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ABSTRACT

The OK-4/Duke storage ring free electron laser (FEL) was commissioned in November, 1996 and demonstrated lasing in the near UV and visible ranges (345-413 nm). During one month of operation we 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 status of the main subsystems including the injector system and the ring itself, and discuss future and in-progress upgrades to these systems. We also describe the parameters measured to date of the injector, the storage ring, the generated optical laser beams, and the backscattered γ-ray beam.

Keywords: storage ring, free electron lasers, γ-ray beams

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. The collaboration was 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 of the 1.1 GeV Duke storage ring was completed in early 1995[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.

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 and a partial blockage of the optical cavity by a misplaced flange. 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 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, later, for measurements of FEL pulse lengths.

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1. STORAGE RING

The Duke electron storage ring has been operational since November, 1994. Almost all experiments on the machine have been done in-house while we have determined operational parameters and been making improvements. The schedule up to now has been one day of operations per week due to the shared klystron with the Mark III laser system. This schedule greatly slows our ability to make changes and test performance. Nevertheless, we have performed enough measurements to determine many parameters of the ring which are summarized in Table I.

Table I. Recent Duke Storage Ring Electron Beam Parameters

Operational Energy [GeV]	0.23-1.1
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, $\sigma E/E$ [d]	
natural (low current)	$2.9 \cdot 10^{-4}$
at 5 mA in single bunch	$1.1 \cdot 10^{-3}$
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	< 9 [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 a streak-camera[5] 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 present limit of the storage ring injection energy is about 270 MeV using 11 SLAC Mark III type linac sections driven by three klystrons[6]. Typical energy injection is usually 262 MeV, a lower energy than preferred, but one which keeps the waveguides from arcing. The klystron which drives the last four sections is also responsible for driving the Mark III infrared laser accelerator section, allowing for only one machine to be operational at a time.

Two options are under consideration to improve the injection system. The first is to upgrade the existing linac injector which will still limit our capability for gamma ray production in which high current and low residual radiation are required. The second, and more promising, option is to build a synchrotron booster capable of efficiently delivering full energy beam with low radiation levels.

Plans are also underway to separate the Mark III laser klystron from the storage ring linac by placing a new klystron in the ring room to drive the last four linac sections. This separation of function would allow simultaneous use of the machines for different experiments or even pump-probe experiments where both lasers may be used at the same time. Early experiments using the synchrotron radiation from a bend magnet, prior to installation of the OK-4, were done using this method by first storing beam in the ring and then quickly switching the shared klystron over to the Mark III to drive the infrared laser. Obviously this was problematical when the ring inadvertently dumped its beam or when the Mark III could not be brought up to lasing in sufficient time relative to the lifetime of the storage ring beam.

There are many plans in the upgrade path for the storage ring to increase its stored current, lifetime, and usefulness to users and their experiments. Presently the ring is limited in synchrotron output power due to the temporary crotch chambers where the laser light and electron beams separate at the end of the south straight section. The temporary crotch chambers do not have absorbers for synchrotron radiation and can not support full energy, full current operation of the storage ring. Although the storage ring is capable of maintaining this kind of output, we keep the current or energy artificially low to keep unprotected vacuum chambers from accidents.

The solution to this problem in our design is a new set of crotch. In place of the temporary chamber wall at the separation point is a large water cooled copper cylinder absorber capable of handling the 1.5 kilowatts of power per magnet eventually delivered in the system at 1.1 GeV and 1 amp current. These new chambers also have larger apertures for the light to pass through resulting in lower fringe losses and easier optical beam transport.

With the addition of the new crotch chambers and the resulting higher currents being stored, the injection system is also being upgraded. Until very recently, operations have used only a single kicker magnet to combine the stored and injected beams just downstream of the septum magnet. When the two beams emerge from the septum magnet with only one kicker operating, they are 25 millimeters apart in transverse space and the kicker deflects both beams. A fair amount of the beam is lost in this method because the single kicker adversely disturbs the closed orbit of the beam. This tends to make filling process time consuming and unstable. The first operation using three kicker magnets was achieved on July 11, 1997. Beam stacking was accomplished quickly with fewer losses than with a single kicker, and 10 milliamps of current were stored in the ring in just a few minutes. Jitter in the timing system, however, injected these electrons across four potential buckets. In order to remove the extra electron bunches a new resonant kick-off system has been developed and installed. The system drives a RF signal into one of the beam position monitor striplines. Locked to a higher harmonic of the ring RF frequency, the kick-offsystem's RF pulse is non-zero when an unwanted bunch is passing by, and is crossing zero when a needed bunch is passing. This system will allow us to keep one, two, or four equally spaced bunches around the storage ring if desired, and with phasing we can target specific bunches for termination.

