Fermi National Accelerator Laboratory

FERMILAB-Pub-92/357

Measurement of the Circulating Muon Flux in the Fermilab Debuncher Ring

A. Bross, M. Gormely, C. Kim, S. O'Day, H. Park

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

Y. Ho, W. Lee, E. Mannel

Columbia University
538 W. 120th Street, New York, New York 10027

M. Murtagh

Brookhaven National Laboratory
Upton, New York, 11973

December 1992

Submitted to *Nuclear Instruments and Methods*

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

MEASUREMENT OF THE CIRCULATING MUON FLUX IN THE FERMILAB DEBUNCHER RING

A. Bross[a], M. Gormely[a], Y. Ho[b], C. Kim[a], W. Lee[b], E. Mannel[b], M. Murtagh[c], S. O'Day[a], H. Park[a]

[a]Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510

[b]Columbia University, 538 West 120th Street, New York, NY 10027

[c]Brookhaven National Laboratory, Upton, NY 11973

Abstract

Using a novel experimental technique, we have measured the flux of pions, electrons, muons, and antiprotons which are injected into and circulate in the Fermilab Debuncher ring. The experimental technique relied upon the use of a non-destructive, rf pickup to measure the bunch structure of the beam on a turn-by-turn basis. The measured muon to antiproton ratio is $\frac{\mu^-}{\bar{p}} = 1.0 \pm 0.2$, and the ratio of muons to protons on target is $\frac{\mu^-}{poT} = 2.0 \pm 0.4 \times 10^{-5}$.

Submitted to *Nuclear Instruments and Methods*

1 Introduction

To date, the only operational μ storage rings have been those built to obtain measurements of the μ (g-2) factor.[1, 2] However, the existence of a high energy μ storage ring would make it possible to produce an intense beam of ν_e's of sufficient energy to open new opportunities in ν_e physics and provide the means to explore, in detail, $\nu_e \rightarrow \nu_\tau$ and $\nu_e \rightarrow \nu_\mu$ mixing. The storage ring approach to these studies is very attractive for several reasons: flux normalization can be very precise; the neutrino energy spectrum is very well understood; and backgrounds should be very small and precisely calculable. It has been pointed out[3] that the Fermilab Debuncher might function as an efficient μ storage ring.

The Fermilab $\bar{p}$ source includes a high-intensity target station, transport beam lines (AP-1 through AP-4), the Debuncher ring, and the Accumulator ring, Figure 1. The Debuncher ring is a 9 GeV storage ring with a circumference of 505 meters. The Debuncher's primary purpose is to reduce, by bunch rotation, the large momentum spread of the $\bar{p}$ beam coming from the production target. It also uses stochastic cooling to reduce the transverse emittance of the beam. The $\bar{p}$'s are stacked and stored in the Accumulator prior to injection into the Main Ring. During normal collider running, the Debuncher accepts negative secondaries which originate at the $\bar{p}$ production target and are transported through the AP-2 beam line. Secondaries whose phase space coordinates lie within the momentum acceptance [8.9 GeV/c $\pm$ 2%] and transverse admittance [$A(x) = A(y) = 25\pi\text{mm} \times mrad$] of the Debuncher ring are injected and captured in the Debuncher. The particle composition of the first-turn beam in the Debuncher is dominated by π's, but it contains e's, $\bar{p}$'s, and μ's as well.

2 Experimental

To estimate the μ flux which is captured in the Debuncher, we use a mixture of experimental data coupled with relatively straight-forward calculations. During normal collider running, π fluxes have been measured at a variety of locations which are shown in Figure 2. The measurements in the AP-2 transfer line, at quads 704, 728, and 733, were made using ion chambers IC-704, IC-728, and IC-733, respectively, while at location D102 in the Debuncher ring, the measurement technique used a non-destructive rf pickup which is sensitive to, and relies upon, the bunch structure of the beam. The measured π fluxes (per 10^{12} protons on target) are summarized in Table 1.

Table 1: Measured π Flux (per 10^{12} protons on target) at Various Locations

Location	π Flux $\pm 20\%$ ($\times 10^8$ particles)
IC-704	100.
IC-728	8.7
IC-733	8.3
D102	5.2

To determine the μ/π ratio at injection into the Debuncher, we have used the ray tracing program DECAY TURTLE and lattice function calculations to simulate π production and the subsequent decay and transport of π's and μ's. The simulation considers only π's produced within a transverse emittance of 22π mm*mrad and discards any π or μ which strikes a magnet pole tip or any π or μ whose momentum lies outside the momentum acceptance of the Debuncher ($\delta P/P = \pm 2\%$). Using this simulation, we have calculated the number of π's and μ's which are injected onto the closed orbit of the Debuncher, and obtain:

$$(\mu/\pi) \text{ Injected into Debuncher} = .018.$$

After three turns (one π lifetime = 1 turn), one finds:

$$(\mu\text{'s (total captured)})/(\pi\text{'s (injected into Debuncher)}) = .025.$$

Then, in order to calculate the ratio of the total number of μ's captured in the Debuncher to the number of protons on target, one uses the number of π's measured at IC-728 and corrects this number (8.7×10^8) by the fraction (0.88) of π's that decay between IC728 and the injection point. Thus the predicted number of μ's captured is $0.025 \times 0.88 \times 8.7 \times 10^8 = 1.9 \times 10^7$, and we have:

$$\frac{\mu\text{'s Captured in Debuncher}}{\text{Protons on Target}} = 1.9 \times 10^{-5}.$$

Since the typical $\overline{p}$/(protons on target) ratio during normal collider operations is $(1.8\pm0.2)\times 10^{-5}$, we predict that $\mu/\overline{p} \simeq 1$ in the Debuncher.

