BNL-104237-2014-TECH

AGS.SN365;BNL-104237-2014-IR

A Study of the Effect of Linear Coupling on the Injection Ion into the Booster

L. Ahrens

October 1997

Collider Accelerator Department

Brookhaven National Laboratory

U.S. Department of Energy

USDOE Office of Science (SC)

DISCLAIMER

November 19, 1997 **AGS Studies Report No. 365**

AGS Complex Machine Studies

(AGS Studies Report No.365)

A Study of the Effect of Linear Coupling on the Injection of Iron Ions into the Booster

Study Period: 21-24 October 1997

Participants: L. Ahrens, C. Gardner

Reported by: C. Gardner

Machine: AGS

Beam: Fe^{10+} Ions

Tools: Tune Meter; PUE's B4, 01, 04; PIP program; Tandem Chopper

Aim: A Study of the Effect of Linear Coupling on the Injection of Iron Ions into the Booster

A Study of the Effect of Linear Coupling on the Injection of Iron Ions into the Booster

L.A. Ahrens and C.J. Gardner

November 10, 1997

1 Introduction

For the past several years, coupling, introduced by skew quadrupoles, has been used during the injection of heavy ions in the Booster to enhance the efficiency of the multiturn injection process. The use of coupling was first proposed by Roser [1] who showed by modeling the process that the enhancement can be quite significant. A coupled injection scheme was then developed for the Booster using existing skew quadrupoles and this has been used ever since for the injection of heavy ions. Although optimum values for the tunes and skew quadrupole currents are specified by the model, the actual values have been determined empirically over the years using the model as a general guide. We have always found, after tuning on the basis of intensity, that the skew quadrupoles do indeed improve the injection efficiency but the efficiency is seldom better than 50 percent. This has led us to wonder from time to time whether or not we are making full use of the coupling as intended by the model. As a first step toward a better understanding of what is actually happening at injection, Gardner [2] has explored the model a bit further and has proposed a number of possible coupling scenarios. These can be tested by observing the turn-by-turn evolution of the injected beam. But until now it has been difficult to make any such observations for reasons having to do with the low intensities involved, the relatively low rigidity of the beams, and the time taken away from the Physics and Biology programs due to the destructive nature of the measurements.

During the most recent heavy ion run, ions of Iron were delivered to NASA for their Biology program, and we had a number of opportunities to explore the injection of Fe^{10+} beam from Tandem. This beam is inherently more stable than the Gold beam delivered for the Physics program because its rigidity at injection is higher (1.21 Tm for iron versus 0.85 Tm for gold), and because it undergoes only one stripping to yield the desired charge state at injection. (Gold requires two strippings—Au^{-} to Au^{12+} in the terminal foil of the Tandem, and Au^{12+} to Au^{32+} before injection into the Booster.) The intensity of the Iron beam is also higher—typically we see electrical beam currents (near the end of the TTB line) of 30–60 μA for Iron (Fe^{10+}) versus 10–30 μA for Gold (Au^{32+}).

To observe the turn-by-turn evolution of the beam at injection, it is necessary to chop the beam so that a short pulse corresponding to each turn can be seen on PUE's (PickUp Electrodes) in the Booster ring. The chopper is located upstream of the first 90 degree bend in the TTB line, and consists of two parallel plates with one plate above and the other below the midplane of the beamline. The upper and lower plates are connected respectively to pulsed and DC high-voltage power supplies, and the beam is deflected vertically by applying voltages to the plates. It was during the course of setting up the chopped beam that we discovered a non-destructive and rather novel technique for getting the turn-by-turn data we need. The chopper is normally set up for this kind of data-taking so that only a half-turn pulse of beam is transmitted down the TTB line and injected into the Booster; the turn-by-turn evolution of the half-turn can then be observed on the PUE's in the ring. In this mode of operation, beam is transmitted down the line only when the upper plate is pulsed with a voltage that just cancels a DC bias voltage applied to the lower plate. Putting only a half-turn pulse (some 5 μs) down the line is, of course, destructive to the Biology and Physics programs; they require the full long pulse from the source (typically 500—1000 μs) which corresponds to several tens of turns around the ring. However, the chopper also can be set up so that all of the long pulse is transmitted except for a half-turn portion which may be selected from any part of the long pulse. In this mode, no bias voltage is applied to the lower plate and beam is transmitted down the line except when a deflecting pulse is applied to the upper plate. The deflecting pulse produces a half-turn gap or "hole" in the long pulse that is essentially invisible to the programs and at the same time provides a turn-by-turn signal on the PUE's. We have found that the turn-by-turn evolution of this "hole" is essentially the same as that of a half-turn pulse of beam by itself. Aside from being non-destructive, this mode of operation has the important advantage that the beam follows the correct vertical trajectory down the line except when the deflecting pulse is applied to the upper plate. In the other mode, the half-turn pulse will have the "correct" trajectory—i.e. the same trajectory as the long pulse which is normally transmitted with no voltage applied to either plate—only if the voltages applied to the upper and lower plates precisely cancel one another; this condition is difficult to verify.

This new technique allowed us to make several turn-by-turn measurements of the injected beam without interrupting the Biology program. With the tunes and skew quadrupole currents adjusted according to one of the injection scenarios modeled in Ref. [2], we found good qualitative agreement between the model and measurements. For the tunes and skew quadrupole currents at which we normally run, the model indicates that we are not making full use of the coupling as originally intended.

2 Model of Injection with Coupling

Before turning to the measurements we review briefly the model of coupled injection presented in Ref. [2].

Heavy ion beams enter the Booster at the exit of the electrostatic inflector located in the C3 straight section. We assume that the beam emittance is small compared to the acceptance of the Booster and define the initial beam ellipsoid to be the smallest ellipsoid that contains the incoming beam distribution. Thus, if we let

$$\xi_0 = \begin{pmatrix} \mathbf{U}_0 \\ \mathbf{V}_0 \end{pmatrix}, \quad \mathbf{U}_0 = \begin{pmatrix} u_0 \\ u_0' \end{pmatrix}, \quad \mathbf{V}_0 = \begin{pmatrix} v_0 \\ v_0' \end{pmatrix} \qquad (1)$$

and

$$\mathbf{Z}_0 = \begin{pmatrix} \mathbf{X}_0 \\ \mathbf{Y}_0 \end{pmatrix}, \quad \mathbf{X}_0 = \begin{pmatrix} x_0 \\ x_0' \end{pmatrix}, \quad \mathbf{Y}_0 = \begin{pmatrix} y_0 \\ y_0' \end{pmatrix} \qquad (2)$$

where u_0, u_0', v_0, v_0' are the initial horizontal and vertical positions and angles (with respect to the equilibrium orbit) of any particle in the incoming beam distribution, and x_0, x_0', y_0, y_0' are the initial positions and angles (also with respect to the equilibrium orbit) of the beam ellipsoid center, then the initial beam ellipsoid is defined by

$$(\xi_0 - \mathbf{Z}_0)^\dagger \mathbf{E}_0^{-1} (\xi_0 - \mathbf{Z}_0) \le \epsilon_b \qquad (3)$$

where $\mathbf{E}_0$ is a real, symmetric, positive definite four-by-four matrix, and ϵ_b specifies the emittance. On the nth pass by the inflector exit, the positions and angles x, x', y, y' of the center of the beam ellipsoid are given by

$$\mathbf{Z} = \mathbf{T}^n \mathbf{Z}_0, \tag{4}$$

where

$$\mathbf{Z} = \begin{pmatrix} \mathbf{X} \\ \mathbf{Y} \end{pmatrix}, \quad \mathbf{X} = \begin{pmatrix} x \\ x' \end{pmatrix}, \quad \mathbf{Y} = \begin{pmatrix} y \\ y' \end{pmatrix}, \tag{5}$$

and $\mathbf{T}$ is the transfer matrix for one turn around the Booster starting at the inflector exit. Similarly, the positions and angles of a beam particle on the nth pass by the inflector are given by

$$\xi = \mathbf{T}^n \xi_0, \tag{6}$$

where

$$\xi = \begin{pmatrix} \mathbf{U} \\ \mathbf{V} \end{pmatrix}, \quad \mathbf{U} = \begin{pmatrix} u \\ u' \end{pmatrix}, \quad \mathbf{V} = \begin{pmatrix} v \\ v' \end{pmatrix}. \tag{7}$$

The beam ellipsoid on the nth pass by the inflector is therefore given by

$$(\xi - \mathbf{Z})^\dagger \mathbf{E}_n^{-1} (\xi - \mathbf{Z}) \leq \epsilon_b, \tag{8}$$

where

$$\mathbf{E}_n = \mathbf{T}^n \mathbf{E}_0 \mathbf{T}^{\dagger n} \tag{9}$$

and $\mathbf{Z}$ is given by (4). Equations (4) and (9) give the complete turn-by-turn evolution of the beam ellipsoid as it goes around the Booster.

