FREE ELECTRON LASERS 1997

Proceedings of the Nineteenth International
Free Electron Laser Conference and
Fourth FEL Users' Workshop
Beijing, China, August 18-22, 1997

Editors
JIALIN XIE
XIANGWAN DU

NORTH-HOLLAND

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Preface

The Nineteenth International Free Electron Laser Conference and the Fourth FEL Users' Workshop were held on 18–21 August 1997 in Beijing, China. The conference and the workshop were organized jointly by: Institute of Applied Electronics (CAEP), Institute of High Energy Physics (CAS), China Institute of Atomic Energy, University of Electronic Science and Technology of China, Peking University, and Institute of Applied Physics and Computational Mathematics (IAPCM). They were attended by about 150 scientists from 13 countries: France (4), Germany (6), India (1), Israel (3), Italy (3), Japan (24), South Korea (5), P.R. China (40), Poland (1), Russia (6), The Netherlands (11), United Kingdom (9), USA (37). Of the more than 200 papers that were presented, either in oral sessions or in poster sessions, 164 papers are published in this volume, covering the following subjects: New lasings (4), Theory and modeling (35), Experiments in progress (23), Accelerators for FELs (29), Optics and undulators for FELs (23), Storage-ring FELs (12), SASE and short-wavelength, high-gain FELs (17), New concepts and proposals (14), FEL applications (6). Besides these contributions, Charles Brau gave the FEL prize talk discussing bright beams and small FELs. This was received with great interest.

Technical visits were arranged on Wednesday afternoon to the Institute of High Energy Physics (CAS), where the Beijing Electron–Positron Collider with the parasitic Synchrotron Radiation Facility and the Beijing FEL Facility are located.

Because of the limited amount of journal pages allotted to the Proceedings and our wish to include as many significant contributions as possible, it was decided that the Proceedings should consist of two parts: Part I, comprising the oral talks, appears as both a special issue of *Nuclear Instruments and Methods in Physics Research A* and in the book edition *Free Electron Lasers 1997*; Part II, consisting of camera-ready copy contributions, only appears in the book edition.

The FEL Proceedings that appeared as special issues of Nuclear Instruments and Methods give a comprehensive account of the developments of FELs. About 20 years have passed since FEL oscillation was first realized. During these 20 years we have witnessed different stages of FEL development. The pendulum swung between the extremes of overexcitement and impatience. Thanks to the endurance and enthusiasm of the researchers in this field, we understand more and more about the physics as well as the technology of the art and science of FELs. Hence, steady, impressive progress has been made in every respect. We are sure that in these Proceedings you will find many new facilities, new experimental results, new applications, new theoretical developments and new simulation results.

The recent progress in SASE is worth special mention. The SASE mode of operation does not require an optical resonator and hence lacks a high damage threshold; high reflectance mirrors do not restrict their operation at very short wavelengths. Theoretical works on SASE were initiated more than 10 years ago. Because the requirements on the quality of the electron beam and the undulator are very stringent for SASE operation, experimental observations at short wavelengths are very scarce. In these Proceedings you will find clear indications of the progress in experimental observations of SASE. The operating wavelength has been reduced from about 10 μm in previous experiments to about 1 μm.

The application of FELs to scientific investigations and industrial processing is of critical importance to win the support of society. For the former, some laboratories have already served as reliable user facilities, and the number is growing. For the latter, the development by Jefferson Laboratory (USA) of an IR demo FEL will be a significant milestone.

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The FEL has already established itself as the fourth-generation light source because of its unique features, such as high brightness, coherence and short pulse. Just like a human being, it has grown from a newborn child to mature manhood. We have learned of its characteristics, which offer new opportunities to the users, and of its technical limitations.

This is the first time that the FEL Conference and FEL Users' Workshop were held in China. We appreciate the opportunity that this gathering brought to us. Undoubtedly, it will stimulate and encourage FEL developments in China.

We would like to express our thankfulness for the technical support from different sources that made this meeting possible. The sponsors are: National Laser Technology Committee (China), Office of Naval Research (USA), International Center for Theoretical Physics (ICTP), and Elsevier Science B.V.

We also want to thank the members of our local organizing committee, especially the conference secretary Zhi Wei Dong, for their hard work and wonderful accomplishments. Finally, the editors gratefully acknowledge the help from Elsevier Science B.V. that makes the Proceedings a beautiful yellow volume in your hands.

Jialin Xie
Xiangwan Du
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Doctor Kwang-Je Kim wins the 1997 International Free-Electron Laser Prize

The International Free-Electron Laser Prize is awarded annually to recognize significant contributions to the field of free-electron lasers. At the 19th International Free-Electron Laser Conference held in Beijing, P.R. China, the 1997 prize was awarded to Doctor Kwang-Je Kim of the Lawrence Berkeley Laboratory. Dr. Kim received the prize in honor of the impact his research has had in the advancement of FEL science and technology, and in recognition of his support of FEL projects and facilities worldwide.

For more than fifteen years Dr. Kim's career has been dedicated towards exploring the frontiers of FEL science and technology. He has worked on FEL gain analysis and simulation, on the understanding of FELs using hole outcoupling, on an analysis of laser driven RF photocathode guns, and on problems related to self-amplified-spontaneous-emission (SASE).

His pioneering analysis of the electron beam dynamics in laser-driven RF photocathode guns led to an understanding which has played an important role in the development of these guns as

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sources of high brightness electron beams. Every group involved in research on RF photocathode RF guns has a copy of his paper close at hand.

