Simulation of a Position-Sensitive Tungsten Pin-Cushion Detector

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Abstract

This paper discusses the results from a simulation of a tungsten pin-cushion detector (TPCD) and its possible use as a position-sensitive gamma ray detector in the GlueX collimator system. The design used in this study consists of eight separate tungsten plates that contain an array of tungsten pins. When gamma rays enter the TPCD, they can produce energetic delta rays known as knock-on electrons. The knock-on electrons leave behind an excess charge on the tungsten plate, which can be measured as a current once a connection to ground has been established. A simulation of a TPCD was done using the physics simulation program GEANT. The simulation tested the effectiveness of the TPCD in measuring the position of a gamma ray beam. In the simulation, a gamma ray beam was directed at different positions on the TPCD and the variation in the current on each of the eight tungsten plates was measured. The data from these simulations were analyzed to find beam position from tungsten plate currents. The magnitude of the detector current was found to be on the order of several hundred pA. The sensitivity of detector current to changes in beam position was quantified. The simulations yielded beam position measurements that had an average error of ±350 μm in a region within 3.0 cm of the beam line. All of this suggests that the TPCD would be well suited for the active collimator system.

The GlueX experiment at Jefferson lab will use gamma rays to excite protons in hopes of producing mesons with unusual J^{PC} numbers, which are called exotic mesons. Observation of exotic mesons will help to confirm the standard model of the strong nuclear force known as QCD. To accurately filter the meson spectrum it will be necessary to use linearly polarized gamma rays. In the GlueX experiment, polarized gamma rays will be produced by collimating a beam of photons created through the coherent bremsstrahlung effect.

In order to maximize the effectiveness of collimation it will be necessary to position the collimator approximately 75 m from the beam source. The large distance between beam source and collimator and the small aperture of the collimator pose a difficultly in reliably centering the beam on the collimator aperture. With proper positioning the amount of energy deposited in the collimator can be kept to a minimum, which reduces secondary particle showering and maximizes the amount of beam flux reaching the experimental target.

The need for precise positioning of the gamma ray beam in GlueX will make the use of a position-sensitive gamma ray monitor necessary. The monitor will have to provide a real-time measurement of the beam position accurate to within a fraction of a millimeter. The simplest design of a position-sensitive detector involves using heavy metals to convert a fraction of the incident gamma rays into a secondary particle shower. The electromagnetic shower creates a net charge on the metal, and if connected to ground, this excess charge can be recorded as a current. If the metal is divided into plates, the induced current in each plate will have a sensitive dependence on the gamma ray beam power and position. Once calibrated, this simple detector can be used as a beam position monitor. The magnitude of the induced current is sensitive to detector geometry, and so finding the ideal detector geometry can reduce the cost of data acquisition equipment and improve accuracy.

A team at SLAC[1] has developed a detector geometry to solve a similar problem. The SLAC team has designed a position-sensitive detector that uses tungsten pins as a radiator, which they call the Tungsten Pin Cushion Detector or TPCD. The SLAC detector geometry consists of four arrays of tungsten pins fixed onto four tungsten base plates. The pin geometry of the detector increases the surface area of the tungsten radiator, which increases the emission of knock-ons produced in an electromagnetic shower. The excess charge on these tungsten "pin-cushions" creates a current, the magnitude of which is related to the beam's position and intensity.

This paper investigates the possibility of using a modified version of the SLAC TPCD as a position detector for the gamma ray beam in the GlueX experiment using a GEANT simulation. The simulations test the sensitivity of the detector to changes in beam position and are analyzed to predict beam position for given detector currents.

DESIGN AND LAYOUT

High-Z metals such as tungsten create large secondary particle showers when illuminated by gamma rays. Gamma rays incident on a tungsten plate can create electron-position pairs that, in turn, can create high-energy delta rays also known as knock-on electrons. Experience at SLAC has shown that gamma rays in the few-GeV range create on the order of one knock-on per radiation length in tungsten. Therefore, tungsten makes an ideal radiator for converting gamma rays into knock-on electrons. If knock-ons can escape, a net charge on the tungsten will accumulate, and if connected to ground, a current signal can be measured. Simulations have shown that with a beam power of 1.4 W on a tungsten plate with a circular area of approximately 100.0 cm^2, a current between 1.0 nA and 0.01 nA will be generated.

