NEW INSTRUMENTS AND MEASUREMENT METHODS

Undulator and laser sources of soft x rays

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The physics of soft x rays is closely tied to fundamental investigations in solid state physics, materials science, plasma physics, astrophysics, and biology. Recent progress in the technology of x-ray sources and optical elements for x rays raises the issue of the wide use of soft x rays in technology (x-ray lithography) and in laboratory and commercial microanalysis. This article gives a review of the present state of undulator and laser sources of soft x rays. In undulators the radiation is emitted by electrons in a spatially periodic magnetic field, and in lasers it is emitted by a plasma formed by focusing a powerful visible or infrared laser on a solid surface. Particular attention is paid in this article to the conceptual possibilities and the results that have been published in the last three years; that is, since publication of the review by D. Attwood, K. Halbach, and Kwang-Je Kim [Science **228**, 1265 (1985)], which also appears in the present issue of Uspekhi Fizicheskikh Nauk. The highest pulsed brightness attained to date has been from x-ray lasers. However, for many problems the most important factor is the time average of the brightness (or flux density). For these problems the undulator is the preferred source. Moreover, undulators afford the possibility of tuning over the spectrum and covering a wider range of wavelength.

The creation of sources of coherent radiation in new regions of the spectrum is one of the fundamental problems facing physics. As regards the soft x-ray region, the solution of this problem promises to provide powerful methods of research, powerful instruments, and, according to some predictions, powerful technological methods for solid state physics, plasma physics, biology, medicine, materials science, and microlithography. The paper of D. Attwood, K. Halbach, and Kwang-Je Kim[1] can be recommended as a good introduction to a number of topics related to the production and use of beams of soft x rays. That article was written four years ago, but subsequent events have shown that the authors perceived accurately the main trends in the development of physics in the soft x ray region. New advances have been seen in the fields of x-ray optics, x-ray lasers and free-electron lasers in the last four years. Simultaneously in the Soviet Union, the European nations, the United States, Japan, and China, progress continues in the construction and modernization of unique, specialized sources of soft x-rays. Cooperative efforts have been established among scientists for the use of these sources, and scientific programs have been worked out aimed at obtaining results for physics and other disciplines. In this sense the review of D. Attwood, K. Halbach, and Kwang-Je Kim[1] remains timely, and so the purpose of the present article is more to give an idea of the up-to-date capabilities of the sources, and, in particular, of the progress that has been made in the generation of coherent beams of soft x rays in the time since Ref. 1 appeared.

1. UNDULATOR RADIATION

It is generally believed that undulator radiation will be employed to obtain beams of tunable, spatially coherent radiation in the wavelength range from 100 to 0.1 Å and below. At the present time in many developed countries and in a number of developing countries about forty specialized sources of synchrotron radiation and undulator radiation, operating at energies of several hundred MeV to several GeV, are built or are under construction.[2,3] The number of investigations carried out with the use of these sources is rising sharply. The year 1988 saw the beginning of publication of the specialized international journal "Synchrotron Radiation News," communicating topics relating to research carried out with the use of synchrotron radiation and undulator radiation in the various centers and new ideas and plans and progress in the construction of new radiation sources. In particular, the storage ring called the Advanced Light Source (ALS), whose construction was discussed in Ref. 1, was started in 1988 and will be commissioned in 1992.[4,5] This ring will cover the energy range from 1 to 1.9 GeV. Its cost is estimated at 98.7 million dollars, and it will include 5 undulators for generating beams of high brightness and intensity in the XUV range and will have the corresponding beam lines for transporting the undulator radiation to the experimental stations. Still more undulators and undulator radiation beam lines are planned for the future.

A distinguishing feature of sources of spontaneous incoherent undulator radiation is the fast increase in the intensity and the hardness of the emitted radiation ($\sim\gamma^2$), an increase that is not limited by the radiation mechanisms. Because of this rapid increase it is possible, by increasing the energy of the particles in the beam, to cover the entire soft x-ray range and pass into the energy range $\varepsilon\gamma > 100$ keV, which is applicable in nuclear physics.

The intensity and the wavelength of undulator radiation emitted in the direction of the undulator axis are given by the expressions

$$I^{\text{inc}} = \frac{2e^2}{3m^2c^4} K\lambda_0 \overline{H^2}\gamma^2 i, \quad \lambda_r = \frac{\lambda_0}{2\gamma^2}\left(1 + \overline{p_\perp^2}\right), \tag{1}$$

where H^2 is the mean square value of the magnetic field of the undulator, $\overline{p_\perp^2} = \bar{H}^2/H_c^2$, $p_\perp$ is the relative transverse particle momentum (in units of mc), $H_c = 2\pi mc^2/e\lambda_0 \approx 10\,700$ Oe×cm$/\lambda_0$, K is the number of periods of the undulator, i is the current of the particle beam, and $2e^2/3m^2c^4 \approx 3.2\cdot 10^{-14}$ W/cm×Oe^{2}A. Of the variables used in Ref. 1, we have redefined N as K and $k^2/2$ as $\overline{p_\perp^2}$. The instantaneous values of $I^{\rm inc}$ and i enter into (1). The same formulas relate the average values $\overline{I^{\rm inc}}$ and $\bar{i}$.

