A NEW TYPE OF MINI CYCLOTRON AS ACCELERATOR MASS SPECTROMETER

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The Facility SMCAMS is the first cyclotron using triangular wave accelerating voltage under high harmonic operation to accelerate negative heavy ions and to be used as an Accelerator Mass Spectrometer (AMS). The differences between conventional cyclotrons and the minicyclotron SMCAMS will be discussed.

1. Introduction

Accelerator Mass Spectrometry (AMS) has rapidly been developed since 1980's. AMS, as a new application of accelerators, has extensively been applied to archaeology, earth and planetary science. material and environmental science, and especially AMS has a bright future in bio-medical application.

However, the existing cyclotrons are in fact inadequate to AMS application due to a number of limitations related to cyclotron technology[1]. As a result, cyclotron AMS has been overwhelmed by tandem AMS over the past decade.

In parallel with the initiative of Berkeley group[2], the miniature cyclotron SMCAMS(Fig. 1) was also submitted at SINR in the late 1985[3]. After careful calculation and analysis, it was realized that the minicyclotron used as AMS could by no means be treated just as a conventional cyclotron, and a series of new ideas and unique technical measures were put forward[1]. In March of 1993, the first radiocarbon analysis was successfully carried out on this new type of AMS facility[1], which has opened a new direction in AMS technique.

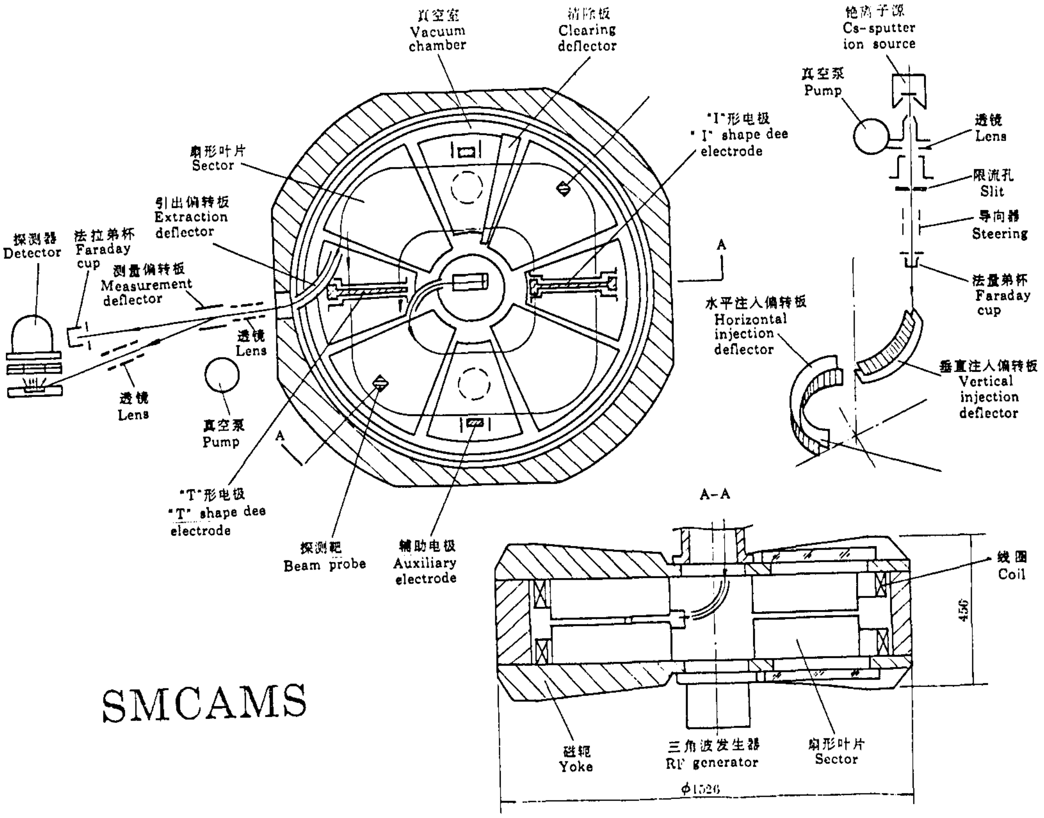

Figure 1: The schematic diagiam of the mini cyclotron AMS

2. Differences between conventional cyclotrons and the minicyclotron SMCAMS

Other than conventional cyclotrons , the minicyclotron AMS is possessed of some peculiarities characterized by its 'miniature' parameter condition, 'high' harmonic operation and 'super sensitive' analysis function, which can be summarized as follows[4]:

