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EMITTANCE AND BUNCH LENGTH MEASUREMENT OF ELECTRON BEAMS FROM THE NSRRC PHOTOCATHODE GUN

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Abstract

A high brightness photo-injector is under development for single pass FEL research at NSRRC. The gun test facility (GTF) equipped with a photocathode rf gun a compensation solenoid, a S-band high power pulse klystron as well as a UV driver laser has been constructed for testing the photocathode rf gun. The gun is fabricated in house and being tested at the GTF. Since the transverse emittance is a key property of the electron beam from the rf gun, multi-slit method is used to characterize the transverse emittance of the electron beam. Another key property of the electron beam is bunch length. An S-band three-cell deflecting cavity is designed to measure the bunch length. The setup and results of emittance measurement as well as the structure design of the deflecting cavity is reported in this contribution.

INTRODUCTION

The aim of the high brightness injector project is to develop a high brightness photo-injector for the proposed NSRRC VUV FEL. The injector system consists of a photocathode rf gun with compensation solenoid, three 5.2m linac, one 3m linac and a bunch compressor which can produces energy 325 MeV with slice emittance 0.8 mm-mrad. The detailed design has been discussed in these proceedings [1]. Before installing the injector system, we set up a gun test facility to test the performance of the rf gun inside the booster area at NSRRC. It is able to generate 2.3 MeV, 250 pC, 8 ps bunch duration beams at rf peak field 58 MV/m [2].

MULTI-SLIT MEASUREMENT

Measuring the transverse beam emittance of beams is of fundamental importance. Due to the space charge effects, the traditional method of measuring the beam profile as a function of the strength of a focusing element is not applicable [3]. Single slit or multi-slit technique can be used. Another issue in the emittance measurement is the stability of the photocathode drive laser. Fluctuations in the energy and size of the drive laser cause shot-to-shot fluctuations in the beam size and emittance. For this reason, single shot measurement by multi-slit method is preferable.

A typical setup for the slit measurement is shown in Fig.1. The space charge dominated electron beam passes through a multi-slit mask. The beam is split into several beamlets which are emittance dominated. Beamlets then drift to a detector screen, whose intensity distribution at downstream can be measured to give the phase space distribution of the beam. The width of each beamlet gives a measure of the width of the transverse momentum distribution at each slit, and the centroid of the beamlets gives the correlated offset of the momentum distribution at each slit.

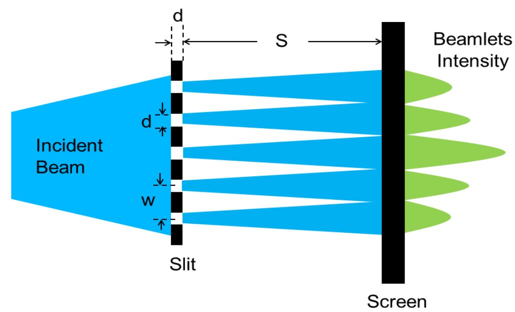

Figure1: Typical setup for emittance measurement.

By measuring the intensity, width and centroid of each beamlet image on the screen, the emittance could be determined. If the screen response is linear, the light intensity integrated over any beamlet spot on a screen is then directly proportional to the number of particles in the beamlet. The rms unnormalized emittance is given by [4]:

$$\varepsilon^2 = \frac{1}{N^2}\left\{\sum_{j=1}^{k}\left[n_j(x_{sj}-\bar{x})^2\right]\sum_{j=1}^{k}\left[n_j\sigma_{x'j}^2 + n_j(\overline{x'}_j-\overline{x'})^2\right] - \sum_{j=1}^{k}\left[n_j x_{sj}\overline{x'}_j - N\bar{x}\overline{x'}\right]\right\}$$

where k is the total number of slits, nj is the total number of particles in the beamlet from the jth slit, x_{sj} is the position of the jth slit on the slit mask, $\bar{x}$ is the mean position of all the beamlets, $\overline{x'_j}$ is the mean divergence of the jth beamlet, $\overline{x'}$ is the mean divergence of all beamlets, and $\sigma_{x'j}$ is the rms divergence of the jth beamlet.

