Fermi National Accelerator Laboratory

FN-324
0400.000

THE LIFETIME OF BUNCHED BEAM STORED IN THE MAIN RING AT 100- AND 150-GEV

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April 14, 1980

Summary

Recent measurements of the beam current lifetime and emittance growth are compared with earlier measurements. The comparison treats residual gas, betatron tunes, momentum offset of the closed orbit, chromaticity, beam intensity, and power supply ripple explicitly; whatever other parameters are significant are controlled implicitly as far as possible by defining a nominal standard storage condition as a reference. The data are interpreted by comparison to a conventional model of diffusion driven by multiple coulomb scattering. This model predicts the general features of the data; processes other than gas scattering are treated by looking at the detailed differences.

Review of Earlier Observations

The first studies of beam survival in the main ring motivated explicitly by interest in colliding beams date from June, 1976.[1] The principal conclusion from the measurements made up to December, 1976 were reported at the 1977 National Particle Accelerator Conference.[2] That paper gives results for stores at several energies between 75 and 200 GeV. The effects of varying the pressure in the vacuum chamber by a factor of two were observed at 135 GeV. A wide variety of early loss patterns were observed, but by ~ 500 seconds all survival curves showed an exponential decrease.[3] The dependence of the exponential time constant on pressure was

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roughly linear as expected from gas scattering, but the scaling with momentum was somewhat slower than $1/p^2$. The current vs. time curves given in the conference paper show that one or more parameters were not adequately controlled in these first attempts because the exponential part of the loss curve begins much earlier for the higher energy stores. In particular, no attempt was made to optimize the tunes. The exponential time constants were about 850 s at 100 GeV and 3000 s at 200 GeV when the ion pump currents showed an average pressure ~ 7×10^{-8} T.[4] The beam bunches were observed to oscillate with amplitudes ~ ±1 ns and eventually broaden to ~ 6 ns width.

The studies carried out between March and August, 1977 are the subject of several articles in the report of the 1977 Fermilab Summer Study.[5] This next generation of studies was more extensive and included the variation of additional parameters. Also, the data collection was made more inclusive by the development of a logging program for the control system. The status of the main ring for colliding beams in late 1977 is summarized in an article by Tollestrup.[6] The investigations included searches for optimum tunes, residual gas pressure variation over a three-to-one range, and comparison of 100 and 200 GeV performance. The growth in the bunch length receives a semi-quantative treatment. In particular, the concept of a threshold width of ~ 3.5 ns is introduced for the instability leading to the broadening. Bunches initially shorter than this length were thought to blowup because of resistive wall effect such that the smaller the initial widths, the greater the final equilibrium width. Other general conclusions from this period are that the diffusion model works well but with a diffusion constant somewhat larger than that calculated from gas scattering and that there is often a sudden transverse growth and/or fast loss of ~ 1% in the first few seconds of a store. Betatron tunes $\nu_x = 19.441$, $\nu_y = 19.435$ seemed to minimize long term beam loss. The decay constant was ~ 2700 s for the most successful 100 GeV stores when the average pump pressure was ~ 5×10^{-8} T. The early slow losses ("nuclear scattering") were slower at 200 GeV than at 100 GeV so that they indicated something besides gas pressure. There appears to have been some confusion in interpreting the beam growth data because the effect of dispersion was not included in interpreting the horizontal profile, but taking the results for the vertical profile only, the conclusion that beam growth does not scale down quite as fast as $1/p^2$ still holds.

The studies discussed below have been conducted since September, 1977, and are covered in more detail because they have not been written up in any generality. The earlier work was directed more or less explicitly to the development of the main ring as a storage accelerator for pp or (in some minds) $\bar{p}p$ collisions. There have been changes in emphasis in the program; the recent efforts have been directed either toward developing the main ring as a part of the $\bar{p}$ source or toward gaining the understanding to successfully collide protons with antiprotons in the Tevatron.[7] Thus, certain enhancements in the main ring which had been seriously considered, like for example a low-β insertion, have been tabled in favor of developing the main ring into a $\bar{p}$ factory and a $\bar{p}$ injector for the Tevatron.[8]

The principal technical developments during the recent period include some improvement in the vacuum, and correction of the chromaticity up to 150 GeV.[9,10-12] The vacuum matter is a little subtle. The average pressure determined from the ion pump currents has changed little in two years. However, there has been an addition of about ~ 50 to the pre-existing ~ 850 30 ℓ/s pumps. These new pumps have been distributed in areas of known high outgassing or conductance limitations. A few additional 600 ℓ/s pumps have been added in areas of especially concentrated gas load. Nearly all pumps including the 600 ℓ/s units are now read back to get the pressure. This readback has been rendered more meaningful by modifying the readout to respond down to 10^{-9} T, and by replacing pumps with high leakage currents.[13] The measurements of bunch width and structure have been improved by an extremely bright 1 GHz oscilloscope (Tektronix 7104) which uses a microchannel plate electron multiplier CRT.

Although this note treats primarily observations made on the beam intensity and transverse growth, the interpretation does draw upon observations of the growth in the longitudinal coordinates as seen with the "2GHz resistive beam current detector". A comprehensive treatment of the longitudinal phase space observations should be available shortly; therefore, only specific obsercations are cited as needed without any systematic attempt to interrelate them or explain them.

Description of Nominal Storage Conditions and Data Collection

The main ring is set up for the studies by introducing a magnet ramp with a 3 second front porch at the desired storage energy, modifying the power supply turn-on scheme so that all active supplies are phased nearly full on during the front porch, and turning off of all extraction devices. The two sets of series sextupoles SEXH and SEXV are usually set for zero chromaticity in both planes. Adequate sextupole excitation is available for full correction to 150 GeV.[14] The injection and acceleration conditions which have been obtained in optimizing for ordinary operation are generally used without change unless the intensity has been very different from that desired, except that the "bunch spreader" (intentional longitudinal dilution for improved rf structure in slow extraction) is turned off. Beam is stored with the vertical and radial slow dampers on and the fast (bunch-by-bunch) vertical damper off. The nominal or reference store is made at 100 GeV with 10^{13} protons at tunes $\nu_x = 19.441$ and $\nu_y = 19.435$ and momentum offset of the closed orbit $\Delta p/p = 0$. These conditions have been chosen because the lifetime is long for this energy and there are many comparable stores from earlier studies.

