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Cs_2Te normal conducting photocathodes in the superconducting rf gun

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The superconducting radio frequency photoinjector (SRF gun) is one of the latest applications of superconducting rf technology in the accelerator field. Since superconducting photocathodes with high quantum efficiency are yet unavailable, normal conducting cathode material is the main choice for SRF photoinjectors. However, the compatibility between the photocathode and the cavity is one of the challenges for this concept. Recently, a SRF gun with Cs_2Te cathode has been successfully operated in Forschungszentrum Dresden-Rossendorf. In this paper, we will present the physical properties of Cs_2Te photocathodes in the SC cavity, such as the quantum efficiency, the lifetime, the rejuvenation, the charge saturation, and the dark current.

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I. INTRODUCTION

The superconducting rf photoelectron source (SRF gun) developed within the collaboration of HZB, DESY, MBI, and FZD has been operated in Forschungszentrum Dresden-Rossendorf (FZD) since 2007 [1]. During gun operation, one of the main purposes is to gain more experience with this new electron source concept, and to prepare the injection service into the ELBE linac at the beginning of 2010.

This new type of injector is a promising candidate of an electron source for new light sources and large accelerator facilities, such as FEL and ERL. The advantages of the SRF gun are continuous wave (CW) operation, high average current, low emittance, and short bunch length. At first, it is based on SRF cavity technology which allows CW mode operation due to the low rf losses in the cavity; second, a proper treatment of the niobium cavity makes it possible to operate the cavity at a very high acceleration field in the cavity and on the cathode surface to reduce the space-charge effect on the low energy electron bunch; third, the electron bunches are produced from the photocathode with a fast response time driven by the laser, so that the bunch length can be as short as picoseconds, and the structure of the bunches can be controlled by shaping the laser pulses.

In this paper, we focus on the photocathode used in the SRF gun. There are several candidates for the cathodes, such as the recent superconducting (SC) cathodes, the ‘‘conventional’’ metallic photocathodes, and the semiconductor photocathodes. The biggest advantage of SC photocathodes is the easy combination with the SC cavity. At BNL, SC photocathodes consisting of Nb and Pb have been well investigated [2]. Nb has a quantum efficiency (QE) in the order of 10^{-5} at cryogenic temperature. The room temperature test of lead in the Pb-Nb SRF gun delivered a good QE of 0.5% by illumination with a 193 nm UV laser, and its cryogenic test confirms the same level [3]. These proved SC photocathodes are ‘‘permanent’’ materials embedded in the back wall of the Nb cavity. The conventional normal conducting (NC) metallic photocathodes, such as Cu or Mg, are most robust for rf guns, but their QEs are pitifully very low, mostly on the level of 10^{-5} [4]. The semiconductor photocathodes, made of alkali antimonides, GaAs(Cs), CsI, or Cs_2Te, have the best QE up to 1%–10% [5]. Among them, Cs_2Te is relative robust and can be rejuvenated after the QE dropping down [6]. Cs_2Te is a p-type semiconductor with the band gap of 3.2 eV and the electron affinity of roughly 0.3 eV. So its photoemission needs a UV drive laser. Because it has picosecond response time and can withstand an electric field as high as 100 MV/m, Cs_2Te is the best candidate for rf guns and is used in several FEL facilities [7].

The need for high bunch charges and high average current requires a high QE semiconductor cathode for the FZD SRF gun, and Cs_2Te seems to be the most suitable due to its advantages mentioned above. However, the compatibility between a NC cathode and SC cavity is a new big challenge: Issues are the thermal isolation between the cathode and the SC cavity, the possible contamination on the Nb cavity surface from the cathode material, field emission, and the multipacting risk in the cathode area. At the same time, a safe load-lock system and an accurate insertion mechanism are needed for the cathode exchanging. Because the Cs_2Te photocathode is sensitive to the contamination, a good vacuum during preparation, storage,