Another symptom of the higher currents is synchrotron radiation emitted in the arcs of the storage ring impinging on the absorbers in the dipole vacuum chambers. Outgassing by synchrotron radiation causes the vacuum pressure to rise. Each dipole has an associated ion pump. Built into the design of the dipole vacuum chamber is space for a strip of getter material which is placed directly adjacent to the wall where material is being ejected by the synchrotron radiation. The getter pumps have not been installed yet, but if they are installed we may see improved vacuum performance.

Improvements also are under way on the storage ring quadrupole power supplies. The 2 kW Power Ten supplies exhibit a warm up period of several minutes over which time the current may drift several milliamps from a level of 10 amps. This is enough to cause orbit distortions affecting operation of the optical klystron laser system. Presently we use a slow feedback system utilizing the readback from the power supply shunt resistors. Readings are averaged over five minutes and then a correction is calculated and applied to the supplies. Over the long term, approximately 20 minutes, the supplies are right on their setpoints, but having to wait 20 minutes every time we adjust the energy setting is too much. We are developing an individual electronic feedback system to the power supplies to stabilize their output and remove the drift and other slow variations such as line voltage drift and load variations caused by changes in magnet temperature. This is made in real time so that no external corrections should be necessary from the operators and the resulting stability will improve ring performance.

The Duke storage ring was commissioned without the benefit of beam position monitors[4] (BPM). Diagnostics on beam position were done using the synchrotron radiation from only four bend magnets in the corners of the ring. Studies on the orbit involved a time consuming procedure of using a certain quadrupole to mis-steer the beam, then applying a correction using nearby dipole magnets to bring the beam back to its original position on a screen monitored by a video camera. The orbit was then calculated from the strength of the dipole correction field and changes in the quadrupole setting. Not only was this time consuming, but the measurements were not very accurate and repeatability was difficult to achieve. 64 stripline BPMs exist throughout the ring, but no electronics have yet been attached to them. We are currently testing two designs of BPM electronics. With a successful test, we should be able to place an order for a full complement of electronics in order to be able to measure the orbit directly.

With the success of the Compton scattered γ-ray experiment[1] the demand for gamma rays in the laboratory will go up as will the demand for quality and brightness of the γ-beam. The present single RF cavity[7] is sufficient to drive the beam and keep it bunched and stored. In gamma-ray mode, however, the ring must operate with two equally separated bunches circulating. With one RF system, both bunches are lasing and both bunches are also colliding with the other bunch's laser light. Lasing increases the energy spread of the electron bunch. This increase in the energy spread reduces the energy resolution of the γ-rays. One method for increasing the gamma-ray output while also maintaining good quality is to ensure that one of the electron bunches does not lase. To this end we propose to install a higher odd harmonic RF cavity which will maintain the compression of one of the electron bunches, but will expand the second bunch longitudinally in space. The expansion lowers the peak current of the bunch below the threshold for lasing, but enough electrons are still available for collision with the optical beam from the first bunch. The RF cavity presently installed runs at the 64th harmonic of the ring revolution frequency. The new cavity will run at the 255th harmonic of the revolution frequency. Not only will the new cavity allow the two bunches to have different bunch lengths, but also will decouple their synchrotron tunes, thereby suppressing multibunch instabilities and removing coupled resonances.

2. FREE ELECTRON LASER

The OK-4 optical klystron first operated on the Duke storage ring in November of 1995 as a spontaneous source. One year later the OK-4 was commissioned as a laser when light was generated in the continuous range 345-413 nm. Several parameters of the optical cavity and OK-4 wiggler are summarized in Table II.

Table II. OK-4 FEL Parameters

Optical cavity		
	Optical cavity length [m]	53.73
	Radius of mirrors [m]	27.27[a]
	Rayleigh range in center of OK-4 [m]	3.3
	Angular control accuracy [rad]	$< 10^{-7}$
OK-4 wiggler [3, 8]		
	Period [m]	0.1
	Number of periods	2 x 33.5
	Gap [cm]	2.25[b]
	K_w / I [1/kA] measured	1.804
	K_w	0-5.4

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

The measured parameters of the OK-4 FEL are summarized in Table III.

