Design of Slit Emittance Meter for 4 D Beam Phase Space Distribution Measurement

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1. Introduction

For high-intensity and high-energy accelerators, the Coulomb force contributes significantly to beam evolution and beam loss generation. The three components required to accurately simulate a linear accelerator are the physics of the accelerating and transport device, the Coulomb force between charges, and the phase space particle distribution of the beam entering the linear accelerator. It is believed that the discrepancy between measurements and simulations is caused by a lack of understanding of the actual initial distribution. We designed a two-slit system to be installed in KOMAC's BTS (Beam Test Stand) to measure the four-dimensional beam phase space distribution using a slit emissivity meter. This paper presents the conceptual design of the slit emittance meter.

2. Methods and Results

In this section, we will focus on.

2.1 Slit Scanner

A beam diagnostic technique called two aperture scanner or slit emittance meter uses two slits installed at a distance L. The beam is directed to its first slit (Slit 1) and chopped into flat beamlets. This beamlet is spread with an initial angular spread. After this, it passes through the second slit (Slit 2) and is measured as the beam current passing through both slits in the collector. By repeating these measurements at various combinations of slit positions, the entire phase space can be reconstructed and the beam emittance can be measured. To reconstruct the phase space of x and y, one pair each must be installed.

The vertical slit measures horizontal projection, and the horizontal slit measures vertical projection.

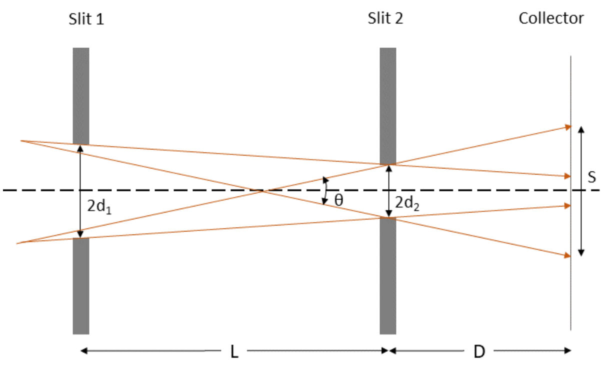


Fig. 1. Two slit scanner.

The notation in the two slit system in Fig 1 is as follows.

d_1, d_2 = half widths of slit 1,2 aperture
L = Distance between two slits
D = Distance between the second slit and the collector

The front slit is used to select a portion of the beam and the back slit is used to measure the angular distribution. The measurement settings corresponding to (x, x') projection are as follows.

x = position of the first vertical slit
x'= *dx/ds* (dx = position difference between two vertical slits, ds = distance between 2 vertical slits)

2.2 Slit Width and Slit Distance

Gaussian beam distribution with normalized phase density equation is

$$f(x,x') = \frac{1}{2\,\pi\varepsilon_0} e^{-\frac{x^2+(\alpha x+\beta x')^2}{2\varepsilon_0\beta}}$$

where α, β= twist parameters at the front slit
ε_0 = real emittance

Due to the geometrical limitation of the two slit system, these are difference between reconstructed and actual emittance and Twiss parameters. And their relations are expressed as

$$\varepsilon_m^2 = \langle x^2\rangle\langle x'^2\rangle - \langle xx'\rangle^2 = \varepsilon_0^2 + \varepsilon_0\left(\beta\frac{d_1^2+d_2^2}{3L^2} + \frac{1+\alpha^2}{\beta}\frac{d_1}{3} - \alpha\frac{2d_1^2}{3L}\right) + \frac{d_1^2 d_2^2}{9L^2}$$

$$\beta_m = \frac{\langle x^2\rangle}{\varepsilon_m} = \beta\frac{\varepsilon_0}{\varepsilon_m} + \frac{d_1^2}{3\varepsilon_m}$$

$$\alpha_m = \frac{\langle xx'\rangle}{\varepsilon_m} = \alpha\frac{\varepsilon_0}{\varepsilon_m} + \frac{d_1^2}{3L\varepsilon_m}$$

where ε_m = emittance measured by two slit system with finite aperture widths d_1 and d_2. The actual emittance is calculated as follows,

$$\varepsilon_0^2 = \varepsilon_m^2 - \varepsilon_m\left(\beta_m\frac{d_1^2+d_2^2}{3L^2} + \frac{1+\alpha_m^2}{\beta_m}\frac{d_1^2}{3} - \alpha_m\frac{2d_1^2}{3L}\right) + \frac{d_1^2 d_2^2}{9L^2}$$

