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REVIEW OF
THE FERMILAB MAIN RING ACCELERATOR STUDY PROGRAM AS DIRECTED TO THE $\overline{\text{P}}$P PROGRAM

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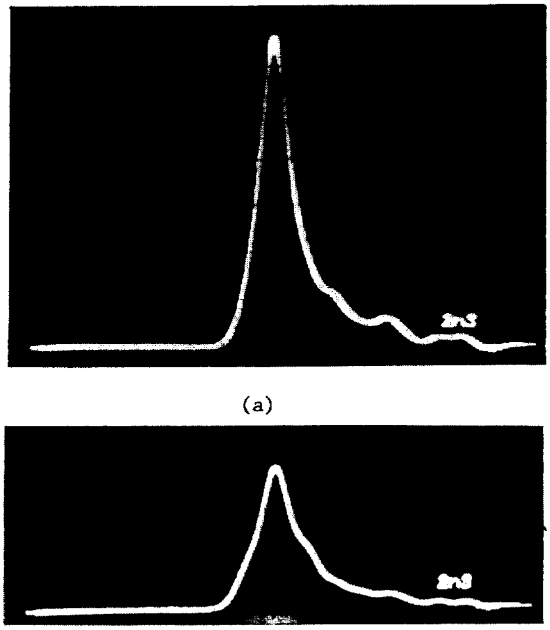
Introduction

Studies of the properties of the Fermilab Main Ring as a storage ring were begun in early 1979 when it appeared that the existing ring and the proposed Tevatron ring could be collided for pp physics. Those studies were directed at measurements of beam lifetime, vacuum effects, longitudinal and transverse beam growth and instabilities at 100, 150, and 200 GeV.1-5) A notable feature of those studies was the observation of irregular increases in bunch length from 2 to greater than 6 nsec during the first few minutes of each store, shown in Figure 1. A less dramatic growth in transverse beam size was observed and found to be consistent with gas scattering at the existing pressure.

More recently the colliding beam goals at Fermilab have been redirected toward 2 TeV c.m. $\bar{p}p$ physics to be done in the Tevatron.[6] The booster-main ring complex will be the proton injector and the source of protons for anti-proton production. Consequently, the emphasis of recent studies in the main ring has been directed at those problems which arise from the beam manipulation necessary for the $\bar{p}p$ scenario. These studies are divided into three categories: 1) true storage studies directed toward revealing problems and techniques likely to apply to storage in the Tevatron, 2) beam manipulations necessary for the production of anti-protons, and 3) beam manipulations necessary for producing single proton bunches containing 10^{11} protons each. Two early efforts at such manipulation are reported elsewhere.7,8)



(a)

(b)

Figure 1. a) Beam bunch at start of store. FWHM about 2 nsec. b) Same bunch after 30 min.

Storage Studies

Beam Lifetime, Tune, Chromaticity

Measurements of the lifetime of stored bunched beam over long times (≃ 30 min.) have been made, mostly at 100 GeV, where decay time constants $\lambda = dI/Idt = 0.89h^{-1}$ have been observed at a betatron tune point $(\nu_x,\nu_y) = (19.441, 19.435)$.9) A few measurements at 150 GeV have shown $\lambda = 0.48h^{-1}$ at the same tune. These measurements were done with special attention given to an improvement of the vertical chromaticity correction so that both ν_x and ν_y were flat to $\Delta\nu \simeq 0.01$ over most of the aperture. The result was a clear improvement over $\lambda \simeq 1.5h^{-1}$ reported in 1979.10) If the operating point is moved over any of the nearby fifth order resonances the lifetime is reduced by more than an order of magnitude. Although the effects of higher order resonances have not been explicitly demonstrated, the fact that there is difficulty in duplicating best results from one study period to the next may reflect sensitivity of the lifetime to seventh and ninth order lines which closely bracket the nominal tune.

Bunch Lengthening

The lengthening described here and similar effects observed at CERN SPS11) might occur in the Tevatron and result in a degradation of achievable luminosity and detector resolution. Several attempts at modeling and analysis of resistive or reactive wall single bunch or coupled bunch instabilities have been directed at these phenomena.12,13,14) Spectrum analysis of beam signals from a nearly full ring (1087 of 1113 buckets occupied) stored at 100 GeV have failed to show convincing evidence for coupled bunch instability at intensity levels of 2x10^{10} protons per bunch.

Single Bunch Storage

The individual bunch vertical damping system can be gated so that selected bunches will oscillate vertically with increasing amplitude until their intensity is reduced by a factor of about one hundred just following injection. In this way a few bunches or a single bunch can be selected for acceleration and storage. The remaining bunches, with reduced amplitude, are nevertheless still large enough so that the low-level rf feedback system operates normally.

