First UV/visible lasing with the OK-4/ Duke storage-ring FEL: design and initial performance

Vladimir Litvinenko, Ying Wu, Bentley Burnham, Seong Park, M. Emamian, et al.

Vladimir N. Litvinenko, Ying Wu, Bentley Burnham, Seong Hee Park, M. Emamian, J. Faircloth, S. Goetz, N. Hower, John M. J. Madey, J. Meyer, P. Morcombe, O. Oakeley, Jennifer Patterson, R. Sachtschale, G. Swift, P. Wang, Igor V. Pinayev, M. G. Fedotov, N. G. Gavrilov, V. M. Popik, V. N. Repkov, L. G. Isaeva, G. N. Kulipanov, G. Ya. Kurkin, S. F. Mikhailov, A. N. Skrinsky, Nikolai A. Vinokurov, P. D. Vobly, Eduard I. Zinin, Alex H. Lumpkin, Bingxin X. Yang, "First UV/visible lasing with the OK-4/Duke storage-ring FEL: design and initial performance," Proc. SPIE 2988, Free-Electron Laser Challenges, (15 May 1997); doi: 10.1117/12.274393

Event: Photonics West '97, 1997, San Jose, CA, United States

Invited Paper

First UV/visible lasing with the OK-4/Duke storage ring FEL: design and initial performance

V.N.Litvinenko, Y.Wu, B.Burnham, S.H.Park, M.Emamian, J.Faircloth, S.Goetz, N.Hower, J.M.J.Madey, J. Meyer, P.Morcombe, O.Oakeley, J.Patterson, R.Sachtschale, G.Swift, P.Wang

FEL Laboratory, Physics Department, Duke University, Durham, NC 27708, USA

I.V.Pinayev, M.G.Fedotov, N.G.Gavrilov, V.M.Popik, V.N.Repkov, L.G.Isaeva, G.N.Kulipanov, G.Ya.Kurkin, S.F.Mikhailov, A.N.Skrinsky, N.A.Vinokurov, P.D.Vobly, E.I.Zinin

Budker Institute of Nuclear Physics, Novosibirsk 630090, Russia

A.Lumpkin, B.Yang

APS, Argonne National Laboratory, Argonne, IL 60439, USA

ABSTRACT

The OK-4/Duke storage ring FEL was commissioned in November, 1996 and demonstrated lasing in the near UV and visible ranges (345-413 nm). The OK-4 is the first storage ring FEL with the shortest wavelength and highest power for UV FELs operating in the United States. During one month of operation we have performed preliminary measurements of the main parameters of the OK-4 FEL: its gain, lasing power and temporal structure. In addition to lasing, the OK-4/Duke FEL generated a nearly monochromatic (1% FWHM) 12.2 MeV γ-ray beam [1]. In this paper we describe the design and initial performance of the OK-4 /Duke storage ring FEL. We compare our predictions with lasing results. Our attempt to lase in the deep UV range (around 193 nm) is discussed. The OK-4 diagnostic systems and performance of its optical cavity are briefly described.

2. INTRODUCTION

The OK-4 /Duke storage ring FEL project is a collaboration of the Duke University Free Electron Laser Laboratory and the Budker Institute of Nuclear Physics established in 1992 [2]. The OK-4 FEL was built and operated in the 240-690 nm range using the VEPP-3 storage ring at Novosibirsk [3]. After commissioning the 1.1 GeV Duke storage ring in November, 1994 [4], the OK-4 FEL made a trip around the globe and came to Duke in May, 1995. It was installed on the Duke storage ring in November of the same year. Modifications of the Duke storage ring vacuum system for the OK-4 FEL and 54-meter long optical cavity were completed by August, 1996. A sophisticated feed-back and control system of optical cavity mirrors was later commissioned. Main part of the OK-4/Duke XUV FEL design, construction and installation team are shown in Fig.1. This photograph was made in front of the OK-4 on August 2, 1996, just one day before the installation of the shielding blocks and the start of OK-4 commissioning.

In August, 1996 commissioning of the OK-4 FEL with its optical cavity was initiated at a wavelength of 193 nm using a temporary power supply for the OK-4 buncher. The results of these runs were inconclusive because of strong ripples in this temporary supply. In addition, the mirror holder clamps were too strong reducing the radius of curvature of the mirrors and making the optical cavity unstable as shown by direct measurement in October, 1996. During the period September-October, 1996, power supplies for the OK-4 wigglers and buncher were brought close to specifications and a new set of mirrors with a central wavelength of 380 nm was installed for the first demonstration experiment. We have used a

 SPIE Vol. 2988 • 0277-786X/97/$10.00

different clamping technique to avoid mirror distortions. An UV streak-camera was brought to Duke from APS (Argonne National Laboratory) and has been used to measure electron bunch length, optical cavity length and FEL pulse length.

Fig. 1. Members of the OK-4/Duke XUV FEL design, construction and installation team at Duke (left to right, front to back): S.H.Park, M. Emamian, I.V.Pinayev, S.Goetz, P.Wang, P.Morcombe, H.Goehring, O.Oakeley, Y.Wu, B.Burnham, G.Detweiler, V.N.Litvinenko, C.Kornegay, N.Hower, J.Meyer, G.Swift, J.Faircloth and J.Patterson.

