I. 20. Development of The RF Separator for The Secondary Beam from The Incident Particles

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The kinematically focused secondary beams of neutrons and some unstable nuclides can be provided by using the heavy ion induced reactions on light nuclei, the $^{1}H(^{13}C,n)^{13}N$ reaction for example. By counting unstable particles produced in the reaction, the yield of the emitted neutrons can be estimated as standard neutron field. From a technological point of view, one of the important facts which severely influence upon the counting yield of the unstable particles is the separation from the incident beam. In this work, the radio-frequency (RF) separator[1,2] was chosen and built up as a device for the α-beam separation, and practical performance was examined by using 14.5 MeV beam. Through the measurements of deflected angle of α-beam on various delay time for the separator RF timing from the cyclotron RF timing, it was confirmed that the RF separator was driven correctly.

Introduction

The kinematically focused secondary beams can be produced by utilizing the endoenergetic Heavy Ion (HI) induced reactions on light nuclei[3]. We could have obtained focused beams of neutron[4] and some radioactive nuclides[5] from the $^{1}H(^{13}C,n)^{13}N$ and $^{1}H(^{15}N,n)^{15}O$ reactions at Tohoku University Cyclotron and Radioisotope Center (CYRIC). Counting radioactive particles created in the reaction makes it possible that the intensity of this focused neutron beam is estimated absolutely. The secondary beam must be separated from the incident HI beam before detection, because the incident particles are still more than the secondary by millions times. We had used the dipole magnet for the separation, however it is impossible that the secondary beam is identified from inelastically scattered particle whose momentum per charge (p/q) is equal.

A velocity selection (time of flight selection in other words) is aimed by using the RF separator for the present work, not only a p/q selection with the dipole magnet. In using this separator behind the magnet, the incident beam is supposed to be rejected by the magnet, and in the second place, the RF separator will deflect radioactive particles and inelastically scattered particles in the different directions because of different TOF from the target to the electrodes of the separator. Between the electrodes high voltage is supplied by amplifying the RF signal that is provided from the synthesizer driving the cyclotron.

Design of the RF separator

Threshold energy of ^{1}H (^{13}C, ^{13}n) N reaction is 41.75 MeV, so incident energy of $^{13}C^{4+}$ ion should be 47 MeV taken into account energy loss at the window of the gas-target to obtain well-focused secondary beams. In this case radio-frequency operating cyclotron is 24.8 MHz and energy of ^{13}N is 26.9 - 28.4 MeV that is to say velocity of 2.00 - 2.05 cm/nsec. So $^{13}C^{6+}$ with velocity of 1.71- 1.76 cm/nsec cannot be thrown out by the magnetic field for selection of $^{13}N^{7+}$. In order to kick the ^{13}C in the different direction from ^{13}N, the RF separator should be established at the distance of 2.45 m from the target, because half the periodic time of the RF is 20.2 nsec.

The block diagram of the RF separator is shown in Fig. 1. The RF signal driving cyclotron is divided for the separator to synchronize the phase of the electric field and the pulsed beam from the cyclotron. We can control the amplitude and phase of the RF signal for the separator with the synthesizer and nano-second delay generator, respectively.

The amplitude- and phase-controlled signal is fed into the high voltage generating stage consisting of a driver, an RF power amplifier and a tank circuit. The tank circuit is composed of three variable capacitors whose capacitance is variable from 30 to 150 pF and three inductors. The capacitors in the output side are connected in series. The inductors in the output side consist of two coils in series, each constructed from a 5 mm diameter copper tube to form a 3.5 turn coil of 60 mm diameter and 60 mm long. The inductors in the input and output sides are arranged coaxially to be supported by a cross-structured acryl. The inductance of these coils is determined experimentally because of the stray capacity. The optimum tuning point is found by minimizing the voltage standing wave ratio through adjustment of three variable capacitors. 10 kV of peak to peak voltage was measured for an input power of 40 W by a 1000:1 high voltage probe. Therefore the Q-factor of this tank circuit is larger than 75. It should be noted that a probe is a large Q-dump load, viz a lower power might be sufficient to obtain 10 kV peak to peak voltage without a probe.

The electrodes consist of parallel oxygen-free copper plates, 20 cm long by 4 cm wide with 2.0 cm spacing. They are supported by four high voltage vacuum feed-throughs withstanding a voltage of 12 kV DC inside the beam duct.

