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Further Studies of Coupled Injection in Booster

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Study Period:	April, May, June, 2000
Participants:	L. A. Ahrens, C. J. Gardner, K. L. Zeno
Reported by:	C. J. Gardner
Machine:	Booster
Beam:	Gold Ions (Au^{32+})
Tools:	PIP
Aim:	Further Studies of Coupled Injection

Further Studies of Coupled Injection in Booster

L.A. Ahrens, C.J. Gardner, and K.L. Zeno

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The FY2000 commissioning of RHIC has given us the opportunity to once again examine the coupled injection of gold ions (Au^{32+}) in the AGS Booster. The basic setup and model of the injection process are explained in Refs. [1] and [2].

1 Observations and Comparison with Model

1. Figures 1 and 2 show the timing of the tune and skew quadrupole currents in K. Zeno's coupled injection setup. Counting from the bottom of Figure 1, the four oscilliscope traces are respectively the vertical tune quad current, the Tandem beam pulse, BPM B6 (horizontal) Difference signal, and B6 Sum signal. The "notch" in the Tandem beam pulse produces Turn-by-Turn Sum and Difference signals as discussed in Ref. [1]. The shift in the vertical tune quad current moves the uncoupled tunes apart and reduces the amount of coupling toward the end of beam pulse. In Figure 3 the tune shift has been moved 1 ms later so that the tunes are constant during injection. The resulting PVT (Position Versus Turn) data and fitted curve are shown in Figure 4. Here the measured normal-mode tunes are close to the values, $Q_1 = 4.7333 = 4 + 11/15$ and $Q_2 = 4.8000 = 4 + 12/15$, for which an injected particle returns to its initial position every 15 turns.

2. Figure 5 shows the horizontal PVT (at the exit of the C3 inflector) predicted by the model for the case in which the uncoupled tunes are $Q_H = 4.757$, $Q_V = 4.777$ and the normal-mode tunes are $Q_1 = 4.7333 = 4 + 11/15$ and $Q_2 = 4.8000 = 4 + 12/15$. The RED curve is the PVT for the case in which the particle is launched (from the exit of the C3 inflector) with vertical position (with respect to

the equilibrium orbit) $Y_0 = 0$. The BLUE-DASHED curve shows the PVT obtained with $Y_0 = 8$ mm. Comparing the two, one sees that the particle launched with $Y_0 = 8$ mm stays further from the inflector. This is consistent with K. Zeno's observation that for optimum intensity, the beam from Tandem needs to be steered high on the beam profile monitor (29MW141) at the entrance to the inflector. The vertical position of the beam centroid at this location is typically ≈ 9 mm.

3. One can also obtain the normal-mode tunes $Q_1 = 4.800$, $Q_2 = 4.733$ with the two uncoupled tunes exchanged, that is with $Q_H = 4.777$ and $Q_V = 4.757$. Figure 6 shows the predicted PVT data in this case. Here the RED and BLUE-DASHED curves correspond to particles launched with $Y_0 = 0$ and $Y_0 = 5$ mm respectively. In this case the particle launched with $Y_0 = 0$ stays further from the inflector.

4. Figures 7 and 8 show the model motion in the X–Y (Horizontal–Vertical) plane corresponding to Figures 5 and 6 respectively. The ellipses shown are the X–Y projection of the four dimensional ellipsoid surface on which the particle travels. Note that although the motion in the X–Y plane is bounded by an ellipse, the particle will not visit the entire ellipse area; it traces out a Lissajous path that touches the ellipse in at most four places. As pointed out by T. Roser, an important factor in keeping the injected particle away from the inflector septum is the orientation of this path. This can be optimized by adjusting the initial vertical position of the particle at exit of the inflector.

5. Figures 9 and 10 show (horizontal) PVT data taken with $Q_H < Q_V$ and $Q_H > Q_V$ respectively. These are to be compared with model Figures 5 and 6. The measured normal-mode tunes for both data sets are close to the values $Q_1 = 4.7333 = 4 + 11/15$ and $Q_2 = 4.8000 = 4 + 12/15$, and there is good qualitative agreement with the model PVT. Although the model predicts that the optimum value of Y_0 should be zero for the $Q_H > Q_V$ setup, we found that the highest injection efficiency in this case was achieved with the beam steered ≈ 5 mm high on the 29MW141 profile monitor. This seems to indicate that something other than coupling requires that the beam be steered high here. Perhaps there is an aperture problem in or near the inflector. Even with tune shifts in place (Q_H was decreased and Q_V was increased) to reduce the coupling at the end

of the beam pulse, we could not get an injection efficiency for this setup as high as that for the $Q_H < Q_V$ setup.

