# BEAM TEST WITH A NEW CONTROL SYSTEM OF ACCELERATION IN HIMAC

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*Abstract*

In the present acceleration system in HIMAC, an acceleration frequency of a direct digital synthesizer is controlled with B-clock of B+ and B- signals that correspond to the 0.2 Gauss increment and decrement on dipole magnetic field. In the tested new control system, we will use only clock pulse whose clock rate is locked to the power line frequency. This makes also the acceleration control system simple and reliable. With this simple system, it is easy to build up the acceleration control system for multiple flattop patterns. This pattern operation is expected to use in the next irradiation system of spot-scan in HIMAC. In this presentation, the used system and results of beam test will be presented with tested data of multiple harmonic waves.

## 1 INTRODUCTION

Since 1994, when the first patient was treated with a carbon beam, more than 3800 patients have been treated at the HIMAC facility. Based on good clinical results, a dedicated compact facility was proposed[1], and several research and development (R&D) activities have been conducted at NIRS. In the HIMAC synchrotron, the present acceleration system[2] with a ferrite core cavity has many feedback loops, which make the system operation intricate. The cavity without a tuning system has a simple structure, and can be easily constructed at low cost. These properties of the cavity come from the low Q-value of about 0.5 with high permeability of core material. As a candidate of core material with high permeability, we have tested several Co-based amorphous cores [3]. After several measurements with the test core, this material seemed to be a good candidate for the core in the compact acceleration cavity. Based on our experiences with the test core, we have developed a new RF high-power system with enough acceleration voltage[4].

For beam tests, we made a low-level RF system with new pattern memory and a direct digital synthesizer (DDS), where the waveform in the DDS can be adjusted with a personal computer via an RS232c port. This provides a simple system with mixed harmonic waves to improve the beam intensity with an improved bunching factor. Though a mixture ratio will not be ideal in the whole acceleration frequency range, there is no need for a control circuit to obtain a mixed harmonic wave with correct amplitude and phase. This simple system has merit as an acceleration system for a dedicated cancer-therapy facility for its simple system. Keeping its simplicity, there seemed to be desired improvement on DDS from beam test results.

To improve the acceleration system further, we should remove B-clock to generate frequency pattern with DDS. The DDS requires smooth frequency change in the beam acceleration, where fast B-clock pulse with small field change is important. This makes the B-clock generator sensitive for the noise. Though the DDS itself is accurate, it outputs frequency error with B-clock noise. To avoid this deterioration of DDS performance, common clock pulse can be used. In HIMAC, clock to generate pattern of lattice magnets are synchronous to power line frequency. This requires also using synchronous clock in the acceleration system. In this paper, we present beam tests with developed RF control system in the HIMAC synchrotron.

## 2 CONTROL SYSTEM WITH A SYNCHRONOUS CLOCK GENERATOR

With an unturned acceleration cavity, constructed control system is simple, which is shown in Fig.1 together with high power parts of an RF amplifier and a cavity. There are only two pattern controls of an acceleration frequency and a voltage. The digital data of 24 bits can be generated with maximum out-put rate of 1 MHz in these pattern memory, and memory length are 1.5M data in the both pattern memory. In the frequency pattern memory, acceleration frequency data are stored as a function of time, and pattern data are generated with 192kHz clock. In this beam test, B-clock was used to generate voltage pattern data as in the acceleration system that is used in the daily operation in HIMAC. These two pattern data control a direct digital synthesizer (DDS) that generate RF signal with controlled amplitude.

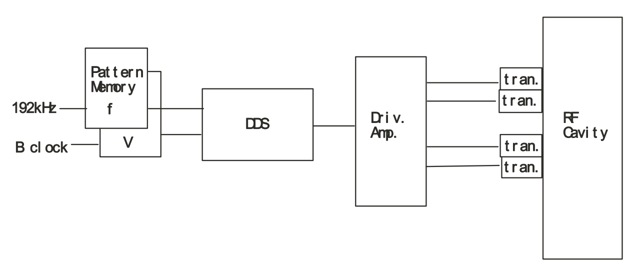


Fig. 1. Acceleration system for the beam test.

