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RF GUNS : A REVIEW

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RFGUNS: A REVIEW

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ABSTRACT

Free Electron Lasers and future linear colliders require very bright electron beams. Conventional injectors made of DC guns and RF bunchers have intrinsic limitations. The recently proposed RF guns have already proven their capability to produce bright beams. The necessary effort to improve further these performances and to gain reliability is now undertaken by many laboratories. More than twenty RF gun projects both thermionic and laser-driven are reviewed. Their specific characteristics are outlined and their nominal performances are given.

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I. INTRODUCTION

The advent of free electron lasers and the perspective of high energy linear colliders boosted the development of high-brightness electron sources. During the last decade, the arrival of RF guns and photocathodes offered a promise to reach the expected performances.

In 1984, G.A. Westenskow and J.M.J. Madey proposed to put a thermionic cathode directly in an RF cavity[36]. The RF gun was born. Meanwhile, Lee et al. reported that very high current densities could be obtained from semiconductor photocathodes[49]. J.S. Fraser and R.L. Sheffield started then to experiment the use of such photocathodes in an RF gun[48,57]. Later, J.M.J. Madey used his thermionic RF gun as a photoinjector thus achieving the "first demonstration of a FEL driven by electrons from a laser irradiated photocathode"[38].

Since that time, many laboratories begun to study RF gun both thermionic and laser-driven. More than 20 projects are identified in this review showing the strong interest manifested for this new bright electron source (fig. 1).

After a brief summary of the beam quality requirements for the different applications, the basic principles of conventional injectors and RF guns are described and their merits are compared. A review of the different projects is then presented including a short description of the most advanced ones. The last part deals with the present understanding of RF gun design and introduces some novel ideas recently proposed.

Previous bright injectors reviews by R.L. Sheffield can be found in references 67, 68 and 71.

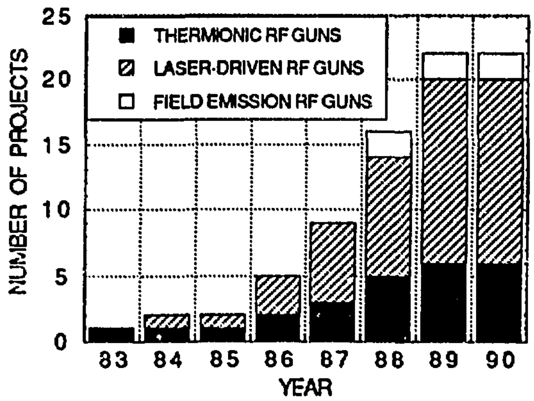

Fig. 1: Current number of RF gun projects

II. HIGH QUALITY BEAM REQUIREMENTS

II.1. Some definitions

Many parameters are used to characterize the quality of an electron beam produced by an electron source or injector. The most important are:

- the pulse format: the beam is made of pulses of a certain length (micropulse length) repeated at a given frequency (micropulse repetition rate) and with some timing jitter. This train of pulses has a certain duration (macropulse length) and is also repeated (macropulse repetition rate). An example of pulse format is shown in figure 2.

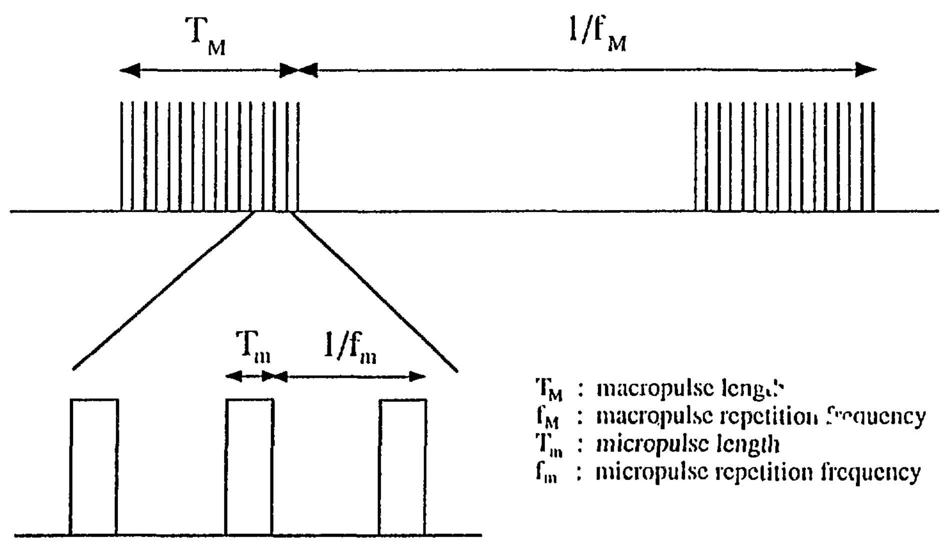

Fig. 2: Pulse format

- the peak current defined as the current in the micropulse.
- the energy spread: the dispersion in energy within a micropulse. It can be expressed either in relative or absolute values.
- the emittance which is a measure of the area of the beam in the phase space. Unless otherwise mentioned, all the emittances quoted in this paper are r.m.s. transverse normalized emittances defined as[2]:

$$\epsilon_{xn} = 4\pi[< x^2 >< (p_x/mc)^2 > - < x(p_x/mc) >^2]^{1/2} \qquad (1)$$

where x is the coordinate of a particle in the beam, p_x is the particle's momentum component in the x direction and $< \ >$ indicates averaging over the electron distribution. This emittance is equal to the phase space area for a Kapchinskij-Vladimirskij distribution[3] or to the area of the phase space ellipse which contains around 90% of the particles ("2σ emittance") of a beam which distribution is gaussian in each coordinate (x, p_x, y, p_y). The unit is π mm mrad (e.g.: $\epsilon_n = 10\ \pi$ mm mrad = 31.4 mm mrad).
- the normalized peak brightness defined as $B_n = 2I/(\epsilon_{xn}\epsilon_{yn})$ where I is the peak current and $\epsilon_{xn}, \epsilon_{yn}$ are the normalized emittances in both transverse directions.

II.2. Beam requirements

Over the recent yea s, the demand for high-brightness injectors producing very short micropulses increased. Essentially two types of accelerators require such injectors: linear accelerators for free-‹ ectron lasers (FEL) and future high energy linear colliders. Some other possible appli‹ ations are also mentioned.

II.2.1. FEL beam requirements

Since the 'irst FEL[6] ever "lased" in 1977, there has been a constant growing interest for this new instrument among the scientific community. The performances of an FEL being closely r‹lated to those of its driving accelerator, the necessity of very bright electron sources quic'ly appeared.

In this paper, FEL will be classified into four categories according to their wavelength:

- infra-red (IR)	$1 < \lambda < 500\ \mu m$
- visible light	$0.1 < \lambda < 1\ \mu m$
- XUV	$0.01 < \lambda < 0.1\ \mu m$
- soft X-ray	$\lambda < 0.01\ \mu m$

So far, linac driven FEL have only been operated in infra-red and visible light regimes.

It is very difficult to explicit general beam requirements for FEL since these requirements depend on the specific design of the electron beam transport system, the undulator and the optical cavity. They also depend on the operating mode of the FEL (eg: oscillator or amplifier). General guidelines can though be given but they have only an indicative value. The electron beam energy is determined by the laser wavelength in relation with the undulator characteristics. The micropulse length should be the same as the desired laser pulse length. The micropulse repetition period needs to be a multiple of the round-trip time in the optical cavity. The timing jitter between micropulses should be much less than the micropulse length in order to preserve a good synchronism between electron bunches and optical pulses. The macropulse length is imposed by the time necessary to build-up the oscillations. The macropulse repetition rate is related to the FEL output power. High peak current is needed to obtain a high gain and a good extraction efficiency. The relative energy spread should be less than $1/4N$ where N is the number of periods of the undulator, in order to assure a good extraction efficiency. An optical gain close to maximum is obtained when there is a spatial overlap of the optical beam and the electron beam through the interaction region. This constraint is fulfilled when the unnormalized transverse emittance is less than the optical wavelength λ; this can be written as $\epsilon_{xn,yn} \leq \lambda\beta\gamma$, where $\beta = v/c$ is the particle velocity and $\gamma = (1-\beta^2)^{-1/2}$.

Crude estimations of the electron beam requirements for the different categories of FEL are given in table 1. The beam properties of an RF linac rely very much on the injector performances. Except for total energy and relative energy spread, all the other requirements are mainly applying to the injector part of the linac.

A more detailed description of FEL beam requirements can be found in references 7, 8 and 9.

Table 1: FEL beam requirements

	IR	Visible	XUV	X-RAY
Wavelength (μm)	1 - 500	0.1 - 1	0.01 - 0.1	< 0.01
Energy (MeV)	10 - 100	100 - 200	200 - 500	> 500
Micropulse length (ps)	1 - 20	1 - 20	1 - 20	1 - 20
Micro. repetition (MHz)	10 - 100	10 - 100	10 - 100	10 - 100
Jitter (ps)	$\ll$ pulse length			
Peak current (A)	> 20	> 50	> 100	> 200
Norm. emit. (π mm mrad)	60 - 500	20 - 60	3 - 20	< 3
Energy spread (%)	< 0.5	< 0.2	< 0.1	< 0.1
Macropulse length (μs)	> 10	> 10	> 10	> 10

II.2.2. Linear colliders beam requirements

Electron-positron colliders with energies much higher than LEP (Large Electron-Positron Collider at CERN) will have to be linear. Therefore a lot of R&D work is underway to find new acceleration schemes[10)]. Whatever scheme will require very bright injectors. In the two-beam accelerator proposed by CERN[11)], the drive-linac also needs a very bright injector.

For the collider linac, all the requirements at the collision point come from the necessity to obtain a very high luminosity. If such requirements could be met by an electron source, the need for a damping ring could be suppressed. For the drive linac, a very high current is needed to produce the RF power for the collider; the pulse format is determined by the collider operating frequency and filling time.

A tentative list of parameters is given in table 2, for both the collider linac and the drive linac. They correspond roughly to the CLIC parameters and are given as an example.

II.2.3. Other possible applications of bright injectors

Synchrotron radiation storage rings and high luminosity colliders (eg: $B\bar{B}$ factory[12,13)], τ-charm factory[14)]) need high-brightness injectors. In these cases, the important parameters are the current intensity and the energy spread: high current is necessary to reduce the injection time and energy spread should be smaller than the booster acceptance.

Another possible application of bright injectors is radiation chemistry. In order to study chemical reactions at the pico-second level, it is necessary to have a bright electron source of a few MeV[15)].

Bright injectors can also be used for the production of infra-red and submillimiter electromagnetic radiation in order to explore the physical properties of materials (eg: precise measurement of dielectric properties[16)]).

Table 2: Colliders beam requirements

	Collider	drive linac
Micropulse length (ps)	0.5 - 1	1 - 2
Micropulse repetition (kHz)	~ 1	15 - 30 10^6
Peak current (kA)	> 1	30 - 60
Norm. hor. emit. (π mm mrad)	< 4	-
Norm. ver. emit. (π mm mrad)	< 1	-
Energy spread (%)	1	-
Macropulse length (ns)	-	10 - 100
Macropulse repetition (kHz)	-	1 - 2

III. CONVENTIONAL INJECTORS

III.1. Injector description

A conventional injector is typically made of two main components: a gun and a buncher. Bright injectors also include a sub-harmonic buncher used to increase the peak current and to reduce the pulse length.

Bright conventional injectors including DC gun, sub-harmonic and harmonic bunchers as shown in figure 3, are used for example in the following linacs: SLC linear collider[17)], ALS storage ring injector[18)] and CLIO FEL injector[19)].

III.1.1. DC-gun

A drawing of a conventional DC-gun is given in figure 4. The electrons emitted by the heated cathode are accelerated by the DC high voltage. Electrodes are shaped to provide the best qualities for the beam at the gun exit for a given current (fig. 5). In the case of a diode gun, the pulse length is controlled by modulating the anode voltage. In order to produce shorter pulses, a triode gun is used. In such a gun, the grid allows a fast control of the cathode emission.

