

# REVIEW ON SUPERCONDUCTING RF GUNS

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## Abstract

Superconducting RF (SRF) photo-injectors worldwide are reviewed. Two groups of SRF guns, with normal conducting cathodes and with superconducting cathodes, are presently under development. The two projects at FZ – Rossendorf are discussed in more details. The experiment with a 1.3 GHz niobium half cell cavity in Rossendorf has demonstrated the stable operation of a SRF gun for the first time. A SRF photo-injector with a 3½ cell cavity for cw operation is planned as a second low emittance injector for the Rossendorf ELBE accelerator with 9.5 MeV energy and average current of 1mA. In the last section we discuss some new technological developments, which could be essential for performance and future application of SRF guns.

## INTRODUCTION

RF photo-injectors with normal conducting cavities are widely used. They are relatively compact and produce high quality electron beams. In most cases they operate at a low duty factor and have relatively low average current. The first photo-injector with a duty factor of 25% was designed by Boeing in 1992 [1]. At present a collaboration between LANL and AES is developing a normal conducting photo-injector, which works in the cw mode. The large amount of RF power dissipation in normal conducting RF structures produces serious cooling problems and limits the field gradient (7 MeV/m in this project) with negative consequences on the obtainable emittance.

Superconducting RF (SRF) photo-injectors offer great promise for cw mode of operation with high average current. The use of a superconducting cavity in a RF photo-injector was proposed at the University of Wuppertal [2], where the first experimental set-up was installed. Photoemission and RF properties of the cavity were studied at 4.2 K and 1.9 K.

At present three laboratories are working on SRF photo-injector projects: a collaboration between BNL and AES [3], the Peking University [4] and the Forschungszentrum Rossendorf [5]. The main difference between these projects is the photo cathodes. While in the BNL – AES collaboration superconducting cathodes are used, the other projects work with a normal conducting Cs<sub>2</sub>Te cathode. In 2002 the successful operation of a SRF photo-injector has been demonstrated for the first time at Rossendorf [6]. In the following section we will concentrate our discussion mainly to the RF properties of the gun cavities and their (possible) contamination by the cathode material.

## SRF GUNS WITH SUPERCONDUCTING CATHODES

### All-Niobium SRF Photo-Injector

A fully superconducting RF photo gun has been developed by a collaboration of BNL and AES [7]. The cavity is a 1.3 GHz cell elliptical half cell terminated by an end wall. RF drive coupler and pickup are both at the beam line end of the cavity. HOM coupler and tuner are not installed for this proof of principle experiment. The niobium sheet of the cavity end wall is used as the photo emitter. Fig. 1 shows a photograph of the cavity. The experimental set up is given in Fig. 2.



Figure 1: Photograph of the BNL/AES all-niobium half cell cavity.

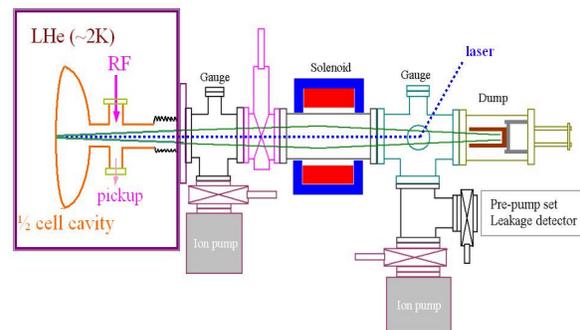


Figure 2: Schematic figure of the experimental set up for the test of an all-niobium SRF photo-injector.

Studies have been carried out to improve the quantum efficiency (Q.E.) of niobium by laser cleaning and utilizing the Schottky effect [8]. An improvement of the Q.E. from about  $2 \times 10^{-7}$  to  $5 \times 10^{-5}$  at room temperature could be reached. After cooling down to 2 K the Q.E. value decreases to  $2 \times 10^{-5}$  for the laser wavelength  $\lambda = 248$  nm and to  $2 \times 10^{-6}$  for  $\lambda = 266$  nm. The relatively low Q.E.

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and the high laser power density set a limit on maximum average current. The reason for the decreasing of the Q.E. value at low temperature is not completely understood yet. A possible explanation could be that the cavity works as a cryopump and the back-bombarding of ions destroys the effect of laser cleaning. An advantage of this gun concept is that a Q-value degeneration of the cavity by particles from the photocathode can be excluded.

