FUTURE DIRECTIONS IN ELECTRON SOURCES*

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Abstract

The emittance-compensated rf photoinjector is in the process of evolving from an experiment in and of itself, to a laboratory instrument, to a workhorse component of large user facilities such as next-generation light sources. In recent years the performance achieved by the standard π-mode design has approached the levels predicted by theory and simulation. The basic design has been scaled from X-band down to less than 1 GHz in terms of operating frequency, and superconducting designs are presently undergoing initial testing at various locations.

The requirements for linac-based light sources will require at least one order of magnitude improvement in beam quality; other applications, such as electron microscopes or high-energy electron lithography, require still greater improvements. The migration towards fully superconducting accelerators provides some additional design challenges. This paper briefly presents requirements for some future applications, and presents four new approaches to extending injector performance: the diamond-emitter photocathode, the planar focusing cathode, the magnetic-mode emittance compensation technique, and the field-emission-gated cathode.

INTRODUCTION

Prediction is very difficult, especially of the future [1]; however, at least some directions for electron source development may be derived from the needs of recently proposed accelerators such as linac-based light x-ray sources. Other directions may be anticipated by considering the state-of-the-art in other fields, such as electron microscopes or high-energy electron lithography. Many requirements arise from the transition from low-average-current to high-average-current applications. The migration towards fully superconducting accelerators provides some additional design challenges.

Broadly speaking, three main directions of development may be identified. The first direction is "merely" the continued improvement and refinement of single-bunch performance towards ever-smaller normalized emittances, combined with an improved control over the general phase-space volume of the beam. (The presentation and paper by Massimo Ferrario [2] will address much of the current work in this direction.)

The second direction is towards customization for a particular application. We as a community are moving away from standardized designs (exemplified by the highly successful SLAC/BNL/UCLA-type π-mode photoinjector design) and towards designs highly optimized for particular applications. This is most visible at the moment in the design of injectors for energy-recovery linacs (ERLs) intended to drive high-average-power free-electron lasers (FELs), but there is also interest in using high-brightness electron beam sources for precision e-beam welding, electron lithography, high-energy electron microscopy, and other "standalone" applications [3].

The third direction is towards high-average beam power, closely paralleling a drive towards superconducting radiofrequency (SRF) accelerator technology. Such sources must not only meet their design goals in terms of beam properties, but must also be physically compatible with cryogenic system requirements and SRF limitations.

Broadly underlying the above directions are drives towards simplification and improved reliability, topics often associated with the needs of user facilities rather than research laboratories. For multi-user facilities built as national facilities, reliability is at the top of the requirements list for almost any accelerator component. It is worth noting that what is considered reliable in a laboratory setting may still have unacceptably high failure rates and maintenance requirements in the context of a mission-critical component of a user facility [4].

Finally, designs for "tabletop" accelerators, for instance for THz radiation production, are becoming more widespread. If such devices prove to be feasible and enter any form of mass market, the required improvements to reliability and simplicity of operation will be of great and broad benefit to injector design regardless of the application.

Nomenclature

Throughout this paper, the term "injector" refers to the portion of the accelerator up to 5 – 10 MeV (or the end of the accelerator, whichever comes first). Also, the phrase "fully SRF" is intended to encompass DC-gun technology followed by superconducting energy booster cavities, as well as superconducting rf guns.

DRIVERS OF FUTURE REQUIREMENTS

Large Accelerators

Proposed large accelerator facilities, such as linear colliders and linac-based light sources, are the most visible drivers for several frontiers of injector development. Certainly, increased beam brightness is a common goal for most "facility" injectors, and this has been given considerable attention over the years. There is very strong interest, however, in developing a more refined control over the entire phase-space volume of the beam. For instance, linear colliders, and some linac-based light sources, assume the use of beams with highly asymmetric emittances, e.g., $\varepsilon_x \sim 100\ \varepsilon_y$. Given an injector capable of producing such "flat" beams of sufficient quality, a linear collider could be made somewhat simpler and signifi-

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cantly less expensive by the elimination of the electron damping ring.

Demands on the injectors of linac-based x-ray light sources will focus on reliability as well as on improving beam brightness. Generally speaking, the single-bunch parameters for both incoherent and coherent linac-based x-ray light sources are quite similar [5]; injectors will have additional demands based on required average beam currents. For instance, incoherent linac-based light sources intended to replace storage ring sources typically require 10 – 100 mA average beam current [6].

