Superconducting RF Photoinjectors; an Overview

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R&D programs based on various approaches at AES, Beijing University, BNL, FZ-Rossendorf, JLab and DESY will lead in the near future to low emittance continuous wave (cw) operating SRF-guns, which are indispensable devices for the cw operating superconducting linacs driving FEL facilities. This contribution covers present status of these programs and progress made since the last SRF2005 Workshop at Cornell University.

PACS numbers:

I. INTRODUCTION

The most demanding component of a cw injector is cw operating RF-gun delivering highly populated (~1 nC) low emittance bunches. RF-guns, both working at room temperature and superconducting, when they generate highly populated low emittance bunches have to be operated at high accelerating gradients to suppress space charge effects diluting emittance. Superconducting RF-guns (SRF-guns) are technically superior to the normal conducting devices, because they dissipate orders of magnitude less power when operating at very high gradients. They can easily work at high duty factor but the challenge here is integration of a non superconducting photo-cathode material with a superconducting cavity in a way preserving its original high intrinsic quality factor Q_o (small cryogenic losses). An alternative approach, technically feasible for miliampere-class SRF-guns, is to use superconducting metal as the photo-cathode. In this case difficulty arises from moderate quantum efficiency (QE) of the superconducting materials. Relatively low QE must be compensated with higher energy pulses of the illuminating laser. This approach has been studied first for niobium cathode at BNL, but the measured QE at 4K was very low ($\sim 10^{-5}$). The recent progress in a complementary approach, with the lead cathode [1], is discussed in the last section of this overview.

II. OVERVIEW OF DESIGNS

Rossendorf 1.3 GHz SRF- injector

The FZR R&D program, which begun 1998, was the first worldwide continuation following original work at University of Wuppertal by A. Michalke [2]. Figure 1 shows Rossendorf SRF-gun cavity and its assembly in cryostat [3, 4]. The gun consists of 3.5-cell 1.3 GHz bulk niobium cavity, a mechanism for exchanging and precise positioning of the Cs_2Te cathode and a choke filter preventing leakage of the RF. The gun in its final version will operate in three various modes: mode for the BESSY FEL facility, FZR laser mode and FZR nuclear physics mode. Recent parameters for the gun are listed in Table 1. The prototype gun cavity was tested four times without cathode at DESY in 2006 and 2007. In all vertical tests the cavity was limited by strong field emission, which E_{peak} onset value varies from 6 MV/m to 20 MV/m. The measured RF-performance, Q vs. E_{peak}, is shown in Fig. 2. After the last test the cavity has been assembled in the cryostat and is under preparation for the test in the ELBE accelerator. The proposed schedule in 2007 for the completed injector is following:

- Cool-down and commissioning in August
- Installation of the laser in August (500 kHz system)
- Test with Cu cathode in October/November
- Installation of cathode transfer system and diagnostics beamline in October/November.

One expects the first electron beam delivery to the ELBE accelerator by the end of this year.

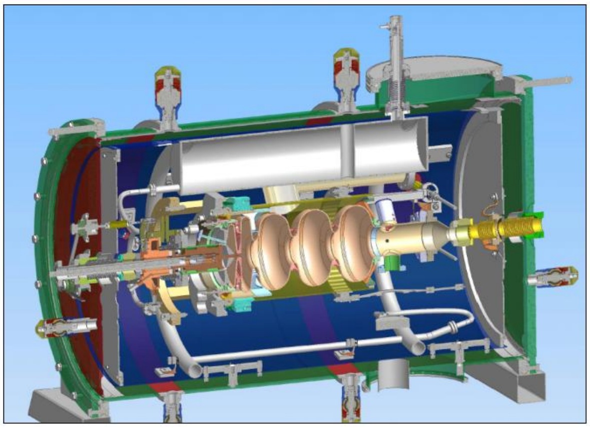

Figure 1: FZR superconducting RF-gun and its assembly in the cryostat. *Courtesy FZR*

Table 1: Parameters for the FZR gun

	ELBE mode	High charge mode	BESSY-FEL
SRF frequency [GHz]	1.3		
E [MeV]	9.5		
Operation mode	CW		
Driving laser λ [nm]	262		
Photocathode	Cs_2Te		
QE [%]	> 1		> 2.5
I_b [mA]	1	0.5	2.5
Pulse duration [ps]	5	15	40
f repetition [kHz]	13 000	500	1
q/bunch [nC]	0.077	1	2.5
ε [µmrad]	1	2.5	3

