OVERVIEW OF RECENT PROGRESS ON HIGH REPETITION RATE, HIGH BRIGHTNESS ELECTRON GUNS*

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Abstract

In the last few years, the formidable results of x-ray light sources based on FELs opened the door to classes of experiments not accessible before. Operating facilities have relatively low repetition rates (~ 10-100 Hz), and the natural step forward consists in the development of FEL light sources capable of extending their rates by orders of magnitude in the MHz regime. Additionally, ERL based x-ray facilities with their promise of outstanding performance also require extremely high, GHz-class repetition rates. The development of such facilities would represent the next revolutionary step in terms of science capability. To operate such light sources, an electron injector capable of MHz/GHz repetition rates and with the brightness required by X-ray FELs or ERLs is required. Such injector presently does not exist. In response to that, many groups around the world are intensively working on different schemes and technologies that show the potential for achieving the desired results. This paper includes a description of the requirements for such injectors, an overview of the pursued technologies and of the results obtained so far by the groups active in the field.

INTRODUCTION

With the advent of 4th generation light sources, X-ray source facilities based on FELs or ERLs, the availability of high brightness electron guns became of paramount importance. Indeed, the x-ray performance of such facilities directly depends on the electron beam quality and in particular on its brightness. Up to many hundreds of pC bunches are usually required with sub-micron normalized emittances in both transverse planes. Storage rings cannot satisfy such a requirement and linac based accelerators are required. The highest brightness obtainable in a linac is ultimately defined by the injector and in particular by the electron gun performance.

The spectacular success of the first x-ray FELs [1-4] is in large part due to the high brightness performance of their electron guns. Such facilities operate at relatively low repetition rates (<~100 Hz), but proposed high average brightness x-ray FELs [5] and FEL oscillators [6] requires MHz-class repetition rates, and proposed ERL-based 4th generation light sources ask for even higher rates beyond 1 GHz [7-10]. The normal-conducting (NC) high-frequency RF technology (1.3-3 GHz) used in the excellently performing electron guns used in existing 4th generation light sources cannot be scaled to repetition rates higher than ~10 kHz (while maintaining the required accelerating fields) because of the excessive power density dissipated on the gun cavity walls [11]. Electron guns capable of 4th generation light source quality beams at MHz/GHz repetition rates presently do not exist, and a number of groups around the world are working on schemes to fill that gap up. This paper includes a review of the requirements for such guns and of the technologies adopted by the different groups, and an overview of the active projects and of their recent results.

HIGH-REPETITION RATE HIGH-BRIGHTNESS GUN REQUIREMENTS

Table 1 contains the list of the requirements that an electron gun has to satisfy in order to operate in a high-repetition rate 4th generation light source.

Table 1: Fourth Generation Light Source Electron Gun Requirements

Parameter	Value or Comment
Repetition rate	from ~1 MHz to ~1.3 GHz
Charge per bunch	from ~1 pC to ~1 nC
Norm. transverse emittance	from ~0.1 to ~ 1 μm with values increasing with increasing charge/bunch
Beam energy at gun exit	> ~500 keV (to control space charge induced emittance increase)
Electric field at the cathode at emission	> ~10 MV/m (for controlling the space charge limit at emission)
Bunch length	from ~100 fs to ~50 ps for controlling charge density
Compatibility with magnetic fields in the cathode/gun area	mainly for emittance compensation but also for advanced beam manipulation
Acceptable dark current	to avoid quenching in the superconductive linac and for controlling radiation doses
Capability of operating high quantum efficiency photo-cathodes	to deliver the required charge and current with available laser technology
Operating vacuum pressure	$\sim 10^{-9} - \sim 10^{-11}$ Torr for cathode lifetime
Capability of an "easy" cathode replacement	requires a vacuum loadlock system
Reliability	compatible with a user facility operation

The requirements in Table 1 have been discussed in detail elsewhere [12], here we want to remark the particular importance that some of those specifications

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have. In order to obtain the required brightness, space charge must be carefully controlled along the gun and the injector. Because of the need of controlling field emission to minimize dark current, and because limitations of some of the gun technologies, the field at the cathode during photoemission can be significantly smaller than in the case of low repetition rate guns. This situation forces the beam into a different beam dynamics regime where relatively long bunches must be used to reduce the charge density and control space charge effects. Simulations [13] and initial experimental results [14] indicate that the desired performance can be obtained if the beam energy and accelerating gradients in Table 1 are achieved. Nonetheless a complete experimental demonstration is still required.