The geometry of a closely-spaced array of pins attached to a base plate is designed to allow a maximum of knock-ons created in the tungsten to escape. To make an effective detector, the tungsten must cover an area comparable to the area of the GlueX primary collimator, about 300 cm^2. The SLAC team discovered that the ideal geometry for the tungsten emitter segments is an array of evenly-spaced tungsten pins on a solid tungsten plate with an average pin density of approximately 19.0 pins per cm^2 and a pin cross-sectional area of about 0.1 mm^2. The tungsten plates should be roughly 2 r.l. in depth and the pins should be 4 r.l. to ensure a sufficient shower development.

The layout of the tungsten pin-cushion detector used in this design consists of eight tungsten emitter plates, each of which covers an angular range of 60°. Four of the plates cover a radial range of 2.5 mm to 2.5 cm, while the other four cover a range of 3.0 cm to 6.0 cm. To decrease electronic cross talk between the tungsten plates, aluminum walls 1.0 mm in thickness are placed between the plates. The tungsten plates are housed in an aluminum cup and covered by an aluminum plate, which creates a Faraday cage to shield the system from ambient electromagnetic interference. The TPCD is housed inside a boron nitride cup to insulate the detector from ground. Boron nitride was used in the simulation because of its high resistivity and durability in high radiation environments. A picture of the TPCD layout is shown in fig. 1.

Each of the eight TPCD plates is read out separately by a current-sensitive pre-amplifier. Once the relation between beam position and current is known, the position of the gamma ray beam can be determined by measuring ratios between the plate currents. The original SLAC design used four tungsten plates. The design in this simulation test used eight plates instead of four in order to cover more area.

SOFTWARE

The simulations of the TPCD were carried out using HDGeant a physics simulation program developed at UConn. In a HDGeant simulation, 300 million photons were produced by a coherent bremsstrahlung generator and directed on a computer model of an 8-quadrant tungsten pin-cushion detector at different beam offsets from nominal alignment.

The vertical and horizontal coordinates of the beam position on the TPCD (with the origin at the center of the TPCD) was constrained to a square that extended 6.0 cm horizontally and 6.0 cm vertically from the origin. Because of the symmetry properties of the TPCD, covering the square in the upper right hand quadrant gives enough information to describe the current response over the entire surface of the TPCD.

The beam was scanned across a grid of ten thousand points each separated by 0.06 cm. For a total of 300 million simulated beam gammas and 10,000 grid points, approximately 30,000 showers were recorded at each point. Some of the results of this simulation are shown in fig. 2. By comparing the simulated beam spectrum with the calculated flux from a coherent bremsstrahlung source, it was observed that 30,000 gammas corresponds to 7.00 ± 0.04 μs of beam time, assuming 1.0 μA of 12.0 GeV electrons on a 10^{-4} diamond radiator.

Every time a gamma ray creates a shower in the tungsten plates, information about the secondaries is recorded, such as the plate where the secondary was produced and the charge excess created on the plate due to escaping secondaries. The current is obtained by dividing the magnitude of the charge excess by the beam run time of the simulation. These quantities are stored in an ntuple and analyzed by the physics analysis program PAW. In PAW, histograms of beam position versus current for each of the eight plates are made and used to measure the performance of the TPCD.

