

Superconducting Photoinjector

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Abstract

One of the frontiers in FEL science is that of high power. In order to reach power in the megawatt range, one requires a current of the order of one ampere with a reasonably good emittance. The superconducting laser-photocathode RF gun with a high quantum efficiency photocathode is the most natural candidate to provide this performance. The development of a 1/2 cell superconducting photoinjector designed to operate at up to a current of 0.5 amperes and beam energy of 2 MeV and its photocathode system are the subjects covered in this paper. The main issues are the photocathode and its insertion mechanism, the power coupling and High Order Mode damping. This technology is being developed at BNL for DOE nuclear physics applications such as electron cooling at high energy and electron ion colliders.

INTRODUCTION

In the past few years we are witnessing the growth of a new class of particle accelerators: high-power, high-brightness electron beams. This emerging technology is enabled by the combination of high-brightness electron sources and high-current SRF Energy Recovery Linacs (ERL). While the current state-of-the-art is at about 10 mA current [1] (the Jefferson Laboratory FEL upgrade), there is interest in much higher currents, in the range of 0.1 ampere to over 1 ampere CW, with emittances that are of the order of under 1 to a few 10's microns normalized rms, depending on the application, in particular on the bunch charge.

What are the applications driving this interest? First, as the Jefferson Laboratory example suggests, high power Free-Electron Laser (FEL) is one candidate. The high-brightness is required for the lasing conditions at UV or shorter wavelength, and significantly higher currents are desirable for high power FEL applications [2]. The energy required for such applications is not very high, in the range of 100 MeV to less than 1 GeV for UV high-power FELs.

The next application is also for the production of electromagnetic radiation, but for mostly spontaneous emission. This is the ERL based light sources [3,4]. For this application the current may be in the range of 100 mA, less for the extremely high brightness X-ray radiation or higher for flux dominant applications. The required energy is between 3 and 10 GeV.

Another application is in an altogether different field, electron ion colliders [5]. In this type of machine a current of hundreds milliampere electrons or polarized electrons is needed at energy of up to 10 or 20 GeV.

A somewhat specialized application is electron cooling of hadron storage rings, in particular heavy ion beams [6]. This application requires electron beams at currents of up to 0.1 amperes but relatively low energies of under 100 MeV. Finally, there are a host of other applications that have been demonstrated but are still under development: X-ray sources via Thomson scattering of laser on the electron beam and terahertz radiation examples.

The electron gun and injector design is arguably the most critical part of the ERL. It is here that the ultimate performance of the ERL is determined: What will be its current, its bunch structure, and its transverse and longitudinal emittances. These parameters can only be degraded in subsequent parts of the ERL, never improved. The gun and injector are also the most dynamic elements, with rapid progress being made. It has some of the most intractable problems, in particular the issue of providing a good photocathode and dealing with severe space-charge interaction and limited space. The flip side of this is that any improvement made in this relatively small element affects the performance of the complete ERL and can easily lead to dramatic improvements.

In this paper we will look at the technology and challenges confronting the development of high-current, high-brightness electron sources and describe the approach taken by the few laboratories which are actively developing this technology: Brookhaven National Laboratory and Advanced Energy Systems, KF Rossendorf, the University of Peking and DESY.

THE CURRENT STATUS OF SRF GUNS

The first pioneering experimental work on a superconducting RF gun took place about 15 years ago in Wuppertal by Michalke [7]. The activity in the area of SRF guns around the world is growing steadily. Successful milestone operation of a SRF gun with a superconducting half-cell cavity were carried out in 2002 at the Forschungszentrum Rossendorf [8], and a new SRF photoinjector for CW operation at the ELBE linac is under development [9]. The conclusion from the successful operation of the half-cell SRF injector cavity at

