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# Low Energy $\bar{p}$ Physics at FNAL

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# Low energy $\bar{p}$ physics at FNAL

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**Abstract**

The charmonium formation experiment is the only low energy $\bar{p}$ experiment at FNAL. This paper describes the performance of the Fermilab $\bar{p}$ Accumulator during fixed target run for the experiment and the planned upgrades. We also discuss the proposal for the direct CP violation search in $\bar{p} + p \rightarrow \bar{\Lambda} + \Lambda \rightarrow \bar{p}\pi^+ + p\pi^-$.

# 1. INTRODUCTION

The Fermilab $\bar{p}$ Accumulator was built as a $\bar{p}$ collection and storage ring for the Tevatron $\bar{p}p$ colliding beam program[1]. However, it was realized [2] that it could also be used for low energy $\bar{p}$ experiment. Up to now, the charmonium resonant formation experiment (E760) is the only low energy $\bar{p}$ experiment at Fermilab. A detailed description of Accumulator operation for E760 can be found in Ref. 3. The same reference also describes the experimental techniques and the measurements of the beam energy and the energy spread. In Table 1 we list some of the parameters of the Accumulator for reference.

Table 1
The Accumulator Parameters

| | |
|---|---|
| maximum total energy | 8.9 GeV |
| $\gamma_t$ | 5.43 |
| circumference | 474.05 m |
| revolution frequency | 0.629 MHz |
| maximum beta function | 33 m |
| maximum dispersion | 8.9 m |
| beta function at E760 | 7 m |
| dispersion at E760 | 0 m |

# 2. FUTURE UPGRADES

## 2.1 Luminosity

The experiment benefits from Fermilab's commitment to improve the $\bar{p}p$ colliding beam program. The planned upgrades, collectively known as Fermilab III, will increase the Tevatron colliding luminosity to better than $5.0 \times 10^{31}$ cm$^{-2}$sec$^{-1}$. $\bar{p}$ production rate will increase from $2.0 \times 10^{10}$ at the end of last collider run to $17.0 \times 10^{10}$ with the new Main Injector. The upgrades and their schedules are listed in Table 2.

Table 2
Planned upgrade

| | 88-89 collider | phase I collider | phase II collider | Fermilab III |
|---|---|---|---|---|
| When | 1989 | 1992 | 1993-??? | ??? |
| What's new | | $\bar{p}$ improvements | Linac | Main Injector |
| Production rate/hr | $2.0 \times 10^{10}$ | $4.0 \times 10^{10}$ | $6.0 \times 10^{10}$ | $17.0 \times 10^{10}$ |

The typical beam lifetime, peak luminosity and gas jet intensity achieved during the 1991 fixed target run are summarized in Table 3. $\tau_{on}$ and $\tau_{off}$ are beam lifetime with gas jet on and off respectively. $L_0$ and d are peak luminosity and gas jet density respectively. we expect the peak luminosity for the next fixed target run after the phase II collider run to increase by a factor of 3.

Table 3
1991 Fixed Target Run Summary

| Energy | $\tau_{on}$(hr) | $\tau_{off}$(hr) | $L_0(10^{30}$cm$^{-2}$sec$^{-1})$ | d($10^{14}$Atoms cm$^{-2}$) |
|---|---|---|---|---|
| 8.9 GeV | | 330 | | |
| $\psi'$ , $^1P_1$ , $\eta_c'$ | 89 | 350 | 9.1 | 0.35 |
| $J/\psi$ , $\eta_c$ | 59 | 240 | 3.5 | 0.35 |

The optimal integrated luminosity as a function of gas jet density is tabulated in Table 4. The integrated luminosity is optimized with the assumption that the overhead for deceleration and change over between data taking and $\bar{p}$ accumulation is 8 hours and the beam lifetime as a function of gas jet density is calculated from $\tau_{on}$ and $\tau_{off}$ in Table 3. In all cases, the optimal data taking time is $\approx 1$ beam lifetime. Note that the integrated luminosity does not scale with the gas jet density because the beam lifetime is almost inversely proportional to the gas jet density. We see that the goal of improving the integrated luminosity by a factor of 5 can be achieved if both the gas jet density and beam intensity increase by a factor of 3.

