CORRECTION OF INTENSITY-DEPENDENT BEAM LOSS IN THE NAL BOOSTER SYNCHROTRON

E. L. Hubbard, R. E. Peters and A. G. Ruggiero
National Accelerator Laboratory*
Batavia, Illinois

Summary

At beam currents above 1.5 x 10^{11} protons/pulse in the 8-GeV booster synchrotron, part of the beam is lost during a time interval of 2 to 4 msec just before transition. Particles are lost from several of the 84 rf beam bunches while the number of particles in the other bunches does not change. Electromagnetic coupling between the betatron motion and the magnet laminations which are not shielded from the beam by a vacuum chamber may induce the head-to-tail effect and cause the loss. This effect is sensitive to the chromaticity, $\xi = (\Delta\nu/\nu)/(\Delta p/p)$. Changing the chromaticity with dc sextupole magnets at three locations in the ring has eliminated the loss for beam currents as high as 4.5 x 10^{11} protons/pulse.

Experimental Observations

During the early operation of the 8-GeV booster synchrotron at NAL,[1] no correction of the magnetic field gradients was used. At low intensities, there was no appreciable beam loss after the first 2 milliseconds in the acceleration cycle. As higher intensities were achieved, the beam intensity was observed to drop just before transition on occasional pulses. A typical beam loss pattern is shown in the upper trace in Figure 1. The loss phenomenon had the following properties:

(i) The loss occurred during an interval of a few milliseconds just before transition and stopped at transition.

(ii) The onset of the loss occurred earlier for higher injected current.

(iii) There was a strong correlation of the amount of the loss with the intensity. The threshold value of the beam intensity was 1.5 x 10^{11} protons/pulse; below this value no beam was lost.

Coherent Vertical Oscillations

At the same time that the loss occurred, a vertical coherent betatron oscillation was observed with a ferrite core transformer type beam position monitor. A typical signal from the position monitor is shown in the lower trace of Figure 1. The oscillation starts spontaneously and grows in amplitude until transition energy is reached. Then the oscillation suddenly stops, and no beam is lost subsequently. The fundamental frequency detected is 142 kHz. The tune calculated from setting this frequency equal to $(n-\nu_z)f_{rev}$ with n = 7 agrees with other tune measurements. Frequency components corresponding to other values of n were also observed.

Missing Bunches

At transition, the beam in the booster is bunched at 52.2 MHz by the RF accelerating cavities. A beam current transformer with a 300-MHz bandwidth was used to observe the RF structure of the beam. To observe losses from the various bunches, a train of beam bunches was displayed on an oscilloscope at several different times in the acceleration cycle. A typical photograph of four pulse trains is shown in Figure 2. The lower trace was 2-1/4 milliseconds before transition. Each trace was taken one millisecond later than the one below it. The oscilloscope was triggered in such a way that pulses from the same beam bunch are lined up vertically. Beam is lost from some of the bunches but not from all of them. The loss is distributed among the bunches in an irregular way indicating that it is caused by a single bunch phenomena. However, a large loss from one bunch is usually accompanied by some loss from its neighbors suggesting some interaction between neighboring bunches.

Effect of Radial Position

The effect would come and go for reasons that were not clear until it was realized that there was a strong correlation between the instability of the beam and its radial position. Systematic beam loss observations were made as the radial position of the beam was moved with the offset program in the radial position feedback system. Programming the radial position 5 mm to the outside of the center of the aperture from injection to transition increased the loss. The loss decreased with the beam programmed 5 mm to the inside. Programming a short excursion to either the inside or outside increased the beam loss when the beam was outside elsewhere in the cycle. A similar excursion had no effect when the beam was toward the inside.

In conclusion, the losses were strongly dependent on the radial position. It was suspected that this dependence of the loss on the radial position was related to a change in tune with radius. Coherent betatron oscillations caused by effects of the type of the resistive wall instability can be reduced by increasing the sextupole or the octupole component in the magnetic fields. Coherent betatron motion can also couple to the synchrotron motion through the head-to-tail effect! Since there is no vacuum chamber inside the booster magnets, and the magnet laminations are exposed directly to the wake fields of the beam, vertical coupling of this kind should be strong in the booster. The strength of the head-to-tail effect depends on the chromaticity.

