BEAM EMITTANCE MEASUREMENT IN THE INJECTION BEAM LINE FOR A CYCLOTRON MASS SPECTROMETER*

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Abstract

A carbon beam was extracted and its properties were measured in the injection beam line built for the study of accelerator mass spectrometry (AMS) based on a cyclotron. The cyclotron AMS has been designed to realize a compact AMS system having mass resolving power of around 4000 for a $^{14}C^-$ beam. The beam line is a prototype to ensure the capability to match beam phase space with acceptance of the cyclotron. It consists of an ion source, Einzel lens, rf buncher, 90° dipole magnet and a beam diagnostic box with a slit system. Some test results of the beam line components as well as measurements of beam phase space are presented.

INTRODUCTION

Accelerator mass spectrometry based on a cyclotron was suggested at the early stage of AMS technology development [1]. The development of cyclotron system had been carried out in different places [2, 3], but the systems constructed could not compete with the AMS system based on a tandem electrostatic accelerator in the aspects of transmission efficiency and system stability. However, it appears that the cyclotron system can be more compact and competitive in some applications with further design optimization and the uses of highly stable components nowadays available. Mass resolving power designed is around 4000, and negative ^{14}C beam is utilized to remove ^{14}N ions [4].

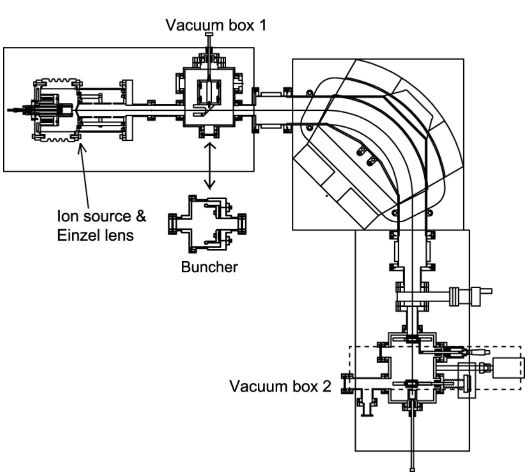

Figure 1: Configuration of the injection beam line.

A cyclotron AMS system has been studied in search of optimal design, and a prototype of its injection beam line has been constructed to test phase space matching of a carbon beam with cyclotron acceptance. The injection line constructed includes an ion source, Einzel lens, rf buncher, 90° dipole magnet and a beam diagnostic box with a slit system. The ion source is a commercial product (Colutron Corp. USA), and other components were built in house.

Arrangement of the beam line components is shown in Fig.1. The beam can be measured at two different locations of the vacuum boxes. The rf buncher used for longitudinal phase-space matching is placed at the location of vacuum box 1. The vacuum box 2 contains a slit and beam diagnostic devices to measure beam emittance. Transverse beam phase space was measured, rf beam bunching being tested.

BEAM MEASUREMENT

The beam line constructed is shown in Fig. 2. Detailed configuration of the extraction electrode and Einzel lens and beam optics calculation results are given in ref. [5]. Positive ions were first extracted using CO_2 gas. The ion source can be switched to a different type with a minor modification in the high-voltage cage.

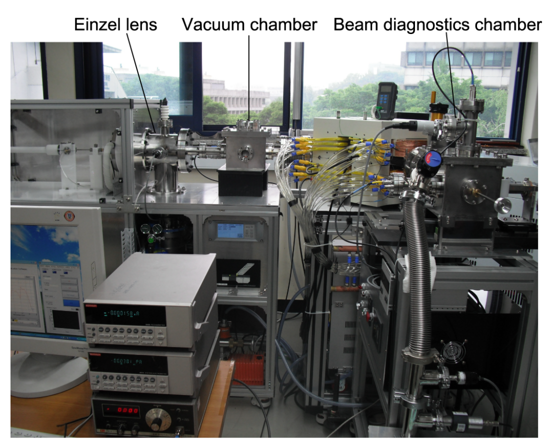

Figure 2: The prototype injection beam line constructed.

Beam Measurement at the Front End

First beam measurement was performed in the vacuum box 1 located at the exit of the Einzel lens. The beam extracted from the source, in which CO_2 gas was not of high purity, contained various kinds of ions. The 2D beam profiles were measured by using a digital camera and a scintillator-CCD camera system [6] at different tuning conditions of the extraction and Einzel lens voltages. The

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beam extraction was tested up to the maximum injection voltage set as 30 kV.