### Superconducting lead cathode

In [8] the measurement of the Q.E. value for lead at room temperature has been published. For the wave length  $\lambda = 248 \text{ nm}$  Q.E. =  $1 \times 10^{-4}$  and for  $\lambda = 213 \text{ nm}$  Q.E. =  $1.7 \times 10^{-3}$  has been obtained. At LHe temperature lead is a superconductor. So one can put a lead layer on the back wall of the half cell cavity shown in Fig.1. With this lead layer as photo cathode, a laser power of 3 W is sufficient to obtain an average current of 1 mA. This corresponds to a bunch charge of 1nC with a repetition rate of 1 MHz.

If it succeeds to install the lead layer inside the superconducting cavity without changing the quality factor and the maximum field strength of the cavity and if the Q.E. value of lead does not change at LHe temperature, then this cathode – cavity arrangement would be ideal for a superconducting RF gun, at least for average currents  $I_{av} \leq 1 \text{ mA}$ .

## SRF GUNS WITH NORMAL CONDUCTING CATHODES

### First operation of a half cell SRF gun

A SRF gun with a half cell cavity and a normal conducting cathode has been successfully tested in Rossendorf [6]. The half cell cavity is of TESLA type and closed by a shallow cone with an opening for the cathode and an additional superconducting choke flange filter. The filter is necessary because the coaxial gap between cavity and photo cathode acts as a RF transmission line. A special support structure insulates the cathode thermally and electrically from the surrounding cavity and holds it at liquid nitrogen temperature. The components are schematically shown in Fig.3. The cathode itself is a copper stem with a  $\text{Cs}_2\text{Te}$  layer. It can be moved with a manipulator from the preparation chamber into the cavity. The cavity was mounted in a test cryostat. RF system, drive laser, diagnostic beam line and control system were installed and photo cathodes were prepared. After several tests, the gun was cooled down to 4.2 K and was in operation during a period of seven weeks (approximately five hours per day). Fig. 4 shows the measurement of the quality factor of the cavity as a function of the peak electric field strength.

The maximum field strength of 22 MV/m was limited by field emission. The insignificant difference of Q values with and without cathode shows good performance of the choke filter.

Fig. 5 presents the cathode emission and accelerated current together with the corresponding electron energy as a function of the laser phase. For a phase window of  $60^\circ$

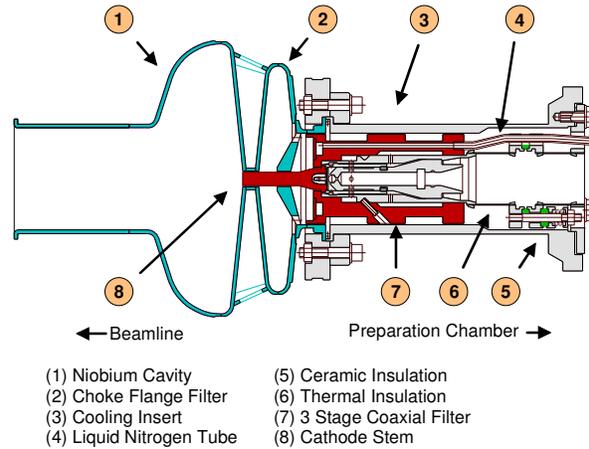


Figure 3: Schematic drawing of the superconducting cavity, choke flange filter and normal conducting photocathode with the liquid  $\text{N}_2$  cooling system.

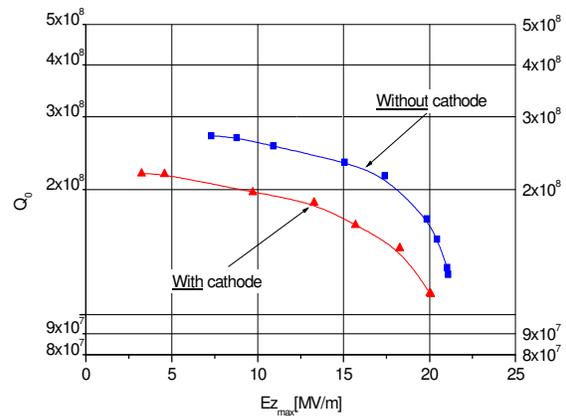


Figure 4: Measurement of the quality factor versus peak electric field at 4.2 K.

complete transmission was obtained. The energy has its maximum value at  $0^\circ$  and decreases for higher phase values.