When $\overline{p_\perp^2} \ll 1$ most of the energy of the undulator radiation is in the first harmonic $n = 1$. The photon energy and the number of equivalent photons emitted by one electron as it traverses the undulator is, according to (1), $\hbar\omega_1 = 2\pi c\hbar\gamma^2/\lambda_0$, and $n_{\rm eff} \approx \alpha K$, where $\alpha = e^2/\hbar c \approx 1/137$. As the electron energy increases, the photon energy and the intensity of the undulator radiation also increase, but the photon flux $\dot{n}_\gamma = n_{\rm eff}\, i/e$ remains unchanged.

The properties of sources of undulator radiation discussed above are conducive to incresing the energy of the accelerated particles in the sources.

One can get an idea of the capabilities possessed by sources of undulator radiation using storage rings of energy ~ 5 GeV by considering the following characteristic example. The source of spontaneous incoherent undulator radiation we consider is based on an electron storage ring and a helical undulator that produces a helical magnetic field. The energy, the average current, the radius of the particle beam in the storage ring, the period, the number of periods, and the magnetic field of the undulator are

$$\varepsilon = 5\ \text{GeV}(\gamma \approx 10^4), i = 0.1\ \text{A},\ r_{\rm b} = 10^{-2}\text{cm}$$

$$\lambda_0 = 2\ \text{cm},\ K = 250,\ H_\perp = 3800\ \text{Oe}\ (p_\perp = 1/\sqrt{2}).$$

For these parameters only the first harmonic of the undulator radiation is emitted along the axis of the undulator, at a wavelength $\lambda_1 = 1.5$Å (10 keV corresponds to 1.24 Å) and an average intensity $I^{\rm inc} \approx 2.5$ kW. Most of the energy of the incoherent undulator radiation is concentrated in the range of angles $\Delta\theta^{\rm inc} \approx 1/\gamma \approx 10^{-4}$. The spatially coherent undulator radiation is concentrated in the angular range

$$\Delta\theta^{\rm sp.coh} = \lambda_1/r_{\rm b} \approx 1.5\times 10^{-6}$$

and has a coherence length

$$l_{\rm coh} = K\lambda_1 = 3.8\times 10^{-6}\ \text{cm}$$

and in the case of a beam having a small angular spread ($\theta_{\rm b} < 1/\gamma K^{1/2} \approx 10^{-5}$) and energy spread ($\Delta\gamma/\gamma \ll 1/K \approx 10^{-2}$), the intensity reaches $I^{\rm sp.coh} = 2Kei\lambda_0 p_\perp^2/(1 + p_\perp^2) r_{\rm b}^2 \approx 0.05$ W (Ref. 6).

At the present time there are two storage rings with such parameters being built. These are the European storage ring ESRF (European Synchrotron Radiation Facility) in Grenoble (France)[3] and the American facility APS (Advanced Photon Source) at the Argonne National Laboratories (see Ref. 4, p. 32). The ESRF storage ring (6 GeV energy, ~400 mA current, with 29 straight sections each 5 m long) will be commissioned in 1994. Its cost is estimated at 3.6 billion French francs. The construction of the APS storage ring (~7 GeV energy, ~400 mA current) begins in 1989 and is expected to take 7.5 years. Its cost is estimated at 456 million dollars. A plan is being developed for a 6-GeV storage ring in Japan.

In parallel with the construction of these two storage rings, plans are underway for carrying out experiments in the near future in parasitic operation (simultaneously with experiments in high-energy physics) of synchrotron and undulator radiation at the American storage ring PEP at Stanford and at the Japanese ring "Tristan" (see Ref. 3, p. 14). These storage rings now operate with colliding $e^\pm$ beams at energies $\leqslant 16$ GeV and $\leqslant 30$ GeV, respectively. The first experiments carried out at the PEP storage ring demonstrated its unique potential for generating synchrotron and undulator radiation. At 8 GeV the sotred current is more than 100 mA. Because the bending magnet fields are small (~3200 Oe at 16 GeV) the emittance of the beam at this energy is very low (~0.12 mm·mrad). There are six long (117 m) straight sections in this ring. In some of these straight sections it is possible to put undulators with a number of periods $K \gtrsim 10^3$. Parasitic operation is in the process of development at the American storage ring CESR (Cornell Electron-Positron Storage Ring), which has a maximum energy of 8 GeV (Ref. 2, p. 15). This ring is also called CHESS (Cornell High-Energy Synchrotron Source). It now has three six-pole undulators with high magnetic fields (~20 kOe). Undulator radiation is generated at the higher harmonics. Radiation down to the wavelength $\lambda \sim 0.1$ Å is used.

2. FREE-ELECTRON LASERS

It is possible to improve significantly the principal characteristics of undulator radiation sources by making use of stimulated and spontaneous coherent mechanisms of emission by the particles in the undulators, i.e., by converting these undulators with certain modernizations to free-electron laser (FEL) operation.

