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REVIEW OF SUPERCONDUCTING RADIO FREQUENCY GUN

R. Xiang†, Helmholtz Zentrum Dresden Rossendorf, Dresden, Germany

Abstract

The success of proposed high power free-electron lasers (FELs) and energy recovery linac (ERL) largely depends on the development of the electron source, which requires the best beam quality and CW operation. An elegant way to realize both high brilliance and high current is to combine the high beam quality of the normal conducting radio frequency photoinjector with the quick developing superconducting radio frequency technology, to build superconducting rf photoinjectors (SRF guns).

In last decade, several SRF gun programs based on different approaches have achieved promising progress, even succeeded in routine operation at BNL and HZDR. In the near future SRF guns are expected to play an important role for hard X-ray FEL facilities. In this contribution, we will review the design concepts, parameters, and status of the major SRF gun projects.

INTRODUCTION

In last decades superconducting RF has been proved as a mature technology for the high-intensity particle accelerators. At the same time, SRF guns are demonstrated to have advantages for CW mode operation [1], potential to produce high brightness and the high current beam required by CW XFEL and ERL facilities [2-5].

H. Chaloupka proposed the first SRF gun idea in the 1988 EPAC, which was composed with a QWR SC cavity with Cs_3Sb photocathode in a chock filter [6]. Soon in 2002 D. Janssen reported the first operation of a SRF gun at Rossendorf, including a 1.3 GHz half-cell cavity and Cs_2Te photocathode in chock filter [7]. After 2002, more gun designs sprout out and achieved excellent progress [8-10]. Presently, two SRF guns are in user operation (HZDR) [11] or produces routine beams for experiment (BNL) [12]. Four guns made promising R&D headway (DESY, HZB, KEK and PKU) [13-16], and one new gun has been planned in SLAC [17]. And more SRF injector research programs are going on [18-21]. This review paper is focused on reporting the recent progress in these projects.

An SRF gun is a complex device merging several advanced technologies: high Quantum Efficiency (QE) photocathodes, superconducting RF cavity, high repetition rate laser, precise synchronization, beam diagnostics and so on. The same as in other high brightness guns, for high bunch charge and high current beam, SRF guns must use robust photocathode with enough QE and the drive laser with high average power. And to produce low emittance beams, SRF guns must have high acceleration gradient, correct emittance compensation, precise synchronization between laser and RF, and proper laser pulse shaping. It was a problem to clean the gun cavity with small cathode hole, but in last years the cleaning process of SC cavities has achieved successful progress.

DIFFERENT APPROACHES OF SRF GUNS

At first glance an SRF gun design is the combination of a SC cavity with high field and the cathode solution to generate electrons in electric field. The other parts, like cryostat, RF couplers, laser, cathode preparation, must match to the choice of cavity and cathode. The most mature SC cavity geometries are TESLA elliptical cavity and quarter wave resonator cavity (QWR). And the cathode solutions include superconducting cathode directly contact to SC cavity, normal conducting (NC) cathode isolated with a DC gap, and NC cathode isolated with an RF chock filter. Table 1 shows the different approaches of the present gun designs, also their main advantages, limitations and their design tasks.

One of the SRF gun approaches is based on elliptic cavity and superconducting (Nb or Pb) photocathodes on cavity back wall, so called all-SC gun. The advantages for this design are that 1) the cavity is possible to generate high gradient comparable to the Tesla cavities, 2) no cathode preparation and exchange is needed, so no contamination to the SC cavity. However, the disadvantage is that the SC cathode materials have so low QE that the request to the drive laser is becoming demanding. Meanwhile the heating effect of the high power laser on SC cavity still need to be demonstrated. At moment there is no QWR cavity with SC cathode option reported.

The NC photocathodes can have much better QE than SC cathodes, is the first choice for high current sources. Hybrid design is to adopt a high gradient cavity and a small DC Pierce gun with NC cathode. The advantages are that 1) high QE cathode is allowed, 2) no contamination comes from cathode to SC cavity. But the cathode field is low due to the limit of DC voltage, so only moderate beam current can be generated and it is challenging to project very low transverse emittance.

