

HIGH INTENSITY AND LOW EMITTANCE GUNS

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Abstract

High brightness electron beam are needed for many applications, ranging from SASE FELs to pulse radiolysis systems, from Compton backscattering tuneable X ray sources to energy recovery linac, from CW FELs to linear collider. They are produced using a high field RF accelerating structure together with a photoemissive electron source: the rapid acceleration process minimizes the space charge effects which tend to spoil the emitted beam properties.

The talk will review the technology and provide the main parameters of these sources as the generated bunch charge, the repetition rate, the mean and peak current, the beam emittance, etc, together with an analysis of gun reliability and technological challenges. I will present the state of the art of the technology of the RF guns, either using metallic or semiconductor photoemitters.

New high repetition rate/CW sources, appearing in the last years, using superconducting cavities, will also be reviewed.

INTRODUCTION

High brightness low emittance electron beam are needed for many application. High intensity (hundreds of mA) high brightness CW electron sources are used for Energy Recovery Linacs (ERL); high peak brightness - high peak current (kA) injectors for short wavelength SASE Free Electron Laser (FEL) and for the generation, by Laser-Compton scattering, of high-brightness, ultra short, energy-tunable X-rays.

The main difference between the ERL injectors and the FEL ones is the repetition rate. The ERL injector must operate in CW mode, while the FEL injector can operate in pulsed mode: of course an increase of the repetition rate will be reflected in the mean power of the FEL radiation. The CW operation of ERL gun produces obvious consequences on the gun cavity power dissipation, the gun vacuum conditions, etc.

As well known, one possible strategy for high brightness beam production, make use of RF photoinjectors, where electron are generated by photoemission on a cathode that is embedded in a standing wave RF structure. Electrons can be therefore promptly accelerated by the high electric field, to reduce and control the space charge effects.

The quality of the electron beam at the end of the system (accelerator, injector, etc), is strongly correlated with the beam quality at the injector itself. Moreover the beam quality can not be easily recovered, but for use of high costly strategies and complicated structures as dumping rings. Therefore the challenges in the production of high quality electron beams are directly transferred to the electron source.

The beam brightness B , defined as

$$B_{\perp} \approx \frac{2I}{\epsilon_{n,x}\epsilon_{n,y}}$$

where I is the beam current, and the $\epsilon_{n,x}$ $\epsilon_{n,y}$ are the normalized transverse emittances, is the parameter used for the beam quality description. For high gain SASE FEL application, brightness of the order of 10^{15} A/m² has to be provided [1]. For SASE FEL application we need emittance values in the order of 1 mm-mrad or less, while ERL application may accept less stringent emittance parameters [2].

Electron can be produced by photoemission process on semiconductors (single crystal as GaAs or polycrystalline as Cs₂Te), on metals (e.g. Cu, Mg, Y, etc.), on cesiated metals, (e.g. dispenser [3]).

This paper analyzes the status of the art of the RF injectors that use photoemission as the process for electron production, and that operate the electron source directly inside the first accelerating structure, i.e. RF photo injectors. I would not include in the discussion the DC high voltage (HV) photoemission electron sources coupled with RF accelerating structure, as the one used for the generation of polarized electron beam.

Injector can be classified in different ways. The technology for RF cavities (NC or SC), the frequency of the RF system (L-band, S-band, C-band, etc), the RF pulse length (CW, pulsed, short/long pulse), the application (ERL, SASE FEL), the process used for the electron production, etc. I used the RF technology as the main parameter in my analysis.

I have considered in the analysis some RF gun that can be considered as "representative" of the different categories and classification.

NORMAL CONDUCTING RF GUN

Normal conducting RF gun operates usually in S or L band in pulsed mode. Moreover, high average power guns operate at lower frequency, as the LANL/Boeing at 433 MHz and the LANL/AES 700 MHz 2 ½ cell RF gun.

"Low" frequency NC RF guns

The "retired" LANL/Boeing, still demonstrates to be the state of the art of high current gun. It produced, 32 mA with a macropulse current of 130 mA (25% duty factor). It operated with K₂CsSb photocathodes, sensitive to green light [4]. The alkali antimonide photocathode lifetime was only of few hours, during the 1992 high duty test, due to not good vacuum inside the gun [5].

New LANL/AES 700 MHz RF gun specification are for 100 mA, 33.3 MHz rep rate pulses, using alkali antimonide photocathode. Excellent vacuum conditions are foreseen using a non resonant cell for pumping [6].