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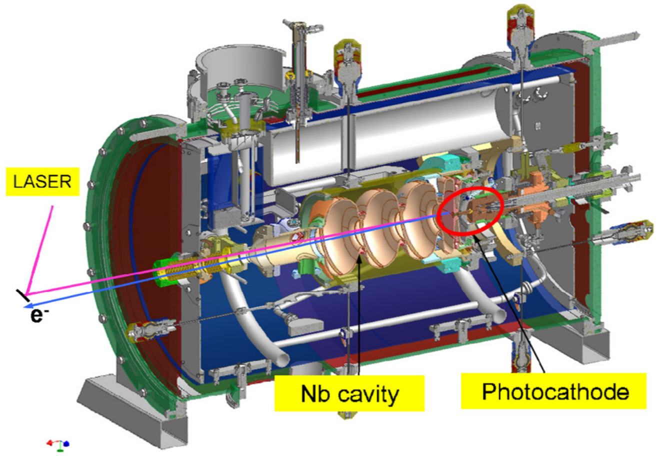

FIG. 1. (Color) Design of the SRF gun cryomodule.

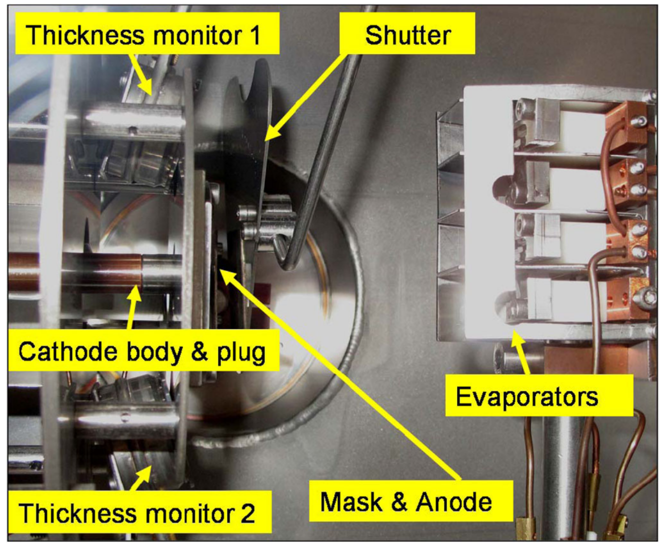

FIG. 2. (Color) Inside view of the preparation chamber.

transportation, and insertion is also an important issue. In this paper, our solutions to these open questions, including success and insufficiency, will be explained in detail.

II. FZD SRF GUN

Figure 1 shows the SRF gun cryomodule, which comprises the 1.3 GHz niobium cavity, tuners, helium tank, LN_2 vessel, magnet shield, photocathode, main power coupler, and so on. The drive laser illuminates the photocathode surface, from which the electrons are excited and escape to the acceleration electric field. Details of the SRF gun design have been published elsewhere [8].

In order to combine the NC Cs_2Te semiconductor and the SC niobium cavity, and at the same time to get the highest electric field on the cathode surface, a special cathode support and cooling system is installed in the cryomodule [9]. With this system, the cathode is electrically and thermally isolated from the SC cavity by a vacuum gap and separately cooled with liquid nitrogen. So the cathode works at 77 K. Up to -10 kV bias voltage can be applied to the cathode to restrain the multipacting in the cathode area and also to produce an additional focusing field for the space-charge dominated low energy beam. In our experiments the photocathode has a long lifetime and relatively stable QE, at least in the case of illuminated by the laser with low and medium energy intensity. On the other hand, there is no obvious degradation found in the cavity quality, since the rf measurement result shows that the cavity with the cathode inside has the quality factor Q_0, the same as the virgin cavity [10].

III. CATHODE PREPARATION

The Cs_2Te photocathodes are prepared separately in the cathode lab and then transported to the SRF gun. It takes only half an hour to exchange photocathodes in the accelerator hall. In this way the time-consuming cathode preparation process does not disturb the gun operation.

Figure 2 shows the inner view of the preparation chamber. The cathode body is made of copper to get a high thermal conductivity for the LN_2 cooling, and the cathode substrate (the small exchangeable plug on top of the cathode body) is made of molybdenum. In fact, Cu was also tested in the preparation lab, but our experience shows that Mo is a better material than Cu for the substrate. Investigations with Rutherford backscattering spectroscopy showed that the interface between Cs-Te film and Cu is blurry. This means that Cs reacts with the Cu surface, while Mo is more chemically stable. So all of the photocathodes used in the tests had Mo plugs. In front of the cathode there is a mask to limit the deposition area to Φ8 mm. The cesium source and the tellurium source are located in equal distance (8 cm) from the cathode surface. There are two thickness monitors to detect the deposition rate of tellurium and cesium, respectively. The arrangement of the thickness monitors and the sources makes the coevaporation possible in this equipment [11].