Data collection procedures have evolved, but, especially since Spring, 1977, the uniformity has been sufficient for the beam survival comparisons. The following discussion is based primarily upon the time dependence of the beam intensity and the horizontal and vertical beam profiles. The beam current is read from a toroid monitor unaffected by the time structure. The profiles are produced by the IBS (ion beam scanner) which collects electrons produced from the residual gas in the vacuum chamber. These quantities are logged along with many others by a control system program at 1/3 s intervals for 10 s, 1 s intervals up to 30 s, 10 s intervals from 30 s to 5 min., and 30 s intervals thereafter. If the program detects a sudden change in a monitored parameter or beam current, it reverts to the 1 s logging interval. The logging tape is analyzed offline to provide the survival curve and Gaussian fits to the digitized IBS data. Additional information recorded generally includes the pressure distribution around the ring, flattop tunes measured by fast fourier transform of the turn-by-turn position of beam excited by a fast pulsed dipole, momentum offset measured by fitting of the radial closed orbit with the x_p function, plots of tune ripple from the quad busses, and time plots of other quantities adjusted to special values during the store by the main ring curves program.

Most Recent Data

The detailed discussion of recent main ring performance will be drawn mostly from measurements made January 3 and January 27, 1980. Table I summarizes the observations on ten stores made on these dates. The table includes the initial conditions, measured quantities, and quantities derived by methods described in the following discussion. During the same study sessions, measurements were made of chromaticity,[12] vertical-radial betatron coupling,[16] bunch width and momentum spread, and survival vs ν_y. These data do not fit neatly into the summary table. Therefore, these results and various supplementary observations from other study sessions are introduced where relevant to the discussion of the storage results.

The stores recorded in Table I do not include any precisely at the reference tunes, because it is not possible to set the measured tunes this close together. The difficulty arises from coupling of the radial and vertical oscillations; in fact, the minimum separation attainable directly measures the magnitude of the linear coupling:[16]

$$|k| = \tfrac{1}{2}\delta\nu|_{min} \approx .007. \qquad (1)$$

Because the coupling in the main ring has never beem smaller than it is now, it is clear that the reference tune adopted from the 1977 summer study report was determined from the value of small changes in the quad currents ("tune bumps") from some nearby measured tune value which would give the quoted value in the absence of coupling. The current procedure is to put the tunes as close together as possible with an average about the average value of the reference tunes. This procedure effectively puts the tunes on the diagonal of the tune diagram well away from the fifth order resonances that cross at $\nu_x = \nu_y = 19.4$ and bracketed by the seventh and ninth order resonances at 19.429 and 19.444 respectively. (Figure 1)

The momentum offsets $\Delta p/p$ are determined by a main ring control system program which fits the horizontal closed orbit with the calculated x_p function. The repeatability of the measurement is to a few hundredths of one percent and it tracks an offset (ROF) applied to the radial feedback loop to about the same precision.

Figure 2 is a plot of main ring beam intensity vs time for store #3 of January 27, 1980. The low loss portion lasting at least 1,000 seconds is linear to the precision of the current readout and is used to calculate $1/I_0(dI/dt)_{t=0}$. There are no early fast losses. The raw data have been corrected for a drift of 5.1×10^7 p/sec measured with beam off.

Figure 3 is a sample of digitized data from the IBS profile monitor. Because of baseline offset and, for the vertical monitor, tilt as well, the digitized data are fit by the form

$$y = a + bx + c \exp [-(x-M)^2/2\sigma^2] \qquad (2)$$

to give the beam width σ^2. A background subtraction using beam-off data would have significantly reduced the coefficients a and b and might have thereby improved the fits, but because much of the background is random, the signal to noise ratio would have been a little worse. Figure 4 gives $\sigma_x^2(t)$ and $\sigma_y^2(t)$ for the same store shown in Figure 1. The straight lines are estimated fits to the data which are used to determine the initial values and growth rates of the widths recorded in Table I. The data points shown in the figure are from 3 to 7 point averages depending on the sampling frequency for the data logging. These data are noisier than those taken during earlier studies; however, the signal levels are in reasonable agreement with the improved vacuum in the vicinity of the IBS. Despite the lower quality of the new data, it is clear that it shows no sudden transverse growth of the beam in the first seconds of the store at levels approaching those reported earlier.[6]

Residual Gas Pressure

The qualitative description of the phenomena responsible for the beam current loss (Figure 2) appears straightforward, viz., multiple coulomb scattering of the beam by gas in the vacuum chamber. Thus, during the period of low loss early in the store, the beam is diffusing outward. When the diffusion has carried some particles out to amplitudes for which the betatron oscillations are unstable, the losses start to accelerate, rather quickly becoming exponential. The time constant is determined by the pressure and composition of the gas and the critical amplitude for the betatron oscillations. The discussion below follows the treatment of this diffusion model by Tollestrup in the 1977 Fermilab summer study which contains references to some of the many earlier discussions.[17]

A refinement of the simple multiple scattering picture is needed to account for the early slow losses. Table I shows that this loss, $1/I_0(dI/dt)_{t=0} \sim 10^{-5}$, does not change drastically with beam energy, but much more complete results come from the pressure experiments reported in the 1977 summer study.[18] It is shown that at that time, when average pressure at the ion pumps was ~ 5 x 10^{-8} T, the early slow losses were independent of energy within errors and corresponded to an average nitrogen pressure of 6 x 10^{-8} T. Despite the agreement within quoted errors, however, the rate measured at 200 GeV was lower ($\lesssim$ 10%) than the rate at 100 GeV in comparisons at three different pressures. The residual gas was found to arise more or less equally from leaks and outgassing and to have an average atomic weight close to that of nitrogen. The gas composition in a known low pressure region had much more of the lighter components including considerable hydrogen. Because the number of leaks has been reduced considerably since 1977, the pressures determined from nuclear scattering given in Table I are based on a composition more characteristic of low pressure sections: 40% H_2, 40% CO, and 20% H_2O. The formula for nuclear scattering loss is:

$$\Lambda = \frac{1}{I_o}\left(\frac{dI}{dt}\right)_{t=0} = \frac{\beta c}{760} \sum_i \frac{\rho_i P_i}{\lambda_i} \qquad (3)$$

where ρ_i [g/cm^3], P_i [T], and λ_i [g/cm^2] are the densities, partial pressures, and collision lengths for the constituents and βc is the proton velocity. The ratio between the pressure determined from pure nitrogen and that determined from the given composition is .57. The effect of assuming greater proportion of heavier elements would be to worsen an approximate agreement with the pressure as measured by the ion pumps while further worsening the discrepancy with the pressure inferred from the transverse beam growth. The molecular fractions have only been measured in areas of good vacuum; the true average composition probably has atomic weight somewhere intermediate between air and the composition quoted. Thus, the evidence favors only small contribution from leaks. Later discussion will indicate that the apparently discrepant results determined from the beam profiles may not be as trustworthy as the results from the survival curves.

The energy dependence of the slow early losses is not well established by the data in Table I which contain only two observations at 150 GeV. However, the similar observations at three different pressures and energies of 100 and 200 GeV reported in Ref. 17 indicate that these losses are consistently lower at the higher energies. The source of this O(10%) effect has not been identified.