The very first OK-4 operation on November 13, 1996, was successful. The OK-4/Duke storage ring FEL demonstrated operation in the near UV/visible range with a tunability of ±18% around the center wavelength of 380 nm. Lasing was demonstrated at injection energy (267.5 MeV) and other operational energies (400 - 550 MeV) which were within the tunability range of the OK-4 wigglers and their power supply. The main problem was the "blind-folded" alignment of the electron beam with the optical cavity in the absence of beam position monitors (BPM). The high gain of the OK-4 FEL (>9% per pass at 3.5 mA/bunch) and low cavity losses (0.6% per pass at 380 nm) helped to solve this problem. We have used our OK-4 diagnostics and lasing for both electron and laser beam alignment. Two days later, using two 500 MeV electron bunches separated by one half of the storage ring circumference and lasing at 380 nm, we demonstrated the generation of 12.2 MeV γ-rays via intracavity Compton backscattering [1]. We demonstrated tunability of the γ-ray energy (up to 15 MeV) by tuning the laser wavelength and/or the energy of the electron beam. We conducted the study and measurements of the main parameters of the OK-4 FEL in parallel with these experiments. 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 to condition one of the klystrons. We expect to resume operation of the OK-4 FEL when conditioning is finished.

In Chapter 3 we present a description of the OK-4 FEL and the Duke storage ring. Chapter 4 gives a brief description of the OK-4 optical cavity and diagnostics. OK-4 FEL commissioning and results are described in Chapter 5. Chapter 6 contains conclusions and discussions of future plans for the OK-4/Duke XUV FEL.

3. THE OK-4/DUKE XUV STORAGE FEL

3.1 Duke storage ring

The Duke 1.1 GeV storage ring has a 34 meter long straight section dedicated for FEL operation. The present lattice has both transverse β-functions of 4 meters at the center of the OK-4 to optimize the gain. The storage ring RF system [5] operates at 178.5 MHz (64th harmonic of the revolution frequency) and can support up to 64 electron bunches. In multibunch mode (two or more bunches) we have used high order mode (HOM) tuners to suppress or reduce multi-bunch instability. The RF system has computer controlled low level electronics. The 150 kW RF cavity has two main and two HOM tuners with a 50 kW transmitter. The transmitter power limits the maximum accelerating voltage to 600 kV. Typical OK-4 FEL operation mode used RF voltage upto 550 kV. The storage ring is equipped with 54 beam-position monitors (BPM) but none of the BPM electronics are available. To operate the OK-4 FEL, we were forced to develop very complicated and labor-intensive methods to measure the orbit [4]. A set of local compensated bumps was used to align the electron beam in the OK-4 FEL. Orbit corrections took a substantial part of the time allocated for commissioning. We are planning to test two types of BPM electronics in the near future and equip the ring with the best units.

Table I. Recent 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, σ_s[ps][d]	
natural (low current)	15
with 5 mA in single bunch	60
Relative Energy spread, σE/E [d]	
natural (low current)	$2.9\cdot10^{-4}$
at 5 mA in single bunch	$1.1\cdot10^{-3}$
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 mode of multibunch injection from the 270 MeV linac; [c] In single injection mode with 1 nsec photocathode gun; [d] At 500 MeV, V_{RF}=500 kV; measured by the streak-camera [9] and dissector; [e] Expected from broad band impedance model with Z/n = 2.75 Ω; [f] Extracted as the top limit from the OK-4 spontaneous radiation spectra.

The existing linac-injector with maximum energy ~270 MeV was operating in photo-injector mode for these experiments [6]. Preparation of the linac for injection took most of our operational time (usually from 9 a.m. until 4-6 p.m.) leaving late evenings for the OK-4 and γ-ray shifts. Other problems were associated with the use of a single kicker for injection and low charge per bunch (0.1 nC, i.e 0.3 mA per shot) from the linac-injector operating in photocathode mode [6] limiting the maximum stored current to 8 mA/bunch. Photocathode operation required additional thermal heating of the cathode providing background thermionic emission in 10-15 buckets. We have also observed time drift of the injection pulses as large as 5 nsec, which must be investigated. Previous injection mode utilized a pulsed gun-kicker providing ~25-50 nsec long train of electron bunches but with substantially higher charge per RF bucket. We are planning to use this injection mode and a resonant kick-off system to store larger currents. We also plan to install two additional kickers to improve efficiency of injection. The main parameters of the low emittance Duke storage ring are published elsewhere [4,7]. An update of the parameters is summarized in Table I. Main parameters have been measured using a number of different techniques and are in good agreement with one another.

