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Experimental Study of the Main Ring Transition Crossing

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Experimental Study of the Main Ring Transition Crossing

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Abstract

A 12 sec long Main Ring cycle was used with an unbunched beam of low intensity to measure the change of the revolution frequency of the beam as a function of the central momentum setting determined by the magnetic field. The transition gamma was determined as the first order term in the change in the revolution frequency versus fractional change in the momentum, but the nonlinear term α_1 could not be determined because of the limited momentum aperture of the Main Ring and the present measurement resolution.

1 Theory

Consider a beam coasting in the center of the vacuum chamber of an accelerator ring with closed-orbit length C_0. Its momentum is always a constant denoted by p_b. If the bending field of the dipoles is changed, this beam will be pushed off-center, because the new magnetic field will support only particles with momentum p_c ($\neq p_b$) in the center of the vacuum chamber. This off-centered beam will now travel in a new closed-orbit of length $C = C_0 + \Delta C$, given by

$$\frac{\Delta C}{C_0} = \alpha_0\delta(1+\alpha_1\delta) + \mathcal{O}(\delta^3)\ , \tag{1}$$

where $\delta = (p_b - p_c)/p_c$. In the above, α_0 is the zero-order momentum-compaction factor and the transition gamma is defined as $\gamma_t = \alpha_0^{-1/2}$, while $\alpha_0\alpha_1$ is the first nonlinear coefficient. The revolution frequency will be changed from f_0 to $f_b = f_0 + \Delta f$, where

$$\frac{\Delta f}{f_0} = -\frac{\Delta C}{C_0}\ . \tag{2}$$

Note that the velocity term is absent in Eq. (2) because there is no change in momentum of the beam when it is moved off-center. Writing it out explicitly, we have

$$\frac{f_b - f_0}{f_0} = -\alpha_0\left(\frac{p_b - p_c}{p_c}\right)\left[1 + (\alpha_1 - \alpha_0)\left(\frac{p_b - p_c}{p_c}\right)\right]\ , \tag{3}$$

where higher-order terms have been omitted. Since usually $\alpha_0 \ll \alpha_1$, the α_0^2 term can be dropped.

Therefore, by varying the dipole bending field setting, which corresponds to a new momentum setting p_c for a centered beam, the revolution frequency f_b of the coasting beam with momentum fixed at p_b will be changed. The slope of the linear plot of f_b versus p_0 or bending field will give α_0 or the transition gamma. Any deviation from linearity will give α_1 [1].

2 Experimental Procedure

We used a long (12 sec) 2D Main Ring cycle in this experiment. The 2D cycle is a 8 GeV cycle with no ramp dedicated to the tuning of the reverse injection for $\bar{p}$ from the Accumulator to Main Ring. The rf was switched off at the beginning of the cycle and the 8.8888 GeV/c momentum beam from the Booster was left to debunch and coast in the Main Ring. All the 18 Main Ring cavities were also mechanically shorted after they were turned off to avoid the unwanted bunching of the beam due to beam loading.

At first we used only one-booster-turn injection with only 11 bunches, so that the momentum spread of the beam was as small as possible. We found out that the beam did not debunch completely, because a strong coherent peak was extremely evident in the beam spectrum. Then we included all the 84 bunches booster batch and no coherent peak was further observed.

Since there is no dedicated Schottky detector in the Main Ring, we used a 6 GHz wall-current monitor to observe the beam spectrum on a HP 3588A signal analyser. We chose to observe the Schottky beam signals at a frequency $n = 20$ times the revolution frequency of 47.451 KHz. Due to the extremely low beam current, higher multiples would lead to a low power response and the signal-to-noise ratio would be too low for our measurement. We took narrow-band Schottky spectra of the beam for 5.12 sec each, corresponding to a sampling frequency span of 78.125 Hz and a resolution of 0.290 Hz. Spectra were taken for different central momentum settings in the Main Ring achieved by changing the injection magnetic field.

The spectra were digitized and stored in computer files, which were later analyzed to compute the difference in the revolution frequency at different central momentum settings. The frequency difference was computed by calculating the cross-correlation function of two Schottky spectra corresponding to two different central mo-

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menta.

3 Limitations of Measurement

The transition gamma of the Main Ring is about 18.8. The momentum aperture of the Main Ring had been measured at injection [2], and was quoted as $\Delta p/p = \pm 0.22\%$ at 50% loss. Assuming $\alpha_1 \sim 1$, one would expect a maximum total frequency change due to α_0 at $f_0 = 20 \times f_{\rm rev} = 949.016$ KHz to be ~ 5.9 Hz, and a change due to α_1 ± 0.013 Hz.

