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Invetisgation of Thermal Emittance Measurement in RF Photoinjector *

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Abstract A new method for the measurement of the thermal emittance in the RF photoinjector is introduced in the paper. The measurement are affected mainly by three factors which are the RF effect, the space charge effect and the error of measurement. According to the theory of emittance growth in the RF photoinjector and the simulation, a new method to eliminate the RF effect is proposed for the thermal emittance measurement in RF photoinjector. Error of measurements is not included, and the space charge effect is also ignored on the condition of the low charge operation mode.

Key words thermal emittance, RF photoinjector, FEL, multi-slit methods

1 Introduction

The research on the RF photoinjector has being improved mainly by application requirements of FELs. In the X-ray FEL SASE projects, beams with its pulse width less than 1μm and peak current of many kAs are required. High quality beam is prominent to optimize the system performance for the coming X-ray FEL projects such as TESLA[1] and LCLS[2,3]. So developing new technique for beams of low emittance and low energy spread for the short-wavelength FEL[4] applications is urgent. The RF photoinjector can produce high quality beams, and it is possible to conserve the quality along the beam line by matching components carefully[5,6]. Some investigations have been carried out, especially simulations for this purpose. Results of several simulations show that the normalized emittance of lower than 1μm with the beam charge of 1nC can be achieved on the 1.3GHz RF photoinjector at the moderate gradient 40MV/m, and in general cases thermal emittance isn't included. Because of very small emittance required, the influence of the thermal emittance can't be completely ignored. Therefore, the thermal emittance measurement is very important for the further RF photoinjector development.

2 Theory for thermal emittance

According to the definition of rms emittance, the beam normalized emittance of RF photoinjector can be expressed as[7]:

$$\varepsilon = \sqrt{\varepsilon_0^2 + \Delta\varepsilon^2}, \tag{1}$$

Where ε_0 is the thermal emittance in the cavity, $\Delta\varepsilon$ is the emittance growth due to the RF effect and the space charge effect

$$\Delta\varepsilon = \sqrt{\varepsilon_{\mathrm{RF}}^2 + \varepsilon_{\mathrm{SC}}^2}.$$

The thermal emittance in the high electric field in the cavity can be estimated by[8]:

$$\varepsilon_{\mathrm{th}} = \frac{R}{2\sqrt{3}}\sqrt{\frac{h\nu - e\phi'}{m_0 c^2}}, \tag{2}$$

where R is the laser radius on the cathode, $h\nu$ the photo energy of the laser ($h\nu = 4.66$eV, for the fourth harmonic of Nd:YAG laser), and $e\phi'$ the work function of the cathode.

There exists a very strong electric field near the surface of the cathode in the cavity, and the field can be treated as constant when the pulse duration of the laser beam is significantly less than the RF period [9]. Due to the Schotky effect, the work function will decrease as following[10]:

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$$e\phi' = e\phi - e\sqrt{\frac{eE\sin\varphi}{4\pi\varepsilon_0}} =$$

$$e\phi - 3.79\sqrt{E\sin\varphi}\times 10^{-5}\quad(\text{eV}), \qquad (3)$$

where $e\phi$ is the work fuction of the cathode, E(MV/m) is the amplitude of electric field near the surface of the cathode , φ is the injecting phase of the laser beam relative to the microwave.

For a Cs_2Te cathode, its work function is: $e\phi = 3.7$eV. When the injecting phase is between 50 and 80 degrees[9] and electric field $E = 40$MV/m, the thermal emittance is approximated to:

$$\varepsilon_{\text{th}}(\mu\text{m}) \approx 0.5R(\text{mm}). \qquad (4)$$

In the following discuss, the injecting phase is fixed at 55 degrees. And the electric field near the surface of the cathode is treated as constant, so it is the same case with the thermal emittance. From Eqs. (2) and (3), the thermal emittance without the electric field effect is approximated to:

$$\varepsilon^0_{\text{th}}(\mu\text{m}) \approx 0.3R(\text{mm}). \qquad (5)$$

Comparing these two emittances, the difference exists. But the former is more important and can be measured in the experiment. And $\varepsilon^0_{\text{th}}$ can be obtained by measuring ε_{th}. ε_{th} will be discussed in the following.

