A TUTORIAL ON ACCELERATOR-BASED LIGHT SOURCES*

M. Borland†, ANL, Argonne, IL 60439, USA

Abstract

Accelerator-based light sources are some of the largest and most successful scientific user facilities in existence, serving tens of thousands of users each year. These important facilities enable research in diverse fields, including biology, pharmaceuticals, energy conservation and production, data storage, and archaeology. In this tutorial, we briefly review the history of accelerator-based light sources. We present an overview of the different types of accelerator-based light sources, including a description of their various operating principles, as well as a discussion of measures of performance. Technical challenges of current and future light sources are also reviewed.

INTRODUCTION

By the early 20^{th} century, it was known that electrical charge was carried by two types of particles, the electron and proton, that are constituents of ordinary matter. Interactions between electrically charged objects and between currents in wires and magnetic fields were recognized as macroscopic manifestations of microscopic interactions between charged particles, mediated by the electric and magnetic fields they produce. Visible light itself was recognized as consisting of mutually-supporting, time-varying electric and magnetic fields, originating in the motions of charged particles. With a growing ability to create and control electric fields $\vec{E}$ and magnetic fields $\vec{B}$, and armed with the Lorentz force equation $\vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$, researchers acquired increasingly precise control of the motion of charged particles. By the 1940's, circular accelerators ("betatrons" and "synchrotrons") could accelerate electrons to nearly the speed of light ($v/c = \beta \approx 1$).

Lienard predicted in 1898 [1] that a charged particle moving on a circular trajectory would radiate, but it was not until 1947 that 70 MeV electrons circulating in a synchrotron were observed to emit visible light [2], leading to the name "synchrotron radiation" (SR). Rigorous analysis [3], shows that only *acceleration* of charged particles produces radiation, which is characterized by magnetic and electric fields transverse to the propagation direction that fall off with the first power of distance.

Analysis also shows that the radiation output is proportional to a high power of the Lorentz factor, $\gamma = 1/\sqrt{1-\beta^2}$. (Note that beam energy E is $E(\mathrm{MeV}) \approx 0.511\gamma$.) Hence, to produce radiation effectively, we need relativistic particles, i.e., $\beta \approx 1$. Because they are very light compared to protons, electrons are far easier to accelerate to relativistic energies, and hence are preferred for radiation generation. The first accelerator-generated x-rays were created by the rapid deflection and deceleration electrons experience when hitting a metal target (bremsstrahlung radiation). A more controlled technique uses a magnetic field to deflect the particle trajectory in a circular arc, which produces acceleration at right angles to the direction of motion.

For circulating electrons with $\beta \ll 1$, radiation is emitted in a broad angular pattern at the revolution frequency. Radiation is emitted most strongly in the forward and backward directions, for which a distant observer sees the greatest acceleration. However, when $\beta \approx 1$ the emitting electron follows closely behind the forward-directed radiation, which has $\beta = 1$. Thus, the forward-directed radiation pulse seen by a distant observer is dramatically shortened, by the factor γ^3, and therefore has much higher frequency by the same factor [3]. Also, the radiation intensity increases by a factor γ^4 because the apparent time taken to "turn the corner" is much shorter, indicating a larger apparent acceleration [4]. Because the apparent acceleration is so much greater for that part of the arc where the observer sees a change of direction, the radiation is narrowly collimated with an rms angle $1/\gamma$, like a moving searchlight. These effects explain the usefulness of SR from high-energy electron accelerators.

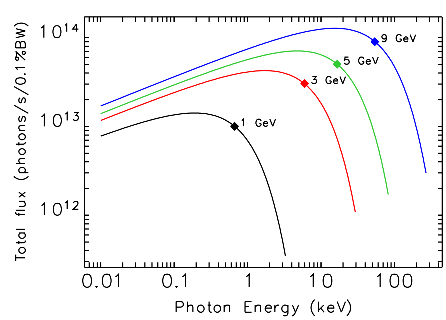

Figure 1: Radiation flux from a 100 mA beam of different energies on a circular trajectory in a 1T magnetic field.

