TECHNOLOGICAL CHALLENGES FOR HIGH BRIGHTNESS PHOTO-INJECTORS

G. Suberlucq, CERN, Geneva, Switzerland

Abstract

Many applications, from linear colliders to free-electron lasers, passing through light sources and many other electron sources, require high brightness electron beams, usually produced by photo-injectors. Because certain parameters of these applications differ by several orders of magnitude, various solutions were implemented for the design and construction of the three main parts of the photo-injectors: lasers, photocathodes and guns. This paper summarizes the different requirements, how they lead to technological challenges and how R&D programs try to overcome these challenges. Some examples of state-of-the-art parts are presented.

HIGH BRIGHTNESS

The brightness is a practical measure of the ability of a beam to be focused in all dimensions. A common definition is given by:

$$B_n = \frac{2 \cdot I}{\varepsilon_{nx} \cdot \varepsilon_{ny}} \left[\frac{A}{m^2 \cdot rad^2} \right]$$

where I is the peak current and ε_{nx}, ε_{ny} are the normalised x and y emittances respectively. To achieve high brightness beams it is necessary to produce a high peak current while maintaining small emittances. Practically, simultaneous optimization of these parameters is difficult to achieve due in particular to space charge forces. A compromise must be reached taking into account the requirements of the application. Table 1 shows some examples of source requirements for the main applications: Linear Colliders (LC) [1], Self-Amplified Spontaneous Emission Free Electron Lasers (SASE-FEL) [1], Energy Recovery Linacs (ERL) [2], Laser Wakefield Accelerators (LWA) [3] and the fourth generation of X ray light sources (GreenField) [4].
The best achieved brightness values are in the range of 10^{13} $A.m^{-2}.rad^{-2}$ in an operational photoinjector ([5] for instance) and a few 10^{10} with thermionic sources.

PHOTO-INJECTORS

The photo-injector was introduced in 1985 [6] and from this time its use has grown exponentially. This is due to its capability to produce transversely and longitudinally well-defined electron beams. The principle of a photo-injector is very simple: electron bunches are generated by laser pulses illuminating a photocathode (PC) installed inside an extracting and accelerating structure. Photoemission gives a current density at least four orders of magnitude greater than thermionic emission – up to 10^5 A/cm^2. If the electric field is strong enough to fight space charge forces, a very high brightness density is possible – up to 5.10^{15} $A.m^{-2}.rad^{-2}/cm^2$ [7].

A photo-injector is a source and therefore availability and reliability are primary concerns and they must be taken into account before selecting components. Depending on specifications such as polarized or unpolarized electrons, high charge per bunch or high mean current, different setups can be selected, and these are in general defined by the PC materials. The photo-emission threshold will define the laser wavelength; the quantum efficiency (QE is the ratio of the number of extracted electrons to the incident photons), the laser output power; and the vacuum conditions and sensitivity to the electric field will define the kind of gun.

Table 1: Some examples of source requirements

	I A	τ_{FWHM} ps	ε_n mm.mrad	B_n $A.m^{-2}.rad^{-2}$
LC	500	8	10	1.10^{13}
SASE-FEL	180	6	2	9.10^{13}
ERL	50	3	1	10^{14}
LWA	1000	0.2	3	2.10^{14}
GreenField	500	< 1	0.1	> 10^{17}

PHOTOCATHODES

Unfortunately there exists no PC versatile enough to fulfil all requirements. Compromises must be made to suit the particular application. For the time being, the PC certainly represents the weak point of a photo-injector and a strong R&D program is required to produce an emitter as reliable as a thermionic cathode.

The photoemission process is well represented by the Three Steps model [8],[9]: (i) photon absorption, (ii) motion of the electron to the vacuum interface and (iii) surface barrier. There are many different photo-emitters each combining different processes associated with the photoemission, we will discuss here only three PC types: metallic, alkali alloys and activated gallium-arsenide.

Metallic photocathodes

These cathodes seem very attractive because they are easy to produce; they can be transported and installed in ambient air; in principle they have an infinite lifetime and a quasi-null relaxation time; in addition, they are able to accept high electric field and poor vacuum conditions. In practice these benefits are not fully realised due to the difficulty of gaining direct access to the metal itself. In many cases it is not enough to chemically clean the surface before using the cathode. An *in-situ* treatment, in general with an electric field and laser light, must be performed before it can be used and must be repeated at a frequency which depends on the vacuum level and the extracted charge.

