© 1977 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from the IEEE.

IEEE Transactions on Nuclear Science, Vol.NS-24, No.3, June 1977

OPERATION OF THE FERMILAB ACCELERATOR AS A PROTON STORAGE RING

C. M. Ankenbrandt, H. E. Fisk, R. P. Johnson, H. W. Miller, H. Pfeffer, A. Tollestrup and F. Turkot Fermi National Accelerator Laboratory* Batavia, IL 60510

Summary

To evaluate its potential for colliding beam experiments a preliminary exploration of the Fermilab main ring operating in the storage ring mode has been made. Beam lifetime and horizontal size measurements have been obtained at 75, 100, 135, and 200 GeV/c. The data, when compared to predictions of a gas scattering model, imply the existence of other additional effects which merit further investigation.

Perspective and Operating Conditions

To investigate the possibility of using the Fermilab main ring as a storage device, beam storage experiments have been carried out at 75, 100, 135, and 200 GeV. Because of the potential increase in luminosity and better localization of the interaction point for head-on collisions between beams, the experiments were performed with the rf power and radial position feedback turned on. The rf power level was 1.3 MV. In the main ring, there exist three active beam dampers which are used to control beam instabilities.¹ Two of these, the slow horizontal and vertical dampers, are used to damp collective beam blow up (1 MHz frequency response) while the remaining vertical damper, the superdamper, is used to damp oscillations of individual rf buckets independently (5 ns rise time). All dampers were on during acceleration of the beam but the superdamper was turned off a few seconds prior to storage. The tune of the machine was near the nominal values of $v_{H}=19.42$ and $v_{V}=19.42$ 19.38. Beam intensity for the 100 GeV storage was 0.6×10^{13} protons and was 1.3×10^{13} protons at the other energies. The pressure as measured by the 900 20-liters/sec main-ring ion pumps varied from 1×10^{-6} torr to something less than 10^{-8} torr which corresponds to the minimum detectable ion current of 1 $\mu A.$ The average pump pressure was 7 x 10^{-8} torr. Because of the geometrical location of the pumps, the average pressure the beam sees is estimated to be 1×10^{-7} torr.



Fig. 1. Beam intensity vs. time for 75, 100, and 200 GeV/c.

Intensity As a Function of Time

Figure 1 shows the beam intensity as a function of time for storage at 75, 100, and 200 GeV. In general, the beam size begins to expand, presumably due to multiple scattering by residual gas molecules in the vacuum chamber, and possibly other mechanisms until the beam reaches the edges of the effective aperture where it is lost.² After about 500 seconds all curves show an exponential falloff with lifetimes which vary from 585 seconds at 75 GeV/c to 3070 seconds at 200 GeV/c. In a standard circular aperture diffusion theory of particle loss, the long time beam lifetime is given by $\tau = 0.85$ <u>(A/π)β</u> <u>γ</u> torr sec. Here A is the transverse phase PX space acceptance, β and γ are $\frac{P}{E}$ and $\frac{E}{m}$ respectively for the beam protons, P is the pressure in torr and X = R/vwhere R is the main ring radius and υ is the tune. 3 In our energy region, for fixed pressure and acceptance, the lifetime should rise with the square of momentum. Figure 2 shows the lifetime versus momentum and the curve $\tau = K_p^2$ which is forced to go through the origin and the 200-GeV point. The points at 75, 100, and 135 GeV are not inconsistent with this curve. An alternative way of presenting the data is to calculate the pressure assuming a fixed acceptance of $1.5\pi~x~10^{-6}$ meter radian. If this is done the pressure varies from 3.0 to 4.5 \boldsymbol{x} 10^{-7} torr (nitrogen equivalent) in the region 75 to 200 GeV.



Fig. 2. Lifetime vs. momentum. The curve is of the form $\tau \propto p^2$.

Horizontal Beam Size Measurements

From horizontal beam profile curves obtained with the residual gas ionization beam scanner (IBS), the beam width may be determined as a function of time. If one assumes the beam distribution to grow in a gaussian manner, the width as a function of time should vary as $x^2 = x_0^2$ $+x_c^2$ t, where $x_c^2 = 7.66 \times 10^8 P/Bp^2$ (nitrogen equivalent multiple scattering). Figure 3 shows the full width at half maximum, 90% width and the 100% width as a function of time for the case of 135-GeV beam. As would be expected, the horizontal beam width reaches a maximum. In this particular case the maximum occurs between 500 and 1000 seconds. Figure 4 shows the square of the FWHM as a function of time for 75, 135, and 200 GeV beam storage. If the slopes from the straight lines shown in

^{*}Operated by Universities Research Association, Inc., Under Contract With the U. S. Energy Research and Development Administration.

Fig. 4, are used to deduce corresponding pressures the results are: $3.4 \pm 1.5 \times 10^{-7}$, $5.1 \pm 2.0 \times 10^{-7}$, and $2.8 \pm 1.5 \times 10^{-7}$ torr for 75, 135, and 200 GeV, respectively.



Fig. 3. Horizontal width vs. time for 135 GeV/c storage. The curves are drawn only to guide the eye.



Fig. 4. The square of the full width at half maximum vs. time for 75, 135, and 200 GeV/c.

