DESIGN STUDY OF AN ACCELERATOR MASS SPECTROMETER BASED ON A CYCLOTRON*

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Abstract

An accelerator mass spectrometer (AMS) based on a compact cyclotron has been studied for biomedical uses. The system will have the mass resolving power of over 2000 to analyze a few different kinds of isotopes for tracing or chronometric dating. High transmission efficiency is a major design goal to compete with an electrostatic tandem AMS. A compact magnet with high stability, a sawtooth harmonic buncher, and a flat-topping rf system are the components needed to achieve the goal. The results of design study for the AMS cyclotron and its injection beam line are presented as well as the results of model tests for the cavity and the rf buncher.*

INTRODUCTION

The biomedical accelerator mass spectrometry (BAMS) was first tried at the LLNL [1]. The BAMS utilizes the technique of radioisotope tracing while the original AMS measures the ratios of the isotopes with a half life less than 100 million years up to the range of 10^{-15} for the fields of such as archaeology and geology. Recently BAMS found an application in the development of a new drug as it allows a normal dose of drug containing radioisotope tracer for clinical trials on the study of human mass balance and metabolites identification. This method of microdosing approved by the FDA can reveal adequate drug candidates more effectively to shorten the clinical trial process, which can save the cost of drug development.

The sensitivity required for usual BAMS is often lower than for radiocarbon dating AMS. Consequently, an electrostatic tandem accelerator with a lower terminal voltage or even a single-state high voltage system can be used for BAMS at the expense of mass resolution. The cyclotron can analyze mass simultaneously with acceleration [2], so that a cyclotron system can be still more compact than the new commercial high voltage systems. The mass resolution of the cyclotron can be written as follows [3]:

$$\frac{m}{\Delta m} = \frac{f}{\Delta f} = \pi h N ,$$

where N is the total turn number and h is the rf harmonic number.

Three AMS cyclotrons have been built in 80-90's at the LBL and in Shanghai [4, 5]. They all reported their systems have the mass resolving power of over 2000 to be able to detect ^{14}C, which is required to separate from ^{13}CH, but detection efficiency was low compared to the commercial AMS system taking a longer time to analyze each sample. The tandem AMS have dominated, and further research on the cyclotron AMS have not been seriously pursued. The most recent result of the cyclotron AMS comes from the Shanghai group mentioning its low efficiency [6]. In fact the Shanghai system was designed and built as a prototype and suffered from instability of the parts such as magnet power supply. Considering all these factors, a new design involving more stable components is perhaps promising especially for the biomedical uses.

CYCLOTRON AMS DESIGN

The previous cyclotron AMS was not successful because of their low efficiencies in counting ^{14}C ions. The loss of the beam in a cyclotron largely occurs when the beam is injected or extracted. To enhance the injection efficiency, we have added a sawtooth buncher and a flat topping rf system to increase phase acceptance as well as to better match with the longitudinal phase acceptance of cyclotron. The injection system consists of an ion source, a high-voltage extraction element, beam focusing elements, an rf buncher and a charge selection system including slits as schematically shown in Fig. 1. A radial injection system is adopted to ease operation and maintenance. The extraction efficiency could be improved with detailed orbit tracking calculations currently underway.

The cyclotron magnet is designed using RADIA [7]. The present system is considered for testing various cyclotron parameters in search of an optimal system [8]. Different isotopes that can be used for biomedical purposes such as ^{26}Al and ^{10}Be are thought to be tested. A set of trim coils are needed to adjust the main coil fields to be highly isochronous at different excitations.

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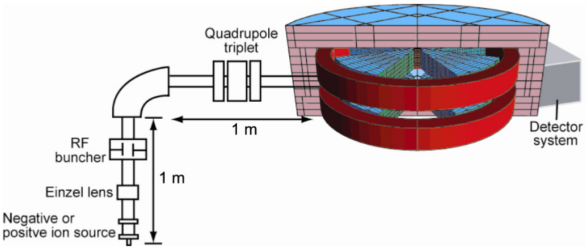

Figure 1: Configuration of the cyclotron AMS currently considered.

A set of the cyclotron parameters is given in Table 1. The wide range of rf frequency can be used to explore the limit of mass resolution. The parameters will be finalized by further numerical studies.

Table 1: Main parameters of the cyclotron.

