UNIQUE FEATURES OF THE OK-4/DUKE STORAGE RING XUV FEL AND MONOCHROMATIC γ-RAY SOURCE.

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Abstract

The OK-4 is the first storage ring FEL operating in the United States. It was commissioned in November, 1996 and demonstrated lasing in the near UV and visible ranges (345-413 nm) with extracted power of 0.15 W [1]. In addition to lasing, the OK-4/Duke FEL generated a nearly monochromatic (1% FWHM) γ-ray beam [2]. In this paper we describe the initial performance of the OK-4 /Duke storage ring FEL and γ-ray source.

1. 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 begun in 1992 [3]. The OK-4 FEL was built and operated in the 240-690 nm range using the VEPP-3 storage ring at Novosibirsk [4]. After commissioning the 1.1 GeV Duke storage ring in November, 1994 [5], the OK-4 FEL made a trip around the globe to Duke in May, 1995. The OK-4/Duke FEL was ready for the first demonstration experiment in November, 1996. The first run on November 13, 1996 with the OK-4/Duke FEL was successful. The OK-4/Duke storage ring FEL demonstrated operation in the near UV/visible range and generated nearly monochromatic 3-15 MeV γ-rays via intracavity Compton backscattering.

2. THE OK-4/DUKE XUV STORAGE FEL

The Duke 1.1 GeV storage ring [5,9] has a 34 meter long straight section dedicated for FEL operation. The present lattice has transverse β-functions of 4 meters in both directions at the center of the OK-4 to optimize the gain. The storage ring RF system [7] operates at 178.5 MHz (64th harmonic of the revolution frequency). Typical OK-4 FEL operation mode applies an RF voltage of 500 kV. The existing 270 MeV injection system limits the maximum stored current to 8 mA/bunch. We plan to improve the efficiency of injection and increase single bunch current to 20-40 mA. Some parameters of the Duke storage ring are summarized in Table I. The main parameters and expected performance of the OK-4 FEL are described in previous publications [4,10]. Table II gives an up-to-date summary of the parameters. The magnetic system of the OK-4 FEL was slightly modified to accommodate a new vacuum chamber and to provide a field-free collision point for the Compton γ-ray source. Two Trans-Rex power supplies (5 kA, 500 V, donated by Fermi Lab) have been repaired, equipped with large external LC filters and are presently used to drive the OK-4 wigglers and buncher. 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 controls of the OK-4 FEL are part of the Duke storage ring computer control system [11]. 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.

Table I. Duke Storage Ring Electron Beam Parameters

Operational Energy [GeV]	0.25-1.1
Circumference [m]	107.46
Impedance of 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	15
with 5 mA in single bunch	60
Relative Energy spread, $\sigma E/E$ [d] natural	$2.9.10^{-4}$
at 5 mA in single bunch	$1.1.10^{-3}$
Peak Current [A] [d] with 5 mA/bunch	12
with 20 mA/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;*
[c] *In single injection mode with 1 nsec photocathode gun [8];*
[d] *At 500 MeV, V_{RF}=500 kV;*
[e] *Expected from broad band impedance model with Z/n = 2.75Ω;* [f] *Extracted from the OK-4 spontaneous radiation spectra.*

Table II. 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 [4,10]	
Period [cm]	10
Number of periods	2 x 33.5
Gap [cm]	2.25 [b]
Kw/I [1/kA]	1.804
Kw	0-5.4

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

We have installed temporary crotch chambers (*without absorbers and smooth transitions*) providing passage of the OK-4 optical beam to facilitate its commissioning. This makes the impedance of the vacuum chambers rather large. According to the bunch length and the OK-4 FEL gain measurements, the impedance of the vacuum chamber is ~2.75 Ohm.

3. COMMISSIONING OF OK-4 FEL AND γ-RAY SOURCE

Three main storage ring operational modes were established (injection energy of 0.265 GeV, at 0.5 GeV and 0.7 GeV the OK-4) along with a number of supplementary modes (between 0.35 and 0.75 GeV) for proper FEL operation. We have created computer tools to vary the OK-4 wiggler current while keeping the betatron tunes stable. It took less than two hours to obtain first lasing. Knowledge of the optical cavity length proved to be very useful [6]. Lasing was demonstrated at a variety of electron energies from 0.265 to 0.55 GeV. A standard operation energy was 500 MeV.

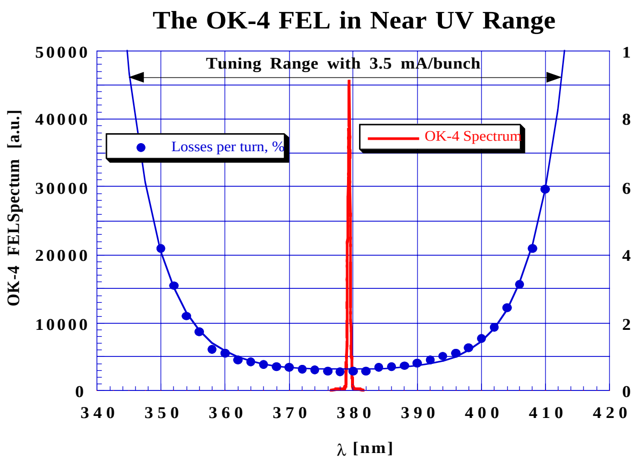

Fig. 1 The tuning range of the OK-4 FEL (with 3.5 mA/bunch at 500 MeV with 500 kV RF voltage) using 380 nm mirrors. The line in the center is a measured time lasing line. This line was tuned ±18% from 345 to 413 nm by changing the current in the OK-4 wigglers. The dots are measured round trip cavity 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: gain >9% at 345 nm with 3.5 mA/bunch, 500 MeV electron beam and 500 kV RF voltage .