Kwange-Je was the first to show explicitly how the radiation-electron beam system evolves from an initial incoherent regime to an exponential gain regime in a long undulator. He was one of the early investigators to study 3-D effects in SASE systems. Further, he led the effort to disseminate complex results in simplified forms suitable for quick calculations of basic parameters in SASE designs.

He has been a constant supporter of FEL projects and proposals worldwide, and as a recognized expert in both FEL and synchrotron radiation he has been an active participant in many facility designs. His insights are always helpful and his enthusiasm is always infectious.

Todd I. Smith
Chairman FEL-Prize Committee


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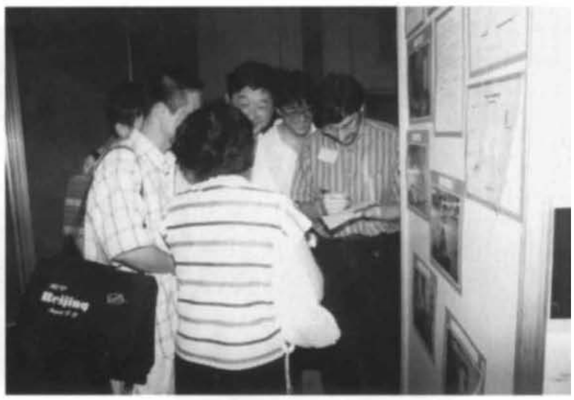


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Part II (The text of these papers is to be found in the book edition of the Proceedings, ISBN 0-444-82978-4.)

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

High-brightness electron beams – small free-electron lasers[1]

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Abstract

At the present time, the normalized brightness of electron beams available for use in free-electron lasers is of the order of 10^{11} A/m^2-steradian. Needle cathodes emitting by field emission have demonstrated high current density, low electron temperature, small emittance, and peak currents exceeding 1 A in microsecond pulses. Photoelectric field emission can be used to control the pulse length. Measurements are underway to measure the emittance and electron energy spread of beams produced by field emission. Using beams with very high brightness, as much as five orders of magnitude beyond those in use now, it is possible to construct compact free-electron lasers at wavelengths from the far infrared to the ultraviolet. Cherenkov and Thomson lasers are discussed in detail.

1. Introduction

The development of newer, shorter-wavelength and more powerful free-electron lasers has been paced by the development of better electron beams, i.e., electron beams with higher current and smaller emittance. The need for smaller emittance follows from the fact that the electron beam must be focused inside the laser beam for the interaction to take place. For the purposes of this discussion, we define the effective emittance ε by the formula [1]

$$\varepsilon = 4\pi\sqrt{\langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2}, \qquad (1)$$

where x is the transverse position of an electron at the point z along the beamline, $x' = \mathrm{d}x/\mathrm{d}z$, and the brackets $\langle\ \rangle$ indicate an average over all the electrons in the beam. To focus the electron beam inside the laser beam, in the absence of gain guiding of the laser beam by the electron beam, it is necessary that [2]

$$\varepsilon < \lambda_{\mathrm{L}}. \qquad (2)$$

For beams in a time-independent field, the emittance decreases with increasing electron energy. Thus, it is useful to define the normalized effective emittance and the normalized brightness [3]

$$\varepsilon_{\mathrm{N}} = \beta\gamma\varepsilon, \qquad (3)$$

$$B_{\mathrm{N}} = \beta^2\gamma^2\frac{\mathrm{d}^2 I_{\mathrm{e}}}{\mathrm{d}\Omega\,\mathrm{d}A} \approx \frac{2I_{\mathrm{e}}}{\varepsilon_{\mathrm{N}}^2}, \qquad (4)$$

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where $\beta = v/c$ is the velocity of the electrons normalized to that of light, $\gamma = 1/\sqrt{1-\beta^2}$ is the electron energy normalized to its rest energy, I_e is the total current, and the approximate formula is valid for a top-hat beam [4]. The normalized quantities are generally dependent only weakly on the electron energy. In addition, the brightness is generally a weak function of the total current.

In the past, dc thermionic emitters, rf linacs, and storage rings have been used to provide the electron beams for free-electron lasers. The status of these three technologies is summarized in Fig. 1. We see there that the highest brightness among conventional sources is still achieved by dc thermionic technology, albeit at low current. Storage rings offer the most graceful means of obtaining high energy, but rf linacs now provide higher normalized brightness. As discussed below, it appears possible using field emission to improve on the brightness by more than five orders of magnitude.

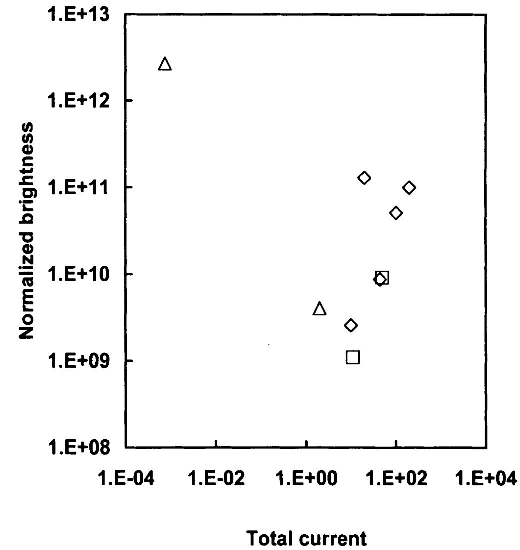

Fig. 1. Normalized brightness of various electron-beam sources used for free-electron lasers: diamonds – rf linacs; squares – storage rings; triangles – thermionic emitters.

