QUASI-ADIABATIC TRANSITION CROSSING IN THE HYBRID SYNCHROTRON

Y. Shimosaki, K. Takayama, KEK, Ibaraki, Japan
K. Torikai, NIRS, Chiba, Japan

Abstract

Non-adiabatic features around the transition energy are well-known to be one of most important beam physics issues in most of circular hadron accelerators. A novel technique to avoid them by the adiabatic motion, a quasiadiabatic, nonfocusing transition-energy crossing (QNTC), was proposed. In a longitudinally separated function-type accelerator, in which particles are confined by an rf voltage or burrier voltages and accelerated by a step voltage, the confinement voltage can be arbitrarily manipulated as long as the particles do not diffuse, while a strict acceleration voltage is necessary for the orbit of a charged particle to be balanced in the radial direction. The introduction of QNTC is most suitable for the longitudinally separated function-type accelerator. This new method was examined in this type of accelerator, both theoretically and experimentally. This was a first and significant application of the hybrid synchrotron. The results will be presented.

INTRODUCTION

The transition energy is a singular point in the acceleration of a proton synchrotron. Most proton synchrotrons consisting of a normal FODO lattice have their transition energy in the middle of acceleration. More or less, these synchrotrons have faced various undesired features when a proton beam crosses the transition energy. The bunch shape in a radio-frequency (rf) bucket is remarkably deformed by an inherently non-adiabatic nature in the synchrotron oscillation in the vicinity of a transition energy in a synchrotron. This is well-known to be caused by a linearly rapid change of the slippage factor in time [1]. The rf bunch is shortened in time space and stretched in momentum space. The former leads to a growth of the line density, inducing undesired coherent instabilities, such as the microwave instability [2], the electron-cloud instability [3] as well as increasing transverse space-charge effects. The latter may restrict the momentum aperture of an accelerator ring. In addition, nonlinear kinematic effects (Johnsen effect [4]) in the synchrotron oscillation should be relatively enhanced, which results in the emittance growth. It is insisted that these awkward situations result in beam loss, which limits the operational capability of an accelerator. The beam intensity and the wall current monitor at the KEK-PS min ring (MR) are shown in Fig. 1. As mentioned, the beam loss is significant around the transition crossing. Moreover, the wall current, which is in proportion with a line density, has the peak due to the shrinking of bunch size as mentioned above.

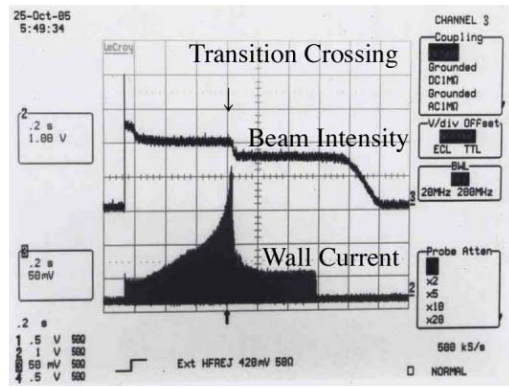

Fig.1 Beam intensity and wall current through the injection porch (50msec), the acceleration period (2msec) and the beam extraction at the KEK-PS MR. Nominal transition crossing (NTC). The injection energy is 0.5 GeV, the transition energy is 5.28 GeV, and the extraction energy is 8 GeV (kinetic energy).

In this paper, an acceleration method to introduce an adiabatic longitudinal motion is proposed. An rf bunch can be stretched in time and shortened in energy space by adiabatically decreasing the rf voltage. Thus, if the adiabatic reduction of the rf voltage is performed for a long time period around the transition energy, the non-adiabatic feature mentioned above should be suppressed. This is called quasiadiabatic, nonfocusing transition-energy crossing (QNTC), here. In a longitudinally separated function-type accelerator [5], in which particles are confined by an rf voltage or burrier voltages and accelerated by a step voltage, the confinement voltage can be arbitrarily manipulated as long as the particles do not diffuse, while a strict acceleration voltage is necessary for the orbit of a charged particle to be balanced in the radial direction. The introduction of QNTC is most suitable for this type of accelerator. In this letter, theoretical analyses of the QNTC are given. In addition, this idea has been demonstrated in the KEK proton synchrotron (KEK-PS), which is being operated as a hybrid synchrotron employing the existing rf for the confinement and induction system for acceleration [6]. Those results are reported here.

