High-Gain Lasing and Polarization Switch with a Distributed Optical-Klystron Free-Electron Laser

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This Letter reports the first experimental results from the world's first distributed optical-klystron (DOK) free-electron laser (FEL), the DOK-1 FEL, at Duke University. The DOK-1 FEL is a hybrid system, comprised of four wigglers: two horizontal and two helical. With the DOK-1 FEL, we have obtained the highest FEL gain among all storage ring based FELs at 47.8% (±2.7%) per pass. We have also demonstrated that the FEL gain can be enhanced by increasing electron bunching using wigglers with a different polarization. Furthermore, we have realized controlled polarization switches of the FEL beam by a nonoptical means through the manipulation of a buncher magnet.

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A free-electron laser (FEL) is a device which transfers the energy from a high quality electron beam (*e* beam) to a form of coherent radiation, i.e., laser light. FELs have been developed to operate in a wide range of wavelengths spanning millimeter-wave, infrared, visible, ultraviolet (UV), and x-ray using different accelerator technologies. FELs operate in one of two distinct configurations: as oscillators, which require optical cavities, and as amplifiers, which do not. Self-seeded single-pass FEL amplifiers [1–5] and related laser seeded amplifiers [6] are well suited to very short wavelengths [e.g., vacuum-ultraviolet (VUV) to x-ray] for which optical cavities are not feasible; however, operation in this wavelength regime requires very high *e*-beam quality. Many oscillator FELs are driven by energy recovery linacs [7] or storage rings. Storage ring FEL (SRFEL) oscillators are well suited to cover longer wavelengths, e.g., from visible to UV and VUV, due to their lower cost and higher operation efficiency.

The SRFEL is a coherent light source: It is spatially coherent due to a single transverse mode in the optical cavity, and it can also achieve an extremely high degree of temporal coherence. In addition, the SRFEL is autosynchronized with other light sources on the storage ring, which enables multicolor pump-probe experiments. Because of these important characteristics, the SRFEL is a versatile UV-VUV light source with a wide range of applications.

Until the recent operation of high-gain single-pass FELs, the SRFEL was the leader pushing the short wavelength limit. The first generation SRFELs [8,9] demonstrated FEL operation from visible to UV with the shortest wavelength at 240 nm. With improved *e*-beam quality, VUV FEL operation below 200 nm was first realized with second generation SRFELs—Duke OK-4 FEL at 194 nm in 1999 [10] and ELETTRA FEL at 176 nm in 2004 [11]. Lasing at even shorter wavelengths has not been possible due to the relative small gain of an SRFEL.

Traditionally, an SRFEL enhances its gain by employing an optical klystron [12], with two wiggler magnets, an energy modulator, and a coherent light radiator, separated by a buncher magnet. The optical-klystron configuration was used at Duke and ELETTRA to achieve lasing in VUV. More than two wigglers can be used to form a distributed optical klystron (DOK) to further increase the FEL gain as proposed by Litvinenko [13]. With a higher gain, the DOK opens the door for SRFELs to achieve shorter wavelength lasing in VUV. The first DOK FEL, named DOK-1 FEL, has recently been developed at Duke FEL laboratory; this Letter reports the first experimental results with this FEL. The DOK-1 FEL has realized the highest FEL gain among all SRFELs and has also demonstrated controlled polarization switches using a nonoptical means for the first time.

DOK-1 FEL at Duke storage ring.—The Duke electron storage ring has been developed as a dedicated driver for FELs [14,15]; it has a 34 m long FEL straight section and can be operated in a wide energy range from 0.27 to 1.2 GeV. The first FEL on the Duke storage ring is the OK-4 FEL, an optical klystron with two horizontal wigglers. The OK-4 wiggler parameters are listed in Table I. Originally developed and operated on the VEPP-3 storage ring at the Budker Institute for Nuclear Physics, the OK-4 FEL was installed and recommissioned in 1996 on the Duke storage ring [16]. Since then, the OK-4 FEL has demonstrated lasing in a wide wavelength range from 2 μm down to 194 nm.

TABLE I. Parameters for OK-4 and OK-5 electromagnetic wigglers. The DOK-1 FEL employs two horizontal OK-4 wigglers and two helical OK-5 wigglers.