We have also used the rf pickup to make a "direct" measurement of the flux of μ's in the Debuncher by measuring the bunch structure of the beam on a turn-by-turn basis. The beam arrives in the Debuncher, at the location of the pickup (D102), in 84 narrow bunches ($\sigma_t \approx$ 1 nsec) with a bunch spacing of about 18 nsec. At this point, the fast particles (π's, μ's and e's) are separated from the slow particles ($\overline{p}$'s) by about 8 nsec, since the distance between the target and D102 is approximately 455 m. Hence, π's, μ's and e's can be distinguished from $\overline{p}$'s by looking at the time structure of the output from the rf pickup. As the beam circulates in the Debuncher, the $\overline{p}$'s are retarded in time with respect to the π's, μ's and e's by approximately 9 ns (or about $\frac{1}{2}$ of a bunch spacing) for each revolution. Therefore, after 1 turn, the $\overline{p}$'s are delayed approximately 1 bunch spacing with respect to the π's, μ's and e's. $\overline{p}$ bunch 1 is in time with bunch 2 of the π's, μ's and e's, $\overline{p}$ bunch 2 is in time with bunch 3 of the π's, μ's and e's, etc. After turn 2, the $\overline{p}$'s are retarded another 9 ns with respect to the fast particles and are again separated in time. Therefore, only for the odd turns are the $\overline{p}$'s separated from the fast particles. The π's decay in a few turns ($\gamma c\tau_\pi \approx$ 1 turn), while the electrons spiral into the low energy edge of the machine, due to the emission of synchrotron radiation, and are completely lost after 14 turns. After turn number 14, the only particles left are μ's and $\overline{p}$'s.

The results of turn-by-turn measurements made in 1987[4] are summarized in Figure 3. In these data, there is no indication of a signal representing circulating μ's - which are expected to be the only fast particles remaining beyond turn number 14. The absence of a "bunched" μ signal for turn 15, however, is not necessarily an indication that there are no μ's in the debuncher. This can be understood by calculating the μ debunching time:

$$T_D = \frac{(\Delta T)_{rf}}{\eta\frac{\delta P}{P}}.$$

For μ's, η = .017 and T_D = 27.6 μsec (17 turns). Thus the μ's are completely debunched after 17 turns and, consequently, induce no signal on the rf pickup. We have checked the rate at which μ's debunch by performing a simulation which uses the longitudinal difference equations to study the bunch shape as a function of turn number in the Debuncher. The results, shown in Figure 4 for a bunch injected (N=1) with $\Delta t = \pm 0.5$ nsec and $\delta P/P = \pm$ 2.0%, illustrate the rate at which the injected μ's debunch and indicate complete debunching in 15 - 17 turns. The rf pickup technique is thus not sensitive to circulating μ's in turns beyond turn 14.

An examination of Figure 4 suggests that it is straightforward to measure the bunched μ signal by killing the electrons in the beam prior to injection into the Debuncher and then measuring the number of fast particles on turns 5 - 11 using the rf pickup. The most appealing method for killing the electrons is to insert a lead radiator at the end of the AP-2 transport line. Between the last two quadrupoles in this line (IQ32 and IQ33), the betatron amplitudes are reasonably small (4 m - 8 m), and the emittance blowup of the μ bunches due to multiple scattering should be small.

We have studied the effectiveness of radiator thicknesses of 0.25, 0.50, and 1.0 radiation lengths on removing electrons from the beam at the end of the AP-2 transport line. The program EGS was used to determine the energy of the leading (maximum energy) electron exiting the radiator for electrons of energy 9.0 GeV incident on the radiator. (The simulation was also checked analytically using a formula from Tsai.[5] The results are shown in Figure 5. If we impose an 8.7 GeV cut on the electron energy for it to be captured in the Debuncher, then, for radiator thicknesses of 0.25, 0.50, and 1.0 radiation length, 40%, 11%, and 0.15%, respectively, of the incident electrons will survive the cut. We have chosen to use a radiator thickness of 1 radiation length in order to guarantee that electrons do not contribute to our μ signal.