In addition to the control of the bunch length, the optimization of the beam brightness also requires control of the spatial distribution of the bunch. A 3D uniform ellipsoidal distribution generates linear space charge forces that do not increase the rms emittance and thus represents the ideal distribution to pursue. Such a distribution is difficult to generate and the so-called "beer can" distribution is often adopted as a reasonable and easier to generate tradeoff. Alternatively a special technique, the so-called "beam blow-out" [15, 16] generates the 3D uniform ellipsoid by starting with a very short (< ~100 fs) and relatively wide beam. Under the action of its own space charge forces this "pancake" beam evolves in the desired ellipsoidal distribution. The technique that has been demonstrated for bunches with charges/bunch <~100 pC [17], generates an ellipsoidal distribution with a very regular longitudinal phase space and a reasonable transverse emittance.

The bunch distribution control requirement makes of photocathodes the most chosen cathode system. A notable exception is represented by the SACLA FEL injector [18] where a thermionic cathode is used in combination of a complex and articulated compression system to successfully generate the high brightness beam. Delivering the required charge and current with the power available by the present laser technology requires using high quantum efficiency photocathodes with QE > ~10^{-2}. Semiconductor cathodes, such as Cs_2Te, GaAs:Cs or CsK_2Sb for example, offer the required QE but are quite reactive and sensitive to ion back bombardment. Because of this, in order to achieve acceptable lifetimes, they require the low operational pressures shown in Table 1. A complete review of photocathode systems can be found in reference [19].

AVAILABLE GUN TECHNOLOGIES

The list of technologies presently pursued for the development of high-repetition rate high-brightness electron guns includes direct current (DC), superconducting RF (SRF) and low frequency (< ~700 MHz) normal conducting (NC) continuous wave (CW) RF guns plus some hybrid configuration.

DC schemes allow for arbitrarily high repetition rates, are compatible with the application of magnetic fields in the cathode/gun area, have demonstrated extremely low vacuum pressures (~10^{-11} Torr) and are compatible with all cathodes presently under consideration. The areas where improvements are still required include higher beam energies at the gun exit and higher gradients at the cathode. Field emission from the gun metallic parts creates charge build up in the gun ceramic insulator generating voltage breakdown and ceramic punctuation when energies higher of the presently achieved ~350 kV are attempted. Relatively recent results from the JAEA group [20] are showing promising progress towards higher energies, more details in the next section.

Electron guns based on SRF schemes allow for very high repetition rates (> ~1 GHz), are potentially capable of high gradients at the cathode, and because of the effective cryopumping performed by the superconducting walls are capable of a very good vacuum performance. Meissner field exclusion does not allow for externally applied magnetic fields forcing the use of cryogenic solenoids for the emittance compensation. Questions on compatibility of semiconductor cathodes with the SRF environment needs to be carefully investigated, even though promising results with Cs_2Te have been demonstrated at the Rossendorf gun [21]. Reduction of multipacting (especially in the RF coupler area) and of field emission at higher gradients is actively pursued by the groups developing SRF schemes. Performance reproducibility of the SRF structures also requires further improvements.

In NC CW RF guns the frequency is lowered below ~700 MHz to make the power dissipated on the gun cavity walls small enough to be removed by water cooling while operating in CW mode with the gradients required for the generation of high brightness electron beams. NC CW RF schemes can achieve repetition rates of hundreds of MHz and are compatible with magnetic fields in the cathode/gun area. If the frequency is lowered down into the VHF range (30-300 MHz) the cooling becomes straightforward and can be performed by conventional and reliable cooling techniques. Additionally, the very long VHF wavelengths allow for significantly large apertures in the vacuum walls with negligible field distortion. This allows creating a high conductance vacuum path to externally located vacuum pumps setting the conditions for the vacuum performance required by semiconductor cathodes. The long period of VHF frequencies makes the beam dynamics practically identical to the one in DC guns but with higher gradients and beam energies. Power density on the cavity walls limits the maximum gradient at the cathode during photoemission to values (~20-30 MV/m) 2 to 3 times smaller than in pulsed high frequency NC RF guns. Repetition rates higher than ~700 MHz, as required in proposed ERL based 4th generation light sources, are beyond the capability of NC CW RF guns.