During the whole period of operation no changes of the quality factor of  $Q = 2.5 \times 10^8$  has been observed. The maximum bunch charge obtained was 20 pC, which corresponds to an average current of 520  $\mu\text{A}$  in the cw mode. It is limited by average power and repetition rate of the laser and by the low quantum efficiency of the photocathode. Due to the long drift space after the gun and the arrangement of optical elements, the transverse emittance could only be measured for bunch charges between 1 and 4 pC. The measured normalized rms emittance values were between 1 and 2.5 mm mrad, in agreement with PARMELA simulation.

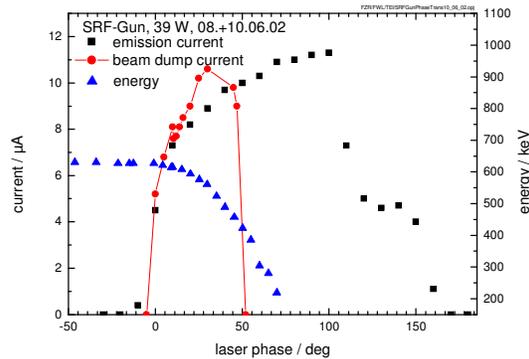


Figure 5: Photo-cathode emission current, accelerated beam current (measured in the beam dump) and corresponding beam energy as a function of the laser phase.

### Rossendorf $3\frac{1}{2}$ cell SRF gun project

The SRF photo-injector research and development in Rossendorf is being continued with a project of a superconducting  $3\frac{1}{2}$  cell SRF gun for the ELBE accelerator [5]. As in the previous gun a normal conducting, liquid nitrogen cooled, and thermally and electrically isolated photo cathode is inside the back wall of the cavity. The coaxial structure around the cathode requires again a superconducting choke flange filter to prevent RF losses.

The new cavity has been designed for a peak electric field of 50 MV/m in the three TESLA cells and 33MV/m in the half cell. Fig. 6. shows the cavity in the press for warm tuning. In an optimisation procedure it was found, that a short half cell (37.7 mm here on the left side of Fig.6) provides better beam parameters.

A new Helium cryostat for 1.8 K is in manufacturing and will be connected to the existing ELBE refrigerator allowing closed circuit operation (see Fig. 7). Two tuners allow tuning the shorted half cell and the three TESLA cells separately and two pick-up probes allow the field measurement in the half – and in the TESLA cells. The beam focussing inside the cavity is very sensitive to the cathode position. In order to get the optimal beam properties, the cryostat contains a special design, which allows moving the cathode in horizontal direction from outside of the cryostat during the gun operation.

The optimal position of the cathode is about 2 mm behind the back wall of the half cell. In this position the value of the radial RF field near the cathode is negative and focussing for the beam [9]. This RF focussing can partially replace the static magnetic field one used in normal conducting RF guns. RF field calculation and particle tracking gives for the  $3\frac{1}{2}$  cell SRF gun energy of 9.5 MeV and for a bunch charge of 0.77 pC a normalized transverse emittance of 0.5 mm mrad. For a bunch charge of 1 nC the emittance of 2.5 mm mrad has been calculated. At the end of 2006 the first beam of the new gun is expected.



Figure 6: Warm tuning of the  $3\frac{1}{2}$  cell gun cavity.

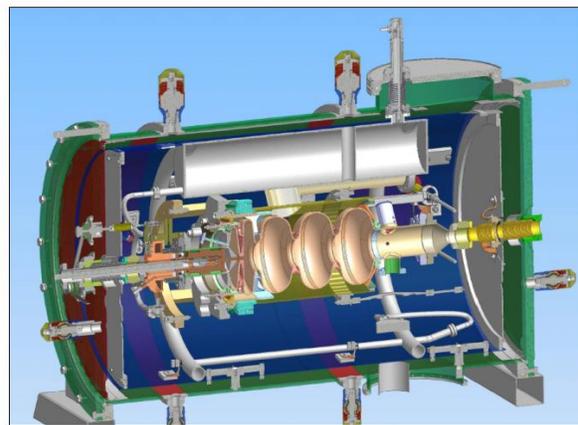


Figure 7: Cryomodule design of the  $3\frac{1}{2}$  cell SRF gun.

