TRANSVERSE COLLECTIVE INSTABILITY
IN THE NAL 500-GeV ACCELERATOR

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Abstract

Vertical collective beam instability occurs during 8-GeV injection into the NAL main accelerator with an intensity threshold of approximately 10^{12} protons and a tune spread of 0.01. Horizontal collective instability has been observed at 5×10^{12} protons with a 0.01 tune spread. Sextupole, octupole, and active feedback damping have been used to control these instabilities. A brief description of these methods and the results obtained is given.

Discussion

Above an intensity of 10^{12}, proton beams in the NAL 500-GeV main accelerator suffer from destructive collective transverse instabilities. As the azimuthal intensity distribution is a significant factor in these instabilities, we begin with a description of the manner in which the accelerator is loaded with beam from the booster synchrotron.

Injection is accomplished by a sequence of twelve booster cycles, during which time the main accelerator is operated as a storage ring at 8.89 GeV/c. RF voltage is held at a fixed frequency (52.813 MHz) at a level sufficient to preserve the 2-ns longitudinal bunch structure of the booster beam. In each cycle 82 of the available 1113 RF buckets are filled. (The 82 buckets filled in a single cycle are known as a batch.) After twelve booster cycles have been completed, 984 of the RF buckets are filled. There is one gap of unfilled buckets between the first and the last booster batch, and a gap of nine unfilled buckets between all other batches.

Both radial and vertical beam breakup have been observed. The vertical instability has a lower threshold, and can occur at any time in the acceleration cycle. The radial instability has not been observed above 50 GeV. We shall focus the discussion of this paper on the vertical instability, as it has the lowest threshold and the most rapid growth rate.

The vertical instability is observed during the loading of the accelerator. After a number of booster batches have been injected, part of the circulating beam breaks into coherent vertical oscillations and is subsequently lost. The growth time for the disturbance is a few tens of milliseconds. A frequency analysis of the signal from a pickup electrode which responds to coherent vertical motion shows a strong peaking at the frequencies of the coherent normal modes:

$$f_c = f_o \, (n - \nu_y)$$

with $f_o = 47.5$ KHz (revolution frequency)

and $\nu_y = 19.3$ (vertical tune).

Only those modes with $n > \nu_y$ are observed. Although there is considerable fluctuation from event to event and mode numbers as high as 40 are seen, the modes with n close to 20 are usually the strongest. The wide range of mode numbers is a consequence of the fact that the disturbance is usually confined to a portion of the machine azimuth. The azimuthal distribution of coherent betatron oscillation amplitude during the development of a breakup which occurred after ten booster batches had been injected is shown below in Figure 1.

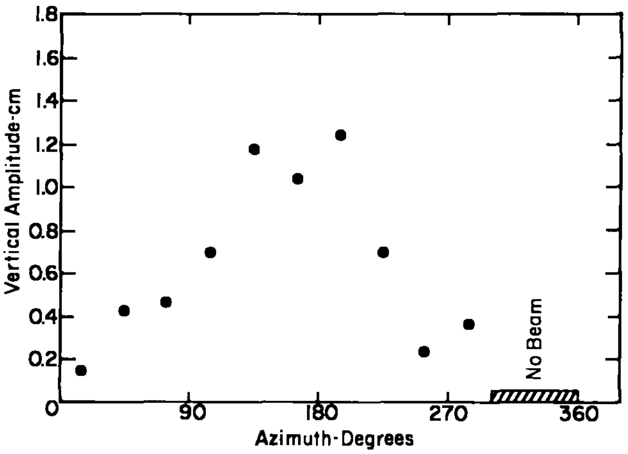

Figure 1. The azimuthal distribution of coherent vertical betatron oscillation amplitude during a well developed beam breakup. Ten booster batches had been injected into the main accelerator with stabilizing octupoles turned on. After injection of the tenth batch, the octupoles were turned off. The azimuthal distribution of the resulting disturbance indicates that a number of low-order normal modes are excited.

