PROGRESS IN SRF GUNS*

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Abstract

In the last couple of years great progress has been made in the commissioning and operation of Superconducting RF (SRF) electron beam sources. Both elliptical cavity designs and reentrant cavities have been developed. This paper reviews recent progress in SRF guns.

INTRODUCTION

Application of the superconducting radio frequency technology to photoemission electron injectors is a very active field of research as discussed in recent review articles [1-3]. SRF has advantages over other electron gun technologies (DC or normal conducting RF) in the high duty factor mode of operation, where SRF structures provide higher accelerating gradients. While simulations [4] show that DC and SRF guns have comparable performance with low- and medium-charge bunches, the latter promise to enable generating high-bunch-charge, high-brightness and high-average-current beams for many advanced accelerator applications such as electron-hadron colliders, electron coolers, and free electron lasers. As it was pointed out in [1], SRF guns are expected to play an important role in future linac-driven FEL facilities.

SRF photoemission electron sources are complex devices requiring co-existence of three sophisticated technologies: high quantum efficiency (QE) photocathodes, superconducting RF structures, and high-repetition-rate synchronizable lasers. As a result, progress with developing SRF guns was relatively slow. Only a few years ago SRF gun development efforts began gradual transition from a feasibility demonstration experiments to generating beams for accelerator applications. Recently, several guns generated their first beams and one served as an injector for an FEL at HZDR [5]. For a historical overview of SRF gun development and an in-depth discussions of challenges associated with SRF photoinjectors, I refer readers to previous reviews of the subject [1-3]. In this article I will concentrate on recent progress with SRF guns designed as injectors (SRF photoinjectors) for various applications.

BRIEF SURVEY OF SRF GUNS AND PHOTOCATHODES

Two types of SRF structures are used in photoemission guns: elliptical cavities and quarter-wave / re-entrant resonators. The first guns utilized elliptical cavity geometries, conventional for the high-β SRF cavities. The guns based on elliptical cavities are developed at BNL (USA), HZB (Berlin, Germany), HZDR (Rossendorf, Germany) and Peking University (China). Later on, several guns were designed using a quarter-wave resonator (QWR) approach, which is especially well suited for generating beams with high charge per bunch. The QWRs can be made compact even at long wavelengths thus allowing generation of long electron bunches and minimizing space charge effects and enabling high bunch charge. The guns of this type have been built so far only in the USA for projects at BNL, Naval Postgraduate School (NPS) and University of Wisconsin.

To generate high-intensity and high-average-current beams, one needs high QE photocathodes with a long operational lifetime. Readily available lasers with wavelengths ranging from IR to UV, wide variety of pulse durations and average power of up to several tens of watts enable possible use of many different materials from two classes: metals and semiconductors [6, 7]. Metal photocathodes (Cu, Mg, Pb, Nb) are robust, but have low QE ($<10^{-3}$) and are suitable only for use in the initial phases of an SRF gun development, when high beam intensities / high duty factors are not required. Coating of metal cathodes with a thin (~18 nm) layer of CsBr can increase the QE to $7\cdot10^{-3}$. Superconducting (niobium or lead) photocathodes have been used in small R&D SRF guns as a way to avoid introduction of a special cathode plug and to reduce RF losses.

Semiconductor photocathodes are the preferred option for many projects as they can provide very good QE, 10% and higher. However, these cathodes are very sensitive to contamination and require UHV conditions for operation. The most developed semiconductor photocathodes for SRF gun applications are GaAs(Cs), Cs_2Te, and CsK_2Sb. Gallium arsenide is the only one of the three suitable for producing polarized electrons, but it is the most sensitive to ion back bombardment, requires an extremely good vacuum, and has a short lifetime. Cesium telluride is the most robust and has demonstrated a very long lifetime in an SRF gun at HZDR, but requires the use of UV lasers. This makes it more difficult to use for high bunch charge: more laser power is needed at the same QE than at longer wavelengths, optics and pulse shaping are more difficult as well. Cesium potassium antimonide can be used with green lasers. It demonstrated very good performance in DC guns [8, 9, 10] and holds the world record of average beam current produced from an RF photoinjector [11]. It is the most preferred option for SRF guns at present. A potential alternative is NaK_2Sb, which has a similar to CsK_2Sb production recipe, but proved to be more robust in experiments with a DC gun at Cornell University [12].