The Mo cathode plug has 10 mm diameter and 99.9% in purity. After mechanical polishing, it is cleaned with isopropanol in ultrasonic bath for 20 min. In the preparation chamber, the plug is degassed at 200°C for 3 hours in a vacuum of 1×10^{-8} mbar. The deposition is done with the standard process or coevaporation in the vacuum of 10^{-9}–10^{-8} mbar. The standard method means that the 10 nm Te film is deposited at first and then activated with cesium. Coevaporation means that Te and Cs are deposited at the same time. The coevaporation preparation takes only half an hour while the standard process needs more than 1 h. A low power 262 nm laser illuminates the cathode surface and the photocurrent is measured during the preparation process.

The cathode is stored in the transport chamber, where the vacuum is in the order of 1×10^{-9} mbar. The process of cathode transfer leads to a vacuum pressure raise for a short period. The reason is that the sliding friction between the surface of vacuum pipe and manipulator results in the gases absorbed on the surfaces released. The QE drops very fast in the first week and then keeps relatively stable in the next months. The QE decrease is attributed to the pollution by the rest gas, because except for the ignorable laser being as weak as 0.6 mW for the diagnostics there is no other action on the cathode. In order to reduce the QE decrease rate, the vacuum in the storage chamber must be improved up to the 10^{-10} mbar range.

Up to six photocathodes can be transported together in the UHV from the photocathode lab to the accelerator hall, where the same load-lock system is installed. After connecting the transport chamber and the vacuum in the load-lock chamber reaches a pressure better than 10^{-9} mbar, the cathodes can be carefully exchanged.

IV. QE AND LIFETIME

The SRF gun requires photocathodes with QE higher than 1%. Up to now, four Cs_2Te photocathodes have been employed in the SRF gun (see Table I). Cathode #090508Mo finished its short service due to a vacuum crash during the cavity warming up. The second cathode, #070708Mo, was drawn out from the gun before the niobium cavity was taken out for frequency adjustment. The third cathode, #310309Mo, worked for three months in the gun and provided a stable electron beam totally for more than 100 hours. The fourth cathode, #040809Mo, worked in the gun for three months without any degradation.

During the beam time the acceleration gradient was set to 5.5 MV/m which belongs to 15 MV/m peak field in the cavity and about maximum 7 MV/m at the cathode. The average current was mostly 1–16 μA. The maximum power of the drive laser was 300 mW, and the pulse energy was up to 2.4 μJ. The pulse length of the drive laser was 15 ps, so the peak power intensity on the cathode surface could reach 5.66 kW/mm^2.

The QE distribution scan is done after the preparation in the preparation chamber. Figure 3 is the QE scanning map of the cathode #310309Mo (three days after the preparation). The cathode was scanned by using the diagnostic 262 nm laser with the power of 0.6 mW, spot size of Φ0.5 mm and scan step size of 0.5 mm. The QE distribution showed a platform with the sharp edge.

The lifetime of the photocathode operated in the gun was found to be comparable with that which was stored in the transport chamber. The long-term behavior of a group of Cs_2Te photocathodes produced in 2009 is presented in Fig. 4. The blue curve with dots is the QE of cathode #310309Mo, which has been in operation in the gun for more than three months. The preparation environment, the substrate material (Mo), and its treatment were the same for all of the three cathodes. The cathode #200309Mo (orange curve with triangle) was coevaporated whereas the other two were prepared with the standard method. The slower QE decrease of #200309Mo may be attributed to the coevaporation, which was found to be a good way to produce Cs_2Te photocathodes with high QE and long lifetime in a short preparation time. The blue curve showing the results for cathode #310309Mo has the same trend as the others though it has been irradiated by the laser and

TABLE I. Cathodes serving in SRF gun.