2. Field emission

Near the tips of sharp needles the electric field can take on very high values even for modest voltages. For example, for a tip radius $R_{tip} \sim 1\,\mu m$, a needle length $a \sim 1$ cm protruding from the surface of the cathode, and an anode-cathode separation of 2 cm, at 50 kV, the electric field at the tip of the needle is $E_{tip} \sim 5 \times 10^9$ V/m.

Around the turn of the century, anomalous emission of electrons was observed under such conditions. A satisfactory explanation was finally developed when the concept of quantum mechanical tunneling was introduced [5]. When the electric field is very strong, the potential barrier at the surface of the metal becomes thin enough for the electrons near the Fermi level to penetrate through the classically forbidden region. The quantum mechanical theory was first derived by Fowler and Nordheim, who showed that the emission at low temperatures (room temperature and below) is given by the formula which now bears their names [6]:

$$J_e = 1.54 \times 10^{-6} \frac{E^2}{\varphi} \exp\left[-6.83 \times 10^9 \frac{\varphi^{3/2}}{E} f(y) \right], \quad (5)$$

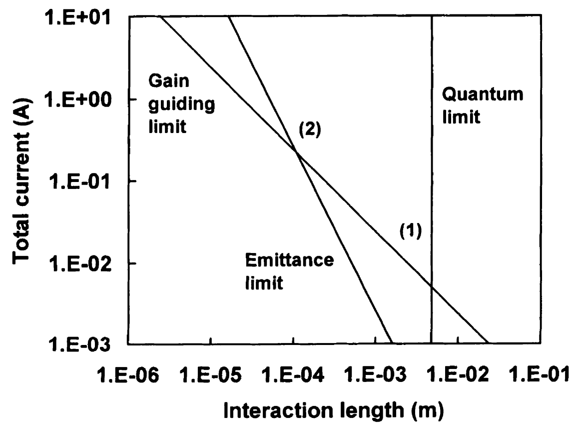

Fig. 2. Window in parameter space where a Thomson free-electron laser can be operated. The intersection labeled (1) corresponds to the maximum length and minimum current before quantum effects become important. The intersection labeled (2) corresponds to the minimum length and minimum current before emittance effects become important.

where J_e is the current density (in A/m^2), E the electric field at the surface (in V/m), φ the work function of the metal (in eV), and $y = 3.79 \times 10^{-5}\sqrt{E}/\varphi$. The function $f(y)$ is a dimensionless elliptical function introduced to account for image forces near the surface. It varies from 1 at $y = 0$ to 0 at $y = 1$, and is actually closely approximated by $\cos(\pi y/2)$. Current is typically emitted over the tip of the needle out to about 30° [7]. Using as an example the needle introduced above, we find that for a work function $\varphi \sim 4.5\,\text{eV}$, which is characteristic of tungsten, the current density is $J_e \sim 10^9\,\text{A/m}^2$, and the total current is $I_e \sim 1\,\text{mA}$.

At sufficiently large current density, space charge becomes important. For a spherical geometry, the space-charge limit is [8]

$$J_e = \frac{4\varepsilon_0}{9a^2}\sqrt{\frac{2e}{m}}\frac{V^{3/2}}{r_{\text{cathode}}}, \tag{6}$$

where ε_0 is the permeability of free space (SI units are used throughout), m the electron mass, e the electron charge, V is the voltage, and a^2 is a slowly varying function of the ratio of the anode and cathode radii. For $10^3 < r_{\text{anode}}/r_{\text{cathode}} < 10^4$, it is found that $5 < a^2 < 10$. In the case discussed above, the space-charge limited current density is $J_e \sim 3 \times 10^{13}\,\text{A/m}^2$. The energy spread of the electrons is predicted to be of the order of a volt in the longitudinal direction, and smaller in the transverse direction [9]. At higher needle temperatures the emission increases due to faster tunneling by electrons thermally excited to higher energy [10].

The experimental results confirm the theoretical predictions in remarkable detail. The current density has been observed to follow the Fowler–Nordheim relation over more than six orders of magnitude, up to a current density $J_e \sim 10^{11}\,\text{A/m}^2$ [11]. Above this value, space-charge effects reduce the field at the surface. Nevertheless, a current density $J_e \sim 3 \times 10^{11}\,\text{A/m}^2$ has been observed in microsecond pulses. The longitudinal energy distribution has been carefully measured, and confirms both the predicted shape and the predicted width of about 1 eV [12]. The largest total current which has been observed is 6.5 A, obtained in microsecond pulses from a cathode with a tip radius of 3 μm [13]. The emittance has not been measured directly. However, the resolving power of field-emission microscopes, about 3 nm, supports the predicted transverse electron temperature of less than 1 eV at low currents [14,15]. If this persists to higher currents, the corresponding normalized brightness will exceed $10^{17}\,\text{A/m}^2$-steradian.

Recently, it has been observed that shining a laser on the tip of a needle turns on field emission at surface electric fields well below those otherwise required for significant emission [16,17]. This phenomenon is attributed to a photoelectric effect, in which the electrons are excited to levels above the Fermi level where the electrons can tunnel through a thinner part of the barrier. The largest total current that has been observed so far is $I_e \sim 2\,\text{A}$, extracted in nanosecond pulses from needles with $R_{\text{tip}} \sim 50\,\text{nm}$ [18]. The corresponding current density is $J_e \sim 10^{14}\,\text{A/m}^2$, which is near the space-charge limit for a needle of this size. The current pulse was observed to follow the laser pulse.

