FIRST LASING AND INITIAL OPERATION OF A CIRCULARLY POLARIZED OPTICAL KLYSTRON OK-5 FEL AND A VARIABLY POLARIZED DISTRIBUTED OPTICAL KLYSTRON DOK-1 FEL AT DUKE*

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Abstract

To improve the capability and performance of its light sources, the Duke FEL lab (DFELL) is upgrading its storage ring based FEL. The existing linearly polarized OK-4 FEL wigglers are being replaced gradually by the next generation OK-5 wigglers capable of producing either linearly or circularly polarized light. In the second phase of this upgrade in 2005, the OK-5 FEL consisting of two wigglers is installed together with the OK-4 FEL in a specially designed magnetic lattice. The circularly polarized OK-5 FEL was first brought to lasing on Aug. 14, 2005. In the following days, the first distributed optical klystron FEL with variable polarization, the DOK-1 FEL, comprised of two horizontal OK-4 wigglers and two circular OK-5 wigglers, was brought to lasing for the first time. In this paper, we report our commissioning experience and initial measurements of both the OK-5 FEL and DOK-1 FEL.

INTRODUCTION

In order to expand the capabilities and improve the performance of its light sources, the Duke FEL lab has undertaken a series of major upgrades of its accelerator systems in the recent years. These upgrades include the development and construction of a booster synchrotron injector for top-off operation [1], a new higher-order-mode (HOM) damped radio-frequency (RF) cavity, next generation variably polarized FELs [2], and two new straight section lattices, one to host FELs, and other other to accommodate the booster injection and future light sources. The fully upgraded light source facility is pictured in Fig. 1. By summer 2005, the HOM-damped RF system has been in operation for about one year, a new straight section lattice has been commissioned to host both OK-4 and OK-5 wigglers, and the booster mechanical installation is near completion.

To provide continued user beam time and manage the risk associated with the upgrade, we put in action a three-phase upgrade plan (Fig. 2). In the first phase, the OK-4 FEL is preserved as the user light source while upgrading the magnetic lattice. In the second phase, two OK-5 wigglers are installed along side the OK-4 FEL. This new optical klystron FEL with two OK-5 wigglers is referred to as the OK-5 FEL throughout this paper. This approach allows us to study the adverse dynamics impact [3] of OK-5 wigglers using beam based techniques. These experimental results together with simulation studies will allow us to devise a compensation scheme to improve the dynamic aperture. In the third phase, two more OK-5 wigglers will be installed in the middle of the straight section [4].

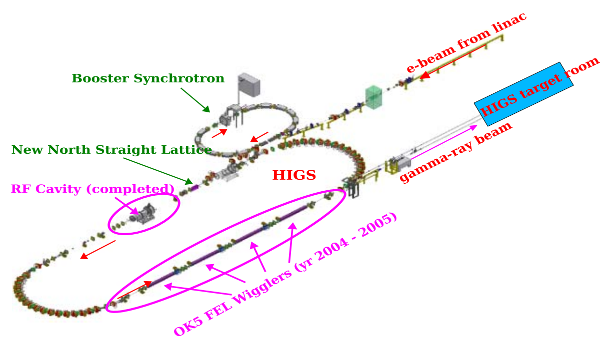

Figure 1: Fully upgraded Duke storage ring light source facility in 2006 with a HOM-damped RF cavity, a new 0.25 – 1.2 GeV booster, one new straight section to hose FELs, and the other new straight for booster injection and future light sources.

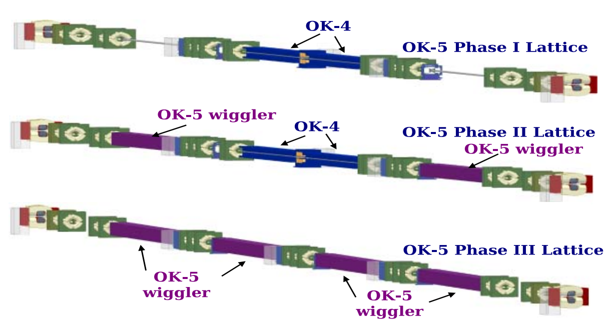

Figure 2: Three phases of the FEL upgrade project. The second phase allows the commissioning of the OK-5 FEL with two wigglers and DOK-1 FEL with two OK-4 and two OK-5 wigglers.

