Beam Acceleration with the Digital Beam Feedback in HIMAC Synchrotron

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Abstract

Beam acceleration in the HIMAC two synchrotrons has been carried out successfully using digital synthesizer, with which fairly stable operations of synchrotrons have been possible. Performances of each apparatus and results of beam test are reported in this paper.

1. INTRODUCTION

HIMAC (Heavy Ion Medical Accelerator in Chiba) Synchrotron is designed to accelerate fully stripped ions from 6 MeV/u upto 800 MeV/u[1]. In this energy range the particle velocity β=v/c changes from 0.11 to 0.84, and an acceleration frequency range is from 1.0 MHz to 7.9 MHz with harmonic number of 4.

Required intensity for radiation therapy is the order of 10^8 ppp in the case of carbon beam. There is also requirement of low beam intensity to be used for the counter experiments where the produced particles in the thick target must be identified with counters in the beam line. The required value is 10^7 ppp or less in the ring.

To satisfy these requirements of wide frequency and beam intensity ranges, we have developed:

1) An acceleration cavity with wide frequency range and maximum acceleration voltage of 9 kV.
2) A signal generator of a direct digital synthesizer (DDS) with which the acceleration frequency can be swept widely in an accuracy of 10 Hz.
3) Digitized feedbacks of beam phase and position which is necessary in the system of the DDS[2].
4) Beam monitors of wide gain range for phase ($\Delta\phi$) and position (ΔR) which can be used for beam feedback in low beam intensity of 10^7 ppp. The gain setting can be changed from 0 to 100 dB with 10 dB step[3].

The digitizing speed must be fast enough to use in the beam phase feedback loop that damp synchrotron oscillation. Since a maximum frequency of 4 kHz was expected in a planning stage, a digitizing speed of 500 kHz has been selected.

2. PERFORMANCES OF HIGH POWER TEST

The high power test of the rf cavity has been performed successfully at the maximum acceleration voltage of 9 kV, though the voltage in the daily operation is 6 kV. The shunt impedance is estimated from the anode current pattern at 6 kV. This is possible in the AB class operation of the tetrode of final amplifier, which was attached just below the cavity as seen in Fig. 1. The estimated values are from 300 to 400 Ω over the frequency range of 1~8MHz, which is shown in Fig. 2. From these values, the average power consumption in the rf cavity is estimated as about 8 kW in daily operation with the operation voltage of 6 kV, and this value is sufficiently lower than the designed maximum value of 30 kW.

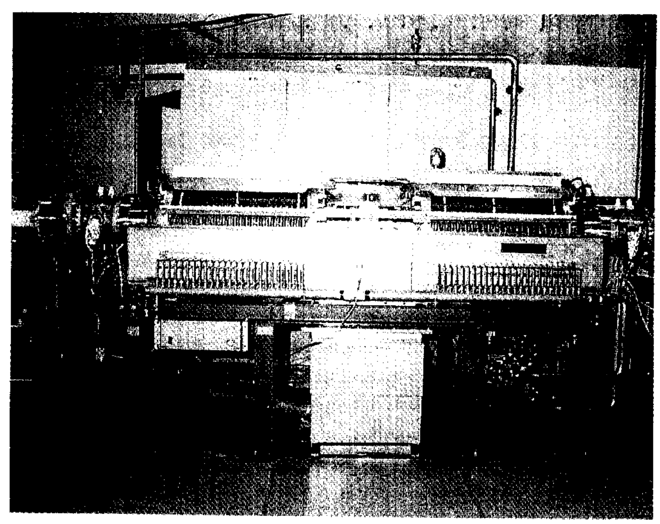

Figure 1. The acceleration cavity that has been installed in the HIMAC ring. The rf amplifier of tetrode has been attached just under the cavity. The pickup electrodes have been installed at both sides of the cavity. Behind the cavity, monitor electronics and ADCs to digitize monitor signals are equipped.

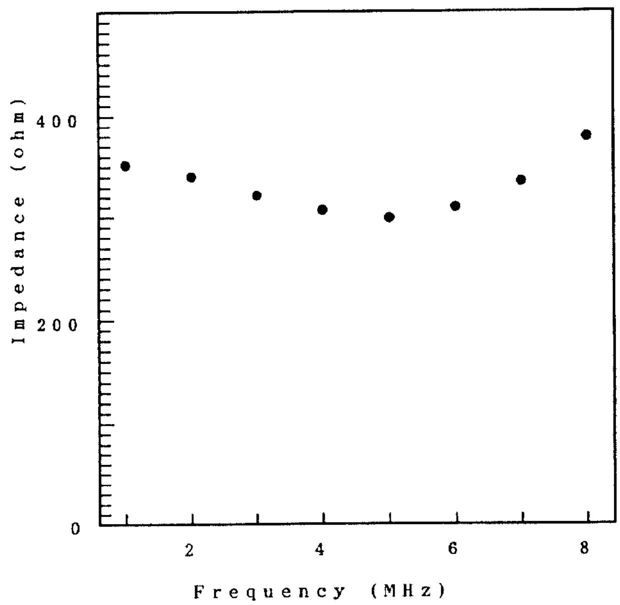

Figure 2. Shunt impedance of the rf cavity at the acceleration voltage of 6 kV.