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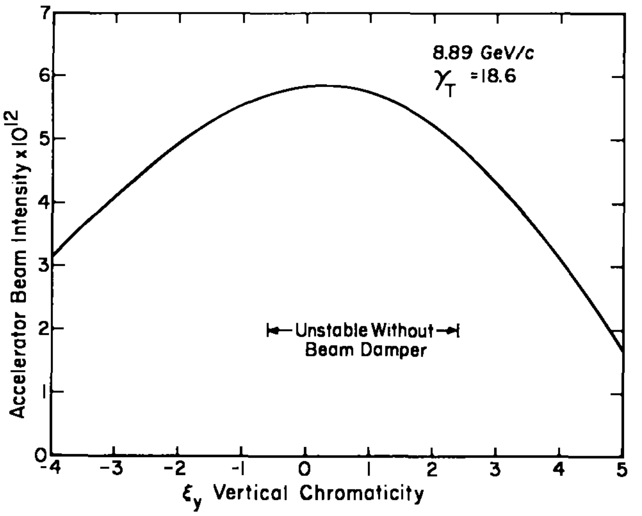

Figure 2. In this experiment the accelerated beam intensity was measured for various values of ξ_y loss with active feedback damping in use. The loss of intensity for non-zero values of ξ_y is due to extraction on non-linear resonances. Without active damping, the region shown was unstable against vertical coherent oscillations.

One of the mechanisms which contributes to the instability appears to be a dipole mode head-to-tail interaction within the RF bunch due to a short range wake field. Such an instability has been described by Pellegrini.[1] As the data in Figure 2 show, the instability occurs at the lowest threshold, when

$$\xi_y = \frac{P}{\nu_y} \frac{\partial \nu_y}{\partial P}$$

is positive ($\gamma < \gamma_t$). A similar condition applies to the radial instability. Furthermore, if the beam is allowed to debunch with RF turned off, it is stable at all intensities. We have explored the regions $19.2 < \nu_y < 19.4$ and $20.2 < \nu_y < 20.4$, and have found that the threshold is essentially independent of tune except in the vicinity of strong non-linear resonances. From this we conclude that the wake field comes either from an object resonant at the RF frequency or from a broadband source such as the vacuum chamber wall. The latter is more likely.

In addition to the short range dipole instability, there is a longer range coupling between bunches. An oscillating bunch will drive bunches following in its wake. In this manner a disturbance originating near the leading edge of a group of filled RF buckets is propagated with amplification toward the trailing edge. An example of such a breakup is shown in Figure 3. We have determined the range of the coupling between bunches by injecting two batches of filled buckets separated by a gap of empty buckets. At an intensity of 4×10^9/bunch, a gap of 20 unfilled buckets is sufficient to significantly reduce the coupling between batches. We have investigated the coupling across gaps as large as 2000 m. At that distance there is still evidence for a weak coupling. This we interpret as a signature of the resistive wall effect. We conclude that both head-to-tail and resistive wall effect are present, and feed one upon the other.

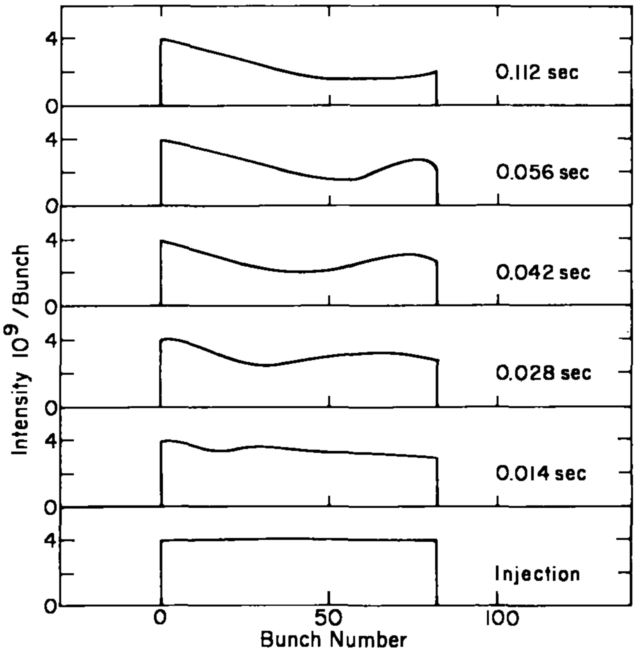

Figure 3. The intensity distribution within a batch of 82 RF buckets at various times during a vertical breakup of the beam. A disturbance originating near the leading edge of the batch began to cause beam loss by 0.014 seconds. It propagated toward the trailing edge of the batch, and was finally stabilized after quite a loss in intensity.

