High-Brightness Injector Modeling*

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Abstract. There are many aspects to the successful conception, design, fabrication, and operation of high-brightness electron beam sources. Accurate and efficient modeling of the injector are critical to all phases of the process, from evaluating initial ideas to successful diagnosis of problems during routine operation. The basic modeling tasks will vary from design to design, according to the basic nature of the injector (dc, rf, hybrid, etc.), the type of cathode used (thermionic, photo, field emitter, etc.), and "macro" factors such as average beam current and duty factor, as well as the usual list of desired beam properties. The injector designer must be at least aware of, if not proficient at addressing, the multitude of issues that arise from these considerations; and, as high-brightness injectors continue to move out of the laboratory, the number of such issues will continue to expand.

INTRODUCTION

This paper is based upon a talk given at the 2004 Advanced Accelerator Conference workshop and on discussions held in the computational accelerator physics working group, and relates specifically to electron beam generation and initial acceleration.

What is an Injector?

An injector can be broadly defined as an accelerator that provides an electron beam to another accelerator. This definition can encompass, for instance, a plasma accelerator; a dc or rf gun, perhaps including a booster tank; an entire linac used to provide beam to a storage ring; or a linac and damping ring used to provide beam to a linear collider. For this paper, the term "injector" will be used to indicate everything from the initial electron source, up to energies of approximately 30 – 60 MeV.

This particular range is singled out because it is here that the beam transitions from nonrelativistic to relativistic motion. It is in this regime that phenomena such as emittance compensation can occur [1]. The allowed approximations change dramatically during this initial acceleration, and some beam parameters, such as beam energy spread, can be larger here (in a relative sense) than anywhere else in the accelerator. The beam quality generally does not get any better than it is at the exit of the injector. And, finally, under this definition an injector is a "keystone" component. By upgrading the injector, assuming the remainder of the accelerator is capable of

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transporting the improved beam quality, the performance of an entire facility can be upgraded at relatively minor expense.

There are, at present, three broadly identifiable cathode technologies in common use for electron beam sources, and three to five (depending on how one counts them) accelerator technologies used to perform the initial acceleration of the beam from those cathodes. Thus, there are 9 – 15 potential separate candidates for discussion as "high-brightness" electron injectors. TABLE 1 indicates which of the combinations are currently in use.

TABLE 1: Electron sources and acceleration technologies: commonly used combinations.

	Thermionic cathode	**Photocathode**	**Field Emitter Cathode**
dc gun	electron microscopes, storage ring injectors, compact FELs	polarized electron sources (SLAC, JLab), recirculating linac/FEL	electron microscopes
Normal-conducting rf gun	storage ring injectors, compact FELs	single-pass FELs, driver for advanced concepts (e.g., plasma)	
Super-conducting rf gun (experimental)		experimental; proposed for some recirculating linac applications	possible applications for electron microscopy and other small devices
Hybrid dc/rf gun (experimental)		candidate for single-pass FEL driver	

This paper does not attempt to cover each of these combinations in detail, nor does it present a detailed description or comparison of the many simulation codes that can be used to model injectors of various types. Rather, I intend to discuss some of the common features to all injector modeling; to identify trends which will have an impact on the field of injector modeling; and to suggest some paths towards improving our injector modeling capabilities. In broad terms, general trends seem to favor the development of rf photocathode guns, although a good case can be made for dc photoinjectors for several key applications.

What Is Brightness?

Electron beam brightness is a single number representing the quality of the electron beam; in general, higher brightness is desirable because it will allow the overall accelerator to function at a higher level of performance. One canonical definition of electron beam brightness is

$$B_n = \frac{2I}{\pi^2 \varepsilon_{n,x} \varepsilon_{n,y}}, \tag{1}$$

where I is the electron beam current, and $\varepsilon_{n,x(y)}$ is the normalized transverse emittance in the x-x' (y-y') plane. In a sense, it represents a measure of the density of the beam in transverse phase space.