Table III Measured Parameters of the OK-4 FEL

Tuning range (3.5 mA / bunch)	345-413 nm
Gain per pass (3.5 mA / bunch, 345 nm)	> 9%
Extracted power (8 mA, 380 nm)	150 mW[a]
Induced electron bunch length, σ_s [ps]	
low current	~ 35
3.5 mA in single bunch	~ 200
Induced energy spread (3.5 mA / bunch), σ_E / E	0.35%
FEL pulse length [ps]	
low current	~ 2.5
3.5 mA in single bunch	~ 20
Linewidth σ_λ / λ	4×10^{-4} [b]
Lasing lifetime	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 ~ 10^{-4}.

A typical spontaneous radiation spectrum from the OK-4 is shown in Figure I. The wiggler and buncher power supplies are two Trans-Rex 500 kW supplies capable of pushing 5000 amps into 100 volts. Careful attention was placed on theoretical models of the external output filters at the time of installation on the ring, but some residual current fluctuations still exist. A special active circuit has been designed as a last stage of regulation of the Trans-Rex current to reduce these low frequency oscillations by at least 20 dB in power. The application of this regulation should get the laser linewidth down to the 10^{-4} level where it is expected to be.

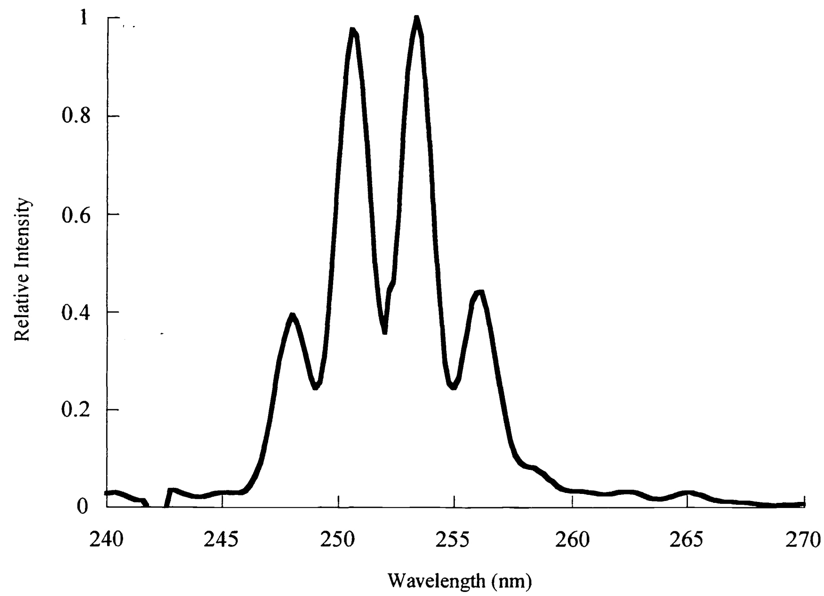

Figure I. Spontaneous radiation spectrum from OK-4 wiggler operating at 490 A, buncher current = 420 A, stored beam current = 2.9 mA.

The fine structure associated with the OK-4 in Figure I is due to the buncher influence on the spontaneous radiation. The peaks can be shifted by adjustment of the buncher current, and if two peaks near the center of the curve are nearly the same height, laser gain can be optimal for two wavelengths simultaneously. An example of this two line lasing is shown in Figure II.

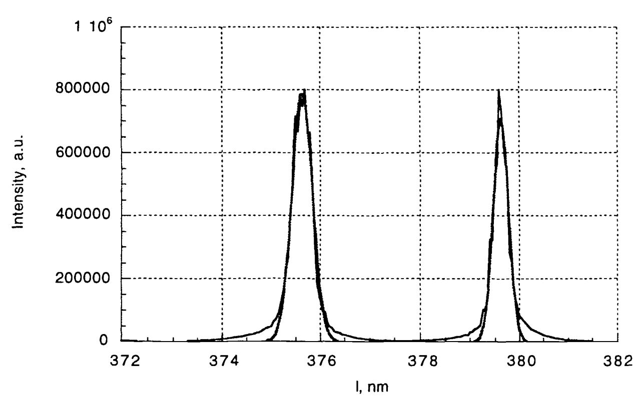

Figure II. Simultaneous two line lasing. Note that this graph is not directly associated with Figure I.

