*The 8th Symp. on Accelerator Science and Technology, 1991, Saitama, Japan*

# BEAM TEST WITH THE HIMAC RF CONTROL SYSTEM

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## Abstract

RF system of the HIMAC synchrotron has been developed and tested in the factory. With the high power system, we could sweep the acceleration frequency from 1MHz to 8MHz with the acceleration voltage of 6KV. The performance of the RF control system has been confirmed with a developed simulator of the synchrotron oscillation. Following these two tests in the factory, we had a beam test of the RF control system at TARN-II in INS(Institute for Nuclear Study, University of Tokyo). This paper describes the beam test and its results.

## Introduction

HIMAC is a heavy ion accelerator for medical use, especially for cancer treatments. This accelerator is designed to use ions from $He^{2+}$ to $Ar^{18+}$. The Required beam energy for cancer treatments is from 100MeV/u to 800 MeV/u. The beam intensity in the synchrotron is from $10^7$ppp to $10^{11}$ppp. The charactaristic features of the RF acceleration system in the synchrotron are

1) wide RF range (from 1MHz to 8MHz).
2) wide beam intensity range between $10^7$ppp and $10^{11}$ppp in the synchrotron.

To fulfill these requirements, a digital control system with a digital synthesizer (Stanford Telecomunication, STEL-1375a) has been developed. We have also prepared to test another RF generator (Anritsu, MG2502B). There are two feedback loop by use of beam position ($\Delta R$) and beam phase ($\Delta\phi$). Especially a $\Delta\phi$ feedback loop must have fast responce to damp the synchrotron oscillation. We have checked the effectiveness of the $\Delta\phi$ feedback loop with the developed simulator in a factory. In the test with the simulator, we found that the $\Delta\phi$ feedback loop could damp the synchrotron oscillation whose frequency is 6KHz. This result is enough, because the maximum frequency is 4KHz in the HIMAC synchrotron. As a next step of the test, we have tried to accelerate the beam by use of the developed RF control system.

## Operation of TARN-II

Before the pattern operation of the synchrotron, the DC operation have been done to optimise the operating parameters. The obtained conditions are summerized in Table-1 with the other machine parameters.

Table - 1
Parameters of TARN-II operation

| | |
|---|---|
| Beam species | $He^{2+}$ |
| Injection energy | 10 MeV/u |
| Top energy | 160 MeV/u |
| Momentum spread | 0.2% |
| Beam intensity | $0.8\times10^7$ ppp |
| Tune number(H/V) | 1.70/1.72 |
| Beam life time | 65 sec |
| B (injection/top) | 2.267/9.379 KG |
| harmonic number | 2 |
| f (injection/top) | 1.1165/4.019 MHz |
| Cycle time | 20 sec |

