THE DUKE XUV FEL STORAGE RING FACILITY

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Abstract

In this paper we present status and developments of the Duke storage ring facility. The Duke storage ring facility provides the unique combination of phase-locked light sources ranging from high power OK-4 XUV FEL to quasi-monochromatic γ-ray beam and IR/X-ray spontaneous radiation.

The XUV OK-4 FEL, which is collaborative project with BINP, Novosibirsk, is in operation since November, 1996. The OK-4 UV FEL is also used for production of nearly monochromatic γ-ray s with tunable energy. We present the results of UV lasing with the OK-4 FEL and selected results of its applications. We will discuss our future plans for extension of this source and status of the construction of dedicated used facility adjacent to the FEL building.

1 INTRODUCTION

At present time, the Duke storage ring FEL facility started the pilot user program utilizing the UV/VUV radiation from the OK-4 FEL. Very intense program of modifications, up-grades and beam-line construction is under way. The new Keck Life Science Laboratory - a two story building to host for the UV, X-ray, γ-ray and IR user stations - is under construction since end of March, 1998. and planned to be completed within one year. General layout of the Duke FEL storage ring facility is shown on Fig 1. The heart of the facility is the OK-4 /Duke storage ring FEL which a collaborative project of the Duke University Free Electron Laser Laboratory and the Budker Institute of Nuclear Physics since 1992 [3]. In the past, the OK-4 FEL was operating 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 prepared 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.

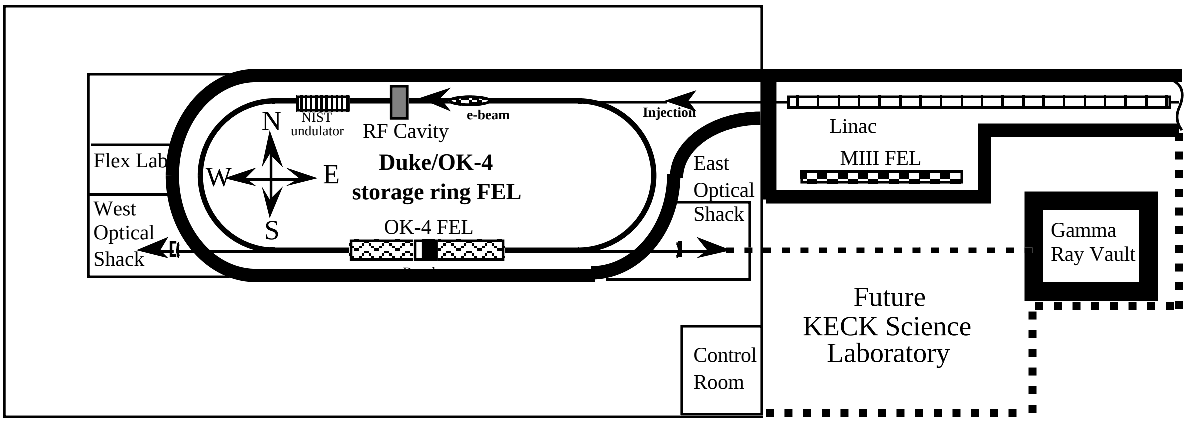

Fig. 1 Layout of the Duke/OK-4 storage ring FEL facility. The 1.1 GeV Duke storage ring is surrounded by 2’ concrete shielding. Two mirrors of the 53.73 m long OK-4 optical cavity and its diagnostics are located outside of the shielding in the optical shacks. These shacks and a flex -lab are used for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

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 low-current 240 MeV linac-injector limits the maximum stored current to 8 mA/bunch. We plan to improve the injector 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 OK-4 FEL 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. 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, σE/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. Three main and large number of supplementary modes were established between 0.25 and 0.55 GeV for the OK-4 commissioning. We have created computer tools to vary the OK-4 wiggler current while keeping the betatron tunes stable.

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

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 0.25 to 0.55 GeV. A standard operation energy was 0.5 MeV.

The OK-4 FEL in Near UV Range

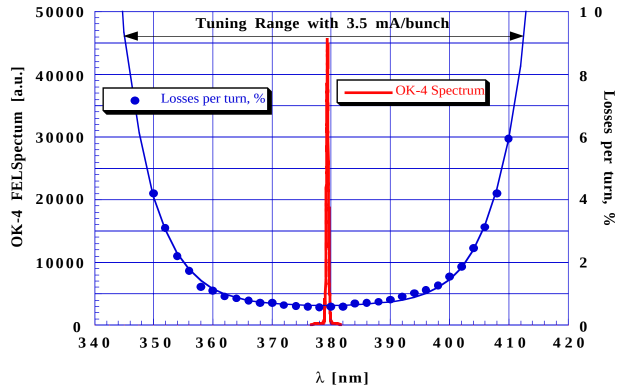

Fig. 2 The tuning range of the OK-4 FEL (with 3.5 mA/bunch at 500 MeV with 500 kV RF voltage) using 380 nm mirrors. The line in the center is a measured time lasing line. This line was tuned ±18% from 345 to 413 nm by changing the current in the OK-4 wigglers. The dots are measured round trip cavity 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 .

