Review of High - brightness Electron Guns

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Abstract

High efficiency and short wavelength Free Electron Lasers and future linear colliders require high brightness electron guns. Due to the recent development of RF guns and laser-driven photocathodes, the beam quality has been significantly improved. In this paper, the state of the art of this new technique is reviewed and some of the more advanced injectors are described. The advantages, drawbacks and promises of these new electron guns are outlined.

I - INTRODUCTION

The new generation of electron accelerators for high power or short wavelength free-electron lasers (FEL), high luminosity linear colliders and bright synchrotron radiation sources has the common requirement of very bright beams combining high peak current and very small transverse and longitudinal emittances. For these machines, the ultimate aim is to use an electron source having a brightness as high as possible and an energy spread as low as possible.

Beam brightness is defined as the ratio of the peak current to the square of the 90% normalized emittance :

$$B = 2\, I_p/(\pi\varepsilon_n)^2 \quad \text{where} \quad \varepsilon_n = \beta\gamma\varepsilon$$

Due to the development, made during the last decade, at Stanford [1] of RF guns and Los Alamos [2] of photocathodes, it appears that one of the best choices is to combine these two ideas : a laser-illuminated photoemitter produces electron bunches which are accelerated at the relativistic velocity by an RF cavity.

By using this photoinjector technology a tenfold improvement of the beam brightness has recently been measured on the LANL-FEL, in comparison to previous results obtained with a conventional thermoionic gun.

After a brief description of the photoinjector scheme, some of the physical and technical aspects of high-brightness beams will be analysed. Since the LANL pioneering work, many Laboratories have begun to study laser-driven RF guns and the more advanced injectors will be reviewed. More details can be found in previous reviews of bright injectors [4].

II - CONVENTIONAL AND RF GUN PRINCIPLE

A conventional injector, for RF linac, consists of a diode or triode like pulsed thermoionic gun combined with sub-harmonic bunchers. Nanosecond bunches are produced through an electronic modulator. The 100 keV electron beam is then compressed in one or many steps by speed modulation. This speed modulation is converted into a space modulation after a drift length and ns pulses are therefore compressed in few ps bunches at the entrance of the linac. As can be seen in figure 1, such an injector needs many components to control the beam and an emittance degradation is generally observed in such a long low energy beam line, particularly for large bunch charges. On the other hand, the initial brightness, given by $B \sim 4.1 \times 10^9$ J ($Am^{-2}\ rad^{-2}$), is limited by the quite low current density delivered by usual thermoionic guns.

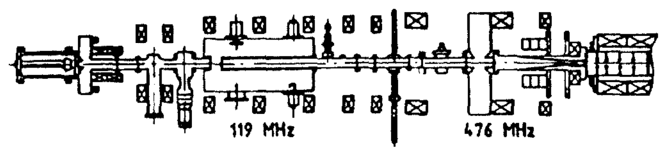

Fig. 1 - Conventional injector with velocity modulation

With such an injector scheme, a 3 to 5 nC, multi-bunch beam can be produced with a normalized emittance of the order of 150 - 200 π.mm.mrad, a pulse duration of 10 - 20 ps (HWHM) and an energy spread of 70 kev (0.5 % at 15 MeV). A more sophisticated bunching scheme (with four sub-harmonic bunchers) is in use on the 38 MeV ISIR linac [5] and up to 70 nC have been produced in the single-bunch mode with a peak current of 3 kA, an energy spread of the order of 1 MeV and a beam emittance of 700 π.mm.mrad. In the multi-bunch beam mode, the charge per bunch is about 3 nC, the peak current is 100 A and the energy spread is 2-4 % at 38 MeV.