3 Results

Our measurements were performed, parasitic to the running of E-760, during the 1991 Fermilab Fixed Target run. A one radiation length lead absorber was inserted into the AP-2 transport line, completely eliminating electrons from the beam. We used a Tektronix DSA 602 digital sampling analyzer to measure the time structure of the signal from the pickup. This instrument has an analog bandwidth of 1 GHz; it samples at 2 Giga-samples/second; and it has a memory depth of 32,000 samples. We could, therefore, capture data for nine turns during a measurement. The data were taken in the following manner. Each measurement was an average over 64 pulses (each pulse containing 84 bunches). We first captured data for turns 1 through 9 and then set the DSA trigger delay to capture turns 9 through 17. The two data sets were normalized such that the $\overline{p}$ flux for turn 9 was equal in both data sets. Figure 6 shows the raw data for approximately 10 bunches for turns 3,4, and 5. In turns 3 and 5, we see the 8 nsec separation between the $\beta = 1$ particles and the $\bar{p}$'s. On the even turns, the $\bar{p}$ bunches are approximately in time with the $\beta = 1$ particles and, thus, the rf bunch structure shows only one peak. Therefore, in order to determine the individual particles fluxes, only data from the odd turns are usable. For each of the odd turns between turns 3 and 11, we averaged 60 of the 84 bunches to produce a "bunch averaged" time structure for each of the turns. The data for turns 5,7,9, and 11 are shown in Figure 7. These data were fit to two Gaussians plus a constant (the fit curves are also shown in Figure 7). From the fit parameters, (amplitude and σ) we could then determine, for each turn, the area under the two Gaussians. These numbers are directly proportional to the flux of $\beta = 1$ particles and $\bar{p}$'s. In order to determine the flux of μ's, we then only had to make a correction for the number of π's remaining at each turn. In order to do this, we used the measured $\beta = 1$ particle flux from turn 1 and assumed that this entire flux was due to π's. We then calculated the number of π's remaining after each turn and subtracted the corresponding number from the measured $\beta = 1$ flux for a given turn to determine the number of μ's. Our results are shown in Table 2 for turns 3-11.

Table 2: Particle Flux Measurements

Turn	Flux($\beta = 1$)	Flux($\bar{p}$)	$\frac{(\beta=1)}{\bar{p}}$	$\frac{\mu}{\bar{p}}$
1	33572	—	—	—
3	6251	2126	2.94	0.80
5	2232	1287	1.73	1.12
7	1597	1171	1.36	1.27
9	1306	1132	1.15	1.14
11	934	1122	0.83	0.83

4 Conclusions

We have measured the ratio of μ's to $\overline{p}$'s in the Fermilab Debuncher ring. We find a $\mu/\overline{p}$ ratio of 1.0 ± 0.2 and the ratio of muons to protons on target is $\frac{\mu^-}{poT} = 2.0 \pm 0.4 \times 10^{-5}$. This is in good agreement with the $\mu/\overline{p}$ ratio expected from measured values for the number of π's injected into the Debuncher and simulations of $\pi \rightarrow \mu$ decay and subsequent μ capture.

References

[1] F. Combley, F.J.M. Farley, and E. Picasso, Physics Reports **68** (1981) 93.

[2] AGS 821, *Muon g-2 Design Report*, March, 1989.

[3] W. Lee and D. Neuffer, in conference procedings, *New Directions in Neutrino Physics at Fermilab*, September 14-16, 1988, pg. 159-173.

[4] Gerald Dugan, private communication.

[5] Tsai, Yung-Su, Review of Modern Physics, Vol. **46**, No. 4, 815, (1974).

Figure Captions

Figure 1. Fermilab Debuncher Ring site map.

Figure 2. The Debuncher ring.

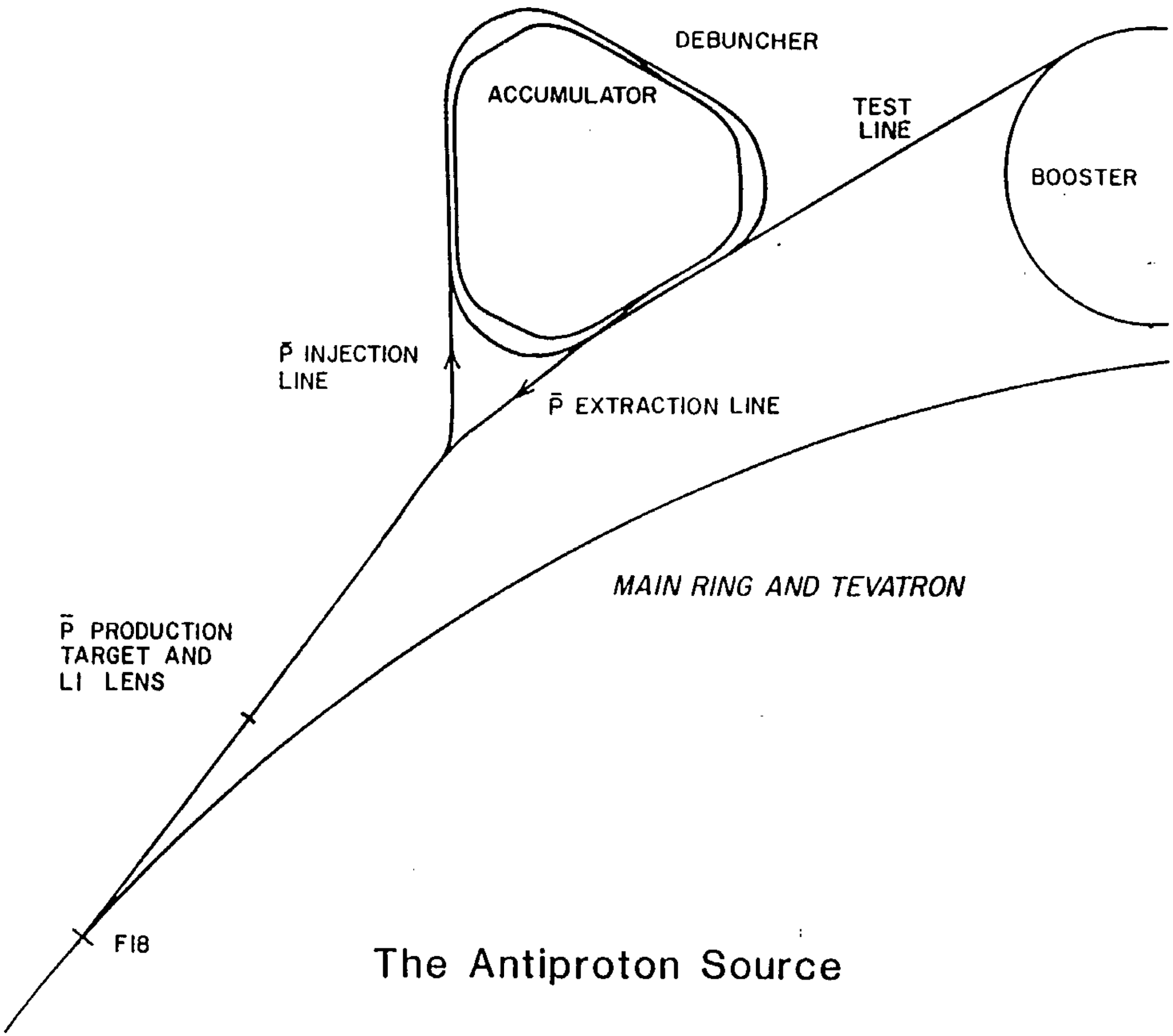
Figure 3. Debuncher rf-pickup analysis of circulating beam.