6. Table 1 gives the model parameters for the $Q_H < Q_V$ setup. Here the normal-mode tunes are $Q_1 = 4.7333 = 4 + 11/15$ and $Q_2 = 4.8000 = 4 + 12/15$; the required skew quadrupole current is 3.7 Amps. X_b and X_b' are the horizontal position and angle of the bumped equilibrium orbit at the inflector exit; the units are mm and milliradians. As discussed in Ref. [1], X_M is the maximum horizontal excursion of the beam ellipsoid center on its passes by the inflector exit; $X_\mathrm{M} + \sqrt{\epsilon_b E_{11}}$ must not exceed 45 mm in order for the injected beam to be inside the Booster acceptance once the injection bump has collapsed completely. Similarly, Y_M is the maximum vertical excursion of the ellipsoid center at the vertical beta maximums in the Booster; $Y_\mathrm{M} + \sqrt{\epsilon_b E_{33}}$ must not exceed 33 mm. (We assume that the closed orbit is centered in the dipoles.) Assuming the incoming beam has an emittance of 1π mm milliradian in both planes, one finds that 50 turns can be injected with 100% efficiency. Tables 2 and 3 give model parameters for two setups with $Q_H > Q_V$. Here 62 and 58 turns respectively can be injected with 100% efficiency. In practice we are able to inject 40 turns with efficiencies ranging from 67 to 78 percent.

7. Figures 11 and 12 show PVT data obtained from (horizontal) BPM B6 and (vertical) BPM D1 shortly after K. Zeno had optimized the injection efficiency. Here one clearly sees the coupling between the two planes. The uncoupled tunes were setup with $Q_H < Q_V$ and the measured normal-mode tunes are again close to 4.733 and 4.800. Although the tunes obtained from the two data sets are in agreement, the Courant-Snyder invariants do not agree. Presumably this is due to the fact that the sum and difference signals from the two BPMs are not calibrated.

8. Figure 13 shows a set of horizontal PVT data taken on another day shortly after the intensity in Booster had been optimized. Here again we have $Q_H < Q_V$, but the measured normal-mode tunes are a bit further away from the values 4.733 and 4.800. Figures 14 and 15 show the predicted PVT at the exit of the inflector in this case. Here, again, we see that the particle stays well away from the inflector for approximately 15 turns; $Y_0 = 8$ mm gives the optimum clearance..

2 Uncoupled Setup

1. In an attempt to understand the need to steer the beam high at the entrance to the inflector, injection was setup without linear coupling (i.e. with the skew quad current set to zero). In this case one might expect to get the highest injection efficiency with the incoming beam vertically steered onto the equilibrium orbit.

2. However, the best efficiency was obtained with the vertical orbit moved away from the inflector. The amplitude of the vertical betatron oscillations at the D1 BPM reported by the PIP program in this case was ± 4 mm. (The Sum and Difference signals have not been calibrated, so the measurements here are only relative ones.) Vertical steering or orbit adjustment to reduce the vertical amplitude resulted in beam loss on the 5th turn after injection, but did not reduce the intensity of the first turn seen on the BPMs. This seems to indicate that there is no obstacle inside the inflector channel itself. (If this were the case, we would expect to see reduced intensity of the first turn.)

3. Beam survival beyond 5 turns could be recovered by moving the injection bump away from the inflector at a faster rate. This seems to indicate some correlation between the vertical position near the inflector and the horizontal aperture there. There was also (apparently) a correlation between the vertical position on 29MW141 and the amplitude of the horizontal oscillations seen at BPM B6; decreasing the vertical position from 9.2 to 2.1 mm increased the horizontal amplitude from ± 12 to ± 15 mm.

4. By moving the vertical equilibrium orbit toward and away from the inflector (with a local three-bump) and observing the resulting beam survival, we verified that the beam was high (with respect to the equilibrium orbit) at the exit of the inflector when it was measured to be high on the 29MW141 profile monitor.

3 Comments

1. T. Roser suggests that for the case of no coupling, steering the beam off the vertical equilibrium orbit may improve the injection efficiency by reducing space-charge forces. Applying the simplified Laslett

formula given by Conte and MacKay [3], we can estimate the incoherent tune shift due to the space-charge force. We have

$$\Delta Q = -\frac{N r_p}{\pi \epsilon \beta^2 \gamma^3} \left(\frac{m q^2}{M} \right) \tag{1}$$

where $r_p = 1.5347 \times 10^{-18}$ m is the classical radius of the proton, N is the number of ions in the ring, ϵ is the rms emittance of the beam, $m = 0.93827231$ GeV/c^2 is the proton mass, $M = 183.4569$ GeV/c^2 is the ion mass, and $q = 32$ is the net charge of the gold ion in Booster. Taking $N = 2.0 \times 10^9$, $\beta^2\gamma^3 = 0.002$, and $\epsilon = 1.0 \times 10^{-6}$ meter-radians, we find that $\Delta Q = -2.6$. Thus we see that if the vertical emittance is kept small, the space-charge force can be quite large.

