_1 \frac{I_b}{\sigma_E^2}.$$

A storage ring FEL lasing is saturated by induced energy spread and consequent reduction of the gain

Table 3
Measured parameters of the OK-4 FEL

Tuning range (3.5 mA/bunch)	345–413 nm
Gain/pass (3.5 mA/bunch, 345 nm)	> 9%
Extracted power (8 mA, 380 nm)[a]	0.15 ± 0.04 W
Induced e-bunch length, σs(ps)	
Low current	~ 35
With 3.5 mA in single bunch	~ 200
Induced energy spread (3.5 mA), $\sigma E/E$	0.35–0.4%
FEL pulse length (ps)	
Low current	~ 2.5
With 3.5 mA in single bunch	~ 20
Line width[b]	$(1–4) \times 10^{-4}$
Lasing lifetime	2–4 h

[a]Measured, 75 mW per mirror. Spontaneous power from the OK-4 and measured transparency of the mirrors has been used for calibration with accuracy ~ 25%;
[b]Time averaged value 4×10^{-4} was caused by ripples in one of power supplies, instantaneous value was ~ 1×10^{-4}.

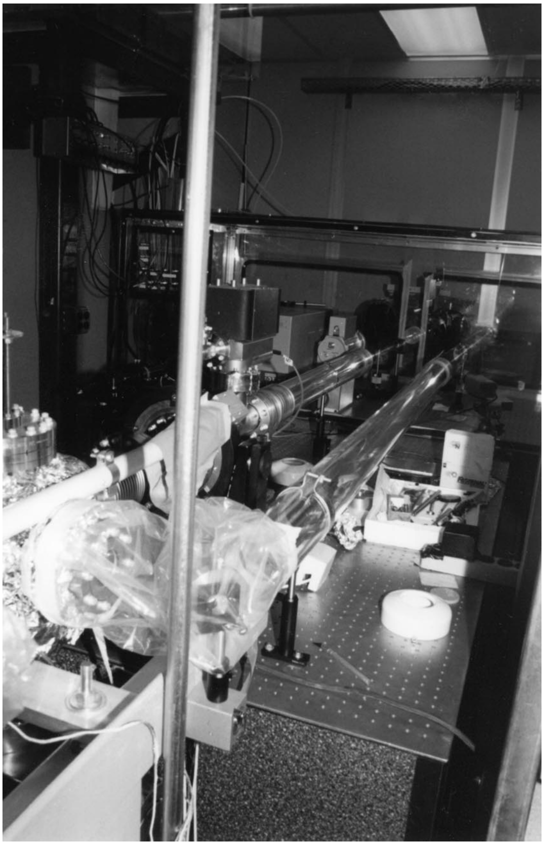

Fig. 5. Photograph of the OK-4 diagnostics located inside nitrogen-purged box in the East Optical Shack.

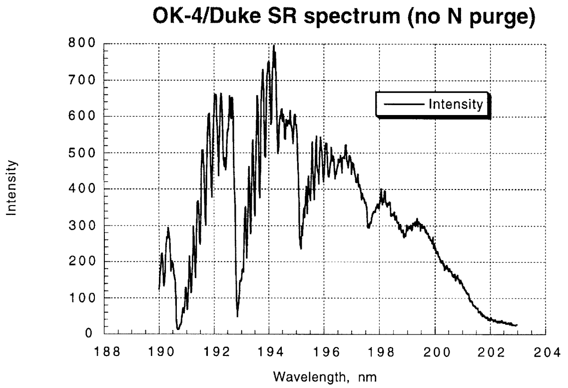

Fig. 6. A Measured spectrum of the OK-4 FEL spontaneous radiation distorted by absorption in the air.

to the level of optical cavity losses. It means that the maximum induced energy spread is proportional to the square root of the bunch current. The lasing power in a storage ring FEL is proportional to the product of induced energy spread and a power of spontaneous radiation [18], which is proportional to the total beam current $I_{tot} = N_b I_b$ (N_b is a number of bunches). Therefore, one should expect dependence of lasing power with optimal tuning as

$$P_\ell \approx \alpha N_b I_b^{3/2};$$

where α depends on the parameters of the ring and the FEL. By operating with one and two electron bunches, we have found that the optimized lasing power fit reasonably well with expected dependence.

4. Present status of the OK-4 FEL

After one month of operation, which was mostly dedicated to γ-ray generation and spectrum measurements, the injector for the storage ring was shut down for seven months. During that time we have finished construction of the east optical shack, designed and built N_2-purged boxes for deep-UV user experiments and diagnostics. A three kicker system for the Duke storage ring has been built and commissioned.

At present, we proceed with development of the instrumentation required for the OK-4 FEL user program. The main requirements of the OK-4 user program is to operate in the 150–250 nm wavelength range with high peak and/or average power.

We are in the process of searching and ordering mirrors covering this wavelength range. Just before this conference, we have measured losses of the optical cavity with a set of used 193 nm mirrors. The losses turned out to be rather high (~12–15% per pass) and we plan to install a new set of mirrors for future experiments. We are preparing a system to measure the reflectivity of all new mirrors prior to their installation. The design of a gain modulator for the OK-4 FEL is in advanced stage and we expect to install it by the end of this year.