Now as shown in Ref.[2], the components of $\mathbf{Z} = \mathbf{T}^n \mathbf{Z}_0$ may be written in the form

$$\mathbf{X} = \mathbf{X}_1 + \mathbf{X}_2, \quad \mathbf{Y} = \mathbf{Y}_1 + \mathbf{Y}_2 \tag{10}$$

where

$$\mathbf{X}_1 = d\mathbf{A}^n (d\mathbf{X}_0 - \overline{\mathbf{W}}\mathbf{Y}_0), \quad \mathbf{X}_2 = \overline{\mathbf{W}}\mathbf{B}^n (\mathbf{W}\mathbf{X}_0 + d\mathbf{Y}_0) \tag{11}$$

$$\mathbf{Y}_1 = -\mathbf{W}\mathbf{A}^n (d\mathbf{X}_0 - \overline{\mathbf{W}}\mathbf{Y}_0), \quad \mathbf{Y}_2 = d\mathbf{B}^n (\mathbf{W}\mathbf{X}_0 + d\mathbf{Y}_0) \tag{12}$$

and

$$\mathbf{A}^n = \begin{pmatrix} \cos n\psi_1 + \alpha_1 \sin n\psi_1 & \beta_1 \sin n\psi_1 \\ -\gamma_1 \sin n\psi_1 & \cos n\psi_1 - \alpha_1 \sin n\psi_1 \end{pmatrix} \tag{13}$$

$$\mathbf{B}^n = \begin{pmatrix} \cos n\psi_2 + \alpha_2 \sin n\psi_2 & \beta_2 \sin n\psi_2 \\ -\gamma_2 \sin n\psi_2 & \cos n\psi_2 - \alpha_2 \sin n\psi_2 \end{pmatrix}. \tag{14}$$

(The two-by-two matrix **W** is defined in Ref. [2]; its explicit form is not needed here.) Here we see that in each plane, the turn-by-turn motion is the superposition of two normal modes of oscillation with tunes, Q_1 and Q_2, given by

$$2\pi Q_1 = \psi_1, \quad 2\pi Q_2 = \psi_2. \tag{15}$$

Futhermore, $\mathbf{X}_1$, $\mathbf{X}_2$, $\mathbf{Y}_1$, $\mathbf{Y}_2$ are each constrained to lie on an ellipse, so that the motion in each plane is the superpostion of motion about two ellipses.

Figure (1) shows the maximum extent of these ellipses for the case in which the uncoupled tunes (i.e. the tunes with no coupling) and the skew quadrupole currents have been adjusted so that the normal-mode tunes are $Q_1 = 4 + 13/15 = 4.866666$ and $Q_2 = 4 + 12/15 = 4.8$. Here the beam ellipsoid center has been launched with initial coordinates $x_0 = 10$ mm and $y_0 = 0$, and the numbered diamonds indicate the positions and angles of the ellipsoid center on the nth pass by the inflector. Inspection of the figure shows that the beam ellipsoid center has a horizontal position of at most 4.75 mm before returning to its initial position at the inflector exit after 15 turns around the machine. Note that although the initial vertical position of the beam ellipsoid center is zero, the coupling introduced by the skew quadrupoles produces oscillations of nonzero amplitude in this plane. This is the price we pay for using coupling to extend the time we can wait before having to move the equilibrium orbit away from the inflector. Inspection of the figure shows that the maximum possible value of the vertical position of the beam ellipsoid center is 5.9 mm. Figure (2) shows the same data with just the horizontal and vertical positions plotted versus turn.

3 Measurement of Tunes

To produce the 15-turn scenario shown in Figures (1–2) the normal mode tunes need to be $Q_1 = 4 + 13/15 = 4.866666$ and $Q_2 = 4 + 12/15 = 4.8$, and, according to the model, this requires that the uncoupled tunes and the skew quadrupole currents be $Q_x = 4.823333$, $Q_y = 4.843333$, and 5.3 Amps. In the Optics Control program, the uncoupled tunes were set to the required values and the tunes were measured (with the Booster Tune Meter) several ms after injection with the skew quad currents programed to fall to zero before the time of measurement. The skew quad currents were then set to be 5.3 Amps during the measurement period and the tunes were again measured. We found $Q_x = 4.81$, $Q_y = 4.83$ with zero current, and $Q_1 = 4.85$, $Q_2 = 4.79$ with 5.3 Amps in the skew quadrupoles. These are slightly shifted from the model values but at the time of the study we considered them to be close enough. (In future studies we will want to pay more attention to getting these tune values right.)

4 Turn-by-Turn Measurements of Injected Beam

With the tunes and skew quad currents programed as described in the previous section, we made several turn-by-turn measurements of the injected beam. We were able to observe the turn-by-turn signals on three PUE's: D1, D4, and B4. These are Vertical, Horizontal, and Horizontal PUE's respectively, with sum and difference signals available in the MCR for D1 and B4. D4 was equipped with special high-gain amplifiers and a signal from each of its plates was also available in the MCR. Figure (3) shows traces of the sum signal from PUE B4. The negative going pulses are due to the half-turn (approximately 5 μs) "hole" passing through the PUE. In both traces we see a first-turn loss followed by a fairly constant series of passes through the PUE. With some local tuning of the equilibrium orbit (i.e. with the C4 three-bump) we were able to eliminate most (if not all) of the first-turn loss. The upper and lower traces show beam survival with the skew quadrupoles ON and OFF respectively. It is clear that survival for more than 5 turns requires that the skew quadrupoles be ON in this situation; presumably it is the coupling introduced that preserves the beam.

To improve the quality of the sum and difference signals, we set up the oscilliscope to average over several tens of shots. The signals were then inverted to make them resemble what one sees for an actual pulse of beam rather than a "hole". These were then analyzed by the PIP program to obtain the position of the "hole" on each pass through the PUE. Traces of the averaged and inverted sum and difference signals for PUE B4 are shown in Figure (4); the position-versus-turn data from the PIP analysis are shown in Figure (5). A similar analysis of the sum and difference signals from vertical PUE D1 yielded the position-versus-turn data shown in Figure (6). Note that the PIP program fits a curve to the data that does not fit very well. This is because the fitting function used in the present version of the program does not allow for the kind of changes in the betatron oscillation amplitude that occur with coupling. Even so, the program does manage to get tunes that make some sense—$Q = 4.864$ for the horizontal data in Figure (5), and $Q = 4.821$ for the vertical data in Figure (6).

5 Comparison with Model

The position-versus-turn data of Figures (5) and (6) are to be compared with the model data shown in Figure (2). Here we see good qualitative agreement between the measurements and model. Both show that in 15 turns the amplitude of the oscillations in the horizontal plane starts out big, gets small and then gets big again; in the vertical plane the amplitude starts out small, gets big, and then gets small again.