Figure 4. μ bunch shape by turn number.

Figure 5. Leading electron energy distributions after radiator thicknesses of a) 0.25, b) 0.50, and c) 1.0 radiation length with an incident electron energy of 9.0 GeV.

Figure 6. Raw data bunch (time) structure for turns a) 3, b) 4, and c) 5. Each channel in x (time) corresponds to 500 psec.

Figure 7. "Bunch averaged" data for turns 5,7,9, and 11. Each channel corresponds to 500 psec.



The Antiproton Source

FIGURE 1

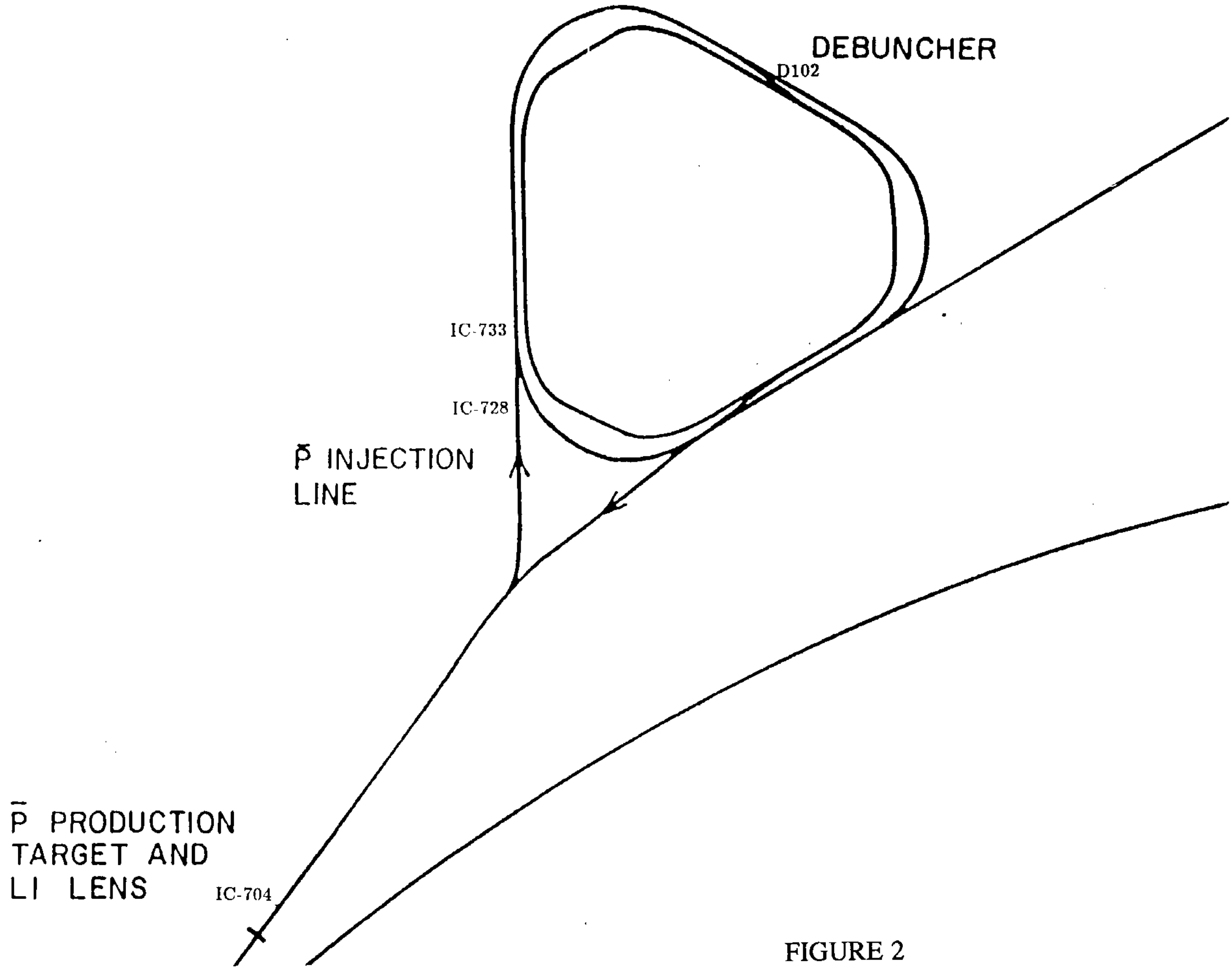
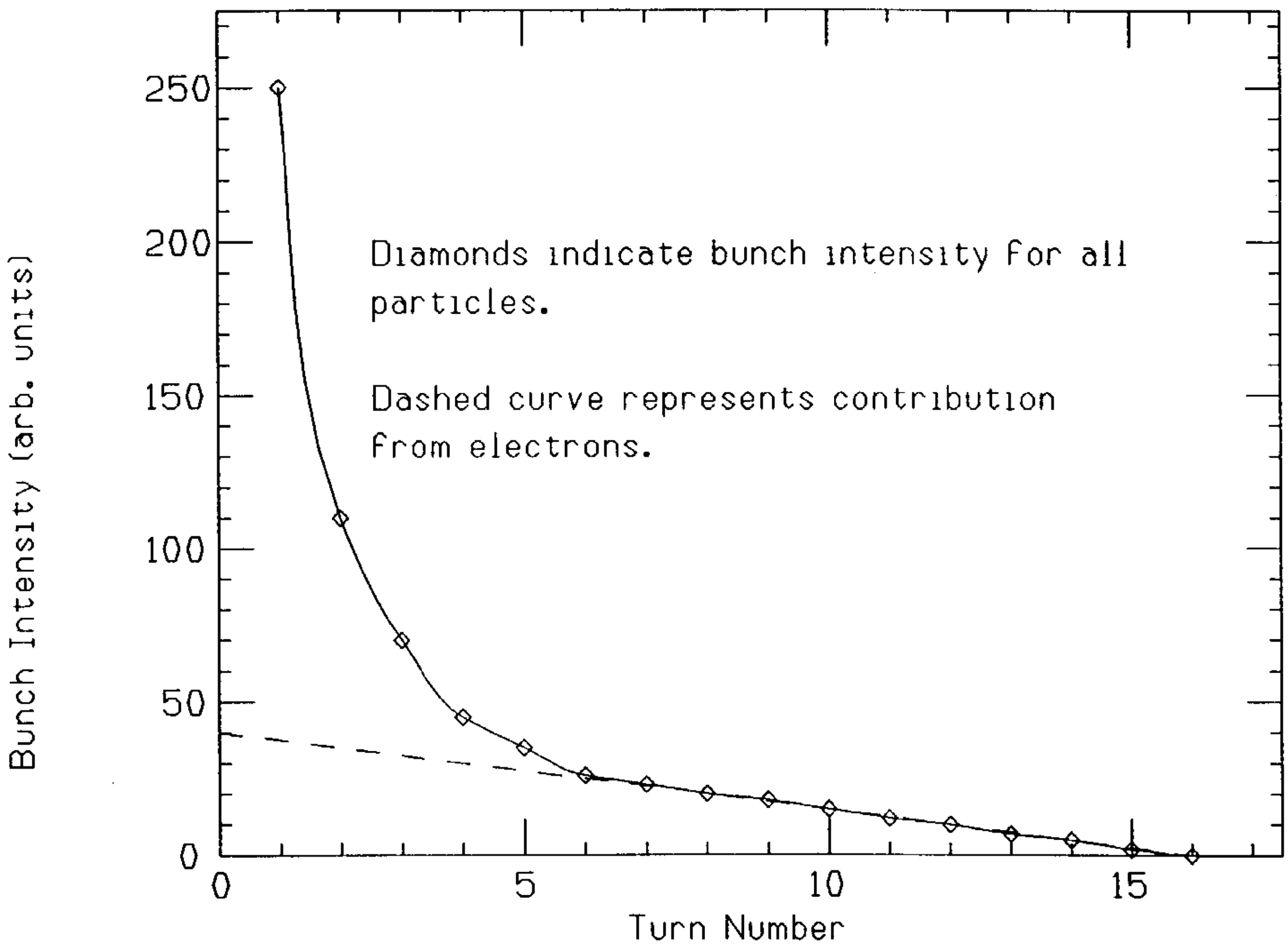

DEBUNCHER
D102
IC-733
IC-728
P̄ INJECTION LINE
P̄ PRODUCTION TARGET AND LI LENS
IC-704

FIGURE 2



Diamonds indicate bunch intensity for all particles.
Dashed curve represents contribution from electrons.
Bunch Intensity (arb. units)
250
200
150
100
50
0
0
5
10
15
Turn Number