When "single bunches" were repeatedly stored at 100 GeV, the bunches were observed to lengthen in just the same way as did many bunches, so the bunch motion responsible for lengthening was clearly not the result of coupled bunch instability. Further studies of the effect were made by making a dynamic measurement of the phase of the single bunch centroid with respect to the accelerating cavity rf. This signal, representing the

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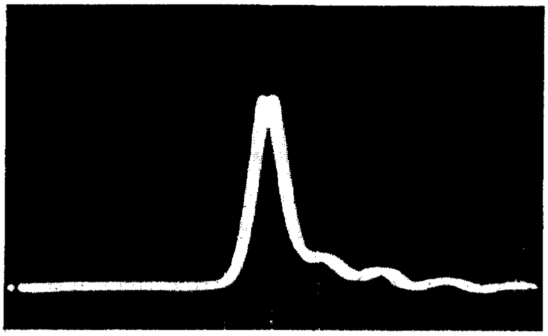
coherent dipole motion of the bunch within the bucket, was integrated, amplified, and fed to a voltage controlled fast phase shifter in the rf drive system so that coherent motion would be damped. By this technique the bunch lengthening was completely eliminated for the duration of a normal store (about 30 minutes). This result is shown in Figure 2. The observed decrease in the bunch amplitude reflects the normal transverse attrition rate noted above. These results are completely consistent with those reported by Boussard et al..[15)] The implication is that, at this intensity, the bunch lengthening is the result of dipole motion excited by phase "noise" in the rf bucket. The "noise", in this case, is apparently the result of the average effect of all of the bunches in the machine reflecting differing components of magnet ripple, and different initial injection conditions.

The time constant of the relatively high Q accelerating cavities is slightly more than the main ring rotation period (20.9 μsec) so, while it is possible to damp the phase motion of a single bunch, several bunches, requiring different correction signals to damp them, present a much more difficult problem. It appears that development of a special damping cavity system may be indicated.

Longitudinal Emittance Measurements

Various of the $\bar{p}$ production and $\bar{p}p$ physics scenarios require relocation or coalescence of beam in the main ring. Because the effective longitudinal emittance can at best be conserved and will almost certainly be increased by such operations, the feasibility of various of the scenarios is strongly affected by the initial longitudinal emittance. There is evidence that the same "rf noise" which causes bunch lengthening during a store may cause irregular longitudinal emittance growth during acceleration. Therefore, a program of measurement of the emittances of individual bunches at 8 GeV and at 100 GeV was started. The technique is to inject several booster batches (of 84 bunches each) into the ring and immediately attenuate (or "remove") all bunches save one, as described above. For the 8 GeV measurements, the bunch is allowed to remain in a stationary bucket for 1 second at the end of which the rf is quickly removed. At the rf turn-off time the bunch width is recorded on one oscilloscope while the debunching rate is recorded by a mountain range display on another oscilloscope. The debunching rate dT/T can be measured directly from the mountain range display and related to the momentum spread through $\eta = \gamma^{-2} - \gamma_t^{-2}$. The two measurements yield the phase extent of the charge in the bucket and the momentum spread so that the bucket area occupied by the charge (longitudinal emittance) can be adduced. The single bunch picture also yields the intensity of the bunch. It is possible, of course, to infer the emittance from the bunch length alone if one assumes that the bunch is matched to the bucket and that the bucket size is known from rf measurements. This measurement assumes no knowledge of the bucket, so that unplanned additions to the rf potential (i.e. reactive wall effects) will not adversely affect the result. Here the "single bunch" operation is crucial. It is impossible to remove the rf voltage quickly and cleanly if there are many bunches in the machine because of beam excitation of the high shunt impedance of cavities.

The data at 100 GeV are accumulated in the same manner except that the bunch is accelerated to a 100 GeV flat field region during which the rf is removed and the debunching rate, intensity, and bunch width are recorded. Figure 3 shows a typical pair of data pictures. We estimate that the numbers extracted from these data represent 95 percent of the beam.



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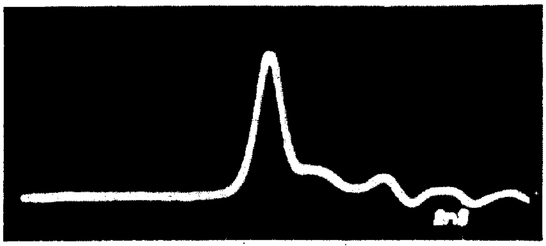
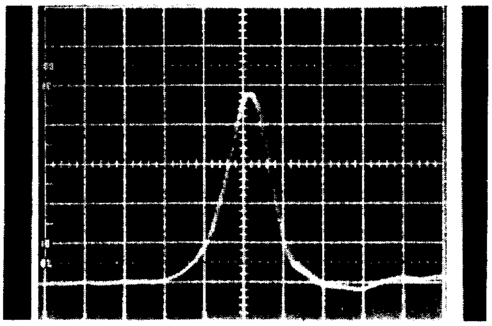


(b)

Figure 2. a) Bunch at start of store with dipole motion within the bucket. b) Same bunch after 20 minutes. Amplitude decreased but length unchanged.