Given measurements of current $I_j^{(m)}$ from the detector plate j, these simulated plots of plate current versus beam position I_j(x,y) can be used to estimate beam position using the method of maximum likelihood. χ^2 is defined as

$$\chi^2(x,y) = \sum_{j=1}^{8} \left(\frac{i_j(x,y) - i_j^{(m)}}{\delta i_j^{(m)}} \right)^2 \tag{1}$$

$$where \quad i_j^{(m)} = \frac{I_j^{(m)}}{\sum_{k=1}^{8} I_k^{(m)}} \ , \quad i_j(x,y) = \frac{I_j(x,y)}{\sum_{k=1}^{8} I_k(x,y)} \quad and \quad \delta i_j^{(m)} = \frac{\delta I_j^{(m)}}{\sum_{k=1}^{8} I_k^{(m)}}$$

and $\delta I_j^{(m)}$ is defined as the uncertainty in $I_j^{(m)}$. The minimization was done using the CERNLIB package MINUIT. MINUIT employs multiple strategies, including a variable metric Gauss-Newton gradient search and a simplex search, to find the values of parameters which minimize the user-defined χ^2.

SIMULATION RESULTS

The simulations were used for three tests of the TPCD design. The first test measured the magnitude of the observed plate currents to find out the sensitivity requirements for the TPCD data acquisition equipment. The second test of the TPCD measured the sensitivity of the detector to changes in beam position. The final test determined the TPCD's ability to reproduce the beam position from detector currents.

In the first test, the simulated gamma ray beam was directed on the TPCD face and the current in each plate was recorded. Table I shows the values of plate current when the beam is centered on the origin (x,y) = (0.0,0.0) and at (0.2,0.2) cm. The detector current at these points ranged between a maximum of approximately 1.0 nA and minimum of 2.0 pA for the nominal beam power of 1.4 W on the collimator face. Currents in this range will be difficult to detect in a high radiation environment but possible with the use of sensitive pre-amplifiers.

To test beam sensitivity the beam was positioned on the TPCD face at four locations: the origin, (0.05,0.05), (0.1,0.1) and (0.2,0.2). The values of the plate current at each of these locations were used to calculate the deviation d_n from the plate currents at the (0.0,0.0) beam position. Defined exactly, the deviation is given as

$$d_n = \sum_{j=1}^{8} \left(\frac{i_j^{(n)} - i_j^{(0)}}{i_j^{(0)}} \right)^2 \quad where \quad n = 1, 2, 3 \tag{2}$$

$$where \quad i_j^{(m)} = \frac{I_j^{(m)}}{\sum_{k=1}^{8} I_k^{(m)}} \quad for \quad m = 0, 1, 2, 3$$

where $I_j^{(0)}$ =current on the j-th plate for position (0.0,0.0), $I_j^{(1)}$ =current on the j-th plate for position (0.05,0.05), $I_j^{(2)}$ =current on the j-th plate for position (0.1,0.1), $I_j^{(3)}$ =current on the j-th plate for position (0.2,0.2), and $\delta I_j^{(1)}$ =current error on the j-th plate for position (0.05,0.05), $\delta I_j^{(2)}$ =current error on the j-th plate for position (0.1,0.1), $\delta I_j^{(3)}$ =current error on the j-th plate for position (0.2,0.2) The fractional change in the deviation between (0.1, 0.1) and (0.2, 0.2) cm was 2.61±0.42. The values of the deviation for (0.05,0.05), (0.1,0.1) and (0.2,0.2) are shown in Table II. Plots of the plate currents at each of these four beam locations demonstrate the sensitive dependence of the individual plate currents on beam position (fig. 3).

The most important test of the design is the ability to estimate beam position based on the plate currents. This test involved first learning how the current varies with beam position for each plate, and then using this knowledge to find a method for converting currents to beam position. A χ^2 function that depends on beam position and the observed currents can be calculated using Eq. 1 1. The minimum of the χ^2 function with respect to position yields the best estimate of beam position. Estimated values of beam position are determined by running simulations in HDGeant with a known and fixed beam position. The actual and estimated values of beam position are compared in Table III. The correspondence between actual and estimated position is good when $|x|<3.0$ cm and $|y|<3.0$ cm. Outside this region, the beam misses the tungsten pins and the resolution rapidly degrades.