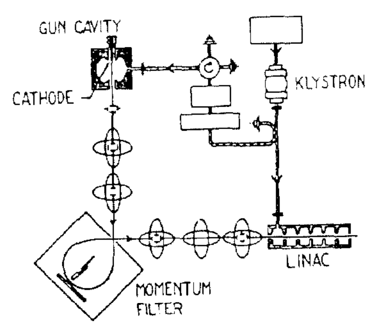

Fig. 2 - Schematic of the MARK III RF gun (Stanford)

If the thermoionic cathode (LaB_6) is located directly in a RF cavity (fig. 2), the beam is accelerated to MeV energy during about one fourth of the RF cycle. The pulse length is therefore very long and has a large energy spread. A momentum filter (α magnet) has to be added at the exit to reduce the energy spread [1]. Typical MARK III performances were : charge per bunch < 0.3 nC, peak current 75 A, micropulse duration 2,6 ps, emittance 2-3 π.mm.mrad, energy spread < 0.5 %. The averaged current is limited by beam loading and backwards accelerated electrons. Therefore, the useful charge per bunch in a RF gun with thermoionic cathode is likely to be levelled down to nC.

Replacing the thermoionic cathode by a laser-driven photoemitter, located in the RF cavity, is the basis of the photoinjector developed in Los Alamos [2]. The injector scheme (fig.3) is now very simple but it has to be pointed out that the difficulties are transfered on laser and photocathodes technologies (§ IV).

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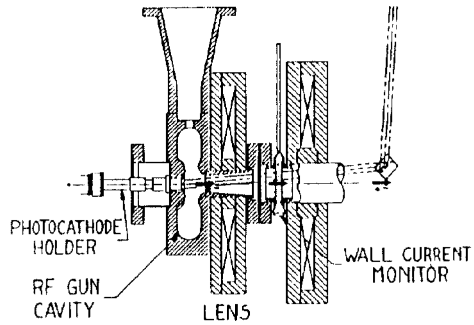

Fig. 3 - Schematic of the LANL photo-injector

A comparison has been made on the 15 MeV LANL FEL-accelerator between the conventional gun and the new mutli-cell (see fig. 9) photoinjector, the performances are summarized on table 1.

Table 1 - Comparison of the performances of the old vs.new injector at the Los Alamos FEL

Electron source	Thermoionic gun	Photoinjector
Emittance	160 π.mm.mrad	40 π.mm.mrad
Energy spread	0.5 %	0.3 %
Charge per bunch	5 nC	5 nC

The brightness is 16 times higher and the energy spread is significantly improved. Peak currents higher than 300 A have been produced on one square cm. The corresponding beam brightness is 4.10^{10} A /(m.rad) ^{2}. At 0.8 nC, a beam brightness of 10^{11} has been achieved at LANL with 17 ps pulse duration and, at BNL, a beam brightness of 5.10^{12} A/(m.rad)^2 is reported for 2 nC, 5ps bunches.

III - PHYSICAL ASPECTS OF HIGH-BRIGHTNESS ELECTRON GUNS

High power FEL-applications impose severe constraints on the beam quality :

. the charge per bunch Q and the peak current I_p have to be as large as possible ($Q > 5$ nC, $I_p > 100$ A) ; indeed the FEL-gain is proportional to the electron density in the bunch,

. the normalized emittance is related to the laser wavelength (λ) by the relationship : $\epsilon_n < \beta\gamma\lambda$ with ϵ_n in π.mm.mrad and λ in μm i.e for $\lambda \sim 1$ μm and $\gamma \sim 100$, $\epsilon_n < 100$ π.mm.mrad. With this condition,the optical gain is close to the maximum whereas the gain is reduced by a factor of 4 if the emittance is 2 times larger [2],

.the relative energy spread should be less than 1/4 N (typically < 0.5 %), where N is the number of wiggler periods, in order to trap the electrons in the potential well produced by the EM laser field and the wiggler field,

. as the beam divergence is proportional to γ^{-1} (the relativistic factor) and as the space charge forces are inversely proportional to γ^2, the electron energy should reach a few MeV at the injector exit. On the other hand, rapid acceleration to relativistic velocity minimizes the axial electron pulse spreading due to repulsion forces.

To fulfill these requirements, laser-driven RF guns have the following main advantages :

- the time structure of the electron bunches is controlled by the laser pulse format, eliminating the need of sub-harmonic bunchers responsable of the emittance degradation,
- the electric field in RF cavities can be made very strong, so that the effects due to space charge repulsion can be minimized.

