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RECONSTRUCTION OF PARTICLE DISTRIBUTIONS AT RFQ EXIT AT SNS BEAM TEST FACILITY*

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Abstract

Fluctuations of beam parameters and uncertainties of quadrupole gradients during measurements have effects on the reconstruction of initial particle distributions. To evaluate these effects, the concept of a distribution discrepancy is proposed. Results suggest effects of fluctuations of beam parameters are small, while uncertainties of quadrupole gradients are the main factors that affect the reconstructed distributions. By comparing the measured distributions with distributions produced by tracking the reconstructed initial distributions, it is proved that the real or quasi-real (closest to real) initial distribution can be obtained as long as the minimum distribution discrepancy is found.

INTRODUCTION

The Beam Test Facility (BTF) at SNS consists of a 65 kV H- ion source, a 2.5 MeV RFQ, a beam line with advanced transverse and longitudinal beam diagnostic devices and a 6kW beam dump (as shown in Fig. 1). One of the main goals of the BTF is to provide a platform for conducting R&D for novel accelerator physics and technological concepts related to high intensity hadron beam generation, acceleration, manipulation and measurement [1]. Of particular importance is to conduct the first direct 6D phase space measurement of a hadron beam [2] which will be used to high intensity beam halo study [3].

Reconstruction of particle distributions from 6D phase space measurement is not trivial. Therefore, reconstruction of a 2D distribution without considering coupling between horizontal, vertical and longitudinal planes can be carried out as the first step, which can help validate the approach of reconstruction of particle distributions and obtaining of the real initial distribution which may be affected by beam parameters and quadrupole gradients, gaining experiences for the eventual reconstruction of 6D phase space particle distributions.

There are usually two methods to reconstruct the initial particle distributions by PIC simulation codes, one is fitting the RMS beam sizes of the measured distributions, the other is a tomography-like technique [4]. At SNS, a more direct method based on emittance data in both transverse directions and the backward tracking ability of PyORBIT is used [5,6], and a dedicated PIC back-tracking simulation code based on PyORBIT has been developed. The simulation code can transform measured particle distributions into bunches for backward tracking, create backward lattice to track the bunch from measurement location to entrance of the lattice. In the work presented here, the lattice is the section of the BTF from the RFQ exit to the first slit (Slit 1) which is used to measure the transverse particle distributions. There are four quadrupoles (Q1, Q2 Q3 and Q4) in the lattice, which can be seen in Fig. 1. This paper mainly focuses on the investigation of influences of beam parameters and quadrupole gradients on the reconstructed particle distributions and how to obtain the real initial distributions.

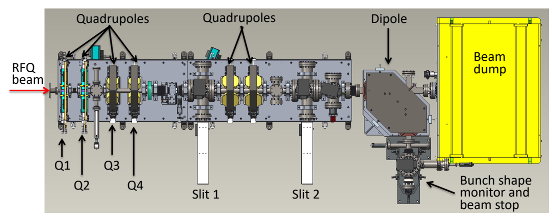

Figure 1: Layout of beam test facility at SNS.

VALIDATION OF BACK-TRACKING SIMULATION CODE

The back-tracking simulation code needs to be verified that it can accurately backward track a distribution before it is applied to the distribution reconstruction.

First, an ideal Gaussian distribution is used to validate the back-tracking code. An ideal Gaussian distribution is generated at the RFQ exit and tracked to the slit 1 by the forward-tracking code. Then the back-tracking code tracks the distribution at slit 1 backward to the RFQ exit with the same quadrupole settings, and the final distribution is compared with the initial distribution. Specifically, corresponding particle coordinates are compared between the two distributions, and the maximum particle coordinates discrepancy in phase space is used as a measure of comparison. The parameters of the initial distributions are α_x =−1.99, β_x = 20 mm/mrad, ε_x = 0.16 mm·mrad, α_y =−1.99, β_y = 20 mm/mrad, ε_y = 0.16 mm·mrad, respectively, and the particle number is ten thousand.