2.1 EXTRA HIGH SENSITIVITY

The basic idea of the minicyclotron AMS specialized for radiocarbon ^{14}C analysis is using the powerful function of the resonance analysis of cyclotron alone to discriminate the radioisotope (^{14}C) from all unwanted particles including stable isotopes of the same element (^{12}C, ^{13}C), atomic and molecular isobars (^{14}N, $^{12}CH_2$, ^{13}CH) and other backgrounds.

The abundance ratio of the ^{14}C is as low as 10^{-12} -- 10^{-15}, and the background, such as ^{13}CH -- the most adjacent background to ^{14}C, is more than 10^8 times as intense as the ^{14}C. Therefore, the AMS must be a super sensitive mass spectrometer. The special demand to such super sensitive AMS is that the AMS not only should efficiently deliver the ^{14}C or the ^{12}C (acceptance of minicyclotron), but also should thoroughly get rid of all kinds of backgrounds (resolution of mass spectrometer).

2.2 EXTRA LOW ENERGY GAIN

The resonance analysis of the minicyclotron has nothing to do with the energy gain of ions. Hence unlike in conventional cyclotrons where maximum energy gain of an accelerated ion is required, the least energy gain per turn is preferred in a minicyclotron AMS to obtain the necessary turn number within the least working area and to improve the beam quality, except that high energy gain is desired for injection and extraction. Hence the minicyclotron-based AMS is really a low energy AMS.

2.3 HEAVY NEGATIVE IONS

Because there do not exist stable negative ions(such as N^-) for the isobars of most radioactive nuclei to be analysed by AMS, and the desired resolution of AMS will greatly be decreased, if negative ions of a sample, rather than positive ions, are analyzed, thus the minicyclotron used as an AMS must be a negative heavy ion cyclotron. Nevertheless, the formidable difficulty for a negative heavy ion cyclotron is that the cross section of dissociation of these accelerated ions especially with extra low energy is so large that their revolution in the mini cyclotron even under extra high vacuum can not be long.

2.4 HIGH HARMONIC OPERATION

The resolution for discriminating $^{14}C^-$ from $^{13}CH^-$ is about 1800. The resolution formula of a cyclotron:

$$R = m/\Delta m = 360° \; nh / \Delta\theta = 2nh \qquad (1)$$

where $\Delta\theta = 180°$ -- the maximum defined amount needed for shifting the r.f. phase of $^{13}CH^-$ ion to the deceleration phase, n-- the corresponding maximum turn number , and h-- the harmonic number, i.e., the ratio of r.f. frequency to ion $^{14}C^-$ revolution frequency. Obviously, the high resolution can be achieved by increasing the product nh. However, the increase of either n or h would put more strict mechanical allowance and great electrical stability as well as the precise isochronous of magnetic field on a minicyclotron itself, hence would jeopardize the particle acceptance of a minicyclotron.

Moreover, large turn number n would : (a). be unfavorable to the operation of negative heavy ion $^{14}C^-$ with extra low energy; (b). enlarge the diameter of the minicyclotron magnet; or (c). tighten the turn spacing so as to damage the injection and extraction of ions.

Therefore, we are forced to meet the high resolution by increasing the harmonic number h(=16). Nevertheless, high harmonic operation would greatly enhance some effects, such as energy spread of beam, r.f. phase grouping and phase shift of ions, coupling effect between longitudinal motion and transversal motion of particles, thus would make beam quality deteriorated and beam density diluted.

It is really a taboo for a cyclotron to be operated with high harmonic. The key cause for it is that the usual sinusoidal wave accelerating voltage is used in all existing cyclotrons including those small cyclotrons used as mass spectrometers with high harmonic operation[5], that is one of the main reasons for them to have very poor beam intensity.