CONCLUSIONS

All simulations discussed in this paper were run using HDGeant and all data analysis was done using PAW and the minimization package MINUIT. There is a high level of confidence that the detector has been faithfully constructed in HDGeant. Currents in the detector are at the expected levels based on experience at SLAC.

TABLE I: A table showing the plate currents for the two beam position (0.0,0.0) and (0.2,0.2).

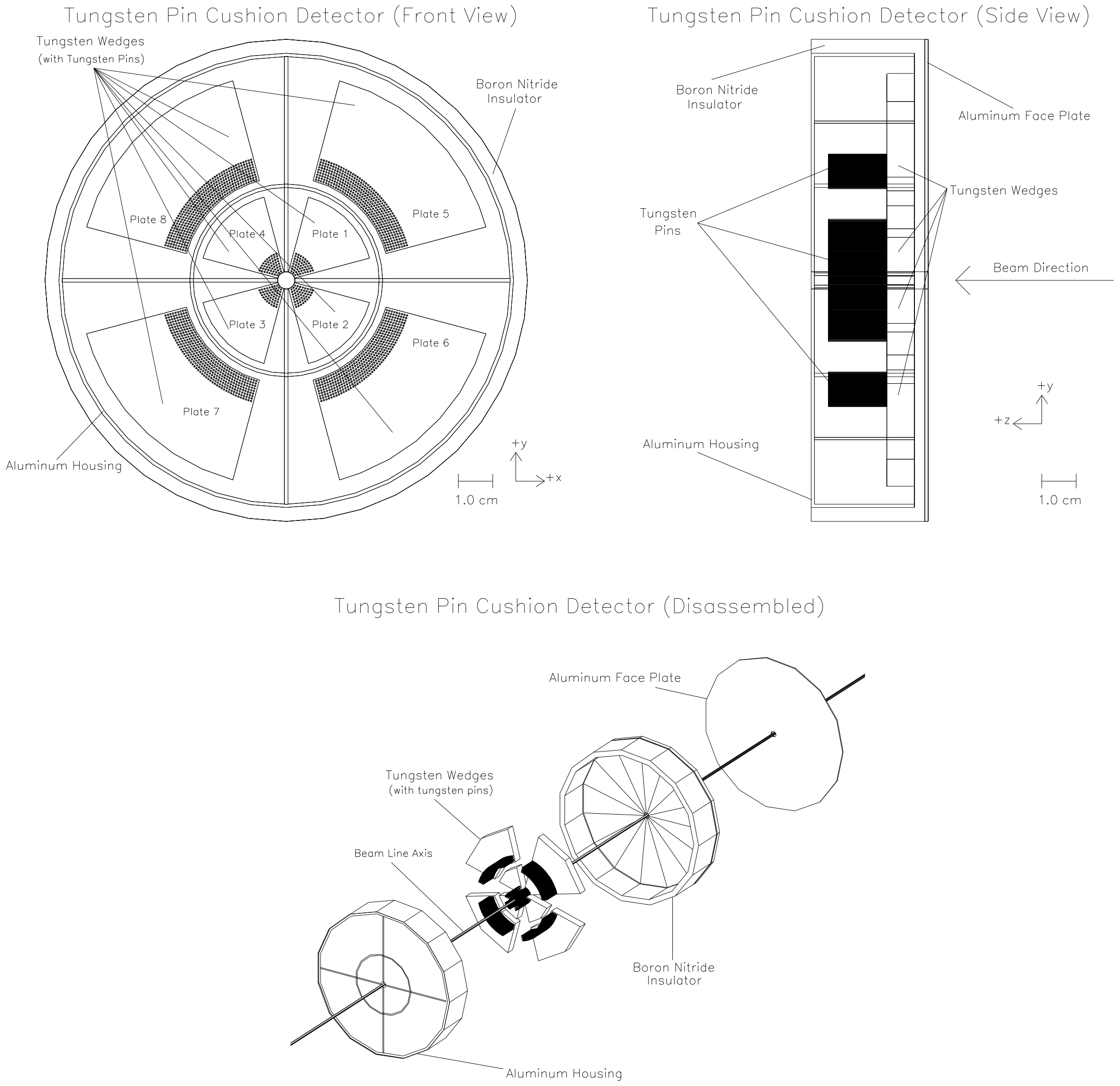
Plate Number	Beam Position (0.0,0.0)	Beam Position (0.2,0.2)
1	$(1.440\pm0.059)\times10^{-11}$	$(1.080\pm0.005)\times10^{-9}$
2	$(1.363\pm0.057)\times10^{-11}$	$(3.947\pm0.030)\times10^{-10}$
3	$(1.485\pm0.059)\times10^{-11}$	$(2.564\pm0.023)\times10^{-10}$
4	$(1.488\pm0.059)\times10^{-11}$	$(4.077\pm0.030)\times10^{-10}$
5	$(2.295\pm0.191)\times10^{-12}$	$(1.097\pm0.013)\times10^{-10}$
6	$(1.888\pm0.184)\times10^{-12}$	$(8.404\pm0.115)\times10^{-11}$
7	$(1.961\pm0.181)\times10^{-12}$	$(6,763\pm0.102)\times10^{-11}$
8	$(2.139\pm0.189)\times10^{-12}$	$(8.379\pm0.116)\times10^{-11}$