For a given peak current, the micropulse length is limited by the cathode-grid capacitance. For a typical current of 1 A, the pulse length is not less than 1 ns. A thermionic cathode can only provide a limited current density which depends on the material and the macropulse length. In the case of long pulses (several tens of μs), the current density is usually a few tens of A/cm^2 [23]. Recently, densities larger than 100 A/cm^2 have been reported[25].

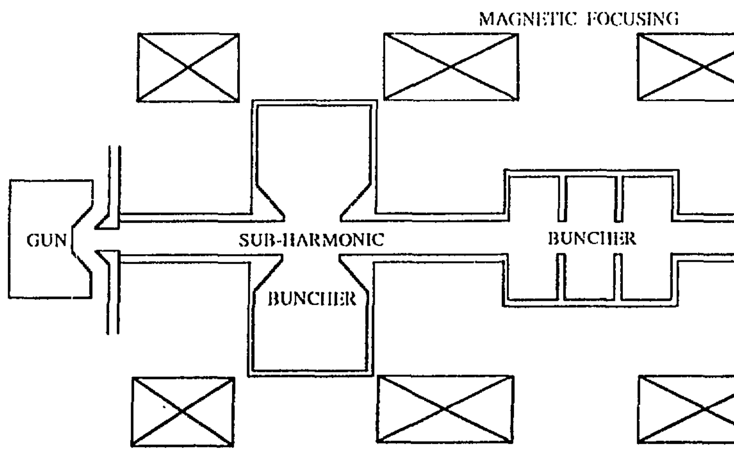

Fig. 3: Conventional injector

The normalized rms emittance of a beam from a thermionic cathode of radius r_c is given by $\epsilon_n = 2\pi r_c [kT/m_0c^2]^{1/2}$ m rad, where k is the Boltzmann constant, T is the temperature of the cathode and m_0c^2 the electron rest energy. For typical parameters, $\epsilon_n = 5.10^{-6}\pi(I/J)^{1/2}$ m rad[48] (where I is the current and J the current density in A/cm^2) and is usually of the order of 1 to 10 π mm mrad. A complete thermionic cathode review is given in reference 24.

The maximum practical DC voltage in a conventional gun is limited to a few hundred kilovolts. Therefore when the beam exits the gun, it is not yet relativistic and thus easily subject to space charge effects. For high current, this means emittance growth and bunch length increase.

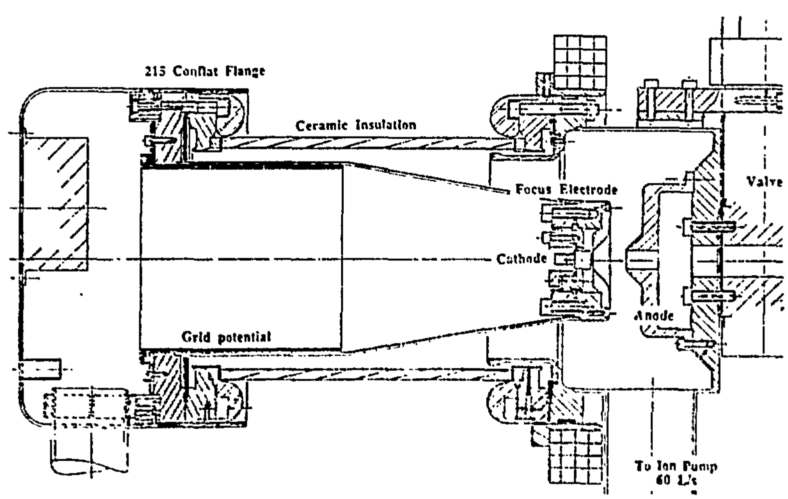

Fig. 4: DC-gun (courtesy of R. Chaput)

COMPUTED BEAM TRAJECTORIES FOR $I/V^{3/2}$ = .055 μPV

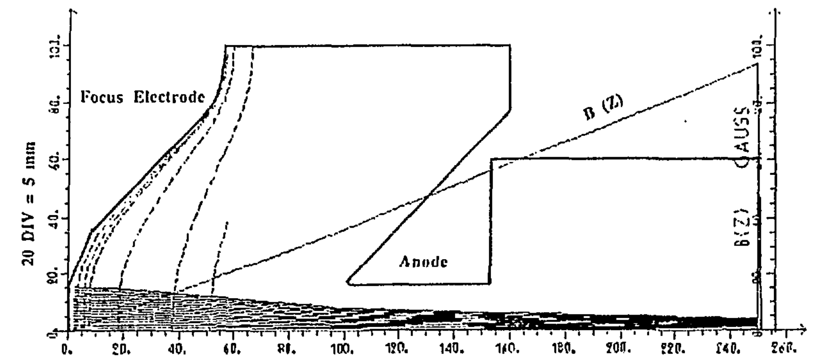

Fig. 5: DC-gun trajectories (Courtesy of R. Chaput)

III.1.2. Sub-harmonic and harmonic buncher

A buncher is an RF cavity used to reduce the pulse length. It is called sub-harmonic buncher when its frequency is a sub-multiple of the linac frequency.

Electrons enter the buncher with different RF phases and thus experience different acceleration forces. This speed modulation is converted into a space modulation after a drift of appropriate length. The gun pulse which is usually much longer then the buncher RF period, is thus transformed into a train of pulses (one per RF cycle) having long tails.

RF choppers[26)] can be used to cut these tails and also to select one pulse within this train. Choppers are usually RF cavities operating with deflecting modes, that allows to select a given phase extension of the beam. They induce current losses, and emittance destruction due to the transverse RF forces they apply to the beam.

A much better way to improve the bunching efficiency, is to try to match the buncher frequency to the gun pulse length. In the case of L or S-band linacs (1.3 or 3 GHz), the harmonic frequency is definitely too high to accept the gun pulse. It is thus more suitable to use one or more sub-harmonic bunchers prior to the harmonic buncher. The one nanosecond gun pulse can then be reduced to a few hundred picoseconds before entering the buncher where it can be further reduced to a few tens of picoseconds. This process increases the peak current by an order of magnitude or more, but does not increase the average current. Unfortunately, it increases the emittance because of the different transverse RF forces experienced by electrons. Energy spread is also increased.

The use of a sub-harmonic buncher imposes a given pulse format (only one out of n RF buckets can be filled if a n^{th} sub-harmonic buncher is used). It also necessitates two or more different RF power sources.

A very complete understanding of sub-harmonic and harmonic buncher physics can be found in reference 27.

III.1.3. Possible additional components

There exists several ways to further improve the beam quality of a conventional injector, including:

- magnetic bunching system: system of magnet(s) having the following properties: achromatic (the system does not introduce orbit displacement due to energy spread), and nonisochronous (the more energetic electrons spend more time in the system than the less energetic ones). Such a system allows to take advantage of energy spread to reduce the bunch length and hence increase the peak current. This bunching process is limited by the nonlinear terms of the transport, the original energy spread and the space charge forces. Moreover, it will produce some emittance growth[77]. References 28 and 29 are two different examples of magnetic bunching systems. Another common system is called "α-magnet" because the beam trajectory in that system looks like the Greek letter "α".
- emittance filter: if slits are placed in a magnetic system, it is possible to select only the core of the beam and thus to reduce the emittance and the energy spread. This system will also reduce the peak current.
- flat-topping[30,52]: the phase or time dependence of the longitudinal and radial forces can be reduced by superimposing a third harmonic field to the fundamental. This procedure known as flat-topping minimizes the growth of the transverse phase space. This system though attractive is difficult to design and operate[31,32].

III.2. State of the art

Figure 6 shows the normalized peak brightness obtained with a few conventional guns and bunchers as a function of the peak current and the pulse length. The following examples have been considered: FELIX[22] gun (1.3 A, 32 π mm mrad, 250 ps), SLC[17] gun (6 A, 30 π mm mrad, 2000 ps), CLIO[20] gun design (1 A, 15 π mm mrad, 1000 ps), BOEING[35] buncher (350 A, 42-64 π mm mrad, 14 ps), ALS Berkeley[18] buncher design (200 A, 160 π mm mrad, 20 ps), LANL[8] buncher (300 A, 240 π mm mrad, 30 ps), SLC[27] buncher (430-580A, 170-300 π mm mrad, 18 ps), CLIO[21] buncher design (100 A, 30 π mm mrad, 15 ps). It can be seen that bunchers increase the brightness of the gun by one order of magnitude. The regions corresponding to FEL and linear colliders requirements appear in figure 6. The brightness of a 1 cm^2 typical thermionic cathode with a current density of 30 A/cm^2 is also given showing that in a conventional accelerator, the brightness of the beam is much lower than the brightness of the cathode

During their travel from the cathode to the end of the accelerator, electrons undergo several physical mechanisms that contribute to the dilution of the phase space and to the current limitation. These mechanisms are essentially space charge effects, RF dynamics effects, beam induced effects (beam breakup, wake fields) and transport aberrations[33]. The first two effects have the strongest influence when the beam is at low energy i.e. within the injector. Beam induced effects and transport aberrations act on the beam within the linac and are more or less harmful depending on several parameters including the linac tank length, the peak current, the cavity design and the alignment.

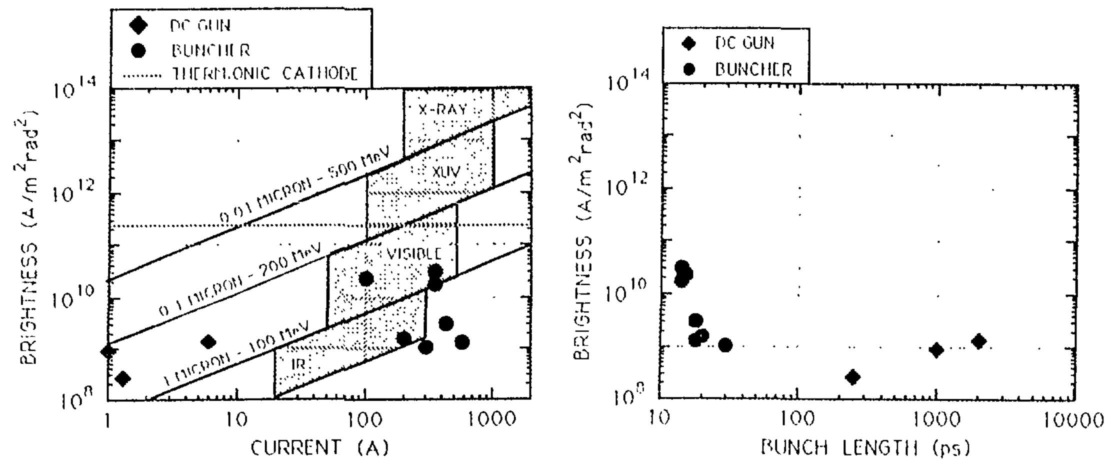

Fig. 6: Conventional injector brightness

While non-relativistic, electrons are very sensitive to space-charge forces. This argument favours a very high field in the gun to minimize the duration of the non-relativistic motion. Because DC fields are practically limited, this requirement suggests the use of RF fields for the gun.

Within the buncher, electrons experience both longitudinal RF dynamics effects (which are necessary to bunch the pulse) and transverse RF dynamics effects. Both effects lead to emittance growth. A better solution would be to generate very short pulse from the gun itself which means to imagine a new type of gun.

Preserving cathode brightness necessarily means avoiding the use of low accelerating field and buncher system. A new type of injector is clearly required that would allow:

- **high accelerating gradient**
- **very short bunch production from the cathode.**

IV. RF GUNS

For several decades already, microtron accelerators have used cathodes directly located in the RF cavity[34]. Once emitted, the electrons are then quickly captured and accelerated. G.A. Westenskow and J.M.J. Madey proposed to apply this solution to linac injectors[36], by putting a thermionic cathode in a pill-box type cavity, thus allowing high accelerating gradient at the cathode.

The short bunch production remained a problem. To solve it, it was necessary to find a way to externally induce electron emission only during a very short time. A laser illuminating a photocathode revealed itself as a good way to do so. Laser-driven RF gun, which was initiated at Los Alamos[48,57] seems to be the ideal way to produce high-brightness beams.

The following paragraphs will describe briefly the principle and main difficulties of the three types of RF gun now under development around the world.

