Longitudinal Instability in the Fermilab Accumulator During Slow Transition Crossing

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Abstract

The Fermilab Accumulator was built primarily as an 8 GeV kinetic energy antiproton storage ring. Recently the Accumulator was modified for use in a medium energy experiment studying charmonium states. The experiment required a circulating antiproton beam with momenta between 6.7 GeV/c and 3.7 GeV/c. In order to decelerate the beam below 5 GeV/c, transition must be crossed. The method adopted for Accumulator transition crossing was to raise the value of γ_t slowly while the antiproton beam circulated in the ring unbunched. During Accumulator transition crossing with this coasting beam, longitudinal instability was observed with a resistive wall current monitor and a dedicated longitudinal Schottky detector. This paper presents the results of measurements in which longitudinal coherent signals and emittance growth were observed. The data is compared to the predictions of a multiparticle computer simulation.

1 Introduction

The Fermilab Accumulator is an 8 GeV antiproton storage ring which collects and stores antiprotons for operation of the Tevatron collider. Since 1987, a medium energy experiment has been conducted in the Accumulator to study the formation of charmonium states ($c\bar{c}$ bound states) [1]. In the experiment, an intense antiproton beam is decelerated to specific energies in the charmonium region between 6.8 GeV and 3.8 GeV, and collided with protons from an internal hydrogen gas jet target.

The design value of the Accumulator transition energy is 5.1 GeV. In order to perform the experiment below that energy, transition must be crossed. Because of the restrictions from the Accumulator RF system and magnet power supplies, the deceleration can only proceed in a rate which is not fast enough for crossing transition without a major disruption of the bunches. Therefor, an alternative method for transition crossing is adopted in the deceleration operation. In this technique, the beam is debunched at an energy slightly above transition, then γ_t is raised to a value such that the beam energy is below transition, and the beam is recaptured.

During the Accumulator transition crossing, longitudinal instability imposes a critical limit on the amount of $\bar{p}$ beam that can be decelerated below transition. The instability causes beam momentum spread to increase and results in the beam intensity loss when beam current is above 10 mA. Measurements in both frequency domain and time domain were made to identify the source of the longitudinal instability. The result from a multiparticle computer simulation is also presented for comparison.

2 Measurements

In transition crossing, the beam was debunched at an energy of 5.286 GeV ($\gamma = 5.634$), and γ_t was raised from either 5.15 or 5.5 to 6.11. The values of γ_t before and after the crossing process were measured by changing the current of the main dipole bus and measuring the corresponding revolution frequency of the beam. The momentum spread of the beam was obtained from the longitudinal Schottky signal, using the relationship

$$\frac{\Delta P}{P} = -\frac{1}{\eta}\frac{\Delta f}{f},$$

where $\eta = 1/\gamma_t^2 - 1/\gamma^2$. The longitudinal Schottky signal was detected by the Accumulator Schottky pickup, a quarter wave length device resonating at 79.3 MHz.

Beam energy loss and momentum blow up was observed during transition crossing. Figure 1 shows the longitudinal frequency distributions of a beam at $h = 127$ before and after a crossing process. The beam was stochastically cooled before the process started. The 10dB width of the momentum spread was 0.25% before the crossing and 0.82% after the process. The energy loss of the beam in the process was determined from the peak shift of the frequency distribution. In figure 1 the frequency shift is 1.36 kHz, from which about 300 Hz results from the change in the orbit length. This gives a result of 14 MeV for the energy loss in the crossing process. Since near transition a small error in the γ_t measurement gives rise a large error in η, these measurement results are subject to about 40% uncertainty.

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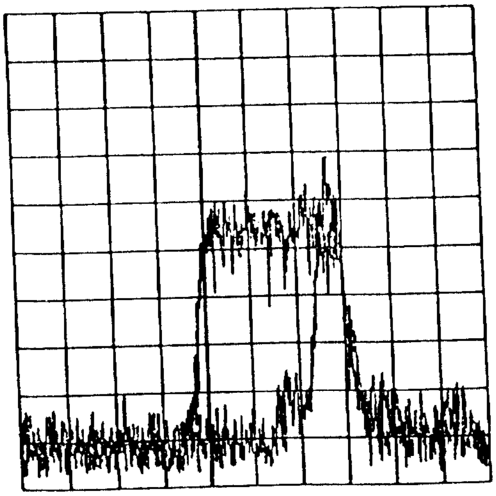

Figure 1: Longitudinal Schottky profiles at $h = 127$ before (narrow trace) and after (wide trace) a transition crossing.