It is also clear from inspection of the B4 Sum signal in Figure (4), that not much beam loss occurs during the 15 turns after the "hole" is injected. We therefore would expect the injection efficiency to be very high during this period and tried to verify this by measuring the beam current in the ring. Figure (7) shows oscilliscope traces of beam current transformers 29XF (near the end of the TTB line) and INJ-XF-DGTL (in the C7 straight-section of the ring). The top trace is the current in the C1 injection bump, which is collapsing. The 29XF trace shows that Tandem is delivering a 500 μs pulse of Fe^{10+} beam with a current of 50 μA. Note the "notch" occuring near the middle of the pulse; this is where the chopper puts a 5 μs gap in the beam. (The 29XF signal does not drop to zero here because its response to the change in current is too slow.) In the 100 μs interval just after the "notch", 10 turns of beam are injected into the booster, and, if no losses occur, the current in the booster ring should increase by 500 μA. The INJ-XF-DGTL trace shows that the current in the ring increases by 400 μA, so the injection efficiency over this time interval is about 80 percent. This is certainly less than expected, but is much higher than the overall efficiency of our normal injection setup.

Under normal running conditions, the uncoupled tunes and skew quadrupole currents were programed to be $Q_x = 4.703$, $Q_y = 4.838$, and 6.62 Amps at injection. Figure (8) shows what the model predicts for this situation. Here the beam ellipsoid center has been launched with initial coordinates $x_0 = 10$ mm and $y_0 = 0$, and the numbered diamonds indicate the positions and angles of the ellipsoid center on the nth pass by the inflector. Inspection of the figure shows that, according to the model, there is not much coupling between the two planes in this situation.

6 Future Refinements

Although there is good qualitative agreement between measurements and the model, we need a more precise comparison of the two in order to properly set up injection according to the model and hopefully get better injection efficiency. To obtain a more precise comparison, the PIP program needs to be upgraded so that:

1) the fitting function contains parameters that allow for coupling between the two planes; and

2) data from horizontal and vertical PUE's can be acquired and analyzed together.

(It would also be helpful if the program provided access to the sums and differences it calculates for each passage of beam through a PUE.)

Although it appears that the turn-by-turn behavior of the "hole" is essentially the same as that of an actual pulse of beam by itself, we need to explore any differences there might be between the two. One might wonder, for example, whether the "hole" experiences space charge forces from the surrounding beam. If so, one might expect a difference between the tunes measured with a "hole" and those measured with a pulse of beam by itself.

7 References

1. T. Roser, "Multiturn Injection with Coupling", AGS/AD/Tech. Note No. 354, November 7, 1991.

2. C.J. Gardner, "Notes on Coupled Motion in a Linear Periodic Lattice and Applications to Booster Injection", AGS/AD/Tech. Note No. 427, February 22, 1996.

COUPLED INJECTION X, XP PROJECTION (Horz)

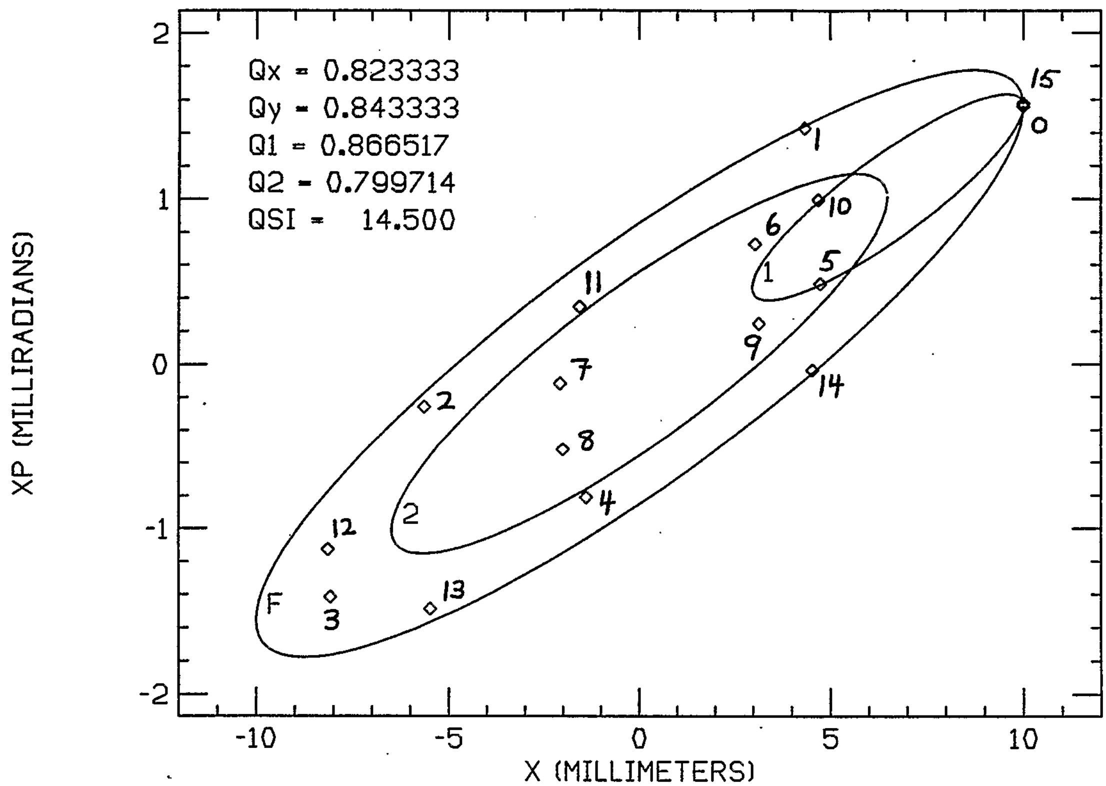
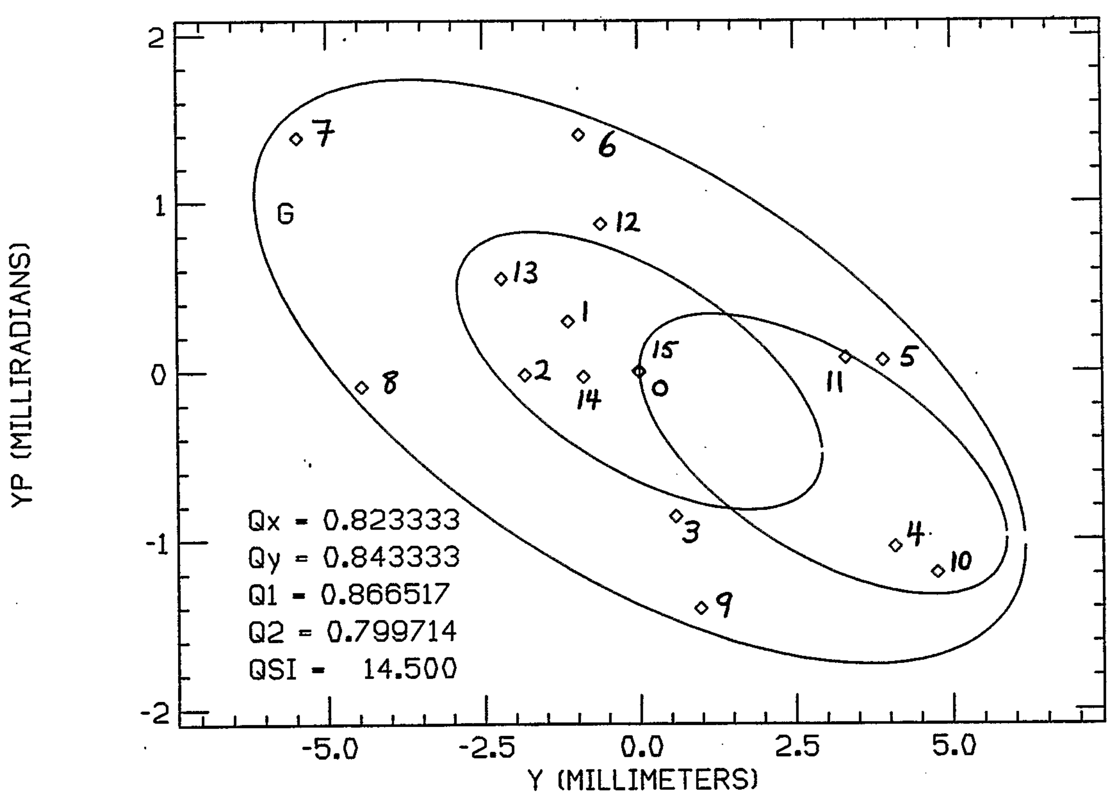


