BEAM STORAGE IN THE MAIN RING

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Introduction

Over the years, there have been many studies of stored beam in the Main Ring. The first such study was late in 1971, when the lifetime of 7-GeV beam was measured as a function of vacuum pressure to try to understand the relatively rapid loss of injected beam.

The motivation for these studies changed in later years. In 1976, studies were begun with an eye toward improving beam lifetime for proton-proton or proton-antiproton colliding beams in the Main Ring. A large amount of work was done at that time and was an important part of the 1977 Summer Study on colliding beams.[1,2] More recently, the interest in colliding-beam possibilities has centered on the Tevatron and the motivation of storage studies in the Main Ring has been more toward the understanding of the physical phenomena and as an example to be translated to Tevatron parameters.

This paper will emphasize the recent studies,[3] with some reference to the earlier work. For the application to colliding beams, both beam lifetime and beam size are important, for they both affect luminosity, and measurement of both will be discussed.

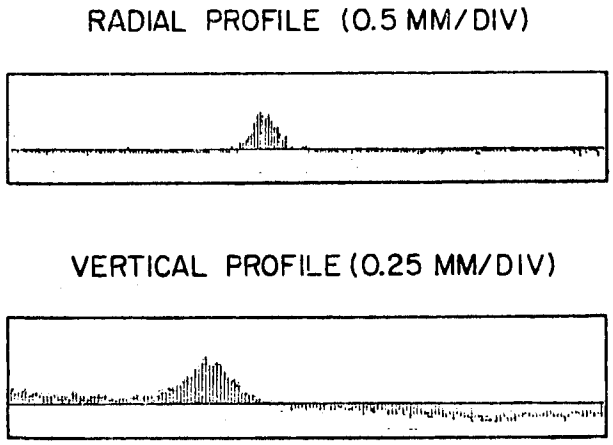
Experimental Methods

Beam is accelerated to the storage energy in the usual way. The ramp is then flat-topped and beam allowed to coast with rf voltage on to keep the particles bunched in buckets. The water-cooling system of the magnets is adequate for dc operation of the Main Ring up to an energy of almost 200 GeV. The quadrupole excitation can be set to fix the **tune** (the numbers of horizontal (ν_x) and vertical (ν_y) betatron oscillations per revolution) to high precision. The "reference" conditions for storage are $\nu_x = 19.441$ and $\nu_y = 19.435$. These conditions are nominal, because coupling between radial and vertical oscillations changes the real tune values slightly and ν_x and ν_y cannot be made exactly equal. The reference tune is chosen to avoid the fifth-order resonances at $\nu_x = 19.4$ and $\nu_y = 19.4$, the seventh-order resonances at 19.429, and the ninth-order resonance at 19.444.

The rf can be used to set the momentum at the center of the aperture with high precision and the beam can be moved in radius by changing this momentum with rf. An important feature is that the tune depends on momentum; the **chromaticities** ξ_x and ξ_y are the rates of change of horizontal and vertical tunes with momentum. The chromaticity can be controlled by use of the

correction sextupoles, which are strong enough to reduce the chromaticity to zero up to an energy of approximately 150 GeV. The largest new element in the recent studies is the careful control and investigation of chromaticity and its effects on beam storage.

Two kinds of measurements of the beam are made. The total circulating current is measured with a magnetic toroid surrounding the beam. This measurement is independent of beam size and shape. The transverse size and shape parameters are measured by the Ion Beam Scanner (IBS), which collects secondary electrons produced in collisions of beam particles with the residual gas. The IBS data are processed digitally by the control system to produce readouts like the one in the figure below. The data are



Beam profile data from the IBS.

logged by the control system and are available for off-line study and analysis. The measurements discussed here deal with intensity and transverse growth, but some qualitative observations have been made of longitudinal growth using a wide-band beam detector.

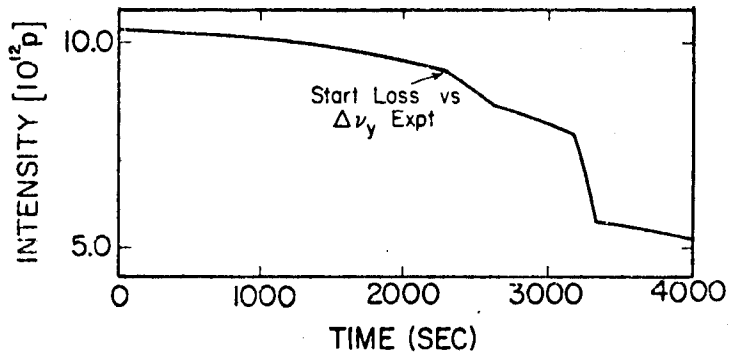
The average vacuum pressure is measured from the current readings of the small ion pumps attached to the dipoles. These pumps have been refurbished and augmented in the last few years and their readouts have been modified to give response at lower pressure. The pressure can also be derived from the lifetime and beam-size measurements, as discussed below.

