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AN EMITTANCE MEASUREMENT SYSTEM FOR A WIDE RANGE OF BUNCH CHARGES

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Abstract

As a part of the emittance measurements planned for the FEL injector at the Thomas Jefferson National Accelerator Facility (Jefferson Lab), we have developed an emittance measurement system that covers the wide dynamic range of bunch charges necessary to fully characterize the high-DC-voltage photocathode gun. The measurements are carried out with a variant of the classical two-slit method using a slit to sample the beam in conjunction with a wire scanner to measure the transmitted beam profile. The use of commercial, ultra-low noise picoammeters makes it possible to cover the wide range of desired bunch charges, with the actual measurements made over the range of 0.25 pC to 125 pC. The entire system, including its integration into the EPICS control system, is discussed.

1 INTRODUCTION

To fully characterize the high-DC-voltage photocathode gun [1] for the FEL injector at the Jefferson Lab, transverse emittance measurements covering a wide range of bunch charges are planned. Such measurements are necessary both to verify that the gun meets the specifications as well as to quantify agreement between the measurements and particle simulations using PARMELA [2]. In this paper we will describe the emittance measurement system and its performance, while the data is described in another paper [1].

2 DESCRIPTION OF THE SYSTEM

The emittance measurements are performed using a variant of the two slit method. Here, we sample the beam using a movable copper disk with a ~50 μm rectangular slot cut in it. The sampled portion of the beam traverses a drift distance L until it reaches a scanning wire device (see figures 1 and 2; see [1] for more details). The wire scanner (or harp) is the standard design used at the Jefferson Lab consisting of a 50 μm tungsten wire supported on a light-weight fork which is attached to a stepper motor through a bellows. For this application, we use one vertical wire instead of the usual three (vertical, horizontal, and 45 degree) wires to accommodate a large variation in beam diameter. The sampling slit and the vertical wire are aligned parallel to better than 1°.

The stepper motor (200 steps per revolution) is driven by an Oregon Micro Systems stepper motor controller in a VME crate (as opposed to the CAMAC based system used on the main accelerator). The data acquisition system (see figure 2) has been designed to provide extremely low noise and a large dynamic range for the beam signal, and low noise and high accuracy for the position readback (for both the slit and the harp position).

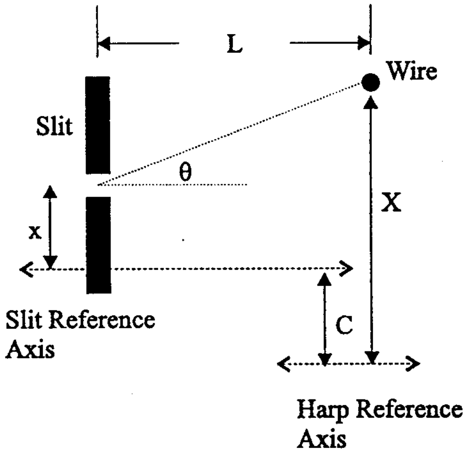

Figure 1 Layout of the emittance measurement system. The beam enters from the left and the transmitted slice hits the wire after drifting a distance L.

We have chosen to use commercial data acquisition devices whenever possible to improve reliability and lower cost. The isolated signal wire from the harp is connected directly to a Keithley 485 picoammeter using a short length of low triboelectric noise coax cable (Belden 9223). The picoammeter has several nice features including autoranging to cover a wide dynamic range, low noise (less than 100 fA), and good linearity over different ranges. The good linearity even applies to pulsed current which allows the emittance measurement to be done with CW or pulsed beam. By connecting the signal wire to the picoammeter with a short length of low noise cable, the opportunity to pick up noise is reduced, and the special cable reduces currents generated while the cable flexes during motion.

The position of the slit and harp wire are measured using a linear potentiometer. We require that the voltage readback be stable enough to resolve positions which are 10% of the wire diameter, or 5 μm. Over the 2.5 inch stroke of the harp there is a voltage change across the potentiometer of about 8 volts. Including the correction for the 45° tilt of the harp this gives a conversion factor of 5.6 μm per 1 mV.