A hybrid scheme including a relatively low voltage DC gun followed by a SRF cavity is being developed by

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a group at the Peking University [22]. The scheme tries to preserve the advantages of both DC and SRF technologies while eliminating some of the disadvantages at the cost of an overall increased complexity. More details in the next section of this paper.

PROJECT RESULT OVERVIEW

DC Guns

Several groups are developing high brightness DC electron guns. The Cornell University design is shown on the left part of Figure 1 [23]. It presently operates at 350 kV limited by field emission and voltage breakdown. A new gun designed to achieve 500 kV is presently under construction. The Cornell group has been testing several different photocathodes, and recently demonstrated average currents with a peak of ~50 mA with GaAs:Cs cathodes, and ~ 8 hours of constant 20 mA average current from CsK_2Sb cathodes without any apparent QE degradation [24]. This last result is quite important because demonstrate the potential of CsK_2Sb to operate in most of 4th generation light sources with high QE and adequate lifetimes. The vacuum pressure during the tests was in the low 10^{-11} Torr. Notable are also the recent emittance measurements at 20 and 80 pC/bunch with values already within the acceptance range for their ERL project.

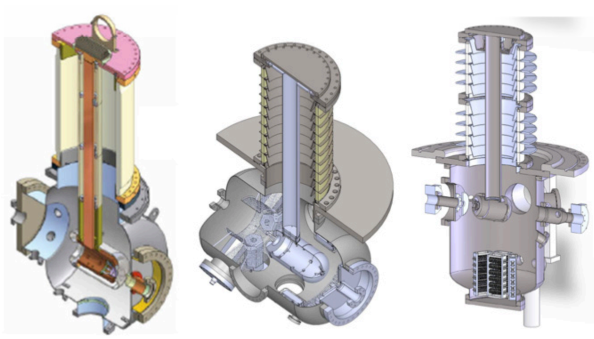

Figure 1: Examples of DC guns under development. Left: Cornell gun. Center: JAEA gun. Right: KEK gun.

Two DC guns are under development in the framework of the Japanese ERL project. The gun from JAEA [20], visible in the central part of Figure 1, adopts a layout inspired to the Cornell DC gun but with a modified ceramic design. The insulator is segmented with segments separated by annular metallic shields to prevent field emitted electron to reach the ceramic. The gun is designed for 500 kV operation and is presently under high voltage conditioning. The gun chamber with the central stem that holds the cathode assembly (but without the cathode assembly) has been already successfully conditioned to 550 kV and operated at 500 kV for more than 8 hours without any voltage breakdown. Subsequently, the cathode assembly was installed inside the gun and the conditioning restarted. The operation is presently in progress trying to overcome some field emission activity at ~ 450 kV. The results from the JAEA gun are pushing the achievable beam energy with DC guns increasing the probability of achieving the 500 kV target in the near future.

In the KEK gun design [25] field emission is minimized by having all the metallic parts of the gun in titanium because of the low secondary emission yield of that metal. Additionally, great attention has been placed in the design of a powerful pumping system with cryopumps and NEG modules for targeting pressures as low as ~ 10^{-12} Torr. To prevent voltage breakdown and ceramic punctuation a segmented ceramic has been used for this gun as well.

Jefferson Lab has a long tradition on DC guns. Their FEL electron source [26] runs reliably at 350 kV since many years and has delivered more than 10,000 C of charge with GaAs:Cs photocathodes. They are also investigating the option of an inverted geometry DC gun [27, 28] where the ceramic is now located internally to the gun vacuum chamber minimizing the ceramic size and the exposition to field emitted electrons.

A DC gun based on the JLab design, but with the ceramic modified to have bulk resistivity, is in operation at 325 kV in Daresbury as part of the injector of the ALICE project [29].