In practice, to avoid any beam loss, we were able to move the beam outward by changing the magnetic field up to 0.20%, which gave us a frequency change of about 5.4 Hz at the $n = 20$ multiple of the revolution frequency. When moving the beam inward, we were able to change the magnetic field up to 0.10% only. For this reason, the determination of α_1 is impossible in this experiment, due to the limitation of the momentum aperture of the Main Ring and also the available resolution of our instruments.

4 Results

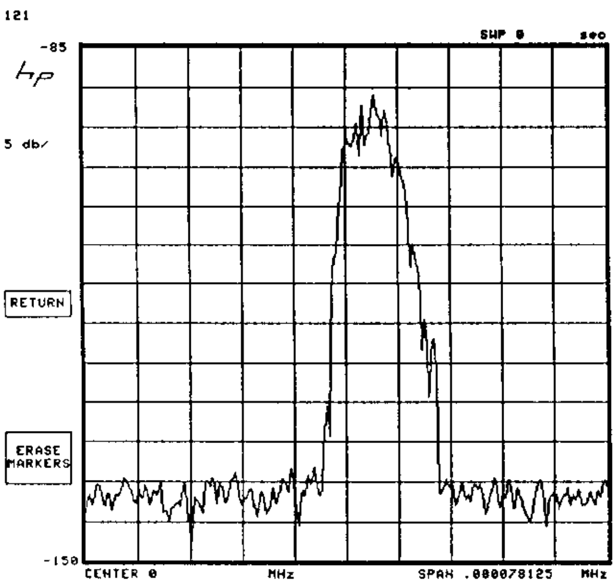

Fig. 1. Schottky scan of unbunched beam at center of vacuum chamber.

The Schottky scan of the unbunched beam at the center of the vacuum chamber is shown in Fig. 1 and the Schottky scan at an offset magnet field setting is shown in Fig. 2. The frequency shift between these two spectra is not obvious visually because the maximum shift was expected to be only ~ 6 Hz. For this reason, the cross correlation of the two spectra $F_1(f)$ and $F_2(f)$, defined by

$$r(f) = \int F_1(f')F_2(f-f')df'$$

was examined. A correlation for the spectra in Figs. 1 and 2 is presented in Fig. 3, which clearly shows a peak. The position of the peak was taken as the frequency shift between the two spectra.

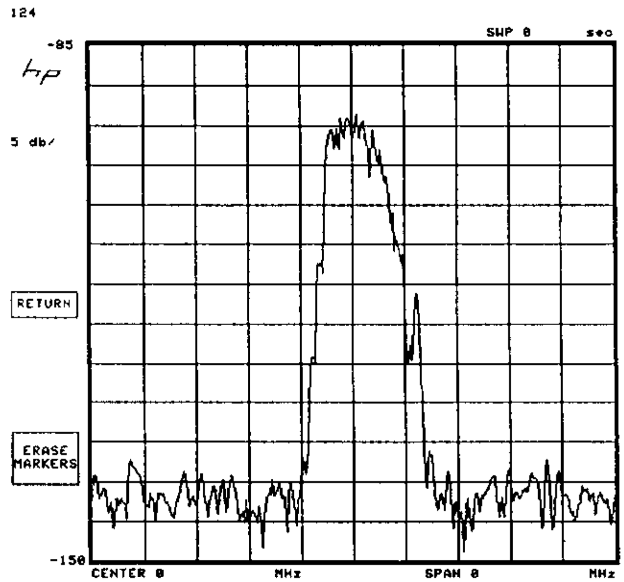

Fig. 2. Schottky scan of unbunched beam at magnetic-field setting corresponding to momentum p_c where $(p_b - p_c)/p_c = 0.002$ GeV/c.

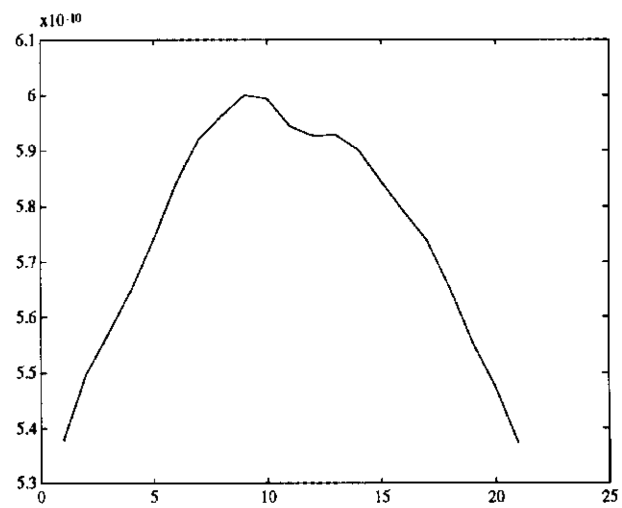

Fig. 3. Cross correlation of the two Schottky spectra in Figs. 1 and 2. The horizontal axis is the frequency shift in relative units.