Fig. 1

Y,YP PROJECTION (Vert)



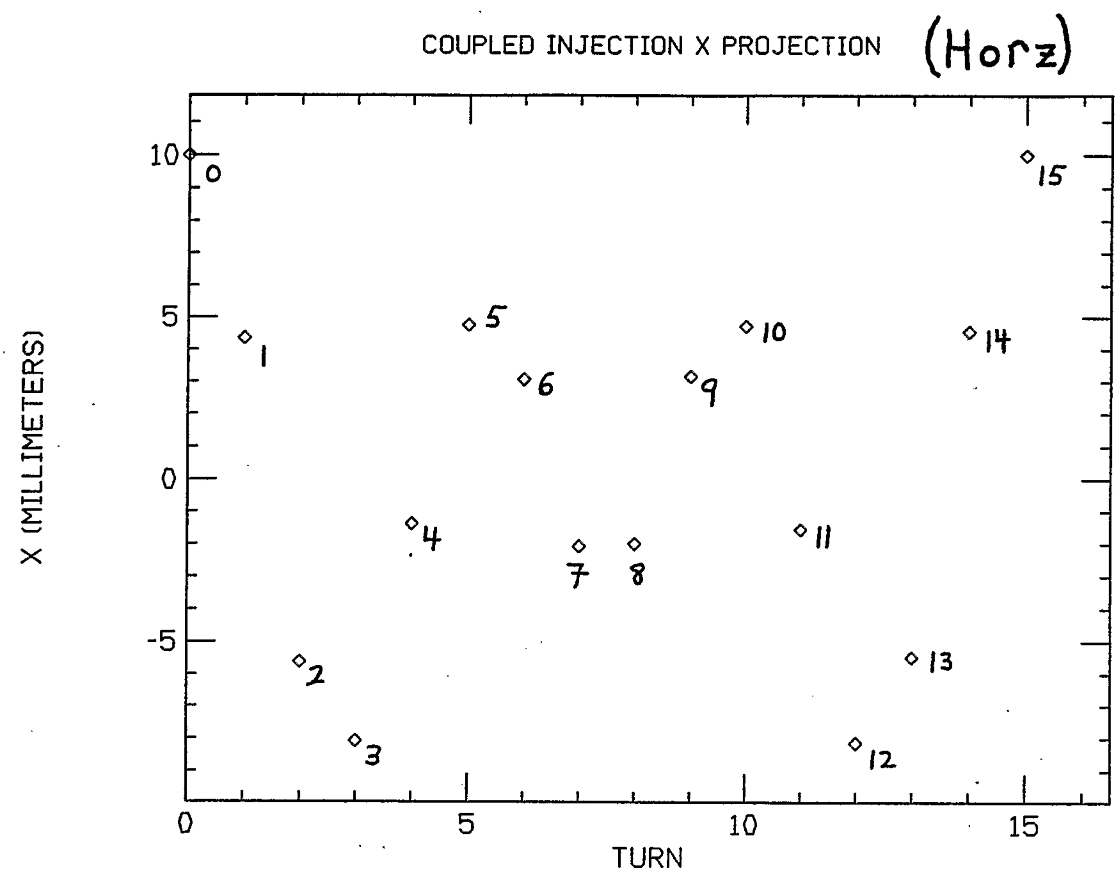
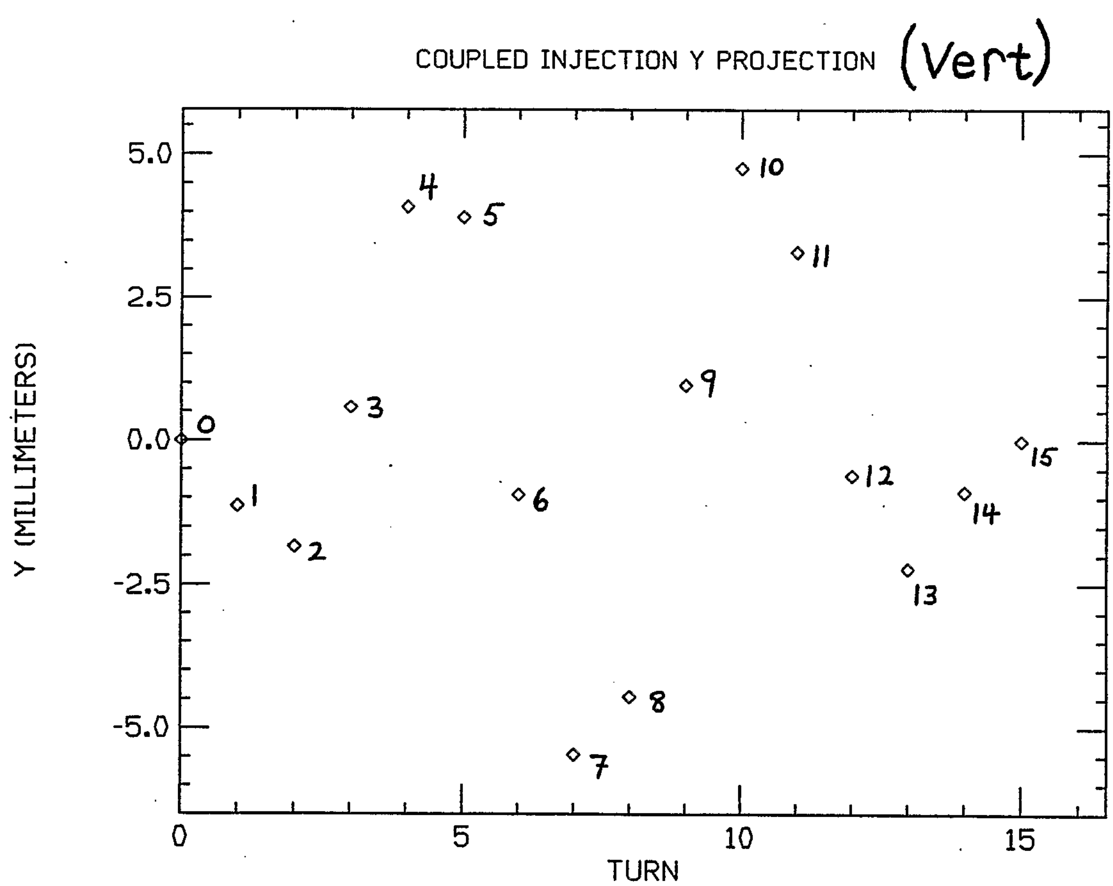

COUPLED INJECTION X PROJECTION
(Horz)
X (MILLIMETERS)
10
5
0
-5
TURN
0
5
10
15
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

Fig. 2


COUPLED INJECTION Y PROJECTION
(Vert)
Y (MILLIMETERS)
5.0
2.5
0.0
-2.5
-5.0
TURN
0
5
10
15
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15