With five-fold increase of the integrated luminosity, we can expect $\approx 7$ pb$^{-1}$ per cycle. The cycle time ($= t_{stacking} + t_{overhead} + t_{data\ taking}$) at optimal running condition described in the previous paragraph is $\approx 90$ hours. To give the readers a feeling for the physics

Table 4
Optimal Integrated Luminosity

| d($10^{14}$Atoms cm$^{-2}$) | Integrated Luminosity |
|---|---|
| 0.35 | $\mathcal{L}$ |
| $2 \times 0.35$ | $\frac{5}{3}\mathcal{L}$ |
| $3 \times 0.35$ | $2\mathcal{L}$ |

opportunities possible, the number of events of $J/\psi \rightarrow e^+e^-$ and $^1P_1 \rightarrow J/\psi + \pi^0$ with the $J/\psi$ sequentially decays to $e^+e^-$ are calculated. The beam energy spread is assumed to be the same as that of the 1990–1991 run during data taking at the $^1P_1$ energy, i.e., $\frac{\sigma_p}{P}$ is $2.0 \times 10^{-4}$. The $J/\psi$ and $^1P_1$ production cross sections and the detection efficiencies are taken from Ref. 3 and 4. We find we can get $1.5 \times 10^5$ $J/\psi \rightarrow e^+e^-$ events per cycle. For the decay mode of $^1P_1$ mentioned above, we obtain 32 events per cycle.

## 2.2 Stochastic cooling requirements

The RMS emittance growth due to beam-gas scattering and intrabeam scattering are given in Table 5. The beam and gas jet intensities are assumed to be those of the 1990–1991 fixed target run. Specifically, the beam current is 40 mA and jet density $0.35 \times 10^{14}$atoms cm$^{-2}$. The beam 95 % emittance is $2\pi$ mm-mrad ( RMS $\epsilon = 0.33$ mm-mrad), and $\frac{\sigma_p}{P}$ is $2.0 \times 10^{-4}$ and $1.5 \times 10^{-3}$ at the $^1P_1$ and $\eta_c$ energies respectively. Note that at both energies, even in the case that the gas jet is on, the intrabeam scattering dominates the beam gas scattering.

Table 5
Horizontal Emittance Growth Rate $\frac{1}{\epsilon}\frac{d\epsilon}{dt}$ (sec$^{-1}$)

| Energy | Beam-gas (Gas Jet Off) | Beam-gas (Gas Jet On) | Intrabeam |
|---|---|---|---|
| $^1P_1$ | $1.30 \times 10^{-5}$ | $3.43 \times 10^{-5}$ | $19.2 \times 10^{-5}$ |
| $\eta_c$ | $3.07 \times 10^{-5}$ | $7.82 \times 10^{-5}$ | $15.4 \times 10^{-5}$ |

In the scenario that the beam intensity will be a factor of 3 higher, the beam heating due to intrabeam scattering will also increase by a factor of 3. But the stochastic cooling rate will be reduced by a factor of 3 because the cooling rate is inversely proportional to the beam intensity. To maintain the same emittances as in 1991 with three times more beam, the stochastic cooling system needs to be improved by a factor of 9 (3 for intrabeam scattering increase, 3 for cooling rate decrease).

