BEAM MONITOR OF HIMAC HEAVY-ION SYNCHROTRON

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Abstract

Design, construction status, and test scheme of the monitor devices for tune, COD, and chromaticity are described. They are equipped to HIMAC heavy-ion synchrotron at NIRS[1] in order to constitute a beam control system.

Introduction

HIMAC, Heavy Ion Medical Accelerator in Chiba, is dedicated to medical use especially for tumor treatment and related biomedical research in a hospital environment. Main acceleration stage of HIMAC is a heavy-ion synchrotron which accepts a heavy ion beam from an injector with an energy of 6 MeV/n, and accelerates it up to 800 MeV/n, then extracts it to the beam transport line. In order to have a stable operation, we are now constructing a control system for HIMAC, and the beam monitor system being a part of it. We describe here an rf-kicker system for tune measurement, a position monitor system for COD measurement and shortly a chromaticity measurement which is a complex of tune measurement. We present the design and the operation scheme of those measurements, and some early results from bench mark tests.

Tune measurement

Tune is measured by the rf knock-out method. The rf knock-out system for tune measurement is shown in Fig. 1 . The kicker has

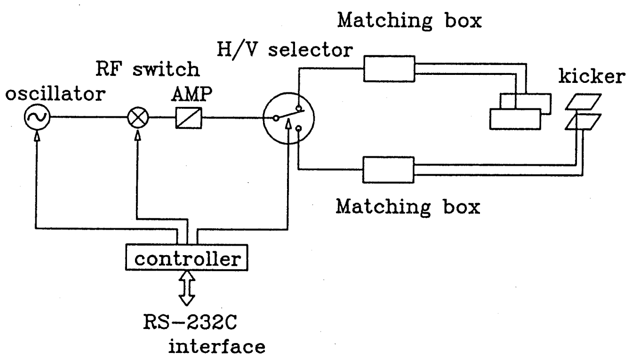

Figure 1. The rf knock-out system for tune measurement.

two pairs of electrodes as vertical (V) and horizontal (H) kickers. They have lengths L = 0.70 m(H) and 0.10 m(V) and gap distances d = 0.15 m(H) and 0.06 m(V), respectively, which are determined by spatial restrictions. The frequency of the oscillator ranges from 0.1 MHz to 2.0 MHz. The power of the amplifier is 100 W with an output impedance of 50 Ω. The controller governs the frequency and the output voltage level of the oscillator, open/close timing of a rf switch, and horizontal/vertical selector, which is controlled by the synchrotron control system of HIMAC (CS) via RS-232C interface. When we measure the tune during the flat base (FB), 100 msec, we have to find a clear reduction of the beam in a short time. Therefore a effective method was looked for.

The designed values of the tune of HIMAC are 3.75 and 3.25 for horizontal and vertical, respectively. The revolution frequency varies from 0.25 MHz at an energy of 6 MeV/n to 1.95 MHz at an energy of 800 MeV/n. When we assume a shift of the tune to be in ±0.25, the required frequency range for an oscillator is from 0.125 MHz to 1.95 MHz where a fractional tune is considered. The amplitude Δa of the betatron oscillation at i-th turn is estimated[2] by

$$\Delta a = \frac{\beta \cdot i}{2} \frac{qeV_0L}{Am_N\gamma v^2 d} \tag{1}$$

where β is a beta function, e is an electric charge, V_0 is an applied voltage between the electrodes, L is the electrode length, γ is a relativistic kinematical factor, and d is the gap distance between the electrodes, q is a charge number, A is the mass number, m_N is the atomic mass unit, and v is a velocity of the ion, respectively. Particle will be lost when its amplitude gets a value d/2 after N_0 kicks. Then V_0 is given by

$$V_0 = \frac{Am_N\gamma v^2 d^2}{N_0\beta qeL}. \tag{2}$$

The required voltage V_0 for a duration time τ of the rf field is given by

$$V_0 = \frac{2\pi R}{\tau} \frac{Am_N\gamma v d^2}{\beta qeL}. \tag{3}$$

The values above are calculated according to the constants ; β = 8.0 m(H) and 8.0 m(V), and the circumference $2\pi R$ = 130 m. The results of V_0 for kicker are presented in Table 1, where the duration time τ is assumed to be 20 msec.

Table 1: Voltages on the kicker electrodes

beam energy	6 MeV/n	800 MeV/n
V_0(H)	18.4 (V)	253.6 (V)
V_0(V)	20.6 (V)	284.6 (V)

The matching box is composed of two parts ; a Transmission-Line Transformer (TLT) and an All Pass Network (APN) which are illustrated in Fig. 2.

