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Beam commissioning of the SPring-8 synchrotron

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The beam commissioning of the SPring-8 synchrotron was started in December 1996. In the first ten days, the coarse tuning of the pulse magnets for beam injection from the linac, and the excitation pattern of the dipole and the quadrupole magnets, were accomplished during energy ramping of the beam. The acceleration of the beam up to 8 GeV proceeded smoothly. From January to February 1997, the fine-tuning of the synchrotron was continued and the operating parameters of all of the synchrotron equipment were decided.

Keywords: beam commissioning; SPring-8.

1. Introduction

The SPring-8 accelerator complex is composed of a linac, a synchrotron and a storage ring. SPring-8 is operated in multi-bunch and single-bunch modes of an electron or a positron beam. The synchrotron accelerates the beam from 1 to 8 GeV with a repetition rate of 1 Hz (Suzuki, Yonehara, Aoki, Tani, Hayashi *et al.*, 1995). A single-turn injection with on-axis technique is adopted as the standard injection method of the synchrotron. During commissioning of the synchrotron, the multi-bunched electron beam from the linac, which had the pulse trains of 40 ns and 1 µs, was used. The synchrotron design parameters are presented in Table 1.

Table 1
Synchrotron design parameters.

Injection energy	1.0 GeV
Maximum energy	8.0 GeV
Repetition rate	1 Hz
Circumference	396.12 m
Revolution frequency	756.8 kHz
Harmonic number	672
Radio frequency	508.58 MHz
Maximum r.f. voltage	18.7 MV
Maximum r.f. power	2 MW
Natural emittance (at 8 GeV)	230 nm rad
Momentum spread (at 8 GeV)	0.126%
Nominal tune (ν_x/ν_y)	11.73/8.78
Natural chromaticity (ξ_x/ξ_y)	−14.4/−11.5

2. Beam commissioning

Beam commissioning of the synchrotron started in December 1996. In the first ten days, the coarse tuning of the pulse magnets for beam injection from the linac, and the excitation patterns of the dipole and the quadrupole magnets, were accomplished during energy ramping of the beam. The acceleration of the beam up to 8 GeV proceeded smoothly. From January to February 1997, the fine-tuning of the synchrotron was continued, and the operating parameters of all of the synchrotron equipment were decided.

2.1. *Injection orbit*

Two septum and two kicker magnets are used for injection (Yonehara *et al.*, 1993). A fluorescent screen monitor with a rectangular hole, which the beam passes through, is used to tune the beam position to the center at the front of the first septum magnet. At first, the excitation currents of these magnets were set to values calculated on the basis of magnetic field measurements. The fine tuning of the excitation currents was performed one by one with observation of the beam position at the second and fourth screen monitors. The second and fourth screen monitors are located in front of the second septum magnet and downstream of two kicker magnets, respectively. After tuning of the injection magnets, one-turn and multi-turn injections were confirmed at an injection energy of 1 GeV with DC operation of dipole and quadrupole magnets. To confirm the one-turn injection, eight screen monitors were used in the synchrotron. For the multi-turn injection, a fast current transformer (FCT) was used. The efficiency of the beam injection was about 60%.

2.2. *Radio-frequency capture*

The energy loss of the beam at 1 GeV is estimated to be 3 keV turn-by-turn and the beam could be rotated about 3000 turns without the r.f. voltage. With the r.f. voltage, the beam existed for 1 s until the next beam was injected and the kicker magnets kicked out the last beam.

2.3. *Tuning and measurement of the betatron tune*

The betatron tune was measured by the r.f. knockout system at the injection energy. To kick a beam in the horizontal or vertical direction, the phase of the r.f. current on four electrodes of the knockout must be reversed alternately and their cables are switched in two connectors. The maximum r.f. power is 50 W per electrode. At the resonance point of the betatron tune, the beam was kicked out in the horizontal or vertical direction and the beam was lost within about 10 ms of beam injection. The resonance condition is shown in equation (1).

$$f_{\rm knockout} = \{n \pm [\nu_{x,y} - {\rm Integer}(\nu_{x,y})]\} \times f_{\rm revolution}, \tag{1}$$

where $f_{\rm knockout}$ is the frequency of the knockout signal, $\nu_{x,y}$ is the betatron tune in the horizontal (x) or vertical (y) direction, $f_{\rm revolution}$ is the revolution frequency and n is zero or a positive integer.

To adjust the betatron tune, the excited currents of the focusing and defocusing quadrupole magnets were tuned finely. The horizontal and vertical tune values were selected to be 11.796 and 8.7833, respectively. From these current values and the results of the magnetic measurements, the excited currents of the dipole and quadrupole magnets at 8 GeV were calculated and the current patterns of the power supplies were determined (Fukami *et al.*, 1995).