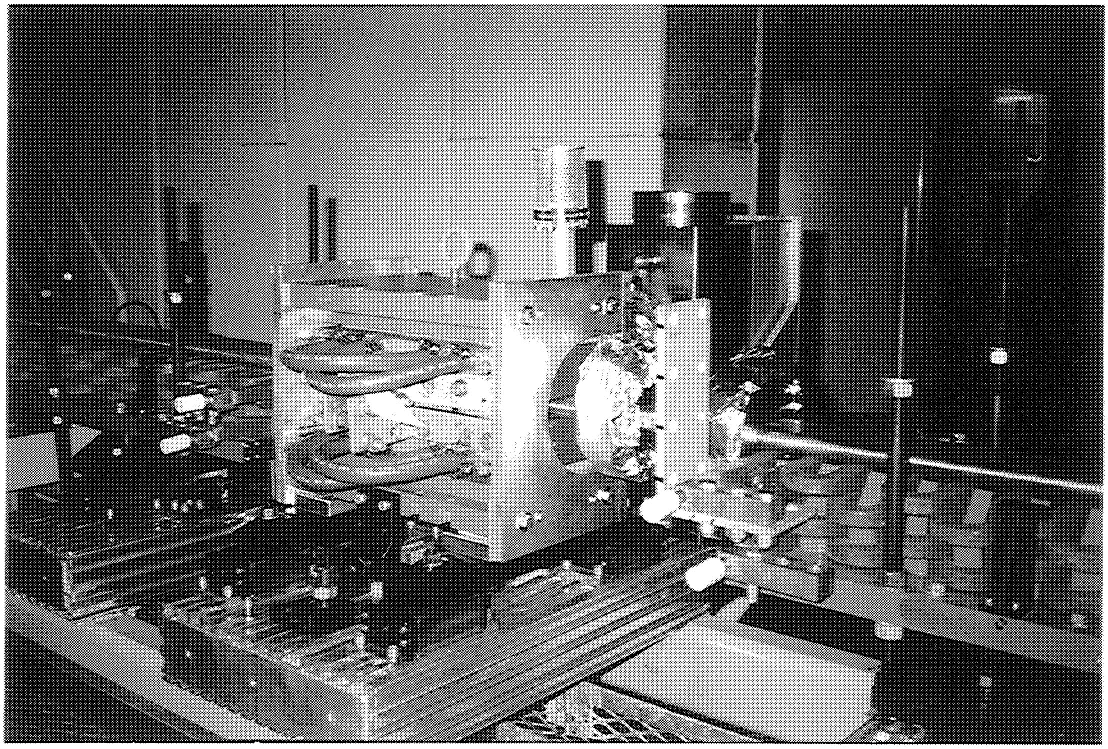

Fig.2. Two electro-magnetic wigglers and the buncher of the OK-4 FEL during installation in the South straight section of the Duke storage ring (October, 1995). The OK-4 buncher (at the center) and vacuum system are fully assembled. The wigglers have their tops off and expose details of the design: the wiggler yoke, the coils and the flat vacuum chambers.

3.2 OK-4 FEL

The main parameters and expected performance of the OK-4 FEL are described in previous publications [3,8]. Table II gives an up-to-date summary of the parameters. Fig. 2 shows the OK-4 magnetic system, comprising two electromagnetic wigglers and a buncher, in the process of installation on the ring. The magnetic system of the OK-4 FEL was slightly modified for installation on the Duke storage ring. 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 free from magnetic field collision point for the Compton γ-ray source. The 11 meter long vacuum chamber has 8 meters of constant cross-section and two 1.4 m long smooth transitions from the 2.2 cm x 7.5 cm flat shape to the 10 cm round pipe. Three ion pumps are located at the center and both ends of the system, providing vacuum pressures in the 10^{-10} torr range.

Two Trans-Rex (5 kA, 500 V) power supplies were donated to Duke by Fermi Lab and were in poor condition. They have been repaired, equipped with large external LC filters and are presently used to drive the OK-4 wigglers and buncher. During the August, 1996 runs only one Trans-Rex was operational and we used an old power supply for the buncher. This power supply had ripples ~2-3% and was the main obstacle to achieve lasing at 193 nm. In November, 1996 both Trans-Rex power supplies were operational.

Nevertheless, the wigglers' power supply had a current limitation at 2.1 kA which limited the maximum energy electron beam we could lase with at 380 nm. Recently, the wigglers' power supply was tested at the design value of the OK-4 wigglers (3 kA). This provides for full 16-fold wavelength tunability of the OK-4 fundamental hammmonic. Overall performance of the OK-4 power supplies is close to specifications (50 ppm DC and ripples) and will be improved in the near future using a second stage of regulation and feedback. The OK-4 wigglers have a set of trim coils which are not used due to the excellent quality of the wigglers' magnetic field. The buncher (a three pole electromagnetic wiggler) is slightly miscompensated and its trim coil has been used. The controls of the OK-4 power supplies are part of the Duke storage ring computer control system [10]. This 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 at injection energy and also at 400, 500, 550, 600, 700 and 750 MeV. Once established, the snapshot can be used to re-establish lasing.

Table II. The OK-4 FEL Parameters

Optical cavity		
	Optical cavity length [m]	53.73
	Radius of the mirrors [m]	27.27 [a]
	Rayleigh Range in OK-4 center [m]	3.3
	Angular control accuracy [rad]	better than 10^{-7}
OK-4 wiggler [3,8]		
	Period [cm]	10
	Number of periods	2 x 33.5
	Gap [cm]	2.25 [b]
	Kw/I [1/kA] measured	1.804
	Kw	0-5.4

[a] Measured; [b] Increased to accommodate new vacuum chamber.

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*. Non-smooth transitions keep impedance of the vacuum chamber rather large causing microwave bunch-lengthening to begin at ~0.1 mA per bunch at 500 MeV and is the main factor limiting the OK-4 gain. We have used a dissector with 15 psec resolution [11], the APS streak-camera, and spontaneous radiation spectrum measurements from the OK-4 to determine parameters of the electron beam in single bunch mode (Table I). According to the bunch-length and the OK-4 FEL gain measurements, the impedance of the vacuum chamber is ~2.75 Ohm. Detailed analysis of these measurements will be published separately.

4. THE OK-4 FEL OPTICAL CAVITY AND DIAGNOSTICS

The length of the OK-4 two mirror optical cavity is equal to one half of the ring circumference. The optical cavity mirrors are designed to have radii of 27.46 m and 4 m Rayleigh range at the OK-4 center to optimize the gain. The mirror substrates from UV grade fused silica were custom made by Lumonics Optics Group (Canada). Two sets of multi-layer dielectric mirrors with central wavelengths at 193 nm and 380 nm were manufactured. The 193 nm mirrors were used for the August, 1996 runs and the 380 nm mirrors for the November, 1996 runs. At our request, the 380 nm mirrors have a top layer of HfO to make the mirrors radiation resistant [3]. The strong absorption of HfO at 193 nm does not allow its use for protection of these mirrors.

