Hyperemittance measurement with an image processing system

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Abstract:

A method, by adopting the pattern recognition technique with an image processing system, is proposed to realize the measurement of the hyperemittance from a pepper-pot method. An example of employing this method is given to analyze an electron beam and it is demonstrated that it can complete the data taking and processing in no more than 2 minutes.

1.Introduction

Hyperemittance is one of the important parameter for evaluating an accelerator. With it and the current intensity the brightness can be calculated. In the past, hyperemittance is measured by indirect methods[1][2][3], and calculated approximately with ε_x and ε_y, namely $\varepsilon_4=\varepsilon_x.\varepsilon_y/2$. The measurement needs high mechanic alignment accuracy and cause much error due to the form factor χ as the theoretical equation is $\varepsilon_4=\varepsilon_x.\varepsilon_y/\chi$. The pepper-pot method in reality can provide information on 4-dimension phase space density distribution that leads to the hyperemittance plot. However, it requires considerable data taking and processing and is too difficult for people to measure it directly. With the development of image processing technique, it's possible for us to solve the problem. In this paper, we propose a method, by adopting the pattern recognition technique[4], to measure the hyperemittance from a pepper-pot method. An example of employing this method is given to analyze an electron beam of L-band high current injector at CIAE.The measurement of hyperemittance enables us to evaluate more reliably the beam character of accelerator.

2. Principle

The hyperemittance, ε_4, is related to hypervolume V_4 enclosing all particle points in 4-dimension trace space T_4, namely[5]:

$$\epsilon_4=\frac{V_4}{\pi^2}=\frac{1}{\pi^2}\iiiint_\Omega dxdx'dydy'$$

The brightness, B, is the average value of the density in T_4 trace space: $B = I/V_4$

The normalized hyperemittance and brightness are defined as : $\varepsilon_{4n}=\beta^2\gamma^2\varepsilon_4$; $B_n=B/\beta^2\gamma^2$.

The principle of the method is shown in Fig.1. The pepper-pot plate contains a regular array of identical holes over it surface . The sampling beamlets thus defined fall on

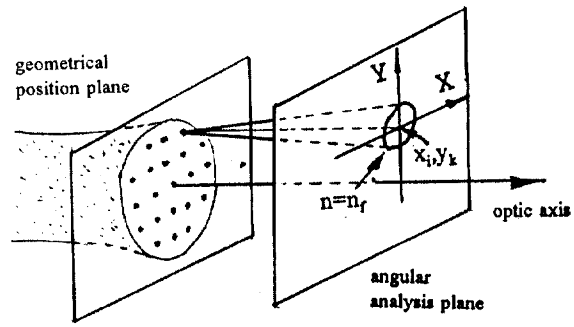


Fig.1 Schematic representation of the principle

the fluorescent screen after a drift distance L, which is situated in the angular analysis plane. If the beamlets don't overlap, the flux incident per unit area of the fluorescent plate at a point (X_J,Y_L) of the spot corresponding to the beamlet from the hole (x_i,y_k) is given by:

$$Js = \rho_4(x_i,y_k,X_J',Y_L').ds/L^2$$

in which $\rho_4(x,y,x',y')$ is microscopic brightness (or density distribution in T_4 trace space) , ds denotes the area of the hole, and $X_J'=X_J/L$,$Y_L'=Y_L/L$. From the formula above , one can conclude: if luminous intensity $n(X_J,Y_L)$ of a point (X_J,Y_l) on the fluorescent plate is linear for the incident density Js, namely : $n(X_J,Y_L) = C\ \rho_4(x_i,y_k,X_J',Y_L')$, then for each hole$(x_i,y_k)$, its corresponding spot on the screen with a brightness distribution will represent the microscopic brightness distribution in gradient space.

In real measurement, the phase volume is defined as that enclosed by the isodensity surface in T_4 trace space. At the first step, we'd measure the area S(x,y) enclosed by isobrightness curve $n=n_f$ on the fluorescent screen (corresponding to isodensity curve $\rho=\rho_f$ in gradient plane).

$$S(x,y)=\iint_{\Sigma f}dx'dy'=(\iint_{\Sigma c}dxdy)/L^2$$

At the second step, integrate S(x,y) on x-y plane where pepper-pot is situated. Then we can calculate the phase volume, namely:

$$V_4=\iint_{\Sigma P}(\iint_{\Sigma f}dx'dy')\,dxdy=\iiiint_\Omega dxdx'dydy'$$

Assume the microscopic brightness distribution in 4-dimension phase space is gaussian distribution, we can derive that for a threshold ρ_f ($\rho_f<\rho_0$), the ratio of current considered to the total current I_0 is[6]:

$$\frac{I_f}{I_0}=1-\frac{\rho_f}{\rho_0}-\frac{\rho_f}{\rho_0}\ln\frac{\rho_0}{\rho_f}$$

3. Method of data processing software realization

When using the pepper-pot method to measure the hyperemittance, one must consider each light spot on the fluorescent screen and calculate the area of every spot from different hole. Therefore the following problems have to be solved in image processing.

