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PHOTOCATHODE STUDY IN SRF GUN-II AT HZDR

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Abstract

HZDR's SRF Gun-II is an excellent demonstration of SRF technology application in the field of electron sources operating in continuous wave mode. As well known, quality of the photocathode is crucial for operational stability and reliability of an SRF gun. In this contribution, various studies on Cs_2Te cathodes, including cleaning, preparation, transport/insertion, RF and beam operation will be summarised. We will look back at the achievements and open issues, and discuss possible improvements and further development.

INTRODUCTION

Development of high-quality electron photo-sources is a key research field in particle accelerator technologies, which is crucial for both fundamental and applied research. It is widely acknowledged that quality of photocathodes plays an essential role in enhancing the stability and reliability of photo-injectors [1]. A "perfect" photocathode should provide a high quantum efficiency (QE) at a standard laser wavelength, long lifetime, fast response and low thermal emittance.

For the development of SRF guns at HZDR, metal cathodes (copper, magnesium) and a type of semiconductor photocathodes, Cs_2Te, have been selected. During last years, with Cs_2Te photocathodes the SRF Gun-II has been able to provide stable beams for accelerator users [2].

HZDR SRF GUN-II AND CATHODES

HZDR SRF gun-II was built for the super-radiant THz source at ELBE SRF accelerator. Currently, the SRF gun-II is providing more than 1000 hours beam time yearly for ELBE.

The SRF gun-II includes a 3½ cell 1.3 GHz cavity with chock cell and a SC solenoid in a cryostat, and a load-lock system for cathode exchange. It is operated with Cs_2Te cathodes driven by a 260 nm laser. The bunch charge is up to 250 pC at the repetition rate of 50 kHz or up to 80 pC at 13 MHz. The kinetic energy is limited to 3.5 MeV by field emission in the SRF cavity.

A highlight of HZDR SRF gun-II is that the cavity gradient has not significantly degraded despite multiple cathode exchanges Even after overheated Cs_2Te evaporated in the gun in 2017, it was possible to recover the cavity.. This well demonstrates possibility of routine operation of an SRF gun.

By now, 31 cathodes have been in use in SRF gun-II, including 2 bulk-Cu plugs, 3 Cs_2Te on Mo plugs, 12 bulk Mg cathodes, and 14 Cs_2Te on Cu plugs (see Fig. 1). Copper was employed as the commissioning cathode. The work function of Cu (4.6 eV) is relatively high, and its quantum efficiency (QE) of 1×10^{-5} at 260 nm is insufficient for routine beam production. In the context of medium bunch charge mode, a magnesium cathode is a promising candidate. Magnesium is a metal with a low work function of 3.6 eV, while its QE can reach 0.5% after ps UV laser cleaning [3]. Despite its lower QE compared to Cs_2Te, Mg offers the benefits of a longer operational lifetime, reliable compatibility, and minimal risk of contaminating the niobium cavity.

Since May 2020, Cs_2Te photocathode (with a band gap of 3.3 eV and an electron affinity of 0.2 eV) has demonstrated favorable QE and a prolonged operational lifetime in the ELBE SRF gun-II [4]. Due to the overheating observed in the cathodes within the SRF gun cavity, the decision was taken to use high conductive copper (OFHC) instead of Mo plugs, despite the inherent challenges associated with utilising copper as a substrate for Cs_2Te. Cs_2Te on Cu plugs have been prepared at HZDR and have demonstrated successful operation within SRF gun-II during the THz user beam time as well as possibility of high average current (up to 1 mA) operation.

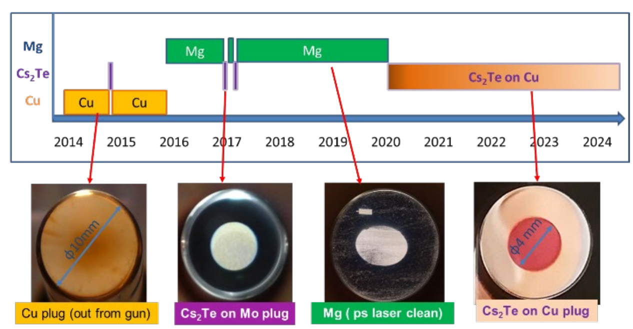

Figure 1: Cathodes used in SRF Gun-II.

