SYNCHRONOUS TRANSFER OF BEAM FROM THE BOOSTER TO THE MAIN RING IN THE KEK PROTON SYNCHROTRON

Y. Kimura, T. Kawakubo, K. Takata, and T. Kamei

National Laboratory for High Energy Physics
Oho-machi, Tsukuba-gun, Ibaraki-ken, 300-32, Japan

Abstract

The KEK main ring is filled with nine successive beam pulses from the fast cycling booster synchrotron during the injection. Booster beams are synchronously transferred into stationary rf buckets of the main ring preserving the booster rf structure. At the transfer, longitudinal phase and momentum of the beam bunch extracted from the booster are matched to those defined in the main ring within errors of $|\Delta p| < 10^{-3}$ and $|\Delta p/p| < 4 \times 10^{-6}$. These voltages define the bunch shape at the transfer, $p_B = p_M \approx 6$ MeV. Booster beams are successively transferred into nine rf buckets prepared in the main ring exactly preserving the longitudinal bunch structure in the booster as illustrated in Fig.1:

Beam Matching in the Longitudinal Phase Space

In this transfer scheme, the beam at the main ring injection should be controlled to have such longitudinal bunch shape that precisely match with stationary main ring rf buckets. The matching of bunch shape in the longitudinal phase space is achieved by making the rf bucket shape of the booster and the main ring identical at the transfer. The present booster magnet is excited by a biased sine wave current of 20 Hz. At around the injection moment, the booster rf bucket shape is the biased sine wave of 20 Hz. After the injection, the longitudinal bunch width can be approximated to be 1 mm. Then, the matching of the bucket height of the booster $p_B$ at the extraction, $p_B = p_M \approx 6$ MeV. Booster bunches are transferred into stationary rf buckets of the main ring exactly preserving the longitudinal bunch structure in the booster as illustrated in Fig.1:

Phase Matching

As stated above, the tolerance for the booster rf frequency at the transfer is $|\Delta f| < 4 \times 10^{-3}$. The booster field is biased sine wave of 20 Hz, and space durations of about 100 µs are available for the booster. Changes of the booster field and rf frequency at this transfer are $\Delta B/B \approx 1 \times 10^{-4}$ and $\Delta f/f \approx 4 \times 10^{-5}$, respectively, and within the required tolerances. Then, the matching of the bunch shape at the transfer and the main ring rf bucket should be done within this period prior to the extraction from the booster.

Among several possible schemes of the phase matching, we adopted the following one, which is entirely based on the present booster design that the harmonic number is one. The principle of the present scheme is to operate the booster in such a way that the booster rf frequency $f_B$ at the transfer is slightly different from the injection frequency of the main ring $f_M$ by $\Delta f = f_B - f_M$. Then, the booster bunch phase slips relative to the main ring rf bucket phase with a speed of $2\pi\Delta f$ rad/sec, and matches with the main ring bucket every period of $1/\Delta f$. The frequency difference of $\Delta f$ should not be too large, otherwise $|\Delta f| < 4 \times 10^{-3}$ causes no significant orbit displacement in the booster, and should not be too small so that $1/\Delta f$ is shorter than 100 µsec which is available for the phase matching. In the usual operation of the present system, $f_B$ and $f_M$ are chosen to be 6.025 MHz and 6.015 MHz, respectively, and the booster beam with the momentum matched with that of the main ring has an average orbit displacement of $|\Delta f| < 4 \times 10^{-3}$ by phase locking the rf oscillator to a synthesizer. The main ring is also regulated to a constant value with an error of $|\Delta B|/B < 10^{-4}$ so that injected beams keep coasting in the main ring with orbits more less than 1 mm. Then, in the injection, the injection momentum is defined with a good accuracy of $|\Delta p/p| < 10^{-5}$. The central momentum of the beam in the booster is also determined by assigning the revolution frequency and the guiding field. Information about radial beam positions has not enough accuracy to know the momentum with such small errors. As described in the followings, booster beams are extracted at a predetermined rf frequency, the matching of the booster momentum to that of the main ring is reduced to preadjustments of the booster field. Corresponding to the required momentum at the injection, the booster rf frequency at the transfer, the peak booster field should be regulated to better than $|\Delta B|/B < 4 \times 10^{-4}$ in its stability and repeatability.

