UV-VUV FEL Program at DUKE storage ring with OK-4 optical klystron

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Abstract

A 1 GeV electron storage ring dedicated for UV-VUV FEL operation is under construction at the Duke University Free Electron Laser Laboratory. The UV-VUV FEL project, based on the collaboration of the Duke FEL Laboratory and Budker Institute for Nuclear Physics is described.

The main parameters of the DFELL storage ring, of the OK-4 optical klystron, and the experimental set-up are presented. The parameters of UV-VUV FEL are given and the possible future upgrades to this system are discussed.

I. INTRODUCTION

In April 1992, Duke University Free Electron Laser Laboratory and Budker Institute of Nuclear Physics signed a Memorandum of Understanding on collaborative efforts in FEL research. As the first step in this collaboration, the OK-4 optical klystron system, including the magnetic system and its power supplies, vacuum system, optical cavity system and diagnostic system will be transferred to Duke FELL for UV-VUV FEL experiments on the Duke storage ring.

The layout of the Duke/OK-4 UV-VUV FEL is shown in Figure 1.

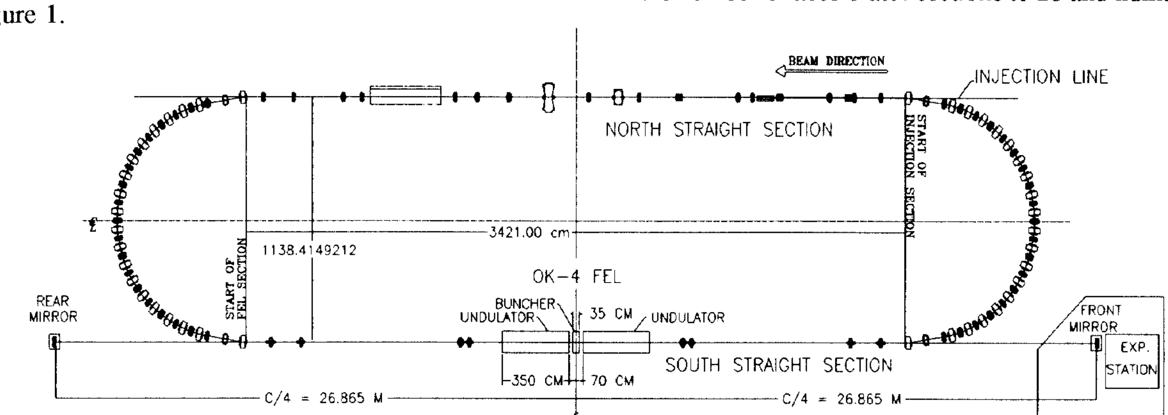

Figure 1. Layout of the Duke/OK-4 UV-VUV storage ring FEL.

A. Status of the Duke storage ring.

The Duke FEL electron storage ring is designed to drive UV and soft X-ray FELs. One of the two 34-meter straight sections is dedicated for FEL installation. The other straight section is used for injection, installation of the RF cavity, diagnostic systems and NIST undulator (soft X-ray source).

Construction of the storage ring and linac-injector started in 1992. Magnetic measurements (excitation curves and 2-D maps) of all magnets in their real environment was performed before installation using an eleven element Hall probe array [2]. The overall accuracy of these measurements was better then 0.01%.

At present, all storage ring magnets and 80% of the vacuum chambers and other hardware have been installed. A vacuum of (0.6-6)E-10 torr was achieved in the ring. The 178 MHz RF cavity [3] (64th harmonic of revolution frequency), manufactured in Novosibirsk, passed high power tests and has been installed on the Duke storage in a shielded cave. The RF system, including RF cavity, circulator and transmitter should be commissioned by Fall 1993.

The 280 MeV injector comprising a microwave electron gun [4], eleven SLAC accelerator sections fed by three S-band klystrons, and low and high energy spectrometers is now under construction. The commissioning of the linac and linac-to-ring transport channel is scheduled for the end of 1993. The energy of the linac will be extended to 1 GeV in 1994 by increasing the number of accelerator sections to 28 and number of klystrons to eight. A fast chopper installed after the microwave gun will form short (~5 nsec) electron bunch trains to fill individual (from a possible 64) electron buckets in the ring. Electrons from the linac will be injected into the storage ring through a vertical chicane and 9-degree septum magnet [5]. Three 200 nsec ferrite kickers [6] will be used for storing the beam.

The initial performance of the ring will be limited by the

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temporary crotch vacuum chambers installed at the ends of the arcs. These crotches will be replaced in 1994 by permanent "RF-smooth" vacuum chambers with ports for FEL, NIST undulator and synchrotron radiation equipped with absorbers capable of operation with (1-2)A average beam current.

The description of the Duke storage ring with combined quadrupole and sextupole magnets in the arcs, modified second order achromat lattice of the arc canceling second order geometrical aberration, etc., can be found elsewhere [5,7,8].