In a free-electron laser the radiation is emitted by bunched beams of particles. The bunching may be carried out in a special buncher at injection into the linear accelerator, during acceleration of the particles in the linear accelerator, in an undulator buncher of beams of accelerated particles, or by an amplified wave in the undulator of the free-electron laser.

If previously bunched beams of particles enter the undulator of the free-electron laser, then we have a parametric free-electron laser, also called a source of spontaneous coherent undulator radiation.

The intensity of the radiation of a parametric free-electron laser that uses a particle beam in the form of a single microbunch or a series of them traveling one after another with a spacing equal to the wavelength $\lambda_{\rm b}$ of the emitted light or to a multiple of it, is given by the expression

$$I_{\rm b}^{\rm coh} = SN_1 I^{\rm inc} \tag{2}$$

where S is the integrated coherence factor, $N_1 = \lambda_{\rm B} ieC \approx 2\times 10^8\ \text{cm}^{-1}\text{A}^{-1}$, $\lambda_{\rm B} i$ is the number of particles in a microbunch, and $\lambda_{\rm B}$ is the period of modulation of the particle density in the beam.[7]

The radiation is emitted with the minimum possible (diffraction limited) angular spread

$$\begin{aligned} \Delta\theta &\approx \frac{1}{\gamma}\left(\frac{1+\overline{p_\perp^2}}{nK}\right)^{1/2}, && r_{\rm b} \ll r_{\rm bs}, \\ &\approx \frac{\lambda_{\rm b}}{r_{\rm b}}, && r_{\rm b} \gg r_{\rm bs}, \end{aligned} \tag{3}$$

in the frequency interval (and with the coherence length $l_{\rm coh}$)

$$\frac{\Delta\omega}{\omega} \approx \frac{1}{K+M} \quad (l_{\rm coh} \approx l_{\rm b}), \tag{4}$$

where $r_{\rm bs} = \lambda_{\rm b}\gamma\left[nK/(1+\overline{p_\perp^2})\right]^{1/2}$, and M is the number of microbunches in the beam or in a bunch, if the beam consists of a sequence of bunches, and $l_{\rm b} = M\lambda_{\rm B}$ is the length of a bunch in the beam.

The degeneracy parameter of the radiation emitted by undulator or free-electron laser sources is given by the expression

$$\delta = \frac{\lambda^3}{2\pi c\sigma} \frac{\partial^2 I}{\partial\omega\,\partial o}, \tag{5}$$

where σ is the cross sectional area of the electron beam and $\partial^2 I/\partial\omega\partial o$ *is the spectral-angular intensity of the radiation* from the source.

In the particular case of sources of spontaneous incoherent undulator radiation or parametric free-electron lasers that use helical undulators, the degeneracy parameters are given, respectively, by

$$\delta_{\rm ur} \approx \frac{\lambda^3 K^2 i}{2\Lambda\sigma {\rm i}_{\rm A}} \frac{p_\perp^2}{1+p_\perp^2}, \quad \delta_{\rm FEL} = SN_1M\delta_{\rm ur}, \tag{6}$$

where $\Lambda = \hbar/mc \approx 3.86\cdot10^{-11}$ cm, ${\rm i}_{\rm A} = mc^3/e \approx 17$ kA, and $1/2\Lambda i_{\rm A} \approx 7\cdot10^5\ {\rm cm}^{-1}\ {\rm A}^{-1}$ (Ref. 8).

The factor SN_1M in (6) takes into account that the radiation of a parametric free-electron laser, in comparison with the spontaneous incoherent undulator radiation emitted by the same free-electron laser when a uniform beam is used, is more intense by a factor SN_1, is concentrated in a solid angle smaller by a factor of $\max\{K, r_{\rm b}^2/\lambda_{\rm u}^2\gamma^2\}$ and is more monochromatic by a factor of M/K $(M \gg K)$.

The value of S is determined by the dimensions and the angular and energy spread of the particle bunches, and by the type of undulator. For a single point-size monoenergetic bunch with a small angular spread moving in a helical undulator, $S = 1/(1+p_\perp^2)$ at the wavelength of the radiation emitted in the first harmonic, λ_1. The factor $(1+p_\perp^2)^{-1}$ comes in because in this treatment we have singled out just the first harmonic, but when $\overline{p_\perp^2} \gtrsim 1$ the higher harmonics begin to be emitted efficiently. For a series of point-size bunches with $M \gg K$ spaced a distance $\lambda_{\rm B} \gtrsim \lambda_{\rm u} + K^{-1}$ apart, the coherence factor can be as much as three times larger than $S = 3/(1+\overline{p_\perp^2})$. If the radius of the beam is $r_{\rm b} \gg r_{\rm bs}$, with $M \gg K$ and $n = 1$, then

$$S \approx \frac{3\lambda^2 K\gamma^2}{\pi^2 r_\pi^2(1+\overline{p_\perp^2})^2} \operatorname{sinc}^2\xi, \tag{7}$$

where $\xi = \pi h/\lambda$ and h is the length of a microbunch.

