Study on proton fraction of beams extracted from electron cyclotron resonance ion source

State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China
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A permanent magnet electron cyclotron resonance ion source PMECR II is used to generate proton ions for radio frequency quadrupole (RFQ) injection at Peking University (PKU). The proton fractions of the extracted beam were measured at the positions both after extraction system of ion source and the end of low energy beam transport line (LEBT). Experiments show that the proton fraction has a rise time within a beam pulse, and its value varies with pulse width and microwave power. The proton fractions measured at different positions are comparable.

INTRODUCTION

A desirable parameter of proton ion source is the proton fraction of the extracted beam, which should be as high as possible, especially if the ion source is used as an injector of an accelerator. Los Alamos National Laboratory (LANL) has reported that their electron cyclotron resonance (ECR) proton source, which works on 75 keV with 600–800 W of discharge power, gives a proton fraction of 85%–90%. Also they have tried adding trace amounts of water to the plasma chamber, and the proton fraction can be improved. Gobin et al. developed an ECR ion source in Saclay as the injector of radio frequency quadrupole (RFQ), and its proton fraction is 83% under 95 keV, 850 W. Kwan et al. developed an ECR ion source in Berkeley for a deuteron RFQ accelerator, which was tested with both proton and deuteron beams. For dc beam the proton fraction was about 92%. For pulsed beam they found the proton fraction has a rise time about 1.5 ms.

The proton fraction of an ECR ion source is also measured at PKU. The ion source is a 2.45 GHz permanent magnet ECR ion source PMECR II. Its outline dimension is about 11.5 cm for diameter and 11 cm for length; its discharge chamber is about 50 mm for length and 64 mm for diameter. A peak current of pulsed proton beam more than 100 mA is easily obtained through a 0.5 mm extraction hole with three-electrode extraction system. To investigate the change of proton fraction through the low energy beam transport line (LEBT), the proton fractions were measured at the positions both after the extraction system of ion source and the end of LEBT. In this paper we call the former as a short beam line and the later, long beam line. The variation of proton fraction with time during a beam pulse as well as with pulse width and microwave power is investigated.

EXPERIMENT SETUP

As shown in Fig. 1, the LEBT test bench consists of an ECR ion source, a first diagnostic section with a Faraday cup (FC1) to measure the beam current behind the extraction system, and an emittance measurement device (EMU1), an electromagnetic solenoid, an observation screen, a Faraday cup to measure the beam current behind solenoid, a second diagnostic section with another emittance measurement device (EMU2), and an analysis magnet with a Faraday cup (FC2). Two turbomolecular pumps are used to keep the vacuum for ion source and LEBT system. The ion source gas pressure is about 7.0 × 10⁻⁵ Pa; the LEBT gas pressure is about 3.0 × 10⁻⁵ Pa.

In the situation of long beam line, the H⁺, H₂⁺, and H₃⁺ species are swept into FC2 sequentially by adjusting the analyzing magnet. The beam signal from FC2 and the magnetic field signal are acquired by computer. For each species measurement, the electromagnetic solenoid current was adjusted to get the maximum beam current. In fact, the experiments showed that the focus strength of the three species is approximately proportional to the square root of the specie’s mass, which means that the three species have almost the same path through LEBT in that case.

As measurements take a longer time, the effect of total beam intensity fluctuation must be eliminated. We used a digital oscilloscope to acquire the beam signal I_total of the

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Author to whom correspondence should be addressed. Electronic mail: zj@pku.edu.cn.

FIG. 1. Scheme of the LEBT test bench.
FC1 and the beam signal $I_{H^+}$ of the FC2 simultaneously. During a beam pulse the values of $I_{\text{total}}$ and $I_{H^+}$ were sampled for 20 times, so 20 ratios of $I_{H^+}/I_{\text{total}}$ can be deduced. Then the average value of the 20 ratios can be obtained. Similarly $I_{\text{H}_2^+}$ and $I_{\text{H}_3^+}$ can be normalized and averaged, too. So the average proton fraction $R_A$ of pulsed beam can be calculated as

$$R_A = \frac{(I_{H^+}/I_{\text{total}})}{(I_{\text{H}_2^+}/I_{\text{total}}) + (I_{\text{H}_3^+}/I_{\text{total}}).}$$ (1)

For the short beam line the analysis magnet is installed after FC1, and the proton fraction $R_A$ can be obtained similarly.