$S_\omega\xi/n_T$ as a function of $\xi G$ is plotted[5] in Fig. 1. $S_\omega$ is the stochastic cooling rate at the center of symmetric beam frequency distribution $f(\omega)$, G is the system gain and $\xi = \pi N f(\omega)/n_T$ where $N$ is the total number of beam particles and $n_T$ is the total number of Schottky bands in the stochastic cooling frequency bandwidth. $S_\omega\xi/n_T$ is proportional to the cooling rate times the beam intensity. We would like to increase it by a factor of

9. We typically ran the cooling system at $\approx$ 1db signal suppression which corresponds to $S_\omega \xi / n_T = 0.6$. In Fig. 1 we see that it is possible to increase the cooling by a factor of 2. To get a factor of 9 improvement, a 8–16 GHz bandwidth system which corresponds to increase $n_T$ by a factor of 2 thus the cooling rate by a factor of 4 is required. Without the higher bandwidth system, we estimate the transverse emittance will be $\approx 4\pi$ mm-mrad and $\frac{\sigma_p}{P} \approx 4.2 \times 10^{-4}$. In other words, the transverse size (95% containment) of the beam at the interaction region is $\pm 0.5$ cm and the beam width (FWHM) $\Gamma_B$ is 1.5 MeV/c$^2$ in the center of mass at $^1P_1$ energy.

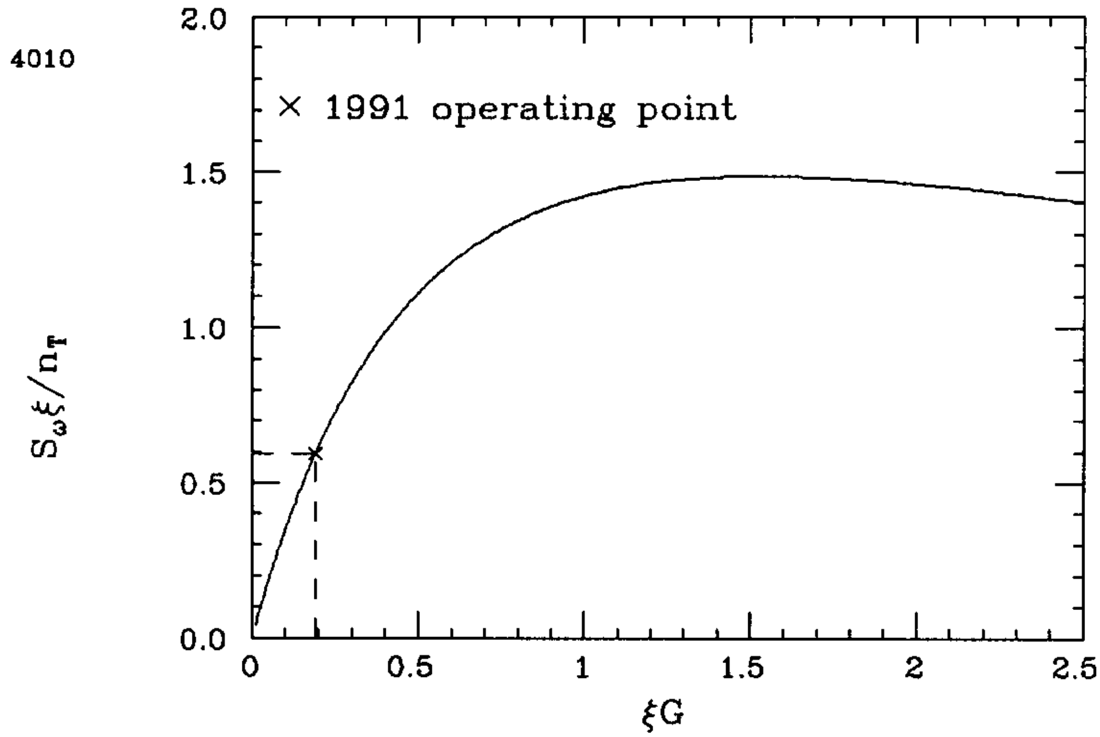


Figure 1: Stochastic cooling

# 3. DIRECT CP VIOLATION in $\bar{\Lambda}\Lambda$ DECAYS

With the high $\bar{p}$ production rate promised in the Main Injector era, a high-precision search for the direct CP violation in $\bar{p} + p \to \bar{\Lambda} + \Lambda \to \bar{p}\pi^+ + p\pi^-$ becomes possible. The experiment will use a stored $\bar{p}$ beam of 1.641 GeV/c interacting with a hydrogen gas jet to produce $\bar{\Lambda}\Lambda$ pairs exclusively. We can expect to measure the CP violating quantity A to an accuracy of $10^{-4}$ to $10^{-5}$.