Nevertheless, in space charge dominated beams the emittance increases very rapidly near the cathode where the velocity is low, and many physical aspects play a role in this initial emittance growth :

- linear and non linear space charge forces,
- non linear time-independent RF fields,
- time-dependent RF fields,
- wake fields effects,
- magnetic focusing,
- current distribution in the radial and longitudinal directions.

A lot of work based on analytical studies and PIC numerical codes has been done to establish a design philosophy leading to the best compromise in minimizing the emittance growth. In this review paper, we will restrict ourself only to general comments on some of these physical aspects.

The normalized transverse emittance is defined as :

$$\epsilon_n = \frac{2}{mc} \left[\langle r^2 \rangle \langle p_r \rangle^2 - \langle rp_r \rangle^2 \right]^{1/2}$$

In fact, in a space charge dominated short pulse, the particle dynamics is quite different in front and at the rear of the bunch, this is mainly due to the energy variation in the bunch. Therefore the emittance consists of two parts : an uncorrelated (thermal) part and a correlated part. Figure 4 shows the calculated slice emittance into a 10 nC, 100 ps bunch [6] just in front of the cathode.

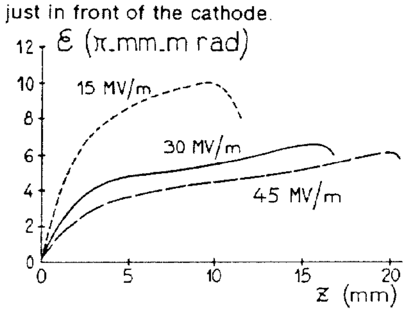

Figure 4 - Calculated slice emittance as a function of the accelerating gradient

The normalized emittance at a given Z is an averaged value over all the beam and is much larger than the sliced one. B. Carlsten [7] has developped a compensation technique which reduces the correlated emittance by focusing the beam with an external lens. The emittance reduction results from non-linear space charge forces after the lens cancelling partly the non-linear space charge forces before the lens. Figure 5 is an example of this emittance reduction as calculated by Parmela and TBCI-SFcodes [8] for a 50 ps, 10 nC, 1.5 MeV beam in the Bruyères-le-Châtel photoinjector.

Such an emittance variation makes it quite difficult to perform any brightness comparisons between different experimental results. Indeed the amount of compensation is very sensitive to the main parameters : bunch charge distribution, accelerating gradient, focusing force, etc...

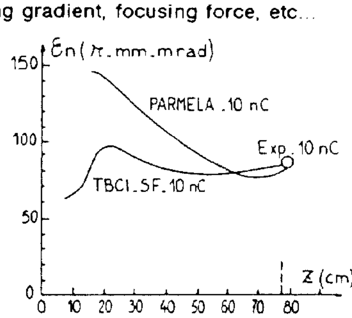

Figure 5 - Comparison of the normalized emittances calculated by PARMELA and TBCI-SF codes. 10 nC, 1.5 MeV, B_{foc} = 1100 G

The emittance growth can be minimized if the space-charge force is made linear in the radial direction by controlling the current density into the bunch, and if the radial cavity electric field is also linear. By optimizing the nose-cone geometry of the RF gun, this last condition can be fulfilled [2] but figure 6 shows that it seems very difficult to do not have a non-linear component of the space charge forces somewhere into the bunch [6].

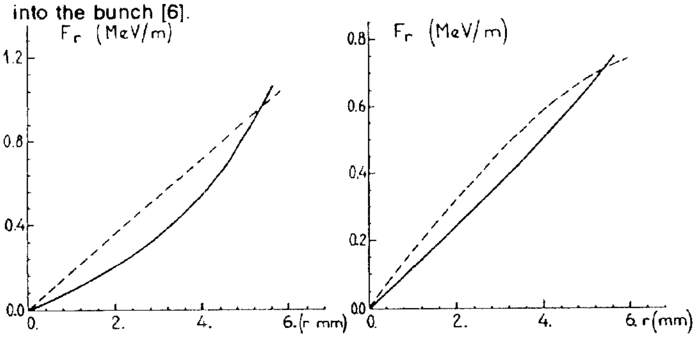

Figure 6 - Radial component of the space charge force for the following parameters : E_o=15 MV/m,τ= 100 ps, Q = 10 nC for two current distributions : uniform density (continuous lines), gaussian density (broken lines) and two axial positions from the cathode : 2,3 mm (left curves) and 9.1 mm (right).

