Characterizing a proton beam with two different methods in beam halo experiments*

JIANG Hong-Ping(蒋洪平)[1)] FU Shi-Nian(傅世年) PENG Jun(彭军) CHENG Peng(程鹏) HUANG Tao(黄涛) LI Peng(李鹏) LI Fang(李芳) LI Jian(李健) LIU Hua-Chang(刘华昌) LIU Mei-Fei(刘美飞) MENG Ming(孟鸣) MENG Cai(孟才) MU Zhen-Cheng(慕振成) RONG Lin-Yan(荣林艳) OUYANG Hua-Fu(欧阳华甫) SUN Biao(孙彪) WANG Bo(王博) TIAN Jian-Min(田建民) WANG Biao(王标) WANG Sheng-Chang(王盛昌) YAO Yuan(姚远) XU Tao-Guang(徐韬光) XU Xin-An(徐新安) XIN Wen-Qu(辛文曲) ZHAO Fu-Xiang(赵富祥) ZENG Lei(曾磊) ZHOU Wen-Zhong(周文中)

Accelerator Center, Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

Abstract: In beam halo experiments, it is very important to correctly characterize the RFQ output proton beam. In order to simulate the beam dynamics properly, we must first know the correct initial beam parameters. We have used two different methods, quadrupole scans and multi-wire scanners to determine the transverse phase-space properties of the proton beam. The experimental data were analyzed by fitting to the 3-D nonlinear simulation code IMPACT. For the quadrupole scan method, we found that the RMS beam radius and the measured beam-core profiles agreed very well with the simulations. For the multi-wire scanner method, we choose the case of a matched beam. By fitting the IMPACT simulation results to the measured data, we obtained the Courant-Snyder parameters and the emittance of the beam. The difference between the two methods is about eight percent, which is acceptable in our experiments.

Key words: characterizing proton beam, quadrupole scans, multi-wire scanners, low energy intensity proton

PACS: 29.20.Ej, 29.27.-a **DOI:** 10.1088/1674-1137/38/8/087002

1 Introduction

The beam halo experiment facility at IHEP consists of an ion source, Radio-Frequency Quadrupole (RFQ)and beam transport line, which is used to characterize the proton beam and to study the beam halo experimentally [1]. The beam transport line is installed at the end of the IHEP RFQ, which accelerates the proton beam to 3.54 MeV and is operated at a frequency of 352 MHz. The block diagram of this transport line is shown in Fig. 1. The blue lines represent the wire-scanners, which are applied to measure the beam-core profile [2]; the first two wire-scanners are used to measure the beam-core profiles for the quadrupole scan method. There are four matching quadrupoles between the RFQ and the 24-quadrupole FODO focusing channel.

In beam halo experiments [3], we first need to properly determine the phase-space properties of the RFQ output beam. We also need to know the measuring accuracy. We therefore choose two different methods to measure the beam parameters. For the quadrupole scan method [4], we change the gradient of one matching quadrupole, and keep the gradients of the other three matching quadrupoles unchanged. We measured the beam-core profiles, with different gradients of the quadrupole. To determine the Courant-Snyder parameters of the beam, we fit the beam-core profiles to IMPACT code [5] simulations. For the multi-wire scanner method [6], the beam was matched by adjusting the four matching quadrupoles to produce equal RMS beam radii at the last 6 wire-scanners. We then used the IMPACT

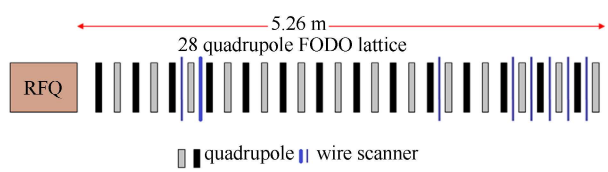

Fig. 1. Block diagram of beam halo experiment transport line.

Received 15 October 2013

∗ Supported by National Natural Science Foundation of China (91126003) and Key Development Program of Basic Research of China (2007CB209904)

1) E-mail: jianghp@ihep.ac.cn

code to simulate the matched case, and compared the results with the measured RMS beam radius.

We then obtained the Courant-Snyder parameters and the emittances of the beam. In this paper, Section 2 describes the quadrupole scan method and its results, Section 3 describes the multi-wire scanner method with its results, and then Section 4 compares the different methods. Finally, conclusions are presented in Section 5.

2 The quadrupole scan method

We simulated beam through the RFQ using the RFQ simulation code PARMTEQM [7], and obtained the beam parameters at the exit of the RFQ. The Courant-Snyder parameters obtained from PARMTEQM are shown in Table 1.