Suppose that a particle with mass of m, velocity of v_L and charge of q gets vertically into the electric field V/d by RF voltage $V = V_0 \sin 2\pi f(t + t_0)$ at the time t = 0. When this particle runs across the field for longitudinal distance of L, the transverse component of velocity v_T is

$$v_T = \int_0^{L/v_L} \frac{q V_0}{m d} \sin 2\pi f (t + t_0)\, dt$$
$$= \frac{q V_0}{2\pi f m d} \left\{ \cos 2\pi f t_0 - \cos 2\pi f \left(\frac{L}{v_L} + t_0 \right) \right\} \qquad (1)$$

and the transverse position y is given as follows :

$$y = \int_0^{L/v_L} \frac{q V_0}{2\pi f m d} \left\{ \cos 2\pi f t_0 - \cos 2\pi f (t + t_0) \right\} dt$$
$$= \frac{q V_0}{2\pi f m d} \left\{ \frac{L}{v_L} \cos 2\pi f t_0 + \frac{1}{2\pi f} \sin 2\pi f t_0 - \frac{1}{2\pi f} \sin 2\pi f \left(\frac{L}{v_L} + t_0 \right) \right\} \qquad (2)$$

Therefore the transverse position Y on the slit position at the flight pass length D distance from the end of the electric field is expressed as

$$Y = y + \frac{v_T}{v_L} D. \qquad (3)$$

Experimental Procedures and Results

The practical performance of this RF separator thus prepared was examined by using 14.5-MeV α particle beam from CYRIC AVF cyclotron. The experimental setup is illustrated in Fig. 2. Then the radio-frequency is 24.783 MHz nearly equal in case of the acceleration of 47-MeV $^{13}C^{4+}$.

At first the α-beam deflected in half the side was measured on various delay time of RF high voltage from the cyclotron RF timing, and its result is shown in Fig. 3. Intensity of α particle was measured as beam-current by Faraday cup behind the slit and normalized with counts of α particles scattered at the Al target. This result shows that the beam was transported in bunches and the deflection of beam depends on the difference in the phase on arrival times of beam. The large spot size of beam is supposed to be the reason why the intensity in case of the deflection on the opposite side to the slit was not zero, but it may not be a problem if the double quadrupole focusing lens are used.

As the next step, the maximum transverse deflected angle was investigated when the input power for the tank circuit is 30 W and 40 W to determine the voltage between the electrodes, Q-factor and inductance of the tank circuit. The following values are substituted for parameters of Eqs. (1) and (2) :

$$m = 4.14 \times 10^{-8}\ \mathrm{eV \cdot s^2/m^2}, \quad v_L = 2.64 \times 10^7\ \mathrm{m/s}, \quad q = 2e\ [\mathrm{C}],$$
$$L = 0.200\,\mathrm{m}, \quad d = 0.020\,\mathrm{m}, \quad f = 24.783 \times 10^6\ \mathrm{Hz},$$
$$2\pi f t_0 = \frac{\pi}{2} - \frac{\pi f L}{v_L} = 0.312\pi,$$

and we can obtain equations to express the relation between RF high voltage and deflection as

$$v_T = 17.3\ V_0\ [\mathrm{m/s}]\ , \qquad y = 6.54\times10^{-8}\ V_0\ [\mathrm{m}]\ .$$

Now D of Eq. (3) is 0.57 m in this experiment, so that the high voltage supplied between the electrodes is calculated from the transverse position Y measured experimentally with the following equation :

$$V_0 = 2.28\times10^{6}\ Y\ [\mathrm{V}]\ .$$

Since Y was measured as 6 mm for an input power of 30 W to the tank circuit and 9 mm for 40 W, the voltage is determined as 14 $kV_{p\text{-}p}$ for 30 W and 21 kV $_{p\text{-}p}$ for 40 W. So the Q-factor of the tank circuit is supposed to be around 140-150.

Conclusion

Through these measurements and calculations it was made sure that this RF separator is good enough for a practical use. Particularly, the RF high voltage of 10-20 kV enough to separate secondary-beam ^{13}N from inelastically scattered ^{13}C could be generated.