To determine the electron temperature and emittance of beams produced by field emission, experiments are being undertaken. To measure the energy spread, the electrons are collected in a Faraday cup connected to the cathode through a variable bias of the order of a few volts. As the bias is increased, electrons with increasing energy are reflected from the cup. By differentiating the current collected as a function of the bias voltage, the electron energy distribution function is obtained. The resolution of the measurement is limited by the focusing of the electrons into the Faraday cup. To achieve an energy resolution better than 100 meV, which corresponds to about ten parts per million at a total energy of 10 keV, the diameter of the aperture at the focusing lens (1 m from the focus) must be less than 6 mm. The total current transmitted by the aperture at the lens is expected to be about 100 nA out of a total emitted current of 30 μA.

To measure the emittance, the solenoidal lens is used to focus the beam at a point 1 m beyond the lens. The emittance-limited spot radius here is $\overline{w}_e \sim 0.2\,\mu\text{m}$, which is too small to measure conveniently. The beam is therefore magnified by a second solenoidal lens to a spot radius $\bar{w}_e \sim 10\,\mu\text{m}$ at a point 1 m away. This beam is large enough to be scanned across a knife edge and the current measured by the Faraday cup. The emittance is then determined in the usual way, by varying the current in the second lens and observing the spot size. The principle source of error is spherical aberration in the first lens [19]. To avoid this, the radius of the aperture at the first lens must be reduced to $w_e \sim 1$ mm. The total current at the Faraday cup is correspondingly reduced to about 10 nA.

The initial experiments are being conducted using a 2-W cw argon laser to generate total currents up to 30 μA. This avoids problems due to space charge. Later measurements will use a Q-switched Nd:Yag laser to generate higher peak currents. The effect of space charge at the cathode is discussed above, and may alter the actual brightness and energy spread of the electron beam. Electron–electron collisions (Boersch effect) may also be important [20].

3. Laser applications

With a 5-order-of-magnitude improvement in electron-beam brightness, several new types of free-electron lasers become possible. We discuss here Cherenkov and Thomson free-electron lasers.

A Cherenkov free-electron laser consists of a dielectric waveguide on a conducting substrate. A wave propagating through the dielectric extends into the vacuum above the waveguide, called the evanescent region. Since it is not an infinite plane wave, the evanescent wave has a longitudinal component of the electric field. When an electron beam travels near the surface of the waveguide parallel to and synchronous with the wave, it interacts with the longitudinal field, which causes the beam to bunch at the optical wavelength in the dielectric and amplify the wave.

The longitudinal electric field in the evanescent region has the form

$$E_x = E_0 \exp(-y/2s)\sin(kz - \omega t), \tag{7}$$

where E_0 is the field at the surface of the dielectric, y the distance above the dielectric-vacuum interface, z the distance in the direction of propagation, and t the time. The wave vector in the waveguide is related to that in free space by $k = k_\infty/\beta$, $\omega = k_\infty c$ is the frequency, and the scale height of the evanescent wave is

$$s = \frac{\beta_R \gamma_R}{2k_\infty}. \tag{8}$$

By matching this to the solution inside the dielectric, we find that the velocity of propagation of the guided wave is

$$k_\infty t = \sqrt{\frac{\beta_R^2}{n^2\beta_R^2 - 1}} \arctan\left(n^2\sqrt{\frac{1-\beta_R^2}{n^2\beta_R^2 - 1}}\right), \tag{9}$$

where t is the thickness of the dielectric, and n the dielectric constant, and the ratio of the power flowing through the dielectric to that flowing through the evanescent region is

$$\chi = \frac{\tan\theta}{n^4}\frac{2\theta + \sin 2\theta}{1+\cos(2\theta)}, \tag{10}$$

where

$$\theta = \arctan\left(\frac{n^2}{\gamma_R^2\sqrt{n^2\beta_R^2 - 1}}\right). \tag{11}$$

The electron dynamics are described by the same pendulum equation as in conventional free-electron lasers, with two differences. In the first place, the electron velocity is synchronous with the wave velocity, so here is no slippage aside from synchrotron motions. In the second place, the electron velocity is typically less than the velocity of light, so it is not valid to make the assumption $\beta \approx 1$. Nevertheless, we may cast the pendulum equations in the same dimensionless form as for a conventional free-electron laser:

$$\mathrm{d}\mu/\mathrm{d}\tau = -\varepsilon\sin\psi, \tag{12}$$

$$\mathrm{d}\psi/\mathrm{d}\tau = \mu, \tag{13}$$

and

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}\tau} = j_e\langle\sin\psi\rangle, \tag{14}$$

where

$$\mu = \frac{k_\infty L}{\beta_R^2}(\beta - \beta_R) \tag{15}$$

is the dimensionless energy,

$$\tau = \beta_R ct/L \tag{16}$$

the dimensionless time, in which L is the length of the grating, and ψ the phase. The dimensionless electric field is

$$\varepsilon = \frac{k_\infty L^2}{\beta_R^3 \gamma_R^3} \frac{eE_0}{mc^2} \exp\left(- \frac{h}{2s} \right), \tag{17}$$

where E_0 is the longitudinal electric field at the surface of the dielectric, and h is the height of the electron beam above the surface, and the dimensionless current density is

$$j_e = \frac{2}{1 + \chi} \frac{I_e}{I_0} \frac{k_\infty^3 L^3}{\beta_R^5 \gamma_R^6 \sigma_x} \exp\left(- \frac{h}{s} \right), \tag{18}$$

where σ_x is the transverse width over which the electron-beam current I_e must be averaged and $I_0 = \varepsilon_0 mc^3/e = 1356\,\mathrm{A}$ is a characteristic current [27]. Since the dimensionless equations are the same as for a conventional free-electron laser, we may take advantage of the solutions which have been worked out for the conventional case.