IV.1. Thermionic RF gun

A thermionic cathode is placed within an RF cavity as shown in figure 7. Electrons are continuously emitted by the cathode but can only be extracted and accelerated during half an RF cycle. The electrons, emitted during the accelerating half-cycle, but with a too large phase (typically larger than 100°) do not have enough energy to reach the cavity output and are accelerated backward to the cathode.

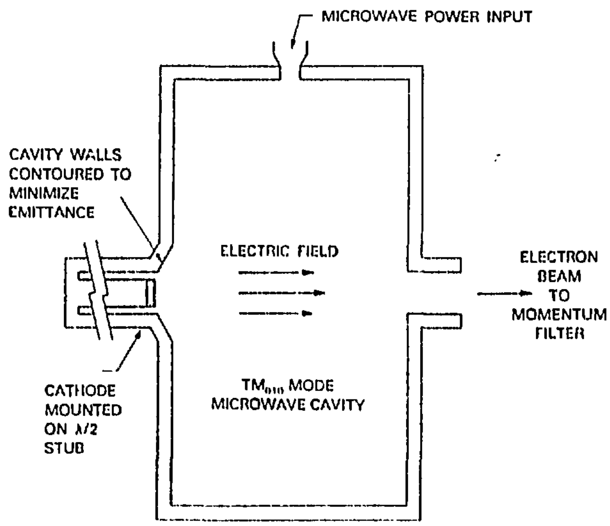

Fig. 7: Thermionic RF gun (from reference 36)

The pulse that can actually exit the cavity is very long (about one fourth of the RF period) and has a very large energy spread. It is thus necessa.y to place after the gun a magnetic bunching system (eg: an "α-magnet") with energy slits to reduce the pulse length, increase the peak current and select a given energy spectrum. A typical thermionic RF gun injector set-up is shown in figure 8.

Thermionic RF guns present several limitations. The back bombarded electrons heat the cathode thus leading to a current increase during the macropulse. This is not suitable for FEL operation that needs constant current. In the long term operation, back bombardment also destroys the cathode. Including a transverse magnetic field at the cathode provides a partial solution to this problem[37]. The long bunch and large energy spread are obvious limitations. They require the use of a magnetic bunching system which induces emittance growth and particle losses. The thermionic cathode can only provide a limited current density.

Thermionic RF guns can produce bright beams but they are not likely to produce very high peak currents.

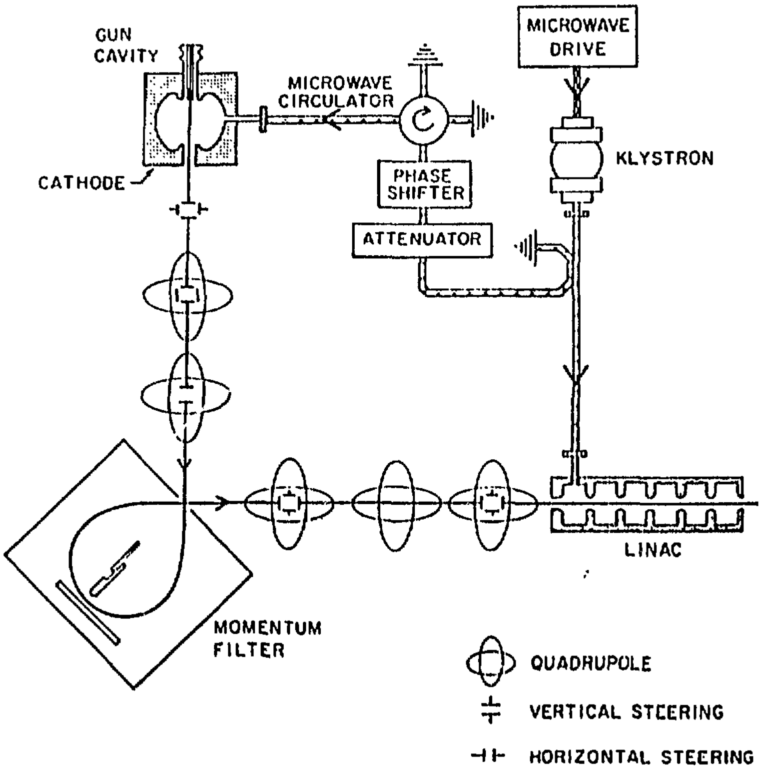

Fig. 8: Thermionic RF gun lay-out (from reference 41)

IV.2. Laser-driven RF guns

A photocathode placed in an RF cavity is illuminated by a laser which delivers short pulses as shown in figure 9. As they leave the cathode, electrons are already bunched. The cavity is shaped and the laser phase with respect to RF is chosen to minimize the emittance.

Beside the advantages already mentioned (high field, bunched beam), laser-driven guns have other attractive features. The pulse format is more flexible than that of conventional injectors (where only one RF bucket out of several can be filled) and that of thermionic RF guns (where all buckets are filled): the electron beam pulse format depends essentially on the laser pulse format which can be varied over a wide range. Photocathodes can deliver much higher current densities than thermionic cathodes: more than 400 A/cm^2 has been reported[49]).

The ideal photocathode should have a good quantum efficiency (number of emitted electrons per incident photon), a good lifetime and be relatively easy to prepare. So far, it is not yet clear what is the best material for the photocathode. Several types have been studied including semiconductor, metallic, needle and thermionic cathodes. Each type has its own limitations.

- semiconductor cathodes like $AsGa$ (SLAC[114]), Cs_3Sb and CsK_2Sb (LANL[54,58]) have very high quantum efficiency and can thus produce very high current densities. They are not easy to prepare and require a great experience and a good knack. They need very good vacuum and have a rather short lifetime. This lifetime is very much dependent on the operating conditions (pulse format, vacuum, laser power,...). Cesiated photocathodes mainly studied at Los Alamos are now experimented in different laboratories. $AsGa$ photocathodes are mainly used for polarized beams.
- metallic cathodes like yttrium or copper (BNL[93]) have a low quantum efficiency and high reflective properties. They can sustain high fields and have long lifetime.
- single needle or array of needles cathodes can be made of different materials (metals like W or Nb_3Ti, carbon). They produce very high currents by photofield emission[99]. However these currents are not very stable. These cathodes are also easily destroyed by thermal effects.
- thermionic cathodes can also work as photocathodes with a quantum efficiency not as good as semiconductor cathodes but somehow better than metallic cathodes. LaB_6 cathodes were used at Stanford for the operation of the first FEL ever driven by a photoinjector[38]. (W, Ba, Ca) cathodes are now being tested at LAL Orsay and are promising[106].

Several other types of photocathodes are also studied.

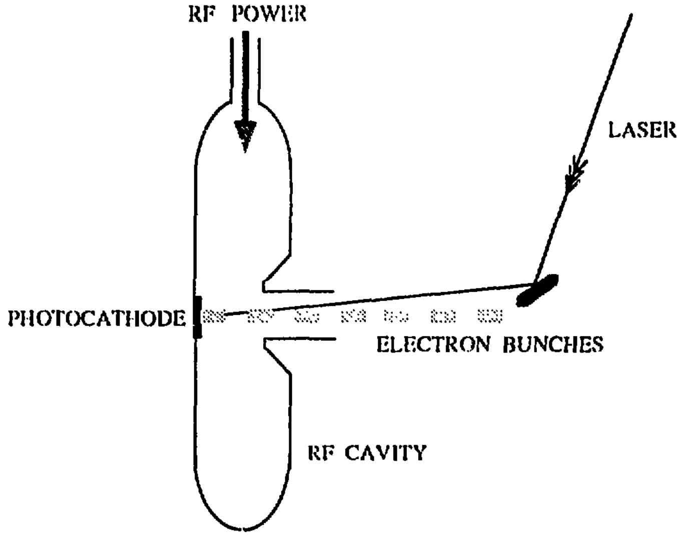

Fig. 9: Laser-driven RF gun

Another difficulty of photoinjectors is the laser. It should provide very short pulses, at the wavelength corresponding to the photocathode spectral response. Given the photocathode quantum yield, the laser micropulse should carry enough energy to extract the desired charge. Laser should be easy to synchronize with RF, i.e. it should be triggered at a determined phase of the RF signal with very small timing jitter. The laser pulse shape should be as uniform as possible in both transverse and longitudinal directions[70]. Most applications requires stable trains of similar micropulses. To obtain long trains of energetic pulses requires high average power lasers which are very difficult to fabricate and thus very expensive.

Lasers allowing the operation of photoinjectors are working in different laboratories and almost fulfill the above conditions. However, some more work is necessary to bring them to a high level of reliability, especially when long stable trains of uniform micropulses are required.

Photoinjectors are very promising candidates for bright injectors. Many laboratories around the world are involved in the R&D needed to solve the remaining technical problems.

IV.3. Field emission RF guns

When placed in a high field, sharp needles can produce electrons by the so-called field emission process. This principle can be used in a RF gun. The difficulty is to find stable operating conditions. When high current is emitted, the needle is heated and easily destroyed.

IHEP Beijing once studied such a gun[42]. LAL Orsay tried to experiment it by putting a needle in a triperiodic 3 GHz, $2\pi/3$ mode buncher[100,101,102]. High currents were accelerated but it was difficult to find stable and reproducible operating conditions.

Field emission RF guns seem not likely to have a brilliant future.

V. Worldwide review of RF gun projects

Following the "pioneers"[36,55], many laboratories launched R&D programs on RF guns. Some are already producing experimental results while others are still at the preliminary design stage. Reviewing all these projects is a difficult task, due to the fast changing situation (many information will be obsolete at the time of publication[1]) and the lack of literature for the most recent projects. Thus, the review presented here is probably incomplete and for some cases not up-to-date. May those who will not find their work reported here or who will find it reported inaccurately, be comprehensive and believe that they are not the subject of a special "censure". Another difficulty met during this review was to produce consistent lists of parameters in order to fairly compare the different projects. Each author uses his units and definitions of the parameters and often all the parameters are not given for the same operating conditions.

The following conventions are assumed. Design data for emittance are always given according to equation (1). When an author uses a different definition, necessary adjustments are made. Experimental data are reported as given in the publications. Since in some cases, real beams have much longer tails than ideal beams and have not necessarily gaussian or uniform profile, the emittance as given by equation (1) might not be appropriate to describe them.

For laser-driven guns, the micropulse length is taken as $4\sigma_b$, where σ_b is the rms bunch length. Rms definition ($1\sigma_b$) is adopted for thermionic guns because of the pulse shape which has a long tail and a very sharp front end. In this case, $1\sigma_b$ includes most of the particles.

