STATUS REVIEW OF SUPERCONDUCTING RF PHOTO-INJECTORS

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Abstract

Superconducting RF (SRF) photo-injectors worldwide are reviewed. The two projects at FZ Rossendorf are discussed in detail: First, the proof-of-principle experiment with a SRF gun containing a 1.3 GHz niobium half-cell cavity, which could demonstrate stable operation of such a photo gun for the first time. Second, the SRF photo-injector project with a 1.3 GHz niobium 3+1/2 cell cavity for continuous-wave operation at 10 MeV and 1 mA. For the future it is planned to operate this SRF gun as a second low-emittance injector at the ELBE accelerator.

INTRODUCTION

RF photo-injectors can produce electron beams with low emittance at high bunch charges. Laser pulses irradiating a photo cathode generate electron bunches of extremely short length and high charge density. The high RF accelerating field at the cathode retains the small longitudinal emittance and prevents an increase of the transverse emittance due to space charge effect. The first photo-injector experiment was carried out at LANL in 1985 [1]. Steady improvements of gun design, lasers and photo cathodes have increased the average current and improved the beam quality. The understanding of emittance compensation in RF photo-injectors [2], its implementation [3] and shaping of the drive laser pulse [4] have further reduced the transverse emittance to about 1 mm mrad at 1 nC bunch charge [4,5].

RF photo-injectors with normal-conducting resonators are widely used. They are compact, relatively easy to construct and produce highest quality beams. In most of the cases they are operated with a low duty factor and have comparably low average current. The first photo-injector with high average current and an operation mode with a duty factor of 25% was designed by Boeing in 1992 [6]. At present, a continuous wave (CW) mode normal-conducting RF photo-injector for 100 mA is under development within a collaboration of LANL and Advanced Energy Systems (AES) [7]. High duty cycle or CW mode operation causes a large amount of RF power dissipation in the normal-conducting RF structure and produces serious cooling problems. Therefore the field gradient is low (e.g. 7 MV/m in the LANL/AES project) with negative consequences on the obtainable emittance.

Superconducting RF (SRF) photo-injectors offer great promise for CW mode operation with high average current. The use of a superconducting resonator in an RF photo-injector was proposed at the University of Wuppertal [8] and a first experimental set-up was installed [9,10]. The resonator was a 3 MHz half cell of niobium with a Cs_3Sb photo cathode inside. Photoemission and the RF properties of the cavity were studied at 4.2 and 1.9 K. At present, three laboratories are conducting SRF photo-injector projects: Peking University [11,12,13], Brookhaven National Laboratory (BNL) [14,15], and Forschungszentrum Rossendorf (FZR) [16,17,18]. In 2002, the successful operation of a SRF photo-injector could be demonstrated for the first time at FZR [19]. However, this type of injectors is still in the research and development phase. The design and construction of superconducting cavities with its specific geometry, the possible interference of the photocathode on them, the cryogenics and the much more complex design of a SRF photo-injector cause additional difficulties and require new technical solutions not proofed up to now. These specific issues will be discussed. After that, we review the different concepts and how these challenges are addressed by the three labs mentioned above.

SPECIFIC ISSUES OF SRF PHOTO-INJECTORS

The most common cavity type used in normal-conducting RF photo-injectors is a 1.5 cell cavity with nearly pill-box geometry operating in the L-band [20,21] and S-band [22]. The superconducting standing wave resonators for linacs possess elliptical shape cavities. These geometries have been adopted to SRF gun cavities. Whereas Piel et al. [8] suggested a reentrant shape cavity, the experiments by Michalke [10] were carried out with a 3 MHz elliptical half cell. The ongoing projects use elliptical 1.3 GHz half cells [14,18] or 1+1/2 cells [11] with approximately TESLA-cell geometry. A SRF gun cavity consisting of 3 TESLA cells and an special designed half cell was proposed by Volkov et al. [23] and a similar cavity design will be applied in the new SRF injector project at FZR [24]. The technological procedures and knowledge of cavity treatment in order to obtain high Q values and accelerating gradients can be adopted from the linac cavities. Critical points are the half cell and especially the cathode openings in it where high electric fields occur. Special tuners have still to be developed in order to tune the full and half cells independently. Difficulties can appear since all couplers (rf-input, HOM) and pick-up have to be installed at one end of the cavity.