If one is working on single-pass free-electron lasers, however, one might prefer to use the Pierce parameter

$$\rho = \left[\alpha \cdot \frac{I}{\sigma_x^2}\right]^{1/3} \propto \left[\frac{I}{\varepsilon_n}\right]^{1/3}, \tag{2}$$

where α represents a number of other parameters including undulator strength and beam energy, σ_x is the beam spot size, I is the peak current, and ε_n is the normalized emittance within the FEL undulator. The higher the Pierce parameter, the smaller the gain length, and therefore the shorter the undulator can be to achieve saturated lasing. Clearly the Pierce parameter is related to B_n but puts relatively greater emphasis on peak current rather than transverse emittance.

If one is interested in designing an injector for a storage ring in which the beam quality is set by the ring properties rather than the injector per se, the "brightness" can be described by a binary condition such as:

$$B_{fill} = \begin{cases} 1 & \text{if } Q_{bunch} \geq Q_{min} \\ 0 & \text{otherwise} \end{cases}. \tag{3}$$

In other words, if the delivered bunch charge Q_{bunch} is above some minimum Q_{min}, the injector brightness (B_{fill}) is enough to meet storage-ring fill requirements; otherwise, the ring cannot be filled quickly enough. Thus, for storage-ring injectors, the main parameter of interest is usually charge per bunch.

For an electron microscopist, low transverse emittance is essential to achieving small beam spot sizes. None of the above definitions of brightness take into account the beam energy spread, however, which is also of critical importance for many electron microscopy applications.

In short, brightness is situational. A clear understanding, and listing, of the goals for a new injector is essential before the design work can start. This must include not only figures-of-merit parameters such as those above, but such items as beam repetition rate, average beam current as well as single-bunch charge, allowable beam loss rates, and so forth.

DIRECTIONS OF DEVELOPMENT

Injector development, as it stands today, can be broken down into three broad categories based on the type of accelerator for which the injector is to provide beam. Injectors for present-day "workhorse" accelerators, such as storage rings dedicated to UV or x-ray science, have been deliberately excluded. While they can be challenging to implement well, they do not represent–or apparently require–significant amounts of development effort at this time, at least as far as modeling capability is concerned. (It is still, of course, possible to design a bad injector for any application.)

"Big Iron" Linacs

"Big Iron" linacs, in analogy to computers, are the largest proposed and under-construction accelerators. These include linear colliders and next-generation linac-based light sources. Examples are the TESLA and NLC/JLC collider designs, the

Linac Coherent Light Source (LCLS) being built at SLAC, and the proposed TESLA X-FEL.

The requirements for collider and light-source injectors are somewhat different. Collider injectors generally need to produce beams with large emittance aspect ratios, also known as “flat” beams with transverse emittance ratios of 100:1 or better, preferably with polarized electrons. Initial efforts towards flat-beam production have shown considerable promise [2], although additional work is definitely needed. Regarding polarized-electron production, there are several ongoing efforts to adapt dc-gun cathode materials to photocathode rf injectors [3].

Next-generation linac-based light source injector requirements are somewhat beyond the state of the art in terms of single-bunch parameters, but otherwise–unlike collider injectors–do not appear to require any unusual beam manipulation. Normalized emittances ten times lower than typically produced today (e.g., a reduction from 1 μm to 0.1 μm), along with higher peak currents, are desirable. For a linac-based light source intended mainly to increase peak brightness over existing third-generation synchrotrons, greater bunch compression (e.g., higher peak current) improves radiation beam brightness faster than reducing the transverse emittance. For an X-FEL injector, taking advantage of emittances lower than about 0.1 μm would require fundamental improvements in undulator technology [4].