Slit Design

The purpose of multi-slit method is to separate the beam into many beamlets. The intensity distribution of beamlets can be measured at some point downstream. In order to reduce the space charge effect and get good resolution of image on the screen, some criteria for the physical size of the slit need to be considered. Since electron beams are space charge dominated after the RF

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gun, we should compare the space charge and emittance terms in the envelope equation for a round beam in drift space:

$$\sigma_0'' - \frac{\varepsilon_n^2}{\gamma^2\sigma_0^3} - \frac{2I}{\gamma^3 I_A \sigma_0} = 0$$

Where σ_x is the beam envelope, ε_n is the normalized emittance, γ is the Lorentz factor, I is the peak current and I_0=17 kA is the Alfven current. The third term is the space charge dominates term and the second term is emittance dominated term. The ratio of these two terms gives a measure of the space charge effect, which i expressed as:

$$R_0 = \frac{2I\sigma_0^2}{I_A \gamma \varepsilon_n^2}$$

When R_0 is much less than 1, the electron beam is emittance dominated and can be analyzed with by the linear transport theory. This guarantees the space-charge force contribution to transverse momentum is insignificant.

The depth of the mask should be thick enough to stop the electron beam or scatter it sufficiently so that it does not affect the measurement of the beamlets. The stopping length of the electron in a material is:

$$\frac{E}{dE/dx} = \frac{E[MeV]}{1.5[\mathrm{MeV}cm^2g^{-1}]\rho[gcm^{-}]}$$

where ρ is the material density and E is the energy of electrons. In our experiment, the electron energy is about 2.3 MeV and we chose stainless steel as the material of the slit mask, so the stopping length should be large than 1.92 mm. Therefore the thickness of the mask, L, is 2 mm. Once we have determined the thickness, the width and slit separation, can be determined by considering the following [2]:

(1) The angular acceptance of the slits must be large than the beam divergence angle :

$$\frac{d}{2L} > \sigma'$$

(2) The rms size of the beamlet on the screen must be large than its size at the slit :

$$\sqrt{12}L\sigma' > d$$

(3) The rms beamlet width on the screen should be smaller than the separation between two neighbors on the screen to avoid beam overlapping on the screen:

$$2S\sigma' < w$$

According to the above criteria, the final design of the slit is shown in the Table.1

Table1: Specifications of the Slit Mask

Parameter	Spec.
The thickness of mask (L)	2 mm
The width of slits (d)	50 µm
The separation of slits (w)	250 µm
The distance between slit and screen (S)	3.5 cm

Experiment Setup

The experiment setup is shown in Fig.2. The slit mask is located at 110 cm downstream from the cathode for sampling the beamlets distribution in the horizontal transverse direction. Because the distance between the slit and the screen is short, we decided to mount a Ce:YAG crystal behind the slit mask on the same holder followed by a 45º mirror for directing the light out a vacuum window to a camera system. Images are acquired using a digital charge coupled device CCD camera (Basler sca640-74gc). The digital output signal is transferred to a PC by gigaE that allows for simpler cabling and long distance data transfer. A2″ diameter focal lens is located approximately 34.9 cm from the screen which focuses the image onto the CCD chip in the camera. The emittance measurement program is implemented as LabVIEW GUI. The program contains image acquisition and processing capabilities. The actuator is controlled by a touch panel computer (AMENS GD035).

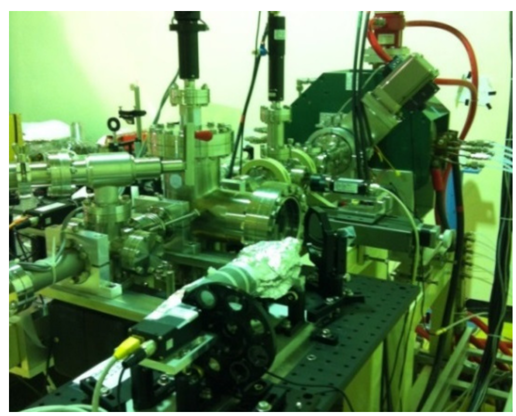

Figure 2: The experiment setup for emittance measurement.

Experiment Result

Fig.3 shows an image of beamlets on the screen obtained by the CCD. In the experiment, the electron bunch is a Gaussian beam with charge 200 pC, bunch length 8ps and beam energy 2.3 MeV. The laser injection phase is 40° and the solenoid field is 1230 gauss. Beamlets image are acquired fifty times continuously. The intensity distribution is integrated over beamlets vertically and is fitted to a sum of Gaussian functions to estimate the size of the beamlets and the overall intensity

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distribution as shown in Fig.4. The measured emittance is around 5.5±0.7 mm-mrad.