The advantage of $\bar{p}p$ interactions comes from the fact that the initial state is CP invariant. This property of the initial state implies that final states must have identical CP symmetry if CP is conserved. Thus the observation of CP odd quantity is a signal of CP violation.

The CP violating quantities are measured by comparing the $\Lambda$ decay with the $\bar{\Lambda}$ decay. In particular, we are interested in comparing the angular distributions of the decays in the center of mass frames of the $\Lambda$ and the $\bar{\Lambda}$.

The angular distribution of the final baryon in the center of mass frame of the initial baryon is $1 + \alpha\mathcal{P}\cos(\theta_{cm})$ where $\mathcal{P}$ is the polarization of the initial baryon. The CP violating observable A of interest to us is usually defined as[6]:

$$A = \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}}, \tag{1}$$

A recent theoretical review[7] estimated this quantity to be between $10^{-4}$ and $10^{-5}$.

In the strong production process, $\bar{\Lambda}\Lambda$ will be produced with equal polarization normal to the production plane. This fact makes the life easier because the experimental observable is the product $\alpha\mathcal{P}$. Following the suggestion[8] by Donoghue et al. we can measure

$$\tilde{A} = \frac{N_p(up) - N_p(down) + N_{\bar{p}}(up) - N_{\bar{p}}(down)}{N} = \frac{1}{2}\mathcal{P}(\alpha + \bar{\alpha}) \tag{2}$$

for $\bar{\Lambda}\Lambda$ decays where up(down) refers to particles above or below the production plane defined by $\vec{p_i} \times \vec{\Lambda}$. Thus up(down) corresponds to $\vec{p_i} \times \vec{\Lambda} \cdot \vec{p_f} > 0 (< 0)$. Such counting asymmetry is relatively easy to measure. The statistical accuracy is

$$\delta A = \frac{1}{|\alpha\mathcal{P}|}\sqrt{\frac{2}{N}}. \tag{3}$$

The $\bar{\Lambda}\Lambda$ production cross section and polarization have been measured by PS 185[9]. The $\bar{\Lambda}$ production is peaked forward. The forward events are hard to detect because of the beam pipe. However, the forward events have small polarization and therefore do not contribute to the measurement ($\delta A \propto \frac{1}{p}$). We will use only the $\bar{\Lambda}$ events in the range of $-0.75 < \cos(\Theta_{cm}) < 0.3$ where $\Theta_{cm}$ is the production angle in the center of mass frame. In this region, the production cross section almost independent of $\cos(\Theta_{cm})$. The production cross section integrated over this region is 16.955 $\mu$b with an average polarization of 0.46.

Substitute in Eq. (3) $\alpha = 0.642$ and $\mathcal{P} = 0.46$, we get $N = 2.29 \times 10^9$ if $\delta A = 10^{-4}$. The efficiency of the detection is estimated from:

$$\epsilon = (Br)^2\ D. \tag{4}$$

Where $Br$ is the branching ratio of $\Lambda \rightarrow \pi p$, $(Br)^2 = 0.41$. $D$ is the combined efficiency which is assumed to be 50 %. We get $\epsilon = 0.2$. The total luminosity required is $6.75 \times 10^{38} cm^{-2}$ to produce $2.29 \times 10^9/0.2 = 1.14 \times 10^{10}$ $\bar{\Lambda}\Lambda$ pairs.