2. The most favorable coupled injection setup obtained this year is one with the uncoupled tunes between 4.735 and 4.765 and with $Q_H < Q_V$. The uncoupled tune separation, $Q_V - Q_H$, is typically .01 to .02 and the skew quadrupole current is typically 4.1 Amps. This is close to the model setup depicted in Figures 5 and 7 and in Table 1. Assuming the incoming beam has an emittance of 1π mm milliradian in both planes, the model predicts that 50 turns can be injected with 100% efficiency. In practice we are able to inject (stack) 40 turns with efficiencies ranging from 67 to 78 percent.

3. The need to steer the beam high vertically at the inflector entrance remains a mystery.

References

[1] C. J. Gardner, L. A. Ahrens, T. Roser, and K. L. Zeno, "Injection of Gold Ions in the AGS Booster with Linear Coupling", Proceedings of the 1999 Particle Accelerator Conference, New York, 1999, pp. 1276–1278.

[2] C. J. Gardner, L. A. Ahrens, and K. L. Zeno, "Studies of Heavy Ion Injection with Linear Coupling (1998)", AGS Studies Report No. 372, September 20, 1998.

[3] M. Conte and W. W. MacKay, "An Introduction to the Physics of Particle Accelerators", World Scientific, Singapore, 1991, pp. 192–194.

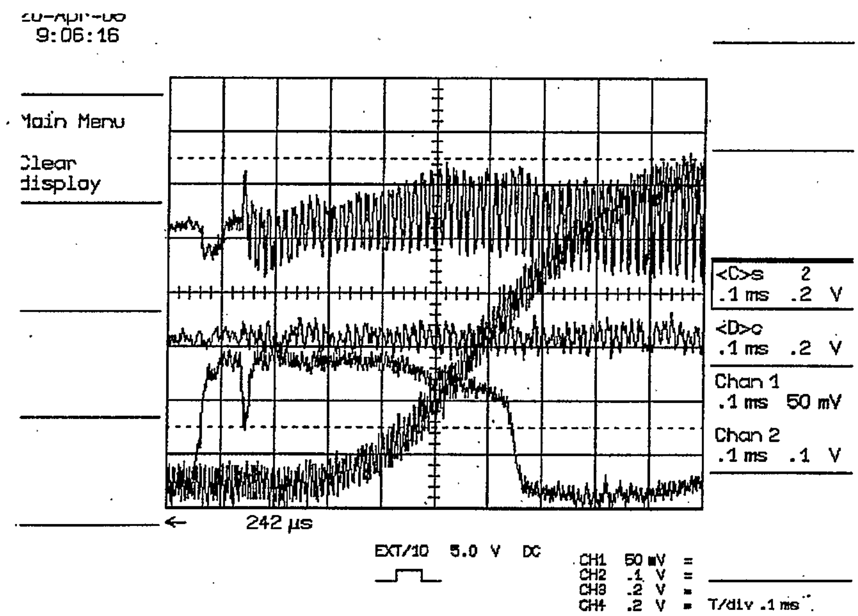

Figure 1: Timing of Tune Shift at Injection.

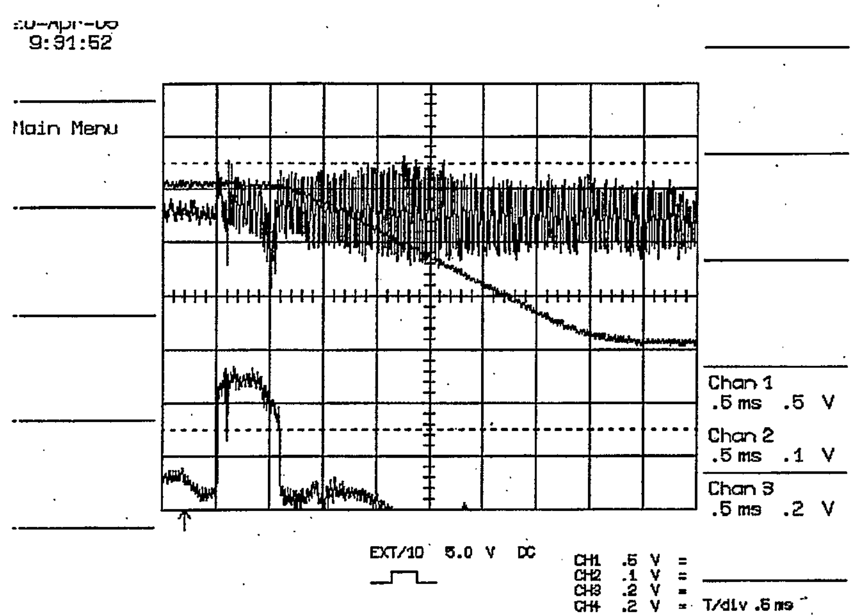

Figure 2: Timing of Skew Quad Current at Injection.