Finally, diamond can be used to boost the photoemission current by a factor of ∼100 and diamond-amplified photocathodes are very promising for high-charge applications, though still require more R&D. For more details on photocathode materials, I refer readers to the recently published reviews [6, 7].

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RECENT PROGRESS

3½ Cell SRF Photoinjector at HZDR

The 3½ cell SRF gun [13] is the first SRF gun in the world to inject a beam into an accelerator. The accelerator is a CW SRF linac, which provides electron beams to a multipurpose facility ELBE. The gun has been in operation since 2007. The maximum bunch charge injected into the linac so far is 120 pC at a repetition rate of 50 kHz with some beam losses, and 60 pC at 125 kHz with 100% beam transmission. The maximum average beam current in CW mode achieved to date is 400 µA. The beam kinetic energy is limited to 3.3 MeV, due to field emission in the SRF cavity in CW mode. Pulsed mode operation allows energy increase to 4 MeV. Cs_2Te photocathodes demonstrated a lifetime of ~1 year with QE of ~1% and a total extracted charge of 260 C.

Earlier this year the ELBE SRF gun delivered electron beam for an infrared FEL allowing it to generate light at 41.5 µm and 49 µm [5]. This is the first FEL in the world operating with an SRF photoinjector. The beam parameters are listed in Table 1.

Table 1: ELBE SRF Gun Beam Parameters for IR FEL

Beam kinetic energy at gun exit	3.3 MeV
Micro pulse repetition rate	13 MHz
Macro pulse duration	2 ms
Macro pulse repetition rate	1.25 Hz
Beam energy at FEL	27.9 MeV
Bunch charge	20 pC
Beam current	260 µA
RMS bunch length	1.6 ps
Normalized emittance	1 mm·mrad

A new SRF gun (of a similar design) is under construction and is expected to deliver an improved performance. The cryomodule for the new gun is ready and the cavity is undergoing vertical testing at JLab. The cavity has reached a peak surface field of 43 MV/m, which would correspond to the beam energy of 8 MeV.

DC-SRF Photoinjector at Peking University

A hybrid DC–SRF gun has been developed for the Superconducting ERL Test Facility (SETF) at Peking University. The unique design combines a compact 90 kV Pierce DC gun equipped with a Cs_2Te photocathode and a 3½ cell, 1300 MHz SRF cavity [14]. The gun is designed to produce a 5 MeV beam with a bunch charge of 60 to 100 pC, rms emittance of 1.2 mm·mrad, and repetition rate of 81.25 MHz for operation in the ERL mode. In addition, the plans are to produce THz radiation using 0.55 ps long bunches with a 20 pC charge per bunch. The gun was recently equipped with a new beam line. A series of experiments has been carried out recently resulting in a beam current of ~300 µA with an emittance of about 3 mm·mrad [15].

SRF Guns for BERLinPro at HZB

A demonstration ERL at HZB, called B*ERL*inPro, will require a low-emittance beam with average current of 100 mA and bunch repetition rate of 1.3 GHz from an SRF photoinjector. To achieve these demanding parameters, a three-stage SRF gun development program was initiated. Each stage would add complexity to the design and improve performance. An eventual gun will include a 1.6 cell SRF cavity, high-QE CsK_2Sb photocathode, and two high-power RF couplers to handle full beam power.

The first beam demonstration experiments at the HoBiCaT facility were using two SRF guns with lead photocathodes (all-superconducting guns). The first gun had a thin layer of lead deposited on the back wall of niobium cavity. The second gun had lead deposited on a niobium plug cathode, which allows decoupling of the cavity preparation from the cathode deposition. Both guns generated beams the bunch charge and beam current were limited by low QE of the lead photocathodes (10^{-5} to 10^{-4}) and available UV laser power [16].

The design of the SRF gun for the stage two is finalized. This gun will accommodate a normal conducting photocathode in an arrangement similar to the ELBE photoinjector and will have two RF power couplers capable of supporting a 4 mA current while providing a kinetic beam energy of 2.6 MeV [17].