Kim and Y.J. Chen [9] (see also C. Travier in [2]) derived scaling laws of the transverse and longitudinal variations as a function of the main parameters. The RF induced transverse emittance scales as :

ϵ_{RF} (π.mm.mrad) = $1.09\ 10^{-10}\ E_o\ f_x^2\ \sigma_x^2\ T_b^2$ (1)

and the space charge induced emittance scales as

$\epsilon_{sc} = 5.67\ 10^4\ Q(nC)\ /\ E_o\ (3\ \sigma_x - 1.5\ T_b)$ (2)

where E_o is the accelerating gradient in MV/m, σ_x the RMS transverse beam size in mm, f the RF frequency in MHz and T_b the RMS bunch length in ps. Assuming, for example, a phase extension of 1/30 of the RF period to limit the energy spread, one obtains : $\epsilon_{RF} = 0.12\ E_o\ \sigma_x^2$ and $\epsilon_{sc} \sim 1.13\ Q\ f\ /\ E_o$ (3)

A minimum is obtained when $\epsilon_{RF} = \epsilon_{sc}$ that is to say :

$\epsilon_{min} \sim 0.37\ \sqrt{Q.f}\ \sigma_x$ and E_o(optimum) $\sim 3\ \sqrt{Q.f}/\sigma_x$ (4)

These crude scaling laws, plotted in figure 7, assume gaussian distributions, short pulses, a bunch phase extension of 1/30 of the RF period and do not take into account magnetic focusing and relativistic effects. With these approximations, a low frequency RF gun is favoured for a given bunch charge, but it has to be pointed out that, at very low frequency, a magnetic compressor will be needed in order to increase the peak current and, during this compression process, a part of the beneficial effect of a low frequency gun can be lost due to emittance degradation (§ VI).

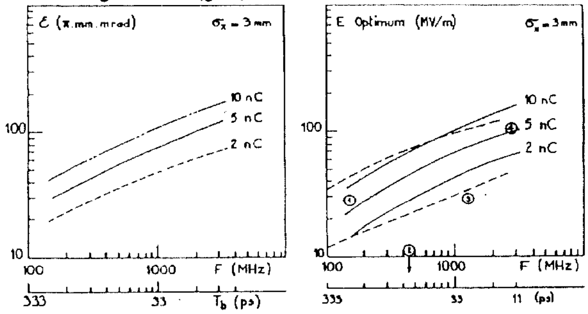

Figure 7 - Emittance and optimum gradient field as a function of the RF frequency. The Kilpatrick limits (dotted lines)(and x 3 which can be reached) is plotted for comparison, F = 1.6 $E^2e^{-8.5/E}$. Hyp : $T_b = T_{RF}/30$ σ_x = 3 mm ; 1 : CEA ; 2 Boeing; 3 : LANL ; 4 : BNL

As will be shown in § V, very different technical choices have been made in the built photoinjectors and quite surprisingly the reported emittance values are of the order of :

ϵ_n (90 %) ~ 10 (± 2) π.mm.mrad per nC.

Complete numerical simulations, solving Maxwell-Vlasov equations in actual geometry, are needed to design an optimized injector for a given set of parameters.

IV - TECHNICAL CONSTRAINTS

The laser-driven RF gun concept is based on two new technologies not commonly employed in the accelerator field namely the photocathode and laser technologies.

Over the last few years, lasers suitable for RF guns have been built. The source is a mode-locked CW oscillator working at 70 - 100 MHz. The pulse can be optically compressed down to 10 - 30 ps using an optical fiber, where the light is first chirped (linearly swept in frequency), and multipass gratings act as a frequency dispersive delay line.

