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DEVELOPMENT OF A PRECISE 4D EMITTANCE METER USING DIFFERENTIAL SLIT IMAGE PROCESSING

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Abstract

We have developed a highly precise 4D emittance meter for X-Y coupled beams with 4D phase- space (x-x', y-y', x-y', y-x') which utilizes an L-shaped slit and employs novel analysis techniques. Our approach involves two types of slit-screen image processing to generate pepper-pot-like images with great accuracy. One which we call the "differential slit" method, was developed by our group. This approach involves combining two slit-screen images, one at position x and the other at position x + the size of the slit, to create a differential slit image. The other method we use is the “virtual pepper-pot (VPP)” method, which combines x-slit and y-slit images to produce a hole (x, y) image. By combining that hole images, we are able to take extra x-y' and y-x' phase-space. The "differential slit" method is crucial for accurately measuring emittance. Through simulations with 0.1 mm slit width using Geant4, the emittance uncertainties for a 5 nm rad and 0.2 mm size electron beam were 5% and 250% with and without the “differential slit”, respectively. In this presentation, we provide a description of the methodology, the design of slit, and the results of the 4D emittance measurements.

INTRODUCTION

In the accelerator the accurate measurement of 4D emittance, the phase space parameters (xx', yy', xy', yx’) is important optimizing x-y coupled particle beam properties. This measurement has been accomplished through two primary methods: the pepper-pot and dual slit scanning techniques. However, each of these methods comes with its own set of limitations, such as resolution and time-consuming.

The recently developed 4D emittance measurement is so-called “the Virtual Pepper Pot (VPP)” method, which is image processing to generate a pepper-pot-like image using x and y axis slit scan data [1].

However, it is important to note that both the dual slit scanning and VPP methods have uncertainties related to the width of the slits. To further enhance the capabilities of the VPP method, this paper proposes an additional improvement: the “Differential Slit” method. This method employs image processing is utilized to generate virtual narrower slit images by the positions of the slit at x and x + slit width. This approach aims to minimize the uncertainties associated with slit size, enhancing the accuracy of emittance measurements.

We describe the method of “differential slit” image processing with VPP method and show precision efficiency using the simulation.

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SLIT DESIGN

The development and application of an L-type slit scanner, which moves to scan X and Y-axis images in a single-axis movement. This slit-scanner design is intended for electron beam testing at PAL-eLABs (or PAL-ITF) [2]. PAL-eLABs utilizes RF photo-cathode guns to generate electron beams with energy up to 70 MeV.

Beam profile imaging is achieved by capturing images through the slit and subsequently viewing them on scintillation screens and/or Optical Transition Radiation (OTR) detectors. These screens and detectors are positioned at distances of 3.5 meters away from the slit.

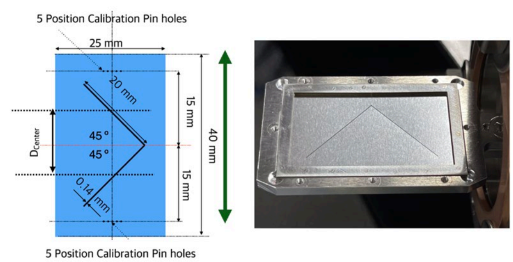

Figure 1: Slit design and manufactured slit scanner.

Two critical aspects of the slit design have been considered: the slit width size and the thickness of the slit plate including its material. Figure 1 shows slit design and manufactured prototype slit. The distance between the X and Y slit centers (D_{center}) is determined considering 15 mm by the beam size to prevent overlapping X and Y slit image in a shot. A thickness and material of slit plate 50 µm stainless steel has been selected to minimize background from 70 MeV beam scattering with plate and slit punching by etching. And 5 pin holes at bottom and top of slit to get in-site position calibration. The prototype slit was succeeded manufacture with 140 µm slit width and 100 µm diameter calibration pinhole.

SIMULATION

The simulation data is generated using the Geant4 [3] and image analyzer OpenCV [4]. Electron interaction with slit and screen are simulated by Geant4. And from energy deposition in the screen to image data by Open CV. The beam condition is used PAL-eLABs [2], 70 MeV and emittance ~10 nm rad and beam is artificially rotate for 4D emittance for the 4D phase space study. And Beam Profile screen using the YAG ($Y_3Al_5O_{12}$) is located 3.5 meters away from a slit. The slit is moved every 20 µm from fully open which is equivalent as 10 Hz beam repetition rate with continuously moving a velocity of 0.2 mm/s. The images vertical resolution is 12 bit which is common resolution of CMOS camera, and they are stored in a scaled 16-bit video format.