For a given gradient and the pulse duration of the laser beam, the relation between ε_{RF} and R is[10]:

$$\varepsilon_{\text{RF}} = f(\varphi, B)R^2, \qquad (6)$$

where $f(\varphi, B)$ is the function of the injecting phase φ and the solenoid field B.

Assuming the electron bean charge is Gauss-distribution, then the emittance growth caused by the space charge effect can be expressed[11]:

$$\varepsilon_{\text{SC}} = \left(\frac{1}{2} - \frac{1}{\pi}\arcsin\frac{1}{\gamma}\right)\frac{m_0c^2}{eE}\frac{Q}{I_{\text{A}}}\frac{c}{5\sigma_r + 3\sigma_z}, \qquad (7)$$

where γ is the beam energy after cavities, E is the amplitude of the electric field on the cathode surface, Q the beam charge, $I_{\text{A}} = 17$kA, σ_r and σ_z are the rms transverse and longitude radius respectively.

From Eq. (7), the space charge effect can be reduced when the beam charge is low and that the RF field is high. So the RF effect is dominant under such conditions. Fig. 1 is the simulated curve of the emittance versus the solenoid field at different injecting phases from 15 to 55 degrees when the space charge effect and the initial emittance are ignored in the L-band RF photoinjecter. The results of simulation show that $f(\varphi, B)$ isn't constant, it changes significantly with different φ and B, and can reach very high values sometimes. So when the thermal emittance is measured in the RF photoinjector, the influence brought by ε_{RF} must be eliminated.

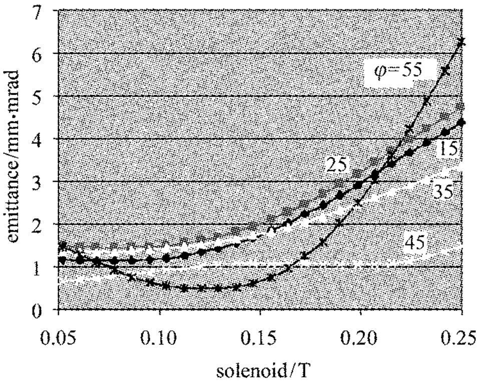

Fig. 1. The simulated curve of the emittance versus the solenoid field B at different injecting phases from 15 to 55 degrees when the space charge effect and the initial emittance are ignored.
Laser spot: radius = 1.0mm, pulse duration = 10.0ps, Gradient: $E = 40$MV/m.

3 Simulation for measurements

When ignoring the space charge effect, from Eqs. (1) and (6), the total emittance can be expressed by:

$$\left(\frac{\varepsilon_{\text{n}}}{R}\right)^2 = \left(\frac{\varepsilon_{\text{th}}}{R}\right)^2 + f^2(\varphi, B)R^2, \qquad (8)$$

where $\left(\frac{\varepsilon_{\text{th}}}{R}\right) = 0.5$ is constant

And the total emittance ε_{n} can be measured downstream the gun by using multi-slit method.

If φ and B are invariable, $f(\varphi, B)$ will also be constant. When the series of measured emittances versus R are measured, the thermal emittance over R can be obtained by using the least square algorithmic.

When E = 40MV/m. φ = 55°, B = 0.10T, and at 0.77m downstream the RF cavity $f(\varphi, B)$ is:

$$f(\varphi, B) = 0.5412\text{mrad/mm}. \qquad (9)$$

Table 1 shows the simulated results of the emittance versus R without and with the space charge effect when the beam charge is 10pC.

Fig. 2 is the simulated curve of $\left(\frac{\varepsilon_{\text{n}}}{R}\right)^2$ versus R^2 without and with the space charge effect when the beam charge is 10pC. From the curve, the relation of thermal emittance and R can be described by:

$$\left(\frac{\varepsilon_{\text{th}}}{R}\right) = 0.5\text{mrad}$$

Table 1.　The simulated emittance versus R without and with the space charge effect.