The aperture diameter in the extraction electrode is 3 mm. Transverse emittance was measured to be approximately 15 π mm·mrad at the extraction voltage of 20 kV and the beam current of 5 μA [4].

Beam Measurement after Bending Magnet

The ratios of ^{14}C to $^{12,13}C$ can be measured for radiocarbon dating when the beam is separated by the bending magnet, i.e. beam currents of $^{12,13}C$ can be measured concurrently while ^{14}C ions are selected by the magnet system to be injected into the cyclotron for mass analysis. The distribution of beam current versus A/q was attained by scanning with the dipole magnet current. Figure 3 shows the beam current distribution around A/q of carbon isotope beams. At the location of the slit in the current system, mass resolving power of the injection beam line is sufficient for continuous monitoring of $^{12,13}C$ beam currents.

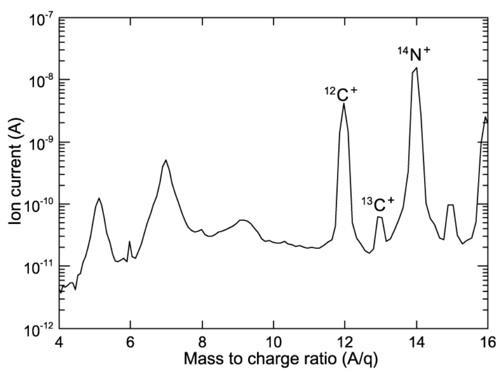

Figure 3: Beam current distribution versus A/q attained by scanning with the current of the dipole magnet.

Transverse emittance of a $^{12}C^{+}$ beam was measured using a moving slit and wire system. The slit opening, which is adjustable, was set to be 1 mm, and the wire was located 15 cm downstream from the slit. The slit is manually moved by a micrometer, and the wire position is scanned by a stepping motor device. Measurement was carried out with the extraction voltage of well below 30 kV since the lifetime of the ion source filament became much shorter for the voltage of above 20 kV at high beam currents.

Table 1: Transverse Emittance Measured

V_{ext} (kV)	**10**	**12.5**	**15**	**17.5**
V_{Einzel} (kV)	7.2	8.7	10.8	12.6
ε_{rms} (μ mm·mrad)	5.3	4.9	5.0	4.1

Transverse emittance of a $^{12}C^{+}$ beam measured at different extraction voltages is given in Table 1. Variation of emittance with extraction voltage was not clearly observed in this voltage range. Different focusing conditions were tried by controlling the voltage of Einzel lens. The phase space of a beam at the extraction voltage of 15 keV is shown in Fig. 4. The beam diverges in the horizontal plane in this case.

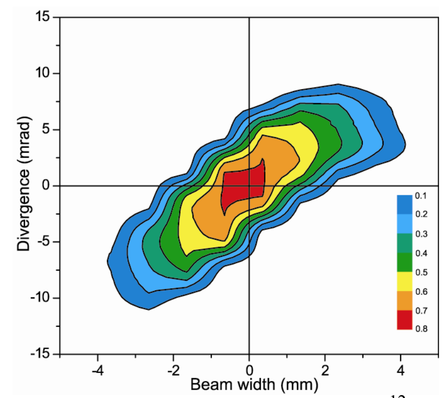

Figure 4: Transverse phase space of a ^{12}C beam at the extraction voltage of 15 kV.

Bunched Beam Measurement

An rf buncher was designed to produce sawtooth waves to reduce the phase width at the longitudinal focal point [7]. The buncher is located upstream of the bending magnet to keep a distance for longitudinal focusing with a lower bunching voltage. The longitudinal emittance is determined by the bunching voltage and the beam phase width. The sawtooth buncher could allow around 70% of a beam to be bunched within the phase width of 30°. The rf frequency of the cyclotron for ^{14}C mass analysis is 11.8 MHz in the rf harmonic number of 20.

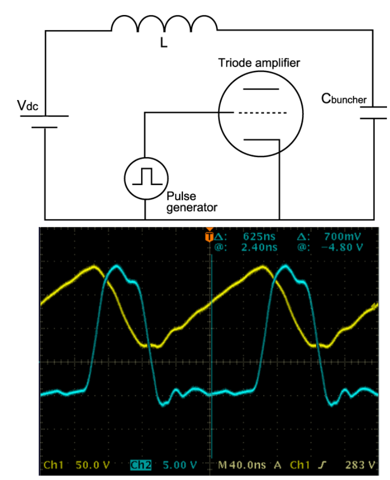

Figure 5: Top: Circuit diagram of the rf driving system for the rf buncher. Bottom: Voltage waves from the pulse generator (blue) and the buncher (yellow).