THEORETICAL APPROACH

The discrete synchrotron equations, which show the turn-by-turn evolution of the particle energy, E, and time difference, Δt, from the arrival time of a synchronous particle at the acceleration device, are described as

$$E_{m+1} = E_m + e\left\{\left(V_c\right)_m + \left(V_a\right)_m\right\}, \quad (1)$$

$$\Delta t_{m+1} = \Delta t_m + \eta_{m+1} T_{m+1} \frac{E_{m+1} - (E_s)_{m+1}}{(\beta_{m+1})^2 (E_s)_{m+1}}, \qquad (2)$$

where $V_a = \rho C_0(dB/dt)$ (ρ, curvature; C_0, circumference; B, bending magnetic field) is the accelerating voltage, β and T are the relativistic beta and the revolution period of the synchronous particle, $\eta = 1/\gamma_t^2 - 1/\gamma^2$ (γ_t, the transition gamma) is the slippage factor. V_c represents the confinement voltage, which varies in time according to

$$V_c(t) = \pm V_{rf} \left| \frac{t}{t_0} \right|^n \sin\{\omega_{rf}(t)t\} \qquad (3)$$

for a finite time period of $2t_0$, in which $t = 0$ corresponds to the transition energy; n is a real number, and n is 0 for the nominal transition crossing (NTC) in a conventional rf synchrotron and $n > 0$ for the QNTC. | | denotes the absolute value. V_{rf} and $\omega_{rf} / (2\pi)$ are the amplitude and frequency of the rf voltage, respectively. The sign of the voltage is changed at the transition crossing to maintain the phase stability. A synchronous particle never see V_c.

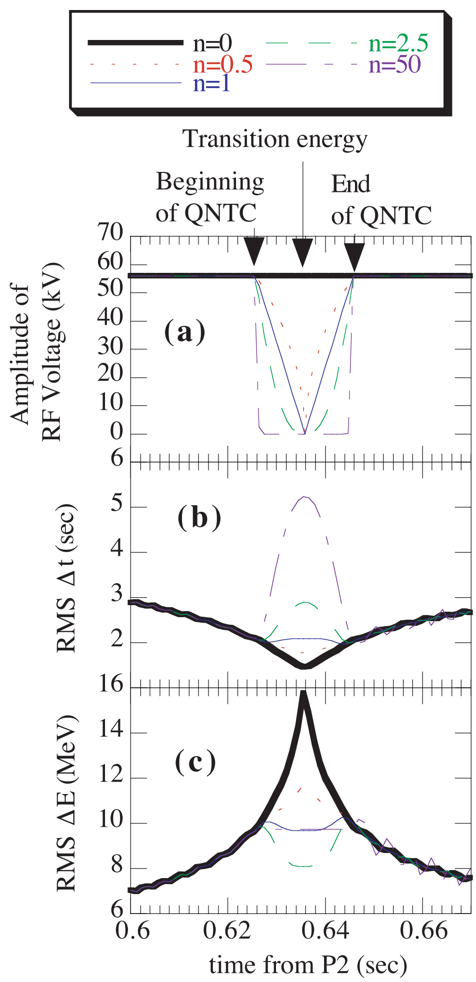

Fig.2 (a) Amplitude of RF voltage, RMS bunch length (b) in time and (c) in energy space.

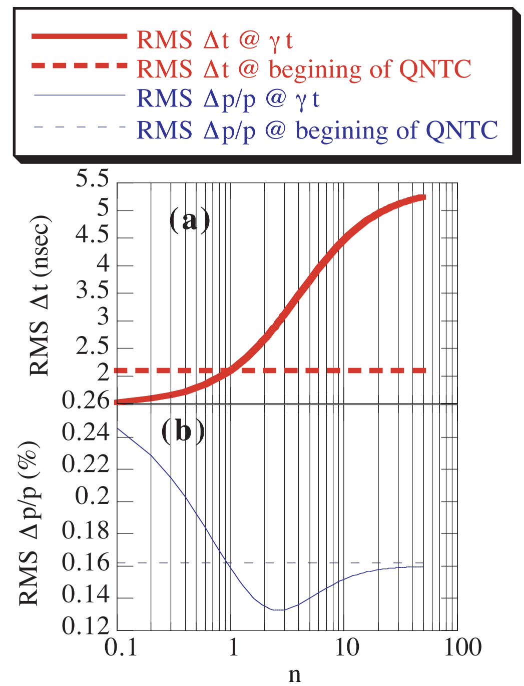

Fig.3 n dependence of bunch width (a) in time and (b) in energy space.

In order to delineate the longitudinal motion for the QNTC in a realistic manner, particle tracking based on Eqs. (1) and (2) was carried out. In this calculation, the machine parameters of the KEK-PS with the 8 GeV ramping pattern were assumed. For the QNTC, t_0 was set to 10 msec in this simulation. The temporal evolutions of the root-mean squares of the bunch length in time and energy space are shown in Fig. 2, in which the amplitude of the rf voltage for confinement is also included. As mentioned above, the results for the NTC ($n = 0$) indicate that Δt shrinks and $\Delta E = E - E_s$ increases in the vicinity of γ_t. In the case of $n = 1$, the bunch shape is maintained to be almost constant during the time period from $-t_0$ to t_0. The RMS size of Δt for $n = 0.5$ and 2 decreases and increases around γ_t, respectively. Their ΔE are in contrast to Δt. Meanwhile, in the case of $n = 50$, the size of Δt increases as $n = 2$, but ΔE is maintained as $n = 1$.