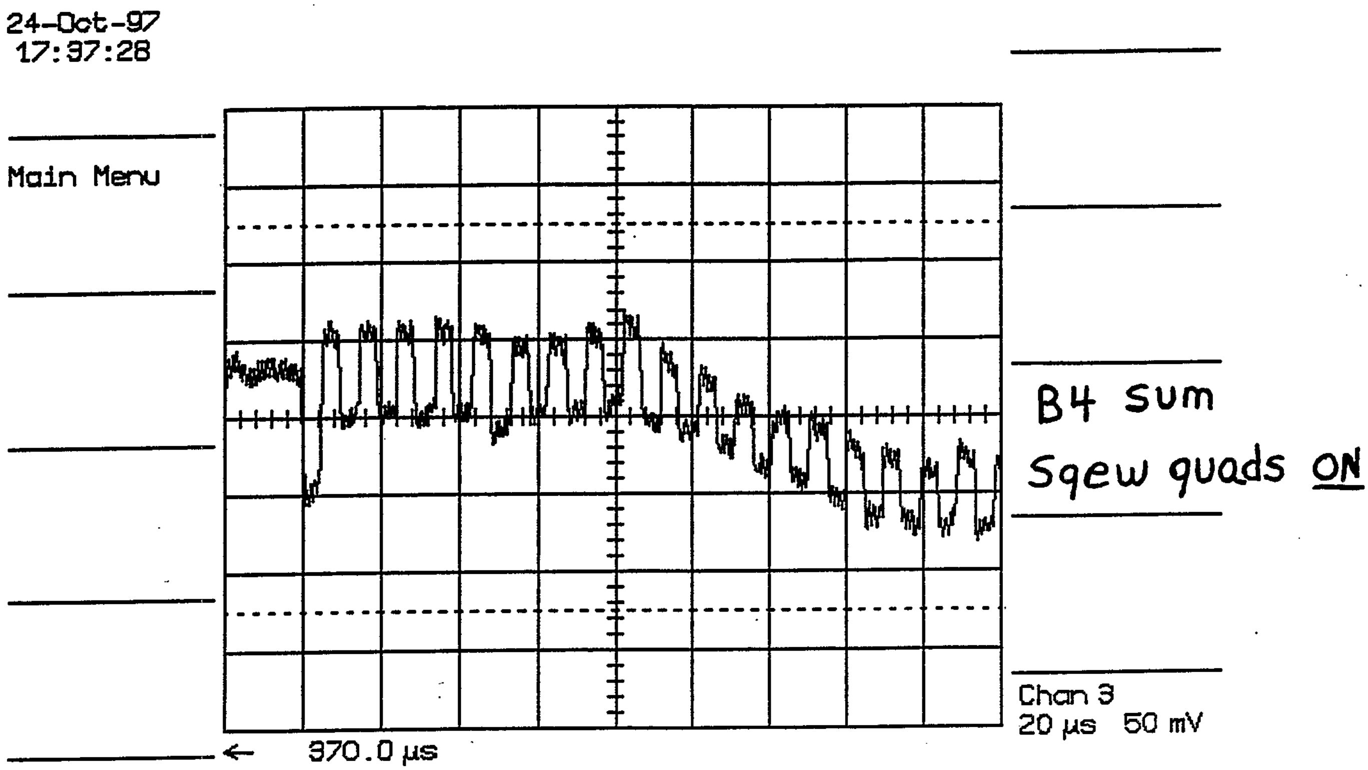
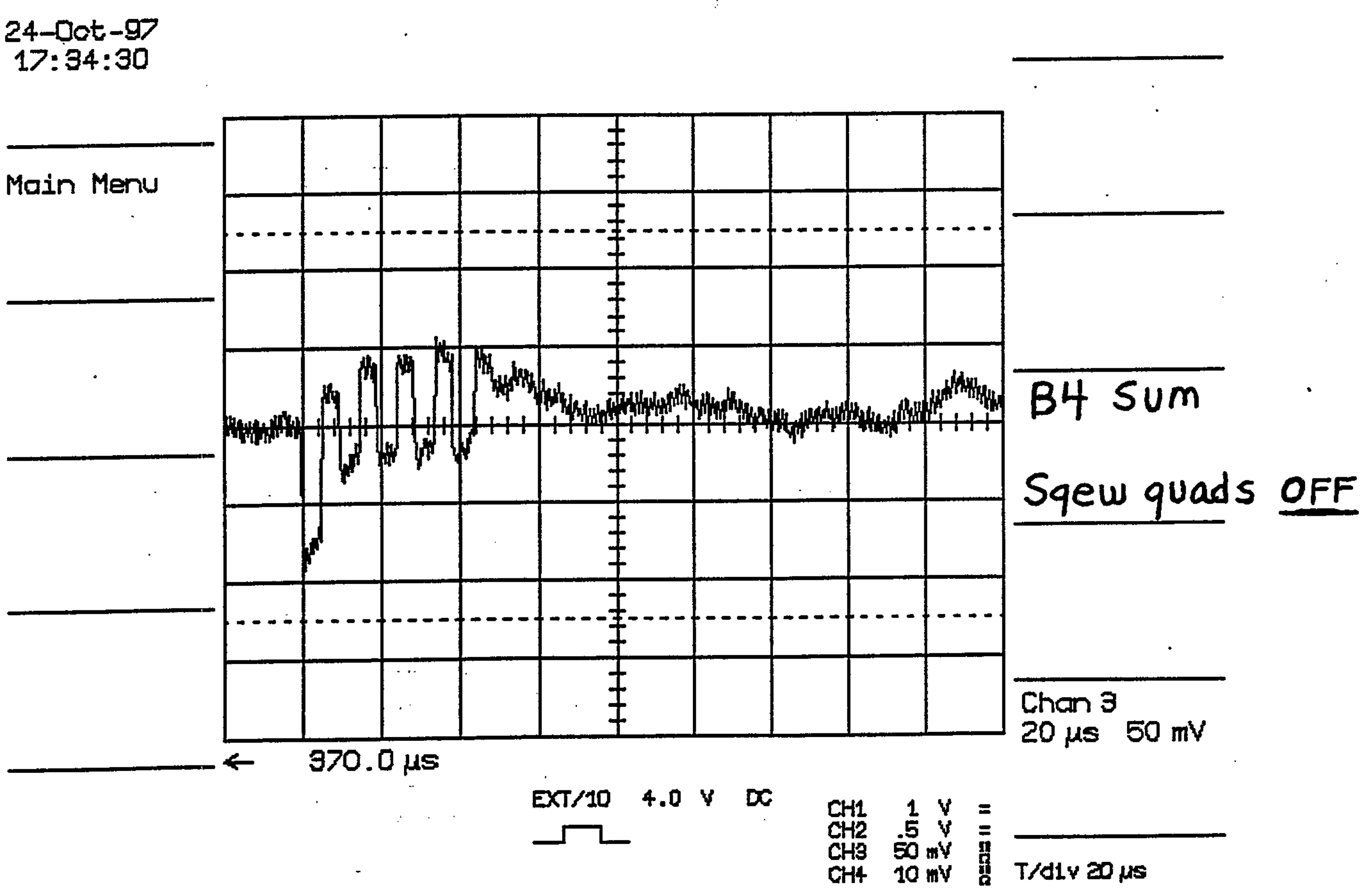

24-Oct-97
17:37:28
Main Menu
B4 sum
Sqew quads ON
Chan 3
20 µs 50 mV
370.0 µs

Fig. 3


24-Oct-97
17:34:30
Main Menu
B4 Sum
Sqew quads OFF
Chan 3
20 µs 50 mV
370.0 µs
EXT/10 4.0 V DC
CH1 1 V
CH2 .5 V
CH3 50 mV
CH4 10 mV
T/div 20 µs

