High Brightness Electron Injectors for 4^{th} Generation Light Sources

LECTURE 1: INTRODUCTION AND MOTIVATION

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Abstract. The objective of this lecture is to justify the importance of injectors for the new generation of light sources based on Free Electron Lasers. This is done from both technical and economic points of view. The evolution of injector technology and the improvement in beam quality over the years is presented.

1. Introduction

The advancement of FEL-based light sources has been made possible in large part by the development of brighter electron sources due to an ever improved understanding of charged particle optics. The importance of low-emittance can be demonstrated by evaluating the ratio of normalized emittance to beam energy required for a FEL to operate at a given wavelength, FEL, as given by the following relation,

$$\frac{\epsilon_N}{\gamma} < \frac{\lambda_{FEL}}{4\pi} \tag{1}$$

Where ϵ_N is the normalized emittance and γ is the reduced beam energy. Thus, it is possible for an FEL to operate at any beam emittance provided the energy is high enough to satisfy this condition. However this is done at great expense, especially for the new x-ray devices being constructed and proposed.

The development of the new light sources for the basic and applied sciences is driven by the four-generation light source. From the injector perspective, the previous generations did not rely as strongly upon the electron beam quality from the source, since the 3rd generation light source consists of an electron storage ring where the beam dynamics of the ring determines the brilliance of the emitted radiation. This is because the electron beam "forgets" its initial injection conditions during its long storage time. In this sense, the injector beam quality requirements for the 3rd generation sources were relatively loose with the operational reliability being more important than beam quality.

This situation is rapidly changing with the rise of 4th generation radiation sources. Since these new sources are based on high-gain, single-pass free electron lasers, they require much brighter electron beams than those used in the 3rd generation sources. To fulfill these more stringent specifications, the injectors for these new sources are nearly all photocathode guns whose cathodes are driven by sophisticated lasers whose emitted electrons are rapidly accelerated in high-electric dc or rf fields. In order to preserve the emittance, the beam is carefully matched using electron optics to the high-energy accelerator section, with a technique referred to as emittance compensation.

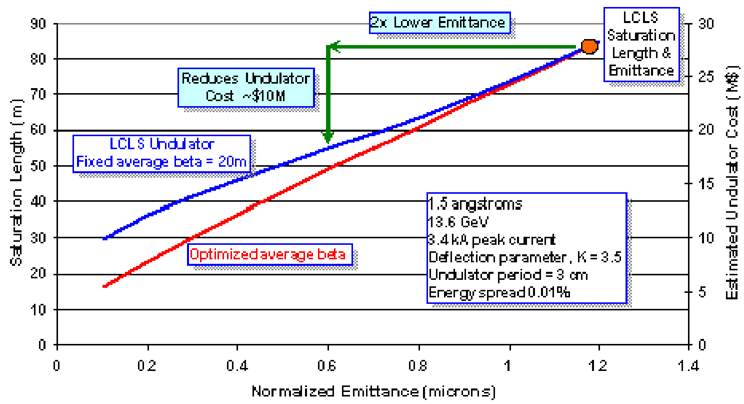

FIGURE 1. Improving the electron beam emittance reduces the gain length which in turn reduces the undulator length and cost required to reach saturated power in the SASE FEL. Calculations compliments of Z. Huang, SLAC

Besides the short wavelength frontier of SASE FEL's, there has been significant progress made in developing high-duty factor and CW FEL's. The greatest advance in this area has been the successful demonstration of an energy recovered linac (ERL) FEL at Jefferson Laboratory which uses a DC, photocathode gun. Other source technologies being developed for this application are normal conducting and superconducting RF guns.

As a final comment, it is appropriate that the photocathode rf gun is the technical basis of the gun technology used in many of the 4th generation SASE FEL's, since its initial conception at Los Alamos Laboratory was motivated by the invention of the FEL which continues to be the principle user of low emittance electron beams.