Figure III shows a lasing line in the OK-4 at 380 nm.

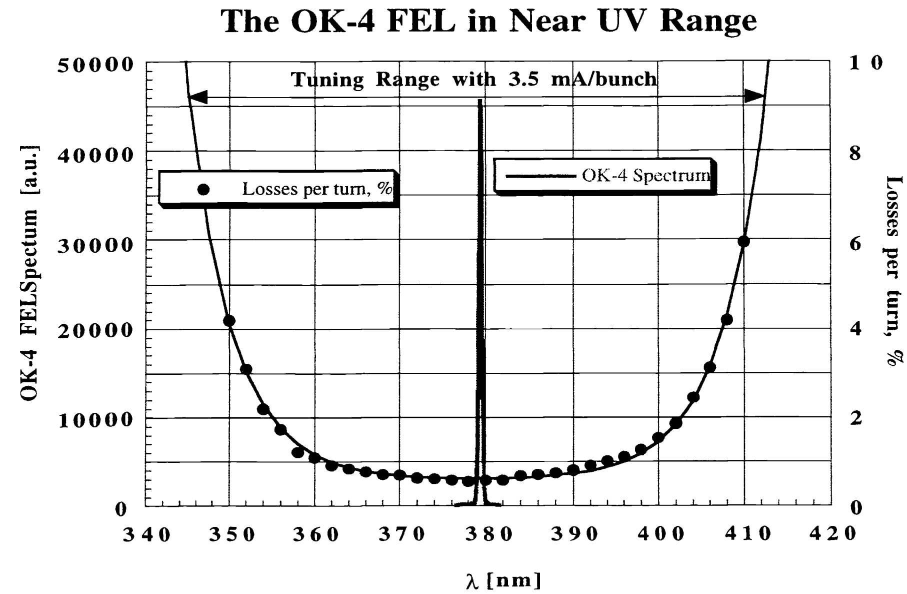

Figure III. The tuning range of the OK-4 FEL (with 3.5 mA/bunch at 500 MeV with 500 kV RF voltage) using 380 nm mirrors. The line in the center is a measured time average lasing line with RMS width of $\sigma_\lambda/\lambda = 4.10^{-4}$ (which is presumably defined by small residual ripples in the power 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.

The first γ-rays observed from theOK-4 were obtained in December of 1996 using a 10 inch by 10 inch NaI detector placed approximately 30 meters from the electron-laser collision point. The flux, corrected for detector efficiency and a lead attenuator, was 2.0×10^5 γ/sec. Comparing this number to the calculated flux of 2.6×10^5 γ/sec shows very good agreement. A second measurement was made using a high purity germanium detector which has an energy resolution of 5 keV for 12 MeV γ-rays. The beam in this case was collimated with a lead collimator in order to monochromatize the γ-rays. Differentcollimators with diameters ranging from 3 to 10 mm were tried. The resulting spectrum of a 3 mm collimator is shown in Figure IV. The figure represents the convolution of the γ-ray energy distribution with the detector response function. Another measurement determined that the polarization of the γ-ray beam was close 100% as expected for a planar undulator like the OK-4. The improvements to the storage ring discussed elsewhere in this paper will also be aimed at improving the resolution of the γ-rays from the OK-4. The data presented here show a resolution of 1%, but improvements may allow us to get to 0.1% resolution in the future.

Several upgrades are in the works for the OK-4 beamline. We plan on purchasing enough mirrors to cover the spectrum from 150 - 420 nm, subject to interest in a given wavelength range. Changing mirrors takes at least one day for each mirror to break vacuum, replace the mirror, close the system, and pump back down.