The beam current vs time also provides a measure of pressure via the multiple coulomb scattering mechanism. The survival curve is corrected for the nuclear scattering loss by adjusting the data on the basis of the initial slope:

$$I = I_o e^{-\Lambda t} \quad (4)$$

where Λ is given by Eq. 3. The survival curve is normalized to unity at t=0 and when expressed in a new variable y should be a universal function:[17]

$$N(y) = (I(t)/I_o)\, e^{\Lambda t} = -\Sigma \exp(-x_m^2 y)/J_o(x_m) \quad (5)$$

where $$y(t) = 1/2(a_o/a)^2 + (D\overline{\beta}/a^2)t. \quad (6)$$

In these expressions x_m is the $m^{\underline{th}}$ zero of the Bessel function $J_1(x)$, $J_o(x)$ is the Bessel function non-zero for x=o, a_o is the rms width of the initial beam, D is the diffusion constant ([D] = m/s), $\overline{\beta}$ = 52m is the average Courant Snyder beta, and a is the critical betatron amplitude or "dynamic aperture". The exact coefficients of the exponential functions in Eq. 5 are the result of assuming an initial Gaussian beam current distribution with $\sigma \ll a$. The general character of N(y) is surprisingly insensitive to plausible choices of the initial condition. The data reduction proceeds by finding the times t_i for which the normalized data have values $N(y_i)$. The points

y_i, t_i are fitted with a straight line which has $(a/a_o)^2$ as its intercept and $D\bar{\beta}/a^2$ as a slope. By taking a_o^2 from the fit to the IBS data, one can calculate the diffusion constant D and critical amplitude a which are tabulated in Table I. If the diffusion arises entirely from multiple scattering,

$$D = (\bar{\beta}/4)(.015)/p\beta)^2 c/X_o \tag{7}$$

where p is the momentum in GeV/c, βc is the proton velocity and X_o is the radiation length. Furthermore,

$$X_o = X_o|_{STP}\ (760/P), \tag{8}$$

where $X_o|_{STP}$ is the radiation length at standard temperature and pressure. For the assumed gas composition and reference momentum

$$D = 86.99/X_o \quad [\mathrm{ms}^{-1}]\ (P = 100\ \mathrm{GeV}). \tag{9}$$

The gas pressures given in Table I are derived from Eqs. 7 and 8. These are generally consistent with the average pressure at the ion pumps. With reasonable values for the vacuum chamber conductance, outgassing, and pumping rates, the true average chamber pressure should be ~ 1.5 times the pressure at the pumps and the pressure derived from beam survival and multiple scattering is perhaps thus a slight underestimate.[18] These observations, therefore, also argue against the presence of large amounts of air in the chamber.

Because none of the stores represented in Table I were sustained long enough to measure a half-life $T_{1/2}$ or a time constant τ for the late loss, these quantities have been calculated from the constants determined by the fitting of Eq. 6. Because N(.1069) equals one half

$$y(T_{1/2}) = 1/2\ (a_o/a)^2 + (D\bar{\beta}/a^2)T_{1/2} = .1069. \tag{10}$$

Because all the higher terms in the sum in Eq. 5 for N(y) decrease more rapidly than the first, the time constant for the loss at late times is

$$\tau^{-1} = x_1^2 D\overline{\beta}/a^2. \tag{11}$$

The values of these quantities given in Table I permit comparison of the recent results to earlier ones which were characterized by observed values of $T_{1/2}$ or τ. For example, the 1977 summer study reported $\tau \lesssim .75$h with comparable ion pump readings, whereas in early 1977 $\tau \lesssim .25$h was quoted for 100 GeV.

The multiple coulomb scattering interpretation of transverse beam growth predicts a linear growth in σ^2 either directly by averaging the effects of coulomb scatters on the betatron oscillations or as an early time limit in the analysis leading to Eq. 5 for the survival function. In either case,

$$\sigma^2(t) = a_o^2 + 2D\overline{\beta}\ t \tag{12}$$

and the slope of the beam width vs time data therefore gives another estimate of the pressure by attributing the diffusion constant D to residual gas. The pressure values determined in this way are higher than those determined from ion pump readings, nuclear scattering, and beam survival from multiple scattering. The D in Eq. 12 should be precisely the same D as that in Eq. 6; if something is really blowing up the beam at the rate shown by the IBS, it should show up in greater losses. The IBS is a somewhat complex device; its precise behavior depends on a number of parameters and is not fully understood. The bulk of the evidence suggests that it overestimates the beam width and that the pressures inferred from the IBS are less accurate than those from other techniques.

The status of main ring vacuum during the recent studies is summarized below. The situation has not been completely stable even during this period, however. The studies of January 3, 1980 were carried out rather soon after the repair of a significant leak and conditions were changing somewhat during the study period. However, January 27, 1980 was a day when the residual pressure was low and had been stable for several days. The conclusions below are particularly appropriate to the latter period:

1. The average pressure at the ion pumps is $\lesssim 4 \times 10^{-8}$ T.
2. The average pressure around the ring is ~ 6×10^{-8} T.
3. The average atomic weight and atomic number as determined by nuclear and multiple coulomb scattering respectively, are approaching that expected from outgassing of an unbaked stainless steel vacuum chamber.
4. The slight momentum dependence of the early slow losses imply a small contribution besides nuclear scattering so that the pressure estimated by this means may be slightly high.
5. The pressure calculated by interpreting the IBS data on beam growth is higher than the true pressure probably for reasons related to the IBS itself.
6. Storage lifetime has improved by more than the improvement in residual pressure.

Other Processes

The motivation for a thorough discussion of residual gas pressure is not to show that all observations are fully explained by it, but rather to have sufficient confidence to place significance on small differences between the data and the predictions of the multiple scattering model. Some discrepancies have been observed ever since the earliest studies which are still observed despite improvements in vacuum, chromaticity, and betatron tunes. These include $(dI/dt)_{t=0}$ larger at 100 GeV than at higher energy, scaling of the exponential time constant τ with momentum somewhat more slowly than the expected $1/p^2$, and faster spreading of the radial profile than the vertical profile. There were other discrepancies common in earlier studies which are not frequently observed now, such as early sudden losses (step loss ~ 1%) in the first few seconds of a store and rapid early increase in transverse beam size.[6]

