ACCELERATION TEST OF RADIOACTIVE NUCLEAR BEAM AT INS

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Abstract

First acceleration test of a radioactive nuclear beam was performed in a radioactive beam facility at INS. The ^{19}Ne beam was produced by bombarding a LiF target with 30 MeV protons from an SF cyclotron, and ionized by a ECR ion source. We succeeded to accelerate the ^{19}Ne^{2+} ions to 0.72 MeV/u by heavy-ion linacs. The intensity delivered to a secondary target is not yet enough. Further improvements will be done to perform experiments using accelerated radioactive nuclei.

1 INTRODUCTION

The construction of an ISOL-based radioactive nuclear beam facility at INS started in 1992 and completed in 1996. Radioactive nuclei, produced by bombarding a thick target with protons or light ions from an SF cyclotron, are ionized in an ion source, mass-analyzed by an isotope separator on line (ISOL), and transported to a heavy ion linac complex through a 60 m long beam line. The linac complex comprises a 25.5 MHz split coaxial RFQ (SCRFQ) and a 51 MHz interdigital-H (IH) linac, and accelerates heavy ions up to 1 MeV/u. Three beam lines including a recoil mass separator (RMS) were prepared for experiments. This facility is a prototype for the exotic nuclei arena (E-arena) of the Japanese Hadron Facility (JHF), in which 3 GeV,10 μA protons is used as a primary beam, and a radioactive nuclei beam is accelerated up 6.5 MeV/u by an extension of the IH linac[1]. The main purpose of the prototype facility is to study various technical problems for the E-arena in the JHF and to perform pioneering works with respect to nuclear astrophysics. In this paper, a result of first acceleration test of a radioactive nuclear beam is reported together with a summary of the outline and the present status of this facility.

2 OUTLINE AND PRESENT STATUS OF RADIOACTIVE BEAM FACILITY

2.1 Target and Ion Source

Production target and ion source technology are crucial part of the ISOL based radioactive technology. High production efficiency of ions, short releasing time and stable operation are required. Three different types of ion sources have been prepared to ionize various elements.

The main part of a surface ionization type is a Ta tube. The inside of this tube is covered with a metal foil with high work function like Re or Ir. This type is effective for atoms with low ionization potentials like alkaline elements. In a plasma type, neutral atoms are ionized by thermal electrons accelerated between a cathode and an anode. Since the forced electron bombardment is the main ionization process, atoms with high ionization potential can be also ionized by this ion source. A 6.4-GHz ECR type with mirror coils is used for the ionization of gaseous elements.

A beam bunching technique is used in the ion sources, when the heavy ion linacs are operated at a pulse mode. The bunching is made by installing an auxiliary electrode just at the exit of the ion source, and applying alternative positive and negative voltages[2, 3]. This bunching method also enables a direct measurement of the ionization efficiency of the ion source[4].

2.2 Mass Separator

The beam ionized by the ion source is selected by a mass separator (ISOL)[5]. The ion optical configuration of this separator is divided into two stage, QQDQQ(F1) and QMDMQ(F2), where Q, D and M stand for the quadrupole, dipole and multipole magnets and F the focal point. The multipole magnets and surface coils in the dipole magnets can be used to eliminate higher order aberrations. The first magnetic quadrupole doublet is movable in the axial direction so as to fit for different types of the ion sources. Designed mass resolving powers ($m/\Delta m$) are 9000 and 800 for the beam emittances of 4 and 40 πmm·mrad, respectively. The whole system is insulated from a ground potential so that a negative potential up to 100 kV can be applied. A full extraction voltage can be used in order to obtain a higher mass resolution. A mass resolving power of 5100 was achieved in the test using a stable beam.

2.3 Low Energy Transport Line

The ISOL and the heavy ion linacs are connected with a 60 m long transport line[5]. The transport line consists of seven electrostatic deflectors and about 134 electrostatic quadrupole singlets. The electrodes of the quadrupoles have a bore diameter of 36 mm. The acceptance of 170 πmm·mrad is obtained when the phase advance per a focusing period is selected to be 77 degree. The beam line level changes from 1.2 m to 2.3 m to across the TARN II ring,

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and again to 1.2 m of the linacs level. The achieved vacuum pressure is in the order of 10^{-7} torr, which is needed to suppress the beam loss due to the collision with the residual gases.

