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THERMAL EMITTANCE MEASUREMENT OF THE CS_2TE PHOTOCATHODE IN FZD SUPERCONDUCTING RF GUN *

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Abstract

The thermal emittance of the photocathode is an interesting physical property for the photoinjector, because it decides the minimum emittance the photoinjector can finally achieve. In this paper we will report the latest results of the thermal emittance of the Cs_2Te photocathode in FZD Superconducting RF gun. The measurement is performed with solenoid scan method 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.

INTRODUCTION

The superconducting rf photo-injector (SRF gun) developed within a collaboration of the institutes HZB, DESY, MBI and FZD has been successfully tested and operated together with ELBE Superconducting linac [1]. It is designed for medium average current beam with CW mode. The main parameters achieved from the present SRF gun were the final electron energy of 3 MeV and rms transverse normalized emittances of 3 mm mrad at 77 pC bunch charge. During the beam time the acceleration gradient was set to 6 MV/m which belongs to 16.2 MV/m peak field in the cavity and about maximum 5 MV/m on the cathode. The average current was mostly 1 µA ~16 µA.

For high average power FEL and ERL sources, the combination of SRF linac and SRF gun provides a chance to produce beams of high average current and low emittance with relative low power consumption. The new application of the SRF gun will improve the beam quality, especially the emittance and the bunch charge. New potential applications with the SRF gun injection are the production of short pulse THz-radiation and the x-rays by inverse Compton backscattering.

Photocathode and laser

The SRF gun requires photocathodes with quantum efficiency (QE) higher than 1% in weeks. The Cs_2Te photocathodes are chosen as the standard photocathodes. They are prepared separately in the cathode lab and then transported to the accelerator hall. The Molybdenum cathode plug has 10 mm diameter and 99.9 % in purity. In front of the cathode there is a mask to limit the deposition area to Ø 8 mm in the centre. The deposition is done in the vacuum of 10^{-9} mbar ~ 10^{-8} mbar [2]. The QE of the fresh photocathodes is between 8% ~15%. The cathode is stored and transported in the chamber with the vacuum in the order of 1×10^{-9} mbar. The process of cathode transfer and also the operation in the SRF gun lead regrettably the cathode QE degradation quickly to 1% ~2%.

Up to now five Cs_2Te photocathodes have been employed in the SRF gun. The present photocathode #250310Mo has served in the gun for three months, with accumulated beam time of over 200 hours, emitting charge about 3 Coulombs.

In order to fulfill the requirements of the SRF gun specifications, a UV laser system has been developed by MBI. The first channel has variable repetition rates up to 250 kHz and the second one is designed to deliver laser pulses with 13 MHz repetition rate. The laser has a Gaussian temporal beam shape with a width of 15 ps FWHM. The maximum power of the drive laser is 300 mW, and the pulse energy is up to 2.4 µJ.

Diagnostic beam line

The diagnostic beam line for SRF gun project has been installed as Fig. 1 [3]. It consists of beam position monitors (BPM), profile monitors based on YAG screens, emittance measurement system (EMS), spectrometer dipole, Cherenkov radiator, Faraday cups (FC), the beam guide elements, dipole magnet to the ELBE beamline and so on. The accuracy of the beam current measurement is 0.01µA.

The multi slits method is used for the transverse emittance measurement in the case of medium bunch charge from 10pC to 100pC. For the low bunch charge solenoid scan method is performed. The solenoid is 1.0 meter downstream from the cathode, and the beam transverse profile is measured 1.7 m far from the solenoid on the YAG screen (SC2 in Fig. 1). The beam size resolution is 0.01mm. The scanning fit function matched to the measurement points very well (Fig. 2), because the bunch charge is quiet low, so wake fields, space-charge effects could be ignored, and also the spatial mode of the drive laser has been cleaned up with a pinhole filter.