The difference in growth rates for vertical and horizontal profiles reflects a process which has also been observed directly during most study periods, viz., the lengthening of the beam bunches. The radial beam width contains a contribution from the momentum spread in the beam. Because the radial and vertical betatron emittances are equal[19]

$$\sigma_x^2 = (x_p \delta p/p)^2 + \sigma_y^2 \qquad (13)$$

where $\delta p/p$ is the momentum spread within the beam and x_p is the dispersion at the profile monitor.[20] The values for $(\delta p/p)^2$ at t=0 (beginning of store) and for the rate of growth are given in Table I. The linear growth in both σ_x^2 and σ_y^2 means that $(\delta p/p)^2$ also increases linearly. The implied value of the initial rms momentum spread of $\sim .5 \times 10^{-3}$ is high by a factor of 2 to 3 when compared to that calculated from the rf voltage and the longitudinal emittance measured at 8 GeV. In fact, however, this value is generally confirmed by recent experiments in which the momentum spread has been measured by turning off the rf and measuring the debunching rate of single bunches.

at 100 GeV.[21] The momentum spread determined from Eq. 13 has contributions both from intrinsic momentum spread within the bunches and from the momentum difference between bunch centroids because the integrating time of the IBS covers many beam turns. Since the earliest storage studies it has been known the bunches ~ 2 ns wide grow to ~ 6 ns during the course of a store. Because the rf voltage is constant, the growth of $(\delta p/p)^2$ implies a growth of longitudinal emittance at the same rate which is a factor of 2 to 3 in 1000 s for the values from Table I. The observation of linear growth is not completely consistent with the qualitative observations of bunch broadening since that generally seems to saturate at the ~ 6 ns width which is much less than the 19 ns bucket width.

An experiment has been performed on the growth of a bunch when the phase feedback loop in the low level rf is modified to correct the phase of that bunch only.[21] In this experiment all of the other bunches were blown up at injection by applying anti-damping with the fast vertical damper. The remaining charge in the blown up bunches was reduced by ~ 2 orders of magnitude so that the radial feedback loop was responding to some vestigal bunches distributed with sufficient azimuthal smoothness for it to function. The basic conclusion was that when the rf phase was adjusted correctly for the unattenuated bunch, it did not oscillate nor spread during the store. This observation strongly implies rf phase noise rather than longitudinal bunch instability as the major factor in bunch growth.

One of the consistent findings of the earlier studies was that gas scattering seemed inadequate to account for the size of the diffusion constant. If one discounts the IBS profile data, there is little evidence of additional diffusion in the new data and the lifetimes are correspondingly longer. The likely mechanism for driving extra diffusion is multiple crossing of non-linear resonances; the major sources of tune modulation are magnet current ripple and synchrotron oscillations. The synchrotron oscillations result in a tune shift

$$\Delta\nu(t) = \xi \ \delta p(t)/p, \tag{14}$$

which for the measured uncorrected chromaticity $\xi_x = -17$, $\xi_y = -11$ and the momentum spread which approaches 1.5×10^{-3} for long times gives $\Delta\nu_x \approx .026$ full width and $\Delta\nu_y \approx .017$. Bend bus ripple of .01% adds an additional ~ .002 to $\Delta\nu_x$ and ~ .001 to $\Delta\nu_y$. Quadrupole ripple which is in phase on the two busses probably contributes about the same amount and like bend bus ripple acts through the chromaticity. Thus, with chromaticity uncorrected as it was in the earlier studies, the tune must cross the seventh and ninth order resonances at a frequency of several hundred Hz. The quad ripple is predominantly 120 Hz, bend ripple is mostly 360 Hz and the synchrotron frequency is just above 120 Hz for 1.5 MV of rf at 100 GeV. With chromaticity well corrected, the principal tune modulation comes from out-of-phase ripple on the quad bus which does not exceed $\Delta\nu = .005$ full width. Therefore, if the tune is carefully set, resonances up to the ninth order can be avoided. The lifetime of $\Delta p/p = 0$ stores at 100 GeV with and without chromaticity correction is given in Table II. The significant increase in lifetime with chromaticity correction indicates the importance of these high order resonances.

Although there have been no direct measurements of the strength of the seventh and ninth order resonances, the effect of the fifth order lines passing through $\nu_x = \nu_y = 19.4$ has proven very strong.

During the two 150 GeV stores on January 27, 1980, the vertical tune was moved down from 19.448 to 19.388 by quad current steps corresponding to $\Delta\nu_y$ = .005 while the radial tune was not varied. Because of the coupling, the actual tune values did not vary quite as indicated by the quad currents so that the tunes at each step would have to be measured at each step to know the tunes exactly. However, this set of tune measurements would be very similar to those made in evaluating the strength of the coupling and the way the tune varies can be inferred to a good approximation from the known coupling. A plot of the fractional loss rate vs the tune step appears as Figure 5. Each tune value was held long enough to give a comparable measure of the loss rate, as little as 30 s at high loss points and up to 300 s at low loss points. As the figure shows losses vary by more than two orders of magnitude over the range, the loss maxima are labeled by the resonance which causes them. All three of the 5th order resonances crossed have a strong effect. Although the figure demonstrates strong effects, it may not properly represent the relative strengths. It was observed in the taking of the data that sometimes a disproportionate fraction of the loss occurred just as the tune was changed. Thus, the rate measured was dependent on details of the way the tune passed through the resonance during the step and probably the location of the endpoint of the tune steps bracketing the resonances. Neither of these variables could be controlled in these studies.

The effect of a fourth order resonance is seen in store #6 from January 3, 1980 for which ν_y = 19.245. The $\sigma_x^2(t)$ and $\sigma_y^2(t)$ are plotted in Figure 6. In such a case, the effects of the resonances are not accommodated by a simple diffusion analysis; perhaps one is seeing here a gross example of the sort of effects that confused some of the earlier observations. Interestingly, however, the beam survival has the typical form with early losses comparable to stores at good tunes; the lifetime is very much shorter. The survival curve analysis for this store identifies higher pressure as the cause of the short lifetime and gives a critical betatron amplitude as large as any of the others. The data calculated from the diffusion model are shown in parentheses in Table I because the underlying assumptions are so poorly satisfied.

Investigations in Progress

The beam storage results described above represent an intermediate stage in attaining the kind of information about beam survival and transverse growth that will be required to store proton and antiproton beams successfully in the Tevatron. More studies are either in progress or in the planning stage.

The question of whether the faster diffusion indicated by the IBS profile monitor is an instrumental affect or an additional phenomenon to be understood may be resolved by observations to be made with a synchrotron light profile monitor which is under development. This device is like those used on electron accelerators, but depends on the rapid variation of the magnetic field at the end of a bending magnet to produce radiation in the visible for protons of 100 GeV or greater energy.[22] It is hoped that this monitor will be adequate not only to give a good determination of the rms width of the beam, but also an indication of the shape or higher moments of the current distribution.

The effects of non-linear resonances will be investigated more quantitatively by using a tune sweep variable in amplitude and rate to look at losses in the neighborhood of resonances with a controlled speed of crossing. This sweep will be realized by driving one of the active filters on the quadrupole bus by a signal generator rather than in the usual way by a signal derived from the ripple current on the bus.

