DEVELOPMENTS AT JAEA AVF CYCLOTRON FACILITY FOR HEAVY-ION MICROBEAM

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Abstract

We have been improving the beam quality of the JAEA AVF cyclotron to form a several-hundred-MeV heavy-ion microbeam with magnetic focusing lenses. An energy spread $\Delta E/E$ of the order of 10^{-3}, obtained by ordinary acceleration using a dee voltage of the fundamental frequency, makes it difficult to focus an ion beam to a spot size of 1 μm in diameter with focusing lenses because of the chromatic aberration. A flat-top acceleration system using the fifth-harmonic frequency is utilized for reducing the energy spread to the order of 10^{-4}. Improvements of instruments of the cyclotron system were carried out. In addition, development of a high performance beam buncher is in progress to accelerate a high quality beam with beam current enough for the microbeam formation. The energy spread of the 260 MeV ^{20}Ne^{7+} beam has been reduced to 0.05% by the flat-top acceleration, and the microbeam with a spot size of approximately 1 μm has been successfully formed.

INTRODUCTION

At TIARA (Takasaki Ion accelerators for Advanced Radiation Applications) facility of Japan Atomic Energy Agency (JAEA; formerly known as Japan Atomic Energy Research Institute), an AVF cyclotron with a *K* number of 110 is utilized mainly for the research in biotechnology and materials science [1]. The cyclotron can accelerate various ions, 5 to 90 MeV protons and 2.5 to 27 MeV/u heavy-ions with acceleration harmonics of 1, 2, and 3. The cyclotron has a pair of λ/4 coaxial-type resonators whose resonance range of 11 to 22 MHz. Layout of instruments in the cyclotron facility is shown in fig. 1. The facility is divided into two areas, light-ion and heavy-ion irradiation rooms. Vertical irradiation ports are available for unfixable samples such as seeds and solutions.

A single-ion hit irradiation system of a heavy-ion microbeam with a collimating micro-aperture is set on the HZ vertical beam port [2]. However, the spot size of the microbeam is limited to 5-10 μm because of the minimum size of the micro-aperture and ion scattering at the edge of the aperture. Irradiation speed is as slow as a few ions per minute since the targeting is controlled by moving a mechanical sample stage. A focusing microbeam system with quadruplet quadrupole magnets was developed and installed on the HX vertical beam port in order to achieve the beam spot size of 1 μm and high speed irradiation of 600 hits per minute by a beam scanner [3].

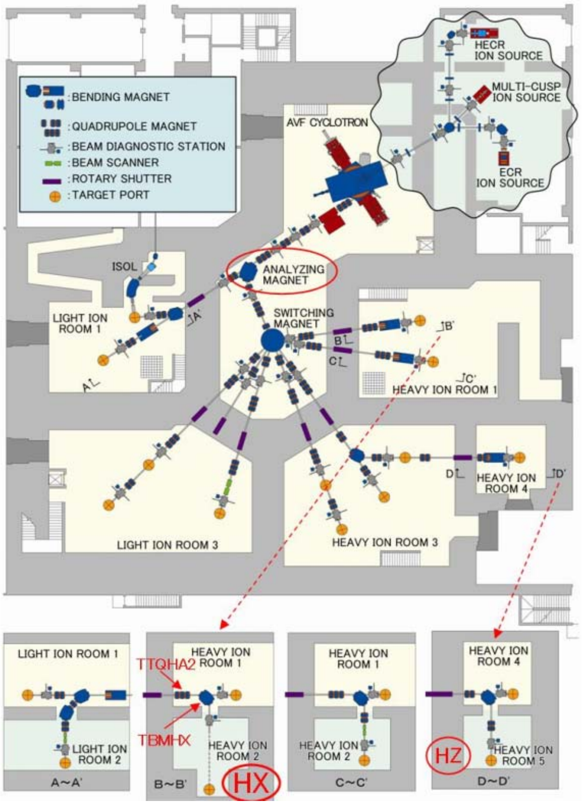

Figure 1: Layout of instruments in the JAEA cyclotron facility. 12 horizontal and 4 vertical irradiation ports are available.

An energy spread $\Delta E/E$ of the beam influences the spot size of the microbeam because it causes chromatic aberration in the focusing lenses. The energy spread of the order of 10^{-4} is required to achieve the beam spot size of 1 μm at the HX port. The energy spread of the cyclotron, however, is on the order of 10^{-3}. In order to reduce the energy spread, we developed a flat-top (FT) acceleration system using a fifth-harmonic frequency, a new central region and a high stabilization system of the cyclotron magnetic field [4,5].

In this paper, we describe various developments at the cyclotron facility to form the heavy-ion microbeam with the spot size of 1 μm.