Pressure Dependence of Beam Lifetime

In an attempt to understand whether all the beam loss is due to gas scattering, two successive storage runs were done at 135 GeV. At the end of the first run, half of the main ring ion pumps were turned off and subsequent storage showed a decrease in beam lifetime. The intensity as a function of time is shown in Fig. 5. The long time lifetimes are 1300 and 950 seconds for the two cases. The ratio of pressures measured at the ion pumps is 1.25. Because of pump geometry with half the pumps turned off, this factor should be multiplied by a number between 1 and 1.75 which would imply the difference in lifetimes can be accounted for chiefly by the vacuum pressure difference.



Fig. 5. Beam intensity vs. time for two different average pressures. See text for details.

Gas Scattering Model

If gas scattering were the only source of loss, the space and time evolution of the beam would be described by solutions of the diffusion equation (Bessel's equation in this case).⁵ If normalized phase space variables are taken to be:

$$x_1 = x/\sqrt{\lambda} = r \cos\theta\cos\phi_x; \quad x_2 = x/\sqrt{\lambda} = r \cos\theta\sin\phi_x; (la,b)$$

 $x_3 = y/\sqrt{\lambda} = r \sin\theta \cos\phi_y; \quad x_4 = y/\sqrt{\lambda} = r \sin\theta \sin\phi_y; \quad (2a,b)$

the solution for the phase space density is:

$$\rho(\mathbf{r},\mathbf{t}) = \Sigma \mathbf{A}_{\mathbf{m}} \mathbf{r}^{-1} \mathbf{J}_{1} \left(\gamma_{\mathbf{m}} \frac{\sqrt{\lambda}}{\mathbf{a}} \mathbf{r} \right) \mathbf{e}^{-\mathbf{t}/\tau} \mathbf{m}; \qquad (3)$$

where $\tau_m^{-1} = \frac{\chi_D \gamma_m^2}{a^2}$; D=0.08 $\frac{P\chi}{\beta^3 \gamma^2}$ (diffusion coefficient);

a=aperture radius and γ_m are the roots of $J_1(\gamma_m)=0$. The coefficients, A_m , are determined from the initial beam distribution at t=0. If $\rho(r,o)$ is assumed to be gaussian the time distribution is given by:

$$N(t) = \sum_{m} \frac{-1}{J_{o}(\gamma_{m})} e^{-\gamma_{m}^{2}y}, y > 0, \qquad (4)$$

where $y = \int \frac{1}{2} \left(\frac{a_0}{a}^2 + \frac{\lambda D}{a^2} t\right)^2$. Here a_0 is the rms width of the gaussian beam distribution in r. Since N(t) is a universal curve as a function of y, values of y and t can be plotted for each set of storage data. If this theory is correct a straight line should be observed. The data plotted this way are shown in Fig. 6, which shows reasonable agreement with straight lines after 500 seconds. The measured time dependence of the intensity distribution before 500 seconds is not completely understandable with this model.



Longitudinal Beam Growth

In addition to growth of the transverse beam size with time there are also data which show longitudinal growth of the beam in individual rf buckets. Typically the rf bunches broaden at their base from 2 us to 5 ns, during approximately the first 50 seconds of storage. Part of the central 2 ns region of the beam pulse sticks up well above the broadened base and exhibits what appears to be synchrotron oscillations. It is important to understand this broadening process because of its serious implications for the length of the interaction region, should the main ring be used as a colliding beam facility.

Conclusions

In conclusion, it appears the beam lifetime is not completely dominated by gas scattering especially at short times, although a diffusion-like process can account for much of the time dependence.⁶ There is some indication the effective aperture of the machine is energy dependent and it is considerably smaller than the physical size.⁷ There is evidence, in more recent experiments that the tune of the machine is very critical during storage and more effort will be needed to understand how the tune affects lifetime. Finally the mechanism for growth of the time width of the rf bunches needs more investigation. Further experiments are planned in which the pressure will be varied at fixed beam energy to aid in separating the vacuum problems from beam dynamic effects.

Acknowledgements

We would like to thank the accelerator operating crew for their assistance during our machine studies and wish to acknowledge coversations with T. Collins, S. Ohnuma, and A. Ruggiero on various aspects of the data.

References

¹R. Stiening and E. J. N. Wilson, Nuclear Instruments and Methods <u>121</u> (1974) 283.

E. Higgins, Q. Kerns, H. Miller, B. Prichard, R. Stiening and G. Tool, IEEE Transactions on Nuclear Science <u>NS-22</u> (1975) 1473.

²N. M. Blackman, E. D. Courant, Phys. Rev. <u>74</u> 140 (1948).

N. M. Blackman, E. D. Courant, Phys. Rev. <u>75</u> 315 (1949).

³W. Hardt, CERN Report ISR-300/GS/68-11 (1968).

⁴C. Bovet, D. C. Johnson, CERN Note MPS/CCI/Note 74-42 (1974).

⁵See Reference 3.

⁶P. A. Sturrock, Annals of Physics <u>3</u> 113 (1958) see e.g. page 150.

⁷R. Stiening and E. J. N. Wilson, Proc. of IX International Conference on High Energy Accelerators, 332 (1974).