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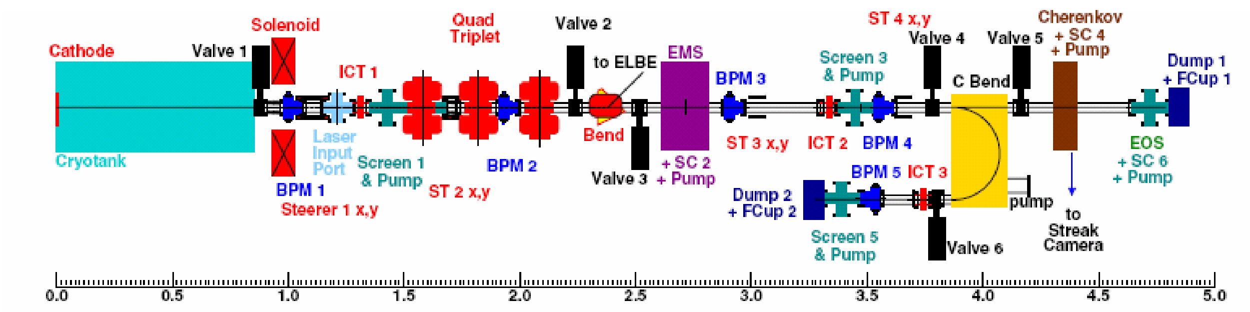

Figure 1: General layout of the diagnostic beam line for SRF gun project [3].

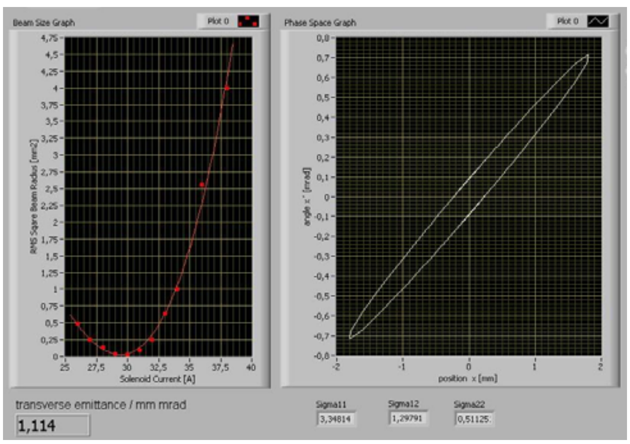

Figure 2: the typical solenoid scan data and the relevant phase space ellipse. The bunch charge is 1 pC, laser spot r_{rms}=1.26mm, beam energy= 2.98 MeV.

The thermal emittance is measured also using solenoid scan method. In this measurement, the transverse emittance from the electron thermal energy and that from the space charge, rf field are all included. So we reduce the laser power to get lowest bunch charge beam to reduce the space charge effect and at the same time to achieve a good resolution. Another reason to reduce the bunch charge is that this method bases on the linear transport matrix neglecting the space charge effect. A simulation with ASTRA [4] is done to get a proper bunch charge range for the thermal emittance measurement (Fig. 3). The laser pulse length is fixed to 15ps FWHM, and the max rf field is set same to practical 16.2MV/m. The rf phase is chosen for the maximum mean energy. The radius of the uniform radial distribution laser spot is 0.75mm. The DC bias on photocathode -5kV is considered and an initial electron kinetic energy of 0.55eV is given to the photoelectrons. The initial, uncorrelated, normalized emittance is 0.63 mm·mrad. From the simulation, the emittance growth due to space charge is negligible when charge is less than 3 pC.

THERMAL EMITTANCE

The term "thermal emittance" means the uncorrelated emittance of the electrons when they escape from the cathode surface. In the former thermionic gun, the thermal emittance is determined through the cathode temperature. For the cold cathode, the thermal energy kT is 0.025eV @ 300K. The photocathode in SRF gun works at LN2 temperature, so kT~0.007eV @ 80K. However, this is not the electron kinetic energy for the semiconductor photocathode.

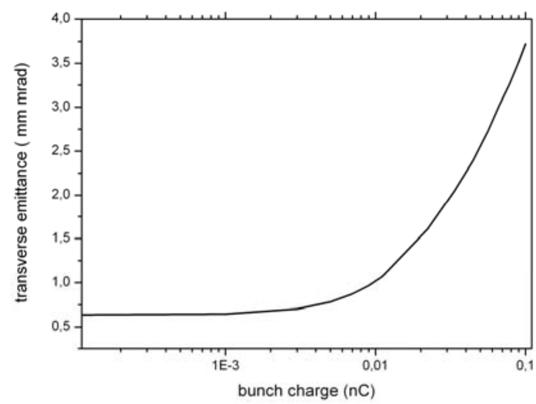

Figure 3: Astra simulation of the rms transverse emittance vs bunch charge. RF field is set to 16.2 MV/m, -5kV bias on photocathode, a kinetic energy of 0.55eV is given to the initial electrons. Laser pulse length is fixed to 15 ps FWHM.