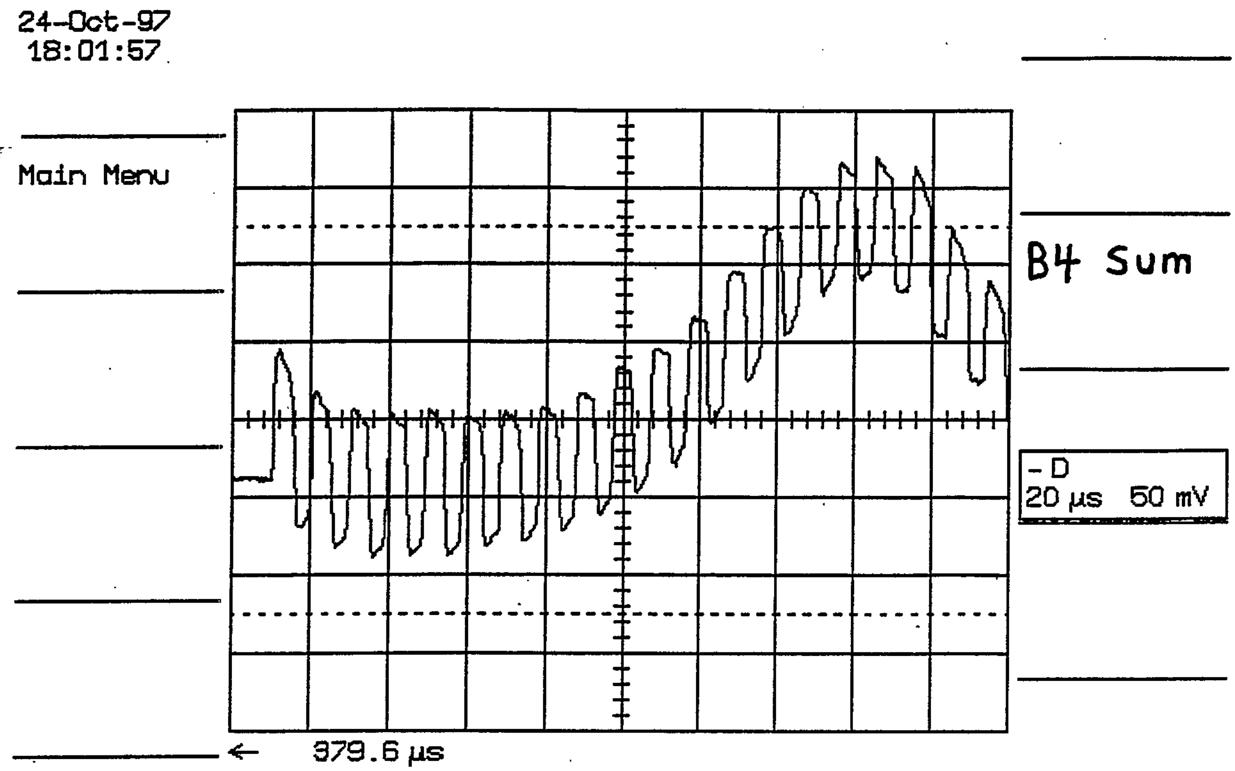
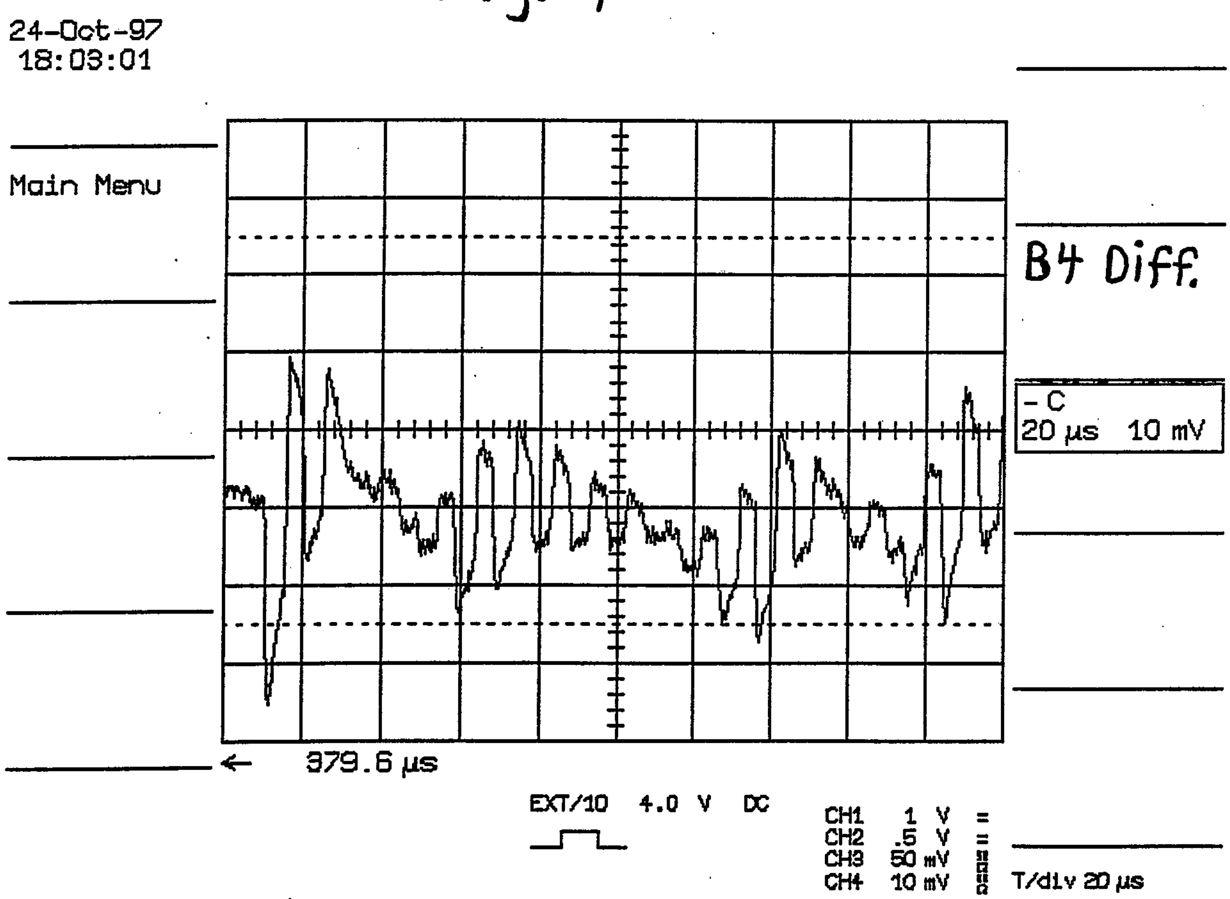

24-Oct-97
18:01:57
Main Menu
B4 Sum
- D
20 µs 50 mV
← 379.6 µs

Fig. 4


24-Oct-97
18:03:01
Main Menu
B4 Diff.
- C
20 µs 10 mV
← 379.6 µs
EXT/10 4.0 V DC
CH1 1 V
CH2 .5 V
CH3 50 mV
CH4 10 mV
T/div 20 µs