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DEVELOPENT AND IMPROVEMENT OF THE CYCLOTRON SYSTEM

AVF Cyclotron

High power tests of the FT system were carried out in the almost whole acceleration region of 55 to 110 MHz. For the lower resonance frequency, we have to set a small gap of the coupling electrode below 10 mm, while a careful operation for aging is needed to defuse small sparks in such a case. For the higher resonance frequency, especially at 102 MHz for 220 MeV $^{12}C^{5+}$ that is a prior beam for microbeam formation, the high power test was successfully carried out. Since the voltage distribution along the acceleration gap of the dee electrode cannot be ignored for the higher fifth-harmonic frequency, we must set the fifth-harmonic voltage higher than the ideal amplitude of 1/25 of the fundamental acceleration voltage, which is calculated from the uniform distribution. The power test showed generation of the fifth-harmonic voltage enough for the effective FT acceleration. However, a large noise originated from the higher fifth-harmonic voltage is sometimes measured by a beam current probe. The phase probe, which consists of 10 pairs of electrostatic pick-up electrodes, was damaged hard by the noise. All of the coaxial cables used for the phase probe were melted and broken down. It seems that the hard damage was caused by the structure of the phase probe. The chassis of the phase probe is supported at one end and its length is roughly equal to $\lambda/4$ of the fifth-harmonic frequency. The phase probe might resonate slightly with the higher fifth-harmonic voltage. The chassis has been sufficiently grounded at 4 points and the coaxial cables were shielded by copper meshes. After that, the phase probe works with better S/N ratio and we can easily tune the isochronous field even if the intensity of the beam is small such as higher-charge state heavy ions. A radial beam probe with a plastic scintillator is being developed to measure the beam phase width and the relative phase to the acceleration rf signal with a higher time resolution. More precise tuning of the isochronous field and the beam phase width will be carried out in the near future.

Besides the main magnetic field, high stability is required for all components of the cyclotron to provide the microbeam steadily. High voltage power supplies for the deflector and the inflector were replaced for the first time since 1991. The new power supplies have a twofold improvement in voltage stability and load regulation as compared to the previous ones. Power supplies for magnets were also improved. The temperature control units of the feedback circuit of the power supplies were replaced to the Peltier device from the oven device for precise temperature control. We are going to remove unstable factors from the cyclotron step by step.

Realignment of the magnets on the beam transport line

The ion beam is finally transported to the HX microbeam port with a bending magnet (TBMHX) installed on the first floor of the heavy-ion room 1. The bending magnet and a triplet quadrupole magnet (TTQHA2) were set near the opening. The floor around the opening has gradually settled down since its construction. As a result, alignment of the magnets was changed. Table 1 shows displacement of the magnets. Each singlet quadrupole magnet of TTQHA2 is numbered 1 to 3 from upstream point. It was obvious that the floor settled down little by little toward the opening. The magnets were realigned on the reference line in 2004 before starting of the regular microbeam tuning. Magnets near the opening in the cyclotron room, a steering magnet and a triplet quadrupole magnet, had been realigned in 2000.

Table 1: Displacement of the magnets near the HX port before realignment.

	Horizontal (mm)	Vertical (mm)
TTQHA2-1	-0.5	-0.55
TTQHA2-2	-0.2	-0.93
TTQHA2-3	0	-1
TBMHX	0.4	-1.4

High performance beam buncher

The requirement of stabilities in the cyclotron magnetic field, the acceleration voltages and its phases for the FT acceleration are eased when the beam phase width is sharply limited in the central region. However, it is difficult to tune the cyclotron and the microbeam focusing lenses with the reduced beam current. Therefore, development of a high performance beam buncher was started to increase the beam current. A saw-tooth waveform is the most suitable as the buncher waveform. An easy method for generating the saw-tooth waveform by repeating charge and discharge of the buncher electrode was introduced [6]. Design of the LCR circuit of the buncher system was made by the PSpice simulator. Figure 2 shows the saw-tooth waveform of the new beam buncher. The method, however, cannot generate high voltage of the saw-tooth waveform with good linearity. A

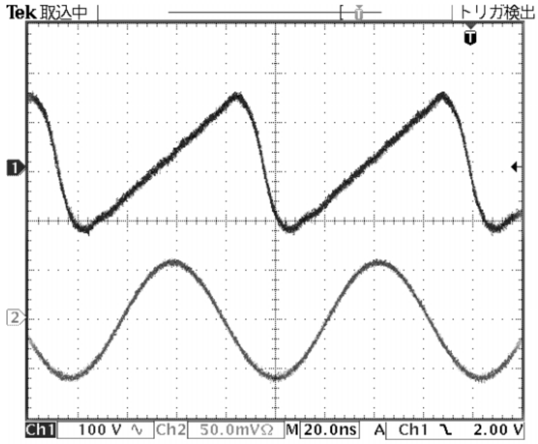

Figure 2: The upper is waveform of the saw tooth beam buncher. The repetition frequency is 12 MHz.

