

Electron sources for accelerators

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Photoemission shines as a source of the bright electron beams required for free-electron lasers and particle-physics accelerators.

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Electron beams are essential in such common technological applications as microwave ovens, radio transmitters, medical x-ray scanners, industrial lamination machines, and ultrahigh-resolution lithography. But they are equally essential in the more exotic world of nuclear and high-energy physics. Because it interacts with nucleons through well-understood quantum electrodynamics, an energetic electron beam may serve as a pointlike probe of the nuclear quark structure (see box 1). Alternatively, the beam can produce highly specialized forms of electromagnetic radiation in what are known as light sources, diverse accelerator facilities used to study the structure and dynamics of substances ranging from biological materials to nanocomposites. To generate its highly tunable light, for example, a typical free-electron laser relies on a relativistic stream of electrons delivered in a train of picosecond pulses (see box 2).

For accelerators, electrons are typically generated through either photoemission or thermionic emission. Field emission, in which electrons tunnel through a potential barrier at a material's surface, is more commonly used in electron-beam lithography and electron microscopy.

Four essential ingredients are required to generate an electron beam:

- ▶ The cathode, a material from which the electrons are extracted. In thermionic emission, a heated surface serves as the cathode; in a photoemission source, the cathode is a light-sensitive material called a photocathode.
- ▶ A source of energy to excite electrons above the material's work function, the difference between its Fermi energy and the vacuum energy. That source can be thermal, in the case of thermionic emission, or electromagnetic (usually laser light), as in photoemission.
- ▶ An electric field to accelerate the electrons and form a collimated beam.
- ▶ A vacuum environment, which prevents the scattering of electrons by gas molecules and protects the cathode from contamination.

Although thermionic emission remains the most prevalent method for generating electrons for accelerators, photoemission offers key advantages. For the many particle-physics experiments that require a polarized electron beam, for instance, gallium arsenide photocathodes are useful. And for many light-source experiments, laser-driven electron sources can generate extremely short, picosecond pulses, each made up of a "bunch" of electrons, since the photo-

emission turns on and off in response to the laser. The electrons can thus be emitted at repetition rates as high as gigahertz and at high duty factors—the ratios of on-beam to off-beam time.

State-of-the-art photoemission electron sources for accelerator applications have evolved over the past 20 years into two main technologies: DC photoguns and RF photoinjectors. What distinguishes them is how the accelerating field is applied to the photocathode. For DC electron sources, the electron beam begins in a photogun, a vacuum chamber in which a static electric field is applied between the photocathode electrode and the anode, as pictured in figure 1a. Limiting the bias to between 100 and 500 kilovolts reduces the risk of electric-field breakdown in the chamber. But those voltages are insufficient to accelerate the electrons to relativistic energies. So, to complete the system, researchers further drive the beam with an RF field using accelerator cavities downstream.

Alternatively, an electron source can be composed entirely of RF stages. An RF photoinjector typically consists of a single, specially shaped vacuum chamber called a cavity that contains the photocathode and accelerates its emitted electrons to relativistic energies using an RF electric field (see figure 1b). The beam from an RF photoinjector, like that from a DC photogun, can also be further accelerated in RF cavities downstream.

Photocathodes can be metallic or semiconducting. The light from high-energy (typically UV) lasers gives electrons in a metal enough energy to overcome the material's work function and escape into vacuum (see figure 2a). Albert Einstein's explanation for the process, the photoelectric effect, won him the Nobel Prize in 1921. Semiconductor photocathodes emit electrons somewhat differently. For example, GaAs is in a class of semiconductors with a so-called direct bandgap. Photons with energy equal to or greater than the bandgap can promote electrons directly from the valence band to the conduction band. Adding cesium and oxygen atoms to the surface of GaAs lowers the semiconductor's surface potential barrier and creates a negative-electron-affinity state. That, in turn, allows emission of electrons from the conduction band (see figure 2b).

