HIGH-BRIGHTNESS ELECTRON BEAMS FOR PRODUCTION OF HIGH INTENSITY, COHERENT RADIATION FOR SCIENTIFIC AND INDUSTRIAL APPLICATIONS

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Abstract
We review the current status and the future prospects in the production of electron and photon beams for higher brightness in spatial and temporal dimensions.

1. INTRODUCTION

Relativistic electron beams with high six-dimensional phase space densities, i.e., high-brightness beams, are the basis for efficient generation of intense and coherent radiation beams for advanced scientific and industrial applications. The remarkable progress in synchrotron radiation facilities from the first generation to the current, third-generation capability illustrates this point. With the recent development of the high-brightness electron gun based on laser-driven rf photocathodes, linacs have become another important option for high-brightness electron beams. With linacs of about 100 MeV, megawatt-class infrared free-electron lasers can be designed for industrial applications such as power beaming. With linacs of about 10 GeV, 1-Å x-ray beams with brightness and time resolution exceeding by several orders of magnitude the current synchrotron radiation sources can be generated based on self-amplified spontaneous emission. Scattering of a high-brightness electron beam by high power laser beams is emerging as a compact method of generating short-pulse, bright x-rays. In the high-energy frontier, photons of TeV quantum energy could be generated by scattering laser beams with TeV electron beams in future linear colliders.

2. BRIGHT BEAMS OF PARTICLES, X-RAYS, AND LASERS

The basic quantity characterizing the beam quality is the invariant emittance

$$\varepsilon_n = \gamma\beta\sigma_x\sigma_{x'} \tag{1}$$

where β is the speed of the electron divided by the speed of light, γ is the Lorentz factor of electron motion, σ_x and $\sigma_{x'}$ are, respectively, the rms beam size and angular divergence. The emittance is important because it determines how small the beam's spot size can be focused or how parallel the beam can be collimated. The beams with small emittance, or high phase space density, are called bright.

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Among other applications, the small emittance of charged particle beams is crucial in generating x-ray beams, for example through synchrotron radiation. The produced radiation is transversely coherent if

$$\varepsilon_x \leq \lambda/4\pi. \tag{2}$$

Here λ is the wavelength of the radiation. Transverse coherence is the condition wherein the x-ray beam has a minimum focal spot or minimum angular divergence.

The fundamental limit on the invariant emittance imposed by quantum mechanics is

$$\varepsilon_n \geq \frac{\lambda\!\!\!^{-}_c}{2} N_e^{1/3}, \tag{3}$$

where $\lambda\!\!\!^{-}_c$ is the reduced Compton wavelength (= 3.8×10^{-3} m for electrons) and N_e is the number of particles.

Storage rings provide high-brightness electron beams because of the radiation damping mechanism (see, for example, [1]). The technology to build high-brightness storage rings has progressed considerably during the last decade due to the construction of "the third generation" synchrotron radiation facilities around the world. At present, the smallest emittance achieved in electron storage rings is

$$\varepsilon = \varepsilon_n/\gamma \geq 5 \times 10^{-9} \text{ m-rad}. \tag{4}$$

The brightness of electron beams in linacs has been limited by that of the gun-buncher system. With the traditional system based on a thermionic gun and bunchers, it has been difficult to produce electron beams of brightness comparable to those in storage rings. Recently researchers at Los Alamos National Laboratory and other laboratories developed a new type of gun based on a laser-driven rf photocathode that eliminated the bunchers [2]. Together with the emittance correction scheme [3], the achievable invariant emittance in an optimized rf photocathode gun is

$$\varepsilon_n \gtrsim 1 \text{ mm-mrad}. \tag{5}$$

The recent development in high power, ultrashort, optical lasers offers new opportunities in beam techniques. Based on the chirped pulse amplification (CPA) concept—a technique for avoiding nonlinear effects in high-gain amplifiers by stretching a short laser pulse to a long pulse before amplification—compact, solid state lasers producing ultra-short optical pulses (10-100 fs) with a pulse energy of about 1 J have been developed for practical use during the last decade [4] (for a review, see [5]). The high electric field within such a high-power laser pulse, when combined with the particle beam technique, gives rise to several interesting schemes for novel radiation sources.