The Gaussian distribution is a good approximation for an emittance-dominated beam [8]. We therefore chose a Gaussian distribution as the initial beam distribution. In the simulation procedure we used 1×10^6 macroparticles per bunch with a computation grid of $64\times64\times128$. In the horizontal scans, for each of the seven values of Q_4 (the fourth quadrupole after the exit of the RFQ), the difference between the measured and the simulated intensity at the wire-scanner position was computed. The sum of the differences was minimized by varying the values of the Courant-Snyder parameters and emittances of the input beam. The Courant-Snyder parameters and emittances obtained by the quadrupole scans are shown in Table 2.

Table 1. Beam emittances and Courant-Snyder parameters obtained from the PARMTEQM simulations.

direction	alpha	beta/(mm·mrad)	emittance (RMS unnormalized)/(mm·mrad)
horizontal (x)	−0.334	0.1067	2.60
vertical (y)	−0.288	0.1992	2.70
longitudinal	−1.564	3.1571	0.315 (normalized)

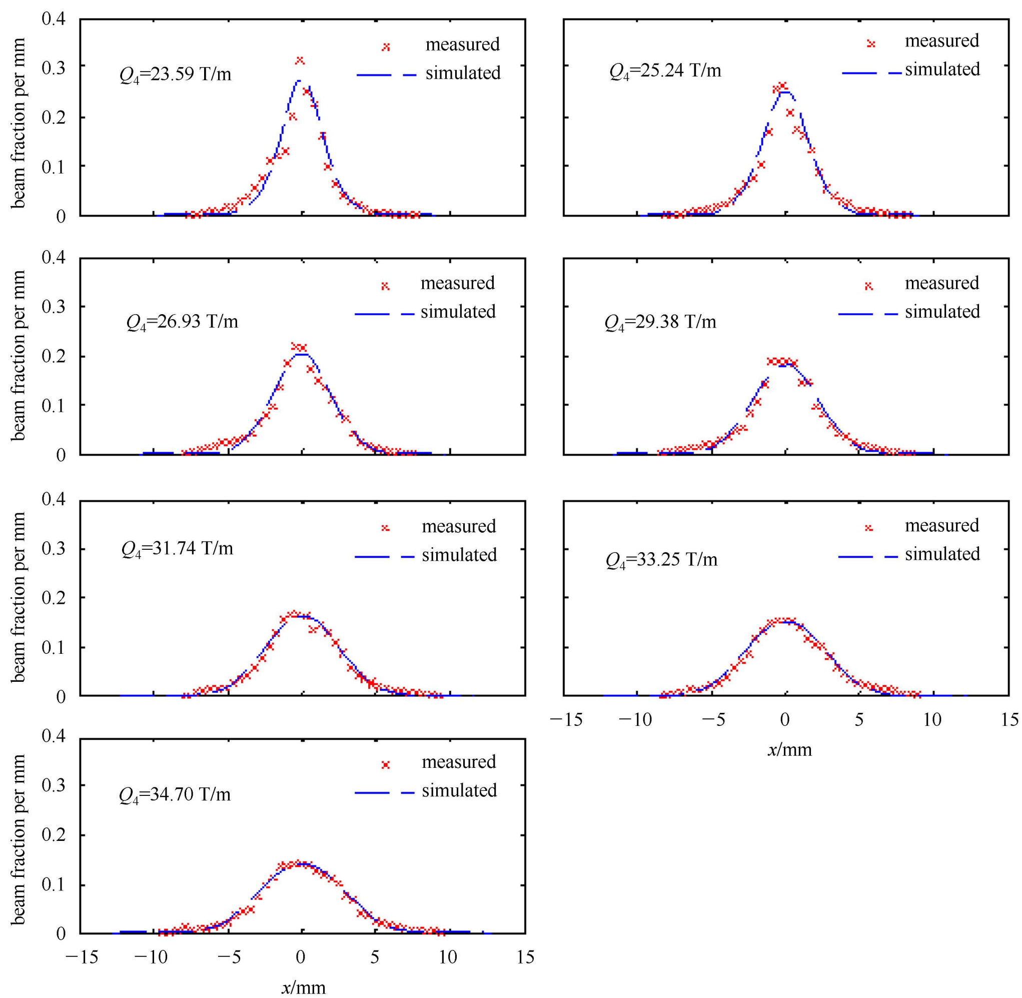

Fig. 2. Comparison of the measured horizontal beam-core profiles and the IMPACT simulations.

