STUDY ON THE INJECTION SYSTEM FOR COMPACT CYCLOTRON MASS SPECTROMETRY*

D. G. Kim, H. C. Bhang, J. Y. Kim, Seoul National University, Seoul, Korea
C. C. Yun, Chung-Ang University, Seoul, Korea
J. W. Kim†, National Cancer Center, Gyeonggi-do, Korea

Abstract

Accelerator mass spectrometry (AMS) using a cyclotron has been studied because it can be compact and economical compared to the commercial Tandem AMS. However, cyclotron AMS previously developed revealed weaknesses in stability and transmission efficiency. To increase transmission efficiency, it is important for the injection system to match not only transverse phase space but also longitudinal phase space with cyclotron phase acceptances. We adopt a sawtooth rf buncher to enhance the efficiency of beam bunching, while keeping the system compact by minimizing the number of beam line elements employed. The design of an injection system from the ion source to the injection point inside the cyclotron was carried out using TRANSPORT and TRACE-3D. A prototype injection beam line is under construction, and progress is reported.

INTRODUCTION

Accelerator mass spectrometry (AMS) using a cyclotron was suggested by Muller [1] a few decades after the invention of radiocarbon dating by Arnold and Libby [2]. The tandem accelerator, however, became dominant because it can easily suppress major unwanted isobar ^{14}N and molecular isobars such as ^{13}CH and ^{12}CH$_2$ by using negative ions and stripping stage, respectively. The cyclotron AMS was tested at the Lawrence Berkeley laboratory [3] and at the Shanghai Institute of Nuclear Research [4]. The capability of mass separation from its isobars for the ^{14}C dating was demonstrated by those systems. However, they suffered from beam instability and poor transmission efficiency.

An injection beam line for the cyclotron AMS has been studied. The transverse and longitudinal phase space matching with the acceptance of cyclotron should be precisely performed by this injection system so as to improve transmission efficiency. We adopt an rf buncher operating with a sawtooth waves and a flat topping rf system for larger longitudinal acceptance of the cyclotron. A schematic configuration of the injection beam line along with a four-sector cyclotron [5] is shown in Fig. 1. We have studied beam optics for different beam line designs to find the optimal system, which also employs a minimal number of system components without compromising transmission efficiency required for AMS.

We are constructing a prototype injection beam line to investigate phase space matching, and expect to further optimize the system based on measurement results later.

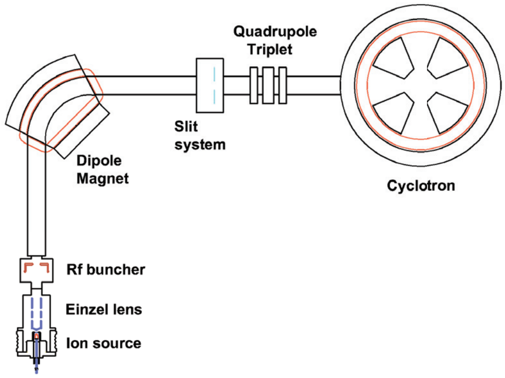

Figure 1: A schematic configuration of the cyclotron AMS system.

INJECTION SYSTEM

The design of an injection beam line, which extends from the extraction of ion source to the injection at the cyclotron, was carried out using TRANSPORT [6] and TRACE-3D [7]. Transverse envelopes of a ^{14}C beam calculated with TRANSPORT are shown in Fig. 2. The rf buncher is located at F1 following the Einzel lens, where the beam is focused. We chose to locate the buncher rather in the upstream of the beam line to reduce the required rf voltage. The ions of different charge to mass ratios are then dispersed by the 90° dipole magnet. The slit system to select the beam is located at the focal point F2. The dipole magnet has edge angles of around 30° to focus the beam vertically. Finally an electrostatic or magnetic quadrupole triplet is used to match transverse phase spaces of the beam with cyclotron acceptance.

The initial conditions of the beam for the given electrode shapes were calculated using IGUN [8] after extraction from the ion source with the voltages of up to 30 kV. The emittance is 0.58 πmm·mrad, and twiss parameters α, β, γ are -10.6, 0.228 mm/mrad, and 4.96×10^2 mrad/mm on both transverse planes. The momentum spread is estimated as 0.038% . The electron temperature was assumed to be 5 eV considering typical temperatures for gaseous discharge plasma [9].

---

* Work supported by National Research Foundation Grant No. 20090073769.

† jwkim@ncc.re.kr

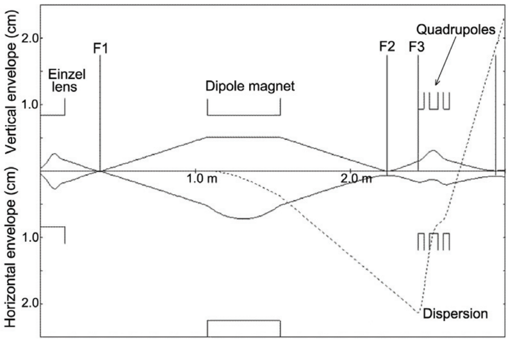

Figure 2: Transverse envelopes of a ^{14}C beam calculated using TRANSPORT.