Polarized electron beams are typically produced through photoemission from GaAs (see box 3), while various semiconductor photocathodes, including GaAs, are used in light sources to produce unpolarized, high-current

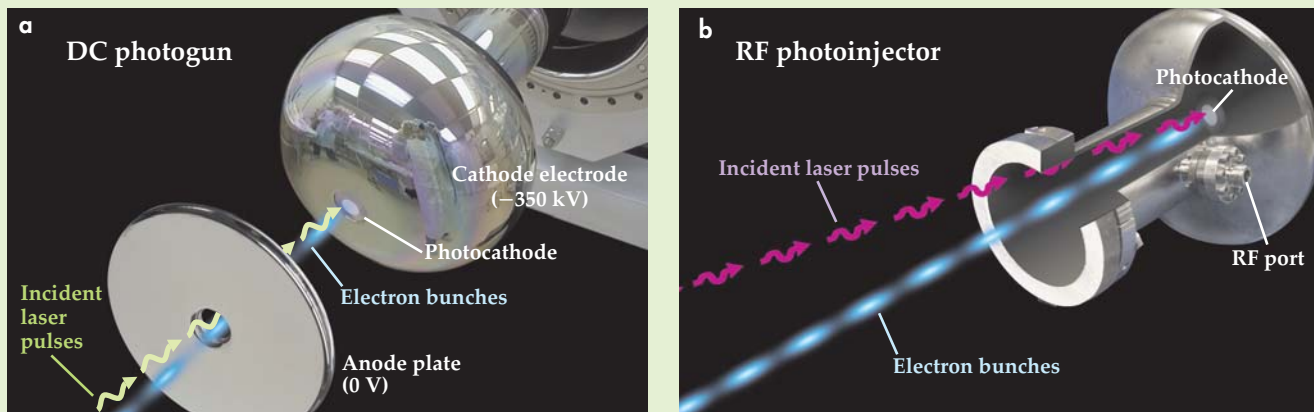


Figure 1. Photoemission using DC and RF electron sources. In both cases a photocathode is illuminated with pulsed laser light to generate a collimated beam made up of a train of electron “bunches.” The emitted electrons gain energy either (a) from the DC electric field produced between the cathode electrode and an anode in a photogun or (b) from an RF electric field applied in a photoinjector.

electron beams.¹ Semiconductor photocathodes other than GaAs typically have a surface with positive electron affinity, where the incident photons must excite the electrons with enough energy to overcome both the bandgap and the difference between conduction-band and vacuum energy levels (see figure 2c).

As the number of photons incident on the photocathode increases, so does the number of electrons emitted, with the relation defined through the material’s quantum efficiency (QE), the percentage of photons at a particular wavelength λ that emit an electron: $I = (\lambda/124) \cdot P \cdot \text{QE}$, where the current I is in milliamperes, λ is in nanometers, and the laser power P is in watts. Different photocathode materials may vastly differ in their quantum efficiencies. The material is often chosen for its suitability for the vacuum environment, the promptness of electron emission, and polarization requirements.

The beam’s eventual application determines the pattern in which the electron bunches must be generated. In a continuous-wave (CW) beam, discrete electron bunches are produced by illuminating the photocathode with a laser at intervals, either at the fundamental frequency of the accelerator or at a subharmonic of it. Electron-accelerator facilities that require high average current tend to operate in CW mode. A pulsed electron beam, in contrast, is made up of a series of many electron bunches produced at a high (often megahertz) repetition rate, with each set of bunches followed by a pause (from milliseconds to seconds) during which no electrons are created. The low-duty-factor operation allows the heat generated at the RF windows and at the photocathode to dissipate and the vacuum to recover between electron pulses. Applications that demand high peak current, rather than high average current, operate in pulsed mode.

Technological challenges

The technical issues surrounding the extraction of electrons from a suitable material and their subsequent acceleration in a collimated beam despite mutual Coulomb repulsions are highly nontrivial and often intertwined. Photocathodes that emit with high quantum efficiencies are notoriously sensitive to their vacuum environment. In devices with a sealed vacuum, such as night-vision goggles or photomultipliers, device processing accounts for the vacuum sensitivity. But in electron sources that must deliver a beam to an accelerator,

the photocathode must operate in ultrahigh-vacuum conditions obtained in the working gun structure that is coupled to the accelerator. But UHV is not easy to achieve and maintain, especially at high average current, when stray electrons striking the chamber and beam-pipe walls release gas atoms that contaminate the vacuum and damage the photocathode.

