MICROBEAM PRODUCTION AT JAERI AVF CYCLOTRON FACILITY

M. Fukuda*, S. Kurashima, S. Okumura, N. Miyawaki, T. Nara, T. Agematsu, I. Ishibori, K. Yoshida, Y. Nakamura, H. Kashiwagi, W. Yokota, T. Kamiya, T. Sakai, M. Oikawa, T. Satoh and K. Arakawa
Japan Atomic Energy Research Institute, 1233 Watanuki, Takasaki, Gunma, 370-1292, Japan

Abstract

A heavy-ion microbeam system is being developed at the JAERI AVF cyclotron facility for applications in biology and biotechnology. For production of the microbeam with a spot size of 1 μm in diameter, the energy spread in the beam is required to be reduced to $\Delta E/E = 2 \times 10^{-4}$ to minimize the effect of a chromatic aberration in a magnetic focusing lens. In order to obtain a homogeneous energy gain distribution, a flat-top acceleration system using a fifth-harmonic voltage has been developed for the variable-energy multi-particle AVF cyclotron. An additional coaxial cavity has been coupled to the main resonator to superimpose the fifth-harmonic voltage on the fundamental one. The range of the fifth-harmonics frequency, 55 to 110 MHz, was fully covered by the flat-top cavity. Stability of the cyclotron magnet has been improved within $\Delta B/B = 2 \times 10^{-5}$ to reduce a beam phase excursion. A center region of the cyclotron has been modified for precise control of beam phase selection required for the flat-top acceleration. Single turn extraction has been achieved by the flat-top acceleration.

INTRODUCTION

A hundreds MeV heavy ion is an excellent probe for the research in biotechnology and life science. The heavy ion brings high linear energy transfer (LET) to a substance by depositing energy in localized region along the ion track. The heavy ion, passing through a cell, causes great damage to DNA included in a cell nucleus. The size of a mammalian cell nucleus approximates 5 through 10 μm. Targeting precision less than a few μm is required for a heavy ion hit inside the cell nucleus.

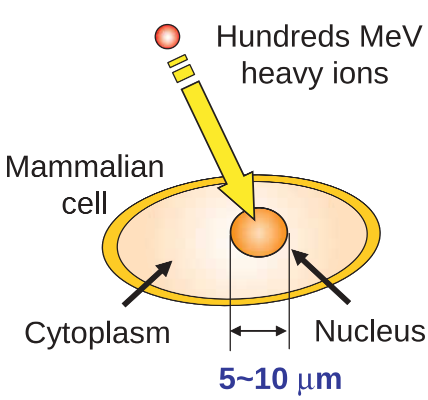

Figure 1: An image of the irradiation of a cell nucleus using the heavy ion microbeam.

* E-mail: fukuda@taka.jaeri.go.jp

A heavy ion microbeam is a powerful tool for elucidation of cellular radiation response [1]. Irradiation of a cell nucleus or a cytoplasm of a cell using the heavy ion microbeam is extremely useful for not only investigation of cell-to-cell communications such as bystander effects, but also analysis of cellular spatial sensitivity, interaction of damages of cellular repair and intra-cellular process like apoptosis. Our goal is the production of the heavy ion microbeam with a spot size of 1 μm or less. An image of the cell irradiation by the heavy ion hit is shown in Fig. 1.

The JAERI K110 AVF cyclotron [2,3] can accelerate a variety of heavy ions up to 27.5 MeV/u. The heavy ions are extensively used for the research in biotechnology and materials science. A heavy ion microbeam irradiation system was installed on one of vertical beam lines of the JAERI cyclotron facility. The microbeam system was equipped with a beam collimator with an aperture of 5 to 10 μm in diameter [1]. The minimum beam spot size was limited to the size of the collimation aperture, which was insufficient in targeting precision for a cell nucleus. In addition, the contamination of halo particles scattered at the edge of the collimator was observed around the main beam spot.