### High current SRF gun

In a joint project of AES and BNL, a high current SRF gun for high current FEL's and electron beam cooling is under development [3]. The principle design is the same as in the Rossendorf half-cell cavity project. But as the consequence of different demands on the beam parameter, the practical realization is quite different. The design scheme is given in Fig. 8.

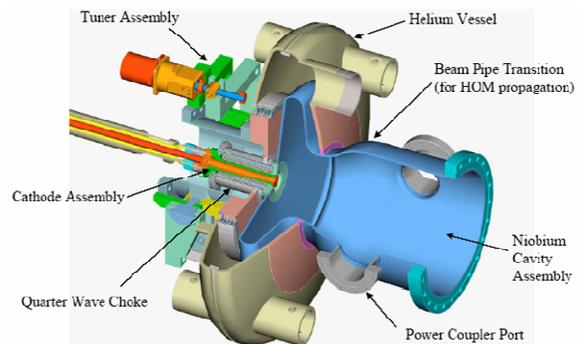


Figure 8: Cavity of the high current gun of the AES-BNL cooperation.

The nitrogen cooled, normal conducting cathode is in a half-cell cavity with the frequency of 703.75 MHz. In order to obtain an average current of 1 A, the laser beam must generate bunch charges of 1.42 nC in the cw mode at the cavity frequency. An acceleration gradient of 20 MV/m delivers beam energy of 2 MeV. This means that each of the two input coupler must be able to transfer an RF power of 1 MW into the cavity. Similarly to the Rossendorf gun, the back wall of the cavity is connected by a choke filter, which prevents the RF leakage of the cavity cell. The scheme of this filter is shown in Fig. 9.

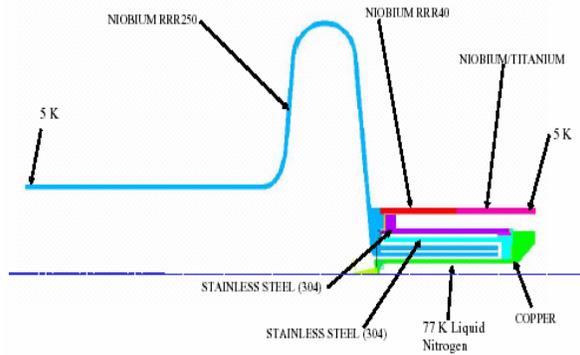


Figure 9: Scheme of the quarter wave choke filter.

The choke is realized by a superconducting quarter wave filter and the cathode is not electrically isolated with respect to the cavity. Thin stainless steel tubes are responsible for the heat isolation between cathode and cavity.

This gun is designed for a transverse emittance of 5 mm mrad, which is sufficient for infrared FEL application. In this project the first beam is expected in 2007.

### The DC-SC gun of the Peking University

At the IHIP of the Peking University the development of a superconducting linac with a superconducting RF photoelectron gun has started [4]. The principle design of this gun is shown in Fig. 9.

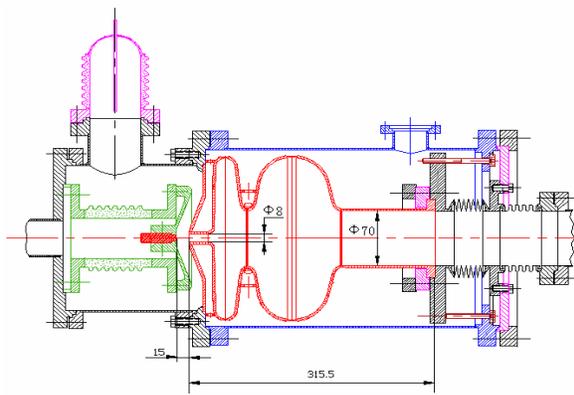


Figure 10: DC-SC gun of the Peking University.

The cavity has the 1/2 cell TESLA structure with the frequency of 1.3 GHz. The back wall of the cavity contains a small superconducting beam tube without cathode. Therefore in this design no coaxial line is connected to the cavity and no choke filter is necessary. The cathode is separated by a vacuum gap of 15 mm from the cavity. A DC voltage of 40 kV accelerates bunches after the cathode with a field strength of 2.7 MV/m. The parameters obtained with this gun are given in Tab. 1.

