A SUPER SENSITIVITY MINICYCLOTRON MASS SPECTROMETER SPECIALIZED FOR CARBON－14 DATING

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ABSTRACT

The structure consideration of a minicyclotron as super－sensitivity mass spectrometer for carbon－14 dating being constructed at this Institute is described. Some new design ideas and techniques are presented.

Key words: Super－sensitivity minicyclotron Mass spectrometer ^{14}C－dating.

I. INTRODUCTION

As a new application of the nuclear techniques, the accelerator mass spectrometer (AMS) has rapidly been developed during the last decade, which provides a new technique in ion beam analysis and provides an effective method for isotope chronology. Recently, such an AMS technique has been applied to material science and biology science. Nevertheless, the present AMS work is mostly being carried out on the existing large accelerators－high energy AMS, it has not been popularized due to its high cost. It is thus preferred that for practical and popular application the AMS ought to be a specialized small accelerator－low energy AMS. Since the early eighties, commercial tandems specialized for dating have been available[1], and the Berkeley laboratory has initiated the building of a small uniform magnet cyclotron for carbon－14 dating[2] Since late 1985, a non－uniform magnet minicyclotron as supersensitivity AMS specialized for carbon－14 dating has been studied, designed and constructed at this Institute.

II. FUNDAMENTAL CHARACTERISTICS

Other than a conventional cyclotron or an ordinary mass spectrometer, a supersensitivity minicyclotron AMS is possessed of some peculiarities[3] arising from its fundamental characteristics－"mini" in size and "supersensitivity" in analysis function－which are characterized by small working radius, high operating harmonic, low reached energy and trace of detected radionuclei. (1) The small working radius makes the penetration effect of the electric field and the magnetic field significant, and thus makes the injection and extraction of the particles complicated, the shimming of the isochronous magnetic field difficult, and the phase grouping effect have to be considered; (2) The high operating harmonic makes some effects greatly enhanced, and thus maked beam quality deteriorated and beam intensity diluted; (3) The low reached energy makes it impossible to use a usual nuclear detector to identify the radionuclei, instead, the single particle detector consisting of dynode and micro channel plate is used[4]. Because such a detector can just count the particle number and can not discriminate the particle kind, it will put crucial condition on the resolution of a minicyclotron AMS; (4) The trace of detected radionuclei makes it necessary that the AMS not only should thoroughly get rid of all kinds of backgrounds (isobar, molecule and multiple particles) which are more than 10^8 times as intense as the radionuclei to be detected, but also should efficiently deliver the detected radionuclei which are so rare that the counting rate for a modern carbon – 14 sample, e.g. NBS standard, is typically of the order of 20 counts per second on tandem AMS[5]. Thus all possible measures must be taken to prevent any backgrounds from reaching the recording apparatus and being measured in error, and some new ideas must be introduced to improve the particle acceptance of a minicyclotron.

Ⅲ. STRUCTURE CONSIDERATION

(1) It is very desirable for a minicyclotron mass spectrometer to be able to promptly change samples and greatly eliminate the memory effect, thus the external injection is recommended. However, choosing external injection result in high expenditure and low injection efficiency. To improve injection efficiency, the deceleration mode of the minicyclotron AMS is then considered.

Nevertheless, the primary shortcoming of the deceleration mode is that the nonnormalized emittance of a beam bunch expands as the particle energy decreases in the course of deceleration. It greatly limits the acceptable initial beam emittance, and makes the adopting of deceleration mode to improve the injection efficiency insignificant. To compensate such an emittance expansion, a reasonable way is to pre – accelerate the particles before they are injected into the minicyclotron. In doing so, the beam emittance will first shrink in the injection line and then expand inside the minicyclotron. It so happens that such an additional voltage on the injection line is also required for raising the energy of the extracted particles to have high counting efficiency[4] and for adjusting the energy of the injected particles to realize the multiradionuclei analysis[6] as well as for pulsing the energy of the injected backgrounds to carry out the sequential measurement.