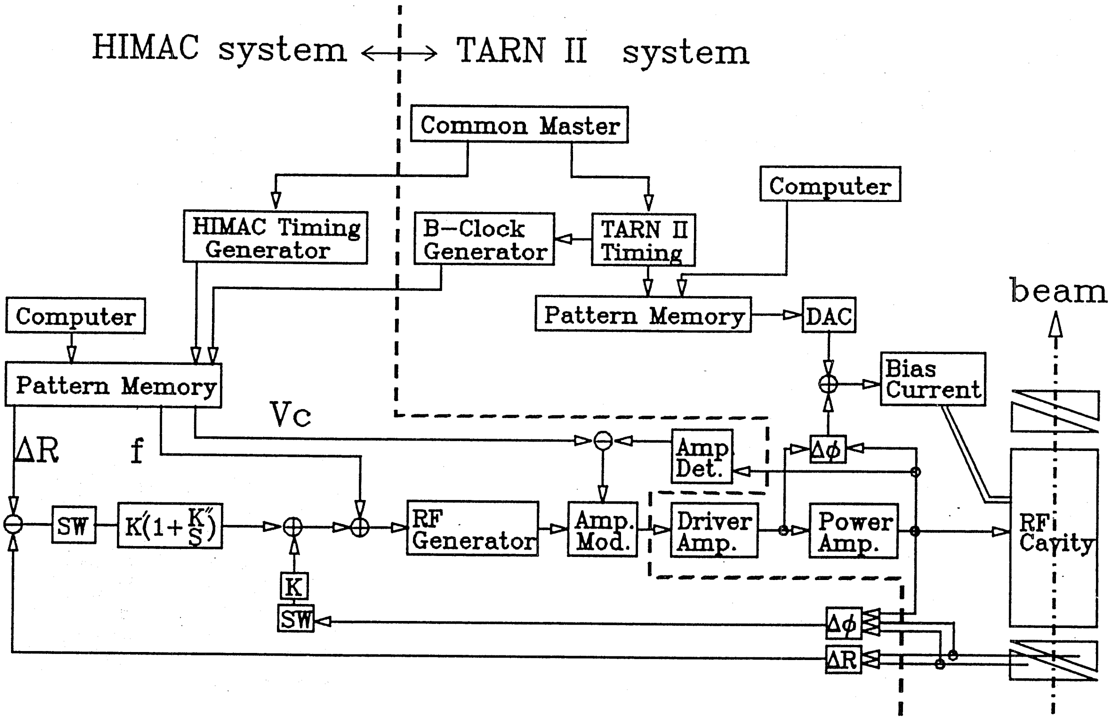

Fig.1 Acceleration system of this test

In the pattern operation the current tracking errors between the dipole magnets and the quadrupole magnets were less than 1.5%.

## Operation of the RF system

To test the control system of the HIMAC with TARN-II, we had to use the high power RF system of TARN-II[1]. In Fig.1, the block diagram of the RF system is shown. To operate the different systems together, a common master was used to start the patterns of the both systems. The timing data of the both systems are listed in Table-2. The B clock in the RF system of TARN-II[2) 3)] is generated every 1 Gauss increment of the dipole magnetic field. This B clock of 1 Gauss step was used to generate the frequency pattern instead of 0.2 Gauss clock which is the design value of the HIMAC system. To see the effect of this step in the acceleration fuction, we have tried to accelerate the beam without the filter which smooth the step function. Though there exists a clear effect of the step function, the beam could be accelerated. We have decided to use the 1 Gauss clock for our digital control system, which has no element to smooth the frequency step.

Table-2
Timing data

| | | |
|---|---|---|
| Master | 0 | s |
| Start of the capture | 3.5 | s |
| $\Delta\phi$ feedback on | 3.7 | s |
| $\Delta R$ feedback on | 3.9 | s |
| Clock change( T -> B ) | 3.99 | s |
| Acceleration start | 4.0 | s |
| Acceleration stop | 8.46 | s |
| Clock change ( B -> T ) | 8.96 | s |
| $\Delta\phi$ and $\Delta R$ feedback off | 9.46 | s |
| RF power off | 9.79 | s |
| Duration of flat top | 1.0 | s |

To caputure and accelerate the beam, the RF bucket area must be larger than the longitudinal emittance of the beam. The RF bucket area (S) depends on the RF voltage(V) and is given with a following formula;

$$S = 16(qVE/(2\pi h|\eta|))^{0.5}\alpha(\sin\phi_s)\beta \qquad (1)$$

where h is the harmonic number, E is the total energy of the particle, $\beta$ is the beam velocity, $\phi_s$ is the synchronous phase, q is the particle charge, $\eta=\gamma^{-2}-\gamma^{-2}$, and $\alpha(\sin\phi_s)$ decreases monotonically when $\phi_s$ increases from 0° to 90°. In the acceleration period, $\phi_s$ is determined with the following equation;

$$V\sin\phi_s = 2\pi R\dot{B}\rho, \qquad (2)$$

here R is an avarage radius of the synchrotron, $\rho$ is curveture, $\dot{B}$ is the ramping rate of the dipole field. Using the longitudinal emittance of the beam of TARN-II, V=1KV and $\phi_s$=3.4° are the solutions which satisfy the both equations of (1) and (2) simultaneously. The frequency of synchrotron oscillation is 1.4 KHz with this acceleration voltage. Increasing the RF voltage from 0 to 1 KV within 10 ms to capture the beam adiabatically, the voltage was keeped constant at 1KV in the acceleration.