SRF Guns

A 3.5 cell 1.3 GHz SRF gun, shown in the top part of Figure 2, is operating since several years in Rossendorf as injector for the ELBE FEL [21]. In the last few years, the gun has been using Cs_2Te photocathodes, and one of such cathodes operated for more than thousand hours with a QEs of ~ 1% delivering more than 35 C of integrated charge. This is an important result that proves the good compatibility of this semiconductor cathode with the SRF environment. The present gun is running at a limited gradient and energy because of a damaged cell. A new upgraded cavity built in collaboration with JLab is presently under construction. Severe multipacting in the cathode area has been significantly reduced by the application of a DC bias to the cathode and by modifying the surface of the cathode holder.

The HoBICaT 1.3 GHz 1.5 cell SRF gun has been built in the framework of the the B*ERL*inPro ERL project [30]. The gun, shown in the central part of Figure 2, delivered the first beam in April 2011 by photoemission from a superconducting lead cathode. A current of ~50 nA was generated by ~6 pC bunches at 8 kHz repetition rate. The energy at the gun exit was ~1.8 MeV and the gradient at the cathode during photoemission was ~5 MV/m. New guns using CsK_2Sb photocathodes are under development to deliver much higher currents (up to 100 mA) with a gradient at photoemission of ~ 10 MV/m. The new guns should deliver their first beam in 2014 and 2015.

Wisconsin University is constructing a 200 MHz SRF gun targeting the very high gradient of 40 MV/m at the cathode during photoemission [31]. This accelerating field will allow to operate the gun in the beam blow-out mode with 1 MHz repetition rate and 200 pC per bunch.

The gun cavity is shown in the bottom part of Figure 2 and consists in a single cell quarter wave resonator designed to accelerate the beam to ~4 MeV. The gun cavity has been built and is presently undergoing through initial RF tests.

The Navy Postgraduate School (NPS) in collaboration with Niowave Inc. and Boing has developed two 500 MHz SRF guns [32]. Both of the systems have been built in record time (less than 10 months) showing an example of remarkable synergy between a research institution and a private company. The first gun is initiating first commissioning at NPS while the second gun is presently under test at Niowave.

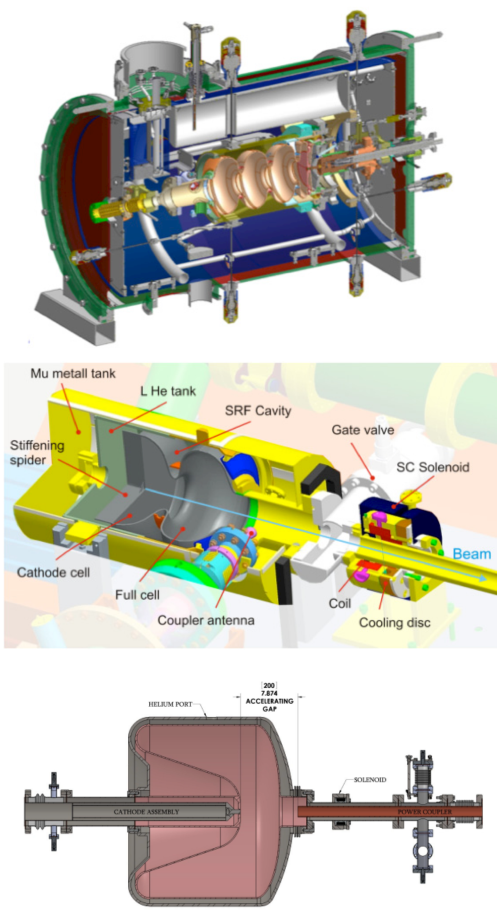

Figure 2: Examples of SRF guns under development. Top: Rossendorf gun. Center: HoBICaT gun. Bottom: Wisconsin gun.

Brookhaven National Laboratory (BNL) is developing several SRF guns. A collaboration with Advanced Energy Systems Inc. has generated a ½ cell SRF gun resonating at ~700 MHz designed to operate at the challenging current of 500 mA with charges per bunches of up to 5 nC [33]. Beam operation is expected in the second half of 2012. A second SRF gun, based on a 112 MHz quarter wave resonator, is designed to generate high charge low repetition rate bunches for the electron cooling experiments [34].