CS2TE PREPARATION PROCESS

The Cs_2Te photocathodes were prepared in the HZDR cathode laboratory and transported to the SRF gun via a vacuum transfer system. In the course of our experiments, the Cs_2Te cathodes on the mechanically polished plugs and those on the diamond-turning finished plugs exhibited nearly identical photoemission quality and also the same dark current in the gun. The plugs were meticulously cleaned in a cleanroom. To maintain the surface free of any contamination, chemical cleaning, dry ice cleaning, and 350°C baking in a vacuum were employed.

During the preparation process, the plug was kept at 120°C by means of a halogen lamp. First, tellurium was

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deposited onto the plug surface through a 4 mm mask. Subsequently, cesium was deposited onto the plug surface through the same mask. Meanwhile, 260 nm and 340 nm LEDs were used to illuminate the cathode as a diagnostic light, and the mask was +200 V biased. Cesium evaporation was stopped when the photocurrent at 260 nm reached its maximum, which resulted in a fluctuation of the Cs/Te ratio from one cathode to another. The latest photocathode was deposited with a 10 nm layer of Te and a 68 nm layer of Cs (see Fig. 2). A minor discrepancy is evident due to a displacement of the mask position.

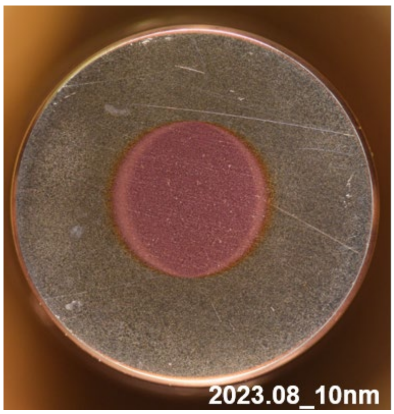

Figure 2: Photograph of Cs_2Te cathode #2023.08_10nm with 10 nm of Te and 68 nm of Cs, about 0.18 mm off centre.

CS_2TE CATHODES IN SRF GUN-II

The typical operational lifetime of a Cs_2Te cathode in the gun is three to six months, during which it provides a charge of more than 10 coulombs. Cathodes are exchanged when the gun is warmed up in a shutdown or when QE of the cathode was not sufficient.

QE Drop Due to CW RF Loading

There is typically a small QE drop during the cathode transport to the gun. However, a pronounced decline in the QE is observed once the RF power is initiated.

The QE tracking for a Cs_2Te cathode is illustrated in Fig. 3. As evidenced by the photograph of the cathode in Fig. 2, the coating exhibited homogeneity with a narrow shadow of the mask along the border. It is noteworthy that the QE measurements taken in the transport chamber (blue points) and the initial QE value obtained in the SRF gun (red point) are similar, indicating that the QE did not significantly diminish during the cathode insertion. However, a pronounced decline in QE was soon evident, particularly following the loading of CW RF power. Subsequently, during the beam operation, the cathode QE remained relatively constant.

Prior to the application of the RF field, a DC bias of –5 kV was applied to the cathode for the purpose of QE measurement, resulting in a photocurrent of approximately 300 nA that was landing on the cavity wall. It is postulated that the reduced QE observed in the cathode centre is a consequence of the return of ions to the cathode. In order to mitigate the impact of multipacting (MP) on the vacuum environment, a dedicated RF start-upprocedure was developed [2]. Initially, only low-power pulsed RF is loaded with a variable DC voltage in order to process the potential multipacting (MP) in the cathode and choke area. Once the pulsed RF reaches 7 MV/m, the duty factor is increased until the CW mode is reached. However, this process may result in the emergence of new MP cases, potentially leading to vacuum issues. Consequently, the QE declines and the QE distribution may alter.

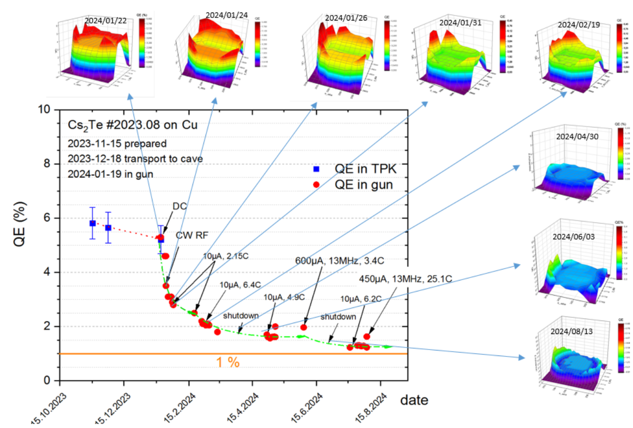

Figure 3: QE tracking of Cs2Te #2021.06.07 with the QE maps in different stages during operation in SRF gun.

