Review of Electron Guns

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Abstract

Most of present and future electron accelerators require bright sources. This review of electron guns therefore focuses on the brightest sources presently available, the photo-injectors. After briefly recalling their principle, the most advanced projects are reviewed. Photocathodes, lasers and photo-injector beam dynamics are then discussed.

1 INTRODUCTION

Numerous applications of electron linacs require high-brightness sources. These include high-energy linear colliders [1], short wavelength free electron lasers [2], wakefield accelerator experiments [3], new accelerator schemes test facilities [4], drive beam for two-beam accelerators [5], coherent radiation sources [6], radiochemistry [7], ...

The brightness being proportional to the peak current divided by the square of the normalized emittance, bright electron sources require intense beams (high charge and short pulse) and small emittances. Figure 1 shows the normalized brightness needed by linear colliders and FEL applications. It also shows the present state of the art of conventional injectors (DC gun + bunchers), thermionic RF guns and photo-injectors. This plot shows that a photo-injector allows on average two (respectively one) orders of magnitude improvement in brightness when compared to a conventional injector (respectively thermionic RF gun).

This potentiality of photo-injectors to produce bright beams has boosted their development. Since their invention 10 years ago at Los Alamos [8], the number of photo-injectors has rapidly increased and currently exceeds 30. Table 1 gives a summary of the main breakthroughs occured during the last ten years in the field of RF photo-injectors.

After a brief description of photo-injector principle, this review only focuses on the nine most advanced projects. Finally, general remarks concerning current trends of R&D in the field of photocathodes, lasers, and beam dynamics in a photo-injector are discussed.

2 PHOTO-INJECTOR PRINCIPLE

To increase the brightness of an electron source, it is necessary to increase its peak current while keeping a very small transverse emittance. This leads to use high electric field to reduce the influence of space charge forces. Since DC fields in a gun are limited to a few hundred kilovolts, it

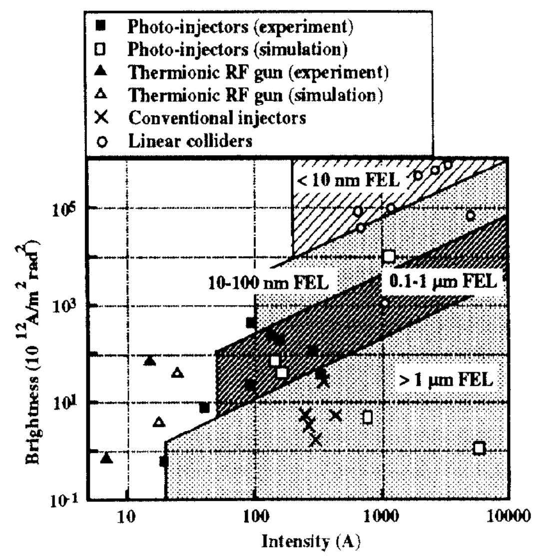

Figure 1: *Brightness required for FEL and linear colliders*

Table 1: Main breakthroughs in photo-injector history

Date	Event	Ref.
1985	First photo-injector at Los Alamos	[8]
1988	First FEL driven by photo-injector at Stanford	[9]
1988	Emittance compensation theory by B. Carlsten	[10]
1989	First S-band photo-injector at Brookhaven	[11]
1989	Analytic theory of photo-injector beam dynamics by K.J. Kim	[12]
1990	First 144 MHz photo-injector at CEA	[13]
1992	First 433 MHz high duty cycle photo-injector at BOEING	[14]
1992	First photocathode in a superconducting RF cavity at Wuppertal	[15]
1993	UV FEL driven by photo-injector at Los Alamos	[16]
1993	First sub-picosecond laser driven photo-injector at LAL	[17]
1994	New analytic theory of photo-injector beam dynamics by L. Serafini	[18]

is more appropriate to use RF fields to extract high peak current from a cathode. Following this idea has led G. Westenskow and J. Madey to design and operate in 1985, the first microwave gun consisting of a thermionic cathode located in an S-band RF cavity [19]. The necessity of high peak current led then to consider short pulses. The electronic grid switching of a conventional DC gun does not allow to produce pulses shorter than a few hundred picoseconds. To obtain shorter pulses, it is natural to think about optical switching. A short laser pulse illuminating a photocathode provides an almost ideal way to produce such short pulses. The combination of acceleration in an RF field and generation of electrons by short laser pulses hitting a photocathode make a quasi perfect bright injector. Today, lasers are able to produce very short pulses (down to less then 1 ps), photocathode can deliver high current densities (several thousands of kA/cm^2) and RF cavities can sustain electric field as high as 100 MV/m.