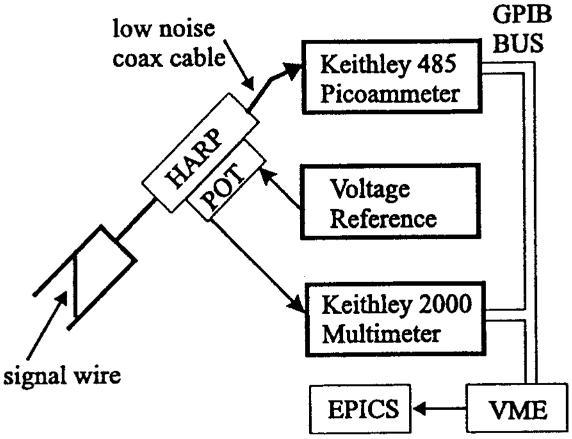

Figure 2 The data acquisition system for the emittance measurement system.

To obtain the desired accuracy in position the voltage readback must be good to within 1 mV. We use a programmable power supply (American Reliance LPS-305) with a measured long term stability (over 8 hours) of ±0.1 mV. A Keithley 2000 multimeter is used to monitor the voltage across the potentiometer. It has numerous acquisition modes, with the best compromise between accuracy and speed being the 'medium speed' mode which averages over one power line cycle, thus reducing pickup from the cables. This position measurement system provides an accuracy over a scan of less than ±1 μm which is better than the stated requirement.

The final component of the system is the EPICS software. It consists of three parts: the GPIB software; a sequence to move the slit or harp and collect and store the data; and a high-level application to organize the emittance measurement and perform preliminary analysis. The GPIB communication is accomplished by using an IP-488 chip (Industry Pack by Green Springs, Co.) on a mv162 board located in a VME crate. The system presently controls 4 picoammeters and 3 multimeters with an update rate of 2 to 3 Hz.

The low-level sequencer software controls the movement of the stepper motors and the readout of the position and current information. It moves the device (harp or slit) from a given initial position to a final position by a certain step size and stops for a delay time at each step before taking a data point. The position and current information are stored during the scan and written out to a file upon completion.

The high-level program overseeing the emittance measurement sequence is written using the Tcl/Tk language [4]. The program takes the user through a number of steps to set up the limits for the scans, performs the emittance measurement (displaying the data as it comes in), does a preliminary analysis of the data, and displays a 3 dimensional plot of the phase space.

3 EMITTANCE CALCULATION

The preliminary calculation of the emittance (and α and β) uses the usual rms definitions

$$\tilde{\varepsilon} = \sqrt{\langle x^2\rangle\langle\theta^2\rangle - \langle x\theta\rangle^2}, \quad \alpha = {\langle x\theta\rangle}/{\tilde{\varepsilon}}, \quad \beta = {\langle x^2\rangle}/{\tilde{\varepsilon}}$$

where x and θ are defined in figure 1. At this point, no correction for background or finite slit (wire) effects are included. Since the slit and the harp have different reference axes, the calculation of the angle must include the offset 'C', which can drift with time. Fortunately, this constant cancels out of the equations as seen below. The angle from the slit to the harp is given by $\theta \cong (X - x - C)/L$. Now, define a new quantity z, where $z = L\theta = X - x - C$. The rms quantities for z become

$$\langle xz\rangle = \frac{\sum w_i (x_i - \bar{x})(z_i - \bar{z})}{\sum w_i} = -\langle x^2\rangle + \langle xX\rangle$$

$$\langle z^2\rangle = \frac{\sum w_i z_i^2}{\sum w_i} - \bar{z}^2 = \langle x^2\rangle - 2\langle xX\rangle + \langle X^2\rangle$$

where w is the current on the wire. The offset 'C' cancels out everywhere in the calculation. Substituting the new rms quantities into the original emittance equation gives

$$\tilde{\varepsilon}^2 L^2 = \langle x^2\rangle\langle z^2\rangle - \langle xz\rangle^2 = \langle x^2\rangle\langle X^2\rangle - \langle xX\rangle^2$$

and similarly

$$\alpha = \frac{\langle xX\rangle - \langle x^2\rangle}{\tilde{\varepsilon}\, L} \quad \beta = {\langle x^2\rangle}/{\tilde{\varepsilon}}\,.$$

These calculations are implemented as follows. The slit position is represented by x_j where j ranges from 1 to M (the number of trials). For each trial, the harp position and harp signal are represented by $X_{i,j}$ and $w_{i,j}$ where i ranges from 1 to N(j). Using these definitions we can find the quantities necessary to calculate the emittance, alpha and beta. For example,

$$\langle xX\rangle = \frac{\sum_{j=1}^{M}\sum_{i=1}^{N(j)} w_{i,j}\, x_j\, X_{i,j}}{\sum_{j=1}^{M}\sum_{i=1}^{N(j)} w_{i,j}} - \bar{x}\,\bar{X}$$

with similar definitions for $\langle x^2\rangle$ and $\langle X^2\rangle$.

