MEASUREMENT OF PRECISE PARTICLE DISTRIBUTIONS IN EMITTANCE PHASE PLANE IN THE JHP LEBT

S. Fujimura and A. Ueno
National Laboratory for High Energy Physics, KEK
Graduate University for Advanced Studies
1-1 Oho, Tsukuba-shi, Ibaraki-ken, 305 Japan

Abstract

A low energy beam transport (LEBT), in which any practical emittance growth due to the lens-aberration would not be caused, was developed for the Japanese Hadron Project (JHP). In the LEBT, we measured the precise distributions in the transverse emittance phase plane of the particles, which were extracted from the volume production H^- ion source (VPIS) operated without cesium. The measured results showed good agreements with the simulation results using the initial particles at the exit of the VPIS generated with Ueno-Yokoya distribution (UY-dst), in which the particles are distributed uniformly in the real space (concerning with x and y) and distributed in Gaussian way concerning with x' and y'. We also detected the unexpectedly strong space-charge neutralization effect only with the residual H_2 gas with a pressure of 3.7×10^{-6} Torr. In this condition, 93% of the beam intensity was neutralized with almost no beam loss due to electron stripping by collisions with H_2 gas.

Introduction

In order to inject a low-emittance H^- beam into a 432-MHz radio-frequency quadrupole (RFQ) linac, a low energy beam transport (LEBT) was developed for the Japanese Hadron Project (JHP) [1, 2]. By the beam dynamics design studies with a computer code BEAMPATH [3], it was revealed that an appropriately designed solenoid magnet had the smallest lens aberration in LEBTs [4]. Therefore, we succeeded in designing the JHP LEBT without any practical emittance growth due to the lens-aberration by using two short and strong solenoid magnets. A new volume production H^- ion source (VPIS) was also developed at the same time with the LEBT. We succeeded in extracting a H^- beam of 16 mA from the VPIS operated without cesium [5].

In this paper, we present the results of the measurement of the precise particle distributions in the emittance phase planes in the LEBT and the measured space-charge neutralization effects produced by the residual H_2 gas. Instead of a commonly used contour plot, we use a new display method of Ueno-Fujimura plot (UF-plt) [5], in order to display the measured particle distributions in the emittance phase plane. In UF-plt, the particle distribution is displayed with light and shade by plotting points, whose number is proportional to the intensity measured at (x, x’), randomly within the rectangle composed with the four positions of (x–dx/2, x’–dx’/2), (x+dx/2, x’–dx’/2), (x–dx/2, x’+dx’/2) and (x+dx/2, x’+dx’/2). Here, dx and dx’ is the steps of the measurements.

Experimental Setup

A schematic drawing of the experimental setup viewing from the upper position is shown in Fig. 1. The vacuum chamber (CHM1) just after the VPIS is pumped out with two 1500 l/s turbo molecular pumps (1500TMPs). The first solenoid electromagnet (SM1) is located 90 mm downstream from the plasma electrode of the VPIS. In a space of 215 mm between SM1 and the second solenoid electromagnet (SM2), the vacuum chamber for the beam diagnostic (CHM2) and the gate valve (GV) are located. SM1 and SM2 have the same shape with a length of 100 mm, a outer diameter of 300 mm and a bore diameter of 50 mm. A 500 l/s turbo molecular pump (500TMP) pumps out CHM2. By moving the movable slit ($EMSL_H$) and the Faraday-cup with slit ($EMFC_H$) horizontally step by step, the horizontal emittance is measured. The vertical emittance is measured by using $EMSL_V$ and $EMFCL_V$. Each slit used in EMSL or EMFC is made of molybdenum plates with a thickness of 0.05 mm and has a gap of 0.2 mm. The distance between the slit of EMSL and the slit of EMFC is 61 mm. Since the alignment error of each slit is ±0.1 mm, which is the error of the real space of the emittance phase space, the error of x’ or y’ space is calculated to be ±1.6 mrad. The beam intensity was measured with the Faraday-cup (FC). A voltage of –1 kV was fed on each bias electrode of EMFC or FC in order to suppress the secondary electrons form each Faraday-cup. EMSL is located almost the same position of the vane-end at the entrance of the RFQ, when the LEBT is connected with the RFQ.

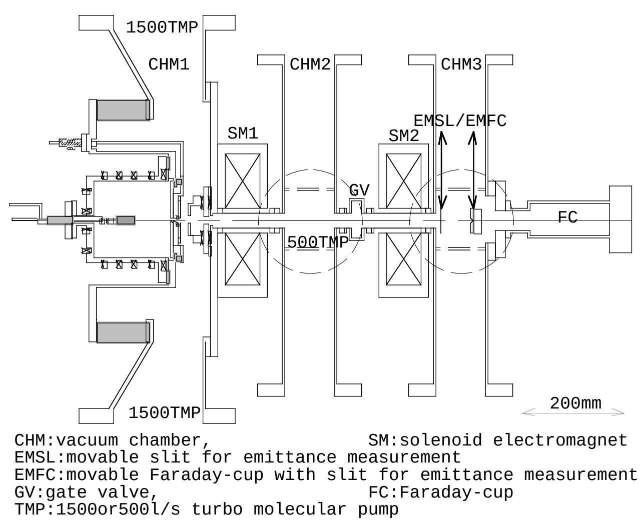


Fig. 1 A schematic drawing of the experimental setup viewing from the upper position.