In this paper, we focus on the phase II upgrade which includes the commissioning of two new FELs: one is a circularly polarized OK-5 FEL and the other is the world's first distributed optical klystron FEL [5] with variable polarizations using two linearly polarized OK-4 wigglers and two circularly polarized OK-5 wigglers. This new FEL is named as DOK-1 FEL, following the same name convention as the OK-4 FEL which started in the Budker Institute

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of Nuclear Physics (BINP), Russia. The idea of polarization manipulation using wigglers of different polarizations can be tracked back to the work of Kim [6]. This paper also reports our initial measurements for the OK-5 FEL and DOK-1 FEL.

A NEW LATTICE FOR FEL WIGGLERS

To host both OK-4 and OK-5 wigglers, a special straight section lattice has been designed and installed. This straight section employs eighteen quadrupoles in nine families in a bilaterally symmetric lattice. Two OK-4 wigglers and two OK-5 wigglers (see Fig. 2) are bridged by two pairs of matching quadrupoles. To provide betatron tuning while keeping the lattice matched to the arc, sophisticated horizontal and vertical tune knobs involving all quad families are developed as a function of the OK-4 wiggler setting. All quads are updated simultaneously using a feed-forward scheme whenever the OK-4 wiggler setting and/or the tune knob setting are changed. A large betatron tuning range, $\Delta\nu_{x,y} = -0.1$ to 0.1, is realized for a wide range of OK-4 wiggler settings. The detailed design of this new lattice was reported in an oral presentation at PAC2005.

While not fully optimized, this lattice is also flexible enough to accommodate two OK-5 wigglers. This allows us to commission the OK-5 FEL independent of the OK-4 settings and allows us to run the OK-4 and OK-5 wigglers simultaneously in a distributed optical klystron mode.

This new lattice was fully installed in 2004, followed by the recommissioning of the OK-4 FEL. However, the reduction of the vacuum chamber size to accommodate the OK-5 wigglers led to two problems: one was the increased vertical impedance which lowered the threshold for single-bunch current; the other was the significantly reduced vacuum conductivity due to a combination of reduced size and increased length of the new vacuum chambers. With a few weeks of intensive vacuum scrubbing using a 100 mA of electron beam (e-beam) current at 1 GeV and with OK-4 wigglers set to their maximum current of 3000 A, the impact of ion trapping was reduced to a level that stable operation with a high single bunch current could resume. The single bunch current limitation due to an increased vertical impedance was successfully dealt with using a newly commissioned transverse feedback system (2005).

OK-5 AND DOK-1 COMMISSIONING

The phase II upgrade (2004–2005) includes the installation of two OK-5 wigglers, their power supplies, and related bussbar system. The parameters of the OK-5 wigglers are compared with those of OK-4 wigglers in Table 1. The OK-5 wigglers are powered by two completely rebuilt power supplies with the maximum current capability of 3000 A [7]. A complex copper bussbar system is designed and installed to carry a large DC current to/from the wigglers. The preparation of the OK-5 wigglers includes the mechanical adjustments of individual end poles, followed by a series of magnetic measurements to map the three-dimensional magnetic field of the wiggler as a function of the wiggler current.

Table 1: OK-4 and OK-5 wiggler parameters. Maximum fields are values at 3 kA of DC current.

	OK-4	OK-5
No. of wigglers	2	4 (2 installed)
No. of regular periods	33	30
Wiggler periods [cm]	10	12
Wiggler gap [mm]	25	40×40
Max. magnetic field [kG]	5.36	2.86
Max. wiggler $K = \frac{e\,B_0}{k_w\,m_e\,c^2}$	5.00	3.18

After about two years of intensive effort, two OK-5 wigglers were installed on the storage ring and powered up on June 16, 2005, which marked the beginning of the OK-5 FEL commissioning. The first OK-5 FEL lasing was achieved on August 14, 2005. In sum, the OK-5 commissioning lasted for 59 calendar days, which overlapped with continued user operation. About one-third of the shifts or about 220 hours were devoted to the OK-5 commissioning. During the commissioning, we had to work out three critical issues – two known problems and one surprise.