Due to the high reflectivity of metals (30 to 90 %), only a small amount of photons can be absorbed; due to high electron-electron scattering in the conduction band, only a small fraction of created photoelectrons can reach the vacuum interface (few ‰); and finally the high work function of metals requires energetic photons to pass through the surface barrier to release photoelectrons (3 – 5 eV). This leads to a low QE (from 10^{-7} to 10^{-3}) and the use of UV light (200-300 nm) which increases the laser power according to the efficiency of the frequency-conversion process (typically 12 %). The low QE induces a limitation of the laser energy density below the plasma generation level, limiting the total emitted charge density below a few nC/mm^2 for ps pulse regime. The emitted mean current is limited to a few µA by the available mean laser power.

Currently, in the ps or sub-ps regimes, magnesium with a QE after conditioning greater than 0.1 % seems to be the best PC for producing a 1 nC electron beam [10]. Copper and niobium are often used to study warm and superconducting RF guns respectively. Metallic PCs are also used to study laser-assisted field emission and multi-photon photoemission.

Alkali Photocathodes

In semi-conductors or insulators, the conduction band is almost or completely empty. Absorbed photons promote photoelectrons from the valance band to at least the conduction band if the photon energy is larger than the gap E_G. To escape into vacuum the photoelectron must have enough energy to overcome the electron affinity E_A which corresponds to the energy gap between the vacuum level and the conduction band. Then, the photoemission threshold is (E_G+E_A). Qualitatively, the ratio E_G/E_A gives an indication of the QE: in general, the higher the ratio, the better the QE. For a one-photon process, with no secondary emission, the photon energy must be in the range $(E_G+E_A) < E_{photon} < 2(E_G+E_A)$. Therefore, it is favourable to produce insulators or semi-conductors with (E_G+E_A) as low as possible and E_G/E_A as large as possible. This has been done extensively for the last 60 years mainly for photo-tube developments [9].

Some alkali-halides such as caesium-iodide (CsI) have been tested in both DC and RF guns, but the photoemission threshold was too high (~ 6 eV) requiring an impractical laser wavelength. Coating the CsI with a thin layer (2 nm) of germanium has been shown to improve the QE at 262 nm [11] however, currently the Mg cathode appears to give better results.

The compounds of the alkali-antimonide family (Cs_3Sb, K_2CsSb, $Na_2K(Cs)Sb$, etc.) work in the visible light region with a QE approaching 40 % and are stable for many years in photo-tubes. Unfortunately it has not been possible to obtain such results in a photo-gun where QE drops in few minutes down to 1 %, producing a significant dark current and limiting the electric field. In spite of a strong R&D program, these drawbacks are not yet overcome. Recently, a new proposal called Secondary Emission Enhanced (SEE) PCs [12] might overcome these disadvantages. It consists of an alkali-antimonide cathode isolated from the rest of the gun by a thin diamond disk, transparent to photons and electrons, and used as an electron multiplication electrode.

Another family, alkali-telluride PCs (Cs_2Te, Rb_2Te, RbCsTe, K_2Te, KCsTe...) have been shown to behave more favourably in a photo-gun [11] despite having larger photoemission thresholds (3.5 – 4 eV) requiring UV light. These PCs were intensively used at DESY in the Tesla Test Facility – 12 cathodes in 4 years [13] – and at CERN in the CLIC Test Facility – 65 cathodes in 10 years [14]. Table 2 summarises the main properties of Cs-Te PCs.

Table 2: Cs-Te photocathode properties [14], [15]

Working wavelength	< 270 nm
Working pressure	< 10^{-9} mbar baked vacuum
Maximum QE	> 20 % @ 262 nm
Operating time with QE > 1.5 %	from weeks to months (see Figures 1 and 2)
Maximum electric field	at least 127 MV/m
Relaxation time	< 2-3 ps (measurement limited by instrumentation)
Dark current	Quasi equivalent to copper
Peak current	at least 10 kA
Single pulse charge	at least 100 nC in 10 ps
Mean current	at least 1 mA (limited by laser)
Mean current density	at least 21 mA/cm^2
Resistance to laser damage (mean power)	at least 6W/cm^2 @ 262 nm

As with the alkali-antimonides, alkali-tellurides must be prepared in an ultra-high vacuum (UHV) environment and they have to be used without breaking it. This means the use of a load-lock system and eventually an UHV transport carrier if the preparation chamber is not attached to the photo-injector.