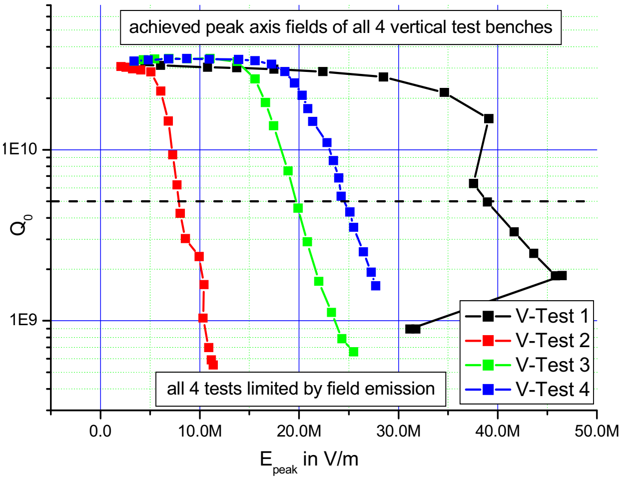

Figure 2: Test result for the SRF-gun cavity prototype of the FZR injector. *Courtesy FZR*

RF-gun at Institute of Heavy Ion Physics

The SRF injector R&D program at IHIP of Peking University began in 2001. The recently proposed RF-gun at IHIP consists of DC Pierce gun and 1.3 GHz 3.5-cell niobium cavity replacing 1.5-cell in the former design. The cavity and RF-gun assembly in cryostat is shown in Fig. 3. The Cs_2Te cathode in this design is exposed to DC electric field and not to RF field as it is done in the FZR gun. The emitted electrons are first accelerated in the DC field before they enter the accelerating superconducting cavity via 8 mm tube. The tube is very deep in cutoff frequency for 1.3 GHz and thus prevents leakage of the RF power towards the DC section. A 0.5-cell prototype of the gun was used in 2003 to verify whole concept and to generate the first time electron beam for acceleration. List of parameters for the 3.5-cell gun version is displayed in Table 2 [5, 6]. All technical drawings for the entire injector have been finished and both the cavity and cryostat are at present in the fabrication stage. The 3.5-cell will be fabricated of large grain niobium. After the test the injector will deliver electron beam to the IR FEL at Peking University.

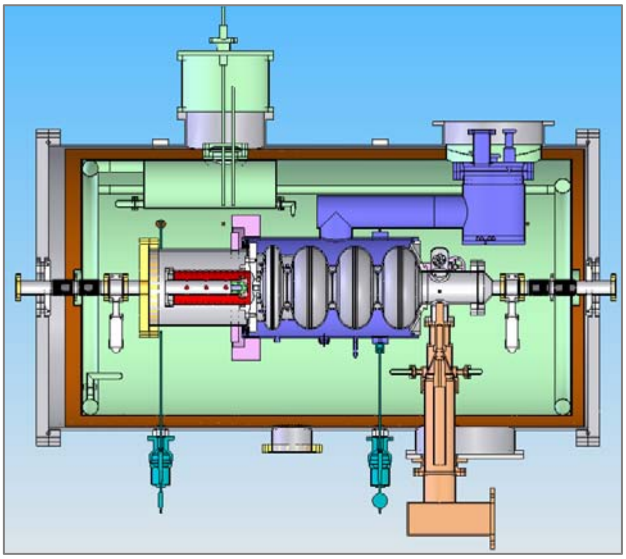

Figure 3: IHIP superconducting RF-gun cavity and its assembly with Pierce DC gun in the cryostat. *Courtesy IHIP PU*

Table 2: Parameters for the 3.5-cell IHIP RF-gun

f	[GHz]	1.3
E_{cath}	[MV/m]	6
q	[pC]	100
E	[MeV]	5
ε	[µm rad]	3.6
I_{peak}	[A]	20
I_b	[mA]	1~5
f repetition	[MHz]	26
Photocathode		Cs_2Te
QE	[%]	1~5
Driving laser λ	[nm]	266