Table 3

PROJECT NAME	LABORATORY	LOCATION	COUNTRY
THERMIONIC RF GUNS			
MARK III → ?	HEPL → SPRL → DFELL	STANFORD → DURHAM	USA
BFELP	IHEP	BEIJING	CHINA
	MITSUBISHI E.C.		JAPAN
	IPT	KHARKOV	USSR
	AET/VARIAN/SSRL	STANFORD	USA
	KEK	TSUKUBA	JAPAN
	NCCU	DURHAM	USA
LASER-DRIVEN RF GUNS			
	LANL	LOS ALAMOS	USA
HIBAF	LANL	LOS ALAMOS	USA
	SPRL → DFELL	DURHAM	USA
ELSA	CEA	BRUYERES	FRANCE
BATF	BNL	BROOKHAVEN	USA
CTF	CERN	GENEVA	SWITZERLAND
AWA	ANL	ARGONNE	USA
SPSHB	BUGW	WUPPERTAL	GERMANY
TEUFEL	TU/EU/UCN	ENSCHEDE	THE NETHERLANDS
MCTD	BOEING	SEATTLE	USA
AFEL	LANL	LOS ALAMOS	USA
ELFA	INFN	MILAN	ITALY
	LAL	ORSAY	FRANCE
ARES	INFN	FRASCATI	ITALY
1 GeV TEST	LLNL/SLAC/LBL	BERKELEY	USA
FIELD EMISSION RF GUNS			
	LAL	ORSAY	FRANCE
	IHEP	BEIJING	CHINA

Table 4

LABORATORY	STATUS JUNE 90	BEGINNING OF DESIGN	BEGINNING OF TESTS	PURPOSE
THERMIONIC RF GUNS				
HEPL → DFELL	TESTED	1983	2/85	FEL
IHEP	TESTED	6/86	2/88	IR FEL
MITSUBISHI	TESTED	?	?	?
IPT	TESTED	?	?	?
AET/VARIAN/SSRL	UNDER TESTS	1988 ?	1989	STO. RING INJ.
KEK	DES./CONST.	1989	1989	FEL/OTHER
NCCU	DES./CONST.	?	1991	MICROWAVE GEN.
LASER-DRIVEN RF GUNS				
LANL	TESTED	1984 ?	1985	RF GUN
LANL (HIBAF)	OPERATING	9/88	5/89	IR FEL
SPRL → DFELL	TESTED	1987 ?	9/88	FEL
CEA	UNDER TESTS	3/86	1989	IR FEL
BNL	UNDER TESTS	1987 ?	1989	NEW ACC. METH.
CERN	CONSTRUCTION	1989	1990	COLLIDER
ANL	CONSTRUCTION	1988	?	WAKEFIELD ACC.
WUPPERTAL	CONSTRUCTION	1987 ?	?	BRIGHT INJ.
TWENTE	CONSTRUCTION	?	?	FEL
BOEING	DES./CONST.	?	?	FEL
LANL (AFEL)	DESIGN	1988 ?	?	IR FEL
INFN MILAN	DESIGN	1988 ?	?	FEL
LAL	DESIGN	9/89	1991	RF GUN
INFN FRASCATI	DESIGN	?	?	Φ-FACT./FEL
LLNL/SLAC/LBL	STOPPED	1987	-	HIGH GRAD. ACC.
FIELD EMISSION RF GUNS				
IHEP	PREL. STUD.	1988 ?	?	FEL
LAL	STOPPED	1988	1/89	RF GUN

When only the charge Q and the bunch length τ are given, the peak current I is calculated in a conservative way assuming a uniform distribution ($I = Q/\tau$).

Table 3 lists the different projects for each type of RF gun: thermionic, laser-driven and field emission. Table 4 gives more detailed information such as project status and purpose. In the following the main projects are briefly described and their original features are outlined.

V.1. Stanford (HEPL) ⟶ Duke University (DFELL)

The first thermionic RF gun was built at Stanford High Energy Physics Laboratory (HEPL) by G.A. Westenskow and J.M.J. Madey[36]. The design work started in 1983. The gun was installed on the Mark III accelerator (dedicated to FEL studies) in February 1985. The klystron and modulator were installed in July 1985. The whole system (RF gun + linac + wiggler) was operated as a laser oscillator in September 1985. The system was then disassembled and moved to the Stanford Photon Research Laboratory where it was lasing again in September 1986. In August 1987, a new momentum filter which increased the peak current was installed. In September 1988, a new gun cavity allowed a more stable operation with longer RF macropulses (9 μs) repeated at a higher frequency (30 Hz). In November 1988, the same gun was operated as a photoinjector and led to the first successful operation of a photoinjector driven FEL[38]. The whole system was then disassembled again in December 1988 to be moved to Duke University Free Electron Laser Laboratory (DFELL) where it was scheduled to be operating again in 1990[39,40].

The thermionic gun consists of a LaB_6 cathode placed in an RF cavity operated at 2857 MHz. The cavity is followed by a transport system including an "α-magnet" with momentum filter and several quadrupoles, as shown in figure 9. In order to control the back bombardment, a transverse magnetic field at the cathode was added[37]. A very complete description of this gun is given in reference 41. A summary of the gun main parameters and performances is given in table 5. After the "α-magnet", 2 to 3 ps electron pulses corresponding to 20 to 40 A peak current are obtained with emittances as good as 4 π mm mrad in the vertical plane.

The same LaB_6 cathode was also used as a photocathode illuminated by a tripled Nd:YAG laser. Because the laser pulse length was still quite long (100 ps), the "α-magnet" was still necessary. Although the experiment was run for only a very short time, this photoinjector gave better results (in terms of current and emittance) than the thermionic gun[38]. The parameters and performances are given in table 6.

V.2. IHEP Beijing

Following Stanford, the Institute of High Energy Physics in Beijing (IHEPB), developed a thermionic RF gun to be used as an injector for the 30 MeV linac of the infra-red FEL[43]. The design work started in 1986[44,45] while the first tests begun in February 1988. The gun is now operating[46] with performances[47] close to that of Duke as shown in table 5.

Table 5: Thermionic RF guns parameters

	DFELL(1)	IHEP(1)	IPT(1)	SSRL(2)	KEK(2)
CATHODE	LaB_6	LaB_6	Ba-Ni	DISP.	LaB_6
CATHODE AREA (cm^2)	7. 10^{-2}	7. 10^{-2}		0.28	7. 10^{-2}
NUMBER OF CAVITIES	1	1	1	2	1
FREQUENCY (MHz)	2857	2856	2797	2856	2856
MAX. ON AXIS FIELD (MV/m)	55	50		60 - 80(3)	40
MAX. SURFACE FIELD (MV/m)	95	85		160	
FIELD AT CATHODE (MV/m)	40	30	60	15 - 20	40
MACROPULSE LENGTH (μs)	9	2	1.4	2	4
MACROPULSE FREQ. (Hz)	30	12.5			25
KINETIC ENERGY (MeV)	~ 1	0.7 - 0.9	0.5 - 0.9	1.7 - 2.5	
CHARGE (nC)	0.078	0.08 - 0.1		0.075	
RMS MICROPULSE LENGTH (ps)	2 - 3	4 - 5	3 - 5		
MICROPULSE FREQ. (Mhz)	2857	2856	2797	2856	2856
PEAK CURRENT (A)	20 - 40	10 - 20		1.5(4)	
NORM. EMIT. (π mm mrad)	10 (4)(5)	30 (10)(6)	≤ 20	44(4)	
NORM. BRIGHT. (10^{10} A/m^2rad^2)	20.3	1.35			
RMS ENERGY SPREAD (KeV)	220	200			

(1) EXPERIMENTAL RESULTS (GUN + α MAGNET)
(2) DESIGN PARAMETERS
(3) IN THE FIRST CELL: 20-30 MV/m
(4) NO α MAGNET
(5) HORIZONTAL (VERTICAL) EMITTANCE DEFINED AS FWHM: $\epsilon = 2\ln(2)\beta\gamma\pi\sigma\sigma'$
(6) HORIZONTAL (VERTICAL) EMITTANCE DEFINED AS: $\epsilon = \beta\gamma\pi x x'$

V.3. Mitsubishi E. C.

Mitsubishi Electric Company has reported the operation of a thermionic RF gun using a LaB_6 cathode[116].

V.4. Institute of Physics and Technology Kharkov

At the second European Particle Accelerator Conference, the Institute of Physics and Technology of Kharkov presented experimental results concerning a thermionic RF gun[117]. The main parameters are given in table 5.

V.5. AET-VARIAN-SSRL

AET Associates, Varian Associates and the Stanford Synchrotron Radiation Laboratory (SSRL) are collaborating to build a thermionic RF gun to be used both as an injector for Varian medical accelerators and for the new SPEAR pre-injector[118]. This gun consists of a one and a half cell side coupled cavity operating at 2856 MHz and using a high-performance, impregnated tungten dispenser cathode coated with an emission enhancing layer in order to lower the effective work function of the activated cathode material[25]. The choice of the ratio between the peak fields in the two cells is made to minimize the back bombardment power. The design parameters are summarized in table 5. The gun has recently been commissioned and works at the design performances producing a 1.5 A, 2 MeV beam.

V.6. KEK

In 1989, KEK started the design of a thermionic RF gun[119,120,121]. To limit the back-bombardment, an attempt is made to use a mesh grid to control the pulse length. Low power RF characteristics of the cavity have already been measured. The main parameters[122] are given in table 5.

V.7. Central University of North Carolina

The Central University of North Carolina (NCCU) is planning to build a thermionic RF gun in collaboration with Duke to be used as a submillimiter wave generator for material properties studies[16]. This gun will basically reproduce Duke's gun and should be commissioned in 1991.

V.8. Los Alamos National Laboratory

Since at least 1984, Los Alamos National Laboratory (LANL) is involved in R&D programs about laser-driven RF gun and related topics like lasertron.

In 1985, Lee et al. demonstrated the possibility of extracting high-current density (over 200 A/cm^2) from Cs_3Sb photocathode illuminated by a frequency doubled Nd:glass laser[49]. The first RF gun design[53] consisted of one cavity operating at 1.3 GHz and incorporating a Cs_3Sb photocathode illuminated by a frequency doubled Nd:YAG laser as shown in figure 10. The cavity shape was designed to minimize the nonlinear components of the radial electric field, assuming a DC approximation[50]. This gun produced a 1 MeV beam of 70 ps pulses with a peak current of 200 A and a normalized emittance of 40 π mm mrad[54].

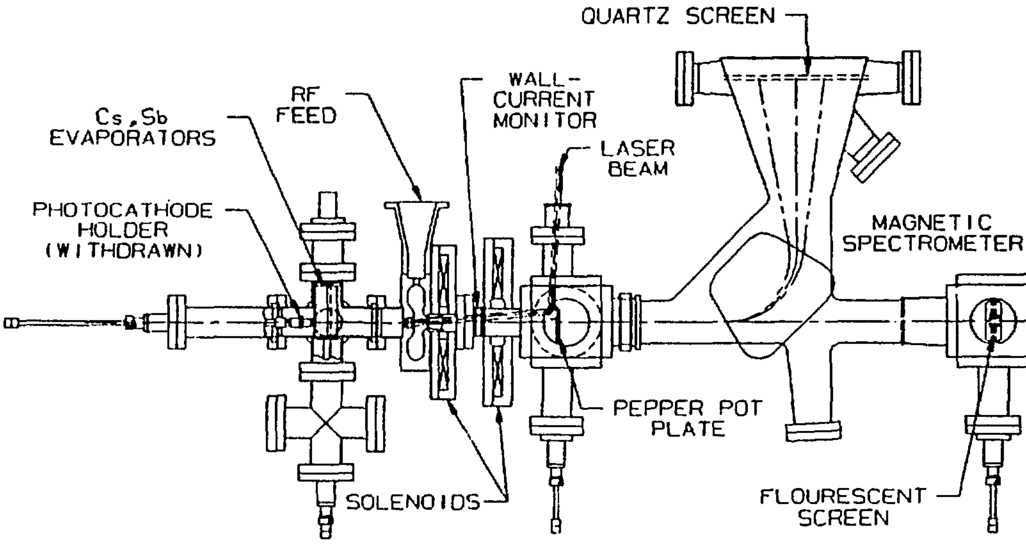

Fig. 10: LANL photo-injector set-up (from reference 55)

A second cavity independently powered and phased was then added to the original one[59]. Meanwhile, the adjunction of a pulse compressor to the laser allowed to generate 16 ps optical pulses. This new gun tested in 1987 and 1988, provided a 2.7 MeV beam[58]. The maximum extracted charge was 13.2 nC corresponding to a peak current of 600 A. No emittance measurement were possible due to the drift space between the second cavity and the "pepper pot" device that led to excessive space charge emittance growth.

During this period, the photocathode lifetime was significantly improved by replacing Cs_3Sb with CsK_2Sb. This lifetime remained though very dependent on the operating conditions. Table 6 summarizes the performances of the two experiments.

During the same period, experiments on RF lasertron were conducted[60].

Based on the gained experience, a new photoinjector was built to serve as an electron source for the HIBAF infra-red FEL[64,65,73]. This new gun which replaced the previous conventional injector is already working and provides a 350 A, 16 ps and 35 π mm mrad beam to the first half (20 MeV) of the linac recently commissioned[74]. This photoinjector has been designed for maximum flexibility in order to do parametrization studies for simulation codes verification[72]. Nominal performances[74] are given in table 6.

Because of the possible industrial use of FEL, it is interesting to develop a very compact device. This work has been undertaken by LANL[66]. A compact FEL named AFEL is now under design. The photoinjector will consist of several cavities powered by one RF source. All flexibility will be removed and the parameters will be chosen for an optimum design according to simulations. This injector should be able to produce a beam brightness of the order of 10^{12} A/m^{2}rad^2 (table 6).