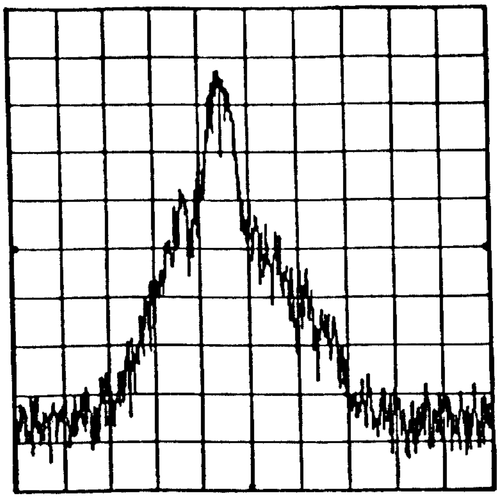

Figure 3: Longitudinal Schottky signal at $h = 127$ in the same transition crossing.

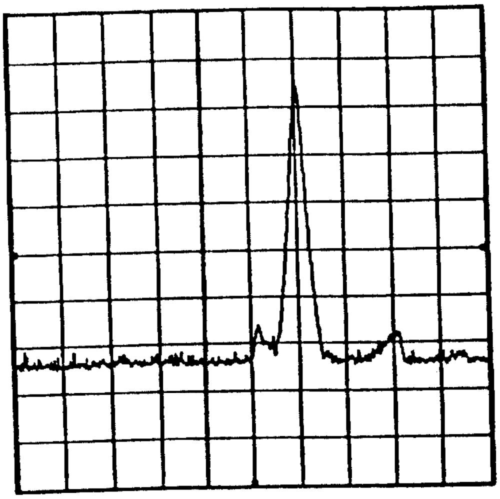

Figure 2: Beam coherent signal at 52.9 MHz in transition crossing, measured by the resistive wall monitor.

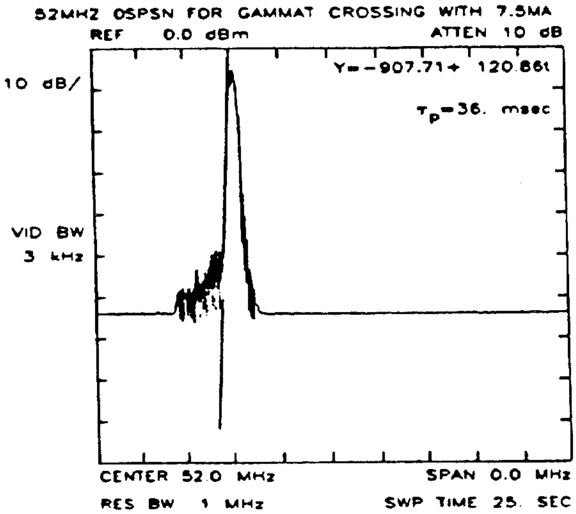

Figure 4: Time evolution of the coherent effect.

In order to discover the sources which caused the momentum blow up and energy loss of a beam in transition crossing, the longitudinal frequency spectrum of the beam was studied as γ_t was being raised. A broadband 3 kHz – 6 GHz resistive wall monitor was used to observe the coherent signal in a wide frequency range. It was found that coherent lines appeared at harmonics of 53 MHz, which was near the resonant frequency of the Accumulator main RF system ARF1. Figure 2 shows the fundamental coherent line at 52.9 MHz. The beam intensity was 5.7 mA. Meanwhile, a sharp peak was observed to rise from the longitudinal Schottky profile, indicating the self-bunching effect of the beam, as shown in figure 3. These observations provided clear evidence that the large shunt impedance of ARF1 was the major source of the beam longitudinal instability in the transition crossing process.

The time evolution of the coherent signal was also measured by using the resistive wall monitor and setting the spectrum analyser to a center frequency near the ARF1 resonant frequency with zero frequency span. The resolution bandwidth of the spectrum analyser was chosen such that at least one revolution harmonic of the beam was covered. Figure 4 shows one measurement result with a beam of 7.5 mA. The sharp rise of the signal occurred when transition was crossed. The rise time of the signal power could be obtained by a linear least-square fit in logarithmic scale. Fitting gave a result of 36 msec.

Transition studies were also done with ARF1 shorted. It was observed that the magnitude of the coherent signal was reduced by at least 50dB, and there was no significant disruption of the beam. Faster transition crossings (6×) also greatly reduced the longitudinal coherent effect, therefore the momentum blow up, of the beam in the crossing process.