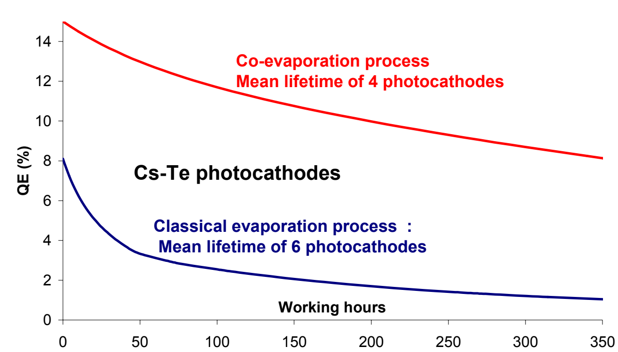

Figure 1: QE and lifetime improvement with the co-evaporation process, measured in the CERN DC gun at 8 MV/m and at a pressure of 10^{-10} mbar.

The preparation consists of firstly evaporating a thin layer of tellurium (about 10 nm) followed by the evaporation of caesium until the photocurrent, produced by the UV light, reaches a maximum. By evaporating both products at the same time following the so-called co-evaporation process [16], recent tests at CERN [15] showed better behaviour in a DC gun (see Figure 1).

Unfortunately this improvement was not so large inside an RF gun, certainly due to the poor vacuum conditions during the experiment. In Fig. 2 we can see the different lifetimes in the DC gun, in a transport carrier and in the RF gun. The decay of the lifetime could be seen as the sum of two exponentials, a fast and a slow decay:

$$QE(t) = QE_1 \cdot e^{-\frac{t}{\tau_1}} + QE_2 \cdot e^{-\frac{t}{\tau_2}}$$

Table 3 gives the values in the different situations described in the Fig. 2.

Table 3: Lifetime parameters (CERN measurements)

QE = f(t)	QE_1 %	τ_1 h	QE_2 %	τ_2 h
Transport carrier	3.85	18.9	9.2	3331
DC gun	2.24	65.9	12.7	780
RF gun	9.2	14	3.4	315

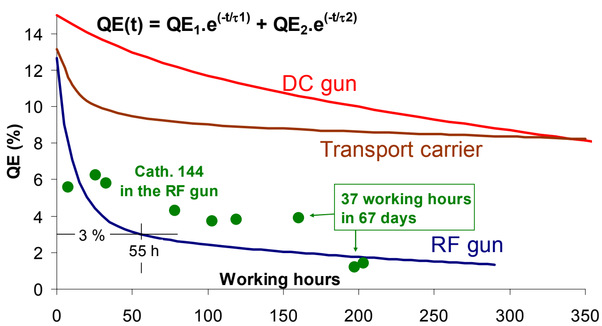

Figure 2: Lifetime measurement of Cs-Te PCs produced by co-evaporation. - ***DC gun :*** Mean lifetime of 4 PCs continuously used in the DC gun at 8 MV/m and $p \leq 10^{-10}$ mbar. - ***Transport carrier :*** Mean lifetime of 5 PCs stored in the transport carrier at $p \approx 3.10^{-11}$ mbar. Time scale is storage hours instead of working hours. - ***RF gun :*** Mean lifetime of 9 PCs in the RF gun at 100 MV/m and a pressure of $2.10^{-9} \leq p \leq 7.10^{-9}$ mbar, including 2 PCs destroyed during RF conditioning. As an example, the dots indicate the lifetime of a PC used in the RF gun.

For an operational source, the minimum lifetime of a PC must be longer than the total time required to produce a new set of PCs including transport and pumping-down time. A set of 4 PCs can be produced and made available in the photo-injector in less than 4 days. For 12 working hours per day, this corresponds to a minimum lifetime of about 50 h which, from Fig. 2, leads to a minimum QE of 3 %.

To try to improve alkali PC properties, and to study the influence of their substrates, an R&D E.U. program was recently set up [17].