To overcome the effect of the high harmonic operation on the acceptance of a minicyclotron, we initiated to adopt a triangular wave accelerating voltage instead of the usual sine-wave accelerating voltage for the 'differential electrode'[6]. Calculation pointed out[7] that the particle acceptance of using a real triangular wave voltage would increase by about 50-fold as compared with that of using sine-wave voltage, and the results of beam tuning also have turned out satisfactorily. It is really a breakthrough for a minicyclotron AMS.

2.5 STRONG PHASE CONVERGENCE AND PHASE DIVERGENCE EFFECT

Under high harmonic operation, the usual phase grouping effect is significantly enhanced and particularly there appear some new types of phenomena of phase convergence, phase divergence and phase orientational shift of particles owing to having wider transition width of r.f. phase within the electric field-penetrated area. Such new phenomena play an important role in designing the accelerating (dee) structure, which has been discussed in detail in paper[8]. Based on the explored new phenomena, we designed a unique accelerating (dee) structure called ' asymmetric differential electrode with varying width and aperture ' in the minicyclotron.

2.6 WEAK ELECTRIC FOCUSING AND STRONG MAGNETIC FOCUSING

To fully make use of the powerful function of the triangular wave voltage, the r.f. phase of particles when crossing the accelerating electrodes should locate at near the center of the linear segment of the triangular wave voltage, otherwise the particles will be affected by the non-linear voltage and particularly because there do exists some non-linearity on both ends of the real shape of the triangular wave voltage. Nevertheless, the force of the electric focusing (phase focusing) will approach to zero at r.f phase near the center of the linear segment of the triangular wave voltage.

To keep ion motion stable, we have to rely on the force of the magnetic focusing by using a sector-focused magnet rather than a uniform magnet. Obviously, a uniform magnet is not appropriate to AMS with cyclotron type where analyzed particles will circle inside the magnet for many turns rather than for less than one turn as it is often the case in a conventional mass spectrometer. In a uniform magnet, (a) the axial betatron oscillation frequency $\mu_z = 0$; (b) the radial betatron frequency $\mu_r = 1$; and (c) the external injection into a uniform magnet is quite complicated and inefficient[9]. Therefore, a non-uniform magnet with high flutter was designed. Particularly, the yoke of the magnet is nickel-coated to constitute the vacuum chamber of the minicyclotron without having a separate vacuum chamber and its isochronous magnetic field will be shimmed by correcting the shape of the sectors without using usual trim coils and harmonic coils.

2.7 EXTERNAL COUNTING OF SINGLE PARTICLE ^{14}C WITH LOW ENERGY

The low final energy of $^{14}C^-$ makes it impossible for the usual nuclear detector to be used to identify the radio nuclei $^{14}C^-$. A new kind of detector has been designed and built by Friedman at Berkeley and then by our group to meet the minicyclotron AMS requirement[10]. Such new detector is constituted by aluminum oxide dynode, micro channel plate and copper anode and is generally useful for detecting ions above 5 keV in application requiring low current rates and background suppression.

Because such a detector can just count the particle number and can not distinguish the particle kind, it ought to be located outside the cyclotron for avoiding the strong unidentical interference of X-rays inevitably induced by the beam hitting inside the AMS facility

2.8 EXTERNAL SIMULTANEOUS INJECTION OF ALL PARTICLES

It is very desirable for a practically applied AMS system to be able to promptly change samples and eliminate the memory effect, thus external injection is preferred. In so doing, it becomes possible for a minicyclotron to adopt a high yield Cs sputter negative ion source and to apply an emitting voltage (20 kV) much higher than the accelerating voltage (500 V). And it is also possible for the emitted beam to be bunched in advance and to be separated at position before entering the minicyclotron. Both techniques now are not available and all particles emitted from ion source are simultaneously and axially injected into the minicyclotron.

As far as the axial injection in cyclotron is concerned, its common method of injection is usually by passing particles through a 'mirror' or a 'spiral inflector'. Considering the fact that the magnetic field at the center of the magnet of the minicyclotron is weak but defocusing, we took the initiative in designing a pair of spherical electrostatic injection deflectors -- ' vertical injection deflector ' and ' horizontal injection deflector ' to focus the beam in both orthogonal directions[11].