3. THIRD-GENERATION SYNCHROTRON RADIATION SOURCES BASED ON ELECTRON STORAGE RINGS

The state-of-the-art light sources, also known as third-generation sources, provide time-averaged spectral brightness approaching 10^{21} in units of photons per seconds, per mm^2, per $mrad^2$, per 0.1% spectral bandwidth, up to about 10 keV photon energy, the radiation consisting of 10-20 ps bursts (see, for example, [6]). They are based on spontaneous radiation from undulators, schematically illustrated in Fig. 1, placed in low-emittance, high-current electron storage rings. The brightness of undulator radiation is much higher than the bending magnet source due to interference of radiation from different parts along the length of the undulator (for a review, see [7]).

The wavelength λ of the undulator radiation is given by the difference in the average forward distances traveled by the light and the electron in one undulator period:

$$\lambda = \lambda_u(1 - \overline{\beta}_z) = \frac{1 + K^2/2}{2\gamma^2}\lambda_u. \tag{6}$$

Here λ_u is the period of the undulator magnet, $\overline{\beta}_z$ is the average forward speed divided by the speed of light, and K is such that K/γ is the maximum deflection angle of the sinusoidal electron trajectory.

Undulator radiation is an incoherent sum of radiation from individual electrons. Therefore, the total radiation phase space of undulator radiation is given by a convolution of the coherent radiation phase space of individual electrons and the electron beam phase space. Since the electron beam phase space area is characterized by the rms emittance ε_x, and the corresponding quantity for coherent radiation is $\lambda/4\pi$, undulator radiation becomes transversely coherent, thus permitting interference techniques such as holography. In view of Eq. (3), the coherence condition is satisfied for radiation wavelengths longer than 100Å for a typical third-generation light source.

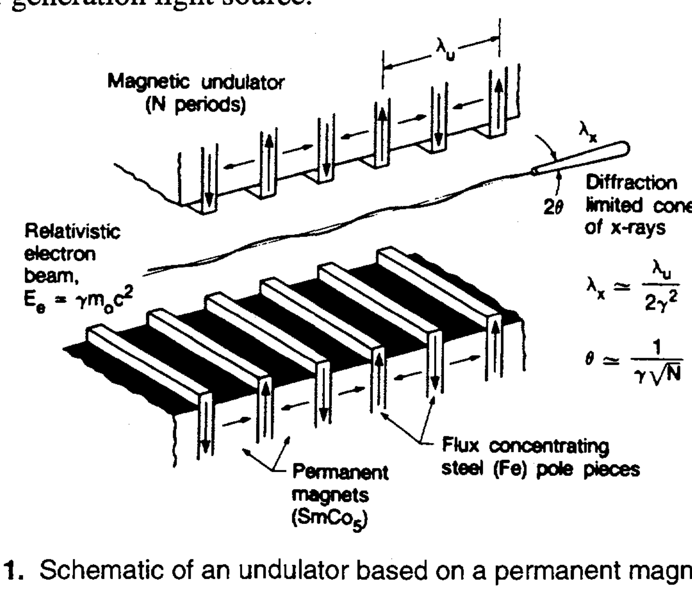

FIGURE 1. Schematic of an undulator based on a permanent magnet design.

Light sources with enhanced performance are possible within the framework of the spontaneous radiation from electron storage rings: Larger circumference rings and/or in-vacuum microundulators could be employed for higher brightness and/or higher photon energy, quasi-isochronous rings may provide shorter time resolution, etc. These topics have been reviewed extensively (see, for example, [6]).

4. FREE-ELECTRON LASERS (FELs)

Normally, the interaction of the radiation beam with the electron beam in an undulator is negligible. However, such interaction does exist and causes periodic energy modulation with period λ in the electron beam. The energy modulation evolves to a density modulation due to the energy dependence of the axial velocity in the undulator, and hence leads to a "stimulated" emission at the same wavelength λ. This provides the amplification mechanism, which is the basic operating principle of free-electron laser (FEL) devices [8].

The FELs, which can be based either on linacs or storage rings, are more versatile than the atomic or molecular lasers in that the wavelength can be chosen arbitrarily by selecting a suitable e-beam energy and undulator magnetic field strength.