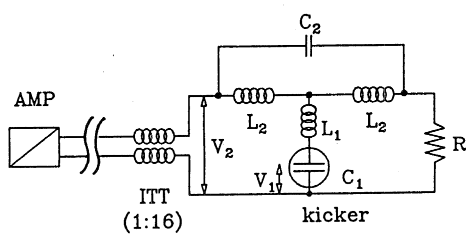

Figure 2. The matching box.

The TLT transduces the impedance from 50 Ω to 800 Ω which reduces the required power for the amplifier from 1.6 kW to 100 W.

APN is adopted in order to induce a high voltage on the electrodes of the kicker. APN is a kind of an impedance converter whose input impedance is equal to the load impedance (R) for all frequency. The relation of V_1 to V_2 is given by

$$\left|\frac{V_1}{V_2}\right| = \left|\frac{4}{\sqrt{(1+2X)^2F^2 - 2(1+4X)F + 4}}\right| \tag{4}$$

where

$$X = \frac{L_2}{L_1} \tag{5}$$

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$$F = \left(\frac{f_{rf}}{f_0}\right)^4 \tag{6}$$

f_{rf} is the frequency of the oscillator and f_0 is given by

$$f_0 = \frac{1}{2\pi\sqrt{L_2 C_1}} \tag{7}$$

The expected voltage gain $\left|\frac{V_1}{V_2}\right|$ is illustrated in Fig.3, where the required voltage gain $\left|\frac{V_1}{V_2}\right|$ for the knock-out within 20 msec is shown by a dashed line.

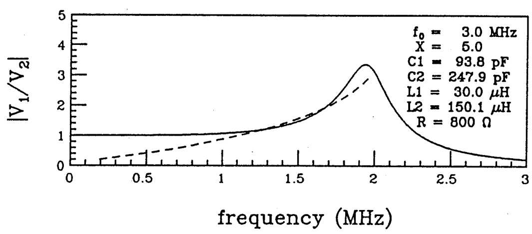

Figure 3. The voltage gain of the APN.

The tune measurement is performed in two patterns in the case as FB. One is a coarse measurement with a sweep of rf frequency (Fig.4 (a)) ; the other is a fine measurement with a fine step of rf frequency (Fig.4 (b)).

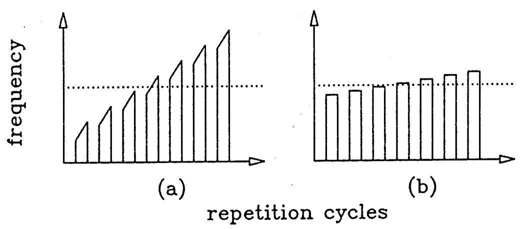

Figure 4. The rf frequency patterns for tune measurement.

The tune is specified by the frequency f_{rf} when the beam intensity is strongly reduced by the rf knock-out. The beam intensity is monitored by the beam monitor of RF cavity which is described elsewhere[3]. There are two possibilities for the tune, as f_{rf} is given by a fractional tune ;

$$(n_1 - \nu)f_r = f_{rf} \tag{8}$$

$$(\nu - n_2)f_r = f_{rf} \tag{9}$$

where f_r is the revolution frequency, and n_1 and n_2 are the larger next and smaller next integers to ν, actually $n_1 = 4$ and $n_2 = 3$, respectively. To determine which relation should be used, the strength of the focusing quadrupole magnet (QF) of the synchrotron is changed. If the strength of QF become larger, the tune will be larger, vice versa.

COD measurement

COD is measured by 12 beam position monitors (POMs) which are the electrostatic position monitors. The POMs have four identical triangular electrodes. Two electrodes in a same configuration are for right (R) and left (L) electrodes. They are placed near quadrupole magnets at each long straight sections of the synchrotron rings where the beta function is large, and are always enclosed by steering magnets. In order to take impedance matching between the R (L) electrodes and transmission line with a impedance of 50 Ω, a simple circuit is used which consists of two transmission lines of same lengths and a resister (100 Ω). By use of them, the R (L) signal of the monitor is simply combined and fed to other circuits (in this case, to an oscilloscope). Fig.5 shows the circuit diagram and a testing scheme of it. The test pulses generated by a signal generator (SG) were fed to a POM, which is monitored by a oscilloscope via a divider circuit. The signals induced on the electrodes were picked-up, fed to circuit, and to the oscilloscope. Those two