R/mm	0.1	0.3	0.5	0.7	0.9
ε_n(0pC*) /mm·mrad	0.051	0.171	0.338	0.567	0.864
ε_n(10pC) /mm·mrad	0.149	0.227	0.368	0.585	0.876

* 0pC means ignoring the space charge effect

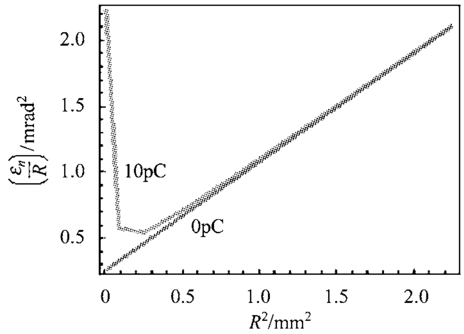

Fig.2.　Simulated curve of $\left(\frac{\varepsilon_n}{R}\right)^2$ versus R^2 without and with space charge effect.

and

$$f(\varphi, B) = 0.5\text{mrad/mm}.$$

From the curve, though beam charge is as low as 10pC, the space charge effect is also important when beam radius is small. Space charge effects can be ignored when $R > 1.0$mm; but space charge effect becomes obvious when $R < 0.5$mm.

4　Measurement method

The multi-slit method is used to measure the emittance in the photoinjector for it can mitigates the space charge effects[12]. The multi-slit method is usually arranged like Fig.3. The metal with many slits stops most electrons of the beam. And other electrons pass through the slits forming many beamlets, drift and hit the screen behind the slits. The images of beamlets on the screen can be used to reconstruct the phase-space with the position of slits. And the emittance of the beam can be calculated basing the phase space.

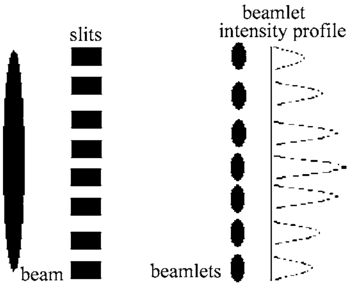

Fig.3.　Arrangement of emittance measurement.

The slits are usually arranged with equal separation w and equal width d. The thickness s of the metal should be as thin as possible when signal-to-noise is enough. After the slits, the space charge effect is significantly mitigated. When ignoring the space charge effect, the movement of electron can be expressed by:

$$x = x_0 + x_0'z, \qquad x' = x_0'. \tag{10}$$

On the screen after the slits, when

$$x_0 < < x_0'L, \tag{11}$$

where L is the distance between the slits and the screen then

$$x_0' \approx \frac{x}{L}. \tag{12}$$

From Eq.(10), the phase space(x_0, x_0') of the beam on the slits can be obtained by the image of beamlets and its position of the slits (Fig.4)[13].

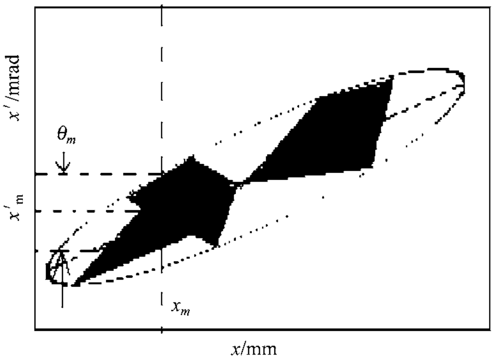

Fig.4.　Phase space of the beam.

Because the shape of the phase space is unknown, the number of the beamlets can't be too small. More beamlets should be employed to reduce the sampling error, the error is:

$$\frac{\Delta\varepsilon}{\varepsilon} \leqslant \frac{1}{N}, \tag{13}$$

where N is the number of the beamlets.

In order to keep the sampling error less than 10%, N should be more than 10, and the beam radius on the slits should also be more than $10w$.