References

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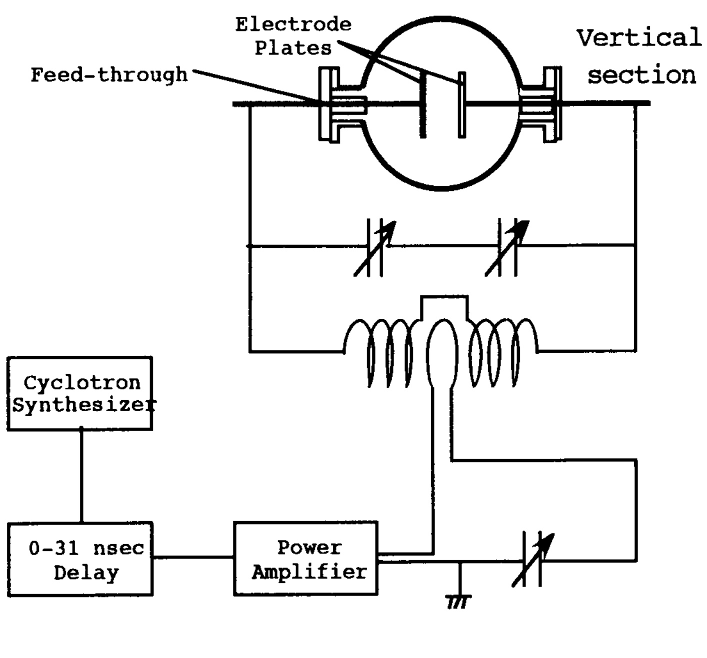

Fig. 1. Block diagram of the RF separator.

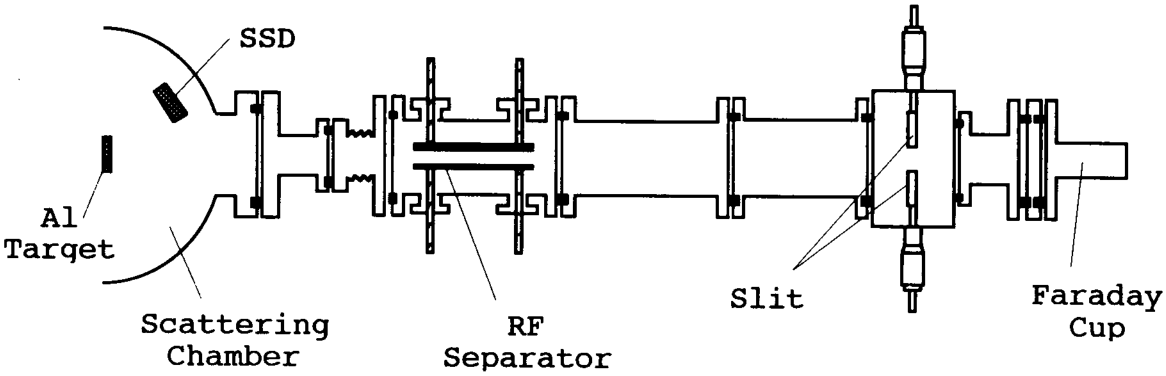

Fig. 2. Experimental arrangement for the measurements of the deflected angle of α-beam from CYRIC AVF cyclotron.

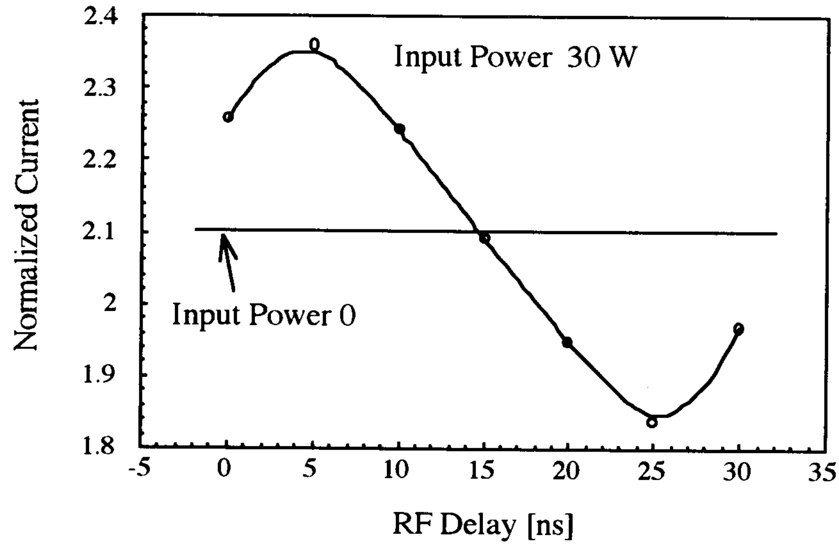

Fig. 3. Dependence of the intencity of α-beam deflected in half the side on the delay time of the RF high voltage from the cyclotron RF timing.