LANL is also participating in the design and construction of photoinjectors for the Milan ELFA FEL[133] and the Twente University FEL[129].

LANL proposed several design for XUV FEL, using a photoinjector[56,61,62]. In view of

Table 6: Laser-driven RF guns parameters

	LANL				DFELL
	PHASE I[1]	PHASE II[1]	HIBAF[1]	AFEL[2]	[1]
LASER TYPE	Nd:YAG	Nd:YAG	Nd:YLF	Nd:YLF	Nd:YAG
LASER WAVELENGTH (nm)	532	532	527	527	355
LASER MICROPULSE LENGTH (ps)	70	16	5 - 30	10	100
LASER MICROPULSE ENERGY (μJ)			4.6		40
CATHODE	Cs_3Sb	CsK_2Sb	CsK_2Sb	CsK_2Sb	LaB_6
CATHODE AREA (cm^2)	1	1	0.5	0.5	
NUMBER OF CAVITIES	1	2	5 1/2		1
FREQUENCY (MHz)	1300	1300	1300	1300	2857
MAX. ON AXIS FIELD (MV/m)			26		55
MAX. SURFACE FIELD (MV/m)	58.9	58.9	59.8	60	95
FIELD AT CATHODE (MV/m)			26		40
MAGNETIC FOCUSING	YES	YES	YES	YES	
MACROPULSE LENGTH (μs)	20	10	10 - 100	10	3
MACROPULSE FREQ. (Hz)	1	10	1		10
KINETIC ENERGY (MeV)	1.1	2.7	6	15	~ 1
CHARGE (nC)	11	13.2	4	5	0.17
MICROPULSE LENGTH (ps)	70	22	15	16	2 - 3[3][4
MICROPULSE FREQ. (MHz)	108.33	108.33	21.67	21.67	95.2
PEAK CURRENT (A)	200	600	270	350	60 - 80[3]
NORM. EMIT. (π mm mrad)	40		35[5]	10	8 (4)[3][6
RMS ENERGY SPREAD (KeV)	66	380	50		300
NORM. BRIGHTNESS (10^{10} A/m^2rad^2)	2.53		4.47	70.9	50.7

(1) EXPERIMENTAL RESULTS
(2) DESIGN PARAMETERS
(3) WITH α MAGNET
(4) RMS VALUE (1σ)
(5) MEASURED AT 17 MeV
(6) HORIZONTAL (VERTICAL) EMITTANCE DEFINED AS FWHM: $\epsilon = 2\ln(2)\beta\gamma\pi\sigma\sigma'$

this application, very small emittances are required. B. Carlsten proposed a very powerful way to reduce the emittance of the injector[62,63,69]. After identifying the four different emittance growth mechanisms: (a) linear space charge, (b) nonlinear space charge, (c) nonlinear time independent RF effect, (d) linear time dependent RF effect, he shows that for a pulse produced by a laser, it is possible to remove most of the correlated emittance (variations in the transverse phase space correlated with longitudinal position) by a proper choice of position and strength of magnetic lenses. Such a theory is not applicable for conventional injectors since bunching introduces mixing between longitudinal and transverse phase space planes. AFEL design is based on this theory which has also been tried elsewhere[79,115].

V.9. CEA Bruyères-le-Châtel

The Commissariat à l'Energie Atomique (CEA) in Bruyères-le-Châtel (France) is building a laser-driven RF gun as an injector for a high-power infra-red FEL[75]. In order to improve the beam characteristics, a frequency of 433 MHz was chosen for the linac and a sub-harmonic frequency of 144 MHz is used for the gun[76,78]. For the first stage, one cavity is used providing a 1 MeV beam. Later, a second cavity will be added. Cs_3Sb and CsK_2Sb photocathodes are used at first. Other types are also tested[83]. The goal is to produce a 50-100 ps, 10-20 nC beam pulse. Design parameters[83] are summarized in table 7. Strong magnetic field are used to contain the beam. The strength and position of magnetic lenses are chosen according to B. Carlsten's theory to reduce the beam emittance[79]. This gun is now under testing. An accelerating field of 25 MV/m on the cathode has been obtained. 20 nC, 100 ps pulses have been accelerated to 1 MeV[80,82].

V.10. Brookhaven National Laboratory

In order to study several ideas related to future particle acceleration methods, Brookhaven National Laboratory (BNL) is building an Accelerator Test Facility (ATF)[84] which will also be used for FEL physics. The injector for the accelerator is a laser-driven RF gun operating at 2856 MHz[85,86]. It consists of a one and a half cell cavity incorporating a photocathode in the end wall of the first cell. The cavity shape was designed so that RF fields cause minimal nonlinear distortion of the phase space. This was obtained by using a Fourier decomposition of the RF fields and by setting the radial field to be linear[85]. Mechanical and RF designs of the cavity are reported in references 87 and 88. The transport system following the gun is described in references 89 and 92.

The gun is designed to operate with a 100 MV/m electric field at cathode. The laser will provide a 4 to 6 ps pulse. 1 nC is expected from the yttrium photocathode. The main design parameters are shown in table 7.

The gun has already been tested with a 20 ns pulse from an eximer laser[90]. A 90 MV/m accelerating field was obtained at the cathode. A peak current of 0.6 A was accelerated to 3.6 MeV. The picosecond Nd:YAG laser is now available and experiments will proceed soon[91].

Meanwhile, extensive studies of yttrium photocathodes are done[93].

Table 7: Laser-driven RF guns parameters

	CEA	BNL	CERN	ANL	BUGW
LASER TYPE	Nd:YAG	Nd:YAG	Nd:YLF		Nd:YAG
LASER WAVELENGTH (nm)	532	266	351/527	248 - 266	527
LASER PULSE LENGTH (ps)	30 - 100	6	6 - 50	1	70
LASER PULSE ENERGY (μJ)	10 - 20	100	500/2000	5000	0.01
CATHODE	CsK_2Sb	YTTRIUM	(1)	YTTRIUM	CsK_2Sb
CATHODE AREA (cm^2)	1 - 2	0.28	~ 1	~ 3	1.13
NUMBER OF CAVITIES	1	1 1/2	1 1/2	1	1(2)
FREQUENCY (MHz)	144.4	2856	3000	1300	500
MAX. ON AXIS FIELD (MV/m)	20	100(3)	100		25
MAX. SURFACE FIELD (MV/m)	23.2	118	134	120	30
FIELD AT CATHODE (MV/m)	20	100	100	92	25
MAGNETIC FOCUSING	YES	NO	NO	YES	
MACROPULSE LENGTH (μs)	400	3.5	≤ 4.5	8	CW
MACROPULSE FREQ. (Hz)	10 - 20	6	10	30 - 60	-
KINETIC ENERGY (MeV)	1.3 - 1.5	4.17	3.9	2	1.87
CHARGE (nC)	1 - 20	1	9	100	2.5
MICROPULSE LENGTH (ps)	~ 100	8	30	8	70
MICROPULSE FREQ. (MHz)	14.4 - 72.2	80	1 PULSE	1 PULSE	125
PEAK CURRENT (A)	150 - 200	125	400 - 500	10^4	35
NORM. EMIT. (π mm mrad)	90(4)	46	≤ 150	1360	
RMS ENERGY SPREAD (KeV)		17	80	400	
NORM. BRIGHT. (10^{10} A/m^{2}rad^2)	0.25	1.2	≥ 0.45	0.11	

(1) METALLIC OR MULTI-ALKALINE
(2) SUPERCONDUCTING CAVITY
(3) EXPERIMENTAL DATA: 90 MV/m
(4) EXPERIMENTAL DATA FOR 10 nC

V.11. CERN

CERN is involved in an R&D program on future high-energy linear colliders[11], the goal being to be able to make a realistic proposal in a very near future. In order to study the injector for the drive linac, CERN is now building an injector test facility named CLIC Test Facility (CTF)[94]. To proceed quickly, CERN is reproducing BNL design for the gun cavity[96]. The expected parameters are nevertheless different since for the CLIC drive linac peak current is more important than emittance. The parameters for the "nominal case"[98] are given in table 7. The transport following the gun is described in reference 97.

In the meantime, semiconductor photocathodes are studied in a DC configuration[95].

V.12. Argonne National Laboratory

Argonne National Laboratory (ANL) is proposing a wakefield accelerator facility (AWA) to demonstrate the feasibility of a true high energy wakefield accelerator[123,124]. For this facility, a L-band photoinjector is being designed. Parameters[125] are shown in table 7. In order to induce wakefields at the level of 100 MV/m, the gun should provide 100 nC, 10 ps bunches. In this case, the emittance can not be kept very small. A cuplike laser wavefront is produced to reduce the bunch length. A low level model cavity was built and measured. Construction of the final prototype will proceed soon.

V.13. Bergische Universität-Gesamthoschule Wuppertal

The originality of this RF gun project is the use of a superconducting niobium cavity operating at 500 MHz[126,127]. The Cs_3Sb photocathode is illuminated by a frequency doubled Nd:YLF laser. Using a superconducting cavity has several advantages. First, it can be operated continuously leading to a CW microbunched electron beam; the cavity shape can be designed for emittance minimization without caring for the shunt impedance; finally, the cryogenic environment helps to achieve very good vacuum necessary for obtaining a long lifetime in the case of semiconductor photocathodes. This project which design parameters[128] are summarized in table 7 is now under construction.

V.14. Twente-Eindhoven-UCN

Twente University, Eindhoven University and Ultra Centrifuge Nederland (UCN) free-electron laser (TEUFEL) will use a racetrack microtron feed by a 6 MeV photoinjector[129,130]. This gun will be made of 6 cavities operating at 1300 MHz and using semiconductor or metallic photocathodes. It will be built at Los Alamos. Design parameters[131] are listed in table 8.

V.15. BOEING

Boeing Aerospace is building a 8 MeV electron linac within its Modular Component Technology Development program to test accelerator component for FEL usage[132]. As part of this program a two cavity 433 MHz photoinjector is being designed. 25% duty factor operation is foreseen. Design parameters are presented in table 8. A model cavity was built and measured.

Table 8: Laser-driven RF guns parameters

	TWENTE	BOEING	MILAN	LAL	FRASCATI	LBL
LASER TYPE	Nd:YLF		Nd:YLF		Nd:YLF	Nd:YAG
LASER WAVELENGTH (nm)			526			532
LASER PULSE LENGTH (ps)			150 - 200	30	20/40	15
LASER PULSE ENERGY (μJ)			20		0.17/17	0.5
CATHODE	CsK_2Sb		CsK_2Sb	DISP.	Cs_3Sb	Cs_3Sb
CATHODE AREA (cm^2)	1	0.63	7	0.28		0.28
NUMBER OF CAVITIES	5 1/2	2	1 1/2	2	3(1)	2 1/2
FREQUENCY (MHz)	1300	433.5	352	2998.5	499.5	1269
MAX. ON AXIS FIELD (MV/m)		38.6	15	70		60
MAX. SURFACE FIELD (MV/m)			22.5	112		67.2
FIELD AT CATHODE (MV/m)	25			52.5	30 - 40	60
MAGNETIC FOCUSING	YES	YES	YES	NO		NO
MACROPULSE LENGTH (μs)	10			2 - 5	CW	0.02
MACROPULSE FREQ. (Hz)	10		> 50	10	-	1 - 5
KINETIC ENERGY (MeV)	6	1.92	3.6	2.9	3.8/6.8	10
CHARGE (nC)	7	10	80	2	0.5/20	1
MICROPULSE LENGTH (ps)	20	60	200	17	21/42	4 - 12
MICROPULSE FREQ. (MHz)	81.25		352		$10^{-3}/3\ 10^{-5}$	423
PEAK CURRENT (A)	350	167	400	118	18.5/350(2)	118 - 212
NORM. EMIT. (π mm mrad)	17	90	640	34	22/424	30 - 50
RMS ENERGY SPREAD (KeV)	50	80	60	< 30	34/195	20 - 30
NORM. BRIGHT. (10^{10} A/m^2rad^2)	24.5	0.42	0.02	2.07	0.77/0.04	1.7 - 2.7

(1) SUPERCONDUCTING CAVITIES
(2) BEFORE MAGNETIC BUNCHING

V.16. INFN Milan

The ELFA FEL project[133,134] in Milan will also use a photoinjector made at Los Alamos. This one will consist of only two cavities operating at 352 MHz. This injector will produce 200 ps, 400 A electron pulses. The main parameters are given in table 8. The design will be completely defined at the end of 1990.

