Injection system of the minicyclotron accelerator mass spectrometer

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Abstract The existing injection system of the SMCAMS (super-sensitive minicyclotron accelerator mass spectrometer) is described together with the discussion of its disadvantages exposed after having been operating for five years, which provides a basis for consideration of improvements to the injection system. An optimized injection system with an analytical magnet added prior to the minicyclotron has been proposed and calculated.

Keywords Minicyclotron, Three-diaphragm lens, Space charge effects, X-rays, Image magnification

1 Introduction

The super-sensitive minicyclotron AMS (SMCAMS), which was set up in 1993 in Shanghai, is dedicated to the radiocarbon analysis, which has been extensively applied to archeology, hydrology, paleoclimate etc. and will bring a profound significance into the biomedical and life-scientific fields in the future. Its unique technical features and key performance, which are quite different from and at some aspects (particularly in the terms of its expense and volume etc.) more superior to the tandem AMS, have been stimulating the involved researchers for more than 10 years.[1]

Apart from the principle difference in analytical methods between the tandem AMS and the minicyclotron AMS, their optical features are also very different. The minicyclotron AMS is more sensitive to the optical features due to its smaller particle acceptance than the tandem AMS, so it is always both of great importance for the stable isotopic ratios and energy-consuming. Two joints, one at the end of injection and the other at the beginning of extraction, are rather difficult to match, particularly the former has shown much trouble during past years' operation.

In this article, several disadvantages of the existing injection system, which were exposed after five years operation, will be discussed in detail and an optimized injection system with an additional analytical magnet is proposed. It will be of benefit to overcoming X-ray interference, to measuring $^{12}C^{-}$ beam current simultaneously while accelerating ^{14}C at the injection stage, and to improving the vacuum condition.

2 Some disadvantages exposed during routine operation

2.1 Problems with the three-diaphragm lens

Negative ions emitted from the multi-sample sputter negative ion source are extracted and weakly focused by the extraction electrode which forms a immersion lens together with the exit of the spherical ionizer(see Fig.1). The following three-

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diaphragm lens provides the ions with a focusing to produce a waist near the entrance of the vertical spherical electrostatic injection deflector. Then going through a horizontal electrostatic deflector which is after the vertical one by a distance of 30 mm, the ions are rotated by 90 degree to be in horizontal. At the exit of the horizontal one the ions are injected into the central region of the minicyclotron. Two sets of electrostatic steerers after next to the three-diaphragm lens are designed to aim the ion beam at the entrance of the first injection deflector in both directions.

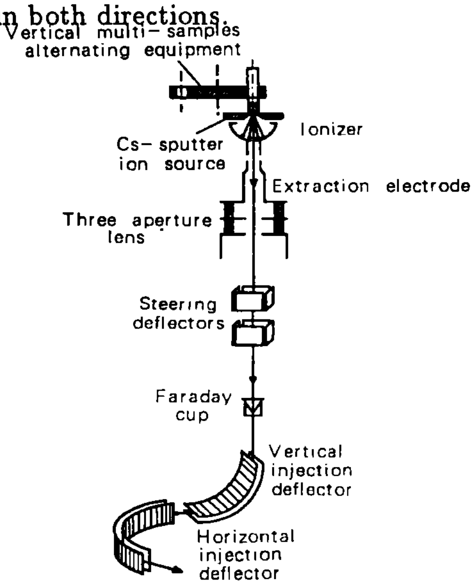

Fig.1 Existing injection system

In the previous design[2], the first one of the three diaphragms, combined to the end of the extraction electrode, usually had a fixed voltage of 20 kV so that the maximum beam current was acquired. The third diaphragm voltage was alternatively set to 17.5, 16.15 and 15.0 kV for the three types of C isotopic ions($^{12}C^-$, $^{13}C^-$ and $^{14}C^-$) to adjust their injection energy during the sequential acceleration, so that the identical injection momentum is obtained to match the fixed magnetic rigidity of ions at the injection radius of the minicyclotron.

Unfortunately, because a small piece of magnet(5mT) had been located nearby the ionizer of the ion source in order to restrain large number of electrons generated in the sputter process, this arrangement had led to different trajectories for the three types of isotopic ions before entering the three-diaphragm lens due to their identical extracting energy and thus different extracting momentum. According to a simplified calculation, the above magnetic field deflects the C negative ions by more than 0.1° and the difference among the three different isotopic ions is 0.01°. Moreover, comparatively large image magnification of the injection system, which will be discussed below, aggravates this effect.

Under present routine operation, the field of small magnet has been decreased to (2mT) to make the trajectory deviation as small as possible, and meanwhile this magnet has been moved from nearby the ionizer to nearby the extraction electrode which now is connected to the third of the diaphragms and thus has the same voltage as the third one to provide identical momentum for the three types of isotopic ions before entering the three-diaphragm lens. The problem as mentioned above is solved and a much easier regulating of the three-diaphragm lens than before is acquired because it equals, in fact, to a single lens. The possibly variant extraction efficiency for different negative ions under different extracting voltages has almost no effect on the results of isotopic ratio measurements, considering the use of standard samples in the measurements.