Activated gallium-arsenide Photocathodes

A semi-conductor type III-V with a negative electron affinity (NEA) given by co-adsorption of caesium and oxygen, is well known as an efficient photo-emitter in the visible and near infra-red region [9]. Gallium-Arsenide crystals with different doping are the most popular material for producing polarized electrons when they are illuminated with a circularly polarized light.

The Ga-As sample is strongly p-doped with zinc or beryllium for instance and, after cleaning under UHV, activated with an oxidized caesium monolayer to produce NEA. The Strained layer or Superlattice overcomes the hh lh mini-band degeneracy and allows electron polarization production of more than 85% but with a significant reduction in QE. One of the best configurations for the time being is a superlattice structure InGaAs-AlGaAs of strained layers giving at 820 nm QE ≈ 0.5% for a polarization greater than 80% [18]. But these PCs suffer from some limitations:

- After reaching a certain level, the extracted charge is no longer proportional to the light intensity. This is known as Surface Charge Limit (SCL) and could be an important issue for a pulse-train production. For instance, for a train of bunches of 1 nC, the minimum time between pulses is about 2 ns;
- the response time is much longer than that of metallic or alkali cathodes and is about 100 ps;
- the peak current is limited to few Amps;
- they are very sensitive to chemical contamination and ion back-bombardment must be avoided requiring UHV in the 10^{-12} mbar range;
- a breakdown voltage could destroy the surface limiting the extracting electric field to a few MV/m.

Nevertheless these PCs are mandatory for polarized electron production and well adapted for producing high mean current (few mA) with low peak current (few Amps). They are routinely used in various electron sources ([19] for instance). A large part of these drawbacks would be overcome with the application of the 2 photon process (Nakanishi's proposal reported in [20]) which allows the use of bulk GaAs without any activation but requiring a powerful laser due to the low QE.

LASERS

The electron beam properties depend mainly on the laser performances: intensity, phase and position are directly related to the laser stability and reliability. The laser beam defines the temporal and transversal profiles of the electron beam. The typical setup is the so-called Master Oscillator Power Amplifier (MOPA). The oscillator is generally synchronized with a sub-harmonic of the accelerating RF voltage with a typical jitter of ≤ 1 ps rms. This is followed by an electro-optic selector which produces the temporal structure of the macro bunch or selects a single pulse that is then injected into the amplifiers (single, multi pass, or regenerative). In the case of short pulses and very high power density, a chirped amplification (pulse stretching) can be used followed by a pulse compressor.

Only solid state lasers are able to fulfil the required temporal stability, but they produce laser emission in the infrared (1 μm range). As previously stated, metallic or alkali telluride PCs require UV light, below 300 nm. This is done by frequency multiplication and/or mixing within non linear crystals.

During the last 10 years considerable progress has been made in the key aspects for the production of a laser beam: the optical pumping, the laser gain medium, the frequency conversion and the laser beam shape.

Optical Pumping:

The optical pumping can be done with lasers, flash lamps or laser diodes. In our application, pumping by laser is mainly used to pump Ti:sapphire with the second harmonic of a Nd:YAG laser (532 nm). Flash-lamps are largely replaced by laser diodes. Because their emission is resonant, the total efficiency is much better (1% for flash-lamps, better than 10% with laser diodes); the thermal load is lower reducing the total volume of the pumping system; high voltage is no more required; and the lifetime is much longer. On the other hand, the emission wavelength of a laser diode is strongly dependent on the temperature, which must be accurately controlled. Stability is a key parameter in our applications, laser diodes allow an order of magnitude gain, returning instabilities in the output laser beam below 1%. We are mainly concerned with two pumping diode families: AlGaAs diodes, which emit in the 800 nm region, are used to pump crystals doped with neodymium ions (the most popular) and InGaAs diodes emitting around 980 nm and used to pump crystals doped with ytterbium ions which is a very promising family.

Laser Gain Medium:

Titanium-sapphire is used for the production of polarized electrons, due to its tuning in the 800 nm region, and to produce sub-picosecond pulses. Neodymium-YAG laser are replaced in many cases by vanadate (Nd:YVO) due to their high gain cross section, strong absorption, wide emission bandwidth and low lasing threshold.