A new heavy ion microbeam irradiation system using a magnetic focusing lens is being developed on a different vertical beam line [4]. The beam focusing system consists of a quadruplet of quadrupole magnets and a series of slits. A schematic image of the microbeam production is shown in Fig. 2. The beam spot size depends mainly on a demagnification of the lens system and a chromatic

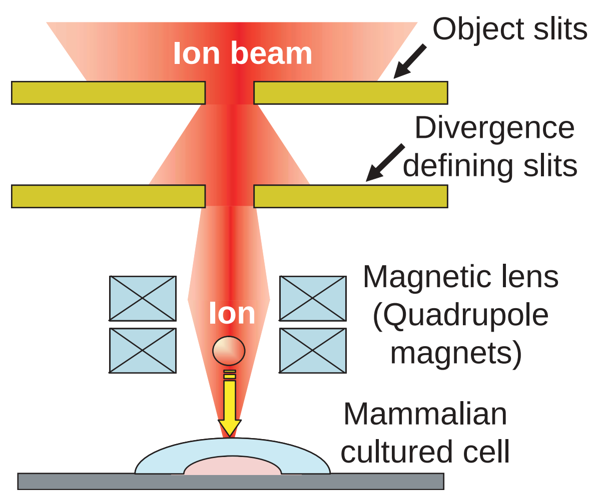

Figure 2: A schematic image of the microbeam production system using the magnetic focusing lens and a set of beam slits.

aberration originating in the energy spread of an ion beam. The energy spread of the order of 10^{-4} is required to achieve the beam targeting resolution of 1 μm.

A stable beam of high quality is the key to the realization of the microbeam production. Extensive improvement of the cyclotron performance is indispensable to supply the well-controlled beam. A flat-top acceleration system has been developed for the JAERI AVF cyclotron to reduce the energy spread for the microbeam production [5]. A center region of the cyclotron has been improved for precise control of beam phase selection to confine the beam phase width to the tolerable region of a flat-topped acceleration voltage waveform. A magnetic field stabilization system for the cyclotron magnet has been developed to avoid the beam phase slip from the tolerable beam phase region [6].

REQUIREMENTS FOR MICROBEAM PRODUCTION

In the microbeam formation system using the magnetic focusing lens and a series of beam slits, a beam spot size can be reduced by increasing the demagnification factor of the lens system. The demagnification factor is restricted by the maximum field gradient of quadrupole magnets. The size of the quadrupole magnets gets large with increase in magnetic rigidity for hundreds MeV heavy ions. A configuration of a quadruplet quadrupole magnets has been adopted to install the focusing lens system in a limited space of the beam line.

A smaller beam spot size can be achieved by decreasing the gap of the object and divergence-defining slits, and by increasing the distance between the two slits for production of the beam with very small emittance. The slit distance was limited to around 2.8 meters due to the existing beam line space for the installation. An ion beam with high brightness is required to keep the beam intensity for practical use.

Suppression of focussing errors, induced by spherical and chromatic aberrations in the lens system, is very significant for the microbeam production. Precise fabrication and alignment of the lens system are required for the focusing error suppression caused by the spherical aberration. Minimization of the energy spread of the beam is absolutely essential for reduction of the focusing error originating in the chromatic aberration. Dependence of the beam spot size on the energy spread and the object size defined by the slits is shown in Fig. 3. In our system, the microbeam with a spot size of 1 μm will be produced by the condition of the object size of 5 μm and the energy spread of $\Delta E/E = 2 \times 10^{-4}$.

The apparatuses of the beam focusing system were installed on an integrated platform to suppress the effects of vibrations. Temperature around the beam focusing system is required to be kept constant to prevent changes of the apparatus dimension.

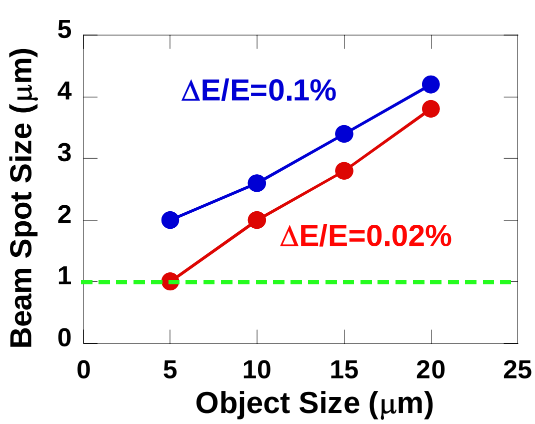

Figure 3: Estimation of the beam spot size depending on the size of the object slit and the energy spread of the beam.