To tune the cavity, there is feedback loop with the phase difference between rf voltage of the control grid in the tetrode and that of the cavity gap. As shown in Fig.3, phase error could be controlled down to about 8°. The cavity impedance varies as $Z_0\cos\theta$ with the phase error θ, where Z_0 is impedance under well tuned condition. Therefore, such a phase error leads to deterioration of less than 1 %, which is sufficiently small for daily operation.

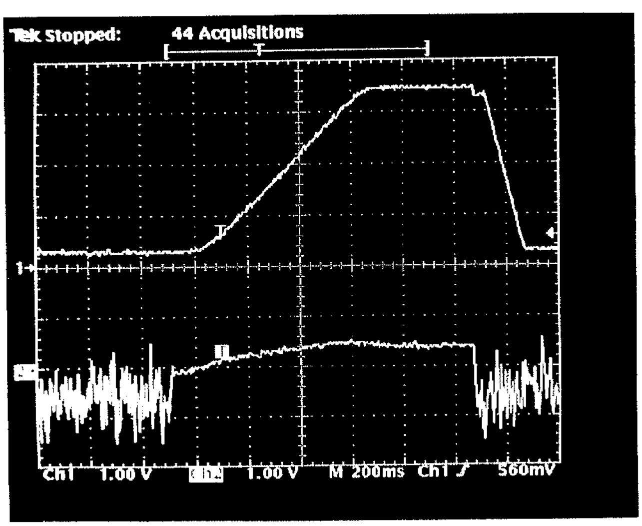

Figure 3. Pattern of phase difference between rf signal of the cavity gap and that of control grid in the tetrode (bottom, 18°/div.) with current pattern of the ferrite bias (top, 100A/div.)

3. PATTERN OPERATION

In a typical case of recent carbon beam, operation pattern of the synchrotron has flat base of 0.1 second, flat top of 0.4 second, and the acceleration and reset periods of 0.75 second, where maximum field gradient of the dipole magnet was 1.3 T/s[4].

3.1 Pattern Operation in the flat Base and Top

Pattern data stored in memory modules are generated with clock pulse of 50 kHz in the flat base and top regions. To capture the injected beam adiabatically, the rf voltage increases linearly from a minimum voltage of 100 V upto 6 kV within 10 ms. Because the synchrotron frequency is 2.9 kHz at the injection energy with capture voltage of 6 kV, this rising speed is sufficiently slow for the adiabatic capture. At the end of acceleration period, the rf frequency is smoothly changed to the flat top value to prevent a frequency jump.

3.2 Accuracy and Response of B-clock

The acceleration frequency is controlled with field strength of a monitor dipole magnet. To obtain the correct frequency from field strength, effective length of the dipole field is taken into account by adjusting curvature in the frequency law. With this correction residual error in the acceleration frequency function is expected less than 0.1%.

In the acceleration system of the DDS with beam feed-back loop, frequency change with step function should be small. Hence we have developed a field clock generator of 0.2 Gauss step, which has minus clock also. The fluctuation of this clock is ±1.5 Gauss with the same field pattern. When the field excitation has been changed, the deviation of the clock value from the field difference between the base and the top is less than 4 Gauss. Concerning a response, there is low pass filter of 4 kHz in the electronics, and the pickup coil is covered with stainless steel of 0.3 mm thickness which is same as that of the dipole chamber. Considering above errors and the finite response, the deviation of the beam position will be less than 4 mm. Compared to the large ring aperture of ±120 mm, this deviation is satisfactorily small.

4. BEAM TEST

Measured momentum spread of the injected beam is ±0.1%, which is consistent with the simulated value. Assuming a filling factor of 0.8, the accelerating voltage of 3.4 kV is required under the condition of the field gradient of 1.3 T/s and the momentum spread of above value. This voltage is consistent to the minimum value of 4 kV with which the beam has been accelerated stably without large loss.

As shown in Figs. 4 and 5, the beam monitors for phase and position work well under the high intensity of 10^8

ppp. When the beam intensity is smaller than 10^7 ppp, we can observe rf noise in the monitor signal at about 1 MHz. This noise arises from leakage of rf power which occur through 60 m long power cable of a ferrite bias winding. The suppression of the rf noise in the beam monitor signals is now under study.