2.2 Large image magnification

The biggest weakness of the existing injection system is its large image magnification. According to the optical calculations with the GIOSP (General Ion Optical System on PC's)[3], the image magnification factor in the existing injection system is more than 5 and it put high demand on both the accurate sample location and the stability of electric parameters in the injection system for precise measurements. The former is quite difficult to meet so that we have spent much vigor on locating samples accurately. The applied voltages on the steerers at present are unreasonably high, which would, in general situation, deflect the ion beam away from entering the vertical deflector unless the image magnification and also the misalignments are employed for interpretation. This, however, has given us a clear proof. The too long drift length after the three- diaphragm lens constitutes a main cause although its primary goal is to ensure certain characteristic length of beam waist so as to lower focusing requirements in the central region of the minicyclotron, where the focus strength is weak due to the low magnetic fields.

2.3 Problems with space charge effects

After taking the space charge effects into account in the checking calculations with the GIOSP, the beam envelope at the entrance of the vertical deflector was much more wider than that expected, which was ignored in the previous design. It would lead to the beam loss in the two electrostatic deflectors and therefore may be a potential factor that causes the isotopic fractionation. However, the analysis of this effect in quantity is impossible because of the complication of charge effects itself and the still existing fluctuations in our system.

The space charge effects has been reported by Oxford.[4] It also exists in the minicyclotron proved by the fact that the three-diaphragm lens must have different focusing among samples for their corresponding maximums of the extracted beam currents. The space charge effects also accounts probably for our poor injection efficiency, whose maximum value of 65% was ever acquired for the primary beam current of about 50μA, and a beam spot with rectangular-shape at the exit of the horizontal deflector ever found during dealing with the matching problems between the two deflectors. The charge effects in our system, moreover, is reinforced by the low injection energy and too long drift length after the three-diaphragm lens.

2.4 Problems due to lack of an analytical magnet

An analytical magnet was removed from the original design scheme of SM-CAMS due to the lack of funds. So all types of the ions have to be injected simultaneously into the minicyclotron. However, not only does it bring about a difficulty to measure the internal beam of each type of the isotopic ions, but also the following problems arise.

2.4.1 X-ray interference: X-rays caused by simultaneous injection of the unwanted ions ($^{12}C^-$, C_2^- while detecting $^{14}C^-$) have constituted a strong interference with $^{14}C^-$ detection. This is also because a MCP(microchannel plate) detector[5,6], which is sensitive to both negative heavy ions and X-rays, is used for counting ^{14}C ions. All the efforts for shielding the X-rays have reduced backgrounds count rates only to 0.5 count/s , a distance still exists to dating application. However, a magnetic analyzer will allow the complete elimination of the X-ray interference because the unwanted ions with high beam intensity will be deflected away before injecting to the minicyclotron.

2.4.2 Unstable loss of $^{12}C^-$: On the existing system, each type of isotopic ions is sequentially accelerated and measured by changing radio frequency and many electric parameters. But unlike the ratio $^{14}C/^{13}C$, $^{13}C/^{12}C$ has proven to be unstable. It arises most probably from the dissimilar loss of $^{12}C^-$ with $^{14}C^-$ and $^{13}C^-$ in the minicyclotron considering its higher beam intensity. However, its mechanism is still not exactly known. The analytical magnet will make it possible to simultaneously measure ^{12}C while accelerating $^{14}C^{-}$ at the injection stage, which will eliminate this effect and shorten the measurement cycle.

2.4.3. Degradation of the vacuum condition: Although about 20 s^{-1} ^{14}C counting rates for Modern samples have been reached on the SMCAMS, a higher counting rates will benefit dating old samples and improving the statistical precision as well as the analysis throughput. But the good beam transmission through the minicyclotron will put a high demand for the vacuum condition inside the minicyclotron since the ^{14}C negative ions with extra low energy have to travel more than 200 m inside it. The curves of beam current vs vacuum is shown in Fig.2. A degradation of the vacuum condition on the order of 10^{-7} Pa has been observed with a vacuum gauge at the side of the vacuum chamber when the ion beam was injected. This observed degradation, however, is smaller than the real one because the gauge is far away from the central region of the minicyclotron. The simultaneous injection of the unwanted ions with high intensity could also cause the unexpected deterioration of the local vacuum due to the sputtering of the unwanted ions on the inner parts or wall, which will bring

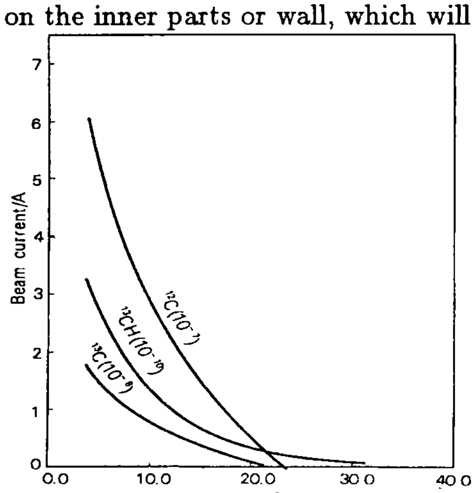

Fig.2 Curves of the beam currents of ^{12}C, ^{13}CH and ^{13}C *vs* vacuum in the minicyclotron

about an unexpected effect on the isotopic ratios. All these problems can be solved or lessened with an additional analytical magnet, through which the unwanted ions with high intensity will be deflected away and not injected into the minicyclotron.