4 RESULTS

The emittance measurement system has been used to characterize the photocathode gun for the FEL injector over a wide range of bunch charges, with actual measurements taken from 0.25 pC to 125 pC. Figure 3 shows a single harp scan for an average beam current of 310 pA (as measured in a faraday cup), with a noise level below 100 fA, the stated noise level for the picoammeter. To obtain such a low noise floor, a delay time of 1 second was introduced after the wire stopped before taking data to allow the wire and cabling motion to damp out [3].

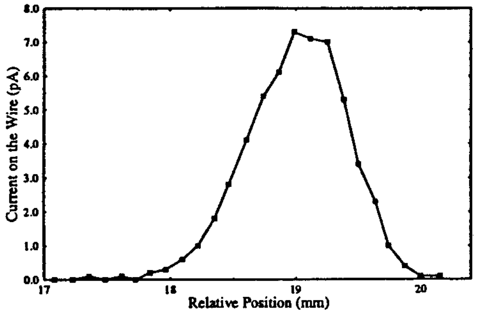

Figure 3 A typical harp scan - the average beam current is 310 pA with noise of less than 0.1 pA.

From the plot, one can estimate that the electronics are sensitive enough to measure currents roughly a factor of 10 lower than this. On the high end, the picoammeter can read to 2 mA, so the measurements could be extended by at least a factor of 100 to over 10 nC per bunch.

Figure 4 shows a three dimensional pseudo-phase space plot of the data. For each slit position (x) a harp scan is performed and plotted (X). The beam parameters can be calculated directly from the raw data as described in section 3.

The emittance measurement system has a number of good features: extremely low noise (< 100 fA); accurate position readback (±1 μm over a scan); a wide dynamic range (< 1 pC to over 10 nC); and it can operate in pulsed or CW mode. On the other hand, the low noise and high accuracy lead to fairly long data taking times: a full measurement including automatic limit determination can exceed 45 minutes. If the scan limits are known, the time for a measurement is reduced to 30 minutes. The low noise and wide dynamic range come at the expense of extended data taking times.

For higher currents where the noise due to cable and wire motion are less important, the measurement process could be speeded up considerably. By setting the delay time from when the wire reaches its position to when the data is acquired to zero and storing the data in the internal memory of the Keithley meters, the total time would be reduced by more than half.

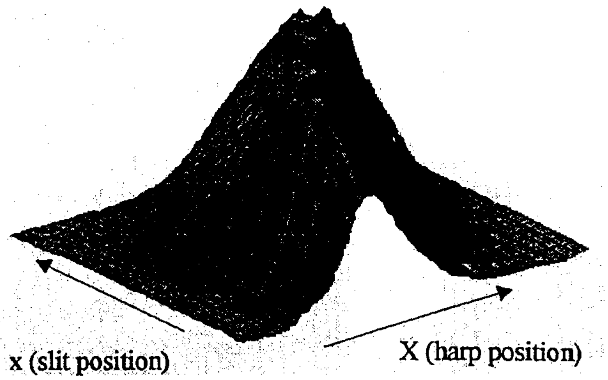

Figure 4 A pseudo-phase space representation of the data. Harp scans for 13 sequential slit positions are shown from front to back

5 CONCLUSIONS

We have developed an emittance measurement system to fully characterize the high-DC-voltage photocathode gun for the FEL injector at the Jefferson Lab. The system allows measurements to be carried out from the emittance dominated to the space charge dominated regimes, with actual measurements performed from 0.25 pC to 125 pC per bunch. The use of commercial low noise, high accuracy measurement devices allows for the required wide dynamic range as well as for reducing costs and development time and increasing reliability.

6 ACKNOWLEDGEMENTS

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