The decrease in S with increasing bunch size becomes appreciable when the length and width of the bunch exceed $l \approx \lambda_{\rm u}/4$ and $r_{\rm bs}$, respectively, and when the angular and energy spreads become larger than $\Delta\theta_{\rm b} = (1+\overline{p_\perp^2})/\gamma(nK)^{1/2}$ and $\Delta\gamma/\gamma = 1/nK$, respectively.

It should be noticed that the requirements on the width of the beam are comparatively weak, because each bunch of a wide beam of particles $(r_{\rm b} \gg \lambda\gamma/(1+\overline{p_\perp^2})^{1/2})$ emits undulator radiation in a narrow, diffraction limited angular range $\Delta\theta \lesssim \lambda/r_{\rm b}$. The radiation diverges by an amount $\sim r_{\rm b}$ in a distance $\sim l_{\rm s} = k_{\rm B} r_{\rm b}^2$, where $k_{\rm B} = 2\pi/\lambda_{\rm B}$. Each bunch of the beam is effectively slowed not only by the field of the bunch itself, but also by the fields of the preceding bunches that are separated from it by distances $\leqslant l_c\lambda_{\rm B}/\lambda_0 \gg \lambda_{\rm B}$.

One should note also that the angle into which the spatially coherent radiation is emitted from the source of spontaneous incoherent undulator radiation is given by the same expression (3) as for the case of radiation from a parametric free-electron laser.

Parametric free-electron lasers can operate effectively without mirrors. The use of high-Q resonators in the long-wavelength range where such resonators exist makes it possible to raise the emission intensity of low-efficiency parametric free-electron lasers by a factor $Q \gg 1$, where $Q \approx 2\pi/(1-k_1k_2)$ is the Q of the resonator and k_1 and k_2 are the reflectivities of the mirrors.[9,10]

One can get an idea of the capabilities of parametric free-electron lasers based on storage rings by considering as an example a parametric free-electron laser which uses a helical undulator and particle beams with the following parameters: $\varepsilon = 1$ GeV$(\gamma = 2\times10^3)$, $i_{\rm b} = 1$ A, $\bar{i} = 0.1$ A, $r_{\rm b} = 10^{-2}$ cm, $l_{\rm b} = 10$ cm, $\lambda_0 = 2$ cm, $K = 250$, $H_\perp = 5360$ Oe$(p_\perp = 1)$, where $i_{\rm b}$ is the current in a bunch.

For this example the radiation is emitted at the wavelength $\lambda = 50$ Å, with an intensity per bunch of $I_{\rm b}^{\rm coh} = 14$ kW$(I_{\rm b}^{\rm inc} = 1.84$ kW, $S = 7.5\times10^{-2}$, and $N_1 = 10^2)$, with an average intensity $\overline{I^{\rm coh}} = 1.4$ kW, a monochromaticity $\Delta\omega/\omega = M^{-1} \approx 5\times10^{-8}$, a coherence length $l_{\rm coh} = l_{\rm b} = 10$ cm, and a degeneracy parameter $\delta \approx 4.5\times10^3$. The efficiency of the free-electron laser in this case does not exceed $\eta = 1/K = 4\times10^{-3}$. At the present time storage rings have beam currents $i_{\rm b} \approx 10^2$ A and $i = 1$ A. Higher values of the current are obtained in resonance linear accelerators ($i_{\rm b} \approx 10^2$–10^3 A and $\bar{i} \approx 1$ A) and in induction linear accelerators ($i \lesssim 10^4$ A) with beam current pulses ~ 0.1 to $10\,\mu$s long.

The efficiency of parametric free-electron lasers can be raised to $\eta = 0.5$ if undulators with variable parameters are used; that is, if the period $\lambda_0(y)$ and the amplitude $H_0(y)$ of the magnetic field are made to vary with the longitudinal coordinate y in a certain way. The rate of energy loss per particle of a wide beam of particles may in this case reach values[8]

$$\frac{d\varepsilon}{dy} = \frac{2}{\pi}\left(\frac{d\varepsilon}{dy}\right)_{\max} \arcsin\frac{y}{(y^2+l_{\rm c}^2)^{1/2}}, \tag{8}$$

where

$$\left(\frac{d\varepsilon}{dy}\right)_{\max} = \frac{\pi^2 mc^2}{2\lambda_{0{\rm i}}} \frac{p_{\perp{\rm i}}^2}{1+p_{\perp{\rm i}}^2} \frac{i}{i_{\rm A}}$$

$$\approx 2.5({\rm MeV\cdot cm}) \frac{p_\perp^2 i}{(1+p_{\perp{\rm i}}^2)\lambda_{0{\rm i}} i_{\rm A}},$$

and the subscript i refers to the initial values of the corresponding quantity.