At high accelerating gradients, field emission from microscopic cracks or impurities on the electrodes or cavity

Box 1. Electron beams in particle physics

Electron beams at nuclear-physics facilities probe the building blocks of matter. The electron energy determines what length scale is probed. A beam whose energy ranges from 1 MeV to 1 GeV, for instance, can probe how quarks and gluons make up protons and neutrons in an atom’s nucleus and study the quark confinement that governs interactions between quarks. Higher-energy machines, such as that at SLAC, the planned 12-GeV upgrade scheduled for Jefferson Lab’s Continuous Electron Beam Accelerator Facility, or proposed electron-ion colliders, probe even deeper into the nucleus. The energies produced in those machines are high enough to investigate constituent quarks and their interplay with the quark sea that makes up a nucleon. Moreover, by aligning the spin states of electrons in the beam, researchers can study the spin structures of nuclei. Tests of parity violations in the standard model, for instance, require highly polarized electron beams.

Electron beams are also used in particle accelerators and colliders to cool proton, positron, or heavy-ion beams. Coulomb interactions between a warm proton beam, with a lot of thermal energy and high transverse momentum, and a cool electron beam, with little thermal energy and low transverse momentum, produce a cooler proton beam with a smaller transverse dispersion and higher luminosity as the beams propagate colinearly. Future TeV electron accelerators, such as the proposed International Linear Collider, could be used in concert with CERN’s Large Hadron Collider to investigate grand unification theories, electroweak symmetry breaking, and extra space dimensions and their connections with cosmology.

Box 2. Electron beams for light sources

An accelerator light source creates photons by passing electrons at relativistic speeds through a static magnetic field. In synchrotron radiation facilities, for instance, bunches of electrons race around a storage ring, emitting light each time the electrons are bent by a dipole magnet. Indeed, the term “light source” was associated directly with such radiation shortly after the invention of the synchrotron in 1947. First-generation light sources produced synchrotron radiation at bending magnets in particle-physics machines, while second-generation light sources were constructed as dedicated machines, built explicitly to generate synchrotron light from electrons circulating in the storage ring. Third-generation light sources added magnetic-dipole arrays to the ring. Alternating magnetic fields in the arrays “wiggle” electrons back and forth, causing them to emit highly collimated beams of radiation.

Fourth-generation light sources typically use an electron beam from a linear accelerator, rather than a storage ring, to generate light. Many of them also use RF energy-recovery technology. Whereas a storage ring continually recycles the electron beam, an energy-recovery linac recycles the

energy. The energy spent accelerating the electron beam is given back to the electromagnetic fields in the cavities by re-injecting the beam at the opposite RF phase (see *PHYSICS TODAY*, March 2002, page 23). ERLs combine the benefits of high peak current typical of linacs with the higher average current (greater than about 10 mA) of storage rings.¹⁴ They also produce electron beams with a smaller angular spread than a synchrotron can offer.

The free-electron laser is an example of a fourth-generation light source that can produce high average power and short,

subpicosecond pulses at wavelengths where other light sources fall short—in producing high-peak-power x rays or high-average-power IR sources, for example (see the article on FELs by William Colson, Erik Johnson, Michael Kelley, and Alan Schwegman in *PHYSICS TODAY*, January 2002, page 35). The relativistic electron beam in an FEL oscillates transversely as it passes through the series of alternating dipole magnets. (A section of such a wiggler magnet is pictured here, covered with rubber hoses that circulate cooling water.) Each oscillation, or bend, in the electron’s path prompts it to spontaneously emit synchrotron light.

Interaction between the spontaneous emission and the

oscillating electrons modulates the electron-beam density; some electrons are accelerated and some decelerated by the combined action of the wiggler magnetic field and the emission’s electric field. The density modulation occurs on the scale of the emitted wavelength—about an angstrom for hard x rays—and effectively increases the emitted light’s power and coherence. The wavelength of the FEL depends on the electron-beam energy and

the period and strength of the oscillating magnetic field, while power depends largely on the current and emittance of the electron beam.

In FELs based on linacs, performance is ultimately limited by the electron-beam quality from the photoinjector. Other fourth-generation light sources, such as Cornell University’s Energy Recovery Linac, Japan’s KEK, and Argonne National Laboratory’s Advanced Photon Source, may be used to generate nearly coherent x rays through spontaneous emission without the lasing that defines an FEL.



walls becomes another significant limitation. Although RF photoinjectors can produce high accelerating fields in pulsed mode, having them do so in CW mode is one of the most significant challenges for RF technologies. The primary reason is that the high gradients combined with the high duty factor result in a lot of heat that can damage the accelerator walls.

