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PROPERTIES OF NORMAL CONDUCTING CATHODES IN THE FZD SUPERCONDUCTING GUN *

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Abstract

The superconducting radio frequency photoinjector (SRF photoinjector) is one of the latest applications of SC technology in the accelerator field. Since superconducting cathodes with high QE are not available up to now, normal conducting cathode material is the main choice for the SRF photoinjectors. However, the compatibility between the cathode and the cavity is one of the challenges for this concept. The SRF gun with Cs_2Te cathode has been successfully operated under the collaboration of BESSY, DESY, FZD, and MBI. In this paper, some experience gained in the gun commissioning will be concluded. The results of the properties of Cs_2Te photocathode in the cavity will be presented, such as the Q.E., the life time, the dark current and the thermal emittance.

INTRODUCTION

The SRF gun developed within the collaboration of HZB, DESY, MBI and FZD has been put into operation in FZD since 2007 [1]. During the gun operation, one of the main purposes is to gain more experience about this new type electron source, and to prepare the service in ELBE linac from the end of 2009.

This new type of injector is a promising candidate of high current and high brightness electron source for the new light sources and big accelerator facility, such as FEL, ERL and so on. At first it is based on SRF cavity technology which allows continued wave mode operation, so the repetition rate can be much higher than the normal conducting RF gun; secondly, good niobium cavity treatment makes it possible to operate the cavity at very high acceleration field in the cavity and on the cathode surface to reduce the space charge effect to the low energy electron bunch; thirdly, the electron bunches are produced from the photocathode with the fast response time driven by the laser, so the bunch length can be as short as pico-second, and the structure of the bunches could be controlled by shaping the laser pulses.

Figure 1 shows the SRF gun cryomodule, which comprises the 1.3 GHz niobium cavity, tuners, Helium tank, LN_2 vessel, magnet shield, photocathode, HOM couplers, main power coupler, and so on. Details of the SRF gun design have been published elsewhere [2]. The 263nm drive laser illuminates the photocathode and the electrons are excited and escape from the cathode surface to the acceleration electric field.

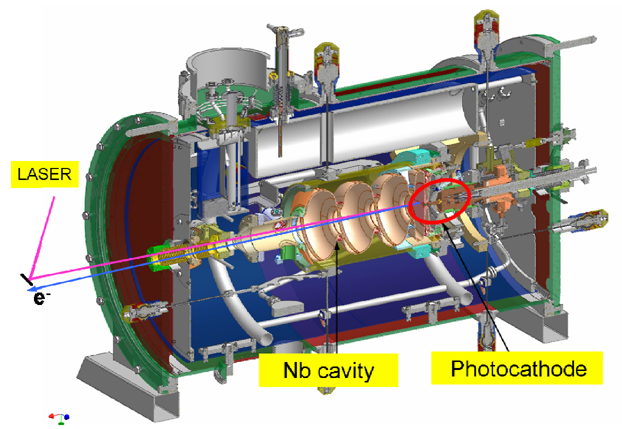

Figure 1: Design of the SRF gun cryomodule.

The same as all of the other RF guns, the photocathode plays an important role in the design and the operation of SRF gun. Since superconducting cathodes with high quantum efficiency (QE) are not available up to now, normal conducting (NC) cathode material is the main choice for the SRF photoinjectors, such as copper, magnesium, Cs_2Te, Cs_2KSb and so on. However, the compatibility between the cathode and the cavity is one of the big challenges for this concept.

In the FZD SRF gun, Cs_2Te is chosen as the standard photocathode. This is the p-type semiconductor. Although it needs UV drive laser, and its preparation requires ultra high vacuum (UHV) and is very sensitive to contaminations, it has been chosen as the best candidate in several FEL laboratories [3], because it has good QE in hundred of hours, and can stand an electric field as high as 100MV/m. However, its physics performance in the cryogenic temperature was still unknown. We will present our experience on the Cs_2Te properties in the temperature of ~ 77K.

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 supporter located in the centre of the half cell cavity is installed [4]. This makes the cathode isolated from the SC cavity by a vacuum gap and cooled extra with liquid nitrogen. In our experiments the photocathode has long lifetime and relatively stable QE, at least in the case of illuminated by the laser with low and medium energy

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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 cathode inside has the quality factor Q_0 as same as the virgin cavity [5].

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 cathode preparation process doesn't disturb the gun running.