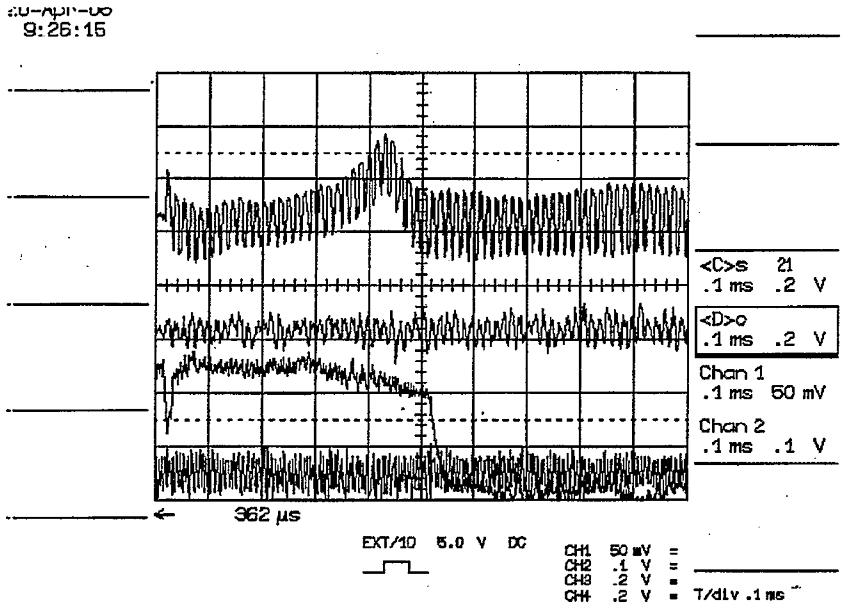

Figure 3: Tune Shift Moved 1 ms Later.

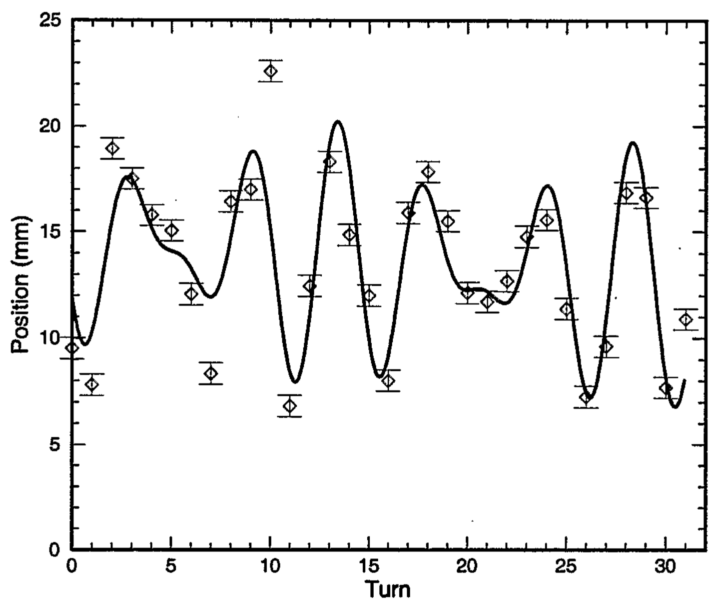

Figure 4: PVT Data and Fitted Curve: $Q_1 = 4.7332(8)$, $Q_2 = 4.7976(6)$.

