Beam Test on Ring Property in HIMAC Synchrotron

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Abstract

The properties of the HIMAC synchrotron rings have been investigated. An approach of a beam extraction by FM and AM rf knockout has also been studied to develop an advanced irradiation synchronized to breathing of a patient for a high quality therapy.

1. INTRODUCTION

The HIMAC is an accelerator facility dedicated to medical applications. The HIMAC has been commissioned since Nov. 1993 and a clinical trial has been started since Jun. 21, 1994 at National Institute of Radiological Sciences (NIRS), Japan[1].

At the first stage of the commissioning of two rings, He^{2+} ions were accelerated up to 230MeV/n and were slowly extracted for the radiation safety inspection. At the next stage, the one ring has supplied C^{6+} ions with the energy of 290MeV/n for biomedical and physical experiments for a clinical trial. The other ring has been operated to study the properties of the ring and an approach of beam extraction. A new method utilizes a transverse rf field resonant with a horizontal tune (rf knockout with frequency and amplitude modulation) in order to extract beam in synchronization with breathing of a patient. The paper reports the ring properties and the experimental results of the beam extraction with a transverse rf field.

2. PROPERTIES OF THE RING

2.1 Working point

At the design stage, working point (Qx, Qy) in an injection period was chosen around (3.75, 3.25), while it was moved to (3.68, 3.25) at flat top after an acceleration. Then the beam was to be slowly extracted by moving the horizontal tune to 11/3. At the commissioning stage, however, the working point was changed to around (3.68, 3.13) in both the injection and acceleration period to suppress a beam loss due to crossing several resonances during the tune movement. Both the horizontal and the vertical tunes were measured by the rf-knockout method. The measured values were agreed within 1% with calculated values by using the ring model based on the field measurements of magnets[2].

2.2 Beta and dispersion functions

The horizontal and vertical beta functions (β_x, β_y) at both center of the focusing (Q_f) and defocusing (Q_d) quadrupole magnets were obtained by measuring tune shifts according to changing quadrupole fields. Measured (β_x, β_y) at the center of the Q_f and Q_d were (19.9m, 2.4m) and (3.7m, 17.4m), respectively, while calculated ones were (18.5m, 3.2m) and (3.0m, 18.8m), respectively.

The dependence of horizontal position displacement on an rf frequency was measured by using the ΔR monitor. The measured value of the horizontal dispersion function was 2.9m at ΔR monitor, which is larger by about 20% than the calculated value at the transition γ_t of 3.7.

2.3 Chromaticity

The horizontal and vertical chromaticity were measured as a function of rf frequency at flat base (the field of 0.1T at dipole magnets) and at flat top (0.7T). Assuming the γ_t of 3.7, the horizontal and vertical chromaticity at flat base were found to be -6.4 and -1.2, respectively, while those at flat top -4.1 and -3.6, respectively. On the other hand, calculated chromaticity were -3.8 in both planes. The difference between the measurements and the calculations at flat base may be caused by the sextupole components of main dipole magnets due to the remanent field. The horizontal chromaticity at flat base and at flat top were corrected to -1.2 and -0.2, respectively, by the sextupole magnets. The vertical chromaticity at flat base and flat top were changed to -2.9 and -4.4, respectively.

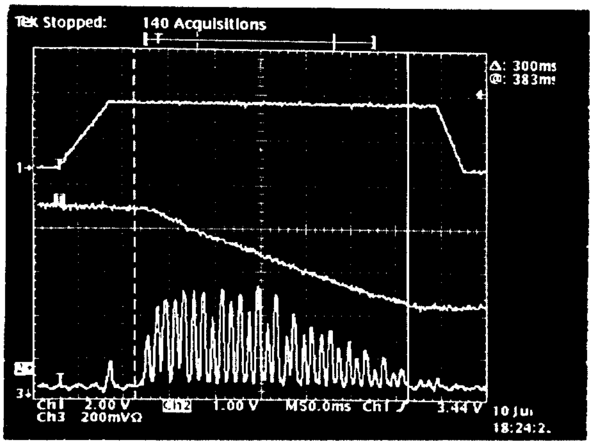

Fig.1 Beam spill in the ordinary extraction. From the bottom, beam spill, circulating beam intensity and current of sextupole magnet.