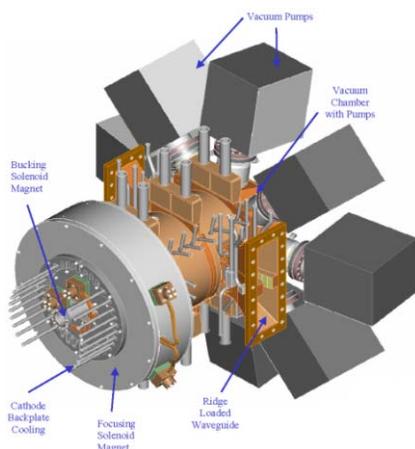


Figure 1: The LANL/AES 700 MHz NC gun.

A new interest in “low” frequency (VHF) RF gun arises from the opportunity, given by the large RF structure, to operate the gun in CW mode, due to the reduced specific power dissipation of the RF cavity itself. Moreover the large RF structure should permit higher pumping speed with respect to S and L-band guns, allowing vacuum conditions good enough for the use of high sensitive photocathodes as GaAs with reasonable photoemitter lifetime. The system would potentially be a competitor with HV DC based gun for polarized electron. Beam dynamics discussions, together with thermal and structural analysis, are presented in references [7] [8] [9].

L band photo guns

L-Band RF photo gun are generally characterized by the operation with long RF pulses (1 ms scale): they are able to deliver long trains of electron bunches.

The Free electron LASer in Hamburg, FLASH, is the unique SASE FEL facility that delivers radiation up to 6.5 nm to users. The electron beam is generated by a 1½ cell L-band RF photo gun (1.3GHz, TM010 mode) powered by a 5 MW klystron [10]. The gun is characterized by a coaxial coupler to keep as perfect as possible the cylindrical symmetry around the beam axis. No RF probe is present: vector sum of forwarded and reflected power is used for the gun control and the gun phase stability obtained is of 0.1 deg (rms). Figure 2 shows a schematic view of the FLASH RF gun.

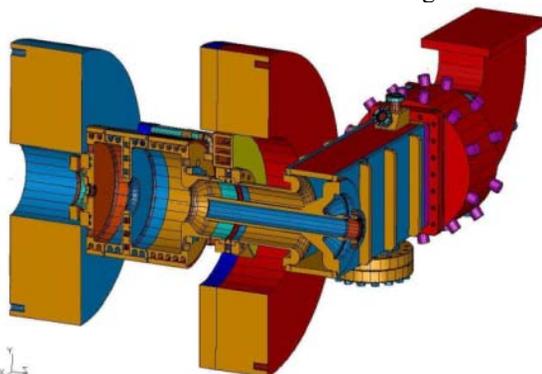


Figure 2: A schematic view of the Flash/PITZ RF gun.

The RF gun currently operates at 41 MV/m on the cathode with an RF power of 3.5 MW. The RF pulse length ranges from 100 μs to 900 μs with a repetition rate of 5 or 10 Hz. The train of 1 nC electron bunches (up to 800 at 1 MHz max.) is generated by photoemission on high QE Cs₂Te photocathodes (QE 5% @ 262 nm). A Nd-YLF laser, developed by Max Born Institute (MBI), produces the UV radiation for the electron photoemission: few nJ/pulse are required for a charge of a few nC on Cs₂Te. The laser stability is quite good: the charge fluctuation of a single electron bunch, from shot to shot, is better than 2% rms. The pulses length in the UV measured with a streak camera is of 4.4 ± 0.1 ps (Gaussian). Cs₂Te photocathodes are produced at INFN Milano and transferred in UHV to DESY: cathode lifetime, in continuous operation (24/7) is between 1 and 3 months [11]. Cathode can be easily changed, via a load lock system, when the QE drop down 0.5%. A picture of the FLASH gun is in figure 3.



Figure 3: FLASH RF gun at DESY.

Concerning the beam quality, recent projected emittance measurements have shown values 1.6 mm-mrad at 127 MeV, 1 nC [12]. The slice emittance estimation from preliminary measurements indicates value ranging between 1 and 1.5 mm-mrad [12].

The Photo Injector Test Facility, PITZ, at DESY in Zeuthen, is a test stand for photoinjector studies, presently dedicated to the development and optimisation of the electron source for the European X ray Free Electron Laser (XFEL). A new gun, able to operate at higher electric field (60 MV/m), with the same RF pulse length and bunch structure as FLASH, is under test. Strong improvements are relative to the power dissipation and water cooling system (> 50 kW), the beam diagnostics and the laser system [13].