A different injection beam line, in which two dipole magnets are employed, was considered. The single dipole magnet of Fig. 2 cannot make the injection line achromatic. The optics of the injection beam line in fact should be considered together with a path of the radial injection inside the cyclotron, where the magnetic field is dispersive. The envelopes computed by TRANSPORT for the case of using two dipoles are shown in Fig. 3. This system is more flexible at the cost of a larger number of beam line components.

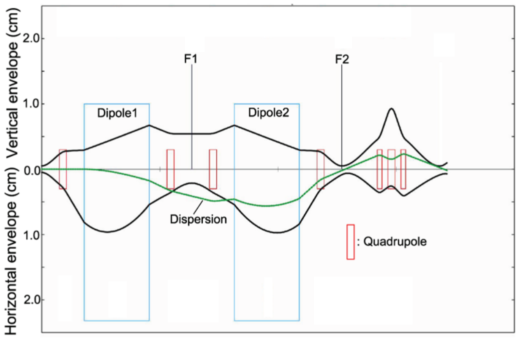

Figure 3: Beam envelopes for the case of using two dipoles and seven quadrupole magnets.

Ion source assembly

A schematic drawing of the ion source and Einzel lens with the electrical connection scheme is shown in Fig. 4. The ion source assembly, which is currently built and being tested, mainly consists of filament, anode, extraction electrode, and gas inlet. The extraction system is designed to extract positive ions, but it can be readily modified for negative ions. The aperture diameters of the anode and the extraction electrode are 0.5mm and 3mm, respectively. The front part of the Einzel lens is designed to accommodate the extraction electrode.

To reduce transverse emittance of the extracted beam, the electric field in the extraction region should be shaped similar to Pierce geometry. The maximum current density can be calculated by the Child-Langmuir equation [10, 11] if the extracted beam current is limited by space charge forces. The beam current in practice is determined by the potential drop across the gap between the anode and the extraction electrode as well as the distance of the gap. The extraction electrode is designed to be replaceable for the adjustment of the gap size.

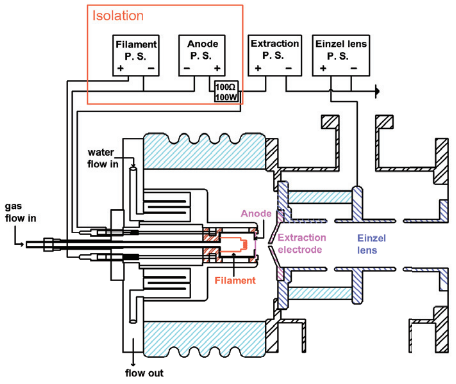

Figure 4: A sectional view of the ion source and the Einzel lens along with electrical connection schemes.

Different shapes of the electrodes in the extraction region were investigated using IGUN. The beam trajectories were calculated considering detailed shapes of the electrodes as shown in Fig. 5. A concern is to reduce beam emittance so far as a high beam current is kept. The result indeed was that beam emittance was smaller when the electrode shape was similar to that of Pierce geometry. We also found beam emittance was more intimately controlled by the electrode shape of the source side because the beam in the lower energy end is more sensitively affected by electric field shaping. We also plan to test different shapes of the anode and extraction electrodes in beam measurements.

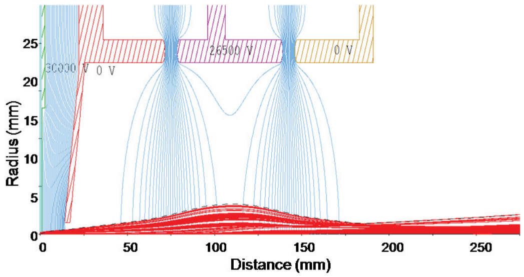

Figure 5: The beam trajectories of $^{14}C^{+}$ ions simulated using IGUN with the extraction electrode and Einzel lens.

Rf buncher system

The sawtooth rf buncher we chose is similar to the one built at GANIL [12], for which a triode tube is used as switching device with an input of square pulses. The rf frequency of the AMS cyclotron beam is around 0.5 MHz [5], and the number of harmonics considered is around 20.

Hence, the frequency of the buncher is in the range of 10 MHz. The buncher was built and tested togeter with its driving circuit in particular to achieve rapid falloff of the voltage to form sawtooth shapes.

The buncher is located right after the Einzel lens, where the beam is transversely focused. This location allows the use of a lower voltage and a longer drift space. This can reduce beam-energy spreads, but the coupling of rf bunching effect with the dipole bending seems to make the width of beam phase bunched at the injection point difficult to be controlled. This issue is a part of this injection line study including beam tests. The final location will be decided afterward.