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In simulation setup, background noise sources are a critical consideration. two primary sources of background noise are identified: beam scattered by the slit plate and camera sensor noise. beam scattered noise is produce using the Geant4. The noise with 50 µm stainless steel with 3.5 m way screen does not significantly affect by analysis. It is uniformly distributed in the screen and its signal-to-noise ratio (SNR) is smaller than 1/1000. The camera noise was randomly generated in simulation, which is approximately 5% of the camera sensor cavity.

ANALYSIS

Analysis involves four steps: position calibration, the differential slit image process, VPP image process [1], and phase space reconstruction.

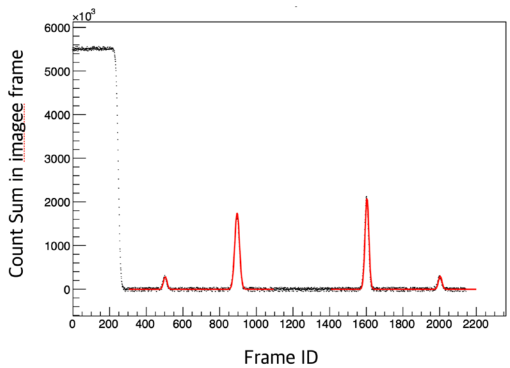

Figure 2: Frame ID vs Sum of count in sensor, left high mesa is signal when slit is opened and four peaks represent calibration pin holes and slits.

In this initial step, position calibration is performed by correlating frame numbers with the sums of signals in the captured images. Figure 2 shows the relationship between frame number and the sum of the signal in the image. In Fig. 2, the highest mesa corresponds to when the slit is fully opened. And the first and last peaks obtained from this calibration process are linked to the position calibration pinhole, enabling the determination of the slit's speed and the matching of frame IDs with positions.

The second step, the **Differential Slit** method is introduced as an innovative approach in this research to enhance precision in data analysis. This method involves the use of two images captured at different slit positions. Specifically, images are selected based on the condition slit position difference is smaller than slit moving step. For this study i^{th} frame and $i{+}7^{th}$ frame is chosen for differential slit image. The image processing is then performed using the minimum pixel pick up using the two images. An example of a differential slit image is show in Fig. 4. Figure 4 a) shows beam particle distribution and slit position green and blue box, and b) and c) are the image on the screen at 3.5 meter away from slit. Figure 3 d) displays the result of the differential slit image obtained by selecting the minimum pixel count, in contrast to images b) and c).

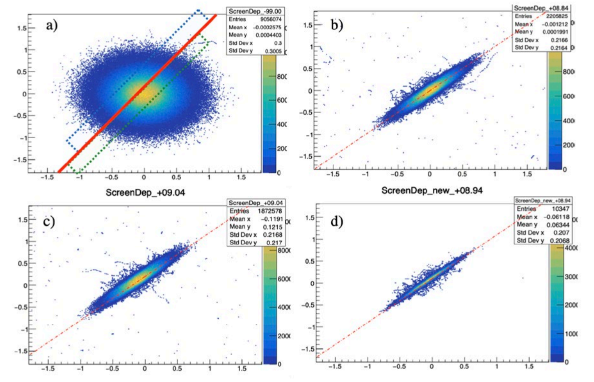

Figure 3: Differential Slit mage processing: a) beam profile at screen and slit position; b), c) screen image by the green and blue dot boxes; d) differential slit image using minimum pixel pick up using the image b) and c).

The VPP Method is employed as the third step in the analysis process. The image processing steps here are similar to those of the Differential Slit Method, utilizing min (cx, cy), where 'c' represents photon counts in the pixel, and 'x' and 'y' denote positions in the x and y axes. Figure 5 describes process of VPP method. It is also using the minimum pixel count selecting. Using the VPP method in combination with the differential slit images yields images that resemble those obtained from a pinhole, enhancing the quality of data.