Cathode no.	Serving time	QE in gun
#090508Mo	2008-5-23 to 2008-6-23	0.05%
#070708Mo	2008-7-21 to 2008-9-19	0.1%
#310309Mo	2009-5-8 to 2009-8-24	1.1%
#040809Mo	2009-8-24 until now	0.6%

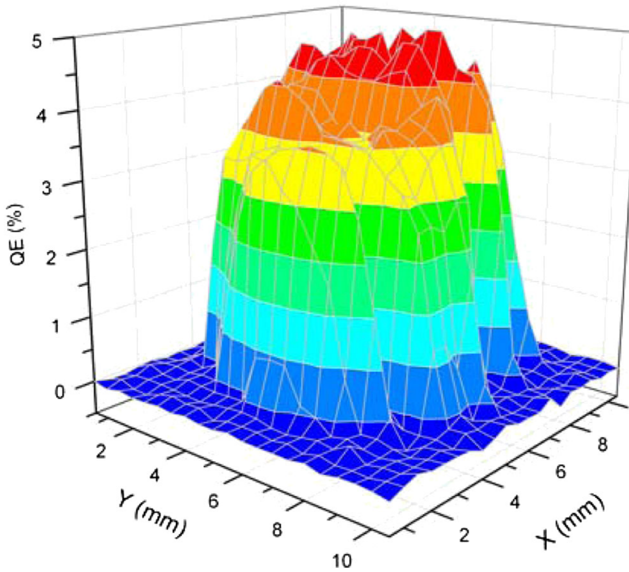

FIG. 3. (Color) QE scanning map for cathode #310309Mo done in the preparation chamber.

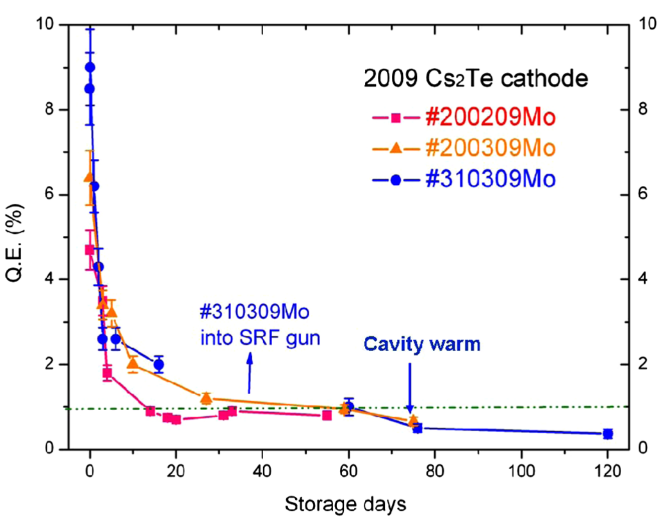

FIG. 4. (Color) Long-term behavior of Cs_2Te photocathodes.

operated in the rf field. So we can say that the operation in the SRF gun does not introduce additional contamination onto the cathode surface.

V. REJUVENATION

Because of the long time storage in the transport chamber and the transportation process, the QE measured in the gun was already lower than that of the fresh cathode. For example, cathode #310309Mo in Fig. 4 experienced from 2% down to 1.1% after the transportation. Figure 5 shows the history of the cathode #070708Mo. This one suffered even more, from 4% to only 0.1%. The range marked with blue ink is the serving period (July 21, 2008 to September 12, 2008) in the SRF gun, in which the QE was relatively stable. After operated in the SRF gun, this photocathode was moved back to the preparation lab for a rejuvenation test. The first step was to heat the cathode to 120°C. The rest gas attached on the surface was desorbed and the QE was slowly but continuously increased from 0.1% up to 0.7%. The second step was to reactivate the cathode with cesium. A layer of cesium film as thin as 10 Å was deposited on the cathode surface, the QE rose quickly in three minutes from 0.7% to 1.5%. In the whole process the UV laser of 0.6 mW illuminated the cathode to detect the photocurrent. According to our experience, the efficient rejuvenation procedure could be done twice. One can get 30%–70% QE of the original fresh QE in the first reactivation procedure, the second time only 10%–20% recovery ability, and the third time we did not find any improvement. This phenomenon provides us a chance to reactive the ‘‘dead’’ photocathode in short time rather than preparing a new one. The fact is, up to now we have not tested the rejuvenated photocathode in the gun because one photocathode serviced for long enough time, and at the same time we have always several backup photocathodes in the transfer chamber. But we will test the reactivated cathode in the gun in the next runs.

VI. CHARGE SATURATION

The photoelectron beam current growths theoretically with laser power. But the current was found increasing not linearly in SRF gun as seen in Fig. 6. At high laser power saturation occurs due to space-charge effects in front of the photocathode. This saturation effect determines the maximum bunch charge and thus the maximum beam current that the SRF gun can achieve.