	OK-4	OK-5
Polarization	Horizontal	Variable
No. of wigglers	2	4 (2 installed)
No. of regular periods	33	30
Wiggler periods [cm]	10	12
Peak field [kG] (at 3 kA)	5.36	2.86

To extend VUV lasing to shorter wavelengths, a DOK FEL was proposed [17,18] to use four variably polarized electromagnetic wigglers, the OK-5 wigglers. To vary polarization, the OK-5 wigglers would employ two independently powered wiggler arrays, one horizontal and the other vertical. The OK-5 wiggler parameters are listed in Table I. Because of the space limitation and concerns for field saturation, wiggler poles were made compact and round. As a result, the wiggler produces strong nonlinear fields which would impact beam dynamics. To study the dynamics effects and minimize adverse impacts to the user programs, we made a decision to develop a new lattice to test two OK-5 wigglers while retaining the OK-4 FEL as the user light source. This hybrid system with two OK-4 and two OK-5 wigglers was hosted in a specially designed magnetic optics (see Fig. 1).

Two outlying OK-5 wigglers, configured in circular polarization, together with a buncher magnet in between, can be operated collectively as an independent optical-klystron FEL; throughout this Letter, we refer to this configuration as the OK-5 FEL. We have also envisioned to operate both OK-4 and OK-5 wigglers at the same wavelengths as a distributed optical klystron. This new FEL is referred to as the DOK-1 FEL throughout this Letter. During the commissioning of these FELs, we encountered and successfully resolved a number of technical challenges as reported in Ref. [19], which led to the first lasing of the OK-5 FEL and DOK-1 FEL in 2005.

High-gain operation.—All of the FEL measurements reported in this Letter were conducted with a single bunch e beam in the storage ring with FEL pulses separated by 358 ns. A higher gain was realized by operating the FEL in the gain-switch (G-switch) mode using an FEL gain modulator, which allowed momentary overlaps of the electron and optical beams in wigglers [20]. The resulting FEL beam had a macropulse structure of tens to hundreds of microseconds. A photomultiplier tube (PMT) was used to measure the turn-by-turn FEL intensity with its output recorded by a fast digital oscilloscope. Special attention was paid to ensure that the PMT responded linearly with the FEL intensity in the entire measurement range.

High-gain operation of the DOK-1 FEL was demonstrated with a 600 MeV e beam, lasing around 450 nm, and a G-switch rate of 12.5 Hz. Macropulses were separated by 80 ms, twice the e-beam energy damping time. Typically, the storage ring was filled with a single bunch current $I_b \approx 20$ mA at 0.274 GeV and ramped to the operation lattice, followed by fine adjustments of the bunchers to optimize lasing. Because of a relatively short beam lifetime (0.6–0.7 hours at 18 mA, 600 MeV, without lasing), the FEL data were taken with the remaining current less than 16 mA. The gain measurements focused on the rising edge of the macropulse.

One of the measured macropulses with a high FEL gain is shown in Fig. 2. With limited resolution of the digital oscilloscope (8-bit), the first peak which clearly stands out of the noise appears on the 86th turn of the e beam after the gain modulator is triggered to allow the FEL interaction. The gain information can be extracted by analyzing the growth rate of the macropulse—the FEL gain at the nth turn of the e beam can be computed as $G_n = (I_{n+1} - I_n)/I_n$, where I_n is the FEL intensity at the nth turn. To obtain reliable high-gain results during the FEL startup with small and noisy signals, we have used an analytical response function for the PMT to fit all turn-by-turn micropulses as shown in the insets in Fig. 2. This procedure provides much enhanced noise rejection, and the subsequent gain analyses use only the amplitude of the fit curves. The evolution of the FEL gain G_n is also plotted in Fig. 2. The maximum FEL startup gain (the net gain plus cavity loss at 0.75% per pass) with $I_b = 15.9$ mA is 47.8% ($\pm 2.7\%$) per pass using measured data from turns 86–92. Without lasing at $I_b = 15.9$ mA, the estimated peak current is 29 A and the estimated energy spread is $\sigma_E/E \approx 1.4 \times 10^{-3}$. This is the highest FEL gain ever achieved by an SRFEL. The FEL gain decreases as the macropulses evolve, which eventually leads to saturation.