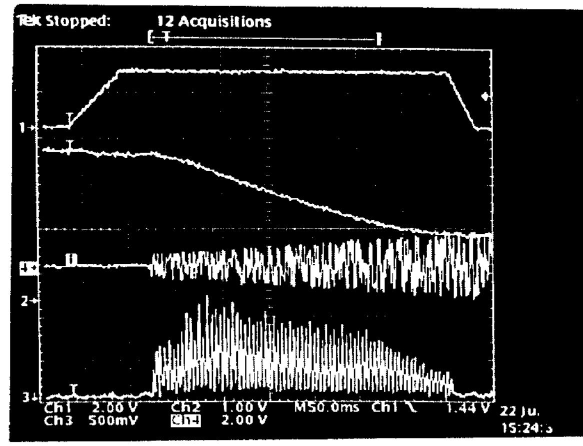

Fig.2 Beam spill in the extraction with the transverse rf field. From the bottom, beam spill, transverse rf field, circulating beam intensity, current of sextupole magnet.

2.4 Beam extraction by the ordinary method

A beam is slowly extracted by using ordinary method with a third order resonance. As shown in fig.1, a beam was extracted by shifting the horizontal tune slowly to 11/3 with exciting the sextupole magnets for producing a separatrix. To suppress the emittance growth of the extracted beam due to separatrix motion, we tuned bump magnets and an electrostatic deflector, in such a way that increasing bump orbit and decreasing deflection angle compensate the change of separatrix during the flat top. The horizontal and vertical emittance were measured by the least square method on the width of beam profile as a function of strength of a quadupole field at the high energy beam transport line; they were 9π and 6π mm•mrad, respectively.

3. BEAM EXTRACTION WITH TRANSVERSE RF FIELD

For an advanced irradiation on a tumor, it is essential to realize an extraction synchronized to breathing of a patient. Since a prompt response to a trigger of irregular interval is necessary, rf kicking is more suitable than ordinary tune shift by magnetic elements. The extraction with the transverse rf field with the mono-frequency was experimentally successful[3] and a similar method with a random frequency was simulated[4]. However, it is also important to reduce the emittance while keeping intensity as flat as possible during the extraction. Thus the extraction with the transverse rf field resonant with the horizontal tune (rf-knockout) have been investigated. Advantages in this method are to obtain a beam with a small emittance in the horizontal plane due to a constant separatrix and to respond quickly to the beam extraction because of using the resonance phenomenon. Since this method utilizes the horizontal emittance growth due to applying the transverse rf field while the separatrix is kept constant, the fields of bump magnets and the voltage of the electrostatic deflector also are fixed.

3.1 Frequency and amplitude modulation

The efficiency of the extraction with the transverse rf field with a mono-frequency was less than that of the ordinary extraction because of tune spread. Further, Intensity of an extracted beam exponentially decreased with time. Therefore, the transverse rf field with a frequency modulation and with an amplitude modulation was tested to improve the extraction efficiency and the time structure of the extraction beam. Fig.2 shows a typical result of the extraction beam at the frequency band width Δf_k of about 6kHz, the amplitude V_k of $440V_{pp}$ (averaged with applied time) and the center frequency f_k of 1.012MHz in C^{6+} beam with the energy of 290MeV/n.

We investigated the extracted beam intensity as a function of the amplitude and the frequency band width of the transverse rf field. As can be seen in fig.3(a), almost all circulating ions are extracted from the ring at higher V_k than $400V_{pp}$. Concerning the dependence of the extracted intensity on the Δf_k, a maximum intensity is obtained at Δf_k of 5kHz as shown in fig.3(b). A calculated band width due to the tune spread is 4.8kHz under the condition of a separatrix area of 40π mm•mrad, a horizontal chromaticity of -0.2 and a momentum spread of $\pm 5\times 10^{-4}$. The intensity at the Δf_k above 5kHz decreases because of reduction of the power density.

The measured horizontal and vertical emittance were 3π and 5π mm•mrad, respectively. The horizontal one was reduced to about 30% in comparison with that in the ordinary extraction.

3.2 Response for beam on/off

To synchronize the beam with breathing of a patient, it is required that the response of the beam to the applied field is as prompt as possible both in on/off direction. As can be seen in fig.4, the beam was extracted within 1ms when the rf field was turned on. The response time seems short enough for the requirement.