When the gain is very large, it may be expressed by the formula [21]

$$G_0 = \tfrac{1}{9} \exp[(\tfrac{1}{2} j_e)^{1/3} \sqrt{3}]. \tag{19}$$

To reach saturation in a single pass, beginning from noise, the overall gain must be very large. For conventional free-electron lasers, Kim finds that saturation occurs when $j_e \sim 2(4\pi)^3 \approx 4000$, which corresponds to $G \approx e^{20}$ [22]. In the high-gain regime, diffraction spreading of the laser beam in the transverse direction is controlled by gain guiding [23]. In this case, the effective width of the optical beam corresponds to a Rayleigh range of the order of the gain length, $L_{\mathrm{gain}} = L/\ln G_0$, so that $\sigma_x \sim \sqrt{2\beta L/k_\infty \ln G_0}$. It is, however, important to focus the electron beam inside the evanescent part of the laser beam. In the absence of space charge, the radius of the electron beam at the focal point is $w_e = \sqrt{\varepsilon L/2\pi}$, which must be smaller than the scale height [24]. For this reason, Cherenkov free-electron lasers are most useful at long wavelengths, typically in the far infrared and beyond.

To illustrate these ideas with an example, we examine a laser $L \sim 5\,\mathrm{cm}$ in length, operating at a wavelength $\lambda_L \sim 250\,\mu\mathrm{m}$ with an electron energy of 50 keV. The scale height of the evanescent wave is $s \sim 10\,\mu\mathrm{m}$. Using an e-beam with a total current of $I_e \sim 10\,\mathrm{mA}$ and a normalized brightness $B_N \sim 10^{15}\,\mathrm{A/m^2}$-steradian, the focused spot radius of the electron beam is $w_e \sim 10\,\mu\mathrm{m}$, which satisfactorily matches the scale height. The energy bandwidth of the laser is $mc^2 \delta\gamma \sim 500\,\mathrm{eV}$, which is much larger than the expected energy spread. The dimensionless current density is then $j_e > 4 \times 10^3$, which satisfies the requirement for reaching saturation in a single pass.

As another application, we consider the possibility of operating in the ultraviolet regime. If we use a laser as the wiggler, in which case the FEL is really stimulated Thomson backscatter, then the laser wavelength is given by the double Doppler shift [25]

$$\lambda_L = \frac{1 - \beta}{1 + \beta} \lambda_P, \tag{20}$$

where λ_P is the pump wavelength. The analysis is similar to that of a conventional free-electron laser, except that since γ is not large, the slip length is not small and we cannot separate distances inside the bunch from the overall length of the laser. Nevertheless, in the time independent case we again obtain the pendulum equations. The dimensionless current density in the moderate-β case is [26]

$$j_e = 4\pi \frac{e}{\varepsilon_0 mc^3} \frac{a_P^2 L^3 J_e}{\gamma^3 \beta^3 \lambda_P}, \tag{21}$$

in which L is the length of the interaction region, and

$$a_P^2 = \frac{e^2}{4\pi^2 \varepsilon_0 m^2 c^5} \lambda_P^2 I_P \tag{22}$$

the dimensionless wiggler vector potential, where I_P is the pump laser intensity.

Although these expressions are derived using the one-dimensional approximation, they should be satisfactory for the case of interest here. The diffraction-limited spot size of the UV beam in the high-gain regime is controlled, again, by gain guiding. In this case, the diffraction-limited spot radius corresponds to a Rayleigh range of the order of the gain length, i.e., to a radius $w_0 \sim \sqrt{\lambda_X L/\pi \ln G_0}$. But in a space-charge dominated beam the radius of the beam at the focus is $\bar{w}_e \sim L\sqrt{K}/2$ where the dimensionless perveance is $K = I_e/2\pi\beta^3\gamma^3 I_0$. So long as the gain-guided radius is no larger than the electron-beam radius, the actual laser spot size approximates that of the electron beam, and the current density is $J_e = I_e/\pi\bar{w}_e^2 \sim 8\beta^3\gamma^3 I_0/L^2$. Since this current density is independent of the total current, we are free to choose the lowest current for which gain guiding is sufficient to make the guided laser radius equal to the electron-beam radius. When this is substituted into the dimensionless current density, we see that j_e is proportional to the interaction length L. Unfortunately, the length of the interaction region cannot be made arbitrarily long because quantum effects (Compton recoil) reduce the gain [28]. Electron bunching occurs on a dimensionless length scale [29]

$$\tau_B = \sqrt{3}/\ln(9G_0). \tag{23}$$

If we argue that the electron phase shift in one bunching length caused by the electron recoil must be less than unity, then we obtain the restriction

$$\frac{4\pi\sqrt{3}}{\ln(9G_0)}\frac{1+\beta}{\beta\gamma}\frac{\lambda_C L}{\lambda_P\lambda_L} \leqslant 1. \tag{24}$$