SRF Guns at NPS

A 500 MHz QWR SRF gun has been built and beam tested for a future FEL at NPS [18]. A niobium cathode on a copper stalk was used in the beam test. The following beam parameters were achieved: a beam energy of >460 keV, a bunch charge of 78 pC, and an rms emittance of 5 mm·mrad [19].

Following this, a new, 700 MHz, Mark II QWR gun was designed, incorporating a number of improvements, enhancements and problem fixes over the Mark I design. The NPS Mark II SRF gun is presently at the test facility of Niowave, Inc. in Lansing, MI. To date the gun has been conditioned to a cavity voltage of 500 kV and has accelerated electron bunches to energies greater than 260 keV. Using a niobium photocathode illuminated by a UV laser, bunch charges greater than 35 pC have been measured. Recent work has cooled the cathode holder with liquid nitrogen, reducing the static cryogenic heat load and lowering the low-field RF losses by 25-30%. Most recently, a single tungsten field emitter tip has been tested and has produced a 100 nA average current beam that has been transported to a diagnostic station and imaged [20, 21, 22].

After testing at Niowave is complete, the gun will be shipped to Los Alamos, where it will be installed it in the LEDA tunnel for further testing. Studies at LANL will focus on increasing the operating gradient; measuring beam properties as a function of various parameters; and

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testing high-QE cathodes. This performance information will be needed to design the next generation of quarter-wave SRF guns with significantly increased performance [23].

WiFEL SRF Gun

To support a future seeded VUV/soft X-ray free electron laser facility, WiFEL, a high-repetition-rate, VHF superconducting RF electron gun is under development at the University of Wisconsin [24]. A QWR geometry was chosen to reduce the size of the cavity at low frequency (199.6 MHz), which allows operation at 4.2 K. The goal is to operate at a cathode field of 40 MV/m and produce 200 pC bunches with a kinetic energy up to 4 MeV and a normalized transverse emittance of less than 1mm·mrad. The design average beam current is 1 mA. The first beam was generated on August 1, 2013. The results will be reported at NA-PAC'2013 [25]

SRF Guns Under Development at BNL

Several SRF guns are under developments at BNL [26]. Two of them were recently assembled into cryomodules and tested without a cathode. The first gun is based on an ½ cell elliptical shape cavity operating at 704 MHz. The gun will use a CsK_2Sb photocathode. It is designed to provide up to 500-mA beam at 2 MeV to an R&D ERL facility. An option of generating THz radiation for users at this facility is under consideration. After the 704 MHz gun cryomodule was assembled and installed in the ERL blockhouse, its commissioning commenced. First, it was tested without a cathode and was able to reach a cavity voltage of 2 MV in CW mode. Conditioning with a copper cathode is under way.

The second gun is a 112 MHz QWR developed to produce high-bunch-charge (1 to 5 nC), low-repetition-rate (78 kHz) 2 MeV electron beam for the coherent electron cooling proof-of-principle experiment [27]. It will use a CsK_2Sb photocathode. The gun cavity and cryomodule were built by Niowave, Inc. and cold tested there. It reached a cavity voltage of 0.92 MV. The voltage was limited to this value administratively due to insufficient radiation shielding at the Niowave test facility. The gun is now at BNL, being installed in the RHIC tunnel for further testing and commissioning.

SUMMARY

SRF photoinjectors have made significant progress during the last several years. A number of guns generated their first beams and one, at HZDR, provided a beam for the first in the world FEL lasing with an SRF gun. By accomplishing this, HZDR/ELBE gun demonstrated feasibility of the SRF gun concept with a normal-conducting Cs_2Te cathode. The photocathodes at HZDR demonstrated very good performance with the lifetime of ~1 year at QE of about 1%. However, for a high average current / high bunch charge operation, CsK_2Sb is preferred as it operates with green lasers, unlike UV laser for the Cs_2Te, which makes it easier to build optical systems. Several QWR guns were developed and three have produced their first beams. SRF guns of this type are very promising for high bunch charge operation. Thus far SRF guns have generated bunch charges up to ~100 pC, which is close to what is required for some projects. The average demonstrated beam current is still below 1 mA and more efforts are needed to boost it. The field is very active. More experiments are coming soon promising new and exciting results.

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