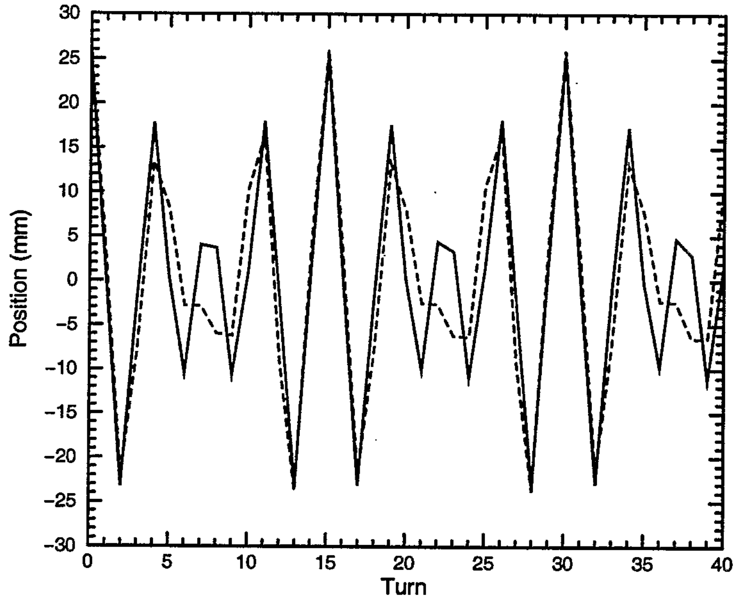

Figure 5: $Q_H = 4.757$, $Q_V = 4.777$. $Y_0 = 0$ (Red). $Y_0 = 8$ (Blue).

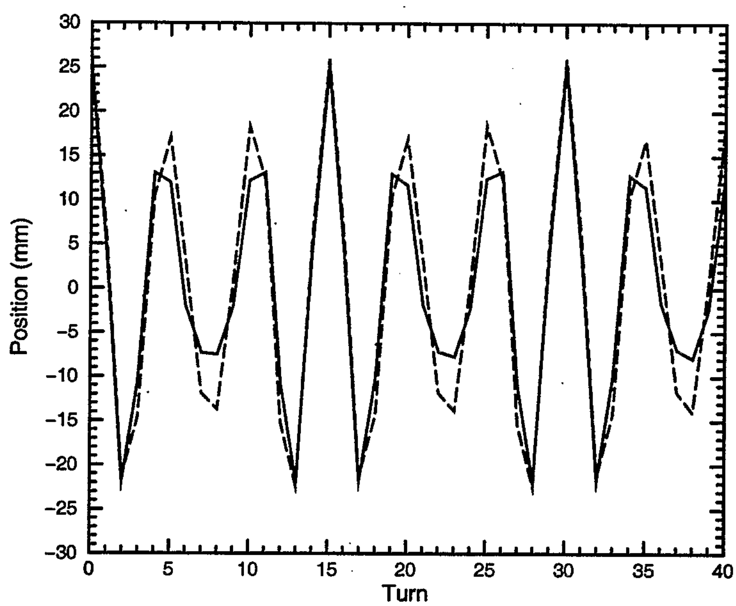

Figure 6: $Q_H = 4.777$, $Q_V = 4.757$. $Y_0 = 0$ (Red). $Y_0 = 5$ (Blue).

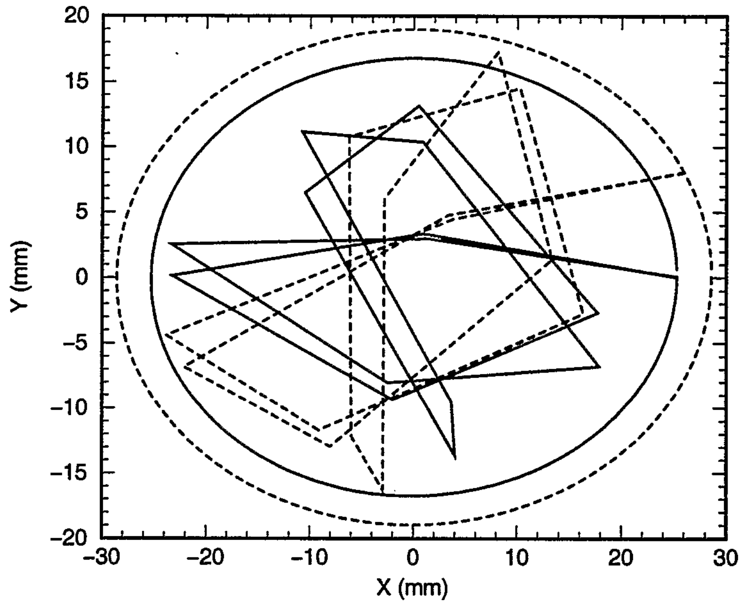

Figure 7: $Q_H = 4.757$, $Q_V = 4.777$. $Y_0 = 0$ (Red). $Y_0 = 8$ (Blue).