Depending on the design of the machine, the injector duty factor may also need to be considerably higher than is typical today, although good progress is being made as well towards extended operation of normal-conducting injectors [5,6] as well as design, construction, and operation of fully superconducting injectors [6,7,8]. Bunch charges in both cases would lie in the 0.1 – 5 nC / bunch range. The average beam current would depend on the application, with next-generation linac-based light sources probably desiring upwards of 10 – 100 mA. This would probably be a more critical requirement for “storage-ring replacement” energy-recovery linac-based light sources, as the high average current is required for average photon beam brightness considerations. For X-FELs, a high average current is desirable but not an absolute requirement, as the coherence of the optical pulse is the main feature of interest.

“Desktop” Accelerators

Strictly speaking, a “desktop” accelerator is not an injector; instead, the entire machine is designed to operate with a final beam energy of several MeV. Still, they are included here because they have many features and problems in common with other applications for high-brightness beams; they also represent both logical extensions of existing research directions and potentially important new “driver” applications for injector research.

This class of machines includes devices, such as electron microscopes, that could benefit from increased electron beam energies while maintaining existing beam quality. Also included are potentially new applications, such as compact x-ray backscatter sources, electron-beam lithography, and THz radiation sources, which can meet their performance goals due to the improved accelerator performance. These machines, size-wise, are at the extreme opposite of the spectrum from the "big-iron" accelerators; they are true desktop machines that allow small laboratory experiments.

Typical requirements for an electron microscope include emittance reductions of 10^3 compared to today's rf electron guns (e.g., 1-nm normalized emittances), and relative energy spreads in the 10^{-5} range or lower. The peak current is relatively unimportant, as long as the average beam current is high enough to support reasonable data acquisition rates; 1 mA would be adequate for many applications.

Beam energies of 1 – 2 MeV are of interest, as beam energies this high are quite difficult to obtain from a true dc source within a reasonably compact package. The advantages of rf-driven injectors are the very high gradients and relatively high final beam energies; the disadvantages include the intrinsic energy spreads imposed by the sinusoidal nature of the rf field [9].

"Mini-Me" Accelerators

Finally, the somewhat facetiously labeled "mini-me"* accelerators are considerably smaller in scale than the "big iron" machines, but much larger than "desktop" accelerators. They typically are intended to operate with extremely high average-power beams, and usually require relatively modest single-bunch beam parameters, for example single-bunch normalized emittances on the order of 3 – 4 μm. The main interest here arises from the desired beam currents (ca. 1 A) and duty factor (true CW operation). The *average* beam power from an electron gun could be in the 1 – 2 MW range; with final beam energies of 100 – 500 MeV, beam powers of 0.5 GW are not unreasonable to assume for a recirculating (energy-recovery) machine. Applications would include radioisotope generation [10], high-power free-electron lasers [11], slow-positron production [12], electron cooling [13], and pulse radiography [14].

As intimated, injector design parameters, with normalized emittance on the order of 2 – 4 μm and bunch charges of ~ 1 nC, are not especially stringent by "big-iron" standards. The combined requirements of 1-A beam current and CW operation, however, introduce several novel challenges. X-FEL and collider injectors, intended to accelerate only a relatively small amount of charge per rf macropulse, can use gun gradients of 100 MV/m or more†, with output beam energies of 4 – 6 MeV. In a "mini-me" accelerator, in contrast, the available gradient is limited by the ability of rf coupling technology to supply rf power to the gun. If, for instance, only 2 MW of power can be supplied to the gun, then a maximum beam energy of 2 MeV (assuming 1-A beam current, and a superconducting gun for negligible wall losses) is possible. This constrains the average gradients available within the electron gun.‡ The use of a superconducting gun–highly desirable to reduce rf power losses on the cavity walls–poses additional constraints on cavity geometry, the use of magnetic focusing fields, and so forth. Also, beam halo modeling will be critical for these applications, especially if the accelerator is to be superconducting.

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* A reference to the second Austin Powers movie, wherein the villain had a 1/9-scale clone of himself made: "Mini-me."