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Rossendorf is addressing the crucial question if the photocathode inside the superconducting cavity reduces the quality factor due to particle pollution. During about 200 hours operation time, such an effect was not seen using CsTe₂ cathodes. It also demonstrates convincingly that a reliable mechanism for inserting a normal-conducting cathode stem into a superconducting cavity does not affect the good performance of the SRF cavity. Following this initial success the Rossendorf group embarked on the design and production of a 3 ½ cell gun which has also various other improvements for getting the smallest emittance out of the device, including careful shape optimization, bunch focusing by a high-order RF mode, symmetrized input coupler and improved tuner system [9]. Other SRF guns have been built and operated. An all niobium RF gun developed by BNL, AES and JLab demonstrated large charge (10 nC) in a short (~10 ns) bunch train [10,11]. The University of Peking started very early on a novel hybrid pulsed DC - a half cell niobium gun [12]. The team at Beijing is now proceeding with a 3 ½ cell gun [13, 14]. Superconducting photocathodes in a superconducting RF gun are pursued by a DESY-JLab-BNL collaboration [15], where good SRF performance has been combined in proof-of-principle ½ cell gun and photoemission has been measured. This led to a new 1 ½ cells gun with sophisticated RF design [16]. Following early successes, a new generation of guns is emerging, where multi-cell guns with improved geometries, focusing and coupling aim at a small emittance at higher average currents, 1 to 10 mA, as called by UV or x-ray FELs.

THE BNL – AES SRF GUN

The main feature of the BNL-AES gun, seen in Figure 1., is the design for a very high current, up to 0.5 ampere, for a variety of applications as described above, in particular for electron cooling and electron-ion colliders. Table 1 shows the parameters of the BNL-AES SRF gun. It has been optimized [17] to obtain a small emittance at a large charge by shaping the gun cavity, selection of its frequency and field.

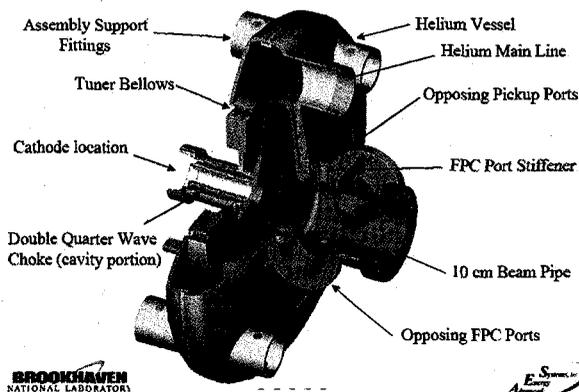


Fig. 1. The BNL-AES SRF electron gun.

The gun design is dictated by the objective of a high current but at a limited (1 MW) CW klystron power. Thus

a single cell design is used, which allows for a high accelerating field at a limited total voltage of 2 MV.

The choice of frequency was dictated by the need to maintain the frequency a harmonic of the RHIC frequency with 360 bunch pattern of 28.15 MHz, lower the frequency to a value where beam breakup threshold current in the ERL will be large and, finally, a frequency where CW MW klystrons are available. That led to the choice of 703.75 MHz.

This SRF gun is equipped with a demountable photocathode capable of being inserted and retracted while maintaining the vacuum integrity and cleanliness of the photoinjector. A schematic of the photoinjector and associated helium vessel is shown in figure 1.

The cavity iris had to be made small for beam dynamics reasons (reduction of effective length of the cavity). That precluded damping all HOMs through the beam pipe.

HOM damping is an important issue. It was found that the beam pipe diameter could be kept at 10 cm, the same dimension as the iris of the cavity and still adequately propagate most of the HOMs. Other benefits of having reduced beam pipe size is simplification of strong coupling of the 1 MW RF power to the beam, as well as reduction of the size of the gate valve needed at the end of the beam pipe, a tremendous weight and cost savings.