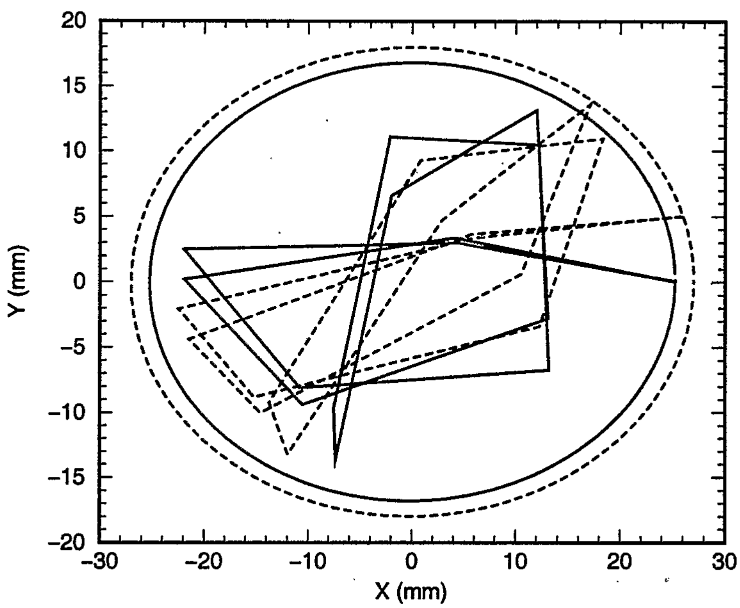

Figure 8: $Q_H = 4.777$, $Q_V = 4.757$. $Y_0 = 0$ (Red). $Y_0 = 5$ (Blue).

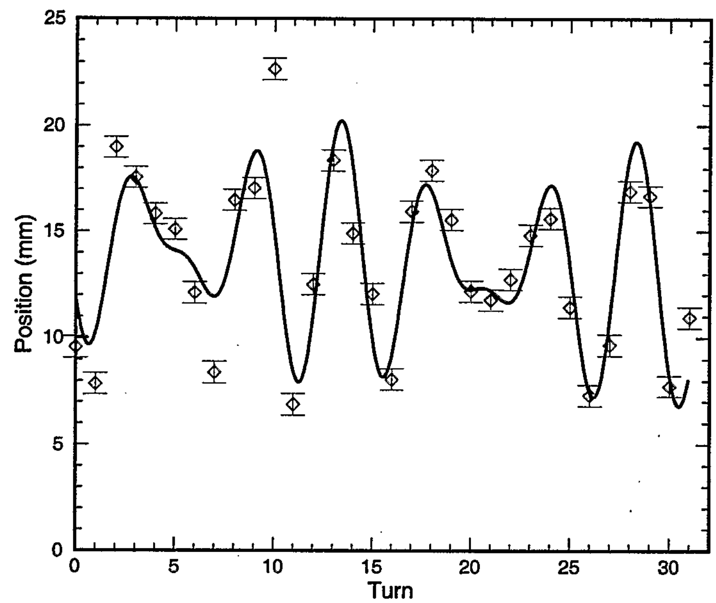

Figure 9: BPM B6 Data. $Q_H < Q_V$, $Q_1 = 4.7332(8)$, $Q_2 = 4.7976(6)$.

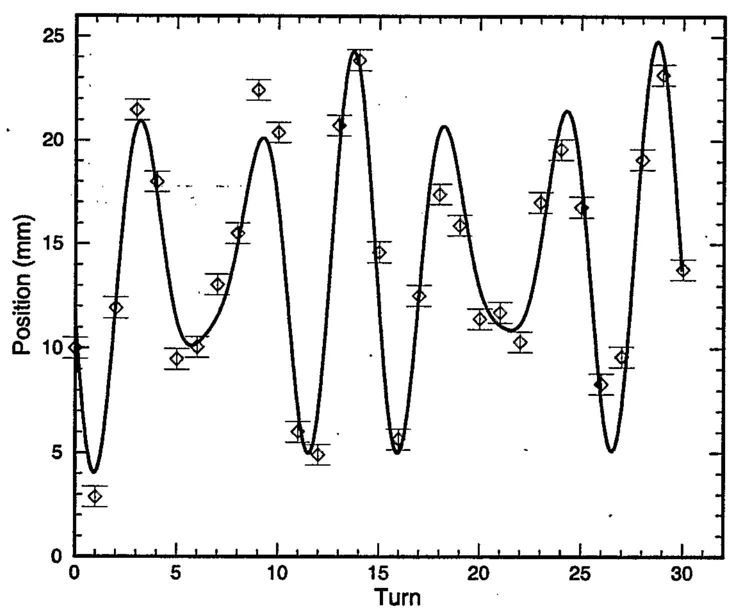

Figure 10: BPM B6 Data. $Q_H > Q_V$, $Q_1 = 4.7320(7)$, $Q_2 = 4.8010(3)$.

Table 1: 15-Turn Injection Scheme with $Q_x < Q_y$ and $Y_0 = 8$ mm.

$Q_x = 4.7567,\ Q_y = 4.7767$					
Layer	X_b	X'_b	Turns	X_M	Y_M
1	41.81	6.59	4	10.58	14.61
2	33.60	5.29	15	18.36	22.69
3	25.82	4.06	15	26.10	30.63
$Q_x = 4.7567,\ Q_y = 4.8800$					
4	18.09	2.86	8	33.80	27.82
5	10.37	1.64	8	41.53	31.51

Table 2: 15-Turn Injection Scheme with $Q_x > Q_y$ and $Y_0 = 0$.