4.1 FEL Oscillator

When the amplification is low, an oscillator configuration may be formed by placing two mirrors, separated by one half of the electron bunch spacing, at both ends of the undulator. The undulator radiation pulses from the initial electron bunches interact with the subsequent bunches, increasing the intensity and the coherence from pass to pass, until the intracavity intensity reaches the saturation level. Such an arrangement is known as an FEL oscillator and produces highly coherent radiation beams with brightness many orders of magnitude higher than that of the undulator radiation.

Storage-ring-based FELs have been successfully operated for user experiments at SuperACO and other laboratories (for a review, see [9]). However, the operation of FEL oscillators has been limited to UV or longer wavelengths. Until recently the shortest wavelength limit for an FEL oscillator had been 2400Å [10], which was limited by the availability of mirrors.

4.2 High-Gain FEL Amplifier and Self-Amplified Spontaneous Emission (SASE) for X-rays

With suitably high electron beam brightness and a long undulator, the amplification in a single pass may be sufficiently high so that the FEL can be operated in an amplifier mode, thus obviating the need for high reflectivity mirrors. If seed lasers are available, the FEL can amplify the input radiation at the fundamental or higher harmonic wavelengths [11]. However, the seeded high-gain amplifier cannot generate x-rays due to the spectral limit of the seed lasers.

If the amplification is extremely high, about 10^7–10^8, then the spontaneous undulator radiation in the beginning part of the undulator can be amplified to an intense radiation, referred to as SASE [12,13,14]. The radiation is fully coherent transversely. Temporally, the spectral bandwidth is typically about 0.1%. Since it is limited neither by the availability of mirrors nor by seed lasers, SASE is currently the only known approach for obtaining tunable, coherent radiation down to 1-Å wavelength, with brightness much higher than that available from the current third-generation synchrotron radiation facilities.

Several experimental projects are either in progress or being planned in laboratories around the world; some of these are listed in Fig. 2. As indicated in the figure, the proof-of-principle experiments for wavelengths longer than 10 μ have already demonstrated a significant level of single-pass gain as well as the start-up from noise. Experiments at APS [15], DESY [16], and VISA collaboration [17], at wavelengths shorter than 5000 Å, are scheduled to take place within one to two years.

Eventually the goal is to achieve SASE at x-ray wavelengths; to date, the only linac available is the SLAC linac [18]. The project is called the Linear Coherent Light Source (LCLS). In this project, a laser-driven rf photocathode gun [2] produces electron bunches, each with a charge of 1 nC, invariant emittance $\gamma\varepsilon_x$ of about 1×10^{-6} m-rad, and a pulse length of about 10 ps. The bunches are compressed to about 100 fs to increase the peak current to about 3.5 kA, and accelerated to high energy (10-20 GeV). It is important to prevent emittance dilution during the acceleration, using techniques developed for the linear collider R&D (for a review, see [19]). Also, the error in the undulator magnetic field needs to be controlled tightly. The peak spectral brightness (during the 100-fs pulse length) of the LCLS would be more than ten orders of magnitude higher than the undulator radiation from third-generation synchrotron radiation sources. In addition, the pulse

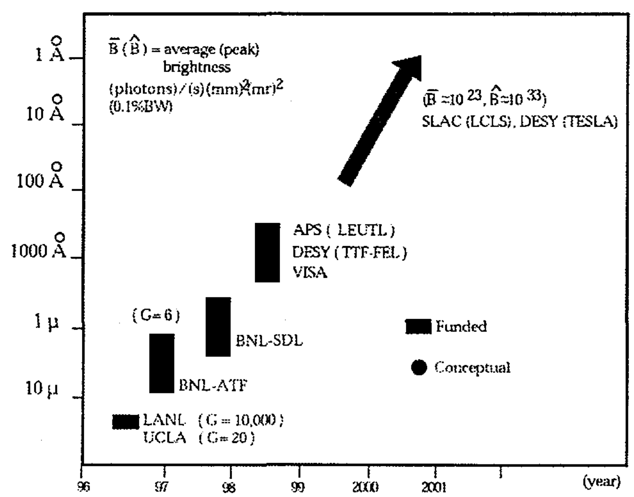

FIGURE 2. SASE projects around the world. The numbers within the parentheses (G=) indicate the experimentally observed gain to date.

length is about a hundred times shorter, thereby improving the time resolution by the same factor. The enhancement of the average brightness is less, due to the smaller repetition rate of the linac. However, the average spectral brightness of LCLS is still 3-4 orders of magnitude higher than the undulator sources. It can be increased further by increasing the bunch repetition rate if a superconducting linac is used, as proposed at DESY, permitting multi-user operation as in the storage-ring-based sources [20].