Extensive studies of the Duke storage ring dynamic aperture [7] have shown that the dynamic aperture of low emittance FODO lattice exceeds the physical aperture of the ring. A ±5% energy acceptance, extraordinarily large for strong-focusing storage rings, has been verified. The main parameters of the Duke storage ring are summarized in Table I.

Table I. Main Parameters of Duke Storage Ring

Operation energy [GeV]	0.25 - 1.0
Ring circumference [m]	107.46
Arc and straight section length [m]	19.52; 34.21
Revolution frequency [MHz]	2.7898
RF frequency [MHz]	178.547
Number of dipoles and quadrupoles	40; 64
Betatron tunes, Qx and Qy	9.111, 4.180
Orbit compaction factor, α	0.0086
Natural chromaticities, Cx and Cy	-10.0, -9.78
Compensated values, Cx and Cy	+0.1; +0.1
Acceptances [mm mrad], Ax and Ay	56., 16.
Energy acceptance, $\Delta E/E$, the ring	>±5.0%
limited by existing RF	±2.8%
Maximum β-functions [m], x and y	13.6, 21.3
Maximum η-function [m]	0.245

Commissioning of the storage ring is scheduled to begin in early 1994. The commissioning lattice [8] is optimized for the OK-4 FEL magnetic system to facilitate the start of the first FEL experiments.

B. Status of the OK-4 optical klystron.

The OK-4 was the first operational UV FEL [10,11] demonstrating lasing down to 240 nm. It still holds the short wavelength record for FELs.

The OK-4 magnetic system is comprised of two 3.5 meter electromagnetic undulators [9] and a buncher (3-pole compensated wiggler) located between them. The use of a buncher distinguishes optical klystrons from conventional FELs and permits the optimization of longitudinal dispersion for higher gain and, as a result, the enhancement of the gain by a factor 5-20.

The OK-4 magnetic system has very high performance. The direct magnetic measurements and experimental results achieved with the OK-4 in Novosibirsk have shown the practically perfect performance of this system. The main parameters of the OK-4 magnetic system are listed in Table II.

The OK-4 optical klystron has been employed for a number of recent FEL experiments on the Novosibirsk VEPP-3 storage ring bypass. This scientific program will be finished in 1993.

Table II. Main Parameters of OK-4 magnetic system

Total length [m]	7.8
Undulator	
Length [m]	3.40
Period [m]	0.10
Peak magnetic field [kGs]	(0.0-5.8)
Undulator parameter, K	(0.0-5.42)
Tuning range (λmax/λmin)	15.67
Buncher	
Length [m]	0.34
Magnetic field [kGs]	(0-12)

Following these experiments, the magnetic and optical systems of the OK-4 optical klystron will be moved to Duke for the first FEL experiments using the DFELL storage ring.

II. DUKE/OK-4 UV-VUV FEL

The tuning range (K vs wavelength) of the fundamental harmonic wavelength of the OK-4 FEL is shown in Figure 2. The parameters of the electron beam are very critical for performance of a short wavelength FEL. The most important Duke storage ring electron beam parameters are given below:

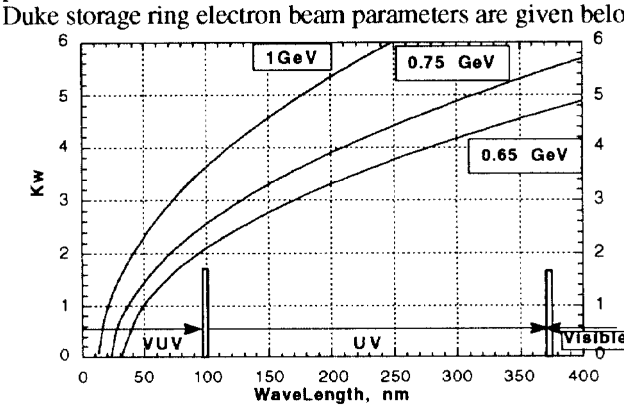

Figure 2. OK-4 tuning range for 0.65, 0.75 and 1 GeV.

Table III. Parameters of electron beam at 1 GeV energy

Average beam current, A	0.1 (1.0*)
Peak current, A	80-130 (350*)
Emittances [mm mrad], εx and εy	0.018; <0.0018
	(0.009; .0045*)
Relative energy spread (low current)	0.0005
at peak current of 130 A	0.0016
Bunch length, cm, (low current)	1.15
at peak current of 130 A	3.7
Beam size in OK-4 [mm], σx and σy	0.27; 0.085

**final specification of the ring.*

At 1 GeV energy, the beam emittance will be practically natural. Intrabeam scattering will affect only the electron beam lifetime (down to 30-45 minutes with 350 A peak current). Maximum achievable peak current will be limited by the impedance of the vacuum chambers, which have RF-smooth connections and transitions.