Table 2. Emittances and Courant-Snyder parameters obtained from the quadrupole scan analysis.

direction	alpha	beta/(mm·mrad)	emittance (RMS unnormalized)/(mm·mrad)
horizontal (x)	3.443	0.4163	3.67
vertical (y)	−0.165	0.1005	5.45

Fig. 2 and Fig. 3 show the comparisons of the measured beam-core profiles with the IMPACT simulation results. We found that the simulated and measured beam profiles agree with each other very well. The measured beam RMS radii were also compared with the simulation results, as shown in Table 3 and Table 4. We find that both the beam RMS radii and the beam-core profiles are in good agreement with the measured results, although in Ref. [9] the beam-core profiles don't agree for larger quadrupole gradients.

3 The multi-wire scanner method

For the multi-wire scanner method, we first need to find the conditions for a matched beam, because the beam emittances remain unchanged when the matched beam is transported in the FODO channel [7]. The beam was matched, using a least-squares fitting procedure that adjusted the first four quadrupoles to produce equal RMS horizontal radius at the last six scanner locations [10]. Under the match conditions, we measured the beam horizontal profiles and beam RMS radii at the seven different locations. Firstly, we used the initial parameters obtained by the quadrupole scan method to simulate the matched beam. Fig. 4 shows the beam RMS radii and beam transverse emittances as a function of distance, where the green line is in the vertical direction and the red line is in the horizontal direction. The points with error bars are the experimental data for the RMS beam horizontal radius.

Table 3. Comparison of the simulated and measured beam RMS radii for the horizontal direction.

Q_4/(T/m)	23.59	25.24	26.93	29.38	31.74	33.25	34.70
experiment/mm	1.48±0.06	1.69±0.06	2.02±0.05	2.11±0.05	2.41±0.04	2.60±0.04	2.70±0.05
simulation/mm	1.47	1.60	1.94	2.18	2.43	2.59	2.75

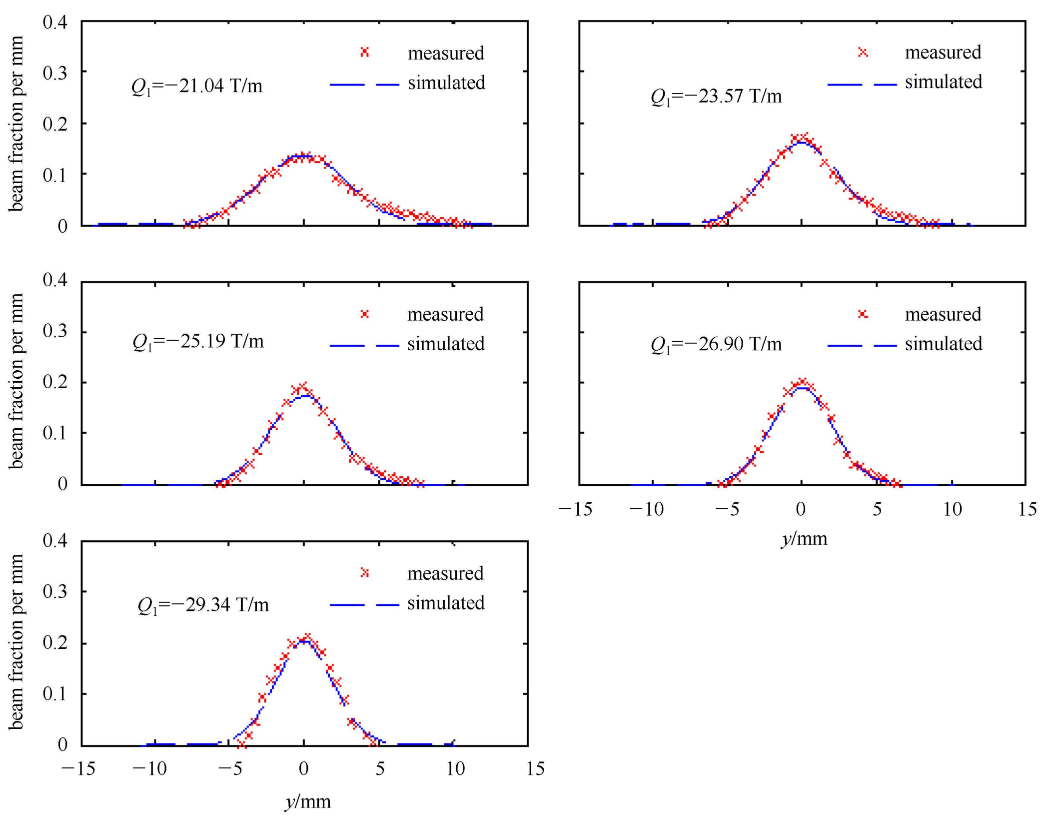

Fig. 3. Comparison of the measured vertical beam-core profiles and the IMPACT simulations.