Figure 2 displays the initial Gaussian distributions (black) and the distributions produced by back tracking (red). It illustrates the two distributions are coinciding completely in both *x*-plane and *y*-plane. Detailed comparison results show that the maximum particle coordinates discrepancies in *x* and *y* planes are (5.65×10^{-5} mm, 5.05×10^{-4} mrad), (5.0×10^{-5} mm, 5.0×10^{-4} mrad) for 0 mA and (6.37×10^{-5} mm, 8.21×10^{-4} mrad), (5.31×10^{-5} mm, 8.6×10^{-4} mrad) for 50 mA, which prove that

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the back-tracking simulation code can reconstruct ideal distributions accurately.

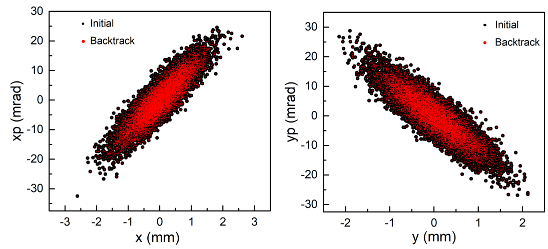

Figure 2: Initial particle distribution and distribution produced by back tracking.

Next, the back-tracking code is tested with measured distributions. If the distributions, produced by forward tracking the reconstructed distributions which are generated by backward tracking the measured distributions, are the same as the measured ones, the back-tracking code is validated. In contrast to the ideal distribution which is generated in both the transverse and longitudinal phase spaces by the forward-tacking code, the measured distributions have no particle distribution in the longitudinal phase space. Thus, a longitudinal distribution is generated by forward tracking the RFQ output distributions and assigned to the measured distributions to form a complete input distribution for the back-tracking code. By comparing the measured distributions with the distributions produced by forward tracking the reconstructed distributions, the maximum particle coordinates discrepancies are (3.47×10^{-5} mm, 1.10×10^{-4} mrad) and (7.89×10^{-5} mm, 8.8×10^{-5} mrad) in *x*-plane and *y*-plane, respectively. This result certifies that the back-tracking simulation code is reliable for measured distributions, too.

RECONSTRUCTION OF INITIAL PARTICLE DISTRIBUTION AT RFQ EXIT

Distribution Discrepancy

Due to the uncertainties of quadrupole gradients and fluctuations of beam current during measurements, the reconstructed initial distribution by one measured distribution may deviate from the real initial distribution. Therefore, the real initial distribution needs to be confirmed by two or more measured distributions produced by different quadruple settings. In order to investigate the influences of beam parameters and quadrupole gradients on the reconstructed distributions and to obtain the real initial distribution, the concept of distribution discrepancy is proposed.

Assume there are two particle distributions in x-xp phase space (red distribution and blue distribution, as plotted in Fig. 3), and their particles are divided by the same grids into different squares according to their coordinates. Then the distribution discrepancy, denoted by DistD, is defined by the following formula:

$$\mathrm{DistD} = \sum_{i,j} \left| \frac{N_{i,j}^r}{TN^r} - \frac{N_{i,j}^b}{TN^b} \right|,$$

Where i and j are the grid number in x and xp direction, r and b mean the red distribution and blue distribution, $N_{i,j}^r$ and $N_{i,j}^b$ stand for the particle number of red distribution and blue distribution in the (i,j) square, TN^r and TN^b are total particle number in the red distribution and blue distribution, respectively. Big grid numbers produce high position and angle resolutions. Here grid numbers 100×100 are chosen in *x-xp* and *y-yp* phase spaces, which means the position and divergency angle resolutions are about 0.05 mm and 0.4 mrad. If the two distributions are reconstructed by two different quadrupole settings, a small distribution discrepancy means they are not only close to each other, but also all close to a specific distribution which is the real initial distribution. While it is difficult to find the real initial distribution which requires the distribution discrepancy to be zero, a quasi-real initial distribution which is the closest to the real initial distribution can be obtained as long as the minimum distribution discrepancy is found.

In order to enhance the reconstruction accuracy, four measured distributions of 20 mA produced by four different quadruple settings are used to find the real or quasi-real initial distributions at the BTF RFQ exit. In this way, every two reconstructed distributions are compared with each other which means there are total six distribution discrepancies. The quasi-real initial distribution is obtained when the maximum distribution discrepancy (max_DistD) among the six reaches the minimum value.