The 3-D OK-4 gain curve at the modest average current of 100 mA in the Duke ring is shown in Figure 3. Finite electron beam emittance and energy spread are taken into account. The finite emittance is responsible for gain drop in the short wavelength range.

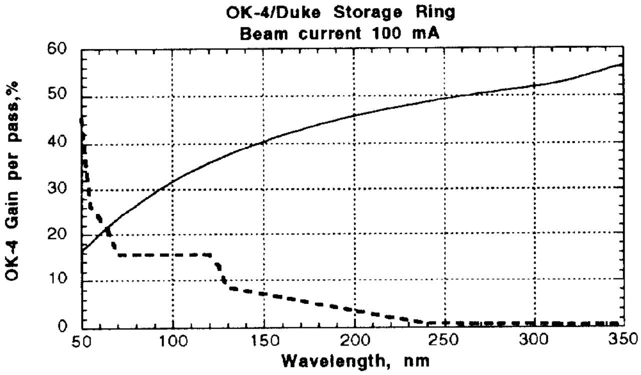

Figure 3. OK-4 gain vs wavelength - solid curve. Dashed curve - lasing threshold gain (adopted from [12]).

The expected OK-4 average CW lasing power for 100mA and 1A average current are plotted in Figure.4. The high energy acceptance of the ring is very essential, because under these conditions the energy spread (excited by lasing) can reach 1%. The energy acceptance of ± 5% will provide an acceptable lifetime. These conditions can occur in the UV range where low loss mirrors are available.

In the VUV range average lasing power will be limited by gain degradation due to electron beam heating (even with the multifacet mirrors [13] we intend to use in this range).

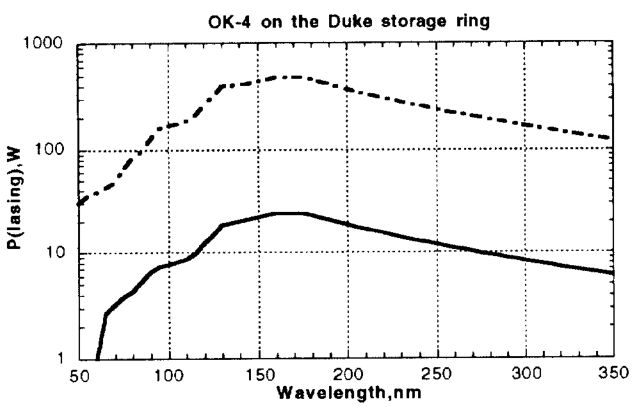

Figure 4. OK-4 FEL lasing power: solid line for 100 mA and dashed curve for 1 A average current.

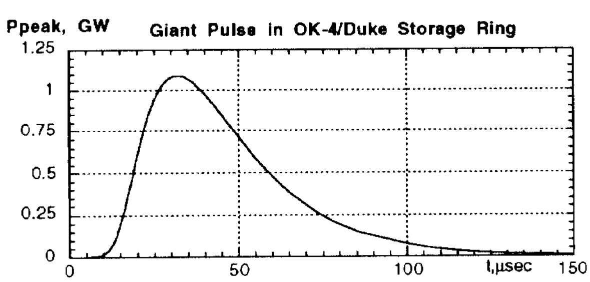

Figure 5. Giant Pulse Envelope (computer simulations).

In a storage ring driven FEL only the average lasing power is limited. Thus, we can redistribute the lasing power using gain modulation [10] to produce giant pulses with gigawatt levels of peak power and 50-100 Hz repetition rate. These techniques were tested both in Novosibirsk [11] and Orsay and results are accurately predictable. A typical giant pulse simulation result for OK-4/DUKE FEL at 200 nm is shown in Figure 5.

The other parameter of OK-4/DUKE UV-VUV FEL are presented in Table IV.

Table IV. Parameters OK-4/DUKE UV-VUV FEL

Tuning range, nm	50-400
Linewidth, $\delta\lambda/\lambda$: natural	(1-3) 10^{-4}
with linewidth narrowing [14]	(5-30) 10^{-7}
Micropulse duration, psec	5-30
Micropulse separation, nsec	358.45
Spatial distribution	TEM_{00}

III. FUTURE UP-GRADES

Possible future up-grades of the Duke storage ring will include:

i. full scale (27 meter long) high gain soft X-ray FEL;
ii. advanced 3 cavity RF-system (64 and 256 harmonics);
iii. lower impedance vacuum chambers;
iv. lower emittance optics.

The lattice for a 27 meter long FEL has been designed [8]. First results with a 26 meter undulator have shown good dynamic aperture.

The distributed optical klystron and phase-shift amplifier with 20-40 dB gain are under study as candidates for future up-grades. The lasing range with these devices can be extended down to 10-20 nm.

Lower emittance lattices (from 9 to 3 nm·rad) as well as electron beam conditioning are under consideration for further wavelength shortening down to the "water window".

IV. REFERENCES

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