FIGURE 3

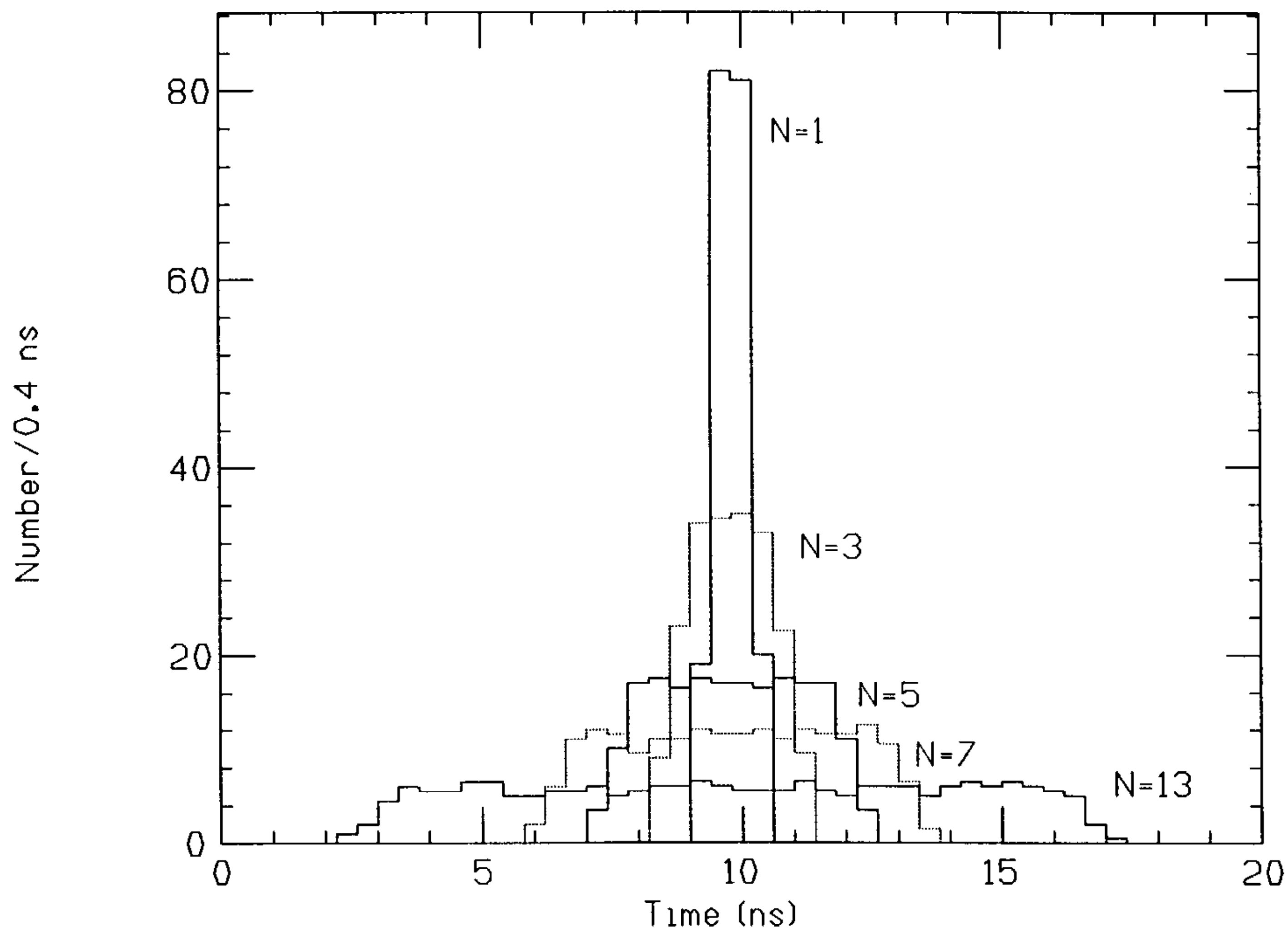
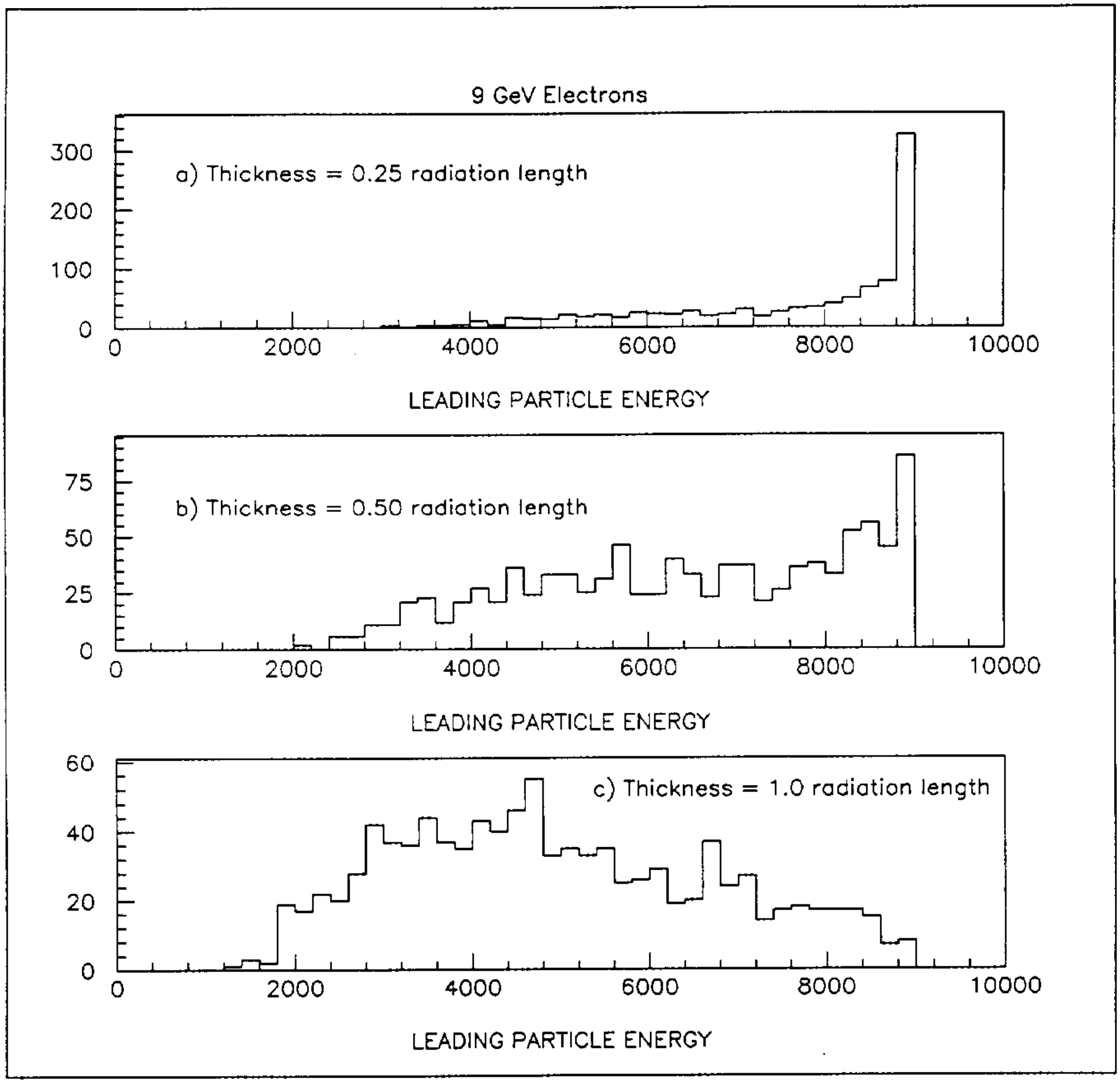