703.75 MHz RF-gun; Collaboration between BNL and AES

Since 2004 BNL and AES develop superconducting RF-gun of a several hundreds miliampere class. The gun of this kind will be needed to generate electron beam for the electron coolers for two rings of RHIC [7]. Other potential future applications for the high current RF-gun are electron injectors for linacs driving MW-class FELs. The version for the RHIC cooler (Fig. 4) consists of half-cell superconducting cavity operating at 703.75 MHz, two input couplers, quarter wave choke filter, and the mechanism for the cathode assembly. Table 3 shows the operation parameters for the BNL/AES gun. The cathode QE has been specified with and without diamond multiplier.

Much effort in the R&D program at BNL is devoted to the diamond electron multiplier capsule. The principle of the multiplier is shown schematically in Fig. 5. Irradiating photons enter the vacuum sealed capsule via laser window coated on the inner side with a photo-

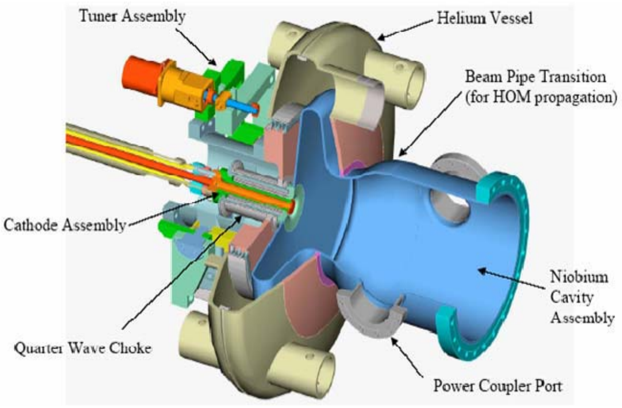

Figure 4: 703.75 MHz superconducting RF-photoinjector. *Courtesy AES*

Table 3: Parameters for 703.75 MHz RF-photoinjector

f [MHz]	703.75
q/bunch [nC]	1.4
ε_n [μm rad]	2
E [MeV]	2-3
P_b [MW]	1
I_b [A]	0.5 (0.1)
f repetition [MHz]	352 / 704 (9.4)
Cathode	CsK_2Sb
QE [%]	1
QE with diamond [%]	>100
Laser λ [nm]	532

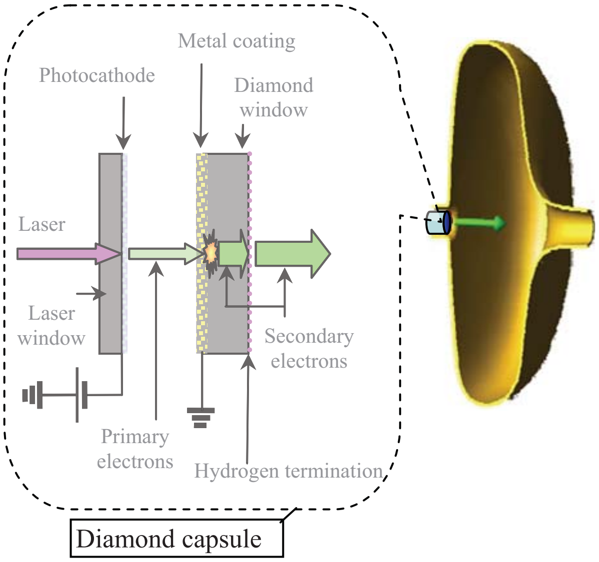

Figure 5: Diamond capsule and its location in the injector cavity. *Courtesy BNL*

emitter and generate primary electrons, which then are accelerated in the static electric field. Subsequently, these electrons pass diamond disc causing the avalanche of secondary electrons accelerated in RF-field of the half cell cavity. The gain of diamond multiplier was measured very recently to be as high as 350, which if achieved in the final device will significantly reduce the required irradiating laser power for the operation [8, 9]. The capsule concept has an additional important feature. It simplifies separation of the non superconducting CsK_2Sb cathode from the superconducting cavity. This should increase lifetime of the cathode and protect the RF-gun superconducting cavity from contamination. The RF performance (losses) of the superconducting cavity with attached capsule has not been tested yet and need to be investigated in the near future. The cavity prototype is in the fabrication stage and will be vertically tested in the next year.