Table 4. Comparison of the simulated and measured beam RMS radii for the vertical direction.

Q_1/(T/m)	−21.04	−23.57	−25.19	−26.90	−29.34
experiment/mm	2.96±0.06	2.46±0.05	2.20±0.08	2.10±0.06	1.96±0.06
simulation/mm	2.94	2.50	2.27	2.10	1.98

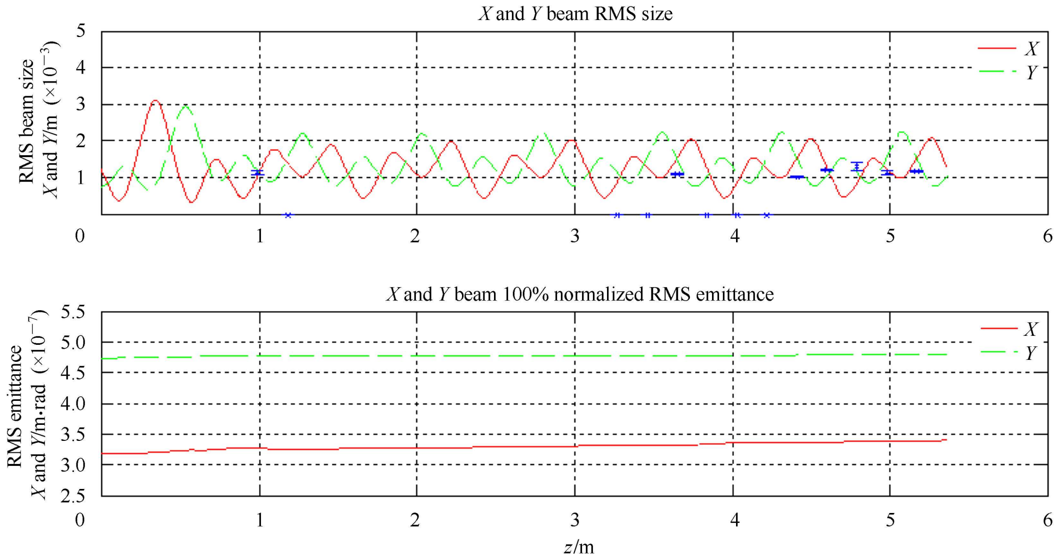

Fig. 4. Beam RMS radius and emittance variation along the beam line using initial beam parameters obtained by the quadrupole scan method.

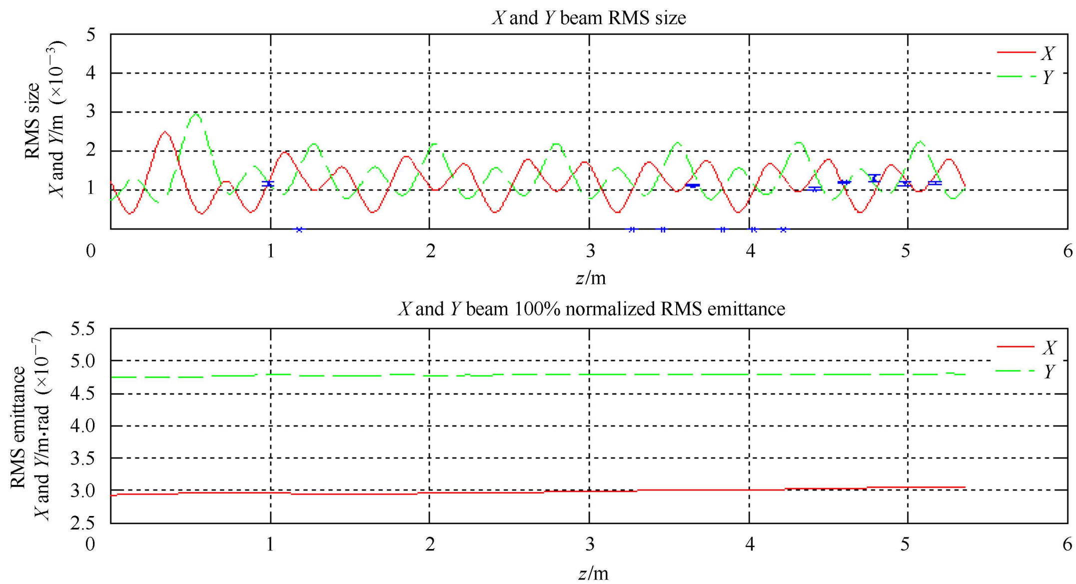

Fig. 5. Beam RMS radius and emittance, variation along the beam line using initial beam parameters obtained from the multi-wire scanner method.