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The magnetic wall losses of a semi-conducting or normal-conducting photocathode are small due to the low magnetic field near the optical axis. On the other side, dielectric losses can occur in the cathode layer. An estimation was done in [17] for a 5 mm diameter photocathode layer of usual thickness. For a 30 MV/m peak field, the loss is about 17 W. A further heat source is the driver laser beam itself and reflected laser light can causes photo emission inside the cavity.

After insertion of a new photocathode, RF conditioning is necessary in normal-conducting RF photo-injectors to obtain stable operation at the desired high field gradient. The RF conditioning reduces field emission, dark current and the probability for RF discharges. The effect seems to be caused by outgasing, surface cleaning and smoothening. RF discharges during conditioning or operation can destroy the surface of the photocathode [25]. Further reasons for a destroyed cathode surface could be laser ablation, thermal stress and electron or ion back bombardment. Similar effects can also be expected for photocathodes in SRF guns. But the consequences are much more serious because particles produced by these effects at the photocathode can move inside the cavity and contaminate its surface. That can course a steady decrease of the cavity's quality factor and maximum acceleration gradient and perhaps limit the operation time of the cavity. In the experiments performed up to now [10,19] such a cavity degradation was not observed. The recurring photocathode exchange can also produce particles. Cavity pollution is regarded as the greatest risk for SRC guns and systematic studies for high gradients and high average currents over long operation periods are still outstanding.

In normal-conducting RF photo-injectors the emittance compensation was developed [2,3]. An external magnetic field, produced by two solenoidal magnetic coils around the gun resonator, improves beam focusing and reduces the transverse emittance coursed by space charge effects. This successful compensation method can not applied to superconducting guns. It has been shown that beam focusing and emittance compensation can be performed by means of the RF field when a proper design of the half cell geometry and suitable cathode position is found [26]. Additionally, a DC high-voltage bias at the photocathode can applied for focusing [19].

DC-SC PHOTO-INJECTOR

A DC-SC photo-injector has been designed and installed at the Peking University Accelerator Facility, Beijing [11,12,13]. The photocathode is outside the cavity with a DC voltage extraction gap and Pierce shaped electrodes. The superconducting cavity has 1+½ cells and operates at a frequency of 1.3 GHz. The DC accelerating gap and the half cell geometry have been optimized by computer simulation and beam parameters have been calculated. Fig. 1 shows the layout of the gun and Table 1 presents some of the parameters and simulation results [11]. The injector is designed to operate in CW mode and high average current. The motivation for the design is mainly to avoid the difficulties connected with a photocathode inside the superconducting cavities. Especially, RF losses due the photocathode, dark current initiated by the RF field, electron emission inside the cavity by reflected laser light can be prevented and the immigration of particles from the photocathode into the cavity can be considerably reduced. The price is a loss in beam quality due to the comparably weak accelerating field in the DC gap, but the transverse emittance seems acceptable for the infrared FEL application planned [27].

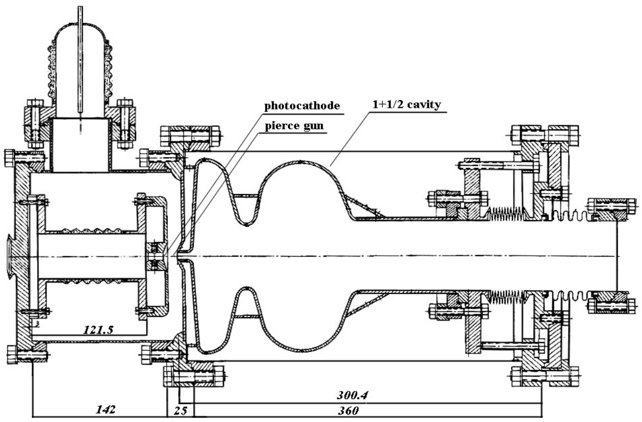

Figure 1: Drawing of the DC-SC photo-injector cavity at Peking University .

