ISBN: 978-3-95450-132-8 doi:10.18429/JACoW-IPAC2014-MOZB01

SUPERCONDUCTING RF GUNS: EMERGING TECHNOLOGY FOR FUTURE ACCELERATORS

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Abstract

This paper gives an overview of Superconducting RF photo injectors (SRF guns) and focuses on the present status of SRF gun development, the technical requirements and the critical issues like cavity design, and photocathode integration. The presentation of the current projects is classified according to their photocathodes and their cavity types.

INTRODUCTION

The development of high brightness RF photoemission electron injectors has become one of the key points for the success of linac based x-ray FELs, such as Flash [1], LCLS [2], or FERMI@Elettra [3]. The performance of this type of photo injectors results from the combination of short bunches directly created by a laser and a photocathode, the strong acceleration by a high RF field and the high final energy at the photo injector exit. For future x-ray light source projects, as they are recommended by the DOE panel [4], a high repetition rate of the pulses is required in addition to the high beam brightness. But present RF photo injectors with high RF frequency and normal-conducting (NC) resonators cannot be scaled to this high duty factors. An alternative solution represents an RF photo injector based on superconducting RF technology (SRF gun) as it was first proposed in 1988 [5]. This concept is in competition with two other technologies: the high voltage DC photo injector and the low-frequency NC photo injector. The DC guns are well established and widely applied, and they can easily produce continuous wave (CW) electron beams [6]. Significant progress has been achieved during the last years: At JAEA the 500 kV DC gun with a segmented insulator was successfully tested [7] for the Japanese ERL light source project [8], and at Cornell University the DC gun of the ERL prototype injector delivered a world record current of 65 mA and a 60 mA beam for a long period from a CsK_2Sb photo cathode [9]. Furthermore they achieved very low transverse emittances for 19 and 77 pC bunches [10]. At LBNL a NC low frequency (186 MHz) CW RF photoemission gun was developed and commissioned [11]. The gun was recently operated with a high quantum efficiency (QE) photocathode (Cs_2Te) and delivered 300 pC bunches with an average current of 300 µA [12].

In general, high-repetition rate, high-brightness electron injectors should deliver electron bunches with pulse repetition rate from 1 MHz to 1.3 GHz in CW. The bunch charges should be between 1 pC and 1 nC, the normalized transverse emittance, depending on bunch charge, between 0.1 and 1 mm mrad, and the typical bunch length should be in the range from 100 fs to 50 ps. The average currents are at least 1 mA but possibly reach 100 mA for ERLs or even more. These high average currents require guns which are able to use high quantum efficiency photo cathodes in combination with vacuum loadlock systems for an easy and fast exchange. Since the cathode life time strongly depends on vacuum level, the operating vacuum pressure in the guns should be 10^{-7} - 10^{-10} Pa. In order to obtain low transverse emittance especially for high bunch charges the electric field at the cathode during emission is a key point. But also the transport of the beam without emittance growth requires a certain beam energy at the gun exit. Typical limits for both parameters are about 10 MV/m and 500 keV, respectively. Other issues are dark current, beam halo, or unwanted beam at all. The reasons can be field emission at gun body surfaces and photo cathodes, parasitic laser pulses or scattered laser light, as well as many others. Since the overall beam loss should not exceed 1-10 µA the suppression ratio must be 10^{-4} -10^{-5} for a 100 mA CW injector. A very detailed discussion of high average current photoelectron injector requirements is given in Ref. [13].

The advantages of SRF guns are the very high bunch repetition rate, as well as the combination of high acceleration field at the cathode and extremely high energy gain. For example, a gun with SC cavity based on TESLA technology [14] can produce up to 1.3 GHz pulses, allow a cathode field at emission of >40 MV/m (The peak field in a TESLA cavity with XFEL specifications is 47.2 MV/m [15].) and a multi-cell design can deliver several MeV at gun exit.

There are several proposed and ongoing accelerator projects in the world which are based on SRF injectors from the outset. The Peking University developed and built a SRF gun for the superconducting ERL test facility (PKU-SETF) designed for a 1.6 mA and 30 MeV beam for an infrared (IR) oscillator FEL [16]. At HZDR an SRF gun is installed and has been recently upgraded with the aim to deliver high-brightness beams with bunch charges up to 1 nC to the ELBE superconducting 40 MeV linac for IR FELs and secondary particle generation [17]. The SRF gun developed and commissioned at NPS was designed for an ERL driving an IR FEL [18]. Another project with an SRF injector is the seeded VUV/soft x-ray FEL with a SC 2.2 GeV linac at the University of Wisconsin [19]. At HZB an SRF injector development program was launched for the B*ERL*inPro 50 MeV, 100 mA ERL demonstrator facility [20]. Two SRF guns are in the commissioning phase at BNL, where the first is part of a R&D ERL project with a 20 MeV and 500 mA beam which serves as a test bench for the eRHIC electron-

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hadron collider upgrade of the RHIC facility [21]. The second SRF gun at BNL is designed for the coherent electron cooling (CeC PoP) experiment at RHIC [22].