$Q_x = 4.7767,\ Q_y = 4.7567$					
Layer	X_b	X'_b	Turns	X_M	Y_M
1	41.81	6.58	4	10.00	10.32
2	34.19	5.38	15	17.61	18.19
3	26.58	4.18	15	25.23	26.05
$Q_x = 4.7767,\ Q_y = 4.7000$					
4	18.96	2.97	9	32.85	22.89
5	11.34	1.78	19	40.47	28.20

Table 3: Same as Table 2 but with Modified Tune Shift.

$Q_x = 4.7767,\ Q_y = 4.7567$					
Layer	X_b	X'_b	Turns	X_M	Y_M
1	41.81	6.58	4	10.00	10.32
2	34.19	5.38	15	17.61	18.19
3	26.58	4.18	15	25.23	26.05
$Q_x = 4.8300,\ Q_y = 4.7567$					
4	18.95	3.01	12	32.85	23.38
5	11.35	1.80	12	40.45	28.78

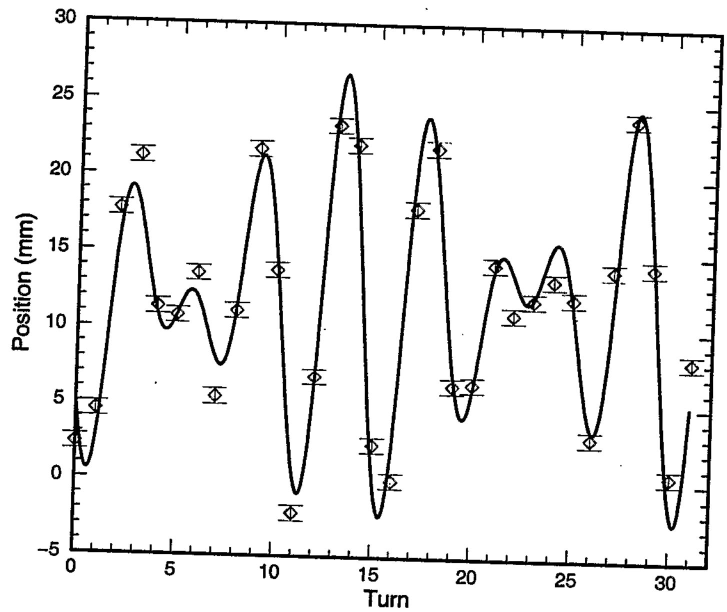

Figure 11: BPM B6 (Horz) Data. $Q_1 = 4.7340(3)$, $Q_2 = 4.7922(3)$.

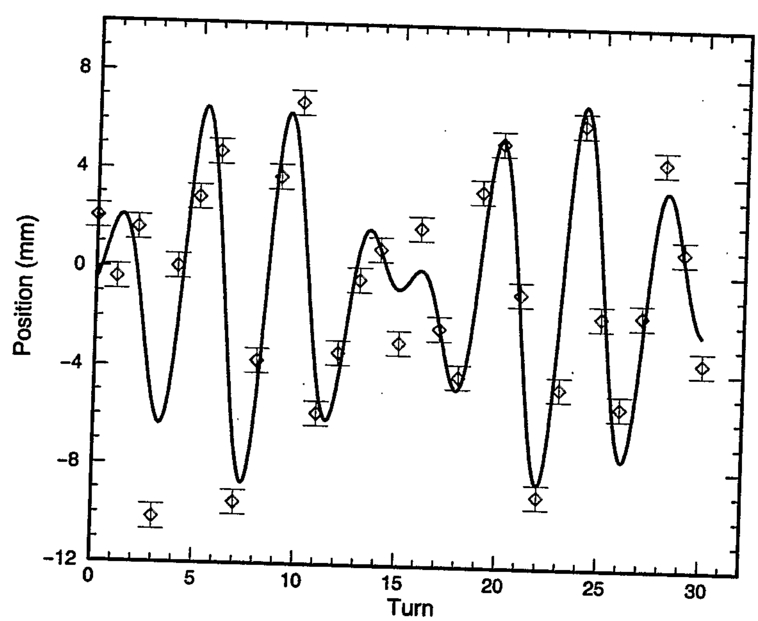

Figure 12: BPM D1 (Vert) Data. $Q_1 = 4.7293(6)$, $Q_2 = 4.7919(6)$.