3 New injection system proposed

In order to lessen both the space charge effects and the high demand on the accurate sample location, one solution is to add an analytical magnet in the existing injection system and optimize the system as short as possible, in the meanwhile its image magnification factor as small as possible. Increasing the ion injection energy to a too high level is impractical to the minicyclotron.

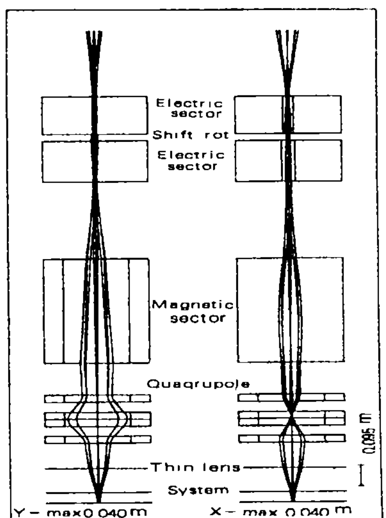

Fig.3 ^{14}C beams envelope calculated to the second order. Images are resulted in both directions at the entrance of the vertical spherical deflector. The image magnification factors have been modified to less than 2.5 in both directions

The GIOSP was used for this optimization calculation. A triplet of electrostatic quadruples with relative strong focusing is employed considering the high primary beam currents. The three-diaphragm lens is retained before the triplet to provide a weak focusing, which is important for lowering the image magnification factor. A 90° analytical magnet(R=300 mm) with double focusing is added to inject relative small beam current (of mass number 14 and alternative 13, which have shown excellent results of isotopic ratios on the existing system) into the minicyclotron and to measure $^{12}C^-$ simultaneously at the injection stage. The resulted image at the entrance of the vertical injection deflector in both directions is more convenient for the following two spherical deflectors which is basically a parallel-to-parallel optical system. The beam envelope calculated to the second order is shown in Fig.3. and the beam intensity distribution in phase space at the exit of the horizontal spherical deflector gives no distortion or too short characteristic lengths(see Fig.4).

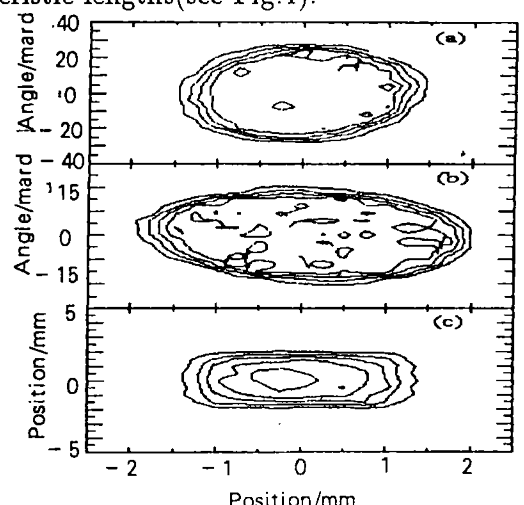

Fig.4 Beam current distributions in the phase space at the exit of the horizontal spherical deflector.

Five curves represent respectively the contour lines of 90, 70, 50, 30, 10 per cent of the maximum beam intensity. (a) In the deflection direction. (b) Perpendicular to the deflection direction. (c) The section of the ion beam. The practical situation will be better because here one fifth of the primary beams (50 μA) was assumed to pass through the two electrostatic deflectors, which exaggerates the charge effects in the deflectors

Another advantage of such an injection system is that it will become a horizontal one, which is obviously more ideal for our routine operation and will lower the requirements of the ion source. Furthermore, no limit is given on the alignment of the magnet because of the imaging features of the injection system in both directions. The initial beam emittance and characteristic length are very important for optical calculation. These values are refered to our ion source manufacture's. The 45 mm·mrad of the initial emittance, 1.5 cm of the characteristic length and 50μA of the primary beam current, which is the usual case during the routine operation, were assumed. The fringing angles at the both sides of the magnet are both 26.565°, the gap is 5 cm. The aperture radius of the quadruples are 2.5 cm and their effective lengths are 3.2, 6.4 and 3.2 cm, respectively. Laminar beam model with uniform density profile is used to take the space charge effects into account, considering heavy ions with low energy.[7]

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