Parameters	Values
B_{avg}	5.48 kG (3 - 9 kG variable)
f_0 (^{14}C)	0.59 MHz
frequency (rf amp)	5-80 MHz
Harmonics	10-30
Injection, ext. radii	13.5 cm, 23.6 cm
Weight	1.1 ton

The stability of the magnet system is a main concern in the analysis of radiocarbon as was for the Shanghai AMS cyclotron. In fact, state of the art magnet system can be stabilized within 10 ppm by adopting a highly stable power source and a feedback system. The feedback system based on an NMR device could be used because the field is nearly flat radially in the sector magnet.

The rf voltage is not high for the AMS cyclotron as a rather large number of turns is used to achieve mass resolution required. The final ion energy considered is in the range of 50-100 kV, and the maximum rf voltage is less than 500 V. Two units of cavity are located in the valleys, and each one has two gaps. A prototype has been designed and built. Fig.2 shows the test setup and flat-topped rf waves on the scope resulted from the added third harmonic component. The gaps are designed to be straight lines, but planed to be modified for better injection and extraction efficiencies.

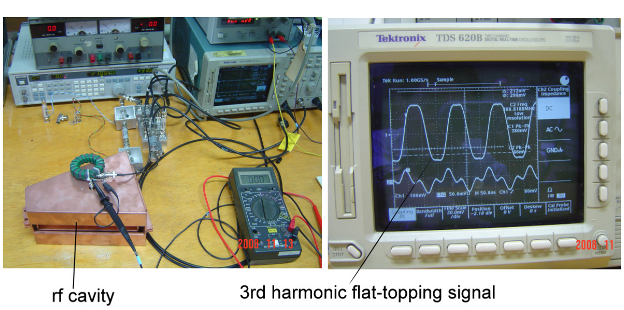

Figure 2: Left: test of the rf cavity, Right: flat-topped rf wave by the third harmonic frequency added.

An ideal shape of the rf voltage versus time for a buncher in the injection line is sawtooth. The system we considered is similar to the one built at GANIL [9], in which a triode rf tube is used as the switching device with an input of square pulse. The design of the buncher was performed with SUPERFISH as shown in Fig. 3 with the axial electric field plotted, and was also checked with a 3D code. The peak voltage of the buncher required depends on the length of the drift and the beam energy spreads allowed. At the voltage of 500 V the drift length is around 1.7 m, and 800 V is needed to reduce it to 1.1 m when the beam energy from the source is 10 kV. To calibrate radiocarbon contents, it is necessary to sweep the rf frequency to accelerate $^{12-14}C$ ions sequentially. The injection line elements are mostly electrostatic for the swift changes of operation parameters.

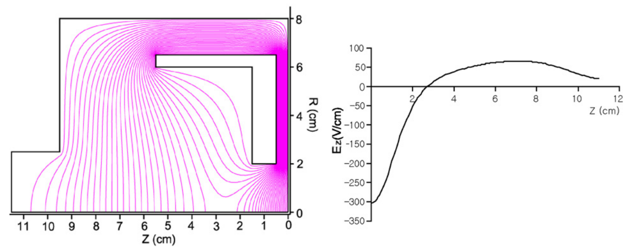

Figure 3: Geometry and electric fields of the buncher calculated by SUPERFISH. Equipotential lines are plotted.

INJECTION SYSTEM DESIGN

To reduce background noise, the injection system needs to have reasonable mass resolving power and fast ion selection capability to choose the particle injected into the cyclotron. This process is also important for the tandem AMS, so that multi-MV tandem system is equipped with so called a recombination beam line.

A possible beam line configuration of recombination type to measure the ratios of carbon isotopes without varying the ion source parameters is given in Fig. 4 along with the beam envelopes. We tried to use a minimal number of focusing elements, and the beam optics was calculated using TRANSPORT/TURTLE [10]. The beam cross-sections calculated at two different locations are shown in Fig. 5 assuming beam emittance of 30 π mm mrad. The carbon isotopes are clearly separated at F1 so that a mechanical device can select ion species for analysis. F3 is the injection point at the cyclotron where the beam is focused.

A simple injection beam line as shown in Fig. 1 was also designed to have similar beam transport characteristics to those of the recombination line at the cost of mass resolving power by the beam line. It currently appears advantageous to choose a simpler line.