The measured radii of the free-standing mirrors are shown in Table II and are within specified limits. The optical cavity is very close to the edge of stability and is extremely sensitive to angular misalignment of the mirrors. Deviations of the mirrors' angular position are amplified by a factor of 60 and translated into the angle of the optical axis. In addition, the cavity has very tight tolerance on the radii of the mirrors which can be modified by thermal and mechanical stresses. Details of the stability analysis and thermal effects on the cavity parameters will be published elsewhere [12]. Fig. 3 shows an 8.3 m long downstream part of the optical cavity vacuum system and the mirror support and alignment system (built in Novosibirsk and modified at Duke) installed on an optical table. After a careful study of the vibration and angular motions of the table and optical cavity mirrors we found them unacceptably large. We cut a slab out of the concrete floor around the perimeter of the table to reduce the vibrations and found substantial improvement. Nevertheless, effects of personnel and equipment movement in the laboratory provided an unacceptable level of vibration and angular displacements. To solve this problem we have built a new mirror adjustment system using a unique unit combining both feedback and controls. The system provides 100-150 Hz feedback bandwidth and 40 nanoradian accuracy of control with 100 nanoradian long-term stability of the angular position of the mirrors without backlash [11]. Typical angular vibrations of the OK-4 mirror on a very quiet evening (with no personnel or equipment moving in the laboratory) with and without the feedback system are shown of Fig.4.

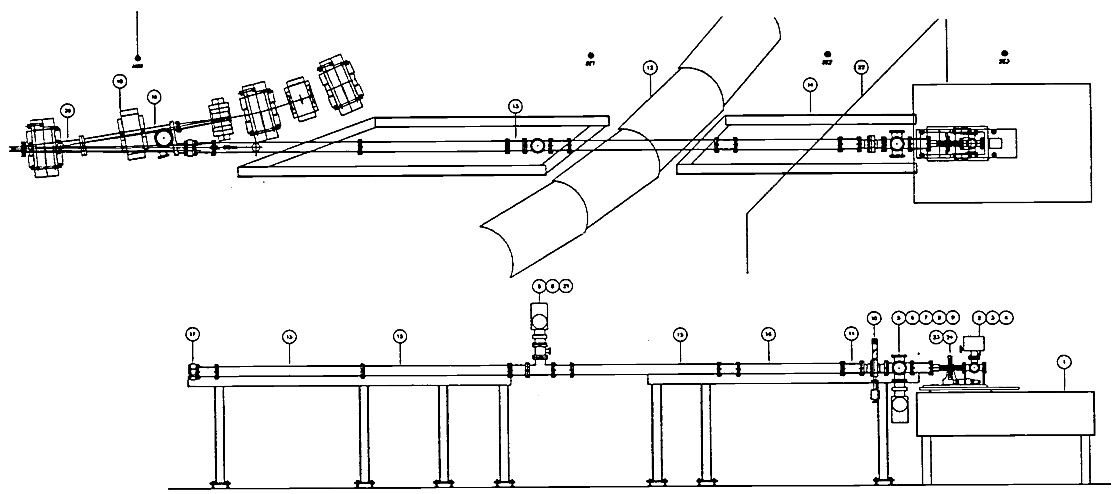

Fig. 3. Layout of the downstream wing of the OK-4 FEL optical cavity. The UHV chamber of the optical cavity penetrates the storage ring shielding and connects with the mirror system. The mirror system is installed on the 6x8 honeycomb optical table. The optical table is anchored to the concrete slab which is cut off from the main floor to reduce the level of vibrations. A similar design is employed for the upstream cavity. The vacuum chamber is terminated by 5 mm thick CaF windows at both ends. A remotely controlled periscope mirror is installed in front of the downstream mirror protecting it from undesirable exposure during storage ring tune-ups, and is used to extract spontaneous radiation from the OK-4 system through an additional CaF window.

The basic diagnostic system brought from BINP [3] together with the APS streak camera were heavily utilized during commissioning of the OK-4. The diagnostics incorporate the following [11]:

- ❑ A two port UV computer controlled monochromator equipped with an UV photomultiplier, CCD arrays, phosphor screens and video camera;
- ❑ CAMAC based precise 20-bit ADCs for tuning and spectrum measurements;
- ❑ Five CAMAC based 10-bit and 8-bit ADCs for fast measurements;
- ❑ EG&G 5202 Lock-in amplifier for optical cavity losses and length measurements;
- ❑ Mirror radii measurement system [12];
- ❑ Optical cavity feedback and control system [11];
- ❑ A stroboscopic dissector with 15 psec resolution;
- ❑ Six photon position monitors for orbit and tunes measurements and cavity control;
- ❑ Two He-Ne laser system with beam expanders for pre-alignment ;

- ❑ Two telescopes with autocollimation;
- ❑ Two vacuum gauges to monitor the vacuum near the mirrors.

During August, 1996 we found that the optical cavity exhibited behavior similar to an unstable one. We have used the precision (±5 cm for 30 m radius of curvature) mirror radius measurement system to measure the distortion caused by the stress from the mirror clamping/cooling device [12]. We found that distortions were asymmetric and caused a reduction of the radius of curvature below the stability threshold (R_c = 26.865 m for our cavity). We have used spring fingers to hold the 380 nm mirrors in the supports and did not observed any problems. High power and high energy operation of the OK-4 will require an efficient way to evacuate the heat generated in the mirror by spontaneous radiation. We are developing different options, including an all metal front mirror, metal turning flats and/or different types of clamps and UHV cooling techniques.