Because the photocathode is isolated to the SC cavity, it is possible to measure directly the photocurrent from the cathode. The precision of the current measurement is 0.1 μA. The sketch plan of the diagnostic beam line is shown in Fig. 7 [12]. The beam current is measured simultaneously from the photocathode and from the Faraday cup 1.5 m downstream from the photocathode, and the solenoid is not used in this measurement. The laser power was measured in the laser room, and then calibrated considering the power loss during the transport into gun, so the laser power shown in Fig. 6 is the real one at the cathode. The rf acceleration gradient in the cavity was 5 MV/m, and the electron beam launch phase was 20°. A DC voltage of -5 kV was applied to the cathode. The actual field magnitude during emission (extracting field) was 3.4 MV/m including the DC field on the cathode surface. The difference between the photocurrent from cathode and the Faraday cup current is considered from two sources: One is the dark current which is not accelerated by the rf field, and the other is the beam loss in the cavity and in the beam line. The first part was measured to 1.1 μA when the laser power was set to zero. As for the second part, a simulation

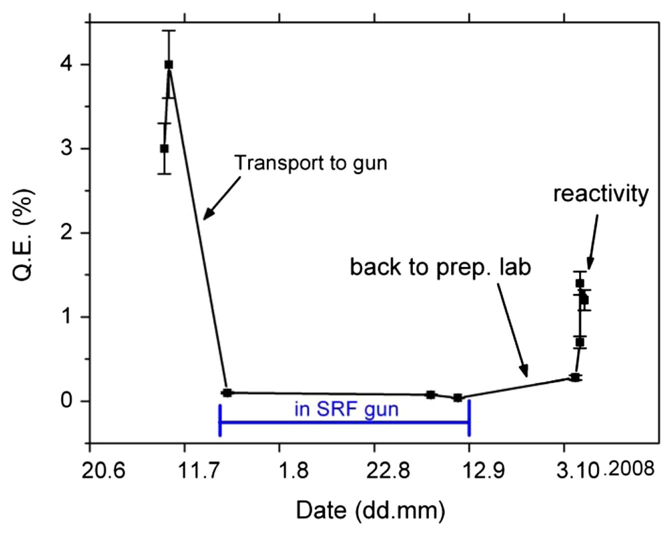

FIG. 5. (Color) History of the cathode #070708Mo. The range from July 21, 2008 to September 12, 2008 is the serving period in the SRF gun.

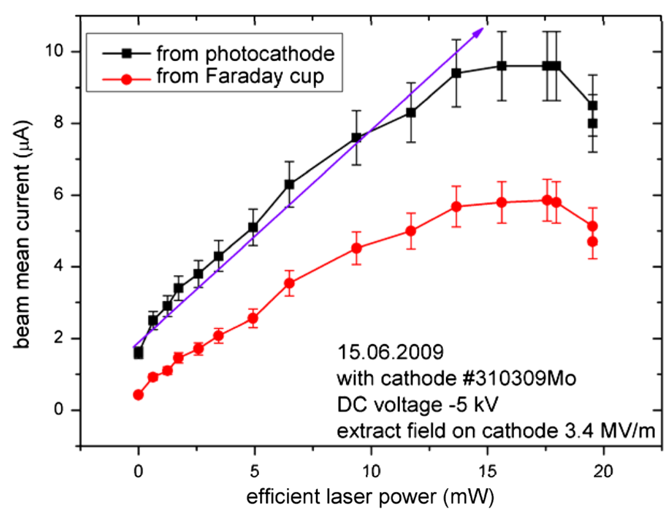

FIG. 6. (Color) Beam current saturation in the SRF gun. The repetition rate of the micropulses was 125 kHz so that the maximum beam current of about 6 μA belongs to a bunch charge of 50 pC. The laser spot on the cathode was Φ2 mm.