The theoretical calculation of the thermal emittance for Cs_2Te cathode has been firstly performed by K. Floettmann with the three-step model [5], and later several studies were done for metals [6,7]. In practical, several groups published the measurement on the thermal emittance of Cs_2Te [8,9] and copper [10] in the normal conducting rf gun with very high electric field.

The thermal emittance depends on the laser spot size, the momentum distribution and the angular distribution of the emitted electrons [5]. Its typical value from the theoretical analysis and the experimental measurement is around 0.3~0.7 πmm·mrad/mm. If a low emittance source with 1 mm mrad is required for an FEL facility, the thermal emittance part must be a significant part in it. The thermal emittance is strongly influenced by the cathode surface status, drive laser spot distribution and the electric field on it [10].

K. Floettmann gave out the equation between the thermal emittance and the electron kinetic energy as following [5]:

$$\varepsilon_{ther,rms} = \frac{x_{rms}}{\sqrt{3}} \cdot \sqrt{\frac{2E_{kin}}{m_0 c^2}} \qquad (1)$$

The UV laser for SRF gun is 262nm, corresponding to the photon energy 4.72eV. The Cs_2Te semiconductor at liquid nitrogen temperature has the same band structure as the one in room temperature. According to Powell's measurement [11], the electrons will be excited to the final state in the conduction band with 4.05eV above the valence band maximum. The work function (band gap) is 3.3eV, and the electron affinity is 0.2eV for a fresh Cs_2Te photocathode film without external electric field. In such case, the electron kinetic energy can be calculated as E_{kin}=4.05-3.3-0.2=0.55eV. But under high rf field and with polluted emission surface and the electron affinity will be changed. Normally the rest gas will increase the electron affinity, which results in the degradation of QE.

The normalized initial transverse emittance can be

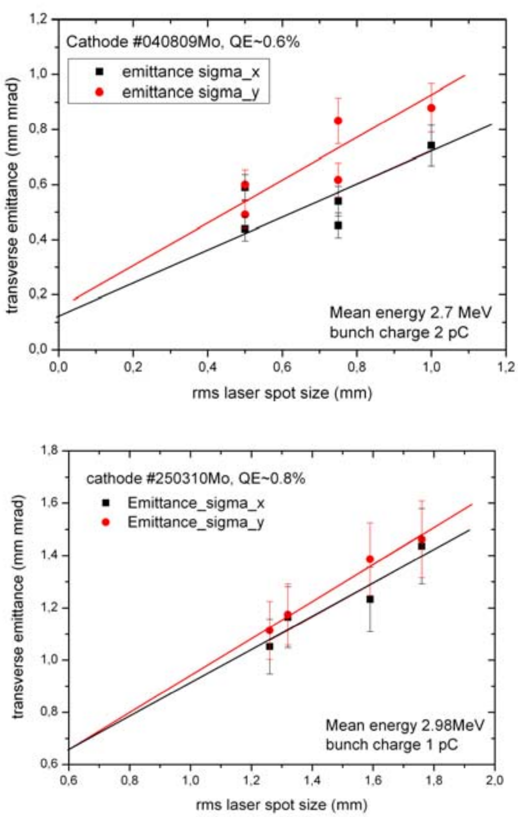

Figure 4: emittance measurement vs laser spot size. (a) cathode #040809Mo with QE 0.6% during the emittance measurement; (b) cathode # 250310Mo with QE 0.8%.

expressed as [8]:

$$\varepsilon_{n,rms} \approx \sqrt{(\varepsilon_{therm})^2 + (\varepsilon_{space\_charge})^2 + (\varepsilon_{rf})^2} \qquad (2)$$

So the thermal emittance is determined by measuring the rms transverse emittance in case of very low space charge effect, or low bunch charge density. Our diagnostics measure accurately the low bunch charge and the transverse profile. The bunch charge used for the thermal emittance measurement is from 0.5pC to 2pC. Another parameter is the rf field on cathode. Later we will see this term can be neglected in our experiment. So the equation 2 can be rewritten as $\varepsilon_{n,rms} \approx \varepsilon_{therm}$.