To demonstrate the effectiveness of the distributed optical klystron in enhancing the FEL gain, it is essential to measure and compare the gains of the DOK-1 FEL vs OK-4 and OK-5 FELs. The measured FEL startup gains as a function of the beam current for three FELs are shown in Fig. 3. With the exception of the "best runs" for DOK-1 FEL, all other FEL runs suffered from certain problems with the FEL cavity mirror feedback system. These problems impacted our measured gain results but in a consistent manner. In all cases, the buncher settings were optimized at a high beam current and remained almost constant with only minor tuning of the buncher 2 at lower beam currents. The typical slippage factors for the DOK-1 FEL lasing were close to those used in obtaining the highest gain of 47.8%: $N_1 = 5.95$ (± 0.05), $N_2 = 19.03$ (± 0.10), $N_3 = 4.95$ (± 0.05) in three buncher sections, respectively.

Good fits of the FEL gain with the e-beam current for three FELs, $G \propto I_b^{2/3}$, indicate that bunch lengthening due to microwave instability plays a dominant role in limiting the FEL gain growth with current. The DOK-1 FEL has much higher gain compared with the OK-4 and OK-5 FELs. Furthermore, the DOK-1 FEL has an enhanced gain compared with a scenario with OK-4 and OK-5

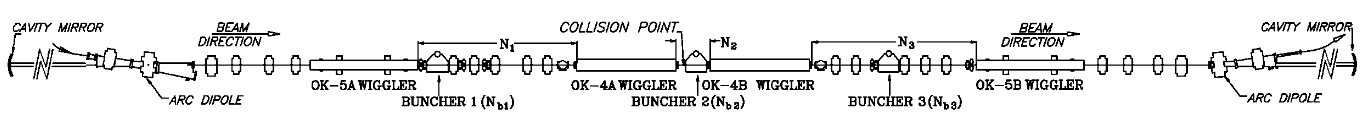

FIG. 1. The schematic of the straight section magnetic lattice for OK-4 and OK-5 FELs. $N_{1,2,3}$ are slippages between electron and FEL beams in three buncher sections, respectively, and $N_{b1,2,3}$ are slippages due to buncher magnets only.

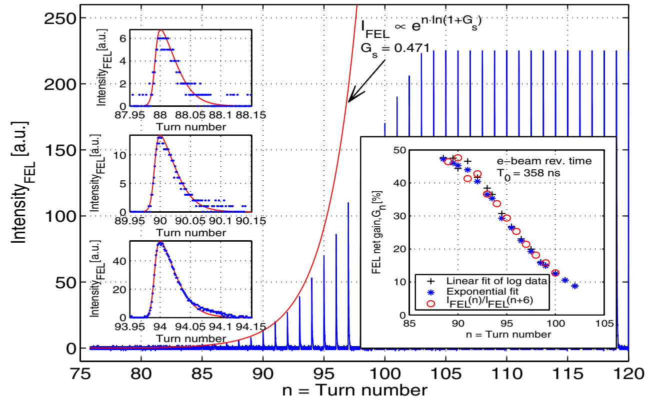

FIG. 2 (color online). A measured FEL macropulse at 450 nm with a 15.9 mA of beam current at 600 MeV and an accelerating rf voltage of 570 kV. The insets on the left show three exemplary micropulses which are fit with a PMT response function. An exponential fit with the startup net gain of 47.1% per pass is plotted to demonstrate its saturation as the macropulse evolves. The inset on the right shows the FEL gain as a function of the turn number. Three analysis methods are used: the linear fit of the logarithmic data, the exponential fit of the data, and a direct calculation from the ratio of nth and $(n + 6)$th data points.

FELs running at the same time but independently without interactions. The DOK-1 FEL gain G_{DOK1} is 2.2–2.3 times the combined gain of the OK-4 and OK-5 FELs $G_{\mathrm{OK4}}(1+G_{\mathrm{OK5}}) + G_{\mathrm{OK5}}$ at 16 mA. This ratio is computed by comparing the performance of three FELs with mirror problems (Fig. 3) and the best performance of DOK-1 and OK-4 FELs (Fig. 3 vs Fig. 4). The best performance of OK-4 FEL (Fig. 4) is about 40%–50% higher than those in Fig. 3. This significant gain enhancement is the result of increased bunching of the e beam provided by multiple wigglers and bunchers in the distributed optical klystron.