Dark current studies are under way both at FLASH and at PITZ: at the moment the dark current is the main limiting parameter of the FLASH L-band gun operation. Recent measurements indicate a significant reduction (factor 10) of the gun dark current at high field (60 MV/m) [14], after cleaning the gun RF cavity with

supercritical CO₂ jet, with the same treatment proposed for SC cavities [15]. Moreover last beam emittance measurements done at PITZ, represent the first demonstration that this gun is able to generate the beam quality required for the XFEL [14].

S-band RF photo gun

The S-band guns derive from the BNL/UCLA/SLAC 1.6 cell design: many of them operate successfully in the worlds. They usually work with short RF pulses (μ s) and at high gradient (> 100 MV/m). Guns are in operation at LCLS, SPARC, Elettra, Sumitomo, and in many others laboratories.

The LCLS (Linac Coherent Light Source) injector has been successfully commissioned recently at SLAC [16]. The RF gun is characterized by various modifications with respect the usual 1.6 cell S-band gun, to increase the gun reliability and the quality of the generated electron beam, in order to accomplish the requested specification to operate LCLS as a facility. Main modifications are the dual feed RF coupling to provide fully rotationally symmetric gun fields, and the racetrack geometry in the full cell to cancel the quadrupole fields. Moreover the frequency separation of the 0 and π modes has been increased of 15 MHz. During the commissioning the gun has demonstrated to operate reliably at 120 MV/m (60 Hz) and at 107 MV/m at 120 Hz, limited only by gun probe heating. Mean power dissipation is about 4 kW. The gun operates successfully for more then 3×10^8 pulses at 30 Hz [17].

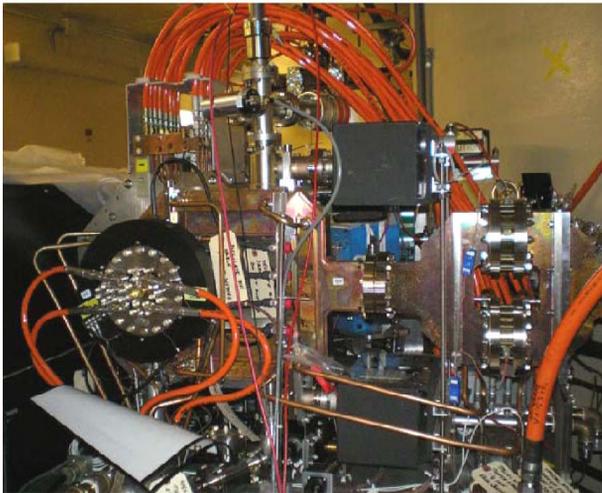


Figure 4: The LCLS dual feed gun with solenoids.

The gun uses a copper photocathode, which is a part of the back plate of the gun. Copper has shown during the gun commissioning a lower QE value than the design one. At the beginning QE was more then a factor 10 less; then after laser cleaning and conditioning, it reaches about one half of the foreseen value. LCLS gun and solenoids are shown in fig. 4. The laser system produces 120 Hz UV pulses ($\lambda = 255$ nm) with energy up to 450 μ J/pulse on

the cathode [18]. The achievement of the requirements for the laser system reliability and stability as the flat top optimisation, are still under way [18]. A summary of the design and the measured beam properties for LCLS is in table.1 [17].

Table 1: Design and measured beam parameter for LCLS.

Parameter	Design	Measured
Final e- energy (GeV)	15	15
Bunch charge (pC)	1000	1000
Initial bunch length (ps)	10	10
Initial peak current (A)	100	100
Proj. norm. emitt. exy μ m	1.2	1.1. to 1.3
Slice norm. emit. exy μ m	1.0	0.8 to 1.0
Single Bunch rep. Rate (Hz)	120	10 – 30
Rf field at cathode (MV/m)	120	115
Laser energy on cathode (μ J)	250	450
Laser diam. on cathode (mm)	1.5	1.3
Copper Cathode QE	6×10^{-5}	3×10^{-5}

LCLS gun dark current measurements and analysis are discussed in [19], together with a simple linear optical model for the interpretation of the dark current images observed during the RF gun processing. Dark current at 120 MV/m was measured: the collected charge/RF pulse, for a diamond turned polycrystalline Cu cathode, is about 0.6 nC.