We have used sextupole, octupole, and active feedback damping to suppress this instability. Initially we used sextupole or octupole damping to destroy the coherence of the beam by introducing a tune spread, but it was found that the tune spread required had a detrimental effect because it became comparable with the spacing between non-linear resonances which extract the beam. This is illustrated in Figure 2, for the case of sextupole damping. In that experiment we varied the strength of the zeroth-harmonic correction sextupoles in a manner in which ξ_x was held constant while ξ_y was varied. During the experiment the average vertical tune was $\nu_y = 19.30$. The momentum spread of the coasting beam was approximately $\delta P/P = 10^{-3}$ full width at half maximum. As the tune spread was increased to the extent that constituents in the beam periodically crossed sextupole and octupole resonances, they were slowly extracted. The region of instability thus occurs at those values of ξ_y which are most desirable from the viewpoint of single particle stability.

In order to be able to store stable beams having very small tune spreads, we have constructed an active damping system. The layout of this system is shown in Figure 4. At

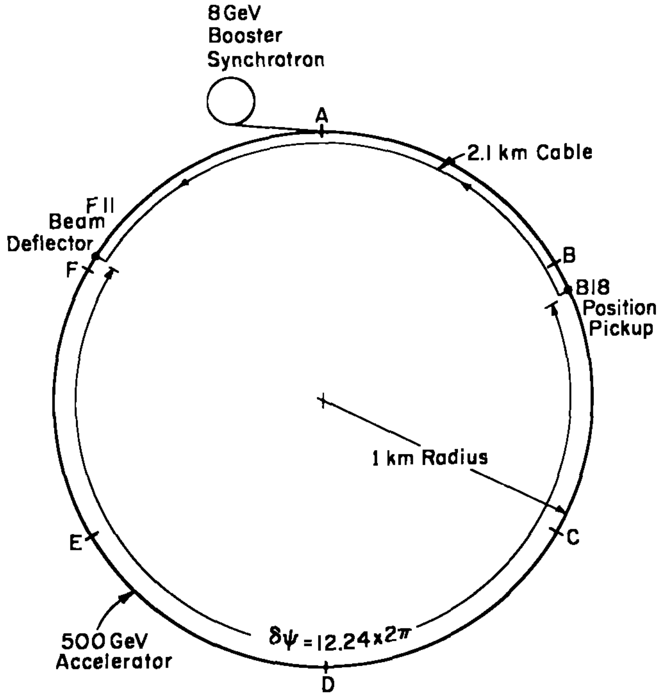

Figure 4. Diagram of the active damping system. The proton beam circulates in a clockwise direction.

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station B18, 53-MHz RF signals from a pair of pickup plates are converted into a 3-MHz bandwidth, intensity independent, vertical position signal by electronic circuitry developed by E. Higgins. This signal is sent in a direction opposite to the beam through 2.1 km of coaxial cable. The beam deflector, which was developed by Q. Kerns, is a pair of 1.2-m long plates with a 5-cm separation. It is capable of producing a peak electric field of ±400 V/cm at frequencies up to 2.5 MHz. The betatron phase shift between the pickup and the damper is $12.24 \times 2\pi$ at a tune of 19.287.

We operate the damper with a gain of 8×10^{-4} mrad/mm. For this gain, the absolute value of the eigenvalues of the once-around-the-ring matrix is $|\lambda| = 0.92$. The measured damping of an induced betatron oscillation agrees with the calculated damping rate.

At present, we employ both radial and vertical active feedback damping systems in the NAL main accelerator. No low mode number instabilities are observed. As a desirable by-product, the dampers remove the betatron oscillations caused by injection errors. As the intensity of the injected beam increases, we intend to extend the bandwidth of the damping system.

References

1. C. Pellegrini, Nuovo Cimento 64A, 447 (1969).

2. E.D. Courant and A.M. Sessler, Rev. Sci. Inst. 37, 1579 (1966).