2.4 RFQ

A split coaxial RFQ (SCRFQ) has been developed to accelerate heavy ions with a small q/A at INS[6]. Design parameters of the SCRFQ are summarized in Table 1. The SCRFQ accelerates ions with a charge-mass ratio greater than 1/30 from 2 to 172 keV/u. The resonant frequency is chosen to be 25.5 MHz to accelerate the ions with $q/A \geq$ 1/60 considering future extension. The duty factor can be operated at 30% to accelerate ions with q/A=1/30 and 100% with $q/A \geq 1/16$. The cavity with 0.9 m in diameter and 8.6 m in length comprises four unit cavities, and each of which is composed by three modules. The intervane voltage was obtained by measuring the endpoint energy of X-rays generated from the cavity. As a result, the resonance resistance (=$V^2/2P$) was 24.55 $\pm$ 0.44 kΩ. Beam tests were conducted using beams from a 2.45-GHz ECR ion source placed at the entrance of the RFQ. The beam transmission efficiency for nitrogen molecules (q/A=1/28) was 90% at a duty factor of 20%, which agrees with the design value.

Table 1: Design parameters of the SCRFQ

Frequency	25.5 MHz
Charge-to-mass ratio	$\geq$ 1/30
Energy	2 $\rightarrow$ 172 KeV/u
Input emittance	291 π mm·mrad
Normalized emittance	0.6 π mm·mrad
Vane length	8.585 m
Number of cells (radial matcher)	172(20)
Max. Intervane voltage	108.6 kV
Max. surface field	178.2 kV/cm
	(2.49 Kilpatrick)
Mean aperture radius (r_0)	0.9846 cm
Minimum aperture radius (a_{min})	0.5388 cm
Max. modulation index (m_{max})	2.53
Margin of bore radius (a_{min}/a_{beam})	1.2
Final synchronous phase	-30°
Focusing strength (B)	5.5
Max. defocusing strength (Δ_b)	-0.17
Transmission (0 mA input)	91.4 %
Transmission (5 mA input)	86.0 %

2.5 Transport Line between RFQ and Drift Tube Linac

A transport system between the RFQ and the drift tube linac comprises a charge stripper (C-foil), a rebuncher and two pairs of quadrupole doublets[7]. The charge stripper is used to increase the charge state of the ions with a small q/A. Beam test with the stripper will be soon performed. The rebuncher is a 25.5 MHz double coaxial quarter wave resonator with six gaps. The power consumption in the cavity is less than 1.5 kW also in a maximum operation.

2.6 Drift Tube Linac

The ions with $q/A \geq$ 1/10 are accelerated from 172 keV/u to 1 MeV/u by a 51 MHz interdigital-H (IH) linac[8]. To obtain a high acceleration efficiency, π-π drift tubes without transverse focusing element were adopted. The linac has four separated tanks. The output energy can be continuously varied in the whole energy range from 172 keV/u to 1 MeV/u by adjusting rf power levels and rf phases. Three sets of quadrupole triplets are placed between tanks. The design parameters of the IH linac are listed in Table 2 together with the results of low power measurements. The power consumptions were obtained from the effective shunt impedance measured by a bead-pull method.

In the tests with beams ($^{14}N^{2+}$ and $^{20}Ne^{2+}$) from the 2.45-GHz ECR ion source, the transmission efficiencies achieved to 90$\sim$100%. The measured spreads of the output energies roughly agree with designed ones. A variability of the output energy was confirmed in a beam test.

Table 2: Main parameters of the IH linac

	tank1	tank2	tank3	tank4
f(MHz)	51	51	51	51
max. q/A	1/10	1/10	1/10	1/10
T_{out}(MeV/u)	0.294	0.475	0.725	1.053
L_{tank}(m)	0.68	0.90	1.16	1.53
D_{tank}(m)	1.49	1.49	1.49	1.34
D_{bore}(cm)	2.0	2.4	2.8	3.2
D_{tube}(cm)	3.8	4.4	4.6	5.2
L_{gap}(cm)	2.9	3.7	4.5	5.3
Cell No.	9	10	11	12
V_{gap}(kV)	200	250	313	370
unloaded-Q	10681	15387	16230	18490
Z_{eff}(MΩ/m)	264	289	268	218
P(kW)	10.5	15	25	39

2.7 High Energy Transport and Recoil Mass Separator

The optical arrangement of the high energy transport downstream of the IH linac comprises QQDQDQQ to make an achromatic condition at a secondary target position. The magnetic rigidity of the system is the same as that of ions with q/A=1/10 and 0.77 MeV/u. Three beam lines were prepared for experiments. One line has a recoil mass separator (RMS) together with a low-background gamma ray detector system[9]. The RMS is designed for low-energy capture reaction study for nuclear astrophysics. It has a mass resolving power of about 60, and the energy spread acceptance of $\pm$5%. The RMS comprises QQEDQQ optical elements, where E is an electrostatic deflector. In recent test, a stable Ne beam (0.72 MeV/u) stripped by a Au thin foil placed at the secondary target position was delivered to a focal plane of the RMS.