We will assume the $\bar{p}$ production rate to be $17 \times 10^{10}$ per hour in the Main Injector era. The maximum luminosity is limited by the $\bar{p}$ production rate. The rate of $\bar{p}$ consumed by the experiment cannot exceed the $\bar{p}$ production rate. The $\bar{p}p$ annihilation cross section ($\sigma$) is 52 mb at the energy of $\bar{\Lambda}\Lambda$ production. We will use 100 mb as a conservative value of the cross section in order to estimate the maximum luminosity. Since

$$L\sigma = \bar{p}\ consumed = \bar{p}\ produced = 17 \times 10^{10}/hour, \tag{5}$$

we find that the average luminosity is $4.5 \times 10^{32} cm^{-2} sec^{-1}$. To accumulate $6.75 \times 10^{38} cm^{-2}$ total luminosity, we need 15 days. Assuming 50% duty cycle, we can reach $10^{-4}$ statistical accuracy in 1 month.

To reach the statistical accuracy of $10^{-5}$ requires 100 times more integrated luminosity. This implies the duty cycle and the efficiency have to be near 100 % to have a reasonable chance of completing the experiment in a reasonable period of time. It also implies the need for strong beam cooling systems to reduce the beam loss as much as possible. We think a dedicated $\bar{p}$ storage ring is required.

Let d be the gas jet density in units of $10^{14}$ atoms/cm$^2$ and f be the beam revolution frequency. If the beam cooling is perfect, we find the lifetime $\tau$ of the beam is $\frac{1}{f}\frac{10^{11}}{d}$ since the beam loss is completely due to $\bar{p}p$ interaction and the interaction cross section is 100 mb. We also assume that we transfer $\bar{p}$ 's from the Accumulator every 8 hours because the Accumulator beam current cannot be too much higher than 100 mA ($10^{12}$ $\bar{p}$ ). Substitute the numbers in Eq. 5, we get

$$\frac{\Delta t}{\tau} = -\ln\left(1 - prod\Delta t \frac{qf}{I_{peak}}\right), \tag{6}$$

where $\Delta t = 8$ hours is the time between transfer and $prod\Delta t = 1.32 \times 10^{12}$ is the total number of $\bar{p}$ 's produced in $\Delta t$. $I_{peak}$ is the peak current of the storage ring and $I_{peak}/qf$ is the peak number of $\bar{p}$ 's. The left-hand side of the equation is plotted in Fig 2 in solid line and the right-hand side in dashed line. The three solid lines correspond to jet density of 1, 2, and $3 \times 10^{14}$ atoms/cm$^2$ and the dashed lines correspond to peak current of the storage ring of 0.25, 0.5, 0.75, and 1 Amp.

We see there are 4 possible solutions. Two of them correspond to $I_{peak} = 0.5$A. The first one corresponds to a smaller ring and higher jet density. The parameters are f=1.8 MHz (a ring of 1/3 the size of the Accumulator) and d=$3\times10^{14}$ atoms/cm$^2$. The beam lifetime is 5 hours. For the second one, the ring is larger but the jet density is lower. We have f=1 MHz (a ring of 5/8 the size of the Accumulator) and d=$2\times10^{14}$ atoms/cm$^2$. The beam lifetime is 14 hours. The jet density in either case is a factor 2–3 larger than planned for the E760 upgrade. If the jet density is limited to $1 \times 10^{14}$ atoms/cm$^2$, the solution will be a small ring (f=2 MHz) with very high peak current ($I_{peak} = 1$ A).

The model used above is simplistic but it gives correct relationships between the gas jet density, the peak current, and the size of the storage ring. Clearly, to get the highest integrated luminosity possible, all three factors have to be considered for a optimal design.

# 4. CONCLUSION

This paper has described the possible physics opportunities with the expected increasing $\bar{p}$ production at FNAL. The stochastic cooling upgrade for the Accumulator is important for the future experiments. The possibility of detecting direct CP violation at the $10^{-5}$ level is very interesting but requires much investment in building a new dedicated $\bar{p}$ storage ring for the experiment.