2. Economics of the Injector

The economic motivation for the continued research and development of high-brightness beams can be illustrated by using the SASE x-ray FEL as a model for computing the costs. The Linac Coherent Light Source (LCLS) design is based upon using the 13.6 GeV electron beam from the SLAC linac to reach saturated laser power within 80 meters of the undulator at a wavelength of 1.5 angstroms. To achieve this requires a normalized emittance of 1.2 microns at a bunch charge of 1 nC. Beams with emittances greater than 1.8 microns are below the lasing threshold. Figure 1 plots the saturation length and the cost for an undulator with this length as functions of the normalized emittance. In 2005 dollars the LCLS undulator cost per unit length is approximately $0.35M/m, making it one of the most costly components. Of course, this is only the cost of the undulator itself, there are further expenses associated with the undulator infrastructure, building, environment etc. A reduction of the emittance by a factor of two results in an approximately $10M savings in cost of the undulator alone.

A much greater cost benefit is realized in terms of the lower required beam energy, as can be seen in Figure 2. Reduced emittance greatly lowers the beam energy and hence the cost and size of the accelerator facility. Even a modest reduction from

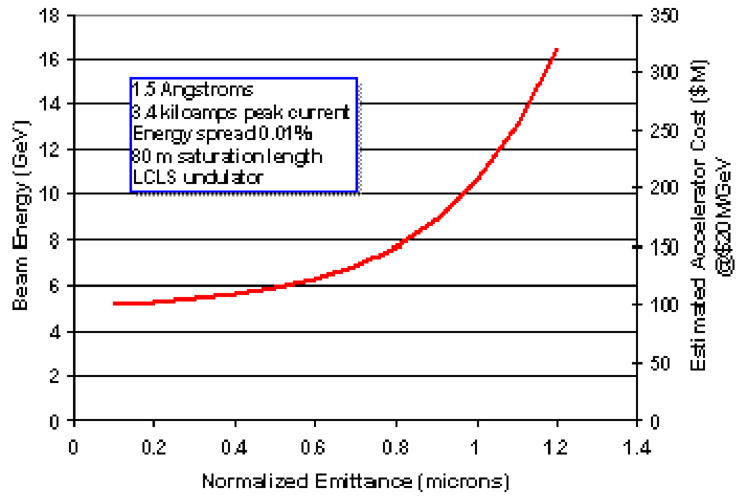

FIGURE 2. A plot of the beam energy required for lasing at 1.5 angstroms as it depends upon the beam emittance at the undulator. The linac cost estimate assumes the cost per unit energy is 20M per GeV.

1.2 to 0.8 microns would lead to a savings of more than $100M in the construction of a green field x-ray FEL.

3. A Brief History of Electron RF Injectors

This section relates the history of the electron rf injector as it is used as the source for accelerators requiring low-emittance beams. As described in the next section, the injector system is defined to consist of a cathode, a gun for rapidly accelerating the electrons from rest, low-energy ballistic compression of the bunch, the booster accelerator and high energy beam-conditioning such as magnetic compression, linearization and laser heater.

The early thermionic injector consisted of a DC thermionic gun followed by a bunch cavity and then the booster. The general scheme is shown in Figure 3. The thermionic gun emits a continuous stream of electrons with a current density determined either by thermionic or space charge limited emission. The cw stream of low-energy electrons from the gun is given a sinusoidal energy modulation by the buncher cavity. This energy or velocity modulation results in ballistic compression and refraction of the charge distribution at the frequency of the buncher cavity forming into a bunch train at the booster entrance.

The limited charge per bunch reached by the simple buncher cavity approach was overcome by beginning the compression at lower RF frequencies to capture more of the electrons into an RF bucket. The injector used for the Boeing/LANL free electron laser experiments (1986-1990) is shown in Figure 4. In this considerably more complicated approach the charge per bunch is increased by using two stages of lower rf frequencies to compress more of the DC beam into the phase acceptance of the booster. The design begins with a 90 keV thermionic gun followed by first a 108 MHz and then 433 MHz prebuncher cavities which used ballistic compression before

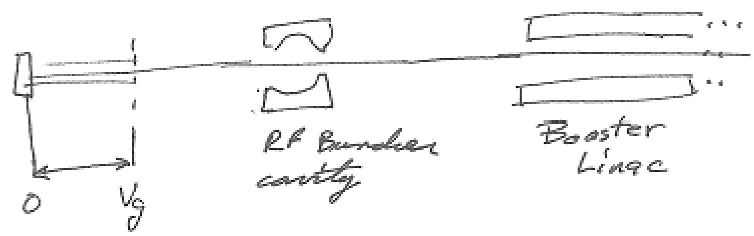

FIGURE 3. An early injector for bunching the beam into the phase space acceptance of the booster linac. In this approach, the DC beam from a thermionic gun is first energy modulated by the buncher cavity which ballistically compresses electrons over less than 180 degS at the buncher cavity.