One may appreciate the possibilities in parametric free-electron lasers based on linear accelerators by considering the example of a free-electron laser in which a helical undulator is used and the particle beam has the following parameters:

$$\varepsilon = 200\ \mathrm{MeV}(\gamma = 4\times 10^2), i_b = 700\ \mathrm{A}, r_b = 5\times 10^{-2}\ \mathrm{cm}$$
$$\lambda_{0i} = 2\ \mathrm{cm}, H_1 = 5360\ \mathrm{Oe}\ (p_{1i} = 1), K\lambda_0 = 40\ \mathrm{m}.$$

In this example the radiation is emitted at a wavelength $\lambda = 600$ Å with an intensity $I_b = 140$ GW with an efficiency $\eta = 0.5$. The rate of energy loss of the particles of the beam is determined for a length $l_s = 25$ m. At this length the amplitude of the electric field of the wave can increase to where the operating region of phase oscillation stability of the particles is larger than necessary for capture of all the particles of the beam by the field. The requirements on the spread in angle and energy of the particles of the beam are relatively low

$$\theta_b < \frac{1}{\gamma}\left(\frac{1+p_\perp^2}{K_{\mathrm{eff}}}\right)^{1/2}, \frac{\Delta\varepsilon}{\varepsilon} < \frac{1}{K_{\mathrm{eff}}},$$

where $K_{\mathrm{eff}} = l_c/\lambda_{0i} \ll K$ and $l_c = \gamma(\pi r_b^2 \lambda_0 i_A / p_\perp^2 i)^{1/3}$ is the length at which capture of a uniform-density beam of particles is complete in the region of stability of phase oscillations in the electromagnetic field of a linearly increasing wave.[8] In the case under consideration, $l_c = 4$ m.

The rate of energy loss of the particles in the beam (8) does not depend on the energy of the particles, and, consequently, it is also independent of the wavelength of the emitted wave. This means that by raising the energy of the accelerator and increasing its length in proportion to the energy, it is possible to go to progressively shorter emission wavelengths, with an increase in the intensity of the free-electron laser that is proportional to the energy. It is important only to have at the entrance to the undulator a density-modulated beam of particles and to satisfy the condition $N_1 \gg 1$. References to literature on the various schemes of beam modulation can be found in Ref. 7.

The most promising method of modulating beams of particles for a free-electron laser operating in the XUV is an undulator bunching system consisting of an undulator called a "modulator" and an external electromagnetic wave. If the wave is converging or if the field of the undulator increases smoothly, then in this system a continuous beam of particles can be converted into a sequence of microbunches, separated from the adjacent bunches by a distance equal to the wavelength of the grouping wave and having a length $\ll \lambda_B/2$. Then the modulated beam is fed into the undulator of a free-electron laser called the "radiator," where radiation and further bunching of the beam occurs at the fundamental or at the higher harmonics of the beam modulation frequency, i.e., at the wavelength $\lambda_{B,m} = \lambda_B/m$, where $m = 1,2,3...$ is an integer.[7] The parameters of the modulator (length, period, etc.) may in general differ from those of the radiator.

It is desirable that the frequency of the external wave be continuously tunable. Free electron lasers of lower power can be used as sources of such waves (at the present time free-electron lasers have sufficient power, ~30 MW in a bunch at optical wavelengths ($\lambda \sim 5000$ Å), to serve as undulator bunchers). It is possible to advance into the XUV cascading free-electron lasers, with frequency multiplication.

Beams of particles, consisting of a single long bunch or a series of long bunches (length $\gg \lambda$) are used in ordinary free-electron lasers and in free-electron laser amplifiers. These bunches always accompany the electromagnetic waves of the spontaneous incoherent undulator radiation. Moreover, they can accompany the radiation wave of the external source, or, in the case of feedback, the waves in the free-electron laser resonator excited by the previous bunches. These waves modulate the beam at their frequency. The degree of modulation of the beam in the direction of its motion at first increases exponentially and then it saturates. The beam of particles, because of its density modulation, begins to generate coherent radiation in the fundamental and in the higher harmonics of the external wave. The maximum amplification α_m of a free-electron laser using a helical undulator and having constant parameters is given for small α_m by

$$\alpha_m \approx 30K^3 p_\perp^2 (1+p_\perp^2)^{-3/2} \frac{\lambda_0^{1/2}\lambda^{3/2}}{\sigma} \frac{i}{i_A}. \tag{9}$$

If the free-electron laser has a low amplification ($\sim 10^{-2}$ to 10^{-1}) then it is necessary to use a high-Q resonator ($Q \gtrsim 10^2$) to develop feedback. Without resonators such free-electron lasers are sources of spontaneous incoherent undulator radiation. When the amplification is high, $\alpha_m \gg 1$, the spontaneous incoherent undulator radiation in free-electron lasers without resonators is amplified by induction processes by a factor of $(1/3)\exp(i/i_{c\pi})^{1/3}$, where i_{sl} is the current for which the value of α_m, as defined by (9), is $\alpha_m \approx 32\sqrt{3}/270 \approx 0.2$. In this case the free-electron laser operates in the regime of superluminescence or self-amplified spontaneous emission. Let us recall in this connection that a parametric free-electron laser is one that operates in the superradiance regime (Dicke radiation).