In the pattern operation of lattice magnets in the synchrotron, clock pulses of 1.2kHz are used to generate pattern data. This clock rate is locked to the power line frequency of 50 Hz, which has fluctuation of 0.2 Hz in maximum. In the clock system for pattern generation of acceleration frequency, clock pulse whose rate must be locked to power line frequency to obtain good tracking between a lattice magnetic field and an acceleration frequency. To obtain this locked clock pulse, we have made a clock generator with digital system as shown in Fig.2. In this circuit, reference clock of 1.2 kHz or 50Hz can be select, where out-put clock rate of 192kHz will be locked to the reference clock. In the beam test, 1.2kHz clock, which is used to generate pattern data of lattice magnets, was used to obtain better tracking between lattice magnetic fields and acceleration frequency.

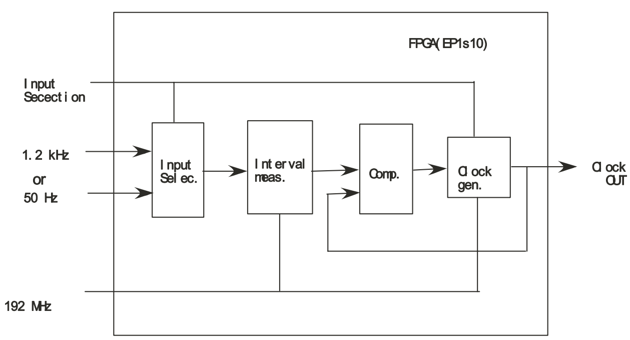


Fig.2. Clock generator for the acceleration system. Out-put clock rate of 192kHz can be locked to input clock of 1.2kHz or 50Hz, which can be selected with an input selection switch.

## 3 OPERATION TESTS

### *3.1 Beam acceleration tests*

To test the performance of developed pattern generation, the cavity was installed in a HIMAC synchrotron as shown in Fig. 3. The transistor amplifier was set at the separated room, and the RF power was supplied with 50 Ω coaxial cable that is about 50 m long. The acceleration is from 6 MeV/u to 400 MeV/u, and corresponding acceleration frequencies are from 1.04 MHz to 6.6 MHz. The frequency pattern was calculated from the preset current pattern of lattice dipole magnet, which was corrected with time shift of about 2ms. In Fig. 4, accelerated beam intensity is shown, which is DCCT (Direct Current Current Transformer) signal. As seen in the figure4, we could accelerate beam well, though there is large deviation of beam position during acceleration period. This large deviation was corrected easily as shown in Fig.5. In the deceleration period, frequency deviation is left to correct. Still we must improve frequency pattern further, stable beam acceleration could be obtained. In the case of beam acceleration with multi flattop pattern, same procedure of frequency pattern generation was applied to get beam acceleration.

Fig. 3. Acceleration cavity installed in the HIMAC synchrotron for beam test.

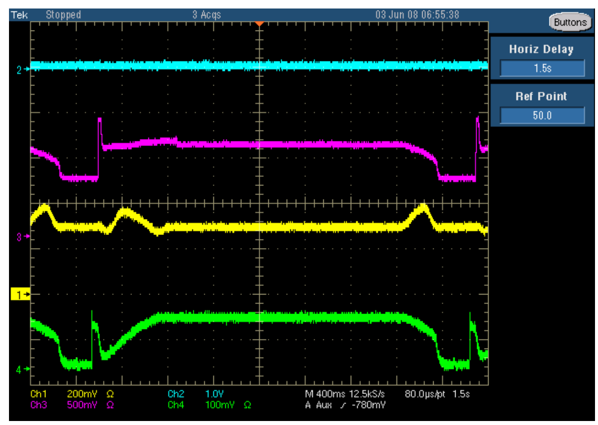


Fig. 4. DCCT signal (lower), beam position (middle), and beam signal of bunch amplitude (upper). Horizontal scale is 0.4sec/div.

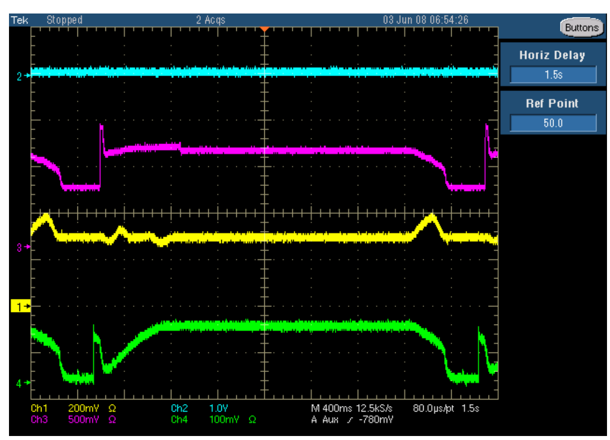


Fig. 5. DCCT signal (lower), beam position (middle), and beam signal of bunch amplitude (upper). Horizontal scale is 0.4sec/div.

