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**FERMILAB-TM-1760**

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October 1991



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# Energy and Energy Width Measurement in the FNAL Antiproton Accumulator

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## Abstract

The Fermilab Antiproton Accumulator has recently been used to produce Charmonium resonances (charm quark, anti-charm quark bound states) in proton-antiproton annihilations using an internal  $H_2$  gas jet target. A measurement of the resonance mass and width may be obtained from a precise knowledge of the antiproton beam energy and energy spread. The beam energy is measured to an accuracy of 1 part in  $10^4$  in the range 6.3 Gev to 4.1 Gev by measuring the orbit length and revolution frequency of the beam. The beam momentum spread is measured to an accuracy of 10% by measuring the beam frequency spread and the parameter  $\eta = (P_{beam}/F_{rev}) \cdot (dF_{rev}/dP_{beam})$ . These two measurement techniques are described in this report.

## I. INTRODUCTION

A goal of Fermilab exp. E760 is to measure the masses and widths of charmonium states in the region 2.9 to 3.8 Gev/ $c^2$ .<sup>[1]</sup> These states are produced by decelerating a stack of  $\bar{p}$ 's from the stacking energy of 8.9 Gev to an energy between 6.3 and 4.1 Gev and then colliding this beam with an internal  $H_2$  gas jet target. While the  $H_2$  jet is on, the beam is stochastically cooled in 3 dimensions so that  $\epsilon_{A,e} \sim 1\pi$  mm-mrad and  $\Delta P/P \approx 10^{-4}$ . The beam energy is scanned in small steps across the charmonium state and the production of charmonium is measured as a function of beam energy. The effective cross section is a convolution of the beam energy spectrum and a Breit-Wigner:

$$\sigma(E_{cm}) = \int_0^{\infty} \sigma_{BW}(E) \cdot S(E - E_{cm}) dE \quad (1)$$

where  $S(E - E_{cm})$  is the beam energy spectrum for beam at center of mass energy  $E_{cm}$ . The resonance parameters can be determined from the above excitation curve if the beam energy spectrum is known.

## II. BEAM WIDTH MEASUREMENT

### A. Frequency Spectrum

The beam momentum spectrum is obtained from the beam revolution frequency spectrum by

$$\Delta p/p = \frac{1}{\eta} \cdot \Delta f/f \quad (2)$$

where

$$\eta = \frac{1}{\gamma^2} - \frac{1}{\gamma_T^2} \quad (3)$$

The beam signal is detected with a coaxial quarter wavelength pickup which resonates at 79 MHz, and the Schottky noise from the pickup is analyzed with an HP8568B spectrum analyzer. For DC beam the number of  $\bar{p}$ 's in a given frequency range is proportional to the Schottky power in that range. The frequency spectrum is recorded once every 3 minutes and the average of 20 to 80 of these spectra is used to determine the beam frequency characteristics. Fig. 1 shows a typical spectrum taken at the 127th harmonic of the revolution frequency. The data is fit to an asymmetric Gaussian with  $\sigma_{low}$  20% larger than  $\sigma_{high}$ . The low energy tail is due to energy losses in collisions with electrons in the  $H_2$  gas jet.

The major uncertainty in determining the beam momentum spectrum is from the uncertainty in  $\eta$  in eq. (2).  $\eta$  is calculated by 2 different methods and, in addition, it

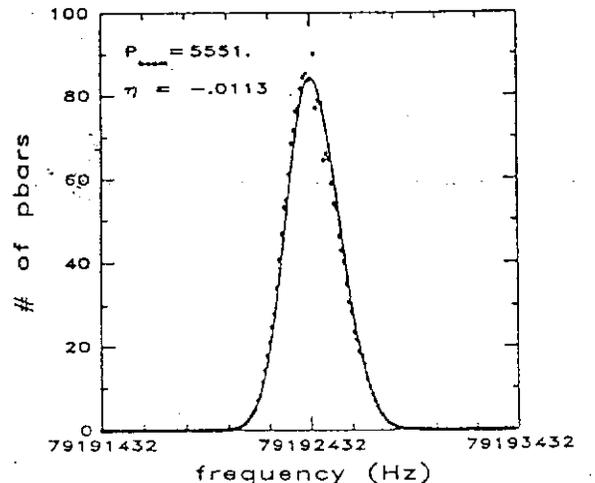


Figure 1: Frequency spectrum. Vertical scale is arbitrary.

\*Operated by the Universities Research Association under contract with the U.S. Department of Energy

can be determined at 2 different beam energies by a 3rd method denoted here as a "double scan."

### B. $\gamma_T$ Measurement

The first method of measuring  $\eta$  uses eq. (3).  $\gamma_T$  is measured by changing the current in the main dipole bus and measuring the relative frequency change as a function of the relative magnetic field change:

$$\gamma_T^2 = \frac{df/f}{dB/B} \quad (4)$$

This method has 2 drawbacks.