The errors caused by the slit size are as follows,

$$\frac{\varepsilon_m-\varepsilon_0}{\varepsilon_0}=\left(1-\frac{1}{\varepsilon_m}\left(\beta_m\frac{d_1^2+d_2^2}{2L^2}+\frac{1+\alpha_m^2}{\beta_m}\frac{d_1^2}{3}-\alpha_m\frac{2d_1^2}{3L}\right)+\frac{1}{\varepsilon_m^2}\frac{d_1^2d_2^2}{9L^2}\right)^{-\frac{1}{2}}-1$$

Beam extracted from 1 MeV/n RFQ has a beam parameter of emittance = 0.16 pi mm mrad (norm. rms), = 0.2476 mm/pi mrad, = 0.1055 mm/pi mrad, = -2.0601, = 1.0014 obtained from a simulation code.

We intended to keep a margin of measured emittance about 10%. For this margin, we estimated required slit width and distance between two slits. The expected change in measured value of Twiss beta according to slit size is shown in the graph below.

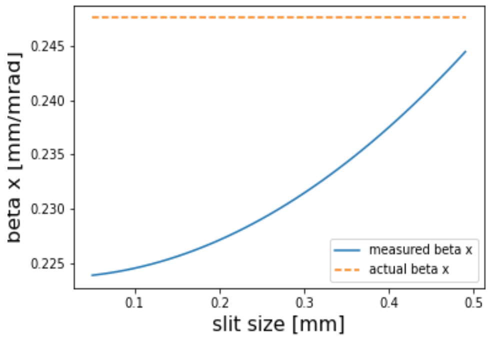


Fig. 2 Expected measured values of Twiss beta x as a function of slit widths

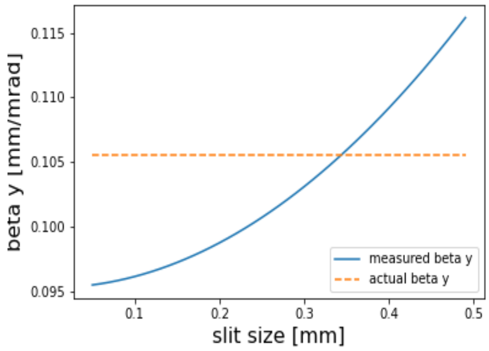


Fig. 3 Expected measured values of Twiss beta y as a function of slit widths

The slit width and distance between slits that satisfy an increase within 10% increase in measured emittance are d_1, d_2= 0.3 mm, L= 500 mm. Assuming d_1, d_2= 0.3 mm, the expected measured value of Twiss alpha according to the distance between slits is shown in the graph below,

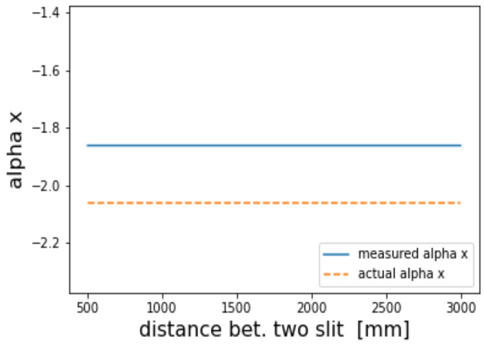


Fig. 3 Expected measured value of Twiss alpha x as a function of slit distance, *L*