NC cathode is also possible to be integrated with RF chock stopper into SC cavities, elliptical or QWR. The advantages of the Tesla cavity with NC cathode are that, 1) cathode has high QE, 2) the cathode field can be very high. On the other hand, the challenge is the contamination risk due to the cathode and the cleaning of the cavity around the small cathode hole. The theoretical peak field in QWR cavity is lower than that in TESLA cavity, but the low frequency RF field in the QWR is suitable for generating long pulse to reduce the space change effect.

As for the choice of NC cathodes, there are several good review papers about photocathodes [22, 23], and there are also studies on the field emission cathodes for SRF gun in last years [24-26]. The state-of-art semiconductor photocathodes are the preferred option for many high current projects. They can provide high QE in a reasonable life time. However, these cathodes are very sensitive to vacuum, making the preparation and exchanging very time consuming. The well-developed semiconductor materials

† r.xiang@hzdr.de

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for photoinjectors are CsK_2Sb, Cs_2Te and GaAs(Cs). CsK_2Sb can be used with green lasers and is currently popular in the SRF guns [12, 14, 15]. It shows good life time in the gun operation at BNL [27]. In order to push limit of the beam project emittance, the intrinsic emittance of the photocathode becomes also an interesting parameter. Several publications show that CsK_2Sb can produce very low thermal emittance [28-30].

Cs_2Te is relatively robust, but it requires UV drive laser. HZDR has demonstrated it in the gun operation with long life time since 2009 [31]. GaAs(Cs) is most sensitive to vacuum and it is the only choice for polarized beam. However, it has not been demonstrated in an SRF gun operation yet.

Compared to semiconducting photocathodes, metallic cathodes are much more robust, so they are suitable for the first gun commissioning, but their low QEs make them difficult for high current purpose. After special laser cleaning process or coating with thin low work function material, the QEs of some metals are possible to reach up to 10^{-3} [32-34].

Table 1: Different Approaches of SRF Guns (Classified with Cavity Geometries and Cathode Solutions)

Cavity type	**Elliptical SRF**	**Elliptical SRF**	**Elliptical SRF**	**¼ wave SRF**
Cathode solution	**SC cathode**	**NC cathode in DC module**	**NC cathode in RF filter**	**NC cathode in RF filter**
potential	high brightness highest rep. rate	moderate brightness, highest rep. rate	high brightness highest rep. rate	high brightness high current
Structure advantage	high gradient, no cathode transport	high QE cathode, no contamination from cathode	high QE cathode, high cathode field	high QE cathode, 4K operation, quasi-DC field
limitation	low QE, cathode exchange	low cathode field	multipacting risk field emission	multipacting risk field emission
present effort	higher gradient, cathode demonstration	higher voltage better cathodes	higher gradients suppressing MP better cathodes	higher gradients suppressing MP better cathodes
Examples (task)	DESY (CW-XFEL) NCBJ (VUV, THz)	PKU (FEL)	HZDR (THz) HZB (ERL,UED) KEK (ERL)	BNL (e- cooling) SLAC (CW-XFEL)

SRF GUN EXAMPLES AND THEIR LATEST STATUS

Elliptical Cavities with SC cathodes (DESY)

DESY SRF gun is the preferred choice for future additional CW operation mode of European x-ray free electron laser (E-XFEL). This R&D project is developing an all-SC RF gun with a lead cathode screwed in the cathode hole on the backside of a 1.5 cell 1.3 GHz cavity (see Fig. 1), under collaboration with TJNAF, NCBJ, BNL, HZB and HZDR [13]. The target parameters of the DESY SC gun can be found in Table 2.

DESY SRF gun cavity enables high gradient, and the designed cathode field can reach 40 MV/m, which is required to generate low emittance beam for the CW XFEL. Because the cavity can be cleaned after the installation of SC cathode and there is no cathode transport and exchange system, the risk of contamination from cathode is low. However, the high work function and low QE of lead increases the requirement of cathode dive laser. Meanwhile the integrated cathode must have reasonable long life time to ensure required user beam time.

For years DESY SRF gun project has invested the substantial effort into the surface treatment of cavities and has achieved successful progress. The fabrication results in correct frequency and the cavity back-wall is mechanical stable. Cavity #16G7 treated with BCP at Zanon reached 56 MV/m E_{peak} on axis, and cavity #16G4 treated with EP at KEK reached 57 MV/m E_{peak} on axis. The next main activities are to test cavities with different cathode plugs vertically and then to test cavities in a horizontal test setup for the first time.