The acceleration frequency is given with the following formula;

$$f(B) = hc/(2\pi R(1+(mc^2/q\rho B)^2)^{0.5}) \qquad (3)$$

where m is the particle mass and c is the light velocity. To derive out this pattern from the memory, a B-clock is used. To determine the capture and the flat top frequencies, there are constant frequency patterns in the memory module, which are derived out with 50 KHz clock(T-clock).

The ferrite bias current pattern is given with the following formula;

$$I(B) = -32.506 + 63.851x - 11.96x^2 + 1.92x^3 \text{ (A)} \qquad (4)$$

where x=f(B) (MHz).

## Beam acceleration

Before the beam acceleration test, we have adjusted the position bias in the $\Delta R$ feedback loop. If the adjustment is not correct, the beam will be lost when the $\Delta R$ feedback loop is turned on. The next step is to adjust the strength of the feedback loop on $\Delta R$ and $\Delta\phi$.

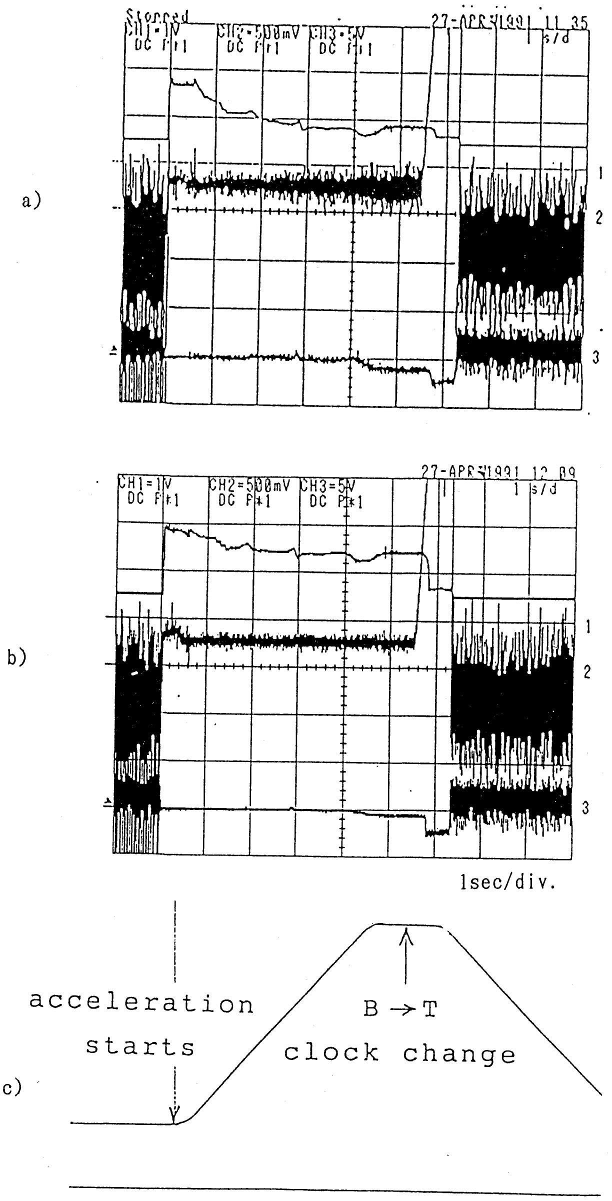

Fig.2. Outputs of the beam monitors. Upper trace is the beam intensity, middle trace is $\Delta R$, and lower trace is $\Delta\phi$ in each picture. Strength of the $\Delta\phi$ feedback loop is a) critical damping b) five times of a). Fig.2-c) shows a corresponding field pattern of the dipole magnet.