It’s also difficult to produce an electron beam with low emittance for light sources and electron-ion colliders. The emittance, defined as the area of phase space that the beam occupies, is a figure of merit for electron-beam quality. A related figure of merit is the beam’s brightness, a quantity proportional to its peak current and inversely proportional to the square of its transverse beam emittance. Researchers in the light-source community are working to produce beams of low emittance—on the order of 1 micron—either with a very high bunch charge (1 nanocoulomb, say) at low duty factors to generate coherent x-ray beams, or with a lower bunch charge (on the order of 0.1 nanocoulomb) at the high duty factors required to generate high average power, coherent IR beams, or spontaneous x rays.

The primary obstacle to achieving either goal is the dif-

ficulty of producing an electron bunch with many electrons while the emittance is kept low. At nonrelativistic energies, mutual Coulomb repulsion between the electrons increases the transverse momentum of each electron. This space-charge effect increases the transverse size of each bunch and can cause it to diverge nonlinearly on its way down the beamline. Quickly accelerating the electron bunch to relativistic energies inhibits the space-charge-induced angular spread of the beam because the space-charge effect decreases with the inverse square of the electron’s momentum. That’s why high accelerating fields are so desirable near the photocathode.

Emittance would not grow if the charge distribution along transverse and longitudinal directions of the electron bunch were uniform. Unfortunately, the charge distribution is nonuniform because the longitudinal profile of each bunch depends on the usually Gaussian profile of a laser used to generate it and on the response time of the photocathode. The divergence of individual transverse slices of each bunch in time, it turns out, is strongly correlated with the slices’ longitudinal position along the bunch. So, if the bunch is passed through an appropriately placed focusing solenoid lens, the divergence can be reversed for each slice, which will remove

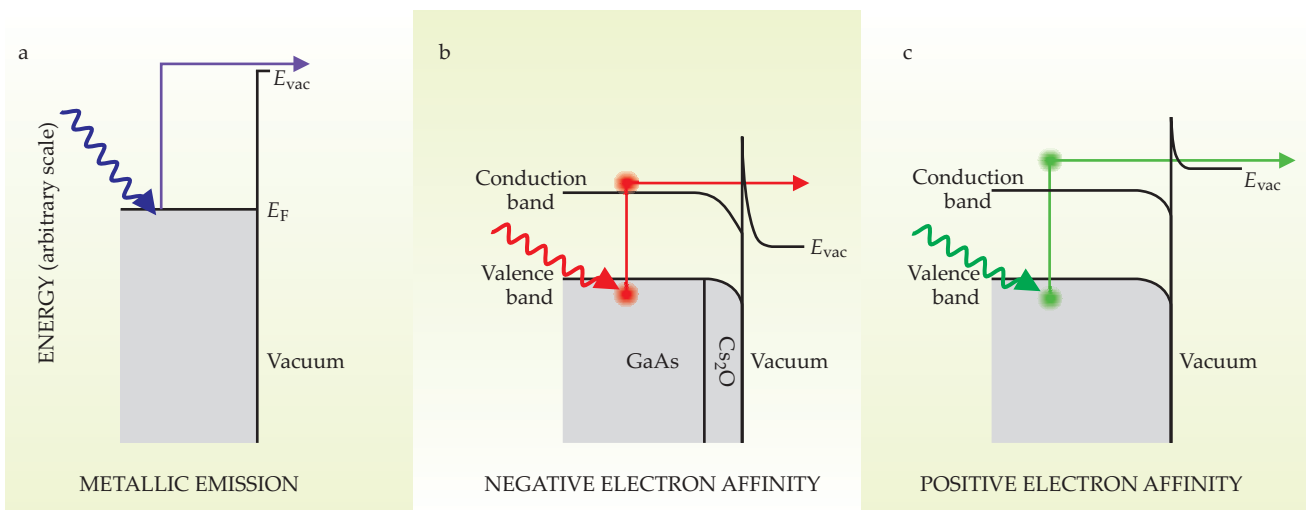


Figure 2. Photoemission from metals and semiconductors. (a) In metals, the electron must absorb enough energy from an incoming photon to overcome the material's work function, the difference between its Fermi level E_F and the vacuum energy level E_{vac} , where an electron is free. Below that threshold energy, typically at UV wavelengths, photoemission cannot occur; above it, the photocurrent is proportional to the light's intensity. (b) In semiconductors, lower-energy light, typically at IR or visible wavelengths, excites electrons across the material's bandgap. Surfaces with negative electron affinity, such as gallium arsenide covered with cesium and oxygen atoms, have a vacuum level below the conduction band. (c) Surfaces with positive electron affinity have the vacuum level above the conduction band minimum and thus require excitation energies that exceed the bandgap.

much of the emittance growth downstream. This is known as emittance compensation,² a central concept in generating very bright electron beams.