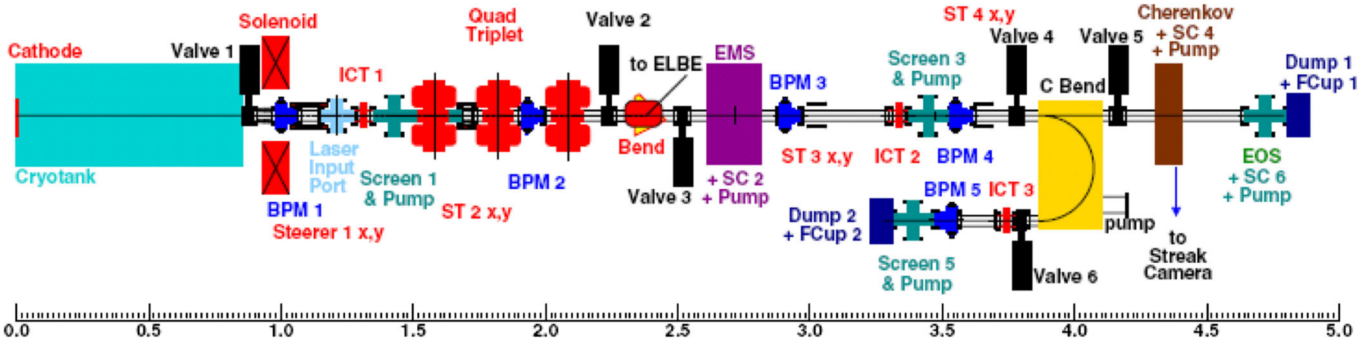

FIG. 7. (Color) General layout of the diagnostic beam line for the SRF gun project [12]. It consists of beam position monitors (BPM), integrated current transformers (ICT), profile monitors based on YAG screens, emittance measurement system (EMS), spectrometer dipole, Cherenkov radiator, electro-optical sampling system (EOS), Faraday cups (FCup), and the beam guide elements: quadruple triplet, steerer coils, and dipole magnet to the ELBE beam line.

with ASTRA has been done to track the electrons emitted from the cathode, and the transportation rate at the given field gradient and rf phase is 80%.

The laser spot was Φ2 mm on the cathode surface, the laser pulse length was 15 ps, and the repetition rate was 125 kHz. The saturation happened when laser power on the cathode was higher than 13.7 mW and the maximum bunch charge was 50 pC at the present rf gradient and launch phase by using the cathode #310309Mo. A higher bunch charge can be achieved by increasing the laser spot size. The bunch charge limit obtained from simulation is about 400 pC for the given parameters. A further increase requires a higher extracting field at the cathode.

VII. DARK CURRENT

Another important parameter of the photocathode in the injector is the dark current. Figure 8 shows the dark current measured in the SRF gun with cathode #310309Mo. The inserted photos are photocathode imagines obtained by using the electron beam optics from the YAG screen (2.7 m from the photocathode). This dark current is due to field emission from two sources: the borders of the gap between the cathode and cavity and the cathode film itself. The detectable dark current starts at 6 MV/m acceleration field independent of the DC bias on the cathode. However, the dark current threshold could be increased by improving the cathode surface condition and by modifying the shape of the cathode tip. For example, the cathode #310309Mo used in this test had modified shape with a round edge other than the old ones in 2008 with a sharp edge, which had a dark current threshold at 5 MV/m only.

Figure 9 shows the photocurrent as a function of the cavity acceleration gradient for a given laser power. An abnormal current peak in the cathode current (red) appears at low gradient. But electrons belonging to this peak are not accelerated through the gun because the signal of the Faraday cup is clearly normal. At the same gradient level multipacting happened during the cavity conditioning. But here we found that the current intensity of this peak in-