Table 1: BNL-AES SRF Gun Specifications

Parameter	Units	Value
Frequency	MHz	703.75
Iris radius	cm	5
Equator Diameter	cm	37.9
Cavity length	cm	25
Beam kinetic energy	MeV	2
Peak electric field	MV/m	35.7
Peak magnetic field	A/m	58740
Stored energy	Joule	8.37
QR _s (geometry factor)	Ω	3.52
R/Q	Ω	96
Q _e (external Q)		37000
Power input	MW	1
Maximum current	mA	500
Emittance at 1.4 nC	μm rms normalized	1.4
Cathode recess	mm	1
Cathode spot size	mm diameter	5
Emission phase	Degrees	25
Longitudinal loss factor	V/pC	0.7
Transverse loss factor	V/pC/m	32

Additionally, a focusing solenoid, constructed from a high temperature superconductor, will be inserted just inside the gate valve in order to help decrease the beam emittance. This will be much easier with the reduced beam pipe size as it will significantly reduce the amount of material needed to make the solenoid, significantly reducing the power needed to drive the solenoid and subsequently the heat generated during its operation.

The gun propagates all but 3 of the HOMs down the beam pipe to be strongly absorbed by a ferrite HOM absorber at room temperature. The three trapped modes can be easily missed by harmonics of the beam repetition frequency and detailed calculations have shown that the effect of long range wake fields can be neglected if the beam amplitude and phase noise are under a reasonable limit. It is expected that the strong coupling of the fundamental power couplers will damp some or all of these modes. Work is in progress on this question.

The gun design accommodates a load-lock cathode insertion mechanism, which is introduced through a double quarter-wave choke joint which accepts a UHV cathode transporter. The photocathode will be extended approximately 1 meter into the photoinjector and positioned at the exact location for operation.

The cathode transporter, in turn, couples to a UHV cathode preparation chamber. The locking mechanism has been designed with UHV requirements and introduction of minimal particulate matter into the cavity. The quarter wave choke joint is much easier to fabricate than the alternative proven design, presently used by Rossendorf, which incorporates a more complex arrangement including an additional, detuned cavity. The quarter wave choke joint concept has undergone preliminary testing and will be subsequently tested using a fully SRF 1.3 GHz photoinjector presently in place at BNL.

PHOTOCATHODE ISSUES

The photocathode is the single most difficult issue for a high-current electron gun.

What are the requirements for a high-current photocathode suitable for this gun?

1. Avoid contamination of the SRF gun.
2. Provide high quantum efficiency.
3. Long life.
4. Prompt emission.
5. Ideally, allow exposure to air to simplify installation.
6. Provide a low thermal emittance.

The initial choice of a cathode for this gun is the multi-alkali photocathode. As described above, there is a provision for inserting an independently cooled, electrically isolated photocathode into the photoinjector. The cathode insertion device is a complicated arrangement that must satisfy a number of different criteria. It must be electrically and thermally isolated from the cavity in order to avoid additional heat loads to the cryogenic system due to the fact that the cathode is maintained at an elevated temperature relative to the cavity and because of the high average current being

extracted from the photocathode. It must also be designed such that when inserted there is a means of avoiding multipacting or other RF losses through the insertion mechanism. This is being addressed using the quarter wave choke joint mentioned above.

The photocathode we have pursued is CsK₂Sb [18], and was selected based on its high quantum efficiency and convenient operational wavelengths. (QE of 2-14% at 532 nm and 10-30% at 355 nm) The fabrication of the photocathode is a process that is highly dependent on the exact deposition system configuration, thus making it difficult to directly import a recipe from another source. The general technique, obtained through our collaboration with David Dowell at SLAC, formerly at Boeing, is to deposit ~200 Å of antimony followed by the deposition of ~150 Å of potassium and then deposition of cesium while monitoring the QE. The cesium deposition is terminated when the QE reaches a maximum.