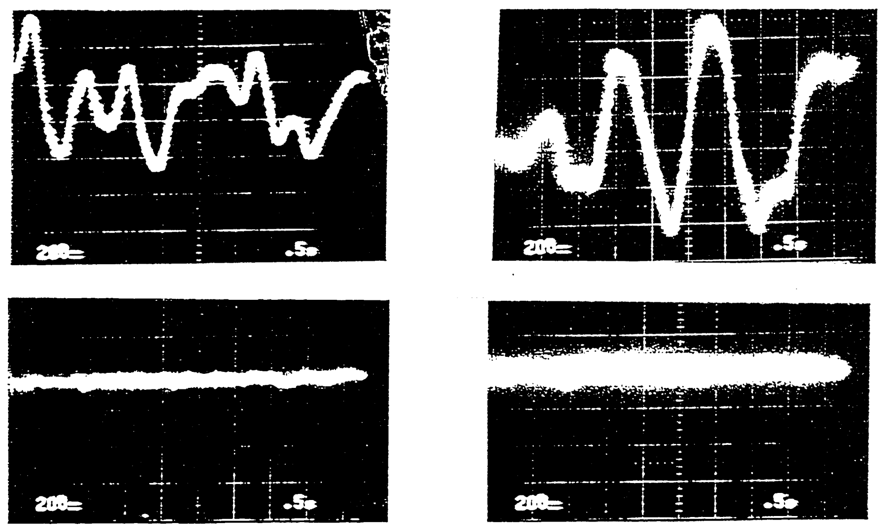

Fig. 4. The typical angular vibration of the optical cavity mirror measured with feedback off (top oscillograms) and on (bottom oscillograms) very late at night with no personnel or equipment moving in the laboratory. The angular position of the mirror was measured by an independent photon beam position monitor with a sensitivity of 24.8 mV/microradian. Without feedback, the mirror exhibited peak-to-peak angular vibration ~30 μrad in the horizontal plane and ~50 μrad in the vertical plane. In addition, a slow long term drift of the slab provided ~100-200 μrad per hour in both directions. Movement of a person in the vicinity of the optical table, or a car passing by outside the building, produced 3-5 times larger oscillations. With feedback on, residual vibrations were at the level of ± .04 μrad, and very high feedback DC gain (~10^4) provided for long term stability at the level of ± .1 μrad.

We have used a UV monochromator to measure spectra of the OK-4 spontaneous radiation. Measuring the spectra at different buncher settings one can determine the energy spread and estimate the emittance of the electron beam [3]. The results of this analysis are shown in Table I. Direct bunch length measurements with a dissector and streak camera were consistent with results extracted from the spectrum measurements. We did not observe diagnostic problems while operating above 200 nm. Operating below 200 nm we observed numerous oxygen and water absorption lines [4]. We plan to install a transport line purged with dry N_2 for operation below 200 nm. During the lasing attempt at 193 nm we used a second port of the monochromator equipped with a phosphor screen and a CCD video camera. We tuned the monochromator to 193 nm and recorded video images of the spectra using a VCR. This was our best attempt at laser observation with the unstable buncher power supply. In November, 1996 we did not have any problems using time averaged diagnostics.

5. COMMISSIONING OF OK-4/DUKE STORAGE RING FEL

We have established three main storage ring modes to operate the OK-4 FEL: injection energy of 260-270 MeV, 0.5 GeV and 0.7 GeV and a number of supplementary modes (350, 400, 550, 600, 650 and 750 MeV). We have measured β-functions in the OK-4 FEL and created computer tools to vary OK-4 wiggler current while keeping betatron tunes stable.

5.1. Lasing Attempt at 193 nm - August 1996.

On August 20, we ramped a single 6.5 mA bunch to 500 MeV and attempted to lase. The electron beam and optical cavity were pre-aligned using the technique described in [11]. We varied the RF frequency in the range ±0.043% (a circumference variation of ±4.6 cm) to synchronize revolution times of the optical and electron bunches. This range is substantially larger than the possible error in the length of the optical cavity. Ripples in the buncher power supply did not allow us to use time averaging diagnostics to study spectrum modifications due to the gain. We used a video system to record the spectra images at the phosphor screen. Each video frame contained a spectrum which is averaged over sampling time and is different from the instantaneous value. We have observed strong evidence of the amplification of spontaneous radiation correlated with peak current and detuning from synchronism. Fig.5 shows a few selected spectra captured by the system. The strange spot shapes of the captured spontaneous radiation and the high level of losses (>5%) in the cavity raised suspicions that the optical cavity is unstable which proved to be correct.