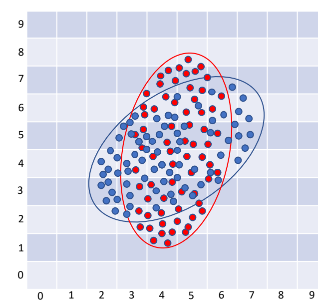

Figure 3: Particle distributions comparison.

Effects of Assigned Longitudinal Beam Distribution and Beam Current

The assigned longitudinal beam distribution is produced by the forward-tracking code with the 20 mA RFQ output distributions. Therefore, a study of effects of the assigned longitudinal beam distribution on distribution discrepancies is conducted by studying the effects of the parameters of the RFQ output longitudinal distribution. The Twiss parameters and emittance of the RFQ output longitudinal distribution are $\alpha_z \approx 0$, $\beta_z \approx 0.6$ mm/mrad and $\varepsilon_z \approx 0.2$ mm-mrad, respectively, according to the RFQ design result [7], and a range around these values (as shown in Fig. 4) is used in the study. The top two and the bottom left plots in Fig. 4 display the relationship between max_DistD and the parameters of the longitudinal distribution at the RFQ exit. They demonstrate that the effects of the assigned longitudinal beam distribution on distribution discrepancies are very small, and consequently,

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the designed RFQ output longitudinal distribution can be used to generate the initial distributions at RFQ exit.

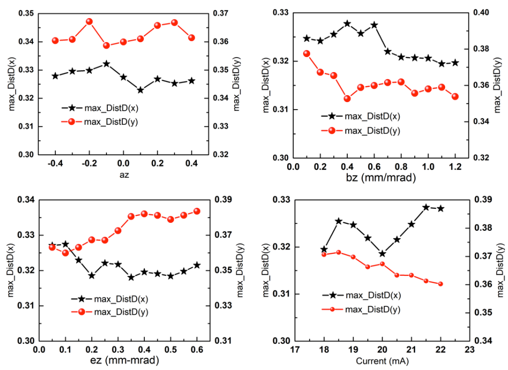

Figure 4: Effects of assigned longitudinal distribution and beam current on distribution discrepancies.

The bottom right plot in Fig. 4 shows fluctuation of beam current has a small effect on distribution discrepancies, too. Thus, 20 mA can be used for the reconstruction of initial distributions.

Effects of Quadrupole Gradients

The quadrupole gradients used for the study are obtained from the quadrupoles control system by comparing the current readings from the power supplies with the known relationship between gradients and currents [8]. The uncertainty of the current readings causes uncertainty in quadrupole gradients. Figure 5 illustrates the relationship between max_DistD and gradient variations of the fourth quadrupole during the fourth measurement, in which the setting gradient is 6.875 T/m according to the current reading. It can be seen from Fig. 5 that a change from −5% to 5% of the gradient causes about 27% and 45% variations of distribution discrepancies in *x-xp* phase space (max_DistD(*x*)) and *y-yp* phase space (max_DistD(*x*)), which means the uncertainty of quadrupole gradients have a great impact on the initial particle distributions at RFQ exit. Figure 5 shows the effects of gradient uncertainty of only one quadrupole during one measurement. There are total four measurements and each quadrupole of every measurement has influence on the distribution discrepancies. Therefore, all the influences have to be investigated to obtain the initial distributions. Due to the large amount of gradient combinations a script was written to handle the calculations and to analyze the results.

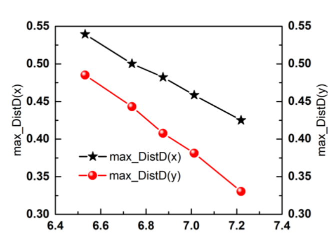

Figure 5: Relationship between max_DistD and gradient uncertainty (c4_G4 means gradient of the fourth quadrupole during the fourth measurement).