4.3 High-Power IR FELs for Industrial Application

Recently, the use of a free-electron laser (FEL) for industrial applications, such as polymer processing, power beaming, defense, isotope separation, etc., is receiving increased attention. These applications require average power from kilowatts to megawatts. FELs are well suited for these applications because they can provide high power, but without high energy density in media. In addition, FELs can be designed to produce coherent radiation, which is important for some applications.

High-power FELs based on superconducting rf linacs are being developed at the Jefferson Laboratory in the USA and at the Japan Atomic Energy Research Institute. Another novel proposal, the so-called ignition feedback regenerative amplifier (IFRA) scheme, consists of an rf photocathode gun; a 100-MeV, low-loss rf accelerator with energy recovery; and a regenerative free-electron laser (FEL) amplifier [21]. A feedback loop from the FEL output to the gun provides the laser power necessary for the high-current operation of the photocathode. Another loop provides the input power for the regenerative FEL amplifier, thus eliminating the need for cavity mirrors. A mode filter in this loop controls the coherence of the output radiation. Since the system is self-coupled, an ignition laser is necessary to start up the operation of both the rf photocathode and the FEL amplifier.

5. GENERATION OF FEMTOSECOND X-RAY PULSES

A time scale of fundamental importance in condensed matter research is about 100 fs, since this is the time scale at which chemical reactions, phase transitions, and surface processes occur. Although the femtosecond (10-100 fs) optical lasers discussed in the previous section can be used for an indirect study of the atomic motion at such a time scale, a more direct probe will be femtosecond x-ray pulses exploring the time evolution of the core levels. Two techniques for generating femtosecond x-ray pulses based on the combined use of the femtosecond optical lasers and the electron beam techniques are described below.

5.1 90° Thomson Scattering

Thomson backscattering could be the basis for a compact source of x-rays using low-energy electron beams [22]. However, the brightness of such a source is limited because the electron beam has, in general, low brightness at low energies. The duration of the scattered x-ray pulse is about the same as that of the electron pulse (assuming the latter is shorter than the former). The duration of the electron pulse length in a linac is usually about 10 ps, and it is difficult to compress it smaller than picosecond level.

However, femtosecond x-ray pulses can be generated in 90° Thomson scattering in which a low-energy electron pulse meets femtosecond optical laser pulses at a right angle ($\alpha = 90°$) [23]. By focusing the electron beam tightly in the transverse direction to a spot size comparable to the length of the laser pulse, femtosecond-long scattered x-ray pulses can be made.

This concept has been tested experimentally with a 50-MeV electron linac and an ultra-short optical laser (λ = 0.8 μm, 100 fs duration, 1 J/pulse), producing 30-keV x-rays of 300 fs duration [24].

5.2 Femto-Slicing Technique

The femtosecond x-ray pulse generation based on 90° Thomson scattering described in the previous subsection is appropriate for low-energy linacs. Another technique appropriate for high energy (~1 GeV) electron storage rings, called femto slicing, is described as follows.

If a 100-fs part of the bunch could be separated, i.e., "sliced out," from the main bunch, the synchrotron radiation from that part can be isolated by a mask, thus producing a 100-fs x-ray pulse. The slicing can be achieved by utilizing the FEL interaction of an ultra-short optical laser pulse with an electron bunch (typically several tens of ps) through an undulator in a straight section of a storage ring [25].