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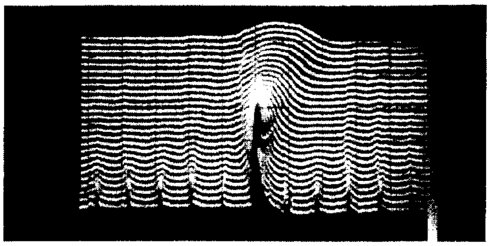
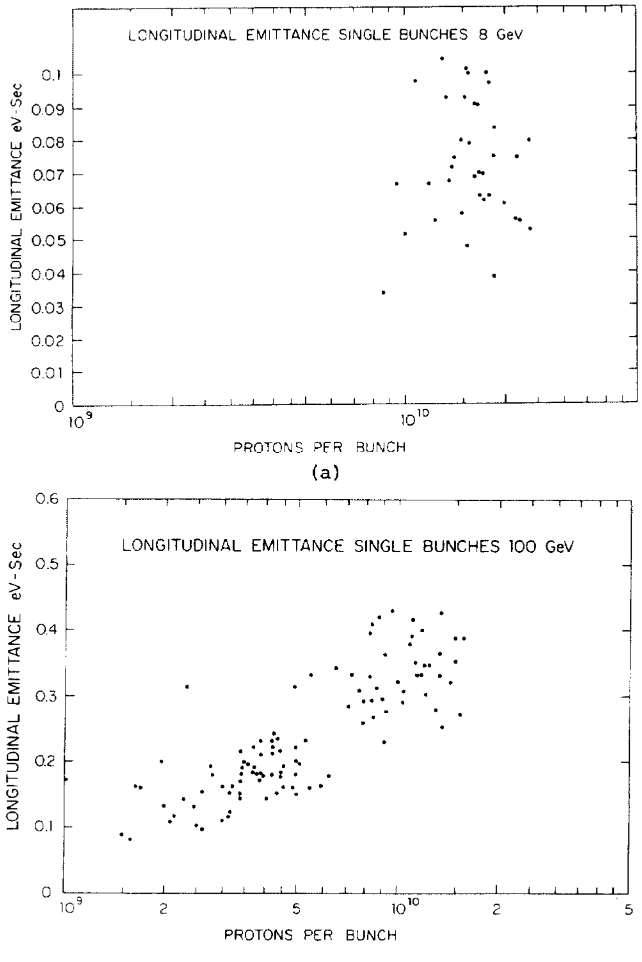


(b)

Figure 3. a) Single bunch at start of debunching. Sweep rate 1 nsec/div.. Intensity derived from bunch area. b) Debunching mountain range display. Sweep rate 20 nsec/div and traces are separated by 1 msec.



(a)

(b)

Figure 4. a) Longitudinal Emittance Data at 8 GeV. b) 100 GeV

In Figure 4a and b the emittance data are shown as a function of bunch intensity for 8 GeV and 100 GeV. All data points are shown to illustrate the wide spread of emittances observed. The 100 GeV results show a clear intensity dependance and at the highest intensities measured (about 2×10^{10} protons per bunch) the data range from 0.23 eV-sec to about 0.43 eV-sec indicating a growth during acceleration of about a factor of four. However, a significant number of bunches are accelerated with only a factor of two growth. These data are consistent, on the average, with those reported by H.W. Miller et al., obtained for the full beam by reducing the bucket area until beam loss is observed.[16) While uniformly large emittances may be acceptable or even desirable for fixed target accelerator operation, the $\bar{p}p$ beam gymnastics suffer from large momentum spreads, so the problem now is to determine what agents are responsible for the growth of some bunches and the relatively high quality preservation of others. The most likely source of the variation appears to be simply the wide range of initial conditions that result from injection of up to thirteen successive proton batches from the booster.

Conclusions and Acknowledgements

We conclude from these and other experiments to trivial to report that the fixed target parameters of the Fermilab main ring can be perturbed in such a way as to accomplish the goals of the $\bar{p}p$ physics program. Further effort is necessary on reduction of the momentum blow-up and improvement of the injection and acceleration stability. Such efforts, we believe, work also to the advantage of the fixed target program.

We wish to acknowledge the assistance, compliance, and forebearance of members of the main ring and operations groups during these studies, which in some instances, carried the architecture of the rf systems to a point where it was clear only to us that it could be reconfigured for normal operation in a reasonable time.

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