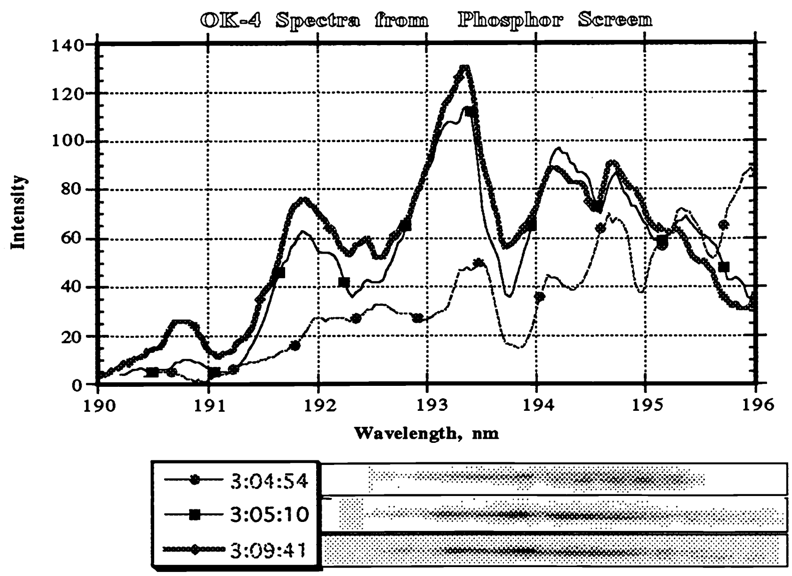

Fig.5. The spectra captured by a video camera from the phosphor screen installed at the exit of the monochromator on August 21, 1996 from 2:40 a.m. until 3:20 a.m. Energy of the electron beam is 500 MeV, K_w = 2.32, the plotted spectra were measured during a RF frequency scan. The period of the fine structure is about 1.3 nm and close to expectations. The video images of the spectra are shown below the graph . ● - time 3:04:54; current is 3.3 mA, maximum intensity around 193 nm is 50; ■ - time 3:05:10; current is 3.2 mA - maximum intensity around 193 nm is 115; ◆ - time 3:09:41; current is 3 mA - maximum intensity around 193 nm is 130.

Later studies (January, 1997) of the recorded images did show that even in these dire circumstances (unstable optical cavity and huge ripples in the buncher power supply) we observed the local saturation of the phosphor screen which may be indicative of lasing. We will repeat the 193 nm run with a stable system and measure a nice narrow lasing line around 193 nm before claiming lasing below 200 nm. We made a few runs in October 1996 with the streak camera measuring the bunch-lengthening of the electron beam. The last run with 193 nm mirrors was to measure the length of the optical cavity. We arranged for one reflection from the upstream mirror and measured the time difference between direct and reflected pulses by varying the revolution frequency. This measurement confirmed that the optical cavity length was within ±0.2 mm from the design length. After recognizing the problems with the optical cavity, we replaced the 193 nm mirrors with 380 nm mirrors (using different mirror clamps).

5.2. Lasing in the UV - November/December 1996.

Demonstration of lasing in the near UV was a much easier task. After two hours of low current operation (to provide out-gassing of the down-steam mirror and to achieve a vacuum reading in the low 10^{-9} torr range) we attempted to lase at injection energy. It took less than two hours of e-beam and optical cavity alignment to obtain first lasing at 380 nm. Knowledge of the optical cavity length proved to be very useful. Within two hours lasing at 400 MeV and 500 MeV was demonstrated as well. A few days later we demonstrated lasing at 550 MeV using the maximum available (at that time 2.1 kA) current in the OK-4 wigglers. Monochromatic γ-rays (with 1% FWHM resolution) 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 [13]. Small emittance of the electron beam ensures a high level of correlation between the observation angle and the energy of the generated γ-rays. These γ-rays were monochromatized by a lead collimator. Most of our shifts were dedicated to these studies and the results will be published elsewhere [1]. Some of the OK-4 FEL parameters were measured in parallel with the γ-ray experiments.

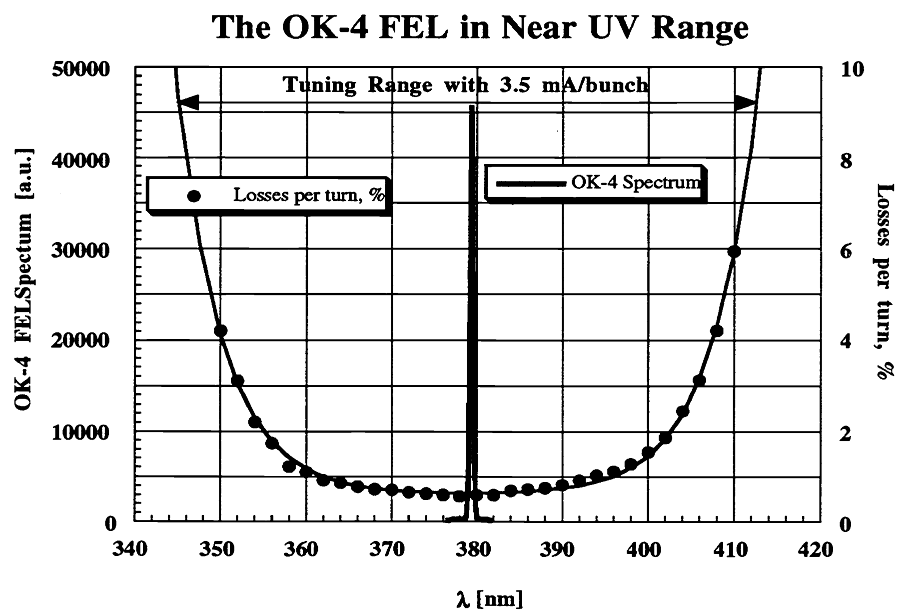

Fig. 6 The tuning range of the OK-4 FEL (with 3.5 mA/bunch at 500 MeV with 500 kV RF voltage) using 380 nm mirrors. The line in the center is a measured time average lasing line with RMS width of $\sigma_\lambda/\lambda=4.10^{-4}$ (which is presumably defined by small residual ripples in the power supplies). This line was tuned ±18% from 345 to 413 nm by changing the current in the OK-4 wigglers. The lasing range is determined by the growth of the cavity losses (mostly due to transparency of the mirrors) to the level of the OK-4 gain. The dots are 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. From the above curve we have concluded that the OK-4/Duke storage ring FEL gain with 3.5 mA/bunch 500 MeV electron beam and 500 kV RF voltage exceeds 9% at 345 nm.