Since the energy gain per turn in SMCAMS is very small, the next key question for improving the injection and extraction efficiency is managing to obtain turn spacing wide enough for particles to clear up the horizontal injection deflector in the first turn and to enter into the horizontal extraction deflector at the last turn. The magnetic perturbation method often used in large cyclotrons to obtain the desired turn spacing is not applicable to the minicyclotron. To meet the high energy gain at both injection radius and extraction radius and keep the least energy gain within working radii, we adopted a pair of 'auxiliary electrodes' and 'width varied electrodes' at both inner and outer radii to obtain the necessary turn spacing of 6 mm[11]. Resulting from the radial components of the electric field on both electrodes, the two main dee electrodes have to be designed to be asymmetric--- one is a ' T ' shape electrode and the other is an ' I ' shape electrode---to compensate the phase divergence in the central region [8].

2.9 ALTERNATE ACCELERATION OF DIFFERENT PARTICLES

To improve the analysis accuracy, the ratio $^{14}C/^{12}C$ and $^{13}C/^{12}C$ must sequentially be measured. Therefore, other than conventional cyclotrons where only one certain ions are accelerated, the $^{12}C^-$, $^{13}C^-$ and $^{14}C^-$ must alternately be accelerated in an appropriate manner of time distribution of minicyclotron operation. It is a more complicated job for a minicyclotron even though without the need of adjusting the magnetic field due to its low energy. Because the mass difference between $^{14}C^-$ and $^{12}C^-$ is as high as 15% and the magnetic field is fixed, some electrical parameters must sequentially be changed by about 15% according to the orbit similarity theory.

During alternate acceleration, two supplementary deflectors must be added . One is the 'measuring deflector' to which a pulsed rectangular voltage is applied while detecting $^{14}C^-$ to deflect them onto the dynode of the detector. This voltage will be suppressed while measuring $^{12}C^-$ or $^{13}C^-$, when they will aim at an adjacent Faraday cup; The other is the 'clearing deflector' to which a pulsed voltage is applied at such a moment when the altemate acceleration starts to be turned into $^{14}C^-$ from $^{12}C^-$ or $^{13}C^-$ case;

2.10 SEQUENTIAL CHANGE OF VARIOUS SAMPLES

The transmission efficiency of different particles ($^{12}C^-$, $^{13}C^-$ and $^{14}C^-$) from the exit of the ion source down to the detector must be calibrated by a standard or known sample. In addition to this, a blank sample is also used to monitor the background noise of the detector. Therefore, the ion source must be equipped with a multi-sample device for sequentially changing various samples in an appropriate cycling manner.

3. Conclusion

In general, the minicyclotron AMS is a high acceptance, high resolution and miniature negative heavy ion cyclotron under high harmonic operation, and it analyses the extra low energy negative heavy ions with trace of abundance and large cross section of dissociation. It can be imagined that there are a lot of difficulties in such a mini cyclotron AMS.

The main difficulty for the minicyclotron AMS is contradiction between particle acceptance of a minicyclotron and resolution of a mass spectrometer. To make the facility SMCAMS successful in getting ^{14}C counts, (a). We focused our attention upon increasing the $^{12}C^-$ beam intensity from two aspects---one is to improve the transmission efficiency in the acceleration region and the other is to improve the injection and extraction efficiency; (b). We adopted a number of measures for thoroughly clearing away interference of backgrounds and for improving the precision of analysis. All these design considerations have resulted in the key breakthrough of the facility SMCAMS[11]. The transmission efficiency in the acceleration region is about 15% which implies that the duty cycle is more than 7.5% under high harmonic of 16; the final beam of ^{12}C is about 500 nA which implies the ^{14}C counting for a modem sample is 5 cps and shows that the facility SMCAMS can now serve the purpose of AMS application.

The new developed AMS facility SMCAMS keeps advantages of both tandem- based AMS and cyclotron-based AMS: (a) It possesses the same capability of accelerating negative ions as in a tandem AMS. Furthermore, the negative ions can directly be extracted for measurement without the need of stripping ; (b) It retains the function of resonance analysis of cyclotron AMS. Moreover, the altemate acceleration can likely be carried out without the need of changing the magnetic field; and primarily, (c) it can be set up at any laboratory for ^{14}C analysis, because of its low device cost and operation charge, and with no expenditure of money on shielding or special building arising from its small size, low energy (50keV), low magnetic field and low power consumption (12 kW). Therefore, it is in prospect for such a mini cyclotron AMS to be popularized.

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