DC photoguns

High-voltage photoguns were first developed at SLAC in 1977 to deliver polarized electron beams for high-energy physics experiments. The polarization requirement led researchers to illuminate a GaAs wafer with IR laser light (see box 3).³ But with GaAs photocathodes, the operational lifetime directly corresponds to vacuum quality in the photogun. The electron beam ionizes residual gases in the chamber, and the positive ions are accelerated back to the photocathode, where they reduce the quantum efficiency by damaging the crystal structure and surface chemistry. Photoguns with the best photocathode lifetimes, defined as the time required for the quantum efficiency to fall to $1/e$ of its initial value, typically operate at pressures below 10^{-9} Pa. The high-polarization photogun at Jefferson Lab's Continuous Electron Beam Accelerator Facility has among the longest lifetimes, measured at 550 beam hours at an average current of $100 \mu\text{A}$.

Besides providing polarized electrons, DC guns can also deliver high-average-current unpolarized electron beams to free-electron lasers. In Jefferson Lab's FEL photogun, GaAs photocathodes with 5% quantum efficiency at green wavelengths have generated CW currents up to 8 mA with 0.5 W of incident laser power, which makes the photogun the highest-average-brightness photoemission source in operation.

Although DC photoguns could, in principle, deliver electron beams having an unprecedented 100 mA of average current by simply scaling up the existing technologies, the photocathodes would suffer impractically short lifetimes, on the order of hours, from deterioration of the vacuum. Research challenges therefore include developing better chamber materials, heat treatments, and vacuum coatings to reduce the amount of gas entering the system from chamber

walls, and using advanced pumping techniques. One pumping technique, for example, involves coating the chamber surfaces with a reactive chemical coating known as a thin film nonevaporable getter pump.

Another challenge involves overcoming the difficulty of accelerating electrons at the photocathode strongly enough from a DC field to achieve beams with low emittance and high bunch charge. The high-voltage electrodes in a DC photogun are hand polished to a submicron finish to minimize field emission and are designed to collimate and accelerate the electron beam to several hundred keV.⁴ Adding a focusing lens at the anode offers some degree of emittance compensation. Accelerating gradients as high as 4 MV/m at the photocathode have been achieved using a 350-kV bias.

Nevertheless, field emission from electrodes or the photocathode surface still presents a challenge to researchers trying to reach the gradients required to maintain a very bright beam at the high bunch charges that future applications may require. Field emission causes pressure bursts, which destroy the quantum efficiency and may even puncture the high-voltage ceramics and create leaks in the vacuum chamber. Electrode coatings that suppress field emission, though, are being tested by Jefferson Lab in collaboration with a team at the College of William and Mary.⁵ And Cornell University researchers are wrestling with minimizing field emission in a DC gun designed to operate at 750 kV. That voltage would represent the highest level yet achieved in DC photogun technology.

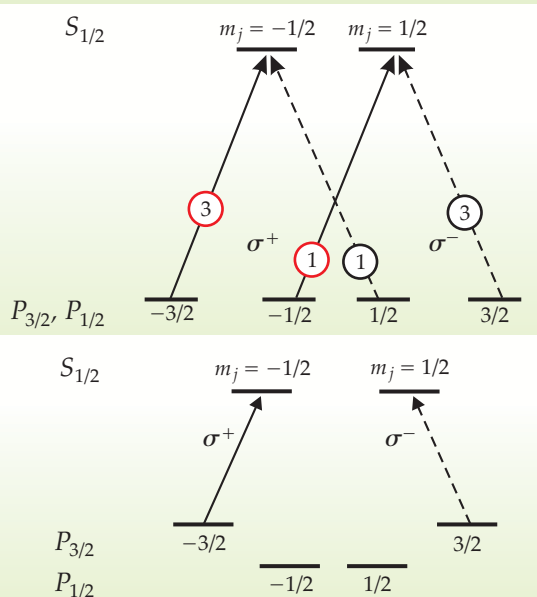
RF photoinjectors

RF photoinjector technology uses either normal-metal or superconducting cavities to generate electron beams. In 1985, after realizing that thermionic guns could not meet the requirements of their FEL, scientists at Los Alamos National Laboratory started developing what became normal-metal RF photoinjectors through experiments^{6,7} meant to improve