1) At small values of  $\eta$  a small relative error in  $\gamma_T$  will yield a large relative error in  $\eta$ :

$$\delta\eta/\eta = \left( \frac{1}{(\gamma_T/\gamma)^2 - 1} \right) \cdot d\gamma_T/\gamma_T \quad (5)$$

2) The NMR probe used to measure  $B$  is within a magnet which shares the same bus with the other dipoles, but is not in the Accumulator ring. Since each dipole has a different current shunt, the measured  $dB/B$  is not precisely the same as seen by the beam.

### C. Synchrotron Frequency Measurement

$\eta$  can be determined from a measurement of the synchrotron frequency of stationary bunched beam:

$$|\eta| = \frac{2\pi H f_s^2 \beta^2 E_{beam}}{f_{r,f}^2 (eV_{r,f})} \quad (6)$$

where  $f_s$  is the synchrotron frequency of small amplitude oscillations. In this method the beam is bunched at  $H=2$  and the frequency difference between the synchrotron sidebands in the beam Schottky signal is measured as a function of rf power. Since  $E_{beam}$  and  $f_{r,f}$  are known very precisely, the major uncertainty in this method comes from the calibration of the rf voltage. The rf gap voltage was measured directly with high voltage probes and an oscilloscope.

### D. Double Scan

Fig. 2 is a graphical representation of this method. Data is collected at pt. 1 and then the beam is bunched and moved to pt. 2 (magnetic field constant) where a 2nd set of data is collected. The magnetic field is then ramped to pt. 3 (energy constant) where data is again collected. This procedure continues through the remaining pts. The 2 sets of data—pts. 1,3,5,... denoted as the central orbit, and pts. 2,4,6,... denoted as the side orbit—are then plotted as 2 excitation curves as a function of  $P_{beam}$  as measured on the central orbit.  $\eta$  is then given by

$$\eta = \frac{\Delta f_{peak}/f_{peak}}{\Delta P_{peak}/P_{peak}} \quad (7)$$

where  $\Delta f_{peak}$  and  $\Delta P_{peak}$  are the difference in revolution frequency and momentum between the peaks of the two

excitation curves. The accuracy of this method depends on how well the beam position can be controlled. Each point on the side orbit should have the same orbit length, and each point on the central orbit should have the same orbit length. To the extent that this is true, errors in the beam energy measurement will not enter into this determination of  $\eta$ . This is accomplished by careful use of the movable 4-8 GHz momentum stochastic cooling pickup. The position of the beam at the A20 high dispersion region is determined by the position of the 4-8 pickup because the beam will tend to center itself under the pickup due to the action of stochastic cooling.

Table 1 lists the values of  $\eta$  obtained by the 3 different measurement techniques. Except when the double scan technique is applicable, we use the synchrotron frequency method of determining  $\eta$  and attach to it an uncertainty of  $\pm 10\%$ .

Table 1  
 $\eta$  measurements

$P_{beam}$ (Mev/c)	Machine lattice	$\eta$ ( $\gamma_T$ )	$\eta$ ( $f_s$ )	$\eta$ (double scan)
4065	1	.0186	.0185	.0182
5550	1	-.0046	-.0053	x
5550	2	-.0104	-.0113	x
5730	1	-.0064	-.0068	x
5730	2	-.0122	-.0135	x
6230	1	-.0109	-.0105	-.0094
6230	2	-.0109	-.0115	x

## III. ENERGY MEASUREMENT

### A. Basic Technique

The relativistic  $\beta$  of the beam particle is given by

$$\beta = fL/c \quad (8)$$

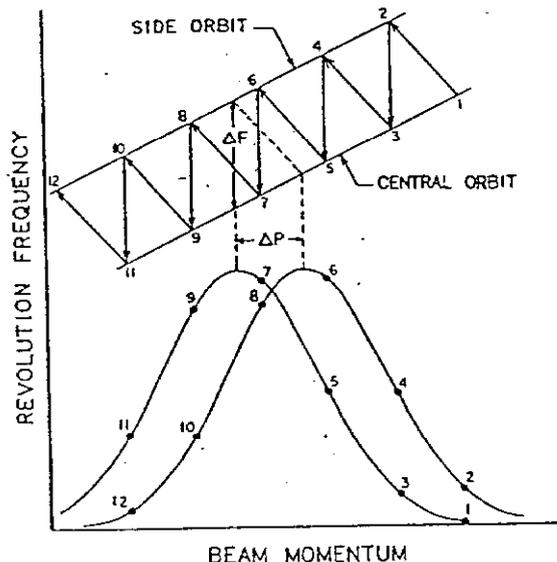


Figure 2: Graphical representation of double scan. Excitation curves are shown also.

where  $f$  is the revolution frequency,  $L$  is the orbit length ( $\sim 474050$  mm), and  $c$  is the speed of light. The error in the beam momentum is then given by

$$\frac{dp}{p} = \gamma^2 d\beta/\beta = \gamma^2 \left( \frac{df}{f} + \frac{dL}{L} \right). \quad (9)$$

$f$  is extracted from the frequency spectrum with an uncertainty of  $2/10^7$  primarily due to the error in the determination of the peak of the spectrum. The spectrum analyzer is calibrated to better than  $1/10^7$  with an HP5335A frequency counter. The major source of error in  $p$  comes from  $dL$  which is calculated from the Beam Position Monitor (BPM) data, and is  $\sim 1$ mm.