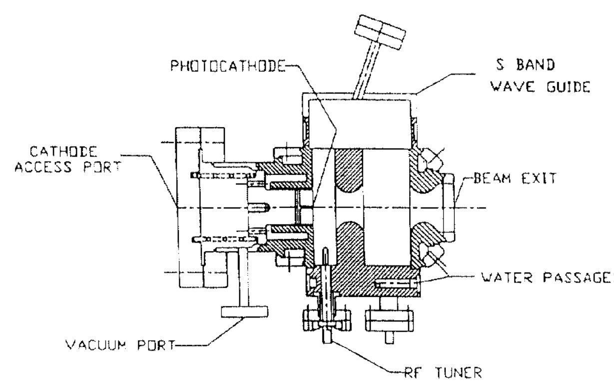

Figure 2: *BNL one and a half cell gun*

3 REVIEW OF ADVANCED PHOTO-INJECTORS

The most advanced photo-injector projects are reviewed below. The main features of each project are discussed. Table 2 summarizes the main parameters of each project. Except for ANL and MIT, the results correspond to experimental data and represent consistent sets of typical parameters. One should therefore be very careful while comparing these data since some of them (eg. emittance) are rather difficult to measure.

3.1 Los Alamos National Laboratory

As already mentionned, the first photo-injector was designed and built at Los Alamos by J. Fraser and R. Sheffield [8]. After this first prototype, LANL has built APEX [20] and AFEL [21] photo-injectors. These devices are sophisticated guns made of several RF cells and using the emittance compensation scheme devised by B. Carlsten [10]. The APEX gun brightness was so high that it allowed the first UV FEL lasing on a linac [16]. AFEL gun is made of 6 cells and produces a very bright electron beam used to drive a very compact FEL. Present studies include a detailed understanding of emittance measurement techniques for these very bright beams.

3.2 Brookhaven National Laboratory

The BNL gun design [22] shown in figure 2 is the most popular one, since it was already reproduced 10 times. The careful design of the cavity shape is intended to completely suppress higher spatial harmonics of the field, thus minimizing the non-linear emittance. The high gradient operation (up to 100 MV/m) allows to produce the very small emittance beams needed by the FEL and advanced accelerator physics experiments done at the Brookhaven ATF facility.

The most oustanding recent result is the convenient use of a magnesium cathode, that proved both to have a relatively good quantum efficiency (5×10^{-4}) and be very robust (lifetime over 5000 hours).

This one and a half gun is now being replaced by a three and a half gun conjointely designed and fabricated by BNL and Grumman [23] and that can work at very high duty cycle (1%). A new laser system is also being assembled. Together with SLAC, UCLA, NRL, and LANL, BNL is now designing an inexpensive gun that would allow smaller laboratories or universities and smaller groups inside big laboratories to afford such a bright gun for any type of application.

3.3 CEA at Bruyères-le-Chatel

At CEA, the photo-injector is made of one 144 MHz cavity and is used as the electron source for the infra-red high power FEL [13]. Recent emphasis has been put on improving the stability and reliability of the system. An amplitude feedback system is being developed to improve the laser stability.

3.4 CERN

The CTF (CLIC Test Facility) was built at CERN to test some components of the CERN Linear Collider project [24] based on the concept of the two-beam accelerator. In order to generate the RF power at 30 GHz necessary to obtain the high accelerating gradient needed for the 30 GHz CLIC accelerating section, one accelerates a train of short intense electron bunches, that can produce RF power through electromagnetic interaction with a so-called tranfer structure. This train of intense short electron pulses is produced by a BNL type RF gun, using a Cs_2Te photocathode. Recently a train of 24 pulses, 14 ps long and 1.6 nC each led to the production of 34 MW of 30 GHz RF power [25]. When running with a single pulse, a charge as high as 14 nC was extracted from this photo-injector. The Cs_2Te photocathode presents a good combination of a very good quantum efficiency (2-5 %) and a good lifetime