The unexpected problem showed up in the early days of the commissioning. Large orbit excursions were observed even when both OK-5 wigglers were by-passed. With further investigation, it was determined that the orbit excursions were caused by the residual magnetic fields of the long wiggler bussbars (about 25 m) below the steel girder supporting the wigglers and magnets. Having found the problem, a solution was devised: two current compensation loops were laid, roughly with the same length of the bussbar, one horizontal, the other vertical. Using beam based techniques, we were able to effectively suppress the bussbar induced orbit excursion in the FEL straight by a factor of 5 to 7 horizontally, and a factor of 6 to 9 vertically in the entire current range from 200 to 3000 A.

The first expected problem was the transverse alignment of e-beam axes in OK-5 wigglers with the FEL optical axis, an issue recognized from early on. In the case of the OK-4 FEL, with two well-aligned wigglers placed closely together, a good lasing condition can be achieved by aligning the common e-beam axis through both wigglers with respect to the optical axis. However, in the OK-5 FEL case, separated by about 20 meters, two e-beam axes in both upstream and downstream OK-5 wigglers need to be aligned with the optical axis, which in practice more than doubles the difficulty of alignment. This problem is further complicated by two practical limitations: first, there are not enough BPMs around the OK-5 wigglers – one BPM is situated at one end of the OK-5 wiggler, a desirable location, however, the other close-by BPM is four correctors and one quadrupole away; second, the lack of power supplies severely limits the capabilities of correctors – not all the orbit correctors in the lattice have been powered and those powered are being fed by power supplies with smaller than designed currents.

The orbit problem was dealt with effectively using a combined local and global orbit feedback scheme developed using a beam based technique, which was a time-consuming process. This scheme allowed completely independent controls of the three electron beam axes, two in OK-5 wigglers and one in the OK-4 FEL. However, because of the limitation posed by the lack of BPMs, no e-beam orbit controls will be possible for secondary collision points in the Compton gamma source.

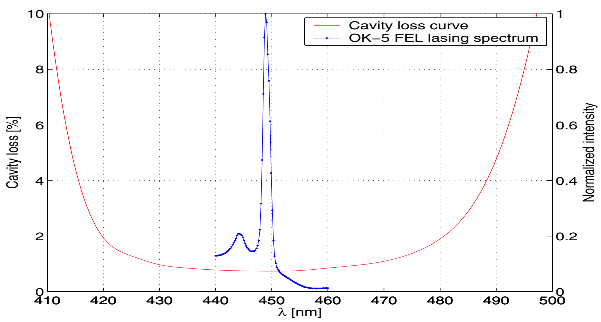

Figure 3: The first lasing spectrum of the OK-5 FEL with about 15 mA of single-bunch current at 274 MeV with a FWHM $\Delta\lambda/\lambda = 3.4 \times 10^{-3}$.

The second known problem is the need to optimize the spontaneous radiation spectra of the OK-5 wigglers. The degradation of wiggler spectra can be caused by wiggler field errors and/or bad e-beam orbits in the wiggler. The wiggler spectrum measurement is performed in an optical lab located upstream; the spontaneous radiation is first reflected by the downstream cavity mirror and then transmitted through the upstream mirror before reaching the monochromator. With bussbar compensations and proper end-trim compensations, reasonably good wiggler spectra were obtained for the upstream OK-5 wiggler. However, persistently poor spectra from the downstream OK-5 wiggler were observed; the spatial distribution of this wiggler radiation contained some wing-pattern which looked like a green "butterfly" when the background radiation was blue. These poor spectra were observed when the wiggler was energized in either horizontal or vertical polarization. Further investigations showed that this was an optical effect stemming from the fact that the fan of the downstream wiggler radiation happened to be focused back to a point by the curved downstream cavity mirror in a location where the spectra were taken. Thus there was no way to separate the on-axis wiggler radiation from the off-axis radiation which showed up in the longer wavelength part of the spectra. This effect was confirmed by a much improved spectrum after closing an aperture downstream from the wiggler. With this, we were convinced that our techniques of bussbar compensation and end-of-wiggler trim compensation were adequate to bring about good spontaneous spectra from both OK-5 wigglers.

