EMITTANCE MEASUREMENTS IN THE HIRFL BEAM LINE

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ABSTRACT

The transverse emittance in the HIRFL beam line has been measured using two different methods. One is the "Three-Position Method" in which the beam sizes at three different locations in a field-free drift space are measured by Three Secondary Emission Multi-Wire Profile Monitors. The other is the "Three-Gradient Method" in which the beam sizes at a particular location are measured by the profile monitor,as a function of the strength of an upstream quadrupole. The emittance calculations,measurement error analysis, the best beam configuration for making optimum emittance measurements, and results of experimental measurements for both methods in the HIRFL beam line are presented in this paper.

1. INTRODUCTION

The optical matching of various HIRFL subsystem as well as the optimization of beam parameters in HIRFL beam line requires accurate determination of the beam emittance and ellipsoid(σ -matrix) at key poits.The phase space and emittance at the exit of SSC also serve as a figure of merit for its operation. Assuming that particle transfer can be treated with the matrix formalism and no coupling motion exists in each transverse degree of freedom,the transverse phase space of a beam then can be characterized by three parameters which define the emittance boundary ellipse in horizontal or vertical direction. In the HIRFL beam line two different methods were used to measure the beam emittance . One is the "Three-Position Method".[1] The other is the "Three-Gradient Method" .[2-3]

2. ERROR ANALYSES

2.1. Three-Position Method

Consider a beam in a field-free drift space. If there are three measurement poits A, B, and C along the beam line at axial position z_1, z_2 , and z_3 respectively,define the origin of coordinates to be at B so that $z_1 = -l_1$, $z_2 = 0$, and $z_3 = l_2$. The beam sizes at the three poits are denoted by r_1, r_2 , and r_3 . Three profile monitors will be set at the three poits to measure the beam sizes. From theory of transfer matrix the beam emittance (horizontal or vertical) is given by

$$\begin{aligned}\varepsilon = & \{2l_1^2r_3^2[l_2^2r_1^2+(l_1+l_2)^2r_2^2]-l_1^4r_3^4 \\ & -[l_2^2r_1^2-(l_1+l_2)^2r_2^2]^2\}^{\frac{1}{2}}/[2l_1l_2(l_1+l_2)]\end{aligned} \quad (1)$$

The standard deviation of emittance is then calculated from the following formulas:

$$\delta\varepsilon = [(\frac{\partial\varepsilon}{\partial r_1})^2\delta r_1^2 + (\frac{\partial\varepsilon}{\partial r_2})^2\delta r_2^2 + (\frac{\partial\varepsilon}{\partial r_3})^2\delta r_3^2]^{\frac{1}{2}} \quad (2)$$

From Eq.2 we can derive that the $\delta\varepsilon$ is minimum when l_1 is equal to l_2 .

If $l_1 = l_2 = L$, the standard deviation of emittance is

$$\begin{aligned}\delta\varepsilon = & \tfrac{4}{\sqrt{2}\varepsilon}[r_1^2(r_1^2-4r_2^2-r_3^2)^2\delta r_1^2 \\ & +16r_2^2(r_1^2-4r_2^2+r_3^2)^2\delta r_2^2 \\ & +r_2^2(r_1^2+4r_2^2-r_3^2)^2\delta r_3^2]^{\frac{1}{2}}\end{aligned} \quad (3)$$

With the aid of Eq.3 and theory of transfer matrix ,the beam configuration for making optimum emittance measurements can be found. The error in emittance measurements has a great dependence upon the location of a beam waist, the waist size and the separation for the three profile monitors.

The effect on the deviation of emittance measurement by moving the location of the beam waist is shown in Fig.1 ,which is corresponding to different waist sizes and a fixed separation for three profile monitors. Figure 1 illustrates that it is alwayse best to have the waist near the center measurement poit ($z_0 = 0$),although for some r_0 this requirement is not as critical. Figure 1 also indicates that for fixed z_0 ,there is a dependence of $\delta\varepsilon$ on r_0 .This is shown explicitly in Fig.2 , which gives the relation between $\delta\varepsilon$ and r_0 for z_0 =0, and several different L . The optimum value of beam size at waist r_0 as a function of L is shown in Fig.3 . Finally, with r_0 at its optimum value and $z_0 = 0$, the minimum deviation of emittance measurement as a function of L is displayed in Fig4 .