FLAT-TOP ACCELERATION SYSTEM

The required energy spread of $\Delta E/E = 2 \times 10^{-4}$ is expected to be obtained by limiting the beam phase width within $|\Delta\phi| \leq 2$ degrees in RF phase in the ordinary acceleration mode using a sinusoidal voltage waveform. Although the restriction of the beam phase width can be achieved by precise control of the phase slit positions, the magnetic field stability of the order of 10^{-6} is required to keep the beam phase slip in the range of the tolerable phase slip. In addition, the beam intensity decreases by the beam phase defining without a well-bunched beam injected into the cyclotron.

The range of the tolerable beam phase slip can be extended by the flat-top acceleration technique. A ratio of energy gain difference ΔE/E for the ordinary acceleration and the flat-top acceleration using the fifth-harmonic frequency is shown in Fig. 4. In the flat-top acceleration, the energy spread of $\Delta E/E = 2 \times 10^{-4}$ is expected to be achieved by confining the beam phase slip within $|\Delta\phi| \leq 8$ RF degrees [7]. In this case, the tolerance of the magnetic field fluctuation causing the beam phase slip is estimated to be $\Delta B/B = 2 \times 10^{-5}$ FW.

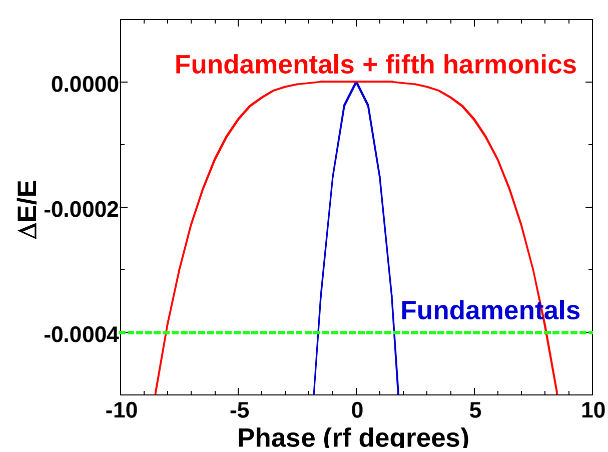

Figure 4: The ratio of energy gain difference ΔE/E for the ordinary acceleration using the fundamental frequency and the flat-top acceleration using both the fundamental and fifth-harmonic frequencies.

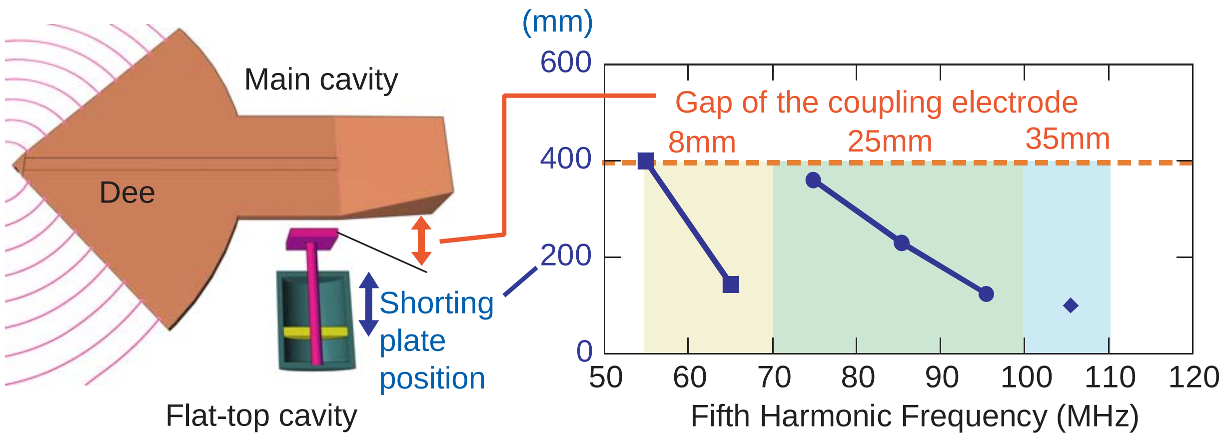

Figure 5: The shorting plate position and the gap between the coupling electrode and the main cavity to cover the full range of the fifth harmonic frequency.