(2) In conventional mass spectrometers, analysed particles move along the uniform magnetic field and circle for less than 360 inside the magnet. Though the magnetic field of a uniform magnet is changeable, and its manufacture is easier and cheaper than that of a non – uniform magnet, a uniform magnet is in fact not suitable for an

accelerator mass spectrometer with cyclotron type where the analysed radionuclei will circle inside the magnet for many turns. In a uniform magnet, the axial betatron oscillation frequency $\nu_z = 0$, there does not exist the magnetic focusing; the radial betatron frequency $\nu_r = 1$, which is sensitive to any electric or magnetic first harmonic. Even though the magnet is assumed to be so perfect that its magnetic first harmonic is negligible, the electric gap – crossing resonance will be inevitable[2]the external injection into a uniform magnet is quite complicated during operation with acceleration mode[7],and its injection efficiency must be very low; and the operation of deceleration mode can also not be adopted, because the detector can not work under the strong magnetic field, and the introduction of a magnetic shielding into the center of the uniform magnet must greatly deform the uniformity of the magnetic field.

Therefore, a non – uniform magnet with high flutter is designed, and its yoke itself constitutes the vacuum chamber of the minicyclotron AMS (Fig.1). On the internal surface of the top and bottom covers of the vacuum chamber are symmetrically sticked four pairs of radial sectors with each about 45° wide and 9 cm high, and the gap between up and down sectors is 2 cm which has the same height as the Dee aperture H. The maximum magnetic field at the center of each hill is about 0.7 T, it is excited by two circular coils which surround the four sectors respectively, and are enveloped in two stainless rings to separate themselves from the vacuum chamber. The isochronous magnetic field will be shimmed by correcting the shape of the sectors and

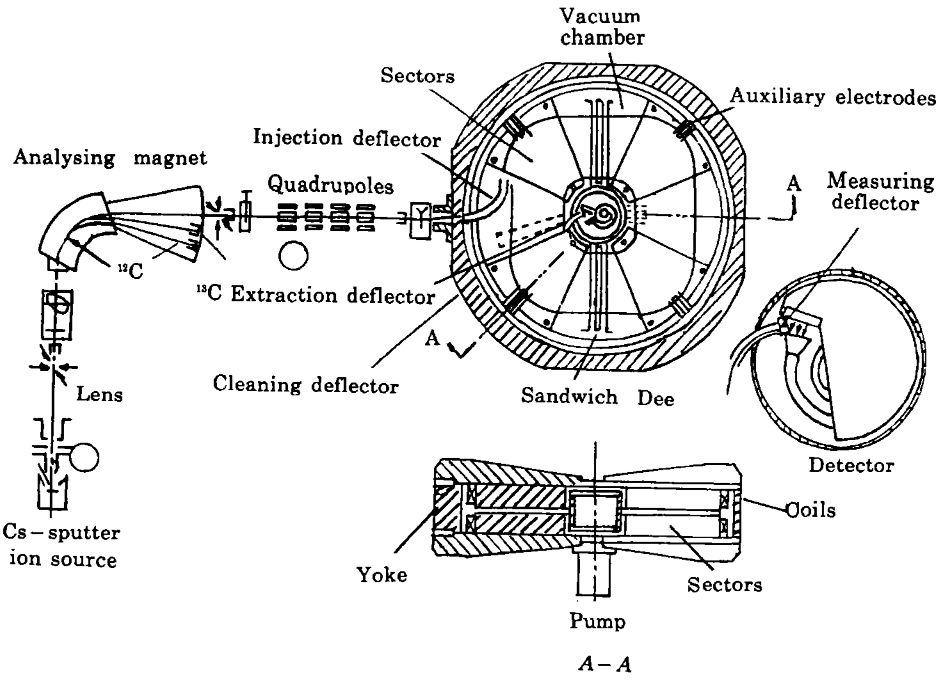

Fig.1 Schatmetic diagram of set up on minicyclotron AMS

without using trim coils. On the two magnet covers in the valley areas are symmetrically cut out 8 sectored holes where is the access for the accelerator parts, and these holes are seated with eight stainless plates on which the accelerator parts are fixed. At the centers of the two covers are cut out holes of 20 cm in diameter to connect with the vacuum pump on the one side and the detector on the other side. The whole magnet is about 40cm in height and 140cm in diameter, its total weight is about 3.5 t.