2.4. *Acceleration and tuning of the ramping pattern*

The power supplies of the dipole, quadrupole and sextupole magnets are operated with a cycle of 1 s (Yonehara *et al.*, 1996). The beam was initially lost during the ramping period because of

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the betatron tune resonance. This was a result of a shift of the start timing between the current pattern of the dipole magnet and those of the quadrupole magnets. Resonance was avoided by shifting the start timing of these patterns. The r.f. accelerating voltage is also operated at 1 Hz. The effective accelerating voltage is achieved by changing the r.f. phase between two klystrons.

2.5. *Measurement and correction of the closed-orbit distortion*

Eighty beam-position monitors (BPM) with four button-type electrodes are used in the measurement of the closed-orbit distortion (COD) (Aoki *et al.*, 1996). Fig. 1 shows the horizontal and vertical CODs at 1 GeV both with and without correction. The maximum horizontal and vertical CODs without correction were 4 and 5 mm, respectively. The COD was corrected by the program *TRACY*, written by Dr Nishimura at LBL (Nishimura *et al.*, 1995). As a result, both of the maximum CODs were decreased to less than 2 mm, and the root-mean-square values of the horizontal and vertical CODs were 0.47 and 0.38 mm, respectively. The means of the horizontal and vertical CODs were −0.44 and 0 mm, respectively. The horizontal COD was not zero. The mean of the horizontal COD was zero when the radio frequency was changed to 4 kHz lower than the design value of 508.58 MHz. This showed that the circumference of the synchrotron is 3.1 mm longer than the design value.

2.6. *Measurement and correction of chromaticity*

The horizontal and vertical chromaticities without correction were measured at 1 GeV; these values were −22.6 and −7.7, respectively. They were decreased to zero by 60 focusing and defocusing sextupole magnets. The correction of the chromaticities was adjusted at the injection energy. If the chromaticities are tuned to be very small, the horizontal and vertical betatron tunes are not shifted when the beam energy is changed by the modification of the radio frequency. The excitation current patterns of the focusing and defocusing sextupole magnets were decided by calculation with the optimum current at 1 GeV. After the correction, the beam currents at 1 and 8 GeV were increased by a factor of five.

2.7. *Extraction orbit*

Four bump, three kicker and four septum magnets are used for beam extraction. After correction of the COD, all the excitation currents were set to the calculated value on the basis of the magnetic field measurement. The beam extraction proceeded without adjustment of the current but with tuning of the timing of the kicker magnets. As the extracted beam orbit was slightly slanted vertically, the local bump orbit was achieved by three vertical correction magnets and the slant was decreased to be negligibly small.

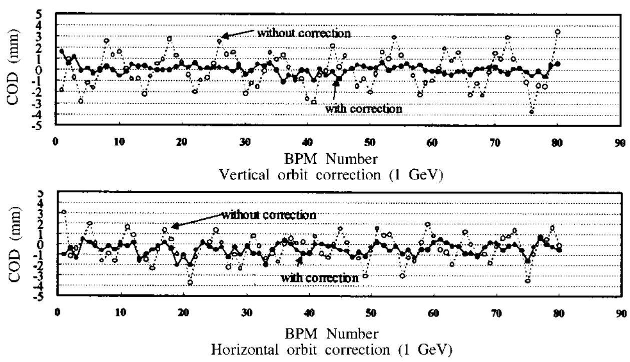

Figure 1
Horizontal and vertical COD at 1 GeV, both with correction and without correction.

2.8. *Timing system*

Fifteen magnets for the injection and extraction are excited by pulsed currents. The dipole, quadrupole, sextupole and correction magnets are excited by patterned currents. The timing system is very important, and high accuracy and low time jitter are required (Suzuki *et al.*, 1993; Suzuki, Yonehara, Aoki, Tani, Kaneda *et al.*, 1995). All of the timing signals are made by counting the radio frequency of 508.58 MHz and a master signal of 1 Hz is used as starting signal.

2.9. *SSBT*

SSBT is the beam transport line from the synchrotron to the storage ring. Its length is 310 m. There are 14 dipole magnets, 40 quadrupole magnets and 21 correction magnets in the transport line. To adjust the beam orbit, 15 fluorescent screen monitors were used in the SSBT. All the excitation currents were initially set to preset values, which were calculated from the beam optics. The excitation currents of the dipole and correction magnets were adjusted to the optimum value according to the beam passing through the center of the each of the quadrupoles. The condition of injection into the storage ring was satisfied by the adjustment. Two strip-line-type position monitors at the end section of the SSBT were used to measure the stability and repeatability of the beam position and angle. The stability and repeatability of the beam position and angle over a period of a few hours were less than 0.1 mm and 0.1 mrad, respectively. The beam currents of the synchrotron and the storage ring are measured by DC transformers. The efficiency of the beam injection from the synchrotron to the storage ring is calculated based on the beam currents and the ratio of their circumferences. The efficiency of the beam injection was almost 100%.