The fifth-harmonic frequency was adopted for the flat-top acceleration in the JAERI AVF cyclotron [7]. The flat-top acceleration using the fifth-harmonic voltage provides the advantages of minimization of the power dissipation in a resonator and the saving of the amplifier power output. The fifth-harmonic voltage, required for flat-topping the energy gain distribution, is smaller than the third-harmonic one. The energy gain per turn of the flat-top acceleration using the fifth-harmonic voltage is larger than the third-harmonic one, since the harmonic voltage with a negative sign is superimposed on the fundamental one.

The flat-top cavity for generating the fifth-harmonic voltage was designed to be sufficiently compact for installation in the limited space around the existing main resonator of the JAERI AVF cyclotron [8]. The main cavity is of movable-short coaxial type. The range of the fundamental frequency is 11 to 22 MHz. The flat-top cavity was mounted on the main cavity through the existing port for a cryogenic pump. The transmission line was coupled by a capacitive coupler, a plate of 150 mm square. The maximum movable range of the shorting plate of the flat-top cavity was limited to 400 mm due to the space restriction. The range of the fifth-harmonic frequency from 55 to 110 MHz was covered by optimizing the size of inner- and outer-tubes of the flat-top cavity, and by adjusting the shorting plate position and the gap between the coupler and the inner tube of the main cavity. The relations of the flat-top cavity parameters are shown in Fig. 5.

Fluctuation of the acceleration voltage directly causes deterioration of the energy spread. In order to achieve the energy spread of $\Delta E/E = 2 \times 10^{-4}$ FWHM, the tolerable stability of the fundamental and fifth-harmonic voltages is estimated to be $\Delta V_1/V_1 = 2 \times 10^{-4}$ FW and $\Delta V_5/V_5 = 1 \times 10^{-3}$ FW, respectively [7]. The fluctuation of the RF phase is required to be reduced to $|\Delta\phi_1| \leq 0.2$ degrees RF FW for the fundamental voltage and $|\Delta\phi_5| \leq 0.04$ degrees RF FW for the fifth-harmonic one.

A power test has been carried out at the fundamental frequency of 17.4 MHz for the acceleration of a 260 MeV $^{20}Ne^{7+}$ ion, used for biological experiments [9]. Power dissipation in the flat-top cavity increased with the gap of the coupling capacitor. After optimizing the parameters for low power dissipation, the flat-topped voltage waveform was successfully observed at the dee voltage pick-up mounted at the outermost edge of the dee electrode [9]. For the practical flat-top acceleration, the voltage waveform varies in amplitude depending on the radial position along the acceleration gap, since the fifth-harmonic voltage distribution has a large variation determined by the fifth-harmonic frequency. In order to flat-top the overall energy gain distribution just before extraction, the fifth-harmonic voltage needs to be increased for compensating the decrease of the energy gain in the region of larger radii.

MAGNETIC FIELD STABILIZATION

The beam phase slip out of the tolerable phase range is brought about by the error of isochronous field generation and by the change of the magnetic field with time. The error of the isochronous field generation is correctable by precisely adjusting currents of main and trim coils. The fluctuation in the magnetic field is a serious problem caused by the variation in temperature of a pole and a yoke of the cyclotron magnet. As mentioned in the previous chapter, the fluctuation of the magnetic field is required to be reduced to $\Delta B/B = 2 \times 10^{-5}$ FW or less.

Originally unstable phenomena of gradual decreases of the beam intensity were observed in the early stage after a start-up or an excitation change of the cyclotron magnet [6]. The beam intensity decreased to half of the initial value several hours after the change of the cyclotron magnet excitation.

On the basis of investigation of the correlation between the magnetic field and yoke temperature changes, we have taken effective measures to stabilize the magnetic field [6]. Water-cooled copper plates were installed between the main coil and the magnet yoke to control thermal conduction from the main coil to the magnet yoke. Cooling water temperatures of the copper plates and trim coils were optimized to keep the pole and yoke temperatures constant according to the excitation level.