Results of the Measurements

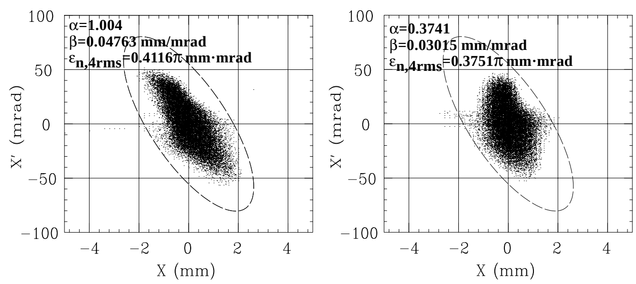
The measured particle distributions in the horizontal phase space at the entrance of the RFQ displayed with UF-plts are shown in Fig. 2; (a) when the vacuum pressure in CHM2 was 3.7×10^{-6} Torr and (b) when it was worsened up to 3.7×10^{-5} Torr by closing the gate valve located between CHM2 and 500TMP. In these measurements, a H^- ion beam of 16 mA was extracted from the VPIS. Ellipses drawn in Fig. 2 show the design acceptance of the RFQ. The TWISS parameters and the normalized emittance of the acceptance are α = 1.05, β = 0.0473 mm/mrad and $\varepsilon_n = 1.5^1$ mm·mrad, respectively. The TWISS parameters and the 4 times of the normalized rms emittance of the measured particle distributions are listed in each figure. By tuning the currents of SM1 and SM2 to the values shown in Table 1, the TWISS parameters of the measured beam was matched with the design value with a matching factor of around 1. By comparing Fig. 2(a) with Fig. 2(b), we can estimate the space charge neutralization factor in the typical operating condition shown in Table 1 by the following way. At first, we estimated the TWISS parameters at the exit of the VPIS by inversely tracing the beam shown in Fig. 2(b) up to the exit of the VPIS by using a simulation code BEAMPATH [3], in which both of the two nonlinear effects of the realistic field and the non-uniformly distributed space charge force are taken into account. In this estimation, we assumed that all of the beam intensity was neutralized by the residual H_2 gas. That is, the equivalent beam current was assumed to be 0 mA. This assumption was considered to be valid because of the following two reasons; (1) the observation of the fluorescence produced by the beam which was not observed in a good vacuum pressure of 3.7×10^{-6} Torr, (2) the coil currents of SM1 and SM2 were close to the design values estimated with a design initial particle distribution at the exit of the VPIS for the zero current beam; $I_{SM1deg}(0)$ = 323 A and $I_{SM2deg}(0)$ = 382 A. On the other hand, the design coil currents of SM1 and SM2 for the beam with a current of 16 mA are 382 A and 424 A, respectively. In this inverse trace, the KV-distribution beam with TWISS parameters listed in Fig. 2(a) was used as the initial beam. The TWISS parameters at the exit of the VPIS were estimated to be α = –0.90 and β = 0.050 mm/mrad. By using thus estimated initial beam at the exit of the VPIS, we simulated the beam optics in the normal direction with various beam currents. The result using the beam with a current of 1.1 mA well represented the TWISS parameters of the particle distribution shown in Fig. 2(a). Therefore, the equivalent current of the beam in the typical operation condition can be thought as 1.1 mA. Since we worsened the vacuum pressure largely (by 10 times) in the measurement shown in Fig. 2(b) compared with it of the typical operation shown in Fig. 2(a), the validity of the assumption of the perfect neutralization in the measurement shown in Fig. 2(b) was also proven with the very small equivalent current of 1.1 mA.

From the two beam currents of I_0 = 16 mA and I = 14 mA measured in the two different vacuum pressures shown in Table 1, we can estimate the cross section of the electron stripping reaction of H^- collided with H_2 by using the following equation.

$$\sigma_{ES} = \ln(I_0/I)/Nl \qquad (1)$$

By substituting the beam length of l= 51.5 cm and the target density of $N = 1.31 \times 10^{12}$ 1/cm^3 calculated from the vacuum pressure of 3.7×10^{-5} Torr, we estimated the cross section as follows.

$$\sigma_{ES} = 1.98 \times 10^{-15}\ (\mathrm{cm}^2) \qquad (2)$$



(a) (b)

Fig. 2 Particle distributions in the horizontal emittance phase space measured at the entrance of the RFQ; (a) when the vacuum pressure in CHM2 was 3.7×10^{-6} Torr in the typical operation and (b) when it was 3.7×10^{-5} Torr.