QE Distribution Evolution During Beam Extraction

Several Cs_2Te cathodes exhibited considerable inhomogeneity of the QE during the operation. For example, #2023.08 illustrated in Fig. 3. Soon after the insertion, DC bias was employed solely for the purpose of examining the cathode without RF. The cathode showed a homogeneous platform with a narrow border. However, following the introduction of a CW RF field, a significant change in QE was observed. The cathode exhibited a non-uniform degradation, manifesting as a "hole" in the center of the cathode. As the operation continued, the right side of the film exhibited a more rapid degradation than the left side. The center platform underwent a continuous decline in elevation, yet eventually returned to a homogeneous state.

Figure 4 shows the laser illumination, beam production and extracted charge versus time. Comparing those curves and the QE in Fig. 3, there is no obvious relation between the charge extraction and the QE change.

It is evident that the vacuum was not the primary factor responsible for the QE degradation. SRF cavity should provide a good vacuum environment around the cathode. Vacuum measurements at the gun exit demonstrated a pressure of 4–5 × 10^{-10} mbar, indicating that no visible accidents had occurred.

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It is postulated that the photoelectrons and dark current impact the cavity wall, resulting in the release of absorbed gases which subsequently contaminate the Cs_2Te surface. However, if the remaining gas molecules were ionized by accelerated photoelectrons and dark current, these ions could also be accelerated by the RF field and the cathode DC field (–5 kV on cathode) and subsequently back bombard the cathode surface.

A further related topic of investigation is whether the presence of X-rays due to the field emission within the SRF gun cavity exerts any influence on the cathode film.

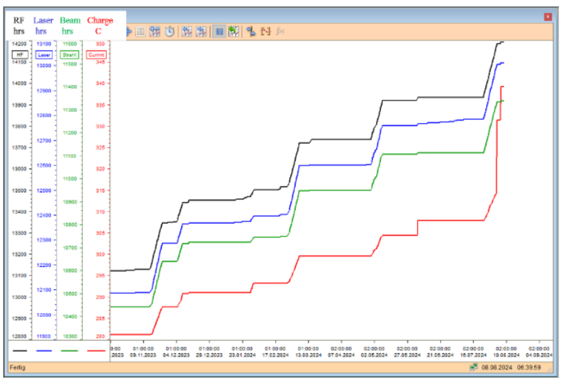

Figure 4: Operation time of the cathode in gun. Black: RF on; blue: laser on; green: beam on; red: integrated charge.

CATHODE TRANSFER SYSTEM

The prepared cathodes are stored in the transport suitcase under vacuum at around 5×10^{-11} mbar (see Fig. 5). Up to six photocathodes can be transported together in the suitcase from the photocathode lab to the SRF gun. An identical system at the gun can adapt the suitcase and transport one of the cathodes into the cavity. During cathode exchange, vacuum can be maintained at the level of 10^{-10} –10^{-9} mbar. An important conclusion is that the cathode transfer is particle free for cathode plug and thus for the gun cavity.

CONCLUSION

For over four years by now, Cs_2Te photocathodes on copper plugs have been successfully applied in the SRF gun-II. We are observing QE evolutions during operation and trying to understand the influence of various factors, including transport, multipacting, RF loading and extracted charge. on the cathode lifetime and QE distribution.

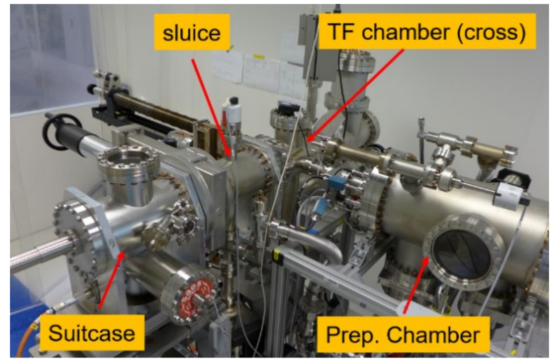

Figure 5: Photo of cathode preparation chamber and the transfer system in the cathode lab.

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