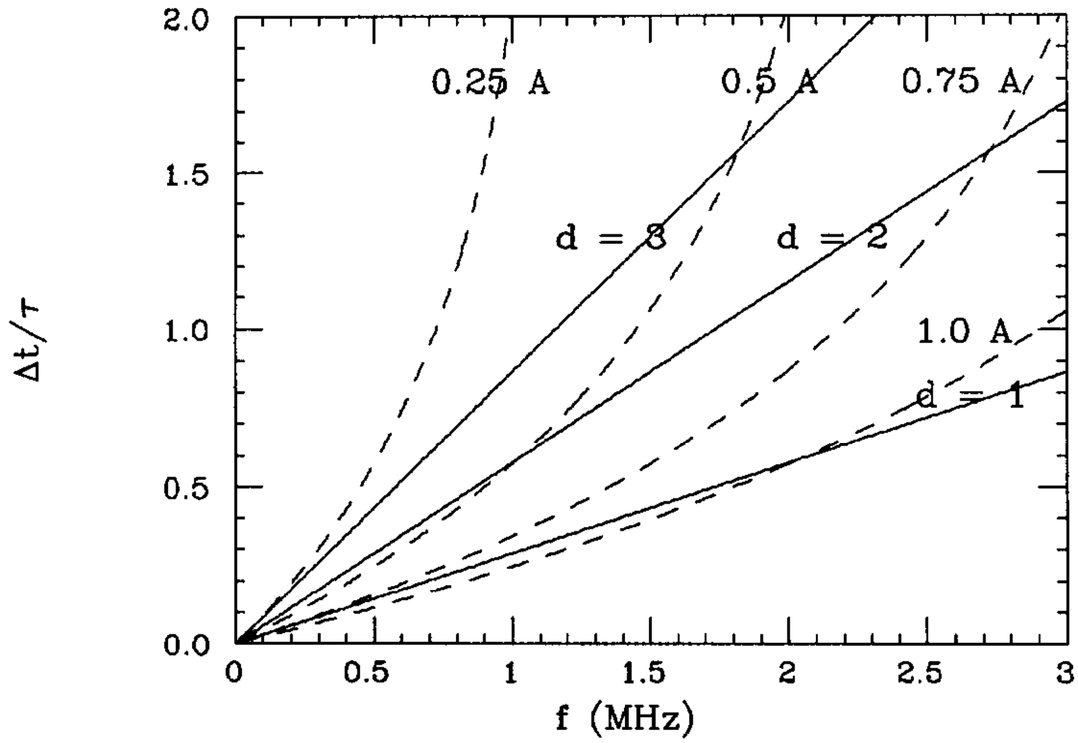


Figure 2: Size of the storage ring

# 5. REFERENCES


1 Design Report: Tevatron I Project, Fermi National Accelerator Laboratory, Batavia, IL (unpublished), Sept. 1984.

2 J. Peoples, Jr., in Proceedings of the Workshop on the Design of a Low Energy Antimatter Facility, edited by D. Cline, World Scientific Publishing Co, Singapore, 144 (1986).

3 E760 Collaboration (T.A. Armstrong et al.), "Measurement of the $J/\psi$ and $\psi'$ Resonance Parameters in the $\bar{p}p$ Annihilations," Fermilab-Pub-92/245-E, September, 1992. To be published in Physics Review D, Feb. 1993.

4 E760 Collaboration (T.A. Armstrong et al.), Phys. Rev. Lett. 69, 2337 (1992).

5 Joseph Bisognano and Christoph Leeman, LBL-14106.

6 J. F. Donoghue, X. G. He and S. Pakvasa, Phys. Rev. D34, 833 (1986).

7 X. G. He, H. Steger and G. Valencia, CERN-TH-6173/91.

8 J. F. Donoghue, B. R. Holstein and G. Valencia, Phys. Lett. B178, 319 (1986).

9 N. Hamann, this conference.