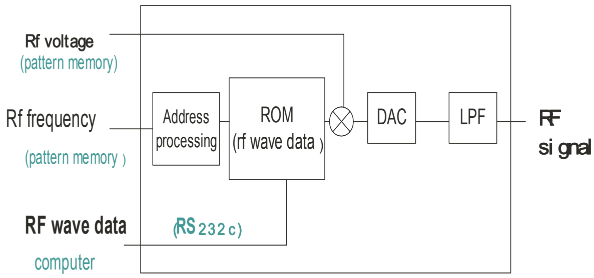


Fig.6. Block diagram of the direct digital synthesizer with arbitrary wave data.

### *3.2 Test of DDS with multi-harmonic operation*

Other merit of a pattern generation with synchronous clock pulse is easy manipulation of an RF waveform during acceleration period. In the beam test with multi-harmonic acceleration [5], a DDS as in Fig.6 was used, where wave data in ROM could be adjustable to obtain higher accelerated beam intensity. To improve his system, another ROM should be added in parallel in this DDS, and the wave data from each ROM can be added with different ratio dynamically during beam acceleration. One waveform is as in Fig.7, which is monitored signal at acceleration gap in the cavity. This wave is used for beam capture. Another waveform is as in Fig.8, which is for beam acceleration voltage. Amplitude of first wave will be constant after beam capture, and amplitude of second wave should be proportional to a ramping speed of the lattice dipole field. In the case of pattern generation with clock pulse, above sum of RF wave with different ratio during acceleration, can be controlled easily as a function of time. With this improved DDS, we can obtain better bunching factor with multi-harmonic wave.

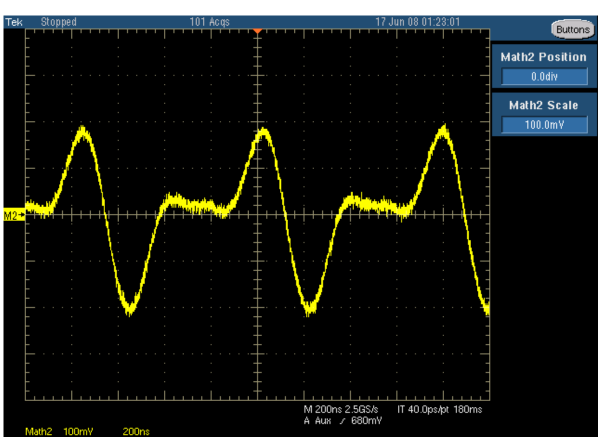


Fig.7. RF wave for beam capture. Up to fourth harmonic waves were added.

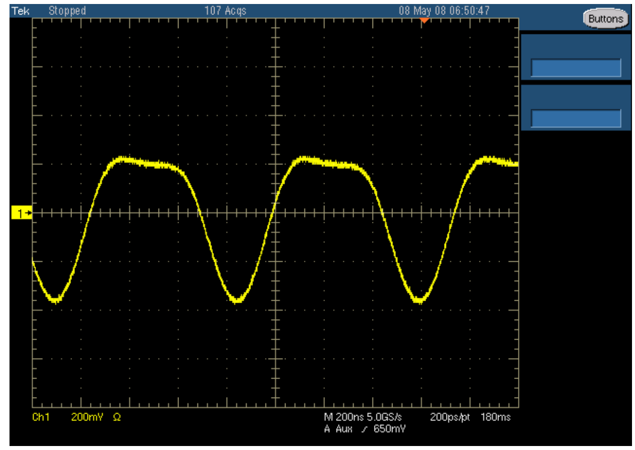


Fig.8. Corrected RF waveform for beam acceleration. Up to fourth harmonic waves were added.

## 4 SUMMARY

We have made acceleration control system with 192 kHz clocks whose clock rate is locked to power line frequency. With this system, we could show to obtain stable beam acceleration. In the multi flattop operation, constructed system seemed to be possible to use. To improve bunching factor, modified DDS with two ROM’s seems to be effective with simple system.

## 5 ACKNOWLEDGEMENTS

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