With the reconstructed phase space (Fig.4), the emittance can be obtained by the following equation[12]:

$$\varepsilon_{\text{rms}}^2 = (\beta\gamma)^2 \left\{ \frac{\sum_m I_m \theta_m^2}{\sum_m I_m} \cdot \frac{\sum_m I_m x_m^2}{\sum_m I_m} \right\} +$$

$$(\beta\gamma)^2\left\{\frac{\sum\limits_m I_m x_m{}'^2}{\sum\limits_m I_m}\cdot\frac{\sum\limits_m I_m x_m{}^2}{\sum\limits_m I_m}-\left(\frac{\sum\limits_m I_m x_m{}' x_m}{\sum\limits_m I_m}\right)^2\right\},\qquad(14)$$

where I_m is the relative intensity of mth beamlet, β is the electron velocity and

$$\gamma=\frac{1}{\sqrt{1-\beta^2}}.$$

From the Eqs. (13), (14) and Fig.4, the minimum emittace for the measurement is approximated to:

$$\varepsilon_{\min}=(\beta\gamma)10w\,\theta_{\min},\qquad(15)$$

where $\theta_{\min}=\frac{d}{L}$.

When the electron energy is 5MeV, $d=10\mu$m, $w=0.5$mm and $L=1$m, according to Eq. (15), the minimum normalized emittace is 0.5mm.mrad. From Fig.2, the lowest emittance to be measured is 0.5mm.mrad, so the measurement meets the requirements.

5 Conclusion

Through the simulation, it is possible to eliminate influences of the RF effect and the space charge effect when measuring the thermal emittance in the RF photoinjector. But in the experiment, there are many other factors affecting the results, such as measurement's error, stability of the facility, and etc.

References

1 Rossbach J et al. Nucl. Instrum. Methods, 1996, **A375**: 269—272

2 TESLA Technical Design Report. March, 2001

3 LCLS Design Study Report. Report SLAC-R-521, 1998

4 Bonifacio R, Pellegrini C, Narducci L. Opt. Comm., 1984, **50**: 373—376

5 Rosenweig J B, Seafini L. Phys. Rev., 1994, **E50**: 1599—1602

6 LI Zheng-Hong et al. High Power Laser and Particle Beam, 2000, **3**: 273—275(in Chinese)
(李正红等. 强激光与粒子束,2000,3:273—275)

7 Gierman S M. Doctor Thesis, UCLA 1999

8 Serafini L, Rosenzweig J B. Phys. Rev., 1997, **E55**: 7565—7590

9 LI Zheng-Hong. CAEP RF Photoinjecter. Mianyang: CAEP, P. H. D Thesis, 2000(in Chinese)
(李正红. CAEP光阴极注入器. 绵阳: 中国工程物理研究院研究生部,博士论文,2000)

10 Kim K J. Nucl. Instrum. Methods, 1989, **A275**: 201—216

11 Kim K J. Nucl. Instrum. Methods, 1997, **A275**: 322—350

12 Lawson J D. The Physics of Charged Particle Beams. 2nd ed. New York: Oxford University Press, 1988

13 Steffen K G. High Energy Beam Optics, DESY, 1966

14 XING Qing-Zhi et al. HEP&NP, 2003, **27**(7): 628—633(in Chinese)
(邢清志等. 高能物理与核物理,2003,**27**(7):628—633)

光阴极RF腔注入器中热发射度的测量研究*

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摘要 论文介绍RF腔光阴极注入器中热发射度的测量方法,在注入器中有三个因素影响热发射度的测量,它们是:射频场效应、空间电荷效应和发射度测量误差。在注入器出口处,电子束发射度由:热发射度、射频场效应引起的发射度增长和空间电荷效应的发射度增长三部分组成。论文从注入器中发射度增长理论和模拟出发,给出了一个能够消除射频场效应和空间电荷效应的热发射度测量方法.

关键词 热发射度 RF腔光阴极注入器 自由电子激光 多缝测量法

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