OVERVIEW OF ELECTRON SOURCE DEVELOPMENT FOR HIGH REPETITION RATE FEL FACILITIES*

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Abstract

An increasing science demand for high-repetition rate (MHz-class) FEL facilities, from IR to X-rays, has been pushing institutions and groups around the world to develop proposals addressing such a need, and some of them have been already funded and are under construction. Such facilities require the development of high-brightness high-repetition rate electron guns, and a number of groups worldwide started to develop R&D programs to develop electron guns capable of operating at this challenging regime. Here we describe the approaches and technologies used by the different programs and discuss advantages and challenges for each of them. A review of the present achievements is included, as well as a brief analysis to understand if the present technology performance is sufficient to operate present and future high repetition rate FEL facilities.

INTRODUCTION

After the success of FEL facilities operating at relatively low repetition rates (~100 Hz) an increasing science demand for high-repetition rate (MHz-class) FEL facilities, from IR to X-rays, has been pushing institutions and groups around the world to develop proposals addressing such a need. Some of them (notably the LCLS-II at SLAC) are already funded and under construction.

It is well known that the ultimate performance of an FEL is already defined at the injector and at its electron gun in particular. The high repetition rate requirement significantly impacts the technological choices for the injector, and while for most of its components solutions already exist, for the electron gun that is not completely true. The low repetition rate successful technology, based on normal-conducting (NC) high-frequency (>~1GHz) RF, cannot be scaled to rates higher than a few kHz because of the increasing power that needs to be dissipated on the structure. In response to that, a number of groups started R&D programs to develop alternative electron guns capable of operating at this difficult regime.

Technologies used and investigated include DC guns, superconducting RF (SRF) guns, normal-conducting (NC) low frequency RF gun, and a hybrid DC-SRF configuration. Figure 1 shows some of the main active groups in the field and their location around the world.

This paper, after an initial analysis of which parameters mainly affect the performance of an electron gun, continues by describing the different technologies used and discusses advantages and challenges for each of them. A (incomplete) review of the present achievements is also included, and in the final part, the question if the present technology performance is sufficient to operate present and future high repetition rate FEL facilities is discussed.

MAIN PARAMETERS DRIVING THE GUN BRIGHTNESS PERFORMANCE

In FELs, the emittance (ε) to wavelength (λ) matching condition for the transverse emittance

$$\varepsilon \approx \frac{\lambda}{4\pi} \quad \Rightarrow \quad \frac{\varepsilon_n}{\beta\gamma} \approx \frac{\lambda}{4\pi}$$

indicates that small normalized emittances (ε_n) should be pursued to keep the energy of the linac as low as possible (β,γ in the equation are the relativistic Lorentz factors). For X-ray machines ($\lambda < \sim 1$ nm) and present gun performance, GeV-class electron beam energies are required. In the case of high repetition rate FELs, such energies are obtained by using long and expensive superconducting linacs.

Emittance appears also in the equations regulating the FEL gain and in general, the optimization of the FEL performance requires high peak currents (kA-class) and normalized transverse emittances as small as possible.

At the injector exit, the beam is relativistic enough to make space charge forces negligible. At this point the emittances are “frozen” and their value define the ultimate transverse brightness that the linac can achieve.

The emittance at the injector exit is given by the quadratic sum of a number of different independent terms:

$$\varepsilon_n = \sqrt{\varepsilon^2_{n\,Therm.} + \varepsilon^2_{n\,Bz@Cat.} + \varepsilon^2_{n\,Space\ Charge} + \varepsilon^2_{n\,Aberr.} + \varepsilon^2_{n\,RF}}$$

where we can recognize the contributions due to the: cathode thermal emittance; presence of a solenoidal field at the cathode; space charge; optics aberrations; and RF.

The optimization game in injectors consists in getting the cathode thermal contribution small and making all the other emittance contributions possibly negligible.

The cathode thermal emittance is given by:

$$\frac{\varepsilon_{n\,Therm.}}{\sigma_r} = \sqrt{\frac{\Delta E_C}{3mc^2}} \qquad \begin{array}{l} with\ \ \sigma_r \equiv rms\,beam\,size@cathode \\ and\ \ \Delta E_C \equiv excess\ energy \end{array}$$

with m the electron rest mass and c the speed of light. The electron excessive energy depends on the cathode material and on the emission process. For example, in the case of photoemission, the excess energy is equal to the difference between the photon energy and the effective work function of the material (including the Schottky barrier reduction induced by the gun accelerating field).