A typical tuning range and one measured lasing spectrum are shown in Fig.6. Tuning within the range was straightforward by variation of the wigglers' current. Optical cavity losses were determined by a measurement of the optical cavity ring down time (see Fig.7). We have tuned the OK-4 lasing wavelength to the desirable value, kicked the electron beam to stop the lasing process, and measured the decay of the captured laser light. The damping time of the kicked beam was ~135 msec, i.e. much longer than the decay time of the laser light in the optical cavity. 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 optical klystron mode had higher gain and allowed us to lase with one or, if desired, two lasing lines (see Fig. 8).

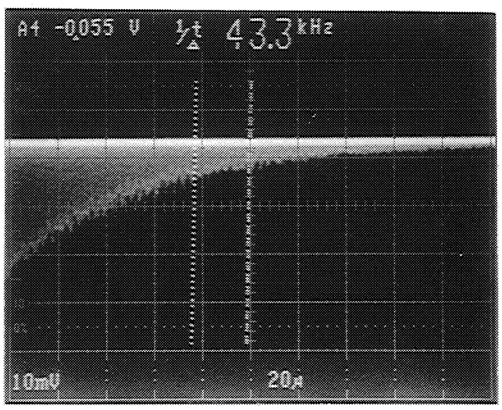

Fig. 7 The ring down of the OK-4 optical cavity at 377.5 nm. Horizontal scale is 20 msec per division.

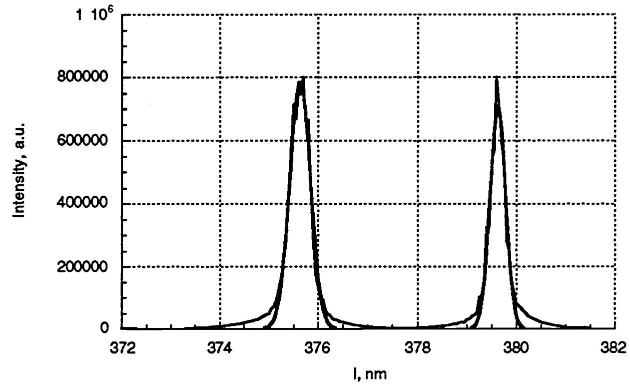

Fig. 8 Simultaneous lasing at two wavelengths in the OK-4/Duke FEL.

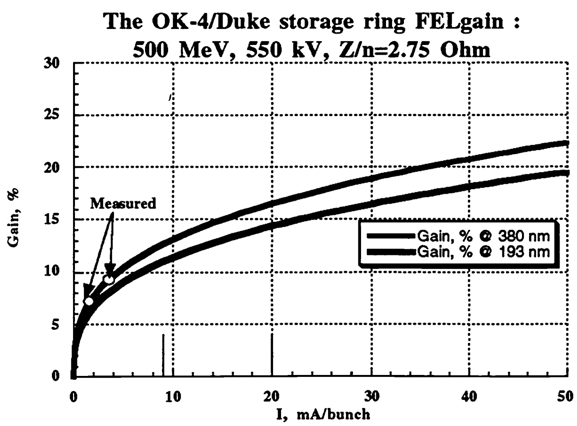

Fig. 9 The measured (dots, 345 nm) and predicted gain (solid lines) for 380 nm and 193 nm of the OK-4.

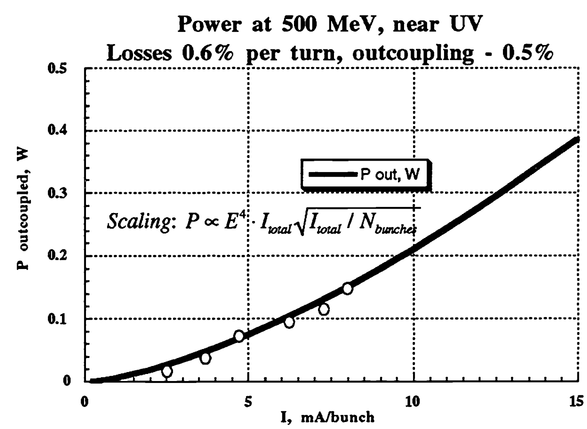

Fig. 10 Measured and predicted extracted lasing power from the OK-4 FEL. More than 80% of the power was extracted.

Figs. 9 and 10 show a comparison of the measured and predicted gain and extracted power from the OK-4 FEL in the near UV. We have used our self-consistent storage ring FEL code [14] and measured broadband (Z/n=2.75 Ohm) impedance model to predict the OK-4 performance. The FEL power was optimized by proper setting of the buncher current. We have used spontaneous radiation as a reference and a set of calibrated filters, a diaphragm, a monochromator and the transparency of the downstream mirror (measured by Lumonics Optics Group) to measure the extracted power. Expected accuracy is ±25%. At the present time we have an UV power meter and plan to repeat our measurements.

Indirect confirmation of the OK-4 FEL power was obtained from the observed γ-ray flux, which was within 20% of the predicted value [1]. The agreement of the measured and predicted values is very reasonable and we can rely on our predictions of the OK-4 FEL gain at 193 nm. With expected cavity losses less than 3% [12], the OK-4 should lase at 193 nm with a beam current of a few mA/bunch. With 10 mA per bunch and existing set of mirrors, we expect to lase within the 188-197 nm range.

Starting from sub-mA currents, the electron bunch length is determined by the microwave instability. During lasing the FEL interaction induces an additional energy spread. We have observed the increase of the energy spread and bunch length by a factor of 2-3 during lasing. Typical RMS values of the FEL pulse were 5-10 times shorter than the electron bunch length. Operating at very low current and using very precise tuning of the revolution frequency, we have registered FEL micropulses as short as 2.5 psec RMS with the APS streak-camera. The duration of these pulses is consistent with Super-modes predicted in [15]. The results of these studies were consistent with our expectations and will be published separately [16]. Table III gives a short summary of the measured OK-4/Duke storage ring parameters.