SPARC (Sorgente Pulsata e Amplificata di Radiazione Coerente) is an INFN facility at Laboratori Nazionali di Frascati dedicated to the study of high brightness electron sources. It consists of an S-band injector, and accelerating sections. The injector is a BNL-like 1.6 cell S-band gun that can deliver 5.6 MeV, 1 nC electron pulses. The photocathode is polycrystalline copper: the measured QE is of the order of 10^{-5} after laser cleaning [20]. It is illuminated by the Ti Sapphire laser 3rd harmonic. The repetition rate is 1 to 10 Hz, and the peak brightness foreseen is 10^{14} A/m². The peculiarity of the facility is the possibility to vary the laser pulse shape (DAZZLER and LCM, Liquid Crystal Mask) and, at the same time, to investigate using a movable emittance meter [21] the behaviour of the beam emittance along a travel of 1.25 meter without any need of opening and venting the beam pipe. SPARC photoinjector experimental parameters are reported in tab. 3 [22], [23]

Table 3: SPARC photoinjector experimental parameters

Charge	200 pC	900 pC
Emittance	0.8 mm-mrad	2.2 mm-mrad
Energy	5.65 MeV	5.55 MeV
Energy spread	1%	2.6%
Pulse length	8 ps	12 ps

Investigations on Mg film produced by Pulsed Laser Deposition (PLD) are in progress [24], while first operation of an Mg cathode (PLD deposition) in the RF gun has shown a QE of 3×10^{-5} (266 nm) [25].



Figure 5: The RF Gun and the emittance meter (long bellow on the left) at SPARC.

S-band gun with semiconductor photocathode are “not so popular” as the ones that operates with a metal cathode. An S-band with semiconductor photocathode (Cs_2Te) is in operation at KEK-ATF, with a QE at least 2 orders of magnitude higher than the one of pure copper [26]. The high sensitivity of semiconductor photocathode to active gas and vapours, forces the presence of a load lock system for photocathode exchange. New RF gun tuning system is discussed in the same reference, together with dark current measurements. After the RF conditioning, at 10 MW incident RF power (2 μs), dark current was of the order 600 pC/pulse with a Mo plug and 4 times more with a Cs_2Te coated Mo plug

SUPERCONDUCTING RF GUN

SC cavities dissipate very low power with respect to NC structures and can be operated more easily in CW mode: therefore a superconducting RF gun, in principle, can produce CW high brightness beams, combining the potentiality of SC cavities with the one of laser driven gun. Some projects are under development in this direction, using both semiconductor and metals as photoemitters.

The compatibility of a cesiated semiconductor photocathode with a SC cavity has been demonstrated at Wuppertal (Cs_3Sb) in 1992 [27] and later the first gun (half cell) with Cs_2Te operated stably at Forschungszentrum Dresden-Rossendorf in 2002 [28]. Nowadays at FZD a $3\frac{1}{2}$ 1.3 GHz SC injector is under test with Cs_2Te cathode: preliminary emittance and charge measurements are in agreement with the expected values [29].

Table 4: Operation modes of the FZD ELBE gun.

Operation mode	ELBE	High Charge	BESSY FEL
Beam energy	9.5 MeV		
Photocath./laser	Cs_2Te / 262 nm		
QE (%)	> 1 %		> 2.5 %
Average current	1 mA	0.5 mA	2.5 mA
Pulse length	5 ps	15 ps	40 ps
Rep. rate	13 MHz	500 kHz	1 kHz
Bunch charge	77 pC	1 nC	2.5 nC
Transv. Emitt.	1 μm	2.5 μm	3 μm

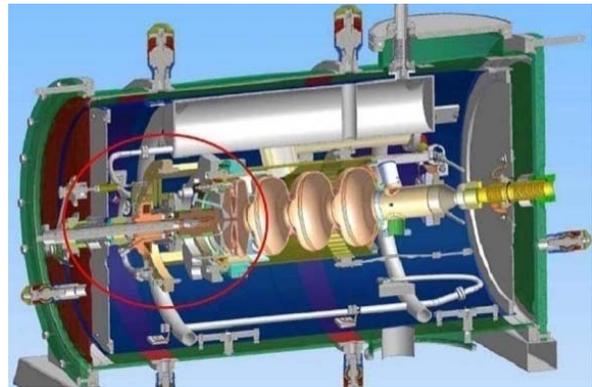


Figure 6: View of the FZD ELBE cryogenic module with the $3\frac{1}{2}$ cell SC gun. The cathode, the choke, the insertion mechanism are in the highlighted area, together with the cathode cooling system.

At FZD/ELBE the cathode stem is retractable and LN₂ cooled; it is connected to the SC cavity through a choke filter. The back wall of the first half cell is inclined to ensure the RF focusing effect. Moreover a recessed cathode is foreseen for further focalisation effect. The laser system (Nd-YLF), developed by MBI, provides 0.5 MHz 12-15 ps 263 nm laser pulse (1 W) for the gun operation in the high charge mode.