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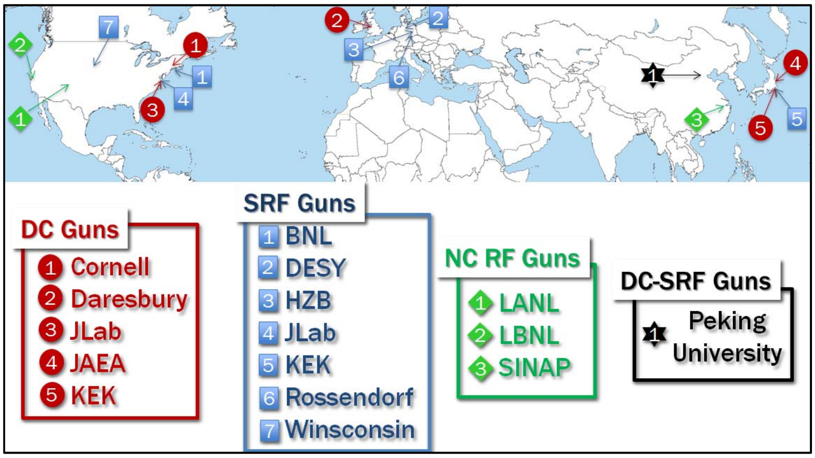

Figure 1: List and location of groups involved in high-repetition rate high-brightness electron sources R&D.

The last equation also shows that a smaller cathode emittance contribution can be achieved by using smaller transverse beam sizes at the cathode. Smaller beam sizes also increase the density of the emitted electrons and the space charge fields associated with them. With increasing density, such fields, which have direction opposite to E_z^{Gun}, the gun accelerating field, will become at certain point strong enough to inhibit any further emission of electrons from the cathode. This space charge limited condition defines the minimum beam radius at the cathode and hence the minimum obtainable emittance and the maximum transverse brightness B_{4D}^{max} (number of electrons over the transverse normalized emittances) that the electron beam can achieve. Two regimes, depending on the transverse to longitudinal beam aspect ratio can be distinguished: the commonly called "pancake" regime where the transverse beam sizes are much larger than the bunch length, and the "cigar" regime where is the longitudinal size to be much larger than the transverse one. The maximum brightness for the pancake regime is given by [1]:

$$B_{4D}^{\max} \propto \frac{E_z^{Gun}}{\Delta E_C}$$

and for the cigar case [2]:

$$B_{4D}^{\max} \propto \frac{\left(E_z^{Gun}\right)^{3/2} \sigma_\tau}{\sqrt{\sigma_r}\,\Delta E_C}$$

where σ_τ is the rms bunch length. Both equations show as the maximum brightness is limited by the excess energy at the cathode (the smaller the better) and by the gun accelerating field (the higher the better). The equation for the cigar case also indicates that the brightness in this specific regime can be increased also by making longer bunches. This additional tuning parameter allows relatively low gradient guns to obtain remarkably good brightness performance but at the expense of the beam longitudinal emittance. While typically FEL applications can somehow tolerate significant increase of longitudinal emittance, beyond a certain length the nonlinearities introduced in the longitudinal phase space inside the gun and in the following accelerating sections can seriously limit the bunch compression capabilities and the maximum achievable peak current.

Space charge forces scales with the inverse of the square of beam energy. This implies that the most critical region where space charge can jeopardize the brightness performance of the injector is in the gun where the beam energy is small. In order to minimize such degradation effects, it is important for the beam energy to approach relativistic values already at the gun exit.

This discussion showed that the two main goals for a gun designer consist in maximizing the gradient (accelerating field intensity) at the cathode during the electron emission, and in providing sufficiently high beam energies at the gun exit.

We will see later in the paper that in the high-repetition rate gun case, the presently available technology limits the gradient at the cathode to values significantly lower than those in low-rep. rate guns based on high-frequency NC RF. This fact significantly affects the performance optimization process and the beam dynamics in the high-repetition rate case, forcing the use of cigar-like beams with significantly longer bunches at the cathode.

Besides gradient and beam energy, other parameter requirements must be satisfied as well by high-brightness high-repetition rate electron guns. A summary of them is shown in Table 1.

HIGH REPETION RATE GUN TECHNOLOGIES

In this section the advantages and the challenges of the different technologies used in high-repetition rate electron gun schemes are discussed.