Fig. 1 shows flux curves for a 100 mA beam of various energies circulating in a 1T magnetic field. The critical photon energy $e_c(\mathrm{eV}) = 665E(\mathrm{GeV})^2B(\mathrm{T})$, which divides the power spectrum into two equal parts, is also marked. This illustrates the increasing ease with which energetic radiation is produced as the beam energy increases, which is one reason electron accelerators are so useful. Before explaining electron accelerators in more detail, we'll briefly discuss some applications of SR.

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† borland@aps.anl.gov

APPLICATIONS

Following the initial observation of synchrotron radiation, several essentially parasitic experiments were performed in the 1950s and 1960s [5], leading to a dedicated facility, Tantalus I, in 1968. This facility demonstrated the utility of SR and encouraged world-wide growth of SR sources, so that today a full account of SR applications would require many volumes. Here, we try to provide a basic understanding of why it is so useful.

We begin by describing the interaction of radiation with matter [3, 6]. When relatively low-energy (i.e., low-frequency or long-wavelength) radiation interacts with matter, it can excite vibrational modes of molecules and hence tends to be absorbed or scattered. (For example, in water this occurs between about 1 μeV and 1 eV.) As the frequency increases, this interaction diminishes and the material may become transparent (as water largely does between about 1.7 and 3.5 eV). With increasing frequency, radiation eventually interacts strongly with the light-weight electrons, and absorption rises dramatically again, only to fall off rapidly as the energy increases to 10's of keV and beyond. Absorption is stronger for denser elements, which have more electrons per unit volume. Narrow absorption spikes are also observed at element-specific energies, corresponding to ionization of core electrons. This element-specificity leads to many applications.

The radiation wavelength is $\lambda_r(\text{Å}) = 12.39/E_p(\text{keV})$, where E_p is the photon energy. Typical interatomic distances in solids are several angstroms [7], corresponding to photon energies of several keV. Hence, such radiation can give us information on the structure of solids, via Bragg diffraction, a field known as x-ray crystallography.

Other SR applications include imaging and spectroscopy. The common hospital x-ray is a simple example of imaging, making use of differences in x-ray absorption of different materials. In spectroscopy, the variation in absorption or scattering with photon energy is used to probe chemical bonds or the electronic structure of materials.

BASICS OF ELECTRON ACCELERATORS

We've seen that energetic radiation can be created using high-energy, free electrons. Electrons can be formed into a highly-directed, pulsed beam with low energy spread, which allows producing radiation with corresponding characteristics. Typical beam characteristics for light sources are rms pulse durations σ_t of less than a few 10's of picoseconds, rms fractional energy spreads σ_δ of less than 0.1%, rms spot sizes $\sigma_{x,y}$ of less than a few 100's of μm, and rms beam divergences $\sigma'_{x,y}$ of less than a few 10's of μrad. Beam quality is characterized by the "brightness," given (with simplifying assumptions) by $B \propto \frac{N_e}{\sigma_x \sigma'_x \sigma_y \sigma'_y \sigma_t \sigma_\delta}$, where N_e is the number of particles in a bunch. Achieving high brightness is one of the major challenges in building light source accelerators.

It is common to speak of beam quality in terms of just four quantities, namely, the energy spread and pulse duration, along with the "transverse emittances," ϵ_x and ϵ_y. In the simplified case used here, $\epsilon_q = \sigma_q \sigma'_q$, where q is x or y. Typical light-source emittances are less than 10 nanometers to as low as a few picometers.

Next, we review the basic components of an electron accelerator, starting with the electron source or "gun." These devices employ a thermally- or laser-excited "cathode" to release electrons, which are accelerated by pulsed DC or radio frequency (rf) electric fields. In linear light sources (LLS), the gun's beam quality is critical, and great effort is expended on gun design, while for circular light sources (CLS), quantity is more critical than quality at this stage (see below). Typical gun beam energies are 100's of keV for DC guns to a few MeV for rf guns. At present, photocathode rf guns produce the highest quality beams since the rapid acceleration reduces space charge effects.