Box 3. Polarized photoemission

Spin-polarized electron beams are produced by photoemission from gallium arsenide photocathodes. Electrons are considered polarized when the two possible spin states along a particular direction are not evenly populated.¹⁵ GaAs emits polarized electrons when the crystal is illuminated with circularly polarized light with a wavelength of 860 nm, which matches the bandgap energy of the material. Following quantum mechanical selection rules, the circularly polarized light excites electrons across the gap from two degenerate valence-band states—the $P_{1/2}$ and $P_{3/2}$ states. Three electrons are promoted to one spin state for every one electron promoted to the other spin state, as pictured here (top), giving 50% possible polarization.

The solid and dashed lines distinguish transitions made using one particular helicity of polarized light, either left-handed σ^- or right-handed σ^+ . Changing the helicity changes the direction of polarization of the electron beam. Depolarizing effects, such as lattice imperfections and inelastic scattering of electrons that occurs during diffusion and emission, generally limit the polarization to around 35%, with quantum efficiencies as high as 10%.



To generate higher-polarization electron beams, researchers mechanically strain the GaAs crystals. The strain lifts the degeneracy of states in the valence band, so the bandgap between one set of states ($P_{1/2}$ and $S_{1/2}$) becomes larger than the other set ($P_{3/2}$ and $S_{1/2}$), as pictured here (bottom). Therefore, incident light with only enough energy to promote electrons from one of the states can theoretically generate a 100% polarized electron beam.

In practice, researchers grow their GaAs on a substrate such as gallium arsenic phosphide, whose different lattice constant provides the mechanical strain. A superlattice structure, with alternating layers of GaAs and GaAsP, can increase both the polarization and the yield of electrons from the material above that achievable with a single strained layer of GaAs. Indeed, scientists at SLAC have achieved 90% polarization from strained superlattice photocathodes,¹⁶ and Jefferson Lab's Continuous Electron Beam Accelerator Facility routinely produces an 85% polarized beam with a quantum efficiency approaching 1%.

the emittance of electron beams with high bunch charges (1–5 nC).

In a normal-metal RF photoinjector, the photocathode sits in a copper RF chamber where the accelerating field is highest (see figure 1b). In pulsed operation, peak accelerating gradients at the photocathode are on the order of 100 MV/m, while in CW operation, power-coupling issues and cavity heating typically limit the field gradients to around 10 MV/m.

Early RF injectors took advantage of high-quantum-efficiency semiconductor photocathodes—such as cesium antimonide and cesium potassium antimonide—driven with green laser light. Indeed, experiments performed at the Boeing Co in 1992 still hold the record for average current, at 32 mA.⁸ Vacuum sensitivity has often limited the lifetime for CsK₂Sb in normal-metal photoinjectors to a few hours even at low-average-current operation.⁹ At Brookhaven National Laboratory, researchers are working on techniques to improve the lifetime of CsK₂Sb cathodes by using diamond windows, which amplify electron yield through secondary emission. Others at the University of Maryland and the US Naval Research Laboratory are trying to extend the lifetime of the cathode surface by rejuvenating it with a cesium dispenser.¹⁰

RF photoinjectors, typically chosen to generate much higher bunch charge than is achievable through DC photoguns, also have less stringent vacuum requirements. Indeed, the vacuum is typically several orders of magnitude poorer than in DC photoguns. Metallic cathodes like copper and magnesium are robust in the vacuum environment of RF systems. And despite their low quantum efficiency, typically 0.001% at the UV wavelengths necessary for photoemission, metallic photocathodes mounted in RF photoinjectors are the predominant technology (at low duty factors) for light sources requiring high peak brightness.