The photocathodes are made of Cs_2Te and a laser with 262 nm wavelength and 81.25 MHz pulse repetition rate is used. Photocathodes have been prepared in a chamber connected with the gun. The Helium bath cryostat will operate at 2 K. The gun is equipped with a coaxial input coupler and a 5 kW solid state power amplifier exists. All components are installed and have been tested, a cool-down to 4 K has been carried out.

ALL-NIOBIUM SRF PHOTO-INJECTOR

In a collaboration of BNL and AES a fully superconducting RF photo gun is being developed [14,15]. The cavity is a 1.3 GHz elliptical half cell terminated by an end wall. RF drive coupler and pick-up are both at the beam line end of the cavity. HOM couplers and tuner are not installed for this proof-of-principle experiment. In the gun the niobium of the cavity end wall is used as the photoemitter. Fig. 2 shows a photograph of the cavity. Studies have been carried out to improve the quantum efficiency (Q.E.) of niobium by different ways of surface treatment, high intensity UV laser cleaning and utilizing the Schottky effect [28]. An improvement of the Q.E. from about $2x10^{-7}$ to $5x10^{-5}$ could be reached. The still comparably low Q.E. and the maximum laser power density, coming from the Kapitza conductivity limit of about 1 W/cm^2 [29] provides a limit of the maximum average current. Advantages of this gun concept are the durability and simple regeneration of niobium by laser

Figure 2: Photograph of the BNL/AES all-niobium half cell cavity.

cleaning. But more important is that a Q-value degradation of the cavity by particles from the photocathode can be excluded. Recently, the cavity has been cooled down to 4 K to measure frequency and Q-value. The other gun components have been installed and are being tested.

SRF PHOTO-INJECTOR WITH NORMAL-CONDUCTING PHOTOCATHODE

Rossendorf ½ Cell Cavity Results

The cavity is a TESLA type half cell 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 photocathode acts as a RF gain. A special support structure insulates the cathode thermally and electrically from the surrounding cavity and held it at liquid nitrogen temperature. The components are shown schematically in Fig. 3. The Cs$_2$Te photocathode can be moved with a manipulator from the preparation chamber into the cavity. The cavity was mounted in a test cryostat, RF system, driver laser, diagnostic beam line and control system 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).

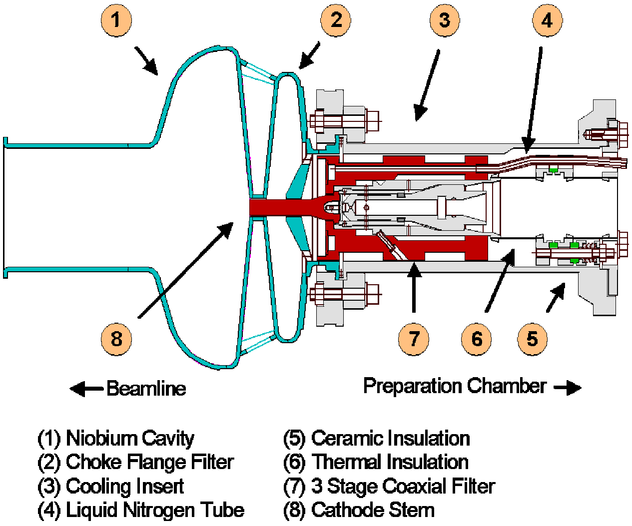

Figure 3: Schematic drawing of the superconducting cavity, choke flange filter and normal-conducting photocathode with liquid N$_2$ cooling system.