PROJECT OVERVIEW

In ref [23] a report about the status of SRF gun projects at its time of publication end of 2010 is presented. Since then several SRF guns produced the first beam: e.g. the 200 MHz QWR SRF gun at the University of Wisconsin on July 31, 2013 [24], the 500 MHz QWR SRF gun at NPS Monterey on June 8, 2010 [25], and the 1.3 GHz 1.5-cell on April 21, 2011 at HZB Berlin. Further progress was made with the CW operation at MHz repetition rates of the SRF guns at PKU [26] and HZDR [27] as well as the first operation of a far-IR FEL with a SRF gun at HZDR [28].

In the overview presented here, we follow ref. [23] and group the SRF gun projects according to the cavity designs and photo cathodes in: (i) SC cathode + elliptical cavity, (ii) NC cathode + DC field + elliptical cavity, (iii) NC cathode + quarter wave cavity, (iv) NC cathode + elliptical cavity.

Superconducting Photocathode and Elliptical Cavity

The first gun using the half-cell back wall as cathode was the “all niobium gun”, constructed at BNL [29]. Later it was found that Pb, also a suitable superconductor for SC RF cavities, has much higher quantum efficiency than Nb [30, 31]. Thus a collaboration of BNL, DESY, JLab, and INS built Nb cavities with arc-deposited Pb spot cathodes [32].

Table 1: Measurement Results of the HZB Guns with SC Pb Photocathode

Parameter	Gun 0.1	Gun 0.2
Cavity	elliptical 1.6 cells	
RF frequency	1.3 GHz	
Cathode	Pb (SC)	
Laser wave length	258 nm	
Laser rep. rate	8 kHz	
Laser pulse length	2.5 ps fwhm Gauss	
Peak field	20 MV/m	27 MV/m
Launch field	5 MV/m	7 MV/m
Kinetic energy	1.8 MeV	2.5 MeV
Bunch charge	6 pC	0.2 pC
CW beam current	50 nA	1.5 nA

In the framework of the B*ERL*inPro ERL project [20] a three stage program for SRF gun development has been established. The first stage was a 1.6 cell hybrid Nb/Pb gun that was installed inside the HoBiCaT cryostat. For this purpose the HoBiCaT bunker was extended to set up a diagnostics beamline and a 258 nm drive laser with 8 kHz repetition rate.. To this day two guns of this type were tested at HZB and the first beam could be delivered on April 21, 2011 [33]. The cavity used during this test was an HZB design (gun 0.1) with a Pb spot deposited on the Nb cavity back wall. The Pb photo cathode was extensively cleaned with high power laser to get a QE of 1 x 10^{-4} at 258 nm. The second cavity was a DESY design (gun 0.2) with a mountable niobium cathode plug. Both cavities were fabricated, treated, and vertically tested at Jlab while the Pb arc deposition was performed at NCBJ. Results of both Pb cathode guns operated in the HoBiCaT facility [34] are summarized in Table 1.

DC-SRF Photo Injector

At Peking University a SRF gun is under development where a relatively low voltage DC gun is connected to a 1.3 GHz elliptical superconducting cavity. The project started with a 1.5 cell cavity [35, 36] whereas later the gun was extended to a 3.5 cell cavity [37]. The first beam was produced in 2004 with the 1.5 cell gun [38]. The present Pierce gun part is designed for a DC voltage of 90 kV and connected via a drift tube of 8 mm diameter and 17 mm in length with the SRF part. The splitting of the gun reduces the contamination risk of the SC cavity by the photo cathodes. Since the cutoff frequency of the tube is well above 1.3 GHz the RF wave cannot propagate and thus a choke filter is not needed. The gun operates with Cs_2Te photo cathodes and a preparation chamber is directly attached to the gun.

The split design has the drawback of a relatively low gradient of about 6 MV/m at the photo cathode but seems to be sufficient for the moderate bunch charge for which the gun is envisaged. The 3.5 cell large grain Nb cavity fabricated at PKU and treated at Jlab [39] reached a relatively high CW acceleration gradient of 14.5 MV/m (29 MV/m peak field) after installation. And recently, an electron beam was produced with 3.3 MeV kinetic energy, and a remarkably high average current of 250 µA in CW [40].