DC Guns

DC guns with thermionic cathodes and energies in the ~100 keV range have been the workhorse electron source since the beginning of accelerators.

The use of photocathodes together with a formidable R&D effort for getting higher beam energies and gradients allowed for a dramatic leap forward in terms of brightness, and in the last decade, ambitious projects targeting beam energies as high as 750 keV were initiated. Since then the technology has progressively improved from the few hundred keVs, and is now slowly approaching the revised ultimate target of 500 keV. Presently demonstrated gradients are typically above 5-6 MV/m and are targeting values as high as 10 MV/m.

Notable strengths of DC guns include:

- DC operation & GHz-class rep. rate capabilities;
- demonstrated operation at moderate energies (~400 keV now approaching 500 keV);
- demonstrated capacity of generating FEL quality beams with sub-micron emittances when used in injector layouts with a sufficient tuning knobs;
- demonstrated record high currents;
- full compatibility with magnetic fields;
- demonstrated excellent vacuum performance;
- compatible with most photo-cathodes. It is actually the only gun technology capable to operate “delicate” GaAs:Cs cathodes.

Table 1: Operational Requirements for High-Brightness High-Repetition Rate Electron Sources

Repetition rate	MHz-class	
Charge/bunch [pC]	~ 10 – 500	Different FEL modes of operation
Normalized emittance [µm]	~ 0.1 – 0.7	Lower values for lower charges
Beam energy at the gun exit [MeV]	~ 0.5 – 3	For controlling space charge
Cathode E field @ emission [MV/m]	~ 10 – 40	Maximum brightness limit; long. Phase space linearity.
Bunch length and shape control [ps]	~1 to ~60	Space charge control; different modes of operation
Cathode/gun area magnetic field compatibility		Emittance compensation; exotic modes: flat beams, …
Dark current [nA]	~100	SRF quencing; radiation damage
Operational vacuum pressure [nTorr]	~0.1-1	High QE semiconduct. cathode lifetime
Loadlock cathode vacuum system		“Quick” cathode exchange
Reliability	>~98%	Required for an user facility

On the challenge front, DC guns are approaching the limit of the technology in terms of cathode gradients and beam energies, making the achievement of significant brightness increase difficult.

Highlights from the groups working on DC guns development include:

- Cornell DC gun delivered record high currents (up to 75mA) with semiconductor cathodes [3] and generated beams with sub-micron emittance with several hundred pc charge/bunch [4].
- JAEA/KEK DC gun generated beams with 500 keV energy and operated mA currents with energies between 350 and 450 keV [5].
- At Jefferson Lab, a compact DC gun with inverted insulator configuration was built and successfully tested generating ~1 mA DC current at 325 keV, very close to the nominal value of 350 keV [6].

Superconducting RF Guns

Superconducting RF (SRF) guns operating in continuous wave (CW) represent a natural and promising candidate to pursue and achieve the high gradient and energy goals, and since the first proposed SRF gun in 1989 [7] the technology has made significant progress [8] achieving several tens of MV/m fields at the cathode (at the electron emission phase) when using superconducting (SC) cathodes. While such cathodes can be readily used for relatively low charge per bunch applications, the new and upgraded high repetition rate FEL proposed schemes require high quantum efficiency (QE) semiconductor cathodes to deliver the few hundred pC charges per bunch at MHz repetition rate using realistic laser beam power. During the last decade or so, several groups have tested such cathodes in SRF guns with somehow mixed results. While the cathode QE degradation and lifetime were in general acceptable, the experience showed that the insertion of the warm cathode in the SRF cavity induces a significant degradation of the gradient (and consequently also a beam energy decrease) limiting the best obtained value so far to ~20 MV/m (references later in the paper). More R&D in that direction is necessary to address the issue.

In general the main advantages of SRF guns consist of:

- potential for high gradients. Demonstrated ~50 MV/m with superconductive cathodes and ~20 MV/m with high QE warm cathodes;
- several MeV beam energies already demonstrated;
- CW operation with GHz-class repetition rate capabilities;
- excellent vacuum performance. Cryo-pumping from the SC cavity walls;

Main challenges:

- overcome accelerating gradient degradation when cathodes are inserted. It is not completely clear if this effect is due to particulates creation by the insertion mechanism or from warm cathode materials;
- improve QE and QE lifetime of semiconductor cathodes when inserted in the SRF structures;
- develop schemes compatible with emittance compensation that overcome limitations due to field exclusion by the SC walls (Meissner effect) or by magnetic field induced quenching of the cavity.