Elliptical Cavities with NC Cathodes in Choke Filer (HZDR, KEK, HZB)

HZDR SRF gun-II HZDR SRF gun-II gun is built for ELBE accelerator as the source of super radiant THz FEL. The Gun-I was the first SRF gun in the world to inject beam into an accelerator for FEL production [35] and the Gun-II is the first one in user operation [36]. Currently the gun-II is providing more than 1000 hours beam time for the ELBE.

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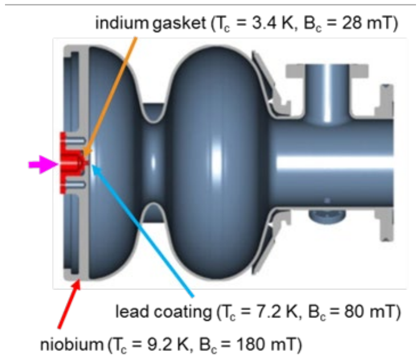

Figure 1: The cavity design of DESY SRF gun, including 1.5 cell 1.3 GHz cavity and lead SC cathode screwed on the back wall of cavity [13].

As shown in Fig. 2, the gun-II includes 3½ cell 1.3 GHz cavity with chock cell and a SC solenoid in a cryostat, and a load-lock system for cathode exchange. Starting from 2017, the SC gun started user operations for terahertz beamline with Mg cathode, and since May 2017 the overheating problem of Cs2Te cathode was successfully solved so currently the gun-II is operated with Cs2Te driven with 262 nm laser. The bunch charge injected into the linac

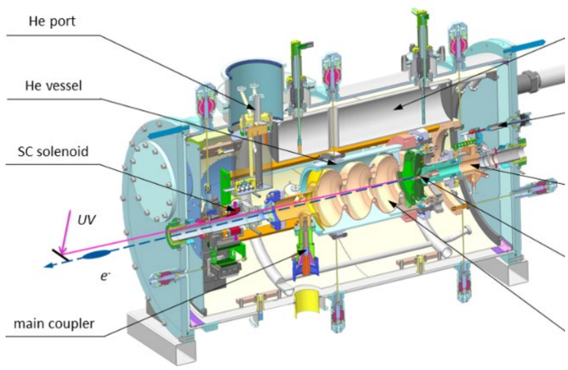

Figure 2: The cryostat design of SRF gun-II at HZDR, including a 3½ cell 1.3 GHz cavity with chock cell and a SC solenoid [36].

is up to 250 pC at the repetition rate of typically 100 kHz. The kinetic energy is limited to 4 MeV due to field emission in the SRF cavity.

A high light of HZDR SRF gun-II is that the cavity gradient has not obviously degraded due to the cathode operation, or the cavity is possible to be recovered even after Cs2Te overheating happened in 2017. This demonstration should help to confident the users of SRF guns. The next plan is to clean the gun-I cavity for upgrading the gun gradient and thus improving the beam quality.

KEK SRF gun KEK SRF gun has been developed since 2013 as the second source for the compact energy recovery linac (cERL) at KEK [15]. It consists of a 1.5 cell SC gun cavity with a choke cell (seen Fig. 3). The vertical tests have been successfully performed with a record high peak field on axis of ~ 75 MV/m without cathode and over 60 MV/m with a niobium cathode rod [37]. The next step

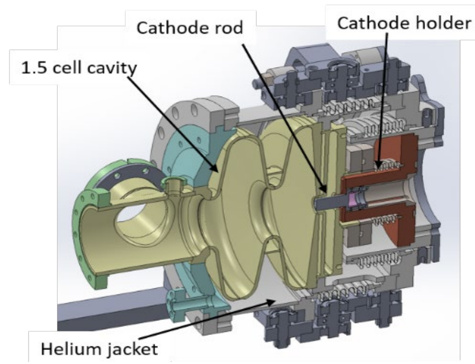

Figure 3: The design of KEK SRF gun #2, consisting of a 1.5 cell SC gun cavity with a choke cell and a NC cathode [37]

is to test the gun cavity with cathode rod in horizontal cryostat.

A special design of the KEK SRF gun is that the cathode laser will illuminate the green cathode from backside through a transparent superconductor substratum [38]. Presently the tests are done with niobium rod, so the laser comes still from the beam line.