Normal-conducting CW RF Guns

Los Alamos National Laboratory (LANL) in collaboration with Advanced Energy Systems Inc. developed and built a 700 MHz NC glidcop gun capable to run in CW and dissipate many hundreds of kW using state of the art cooling techniques [35]. The gun, visible in the left part of Figure 3, has been fully RF conditioned and is now undergoing the first beam tests.

A NC CW RF gun resonating at 186 MHz in the VHF band is under commissioning at the Lawrence Berkeley National Laboratory (LBNL) in the framework of the APEX project [36]. A CAD view of the gun is visible in the right part of Figure 3. The single cell reentrant nose gun cavity has been designed to accelerate the beam at 750 keV with a gradient at the cathode during photoemission of ~ 20 MV/m. More than 100 slots in the cavity side wall allow for a large vacuum conductance while minimally perturbing the field in the cavity. The 20 NEG modules each with 400 l/s pumping speed located in a plenum around the cavity wall should allow for the required pressures to operate semiconductor cathodes. The cavity has been conditioned to full power and the first photoemitted beam was successfully generated at the nominal energy by photoemission from the molybdenum cathode dummy plug presently installed in the cavity [37]. Test with high QE semiconductor cathodes (Cs_2TE and CsK_2Sb) are scheduled in the near future after vacuum conditioning of the cavity.

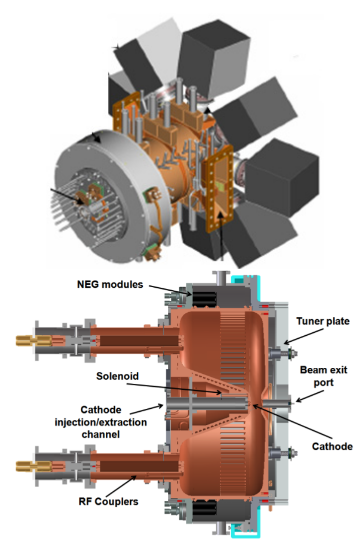

Figure 3: Examples of NC CW RF guns under development. Left: Los Alamos gun. Right: The VHF gun of the APEX project at LBNL.

A low frequency NC CW RF gun is also being considered for the injector for the XFELO at Argonne National Laboratory [38]. The gun, inspired to the LBNL VHF gun, will generate MHz electron bunches with several tens of pC and normalized emittance of few tenths of μm. A B_6Ce thermionic cathode, similar to the one used in the SACLA injector [18], followed by an articulate compression system to reach the desired bunch lengths is under consideration.

Hybrid Gun Schemes

A group at Peking University is developing a hybrid gun scheme (visible in Figure 4) where a relatively low voltage 100 kV DC gun with a Cs_2Te photocathode is connected to a 3 and ½ cell SRF cavity [22]. The rationale beyond such a scheme is to benefit of the advantages of the single technologies while mitigating the disadvantages. The DC gun allows decoupling the cathode from the SRF environment. Magnetic fields in the cathode area can be potentially applied for an optimal initiation of the emittance compensation process. The voltage and the gradient of the DC gun (~6 MV/m), although relatively low, should be sufficient to operate the gun at the nominal charge per bunch (60 pC) with the required brightness. First beam from the Cs_2Te cathode was successfully delivered during a recent (more than a week long) test during which the QE of the cathode never dropped below 1%.

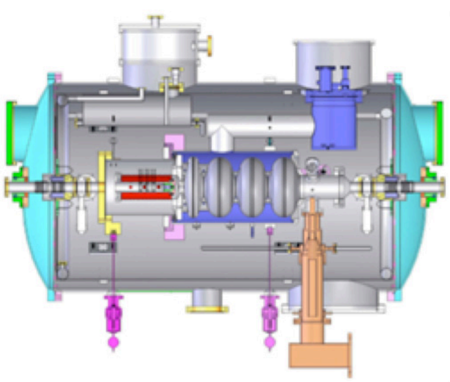

Figure 4: The hybrid DC-SRF gun of Peking University.

CONCLUSIONS AND ACKNOWLEDGMENTS

The field of high-repetition rate high-brightness electron guns is presently undergoing through an exciting phase where the activity of many groups around the world pursuing different technologies is generating very encouraging results. The present trend allows to optimistically state that the realization of an electron gun capable of satisfying all requirements needed by a 4th generation light source is close to become a reality.

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