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Effect of Sextupoles

To cure this effect we installed 12 air core sextupoles in groups of four at three positions located symmetrically around the booster ring at locations in the lattice where the vertical betatron amplitude function B_y is a maximum. At the maximum excitation current of ±40A, these sextupoles introduce a chromaticity

$$\xi_x = \pm 0.2 \qquad \text{and} \qquad \xi_y = \pm 0.6.$$

With the current in the sextupoles above 25A, no beam loss of the type described here has been observed for beam intensities up to 5×10^{11} protons/pulse, the highest intensity achieved, so far in the booster. At beam intensities above 1.5×10^{11}, loss is observed when the sextupole current is below 15A. The loss increases as the current in the sextupoles decreases, and when the polarity is reversed, the threshold intensity also decreases until loss is observed at 1.0×10^{11} protons/pulse with -40A in the sextupoles. But in this case, a different instability process seemed to occur much earlier in the cycle.

The chromaticity at various times in the booster cycle is shown in Fig. 3 for the uncorrected machine and for the value of sextupole correction in use. The twelve installed sextupoles, at the current of +25A, have the effect of cancelling completely the residual chromaticity of the machine at the transition on the vertical plane, but not on the horizontal plane.

Figure 4 shows the dependence of the vertical tune at transition on the radial position of the beam with the sextupoles on and off. With the sextupoles off, it is seen that the chromaticity is reduced by moving the beam inward. This agrees with the earlier observation that the beam loss was less severe with the beam to the inside. Also, there is a significant increase in the octupole component of the fields toward the inside which should make both the head-to-tail effect and transverse coherent instability effect less severe.

The Theory

We exclude the possibility that the beam decay observed at transition is due to a transverse coherent instability enhanced by the coupling of the beam to the lamination of the magnet. This mode of instability should happen much earlier in the cycle (low γ) and is not affected by the crossing of the transition energy. We believe, instead, that it is caused by the head-to-tail effect. The head-to-tail effect instability exhibits a growth rate which is just proportional to $\rho_0\xi/\alpha$, where ρ_0 is the coupling factor between the beam and the surrounding media, ξ the chromaticity, and α the momentum compaction which is zero at transition and flips sign crossing the transition. Well below and above the transition energy, α is relatively large and the growth time is also relatively small and the effect not noticeable. But at transition $\rho_0\xi/\alpha$ becomes very large and the head-to-tail effect can cause the beam to decay. The sign of the quantity $\rho_0\xi/\alpha$ is important to decide if the instability occurs before or after the transition.

The head-to-tail effect has been theoretically discovered by C. Pellegrini[2] and M. Sands.[3] The theory was worked out only for the case of storage rings where the energy is constant. Thus, we had to modify the results of the theory to include also the case with time dependence, which is important when, for instance, the beam is crossing the transition energy.[4]

The instantaneous growth rate of the n-th mode (n = 0 corresponds to center-of-mass oscillations and n > 0 to throbbing oscillations with center-of-mass at rest) is, at the time t,

$$\mu_n(t) = \frac{N\rho_0}{8\pi^2\omega_0} F_n(x) \qquad x = \frac{2\omega_0 A}{\frac{1}{\gamma_T^2} - \frac{1}{\gamma^2}}\,\xi$$

where N is the number of particles per bunch, ω_0 the angular frequency of the betatron oscillations, A the half length of the bunch in unit of time, and the other quantities have the usual definition. We assumed that ρ_0 is given by the coupling to the lamination of the magnet. To calculate $F_n(x)$, we simulated each crack of the lamination by a cavity and calculated the wake field induced by the motion of a charged particle. Because of the very low figure of merit of the lamination, the wake field decays rather fast, say, in a length which, at most, extends over two or three bunches. For our purposes, we approximated the wake field with a rectangular function, which is zero in front of the particle and just ρ_0 behind. Besides, we disregarded any bunch-bunch effect. With these assumptions and approximations, considering only the mode n = 0 (experimentally observed), we have

$$F_0(x) \sim 8x \left(\frac{\sin\frac{x}{2}}{\frac{x}{2}}\right)^2$$

ρ_0 is positive for short bunch, and negative for A ≳ 0.5 nsec. In the booster case A ~ 1 nsec and $\rho_0 \sim -20\ \text{sec}^{-2}$. Thus, the vertical motion is unstable below transition if the chromaticity ξ is positive. This is in agreement with the experimental observations.* We found also agreement between the measured chromaticity ($\xi = 0.6$) and the calculated one for the threshold value of $N = 1.5 \times 10^9$ protons/bunch. These values yield a maximum calculated blow-up of the beam size of a factor of 2, which is actually the amount of the vertical aperture available in the booster.