Transverse emittance is measured versus rms laser spot size for different photocathodes as shown in figure 4a and 4b. The laser spot size was adjusted by changing the aperture diameter. One can calculate the mean initial electron kinetic energy from the slope of the linear fitting by differentiating the equation 1:

$$E_{kin} = \frac{3}{2} m_0 c^2 \left(\frac{d\varepsilon_{ther,rms}}{dx_{rms}} \right)^2 \qquad (3)$$

For cathode #040809Mo in Fig. 4a, the slope of $\varepsilon_{rms,x}$ is 0.6 mrad, that of $\varepsilon_{rms,y}$ is 0.78 mrad. From equation 3, the average kinetic energy of the emitted photoelectrons E_{kin} was calculated as 0.38±0.1 eV, which means that the electron affinity is E_A=0.37±0.1 eV.

For cathode #250310Mo in Fig. 4b, the slope of $\varepsilon_{rms,x}$ is 0.64 mrad, that of $\varepsilon_{rms,y}$ is 0.71 mrad. The average kinetic energy E_{kin} was 0.35±0.04eV; the electron affinity is E_A=0.40±0.04 eV, about 0.2eV higher than that of the fresh cathode.

This is reasonable, because the cathode surface has been polluted by the rest gas during the transportation, which increases the surface barrier (electron affinity). From this point, the QE found much lower than the fresh cathode can also be explained: less electrons escaped from the cathode surface because of the higher energy barrier.

The measurements performed on the PITZ rf gun showed that the electron affinity at zero accelerating field is 0.45±0.10 eV for a cathode with QE of about 3% [8]. And another method by measuring QE dependence on rf phase gave out the value of 0.44eV for the same cathode [12].

RF FIELD EFFECT

From equation 2, the electric field on the cathode surface contributes to the measured transverse emittance. The rf field contribution depends on the field amplitude and also on the laser pulse length. Because with the long temporal pulse length the different beam slice meets different transverse rf force. In our measurement, the laser pulse length cannot be adjusted, which is 15ps FWHM or 6.37 ps rms. The second laser system is hopeful to produce shorter laser pulses. An ASTRA simulation is done to show the fluency of the pulse length on the initial emittance. This doesn't mean that a beam with short pulse length can have lower emittance. In the beam dynamics, the shorter pulse length will lead to larger charge density and then stronger space charge effect on the emittance.

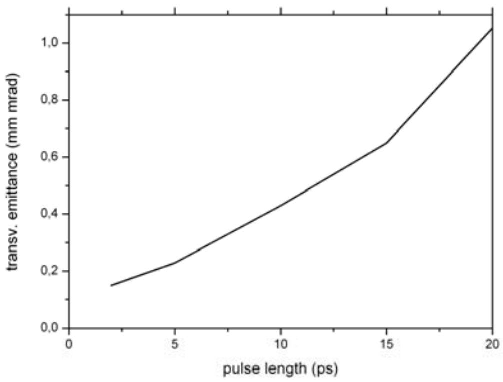

Figure 3: ASTRA simulation to show the fluency of the pulse length. The bunch charge is 1pC. The rf phase is set for the max mean energy.

The high electric field on cathode surface will lower the barrier, so called Schottky effect, described by the equation [12]:

$$E_A = E_A(0) - \sqrt{\frac{e^3}{4\pi\varepsilon_0}\beta E_{cath.}} \tag{4}$$

where $E_A(0)$ means the electron affinity without rf field, and β is an experiential field enhancement factor. In the normal conducting rf gun with field amplitude of 24MV/m~39MV/m the second term has been considered [8].

In our present SRF gun, the field on cathode surface is quite low. If the laser injection phase is chosen as $ø=30^o$, the actual electric field on cathode is only E_{cath} =2.5 MV/m. Thus in this paper this term is neglected. If the cavity gradient is greatly improved by applying the new 3+1/2 cavity, the thermal emittance increased by the Schottky effect must be included. At the same time, the QE could be higher for the same photocathode surface status because the reduced electron affinity.

Also, the dark current excited by the field emission is about 0.14μA with the cavity gradient of 6MV/m, compared to the photoelectron peak current 1pC/6.37ps=0.16A, we will say this dark current can be ignored for the measurement.

SUMMARY

The thermal emittance of Cs_2Te photocathode in SRF gun is measured. The space charge effect and the rf field contribution are negligible, and the average electron kinetic energy is calculated. The electron affinity is estimated as ~0.4eV for the cathodes with QE ~1% , which is about 0.2eV higher than the fresh cathode.

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