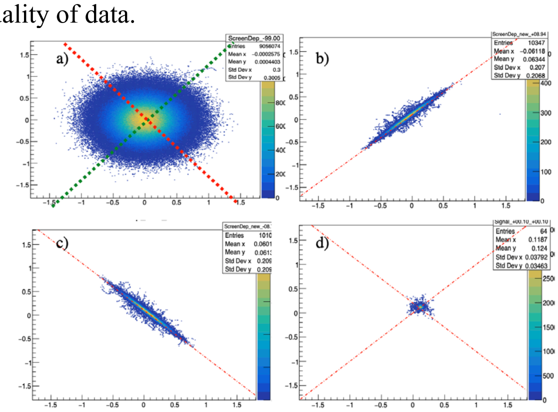

Figure 4: VPP image processing: a) beam profile at screen and slit position; b), c) differential image by the green and blue dot lines; d) pin hole image from the VPP image process using b) and c).

In the final step, phase space reconstruction is carried out which is shows in Fig. 5. This involves using the x and y pinhole images obtained from the previous steps. Phase space was reconstructed. And through 2D-Gaussian fitting, emittance and Twiss parameters are analyzed in the Fig. 5 red ellipse.

RESULT

As a result of these analysis steps, the entire process takes approximately 10 seconds using GPU processing. Table 1 shows the input and reconstructed parameters of each phase-space. In the result, emittance uncertainties from input are less than 10%. But without the difference slit method, the result of emittance uncertainty higher

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than 250%. Overall, these four steps enable a comprehensive and precise analysis of the experimental data, providing valuable insights into the behaviour of the system under study.

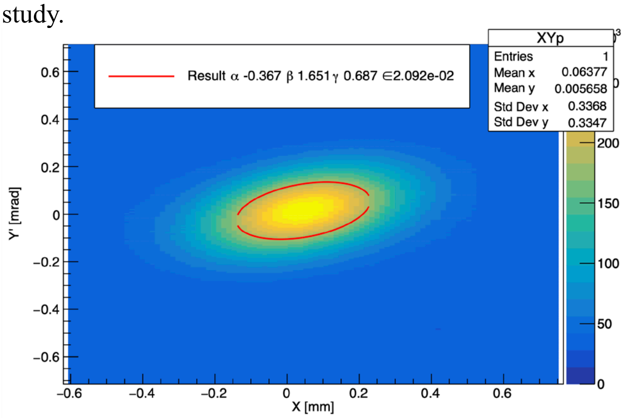

Figure 5: Phase reconstruction and emittance and Twiss parameter analysed by 2D Gaussian fitting.

Table 1: The Result of Input and Reconstructed

Phase Space	α	β	ε
X-X' in	4.467	4.390	7.449
X-X' out	3.871	4.549	7.650
X-Y' in	-0.379	1.377	23.73
X-Y' out	-0.367	1.651	21.24
X-X' in	-0.479	0.826	23.87
X-X' out	-0.467	1.000	22.16
X-Y' in	1.914	2.161	9.137
X-Y' out	1.821	2.496	8.932

EXPERIMENT PLAN

The experiment plan the slit-based analysis method at PAL-eLABs is shown below.

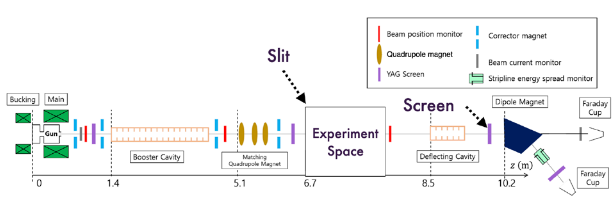

Figure 6: PAL-eLABs lattice layout.

Figure 6 shows the lattice of the PAL-eLABs. The slit will be installed experiment space and the screen will be used at before Dipole Magnet. The x-y coupling beam for 4D emittance such as rotation beam is tuning by bucking coil or skew quadrupole magnet after the accelerator. After the successful measurement. The slit will be applying in Korea-4GSR LINAC to measure x-y coupling.

SUMMARY

The VPP method with L type slit is a significant advancement of measurement time efficiency compared to traditional dual slit scan method. And the differential slit method introduced in this paper represents an additional step forward in improving measurement precision. Only applying one step of analysis without any instrument improves uncertainty from slit width. In this simulation study using 100 µm slit width of 50 µm stainless steel with this method, the uncertainty is dramatically improved from 250% to 10% which is small step but great achievement. Consequently, this method is becoming a crucial technique in any slit-screen experiment.

ACKNOWLEDGEMENTS

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