Following the gun, the electron beam typically enters a linear accelerator ("linac"), which boosts the energy by several orders of magnitude using synchronized rf fields in a series of long, multi-cell rf cavities. For LLS, rapid acceleration and careful beam control is essential to preserving beam quality. For CLS, the beam is typically injected into a circular "booster synchrotron" as soon as practical, at an energy of a few hundred MeV. In a booster, the beam circulates past the same rf cavities repeatedly, acquiring a very large energy (typically several GeV) with comparatively moderate expense. Because of radiation emitted in the synchrotron, the final beam quality has little relation to the beam quality entering the synchrotron, hence, the relatively relaxed attitude toward gun beam quality.

The Lorentz equation states that, in addition to using electric fields $\vec{E}$ to accelerate electrons, we can use magnetic fields $\vec{B}$ to bend their paths. For example, a locally constant vertical magnetic field will bend to the left or right the path of a horizontally traveling beam. Such a field is created using a magnet with one north and one south pole, i.e., a dipole magnet. Dipole magnets are used to bend the beam path into a closed loop in a synchrotron or CLS "storage ring." Since the degree of bending depends on the electron energy, dipole magnets can be used for energy analysis and energy-dependent beam manipulation in linacs.

Of course, in addition to changing the beam path, dipole magnets also cause the beam to radiate and thus lose energy. If we bend through an angle θ on an arc of radius ρ, the energy loss is [3] $\Delta E(\text{MeV}) = 1.41 \times 10^{-2}(E(\text{GeV}))^4\theta/\rho$. In addition, because of the quantum nature of the radiation emission, the beam's rms energy spread σ_E will increase according to [8] $(\Delta\sigma_E(\text{MeV}))^2 = 4.12 \times 10^{-5}\theta(E(\text{GeV}))^7/\rho^2$.

Whether we build a linear or circular accelerator, we must control the transverse beam size. For beams above a few MeV, this is done using "quadrupole" magnets, which act as magnetic lenses. Unlike lenses in light optics, quadrupoles focus in one plane (e.g., horizontal) and defocus in the other (e.g., vertical). However, a series of quadrupoles of alternating polarity can produce focusing in both planes. Quadruoples and dipoles are almost always electromagnets, allowing them to be readily fine-tuned to optimize machine operation. Good optical design is essential in CLS to obtain low emittance by reducting the effects of quantum radiation excitation.

For many applications, additional magnet types are required. "Steering magnets" are small dipoles that can be adjusted to fine-tune the beam trajectory. Sextupoles are six-pole magnets used to correct chromatic (energy-dependent) aberrations inherent in quadruople focusing.

RADIATION-PRODUCING DEVICES

The first SR sources used radiation from dipole magnets, in part because dipole magnets are necessary to any circular accelerator, so radiation is produced automatically. However, dipoles produce a broad fan of radiation in the deflecting plane. Although this can provide radiation to a series of experiments, each receives only a fraction of the emitted radiation, and much is wasted.

An improved concept [9] is to send the electron beam through a periodic series of N short, strong dipole magnets of alternating polarity, so the beam executes a sinusoidal oscillation with no net deflection. When the maximum deflection angle $\theta_{\max}$ satisfies $K = \gamma\theta_{\max} \gg 1$, this is called a wiggler magnet. It gives N times as much flux as a single dipole, and, since the wiggler imparts no net deflection, the field can be much stronger, giving higher energy radiation.

If $K \lesssim 1$, an electron's radiation from individual poles fully overlaps and adds coherently at certain wavelengths. This results in a dramatically narrower radiation spectrum peaked at a series of harmonics $\lambda_i = \lambda_u(1 + K^2/2)/(2i\gamma^2)$, where λ_u is the period of the undulator and $i = 1, 2, 3, \ldots$ is the harmonic. Fig. 2 compares the computed [10] brightness for an APS bending magnet, wiggler, and undulator, which makes it clear why experiments that need high brightness are best done with undulator sources. For the undulator source, we see a series of sharp peaks at the odd harmonics, with generally lower, broader peaks at the nominally disallowed even harmonics[4]. The location of the peaks can be tuned by varying magnet gap, and thus the magnetic field. For historical reasons, undulators and wigglers are known collectively as "insertion devices" (IDs). Helical IDs are also possible and create elliptically polarized radiation.