The successful resolution of the above three critical problems enabled us to accomplish the first OK-5 FEL lasing with circular polarization on Aug. 14, 2005 at the injection energy of 274 MeV. Additional help came from a large single bunch current and good alignment of the mirror cavity. In fact, we were able to injection more than 20 mA into a single bunch before starting the FEL tuning. Good mirror alignment was critical because we did not have any orbit control in the OK-5 wigglers; we did, however, establish fixed good e-beam orbits in wigglers before lasing using the beam based techniques. Fig. 3 shows the measured first lasing OK-5 FEL spectrum.

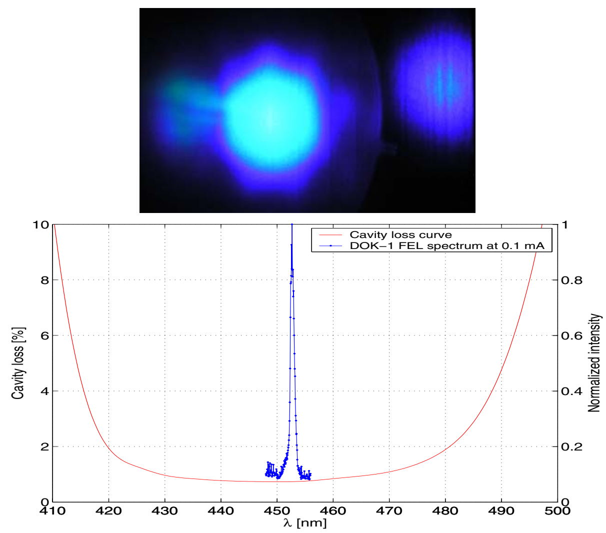

Figure 4: First demonstrations of DOK-1 FEL lasing at 450 MeV. Upper figure, the laser image on a diagnostics screen with the DOK-1 FEL lasing with 9.6 mA of single bunch current; Lower figure, the measured DOK-1 FEL spectrum with 0.1 mA of single bunch beam current.

Upon realizing the OK-5 lasing, we turned our attention toward demonstrating lasing of a combined system with two horizontal OK-4 wigglers and two circular OK-5 wigglers as the world's first distributed optical klystron FEL. This new FEL, named as DOK-1 FEL, was first brought to lasing on Aug. 16, 2005. Because of built-in beta-function and tune compensations, bringing up the OK-4 wigglers in a OK-5 lattice was an easy task. A distributed optical klystron was originally proposed to boost the FEL gain [5]. This was demonstrated with the DOK-1 FEL by measuring the threshold current for lasing. Using a 450 MeV e-beam, OK-5 FEL and OK-4 FEL were able to lase with an e-beam current as low as 0.75 and 0.5 mA, respectively, with limited time for optimization. However, the DOK-1 FEL was able to lase with 0.1 mA of current, possibly at an even lower current. Fig. 4 show DOK-1 lasing beam image (upper plot) and measured lasing spectrum with 0.1 mA of single bunch current (lower plot).

By combining the linearly polarized OK-4 wigglers and circularly polarized OK-5 wigglers, the polarization of DOK-1 FEL is in general elliptical and can be varied. This is the first operational FEL device which can be used to demonstrate polarization switch [6], a unique feature awaiting further exploration.

FIRST FEL MEASUREMENTS

One of our first FEL experiments was to measure the FEL startup gain. Running in a Q-switch mode, the FEL gain was measured by fitting the exponential growth of giant pulses for OK-4, OK-5, and DOK-1 FELs as shown in Fig. 5. With a similar current, the OK-4 had a higher gain than OK-5 FEL which probably was the result of a better overlap of the optical beam and e-beam. With a lower current at about 4.3 mA, the DOK-1 FEL had a startup gain of about 11%, more than doubled that of the OK-4 FEL. Together with the measured lower threshold current for lasing, this experiment demonstrated a significant improvement of the FEL gain of a distributed optical klystron.