Fig. 4 shows the measurement of the quality factor of the cavity in dependence on the peak electric field strength. The maximum field strength of 22 MV/m is limited by field emission. The insignificant difference of Q-values with and without cathode shows the good performance of the choke filter.

Fig. 5 presents the cathode emission and accelerated (dump) current together with the corresponding electron energy as a function of the laser phase. For a phase window of 60° complete transmission was obtained. The energy has its maximum value at 0° and decreases for higher phase values.

During the whole period of operation no changes of the quality factor of $Q = 2.5\times10^8$ of the cavity were measured. An electron energy of 900 keV has been obtained. The

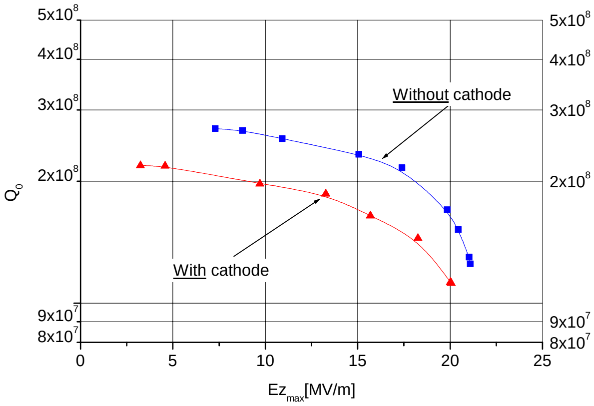

Figure 4: Measurement of quality factor versus peak electric field at 4.2 K.

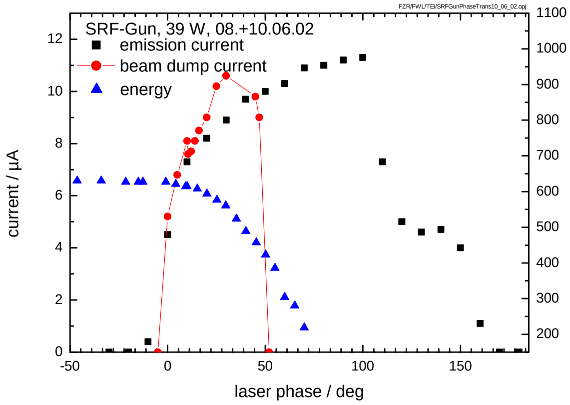

Figure 5: Photocathode emission current, accelerated beam current (measured in the beam dump) and corresponding beam energy as a function of the laser phase.

