A MASS SPECTROMETER FOR MEASURING A HIGH CURRENT ION BEAM WITH A BIG RANGE OF THE CHARGE-TO-MASS RATIO*

Zhou Bowen[1#], Sun An[1,2], Zhang Liping[3], Fan Yikui[2], Liu Guoqing[2], Zuo Xiuquan[3], Zhou Pengbo[3]

[1] PLAI, Nanjing University, Nanjing, Jiangsu Province 210046, China

[2] ADS-SRF Inc., Zongze Road 98, Zhenjiang, Jiangsu Province 212009, China

[3] Road Construction Technology & Equipment, Chang'an University, Xi'an 710064, China

Abstract

In order to analyze a high-current mixed-ion beam's physical properties with a current of 100 mA and a charge-to-mass ratio range from 1:1 to 1:48, a mass spectrometer has been developed to measure the beam's current, profile and ratio of the different ions by Nanjing University and Andesun Technology Inc. The main part of the mass spectrometer is a mass analyzer, which is used to measure the different ion's beam current at the same time. This paper introduces the design of the mass analyzer.

INTRODUCTION

A high-current mixed-ion beam with a current of 100 mA is produced by an ion source, which is used to test the material properties. In order to know the component of the beam and the charge-to-mass ratio with a range from 1:1 to 1:48, a mass spectrometer is needed to be developed.

A mass spectrometer is normally composed of the sampling system, ion source, mass analyzer and ion detector. Here the mass analyzer is the key part. Normally, a dipole magnetic field with the uniform distribution is used to separate the ions with the different mass-to-charge ratio in a mass analyzer. Generally, the shape of the mass analyzer has two kinds, namely, fan-shaped and semicircular-shaped [1-4]. The ion trajectory in the semicircular-shaped one is shorter than that in the fan-shaped one. The shorter trajectory means the less energy loss, and that the lower accelerating voltage can be used to test the beam's properties. Other word, the semicircular-shaped structure can be easy to distinguish ions for the same accelerating-voltage beam.

The mass-to-charge ratio with a large range could cause much difficulty to design a mass analyzer [5, 6]. In order to measure such a beam, a semicircular-shaped mass analyzer has been chosen, and magnetic field's distribution has been analyzed in detail. In the paper, the design of the mass analyzer has been introduced.

TRAJETORY ANALYSIS OF THE ION

The dimension of the mass analyzer is decided by the ion trajectory. The ion trajectory is decided by the intensity of the magnetic field. For the semicircular-shaped mass analyzer, the start point of the ion trajectory is normally set on the same edge where the detectors are

located. Based on this consideration, we have analyzed the ion trajectory and decided the dimensions of the mass analyzer.

For an ion beam, its physical property can be described by following parameters:

1) Ion's electrical quantity q, here $q=ze$, in which z is the positive integer, and q is the unit charge.
2) Ion's mass m, here $m=nu$, in which n is the positive integer, u is unit of atomic mass.
3) Ion's charge-to-mass ratio η, here $\eta=q/m=ze/nu$.
4) Beam's transverse diameter d.

The ion beam is moving in a dipole magnetic field with an induction intensity B, whose direction is –x. Before entering the magnetic field, an ion has been accelerated in -z direction by an accelerating voltage U, the ion's velocity is:

$$\vec{V} = \vec{Vx} + \vec{Vy} + \vec{Vz}.$$

The angle α, β and θ of the velocity in a rectangular coordinate system are shown in Fig. 1.

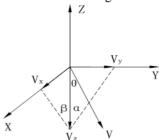Figure 1: Angle of the velocity in the coordinate system.