TABLE II: A table showing the deviation for the (0.05,0.05) (0.1,0.1) and (0.2,0.2) beam positions, which were calculated in the second test of TPCD performance.

Beam Position	Deviation
(0.05,0.05)	0.198±0.066
(0.1,0.1)	0.422±0.056
(0.2,0.2)	1.521±0.043

The simulations of the TPCD showed that the detector performed well at measuring beam position in the region $|x|<3.0$ cm and $|y|<3.0$ cm. However, the TPCD did not perform well at estimating beam position outside this region. The TPCD demonstrated relatively high sensitivity to small changes in beam position close to the beam axis. This makes the TPCD ideal for precision stabilization of the beam position.

The simulation described in this paper has its limitations. It is not possible to determine the contribution to noise from ambient electromagnetic interference or how effective the aluminum housing is at shielding against it. The simulation cannot help calculate the capacitance between the detector and the collimator system and cannot yield insight on how to avoid ground loops. These questions can only be addressed with a test of an actual TPCD prototype. The construction of a TPCD is planned and should give more insight into its actual performance.



Tungsten Pin Cushion Detector (Front View)

Tungsten Pin Cushion Detector (Side View)

Tungsten Pin Cushion Detector (Disassembled)

FIG. 1: Different views of the tungsten pin cushion detector. Note that the front view shows what number refers to what plate.

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[1] G. Miller and D. R. Walz, Nucl. Instr. and Meth. **117**, (1974) 33-37.