† The attainable gradient depends on the accelerator technology chosen. Generally, for rf injectors, the higher the frequency, the higher the possible gradient; the 100 MV/m figure is typical for S-band (~ 3-GHz) injectors.

‡ For a "synchrotron replacement" linac-based light source with, say, 100-mA beam current, assuming a 5-MeV beam energy from the injector corresponds to 500 kW beam power. Thus, this injector can still use gradients comparable to those intended to produce small bunch counts.

Common Threads

These three directions for injector development are quite different, yet there are common themes. First, all of them demand higher performance levels than are routinely achieved by today's injectors, although in very different ways. Next, with few exceptions, these injectors tend to be quasi-standalone components. That is, the performance of the entire facility or installation could be upgraded by improving and replacing the injector component. (This is less true of the desktop applications, in which the injector or gun represents a far higher proportion of the entire machine; by the same token, however, the cost of replacing the entire system would be far less.)

Injector reliability is key to the performance of the entire facility, in terms of uptime. Backup injector capability would therefore be a significant benefit; however, this itself would require very careful planning and modeling. In general, the higher the beam quality, the easier it is to corrupt that beam quality, and great care must be taken such that a "backup" injector does not have intrinsically reduced performance compared to the primary.

THE MODELING PROCESS

The intent of modeling, at the end of the day, is to determine the behavior of a corresponding physical system. The overall goals for the injector determine the type and level of details included in the modeling process. Increasingly, this means more than "simply" propagating a single beam bunch with its self-field and externally applied fields … although this in itself is not a trivial task.

At some level, the modeling process, from the beam-physics perspective, comes down to solving the relativistic equations of motion for every particle in the simulation simultaneously and incorporating beam-field and beam-cavity interactions, preferably in a self-consistent fashion. That being done, the basic modeling problem is solved.

Increasingly, however, modeling also means physical device design; one may think of a design-process "life cycle" ranging from the initial test of a new idea, through inclusion of more physical effects such as wakefields and non-uniform beam emission from the cathode, through interactions with engineering codes for cavity structural design and rf heating calculations. Some of the high-power injector designs, in particular, require great care for issues such as cavity rf power feeds and cooling concerns. It does no good to expend great effort on the "physics" design of a cavity if it cannot be practically realized; therefore, including "fabrication" issues such as thermal distributions and heat load calculations early in the modeling process is warranted.

Modeling the Beam – Some Selected Issues

Deciding what approximations can be used in the modeling process, and when, is critically important. Consider an rf photoinjector, which typically uses a ps drive laser to induce electron emission from a cathode surface located inside an rf cavity. When the laser first strikes the cathode, electrons are emitted with energies of a few eV.

Gradients in rf photoinjectors can, depending on the rf frequency, reach gradients of 120 MV/m or more[§]; the electrons will be rapidly accelerated away from the cathode surface. By the time the end of the laser pulse reaches the cathode surface, typically 2 – 20 ps later, the electrons emitted by the head of the laser pulse can have kinetic energies of a few hundred keV. The beam will therefore have a tremendous energy spread; the "head" of the beam will be quasi-relativistic, while the "tail" of the beam will be almost stationary. The situation is even worse with thermionic-cathode rf guns. While there are various ways of dealing with the beam under these conditions, any simulation code chosen should be able to accurately simulate non- and quasi-relativistic beams with large energy spreads, and the user should be aware of which method or methods the code used.

Electron Emission

While on the subject of electron emission from the cathode, it should be noted that most injector codes include only very crude models for beam emission. Particle emission, whether from a photocathode, thermionic cathode, or field emitter, is a microscopic and quantum phenomenon; the details differ considerably both between broad categories of emitter and between different types of the same category (e.g., metal vs. semiconductor photocathodes). It is known that nonuniformities in the beam emission as a function of position, induced either by variations in the drive laser intensity or cathode quantum efficiency as a function of position, can have a severe impact on the beam quality from photocathode rf guns [15]. Intrinsic physical effects, such as "thermal" emittance and local quantum efficiency variations, require further study both from the standpoints of integrating them into existing codes as well as ameliorating their detrimental effects on ultra-low-emittance beam production.