Figure 2 shows the inner view of the preparation chamber. The cathode plug is made of copper to get high thermal conductivity to the LN_2 cooling, and the cathode substratum is made of copper or molybdenum. In fact, our experience shows that Mo is a better materiel than Cu for the substrata. Because the substratum research with Rutherford Backbombardment Spectrum (RBS) showed that the interface of the Cs-Te film and copper is blurry. Cesium reacts with copper surface. But Mo is more chemically stable. So all of the photocathodes used in the gun are deposited on the Mo tip. On both sides of the cathode plug, there are two thickness monitors to detect the deposition rate of tellurium and cesium respectively. In front of the cathode there is a mask to limit the deposition area to ф8mm and to be used as anode. Cesium source and tellurium source are located in equal distance and angle to the cathode centre. The arrangement of the thickness monitors and the sources makes the co-evaporation possible in this facility.

The Mo cathode plug is ф 10.0mm, 99.9% in purity. After mechanical polishing, it is cleaned with Isopropanol in ultrasonic bath for 20 minutes. In preparation chamber, the plug is degassed at 200 ^{o}C for 3 hours in the vacuum of $1*10^{-8}$mbar. The deposition is done with the standard process or co-evaporation developed by CERN [6]. The standard method means that 10nm Te film was deposited at first and then activated with Cesium; Co-evaporation means that Te film is deposited and activated with Cs at the same time. The co-evaporation preparation process takes only half an hour while the standard one needs more than one hour. The photocurrent was used to diagnostic the preparation process. The Q.E. drops very fast in the first week and then keeps relatively stable in the next months. The Q.E. decrease is attributed to the pollution by the rest gas, because except the ignorable laser as weak as 0.6mW for the diagnostics there is no other action on the cathode. In order to reduce the decease rate the vacuum in the storage chamber must be improved up to 10^{-10}mbar range.

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 vacuum to drop down 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. But this vacuum drop is found harmless for the cathode QE in our experiments.

After the preparation, up to 6 photocathodes can be transported in the UHV from the photocathode lab to the accelerator hall, where stands a same load-lock system to connect the transport chamber. After the vacuum in the load-lock chamber reaches good 10^{-9} mbar, the cathodes can be carefully exchanged.

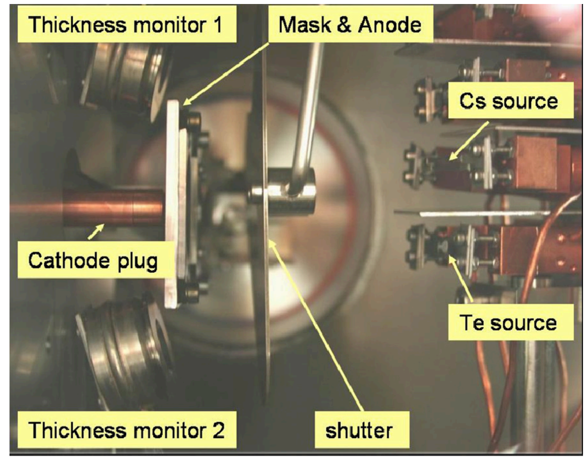

Figure 2: The inside view of the preparation chamber.

QE AND LIFETIME

The design of SRF gun requires a photocathode with QE higher than 1%. Up to now four Cs_2Te photocathodes have been employed in the SRF gun (see table 1). Cathode #090508Mo finished its short service because of the vacuum crash during the cavity warming up. The second cathode, #070708Mo, was drawn out from the gun before the cavity was taken out for frequency adjustment. The third cathode, #310309Mo worked for three months in the gun, which provided stable electron beam totally for more than 100 hours with the integrated charge of 0.8 C. During the beam time the acceleration gradient was set as 5.5 MV/m which belongs to 15 MV/m peak field in the cavity and about 7 MV/m at the cathode. The average current was mostly 1 μA ~16 μA. The fourth cathode is working in the gun till now.

Table 1: Cathodes Serving in SRF Gun

Cathode NO.	Serving time	Q.E. 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 till now	0.6%

Because of the long time storage in the transport chamber the QE measured in gun is already lower than that of the fresh cathode. The life time of the photocathode working in the gun is found comparable with the ones stored in the preparation chamber. To be a reference, the long term behaviour of the same group Cs_2Te photocathodes produced in 2009 are presented in Figure 3. The blue curve is the QE of cathode #310309Mo, which has been in operation in the gun for more than 3 months. The preparation environment was the same for all of the three cathodes, and the substrata were the same material and treated in the same way. #200309Mo (orange) was co-evaporated and the other two were standard prepared. The slower decrease of #200309Mo (orange) may be attributed to the co-evaporation, which was found to be a good way to produce Cs_2Te photocathodes with good QE and good life in short preparation duration. According to the gun specification, 1% QE is sufficient for operation and the life time could be longer than 60 days. The power of the drive laser was ≤ 300mW, and the pulse energy is ~2.4 μJ. The pulse length of the drive laser was 15ps, so the peak power intensity on the cathode surface could reach 5.66kW/mm^2. The blue curve #310309Mo has the same trend as the others though it has been hit by the laser and operated in the rf field and the others are stored in UHV without any other action on it. So, we can say, the operation in the SRF gun does not introduce additional pollute onto the cathode surface.