**$I_{ave}=200 \mu A$  ,  $E=0.5 MeV$  ,  $Q = 50 pC$  ,  
 $L_{laserpuls}=6 ps$  ,  $\epsilon_{rms}=5.4 mm mrad$ .**

**$I_{ave}=70 \mu A$  ,  $E=0.59 MeV$  ,  $Q = 18 pC$  ,  
 $L_{laserpuls}=6 ps$  ,  $\epsilon_{rms}=2.8 mm mrad$ .**

Table 1: Parameters of the DC-SC gun of the Peking University.

The advantage of this design is that no choke filter is necessary and that the cathode is outside of the cavity. Therefore the probability for contamination of the cavity is reduced. On the other hand in this design the main advantage of a RF gun – the high field gradients at the cathode surface is lost.

## NEW DEVELOPMENTS IN SRF GUN TECHNOLOGY

In this section we will discuss some new developments, which could be essentially enforce the further development of SRF guns.

### Diamond amplifier

In [10] a diamond amplifier is proposed, which could drastically reduce the power of the photo cathode laser and the particle emission of the photo cathodes. The scheme of this amplifier is shown in Fig. 11.

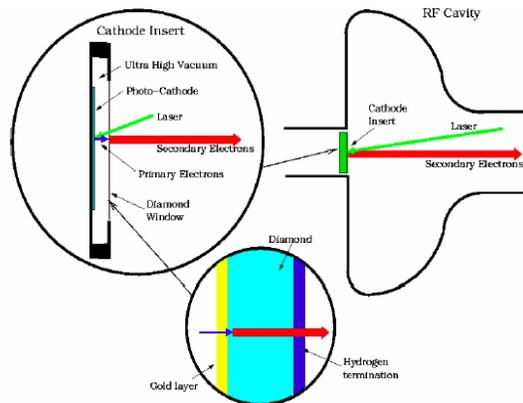


Figure 11: Scheme of the diamond amplifier

The laser beam goes through a thin diamond layer and produces primary electrons on the surface of the photocathode. These electrons are accelerated in the vacuum gap between the cathode and the diamond layer by a RF field and create a large number of secondary

electrons in the diamond layer itself. The secondary electrons reach the surface and leave the diamond layer.

The advantages of this amplifier are the multiplication of the number of primary electrons by about two orders of magnitude and the protection of the superconducting gun cavity from possible contamination by the cathode.

### Magnetic RF modes in superconducting cavities

For compensation of transverse emittance growth in normal conducting RF photo guns a static magnetic field is applied. In superconducting RF guns it is possible to replace the static field by a magnetic RF field (TE – mode), which is excited in the cavity together with the accelerating mode. The results of simulation for the 3½ cell Rossendorf gun project is published in [11]. Fig. 12 shows the result of field calculation and in Tab.2 the results of particle tracking are given. In this calculation the maximum sum of surface fields for both modes is 144 mT and below the quench limit. Depending on the TE mode phase the emittance changes between 0.78 and 0.98 mm mrad only.

ETM field pattern (1300 MHz) BTE field pattern (3802 MHz)

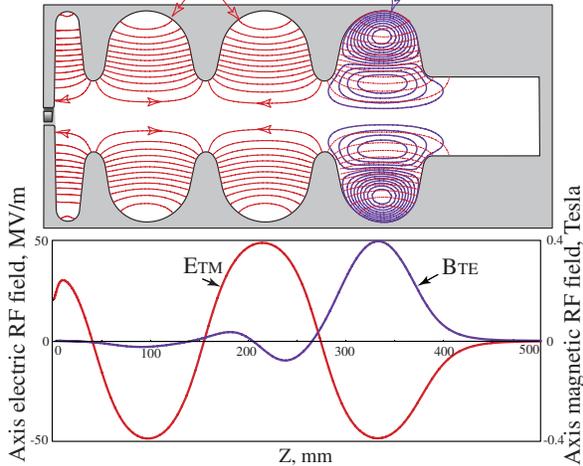


Figure 12: Field distribution of the  $TM_{010}$  mode (1300 MHz) and of the  $TE_{021}$  mode (3802 MHz).

Bunch transv. norm.emitt., mm mrad	0.78÷0.98
Rms Beam Size, mm	3.06
Longitudinal Emittance, keV mm	72.4
Average Energy, MeV	8.82
Rms Energy Spread, keV	53.9
Rms Bunch Length, mm	2.79

Table 2: Results of tracking.

## CONCLUSION

New ideas and developments enhance performance of superconducting RF guns. Several projects are under way and allow the prediction, that in the next three years the first SRF gun will work as linac injector in routine run.

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