Combining these ideas, we arrive at the formula

$$j_e \sim 16a_P^3\left(\frac{\lambda_L}{\lambda_C}\frac{\beta\gamma}{1+\beta}\right)^{3/2} \tag{25}$$

for the optimized performance of a Thomson free-electron laser. To reach saturation, we again require that $j_e \sim 2(4\pi)^3$. For an electron energy of 150 keV ($\beta \sim 0.6$), and a pump wavelength $\lambda_P =$ 353 nm (tripled Nd:YAG), the laser wavelength is $\lambda_L \sim 80$ nm, which is in the ultraviolet. The electron-beam current is only $I_e \sim 5$ mA. The difficulty is that the pump laser intensity must be constant in time and space. Although the dimensionless wiggler intensity is only $a_P^2 \sim 3\times10^{-3}$, the wiggler is quite long ($N_W \sim 3\times10^4$ wiggler periods), so the laser intensity must be constant to about one percent, even allowing for the expansion of the laser bandwidth by the high gain. The required pump uniformity can be achieved by making the laser pulse longer than the minimum necessary to fill the laser volume during the electron transit, and by making the pump laser Rayleigh range longer than the interaction region. To keep the phase shift in one bunching length less than unity, we require that

$$2\pi\frac{1+\beta}{\beta^2}\frac{L}{\lambda_P}\frac{\sqrt{3}}{\ln(9G_0)}\Delta a_P^2 < 1. \tag{26}$$

If we estimate the effects of diffraction and pulse length by the formulas

$$\Delta a_P^2 = L^2/8z_P^2, \tag{27}$$

where z_P is the Rayleigh range of the pump pulse, and

$$\Delta a_P^2 = \tau_{\min}^2/2\tau_P^2, \tag{28}$$

respectively, where $\tau_{\min} = (1+\beta)L/\beta c$ is the minimum length and τ_P the actual length of the pump pulse, we find that the pump laser pulse energy required to reach saturation is

$$U_P = 2\pi^4 I_0 V_0\frac{(1+\beta)^2}{\beta^3}\frac{L^2}{\lambda_P c}, \tag{29}$$

where $V_0 = mc^2/e \sim 0.511$ MeV. In the case discussed above, this corresponds to $U_P \sim 400$ J in $\tau_P \sim 100$ ps. Clearly, we can reduce the pump energy by decreasing the interaction length, at the price of increasing the electron-beam current. There is a limit to this, however, when the focal region becomes so short that the emittance becomes important in determining the beam waist. This occurs when

$$L^2 = 32\beta^4\gamma^4\frac{I_0}{I_e B_N}. \tag{30}$$

As the focal radius becomes shorter, the required current increases to maintain gain guiding. The sum of all these restrictions leaves a window in parameter space as shown in Fig. 2. The operating point discussed previously corresponds to the minimum total current at the length limit imposed by quantum effects. If we decrease the interaction length to the point where emittance becomes important, the pump laser energy is only $U_P \sim 10$ J in $\tau_P \sim 3$ ps, but the required electron beam current is increased to 200 mA.

4. Conclusion

Due to the enormous current density possible by using field emission from needle cathodes, it appears possible to extend the brightness of electron sources for free-electron lasers by five orders of magnitude or more. Photoelectric field emission has demonstrated nanosecond control of electron-beam currents in excess of 1 A, but the detailed properties of field-emission sources (energy spread and emittance) have not been measured at high current. Experiments are underway to determine these properties at total currents up to about 1 mA. Beyond this point, space-charge makes it impossible to focus the beams as required to resolve the expected energy spread and emittance.

Using beams with normalized brightness as high as 10^{15}–10^{17} A/m^2-steradian, it is possible to build compact lasers at wavelengths from the infrared to the ultraviolet. For example, a Cherenkov free-electron laser operating at a wavelength of 250 μm can reach saturation in a single pass at a total electron-beam current of only 10 mA. Similarly, a Thomson free-electron laser operating at a wavelength of 80 nm can reach saturation in a single pass at a total electron-beam current of only 5 mA.

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NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

First UV/visible lasing with the OK-4/Duke storage ring FEL

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Abstract

In this paper, we report first lasing results in the near-UV and visible spectral ranges with the OK-4/Duke storage ring – the first storage ring FEL operating in the United States. The OK-4/Duke FEL was commissioned in November 1996 and demonstrated lasing in the 345–413 nm range with extracted power of 0.15 W. In addition to lasing, the OK-4/Duke FEL generated a nearly monochromatic (1% FWHM) γ-ray beams. In this paper, we describe initial performance of the OK-4/Duke storage ring FEL and γ-ray source in this demonstration experiment. We briefly discuss the present status of the project and its future user program. © 1998 Published by Elsevier Science B.V. All rights reserved.

1. Introduction

The Duke University Free Electron Laser Laboratory (DFELL) and the Budker Institute of Nuclear Physics (BINP) have collaborated on the OK-4/Duke storage ring XUV FEL project since 1992 [1]. The OK-4 FEL was built and operated in the 240–690 nm range using the VEPP-3 storage ring at Novosibirsk [2]. After commissioning the 1.1 GeV Duke storage ring in November 1994 [3], the OK-4 FEL made a trip around the globe and came to Duke in May 1995.

The OK-4/Duke FEL was prepared for the first demonstration experiment in November 1996. An UV streak-camera was brought to Duke from Argonne National Laboratory (APS) and has been used to measure electron bunch length, optical cavity length, and FEL pulse length [4].

After commissioning all critical OK-4/Duke FEL subsystems, the very first run on 13 November 1996, was successful. The OK-4/Duke storage ring FEL demonstrated operation in the near UV/visible range with a tunability of $\pm$ 18% around the center wavelength of 380 nm. Two days later we demonstrated the generation of nearly monochromatic 3–15 MeV γ-rays [5] by tuning both the laser wavelength and the energy of the electron beam.