Lead-Niobium RF-photoinjector

Low quantum efficiency of niobium, measured several years ago at BNL, was the motivation for testing alternative superconductors as photo-emitters to continue the BNL concept of all Nb superconducting RF-gun. DESY, BNL, Stony Brook University, JLab, Institute for Nuclear Studies (INS) in Poland and SLAC collaborate to build a hybrid Pb-Nb SRF-photoinjector with lead spot as the emitter. Lead, which critical temperature T_c= 7.2 K is not very different from T_c of niobium, is commonly used superconductor in acceleration. It demonstrates much higher QE than niobium. Tests results of lead QE at room temperature was reported by the collaboration in [10] and was very recently confirmed at cryogenic temperatures [11]. The summary of QE measurement at 300 K as function of photon energy E_p for niobium, bulk lead and lead samples deposited with various techniques is shown in Fig. 6. The highest QE of 0.55% has been measured for the arc-deposited sample illuminated with 6.5 eV photons. For 5.8 eV photons (fifth harmonics of 1064 nm infrared laser) QE of that sample was still 0.25%. QE of the electroplated and magnetron deposited samples at this photon energy is 0.17%. Emitting of 1 nC bunch at this QE will require 3.4 μJ energy per pulse only and consequently, 3.4 W power at 213 nm will be required to generate 1 nC bunches at 1 MHz repetition rate.

In this hybrid Pb-Nb gun small emitting spot of lead (Ø<3 mm) will be located in the center of back wall of the half-cell of 1.6-cell cavity (Fig. 7), which will be made of high purity niobium and equipped with two HOM couplers, input coupler and pickup probe for the

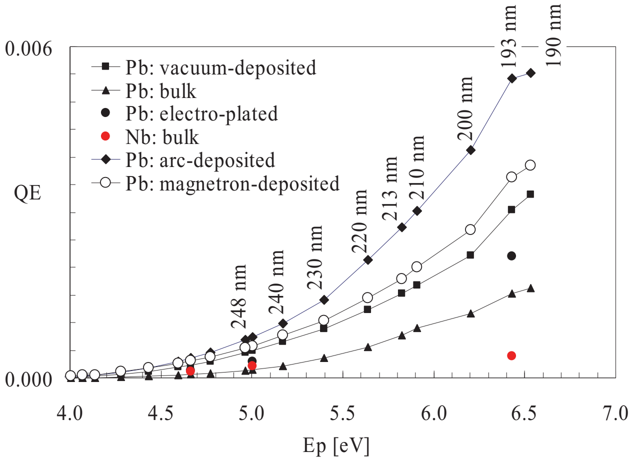

Figure 6: Measured QE of lead deposited with various coating methods. Bulk Pb and Nb data are displayed for comparison.

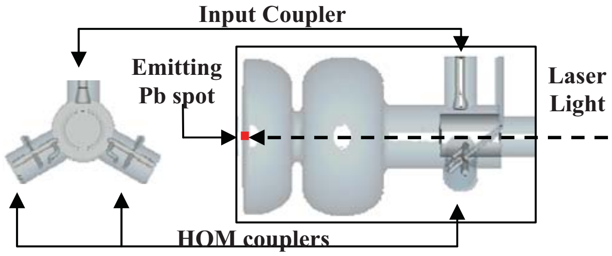

Figure 7: 1.6-cell SRF-gun cavity with two HOM couplers and port for the input coupler.

Table 4: Parameters for Pb-Nb SRF-photoinjector

f [MHz]	1300
q/bunch [nC]	~1
ε_n [µm rad]	1
E [MeV]	6
P_b [kW]	6
I_b [mA]	1
f repetition [MHz]	1
Cathode	Pb
QE [%]	0.17
Laser λ [nm]	213

operation. The parameter list for the hybrid injector is given in Table 4.