Another radiation source is a backscattered laser beam, which acts like a very short period undulator. The backscattered wavelength is $\lambda_b = \lambda_L/(4\gamma^2)$, implying that 1 Å radiation can be created with a 23 MeV electron beam and $\lambda_L = 800$ nm laser. Hence, this approach promises x-ray production using small, inexpensive accelerators [11]. At present, the x-ray intensities are not competitive, but may become so as accelerator and laser technology improves.

STORAGE RING LIGHT SOURCES

In an electron storage ring, dipoles are used to bend the beam path so that it closes on itself, with quadrupoles

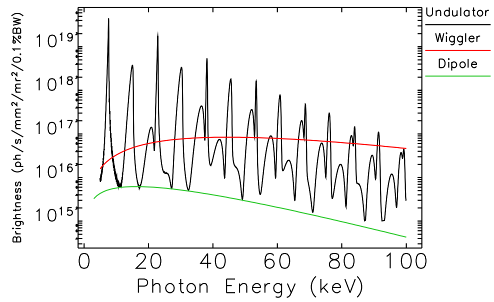

Figure 2: Average x-ray brightness for APS with different radiation sources. Dipole: 0.6 T. Wiggler: $B = 1.0$T, $\lambda = 8.5$ cm, $N = 28$ Undulator: $K = 1.3$, $\lambda = 3.3$ cm, $N = 72$. Non-zero emittance and energy spread lead to significant even-harmonic radiation.

placed along the beam path to provide focusing. Modern rings are optimized for IDs, which require relatively long (e.g., 5 m) "straight sections" that are free of dipoles, quadrupoles, and other infrastructure. The region from one straight to the next is called "cell," with most rings having a highly periodic and symmetric configuration of infrastructure components in each cell. Typical sources have 20 to 50 straights, with most being used for IDs. Several are needed for pulsed beam-injection magnets and for the rf cavities used to restore energy lost as SR. Typically the radiation loss per turn is a few MeV.

The rf cavity frequency must be a multiple h of the revolution frequency, which results in the existence of h "rf buckets" into which bunches may be injected. Typical revolution frequencies are 200 kHz to 2 MHz with $300 \lesssim h \lesssim 2500$. Rings employ various "bucket filling patterns," e.g., filling all buckets, filling every n^{th} bucket, or filling a few buckets to high intensity. The latter serve users who perform time-resolved experiments.

Quantum randomness of radiation emission causes emittance growth, while loss of energy into SR and its replacement by the rf systems causes emittance damping [8]. The balance between these produces an equilibrium horizontal emittance $\epsilon_0 \propto E^2/N_d^3$ [12], where N_d is the number of dipoles in the ring. As a result, the beam quality is not determined by the quality of the injected beam, but by the cell design and beam energy. A common configuration is to have two dipoles and several quadrupoles per cell, an embellishment of the Chasman-Green lattice [13]. One clear, but expensive, route to low emittance is to build a large, densely-packed ring, making N_d large.

Modern light sources in the 3 to 8 GeV range have circumferences of 250 to 1500 m, horizontal emittances of 1 to 4 nm, and vertical emittances of 5 to 50 pm. Typical stored beam currents I are 100 to 300 mA, with higher currents at the lower-energy sources, where emitted radiation power ($\propto IE^4/\rho$) is less.

The 1-nm, 6-GeV PETRA-III ring [14], once a large 15-GeV particle collider, is presently the lowest-emittance ring-based light source, due to a large circumference and "damping wigglers." These wigglers increase the emittance damping term by causing the beam to emit a large amount of radiation. The innovative 3-GeV MAX-IV design [15] targets 0.25 nm using damping wigglers and seven dipoles per cell (increasing N_d significantly).