The rf driving circuit of the buncher employs a triode amplifier, which is used as a switching device with pulse signals applied to the grid of the triode as shown in Fig. 5. Figure 5 also shows the pulse signal and the resulting bunching voltage wave. The V_{dc} was 280 V, and the $V_{p\text{-}p}$ of sawtooth wave of over 100 V was achievable. A DC bias voltage of 10 V was added to the pulse signal so as to increase the $V_{p\text{-}p}$. Higher bunching voltage will be tested using a power supply with the V_{dc} of over 400 V.

Figure 6 shows voltage waves measured on an oscilloscope with the buncher turned on at the rf frequency of 5 MHz. The sawtooth wave came from a pick-up port of the buncher, which is a capacitive pick-up, and bunched-beam currents were measured using a fast Faraday cup installed in the beam diagnostic chamber. A CO^{+} beam was used at the beam current of 1.9 μA. Higher currents caused prompt damage on the filament of the ion source. The beam-current signal was amplified before being displayed on the scope. Broadening of the signal is due to multiple swapping for clear display on the analogue scope. We are currently testing with a digital scope for individual display of the signal. The structure of the bunched beam current was seen, but rf noise from the buncher system obscures the bunched-beam signals.

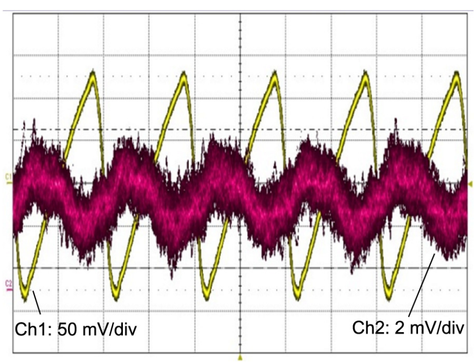

Figure 6: Voltage wave from the buncher (sawtooth in yellow colour) and the bunched-beam signal displayed on an analogue scope.

PHASE SPACE MATCHING

The phase space matching of a beam at the injection point inside the cyclotron is crucial to enhance transmission efficiency. Figure 7 shows a result of beam optics calculations using Trace3D [8]. Transverse emittance of the initial beam is assumed to be 30 π mm·mrad, and a quadrupole triplet is used for transverse focusing. A current scheme for the beam injection onto the first equilibrium orbit of the cyclotron is in the radial direction. The magnetic field along the beam path inside the cyclotron is roughly simulated by dipole magnets with field gradients. It appears that good matching can be achieved by this injection method, but detailed simulation by orbit tracking employing more realistic magnetic field of the cyclotron is needed to ensure design optimization.

The buncher voltage needed for a ^{14}C beam extracted at 30 keV is about 410 V for longitudinal focusing at the injection point. The beam energy spread induced by this voltage is related to extraction efficiency. The energy spread by rf bunching should be smaller nominally than the voltage gain per turn by the cyclotron cavity for high extraction efficiency. However, high cavity voltage reduces the total number of turns and thus mass resolution if the final beam energy at the extraction is kept the same. Considerations on both the injection beam line and the cyclotron design are required for optimization.

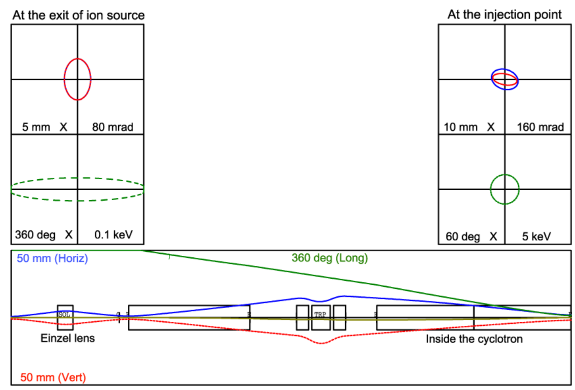

Figure 7: Beam optics calculation for the injection beam line by using Trace3D.

CONCLUSIONS

A prototype injection beam line is constructed, and beam measurement in transverse phase space has been made. The longitudinal phase space formed by an rf buncher will be further measured utilizing a digital scope with rf noise from the bunching system highly suppressed. Extraction of negative ions will also be tried for the present ion source. It seems the radial injection scheme for a cyclotron AMS system is viable if phase space matching is properly done by considering dispersion along the beam path inside the cyclotron.

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