ripple component makes it difficult to compress the beam current effectively within 10 degrees. Therefore, we decided to use the saw-tooth waveform beam buncher as a pre-buncher of the sinusoidal beam buncher located at 3.4 m downstream. In the beam tuning by the FT acceleration, the beam current was increased by 50% compared with previous one when the beam bunchers were simultaneously operated. It is enough beam current for the microbeam tuning. Since the beam bunchers cannot increase the beam current equally for all ion beams, we have to progress the performance of the system.

BEAM DEVELOPMENT AND MICRO-BEAM FORMATION

Beam development of 260 MeV ^{20}Ne^{7+} by the FT acceleration is continuously being carried out. As a result of the improvements of the cyclotron, a clear turn separation of the beam bunches was successfully observed by the deflector probe with a differential head as shown in fig. 3. On the other hand, no turn separation was observed in the case of the ordinary acceleration only with the fundamental acceleration voltage. Extraction efficiency at the deflector was greatly improved from 60% to 95% by the FT acceleration. In order to confirm the reduction of the energy spread of 260 MeV ^{20}Ne^{7+}, a micro-slits system, which measures the beam spread caused by energy dispersion in the analyzing magnet, was developed [7]. As a result, it was shown that the energy spread was reduced from $\Delta E/E$ = 0.1% to 0.05% in FWHM by the FT acceleration. The energy spread of $\Delta E/E$ = 0.02% will be achieved by fine-tuning of the voltage ratio and/or relative phase setting of the fundamental and the fifth-harmonic frequencies. We are going to increase constantly a variety of the FT accelerated ion beams, especially carbon and argon beams.

Beam tuning for microbeam formation is in progress with the 260 MeV ^{20}Ne^{7+} beam at HX port. The microbeam formation system is consists of object micro-slits, divergence defining slits and quadruplet quadrupole magnets. The ion beam is roughly focused by observing the spot size on a scintillator. After that, the microbeam is formed by repeating careful tune of the parameters and observation of a secondary electron image of a fine copper mesh (1000 lines/inch). A CR-39 plastic film was irradiated by a single ion in a pattern of 5 x 5 points with a pitch of 5 µm and is shown in figure 4. The spot size of the microbeam was estimated to be less than 1 µm from an analysis of figure 4. This is the highest beam energy as the heavy-ion microbeam with the spot size of 1 µm in the world [3].

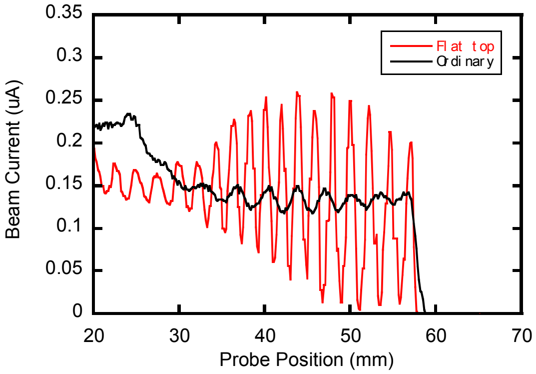

Figure 3: Radial beam current distribution of 260 MeV ^{20}Ne^{7+} measured by the differential deflector probe. The Acceleration frequency, acceleration harmonics and the number of revolutions are 17.475 MHz, 2 and 265 respectively.

The spot size of the microbeam, however, is deteriorated by small change of operational parameters of the cyclotron and a plasma condition of an ECR ion source (HECR) caused by temperature variation of the cooling water. We will further stabilize the performance of the cyclotron and develop a cooling water-free highly-stabilized ECR ion source only with permanent magnets.

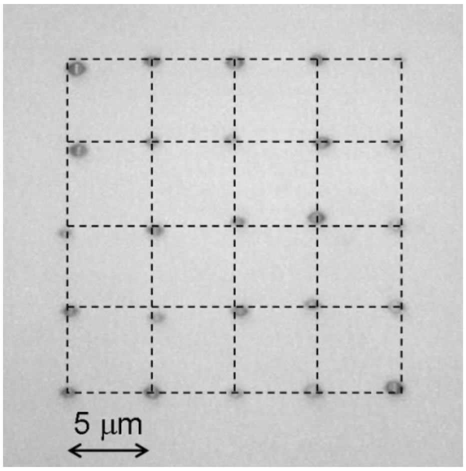

Figure 4: Single-ion hit pattern on a CR-39 plastic film. The film was etched by a solution after irradiation.

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