Why PIC is not the Solution

Some simple calculations comparing the real-space area (volume) of, say, an S-band injector to the real-space area (volume) of a beam provide a rough approximation of the number of cells a uniform-mesh PIC code would require to adequately model the beam. For present-day injectors with emittances on the order of 1 μm and an aspect ratio of approximately 1:1, a 2-d (z-r) simulation requires on the order of $1.1 \cdot 10^5$ cells, while a 3-d (x-y-z) simulation requires on the order of $4 \cdot 10^7$ cells. These are certainly within reason for present-day computer capabilities available to the individual researcher. Assuming present-day bunch lengths, but normalized emittances on the order of 1 nm (e.g., for electron-microscope applications), a 2-d uniform-mesh PIC model would require around $3.3 \cdot 10^8$ mesh cells; the 3-d simulation, $1.3 \cdot 10^{12}$ cells. If one is interested in examining fine structure within a beam, such as local space-charge waves, the cell count will rise accordingly.

Some of the more commonly used injector codes, such as PARMELA, attempt to deal with this issue by using a "local PIC" with a mesh overlaid on the beam only. Often other effects, such as wakefields and beam loading, are then treated analytically, if they are addressed at all.

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§ This is a typical number for a SLAC/BNL/UCLA-style "US" S-band (2.856-GHz) 1.6-cell photoinjector. "Euro" S-band (3.0-GHz) photoinjectors have very similar performance characteristics.

Other Interactions

The beam interacts not only with itself, but also with its surroundings. The "surroundings" (which I will refer to as fields and cells or cavities, but which really should be taken to mean the local electromagnetic and structural features in general) will interact with themselves (for instance cavity wall heating can lead to frequency shifts, leading to a change in the field pattern and stored energy, leading to different wall heating.)

To date, most high-brightness injector simulations have concerned single-bunch effects and do not take into account the influence of local geometry on the beam, other than via the application of externally generated fields; wakefield effects in the gun and transport lines have been generally ignored, for instance.

Unfortunately, designs for extreme injectors (such as those required for the "mini-me" and "desktop" accelerators) will have to take into account effects that could be readily ignored before. Consider, for instance, the effects of a 1-μm head-tail displacement due to a time-dependent kick somewhere within the injector. If the beam starts off with an emittance of 1 μm, the fractional projected emittance growth will be on the order of 10^{-3}. This will in all likelihood be noticed neither by the experiment nor the simulation (which likely does not include the kick in the first place). For a beam with a 1-nm emittance, however, the fractional projected emittance growth will be on the order of 3. An electron microscope application certainly would notice such an effect. Since, as discussed above, basic scaling considerations would seem to preclude a uniform-mesh PIC approach to model the beam and cavity together, we as a community must become more clever in how we model not only the fields in the cavities, but also the interaction of the beam with its environment, and the interaction of the environment with itself.

FUTURE NEEDS

It is critical to have available, at a minimum, a detailed description of the algorithms used by a given simulation code. This is needed for two reasons. First, it allows the user to understand how the code is intended to operate, and thus at what point(s) the code may be expected to fail to adequately model a problem. Second, it allows for greater understanding when comparing different codes: Are they, in fact, modeling the same thing? If so, how closely? If not, how and where should we expect the results to diverge? and so forth. Sadly, this is not provided for some of the more commonly used injector codes.