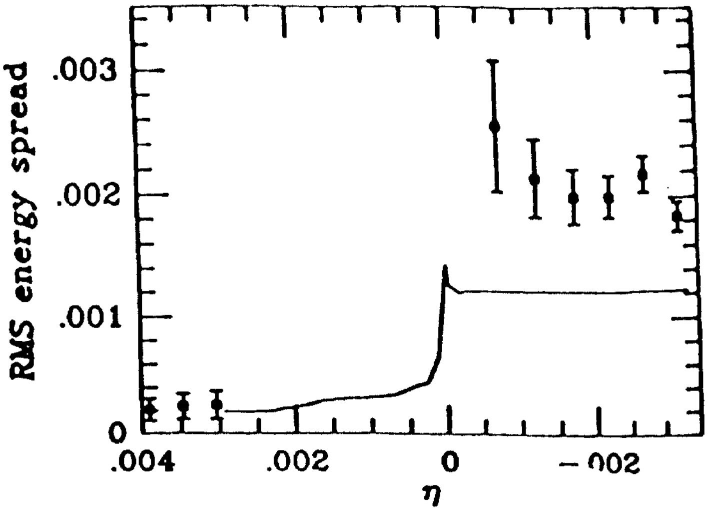

Figure 5: Measured and simulated beam rms energy spread as a function of η. The solid line represents the simulated result. The error bars is determined by the accuracy in measuring the frequency spread.

3 Simulation

Computer simulations of the Accumulator transition crossing process have also been performed with ESME [2] which does multiparticle tracking in longitudinal phase space. In the simulation, ARF1 is modeled to have a resonant frequency at 52.9 MHz, a quality factor of 200, and a shunt resistance of 60 kΩ. Since the beam-induced voltage in ARF1 produces a periodic beam structure with a fundamental frequency of about 53 MHz which is 85 times of the revolution frequency, simulation of the effect of ARF1 on the beam is restricted within 1/85 of the ring with periodic boundary conditions. The initial distribution of the beam is generated such that it is Gaussian in energy and randomly uniform in azimuth. To get the Fourier spectrum of the beam current, the azimuth is divided into 16 bins which will give 8 terms in the current spectrum. The total number of macro-particles used for the simulation is 10000, which results in about 625 particles in each bin and therefore about 4% statistical fluctuation.

Simulations have been done where the effects of space charge and non-linear dependence of path length on momentum are ignored. According to the simulation, in the crossing process there is no real bunching of the beam in the usual sense, *i.e.*, bunching when an external RF voltage is present. When $|\eta| \lesssim 1 \times 10^{-4}$, the periodic coherent structure is continually smeared due to the frequency spread of the beam. Dramatic change in the beam distribution in longitudinal phase space occurs when $|\eta|$ is smaller than 10^{-4}. The energy loss in the crossing process is approximately 9 MeV. In figure 5 the simulated rms energy spread in the crossing process is compared to that from the measurement. The error bars only represents the error in measuring the frequency spread. There is at least additional 40% of uncertainty coming from the η measurement. These results agree with the measurements within the error limit. Figure 6 shows the Fourier component of the beam at 53 MHz as function of time. The sharp peak appears when transition is crossed. The power rise time is obtained by a linear-least square fit in logarithmic scale, and the result gives a value of 36.4 msec. This agrees well with the measurement.

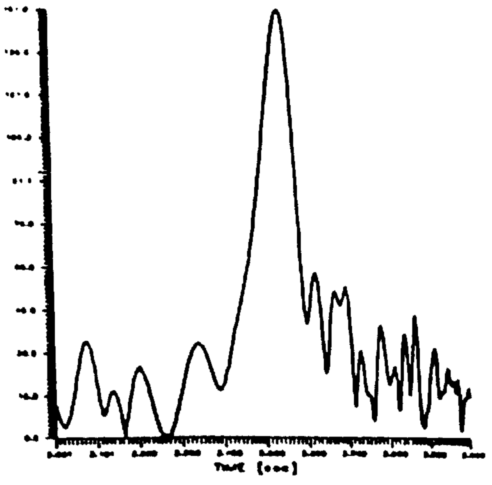

Figure 6: The Fourier component of the beam current at 53 MHz.

Simulation also shows that space charge and non-linear dependence of path length on momentum do not significantly affect beam behavior in the transition crossing process.

4 Conclusion

It has been discovered that ARF1 results in the major energy loss and energy spread blow up of a beam in the crossing process. The simulation results agree with the measurements. Similar technique will be used in the future to find other impedances that may cause problems at higher intensities.

References

[1] V. Bharadwaj, *et al.*, "Operation of the Fermilab Accumulator for Medium Energy Proton-Antiproton Physics", Proceedings of the 2nd EUROPEAN PARTICLE ACCELERATOR CONFERENCE, June 12-16, 1990, pp.617-619.

[2] S. Stahl and J. M. Maclachlan, "User's Guide to ESME v. 7.1", Fermilab internal note TM-1650, February 26, 1990.