To gain new insight into how additional wigglers enhance the FEL gain, we designed an experiment to make a transition between the OK FEL and DOK FEL operations. In this experiment, the OK-4 FEL remained lasing at all times, while the OK-5 wiggler current was ramped up and down to tune in and out of lasing. Scaled to $I_b = 16$ mA, when OK-5 wigglers are tuned to lasing, the system becomes the DOK-1 FEL with a maximum gain of about 48%; when detuned, the system is degraded to approach the OK-4 FEL operation with a maximum gain of about 13%. The measured tuning range is $\frac{\Delta\lambda}{\lambda} \approx 0.039$.

This experiment clearly demonstrates that additional e-beam bunching can be realized using nonlasing wigglers with a different polarization. By exchanging the roles of OK-4 and OK-5 wigglers, this effect can be used to enhance OK-5 FEL lasing with circular polarization by partially tuning in horizontal OK-4 wigglers to increase bunching.

Controlled polarization switch.—The DOK-1 FEL is a versatile light source. In addition to an enhanced gain, it is capable of changing the polarization of the FEL without the use of optics. Switchable polarization of the FEL beam is critical for many important applications in which the contrast mechanism requires the use of photons with different polarizations. To achieve it, Kim [21] proposed the idea of using crossed-planar wigglers in a high-gain FEL, which has yet to be realized experimentally. Influenced by this idea, the DOK-1 FEL was envisioned and developed to demonstrate the controlled switch of polarization by implementing independent controls for the OK-4 and OK-5 wigglers, bunchers, and e-beam orbits in the wigglers.

The DOK-1 FEL polarization was tuned from linear to elliptical by a small adjustment of the buncher 1 only (see Fig. 5). Because a polarimeter with a rotating quarter-wavelength plate was used, the accuracy of the polarization measurement depended highly on the intensity stability of the FEL. With a reasonably stable beam, the measured degrees of polarization in Fig. 5 had a rms error of about 1%–2%. During tuning, the FEL remained almost fully

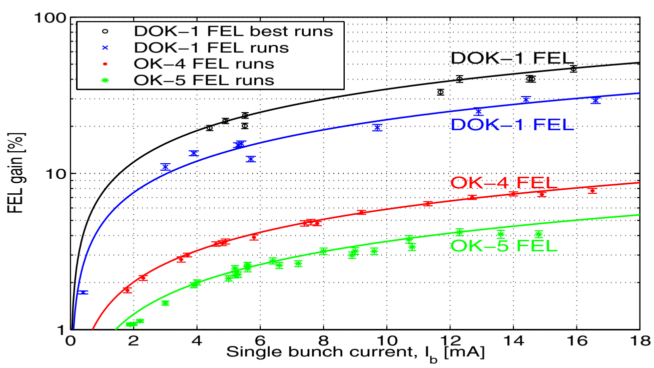

FIG. 3 (color online). Measured FEL startup gains as a function of beam current for DOK-1, OK-4, and OK-5 FELs at $\lambda = 450$ nm with a 600 MeV e beam and an accelerating voltage of 570–608 kV. All data are taken using the same PMT and analyzed using the same technique as illustrated in Fig. 2. Also plotted are the rms gain errors dominated by the limited resolution of the oscilloscope and the noise in low intensity signals. The fit gain curves show the current dependency $I_b^{2/3}$.