The dependence of RMS size at γ_t on n is shown in Fig. 3. For $0 \le n \le 2$, the bunch size at γ_t increases in time and decreases in energy space as an intrinsic nature of the adiabatic beam dynamics. Meanwhile, nature is not satisfied for too high n as shown in Fig. 3(b). This seems that a non-adiabatic motion is induced by rapidly changing of the rf voltage. Only $n = 1$ maintains the bunch shape almost constant in phase space (some analytic results are given in Ref. [7]).

EXPERIMENTAL RESULTS

The QNTC experiment was carried out in the present KEK PS, which has been operated as a hybrid synchrotron, that is, particles are confined by the rf voltage and accelerated by the step-voltage. The QNTC with n = 1 was employed because it was the unique solution for maintaining a constant bunch size. The amplitude of the rf voltage, which has to obey the programmed voltage V_p, is controlled by an automatic voltage controller [8]. A triangular pulse with a negative amplitude was superimposed on the existing V_p to generate the rf voltage for the QNTC, where t_0 was set to 0.125 sec in an acceleration time period of 1 sec (see Fig. 4).

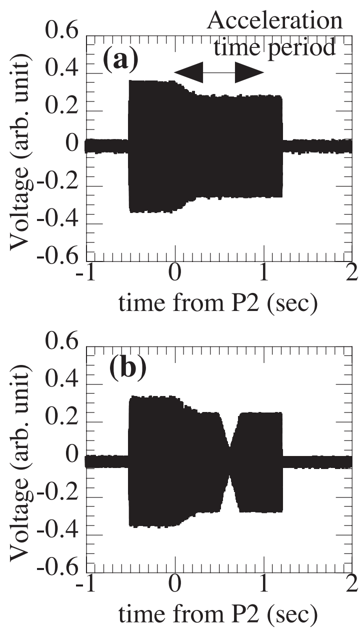

Fig.4 RF Voltage for (a) NTC and (b) QNTC (n = 1).

The bunch length in the vicinity of γ_t, measured by the wall current monitor, is shown in Fig. 5, in which V_p (exp) means the amplitude of the rf voltage used in the experiment. The bunch length for the QNTC was nearly constant and longer than that for the NTC as be expected.

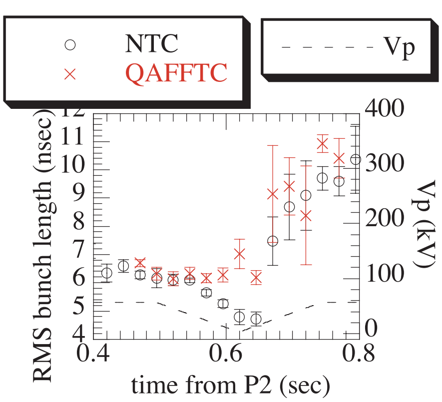

Fig.5 RMS bunch length for NTC and QNTC.

The temporal evolution of the beam intensity and the wall current for the QNTC with n = 1 are shown in Fig. 6 (the case of the NTC is shown in Fig. 1). The beam loss for the QNTC was substantially suppressed, compared to that for the NTC, although the amplitude of the rf voltage was deformed by 1/4 of the accelerating time. In addition, the signal of the wall current for the QNTC (Fig. 6) became flatter around the transition crossing than that for the NTC (Fig. 1). This is due to the constant bunch width of the QNTC with n = 1.

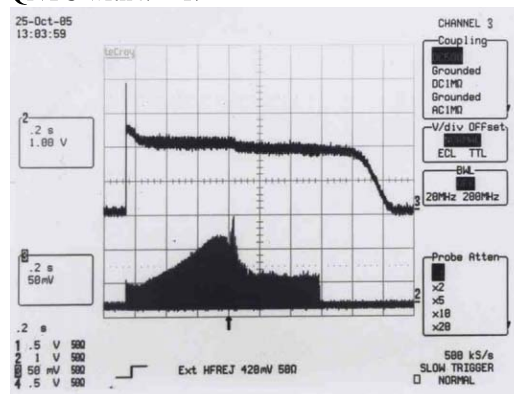

Fig.6 Beam intensity and wall current in the case of QNTC (n=1).

CONCLUSION

It is insisted that the experiment has manifested a big figure of merit that the separation of acceleration and longitudinal confinement provides. This is one example of big freedoms of beam-handling that the induction synchrotron concept [5] introduces in circular accelerators. The present quasiadiabatic, nonfocusing transition-energy crossing technique is available for an rf synchrotron, in which a higher harmonic RF is utilized for the acceleration [9] as well as the induction step voltage.

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