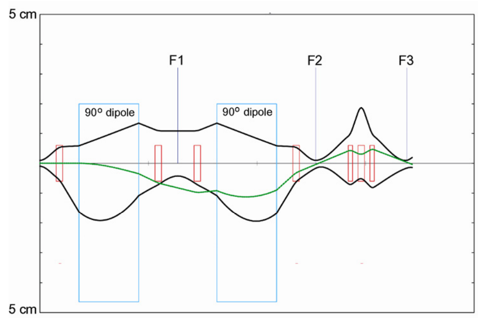

Figure 4: Configuration of the injection line and beam envelopes calculated with TRANSPORT. The lower and upper half shows transverse and vertical envelopes, respectively.

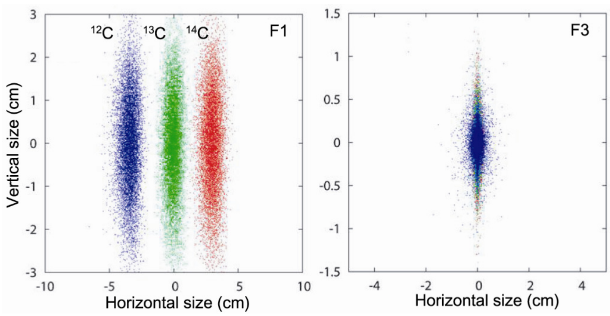

Figure 5: Left: 2D beam distributions of three carbon isotopes at F1. Right: three beam distributions overlapped at F3. The locations are indicated in Fig. 4.

POSITIVE ION AMS CYCLOTRON

The cyclotron AMS was first suggested to use positive ions of radiocarbon [2]. Considering difficulty to separate ^{14}N from ^{14}C by the cyclotron alone, Muller suggested utilizing the difference in energy losses of the two ions because it depends on the ratio of nuclear charge to mass, which differs by over 10%. A simple calculation with SRIM [11] tells that the beam energy of a few MeV/u is minimally needed to have a measurable difference in the range. To clarify the result, we used GEANT simulations [12] for a realistic beam with an energy spread of 0.1% for two beam energies of 2 and 3 MeV/u as shown in Fig. 6. The detector called a multilayer Faraday cup consists of aluminium foils of 3 μm thick separated by vacuum. In practice the ratio of ^{14}N to ^{14}C is in the order of 10^{12}, and thus the relative beam current of ^{14}C is very low. It is critical to reduce background radiation so that it may be comfortable to use at least 3 MeV/u. At the beam energy of 3 MeV/u, the nitrogen beam is completely stopped after the 12th foil. Thus a solid state detector can be used to detect ^{14}C ions as for the tandem AMS.

A compact superconducting cyclotron may be a viable option for AMS using positive ions. The beam energy from the cyclotron depends on the charge state from the ion source. Carbon ions can be produced at the charge state of 1+ with high efficiency, but then the cyclotron K value for the final energy of 3 MeV/u is 580 MeV, which means the system is not practical. It seems at least 3+ charge states should be produced with high efficiency. The state of the art superconducting ECR ion source seems to meet this requirement, but such an ion source is a massive device. The possibility of a positive-ion AMS system may depend on the ion source development.

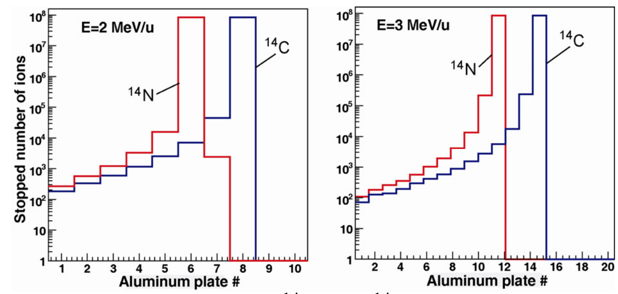

Figure 6: Distributions of ^{14}N and ^{14}C ions stopped in the Bragg peak detector composed of 3 μm thick aluminium foils calculated for two different beam energies by GEANT.

CONCLUSION

The cyclotron AMS seems to be practical for the application to biomedicine. A cyclotron AMS system has been designed to have large phase acceptance to increase transmission efficiency compared to the previously built AMS cyclotrons. Some components such as buncher and rf cavity have been prototyped and tested to ensure their design and performance. Consideration has been given to the design of the injection system, which controls the matching of beam phase spaces and sweeps carbon isotopes quickly for sequential analysis. A beam optics study for the cyclotron is underway. Also, possibility of using positive ions for the AMS has been explored. It seems that a main issue is to develop an efficient ion source to produce multi-charged ions.

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