(3) In the fifties, a number of small cyclotron mass spectrometers appeared. All of them, however, ended in failure to get the abundance sensitivity of higher than 10^{-6} due to their poor particle acceptance. One of the reasons for it is that the ordinary sine – wave dee voltage was used in all those machines with high harmonic operation. Then we adopt a non – sinusoidal wave dee voltage in our minicyclotron. It is clear from our calculation[8] that the shape of the non – sine wave should be a triangular wave for our sandwich dee structure, which causes the particle acceptance to increase by more than a hundred – fold as compared with that of using a sine – wave dee voltage (table 1). Such as improvement also implies that the restraints on the mechanical allowance and the electrical instability have greatly been alleviated.

Table 1

Comparing the effect of SW with that of NSW on the maximum energy spread

SW(sine wave)			NSW (non – sinusoidal wave)		
ε_x = 4mm – mrad	ΔT_0	ΔE_m%	ε_x = 4mm – mrad	ΔT_0	ΔE_m%
$\Delta E_0 = 0$	0°	0.46	$\Delta E_0 = 0$	0°	–0.087
$\Delta E_0 = +0.2\%$	–2°	1.8	$\Delta E_0 = +0.2\%$	–20°	1.3
	–2°	1.38		–20°	0.79
$\Delta E_0 = -0.2\%$	–2°	–0.66	$\Delta E_0 = -0.2\%$	–20°	0.56
	–2°	–0.78		–20°	–0.79

The possibility of adopting the triangular wave voltage in a minicyclotron AMS is based upon the fact that, unlike a conventional cyclotron where the maximum energy gain is required, the least energy gain is preferred to make the turn spacing tight enough. Therefore, only very low dee voltage is needed. However, the rf ramp generator with peak to peak of 1 kV, which is already not easy to make, can only produce 1— 2 mm turn spacing which is not enough for clearing both the injection deflector and extraction deflector. Then the auxiliary electrode are suggested to meet the contrary demande. They will be placed at 45° or 90° apart from the azimuthal position of the main dee electrode. In so doing, the expensive phaser and phase stabilizer can be saved, if the harmonic number is equal to the integral times of 8, say, $h = 16$.

(4) For dating application, the ratio of the radionuclei to their corresponding stable isotopes such as $^{14}C/^{12}C$ and $^{14}C/^{13}C$ must be measured. Since the ^{12}C and ^{13}C are

measured on the two Fraday cups at the exit of the analysing magnet, the transmission efficiency of ^{14}C from the analysing magnet down to the detector must be calibrated by standard or known samples all the time. To improve the precision of measurement, the sequential measurement of $^{12}CH_2$ and ^{14}C is introduced. During the measurement of $^{12}CH_2$, one parameter which should be changed is the rf frequency, and the other electrical parameters which ought to be changed only for about one thousandth can keep unchanged. Of course, it would be better to have sequential measurement of ^{12}C and ^{14}C, but all the electrical parameters must promptly be changed for about 15%. At present time, we are not quite sure if it will work well.

During sequential measurement, two additional deflectors have to be supplemented. One is the 'measuring deflector' to which a pulsed rectangular voltage is applied while detecting ^{14}C to deflect it onto the dynode of the detector. This voltage will be suppressed while measuring $^{12}CH_2$ or ^{12}C, when the background particles emitted from the 'extraction deflector' will aim at a Fraday cup; The other is the 'cleaning deflector' to which a pulsed voltage is applied at the moment when the sequential measurement is turning into ^{14}C measurement from $^{12}CH_2$ or ^{12}C measurement.

Ⅳ.CONCLUSION

Such a minicyclotron AMS will keep the advantages of the high energy AMS: super sensitivity (10^{-12} – 10^{-16}); trace of sample (<1mg); short measuring time (<1 h); and extended dating age (>30000 year), and primarily it can be set at any dating laboratory for utilitarian applications, because of its compact and small size, low device cost and operation charge, convenience for operating, and especially with no expenditure of money on shielding or special building. Therefore, it is in prospect for such a minicyclotron to be commercialized.

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