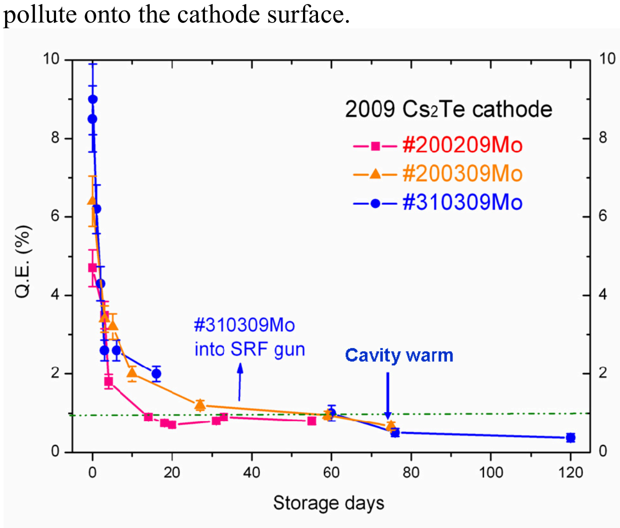

Figure 3: Long-term behavior of Cs_2Te photocathodes.

THERMAL EMITTANCE

The thermal emittance of Cs_2Te is an interesting physical property, because it decides the minimum emittance that a photoinjector can reach. This is the first time to measure the thermal emittance in the cryogenic temperature and with high rf field on it. The measurement is done by using the beam with very low bunch charge and relative large laser spot on cathode, in order to reduce the space charge effect as much as possible, and meanwhile to eliminate the wake fields and the effect from beam halos.

The transverse emittance is measured with solenoid scan method, which is suitable for the low bunch charge measurement. The laser is cut by an aperture to get a hard-edge spot on the cathode with diameter 2.8mm, and only the laser power is changed. The dependence of the transverse emittance on the bunch charge has been measured as figure 4. The black squares are the experimental data of horizontal transverse emittance, and the red dots are vertical transverse emittance. The blue triangles are the average of the two series data. The linear fit of the average data is made to get a correlation between the transverse emittance and the bunch charge. It can be noted that at Q=0 pC for the linear fit there is a residual emittance term of 0.94 πmm·mrad. It is believed that in this term, the initial thermal emittance is the main part because the space charge in the bunch is so low that the beam size expansions in the rf field is very little and the rf contribution to the emittance is also small [7]. The intrinsic thermal emittance of the beam is $\varepsilon_0 \leq 0.94 \pm 0.13\pi mm \cdot mrad$, which means 0.67±0.1 πmm·mrad / r(mm).

This value is some higher than the theoretical analysis 0.43 πmm·mrad / r(mm) from Klaus Floettmann [8] and the data from Powell [9]. This difference can be explained that, the initial emittance is influenced by the cathode surface irregularities, contamination, cathode temperature, electric field on surface, etc. Because the specimens in Powell's experiment were fresh film prepared in a vacuum better than 10^{-10}mbar. But the vacuum in our preparation chamber and transfer system is only 10^{-9}mbar, and the measurement was done with a two-month-old cathode. So the main reason for the difference is of the cathode surface pollution.

According to Floettmann's analysis, the cathode temperature has no obvious effect on the cathode thermal emittance. However, Clendenin in reference [10] mentioned that the thermal emittance could be reduced by a factor of $\sqrt{3}$ if the cathode is cooled down to ~100K. A better vacuum is required to reduce the effect of pollution on the surface barrier, and then more information about the relationship between the cathode temperature and the thermal emittance can be achieved.

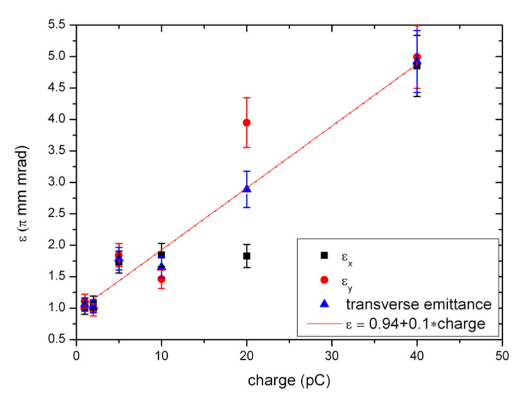

Figure 4: The normalized transverse emittance of the electron beam with laser spot r=1.4mm. The black squares are the experimental data of horizontal transverse emittance and the red dots are vertical transverse emittance, and the blue triangles are the average emittance. The intercept of the fit gives out the original thermal emittance from the cathode.