There are several lines of investigation active in the study of the longitudinal behavior of the beam and rf manipulations. Of direct concern for the better understanding of the phenomena discussed in this note are more detailed obser ations of the momentum spread at long times to correlate with the observations on radial beam growth and a study of the survival of a single bunch which has been stabilized against longitudinal spread by modification of the phase loop of the low level rf. The survival of a non-spreading bunch compared with ordinary stored beam would indicate the importance of losses from the bucket or due to momentum dependent mechanisms.

Conclusion

The most important development in the last two years for enhancing the survival of beam stored in the main ring has been the correction of the chromaticity. The ongoing efforts to improve vacuum should lead to a proportionate improvement in lifetime because the role of non-linear resonances seems to be small at optimum tune with the present vacuum. With an average pressure of about 6×10^{-8} T of mostly low Z gasses, the half life is about 1.3 hours at 100 GeV and 2.5 hours at 150 GeV. The effect of power supply ripple is limited, with the present chromaticity, to the sweeping of resonances above the ninth order if the tune is carefully set. One infers that such resonances are not a major factor in the present circumstances, but the significant improvements expected in the near future in this regard may be detectable, particularly as the vacuum improves. A more direct effect of improved power supply performance may be through reduced longitudinal diffusion driven by phase noise arising from bend field variation. Although the observations suggest the beam losses occur out of the betatron acceptance and not out of rf buckets, this is not very well established and there may be effects of momentum spread through dispersion or possibly from the little remaining chromaticity.

The beam survival for good tunes appears to be dominated by gas scattering, but there are small discrepancies which have been observed fairly consistently both in the early and the most recent studies which may imply unidentified or misconstrued pehnomena at just about the level for reliable observation. One of these is a slight energy dependence of the early slow losses which would not be present if these losses were entirely the result of nuclear scattering. These losses seem slightly greater at 100 GeV than at either 150 or 200 GeV. On the other hand, the late exponential losses appear to scale a little more slowly than p^{-2} so that late losses are slightly higher than predicted at the higher momenta. Transverse beam growth is qualitatively in accord with gas scattering predictions, although somewhat faster than predicted from the survival data if the IBS profiles are taken at face value. The correlation between radial and vertical beam growth is consistent with current measurements of the momentum spread, although better data for the momentum spread at long times would allow a more stringent comparison to be made. In large measure, the newer data are described by the gas scattering predictions. The elucidation of the discrepancies, if they persist in later measurements, will require enhancement of the signal by improved vacuum or intentional enhancement of their source. The lifetime is already too long to hope to measure the effects well simply by improving the statistics by repeated observations under current conditions.

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12. J. MacLachlan, "Improved Chromaticity Correction in the Main Ring for Beam Storage at 100 and 150 GeV", Fermilab Internal Accelerator Experiment, EXP-102, April, 1980.

13. S. Pruss, private communication, April, 1980.

14. Correction is less complete at 150 GeV; See Reference 12.

15. "The Storage Mode Sequencer Program", originally written by I. Gaines (1977), modified and documented by A. Thomas (1979).

16. J. MacLachlan, "Coupling of the Radial and Vertical Betatron Oscillations on 100 GeV and 150 GeV Flattop", Fermilab Internal Accelerator Experiment, EXP-93A, April, 1980.

17. A. V. Tollestrup, "Effects of Multiple Scattering in the Main Ring During Storage", Ref. 5 op. cit., pp. 243-252.

18. H. E. Fisk and F. Turkot, "Characteristics of Vacuum in the Main Ring as Related to Beam Storage", Ref. 5. op. cit., pp. 221-242.

19. C. Moore, private communication, April, 1980.

20. A. Ruggiero has pointed out that the large momentum spread in the stored beam serves to reconcile the profiles measured in the radial and vertical planes.

21. Unpublished experimental data, principally the work of J. Griffin.

22. A similar monitor has given good results at the CERN SPS.

Quantity units \ Date, Store #	January 3, 1980						January 27, 1980				
	1	2	3	4	5	6	1	2	3	4	
Energy [GeV]	100	100	100	100	100	100	150	150	100	100	INITIAL
I_o(initial Int.) [10^{12}p]	12.2	13.2	13.1	12.5	12.5	12.6	10.6	2.9	10.3	2.9	
ν_x	19.443	19.443	19.444	19.447	19.448	19.443	19.424	19.424	19.447	19.447	
ν_y	19.432	19.432	19.428	19.424	19.428	19.245	19.448	19.448	19.432	19.432	
$\Delta p/p$(closed orbit) [%]	-.051	-0.47	-.202	+.119	-.319	-.100	+.065	+.065	-.004	-.004	
$\bar{p}$(avg at ion pumps) [10^{-8}T]	5.0	5.0	5.0	4.8	4.8	4.8	3.8	3.8	3.8	3.8	
$\sigma_x^2(0)$ [mm^2]		3.30		2.80		2.55	2.50	1.72	3.60		MEASURED
$\sigma_y^2(0)$ [mm^2]		2.10		1.99	1.75	1.90	1.46	1.22	1.85		
$d\sigma_x^2/dt$ [$10^{-3}mm^2/s$]		6.6		5.01		(4.07)	2.14	~2	3.12		
$d\sigma_y^2/dt$ [$10^{-3}mm^2/s$]		3.03		3.34	4.31	(5.1)	1.14	~2	2.25		
$1/I_o(dI/dt)_{t=0}$ [10^5p/s]	4.1	4.1	4.1	3.1	3.7	(5.0)	2.2	1.9	2.6	2.7	
p_{NS}(fr nucl scat.) [10^{-8}T]	9.5	9.5	9.5	7.2	8.6	(12)	5.1	4.4	6.0	6.3	DERIVED
p_{MCS}(fr $d^2\sigma_y/dt$) [10^{-8}T]		10		11	14	(17)	8.5	~15	7.5		
p_{MCS}(fr I(t)) [10^{-8}T]		6.3	6.0	5.2	4.8	(33)	5.1	4.8	4.8		
a("dynamic aper.") [mm]		6.0	6.2	5.5	5.6	(6.6)	5.3	4.8	7.4		
$(\delta p/p)^2_{t=0}$ [10^{-6}]		.30		.20		.16	.28	~.12	.44		
$d(\delta p/p^2)/dt$ [10^{-9}/s]		.76		.42			.25		.22		
τ(long time decay) [h]		1.04	1.12	1.05	1.12	(.24)	2.17	1.97	1.11		
$T_{1/2}$(half life from I(t)) [h]		1.2	1.3	1.2	1.3	(.28)	2.6	2.3	1.5		