A Pockels cell gates the pulse train producing a macropulse burst of 10 to 200 μs at 1 - 20 Hz repetition rate. The macropulse is amplified by cascaded amplifiers giving an energy per micropulse of the order of 10 μJ for green light where the quantum efficiency is large.

Different schemes are used to stabilize the pulse train in amplitude (~ 1 %) and in phase (~ 1 ps). Figure 8 gives, as an example, the CEA drive laser configuration.

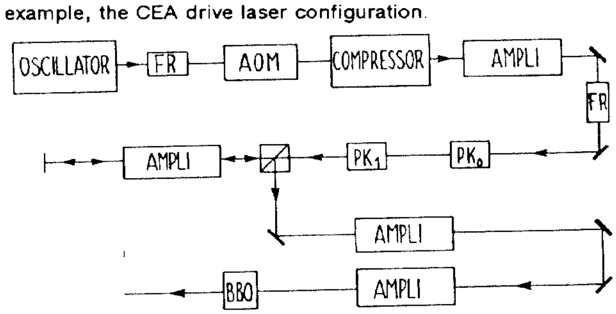

Figure 8 - Drive laser used for the CEA-Injector - FR : Faraday Rotator - PK : Pockels Cell - AOM : Acousto-Optic Modulator

The fundamental relationship between drive laser micropulse energy E, photocathode quantum efficiency (QE) and charge (nC) per micropulse for a drive laser wavelength (λ) is given by : Q(nC) = 8.1 QE (%) x E (μJ) . λ (μm)

i-e with QE ~ 1 % and Q = 10 nC, an energy of 2.4 μJ per pulse is needed.

The main drawback of this laser-driven RF gun is due to the limited lifetime of the photocathode. An ideal photocathode should have a good quantum efficiency (~ 1 %) (if not the laser energy has to be increased and thermal effect can be prohibitive) a long lifetime and a good ability to withstand high accelerating fields. Several types of photocathodes have been tested :

- <u>semiconductor cathodes</u> CsK_2Sb are in use at LANL, Boeing and CEA. The quantum efficiency is in the range of 2 to 6 %. These cathodes are prepared, in situ, in a high vacuum preparation chamber by evaporating alternatively Sb, K and Cs and controlling the photoemission with a mW laser during the process. Lifetimes of ten hours have been obtained at LANL when the pressure in the RF cavity is low enough (< 10^{-9} torr) and after discharge cleaning. 5 to 10 nC per bunch are produced with a repetition rate of about 1000 bunches/sec. The overall extracted charge, during a lifetime, is typically ~ 0,1 C. CsI cathodes are used at CERN in a BNL-like gun (fig. 10) with a 213 nm, (5 ω of the Nd:YAG) long pulse laser (7 ns). The quantum efficiency is 1-2 % and the charge per RF cycle is of the order of 2 nC. A lifetime in excess of 100 hours has been measured [10]. Taking into account the pulse format, the overall extracted charge is about 0.15 C. CsI cathodes can be transfered from the outside but need an UV light-source.

- metallic cathodes (copper, yttrium or samarium) are studied in the Brookhaven Accelerator Test Facility (see fig. 10). A consequence of the choice of these metals is the need for UV-laser light (266 nm, the frequency quadrupled Nd:YAG) to excite the photocathode. For copper, the quantum efficiency is of the order of 10^{-4} and 2 nC electron bunches were measured with 170 μJ UV-laser light. This low QE metallic cathode is well suited for single-bunch mode, but for a 5 nC multi-bunch operation (for example at 20 MHz and a 10^{-2} duty cycle) the average laser power would be prohibitive : P ~ 50 W in the UV range.

Other types of photocathodes are studied in different Laboratories : array of needles, AsGa, CeB6 , LaB6, dispenser and metallic matrix (Ag-Al-Li) photoemitters, field-assisted and surface plasmon excitation-assisted photoemission [4, 8]. Quantum efficiencies of 10^{-3} - 10^{-2} can be obtained in some cases and it has to be proved that these cathodes can compete with the bialcaline ones in actual injectors.