DARK CURRENT

Another important parameter for the photocathode in the injector is the dark current. Figure 5 shows the dark current measured in the SRF gun with cathode #310309Mo and the imagines of the cathode at different RF gradient. This dark current is considered due to field emission and comes from two sources: the gap between the cathode and cavity and the cathode itself. The detectable dark current starts from 6 MV/m independent of the DC bias on the cathode. This threshold is higher than the one measured in 2008 with cathode #070708Mo, which was 5 MV/m, so the dark current threshold could be modified by improving the cathode surface condition and changing the shape of cathode tip, for example, applying a round edge with small radius for cathode tip.

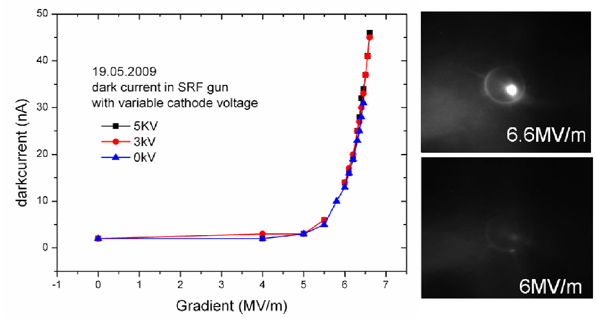

Figure 5: Dark current measured in the SRF gun with cathode #310309Mo.

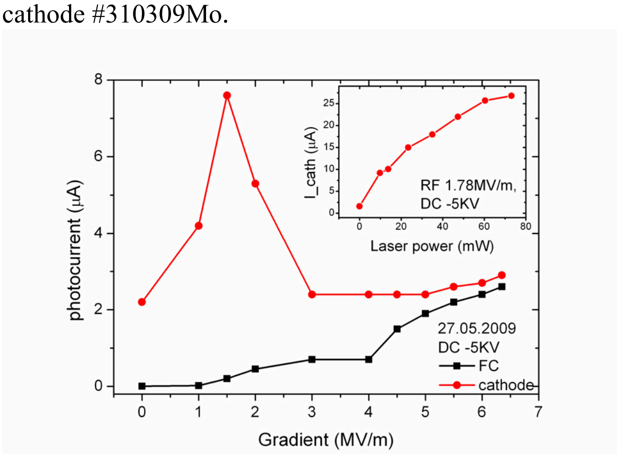

Figure 6: photocurrent scanning vs. cavity gradient and the laser power. The current was measured from different positions: Faraday cup (black curve) and the cathode (red one). The inset window shows the cathode current scan vs. laser power at the gradient of 1.78MV/m, where the high current appeared.

Figure 6 is a photocurrent scanning vs. cavity gradient, in which an unusual current peak emitting from the cathode (red) appears in the low gradient zone. But it is not accelerated through the gun because the signal of Faraday cup is clearly normal. In fact the multipacting happened in the same gradient. In the inset window the current intensity of this peak increases with the laser power illuminating the cathode, i.e. the number of the primary photo-electrons. So we assume that this peak comes from the second electron emission /multipacting and probably also the ion back bombardment on the cathode area. The good news is that this phenomenon didn't appear in the normal running of SRF gun which was set at higher gradient, thus it is less harmful for the photocathode emitter film. Another reason to ignore this emission is that when the DC bias increases to -7KV, the phenomenon is eliminated.

OUTLOOK

In order to increase the cathode fresh QE and to reduce the degradation during the storage and the transportation, plenty effort will be made to improve the vacuum in the preparation chamber and the transfer system in the near future. NEG pumps are used in our vacuum system and the next group of photocathodes is expected to have much better QE and longer life time.

Negative Electron Affinity (NEA) GaAs-type is considered as the alternative photocathode for the SRF gun. The first reason is that GaAs-type cathode needs green drive laser, which will save the work on laser building if higher bunch charge is needed in the future. The second reason is that the GaAs-type cathode has much lower thermal emittance than Cs_2Te photocathode. The third one is that polarized electrons from GaAs-type cathode (driven by polarized photons) may provide new application for ELBE user facility. But there are still a lot of open questions in the preparation and the operation in the SRF gun, such as ion bombardment, electron bombardment, dielectric rf power loss and slow response time. Some theoretical work has been done to research the possibility to apply this promising cathode in the SRF gun [11].

SUMMARY

A Superconducting RF photoinjector has been successfully installed and tested in FZD ELBE hall. With this facility, plentiful experiments have been performed to measure the photocathode properties in the low temperature. The contamination between the cavity and the cathode is up to now not found in the careful operation. Stable Cs_2Te photocathode with QE 1% has been achieved, and the lifetime is measured as long as two months. Dark current and the thermal emittance of Cs_2Te have been measured in the SRF gun.

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