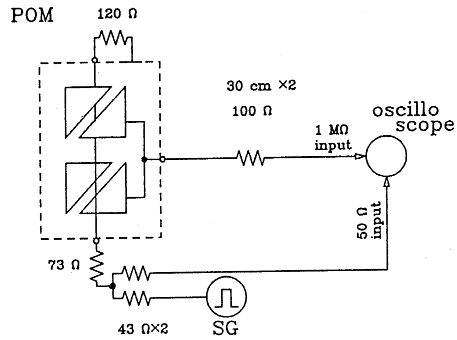

Figure 5. The circuit and the test scheme.

cables had same lengths of 30 cm and impedances of 50 Ω. Fig.6 shows the original signal of SG (lower) and the signal of the circuit (upper) seen in the oscilloscope. We can see clearly the POM signal has a same shape as that of SG.

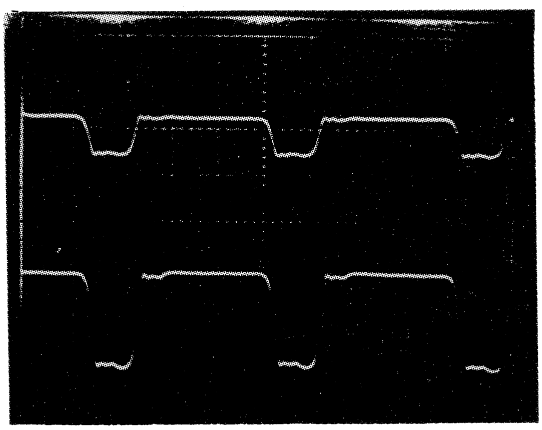

Figure 6. The signals of the sum circuit (upper) and SG (lower), where the grids were in 5 mV/div. and 0.2 V/div., respectively, and 50 nsec/div. in common.

The R and L signals are amplified and transmitted to the ΔR processor by FET amplifiers. The first amplifier has 100 kΩ input impedance which corresponds to the thermal noise voltages of 0.6 and 0.08 nV at 1 and 8 MHz, respectively. These values are small enough compared with FET noise voltage of 1.2 nV. Here the thermal noise voltage is given by

$$V = 4kT\Delta f \frac{R}{1 + (2\pi f C R)^2} \tag{10}$$

where k is the Boltzman constant, T is a temperature, f and Δf are the observing frequency and its band width, C is the capacitance of the pick-up electrode, and R is the input resistance.

The R and L signals selected by rf switch (RF SW) are converted to a constant frequency signal of 50 MHz at first and then 455 kHz by heterodyne double balanced mixer (DBM), then processed to R + L and R − L signals (Fig.7). The ΔR signal is given by ΔR processor from these R+L and R−L signals. In the ΔR processor, an amplitude to phase conversion method (AM/PM conversion ; APC) is adopted[4]. For the observation of COD, five modes of measurements are planned according to the synchrotron operating pattern, which are shown in Fig.6a ~ 6e. First is a selected POM and given timing mode (Fig.6a), from which we can know the trend data of the COD at the location of the POM. Second is a selected POM and varying timing mode (Fig.6b), from which we can know the variance of the COD within a pattern at the location of the POM. Third is a changing POMs and given timing mode (Fig.6c), from which we can know the COD at all POMs. Forth is changing POMs and varying timing mode (Fig.6d), from which we can know the all information on the COD at any phase in the pattern and of all

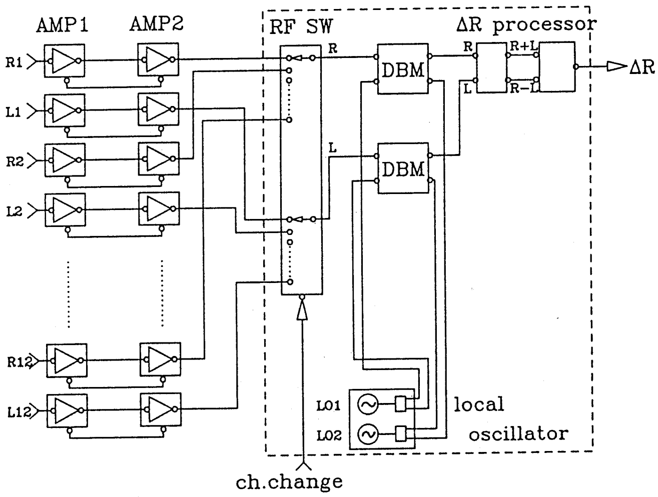

Figure 7. ΔR processor.