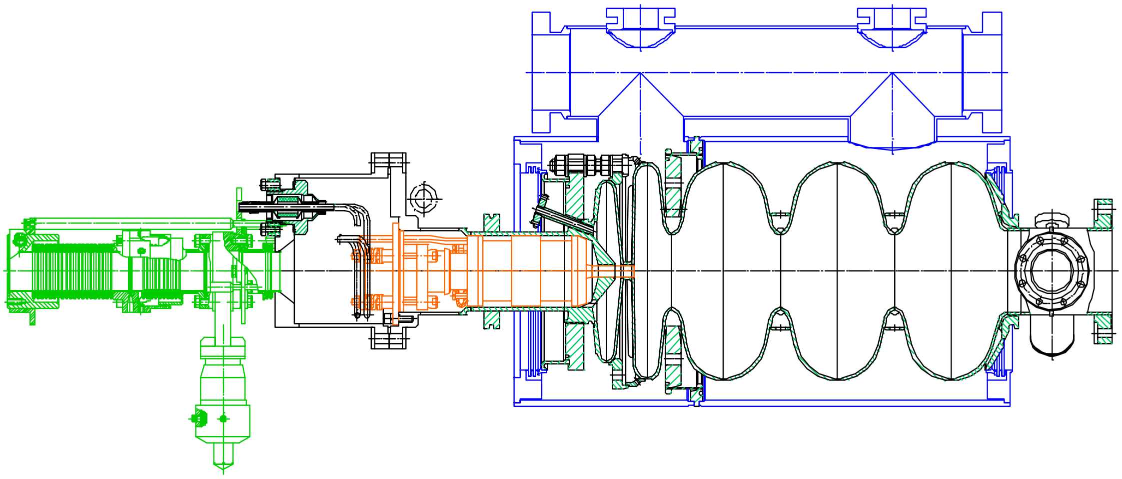

Figure 6: Layout of the FZR 3+ ½ cavity with choke flange filter, helium vessel, and photocathode liquid nitrogen cooling system.

maximum bunch charge obtained was 20 pC, which corresponds to an average current of 520 μA in the cw mode. It is limited by average power and repetition rate of the laser and by the small quantum efficiency of the photo cathode. 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 values were between 1 and 2.5 mm×mrad in agreement with PARMELA calculations.

Rossendorf 3+½ Cell Cavity Project

The SRF photo-injector research and development is being continued with a project of a superconducting CW injector [24] for the ELBE electron accelerator [30]. The design of the cavity and beam dynamical simulations have been performed. The new cavity, operating at 1.3 GHz, will consist of three TESLA cells and an optimized half cell. As in the previous gun project, a normal-conducting, liquid nitrogen cooled, and thermally and electrically insulated photocathode will be inside the half cell of the cavity. The coaxial structure requires again a superconducting choke flange filter to prevent RF losses. Fig. 6 presents the layout of the niobium cavity with helium vessel and liquid N_2 cooling system for the cathode. A new Helium cryostat for 1.8 K is being designed and will be connect with the existing ELBE helium refrigerator allowing closed circuit operation.

The cavity has been designed for a peak electric field of 52 MV/m in the TESLA cells and 33 MV/m in the half cell. In an optimization procedure it was found that a shorter half cell (37.7 mm) and slightly modified first TESLA cell provides better beam parameters.

The injector will operate in CW mode with an average current of 1 mA and an electron beam energy of about 10 MeV. In the ELBE standard operation regime the pulse repetition rate will be 13 MHz and the bunch charge 77 pC. A second operation regime with a reduced repetition rate of 1 MHz will be installed for studying the gun behavior for high bunch charges up to 1 nC. From beam dynamic simulation normalized transverse emittances (rms) of 0.5 mmxmrad for 77 pC and 2.5 mmxmrad for 1 nC have been obtained.

SUMMARY

In Table 1 a summary of the existing projects is presented. SRF photo-injectors can operate in CW mode with high acceleration gradients and they have potential to produce beams with high average current and low emittance. But they are still in the research and development phase. For the various difficulties arising from the use of superconducting cavities in photo-injectors, hopeful approaches are found but experimental proofs and long-term test are outstanding.

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Table 1: Summary of SRF photo-injector projects.

	Peking University	**BNL**	**FZ Rossendorf**	
Gun Type	DC-SC gun	all-niobium gun	normal-conducting cathode	
Resonator cells	1 + ½	½	½	3 + ½
RF frequency	1.3 GHz	1.3 GHz	1.3 GHz	1.3 GHz
Cathode	Cs$_2$Te	Nb	Cs$_2$Te	Cs$_2$Te
Q.E. @ 262 nm	0.01	5x10^{-5}	0.0025	0.05
peak electric field	30 MV/m	45 MV/m	22 MV/m	52 MV/m
beam energy	2.6 MeV	2.2 MeV	0.9 MeV	10 MeV
transverse emittance (rms)	8 mm mrad @ 60 pC	< 1 mm rad @ 1 pC	2 mm mrad @ 4 pC	2.5 mm mrad @ 1 nC
possible cavity contamination	not expected	no	not observed	not measured yet
project status	cool down 4 K	Q measured at 4 K	operation at 4 K in 2002	project started

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