The macrostructure of the FEL exhibited typical modes: pulsed, stochastic and DC depending on the RF frequency and tuning of the e-beam orbit in the OK-4. Oscillations of the laser power were caused by ripples in our power supplies. We plan to reduce these ripples to an acceptable level. We have used a crude "gain modulation" by applying 60 Hz AC voltage to one of our trim dipoles. In turn we observed repeatable macro-pulses with 120 Hz rep-rate. A proper gain modulator is in the process of design and construction. It will be used for generation of giant- and super-pulses in the OK-4 FEL. In this mode we expect harmonic generation in the VUV.

Table III. Measured Parameters of the OK-4 FEL

Tuning Range (3.5 mA/bunch)]	345-413 nm
Gain per pass (3.5mA/bunch, 345 nm)	>9%
Extracted Power (8 mA, single bunch, 380 nm)	0.15 W [a]
Induced e-bunch length, σ_S[ps]	
low current	~35
with 3.5 mA in single bunch	~200
Induced energy spread (3.5mA/bunch), σ_E/E	0.35%
FEL pulse length [ps]	
low current	~2.5
with 3.5 mA in single bunch	~20
Linewidth σ_λ/λ	$4 \cdot 10^{-4}$ [b]
Lasing life-time	2-4 hours

[a] Measured; 75 mW per mirror. Accuracy ~ 25%;

[b] Time averaged value presumably caused by ripples in power supply, instantaneous value should be $\sim 1 \cdot 10^{-4}$.

Absence of absorbers and permanent crotch chambers prevent us from operating at 1 GeV with full 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 [17], which are nearly completed, are needed for full power (~100 W) operation of the OK-4/Duke storage ring FEL.

6. CONCLUSIONS AND PLANS

Commissioning the OK-4/Duke storage ring FEL demonstrated high performance of the cavity alignment, feedback, and control systems and reasonably high gain. Initial evaluation of the OK-4 FEL parameters is in good agreement with our predictions. We do not expect serious problems when we attempt to lase below 200 nm in the near future.

The gain modulator, the permanent crotch-chambers with absorbers, an UV optical room for the downstream mirror, and nitrogen purged beamlines are in progress. Later this summer we plan to begin use of the OK-4 coherent and spontaneous radiation for user experiments. The user program includes eye surgery, studies of PMM, photo-absorption and spectroscopy.

7. ACKNOWLEDGMENTS

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, J. Gustavsson, M. Johnson, L. Kennard, C.Kornegay, H.Mercado, and J. Widgren (Duke University FEL Lab), V.V. Anashin, A. Bulygin, E.I.Gorniker, A.D.Oreshkov, V.M.Petrov, T.V.Shaftan, I.K.Sedlyarov, E. Szarmes. V.G.Vesherevitch (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, J.L.Lancaster (Duke University) and R.Jones (NCSU) 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, J. Gustavsson and J. Widgren for keeping it operating all days and nights 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 (TUNL) for γ-ray measurements and characterization. In addition we would like to thank K.D.Straub for the development of the OK-4 FEL user program.

REFERENCES

[1] V.N.Litvinenko et al., "Gamma-ray Production in a Storage Ring Free Electron Laser", submitted for publication in Physics Review Letters.
[2] V.Litvinenko, J.M.J.Madey and N.A.Vinokurov, Proc. of 1993 Particle Accelerator Conference, Washington, DC, May 17-20,1993, v.2, p.1442.
[3] V.N.Litvinenko, "The optical klystron on VEPP-3 storage ring bypass - lasing in the visible and the ultraviolet", Thesis, Novosibirsk, 1989;
I.B.Drobyazko et al., Nucl. Instr. and Meth., A282 (1989) 424.
[4] V.N.Litvinenko et al., Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, V.I, p. 213.
[5] P.Wang, G.Kurkin, Y.Wu., Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p. 1841.
[6] P.G.O'Shea et al., "Single bunch injection...", to be published; P.G.O'Shea et al, Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p. 1090.
[7] Y.Wu et al., Nucl. Instr. and Meth., A375 (1996) p. 74.
[8] V.N.Litvinenko et al., Nucl. Instr. and Meth., A375 (1996) p. 46.
[9] A.Lumpkin, B.Yang, Argonne National Laboratory, Private communication.
[10] Y.Wu, B.Burnham, V.N.Litvinenko, "The Duke Storage Ring Control System" Proc. of 1995 Particle Accelerator Conference, Dallas, TX, May 1-5, 1995, p.2214.
[11] I.V.Pinayev et al., "Diagnostics for the OK-4/Duke storage ring XUV FEL", Presented at 18th International FEL conference, Rome, Italy, August 26-31, 1996, to be published.
[12] S.H.Park et al., "Study of stability and thermal distortion of the optical resonator for the OK-4 /Duke XUV FEL", Presented at 18th International FEL conference, Rome, Italy, August 26-31, 1996, to be published.
[13] V.N.Litvinenko and J.M.J.Madey, Nucl. Instr. and Meth., A359 (1996) 580;
V.N.Litvinenko and J.M.J.Madey, SPIE v.2521 (1995) 55.
[14] V.N.Litvinenko, Nucl. Instr. and Meth., A359 (1995) 50;
V.N.Litvinenko et al., Nucl. Instr. and Meth., A358 (1995) p.334, p.369.
[15] G.Datoli et al., Phys. Rev. A (April, 1988).
[16] V.N.Litvinenko, A.Lumpkin, et al., "Study of the microtemporal structure of the OK-4/Duke UV FEL", to be published.
[17] V.N.Litvinenko et al., SPIE v.2522 (1995) p. 473.