6. RADIATIVE LASER COOLING AND HIGH-BRIGHTNESS X- AND GAMMA-RAY BEAMS

The key to high-brightness radiation is small particle beam emittance. In linacs, the invariant emittance $\gamma\varepsilon_x$ is determined by the gun. At present, the best performance for an electron beam is that offered by the laser-driven rf photocathode ($\gamma\varepsilon_x \approx$ 1-2 mm-mrad for 1 nC bunch). In the electron storage ring, the emittance is determined by the radiative cooling due to synchrotron radiation in bending magnets and quantum excitation. The value of the emittance achieved in third-generation synchrotron radiation rings is similar to that from the laser driven rf photocathode gun.

Radiative cooling does not take place in a linac. For a storage ring, it is not effective either at low energy ($\leq$ 500 MeV) because of insufficient synchrotron emission or at high energy due to the increased quantum excitation. It is therefore important to consider other methods for cooling particle beams.

There are several schemes to cool the particle beams (for a review, see [26]). The radiative laser cooling of an electron beam [27] and that of a non-fully stripped ion beam [28] are particularly interesting from the point of view of radiation generation: both are based on backscattering with high power optical beams. The scattering process reduces the invariant emittance because the scattered radiation is predominantly in the direction of the particle motion.

6.1 Radiative Laser Cooling of Electron Beams

Radiative laser cooling of an electron beam was originally proposed for application to improve beam qualities for a TeV linear collider [27]. The scheme is to Thomson back-scatter GeV electron beams with a high power optical beam to decelerate a significant fraction of the e-beam energy, and then reaccelerate.

A more gentle variant of the idea is to cool a low energy (<~10 MeV) electron storage ring [29]. The laser pulse is stored in an optical cavity containing a straight section of the storage ring. As the electron beam passes through the straight section it collides head-on with the optical pulse, producing Thomson backscattered x-rays while simultaneously cooling the electron beam. The usual radiative cooling due to synchrotron radiation is negligible for such a low energy ring. The electron optics must be designed so that the interaction region in the straight section is dispersionless to minimize the quantum excitation.

6.2 Radiative Laser Cooling of Relativistic Ion Beams and Generation of Diffraction-Limited Gamma Rays

The idea here is similar to the cooling in the low energy electron ring discussed in the previous section, except that the compact, low energy electron ring is replaced by a large ring storing non-fully stripped, relativistic heavy ion beams [28]. For efficient scattering, the laser wavelength must be chosen so that $\lambda_L = 2\gamma\lambda^*$, where λ^* is the wavelength corresponding to one of the transition energies of the ion in its rest frame. In radiative laser cooling, the laser bandwidth is chosen to be broad, to cover the Doppler bandwidth of the whole ion beam so that the laser beam interacts with all ions in the beam with an average cross section $\overline{\sigma} = \lambda^* r_0 (\lambda_L/\Delta\lambda)$, where $r_0 = e^2/MC^2$, where M is the mass of the heavy ion. The *radiative* laser cooling discussed here is different from the well-known laser cooling employing narrow bandwidth lasers.

As an example, a beam of N-like Xe ions stored in RHIC with $\gamma = 97$ can be cooled with a laser wavelength λ_L = 3954Å, in near resonance with the transition between the states $(2S^2 2P^3)^4S3/2$ and $(2S^2 2P^3)^4P3/2$. With 2×10^9 ions per bunch and a bunch spacing of 224 ns, the beam can be cooled with a 100-kW laser beam consisting of 24-mJ pulses. Such high power is not available at the present time but may be achieved inside an FEL cavity.

7. PHOTON BEAMS IN THE TEV ENERGY RANGE

Compton scattering of an optical laser pulse with electrons in the TeV energy range gives rise to scattered photons that are also in the TeV energy range. The high energy gamma photon can be used for scattering with either TeV electrons or other TeV gamma photons [30]. Therefore, if a linear collider for e^+e^- collisions with TeV energy is constructed in the future (for a review, see [19]), it would make sense to provide a second interaction region for gamma-gamma collisions to provide alternative experiments not easily provided by e^+e^- collisions. An example of a gamma-gamma collider based on the NLC design has been worked out (for a summary, see [31]).

The gamma-gamma collider may be regarded as the ultimate energy frontier for high-brightness radiation.