A typical tuning range (obtained by variation of the wigglers' current) and one measured lasing spectrum are shown in Fig.1. Lasing was reasonably easy because the OK-4 gain was at least 10 times higher than its 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 and conventional FEL mode (buncher off). In all cases the optical klystron mode had higher gain and power. Figs. 2 and 3 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 [13] and broadband impedance model to predict the OK-4 performance. 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.

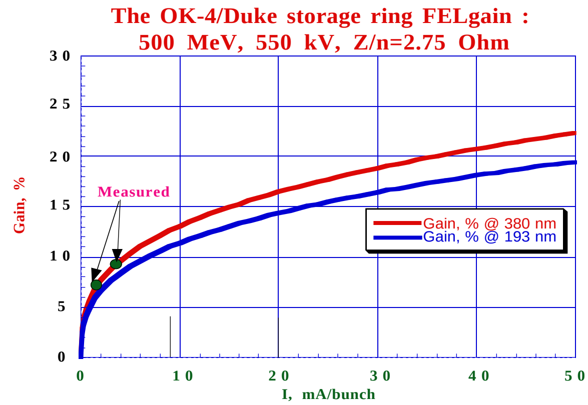

Fig. 2 The measured (dots, 345 nm) and predicted gain (solid lines) for 380 nm and 193 nm of the OK-4.

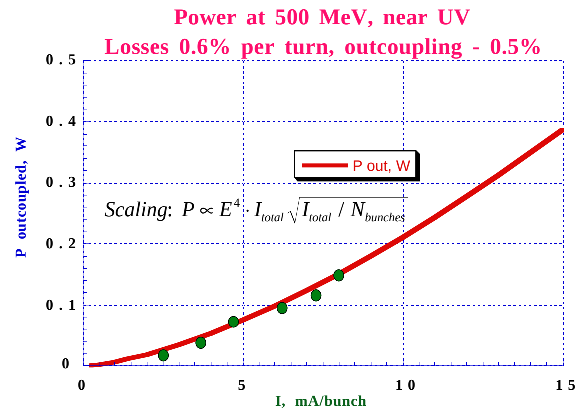

Fig. 3 Measured and predicted extracted lasing power from the OK-4 FEL. More than 80% of the power was extracted.

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, 380 nm)	0.15 W
Induced e-bunch length, σs[ps]	
low current	~35
with 3.5 mA in single bunch	~200
Induced energy spread (3.5mA/bunch), σE/E	0.45%
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 ~$1 \cdot 10^{-4}$.*

With expected cavity losses less than 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 existing set of mirrors, we expect to lase within the 188-197 nm range. We have observed an 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 [14]. Table III gives a summary of the measured OK-4/Duke storage ring parameters.

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 [12]. Small emittance of the electron beam ensures a high level of correlation between the observation angle θ and the energy of the generated γ-rays:

$$E_\gamma = \frac{4\gamma^2 E_{ph}}{1+(\gamma\theta)^2 + 4\gamma E_{ph}/mc^2};\ E_{ph} = \hbar\omega; \gamma = \frac{E_e}{mc^2}$$

A simple collimator can be used to select the most energetic γ-rays near θ=0. Using a lead collimator with 3 mm diameter (located 30 m downstream from the collision point) and a Ge detector we measured the 1% FWHM energy resolution of the γ-rays. We demonstrated the tunability of γ-ray energy within the 3-15 MeV range tuning both the laser wavelength ($\pm$18%) and the energy of the electron beam (265-550 MeV). Most of our shifts were dedicated to these studies and the results will be published elsewhere [2].

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 in December, 1997 to condition one of the klystrons. We expect to resume operation of the OK-4 FEL when conditioning is finished.

4. CONCLUSIONS AND PLANS

Commissioning the OK-4/Duke storage ring FEL demonstrated high performance 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, and nitrogen purged beamlines are in progress. The gain modulator will provide for high intracavity power and generation of coherent VUV harmonics. Later this year we plan to begin use of the OK-4 coherent and spontaneous radiation as well as monochromatic γ-rays for user experiments. The user program includes nuclear γ-ray spectroscopy, UV cornea surgery, studies of PMM, photo-absorption and spectroscopy.

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 [15] are needed for full power (~100 W) operation of the OK-4/Duke storage ring FEL and full flux operation of the γ-ray source (10^9-10^{11} γs/sec). We plan to install them in 1998. Long term plans for the OK-4 include extension to the VUV range.

5. ACKNOWLEDGMENTS

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