Highlights from the R&D activities from groups operating with SRF gun are listed as:

- DESY 1.3 GHz gun demonstrated ~50 MV/m at the cathode with Nb cathodes and ~27 MV/m with Pb [8];
- KEK is developing an SRF gun that uses a thin SC metallic layer over the warm high-QE cathode material jointly with cathode back illumination to shield the high QE material from the RF in the attempt of overcoming the gradient degradation induced by the warm cathode [9];
- the group at HZB in Berlin, after the first promising results with Gun 0, their first SRF gun (~27 MV/m on Pb cathode), is now getting ready to test Gun 1, their new SRF gun [10];
- the HZRD 1.3 GHz SRF gun in Rossendorf confirmed many years of operation with warm cathodes and is now planning for several upgrades and the testing of transverse focusing by exciting high order modes in one of their cells [11];
- the Wisconsin 200 MHz SRF gun generated beams from Cs_2Te cathodes at ~2.0MeV with ~20MV/m gradient. Gradients up to 29MV/m were generated without the semiconductor cathode [12];
- the BNL 113 MHz Gun, using a CsK_2SB cathode delivered high charges per bunch (3.7 nC), and 2μm ε_n at 250pC and 15MV/m at the cathode [13].

Normal-Conducting CW RF Guns

High-frequency (> ~1 GHz) normal-conducting radio-frequency (RF) guns have already demonstrated high gradients and beam energies delivering beams with the brightness required by X-ray FELs. On the other hand, as mentioned before, the average power density in the cavity structure limits the practical repetition rate in the few kHz range. By decreasing the RF frequency, the size of the cavities increases with a beneficial reduction of the power density on the structure walls and higher duty cycles can be achieved. For example, the Boeing gun has achieved 25% duty cycle operation at 433 MHz [14], and a group at Los Alamos developed a 700 MHz normal-conducting RF gun where a sophisticated and state of the art cooling system allowed to operate the gun in CW mode [15]. A lower frequency scheme that has been proven in operation, is the gun used at the ELSA 19 MeV linac [16], where the 144 MHz gun has produced high charge-low emittance beams at a moderate duty cycle (150 μs macropulse at 10 Hz repetition rate).

In 2006, our group at the Lawrence Berkeley National Laboratory (LBNL) proposed and later developed [17] the VHF-Gun, a CW room-temperature photo-gun operating at 186 MHz (the 7th sub-harmonic of 1.3 GHz) in the very high frequency (VHF) range. The VHF-Gun, based on conventional and reliable mechanical and RF technologies, targeted nominal values of 20 MV/m gradients at the cathode during photoemission and of 750 keV beam energy at the gun exit. By lowering the gun cavity frequency down into the VHF range, the power load on the cavity walls during CW operation is dramatically reduced to densities that can be removed by conventional cooling techniques while accepting a moderate decrease of the maximum field at the cathode. Additionally, the long RF wavelength allows for the design of an efficient vacuum system using a large number of large apertures along the cavity wall to provide, with negligible field distortion, a high-vacuum conductance path towards an external plenum heavily equipped with vacuum pumps. The scheme demonstrated the capacity of providing the extremely low pressures required for using the reactive semiconductor cathodes with QE lifetimes compatible with the operation of a user facility [18, 19].

The NC CW RF gun technology advantages are:

- capability of operating in CW mode with up to hundreds of MHz repetition rates;
- for VHF frequency guns the beam dynamics is similar to DC guns but with much higher gradients and beam energies;
- in the VHF frequency range the design is based on mature and reliable RF and mechanical technologies;
- the scheme is fully compatible with magnetic fields;
- vacuum pressures compatible with high QE semiconductor cathodes;
- potential for higher gradients at the cathode and beam energies.

The main disadvantage for this technology is represented by the fact that high gradients and energies require high RF power.

NC CW RF gun highlights include:

- the Los Alamos 700 MHz RF gun demonstrated CW operation with ~800 kW RF power dissipated on the cavity wall [15];
- the LBNL VHF-Gun demonstrated at the APEX injector facility all formal requirements for LCLS-II, including the generation of the quality beams required by high-repetition rate X-ray FELs [20];
- LBNL is fabricating a VHF-Gun (close version of the APEX gun) that will drive the LCLS-II injector;
- the 250 MHz VHF-gun built at SINAP in Shanghai successfully underwent low power RF tests [21].