### B. Orbit Length Calculation

The orbit length is given by

$$L = L_{ref} + \delta L \quad (10)$$

where  $L_{ref}$  is the known orbit length of a reference orbit obtained from an energy scan of an accurately measured charmonium state. The uncertainty in  $L_{ref}$  is determined by the uncertainty in the mass of the resonance:

$$\delta L_{ref} = \frac{L_{ref} \cdot M_{\Psi'} \cdot \delta M_{\Psi'}}{p^2 \cdot \gamma} = .7mm. \quad (11)$$

The length along an arbitrary path is given by

$$L = \int \left[ \left( \frac{dz}{ds} \right)^2 + \left( 1 - \frac{z}{r} \right)^2 \right]^{1/2} ds \quad (12)$$

where the integral is over a reference curve  $s$ ,  $z$  is the lateral displacement from the reference curve, and  $r$  is the local radius of curvature. In our case  $\frac{z}{r}$  and  $\frac{dz}{ds}$  are  $\ll 1$  and eq. (12) can be reduced to

$$L = \int ds + \int \frac{z}{r} ds = L_{ref} + \sum_{i=1}^{30} \frac{z_i}{r_i} l_{dipole} \quad (13)$$

where the sum is over the 30 main dipoles in the Accumulator. The contributions from other magnets is negligible.

In the simplest approximation, the  $z_i$  at the center of the dipoles can be calculated from the orbit difference measurements ( $\Delta BPM_j$ ) at the nearest BPMs by extrapolating through the quadrupoles using the thin lens approximation. In this case

$$\delta L = \sum_{j=1}^{48} C_j \cdot \Delta BPM_j \quad (14)$$

where  $\Delta BPM_j$  ranges from 0 to  $\pm 5$ mm.

This estimate of  $\delta L$  does not account for a possible difference in curvature between the reference orbit and current orbit. To correct this, a more generally applicable technique has been developed. The deviation from the reference orbit is treated as a superposition of dipole kicks

from all of the horizontally bending dipole elements in the Accumulator plus a  $\Delta p/p$  error:

$$z_j(\bar{\theta}, \Delta p/p) = \frac{\sqrt{\beta_j}}{2 \sin \pi \nu_x} \sum_{i=1}^{N_d} \sqrt{\beta_i} \theta_i \cos(\pi \nu_x - \Delta \phi_{ij}) + D_j \frac{\Delta p}{p} \quad (15)$$

where the sum extends over all dipole elements in the Accumulator.  $\bar{\theta}$  and  $\Delta p/p$  in eq. (15) are determined from a least squares fit to the BPM difference measurements subject to the constraint that the net  $\Delta p/p$  effect of the dipoles is zero. The resulting  $\bar{\theta}$  and  $\Delta p/p$  are then used to calculate the  $z_i$ .

### C. Beam Position Monitors

Most of the error in the orbit length measurement comes from the BPMs. The orbit length is calculated from a large number of closed orbit measurements averaged together, and thus the error is dominated by systematics. Drift of electrical offsets, nonlinearities in the electronics, miscalibration, and a finite-sized LSB in the ADC all contribute a total estimated error in  $\delta L$  of  $\sim 1$ mm. During the double scan, any measured orbit length deviation must come from either variations in the dipole power supply regulation or systematic BPM errors. The orbit deviation at location  $i$  from  $N$  random dipole kicks around the ring is given by

$$\langle \delta z_i^2 \rangle^{1/2} = \frac{(\beta_i \langle \beta \rangle)^{1/2}}{2\sqrt{2} \sin \pi \nu} N^{1/2} (\delta \theta)_{rms}. \quad (16)$$

Using  $(\delta \theta)_{rms}/\theta = 1.4 \times 10^{-5}$  gives  $dL \approx .17$ mm from dipole regulation and ramps. The observed orbit deviations during the double scan were  $\sim 1$ mm, and therefore we conclude this comes almost entirely from the BPMs.

Several problems with the BPMs have recently been corrected and it is believed that the systematic error in  $\delta L$  can be reduced to  $\sim .25$ mm.

## IV. CONCLUSIONS

The momentum width of stochastically cooled coasting beam in the Accumulator can be measured to an accuracy of 10%, and several different measurement techniques provide independent checks on this. Beam energy can be measured to an accuracy estimated to be  $1/10^4$ . Further reduction in this error is expected with a more exact orbit length calculation and an improved BPM system.

## V. REFERENCES

- [1] V. Bharadwaj et al., "Operation of the Fermilab Accumulator for Medium Energy Proton-Antiproton Physics," in *Proceedings of the European Particle Accelerator Conference, Nice, France, June 1990*, pp 617-619.