Improvement of beam quality by phase bunching in the central region of the TIARA AVF cyclotron

RCNP

Nobumasa Miyawaki

2025-9-29

Abstract

The beam quality and intensity were remarkably enhanced by realizing phase bunching in the central region of an azimuthally varying field (AVF) cyclotron in the Takasaki Ion Accelerators for Advanced Radiation Application (TIARA) facility. The mechanism of the phase bunching generated between the first and second acceleration gaps was clarified geometrically, and the phase bunching method was properly generalized for an external beam injection system of a cyclotron. Performance of the phase bunching was evaluated both from simulation of beam trajectories using a geometric model and from measurement of internal and external beam phase distributions with a plastic scintillator. Development of the phase bunching technique effectively contributed to the world's first formation of a high-energy heavy ion microbeam with a beam spot size of 1 μm in diameter. The details are described as follows.

In the AVF cyclotron of the TIARA facility, we started the challenging project to develop a high-energy heavy-ion microbeam formation system using a set of quadruplet quadrupole magnets and a pair of micro slits for living cell irradiation with a precision of 1 μm. The purpose of this study is to provide a high-quality beam within a beam pulse width of 3 RF degrees FWHM required for an energy spread of $\Delta E/E = 0.02\%$ to reduce chromatic aberration for minimization of a beam spot size. We have advanced a new phase bunching technique to improve the beam quality and transmission in the extraction region of an AVF cyclotron.

Phase bunching is a phenomenon in which charged particles are bunched longitudinally and spread transversely during the first few turns of acceleration in a cyclotron. Although existence of the phase bunching was indicated in some reports by simulations, no measurement results were presented so far. In order to clarify the conditions under which phase bunching is generated, a geometric trajectory analysis model was created, and four parameters were found to contribute to phase bunching: the opening angle of the Dee electrode and the span angle between the first and second acceleration gaps, acceleration harmonic modes (h), and the ratio of the ion source extraction voltage to the acceleration voltage at the first acceleration gap. Phase bunching technology has been applied to the new central region of the TIARA AVF cyclotron, and the calculation result of the model showed that phase bunching was generated in the beam condition for $h = 2$, but not for $h = 1$. The effect of phase bunching in the geometric model calculation results, in which the initial phase width of ±20 RF degrees decreased to within ±5 RF degrees, was almost consistent with the results of the orbit simulation using the Runge-Kutta method. Therefore, we confirmed that the geometric model correctly explained the mechanism of phase bunching occurrence.

To confirm realization of phase bunching by measuring the actual beam, we developed a new probe equipped with a plastic scintillator that enables measurement of the beam phase distribution inside the cyclotron. The emitted scintillation light from the plastic scintillator was transported by an optical cable connected to a photomultiplier tube placed outside the iron yoke, where the magnetic field effect is small, and converted into an electrical signal for analysis.

The measurement of the beam phase distribution inside the cyclotron showed that the phase bunching effect of beam phase width reduction without a buncher results in a 14.7 RF degree FWHM phase width for h =2 and a DC beam injection. Furthermore, when the buncher was used, the beam phase width for the phase bunching beam condition was reduced to 5.5 RF degrees FWHM compared to 13.2 RF degrees FWHM for the beam condition without phase bunching, indicating that the phase bunching was effective even when the buncher was used. The measured beam phase distribution for each buncher phase, which was able to control the initial phase of the beam, was consistent with the geometric model calculation results, regardless of the presence or absence of phase bunching, and this also confirmed validity of the geometric model explaining the mechanism of phase bunching.

In the beam phase distribution measured after extraction from the cyclotron for the case of no phase bunching, several local peaks appeared in specific phases of the internal beam phase distribution due to beam loss in the extraction device. However, in the case of phase bunching, two peaks appeared in the external beam phase distribution with almost the same range as the internal beam phase distribution. The main component of the two peaks was 2.0 RF degrees FWHM, which satisfied with the beam phase width condition required for microbeam formation. Measured extraction efficiency, defined as the ratio of the beam currents before and after extraction, for the case of phase bunching was more than twice as large as the case without phase bunching. In particular, the use of the buncher increased the extraction efficiency to 95.6% with phase bunching compared to 41.7% without phase bunching, clearly demonstrating the effect of phase bunching on the extracted beam current.

To investigate the effect of phase bunching on beam extraction efficiency, we measured the correlation between the beam phase and the position of a phase slit that radially restricts the beam trajectory in the cyclotron, and estimated the radial spread of the beam before extraction by geometric model calculation. For h = 1 without phase bunching, a large change in both the longitudinal and transverse directions as the initial phase changed was observed, whereas the only radial beam spread was almost exclusively changed for the h = 2 condition with phase bunching. As a result, the calculated and measured radial spreads at the first acceleration gap were consistent even with and without phase bunching, but the calculation results of the beam spread near the extraction radius showed that the beam spread with phase bunching was much smaller than that without phase bunching. Furthermore, a horizontal 80% emittance measured at the exit of the cyclotron using an actual beam with phase bunching was 0.32π mm·mad, much smaller than the value of 0.84π mm·mad without phase bunching, which was almost equal to the calculation result of the internal beam. Thus, phase bunching significantly improved the beam quality and clearly increased the extraction efficiency. The improved beam quality due to phase bunching allowed formation of the microbeam by focusing the beam to a spot size of 1 μm without the contribution of the flat-top acceleration system.