The change of the magnetic field after starting-up the cyclotron is shown in Fig. 6. The reduction of the magnetic field fluctuation down to $\Delta B/B = \pm 1 \times 10^{-5}$ has been achieved by the stabilization measures. The magnetic field stability fulfils the requirement for the tolerable value [10].

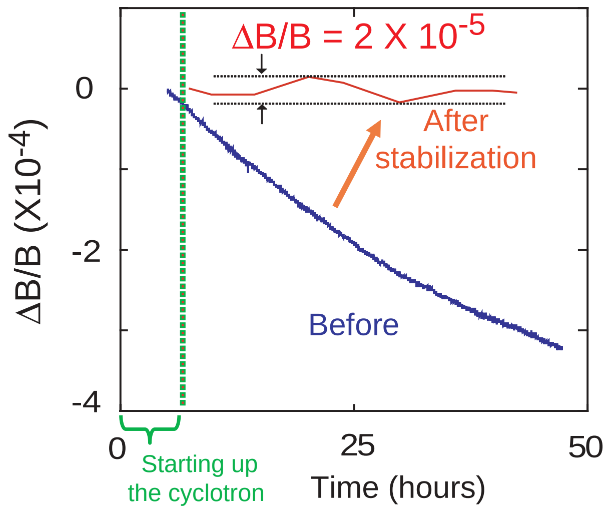

Figure 6: Variations of the magnetic field of the cyclotron before and after implementing the stabilization measures.

CENTER REGION

The center region of the JAERI AVF cyclotron has been substantially modified to improve the beam phase selection for realizing the tolerable beam phase width of $|\Delta\phi| \leq 8$ RF degrees. The original design of the center region had been insufficient for the precise control of the beam phase width, even if a beam phase slit was narrowed greatly. The positions of an inflector and a puller were reconsidered to optimize the correlation between a beam phase and an orbital position at the beam phase slit. The design of the spiral electrode itself of the inflector has not been changed.

The schematic layout of the new center region is shown in Fig. 7. Acceleration harmonic modes of h = 1, 2 and 3 are available for covering a wide range of energy. The inflector and the puller were individually designed for each acceleration harmonic mode. The inflector and puller electrodes are required to be exchanged frequently to switch the acceleration harmonic mode. In order to increase efficiency of the cyclotron operation as high as possible by saving the time for changing the puller, the position of the puller gap has been made common for h = 1 and 2 by separating the inflector electrode from its RF shield, which had been integrated so far.

The fixed puller gap was incompatible with the acceleration harmonic mode of h = 3, since precision of the beam phase selection for h = 3 was insufficient. We have rotated the inflector electrode for h = 3 by 180 degrees. The injected beam was extracted to the tip of the other dee electrode.

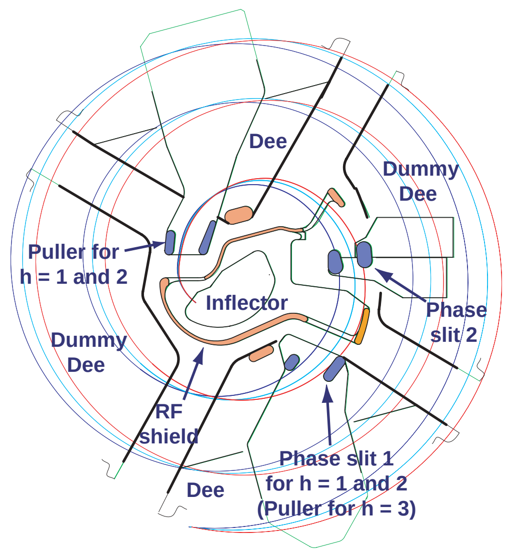

Figure 7: A schematic layout of the newly designed center region for h = 2. Trajectories of the particles with initial beam phase of -15, 0 and +15 RF degrees are drawn.