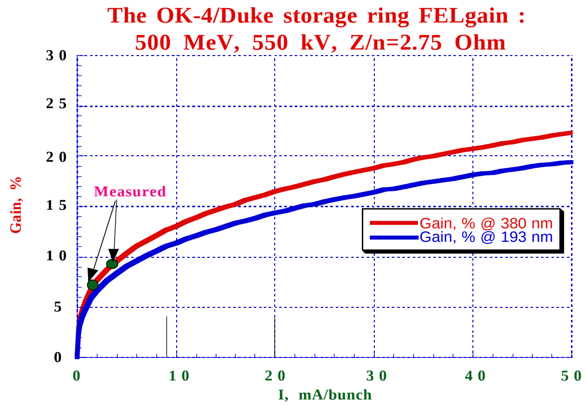

Fig. 3 The measured (dots, 345 nm) and predicted gain (solid lines) for 380 nm and 193 nm of the OK-4.

A typical tuning range (obtained by variation of the wigglers' current) and one measured lasing spectrum are shown in Fig.2. 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. 3 shows a comparison of the measured and predicted gain for 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. With expected cavity losses less than 3% [1], the OK-4 should lase below 200 nm with a beam current of a few mA/bunch.

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), $\sigma E/E$	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 averagedvalue presumably causedby ripples in power supply, instantaneous value should be ~$1 \cdot 10^{-4}$.*

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 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. 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 (±18%) and the energy of the electron beam (265-550 MeV). Most of our shifts were dedicated to these studies and the results were 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. There were very few regular operation of the injector in 1997 and the OK-4 FEL program was not continued.

4 USER PROGRAM AND PLANS

The pilot user program [8] for Duke FEL storage ring facility [8] includes the deep-UV surgery (keratectomy and tissue welding), photo-emission electron microscopy (PEEM), isotope separation, time-resolved photo-chemistry (pump-probe UV/IR) and intense nuclear γ-ray physics program. Initial applications has been started by late 1997 and substantial progress has been achieved towards the full performance of the facility. The gain modulator required for high peak power operation of the OK-4 FEL has been commissioned in February 1998. 34 units of BPM electronics (Bergoz, France) has been installed on the storage ring and will be commissioned In May, 1998. The permanent crotch-chambers with absorbers, nitrogen purged beamlines and user interfaces are in progress. We do not expect serious problems to lase below 200 nm in the near future. Later this year we plan to have regularly scheduled runs for user experiments.

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REFERENCES

[1] V.N.Litvinenko et al., SPIE v.2988 (1997) p.188.
[2] V.N.Litvinenko et al., Phys.Rev. Lett., V.78, N.24, 16 June 1997, p.4569
[3] V.Litvinenko et al.,, Proc. of PAC'93 ,1993, p.1442.
[4] I.B.Drobyazko et al., NIM A282 (1989) 424.
[5] V.N.Litvinenko et al., Prtt., V.78,1995, p. 213.
[6] A.Lumpkin et al., "Initial applications of a Dual-Sweep streak camera for the Duke SR OK-4 source", Pr N.24, 16 June
[7] P.Wang et al., Proc. of PAC'95, 1995, p. 1841.
[8] Y.Wu et al., "Duke FEL Storage Ring Light Sources and Aplication", FELFA'98, February 1998, Kyoto, Japan
[9] Y.Wu et al., NIM A375 (1996) p. 74.
[10] V.N.Litvinenko et al., NIM A375 (1996) p. 46.
[11] Y.Wu et al., Proc. of PAC'95, 1995, p.2214.
[12] V.N.Litvinenko, J.M.J.Madey, NIM A359 (1996) 580; V.N.Litvinenko et al., SPIE v.2521 (1995) 55.
[13] V.N.Litvinenko, NIM A359 (1995) 50; V.N.Litvinenko et al., NIM A358 (1995) pp.334, 369.
[14] G.Datoli et al., Phys. Rev. A (April, 1988).
[15] V.N.Litvinenko et al., SPIE v.2522 (1995) p. 473.