At the start of the regular operation, the tuning of the main ring injection parameters are performed with the following procedure. All the booster parameters are set to the predetermined values and booster beams are transferred into the main ring without applying rf voltage. The main ring injection field is adjusted so that the injected beam circulates on the injection closed orbit with an average orbit deviation less than about 1 mm. After setting of the injection field, the injection line is tuned to make coherent betatron oscillation amplitudes due to injection errors minimum. The main ring rf frequency at the injection is determined by measuring the revolution frequency of injected beam. At the same time, the momentum spread of the booster beam can be known from observations of the bunch width widening after the injection due to bunching in the main ring.

Momentum Matching

During the injection period, the main ring rf frequency is set to a fixed value with an error of $|\Delta f| < 4 \times 10^{-3}$ by phase locking the rf oscillator to a synthesizer. The main ring is also regulated to a constant value with an error of $|\Delta B|/B < 10^{-4}$ so that injected beams keep coasting in the main ring with orbits more less than 1 mm. Then, in the injection, the injection momentum is defined with a good accuracy of $|\Delta p/p| < 10^{-5}$. The central momentum of the beam in the booster is also determined by assigning the revolution frequency and the guiding field. Information about radial beam positions has not enough accuracy to know the momentum with such small errors. As described in the followings, booster beams are extracted at a predetermined rf frequency, the matching of the booster momentum to that of the main ring is reduced to preadjustments of the booster field. Corresponding to the required momentum at the injection, the booster rf frequency at the transfer, the peak booster field should be regulated to better than $|\Delta B|/B < 4 \times 10^{-4}$ in its stability and repeatability.

At the start of the regular operation, the tuning of the main ring injection parameters are performed with the following procedure. All the booster parameters are set to the predetermined values and booster beams are transferred into the main ring without applying rf voltage. The main ring injection field is adjusted so that the injected beam circulates on the injection closed orbit with an average orbit deviation less than about 1 mm. After setting of the injection field, the injection line is tuned to make coherent betatron oscillation amplitudes due to injection errors minimum. The main ring rf frequency at the injection is determined by measuring the revolution frequency of injected beam. At the same time, the momentum spread of the booster beam can be known from observations of the bunch width widening after the injection due to bunching in the main ring.
about 2 mm inside of the central orbit at the transfer. The frequency difference of $\Delta f = 10$ kHz is just enough to complete the phase matching within 100 nsec.

The most distinctive of the present scheme is that it is unnecessary to conduct any auxiliary managements of the booster rf system for the phase matching, and the beam orbit in the booster can be kept constant during the phase matching process. As the rate of the phase slip between the booster bunch and the main ring rf bucket is precisely predetermined, if we check the time $t = 0$ when the phase difference becomes a definite value ($\Delta \phi$), we can predict without measuring that the bunch synchronizes with the main ring rf bucket at $t = T_d = (\Delta \phi)/2 \pi f_y$. The booster bunch is triggered at $T_d$ after the phase difference is measured to be ($\Delta \phi$). In the actual system, however, the bunch is not extracted from the booster exactly at $T_d$. Since there are nine rf buckets in the main ring which are successively occupied by booster beams, and a bunch should be transferred into one of unoccupied buckets whose position around the main ring circumference at $T_d$ can't be pre-adjusted. Therefore, the extraction time has an uncertainty of $\Delta t$ after $T_d$ in which an assigned and unoccupied bucket circulating in the main ring comes to the proper position for the bunch transfer. This time delay ranges from zero to one main ring revolution period, and causes a phase error in the phase matching. As the maximum of $\Delta t$ is about 1.5 nsec for $f_y \simeq 6$ MHz, the phase error due to $\Delta t$ is $5.6^\circ$ for $\Delta f = 10$ kHz ($1/(\Delta \phi/dt) = 3.6^\circ$/nsec).

In the beam extraction from the booster and the injection into the main ring, we use three types of deflecting elements, septum magnets, bump magnets, and kicker magnets! The kickers should be pulsed only for a duration of one bunch length (70 nsec) and triggered at $t = T_d + \Delta t$. While the septum and bump magnets are excited with a half sine pulse of relatively wide width to ease the construction of the magnets and power supplies. The most suitable pulse width is about a few nsec. for the septum, and 10 $\sim$ 40 nsec. for the bump magnet. In the present system, the pulse width of the septum field is chosen to be 4 nsec so that at the peak the field is constant within an error in the deflection angle of $<0.2$ mrad over a duration of 100 nsec which is required for the phase matching. The septum magnets are triggered at 2 nsec before the booster field reaches the peak. The pulse width of the bump magnets for the booster extraction is 35 nsec, which provides a constant field width of about 2 nsec at the peak corresponding to the uncertainty $\Delta t$ in the extraction time. The bump magnet is triggered at 17.5 nsec before the booster bunch synchronizes with the main ring rf bucket. This requirement is easily satisfied in the present matching scheme by choosing $T_d = 17.5$ nsec. Figure 2 illustrates the time sequence of the present synchronous beam transfer system.