POMs. The last is also changing POMs and varying timing mode (Fig.6e), from which we can know the COD data of all POMs within short phases of the synchrotron pattern.

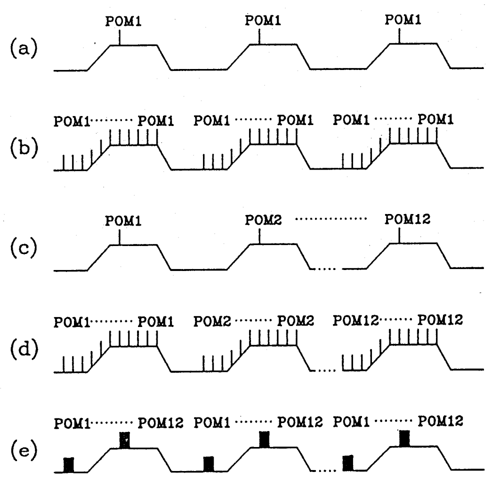

Figure 8. The modes of the COD measurement.

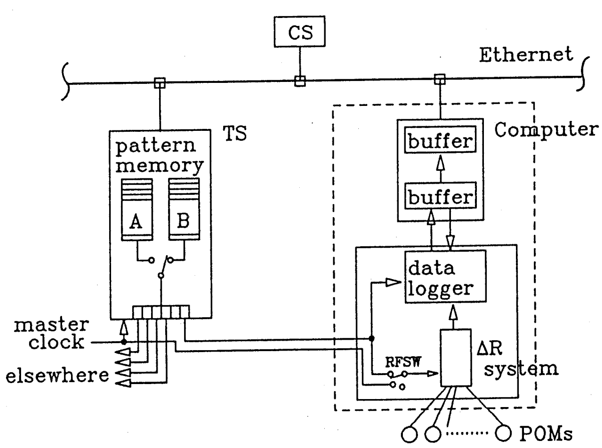

Figure 9. The COD measurement system.

The selection of the POMs, and the mode of the measurements are set by synchrotron control system (CS) through Ethernet line. The trigger timing for the measurement is set in the pattern memories of the timing system (TS) of the synchrotron by CS, where there are two pattern memories for the normal operation (A) and the COD measurement (B). According to the selected mode, CS stores the trigger pattern in the memory B, and the computer specifies the selection of the RF SW and the number of ΔR data to be stored in the data logger. Then it sends a start signal to the pattern memory, and the ΔR measurement starts. The pattern memory sends the trigger signal to the RF SW and the data logger for the timings of the POM selection and data taking, respectively. If we set those modes of changing POMs, the trigger signals or the master signals are fed to the RF SW. When the data logger have acquired the data, it sends a complete signal to the computer. The ΔR data are transferred to the computer where a selection of the data is done according to the requirement of the operator if necessary, then they are transferred to CS through Ethernet line.

Chromaticity measurement

The chromaticity ξ is given by

$$\xi = \Delta\nu \frac{\mathrm{p}}{\Delta \mathrm{p}} \tag{11}$$

where $\Delta\nu$ is the shift of tune, p and Δp are the beam momentum and its shift, respectively. For the accuracy of the estimation, f_r and Δf_r are used for Δp and p, which are the frequency and its shift of the revolution frequency. In order to know the relation between p and f_r, the relation below is used

$$\frac{\Delta \mathrm{B}}{\mathrm{B}} = \gamma_{tr}^2 \frac{\Delta f_r}{f_r} + \frac{\gamma^2 - \gamma_{tr}^2}{\gamma^2} \frac{\Delta \mathrm{p}}{\mathrm{p}} \tag{12}$$

where B and ΔB is the magnetic field and its shift of the magnets of the synchrotron. γ is a kinematical factor, and γ_{tr} is the γ at the transition. In a chromaticity measurement, ΔR feedback[3] in the rf system of the synchrotron is disconnected, and the ΔR is changed according to the Δf specified by a operator, while the magnetic field of the magnets is kept to be constant, $\Delta B = 0$. Then the tune is measured in the way of the rf knock-out method which is described in the above. The tune and ΔR data are fitted by a straight line fit, and the chromaticity is given by the slope of the fitted line.

Present status

A control system for the synchrotron (CS) is now planning. It coordinates the individual control systems of the devices including the tune, COD, and chromaticity measurements described here.

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