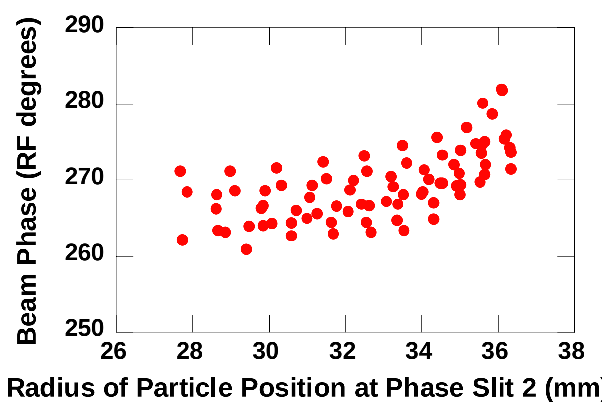

Figure 8: A simulated correlation between the beam phase and the radial position of particles passing the beam phase slit 2 for h = 2.

Central rays in the center region for the initial beam phase of ϕ_0 = -15, 0, +15 RF degrees are shown in Fig. 7. An example of a simulated correlation between the beam phase and the radial position of the orbit at the beam phase slit 2 for h = 2 is shown in Fig. 8. In this case, the beam phase width of $|\Delta\phi| \leq 8$ RF degrees can be achieved by placing the beam phase slit in the radius range from 28 to 34 mm. The practical phase width of the beam extracted from the cyclotron, measured by a plastic scintillator, was about 6 RF degrees FWHM obtained by setting the slit size of about 3 mm.

BEAM DEVELOPMENT

A flat-top accelerated 260 MeV $^{20}Ne^{7+}$ ion beam has been developed first for the microbeam production. Turn separations in the large radius region before extraction has been clearly observed by the new beam phase selection system.

Single-turn extraction, which is an indispensable condition to obtain the energy spread of $\Delta E/E = 2 \times 10^{-4}$, has succeeded by optimizing operation parameters of the cyclotron, such as the ratio of the fundamental and fifth-harmonic voltages, the magnetic field and the beam phase width. A pulsated beam with a pulse width of around 100 ns was injected into the cyclotron. One or two natural beam bunches were generated in the cyclotron by periodic acceleration. The single-turn extraction was proved by the fact that the number of the beam bunches extracted from the cyclotron corresponded to the initial bunch number.

Although the energy spread of the extracted beam has not been measured precisely yet [11], it was obvious that the energy spread of the flat-top accelerated beam was smaller than the ordinary acceleration. The energy spread is expected to be reduced to $\Delta E/E = 5 \times 10^{-4}$ or less.

In the preliminary development of a 260 MeV $^{20}Ne^{7+}$ microbeam, a tight beam tuning is needed for fine adjustment of the transferred beam to the axis of the microbeam production system. We have realized that some magnets for beam transport shifted downwards by a few mm due to the dip in a building floor. The magnet alignment errors will be corrected soon. Unstable phenomena such as fluctuations of the beam intensity and the beam spot position have been observed during the microbeam development. We will try to find the causes of the instability.

A spot size of the microbeam, measured by a CaF_2(Eu) scintillator telemicroscope and supersensitive camera, is estimated to be 10 through 30 μm in diameter at the moment. Optimization of the microbeam production system is now in progress.

REFERENCES

[1] Y. Kobayashi, et al., Nucl. Instr. and Meth. B 210 (2003) 308

[2] K. Arakawa, et al., Proc. 13th Int. Conf. on Cyclotron and their Applications, Vancouver, Canada, 1992, 119.

[3] Y. Nakamura, “Status Report on JAERI-AVF Cyclotron System,” this Conference.

[4] M. Oikawa, et al., Nucl. Instr. and Meth. B 210 (2003) 54.

[5] M. Fukuda, et al., Nucl. Instr. and Meth. B 210 (2003) 33.

[6] S. Okumura, et al., Proc. 16th Int. Conf. on Cyclotron and their Applications, East Lansing, USA, 2001, 330.

[7] M. Fukuda, et al., Rev. Sci. Instrum. **74** (2002) 2293.

[8] S. Kurashima et al., Proc. 16th Int. Conf. on Cyclotron and their Applications, East Lansing, USA, 2001, 303.

[9] S. Kurashima, “Development of the Flat-Top Acceleration System for the JAERI AVF Cyclotron,” this Conference.

[10] S. Okumura, et al., NUKLEONIKA 48 (2003) 35.

[11] S. Okumura, “Instrumentation for Measurement of Beam Energy Spread,” this Conference.