2.10. *Single-bunch operation*

An experiment in which the multi-bunch beam from the linac is changed into a single-bunch beam by the r.f. knockout system was tested in the synchrotron. Fig. 2 shows a block diagram of the r.f. knockout system for single-bunch mode operation. A beam length of 1 μs or 40 ns for the multi-bunch mode is injected into the synchrotron; most beams are kicked out by the vertical betatron resonance with the r.f. knockout and only one bunched

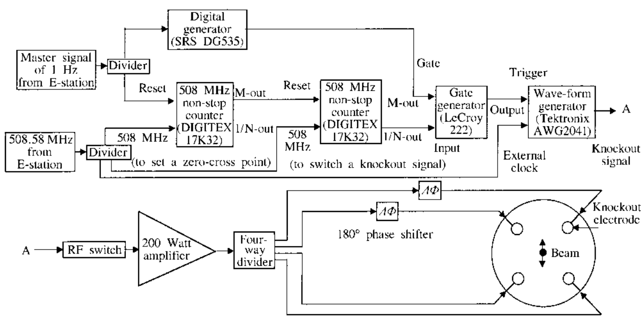

Figure 2
Block diagram of the r.f. knockout system for single-bunch-mode operation.

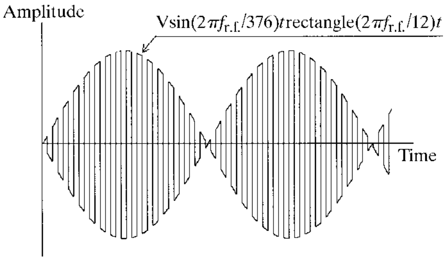

Figure 3
The signal for the r.f. knockout. The signal is generated by composition of a sine wave resonating with vertical betatron oscillation and a rectangular pulse of $f_{\rm r.f.}/12$, where $f_{\rm r.f.}$ is a radio frequency of 508.58 MHz.

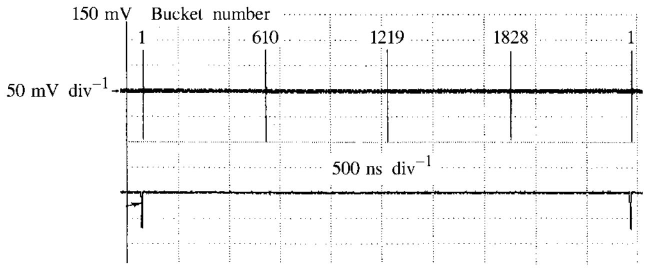

Figure 4
The waveform of four equally spaced bunches injected into the storage ring. The upper waveform shows the bunches, which were measured by a strip-line-type monitor. The lower waveform is a trigger signal, which is synchronized with the revolution frequency of the storage ring.

beam remains. The knockout signal is generated by composition of a sine wave resonating with vertical betatron oscillation and three rectangular pulses of frequency $f_{\rm r.f.}/12$, $f_{\rm r.f.}/21$ and $f_{\rm r.f.}/32$, where $f_{\rm r.f.}$ is a radio frequency of 508.58 MHz. The least common multiple of 12, 21 and 32 is the harmonic number of 672. There are only two points of phase that the beam is not kicked out commonly by three rectangular pulses. If the beam is not injected at one point of phase and is injected at the other point, only one bunched beam remains. The three kinds of rectangular pulses are switched at an interval of 40 ms, one after another. Fig. 3 shows the signal for the r.f. knockout, and Fig. 4 shows the waveform of four equally spaced bunches injected into the storage ring. The harmonic number of the storage ring is 2436 and the interval of a single bunch is 609 buckets.

3. Problems with beam commissioning

There were many problems during beam commissioning. Two r.f. couplers leaked out at an input power of 250 kW in the r.f. conditioning. Two dummy loads were broken by considerable discharge during r.f. conditioning. A beam duct for a dipole magnet leaked out as a result of the thermal stress of the synchrotron radiation. The polarities of focusing and defocusing sextupole magnets were mistaken during wiring of the power supplies. Finally, some of the power supplies of quadrupole and dipole magnets in the SSBT had a number of problems.

4. Conclusions

The beam commissioning of the synchrotron proceeded smoothly and the beam is now supplied steadily to the storage ring. In October 1997, the first experiments started on the beamline.

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