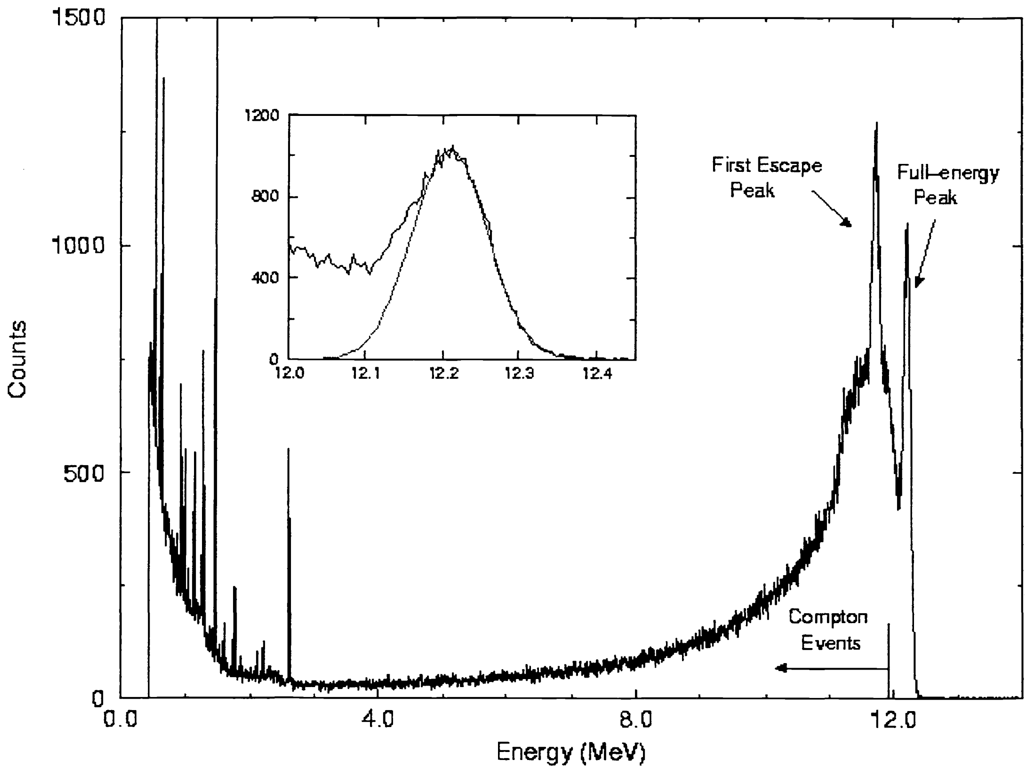

Figure IV. Full γ-ray spectrum produced in the Duke OK-4 optical klystron. The full energy peak at 12.2 MeV is evident as well as the first escape peak. The inset shows a Gaussian fit to the full energy peak with a full width half maximum of 120 keV.

Tests of the mirrors showed a significant distortion of the surface when the mirror was seated and clamped to its holder. Even a small amount of pressure from the clamps showed a noticeable distortion in the radius of curvature. Studies are under way using a finite element program to simulate the distortions in the surface under different conditions. In conjunction with the design team, these tests will yield a new holder which will minimize distortions in the mirror surface.

Other FEL improvements include a vacuum optical station, an in-situ circular polarizer, and a ring resonator[9]. The vacuum optical station will allow experiments in the vacuum ultraviolet where absorption in the atmosphere is large. We are in the process of setting up a nitrogen purged optical station as a first step to the vacuum station. Diagnostics in the endstation include a Russian made monochromator, photomultipliers, power meter, dissector, and phosphor screens. A new spectrograph is also being developed, and a proposal for a Hamamatsu streak camera is under review. The monochromator has three gratings which can be interchanged offering acquisition in the ranges 100 - 500 nm, 200 - 1000 nm, and 400 - 2000 nm.

The in-situ circular polarizer is a set of plates which can be placed directly in the laser beam optical cavity in order to create a circularly polarized beam from the original plane polarized beam. This polarizer will be used for the generation of circular polarized γ-rays[10] for special nuclear physics experiments.

For high power UV applications we propose designing a ring resonator which reflects the optical beam at grazing incidence from many mirrors. In our case a 180 degree turn would take reflections from ten mirrors. Another parabolic mirror may also be placed at the center of the resonator beam path for extra focusing.

3. SUMMARY AND CONCLUSIONS

The OK-4 and storage ring performancehave met our expectations given existing constraints of hardware. With the current system in place we do not expect any serious problems to lase below 200 nm in the near future. Continued upgrades in the storage ring magnets, power supplies, vacuum chambers, optical cavity, and many other systems will further improve the output power and stability of the OK-4 beam. A new extension on the building is planned for the Fall of 1997. This new wing will contain experimental areas for users including a γ-ray target room for nuclear physics experiments. The expansion of the user program on the OK-4 and Duke storage ring will open up many opportunities for experimenters worldwide.

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