A short test beam line for emittance and energy measurement is under building so that the beam test with small beam current (< 500 keV, < 1 μA) can be performed soon.

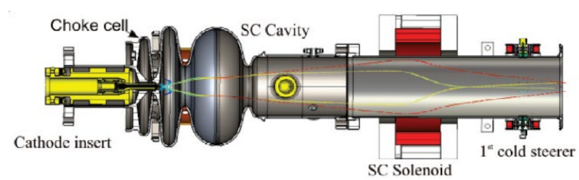

Figure 4: The key parts of HZB SRF gun, including a 1.4 cell cavity with choke cell, NC CsK_2Sb cathode and a SC solenoid [14].

HZB BERLinPro SRF gun HZB SRF gun is designed for BERLinPro ERL facility, aiming to provide 100 mA beam with 1.3 GHz repetition rate. The latest version is 1.4 cell cavity with choke cell, NC CsK2Sb cathode and a SC solenoid as shown in Fig. 4 [14]. In 2017 the first beam was achieved with a copper cathode. But after the first cathode exchange, high field emission and cathode overheating appeared, strongly degrading the cavity performance. Because two gun cavities had surface defects on back wall close to cathode, the present focus is the cavity repairing and refurbishment program. Meanwhile, a third cavity is currently planned to be build (Athena cavity). Setup and RF Commissioning will start in the mid of 2021 in order to check the performance of the SRF gun cavity and the RF system. The beam operation with SRF gun and SRF booster is planned for 2022 with the possibility of Proof-of-concept UED/UEM test based on the SRF gun [39].

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Elliptical Cavities with NC Cathodes in DC Gun (PKU)

PKU has the unique Hybrid design, combining a compact Pierce DC gun with a 1.3 GHz SRF cavity. This simplifies the cavity design and no contamination risk comes from the photocathode. The last DC-SRF gun with 3.5 cell has been in the operation with mA-level average current since 2014 [40].

In 2021 PKU finished the installation of the updated version, which was designed specially to improve the emittance. The new gun consists of a 1.5 cell cavity with 100 kV DC bias and green K_2CsSb photocathode [41]. The key parts of DC-SRF-II is shown in Fig. 5. The gun is designed to produce bunch charge of 100 pC with rms emittance as low as 0.37 mm mrad, and repetition rate of 1 MHz. The commissioning of the new gun is successful, generating the first beam on 29 April 2021 [42].

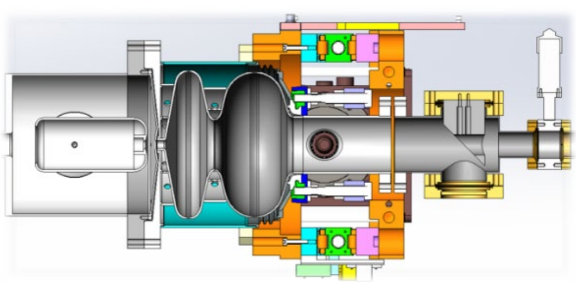

Figure 5: The new DC SRF gun at PKU consists of a 1.5 cell SC cavity and a 100 kV Piece gun. Green photocathodes should be used to generate 100 pC bunch charge [41].

QWR Cavity with NC Cathode in Choke Filer (BNL, SLAC)

BNL CeC SRF gun The BNL SRF gun was built for the coherent electron cooling (CeC) proof of principle (PoP) experiment at the Relativistic Heavy Ion Collider (RHIC) [43], and has been in routional operation since 2016 [44]. Figure 6 shows the Gun assembly with the cathode insertion system. The gun consists of a 112 MHz quarter wave resonator (QWR) developed by BNL in collaboration with Niowave. The electrons are generated by a CW photoinjector using green laser light on a CsK_2Sb cathode. Intensive study about multipacting has been performed for this gun and developed a process of crossing the multipacting barriers from zero to the operational voltage [45].

One of the high lights is the demonstration of green cathode CsK_2Sb in the gun. The typical cathode lifetime for the high bunch charge (~nC) operation is one to two months [27].

The next plan is to increase the average current of unpolarized electron beams to 100 mA, to demonstrate sufficient lifetime of Cs_2Te-coated GaAs photocathode in the Fig. 6: BNL SRF Gun assembly with the cathode insertion sys-tem [46].