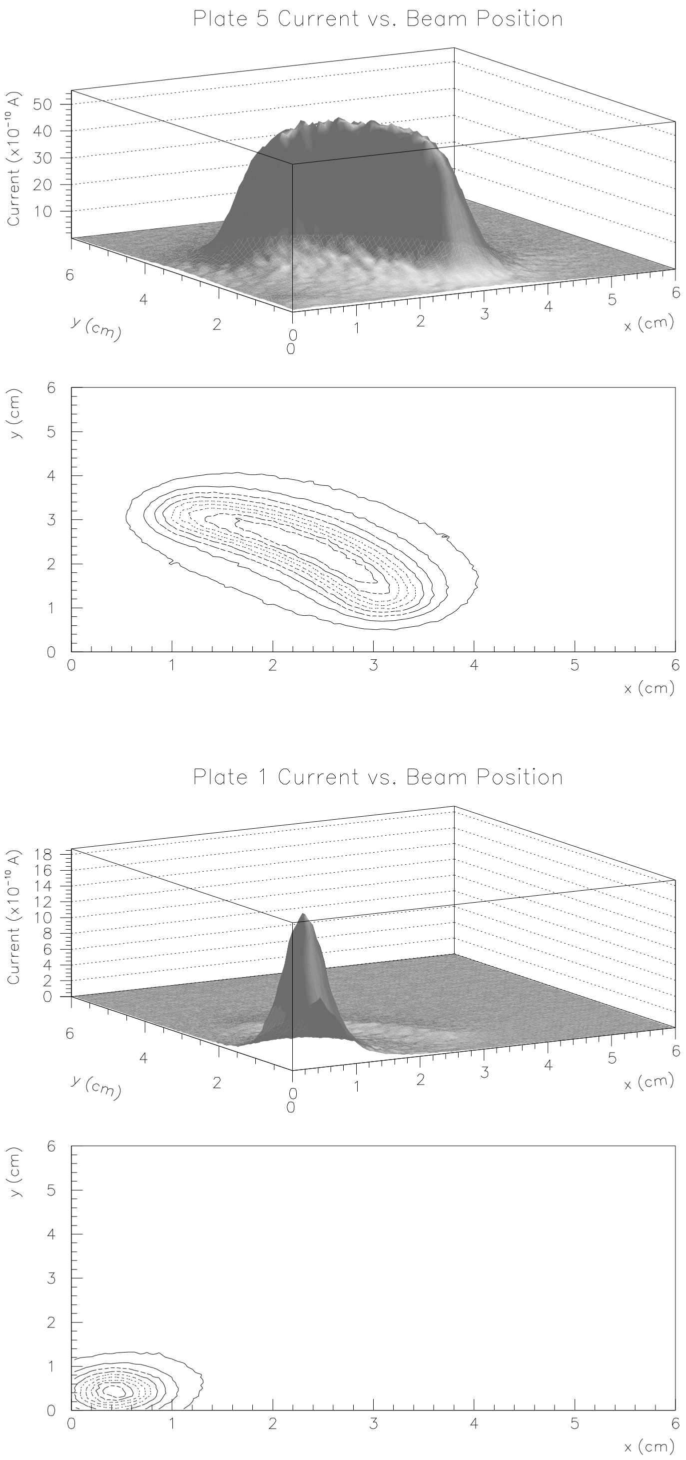

FIG. 2: Graphs of plate current versus x and y beam position for plates one and five. The information from these graphs was used to determine beam position from plate current in the final test of TPCD performance.