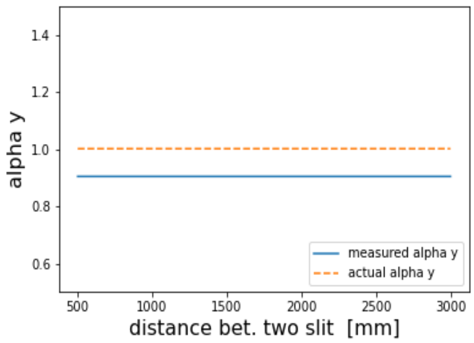


Fig. 4 Measured value of expected Twiss alpha y as a function of slit distance, *L*

From this study, if the beam emittance and twiss parameter are measured by installing two slits of width = 0.3 mm and at the distance L = 500 mm, one can find out the discrepancy between the actual and measured values of beam parameters and can obtain the actual emittance and Twiss parameter by deriving the scaling value.

2.3 Slit-Collector Distance

To estimate the beam size at the collector or Faraday cup location, we calculated the beam penumbra at the final measurement location. Maximum beam size S (penumbra) is defined as follows.

Penumbra $S=(2d_1+2d_2)(L+D)/L-2d_1$

The angle θ in Fig. 1 is $\tan(\theta/2)=(d_1+d_2)/L$. For small angles of θ, a quasi parallel beam is required. For this purpose, a very small (d_1+d_2) or large L value must be set. However, since the acceptance of these systems is $(d_1d_2)/L$, small angle θ requirements can be optimized by reducing d_1 and d_2 and increasing the distance between the two slits.

When $d_1=d_2=$0.3 mm, L = 0.5 m, S and θ are obtained as follows,

$S=0.30$ mm, and θ = 0.0024 rad

2.4 Slit Scanner System in BTS

Slit is designed based on above considerations and also to accommodate maximum beam size of 60 mm.

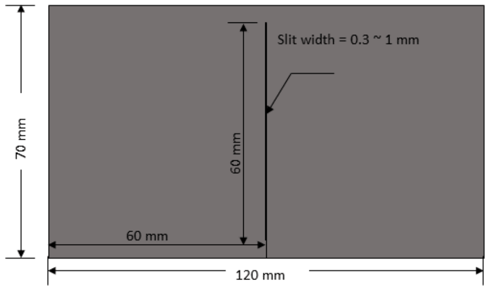
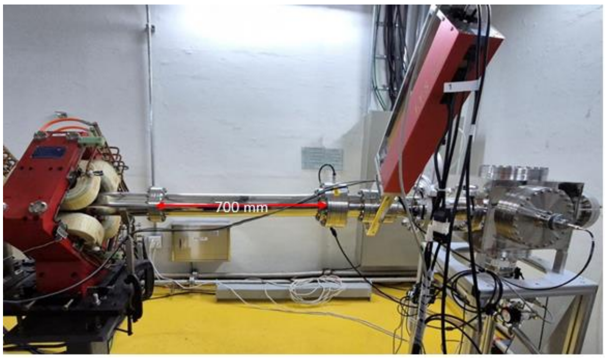
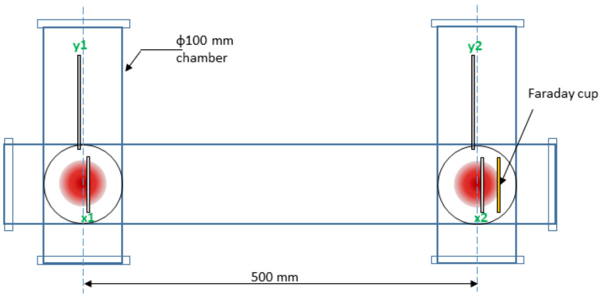


Fig. 5 Slit dimensions



(a)



(b)

Fig. 6 Two slit system will be installed in (a), BTS beamline and its layout is shown in (b)

3. Conclusions

Slit emittance meter is designed to measure 4 D phase space beam distribution. There is the discrepancy between the actual and measured values of beam parameters, so we derived the scaling value to obtain the actual emittance and Twiss parameter from the geometry of the two slit system. It will be installed in the BTS beamline at KOMAC.

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