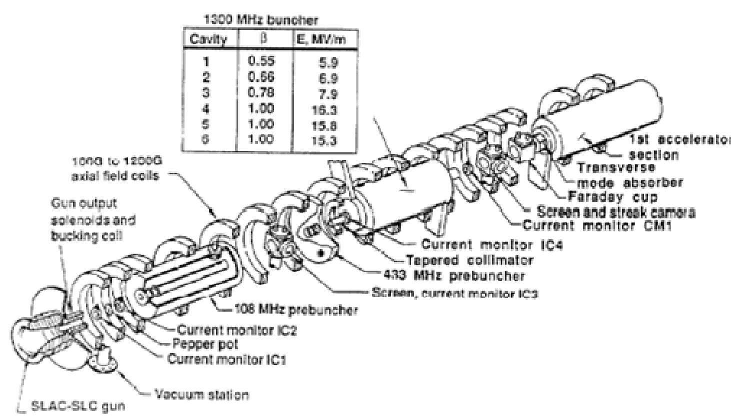

FIGURE 4. The sub-harmonic thermionic injector used in the early FEL experiments.

final RF compression in a tapered phase velocity buncher at the main accelerator frequency of 1300 MHz. The phase velocity and field of each cavity of this rf structure is given as an insert of Figure 4.

The next stage of development was driven by the need for fast and precise control of the electron pulse shape for better beam quality and to reduce halo and beam loss. The pulsed thermionic cathode was replaced by a much faster laser driving a photo-cathode, and the photo-cathode was put into the RF cavity. With this development, the emittance was 10-times or more lower than that of the thermionic injector. However there were and remain problems with the photo-cathode gun. Principally the laser and the cathode are problematic. Developments in laser technology have solved many of the laser problems and the advent of diode pumped solid state lasers has given us a stable and reliable source of photons. In contrast, there have been few improvements in photocathode technology in recent years, as most of the photo-sensor market is based on solid state diodes like charge-coupled-devices used in digital cameras. And even photo-multiplier tubes are being replaced by avalanche

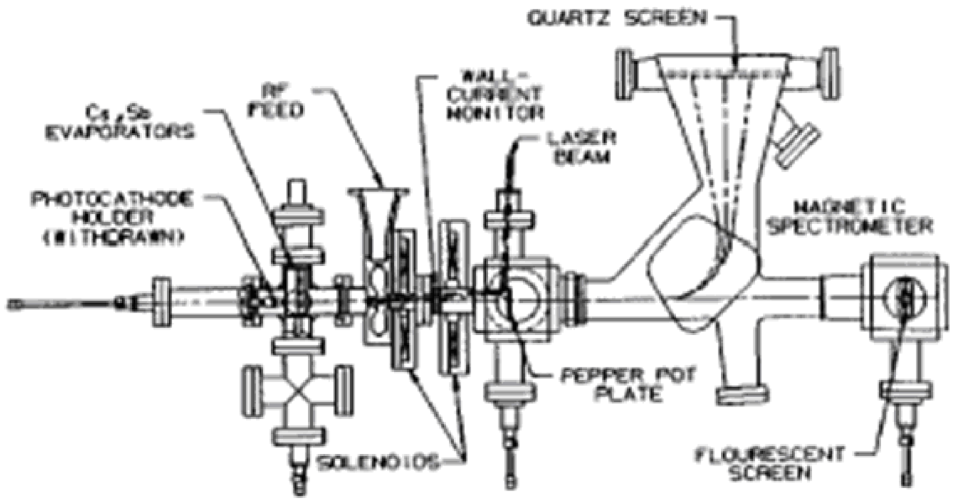

FIGURE 5. The first RF photocathode gun operated at Los Alamos National Laboratory in 1985.