FIGURE 4



9 GeV Electrons
a) Thickness = 0.25 radiation length
b) Thickness = 0.50 radiation length
c) Thickness = 1.0 radiation length
LEADING PARTICLE ENERGY
LEADING PARTICLE ENERGY
LEADING PARTICLE ENERGY
0
2000
4000
6000
8000
10000
300
200
100
75
50
25
60
40
20

FIGURE 5

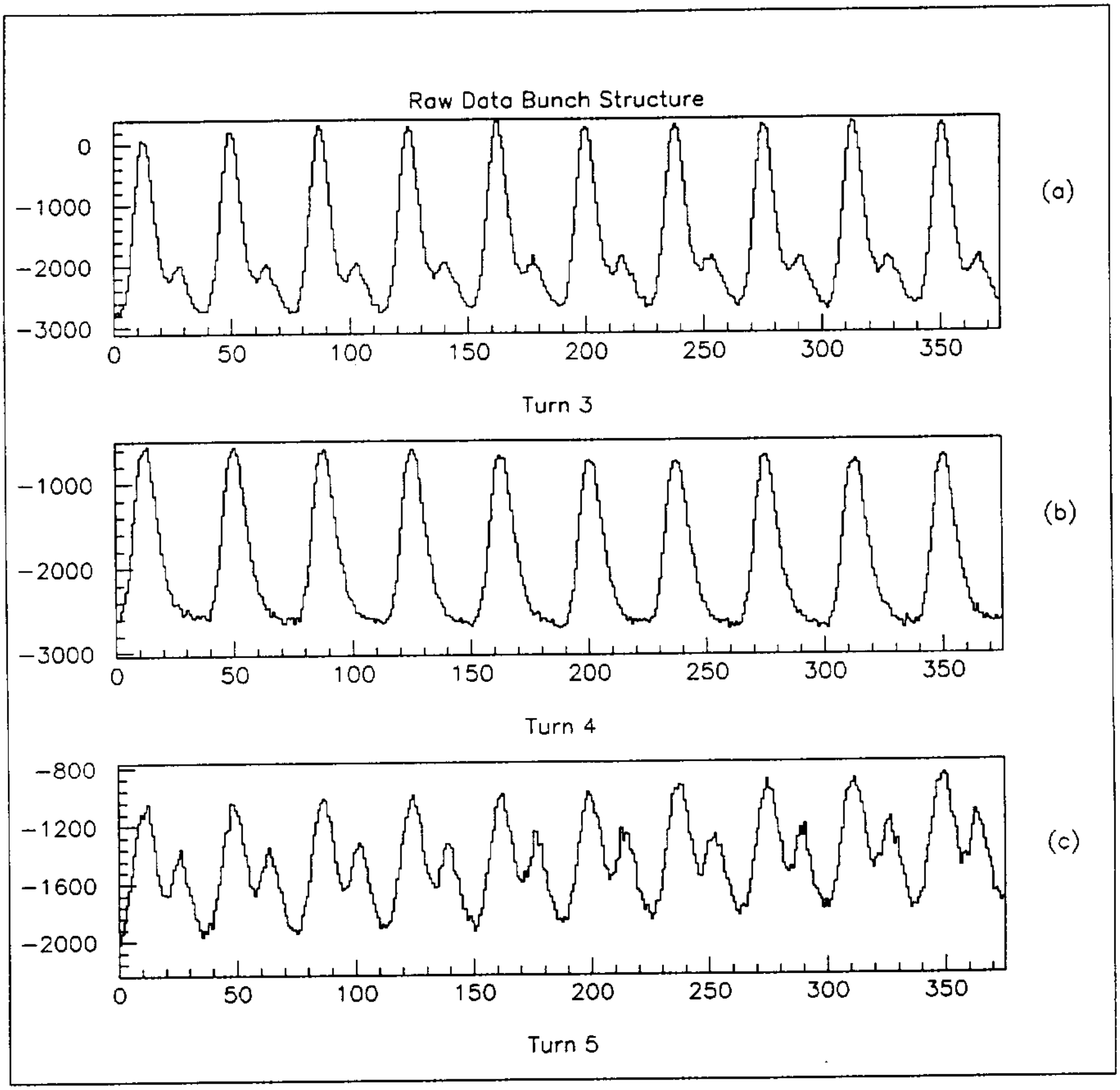

Raw Data Bunch Structure