DC-SRF RF Guns

The pros of the DC-SRF hybrid configuration are:

- brings the cathode out of the cryogenic environment;
- allows for a beam energy higher than in DC guns;

The disadvantages include: gradient limitation at the cathode and an increased system complexity.

The 3.5 cell hybrid at Peking University recently demonstrated 1mA macropulse current and started to run user experiments with THz and ultra-fast electron diffraction [22].

Table 2 summarizes the present performance of the guns developed by groups operating in the field (apologies for those involuntarily missing).

Table 2: Present performance level for high-brightness CW electron guns.

Group	Technology	Cathode E_z at emission (goal)	Cathode E_z at emission (measured)	Beam energy (goal)	Beam energy (measured)	ε_n at charge (measured)	Current/ repetition rate (measured)
Cornell	DC	~6 MV/m	~5 MV/m	0.5-0.75 MeV	~0.4 MeV	~0.2µm/20pC ~0.3µm/0.1nC ~0.6µm/0.3nC	20-65 mA/ 1.3 GHz
Daresbury (JLab-type Gun)	DC	~3.3 MV/m	~3.1 MV/m	0.35 MeV	0.325 MeV	~5µm/50pC	~8mA/81.25MHz 100ms @ 20Hz
JAEA/KEK	DC	~6.7 MV/m	~6.7 MV/m	0.5 MeV	0.45-0.5MeV	~1.1µm/7.7pC	~1 mA/1.3GHz
JLab	Inverted DC	~4.5 MV/m	~3.9 MV/m	0.35 MeV	~0.3 MeV	To be measured	~1mA/DC
BNL	112 MHz SRF	22.5 MV/m	~15 MV/m	2 MeV	~1.2 MeV	~2µm/0.25nC	Up to 3.7nC
DESY	1.3 GHz SRF	~40 MV/m	~40MV/m Nb cath. ~22MV/m Pb cath.	3.7 MeV	To be measured	To be measured	To be measured
HZ Berlin (Gun 0.2)	1.3 GHz SRF	~9 MV/m	~10MV/m Pb cath.	2.3 MeV	2.5 MeV	1.9µm/mm rms Pb	Not available
HZ Rossendorf	1.3 GHz SRF	9 MV/m	~9 MV/m	4.5 MeV	~4.5 MeV	~0.3µm/3pC ~5µm/0.09nC	20mA/100kHz
KEK	1.3 GHz SRF	25 MV/m	To be measured	2 MeV	To be measured	To be measured	To be measured
Wisconsin	200 MHz SRF	40 MV/m	29MV/m no cath. 20 MV/m Cs_2Te	4 MeV	2.9MeV no cath. 2 MeV Cs_2Te	~1.5µm/0.1nC	Not available
LANL	700 MHz NC RF	~10 MV/m	~9.8MV/m	2.7 MeV	2.5 MeV	Not available	Not available
LBNL	186 MHz NC RF	19.5 MV/m	> 21 MV/m	0.75 MeV	> 0.8 MeV	~0.2µm/20pC	0.3 mA/1MHz
Peking University	DC SRF	5 MV/m	~2.6 MV/m	5 MeV	~3.4 MeV	~2µm/20pC	0.55mA/81.3MHz

IS THE PRESENT PERFORMANCE SUFFICIENT?

The question that needs to be answered now is: are the achievements presented in the previous section sufficient to satisfy the requirements of present high repetition rate X-ray FELs being proposed and under construction? The answer is yes for most of the cases. Indeed, the gradients and beam energies already demonstrated are sufficient to generate the presently required charges (~10-500 pC) and associated emittances (~0.1-0.8 µm). On the other hand, some proposed upgrades, such as the high-energy upgrade of the LCLS-II at SLAC for example, would require a significantly better performance (~0.1 µm with 100 pC) to extend their lasing spectrum up to ~20 keV photon energies. Initial simulations show that gradients at the cathode greater than ~30MV/m and few MeV beam energies at the gun are required to obtain those results.

In order to achieve those new target values, SRF schemes need to continue the R&D to solve the gradient degradation issue associated with the use of warm cathodes. LBNL is instead proposing APEX-2, an upgraded two-cell version of their APEX VHF-Gun capable of gradients larger than 30 MV/m and beam energies approaching 2 MeV [23].

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