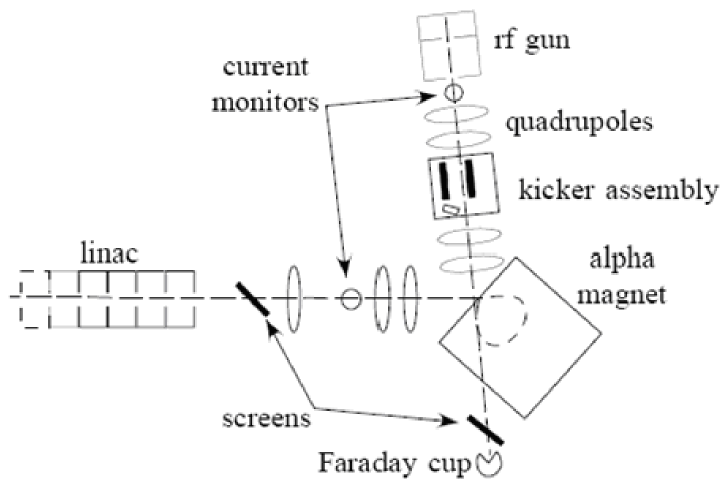

FIGURE 6. The thermionic RF gun system with an alpha magnet for compressing the electron bunches.

photodiodes. The market for vacuum electron tubes is declining and being replaced by solid state devices.

And in the future, perhaps even the large, microwave accelerator will be replaced with an optical scale device. [Mangles, S.P.D. et al., Nature **431**,535-538(2004); Geddes, C.G.R. et al., Nature **431**,538-541(2004);Faure, J. et al. Nature **431**,541-544(2004)].

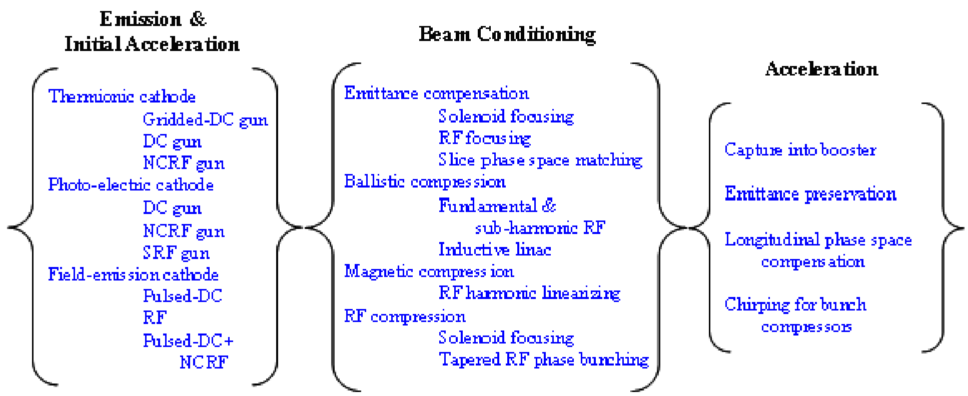

FIGURE 7. The basic parts of the electron injector.

4. Elements of Electron Injectors

The electron injector can be divided into three major parts, each according to their function. These components are the cathode-gun source, the beam conditioner and the accelerator, as shown in Figure 7. The source can be further divided into categories based upon the emission mechanism and the external field type. Here we consider three cathode types defined by the three emission phenomena: thermionic, photo-electric and field-emission. These are then matched with the commonly used accelerating fields of DC, normal conducting RF (NCRF), superconducting RF (SRF) and pulsed DC. The commonly used pairings are shown in Figure 7. Although laser-plasma and laser accelerators are undergoing rapid development, they are not included here, but will be discussed in a later section. The second major component of the injector is the beam conditioner. Beam conditioning is defined as those processes used to manipulate the transverse and/or longitudinal electron distributions or to match the beam's properties to a subsequent beamline system. An example of beam manipulation is emittance compensation where the linear space charge forces are balanced by external focusing forces. Beam conditioning is also used to match from one optical component to another, such as the transverse phase space optics for matching the beam to the undulator, or between the gun and the first accelerator.

The final component is the accelerator whose function is obvious, and needs to maintain the beam quality. In this discussion we only consider the RF accelerator and its parts needed to preserve the beam emittance.