Let us note that in high-efficiency free-electron lasers and free-electron laser amplifiers it is necessary to use undulators with variable parameters. In the front part of the undulators the particles of the beam are modulated in density by the external wave and are captured in the region of stable phase oscillations. In the remaining, longer part of the undulator the bunches are slowed by the parametric free-electron laser scheme discussed above. Therefore, relations (2)–(9), which describe the operation and characteristics of parametric free-electron lasers, are valid for ordinary but highly efficient free-electron lasers. Parametric free-electron lasers represent the ultimate in the capabilities of free-electron lasers.

Up to the present time more than ten experimental versions of free-electron lasers based on various charged particle accelerators and storage rings have been built and tested. They span a wide wavelength range, from decimeter waves to the ultraviolet. Physics experiments employing free-electron laser beams have been started. An overall idea of the state of free-electron lasers and the prospects for their development can be obtained from the published Proceedings of the Ninth International Conference on Free-Electron Lasers held in Virginia (USA) in September 1987.[11] We shall discuss at some length some of the achievements in this field.

Under the sponsorship of the Strategic Defense Initiative[12,13] in the United States two powerful free-electron lasers, operating in the infrared and visible ranges have been constructed.

At the Lawrence Livermore National Laboratories (California) the free-electron laser amplifier "Palladine," based on the ATA (Advanced Test Accelerator) linear induction accelerator and operating at 10.6 μm, has been commissioned.[14] This free-electron laser has attained a power of

1 GW in a pulse of length ~50 ns with an efficiency $\eta = 5\%$. The input power was ~2 MW. The amplification was 27 dB(10^3). The operation was carried out at the full energy of the ATA accelerator, 45–50 MeV, and the current was reduced from 10 kA to 700 A to decrease the angular divergence of the particle beam.

The Boeing company has commissioned a free-electron laser operating in the visible range, at 5000 Å (Ref. 15). The pulse power is ~ 1 GW and the average power is 30 kW at an efficiency $\eta \approx 7\%$. In this free-electron laser a resonance linear accelerator is used, with an energy of 120 MeV, a current in a bunch of 100 A, and a bunch length of 20 ps (~6 mm). The linear accelerator is supplied by rf power at 1.3 GHz. The undulator has a period of 2.5 cm, a length of 5 m and a field of ~ 10 kOe modulated by ~12%. The distance between mirrors of the free-electron laser is 55 m. With the use of such a large distance and a grazing incidence arrangement the thermal dissipation from the mirrors is ~300 kW/cm^2. The problem of mirror heating limits the power of this free-electron laser. In the future this free-electron laser will be used as a master oscillator for a free-electron laser power amplifier, planned for construction in 1990 (one more linear accelerator and undulator of length ~10 m with variable parameters). In this two-cascade scheme a free-electron laser of intermediate power can be raised in power to several MW.

About 225×10^6 dollars will be spent in the free-electron laser programs in the United States in 1989. A large part of this money will go to the Boeing program.[35]

In the Soviet Union at the Institute of Nuclear Physics, Academy of Sciences of the USSR, Novosibirsk, a free-electron laser of the optical klystron type has been commissioned at the VEPP-3 storage ring.[16] It covers the wavelength range from 10 000 to 370 Å, i.e., the visible and the ultraviolet ranges. Experiments have been carried out at an energy of 350 MeV (the maximum energy is 2 GeV), the average current is 10 mA (maximum 80 mA) and the pulsed current is 10 to 100 A. The free-electron laser uses two identical undulators 3.4 m long, separated by dispersion magnets. The period of the undulator is $\lambda_0 = 10$ cm, and the magnetic field amplitude varies from 0 to 5.4 kOe, which provides continuous frequency tuning of the free-electron laser. An average of ~10 mW is achieved at $\lambda = 6000$ Å. The pulsed power, depending on the operating conditions, varies from 10 W to 1 kW.

3. X-RAY LASERS

In the popular literature this term in the last few years has come to mean x-ray lasers with nuclear pumping, a component of the Strategic Defense Initiative (SDI) intended for damaging objects in space (see Refs. 12 and 13). Unlike this kind of laser, laboratory x-ray lasers, as discussed in Ref. 1, do not, of course, have this purpose and do not use nuclear pumping.

The idea of extending laser action to the x-ray region was discussed early in the 1960s, right after the invention of the first lasers. The basic principles of operation of x-ray lasers and ways to realize these principles were laid out in the 1970s and the beginning of the 1980s. At the present time x-ray lasers have been built at 4–5 scientific centers and experiments are being performed on them regularly. The first experiments have been made with the use of x-ray lasers as a laboratory instrument for interferograms of microscopic objects and for imaging biological specimens.

The active medium of an x-ray laser is an elongated plasma volume with a length of several centimeters and a cross sectional area 0.01 to 0.1 cm. The plasma is created by focusing the radiation of a high-power visible or infrared laser onto the surface of a special target (or near it). The plasma has a temperature of several hundred electron volts. The laser effect arises on transitions of multiply ionized atoms of the elements of the target. Generation occurs either with a single pass (without mirrors) or with two or three passes (with the use of multilayer x-ray mirrors). The generation pulse length is 10^{-10} s to 10^{-8} s and is usually determined by the lifetime of the plasma. The maximum energy in a pulse achieved to the present time is ~10 mJ, and the best divergence is ~10 mrad. The generation wavelength and the elements for which these wavelengths are obtained are given in Table I (see also Ref. 34).