Table 2: Parameters for the main photo-injectors

Parameter	CEA	LANL	ANL	BNL	CERN	KEK	UCLA	LAL	MIT
Purpose	FEL	FEL	Wakefield accelerator	Advanced accelerator	Linear collider	Linear collider	FEL	Linear collider	High gradient
First operation	1990	1992	-	1989	1990	?	?	1993	-
Number of cavities	1	11	1	1.5	1.5	1	1.5	2	1.5
Frequency (MHz)	144	1300	1300	2856	2998	2856	2856	2998	17136
Cathode field (MV/m)	28	20	90	70	100	40	83	50	250
Cathode	Cs_3K_2Sb	Cs_2Te	Y	Cu	Cs_2Te	CsSb	Cu	Cu	Cu
Quantum efficiency (%)	3	5	0.05	0.001	2	?	?	5×10^{-4}	0.001
Lifetime	1 h	months	?	∞	70 h	?	∞	∞	?
Laser	YAG	YLF	Kr-F	YAG	YLF	YAG	YAG	Ti:sa	Ti:sa
Wavelength (nm)	532	263	248	266	262	532	266	260	260
Pulse length FWHM (ps)	20-50	6	3	15	8	10	4	0.2	2
Energy (μJ)	20	50	12000	300	1	100	300	250	200
Spot size FWHM (mm)	2-7	4	20	0.1-1	5	?	0.6	4	1
Energy (MeV)	2	16	1.7	3	4	0.9	3.5	2.2	2.8
Charge (nC)	0.5-5	3	100	0.5	4	3.2	0.5	0.11	0.1-1
Pulse length FWHM (ps)	20-50	20	14	11	13	?	5	?	1.5
Jitter (ps)	3	< 1	<10	<1	<1	?	?	?	2
Normalized rms emittance (π mm mrad)	4@1nC	5	130	4	?	?	10	?	3@1nC

(several months).

3.5 *KEK*

A 1 cell S-band RF gun was developped at KEK in view of JLC linear collider [26]. This gun is the only one working with relatively high accelerating gradient (40 MV/m) and using an alcaline cathode (CsSb). A special emphasis has therefore been put on the vacuum system design with the use of NEG pumping. Since linear colliders need polarized sources, KEK is working on the subject of polarized photocathodes [27].

3.6 *University of California at Los Angeles*

The UCLA RF gun is a modified BNL gun. It allows 70 degree laser illumination of the cathode that produces an enhancement of the quantum efficiency when compared to normal incidence. Extensive measurements and comparison to simulation were made and proved to be satisfactory [28].

3.7 *Laboratoire de l'Accélérateur Linéaire Orsay*

A two decoupled cell S-band RF gun was recently put into operation at LAL [17]. The cathode is illuminated by a Ti:sapphire laser that produces 0.2 ps pulses [29]. This project is the first sub-picoseconde laser driven photo-injector.

3.8 *Argonne National Laboratory*

In order to do wakefield accelerator experiments, it is necessary to generate a very intense and short electron bunch [3]. At ANL, a photo-injector designed to produce 100 nC pulses is being commissioned. To maintain a pulse as short as possible in spite of the enormous space charge forces, a concave shape of the laser wavefront is created [30]. To probe the wakefield excited by this intense pulse, a second pulse is generated by a 7 cell photo-injector. An alternative design for this witness beam gun is a dielectric loaded cavity that allows to produce a perfectly linear accelerating field [31].

3.9 *Massachussets Institute of Technology*

The MIT photo-injector is a one and a half BNL type gun scaled at 17 GHz [32]. The use of such a high frequency makes possible very high accelerating gradient. 250 MV/m is envisaged for this gun now under commissioning.

4 PHOTOCATHODES

A good photocathode for photo-injector operation should ideally have a high quantum efficiency (> 1 %) at infrared or visible wavelength, have a long lifetime (> several months) under moderate vacuum conditions, and be easy to prepare and install in the gun cavity. Such a perfect cathode does not exist yet, but progress were made recently, especially with Cs_2Te and Mg cathodes. Table 3 shows the most commonly used photocathodes and a summary of their main advantages and drawbacks.

The only photocathode presently available to generate polarized electron is GaAs. However this cathode that is extensively studied [33] has never been used in an RF gun so far [34].

The choice of the photocathode to be used depends on the type of applications. It depends of course on the charge required from a single pulse, but also on the pulse format via the existence or not of a suitable laser. The typical cases are the following:

Table 3: Main photocathodes used in photo-injectors

Cathode	Advantage	Drawback
Cs_3Sb, CsK_2Sb, ...	high quantum efficiency 0.5 μm laser	difficult to prepare short lifetime do not sustain high field expensive preparation chamber and transfer system need good vacuum
Cs_2Te	high quantum efficiency long lifetime sustain high field	need UV laser expensive preparation chamber and transfer system response to train?
Cu, Y, Mg	no preparation chamber long lifetime fast response sustain very high field sustain bad vacuum	low quantum efficiency (except Mg) need UV laser
LaB_6, WCaOBaO	no preparation chamber long lifetime	low quantum efficiency need UV laser need to be heated prior to operation

- if a single pulse of charge below 5 nC, is required, a Mg photocathode is probably the best choice.
- if train a pulses of charge less than a few nC are required, then one should probably go to Cs_2Te.
- for very high repetition rate or very high duty cycle and high charge, it is probably difficult to avoid CsK_2Sb.