V - PHOTOINJECTOR DESCRIPTION AND EXPERIMENTAL RESULTS

After the pioneering LANL work, many Laboratories have started development programs on laser-driven RF guns. A complete review has been published by C. Travier [4] and we will only describe four of these injectors briefly.

. At Los Alamos, the initial photoinjector (fig.3) has been converted into a new multicell (5 1/2) accelerator structure, as shown in figure 9.

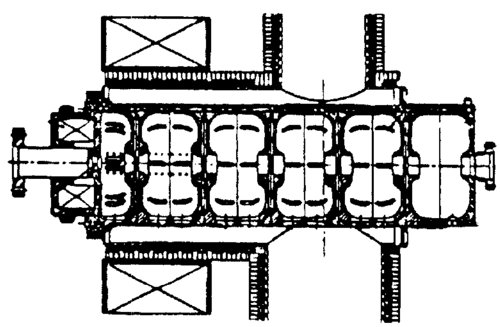

Figure 9 - Cutaway view of the LANL photoinjector.

The accelerator operates at 1300 MHz and with a high-gradient (26 MV/m) at the cathode) ; the length is 0.6 m and the injector produces 6 MeV, 300 A, 15 ps electron pulses at a 22 MHz repetition rate. Table 1 gives the emittance and energy spread. This injector is now installed on a 40 MeV linac for FEL studies and lasing has been demonstrated in the IR range. Under operating conditions [12], at 2.10^{-9} torr, with a 0.1 A average macropulse current (during ~ 100 μs) and 10^{-4} duty cycle, the cathode (CsK_2Sb) lifetime is 5-15 h. The limitation on lifetime is assumed to be caused by electron stimulated gas desorption.

. The Brookhaven 1 1/2 cell gun is shown in figure 10 ; the structure operates at 2856 MHz [11]. The strategy used to control emittance growth due to space charge, is to use very high-gradient accelerating field (~ 100 MV/m).

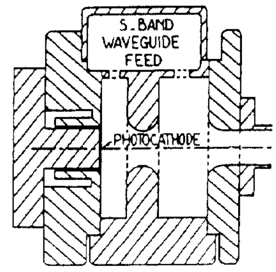

Figure 10 - The BNL RF gun

The copper cathode is illuminated with 170 μJ of 266 nm laser light. The quantum efficiency is of the order of 10^{-4}. Bunches of 2 nC, 5 ps, and 130 A peak current have been accelerated at 4.6 MeV. The measured (90 %) emittance is 16 π giving a beam brightness of about 5.10^{12} A/(m.rad)^2. Many Laboratories have build BNL-like RF guns. Rockwell International uses a LaB6 photocathode having a quantum efficiency of 3.10^{-4} with an infinite lifetime. At CERN a CsI cathode is used with a 8μs - 213 nm laser ; 46 nC distributed over 22 micro-bunches were extracted with 30 μJ laser energy. The photocathode quantum efficiency remains almost constant over 100 hrs. At LAL-Orsay, the two cells are independently powered and phased and the cell nose-cones have been specially designed to minimize the linear RF dependent effects on emittance [22]. At UCLA, a pure copper cathode is also used (QE~ 0.6 10^{-4}) in their BNL like photoinjector.

. Boeing Aerospace has build a two cell 433 MHz photoinjector [14] (figure 11) designed for a high duty factor (25 %) [13].

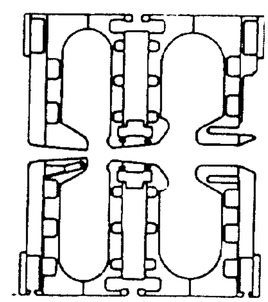

Figure 11 - The Modular Component Technology Development (MCTD) of the Boeing-FEL.