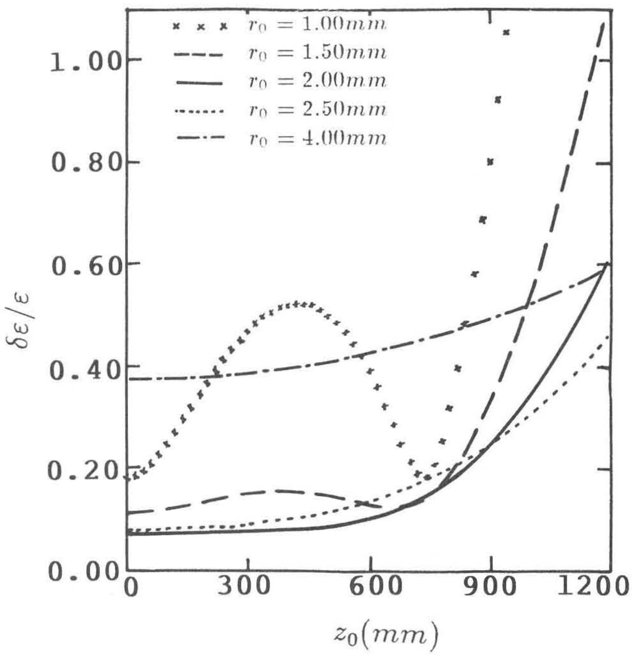

Fig.1. Deviation of emittance measurement $\delta\varepsilon$ versus location of beam waist z_0, for different waist sizes r_0. Here $L = 750.0mm$ and $\varepsilon = 8.00mm\ mrad$ The measurement error of the beam size at each poit is taken to be $\delta r = 0.13mm$ from the profile monitor and other consideration.

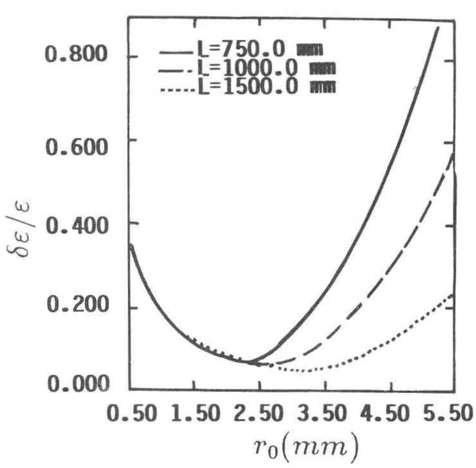

Fig.2. Deviation of emittance measurement $\delta\varepsilon$ versus waist size r_0, for different profile monitor separation L. Here $z_0 = 0.00mm, \varepsilon = 8.00mm\ mrad, \delta r = 0.13mm$.

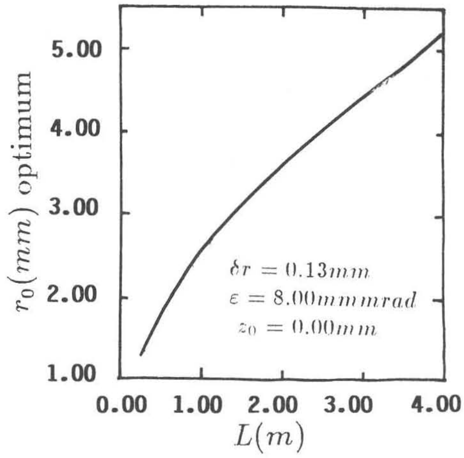

Fig.3. Waist size r_0 for optimum emittance measurement versus profile monitor separation L.

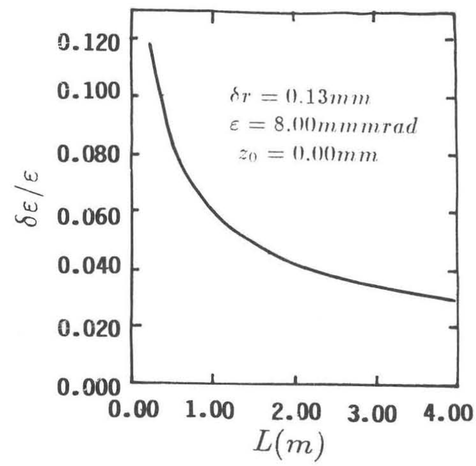

Fig.4. deviation of emittance measurement $\delta\varepsilon$ at optimum waist size r_0 and optimum waist location z_0 , as a function of profile monitor separation L.