The block diagram of the electronics system for the phase matching is shown in Fig. 3. The phase matching process is initiated by a signal indicating that the booster rf frequency reaches the predetermined value. A delayed coincidence unit is gated by this signal for about 200 nsec. Two inputs to the coincidence are booster and main ring rf frequency signals which are shaped to 2 nsec wide timing pulses. In the input from the main ring rf signal, a time delay of $(\Delta \phi)/2 \pi f_y$ is inserted so that the phase difference between the booster bunch and the main ring rf bucket is $(\Delta \phi)$ when the two signals give a coincidence output. The resolution of the present coincidence system is shown to be 0.2 nsec and causes a phase matching error of about $1^\circ$. A preset counter initiated by the coincidence output clocks $T_d$ by counting the Booster rf frequency signal. Then, an output of the preset counter gives the time when the booster bunch synchronizes with the main ring rf bucket. This signal indicating $t = T_d$ opens a gate for the booster rf signal fed to an empty

bucket selector. The selector circuit is essentially a series of gate units with common signal inputs of the booster rf frequency pulse. Each gate is conditioned in two ways. The first is given from a ring counter circuiting with the main ring rf frequency signal and assigns $\# 1 \sim \# 9$ gate unit to $\# 1 \sim \# 9$ rf bucket of the main ring, and the second is given in such a way that only one of nine gate units is sequentially opened after the preceding one is closed by bunch transfer to the corresponding main ring rf bucket. Then, the bucket selector generates a timing signal synchronized with the phase of an assigned main ring rf bucket unoccupied by a beam bunch, which triggers the kicker system.

Figure 4 shows a signal of the fast bunch current monitor during the injection period, and the successive injections of nine booster pulses are seen together with a beam loss in the main ring after the injection. Extensive investigations are under way on origins of this beam loss. A typical example of beam bunches which are captured by the nine main ring rf buckets and accelerated to the top energy (8 GeV) is shown in Fig. 5. The fine tuning of the phase matching is performed by adjusting the time delay inserted in front of the delayed coincidence. Errors in the phase matching are observed as a phase oscillation of the injected bunch around the center of the main ring rf bucket (Fig. 6). The measurements indicate that errors of the present matching system are about $|\phi| \sim 10^\circ$ and $|\delta p/p| \sim 4 \times 10^{-7}$ in phase and momentum, and slightly exceed the design value of the tolerances. In the present booster, intensity dependent beam instabilities are observed both in transverse and longitudinal phase space and cause fluctuations of the momentum at the transfer and mismatching of the bunch shape with the main ring rf bucket. By damping these effects, we expect the matching errors will be reduced further.

Acknowledgements

We would like to thank the members of the KEK RF group for the collaborations in the construction and operation of the present system.

References

1. Y. Arakita et al., contribution to this conference.
2. N. Sasaki et al., contribution to this conference.
3. M. Kondo et al., contribution to this conference.
5. A. Ando et al., contribution to this conference.

Fig. 1 Multiple booster pulse injection into the main ring.

1462
Qi-0s 1 phase difference between booster bunch and main ring rf bucket.

At 2 ms before booster B top, excite extraction and injection septum magnets.

At 100 μs before B top, start measuring $\Delta \phi$, 

$$f_B = f_M + 10 \text{ KHz}$$

Excite booster extraction bumps with rise time of 17.5 μs.

Start looking for empty bucket.

Extraction and injection by fast kickers.

$t = 0$, $\phi_B - \phi_M$ is measured to be $\phi = 63^\circ$.

Fig. 2 Time sequence of transferring the booster bunch to the main ring synchronously.

Fig. 3 Block diagram of the electronics system for the phase matching of the booster bunch with the main ring rf bucket.

Fig. 4 Successive injections of nine booster pulses into the main ring observed by a fast bunch current monitor, which indicate a significant beam loss after the injection. ( Horizontal = 50 msec/ div )

Fig. 5 Beam bunches in the main ring at the flat top ( 8 GeV ). Summed intensity of nine bunches is $5.4 \times 10^{11}$ protons. ( Horizontal = 200 nsec / div )

Fig. 6 Evolutions of beam bunches in the main ring after injection for correct ( left ) and incorrect ( right ) phase matching. Horizontal sweep is triggered by a signal clocked with main ring rf frequency. ( Horizontal = 50 msec / div, vertical = 100 rf clocks / sweep )