The design parameters of the DC SRF gun are presented in Table 2. Beside the future use as injector for the PKU ERL [16] the high energy gain of the 3.5 cell gun allows a direct application as a coherent THz source [41], which will be started soon.

Normal-Conducting Photocathode and Quarter-Wave Resonator

SRF guns with quarter wave resonators were built and commissioned by Niowave Inc. for BNL, NPS, and University of Wisconsin. Quarter wave structures allow a more compact design at low frequencies. The advantages of low frequency are lower RF losses, smaller HOM effects, less transient effects for long bunches, and a rather constant field in the acceleration gap. Furthermore, high power CW RF sources and couplers are available.

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Table 2: Design Parameters of DC-SRF Injector at PKU

Operation mode	ERL mode	THz mode
Cavity	elliptical 3.5 cell	
RF frequency	1.3 GHz	
Photo cathode	Cs_2Te (NC)	
Laser wave length	266 nm	
Laser rep. rate	81.25 MHz	
Laser pulse length	10 ps fwhm Gauss	
Acc. gradient	13 MV/m	15 MV/m
Bunch charge	60-100 pC	20 pC
CW beam current	8.1 mA	1.6 mA
Transv. emittance	1.2 µm	2.1 µm
Bunch length	3 ps rms	0.55 ps rms

The University of Wisconsin has commissioned a 200 MHz quarter wave SRF gun. The gun was designed for the WiFEL project, a high average power and coherent seeded VUV/soft x-ray FEL light source [19]. Therefore it should achieve a peak electric field at cathode of 45 MV/m, and an energy gain of 4 MeV [42]. A SC solenoid [43] and a cathode holder assembly for future use of Cs_2Te photo cathodes are integrated to deliver 1 mA CW beam at 5 MHz repetition rate. The high and rather flat field in the cavity will allow bunch charges of 200 pC with less than 1 µm transverse emittance by applying the so-called blow-out mode [44]. After plasma treatment of the cavity a CW peak field of 20 MV/m with cathode inside was achieved. The first beam was produced in 2013 with 12 MV/m delivering 1.1 MeV and 50 nA from a Cu photo cathode [24].

The Navy Postgraduate School (NPS) has developed two SRF guns with quarter wave resonators. Both of the systems have been built by Niowave Inc. in collaboration with Boeing. The first gun using a 500 MHz resonator, an integrated SC solenoid, and a cathode assembly capable for high QE NC photo cathodes has been installed and commissioned at NPS. The gun served to explore SC injector technology for the future NPS IR-FEL [18]. The first beam was achieved on June 9, 2010 [45] and further beam tests with a Nb cathode delivered a maximum kinetic energy of 470 keV and a bunch charge of 78 pC. The later was limited by the low photo cathode QE of 1-2 x 10^{-6} and the available laser pulse energy [46].

A 112 MHz quarter wave resonator SRF gun was developed by collective efforts of BNL and Niowave Inc. [47]. The gun is designated to produce high charged bunches for the coherent electron cooling experiment at RHIC [22]. The gun uses the advantages of the quarter wave design to produce long pulses with charges of 1-5 nC at a repetition rate of 78 kHz, and 2 MeV kinetic energy. After cold tested at Niowave in 2013 the gun is now installed in the RHIC tunnel at BNL [48].

Normal-Conducting Photocathode with Elliptical Cavity

HZDR operates a 3.5 cell SRF gun at the superconducting ELBE linac since 2007. The gun is designed to deliver low emittance beams with high bunch up to 1 nC at a moderate average current of 1 mA (see design parameters in Table 3). The 1.3 GHz Nb cavity consists of three TESLA cells and a specially designed half-cell. Another superconducting cell, called choke filter prevents the leakage of the RF field towards the special cathode support system. The normal conducting photocathode is installed in this system, which is isolated from the cavity by a vacuum gap and cooled with liquid nitrogen [49]. This design allows the application of NC photocathodes of high QE. Up to now only Cs_2Te photo cathodes have been used. These cathodes showed excellent lifetime in the SRF gun, e.g. one cathode was in the gun for more than one year providing totally beam time of over 600 h and 265 C at a maximum average current of 400 µA [27]. Most of the time the SRF gun was operated for R&D purposes, but also dedicated user experiments at ELBE have been done. Thereby one highlight was the first operation of the far infrared FEL with the SRF gun [28].