Two half-cell cavities have been built to measure lead QE at 2 K and to test performance of superconducting cavities illuminated by laser. Both cavities are shown in Fig. 8. The left one was built at TJNAF. This cavity has opening in center of the back wall, which is vacuum sealed with a niobium plug. The plug can be easily coated with an emitting material. The TJNAF cavity is very helpful to test various coating methods and various superconductors as photo-emitters. It can be an alternative solution to the second cavity, built at DESY (Fig. 8 right), in which technically difficult coating is done directly on the back wall. An additional difficulty in this version is that the emitting spot must withstand cleaning procedures. Two of them: chemical treatment and high pressure water rinsing, can degrade QE. Unfortunately, both procedures are essential for good performance of the superconducting cavity, which in that concept should operate at 50÷60 MV/m peak field. Two features make this version very attractive. Smooth back wall does not enhance locally electric field in the vicinity of the cathode and there is no electric contact in high field region, which usually reduce Q_o of the cavity. Both cavities were tested in 2006 and 2007. The results with lead cathodes[1] are shown in Fig. 9. Both cavities reached peak field of ~40 MV/m. The DESY cavity is more difficult to clean and hence demonstrated heavy radiation at the highest gradient [12]. For the preliminary experiment on the relaxation time of broken by irradiation Cooper pairs, the superconducting wall of the TJNAF cavity was exposed to 0.75 W of the excimer laser light at 248 nm. The laser pulses were 5.3 ns long (FWHM) and the highest repetition rate was 250 Hz. For that experiment the cavity had to be attached to a straight vacuum tube oriented vertically upward, to enable direct irradiation with the laser light via the sapphire window installed at the top-plate of the vertical cryostat.

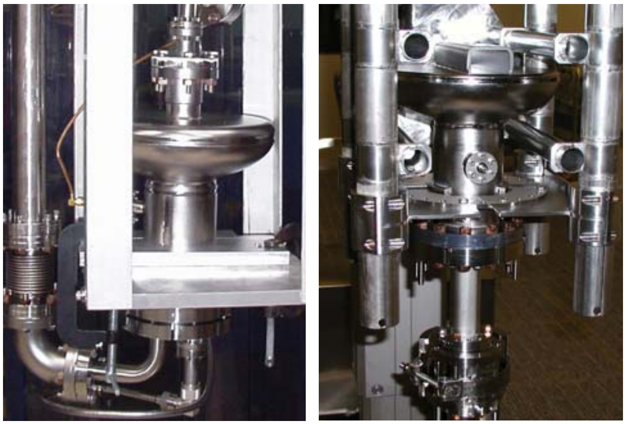

Figure 8: Test half-cell cavities built at TJNAF (left) and at DESY (right).

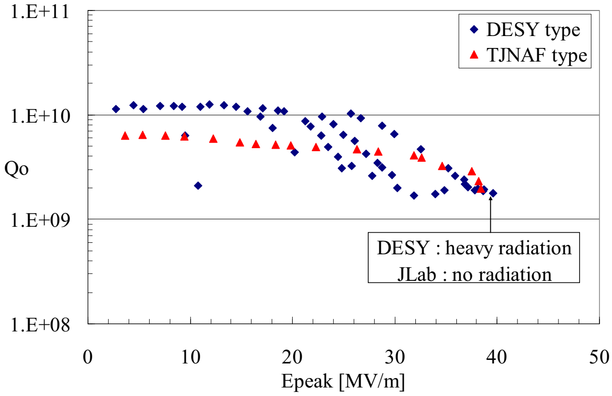

Figure 9: Test results of the two half-cell cavities.

The 3 m long vacuum tube contaminated the cavity with particulates and degraded its performance. At 3 MV/m Q_o was only $2.25 \cdot 10^9$, almost 3 times lower than Q_o measured at this gradient in the RF-performance test. When the Nb wall was irradiated with the maximum available laser power, Q_o dropped to $\sim 1.6 \cdot 10^9$, but the cavity did not quench and behaved still very stable. The additional dissipation, due to the locally broken Cooper pairs in the irradiated area, was 5.2 mW. The surface resistance, r_s , of the irradiated area increased during the laser pulse by a factor of 630. The ratio of r_s after and before the irradiation indicates that the concentration of quasi-particles rose to their equilibrium concentration at 8 K. According to the theoretical model, their relaxation time is shorter than 100 ps at this temperature.

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[1] The emitting 4 mm diameter lead spot at the center of the back wall of the DESY cavity was deposited by the arc-discharge method at A. Soltan INS. The 7 mm diameter plug of the TJNAF cavity was electroplated with lead at Stony Brook University.

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