High-Average-Power Accelerators

There are a number of upcoming applications for moderate-energy, moderate-beam-brightness, high-current linacs. These include infrared free-electron lasers (IR-FELs) driven by energy-recovery linacs operating at about 100 MeV. Such sources typically require average beam currents of about 1 A, transverse normalized emittances less than 10 μm, and longitudinal emittance less than 50 π kV ps. A principal challenge for these devices is the longitudinal emittance, which generally has not been given as high a priority in high-brightness injector designs. Clearly drivers for high-average power and fully SRF injector development, these machines are also primary drivers of the trend towards customization of the injector for a specific task.

Novel Uses for Injectors

Recently there has been significant interest in using high-brightness electron sources outside their traditional roles as linac drivers. In particular, there appears to be growing interest in using laser-driven injectors for time-resolved electron microscopy [7,8]. Compact, high-brightness beam sources also offer interesting possibilities for THz radiation generation, electron lithography, and other "small-scale, wide-use" application areas. Beam sources for such applications would require customization, simplification, and higher average beam power, as well as high reliability.

EXTENDING CAPABILITIES

This paper describes four recent (and ongoing) developments in injector design. Although very different, all are aimed at extending the performance of high-brightness electron injectors in the directions of reliability, simplicity, or high-power capability. The result is an extended performance space for electron injectors, as well as improving the ability to customize injectors for specific applications.

The topics presented here represent only a small cross-section of the ongoing work in high-performance electron source design; in the space provided there is insufficient room to do justice even to the topics selected, let alone the field as a whole.

Diamond-Emitter Photocathode

The diamond-emitter photocathode concept, being developed by Brookhaven National Laboratory, is a "structured" cathode. That is, the electrons emerging from the photoemitter are not released directly into the electron gun. The cathode as a whole is "immersed" in the electric field in the gun. Electrons emitted from the photocathode are accelerated through a small gap before impacting the back of a diamond plate. Secondary electrons emitted at the impact site are pulled through the diamond by the electric field in the gun, eventually exiting through the front of the window and into the gun proper [9]. A monolayer of gold atoms on the back of the diamond plate provides a current path so as to avoid charging up the diamond. The overall geometry is illustrated schematically in Figure 1.

This arrangement serves two purposes. First, ideally, the diamond can act as an electron amplifier, increasing the effective quantum efficiency (QE) of the photocathode to potentially much greater than unity. This has significant implications for the required drive laser power to achieve a given beam current, and may prove to be a key feature in future high-current, high-brightness electron sources.

Second, the actual photocathode is encapsulated; this serves both to protect the cathode from the cavity, and the cavity from the cathode. RF guns are notoriously harsh environments for high-QE cathodes, with typical lifetimes on the order of hours [10]. By isolating the high-QE cathode surface from cavity "events" such as arcing, the lifetime of the cathode may be dramatically extended. Similarly, SRF cavities and some DC guns are rather unforgiving of contaminants [11], especially those – such as cesium – having low work functions. Since such materials are common components of high-QE cathodes, encap-

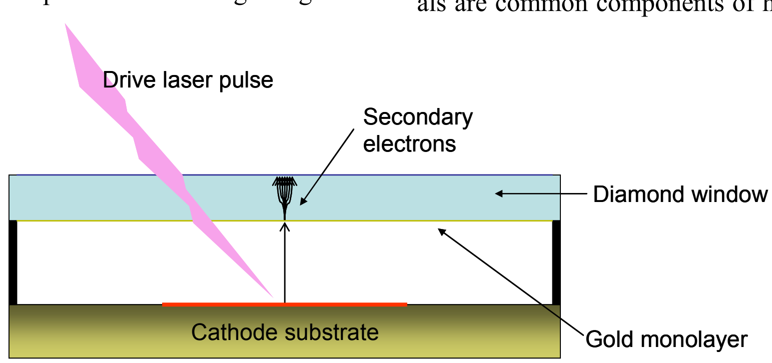

Figure 1: Diamond amplifier cathode schematic (not to scale).

sulating the cathode helps to protect the cavity into which it has been inserted. Encapsulation also may permit the use of residual-pressure methods, such as those used in photomultiplier tubes, to help extend the lifetime of the photocathode by "bathing" it in a low-pressure Cs gas [12].

Planar Focusing Cathode

The emittance-compensated photoinjector uses a solenoid lens either surrounding (typical of L-band and lower-frequency guns) or immediately following (typical of S-band guns) the final full rf cavity. The solenoid field, and thus the focusing strength, may be varied completely independently of the rf gradient inside the gun, and this tunability is essential during injector tune-up and commissioning. The solenoid lens, however, can introduce aberrations due to current crossovers that break the symmetry of the solenoid; the focusing force is also energy dependent and therefore includes chromatic aberrations. Finally, the emittance compensation process is fairly sensitive to the kick delivered by the solenoid lens to the beam, as the resulting oscillations must be properly captured and damped in following linac sections.