The technological challenges presented by using a CsK₂Sb photocathode in a SRF photoinjector revolve around the vacuum conditions to which the photocathode is exposed. All the multi-alkali photocathodes require extremely good vacuum conditions, 10⁻¹⁰ Torr or better, in order to maintain their designed QE for a reasonable length of time. At BNL we demonstrated over 2 months storage of CsK₂Sb photocathodes in 2x10⁻¹⁰ Torr vacuum. Vacuum degradation during operation in the gun should not be a problem in an SRF photoinjector as it is maintained at 2K.

The temperature of the photocathode in the gun is reduced to below room temperature. The operation of the CsK₂Sb photocathode has been tested down to 170 K and has seen only a 10% decrease in QE.

Another possible approach to photocathodes has been proposed and is under investigation [19]. The idea is to "amplify" the emission from a photocathode. A thin (of the order of 30 micrometers) diamond window is positioned between the photocathode and the gun. The diamond has a thin metal coating facing the photocathode, and a monolayer hydrogen facing the gun. A DC voltage is applied between the metal layer on the diamond and the photocathode. The primary electrons are generated in the photocathode by a laser, accelerated in the gap between the photocathode and the diamond and strike the diamond with 5 to 10 KeV. The primary electrons produce a large shower of secondary electrons and holes (using about 13 eV of primary energy per electron-hole pair). The electrons and holes are separated quickly by the field in the diamond (produced by the RF gun). The holes are absorbed into the metal layer. The electrons drift through the diamond, thermalizing to a small fraction of an electron volt in the process, and exit the diamond to the gun. A critical element here is endowing the diamond side facing the gun with a negative electron affinity, by bonding hydrogen to the diamond's dangling bonds.

The emission is prompt and has very low thermal energy. The diamond properties are such that the heat generated by the various processes (mainly the primary energy deposition, RF heating of the metal layer and the

heat generated by the transport of the electrons through the diamond) is conducted efficiently to the walls with an insignificant temperature gradient. In addition, the mechanical strength of the diamond promises that the capsule may hold atmospheric pressure for transporting the evacuated photocathode. The hydrogenated diamond surface is very robust, and can be carried through air for installation without losing its negative electron affinity.

The main difficulty with the diamond amplification process is trapping of electrons in the surface boundary layer, either a hydrogenised diamond facing an anode (emission measurement) or a metal coating on the diamond, serving as an anode (transmission measurement).

In the work done so far we demonstrated that the expected gain of about 77 secondary electrons per 1 keV of a single primary electron's energy can be achieved in transmission measurements by removing trapped electrons either by the transmission of holes (while the field in the diamond is reversed) or by a small amount of light (such as a laser pointer). This can be seen in Figure 2, where gain (defined as the ratio between the collected anode current and primary current) is shown as a function of the field in the diamond for various primary electron energies. The loss in the metal layer is measured to be 3.5 keV. At every primary energy we see the gain curve for "single pulse", which avoids the accumulation of trapped charge, and a curve for continuous operation using a few milliwatts of green laser for de-trapping.

Work is in progress on hydrogenised diamond, in which the trapping is deeper.

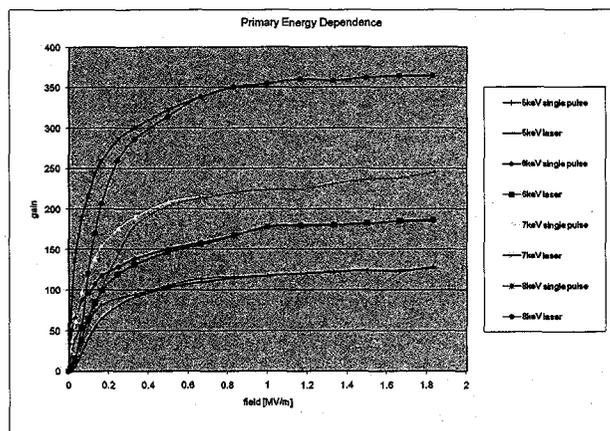


Fig. 2. Gain in transmission with trapping eliminated.

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