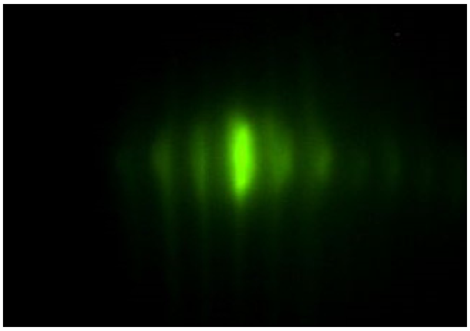

Fig.3: The image of beamlets from the CCD.

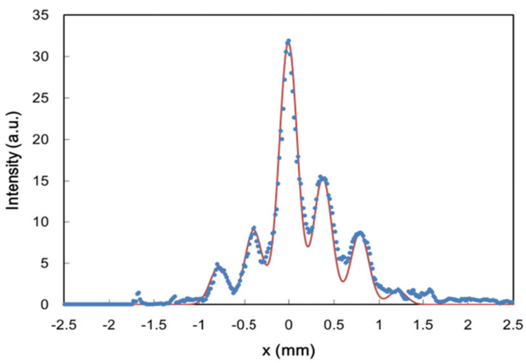

Figure 4: The horizontal beamlets distribution and the fitting curve.

RF DEFLECTING CAVITY DESIGN

In order to measure bunch length, we decided to use rf deflecting cavity, which can convert the longitudinal distribution to transverse distribution. The longitudinal bunch profile can be obtained as the transverse profile. Consider a simple drift space of length L between a deflecting cavity and a screen. The bunch length after passing through the deflecting cavity is expressed by [5]:

$$y_b = \frac{\omega_{RF} L L_B V_T}{2cE/e}$$

where ω_{RF} is the angular frequency of the deflecting voltage, L_B is the bunch length, V_T is the peak deflecting voltage, and E is the beam energy in eV units. We want to measure bunch length at after the rf gun and the first linac section in our system with beam energy 2.3MeV and 95 MeV respectively. According to the above equation, the design parameters are shown on Table.2.

We used the 3D EM simulation code CST for designing an rf deflecting cavity and beam tracking. The cavity is a 3 cell structure operating on π mode, standing wave, dipole (TM110) mode at 2998 MHz. There are two degenerate modes for TM110 mode which can be separated by introducing azimuthal asymmetry. Two circular coupling holes are introduced on the cavity walls between cells to break the degeneracy. The radii of each cell are adjusted to obtain the field flatness while keeping the beam iris dimensions unchanged. Fig.5 shows the magnetic field inside the cavity.

Table 2: Parameters for Deflecting Cavity Design

Parameter	Spec.	
Beam energy	2.5 MeV	95 MeV
Beam size	300 μm	300 μm
Drift length	0.5 m	0.5 m
Deflecting voltage	0.08 MV	3.02 MV

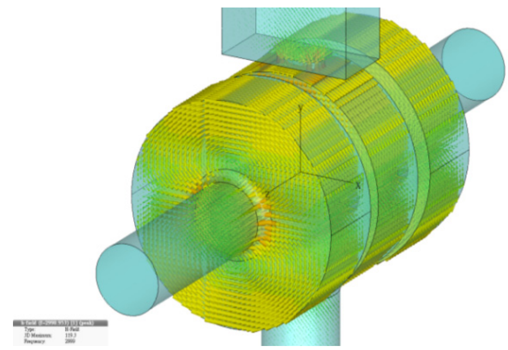

Figure 5: Magnetic field distribution in 3 cell deflecting cavity by CST.

SUMMARY

A multi-slit emittance measurement tool has been designed and manufactured at NSRRC. The main parameters of the slit were chosen to ensure it can be used to measure the emittance of a low energy, space-charge dominated, electron beam. The measurement results indicate that the emittance of the Gaussian electron beam produced by the photocathode RF gun is about 5.5mm-mrad. The investigation of the beam emittance related to different operating parameters of the rf gun will be carried out in the near future. Laser shaping technique will also be tested to reduced beam emittance. We are also developing an rf deflecting cavity for electron bunch length measurement. The design of the 3 cell deflecting cavity is in progress. The cavity will be installed in the high brightness injector system next year.

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