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*Observe that in Ref. (4) the approximation of very short bunch was used, which is not the case in the booster and, hence, would yield the wrong sign of the chromaticity.

Acknowledgements

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References

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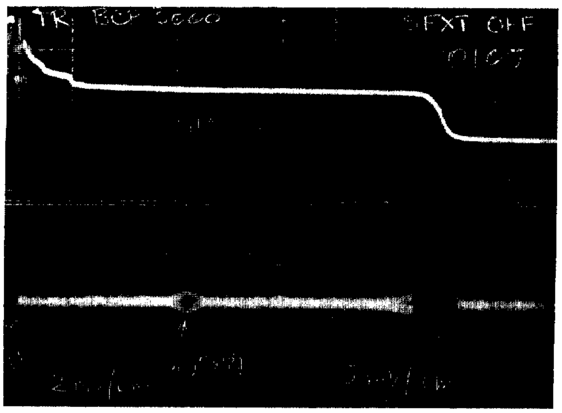

Figure 1

Upper trace. Beam intensity vs. time at 2 msec/div. Transition is at 17 msec. Beam loss just before transition is characteristic of the "missing bunch" effect.

Lower trace. Vertical coherent oscillation amplitude on same time scale as upper trace.

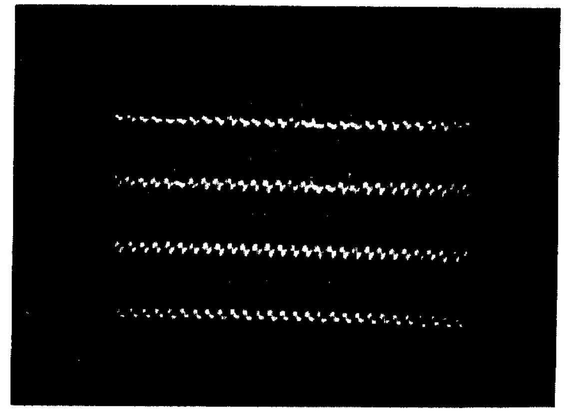

Figure 2

RF bunch structure of beam. Time in the booster acceleration cycle is as follows: lower trace 2-1/2 msec before transition, second trace 1-1/2 msec before transition, third trace 1/2 msec before transition, upper trace 1/2 msec after transition. Pulses from the same bunch are lined up vertically.

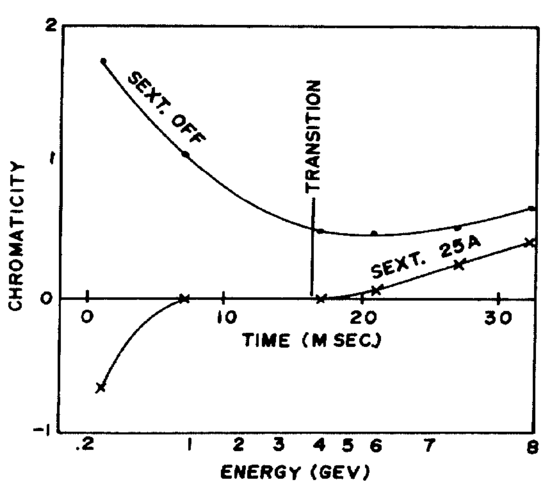

Figure 3

Variation of chromaticity $\xi = \Delta\nu/\nu / \Delta p/p$ with time in booster acceleration cycle with sextupoles on and off.

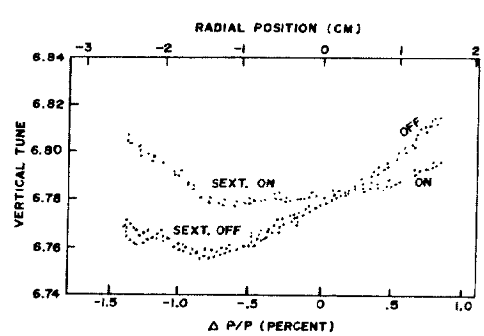

Figure 4

Comparison of radial variation of vertical tune for sextupoles set for best correction of beam loss (25A) and for sextupoles off.