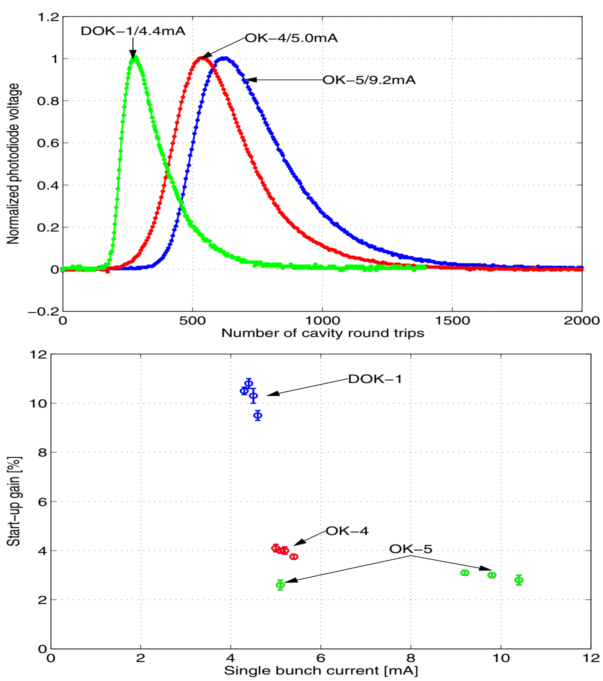

Figure 5: Measurements for the startup gain of the OK-4, OK-5, and DOK-1 FELs at 450 MeV. Upper plot: measured giant pulses produced by the three FELs with different currents; Lower plot: the start-up gain of the three FELs obtained by fitting the rise of the giant pulse to an exponential growth curve.

The first measured total extracted FEL power for both OK-5 and DOK-1 FELs at 450 nm, the wavelength of the lowest mirror transmission, with a 450 MeV e-beam is shown in Fig. 6. A total of 23 mA of single-bunch current was injected at 274 MeV and ramped to the operation energy of 450 MeV. Some initial tuning was necessary to bring out the lasing while the current decayed rapidly due to a poor beam lifetime. The maximum extracted power was 38 mW (17.5 mA) and 62 mW (16.6 mA) for the OK-5 FEL and DOK-1 FEL respectively. The decay of the power seemed to be a linear function of the beam current. The big drop of the DOK-1 power around 14 mA was caused by a sudden change of the FEL cavity optical axis, a problem likely related to the mirror feedback control.

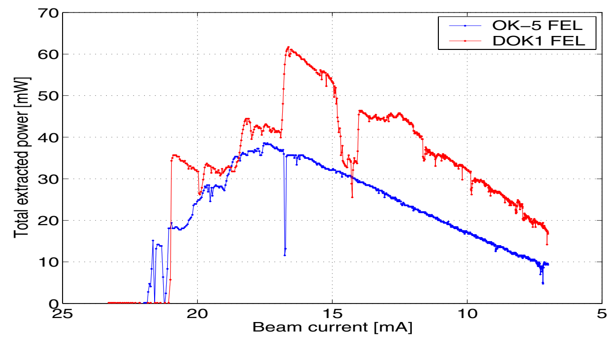

Figure 6: Measured total extracted power vs the single bunch current for OK-5 and DOK-1 FELs at 450 MeV.

SUMMARY AND ACKNOWLEDGMENT

In this paper, we reported the first lasing of a circularly polarized OK-5 FEL and of a variably polarized DOK-1 FEL, the first distributed optical klystron FEL in the world. Using the DOK-1 FEL, a much improved FEL gain has been demonstrated. This will allow us to operate a distributed optical klystron to achieve VUV lasing below 180 nm at Duke. However, a couple of challenges remain. One is the significant degradation of the beam dynamics due to OK-5 wigglers [3], which prevents top-off injection with the OK-5 FEL and results in a very short beam lifetime. The second is the full control of the FEL interactions and collision points for Compton gamma production. We are working on a compensation scheme to improve beam dynamics using octupoles and developing improved OK-5 vacuum chambers to allow more BPMs and correctors.

The first lasing of OK-5 and DOK-1 FELs is the work of not only the scientific teams, but also that of the engineering teams. We would like to acknowledge the critical contribution of the members of DFELL engineering and operation teams: M. Busch, M. Emamian, J. Faircloth, S. Hartman, J. Marty, O. Oakley, J. Patterson, M. Pentico, V. Rathbone, G. Swift, P. Wallace, P. Wang. In addition, we would like to thank I. Pinayev (BNL) for his contribution in developing FEL diagnostics and V. Litvinenko (BNL) for his important contribution in initiating and leading the OK-5 FEL project until spring 2003.

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