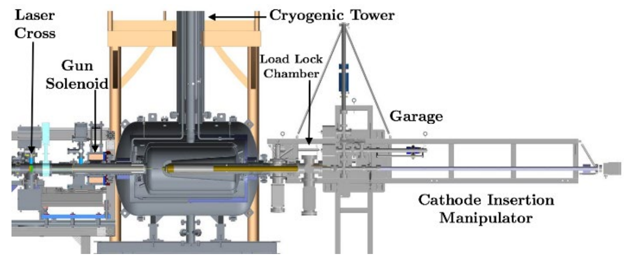

Figure 6: BNL SRF Gun assembly with the cathode insertion system [46].

CeC SRF gun using 532 nm and 780 nm laser, to study towards the lower emittance for 100 pC bunch charge, and to develop restoration techniques [46].

SLAC SRF gun In order to reach the low emittance requirement of LCLS-II-HE project, an SRF gun Rpersona&D program is being recently launched, in which SLAC will partner with labs with SRF experience to build a gun prototype.

The gun will be similar to the WiFEL design [47] but with a smaller cathode-to-anode distance and a smaller exit beam pipe diameter. The RF frequency will be 185.7 MHz. Also, the RF coupler will be on the side of the cavity instead of along the beam tube. The new design is supposed to generate 1.8 MeV beam with bunch charge of 100 pC and transverse emittance <0.1 µm [17].

The goal in the next three years is to demonstrate stable CW operation of the gun at a cathode gradient of at least a 30 MV/m. In parallel, LCLS-II-HE proposes to build a 75 meter long tunnel that would run parallel to the current LCLS-II injector and be equipped with a production version of the SRF gun together with an SRF buncher cavity and LCLS-II cryomodule [17].

SUMMARY AND OUTLOOK

SRF guns made excellent progress in last years. It has been proved as a routinely operational source, and has the potential to reach high brightness requirement of future CW XFELs and high average current for ERLs. SRF guns at HZDR and BNL have achieved routine operation, and several new guns are under R&D at DESY, HZB, KEK, PKU and SLAC (Parameters overview in Table 2).

Proper cathode solution is a key for the successful gun operation. There are different solutions of cathodes integration. Metallic cathodes, Cs_2Te and CsK_2Sb have been proved safe in the gun operation. A future plan at BNL will demonstrate the polarized SRF gun with GaAs photocathode.

Present effort for all of the gun projects are to achieve high cavity gradient in operation for low beam emittance, and to further improve the photocathodes with high QE, long life time.

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Table 2: Summary of SRF Gun Performances (*Design Value)

	DESY	**PKU**	**HZDR**	**KEK**	**HZB**	**BNL**	**SLAC**
Cavity type	1.5 TESLA	1.5 TESLA	3.5 TESLA	1.5 TESLA	1.4 TESLA	QWR	QWR
RF freq. (MHz)	1300	1300	1300	1300	1300	113	185.7
Operation temp. (K)	2	2	2	2	2	4	4
Gradient E_{acc} (MV/m)	21	14	8	~16	16	~21	20
$E_{cathode}$ (MV/m)	40	6	14	52.5	24-27	~15	30
kinetic energy (MeV)	3-4		4	2	2.5-3	1.5-2	
Current (µA)		100*	20		6000	140	
Dark current (nA)		-	60		4.5@9.5 MV/m w.o. cath		
Cathode	Pb	CsK_2Sb	Mg, Cs_2Te	CsK_2Sb	Cu or CsK_2Sb	CsK_2Sb	green
Laser wave-length (nm)	UV	519	262	532 (plan)	521-523	532	532
Rep. Rate (kHz)	1000-100	1000	25-250	1.3 GHz	Up to 1.3 GHz	78	-
Pulse length rms (ps)	-	20	2.3		3-12	400 (CeC)	
Bunch charge (pC)	20-250*	100*	0~250	80*	77*	100-20000	100*
Transv. rms emit. (µm)	0.4-0.8	0.37	2-15		<1	0.15 µrad@100 pC	0.1
Energy spread (keV)		2.75	5-25		1.7	0.5	
status	R&D	R&D	user operation	R&D	R&D	operation	in plan

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