The relationship between ion speed and its energy can be described by $0.5mv_z^2=Uq$. Then the v_z can be written as:

$$|\vec{v}_z| = \sqrt{2\eta U} \tag{1}$$

And

$$|\vec{v}_y| = |\vec{v}_z| \tan \alpha \tag{2}$$

$$|\vec{v}_x| = |\vec{v}_z| \tan \beta \tag{3}$$

The velocity on the y-z plane can be written as:

$$v_{y-z} = \sqrt{v_z^2 + v_y^2} = v_z \sqrt{1 + \tan^2 \alpha} = \frac{v_z}{\cos \alpha} \tag{4}$$

On the y-z plane, the ion is moving on a circle with a uniform speed due to Lorentz force. Its action is described by

$$\frac{mv_{y-z}^2}{R} = qv_{y-z}B \tag{5}$$

Combining equation (1), (4), (5), the radius of the circle is obtained as:

$$R = \frac{mv_{y-z}}{qB} = \frac{v_z}{\eta B \cos\alpha} = \frac{\sqrt{2U}}{\sqrt{\eta}B\cos\alpha} \qquad (6)$$

Supposing ion's initial position is $(y_0, 0)$ $(-d < 2y_0 < d)$, the center of the circle is:

$$A(y,z) = A(y_0 + R\cos\alpha, R\sin\alpha) \qquad (7)$$

The trajectory of the circular motion can be described as:

$$[y - (y_0 + R\cos\alpha)]^2 + (z - R\sin\alpha)^2 = R^2 \qquad (8)$$

After deflecting in the magnetic field, ions will hit on the x-y plane. Setting $z=0$, the y can be obtained from equation (8):

$$y = y_0 + 2R\cos\alpha \qquad (9)$$

Substituting equation (6) into the formula (9), we have:

$$y = y_0 + 2\frac{\sqrt{2U}}{\sqrt{\eta}B} \qquad (10)$$

Equation (10) shows that the final y-coordinate value is independent of the beam radiation angle α. We define the equivalent motion radius as:

$$R' = \frac{\sqrt{2U}}{\sqrt{\eta}B} \qquad (11)$$

The equation (11) displays the equivalent motion radius is inversely proportional to one half power of charge-to-mass ratio, in the condition that the value of accelerating voltage U and magnetic induction intensity B are constant.

For the ion H^+, C^+_n (n=1~4), O^+, their equivalent motion radius are arranged as:

$$R'_1 : R'_{1/12} : R'_{1/16} : R'_{1/24} : R'_{1/36} : R'_{1/48}$$
$$= 1 : 2\sqrt{3} : 4 : 2\sqrt{6} : 6 : 4\sqrt{3}$$
$$\approx 1 : 3.464 : 4 : 4.899 : 6 : 6.928 \qquad (12)$$

In order to ensure different kinds of ions do not overlap when they hit the x-y plane, the following condition must be satisfied:

$$2\Delta R'_{min} \ge d \qquad (13)$$

Where $\Delta R'_{min}$ is the minimum difference of equivalent radius, and can be written as:

$$\Delta R'_{min} = R'_{1/2} - R'_1 = (\sqrt{2} - 1)R'_1 \qquad (14)$$

Taking above formula into equation (13), we find:

$$R'_1 = \frac{\sqrt{2U}}{\sqrt{\frac{e}{u}}B} \ge \frac{d}{2(\sqrt{2}-1)} \qquad (15)$$

$$B = \frac{\sqrt{2Uu}}{\sqrt{e}R'_1} \qquad (16)$$

From entering the magnetic field to leaving it, the flight time of the ions is:

$$T = \frac{R(\pi - 2\alpha)}{v_z/\cos\alpha} = \frac{\pi - 2\alpha}{v_z} \qquad (17)$$