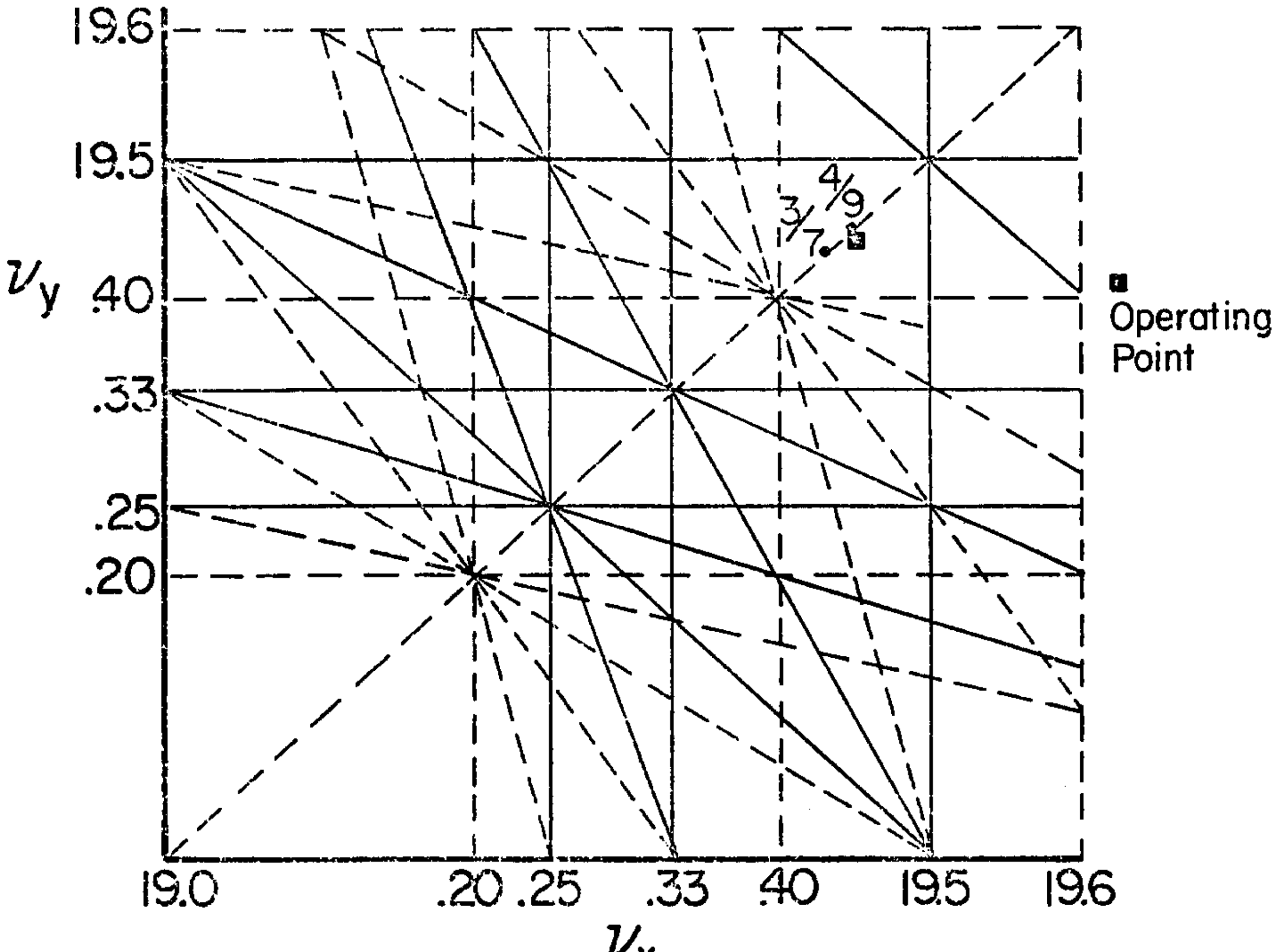
TABLE 1

TABLE II

100 GeV BEAM SURVIVAL

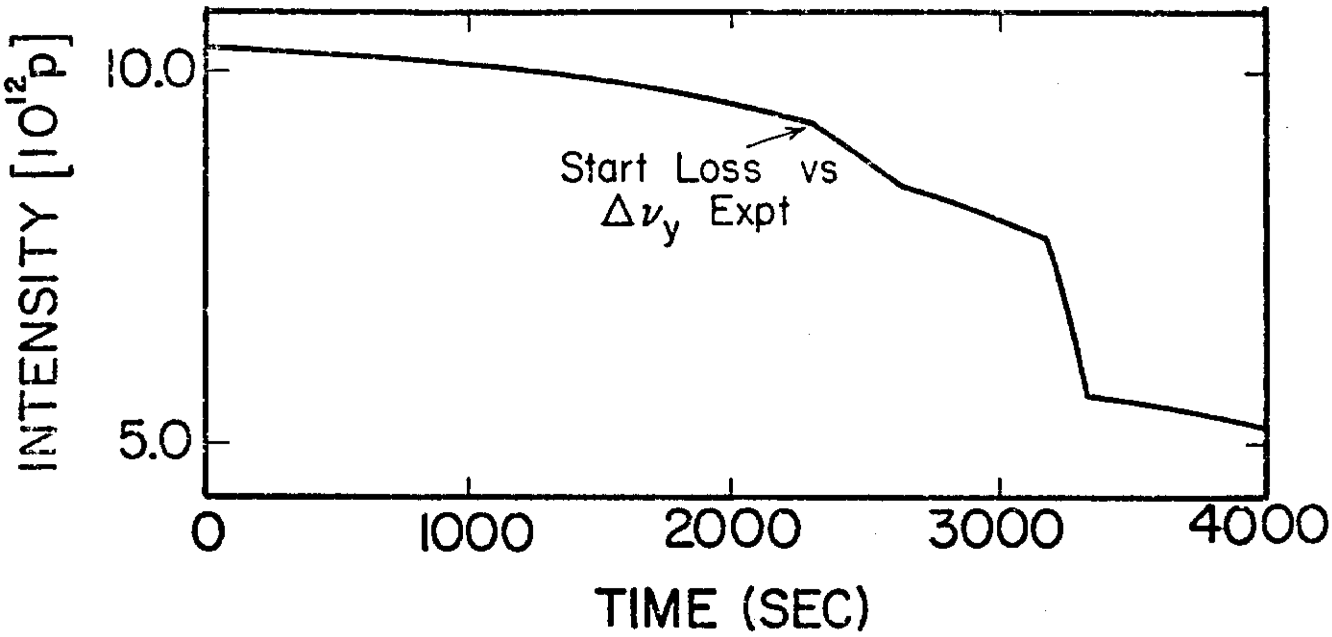
(CLOSED ORBIT $\Delta p \equiv 0$)