. For the CEA-Bruyères-le-Châtel FEL program, a low frequency (433 MHz) linac has been built and is currently being tested. In order to improve beam characteristics and to reduce space charge effects on emittance, a 144 MHz sub-harmonic RF gun is used (see figure 12). Beam bunches of 1-10 nC have been produced with 30-100 ps pulse durations. The measured emittance is of the order of 80-90 π.mm.mrad at 8-10 nC.

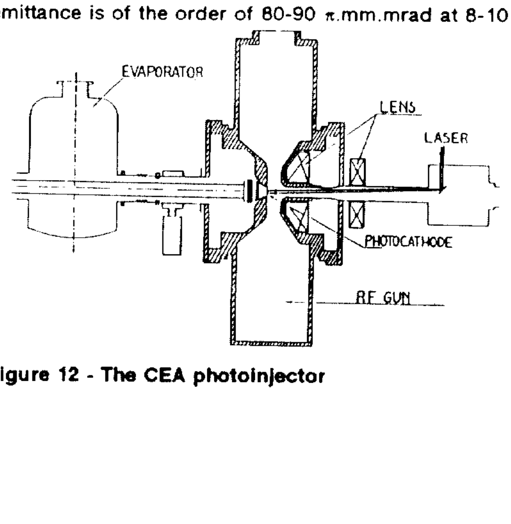

Figure 12 - The CEA photoinjector

The main parameters of these four photoinjectors are summarized in table II.

Table II - Main photoinjector parameters

	LANL	CEA	Boeing	BNL
Frequency (MHz)	1300	144	433	2856
Bunch charge (nC)	1 - 5	1 - 10	1 - 8	2
Energy (MeV)	6	1.5 - 2	2	4.6
Quantum efficency (%)	2 - 5	1 - 3	2	10^{-2}
Cathode lifetime (hours)	~ 5 - 15	~ 1	~ 1	> 700
Number of cells	5 1/2	1	2	1 1/2
Emittance (π.mm.mrad) (90 %)	50 (à 5nC)	90 (à 10 nC)	-	16
Accelerating gradient (MV/m)	26	25 - 30	-	100
Laser pulse duration (ps)	17	30 - 200	70	5

VI - DEVELOPMENTS

Novel ideas have been proposed to neutralize the emittance blowup by using an unsymmetrical RF cavity or a muti-mode RF gun [14] ; numerical simulations show the possibility to improve, by a large factor, the beam brightness.

An other way to increase the brightness is to compress the bunch magnetically without degrading the emittance too much.

Different magnetic bunch compressors have been suggested. Following Parmela calculations [16], using a coherent energy spread into the pulse of 2.9 %, the 10 nC bunch will be compressed by a factor of 3.3 and the peak current reaches 330 A at the exit of the proposed Bruyères-le-Châtel compressor [15]. A further compression by a factor 3 can be obtained in the high energy part of the linac (15 MeV) [17] giving a 1000 A, 10 ps beam at the wiggler entrance with an emittance which should be maintained below 200 π.mm.mrad.

Other magnetic compressor schemes have been discussed in [18] and [19] and it has to be pointed out that, for a complete optimization of the beam brightness, all the components, including linac with F + 3 F flat-topping option, beam transport linac, bending and focusing magnets, have to be taken into account.

Developments on new robust photocathodes have already been mentioned above (§ IV) and it is worth noticing that photoemission of metallic cathodes illuminated by femtosecond laser pulses may lead to quantum efficiencies, due to multiphotonic nonlinear effects, surpassing that of the linear process at about 10^{10} W/cm^2. This may solve the limited lifetime issue of present semiconducting photocathodes. Laser technology is now emerging for these ultra short pulses and some test experiments are already in progress [20, 21] .

VII - CONCLUSIONS

The photoinjector scheme, invented by LANL 10 years ago, is now in use in different Laboratories. This technique produces bright beams and opens the way to a wide field of applications : compact FEL where the gun is integrated into the linac structure (figure 9), short wavelength FEL, bright injectors for future colliders and bright synchrotron sources. New developments should solve the cathode limited lifetime issue and, through sophisticated numerical simulations, an optimized overall scheme (including injector, linac and beam lines) may now be considered.

Achnowledgements :

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