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The main problem for these experiments was the "blind-folded" alignment due to the absence of electronics for beam position monitors (BPM). The relatively high gain of the OK-4 FEL helped to overcome this problem. Experiments, dedicated mostly to the production and characterization of γ-ray beam, continued for about a month. In parallel with the γ-ray production, we had performed a number of measurements of the OK-4/Duke FEL parameters. In this paper, we focus on the first lasing with the OK-4/Duke storage ring FEL and its main parameters. The first unsuccessful attempts to lase with the OK-4/Duke FEL in August 1996 without several critical systems in place were presented at the previous FEL Conference and published elsewhere [6]. Initial performance and predictions for the OK-4/Duke monochromatic γ-ray source, a pleasant side-product of intracavity Compton scattering, are described in Refs. [5,7–9]. Details of the OK-4/Duke FEL micro-temporal structure are also discussed elsewhere [4,10].

Operation of the OK-4/Duke FEL was interrupted in the middle of December 1996 by an administrative decision of the DFEL laboratory to condition a klystron used to drive the last four sections of the linac-injector. This break continued for seven months. During this period of time, the Duke storage ring and the OK-4 FEL diagnostic systems were undergoing modifications.

2. The OK-4/Duke XUV storage FEL

Schematic layout of the 1.1 GeV Duke storage ring and the OK-4 XUV FEL facility is shown in Fig. 1. The OK-4 FEL is installed in the south straight section dedicated for FEL operation. The present lattice is optimized for maximum OK-4 FEL gain and has both transverse β-functions of 4 m at the center of the OK-4. The 11 m long vacuum chamber for the OK-4 magnetic system has 8 m of constant cross-section and two 1.4 m long smooth transitions from the 2.2 cm × 7.5 cm flat shape to the 10 cm round pipe. Three ion pumps are located at the center and two ends of the OK-4 system, providing vacuum in the 10^{-10} Torr range. For installation on the Duke storage ring, the magnetic system of the OK-4 FEL was slightly modified. The gap in the OK-4 was increased to 2.25 cm to accommodate a new vacuum chamber. The buncher was shifted from the center of the OK-4 to provide a magnetic-field-free collision point for the Compton γ-ray production.

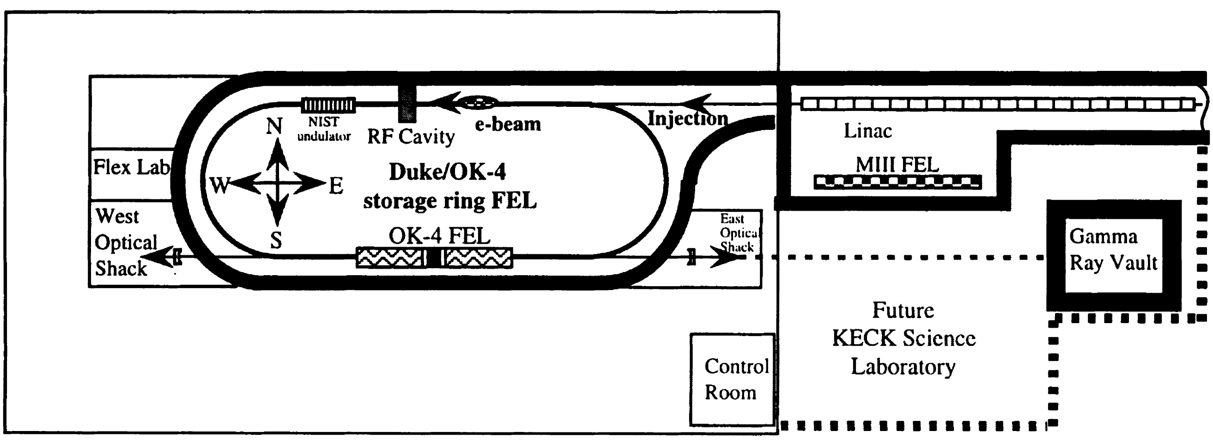

Fig. 1. Layout of the Duke/OK-4 storage ring FEL facility. The 1.1 GeV Duke storage ring is surrounded by 2′ concrete shielding. Two mirrors of the 53.73 m long OK-4 optical cavity and its diagnostics are located outside of the shielding in the optical shacks. These shacks and a flex-lab will be used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

Table 1
Duke storage ring electron beam parameters

Operational Energy (GeV)	0.25 – 1.1
Circumference (m)	107.46
Impedance of the ring, Z/n, (Ω)	2.75 ± 0.25
Stored current (mA)[a]	
Multibunch	155
Single bunch	20[b]/8[c]
Bunch length, σs (ps)[d]	
Natural (low current)	15
With 5 mA in single bunch	60
Relative energy spread, $\sigma E/E$[d]	
Natural (low current)	2.9×10^{-4}
At 5 mA in single bunch	1.1×10^{-3}
Peak current (A)[d]	
With 5 mA in single bunch	12
With 20 mA in single 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 thermionic gun;
[c]In single bunch mode with photocathode gun;
[d]At 500 MeV, $V_{RF} = 500$ kV; measured by the streak-camera [4] and dissector;
[e]Expected from the broad band impedance model with $Z/n = 2.75\,\Omega$;
[f]Extracted as the top limit from the OK-4 spontaneous radiation spectra.

Table 2
Some of the OK-4 FEL parameters

Optical cavity	
Optical cavity length (m)	53.73
Radius of the mirrors, measured (m)	27.27
Rayleigh range in OK-4 center (m)	3.3
Angular control accuracy (rad)	better than 10^{-7}
OK-4 wiggler [1,14]	
Period (cm)	10
Number of periods	2×33.5
Gap (cm)	2.25
Kw/I (1/kA)	1.804
Kw	0–5.4[a]

[a]At the time of November 1996 experiment Kw was limited to 3.8. At present time, Kw is limited to 4.5 by the power supply.