Low emittance rings face several challenges [16]. Small emittance results in small beam size and divergence, which challenges beam diagnostics and stabilization systems. Because of the strong focusing required for low emittance, both quadrupoles and sextupoles become stronger, making alignment more critical. Lower emittance implies higher particle density in the bunch and hence more frequent collisions between electrons, leading to shorter beam lifetime (Touschek effect); this requires more sophisticated tuning of sextupoles and may force the use of a large number of bunches, which restricts timing modes.

Because of the short beam lifetime, modern rings rely on "top-up" operation [17], which involves frequent injection of small amounts of beam to maintain the circulating current at a near-constant level. As lifetime drops with decreasing emittance, the top-up interval must be made shorter, which can disrupt some experiments unless injection is carefully tuned. Collective instabilities, in which the electromagnetic field of the beam interacts with the vacuum chamber, also become worse with lower emittance, favoring the use of a large number of bunches.

Several groups are investigating so-called Ultimate Storage Ring (USR) light sources, some of which promise emittances in both planes of a few 10's of pm [18]. These large rings use a similar concept [19] to MAX-IV, namely, a large number of dipoles (e.g., 10) between straight sections, but with multi-km circumferences that put much smaller emittances within reach. In addition, these rings will operate on the so-called coupling resonance, which results in equal emittances $\epsilon_x = \epsilon_y = \epsilon_0/2$ in both planes. This requires a new mode of operation, called "swap-out," in which trains of depleted electron bunches are ejected and replaced with fresh, full-intensity bunches [20]. Challenges for USRs are very similar to the familiar challenges for existing high-brightness rings, which means one can move forward with some confidence based on decades of experience [16].

ENERGY RECOVERY LINACS

In rings, the emittance is a result of an equilibrium between quantum excitation and radiation damping, so that even in modern rings, the emittance is large compared to a high quality linac beam of the same energy. For example, a state-of-the-art photoinjector beam, if accelerated to 6 GeV, would have an emittance of 50 pm or less in both planes—compared to 1 nm by 10 pm in PETRA-III. In addition, ten-fold smaller emittances appear possible from simulations of next-generation injectors [21]. However, because linacs typically discard the high-energy electrons after one pass, rings deliver six orders of magnitude higher current than typical linacs—a seemingly decisive advantage.

The Energy Recovery Linac (ERL) concept [22] addresses these issues, by recirculating the beam and bringing it back into the linac—with a 180-degree phase change—for deceleration and disposal. By conservation of energy, the decelerated beam puts energy back into the linac rf cavities, where it is available to accelerate fresh beam, thus dramatically reducing power consumption. Superconducting cavities are advantageous to further reduce power consumption in continuous operation. The recirculation arcs are similar to a storage ring, but since the beam passes only once through this system, its brightness is similar to what's provided by the injector.

Presently-operating ERLs have low beam energy (under 200 MeV) and modest average current (10 mA), but create fully coherent infrared (IR) and THz radiation (e.g., [23]). However, there is interest in building high-energy ERLs to produce temporally incoherent x-rays [24]. Compared to present rings, these promise similar flux but $10^2 \sim 10^3$ higher brightness, comparable to large USR concepts. Like USRs, projected x-ray ERLs promise equal emittances of $\sim$ 10 pm in both planes, but with smaller energy spread to improve brightness of high undulator harmonics. Significant challenges must be faced, including production of ultra-low emittance beams with long cathode lifetime at high average current, beam loss control, minimization of cryogenic power, and avoidance of multi-pass beam breakup, to name a few.

LINAC FREE ELECTRON LASERS

Undulator radiation is very bright at odd harmonics of λ_1 because each individual electron emits radiation in phase all along the device. In general, however, the N_e electrons in a bunch enter the undulator at random relative times, so the radiation intensity is $I_r \propto N_e$ due to incoherent addition of the fields from many electrons. If electrons could instead be gathered in phase-locked "microbunches" separated by λ_1, then ideally $I_r \propto N_e^2 \sim 10^{18}$, a tremendous enhancement.