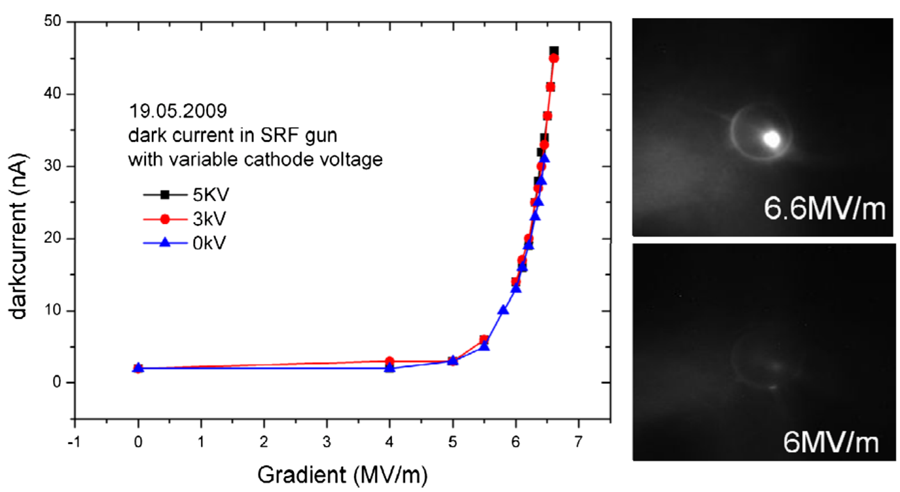

FIG. 8. (Color) Dark current measured in the SRF gun. The inserted photos are photocathode imagines obtained on the YAG screen (2.7 m from the photocathode) by using the dark current electrons and the solenoid.

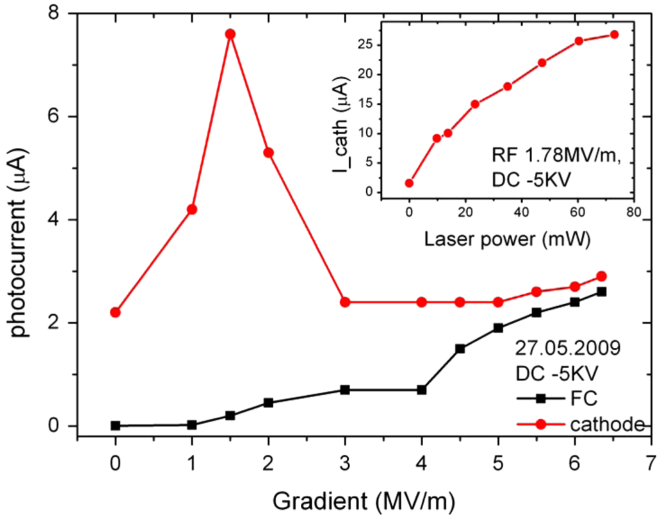

FIG. 9. (Color) Measured photocurrent versus cavity gradient with constant laser power. The current was measured at different positions: Faraday cup current (FC, black squares) and cathode current (red circles). The inset shows the cathode current scan vs laser power at the gradient of 1.78 MV/m, where the peak in the cathode emission current appeared.

creases with the laser power illuminating the cathode (the inset of Fig. 9), i.e., the number of the primary photoelectrons. So we assume that this peak comes from the secondary electron emission in the cathode area induced by the primary photoelectrons. The good news is that this phenomenon did not appear in the normal running of the SRF gun which was set at a higher rf gradient. Thus it is less harmful for the photocathode emitter film. Another way to suppress this emission was to increase the DC bias to −7 kV.

VIII. OUTLOOK

In the near future, the vacuum in the preparation chamber and the transfer system will be greatly improved to increase the cathode fresh QE and to reduce the degradation during the storage and the transportation. For this goal nonevaporable getter pumps [13] will be installed in our vacuum system. Then the next group of photocathodes prepared is expected to have much better QE in the SRF gun.

The negative electron affinity GaAs cathode is considered as an alternative photocathode for the SRF gun. The first reason is that GaAs cathodes require 600–800 nm drive laser but no UV laser, which will save cost for the laser if higher bunch charge is needed in the future. The second reason is that the GaAs cathode has a much lower thermal emittance than the Cs_2Te photocathode. So it is possible to reduce the transverse emittance to lower than 1π mm mrad for 1 nC bunch charge. The third reason is that polarized electrons from GaAs cathodes (driven by circularly polarized photons) may provide new applications for the ELBE user facility, and the polarized electron source based on the SRF gun may be another choice for the international linear collider (ILC) and electron-ion collider (eRHIC). But there are still a lot of open questions in the preparation and the operation of GaAs in the SRF gun, such as ion bombardment, electron bombardment, dielectric rf power losses, slow response time, and so on. Some theoretical work has been done to study the possibility to apply this cathode in the SRF gun [14].

IX. SUMMARY

A superconducting rf photoinjector has been successfully installed and tested at FZD. With this gun, plentiful experiments have been performed to measure the photocathode properties at low temperature. Up to now, a contamination of the cavity from the cathode has not been found. Stable emission from Cs_2Te photocathodes with QE 1% has been achieved with a lifetime of at least three months. The dark current of the Cs_2Te cathodes has been measured.

ACKNOWLEDGMENTS

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