Considerable progress is in hand, both for crystals and doping. Ytterbium now tends to replace neodymium as doping ions. Yb^{3+} has the following advantages: longer lifetime of the excited upper state giving a better energy storage; only 2 electronic levels suppressing absorption in the excited state; a low quantum defect ($1-\lambda_{Laser}/\lambda_{Pump}$) reduces the heating during lasing by a factor of five. The main disadvantages are a lower gain and a higher lasing threshold. Nevertheless ytterbium does allow short pulses – about 1 ps or less – and high power.

Many crystals are doped with Yb: in addition to the popular YAG and YLF, new materials such as potassium tungstate (KGW, KYW) are used to produce short pulses (~ 0.1 ps) with a small tuning range between 1020 and 1060 nm. Apatite crystals such as SFAP or SYS also deliver fs pulses but are still difficult to produce. However, in general we need a MOPA setup; this leads to the use of the same wavelength for both the oscillator and the amplifiers, so Nd:YLF should still be taken into account in a new design [21]. For passively mode-locked applications with high power and short pulses, fiber lasers are now being used to replace crystal lasers.

Frequency Conversion:

This is produced by a non linear process (multiplication and mixing) inside crystals like KDP, KTP, BBO, LBO, CLBO etc. In spite of some new crystals, it is certainly the part where progress is the slowest. An efficiency of 50-55% can be expected to convert infrared into green light (2nd harmonic generation), but only 25-30% to convert green light into UV (4^{th} harmonic generation), giving a total efficiency of about 12-15%.

Laser Beam Shape:

More and more requests are coming from photo-injector users to obtain square laser beam profiles on both the transversal and longitudinal planes [22]. For a "top hat" shape in the transversal plane, refractive optics with low dispersion are commercially available and convert a collimated Gaussian pulse into a square pulse with more than 75% of the energy in the plateau. But tight specifications, in particular for FEL applications, are not yet fulfilled.

Two different systems are under development to produce a square temporal profile: Liquid Crystal Modulator (LCM) and Acousto-optic Programmable Dispersive Filters (AOPDF), also called "Dazzler". Plateau lengths of 6 ps with 0.5 ps rise and fall times are commercially available. But operating wavelengths are from the visible to the near infrared and the damage threshold is rather low. Amplification and frequency conversion degrade the square temporal profile. Strong R&D programs are under way (see [17] for instance).

GUNS

The electrons produced by the laser-illuminated PC have to be accelerated as fast as possible in order to reduce the space charge effects. To do this, high electric fields are required and the best candidate is a radio-frequency cavity. Nevertheless, in some cases, RF guns are not suitable and DC guns or combination RF/DC guns are more useful.

DC Gun

Polarized electron production with a GaAs PC requires a relatively low electric field (few MV/m) and very good vacuum. This is a typical application for DC guns, but they are limited by their perveance to a production of electron pulses with a peak intensity of a few amps. Developments are ongoing to increase the HV up to 750 kV with an electric field of 15 MV/m [2].

RF Gun

RF gun photo-injectors are now intensively used in many applications from 470 MHz up to 17 GHz. But in most cases they are working in the L or S band. The PC is seated in the first half cell of the gun where there is a high electric field. One of the most popular is the 1.5 cell gun

[23] which was upgraded to a "1.6" cell one for emittance optimization. Electric fields higher than 100 MV/m are currently obtained. In order to accelerate high charge electron beams, a 2.5 cells gun was developed [24]. To produce high charge in a train of many pulses (more than 2300), new developments are ongoing to maintain relatively low emittances (6.10^{-5}m.rad) and to decrease the operational pressure to close to 10^{-10} mbar [17].

For producing cw high mean current, up to 100 mA, superconducting RF guns are being designed. For compatibility with the available mean laser power and with the superconducting properties of the cavity, the PC must have a QE greater than a few %. For this purpose, a liquid nitrogen temperature Cs-Te PC is under development [17].

Other Guns

To extract faster electrons from the PC, higher electric fields are required. Over a 1 or 2 mm gap, up to 1 GV/m could be obtained with a pulsed DC gun producing pulses in the MV range in a few ns. This would be followed by a conventional RF booster. High peak currents (1 kA) in a few hundred of fs are expected with an emittance as low as $1.\pi$.mm.mrad [3].

Due to the sensitivity of GaAs PCs, all attempts to produce an RF polarized electron gun have failed [20]. A possible alternative is the use of a Plane Wave Transformer (PWT) which allows much better pumping conditions. A new design under study could possibly achieve and maintain during operation, vacuum in the 10^{-11} mbar range at 55 MV/m [25].