(a)
Turn 3
(b)
Turn 4
(c)
Turn 5
0
−1000
−2000
−3000
−800
−1200
−1600
−2000
0
50
100
150
200
250
300
350

FIGURE 6

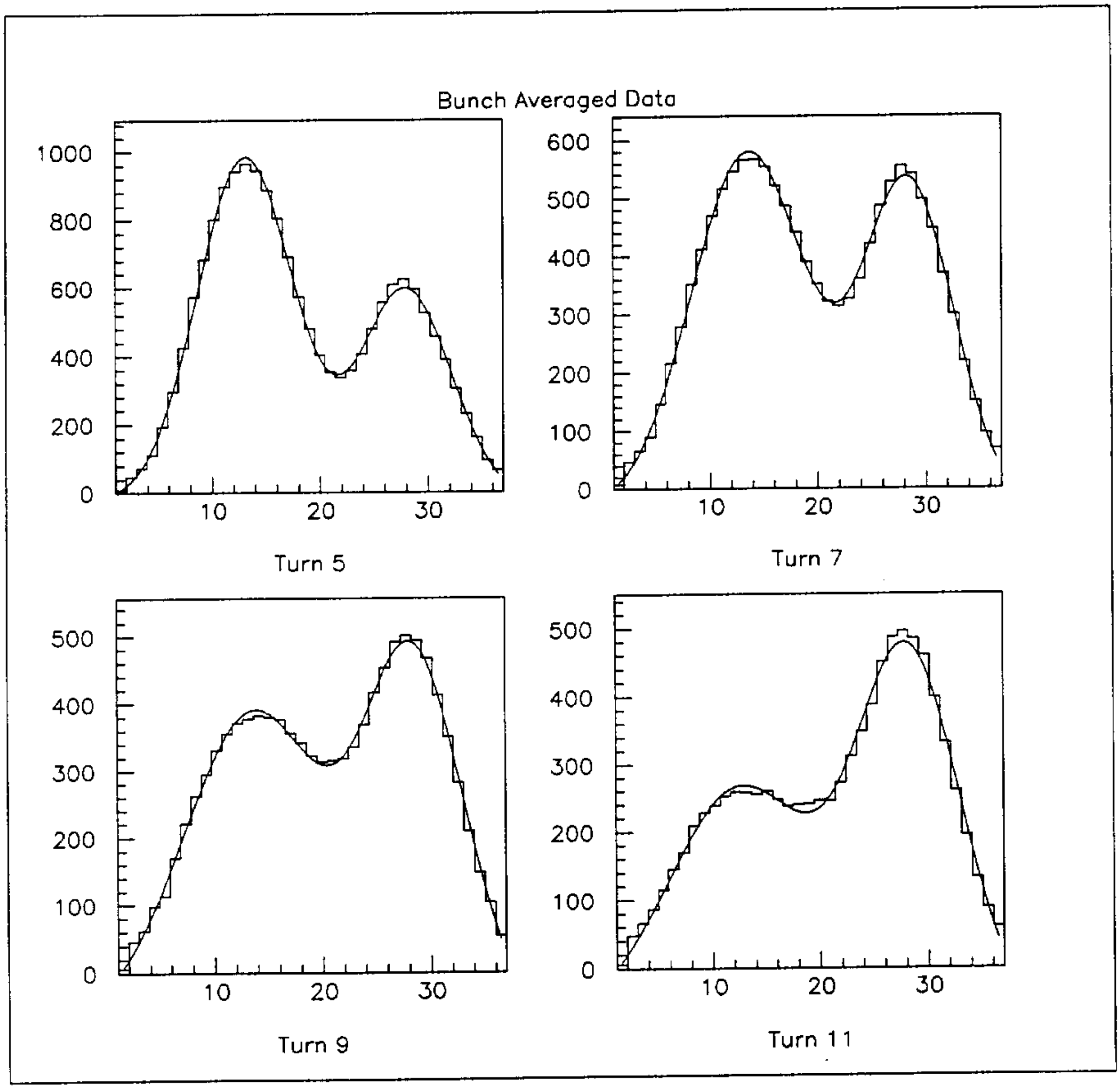

Bunch Averaged Data
1000
800
600
400
200
0
10
20
30
Turn 5
600
500
400
300
200
100
0
10
20
30
Turn 7
500
400
300
200
100
0
10
20
30
Turn 9
500
400
300
200
100
0
10
20
30
Turn 11

FIGURE 7