5 LASERS

One of the key components of a photo-injector system is the laser. Amplitude, phase and position stability of the electron beam depend almost completely on the laser performances. A laser is typically made of an oscillator that generates a continuous train of pulses of small energy (few nJ). This oscillator is synchronized via an appropriate electronic system to a sub-harmonic of the RF frequency (typically 100 MHz). One single pulse or a train of a few hundred pulses is then selected through a Pockells cell and is then amplified. There exist several types of amplifiers (single pass, multiple pass, regenerative, ...) and according to the energy desired, it might be necesssary to have several amplifier stages. When the oscillator pulse is very short, one has to extend the pulse temporally before amplification to avoid damage of the amplifier cavity components. The pulse is then compressed back to its original duration. This technique is called the chirped pulse amplification. The oscillators used so far for photo-injector applications produce infra-red light. To obtain usable light for the photo-cathode, it is therefore necessary to generate higher harmonics. This is done by using non-linear crystals, with a typical efficiency of 10-15% from the fundamental to the third harmonic.

Nd:YAG and Nd:YLF (eg. [35]) are the most commonly used systems in existing photo-injectors. They typically produce pulses of 6-15 ps, with up to 300 μJ of energy in a single pulse. More recently the advent of Ti:sapphire has open a way down towards the very short pulses (eg. [29]).

The recent progress of diode pumping made possible the design of very compact, stable, reliable and relatively cheap Nd:YLF oscillators. More work has yet to be done to improve the performances of amplifiers and harmonic generation in terms of output energy, amplitude stability and beam quality.

Sophisticated feedback and feedforward loops are now being envisaged to improve the different types of stability. Temporal and spatial filters allow in principle to produce any longitudinal and transverse profile, at the expense of energy. These features are interesting to do experimental tests of theoritical schemes developped to reduce the transverse emittance.

The R&D on short pulse lasers relevant foWashington, May 17-20,r photo-injector application is described in detail in references [36, 37].

6 BEAM DYNAMICS

RF gun beam dynamics was worked out in an analytical manner by K.J. Kim [12]. This simple model provides the gun designer with handy formulas for the different gun parameters, and are especially useful to understand the scaling of these parameters with such variables as the bunch length, the spot size on cathode, the peak accelerating field or the bunch charge. An improved model giving more accurate results, especially for the transverse bunch dimension was recently derived by L. Serafini [18].

Most of the theoritical work done on RF gun beam dynamics concerns the possibility to obtain smaller emittances, either by compensating the correlated emittance generated mainly in the first cell, or by removing the causes of extra emittance growth. Most of these techniques are reviewed in reference [38]. Not all of them were experimentally proven or even tested. The most successfull one is the compensation of the correlated linear space charge induced emittance by the use of a magnetic focusing solenoid, due to B. Carlsten [10]. This technique experimentally proven at Los Alamos allows a ten fold reduction of the emittance. Once thought unapplicable at high frequencies and high gradient, it will soon be implemented at BNL [39].

Besides emittance compensation schemes, recent ideas being studied include travelling wave RF gun [40] and asymetric guns for linear colliders [41].

7 CONCLUSION

Ten years after its invention, the photo-injector has reached the point where it is used daily at users facility (cf BNL), and where it opened the way to new results such as UV FEL and the generation of 30 GHz power. When the remaining problems mainly concerning the laser stability and reliability will be solved, and that should not take too long, the photo-injector will be ready to replace the conventional DC gun + buncher injector for any kind of application. It will then be possible to have a 100 times brighter injector, 10 times more compact, and probably for less than half the price.

8 ACKNOWLEDGEMENTS

The data for the different projects were kindly provided by I. Ben Zvi, S.C. Chen, S, Joly, I. Madsen, R. Sheffield, P. Schessow, M. Yoshioka. Discussions with P. Georges were appreciated when writing the laser section. This paper benefited from the discussions of the source working group during the last Advanced Accelerator Concepts Workshop at Lake Geneva, WI.

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