SUMMARY

In twenty years photo-injectors have undergone a strong development because of the multiplicity of their applications. At the same time requirements have become more and more demanding. In particular the next generation of X-ray sources requires a 6 orders of magnitude greater brightness than is possible with thermionic sources and still a hundred times more demanding than what is achievable with today's photo-injectors. PCs continue to be the weak element of a photo-injector and require a strong R&D program. Steady progress is ongoing on lasers, mainly in terms of stability and reliability. Except for polarized electron production, RF guns are now routinely used. New guns like pulsed DC/RF gun or PWT are under development to minimize emittances or to improve vacuum conditions.

REFERENCES

[1] S. Schreiber, "Performance of the TTF Photoinjector for FEL Operation", Proc. of the workshop The physics and applications of high brightness electron beams, Chia Laguna, Sardinia, July 2002
[2] S. M. Gruner & M. Tigner, eds. "Study for a proposed Phase I ERL Synchrotron Light Source at Cornell University, JLAB-ACT-01-04, 4 July 2001
[3] Alpha-X project, http://phys.strath.ac.uk/alpha-x
[4] K-J. Kim, "High-brightness electron beam for X-ray FELs", COOL03, Mt Fuji, Japan, May 2003
[5] S. Schreiber *et al.* "Improved operation of the TTF photoinjector for FEL operation", Proc. of EPAC-2002, Paris, June 2002.
[6] J.S. Fraser *et al.* "High-brightness photoemitter development for electron accelerator injectors," Proc. of Laser Acceleration of Particles AIP Malibu, 1985.
[7] J. Smedley *et al.* "Emittance measurements with a pulsed power photo-injector", Proc. PAC'03, Portland, May 2003.
[8] W.E. Spicer, "Photoemissive, photoconductive and optical absorption studies of alkali-antimony compounds", Physical review, 112(1)-1958
[9] A.H. Sommer, Photoemissive materials", Robert E. Kreiger Publiching Company, N-Y 1980
[10] X.J. Wang *et al.*, "Mg cathode and its thermal emittance", Proc. EPAC 2000, Vienna, June 2000
[11] E. Chevallay *et al.*, "Photocathodes tested in the DC gun of the CERN photoemission laboratory", NIM A 340 (1994) 146-156.
[12] I. Ben-Zvi *et al.*, "Secondary emission enhanced photoinjector", BNL-C-AP#149, April 2004.
[13] S. Schreiber *et al.*, "On the photocathodes used at the TTF photoinjector", PAC'03, Portland, May 2003.
[14] H.H. Braun *et al.*, "The photoinjector option for CLIC: Past experiments and future developments", Proc. PAC'01, Chicago, June 2001
[15] G. Suberlucq "Drive beam photo-injector option for the CTF3 nominal phase", Proc. CTF3 Review, CERN, October 2001.
[16] C. Ghosh and B.P. Varma, "Preparation and study of properties of a few alkali antimonide photocathodes", J. Appl. Phys. 49(8), August 1978.
[17] JRA2 in the CARE proposal "Charge production with photo-injectors", http://www.infn.it/phin/
[18] T. Nakanishi *et al.* "Polarized electron photocathodes and guns developed by Nagoya collaborators", PST'99, Erlangen September 1999.
[19] Jefferson Lab, Electron Gun group, http://www.jlab.org/accel/inj_group/
[20] D. Edwards, edit., "Polarized RF guns for linear colliders", ICFA workshop, Fermilab, April 2001
[21] I.N. Ross *et al.*, "A high performance diode-pumped Nd :YLF amplifier", CERN, CTF3-Note 48, 07/2002
[22] L. Serafini, "Beam Dynamics Studies of High Brightness e- beam production at SPARC", 2nd Orion workshop, SLAC, February 2003.
[23] K. Batchelor *et al.*, "Operational Status of the Brookhaven National Laboratory Accelerator Test Facility", Proceedings of the 1989 PAC Conference
[24] R. Bossart *et al.*, "A 3 GHz photoelectron gun for high beam intensity", CERN-CLIC Note 297
[25] D. Yu *et al.*, "Development of a polarized electron gun based on an S-band PWT photoinjector", PAC'03, Portland, May 2003, p. 2129.