V.17. Laboratoire de l'Accélérateur Linéaire Orsay

The Laboratoire de l'Accélérateur Linéaire in Orsay (LAL) is designing a two cavities S-band photoinjector[105] that will use a dispenser cathode as a photocathode[106]. The use of such a cathode will also allow the thermionic operation of the gun. The first cavity is designed to minimize the linear RF dependent effects on emittance[103] because it is envisaged to accelerate relatively long bunches (up to 30 ps). The second cavity independently powered and phased is used to reduce the energy spread. The design includes many knobs to allow a detailed study of RF gun physics. A typical set of parameters used for present simulation is given in table 8. A model cavity is now under construction.

V.18. INFN Frascati

The Frascati ARES project of Φ-factory will use a superconducting linac injector with a laser-driven RF gun[135]. This linac could also be used for high gain single pass FEL studies. The gun will be made of two and a half 500 MHz superconducting cavities. A extra decoupled half cavity is used to recover the RF induced emittance. Two operation modes are foreseen: low charge and high repetition rate and high charge, low repetition rate. A two stage magnetic bunching system is used to further increase the current up to 400 A still keeping a very small emittance. The main design parameters corresponding to the two modes of operation are given in table 8.

V.19. Livermore-Stanford-Berkeley

As part of an experimental program from the Livermore-Stanford-Berkeley (LLNL-SLAC-LBL) collaboration on the relativistic klystron, an RF gun design was presented in 1988[108]. This gun is made of two and a half cell cavity operating at 1269 MHz with a Cs_3Sb photocathode. The cavity shape is the same as that of BNL. Several sets of parameters were studied[110,111] (table 8). For this study, K.J. Kim developed a powerful analytic theory of RF gun dynamics in the case of very short pulses[109,112]. This project was finally stopped for lack of funding[113].

V.20. State of the art

Figure 11 shows the normalized peak brightness of RF guns (both thermionic and laser-driven) as a function of the peak current and bunch length. The FEL and collider requirements are plotted. These figures are only indicative and should be used with some care. A few general conclusion can though be drawn. Thermionic RF guns can produce very high brightness but give only limited peak current when compared to conventional injectors.

Their pulse length is however shorter. Laser-driven guns can produce high current and very bright beams, somewhat better than conventional injectors. Recent optimized designs show that laser-driven guns could produce beam brightness more than one order of magnitude higher than that of the best conventional injectors. Needed performances for X-ray FEL or colliders are not yet reachable. It is worth reminding here that laser-driven gun advantages also include a more flexible pulse format.

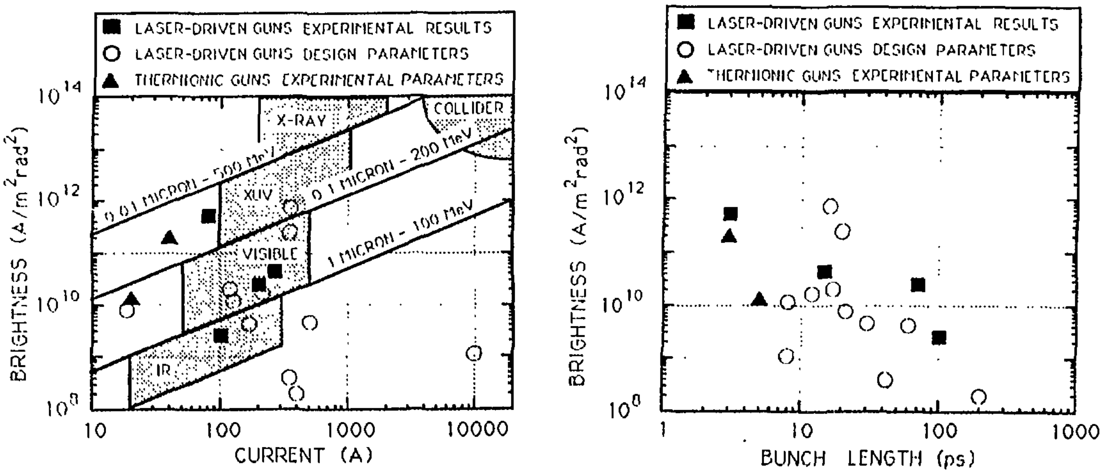

Fig. 11: RF gun brightness

Figure 12 shows the maximum on axis and surface electric field used in the different projects as a function of the frequency. The practical limit corresponding to two times the Kilpatrick criterion[4,5] is also shown. Figure 13 shows the bunch length versus the RF frequency. For almost all the projects the bunch length is less than one twentieth of the RF period. Such short beam are necessary to reduce the RF induced emittance growth.

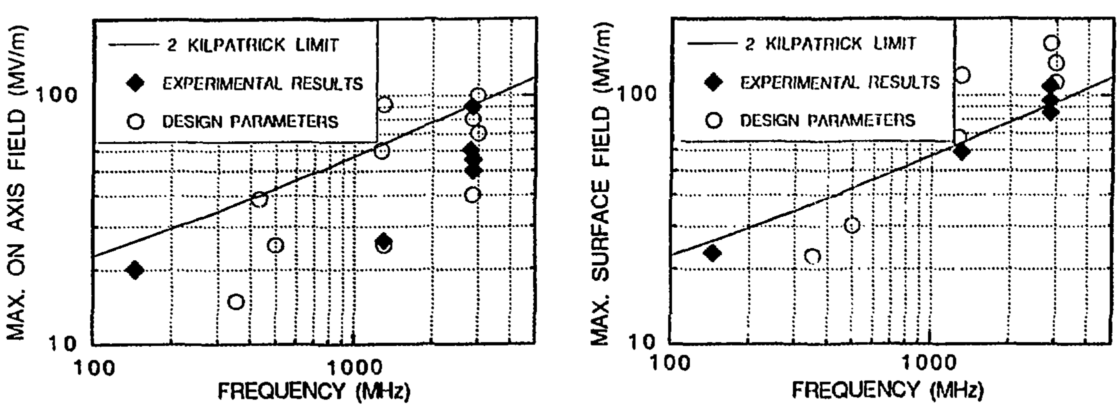

Fig. 12: Maximum electric field

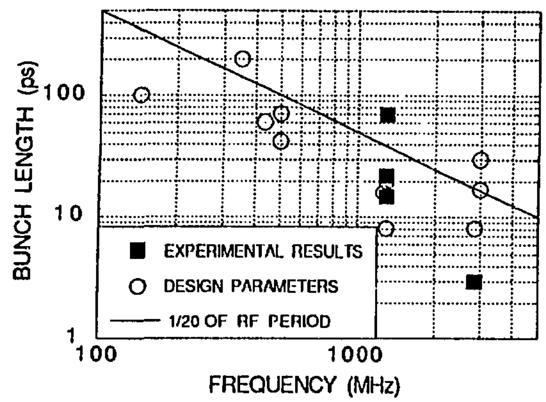

Fig. 13: Bunch length

VI. RF GUN DESIGN PHILOSOPHY

To design a bright injector, it is necessary to maximize the current and minimize the emittance. Meanwhile a short pulse is often required. In order to obtain the best performances, it has been shown that one should consider both the RF gun itself (one or more cavities) and the transport line (magnetic lenses).

For the gun, the parameters to choose are: the number of cavities, the RF frequency, the cavity shape (electric field profile, ratio between maximum on axis field and surface field, RF focusing), the accelerating gradient of each cavity, the phase shift between cavities, the cathode material and size, the laser phase. The beam transport design includes the number, location and strength of the magnetic lenses, the location of the measurement devices.

It is out of the scope of this review to give a complete optimized bright injector design. However from simple scaling laws proposed by K.J. Kim[112)], one could pick up some ideas showing the trend. For gaussian distributions and short pulses, the emittance contribution due to RF fields (ϵ_{RF}) and space charge forces (ϵ_{sc}) expressed in π mm mrad are given by:

$$\epsilon_{RF} = \frac{4\sqrt{2}\pi^2 c E_0 f^2 \sigma_x^2 \sigma_b^2}{m_0 c^2} = 1.09\ 10^{-10} E_0 f^2 \sigma_x^2 \sigma_b^2 \quad (2)$$

$$\epsilon_{sc} = \frac{2\pi m_0 c^2 I c \sigma_b}{c E_0 I_A sin\Phi_0 (3\sigma_x + 5c\sigma_b)} \simeq 56.7 \frac{I\sigma_b}{E_0(3\sigma_x + 1.5\sigma_b)} \quad (3)$$

where f is the RF frequency in MHz, E_0 the maximum gradient in MV/m supposed the same in all cells, I the peak current in A, σ_b the rms bunch length in picoseconds, σ_x the rms transverse beam size in millimeters and I_A the Alfvén current. For short bunches, $sin\Phi_0 \sim 1$. The real bunch length is equal to 2 to 4 σ_b depending on the beam longitudinal distribution.

As ϵ_{RF} is proportional to E_0 and ϵ_{sc} inversely proportional to E_0, the minimum emittance is obtained when $\epsilon_{RF} = \epsilon_{sc}$. The optimum E_0 that minimizes the emittance is then:

$$E_0 = E_{opt} = 7.2\ 10^5 \frac{\sqrt{I}}{f\sqrt{(3\sigma_x + 1.5\sigma_b)}\ \sigma_x \sqrt{\sigma_b}} \tag{4}$$

The minimum emittance is equal to:

$$\epsilon_{min} = \epsilon_{RF} = \epsilon_{sc} = 1.57\ 10^{-4} \frac{\sqrt{I} f \sigma_x \sigma_b^{3/2}}{\sqrt{(3\sigma_x + 1.5\sigma_b)}} \tag{5}$$

These formulas show the dependence of ϵ_{min} and E_{opt} with the frequency, the current and the transverse and longitudinal sizes of the bunch.

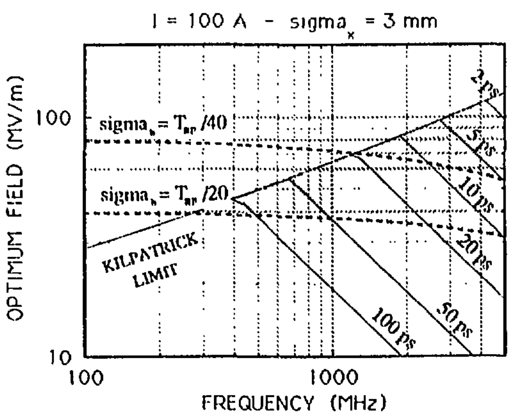

Fig. 14: Optimum electric field

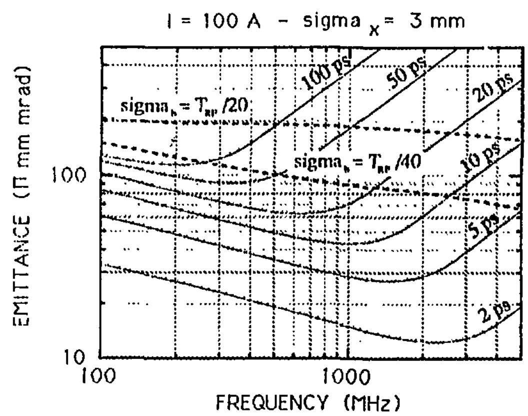

Fig. 15: Minimum emittance

Figure 14 shows the optimum field necessary to minimize the emittance as a function of the frequency for a current of 100 A, a bunch size σ_x of 3 mm and different pulse lengths. Since the above formulas are only valid for short pulses, fractions of the RF period are shown to indicate what are the reasonable bunch lengths to consider. The practical limit of two times the Kilpatrick value is also represented showing that it is not always possible to reach the optimum field. From this picture it appears that low frequency requires very high field.

The corresponding minimum emittance is shown in figure 15. When the optimum field is higher than the practical limit, the emittance is calculated for this practical field limit and thus is not the minimum but only the best achievable emittance for the given conditions.