To investigate the longitudinal phase space motion by the buncher in the beam line, a particle-tracking program was written. The effects of rf bunching for different rf voltages are shown in Fig. 6 as a function of drift space. TRACE-3D was also used especially to check the effect of the 90° dipole magnet in bunching. While the tracking program can handle arbitrary shapes of the electric fields including sawtooth waves, TRACE-3D assumes sinusoidal waves. The result of TRACE-3D calculations manifests wider phase widths at the longitudinal focal point compared to the sawtooth bunching.

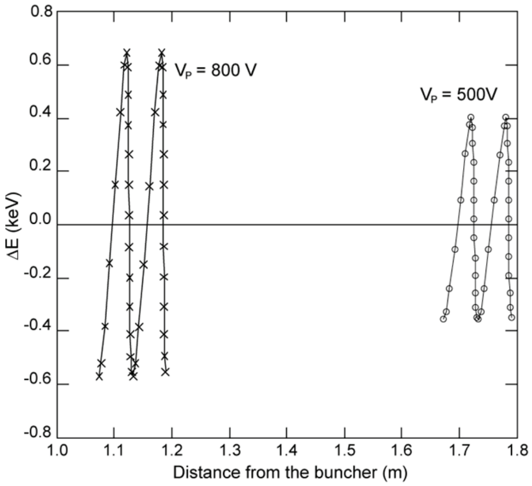

Figure 6: Beam energy spreads versus the distance of drift space for two different rf voltages.

Design of dipole magnet

A 90° dipole magnet has been designed using RADIA [13]. The magnetic rigidity of a ^{14}C beam at 30 keV is approximately 0.1 Tm. Thus the required magnetic field is about 3 kG for the bending radius of 30 cm. The profiles of the magnetic fields for two different shapes of the yoke are shown in Fig. 7. In the case of two-way flux return yokes indicated as A, the magnetic field strength is stronger, but asymmetry of the field along the radial direction is observed. The good field region in the radial direction needs to be over 2 cm, which asks for further pole shaping. The total current for the maximum magnetic field is about 6400 A.

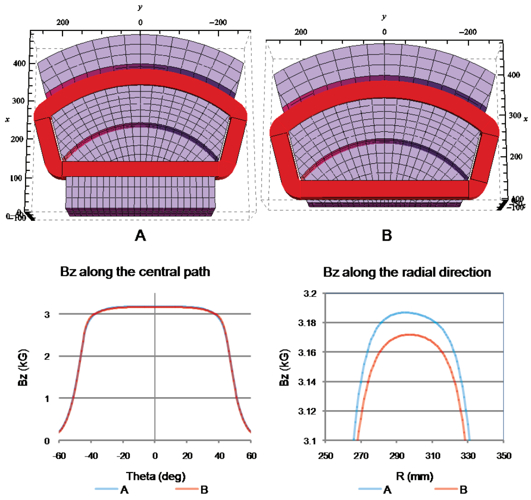

Figure 7: (Upper) Two different configurations of the yoke, and (Lower) profiles of the magnetic fields along the radial and azimuthal directions at the excitation current of 6400 A.

CONCLUSIONS

The injection beam line is a major part in the cyclotron AMS system to achieve the goal of high transmission efficiency. Comparison of the beam optics calculations with beam measurements will help in better matching the beam phase space to cyclotron acceptance. We expect that optimal injection line design will be revealed by this work.

REFERENCES

[1] R. Muller, Science 196 (1977) 489.

[2] J. Arnold and W. Libby, Science 110 (1949) 678.

[3] K. Bertsche, Nucl. Instr. and Meth. A 301 (1991) 171.

[4] M. Chen et al., Nucl. Instr. and Meth. B 92 (1994) 213.

[5] J. Kim et al., J. of Korean Phys. Soc. 54 (2009) 580.

[6] PSI Graphic Transport Framework by U. Rohrer based on a CERN-SLAC-FERMILAB version by K.L. Brown, Ch. Iselin and D. Carey, CERN 73-16 Villigen, (2007).

[7] R. Becker and W. Herrmannsfeldt, Rev. Sci. Instr. 63 (1992) 2756.

[8] K. R. Crandall and D. P. Rusthoi, Los Alamos National Laboratory Report LA-UR-97-886 (1997).

[9] B. H. Wolf, Handbook of ion sources, CRC Press, New York, (1995).

[10] C. D. Child, Phys. Rev. 32 (1911) 492.

[11] I. Langmuir and K. T. Compton, Rev. Mod. Phys. 3, (1931) 251.

[12] A. Chabert et al., Nucl. Instr. and Meth. A 423 (1999) 7.

[13] P. Elleaume et. al., Proc. of the 1997 Part. Accel. Conf. p.3509 (1997).