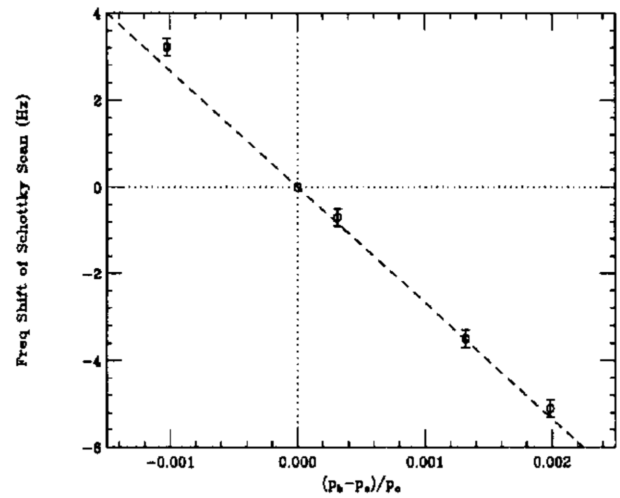

Fig. 4. Plot of frequency shift of Schottky scan versus $(p_b - p_c)/p_c$. The slope of the fit is related to the negative of α_0.

The frequency shifts as a function of the relative change in the central momentum settings are plotted in Fig. 4. The errors in the measured points come mainly from the determination of the frequency shifts by the cross-correlation functions. Since the best fit to our data is a straight line, only α_0 was determined. Our data give an $\alpha_0 = (2.827 \pm 0.081) \times 10^{-3}$ which corresponds to a $\gamma_t = 18.84 \pm 0.27$, to be compared with 18.854 ± 0.006 measured in a debunching experiment around transition energy [3].

5 Discussions

(1) We had chosen to make the measurement at injection. At this momentum, the frequency-slip factor $\eta = \alpha_0 - 1/\gamma^2$ has the largest absolute value, enabling fast debunching. However, the betatron beam size at injection is usually very large, which limits our ability to move the beam transversely. This experiment should have been performed at 150 GeV/c where the betatron beam size is about 4 times smaller. Unfortunately, there is no easy way to change the magnetic field setting by small steps at that momentum.

(2) The method is especially advantageous for a small ring with a large physical aperture, or a large possible $\Delta C/C_0$, so that the frequency shift in Eq. (2) is large. Unfortunately, the Fermilab Main Ring is a big ring with small physical aperture. Therefore, this is in fact not a good method to measure the momentum-compaction factor of this ring.

(3) This method of measurement of α_0 and α_1 is very advantageous for small rings. Because the beam stays at a fixed momentum all the time, no velocity factor comes into play. For example, in Eq. (3), the coefficient of the linear term is exactly α_0 and not η, so that α_0 will not be masked by the velocity factor which can be substantial sometimes. Also the coefficient of the first nonlinear term is α_1 instead of the usual [3] $\alpha_1 + \frac{3}{2}$. Thus the error in determining α_1 can be very much reduced.

(4) One may raise the question whether the changing of the magnetic bending field will alter the momentum of the coasting unbunched beam as a result of Faraday's induction. The Fermilab bending magnets have a left-right horizontal symmetry. Therefore, approximately one half of the magnetic field will return through the inside of the ring and one half outside. The net flux linking the coasting beam should be approximately zero and there should not be any significant induced emf produced. On the other hand, we can also make an extreme estimation by assuming that no return flux goes through the inside of the ring. In that case the energy gained by the beam will be

$$\Delta E_b = \frac{eA\Delta B}{T_0} , \tag{4}$$

where ΔB is the change in average bending magnetic flux that passes through an area A on the inside of the circulating beam and T_0 is the revolution period. However, this change in magnetic field intends to change the momentum p_c of the particles at the center of the vacuum chamber by

$$\Delta p_c = e\rho\Delta B , \tag{5}$$

with ρ equal to the radius of curvature of the ideal orbit. Thus, the change in momentum of the coasting beam due to induction relative to Δp_c is

$$\frac{\Delta p_b}{\Delta p_c} \approx \frac{A}{C_0\rho} , \tag{6}$$

where C_0 is the circumference of the ring. Now the horizontal field aperture of the magnet is of the order $\ell \approx 10$ cm while the bending radius of the Main Ring is of the order 10^5 cm. With the flux penetrating area $A \approx \ell C_0$, Eq. (6) shows that the maximum possible $\Delta p_b/\Delta p_c$ is only about 10^{-4} which is extremely small.

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[3] K.Y. Ng, C.M. Bhat, I. Kourbanis, J. MacLachlan, M. Martens, and J. Shan, *Debunching Studies at Energies Close to Transition,* these proceedings.