For the sake of simplicity a constant beam size was assumed for all frequencies. Actually the beam size can be varied with the frequency. Larger beam sizes are possible at lower frequencies thus reducing the corresponding optimum field.

Figures 14 and 15 provide a quick estimate of RF gun performances. For higher current, the results are easily scaled since both E_{opt} and ϵ_{min} are proportional to the square root of the current. When very short pulses and high current are required, two designs are possible[72]:

a high frequency (> 1 GHz) design for which short pulses are directly produced with short laser pulses and a low frequency (< 1 GHz) design for which long pulses are produced in the gun and then compressed in a magnetic bunching system. High frequency designs work in the RF emittance regime while low frequency designs work in the space charge emittance regime.

The above simple formulas do not give any guidance on how many cells to use for an optimized RF gun. Los Alamos recent design favours many cells to accelerate the beam up to more than 15 MeV. At this energy the beam is very stiff and not subject to space charge forces any more.

Kim's formalism does not take into account the effect of magnetic lenses. B. Carlsten gave simple formulas[62,63)] to estimate the position and strength for these lenses as required to minimize the emittance at a given location.

Though powerful, these simple formalism are not sufficient to describe the complex RF gun physics. While designing a RF gun, computer codes should be used. Many codes are available for this purpose. The most widely used are: PARMELA[136)], MASK[137)], TBCI-SF[138)], PRIAM[139)], ITACA[140)], RFGUN[141)], OAK[142)], ATHOS, EM-LEL, VLAMINCK[81)].

VII. Novel ideas

A few novel ideas were recently presented in the field of high-brightness injectors. Though they might seem exotic, it was interesting to mention them.

VII.1. Extra cavity to reduce emittance

As mentioned earlier, the Frascati design includes a separately phased extra half cavity used to compensate the RF induced emittance[135)]. This extra cavity allows to have the injection phase as a free parameter. It is then possible to exit of the gun with the minimum emittance and a small divergence, which is not the case for the normal RF gun according to K.J. Kim's formalism[112)]. This idea was also separately studied at LAL by J. Gao[104)] who is also proposing to use an unsymmetrically cylindrical cavity for the same purpose[107)].

VII.2. Electron RFQ

The well known RFQ concept used for heavy-ions injectors is applied to the design of an electron source[143)].

VII.3. Space-charge compensated RF gun

Space-charge forces within the electron beam can be cancelled by an appropriate energetic positron beam injected from the back of the gun through the photocathode. This scheme increases the brightness by at least two orders of magnitude[144)].

VIII. CONCLUSION

During the last five years, an increasing interest for RF guns was shown in many laboratories as can be seen in figure 1.

After the first encouraging results obtained at Stanford and Los Alamos that proved the feasibility of the concept, other laboratories are now producing experimental results (CEA, BNL) for photoinjectors and (Beijing, Mitsubishi, SSRL, Kharkov) for thermionic guns. Moreover several other laboratories will be ready very soon for experiment (Wuppertal, CERN, LAL, ANL, Twente, Frascati, Milan, KEK...)

The multiplicity of experiments will allow to cross-check the results. The increasing endeavour on the subject will certainly produce adequate solutions for the remaining technical difficulties within a few years. RF guns will then leave the R&D phase to enter the routine operation stage. They will thus be definite and reliable candidate injectors for almost any kind of linear accelerators that will be built from then onward.

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REFERENCES

Abbreviations

NIM: Nuclear Instruments and Methods in Physics Research.

PAC87: Proceedings of the 1985 IEEE Particle Accelerator Conference, Vancouver, BC, May 13-16, 1985, IEEE Transactions on Nuclear Science, Volume NS-32, Number 5.

LAC86: Proceedings of the 1986 Linear Accelerator Conference, Stanford, CA, June 2-6, 1986, SLAC-Report-303, September 1986.

PAC87: Proceedings of the 1987 IEEE Particle Accelerator Conference, Washington D.C., March 16-19, 1987, IEEE 87CH2387-9.

EPAC88: Proceedings of the 1988 European Particle Accelerator Conference, Rome, June 7-11, 1988.

LAC88: Proceedings of the 1988 Linear Accelerator Conference, Williamsburg, VA, October 3-7, 1988, CEBAF-Report-89-001, June 1989.

PAC89: Proceedings of the 1989 Particle Accelerator Conference, Chicago, IL, March 20-23, 1989.

FEL89: Proceedings of the 1989 FEL Conference, Naples, FL, 1989, to be published in Nuclear Instruments and Methods.

JAP89: Proceedings of the 14^{th} Meeting on Linear Accelerator, Nara, Japan, September 7-9, 1989.

EPAC90: Proceedings of the 1990 European Particle Accelerator Conference, Nice, June 12-16, 1990, to be published.

FEL90: Proceedings of the 1990 FEL Conference, Paris, September 17-21, 1990, to be published in Nuclear Instruments and Methods.

General

[1] paper submitted on August 10, 1990.

[2] C. Lejeune, J. Aubert, "Emittance and Brightness: Definitions and Measurements", Applied Charged Particle Optics, Ed. A. Septier, Advances in Electronics and Electron Physics, Supp. 13A, Academic Press, New York, 1980.

[3] J.M. Kapchinskij, V.V. Vladimirskij, "Limitations for Proton Beam Current in a Strong Focusing Linear Accelerator Associated with the Beam Space Charge", Proceedings of the International Conference on High Energy Accelerators, CERN 1959, p. 274.

[4] W.D. Kilpatrick, "Criterion for Sparking Designed to Include both RF and DC", Rev. Sci. Instrum., 28, p. 824, 1957.

[5] S.O. Schriber, "Factors Limiting the Operation of Structures Under High Gradient", LAC88.

RF gun applications

[6] D.A.G. Deacon, L.R. Elias, J.M.J. Madey, G.L. Ramian, H.A. Schwettman, T.I. Smith, "First Operation of a Free Electron Laser", Phys. Rev. Lett., vol. 38, pp. 892-894, 1977.

[7] J.C. Golstein, "Electron Beam Requirements for Soft X-Ray/VUV Free Electron Laser", in ICFA Workshop Proceedings, BNL 52090, 1987.

[8] S. Penner, "RF Linac Based Free Electron Lasers", PAC87, p. 183.

[9] M.W. Poole, "Infra-red FELS", Proceedings of the CERN Accelerator School, Chester, 6-13 April 1989, CERN 90-03, p. 306, 1990.

[10] W. Schnell, "New Developments in Accelerator Technology", CERN-LEP-RF/89-70, 1989.

[11] H. Henke, "Study Work on the CERN Linear Collider (CLIC)", CERN-LEP-RF/89-62, 1989.

[12] T. Nakada, "Feasibility Study for a B-meson Factory in the CERN ISR Tunnel", CERN 90-02, PSI RP-90-08, 1990.

[13] "Investigation of an Asymmetric B Factory in the PEP Tunnel", LBL PUB-5263, SLAC-359, CALT-68-1622, 1990.

[14] J. Gonichon, J. Le Duff, B. Mouton, C. Travier, "Preliminary Study of a High Luminosity e^+e^- Storage Ring at a C.M. Energy of 5 GeV", LAL/RT 90-02, 1990.

[15] J. Belloni, "Projet d'action concertée en vue de la création d'un centre de cinétique rapide", in french, unpublished, Laboratoire de Physico-chimie des Rayonnements, Orsay, 1990.

[16] C.R. Jones, "NCCU Project Overview. A Novel Electron Beam Source for the Far-Infrared", unpublished, North-Carolina Central University, 1990.

Conventional injectors

[17] J.C. Sheppard et al., "Commissioning of the SLC Injector", SLAC-PUB-4099, 1986.

[18] R.H. Miller, C.H. Kim, F.B. Selph, "Design of a Bunching System for a High Intensity Electron Linac", LBL-25237, ESG-41, 1988.

[19] J.M. Ortega et al., "CLIO: Collaboration for an Infrared Laser at Orsay", NIM A285 (1989), pp. 97-103.

[20] R. Chaput, "Electron Gun for the FEL CLIO", EPAC90.

[21] M. Ageron et al., "Rapport d'étude du projet de laser à électrons libres sur accélérateur linéaire HF de 3 GHz, CLIO", in french, LAL/RT-89/04, 1989.

[22] P.W. Van Amersfoort et al., "Commissioning of the Electron Accelerator for FELIX", EPAC90.
[23] W.A. Barletta et al., "Enhancing the Brightness of High Current Electron Guns", NIM A250 (1986) pp. 80-86.
[24] L.R. Falce, "Thermionic Cathodes: a Review", these Proceedings.
[25] W.C. Turner et al., "High-Brightness, High-Current Density Cathode for Induction Linac FEL", LAC88.
[26] C. Bourat, "Système de découpage sous-harmonique d'un faisceau d'électrons pour injecteur d'accélérateur linéaire", in french, Thèse No. 413, Université de Paris-Sud, Orsay, 1988.
[27] M.B. James, "Production of High Intensity Electron Bunches for the SLAC Linear Collider", (PhD. Dissertation), SLAC-319, UC-28 (A), 1987.
[28] D. Tronc, J.M. Salomé, K.H. Bockhoff, "A New Pulse Compression System for Intense Relativistic Electron Beams", NIM 228 (1985), pp. 217-227.
[29] G.L. Cox, "A Five-Picosecond Electron Pulse from the ANL-L-Band Linac", PAC89.
[30] C.E. Hess, H.A. Schwettman, T.I. Smith, "Harmonically Resonant Cavities for High Brightness Beams", PAC85, p. 2924.
[31] T. Enegren, L. Durieu, D. Michelson, R.E. Worsham, "Development of Flat-Topped RF Voltage for TRIUMPH", PAC85, p. 2936.
[32] T.I. Smith, "Production of Intense Low Emittance Beams for Free Electron Lasers Using Electron Linear Accelerators", NIM A250 (1986), pp. 64-70.
[33] T.I. Smith, "Intense Low Emittance Linac Beams for FEL", LAC86.
[34] S.P. Kapitza, V.N. Melekhin, "The Microtron", ed. by E.M. Rowe, Harwood Academic Publishers, 1978.
[35] A. Yeremian et al., "BOEING 120 MeV RF Linac Injector Design and Accelerator Performance Comparison with PARMELA", PAC89.

Stanford/Duke

[36] G.A. Westenskow, J.M.J. Madey, "Microwave Electron Gun", Laser and Particle Beams (1984), Vol. 2, Part 2, pp. 223-225.
[37] C.B. McKee, J.M.J. Madey, "Computer Simulation of Cathode Heating by Back Bombardment in the Microwave Electron Gun", FEL89.
[38] M. Curtin et al., "First Demonstration of a FEL Driven by Electrons from a Laser Irradiated Photocathode", FEL89.
[39] S.V. Benson et al., "Status Report on the Stanford Mark III Infra-red Free Electron Laser", NIM A272 (1988), pp. 22-28.
[40] S.V. Benson's presentation at the "Colloque sur les applications dans l'infrarouge du laser à électrons libres", Paris, October 23-25, 1989.
[41] G.A. Westenskow, J.M.J. Madey, L.C. Vintro, S.V. Benson, "Owner's Manual for the Microwave Electron Gun", HEPL Technical Note, TN-86-1, 1986.

IHEP Beijing

[42] J. Xie, H. Liu, R. Zhang, "Microwave Electron Gun with Field Emission Cathode", in chinese, submitted to Acta Electronica Sinica, 1989.
[43] J. Xie et al., "Design Considerations of the Beijing Free Electron Laser Project", NIM A272 (1988), pp. 40-49.
[44] J. Gao, J.L. Xie, "RF Gun Development at IHEP for BFELP", FEL90.
[45] H. Liu, "Simulation of RF Gun Injector for Beijing Free Electron Laser", submitted to NIM, 1989.

[46] J. Xie et al., "Design and Progress of the Beijing Free Electron Laser Project", to be published in High Power Laser and Particle Beams, Beijing, 1990.
[47] S. Zhong, private communication.