From Fig. 4 we can see the simulation is not well fitted to the experimental beam radius, the beam is not perfectly matched, and the beam horizontal emittance grows with distance. The beam is a little mismatched. We therefore changed the initial parameters in the simulation, then found new parameters and obtained results more consistent with the measured results. We show the simulation and measurement results in Fig. 5. We can see that the beam is matched better, the simulation fits the experimental beam RMS radius, and the horizontal beam emittance is nearly constant. We then obtain the transverse beam parameters and emittances, shown in

Table 5. Due to the lack of a vertical wire scanner at the FODO channel, we used the vertical beam parameters obtained by the quadrupole scan method as the initial parameters in the simulation procedure.

Table 5. Emittances and Courant-Snyder parameters obtained from the multi-wire scanner method.

direction	alpha	beta/(mm·mrad)	emittance (RMS unnormalized)/(mm·mrad)
horizontal (x)	3.2865	0.4466	3.37
vertical (y)	−0.165	0.1005	5.45

4 Comparison of different methods

We have measured the initial beam parameters with two different methods and obtained the beam parameters predicted by PARMTEQM. We now compare the results of all three methods for the Courant-Snyder parameters and beam emittances in the horizontal direction, shown in Table 6.

We can see that the difference between the quadrupole scan method and the multi-wire scanner method is about eight percent, which is acceptable in our experiments. We believe we have obtained the correct beam parameters. However, the Courant-Snyder parameters predicted by PARMTEQM differ greatly from the measurement results, and the emittance is also smaller than the measurement results. Due to the lack of measurements at the entrance of the RFQ, we do not know the beam parameters at the entrance of the RFQ in the simulations.

Table 6. Comparison of beam parameter results.

method	alpha	beta/(mm·mrad)	emittance (RMS Unnormalized)/(mm·mrad)
quadrupole scans	3.443	0.4466	3.67
multi-wire	3.287	0.4163	3.37
PARMTEQM	−0.334	0.1067	2.60

5 Conclusions

We have measured the beam parameters for the beam halo experiment facility at IHEP using two different methods: quadrupole scans and multi-wire scanners. The two measurement results have a difference of about eight percent, which is acceptable in our experiments. We believe these are the correct beam parameters, so these two methods can be used to characterize the beam independently. For the quadrupole scan method in particular, both the beam RMS radii and the beam-core profiles are in good agreement with the measured results. Obtaining the correct beam parameters is very important to properly simulate the beam dynamics and to study the beam halo in future experiments.

References

1 JIANG H, FU S, CHEN P et al. Macroparticle Simulation Studies of a Beam-Core Matching Experiment. Proceedings of the 4th International Particle Accelerator Conference. Shanghai, China, 2013. 3860–3860

2 RUAN Yu-Fang, HAN Lu-Xiang, LIU Hua-Chang et al. Chinese Physics C (HEP & NP), 2010, **34**(10): 1655

3 PENG Jun, HUANG Tao, LIU Hua-Chang et al. Chinese Physics C (HEP & NP), 2013, **37**(3): 037002

4 Schulze M E, Allen C K, Colestock P L et al. Characterization of the Proton Beam from the 6.7 MeV LEDA RFQ. Particle Accelerator Conference, 2001. PAC 2001. Proceedings of the 2001. IEEE, 2001, **1**: 591–593

5 QIANG J, Ryne R, Habib S et al. An Object-Oriented Parallel Particle-in-Cell Code for Beam Dynamics Simulation in Linear Accelerators. Supercomputing, ACM/IEEE 1999 Conference. IEEE, 1999. 55–55

6 Ross M C, Seeman J T, Bong E et al. Wire Scanners for Beam Size and Emittance Measurements at the SLC. IEEE Particle Accelerator Conf., San Francisco, CA. 1991

7 Crandall K R et al. RFQ Design Codes. Los Alamos National Laboratory report LA-UR-96-1835 (revised February 12, 1997)

8 Reiser M. Theory and Design of Charged Particle Beams. 2nd edition. New York: Wiley and Sons, 2008

9 Lysenko W P, Gilpatrick J D, Rybarcyk L J et al. Determining Phase-Space Properties of the LEDA RFQ Output Beam. arXiv preprint physics/0008186, 2000

10 Wangler T P, Allen C K, Chan K C D et al. Experimental Study of Proton-Beam Halo Induced by Beam Mismatch in LEDA. Particle Accelerator Conference, 2001. PAC 2001. Proceedings of the 2001. IEEE, 2001, **4**: 2923–2925