As in the case for beams of undulator radiation, x-ray lasers are considered for use in microscopy, microlithography, and for their action on materials and matter at the microscopic level.

A contact x-ray microscope based on an x-ray laser operating at a wavelength $\lambda = 182$ Å (Fig. 1) has been developed at Princeton University.[17] The active medium of the x-ray laser is a plasma formed by the radiation of commercial CO_2 laser (of energy ~1 kJ, pulse length 80 ns) focused onto the surface of a carbon disk. A strong magnetic field (~90 kG) is applied along the axis of the disk, and it inhibits the sideways expansion of the vaporizing plasma. As a result a cylindrical plasma volume ~2 cm long is formed along the axis of the disk, containing multiply charged carbon ions. This plasma cools off because of expansion transverse to the magnetic field and radiation losses. In the plasma nonequilibrium recombination develops, with the formation of inversion on the 3-2 transition of the C VI hydrogen-like ion ($\lambda = 182$ Å). According to calculations, the maximum amplification is achieved at a distance 1–2 mm from the axis in a band of width ~0.5 mm, which is in qualitative agreement with the tubular shape of the beam of the generated radiation. The maximum energy of the x-ray pulse is obtained with a CO_2 laser energy of ~300 J and is 1 to 3 mJ at a pulse length of 10 to 30 ns and a divergence of 5 mrad. The coefficient of transformation of laser energy into x-ray energy is thus not above $\sim 10^{-5}$, but even this is sufficient for experiments in physics and biology. In the work reported in Ref. 17 a single pulse was enough to obtain contact images of a micromask (a grid) on an x-ray photographic film and on an x-ray photoresist, with a resolution better than 0.1 μm. The grid was placed between the photographic film (or the photoresist) and a VUV-dense filter, which filtered out the ultraviolet light. The filter was a film of silicon nitride 120 nm thick with a 100 - nm layer of aluminum deposited on it. The commercial CO_2 laser had a repetition rate of $\sim 10^{-1}$ to 10^{-2} Hz. Thus, the laboratory x-ray laser at Princeton has already today many of the parameter values necessary for practical application. Using multilayer x-ray optics, which in this range have a reflectivity of about 40%, the authors of Ref. 17 hope to improve the divergence and increase the brightness of the beam substantially.

TABLE I. X-ray lasers. As a rule generation is observed without a resonator in the superradiance regime. In Refs. 35–37 two-pass lasing was obtained at the wavelengths 182, 206, and 132 Å with the use of multilayer x-ray mirrors.

λ, A	Ion, Isoelectronic Series	Transition	*g*, cm^{-1}	*gl*	Ref.
284.67	Cu XX, [Ne]	3p—3s	1.7		[18]
279.31			1.7		
221.11			2		
232.24	Ge XXIII, [Ne]	3p—3s	4.1	6	[18]
196.08			3.1		
209.6	Se XXV, [Ne]	3p—3s	5.5	16	[19]
206.3					
157.1	Y XXX, [Ne]	3p—3s			[20, 21]
155.0					
141.6	Mo XXXIII, [Me]	3p—3s	0.16		[22]
139.4			0.16		
132.7			1.3		
131.0			2.0	12	
106.4			0.8	6	
71.00	Eu XXXVI, [Ni]	4d—4p	1.1	4	[23]
65.83			0.6		
56.09	Yb XVII, [Ni]	4d—4p	1	4	[23]
50.26			1		
182	C VI, [H]	3—2		6.5	[24]
182	C VI, [H]	3—2	3	4	[25]
182	C VI, [H]	3—2	3	3.5	[26]
80.91	F IX, [H]	3—2	5.5		[27]
154.7	Al XI, [Li]	4f—3d	2.5		[28]
154.7	Al XI, [Li]	4f—3d		3—4	[29]
129	Si XII, [Li]	4f—3d		1—2	[29]
105.7	Al XI, [Li]	5f—3d	0.5—1		[30]
65.2	S XIV, [Li]	5f—3d			[31]
305	Al XII, [He]	$5^1D—4^1P$			[32]
130.5		$4^1D—3^1P$			
46	Al XII, [He]	$3^1S—2^1P$	9.8		[33]
45		$3^1D—2^1P$	7		
42.4		$3^1P—2^1S$	4.4		

The table gives the following information: λ, the generation wavelength; the type of ion and the transition on which generation occurs; g (cm^{-1}), the amplification; gl, the product of the amplification and the length of the active medium. In references 18–33 the active medium is a plasma created by a high-power laser emitting in the visible or the infrared.