At BNL a SC photoinjector is under development for the BNL ERL project. It consists of a $1\frac{1}{2}$ cell 703 MHz gun, designed to operate with the high QE photoemitters (K_2CsSb) or the diamond amplified photocathode [30]. The BNL R&D ERL gun injector electron beam parameters are summarized in tab. 5. [31]

Table 5: BNL R&D ERL injector beam parameter.

Charge/bunch (nC)	0.7	1.4	5
Injection energy (MeV)	2.5	2.5	3
Aver. beam current (A)	0.5	0.5	0.05
Bunch rep rate (MHz)	700	350	9.38
Norm emit ex/ey (μm)	1.4/1.4	2.2/2.3	4.8/5.3

The first half cavity has been designed with an inclined back wall and should operate with a recessed cathode that ensures an RF focusing effect.

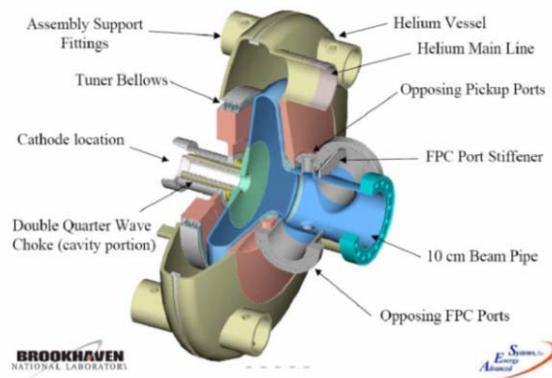


Figure 7: The BNL-AES SRF electron gun.

The cathode stem is thermally and electrically insulated to avoid additional heat load to the SC cavity cooling system. In fact, also using high QE cathode as the K_2CsSb , the power dissipation due to the cathode laser illumination is not negligible. Activity is under way on a half cell prototype by AES [32].

A different strategy is used in the BNL/JLAB/DESY collaboration for a “full” SC gun. The basic idea was to use the first cavity back wall as the photocathode. No retractable cathode system should be needed and no RF choke joint have to be provided. The photoemissive material can be the same niobium cavity end plate. In this case the low Nb quantum efficiency forces to use a high power and/or short wavelength laser system ($\lambda < 250$ nm). Another envisaged possibility is to coat one small part of the back wall of the gun cavity with lead that demonstrated higher QE than the pure Nb one [33], [34]. Critical points in this case are the final SC cavity treatment (high pressure rinsing for instance) and the procedure to be used in case of need of cathode refurbishment. The first results are quite promising and future test are under way.

DISCUSSION AND CONCLUSIONS

The normal conducting S and L-band guns can provide the high brightness high peak current needed for the FEL operation. The L-band gun operates with high QE cathode and the present laser technology gives the possibility to generate multi bunch pulses (MHz rep rate). On the contrary the S-band gun generally operates with metal cathode (low QE) and this fact implies that the laser system had to provide quite high peak power: the maximum repetition rate is therefore limited to hundreds of Hz. In the case of NC ERL gun, the critical point is the power dissipation in the gun. In the case of L-band for instance, the maximum average power dissipation is less than 100 kW. Lower frequency NC RF gun can be considered for the ERL application as the AES/LANL proposal.

Major challenges for NC gun are the dark current, the RF contact between cathode and cavity (for exchangeable cathode), the cooling and the temperature stabilization, the uniformity of the laser system and the vacuum (that affect cathode lifetime also for metal cathode).

The SC gun technology is approaching a point in which can be used reliably for FEL and ERL SC gun. The FZD/ELBE and the BNL ERL are going in this direction: the first one is close to this point. The operation of high QE cesiated cathode will take surely profit of the cryogenic environment and of the extreme low pressure of the vapour and gases as water, oxygen and CO_2 .

Major challenges are relative to the long term reliability of these systems, in particular concerning the compatibility of SC cavities and cesiated photocathodes. Moreover another critical point is the need of different strategies for the compensation of the emittance growth, due to the not possible operation of the SC gun cavity in magnetic field. The approach of a fully superconductive

gun system (cavity and photocathode) is a promising approach, due to the complete elimination of the choke joint that may increase the system reliability.

One final consideration: the results obtained at RIKEN Spring-8 by T. Shintake, using a thermionic electron source, demonstrates that the RF gun is not the only possible choice for producing high quality electron beams also for single pass X ray FEL [35].

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