DATE	ξ_x	ξ_y	$T_{1/2}$[S]	$\frac{1}{I_\bullet}(\frac{dI}{dt})_{t=0}$ [10^{-5}S]	P_{pump} [10^{-8} T]
1/79	-17	-11	2000	11.4	4.5
			1646	16	4.5
	0	-11	2070	8.8	4.5
			1985	5.9	4.5
			2951	6.5	4.5
1/80	0	0	4320	4.1	5.0
			5400	2.6	3.8



Tune Diagram—Resonances to 5th Order

FIGURE I

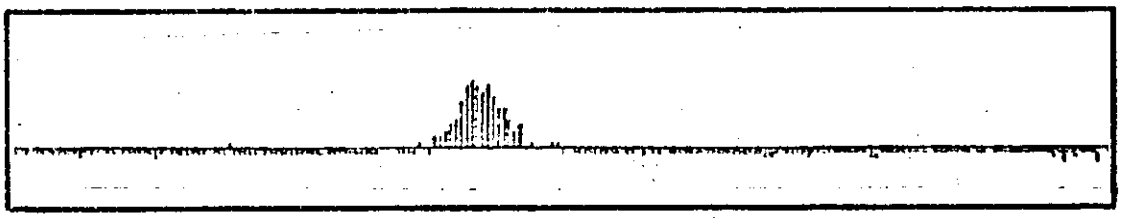


BEAM INTENSITY vs TIME 100 GeV

FIGURE 2

BEAM PROFILE DATA FROM THE IBS

RADIAL PROFILE (0.5 MM/DIV)



VERTICAL PROFILE (0.25 MM/DIV)

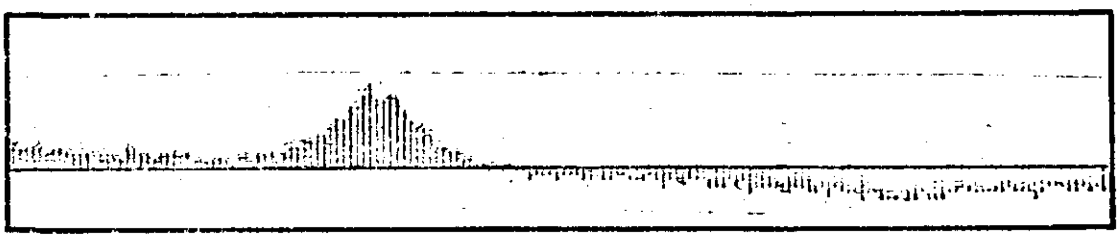
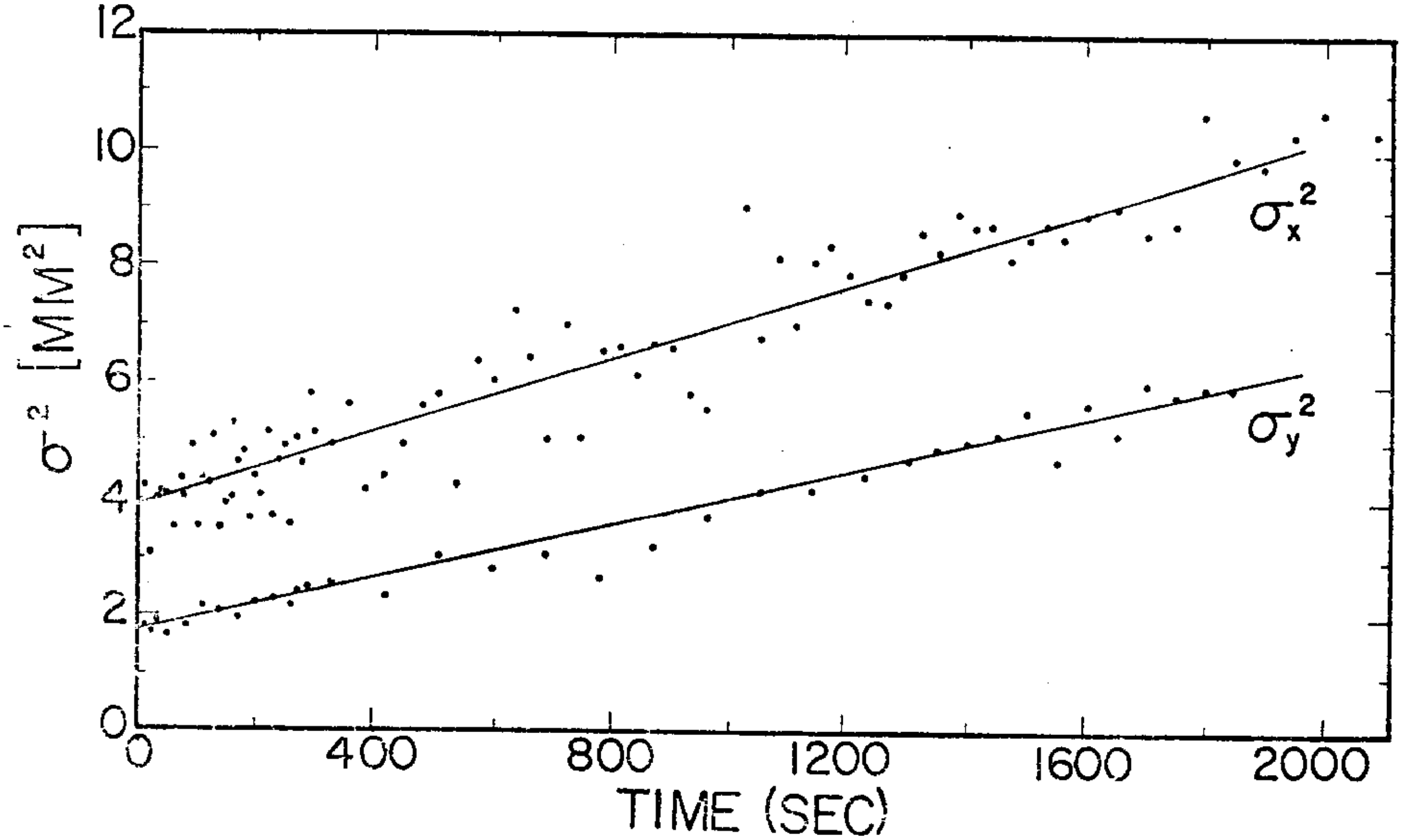
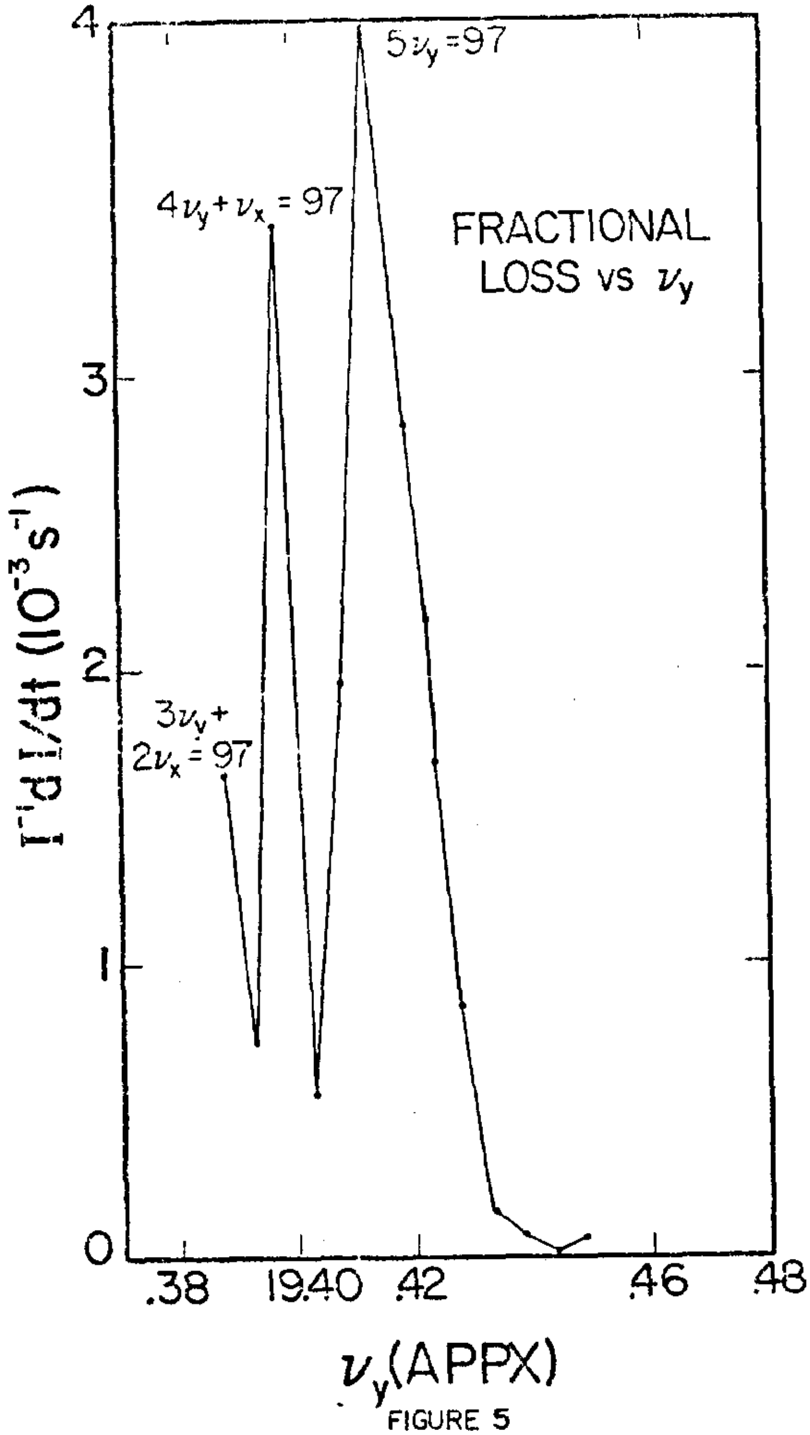