Code Extension Capabilities

The ability to expand the capabilities of an existing code according to one's needs for a current project would be quite useful. This generally requires both a good working relationship between the code developer and users, and substantial time. The author is aware of only one code at present–General Particle Tracer (GPT), a commercial code [16]–that has the capability for an end-user to incorporate required changes directly. The user may define a new "element" (which can be a model for a physical device such as a quadrupole, a new space-charge routine, a free-electron laser interaction model, a data-output routine, etc.) by writing a C subroutine, which is then compiled and linked into the code directly by the end user. From a computation standpoint, the new element is treated identically to preexisting elements. Source code is provided for all "native" GPT elements. Not only does this neatly address the question of understanding what the code is actually doing, but it also provides the user with multiple examples and starting points for additional element development.

Information Exchange

To be truly useful, an injector code must be able to exchange information readily with other codes. These can include "outbound" information, such as particle beam dumps to a linac tracking code, and "inbound" information, such as particle starting coordinate inputs from a cathode-simulation code or field maps from a cavity design code. To date, most injector codes the author is familiar with use a blend of nonstandard input and output formats. This is harmful, in both the short and long term, for several reasons. First, it makes code-to-code comparisons more difficult than it needs to be, thereby decreasing the likelihood that it will be done. Second, the users typically must write their own input and output converters to translate the output of the injector code into, say, their linac tracking code. Thus, instead of one point-of-failure for the data format conversion, which many people will be checking (e.g., written by the code developer and examined by the community), there are multiple potential points of failure, with relatively little scrutiny in comparison (e.g., each user writes an individual conversion routine tailored specifically to local needs). Finally, the user may be faced with changes to the file format any time a new version of the injector code is released. This can happen, for example, with binary-format output files when the code developer changes or upgrades compilers, even if no changes are made to the I/O routines in the simulation source code. If the user is lucky, the "broken" converter will fail to operate. If the user is not lucky, the "broken" converter will still appear to work but will generate incorrect data.

It is also interesting to contemplate an "injector markup language" allowing an automated comparison of various codes. Since there are many different ways of specifying beamline layout, cavity fields, etc., a parser would be required to translate the common input file into the "dialect" of a particular code; this would also require, for instance, the ability of the parser to generate rf field maps in whatever form the simulation requires. Such a capability is probably not practical in general, but one could consider implementing it for similar families of codes, e.g., true PIC codes, pseudo-PIC codes using field maps, etc.

Beam-Environment Interaction

Perhaps the most critical need for modeling future injectors, from a capabilities standpoint, is improving the ability to model the beam's interactions with its surroundings, for instance in the form of wakefields in both single- and multi-bunch environments. This is a common theme, although for different reasons, for most advanced electron injector design. Due to the scaling considerations listed above, at least some of these interactions will require analytic or quasi-analytic treatments; also, meshing with multiple-length scales, or overlapping meshes, is another possibility that requires further development.

Naturally, this includes improved cathode emission modeling. While truly integrated emission models would be desirable, a reasonable start would be to use a stand-alone code to generate a starting beam distribution that could be loaded into a beam dynamics code. As before, however, data format standardization would be of great benefit here.

Physics-Engineering Code Interchange

If the injector being simulated cannot be physically realized, its projected performance is irrelevant. The ability to exchange information readily with "engineering" codes such as ANSYS and FEMlab, therefore, is useful for an injector code (or suite of codes) to have. Developing the cavity design, for instance, concurrently from both the thermal-management and beam-physics perspectives, will help to prevent injector designs that do not perform to specification.

CONCLUSIONS

High-brightness injector modeling is a very broad topic, due both to the number of choices for acceleration technique and the different applications that seek to make use of high-brightness beams. There are a number of avenues of future development, some of which are considerably different than those typically pursued by "traditional" high-energy machine injector designers. These include extremely high-power machines and ultra-low-emittance injectors, each of which present their own unique needs as well as opportunities.

There are a number of issues and needs in common with most future injector development, however; these include improved code documentation and input/output specification, beam-environment interaction modeling, and improved data exchange with engineering codes.

In closing, this is an exciting time for high-brightness injector development. There are a wide range of interesting problems available for study and many opportunities for advancing the state of the art.

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