3 FIRST ACCELERATION TEST OF RADIOACTIVE NUCLEI

First acceleration test of ^{19}Ne^{2+} ($T_{1/2}$=17.3 s) was conducted in the spring of 1997. The ^{19}Ne beam was produced using ^{19}F(p, n) reaction with 30 MeV-protons from the SF cyclotron. The used target materials were LiF+C in a powder form with a size of about 1 μm and heated up to 400°C The production rate in the target is estimated to be 2×10^9 with 1 μA, 30 MeV protons. The ECR ion source was in a pulse operation, 2.0 ms in width and 100 Hz in repetition rate, which were determined by the operation of the linac complex. The IH tank-1 through tank-3 were operated to accelerate ^{19}Ne up to 0.72 MeV/u. The rf amplitudes and phases of linacs were set to parameters determined by acceleration tests with stable beams. The ^{19}Ne-transmission efficiency of the linac complex is estimated to over 80% from the contaminated beam current measured by Faraday cups.

In order to measure the beam intensity, the ^{19}Ne beam was stopped at plates or Faraday-cups placed on transport lines. The 511 keV γ-rays by β^+-decay were measured by Ge or CsI detectors. The full-energy detection efficiency of these detectors were calibrated by a standard source of ^{22}Na in advance. The efficiencies of the Ge and CsI detectors are $0.5\sim3\times10^{-3}$ and $0.3\sim1.4\times10^{-4}$, respectively. Figure 1 shows an example of the time spectrum of ^{19}Ne^{2+} intensity measured by a Ge detector at the secondary target position. The intensity of ^{19}Ne delivered here was not yet enough. The following improvements will be done after this test;

- The production efficiency of ^{19}Ne ions in the ECR ion source decreases at the primary beam intensity over several hundreds of nA. This seem to be due to undesirable out-gas generated from the target. The target temperature during irradiation of the high power beam must be also controlled at optimum one.
- To produce the ^{19}Ne beam, a LiF was used as a target material. A large amount of ^{19}F ions (a mass difference from ^{19}Ne is about 1/5500) was also produced. It is difficult to separate this contaminant completely by the ISOL. Different target materials may be chosen to avoid it.
- The transmission efficiency of the 60 m long transport line exceeded 70% in the test using a stable beam. But it was worse in this test. We need to search for the optical parameters to optimize the intensity of the ions of interest. Moreover, the beam from this line can not be well matched for the RFQ. More optical elements may be needed to match it.
- The IH tanks have not been operated with a duty factor higher than 20% under maximum powers. In final stage of the commissioning, a challenge of the higher duty operation will be conducted.

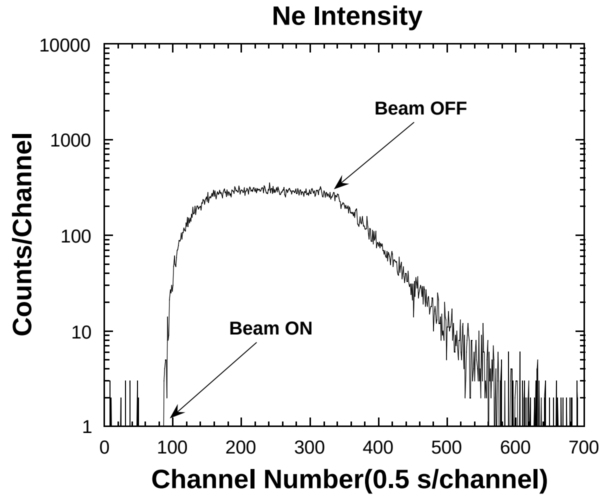

Figure 1: Time spectrum of ^{19}Ne^{2+} intensity measured by a Ge detector at the secondary target position. The intensity of primary protons was 100 nA.

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