**EXPERIMENT RESULTS**

**Variation of proton fraction with time**

Figure 2 shows the change of $H^+$, $H_2^+$, and $H_3^+$ fractions within one beam pulse as a function of time. The data in Fig. 2 were obtained with extraction voltage of 45 kV, beam pulse of 1 ms at 100 Hz, and microwave peak power of 2.18 kW on short beam line. From Fig. 2 we can see the pulse shape of $H^+$, $H_2^+$, and $H_3^+$ is quite different, which indicates that the fraction of molecular species is higher at the beginning of discharge and then decays slowly, while the proton fraction increases with a rise time about 600 $\mu$s and then approaches its equilibrium value $R_{\text{FT}}$. That rise time is shorter than Kwan’s report. The long rise time indicates that the molecular species are easier to produce at the initial stage of discharge, and then to be further ionized to atomic ions progressively. Here we define $t_r$ as the time when the proton fraction approaches 95% of its equilibrium value and $R_I = t_r/\tau$, where $\tau$ is the pulse width. In Fig. 2 $t_r$ is about 430 $\mu$s.

**Rise time and its effect on $R_A$**

Figures 3 and 4 show the rise time $t_r$ and ratio $R_I$ as well as the proton fractions $R_{\text{FT}}$ and $R_A$ as a function of pulse width. The experiments were carried out on short beam line and the measurement error is about 3%. The extraction voltage was 45 kV and beam pulse repeat frequency is 100 Hz. Figures 3 and 4 indicate that the average proton fraction $R_A$ increased and the ratio $R_I$ decreased when pulse width increased, but the rise time $t_r$ and the proton fraction $R_{\text{FT}}$ have no obvious variation with pulse width. Figure 5 shows the

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**FIG. 2.** (Color online) Ion species varying as a function of time.

**FIG. 3.** (Color online) $R_I$ and $t_r$ vs pulse width.

**FIG. 4.** (Color online) Proton fraction vs pulse width.

**FIG. 5.** $t_r$ vs microwave peak power.
rise time as a function of microwave peak power. Higher microwave power can shorten the rise time.

$R_A$ variation with pulse width and microwave power

The proton fraction $R_A$ was measured under different pulse widths and different microwave peak powers on both long and short beam lines. For the short beam line an electrostatic lens was inserted between extraction electrode and FC1. The measurement error was about 3% for long beam line, and about 4% for short beam line.

Figure 6 shows that the average proton fraction $R_A$ increases with the increasing pulse width for both beam lines. This is because the ratio $R_t$ decreases with longer pulse width (Fig. 3), which means the equilibrium proton fraction $R_{eq}$ has more weight in $R_A$. Figure 7 shows the variation of proton fraction $R_A$ with different microwave peak powers for both beam lines. When microwave peak power increases, the proton fraction $R_A$ also increases. This is due to the decrease of rise time $t_r$ (Fig. 5), which leads to a reduced $R_t$ for a fixed pulse width. The data with unit milliampere in Fig. 7 are the beam current measured by FC1, which also increases with microwave peak power.

We also measured the proton fraction of PMECR III (Ref. 9) with long beam line, its proton fraction is about 85% when the extraction voltage was 45 kV, and the microwave power was fixed at microwave average power of 250 W with a duty fraction of 1/5.

CONCLUSIONS

For a pulsed running of an ECR ion source, the proton fraction has a quite long rise time (at least several hundred microseconds) to reach its equilibrium value, which makes the average proton fraction during whole pulse lower than its equilibrium value. Especially when the pulse width is comparable with the rise time, the reduction may be remarkable. So it might be worth while to use longer pulse width and throw away the initial part of the beam pulse, when the beam will inject into a RFQ accelerator. For example, if the RFQ is working on a pulsed mode with the rf pulse of 0.6 ms, we can extract a beam with 1.1 ms pulse from ECR source but only synchronize the later 0.6 ms to RFQ, so that we can get more accelerated proton beam after RFQ accelerator.

The experiments show that there is no big difference between the proton fractions measured on long and short beam lines. So the results of short beam line can be taken as the basis to design a RFQ. We are going to optimize the proton fraction further by changing the material of the inner layer of discharge chamber and using hybrid gases.

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