In x-direction, ions make uniform linear motion, its velocity is $v_x = v_z\tan\beta$. Here β is beam radiation angle in x-direction. The distance that ions move in x-direction is:

$$X = v_x T = R'(\pi - 2\alpha)\tan\beta \qquad (18)$$

The relationship between α, β and θ is:

$$\sqrt{\tan^2\alpha + \tan^2\beta} \le \tan\theta \qquad (19)$$

Combing equation (18) and (19), the X can be approximately expressed as:

$$|X| \approx \pi R'\tan\theta \qquad (20)$$

DIMENSION ANALYSIS

For our condition, the beam section diameter is 0.02 m, radiation angle θ is 10°, the accelerating voltage is 100 kV, and the energy dispersion $\Delta U \le 0.01U$. According to equation (15), the value of the equivalent radius of H^+ is:

$$R'_1 \ge \frac{0.02}{2(\sqrt{2}-1)} \approx 0.02414\,\text{m} \qquad (21)$$

Considering error such as energy dispersion and energy loss, the minimum R_1' would be:

$$R'_1 = 0.025\,\text{m}$$

Using equation (16), we found the magnetic induction intensity B=1.82 T.

Actually, the magnet of 1.82 T is hard to produce and very expensive, thus, we change B_0 into 0.46 T.

Combining the equation (11), (12), (20), the equivalent radius R' of the different ions and lateral drift distance X can be obtained. Their final values are listed in Table 1. Figure 2 shows the equivalent moving trajectory of 7 different ions on the y-z plane.

Table1: n/z, R' and X of Different Ions

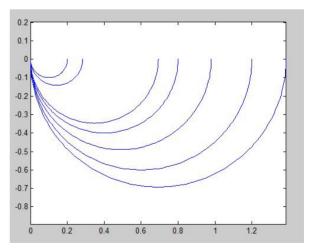| type	H^+	C^+	O^+	C_2^+	C_3^+	C_4^+
n/z	1	12	16	24	36	48
R'(m)	0.1	0.35	0.4	0.49	6	0.69
X (m)	0.056	0.19	0.22	0.27	0.33	0.38

Figure 2: Equivalent moving trajectory of 7 different ions on the y-z plane.

DISCUSSIONS

Relativistic Effect

Considering the condition that the accelerating voltage is 100 kV, and the velocity in x-direction is maximum

when $\eta=e/u$, the H^+ get the maximum velocity 4.376×10^8 m/s. Taking relativistic effect into consideration, for the H^+, the increment of mass is

$$\Delta m = (\frac{1}{\sqrt{1-(\frac{|\vec{v}_{z,\max}|}{c})^2}}-1)m_0 = 0.0001m_0$$

The new charge-to-mass ratio is $\eta'=q/(m+\Delta m)\approx\eta$. So there is no problem to deem that charge-to-mass ratio does not change, that is, we can neglect the relativistic effect.

Energy Dispersion

In fact, the value of accelerating voltage is not a constant. The energy dispersion will influence the z-direction velocity of the ions, and bring about error of the moving radius in the magnetic field. So, we take the energy dispersion into consideration, and modulate the strength and size of magnetic field.

The real accelerating voltage is $U=U_0+\Delta U$, where U_0 is the ideal voltage, and ΔU is its deviation. Normally, $\Delta U \ll U_0$. The actual equivalent radius is:

$$R' = \frac{\sqrt{2U_0}\sqrt{1\pm\frac{\Delta U}{U_0}}}{\sqrt{\eta}B} \approx \frac{\sqrt{2U_0}}{\sqrt{\eta}B}(1\pm\frac{\Delta U}{2U_0}).$$

Because of energy dispersion, the difference between ideal and actual equivalent moving radius is:

$$\Delta R' = \frac{\sqrt{2U_0}}{\sqrt{\eta}B}2\frac{\Delta U}{2U_0} = R'_0\frac{\Delta U}{U_0},$$

$$R'_0 = \frac{\sqrt{2U_0}}{\sqrt{\eta}B},$$

Where is the ideal radius. It's easy to find that the ratio between ΔR and R_0' is equal to the ratio between ΔU and U_0, that means larger the energy dispersion is, the bigger size of the magnetic field should be.

CONCLUSION

A 0.46 T magnetic field is used in this mass spectrometer. Its size is about 1.4m×0.7m×0.4m. After a flight time, ions will be captured by ion detector, and ion ratio in the beam can be calculated out by the current value. A further simulated calculation is needed to verify the feasibility of this mass analyzer.

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