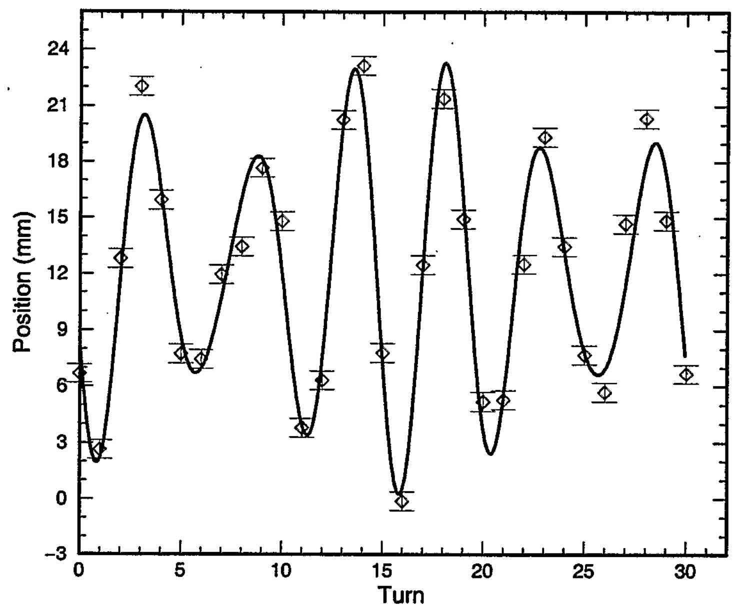

Figure 13: BPM B6 (Horz) Data. $Q_1 = 4.7960(3)$, $Q_2 = 4.7420(7)$.

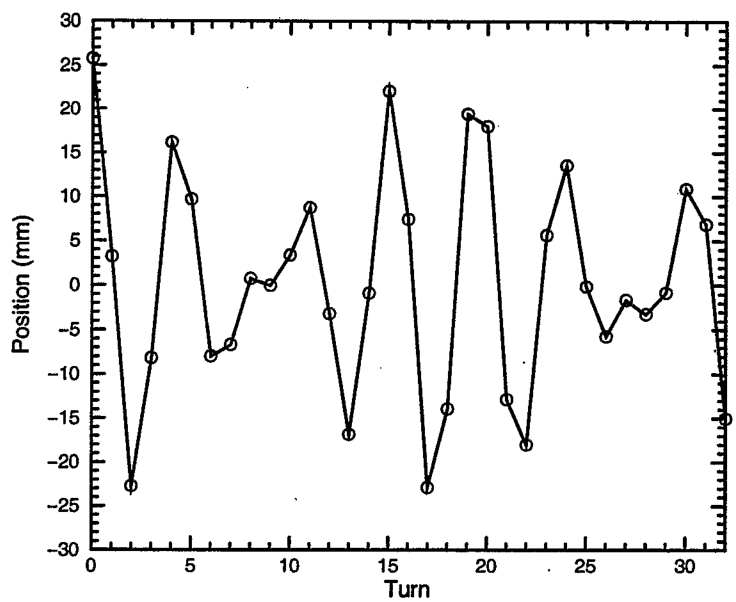

Figure 14: Model Turn-by-Turn with $Q_1 = 4.7960$, $Q_2 = 4.7420$.

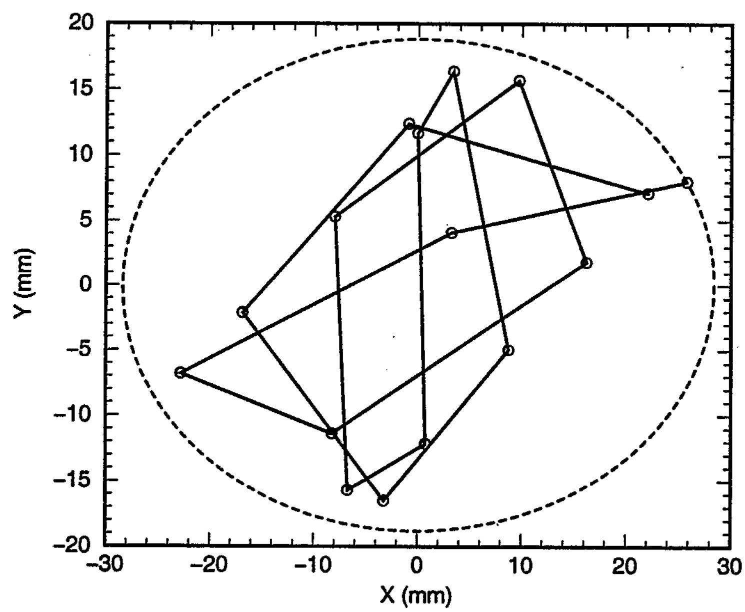

Figure 15: Model Turn-by-Turn with $Q_1 = 4.7960$, $Q_2 = 4.7420$.