As shown in Fig. 4, there is no significant beam loss during the acceleration, though there are jumps of the acceleration frequency corresponding to the dipole field change of 0.2 Gauss. These frequency jumps are not negligibly small because its step heights are about 20 % of the rf bucket height. Though this jump cause emittance growth in the longitudinal phase space, it is inevitable in the digital acceleration system with the DDS.

Though there is the large position deviation in the flat top which is due to the adjustment of the frequency in a slow extraction process, the center of beam position is well controlled within 5 mm during acceleration. This indicate sufficient accuracy of the B-clock generator and the frequency function. Also the emittance growth with the frequency step change due to 0.2 Gauss clock seems to be small. Therefore the DDS and the accurate B-clock made it possible to accelerate the beam stably even without the beam feedbacks of position and phase.

The beam acceleration with feedbacks of position and phase is shown in Fig. 5 and one can see the well controlled beam position during acceleration. By using the feedback loops the beam intensity has been increased by about 30 %. However sudden beam losses of about 20% during acceleration occurred once in a way, this phenomenon is being investigated.

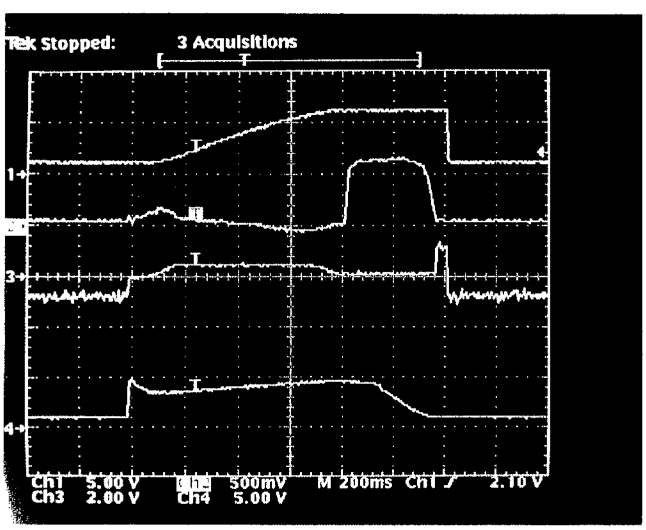

Figure 4. Beam acceleration without beam feedbacks of phase and position. From the bottom, beam signal of amplitude of fundamental frequency, beam phase (80°/div.), beam position (10mm/div.), acceleration frequency (5MHz/div.).

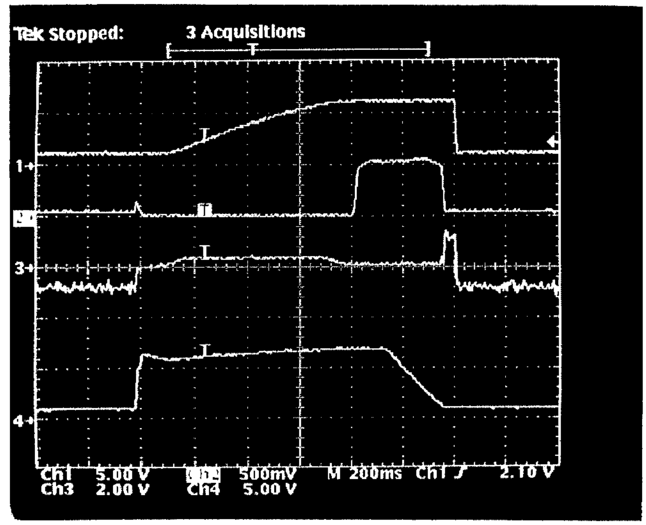

Figure 5. Beam acceleration with beam feedbacks of phase and position. Patterns and its scale are same as in the Fig. 4.

5. ACKNOWLEDGEMENTS

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6. REFERENCES

[1] Y.Hirao et al., "Heavy Ion Synchrotron for Medical Use," Nucl.Phys.A538,541c(1992).
Y.Hirao et al.,"Heavy Ion Medical Accelerator in Chiba,"NIRS-M-89,HIMAC-001,1(1992).

[2] M.Kanazawa et al., "The RF System of the HIMAC Synchrotron," EPAC92,1179(1992).
E.Takada et al., "Successful Application of Digitally Controlled RF Acceleration System for HIMAC Synchrotrons" HEACC'92,763(1993).

[3] M.Kanazawa et al., "Beam Monitors for RF Feedback Control in HIMAC Synchrotron," Proceedings of the Workshop on Advanced Beam Instrumentation, Vol.2,505(1991).

[4] K.Sato et al., "Status Report on HIMAC," this conference.