It is possible to design a cathode-region rf-based focusing scheme that, in effect, "pre-compensates" the emittance as the beam leaves the cathode. The overall appearance is similar but not identical to Pierce-type DC gun geometries. Typical variants of this scheme include the use of a concave cathode and a recessed cathode. (Both of these features have been used in the design of high-brightness superconducting rf guns [13] to avoid placing a magnetic solenoid near the SRF cavity.) There are significant problems with these schemes, however, including a strong correlation between focusing force and accelerating gradient. (Changing the depth of a recessed cathode alters the net focusing applied, but also alters the gradient at the cathode surface as well; the change in position also usually results in a change in the longitudinal emittance and energy spread.)

A method has been devised by the author and John Noonan (Argonne National Laboratory) to combine the advantages of cathode-region focusing (simplicity, symmetry, achromaticity) with the advantages of a solenoid (independent adjustment of focusing strength). A planar focusing cathode provides a planar emission surface at a fixed longitudinal position, immediate radial focusing at the surface of the cathode, and allows – to an extent – independent adjustment of the radial focusing and accelerating gradient. The scheme relies on the use of a dielectric cathode, probably "flashed" with a very thin conducting layer to avoid charge-up [14]. For the results reported here, the dielectric properties of A35 ceramic have been used.

The basic geometry is shown in Figure 2. The radial electric field varies linearly with radius over the area of interest for beam emission. The beam is given a radial focusing kick as it leaves the cathode surface. The focusing strength, proportional to dE_r / dr can be varied independently (to a point) of the gun gradient by adjusting the depth of the shunt bar behind the cathode. Moving the shunt bar closer to (farther from) the back of the cathode decreases (increases) the net applied focusing. One can then choose the desired combination of radial focusing and accelerating gradient at the cathode surface.

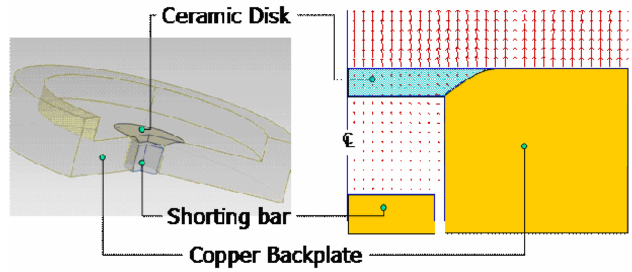

Figure 2: Planar focusing cathode geometry.

Figure 3 shows emittance as a function of distance for a 1-nC beam from an S-band gun fitted with a planar-focusing cathode, for the normal case of a solenoid, with a fixed-focus metal recessed cathode, and with a planar-focusing cathode. All curves were calculated with PARMELA [15]. The simulation assumes a standard tri-flattop distribution at the cathode, and does not include thermal emittance.

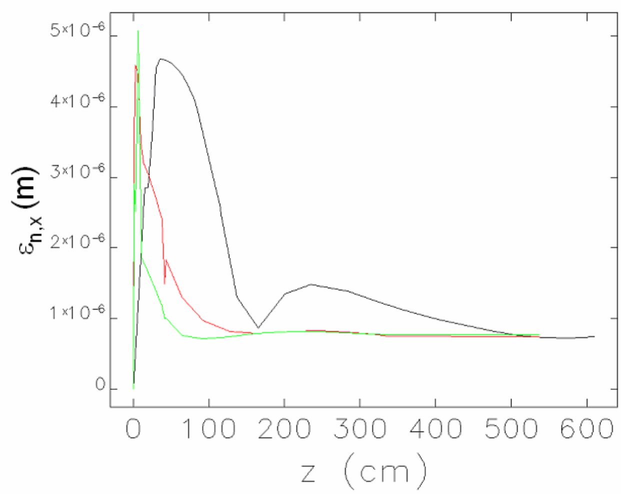

Figure 3: Normalized emittance vs. distance for an injector with solenoid focusing (black), fixed-focus recessed cathode (red) and planar focusing cathode (green).

The most notable feature is the lack of significant emittance oscillation for the fixed-recess and planar focusing cases. The calculated normalized emittance at the end of the beamline is approximately 0.8 μm. Construction of a prototype and high-power tests are in the early planning stages.

Magnetic-Mode Emittance Compensation

Klaus Flöttmann and Dietmar Janssen have recently proposed using a magnetic (TE) mode to provide focusing for emittance compensation in superconducting rf guns [16]. This approach is quite elegant on several counts.

By using a TE mode, this approach avoids the possible complications of high-field solenoid magnets in close proximity to superconducting cavities [17]. It allows for

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independent adjustment of the accelerating gradient and focusing strength, however, and is intrinsically compatible with superconducting gun design requirements.