3.3 The ordinary extraction with the rf field

A beam ripple of a beam extracted by the ordinary method has been improved owing to reduction of a current ripple of the Q_f power supply to a few ppm with the frequency of 50 and 100Hz[5]. The frequency modulation with 5kHz band width was spread about hundred times during the beam extraction to obtain the flat distribution of the beam spill, as can be seen in fig.4. The transverse rf field was therefore applied to the ordinary extraction. As shown in fig.5, the beam ripple seems to be reduced in comparison with that in the ordinary extraction as shown in fig.1. Details will be presented elsewhere[6].

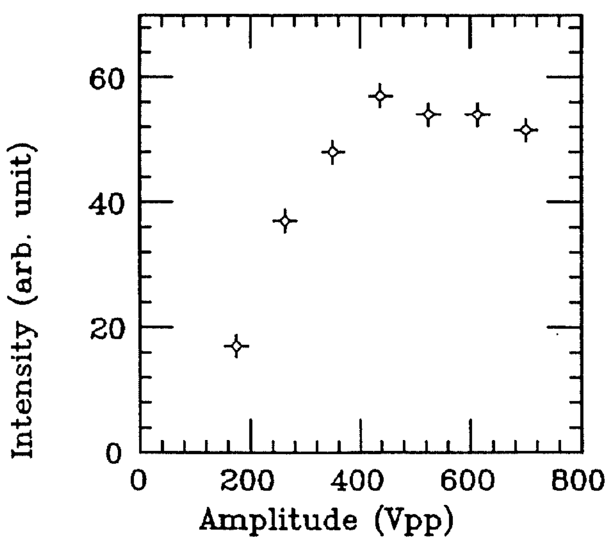

Fig.3(a) Dependence of the extraction intensity on the amplitude at the Δf_k of 6.3kHz.

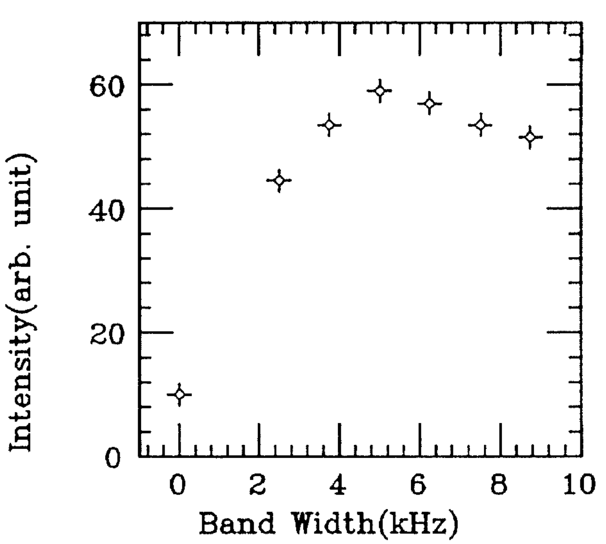

Fig.3(b) Dependence of the extraction intensity on the frequency band width at the V_k of 440V.

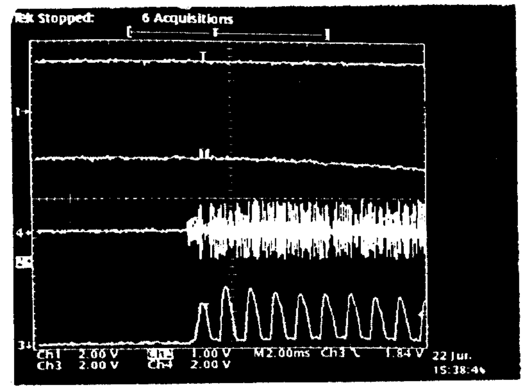

Fig.4 Beam response when the rf is turned on. From the bottom, beam spill, rf field, circulating beam intensity, current of sextupole magnet.

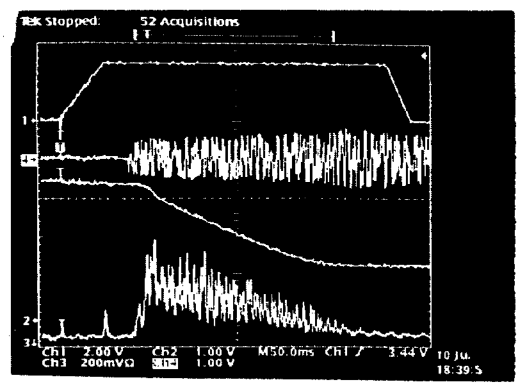

Fig.5 Beam spill by applied transverse rf field to the ordinary extraction. From the bottom, beam spill, circulating beam intensity, rf field and sextupole field.

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