Table 1
Parameters of the LEBT

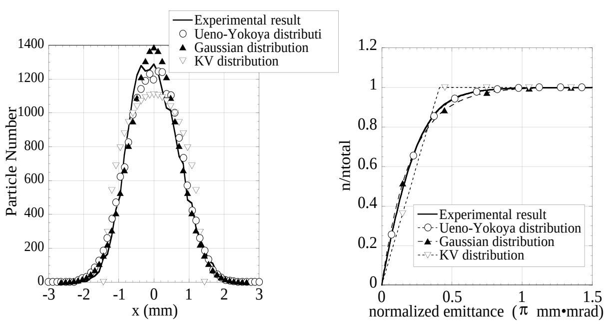
	(Typical)	(500TMP-GV close)
Beam energy (keV)	50	50
Vacuum pressure in CHM1 (Torr)	1.6×10^{-5}	1.6×10^{-5}
Vacuum pressure in CHM2 (Torr)	3.7×10^{-6}	3.7×10^{-5}
Beam Intensity at FC (mA)	16	14
Coil current of SM1 (A)	335	←
Coil current of SM2 (A)	360	←
4 times normalized rms emittance (^{1} mm·mrad)	0.4116	0.3751

Comparison of Measurements with Simulations

We measured both of the two particle distributions in horizontal and vertical emittance phase planes [5]. However, it is practically impossible to find out the correlation of these tow distributions, since the enormous number of the same precise measurements with different conditions are necessary.

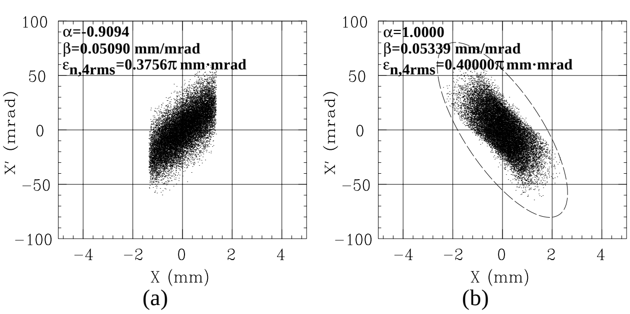
Therefore, we compared the measured particle distribution shown in Fig. 2(a) with the simulation results using the three types of theoretical initial distributions with TWISS parameters and 4 times of normalized rms emittance of α = –0.90, β = 0.050 mm/mrad and $\varepsilon_{n,4rms} = 0.41^1$ mm·mrad at the exit of the VPIS; Gaussian distribution, KV distribution and UY distribution. The beam profiles of the measurement and the simulated results are shown in Fig. 3(a). As can be seen from this figure, the result using UY-distribution well represents the measured profile. The profile simulated with

Gaussian-distribution has a higher peak and it with KV-distribution has a lower peak than the experimental result. Also the relationship between emittance and the beam fraction containing in the emittance simulated with UY-distribution showed a good agreement with the experimental result. Figures 4(a) and 4(b) show the particle distribution generated with UY-distribution at the exit of the VPIS and the particle distribution at the entrance of the RFQ simulated with the initial UY-distribution. By comparing Fig. 2(a) with Fig. 4(b), there are two agreements in these two distributions; (1) each distribution has a lozenge shape and (2) a pair of two opposite sides of each lozenge has lighter distribution compared with the other pair of sides. It is noted that the measured shape of the distribution is not an ellipse. On the other hand, the simulated phases of the sides with light distribution in the emittance phase space is slightly different from the measured results. Since we did not include the focusing effects of the extraction and acceleration gap, this focusing effects seem to cause this discrepancy.



(a) (b)

Fig. 3 Comparison of the experimental results with the simulated results; (a) the beam profiles and (b) the relationships between the normarized emittance and the beam fraction in the emittance.



(a) (b)

Fig. 4 Particle distributions in the horizontal emittance phase space; (a) the initial distribution generated with UY-dst and (b) the simurated results with an equivalent beam intensity of 1.1 mA at the entrance of the RFQ.

Conclusion

The particle distributions at the entrance of the RFQ were measured with the errors of ±0.1 mm in real space and ±1.6 mrad in x' or y' space. The 4 times of the normalized rms emittance of a H^- beam of 16 mA was measured to be 0.4π mm·mrad. By plotting the measured particle distributions with a new display method of UF-plt, the detailed structure of the distributions were revealed. The measured distribution showed good agreements with the simulation results using the newly proposed initial distribution of UY-distribution, in which the particles are distributed uniformly in the real space (concerning with x and y) and distributed in Gaussian way concerning with x' and y'.

We detected the unexpectedly strong space-charge neutralization effect only with the residual H_2 gas with a pressure of 3.7×10^{-6} Torr. In this condition, 93% of the beam intensity was neutralized with almost no beam loss due to electron stripping by collisions with H_2 gas. By worsening the vacuum pressure and measuring the total beam intensities, the cross section of the electron stripping reaction of H^- collided with H_2 was also estimated to be 1.98×10^{-15} cm^2.

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