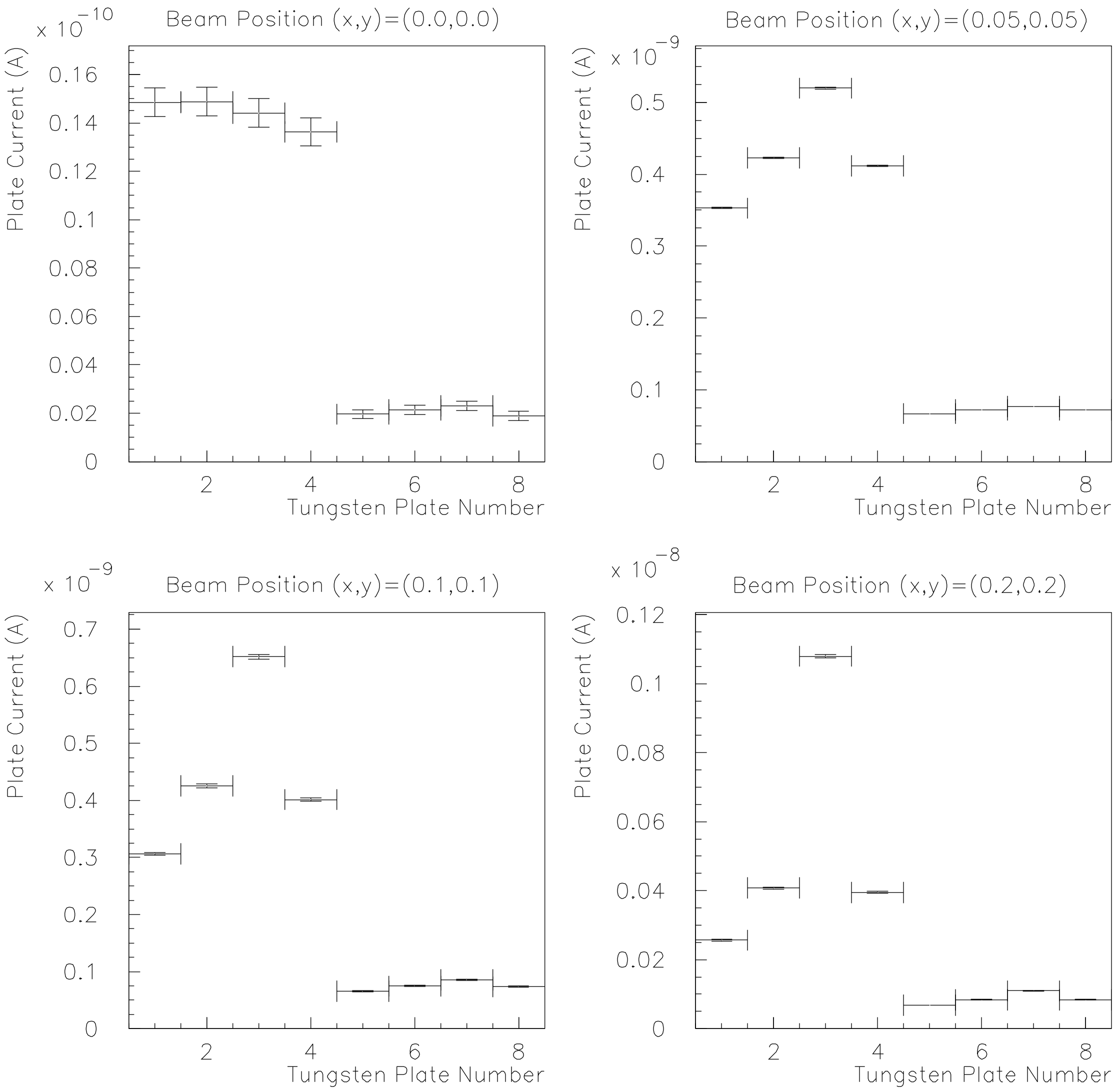

FIG. 3: Comparison of the tungsten plate currents for beam positions (0.0,0.0) (0.05,0.05) (0.1,0.1) and (0.2,0.2).

TABLE III: A table comparing the actual beam position to the position found though the χ^2 minimization procedure.

Beam Position (actual)		Beam Position (simulated)	
x (cm)	y (cm)	x (cm)	y (cm)
0.0	0.0	-0.018(-0.100 +0.096)	-0.043(-0.127 +0.109)
0.05	0.05	0.026(-0.005 +0.005)	0.023(-0.006 +0.006)
0.1	0.1	0.071(-0.018 +0.019)	0.069(-0.020 +0.020)
0.2	0.2	0.175(-0.019 +0.020)	0.181(-0.020 +0.021)
1.0	1.0	0.961(-0.056 +0.069)	0.996(-0.062 +0.068)
3.0	3.0	3.570(-0.087 +0.126)	3.387(-0.061 +0.061)
6.0	6.0	5.832(-0.132 na)	5.981(-0.043 +0.020)
0.1	0.0	0.064(-0.018 +0.020)	-0.034(-0.017 +0.017)
0.2	0.0	0.165(-0.020 +0.022)	-0.029(-0.015 +0.015)
1.0	0.0	1.043(-0.057 +0.036)	-0.034(-0.038 +0.037)
3.0	0.0	3.036(-0.292 +0.095)	-0.031(-0.044 +0.043)
6.0	0.0	5.444(-0.211 +0.162)	-0.029(-0.110 +0.066)
0.2	0.1	0.167(-0.020 +0.023)	0.076(-0.016 +0.017)
1.0	0.2	1.008(-0.038 +0.039)	0.165(-0.040 +0.046)
3.0	1.0	2.912(-0.174 +0.067)	0.866(-0.043 0.121)