Since λ_1 is $0.1 \sim 1$ Å for x-ray sources, one might wonder how such microbunching could be produced. If a electrons interact with electromagnetic radiation in an undulator magnet, the radiation and electrons exchange energy. Electrons that lose energy will fall back, while those that gain energy move forward, relative to the average forward velocity of the bunch, resulting in microbunching at wavelength λ_1. This leads to stronger emission at that wavelength, which can further enhance microbunching. This is the principle behind the free-electron laser (FEL) [25].

FELs fall into two broad groups: oscillators (FELOs) and amplifiers (FELAs). In FELOs, a periodic series of electron bunches passes through an undulator inside an optical cavity. Each bunch interacts with and amplifies the radiation stored in the cavity, which consequently builds up over time, eventually reaching a saturation level determined by the beam properties and mirror reflectivity. Although interest in x-ray FELOs was recently revived [26], present FELOs work in regimes where efficient mirrors exist (e.g., UV to IR).

Presently, FELAs offer the best option for x-ray applications, utilizing "self-amplified spontaneous emission" (SASE [27]), in which ultra-bright electron beams allow rapid growth and saturation in radiation intensity in a single pass through a long undulator, with radiation output many orders of magnitude above the spontaneous level.

The Linac Coherent Light Source (LCLS[28])—the world's first hard x-ray FEL—illustrates beam and system requirements. It starts with a photocathode rf gun that delivers 250 pC electron bunches with $\sigma_t = 2$ps into a linac for acceleration to 250 MeV. At this energy, a magnetic "chicane" (see below) is used to compress the bunch to $\sigma_t = 0.4$ ps, after which the beam is further accelerated to 4.3 GeV. A second chicane compresses the bunch to $\sigma_t = 23$ fs, giving a peak current in the bunch center of 3 kA. The beam is further accelerated, up to a maximum energy of 14.1 GeV, at which energy the emittance is 20 pm (i.e., the "normalized emittance" $\epsilon_n = \epsilon\gamma$ is 0.5μm.)

In general, use of dipole magnets is avoided in machines like LCLS to avoid ruining the beam quality. However, they are used for bunch compression (Fig. 3). This technique results in emittance growth due to coherent SR (CSR) emitted by the bunch [29], which interacts with the bunch itself and may contribute to a microbunching instability [30] that ruins beam quality.

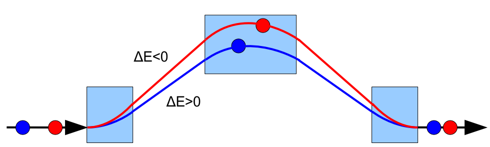

Figure 3: Bunch compression using a three-dipole "chicane," which has energy-dependent time-of-flight.

Compared to storage rings, SASE FELs are still in their infancy, with only a handful of operating x-ray facilities. Because the radiation starts from spontaneous "noise," there is significant pulse-to-pulse intensity and spectral broadening. These issues could be mitigated by "seeding" the FEL process with an external laser, but such lasers exist only for long-wavelength FELs. One scheme [31] is to split the undulator in two parts, and use radiation from the first part to seed the second. Between the undulators, the radiation is spectrally filtered by a Bragg crystal, so that microbunching in the second undulator is seeded by a very narrow bandwidth signal.

High-energy rings routinely deliver useful photon flux at 30 keV or more, which is a challenge for FELs as it requires higher beam energy and higher quality electron beams. Storage rings also serve dozens of simultaneous, independent users, which is difficult for FELs as it requires a higher linac pulse rate, which drives up power consumption. In spite of these issues, for certain types of experiments, FELs have a decisive advantage due to high peak brightness, ultrashort pulses, and full transverse coherence. Hence, there is significant activity world-wide to build soft x-ray and x-ray FELs, with several new facilities expected to begin operation in the next few years.

CONCLUSION

We have briefly reviewed the principles and state of accelerator-driven light sources. Various types, including ring- and linac-based sources were highlighted, along with an indication of future directions and challenges. Many challenges exist as sources are pushed to higher performance, but ideas and intellectual excitement abound.

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