3.1 Light spot recognition.

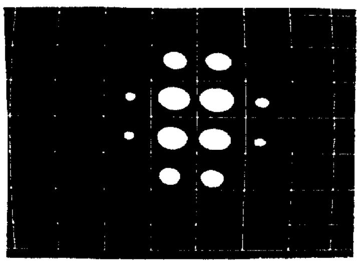


Fig.2 Principle of light spot recognition by divided region

Divide the whole image into a lot of small rectangular region and see if every spot is in the expecting region corresponding to a certain hole on the pepper pot. Using this method we can recognize easily every spot originating from different holes. As shown in Fig. 2.

3.2 Calculation of the area and perimeter of light spot.

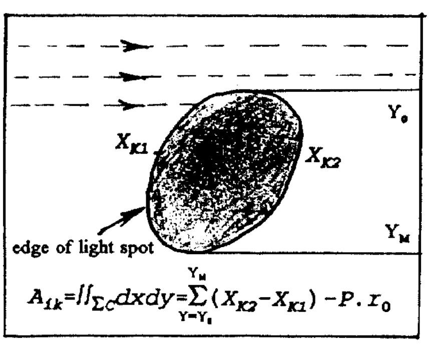


Fig.3 Principle of edge recognition and area calculation

The holes on the pepper pot on the one hand define the system solid angle resolution : $\Delta\omega = (\pi r_0^2+S)/L^2$ (where S is the area resolution of the fluorescent screen and r_0 is the radius of the hole on the pepper pot); On the other hand, the hole makes the light spot grow along the boundary of ideal spot. If the perimeter of the spot is P, then the area increased is $P.r_0$. So that it's necessary to calculate the perimeter of the spot. We have adopted the image recognition technique to solve the problem. After finding the edge of spots, we can not only calculate the perimeter but also the area A_{ik}, as shown in Fig.4, which is precise and fast. By this way, we compress greatly the amount of data processing.

3.3 Hypervolume calculation by dualistic interpolation.

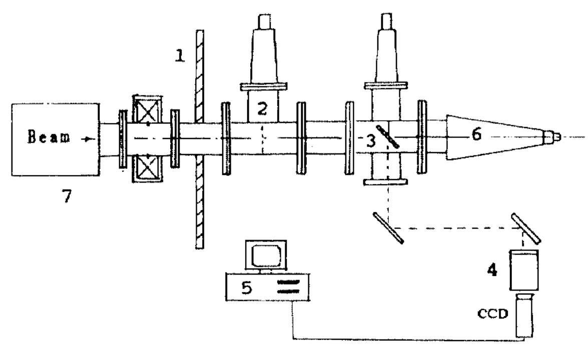
In order to solve the problem of limited hole on pepper-pot (avoid the overlap of spots), we adopt dualistic Laplace interpolation to calculate the gradient space integration S(x,y) in x-y plane. The interpolation formula is:

$$S(x,y)=\sum_{r=i}^{i+2}\sum_{s=j}^{j+2}\left[\prod_{\substack{k=i\\k\neq r}}^{i+2}\frac{x-x_k}{x_r-x_k}\right]\left[\prod_{\substack{l=j\\l\neq s}}^{j+2}\frac{y-y_l}{y_s-y_l}\right]f(x_r,y_s)$$

Then integrate S(x,y) on x-y plane:

$$\epsilon_4=\frac{1}{\pi^2}\iint_{\Sigma P}S(x,y)\,dxdy$$

4. Application of the method



1.Magnetic shielding 2.Pepper-pot Plate 3.Fluorescent screen 4. Lens 5.Image Processing System 6.Faraday cup 7 Buncher

Fig.4 Schematic of measure facility for hyperemittance

At the outlet of the L band high current injector at CIAE, the hyperemittance is measured by the method mentioned above. The current intensity is 80 A, pulse width 30ps and the beam energy is about 2 Mev.The pepper-pot holes are 0.8 or 1. 0 mm in diameter and drilled on a 2.5mm×2.5mm or 3.0mm×3.0mm grid pattern on copper plate 2mm thick[7]. The beamlets through the pepper-pot holes propagate a distance of 120mm to the fluorescent screen which is used to record the pepper-pot images into a CCD camera .