Nevertheless, due to strong field emission of the cavity, the SRF gun I could not reach the design specifications. Instead the maximum gradient (peak field) was only 17.5 MV/m in CW which belongs to a kinetic energy of 3.3 MeV.

Table 3: Design Parameters of the ELBE SRF Guns at HZDR

Operation mode	FEL mode	High charge mode
Cavity	elliptical 3.5 cell	
RF frequency	1.3 GHz	
Photo cathode	Cs_2Te	
Laser wave length	258 nm	
Laser rep. rate	13 MHz	100-500 kHz
Laser pulse length	3 ps fwhm	12 ps fwhm
Peak field	50 MV/m	50 MV/m
Bunch charge	77 pC	1 nC
CW beam current	1 mA	≤ 0.5 mA
Kinetic energy	9.5 MeV	9.5 MeV
Transv. emittance	1 µm	2.5 µm

The ELBE SRF gun II was built to overcome this gradient limitation. Therefore the cavity was built and treated in collaboration with JLab [50]. Between April-May

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2014 the old gun could be replaced by the new one, and in June the cool-down was done. Right after that the first beam with a copper cathode was produced at a moderate gradient (16 MV/m peak field), delivering a 20 nA and 3.2 MeV beam. In the near future the commissioning is being continued towards higher gradients and to insert Cs_2Te photo cathodes.

At BNL a 704 MHz SRF gun with a half-cell elliptical cavity is installed at the R&D ERL which is in the commissioning phase [51, 52]. The challenge of this SRF gun design is the extremely high average current of 500 mA. The ERL will serve as a test bench for the electron-hadron collider eRHIC, which will need an electron current of 300 mA. Table 4 lists the design parameters of the gun. Although the beam energy is reduced to a lowest acceptable value the beam power is still 1 MW which requires enormous efforts. The gun has two fundamental power coupler of 500 kW manufactured by CPI which were successfully conditioned [53]. Beam line ferrite loads for strong HOM damping and a copper cathode stark for multi-alkali photocathodes with a sophisticated quarter-wave choke have been developed [54]. The gun achieved the design value of 2 MV without cathode. Commissioning with a copper cathode started in summer 2013 with the task to reach the design value of 2 MV in CW [49].

Table 4: Design Parameters of the BNL 704 MHz Gun

Parameter	
Cavity	elliptical 0.4 cell
RF frequency	703.5 MHz
Photo cathode	CsK_2Sb
Laser wave length	527 nm
Laser rep. rate	704 MHz
Laser pulse length	20 ps fwhm
Acceleration field	29.4 MV/m
Bunch charge	700 pC
CW beam current	500 mA
Kinetic energy	2.5 MeV
Transv. emittance	1.4 µm

HZB continues the SRF photo injector development for the ERL demonstrator facility with gun 1.1, which should demonstrate the beam dynamic requirements for the ERL at the designed charge of 77 pC and up to 4 mA beam currents [34]. The basic design of this gun fulfils already the requirements for the final 100 mA operation. A new 1.4 cell cavity design was developed [55], to obtain a high launch phase at maximum energy gain, and to optimize the structure with respect to less dark current problems. The gun will apply high QE CsK_2Sb photocathodes. A summary of the gun parameters is given in Table 5. The cathode insert and support system, as well as the choke filter solution will be adopted from the HZDR gun design. Two CW-modified TTF-III coupler for 10 kW each, and a blade tuning system will be used. The beam tube is enlarged to allow for the propagation of the lowest dipole modes towards the beam tube HOM absorbers.

Table 5: Design Parameters for the HZB ERL Gun 1.1

Parameter	A4 Paper
Cavity	elliptical 1.4 cell
RFfrequency	1.3 GHz
Photo cathode	CsK_2Sb
Laser wave length	515 nm
Laser rep. rate	1.3 GHz
Laser pulse length	20 ps fwhm Gauss
Acceleration field	20 – 30 MV/m
Bunch charge	77 pC
CW beam current	4 mA
Kinetic energy	≥ 2.3 MeV
Transv. emittance	1.0 µm

SUMMARY

During the last several years the number of institutes conducting R&D in the field of superconducting RF injector technology has significantly grown up, and encouraging results have been achieved. In this paper an overview of several SRF gun projects which are in commissioning phase or already delivering beams for the accelerators is given.

ACKNOWLEDGMENT

The author would like to thank the whole ELBE team for their help and assistance within the SRF gun project. Especially I would like to thank the following colleagues who providing materials for this paper: Robert Legg (Jlab), Sergey Belomestnykh (BNL), Kexin Liu (PKU), Andrew Burrill (HZB), and Thorsten Kamps (HZB).

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