8. CONCLUSIONS

The art of synchrotron radiation generation has advanced remarkably during the last decade through the development of low-emittance, high-current electron storage rings, together with the development of precision magnet designs for undulators. There have also been similarly remarkable developments in linac technology, in the development of rf photocathode guns, and in minimizing the emittance dilutions. The working principles of FEL oscillators and amplifiers have been demonstrated in long wavelength regions. The development in ultrashort pulse, high power lasers has been spectacular. In this paper, we have reviewed some of these developments, as well as some future possibilities in the techniques for generating radiation and particle beams with higher intensity, higher spatial and temporal resolution, and/or shorter wavelength coverage.

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REFERENCES

[1] M. Sands, SLAC-121 (1970).

[2] Sheffield, R. L. (1989). In *Physics of Particle Accelerators,* edited by M. Month and M. Dienes, AIP Conf. Proc. **184**, 1500.

[3] Carlsten, B. (1989). *Nucl. Instrum. Methods A* **285**, 313.

[4] Strickland, D. & Mourou, G. (1985). *Opt. Commun.* **56**, 219.

[5] Perry, M. D. & Mourou, G. (1994). *Science* **264**, 917.

[6] Winick, H. (1998). These proceedings.

[7] Kim, K.-J. (1989). In *Physics of Particle Accelerators*, edited by M. Month and M. Dienes, AIP Conf. Proc. **184**, 565.

[8] Madey, J. M. J. (1971). *J. Appl. Phys.* 42, 1906.

[9] Couprie, M. E. (1997). *Nucl. Instrum. Methods A* **393**, 13.

[10] Drobyazko, I. B. *et al.* (1989). *Nucl. Instrum. Methods A* **282**, 424.

[11] Yu, L.-H. (1991). *Phys. Rev. A* **44**, 5178.

[12] Bonifacio, R., Pellegrini, C. & Narducci, L. M. (1985). *Opt. Commun.* **50**, 6.

[13] Kim, K.-J. (1986). *Phys. Rev. Lett.* **57**, 1871.

[14] Wang, J.-M. & Yu, L.-H. (1986). *Nucl. Instr. Methods A* **250**, 396.

[15] Milton, S. V., Galayda, J., Gluskin, E., (1998). In Proc. of the 1997 Particle Accelerator Conference, 877-879.

[16] Rossbach, J. *et al.* (June, 1995). DESY Report TESLA-FEL 95-03.

[17] VISA Collaboration Report, BNL, 1998.

[18] Pellegrini, C. (1992). In *Proc. of Workshop on 4th Generation Light Sources*, edited by M. Cornacchia and H. Winick, SSRL Report 92/02.

[19] Loew, G. (1995). International Linear Collider Technical Review Committee Report, SLAC-R-95-471.

[20] Brinkman, R., Materlik, G., Rossbach, J., Schneider, J. & Wiik, B.-H. (1997). *Proc. of FEL'96.*

[21] K.-J. Kim, A.A. Zholents, and M.S. Zolotorev, LBNL preprint, LBNL-40797 (1997).

[22] Sprangle, P., Ting, A., Esarey, E. & Fisher, A. (1992). *J. Appl. Phys.* **72**, 5032.

[23] Kim, K.-J., Chattopadhyay, S. & Shank, C. V. (1994). *Nucl. Instrum. Methods A* **341**, 351.

[24] Schoenlein, R. W., Leemans, W. P., Chin, A. H., Volfbeyn, P., Glover, T. E., Balling, P., Zolotorev. M., Kim, K.-J., Chattopadhyay, S. & Shank, C. V. (1996). *Science* **274**, 236-38.

[25] Zholents, A. A. & Zolotorev, M. S. (1996). *Phys. Rev. Lett.* **76**, 916.

[26] Sessler, A. M. (1996). LBL-38278.

[27] Telnov, V. (1997). *Phys. Rev. Lett.* **78**, 4757.

[28] Bessonov, E. G. & Kim, K.-J. (1996). *Phys. Rev. Lett.* **76**, 431.

[29] Huang, Z. & Ruth, R. D. (Sept. 1997). *Laser Electron Storage Ring*, SLAC-PUB-7556.

[30] Telnov, V. (1995). *Nucl. Instr. Meth. A* **355**, 3.

[31] Kim, K.-J. (1997). *Nucl. Instr. Methods A* **393**, 530-35.