The beamlets through the pepper-pot holes should be emittance dominated. This is justified by estimating the contribution of emittance and space charge to the beamlet's expansion in drift space,using the envelope equation[1]:

$$\left(\frac{dr}{dz}\right)^2-\frac{I_0 e}{\pi\epsilon_0(\gamma\beta c)^3}\ln\frac{r}{r_0}-\frac{\epsilon^2}{r_a^2}=0$$

where I_0 is beamlet intensity, r_a is electron beam radius at pepper-pot plate, r_0 is the hole radius, r is beamlet radius, ε is the transverse emittance. Estimation for our case shows that the third term in the equation is more than two order of magnitude higher than the second term so that the beamlets are emittance dominated.

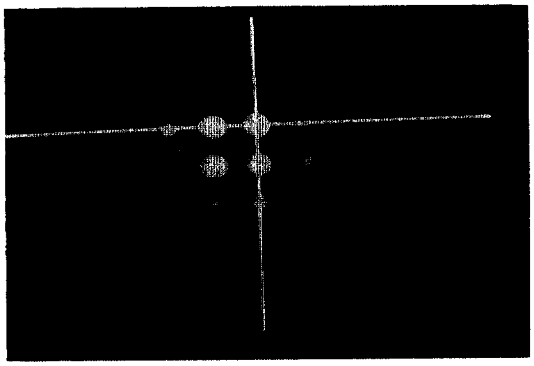


Fig.5 Electron beam "image" on the fluorescent screen

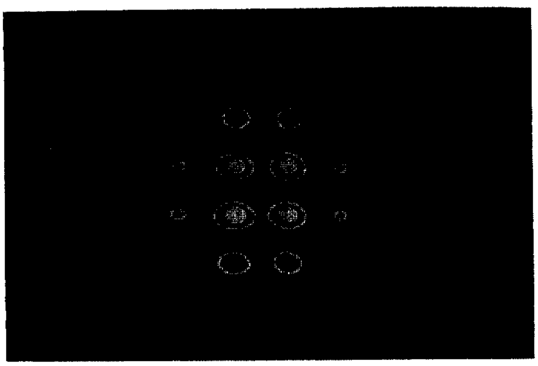


Fig.6 Plot of boundary of the light spot

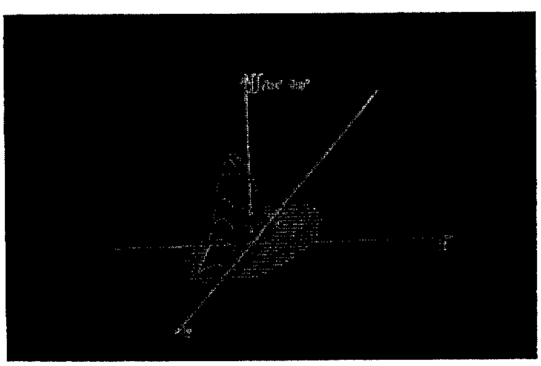


Fig.7 ∫∫dx'dy'—xy plot

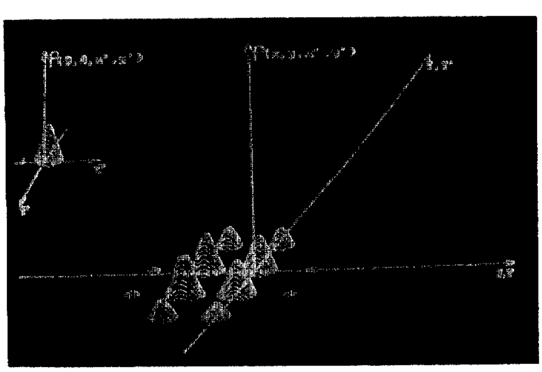


Fig.8 Plot of hyperemittance pattern in T4 trace space

The following is a preliminary result obtained in1993. Fig 5 shows the beam image on the fluorescent screen with a cross cursor indicating the center light spot. Fig.6 shows the found boundary of light spot. Fig.7 shows the ∫∫dx'dy'--xy plot. Fig.8 is the pepper-pot hyperemittance pattern in 4-dimension trace space. The hyperemittance measured at the outlet of the injector is 1.86×10^{-4} (cm-rad)^2, and the brightness is 3.21×10^{8} (A/(m.rad)^2). The measuring error of the hyperemittance is estimated to be less than 12% arising mainly from the error in measuring the area of the light spot.

Two other effects which may cause errors in the measurement should be mentioned. First is the thickness of the pepper-pot plate (2mm) which diminishes the transmitted intensity for large divergence yields a systematic error in measuring the spot area; Second is the influence of slit scattering. These effects[8][9] can be neglected with respect to the error of 12% for accuracy of the measured hyperemittance.

5.Conclusion

The L-band high current injector at CIAE will be completed soon. Our diagnostic system is effective in testing the machine parameters. The successful measurement of hyperemittance will benefit us to evaluate the injector. The method, in principle, can apply to measure the hyperemittance of other particle bunch. It will enable the scientists to evaluate more reliably the beam character of accelerator in different labs.

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