The first laboratory x-ray laser was built at the Lawrence Livermore Laboratories under a program of research on high-power neodymium-glass lasers intended for laser nuclear fusion (Refs. 1, 18 and 29). At the present time the Livermore x-ray laser serves as the basis of one of the channels of the laser installation "Nova," which has a total energy of ~100 kJ. Its parameters and instrumentation are continuously being upgraded. As a result, the use of neon-like and nickel-like ions of increasingly higher ionization multiplicity has made it possible in the past few years to progress into the short-wavelength region of the spectrum from 206 Å (the [Ne]-like Se XXV ion) to 50 Å (the [Ni]-like Yb ion) (see Table I). In addition, the selenium laser is regularly used for physics experiments. Its principal characteristics at the present time are the following. The active medium is a plasma of the [Ne]-like Se ions, formed by focusing the second harmonic of a Nd laser on the surface of an aluminum foil covered with a thin layer of selenium (~100 Å). The flux density of the second harmonic at the surface is $q\sim6\times10^{13}$ W/cm^2, the pulse length is 10^{-10} s, and the energy is 1 to 3 kJ. The length of the active medium is $l = 4$ cm, the electron density is $n_e \approx 10^{20}$ cm^{-3}, and the temperature is $T_e \approx 1$ keV. The x rays are generated most efficiently at two wavelengths, λ = 206 Å and 209 Å; the energy in a pulse is ~10 mJ, the pulse length is ~0.2 ns, and the radiated power is 0.5-5 MW. This means that the coefficient of conversion of laser pump radiation into radiation from the x-ray laser is of the order of ~10^{-5}, the same as for the Princeton laser. The measured gain in a single pass is e^{16}. With the use of resonators made from multilayer total-reflecting and semitransparent x-ray mirrors two- and three-pass lasing has been obtained. The divergence of the x-ray beam is 6 mrad. A holographic experiment was performed with this instrument[19] (see Fig. 2). Preliminary measurements were

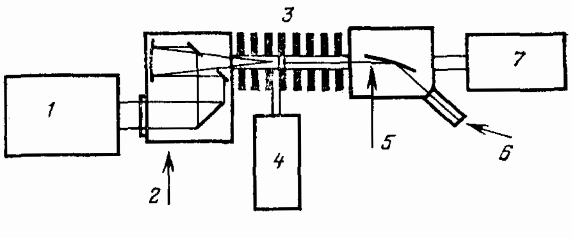

FIG. 1. Use of x-ray laser for contact microscopy (Princeton University). 1) CO$_2$ laser (1 kJ, 10-20 GW); 2) vacuum chamber with adjustable mirrors; 3) magnet (100 kG); 4) radial spectrometer; 5) beam from x-ray laser; 6) x-ray contact microscope; 7) axial spectrometer.

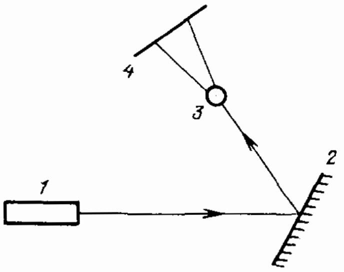

FIG. 2. Interference experiment with an x-ray laser (Lawrence Livermore Laboratories). 1) Selenium x-ray laser; 2) multilayer mirror; 3) specimen; 4) photographic film.

made of the correlation parameters of the beam. The longitudinal and transverse coherence lengths were, respectively, $l_\parallel = \lambda^2/\delta\lambda = 100\ \mu$m and $l_\perp = \lambda/\Delta\theta = 3.5\ \mu$m, and the effective size of the source was $\sim 70\ \mu$m. A multilayer x-ray mirror was placed 5 m from the output end of the laser at an angle of 60° to the beam to direct the beam to a carbon fiber 8 μm in diameter. An interference pattern containing 5-6 rings of diameter from 50 to 400 μm was obtained as a result of the coherent superposition of the transmitted and scattered beams on the photographic film placed at a distance 5.08 cm from the fiber. The mirror, having a selective absorption $\lambda/\delta\lambda \sim 10$, was able to cut off much of the spontaneous plasma radiation and increase the coherence of the beam. This mirror was made up of 20 pairs of alternating layers of Mo (98 Å thick) and Si (30 Å) and has a reflection coefficient $R = 20\%$ at $\lambda = 206$ Å. The surface of the mirror substrate had an rms surface roughness σ of about two angstroms. Estimates show that in order not to destroy the coherence of the beam it is sufficient that $\sigma \approx \lambda/10 \approx 20$ Å. The films were shielded from the visible light by an aluminum filter $\sim 2.3\ \mu$m thick having a surface roughness of ~ 6 Å. The authors have drawn the following conclusions. 1) Laboratory x-ray lasers have sufficient brightness to obtain holograms of microobjects in one shot ($\tau \approx 0.2$ ns). 2) The x-ray mirrors have adequate smoothness, flatness, and reflection coefficient to be used in interference and holographic experiments. 3) Future directions in research will be in increasing the coherence and reducing the wavelength of the laser radiation.

In conclusion let us note that laboratory x-ray lasers undoubtedly have a higher pulse brightness than any other source. For many problems, however, the important factor is the time-average brightness (or flux density). For problems of this sort the better sources are undulators, which, in addition, allow tuning over the spectrum and covering a wider range of wavelengths.

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