2.2. Three-Gradient Method

Consider a section of a beam line in which a quadrupole is separated from a downstream profile monitor by a field-free region. In beam transfer principle,any three independent settings of the quadrupole are corresponding to three independent beam sizes at the profile monitor and three different transfer matrixs , and this can be used to solve for the three unknowns σ_{11} , σ_{12} , and σ_{22} , from which the beam emittance can be calculated. But in practice the emittance measurement is sensitive to the accuracy in determining the beam size. A series of profile measurements are taken by varying the strength of the quadrupole so that we could try to solve for those three unknowns by the least square method.

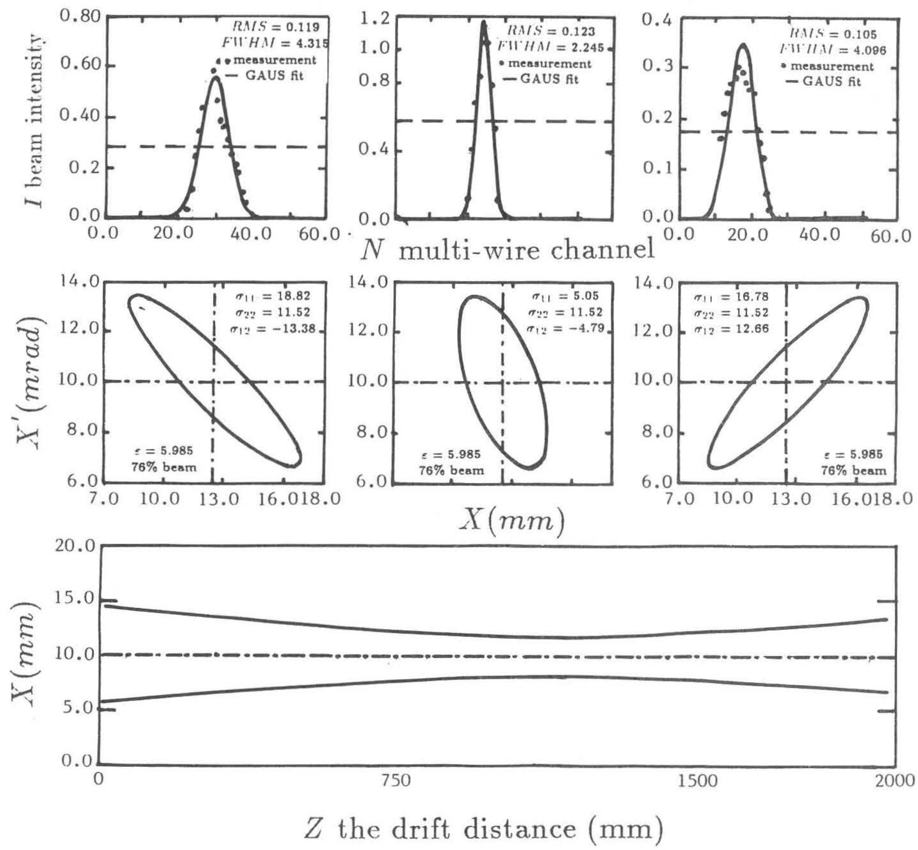

Fig.5. Display of emittance measurement results in horizontal direction.top: beam profiles at the three locations,middle:the beam ellipses, bottom: beam envelope in the measurement chamber.

With the use of the least square method and standard propagation of error calculations, the error in the emittance measurement is given by

$$\begin{aligned}\delta\varepsilon = & (\sigma_{11}^2\delta\sigma_{22}^2 + \sigma_{22}^2\delta\sigma_{11}^2 + 4\sigma_{12}^2\delta\sigma_{12}^2 \\ & -4\sigma_{11}\sigma_{12}\rho_{1222}\delta\sigma_{12}\delta\sigma_{22} \\ & +2\sigma_{11}\sigma_{22}\rho_{1122}\delta\sigma_{11}\delta\sigma_{22} \\ & -4\sigma_{12}\sigma_{22}\rho_{1112}\delta\sigma_{11}\delta\sigma_{12})^{\frac{1}{2}}/2\varepsilon\end{aligned} \tag{4}$$

where $\varepsilon = (\sigma_{11}\sigma_{22} - \sigma_{12}^2)^{\frac{1}{2}}$
in which $\delta\sigma_{ij}$ is the error in determination of σ_{ij} and ρ_{ijkl} is the coefficient of interrelation between σ_{ij} and σ_{kl} .

3. EXPERIMENTAL RESULTS

Emittance measurements in the HIRFL beam line ,based on the above analyses, are made with an automatic emittance measuring system. In order to determine the beam size from the beam profile a Gaussian distribution is fitted to the profile data.