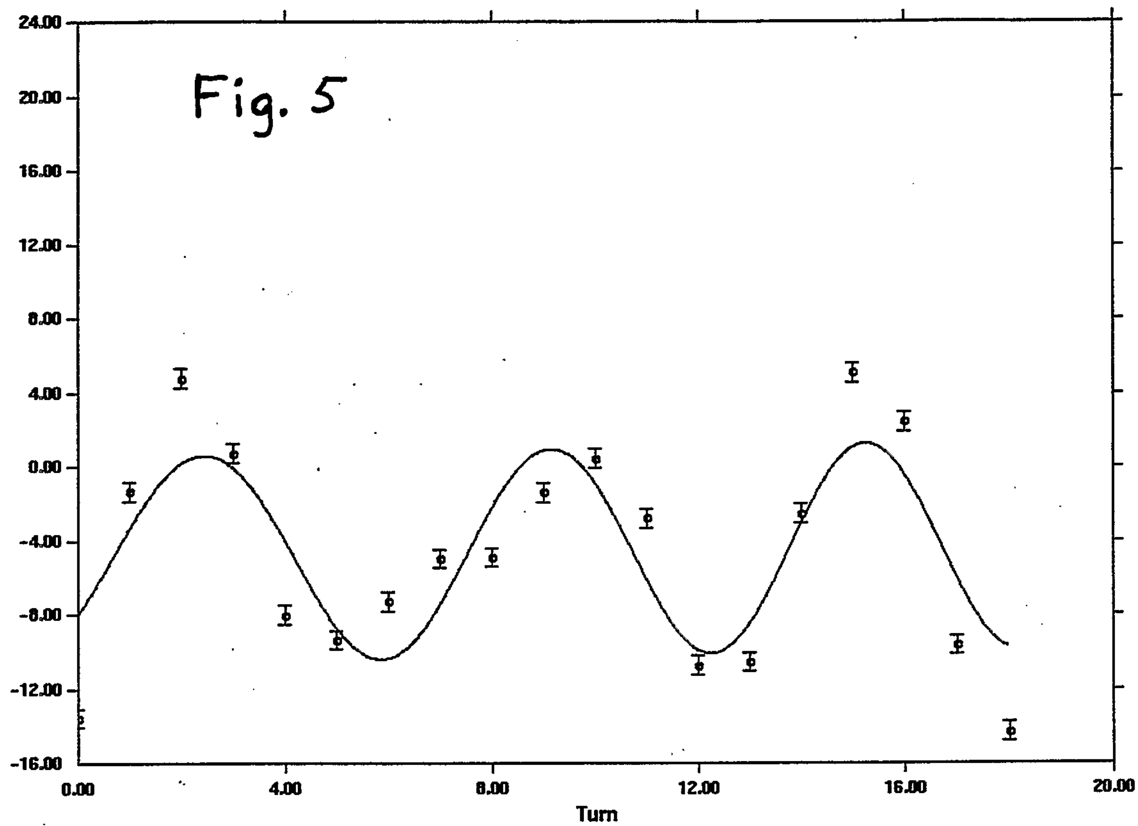


Fig. 5
24.00
20.00
16.00
12.00
8.00
4.00
0.00
-4.00
-8.00
-12.00
-16.00
0.00
4.00
8.00
12.00
16.00
20.00
Turn

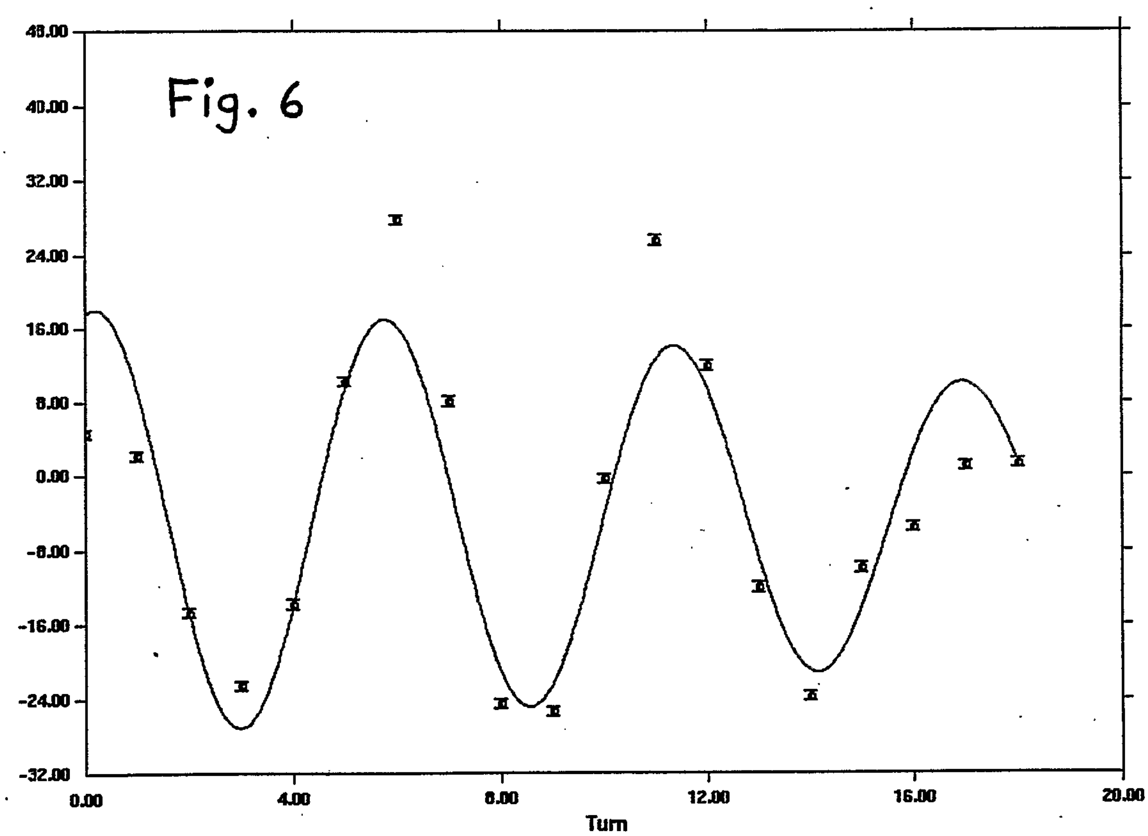


Fig. 6
48.00
40.00
32.00
24.00
16.00
8.00
0.00
-8.00
-16.00
-24.00
-32.00
0.00
4.00
8.00
12.00
16.00
20.00
Turn

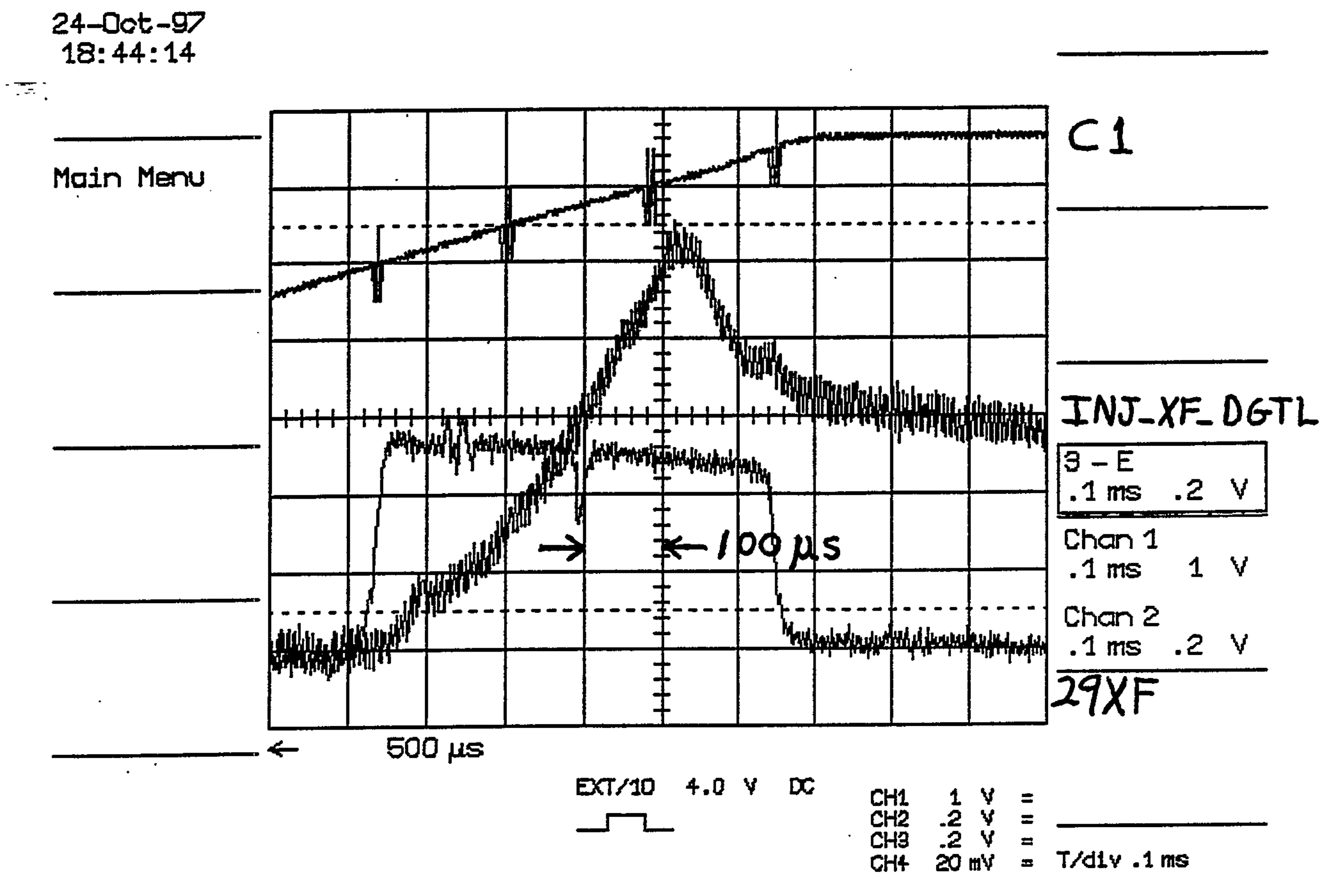

24-Oct-97
18:44:14
Main Menu
C1
INJ_XF_DGTL
3 - E
.1 ms .2 V
Chan 1
.1 ms 1 V
Chan 2
.1 ms .2 V
29XF
100 µs
500 µs
EXT/10 4.0 V DC
CH1 1 V =
CH2 .2 V =
CH3 .2 V =
CH4 20 mV =
T/div .1 ms