At present time most of the OK-4 FEL diagnostics are located inside a Plexiglas box which is connected hermetic tubes with CaF_2 windows of the OK-4 optical cavity as shown in Fig. 5. Similar systems are built for our user programs. The system should allow us to operate down to 150 nm. Nitrogen purge is essential for operating below 200 nm. As shown in Fig. 6, absorption in the air makes FEL spectra impossible to analyze.

Absence of absorbers and permanent crotch chambers prevents us from operating at 1 GeV with a large current and limits us to 10 mA at 750 MeV. With these beams we could not go far above a few watts of average laser power. The permanent crotch chambers and absorbers [20], which are nearly completed, are needed for full power (~100 W) operation of the OK-4/Duke storage ring FEL. It seems feasible that this system will be completed within a year and will provide the basis for a large number of synchrotron radiation beamlines.

5. Conclusions and plans

Commissioning the OK-4/Duke storage ring FEL demonstrated high quality of the cavity alignment, a good performance of the feedback and control systems, and a reasonably high gain. Initial evaluation of the OK-4 FEL parameters is in good agreement with our predictions. We do not expect serious problems with the attempt to lase below 200 nm in the near future. The development of the gain modulator, the permanent crotch-chambers with absorbers, and nitrogen purged beamlines are all in progress. Later this year we plan to use the OK-4 coherent and spontaneous radiation for user experiments. The pilot user program includes the UV cornea surgery, photo-electron emission microscopy, and nuclear γ-ray spectroscopy. These user systems are in the process of installation into the East and the West optical shacks (see Fig. 1) where they will share space with the OK-4 control and diagnostic systems.

This situation will drastically change with the construction of sizable extension of the existing FEL laboratory (Fig. 1) with dedicated areas for most of the existing and future OK-4 users.

Acknowledgements

This work is supported by US Office of Naval Research Contract #N00014-94-0818, AFOSR Contract No. F49620-93-1-0590, DURIP-95 Grant F49620-95-1-0476 and Russian Academy of Sciences. The authors are grateful to P. Cable, G. Detweiler, H. Goehring, M. Johnson, L. Kennard, C. Kornegay, H. Mercado, E. Szarmes from Duke University FEL Lab, V.V. Anashin, A. Bulygin, E.I. Gorniker, A.D. Oreshkov, V.M. Petrov, T.V. Shaftan, I.K. Sedlyarov, V.G. Vesherevitch, E.I. Zinin from BINP, Novosibirsk, for their important contributions to the design, construction and commissioning of the OK-4 FEL. The authors would like to thank P. G. O'Shea from Duke University FEL Lab, R. Jones from NCSU and J. L. Lancaster from Duke University for providing single-bunch injection capability. In addition we would like to acknowledge P.G. O'Shea for supervising operation of the linac injector and, operators J. Gustavsson and J. Widgren for operating the linac injector during the OK-4 FEL commissioning. The authors would like to thank R.S. Canon, C.R. Howell, N.R. Roberson, E.C. Schreiber, M. Spraker, W. Tornow and H.R. Weller from TUNL for γ-ray measurements and characterization.

References

[1] V. Litvinenko et al., Proc. PAC'93, 1993, p. 1442.
[2] I.B. Drobyazko et al., Nucl. Instr. and Meth. A 282 (1989) 424.
[3] V. Litvinenko et al., Proc. PAC'95, 1995, p. 213.
[4] A. Lumpkin et al., Initial dual-sweep streak camera measurements on the Duke storage ring OK-4 UV/visible FEL, Nucl. Instr. and Meth. A, these proceedings.
[5] V.N. Litvinenko et al., Phys. Rev. Lett. 78 (24) (1997) 4569.
[6] V.N. Litvinenko et al., SPIE 2988 (1997) 188.
[7] S.H. Park et al., The OK-4/Duke monochromaticγ-ray source: performance and predictions, Nucl. Instr. and Meth. A, these proceedings.
[8] V.N. Litvinenko, J.M.J. Madey, Nucl. Instr. and Meth. A 359 (1996) 580.
[9] V.N. Litvinenko, J.M.J. Madey, SPIE 2521 (1995).
[10] V.N. Litvinenko et al., Microtemporal structure in the OK-4/Duke storage ring UV FEL: theory and experiment, to be published.
[11] Y. Wu et al., Nucl. Instr. and Meth. A 375 (1996) 74.
[12] P. Wang et al., Proc. PAC'95, 1995, p. 1841.
[13] Y. Wu, et al., Proc. PAC'95, 1995, p. 2214.
[14] V.N. Litvinenko et al., Nucl. Instr. and Meth. A 375 (1996) 46.
[15] V.N. Litvinenko, V.M. Popik, T.V. Shaftan, N.A. Vinokurov, Nucl. Instr. and Meth. A 331 (1993) 26.
[16] G. Datoli et al., Phys. Rev. A (1988).
[17] V.N. Litvinenko, Nucl. Instr. and Meth. A 359 (1995) 50.
[18] V.N. Litvinenko et al., Nucl. Instr. and Meth. A 358 (1995) 334.
[19] N.A. Vinokurov, A.N. Skrinsky, Preprint 77. Institute of Nuclear Physics, 1977, Novosibirsk.
[20] V.N. Litvinenko et al., SPIE 2522 (1995) 473.