In the emittance measurements with "Three-Position Method", the profile monitors seperation in the measurement chamber is only 750.00 mm. So we should try to make the beam waist near the center profile monitor and take the waist size to be $1.9 - 2.3mm$ as possible as we could. Figure 5 shows the results of emittance measurements in horizontal direction with the "Three-Position Method". From Fig.5 we can see that the beam configuration is not in the best state. This is a main source that error comes from. The results will be better if the profile seperation is greater.

In the emittance measurements with "Three-Gradient Method", fourteen settings of the quadrupole have been performed to get a series of profile measurements at one location. Figure 6 indicates the dependence of the beam size at the profile monitor on the quadrupole strength in the "Three-Gradient Method". Both experimental results and theory fitting from matrix elements are presented in Fig.6. Experiments indicate that in order to get a good result in the "Three-Gradient Method", the range of the quadrupole strength should generate a waist at the profile monitor and cover both sides of the waist equally.

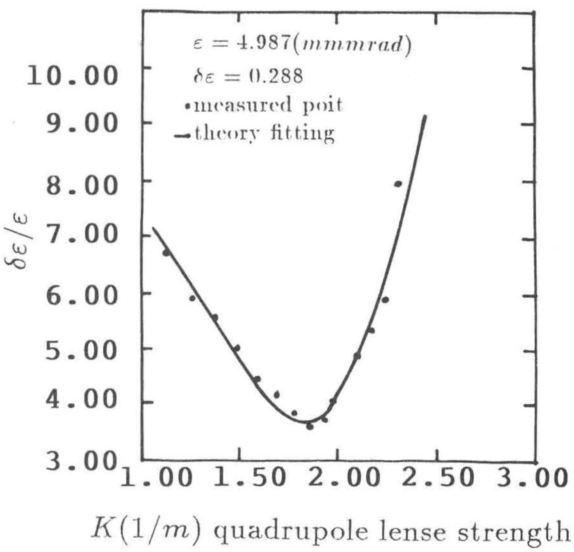

Fig.6. Dependence of the beam size at the profile monitor on the quadrupole strength.

The dependence of beam emittance on the beam percentage is shown in Fig.7, in which both experimetal results measured with "Three-Gradient Method" and theory curve based on Gaussian ditribution are provided.

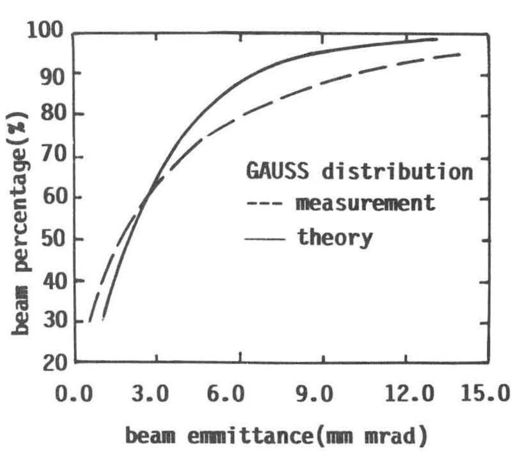

Fig.7. Dependence of emittance on the beam percentage in horizontal direction.

4. SUMMARY

Emittance measurements in the HIRFL beam line have been made using two different methods. From measurement results of the two methods it seems that they are not in very good agreement with each other. But some calibrations and revisions can be made to the measurement results if we take various errors into accout. After revisions,the horizontal emittances measured with two methods are as follows:

with Three-Position Method :

$$\varepsilon = 5.43 \ mm \ mrad \qquad 76\% \text{ beam}$$

with Three-Gradient Method :

$$\varepsilon = 4.99 \ mm \ mrad \qquad 76\% \text{ beam}$$

So we think the emittance measurement results using the two methods are consistent with each other in the error permission. Another emittance measuring system using slit and multi-wire profile monitor will also be put into operation in the near future.

5. REFERENCES

1) Jacobs.K.D, "Emittance Measurements at the Bates Linac" in **Proceedings of 1989 IEEE Particle Accelerator conference**(Chicago,1989) pp.1526-1528 .

2) Strehl.p , "Beam Diagnostic Devices for a Wide Range of Currents" Presented at the Ninth international Conference on cyclotrons and their Applications, pp.545-554.

3) Sheppard.J.C, "Emittance Calculations for the Stanford Linear Collider Injector" IEEE Trans.on Nucl. Sci. **NS-30,NO.4**, 2161(1983).