Fig. 7

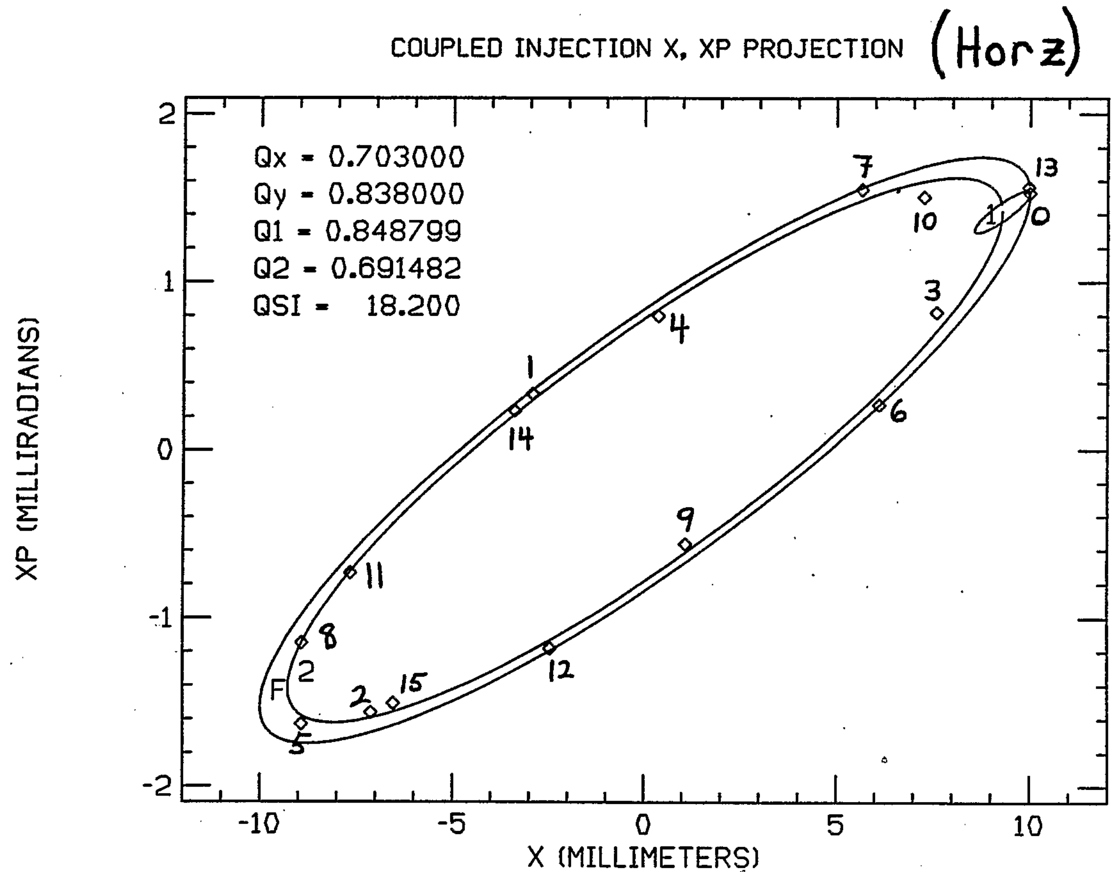
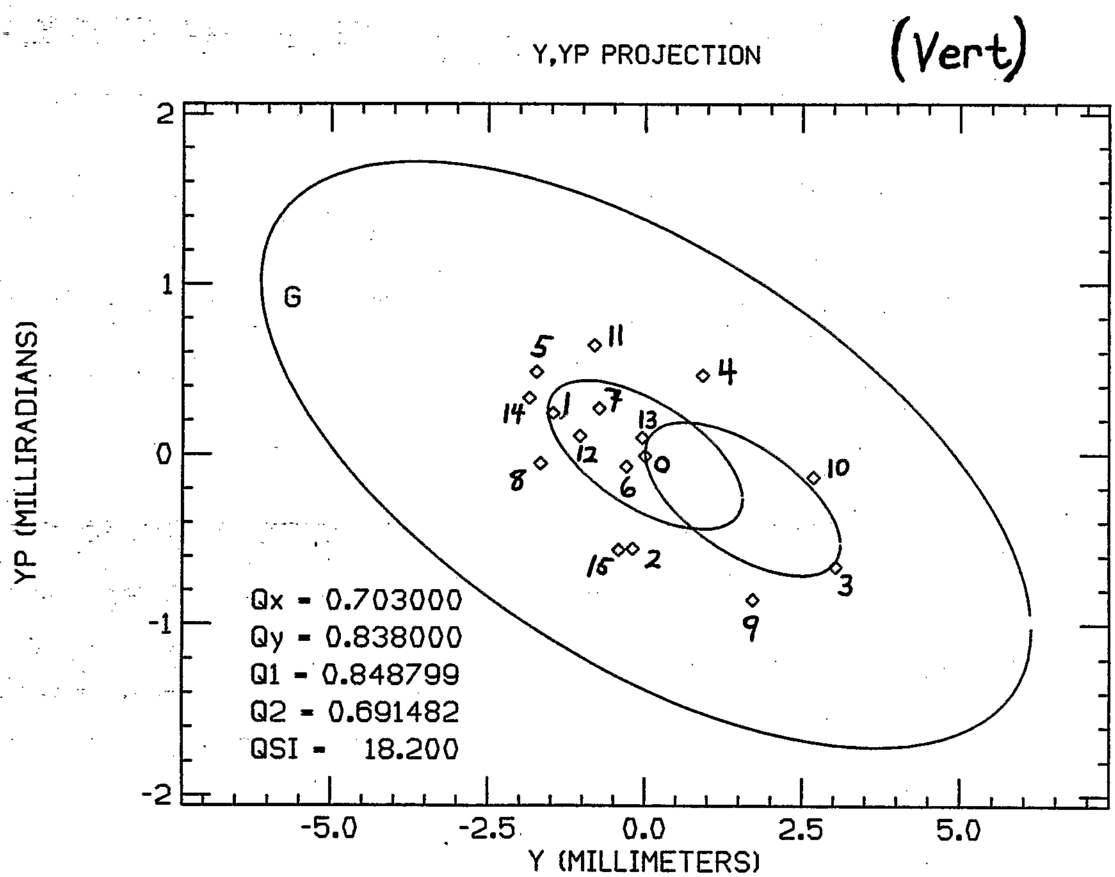

COUPLED INJECTION X, XP PROJECTION
(Horz)
Qx = 0.703000
Qy = 0.838000
Q1 = 0.848799
Q2 = 0.691482
QSI = 18.200
XP (MILLIRADIANS)
X (MILLIMETERS)
F
-10
-5
0
5
10
2
1
0
-1
-2

Fig. 8


Y,YP PROJECTION
(Vert)
G
Qx = 0.703000
Qy = 0.838000
Q1 = 0.848799
Q2 = 0.691482
QSI = 18.200
YP (MILLIRADIANS)
Y (MILLIMETERS)
-5.0
-2.5
0.0
2.5
5.0
2
1
0
-1
-2