Experimental Results

The lifetime of stored beam can be varied over several orders of magnitude by detailed tuning. If the tune is close to

a nonlinear resonance, other effects discussed below will drive the beam through the resonance and increase beam size.

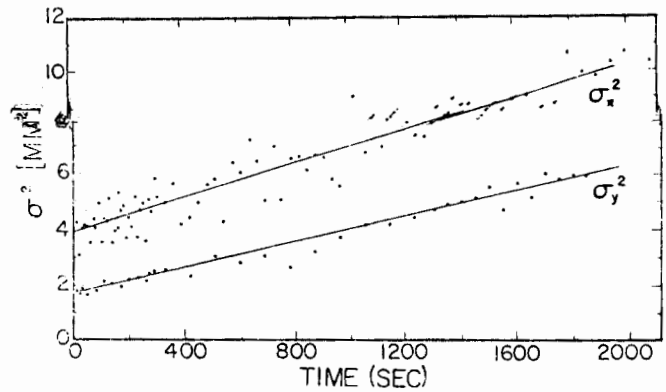
The earlier studies had occasions of rapid early loss. The present studies have not as a rule found such rapid early losses. Instead, the loss patterns appear to have two parts. First, there is a slow early loss in which the intensity decreases linearly with time. By approximately 500 to 1000 seconds, the loss has settled into a pattern of exponential decay. These two regimes are seen roughly in the plot below, in which other experiments are also done after the first 2000 seconds.



Beam intensity vs time 100 GeV.

The early linear beam loss is interpreted as caused by nuclear scattering by the residual gas. A single nuclear scattering can change the orbit of a proton enough to make it leave the vacuum chamber. But a single Coulomb scattering by the electric charge of the residual gas nuclei will not make a large enough change in the proton orbit to make it leave. Instead, multiple Coulomb scatterings make the beam grow gradually in size. There is some amplitude beyond which the motion is unstable and particles grow to this amplitude, then leave the chamber. This multiple Coulomb scattering is responsible for the long-time exponential beam loss. This interpretation is reinforced by rough agreement of the pressure calculated from the multiple-scattering lifetime with the measured pressure. The data indicate that the composition of the residual gas is largely lighter molecules, which is in agreement with compositions measured in low-pressure regions. This composition is what one expects from outgassing of an unbaked stainless-steel chamber. The average pressure around the ring is approximately 6×10^{-8} Torr.

The multiple Coulomb scattering interpretation of transverse beam growth predicts a linear growth with time of the mean-square beam size σ^2 and this growth is observed, as can be seen in the figure on the following page, showing IBS data. The pressure can



Beam width σ^2 vs time at 100 GeV.

be calculated from the measured growth rate of beam size. The pressures calculated from beam-size growth are larger than those calculated from beam survival data. This discrepancy is not fully understood, but the evidence suggests that the overestimate may be an instrumentation effect of the IBS.

Earlier studies had given larger scattering rates. The studies discussed here give smaller diffusion rates and improvements in lifetime longer than could be expected from the improvement in pressure. It is believed that the larger diffusion rate in the earlier studies came from multiple crossing of nonlinear resonances. The tune can shift from real changes in momentum arising from longitudinal synchrotron oscillations or from apparent changes in momentum arising from magnet current ripple. In the recent studies, these tune changes can be made much smaller because the chromaticity can be corrected. We have investigated the effect of chromaticity correction in some detail. Our data show that we can double the lifetime of the beam by proper chromaticity correction. This lends credence to the interpretation of nonlinear resonance crossing as the cause of increased diffusion.

Conclusions and Future Studies

The results of chromaticity correction and the qualitative agreement of the scattering picture make it possible to take a reasonably optimistic view of possible colliding-beam lifetimes in the Tevatron. Lifetimes of more than two hours have been achieved in the Main Ring. At the same time, the quantitative agreement certainly needs more study and some new instrumentation is being prepared for this work.

There are also other phenomena. We have observed beam-bunch lengthening during our transverse studies and this effect is connected with the differences observed in horizontal and vertical

growth rates. RF noise is believed to be an important factor in this phenomenon. Bunch lengthening and its effects on luminosity are being studied.

References

1. C. M. Ankenbrandt et al., Beam Storage in the Main Ring at High Energies, IEEE Trans. Nucl. Sci. **NS-24**, June, 1977, p. 1872.
2. Colliding Beams at Fermilab, 1977 Summer Study, Fermi National Accelerator Laboratory, p. 97-243.
3. J. A. MacLachlan, The Lifetime of Bunched Beam Stored in the Main Ring at 100 and 150 GeV, Fermilab Report FN-324, April 14, 1980.