Los Alamos

[48] J.S. Fraser et al., "High-Brightness Photoemitter Injection for Electron Accelerators", PAC85, p. 1791.
[49] C.H. Lee et al.,"Electron Emission of Over 200 A/cm^2 from a Pulsed-Laser Irradiated Photocathodes", PAC85, p. 3045.
[50] M.E. Jones, W.K. Peter, "Particle-in-Cell Simulations of the Lasertron", PAC85, p. 1794.
[51] J.S. Fraser, "Electron Sources for Advanced Accelerator Experiments", Proceedings of the AIP Workshop, Madison, 1986.
[52] J.S. Fraser, "Electron Linac Injector Developments", LAC86.
[53] J.S. Fraser, R.L. Sheffield, E.R. Gray, "A New High Brightness Electron Injector for Free Electron Lasers Driven by RF linacs", NIM A250 (1986), pp. 71-76.
[54] J.S. Fraser et al., "Photocathodes in Accelerator Applications", PAC87.
[55] R.L. Sheffield, "High-Brightness Electron Injectors", in ICFA Workshop Proceedings, BNL 52090, 1987.
[56] B.E. Carlsten, K.C.D. Chan, "Preliminary Injector Accelerator and Beamline Design for RF-Driven XUV Free Electron Lasers", NIM A272 (1988), pp. 208-217.
[57] R.L. Sheffield, E.R. Gray, J.S. Fraser, "The Los Alamos Photoinjector Program", NIM A272 (1988), pp. 222-228.
[58] R.L. Sheffield et al., "RF Photoelectron Gun Experimental Performance", LAC88.
[59] E.R. Gray, J.S. Fraser, "Design and Construction of the Photocathode Electron Gun Cavity", LAC88.
[60] P.J. Tallerico et al., "An RF-Driven Lasertron", LAC88.
[61] B.E. Newman, "XUV Free Electron Laser Development at Los Alamos", LAC88.
[62] B.E. Carlsten, "New Photoelectric Injector Design for the Los Alamos National Laboratory XUV FEL Accelerator", NIM A285 (1989), pp. 313-319.
[63] B.E. Carlsten, R.L. Sheffield, "Photoelectric Injector Design Considerations", LAC88
[64] B. Carlsten et al., "Accelerator Design and Calculated Performance of the Los Alamos HIBAF Facility", FEL89.
[65] W.D. Cornelius et al., "The Los Alamos High-Brightness Accelerator FEL (HIBAF)", FEL89.
[66] J.C. Goldstein, "Compact RF-Linac Free Electron Lasers", FEL89.
[67] R.L. Scheffield, "Photocathode RF gun", in Physics of Particle Accelerators, AIP, New York, pp. 1500-1531, 1989.
[68] R.L. Sheffield, "High-Brightness Electron Injectors: A Review", PAC89.
[69] B.E. Carlsten, "Photoelectric Injector Design Code", PAC89.
[70] D.K. Remelius et al., "Generation and Amplification of Temporally Square Optical Pulse for the FEL Photoelectric Injector", PAC89
[71] R.L. Sheffield, "High-Brightness Electron Sources", EPAC90.
[72] B.E. Carlsten, "Photoelectric Injectors for High-brightness Electron Beams at Los Alamos National Laboratory", these Proceedings.
[73] D.W. Feldman, "The Los Alamos High-Brightness Accelerator FEL (HIBAF) Facility", LA-UR-90-997, 1990.
[74] R.L. Sheffield, private communication.

CEA

[75] R. Dei-Cas, "Photo-Injector, Accelerator Chain and Wiggler Development Programs for a High Peak Power RF Free Electron Laser", NIM A285(1989), pp. 320-326.
[76] S. Joly, "A High-Brightness Photo-Injector for a Free Electron Laser Proposal",EPAC88.
[77] J. Frehaut, "Croissance de l'émittance dans la boucle de retour du projet ELSA", in french, PTN-632/89, CEA-DAM, Bruyères- le-Châtel, 1989.
[78] S. Joly et al., "Status Report on Developments for the Main Components of a High-Peak Power FEL", Proceedings of the International Congress on Optical Science and Engineering, Paris, April 24-28, 1989.
[79] J. Frehaut, "Expérience ELSA: dynamique du faisceau entre le photo-injecteur et le pré-accélérateur", in french, PTN-755/89, CEA-DAM, Bruyères- le-Châtel, 1990.
[80] S. Joly et al., "Progress Report on the BRC Photo-Injector", EPAC90.
[81] J. Frehaut et al., "Beam Dynamics Studies in a Low-Frequency High-Peak Power Laser-Driven RF Gun", EPAC90.
[82] R. Dei-Cas et al., "Photo-Emission Studies at Bruyères-le-Chatel for FEL Applications", these Proceedings.
[83] S. Joly, private communication.

BNL

[84] K. Batchelor et al., "The Brookhaven Accelerator Test Facility", PAC89.
[85] K.T. McDonald, "Design of the Laser-Driven RF Electron Gun for the BNL Accelerator Test Facility", DOE/ER/3072-43, Princeton University, 1988.
[86] K. Batchelor et al., "Development of a High-Brightness Electron Gun for the Accelerator Test Facility at Brookhaven National Laboratory", EPAC88.
[87] K. Batchelor, J. Sheehan, M. Woodle, "Design and Modelling of a 5 MeV Radio Frequency Electron Gun, BNL-41766, 1988.
[88] M.H. Woodle, K. Batchelor, J. Sheehan, "Mechanical Design of a RF Electron Gun", LAC88.
[89] X.J. Wang et al., "The Brookhaven Accelerator Test Facility Injection System", PAC89.
[90] K. Batchelor et al., "Operational Status of the Brookhaven National Laboratory Accelerator Test Facility", PAC89.
[91] K. Batchelor et al., "Operational Status of the Brookhaven National Laboratory Accelerator Test Facility", EPAC90.
[92] Z. Parsa, L. Young, "On design and Analysis of a High-Brightness Electron Source", EPAC90.
[93] J. Fisher, "Photocathodes and Pulsed High Fields", these Proceedings.

CERN

[94] Y. Baconnier et al., "A CLIC Injector Test Facility", CLIC Note 65, 1988.
[95] Y. Baconnier et al., "CLIC Studies: The DC Test Bench for Laser-Driven Photo-Emissive Cathodes", EPAC90.
[96] H. Kugler et al., "Beam Dynamics Simulations of the RF Gun, Particle Source of the CLIC Test Facility", EPAC90.
[97] A.J. Riche, "The Proposed Beam Optics for the CLIC Test Facility and the Instrumentation Lay-Out", CERN-PS-LP (CTF) NOTE 90-29, 1990.
[98] J.P. Delahaye, private communication.

LAL Orsay

[99] M. Boussoukaya, H. Bergeret, R. Chehab, B. Leblond, J. LeDuff, " High Quantum Yield from Photofield Emitters", NIM A279 (1989), pp. 405-409.
[100] G. Bienvenu, "Prémices pour un canon HF", in french, LAL/SERA 89-76, 1989.
[101] S. Zhong, "Numerical Simulation of RF Gun", LAL/SERA 89-108, 1989.
[102] P. Brunet, "Pointe émissive dans le groupeur - Fonctionnement à très fort champ HF", in french, LAL/SERA 89-72, 1989.
[103] J. Gao, "Theoretical Investigation in the Optimization Design of Microwave Electron Gun", FEL90.
[104] J. Gao, "A Proposal for Multi-Cavity RF Gun System with Small Emittance Growth", LAL/SERA 90-44, 1990.
[105] C. Travier, J. Gao, "LAL (ORSAY) RF GUN PROJECT", EPAC90.
[106] H. Bergeret, M. Boussoukaya, R. Chehab, B. Leblond, J. LeDuff, "Short Pulse Photoemission from a Dipenser Cathode", these Proceedings.
[107] J. Gao, "A Cylindrically Unsymmetrical Cavity Used in a Multi-Cavity RF Gun System as an Attempt to Reduce Emittance", LAL/SERA 90-188/RFG, 1990.

LLNL-SLAC-LBL

[108] S. Chattopadhyay et al., "Conceptual Design of a Bright Electron Injector Based on a Laser-Driven Photocathode RF Electron Gun", LBL-25699, ESG Note-55, 1988.
[109] K.J. Kim, Y.J. Chen, "RF and Space-Charge Induced Emittances in Laser-Driven RF Guns", EPAC88.
[110] Y.J. Chen, "Simulations of High-Brightness RF Photocathode Guns for LLNL-SLAC-LBL 1 GeV Test Experiment", LLNL pub., UCRL-99675, 1988.
[111] Y.J. Chen, "Simulations of High-Brightness RF Photocathode Guns for LLNL-SLAC-LBL 1 GeV Test Experiment", PAC89.
[112] K.J. Kim, "RF and Space-Charge Effects in Laser-Driven RF Electron Guns", NIM A275 (1989), pp. 201-218.
[113] K.J. Kim, private communication.

Other projects

[114] C.K. Sinclair, R.H. Miller, "A High Current, Short Pulse RF Synchronized Electron Source for the Stanford Linear Collider, IEEE Trans. Nucl. Sci. NS-28 (3) (1981), p. 2649.
[115] H. Hanerfeld et al., "Higher Order Correlations in Computed Particle Distributions", SLAC-PUB-4916, March 1989.
[116] S. Nishihara, M. Kimura, "Development of RF Electron Gun", in japanese, JAP89.
[117] A. N. Dovbnya et al., EPAC90.
[118] E. Tanabe et al., "A 2-MeV Microwave Thermionic Gun", SLAC-PUB 5054, August 1989.
[119] H. Kobayashi et al., "Development of Microwave Electron Gun with a Mesh Grid", in japanese, JAP89.
[120] T. Urano et al., "Trial Manufacturing of a Pillbox-Type Cavity for an RF Gun", in japanese, JAP89.
[121] T. Urano et al., "R&D of Thermionic RF Gun", JAP89.
[122] A. Enomoto, private communication.
[123] W. Gai et al., "Advanced Accelerator Test Facility (AATF) Upgrade Plan", PAC89.
[124] P. Schoessow et al., "The Argonne Wakefield Accelerator", EPAC90.

[125] W. Gai, private communication.
[126] H. Chaloupka et al., "A Proposed Superconducting Photoemission Source of High-Brightness", EPAC88.
[127] H. Chaloupka et al., A Proposed Superconducting Photoemission Source of High-Brightness", unpublished, 1990.
[128] A. Michalke, private communication.
[129] J.I.M. Botman et al., "Update on the Micro FEL-TEUFEL Project", EPAC90.
[130] G.J. Ernst et al., "Status of the Dutch "TEUFEL" Project", FEL89.
[131] G.J. Ernst, private communication.
[132] J.L. Warren et al., "Design of MCTD Photoinjector Cavities", PAC89.
[133] R. Bonifacio et al., "The ELFA Project: Guidelines for a High-Gain FEL with Short Electron Bunches", NIM A289(1990), pp. 1-13.
[134] G. Bellomo et al., "The Photocathode Injector and the Superconducting Linac for the ELFA project", EPAC90.
[135] L. Serafini et al., "Design of the SC Laser-Driven Injector for ARES", EPAC90.

Computer codes

[136] K. Crandall, L. Young.
[137] A. Palevsky, A.T. Drobot, Proceedings of the 9^{th} Conference on Numerical Simulation of Plasmas, Northwestern University, Evanstan, IL, 1980.
[138] F. Ebeling, P. Schuett, T. Weiland, "Selfconsistent Simulation of High Power Tubes with TBCI-SF", EPAC88.
[139] G. Le Meur, these Proceedings.
[140] L. Serafini, C. Pagani, "ITACA: a Computer Code for the Integration of Transient Particle and Field Equations in Axi-Symmetrical Cavities", EPAC88.
[141] M. Borland, "RFGUN - A Program for Simulating RF Guns", SSRL ACD Note 78.
[142] A. Dubrovin, "Etude conceptuelle et réalisation d'une maquette de lasertron", in french, LAL 90-02, 1990.

Novel ideas

[143] L. Picardi, P. Raimondi, C. Ronsivalle, "Electron-RFQ: A Possible Novel Electron High-Brightness Current Injector", EPAC90.
[144] L. Serafini, C. Pagani, A. Peretti, "Space Charge Compensated RF Gun: A New Way to Ultra High-Brightness Electron Beams", EPAC90.