It also appears, contrary to intuition, that the magnetic mode frequency need not be an exact harmonic of the accelerating mode. In effect, the beam can enter the cell with the magnetic mode at arbitrary phase (relative to the magnetic mode) and undergo a reasonably well-matched emittance compensation process. Although there is some dependence of emittance (and other beam parameters) on the entrance phase, the dependence is fairly modest. Thus, although one could argue that one would want to use exact harmonics for an operational system (so as to obtain the most stable operation possible), initial tests can in principle be performed without requiring significant changes to an existing gun, if a suitable mode at some frequency exists.

Field-Emission Gated Cathode

In recent years there has been considerable interest in injectors operating with multiple frequencies and rf modes in the same cavity. The original intent was to use the addition of a third-harmonic TM mode in the same cavity as the fundamental mode to reduce or eliminate rf-induced emittance growth in the injector [18,19,20]. The magnetic-mode focusing scheme described can be considered a part of this trend.

Another field-addition scheme has recently been proposed [21], with somewhat different intent. Rather than using the combined fields to reduce the rf emittance growth, or to provide focusing to the beam, the net fields are used to shift the peak of the rf waveform from +90 deg. to approximately +50 deg. The purpose is to allow gating of a field-emission cathode, such that the peak emission occurs at a time compatible with good beam dynamics and transport within the gun. The gating of the field emission is controlled by the rf field at the cathode rather than by a physical gate at the cathode surface, as is normally the case.

The resulting configuration allows the production of beam during every rf period, without the use of a drive laser, but constrained to a relatively small – and useful – part of the rf period. Thus, the technique in some sense combines aspects of both photoinjectors (gated emission) with thermionic cathode injectors (no drive laser, CW operation). The initial simulations have been aimed towards constructing high-energy (1 – 2 MeV) electron microscopes, but the basic design appears to scale well up to average beam currents of ~ 50 mA, with a very consistent performance scaling of about 2 nm normalized emittance per mA average beam current across several orders of magnitude in beam current. Figure 4 shows scaled emittance (in nm/mA) vs. emission current density, for a variety of average beam currents.

High-current ERL-based light sources are one possible application for this gun design. Besides electron microscopy, potential "standalone" applications for this source include radiation generation at various frequencies, electron beam welding, and electron beam lithography. The source designers are presently working towards construction of a prototype source [22].

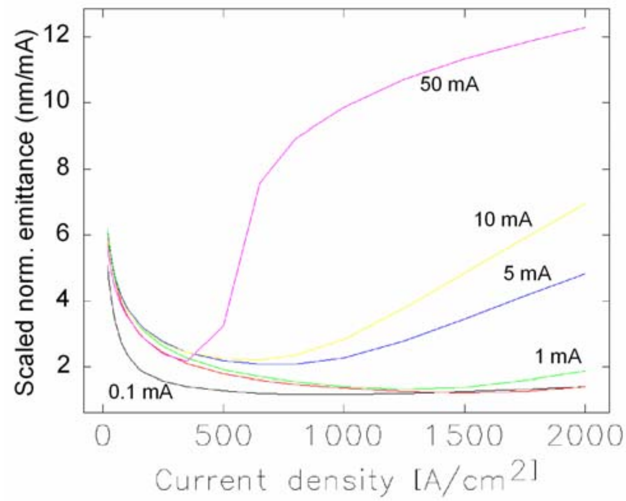

Figure 4: Scaled performance curve for a field-emission gated cathode rf gun.

OTHER FRONTIERS

The methods used to design injectors deserve special note, as these are undergoing a renaissance with the advent of inexpensive, high-performance cluster-based supercomputers, both from the standpoint of optimization and improved fidelity of modeling. Regarding the former, the work done at Cornell University on their DC injector is particularly impressive [23].

There are also ongoing efforts to dramatically improve the models used to calculate the fields in the injector, and in particular to better simulate electron emission from the cathode; these efforts [e.g., 24,25,26] will be critical to modeling efforts for ultra-low-emittance source designs. Likewise, improved understanding of beam halo formation and propagation [27] will be critical to the design and operation of high-average-power accelerators.

CONCLUDING THOUGHTS

The best way to predict the future is to invent it [28]. High-brightness electron sources are at both the literal and figurative leading edge of high-performance accelerator design, and the success of many future accelerators rests on the ability of the injector design community to fill these needs.

There are many challenges associated with these next generations of electron sources, some of which arise from the requirements of user facilities, some from the novel (to the average injector designer) applications, and some simply from the degree of customization required. These challenges have captured the interest and imagination of the injector design community, and the community has responded with vigor and enthusiasm.

The future of injector design appears to be headed towards higher beam powers, higher reliability, novel applications, and better beam quality; in short, it appears very bright indeed.

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