As the beam intensity is low, the low pass filter of 1KHz was inserted in the $\Delta R$ position monitor. From this fact the strength of the $\Delta R$ feedback loop was set at weak value. About the $\Delta\phi$ feedback, the strength of the critical damping condition was not enough. As shown in Fig.2, the best strength of the $\Delta\phi$ feedback loop was about five times stronger than the strength of the critical damping condition. To make the frequency range, which $\Delta R$ feedback loop corrects, small, the parameter in Eq.(3) was adjusted. The obtained result of the correcting frequency is shown in Fig.3. Though the correcting frequency has been made small, there was the frequency pattern which could not be corrected with the parameter in the Eq.(3). This error pattern, which is large at the beginning of the acceleration, can be attributed to the slow B-clock response.

## Conclusion

Using the digital control system with the digital synthesizer, we could accelerate the $He^{2+}$ beam from 10MeV/u to 160MeV/u. These energies correspond to the acceleration frequencies of 1.1 MHz and 4.0 MHz. The tuning of the control system was very simple and easy to succeed the acceleration. This is the charactaristic feature of the digital control system and important in the medical accelerator. (We have also tested the synthesizer of Anritsu (MG2502B), but we couldn't accelerate the beam beyond the acceleration frequency of 2MHz.) The acceleration efficiency was about 55%. The possible reasons of the beam loss are;

1) The low beam intensity which makes large noise in the beam monitors, which is due to white noise in the FET of the first amplifier.
2) The RF noise whose effect was enlarged with the low beam intensity.
3) The B-clock step of 1 Gauss which make the longitudinal beam emittance growth. (In the analog system, we can use the filter to smooth this B-clock step.)

Improving these things with the longer beam monitor electrode and the B-clock step of 0.2 Gauss in the HIMAC synchrotron, it will be possible to accelerate the beam without a beam loss.

## Acknowledgements

We would like to express our gratitude to Dr.Y.Irie, Dr.S.Ninomiya, and the members of the Division of Accelerator Research of NIRS for their support. We also wish to thank the members of Accelerator Research Division of INS for their strong support in operation of the SF cyclotron and the TRAN-II.

## Reference

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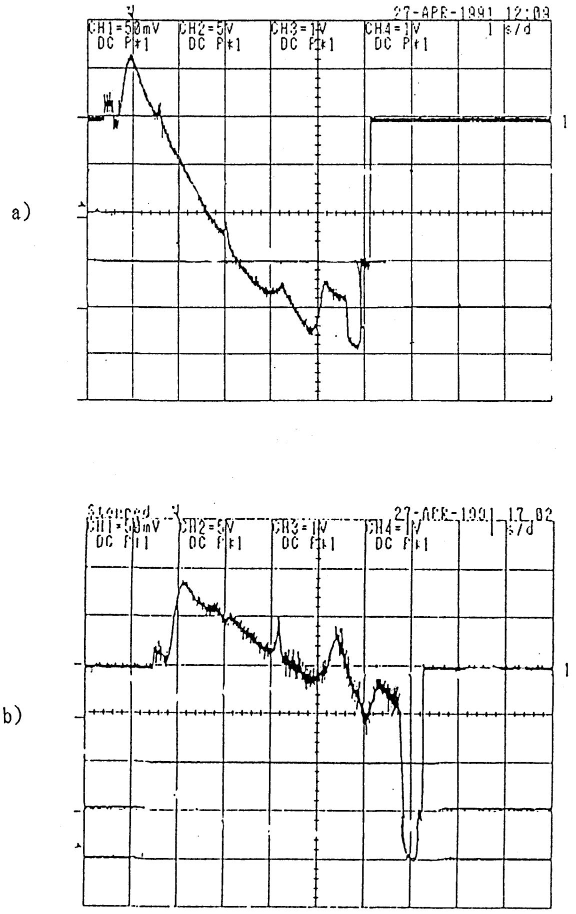

Fig.3 Correcting frequency with $\Delta R$ and $\Delta\phi$ feedback loops in acceleration. Horizontal scale; 1sec/div., vertical; 4KHz/div.. a) uncorrected b) corrected.