The high accelerating gradient in normal-metal RF photoinjectors produces a low-emittance beam. Attempting to increase the average beam current by increasing the duty factor is difficult, however. Simply scaling RF technology to the source requirements for a 100-kW IR-wavelength FEL—about 100 mA CW—would require nearly 50 kW of UV laser light—enough to vaporize the photocathode. In addition, UV drive lasers require several frequency-doubling stages, which makes achieving high average power more complicated than it would be in longer-wavelength systems. Moreover, the scattering of UV light in the chamber would prompt unwanted photoemission from the copper photoinjector cavity. That makes semiconductor or multi-alkali photocathodes, such as CsK₂Sb, whose quantum efficiency is high at visible wavelengths, a good choice for high-average-current RF photoinjectors. The scattered visible light will not cause field emission.

Another major concern is getting sufficient RF power into the photoinjector accelerating cavities without overheating and damaging the system. For a system delivering an average current of 100 mA, 1 MW of RF power would need to be transmitted to the cavity through the windows. Preventing the likely damage from that thermal load presents a real technological challenge.

Superconducting solutions

Superconducting RF technology, widely used in accelerators,¹¹ is now being investigated as a third option for producing electron beams with low emittance, high bunch charge, and high average current. SRF photoinjectors operate much like normal-metal RF photoinjectors do, but with superconducting niobium cavities kept at cryogenic

temperatures, they suffer little of the resistive losses of normal-metal injectors.

The first SRF photoinjector was developed in Germany at the University of Wuppertal in 1992. Ten years later a cesium telluride photocathode with quantum efficiency around 2–3% at 266 nm was tested successfully in the only operational SRF photoinjector, at Rossendorf, Germany.¹² The gradient achieved there was 20 MV/m, and future SRF photoinjectors are expected to achieve gradients up to 50 MV/m.

The appeal of SRF photoinjector technology lies in the combination of excellent vacuum and high gradients. Together, those could provide high average currents, low emittance, and long-lifetime operation, mainly because the system would not suffer from the cavity walls overheating. But considerable technological challenges must first be resolved before the SRF photoinjectors are used routinely. The challenges include managing the heat generated when the RF fields and the incident laser interact with a normal-metal photocathode, avoiding contamination of the SRF cavity when photocathodes are replaced, developing SRF-compatible emittance-compensation techniques for high-charge electron beams, and preventing damage to RF windows when the field gradient and duty factors are high.

The next generation

Early successes at SLAC, Los Alamos, Brookhaven National Laboratory, and Boeing have led to the adoption of photoinjectors for a wide array of electron accelerators worldwide. Current research is directed toward increasing the polarization, bunch charge, average current, and cathode lifetimes, while maintaining low emittance in most cases (see box 1).

Improving the vacuum and beam handling in DC photoguns is most likely to generate longer lifetimes and greater bunch charge in highly polarized beams, though advocates of SRF technology are exploring whether operating a GaAs photocathode in an SRF photoinjector is feasible. The light-source community, beginning to operate what it calls its fourth-generation energy-recovery linac machines, is striving for electron sources that deliver 100-mA average current (see box 2). Visible-wavelength lasers coupled with high-quantum-efficiency photocathodes may offer the most promising route for those high-current light sources. Meanwhile, research on DC photoguns coupled to SRF injectors capable of producing 100 mA is under way at Jefferson Lab in collaboration with scientists at Advanced Energy Systems Inc, Cornell, and other labs. Los Alamos researchers are collaborating with those at AES to develop a high-average-current RF photoinjector, while Rossendorf and Brookhaven researchers, also in collaboration with AES, are developing SRF photoinjectors. And scientists at SLAC have just achieved 1.2-micron emittance at 1-nC bunch charge to drive the Linac Coherent Light Source x-ray FEL there. Their normal-metal RF system promises the highest peak electron brightness and therefore the highest peak photon brightness of any fourth-generation light source under construction.¹³

Other frontiers remain. Understanding and reducing the sources of halo — electrons that reside just outside the beam — are active areas of research in all electron-source technologies. Cooling the photocathode is another problem. GaAs can reach 200 °C when illuminated with 25 W of green laser light. At that temperature, its surface chemistry is unstable; moreover, the consequent heating in an SRF photoinjector might cause the accelerating fields to collapse. The quest for more robust, higher-quantum-efficiency, and higher-polarization photocathodes is an active research field around the world.¹

For all photoemission electron sources, still other tech-

nological challenges stand in the way of meeting beam specifications for future accelerators and light sources. But problems notwithstanding, tremendous research efforts are under way, and the development of electron sources appears bright. With continued steady progress, the future looks even brighter.


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