FIGURE 3



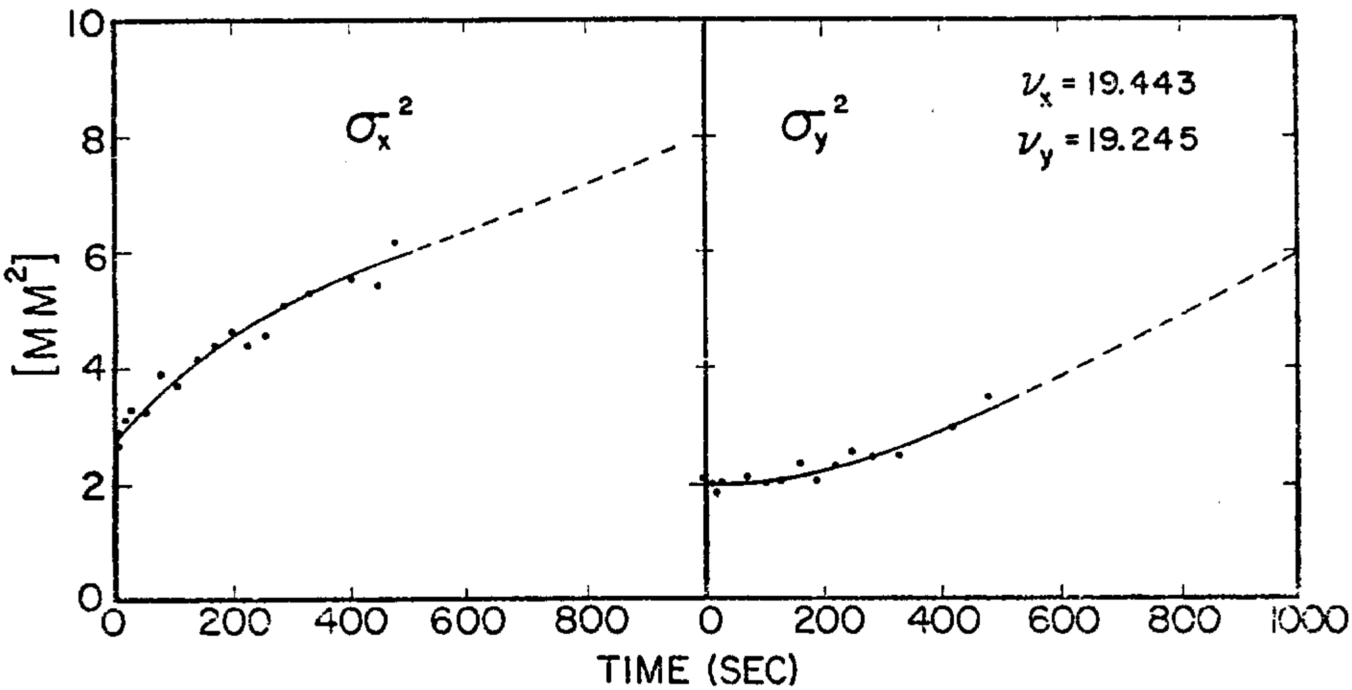
BEAM WIDTH σ^2 vs TIME at 100 GeV

FIGURE 4



4
3
2
1
0
$5\nu_y = 97$
$4\nu_y + \nu_x = 97$
$3\nu_y +$
$2\nu_x = 97$
FRACTIONAL
LOSS VS ν_y
$I^{-1} dI/dt$ ($10^{-3}s^{-1}$)
.38
19.40
.42
.46
.48
ν_y(APPX)

FIGURE 5



BEAM WIDTH σ^2 vs TIME at 100 GeV

FIGURE 6