The main parameters of the low emittance Duke storage ring are published elsewhere [3,11] and briefly summarized in Table 1. For experiments reported in this paper we have operated the Duke storage ring in energy range from 270 MeV (injection energy) to 550 MeV. We were not able to operate at wavelength of 380 nm above 550 MeV due to the limitation of wigglers power supply (see the note attached to Table 2).

The existing injection system limited the maximum stored current to 8 mA/bunch. In future, we plan to improve efficiency of injection and increase the current to 20–40 mA/bunch.

The storage ring RF system [12] operates at 178.5 MHz which is the 64th harmonic of the revolution frequency. The RF frequency is generated by a SAW master oscillator which is controlled by a 16-bit DAC via the Duke storage ring control system [13]. Typical OK-4 FEL operation mode used RF voltage of 500–550 kV. A short list of up-to-date OK-4 FEL parameters is summarized in Table 2. Other parameters and expected performance of the OK-4 FEL are described in previous publications [2,14].

Two Trans-Rex power supplies, donated by Fermi Lab, have been repaired, equipped with external LC filters and are presently used to drive the OK-4 wigglers and buncher. Overall performance of the power supplies is close to specifications (with about 100 ppm stability) and will be improved in the near future by using a second stage of regulation and an active feedback from the OK-4 FEL diagnostics. We also plan to extend the operation range of the wiggler power supply from the present limit of 2.5 kA to 3 kA required for full range OK-4 FEL tunability.

The controls of the OK-4 FEL systems are part of the Duke storage ring control system [13]. The control 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. A number of lattices (snapshots in control system terminology) were created to operate the OK-4 FEL. Once created, the snapshots can be used to re-establish lasing. In addition, we have demonstrated continuous lasing in the OK-4 FEL during the ramping from the injection energy to 500 MeV.

The RF-smooth crotch chambers providing passage of the optical beam have been designed but are still in the process of manufacturing. In order to facilitate commissioning of the OK-4 system, we have installed temporary crotches *without absorbers*. A rather large vacuum chamber impedance due to the non-smooth transitions of the temporary crotch-chambers causes microwave bunch-lengthening to begin at ~ 0.1 mA per bunch at 500 MeV. This is the main factor limiting the OK-4 FEL gain. We have used the APS streak-camera [4], a dissector with 15 ps resolution, and spontaneous radiation spectra from the OK-4 to determine the parameters of the electron beam in the single bunch mode (Table 1). According to the bunch-length and the OK-4 FEL gain measurements, the impedance of the vacuum chamber is about 2.75 Ω.

One of the main challenges for the OK-4/Duke storage ring FEL was a 57 m long optical cavity which required mirrors with extremely high precision radii and a sophisticated mirror control and stabilization system. Description of the mirror control and feed-back system as well as brief description of the OK-diagnostics can be found elsewhere [6]. A 30-m-long mirror radii measurement system similar to that described in Ref. [15] has been used to measure 27.26 m radii of the custom made mirrors (by Lumonics Optics Group, Canada) with an accuracy of a few cm. We found that the original clamping scheme of the mirrors had reduced their radii below stability limit for the OK-4 optical cavity. At the present time we are using a different clamping technique.

3. Commissioning of OK-4 FEL

During the preparation for the OK-4 operation, we have established three main storage ring modes at energies of 270 (injection), 500, and 700 MeV and a number of supplementary modes (at 350, 400, 550, 600, 650, and 750 MeV). In addition, we have measured the β-functions in the OK-4 FEL and created computer tools to vary OK-4 wiggler current while keeping betatron tunes stable. The main problem was the absence of electron beam position measurement electronics which could have provided us with information about electron beam orbit. We were forced to use labor intensive and inaccurate ways to find approximate position of the electron beam.

Fortunately, the OK-4 FEL has a rather high gain and demonstration of lasing in the near UV was a relatively easy task. It took about 2 h of e-beam and optical cavity alignment to obtain first lasing at 380 nm. Knowledge of the optical cavity length obtained with the use of the streak-camera [4] proved to be very useful. Lasing at 400 and 500 MeV was demonstrated during the same shift. Later we achieved lasing at 550 MeV using the maximum current available (at that time 2.1 kA) in the OK-4 wigglers.

Two days after first lasing, the monochromatic γ-rays (with 1% FWHM resolution, monochromatized by a lead collimator) 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 [8,9]. Most of our shifts were dedicated to the study and characterization of the γ-ray beam, and the results are published elsewhere [5,7]. Most of the OK-4 FEL parameters reported here were measured in parallel with the γ-ray experiments. Tuning within the reflectivity bandwidth of the optical cavity was straightforward by variation of the wigglers current. A typical tuning wavelength range and one of many measured lasing spectrum are shown in Fig. 2. Optical cavity losses were determined by a measurement of the optical cavity ring down time. Lasing was reasonably easy because the OK-4 gain was at least 10–20 times higher than 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 (buncher on) and conventional FEL mode (buncher off). In all cases the use of the buncher increased the FEL gain and allowed us to lase with one or, if desired, two lasing lines.

FEL power reaches maximum electron beam and optical pulse when the round-trip times are equal, i.e. at perfect synchronism. We measured dependencies of the OK-4 FEL power on detuning $\delta = C_o/\beta - 2L_c$ (where C_o is circumference of the ring, L_c is the optical cavity length and $\beta = v_e/c$) from exact synchronism by varying the RF