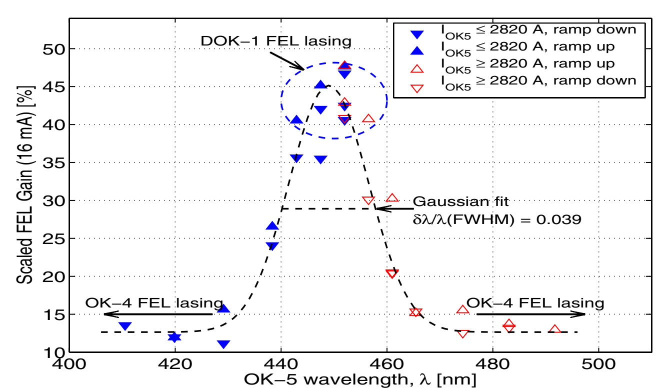

FIG. 4 (color online). DOK-1 FEL gain as a function of OK-5 wiggler detuning. The gain is scaled using $I_b^{2/3}$, for $I_b = 16$ mA. Starting from a current setting optimized for maximum gain, $I_{\mathrm{OK5}} = 2820$ A, I_{OK5} is first ramped up to 3000 A, then back to 2820 A ($I_b = 12.3$–5.5 mA); next, I_{OK5} is ramped down to 2640 A, then back to 2820 A ($I_b = 11.7$–4.4 mA).

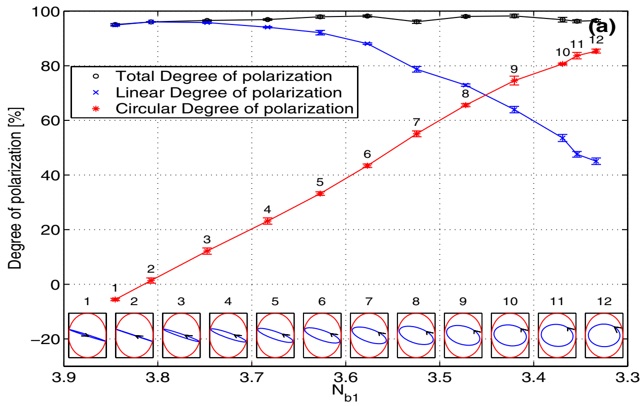

FIG. 5 (color online). Measured polarization of the DOK-1 FEL at 450 MeV as the buncher 1 setting is tuned: N_{b1} from 3.85 to 3.33. The insets show the evolution of the polarization ellipses.

polarized with the total degree of polarization varying between 95% and 98%. In the meantime, the linear polarization was reduced from 95% to 45% while the circular polarization was increased from −6% to 85%. The polarization switch between linear and elliptical was realized with both 450 and 600 MeV *e* beams with reasonable reproducibility. Better controls of polarization can be obtained with a polarization feedback system.

We recognize that the downstream OK-5B wiggler (see Fig. 1) is the main emitter of circularly polarized light. Initially, to suppress the circular polarization, the upstream OK-5A wiggler is tuned out of phase from OK-5B with $N_{b1} = 3.85$. In addition, both OK-4 wigglers are mostly in phase between themselves. By reducing the buncher 1 current, the OK-5A is tuned gradually to be in phase with OK-5B, resulting in significant enhancement of the circular polarization at $N_{b1} = 3.33$, with $\Delta N_{b1} = -0.51$. The change of the relative phase between two OK-5 wigglers is expected to be about -0.51 (± 0.20). A large uncertainty in the phase change can be attributed to the uncertainties in experimental setups. At this point, the total polarization is elliptical since the OK-4 wigglers contribute a horizontal component. As the polarization is switched from linear to elliptical, the full spectra width is reduced from 1.30 to 0.81 nm, the current-scaled intensity of the FEL is increased by a factor of 2, and the lasing wavelength is shifted from 455 to 453 nm. The increased FEL power indicates the overall increase of the FEL interaction by bringing two OK-5 wigglers in phase.

The operation of the first distributed optical klystron, DOK-1 FEL, has demonstrated that DOK FELs are capable novel light sources with a high level of versatility. First, a much enhanced gain in DOK FELs over OK FELs will allow SRFELs to become powerful VUV light sources between 200 and 100 nm. For example, we expect the DOK-1 FEL to achieve a gain of 20%–30% at 150 nm [17] with a bunch current of 40–50 mA. Such a high gain will make it possible to operate SRFEL oscillators at VUV wavelengths by overcoming the high loss of dielectric multilayer cavity mirrors. The higher FEL gain also opens the door for VUV FEL oscillators approaching 100 nm and beyond with a ring-resonator design. Second, as shown by the DOK-1 FEL, DOK FELs are promising VUV light sources capable of polarization switch. The repetition rate of polarization switch can be significantly increased to hundreds of hertz or more using specially designed fast buncher magnets. Furthermore, DOK FELs can be used as a multicolor light source with phase synchronization when used to generate coherent harmonic radiation.

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