Generation of Initial Particle Distributions

It has been found that the minimum max_DistD(*x*) and max_DistD(*y*) do not occur at the same gradient setting combination during data analysis, in other words, max_DistD(*y*) is 0.460 when max_DistD(*x*) is the minimum value of 0.256, while max_DistD(*x*) is 0.430 when max_DistD(*y*) is the minimum value of 0.261. The initial particle distributions should take place when both max_DistD(*x*) and max_DistD(*y*) have relative small values with the same quadrupole settings. Hence, to facilitate finding the best pair of max_DistD(*x*) and max_DistD(*y*) the average and difference values are calculated, and finally max_DistD(*x*) = 0.281 and max_DistD(*y*) = 0.270 are found to be the best result. Figure 6 displays the initial distributions when max_DistD(*x*) = 0.281 and max_DistD(*y*) = 0.270, which are the combined results of the four separate reconstructed initial distributions and are considered to be very close to the real initial distributions.

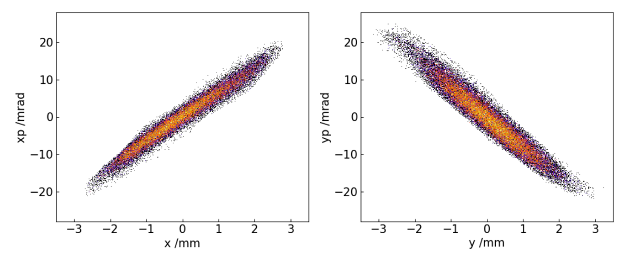

Figure 6: Generated particle distributions at RFQ exit.

The particle distributions in Fig. 6 are forward tracked to the first slit where the tracked distributions are compared with the measured ones, and Fig. 7 displays one of the comparison results. In Fig. 7, the red plots are the measured distributions and the black plots are forward tracked distributions. It demonstrates the measured distributions and the tracked distributions agree well with each other except for a small area with low particle density in both *x-xp* and *y-yp* phase spaces in the tracked distributions. The Twiss parameters and emittances of the measured and tracked distributions are also nearly the same (as listed in Table 1). Considering the measurement errors, these results suggest the reconstructed initial particle distributions in Fig. 6 are reliable and using the minimum distribution discrepancy to obtain the real or quasi-real initial distributions is reasonable.

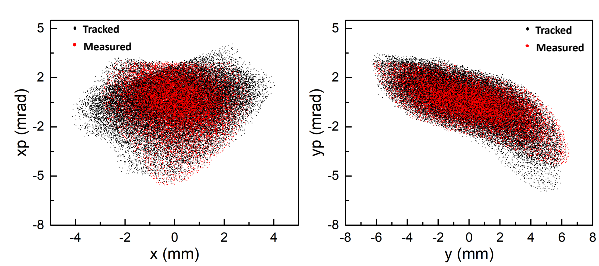

Figure 7: Comparisons between measured distributions and forward tracked distributions which are produced by using the generated initial distributions as input.

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Table 1: Twiss Parameters and Emittances of the Measured and Tracked Distributions

Distribution	Measured	Tracked
α_x	0.11	-0.10
β_x (mm/mrad)	0.80	1.09
ε_x (mm·mrad)	1.71	1.81
α_y	0.91	0.95
β_y (mm/mrad)	3.10	2.79
ε_y (mm·mrad)	2.27	2.25

The above results were obtained by using the "Hard Edge" magnetic fields of the quadrupoles, meanwhile, using the measured field distributions of the quadrupoles could produce the same results.

CONCLUSION

In order to evaluate the effects of fluctuations of beam and uncertainties of quadrupole gradients on the reconstruction of initial particle distributions the concept of distribution discrepancy is proposed. Studies using this concept suggest the effects of beam parameters are very small. It has been found that variations of quadrupole gradients influence the initial distributions greatly, therefore, all the possible combinations of quadrupole gradients have to be studied. The combination which produces small distribution discrepancies in both *x-xp* and *y-yp* phase spaces is considered to be able to generate the initial particle distributions which are very close to the real ones. Distributions produced by forward tracking the reconstructed initial distributions are compared with the measured ones, and results show they agree well with each other, which suggests using the minimum distribution discrepancy to obtain the real or quasi-real initial distributions is reliable.

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