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EMITTANCE DILUTION IN TRANSFERS FROM THE MAIN RING TO THE TEVATRON

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This paper delineates the steps taken to understand the sources of an apparent growth in emittance which was observed in proton and antiproton transfers from the Main Ring (MR) to the Tevatron (TEV) in Collider Run I, and which then lead to the discovery of the main source.

Keywords: Emittance dilution; Tevatron

I. INTRODUCTION

An apparent growth in emittance was observed in proton and antiproton transfers from the Main Ring to the Tevatron in Collider Run I, and Figure 1 shows some examples from the early part of Run I. This paper delineates the steps taken to understand the sources of this apparent growth which then led to the discovery of the main source. The initial analysis was restricted to the vertical plane for simplicity (i.e. the vertical dispersion in the TEV is zero and we can extract the vertical emittance from one flying wire). At the time the observed coupling was treated as a nuisance. The emittances in this paper are derived using the Fermilab convention: $\varepsilon = (6 * \pi * \sigma^2 * \gamma * v)/(\beta * c)$ and the error bars shown are not systematic errors, but rather an indication of the repeatability of consecutive measurements.[1]

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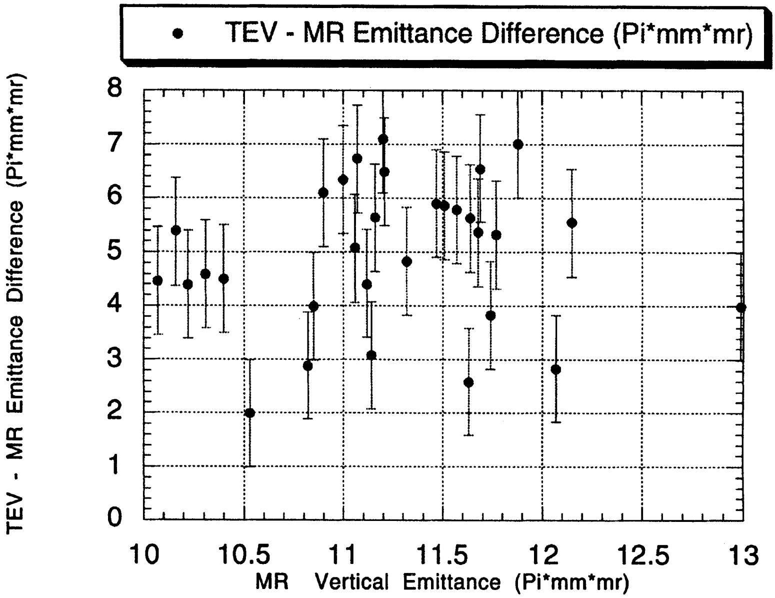

FIGURE 1 The difference between the measured Tevatron emittance and the measured Main Ring emittance plotted as a function of the Main Ring emittance.

The analysis is based upon 5 data sets:

1. ILAM studies 2/23/92 (TEV log 34, p. 205)
2. IQUAD studies 3/2/94 (TEV log 34, p. 281)
3. TEV vs MR studies 3/2/94 (TEV log 34, p. 282)
4. SHOTS before 4/8/94
5. SHOT 4749.

The first step in the analysis was to get rid of the word apparent in the first paragraph. The beam size measured at the flying wire is assumed to be related to $\beta\varepsilon$ and hence if our assumption about the beta function at the flying wire is wrong, then our extracted value for the emittance will be wrong. In comparing the two machines we need to know the beta function at both flying wires; if either or both are wrong (barring a common systematic error) then our growth comparison will be erroneous. However, during the regular tuning of reverse injection for a shot, there is an opportunity to measure the emittance of the same bunch after it has been injected into the TEV and then reinjected into

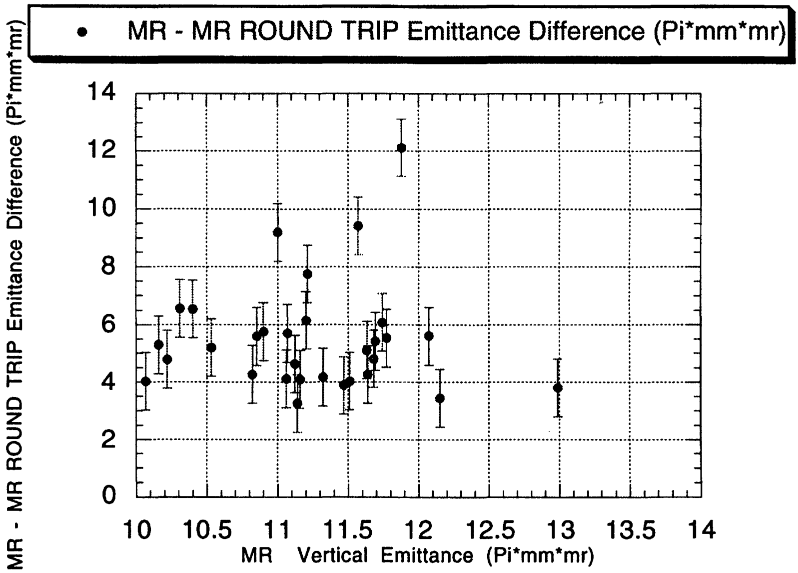

FIGURE 2 The measured difference in Main Ring vertical emittance before injection into the Tevatron and after reinjection into the Main Ring from the Tevatron.

the Main Ring. Figure 2 gives some examples of this common comparison. It should be noted that the procedure utilized implies that the wire is flown in the same direction for both flies. It is evident that in the range of MR emittances from 10–13π mm mrad there is a minimum blow up of 3–4π mm mrad, and it is possible to do worse.

II. DATA ANALYSIS

The analysis of this report is mainly based upon Chapter 7 in Edwards and Syphers.[2] An important point derived by them (their Table 7.1) is that there is a functional difference in the dependence of the blowup of the initial emittance between an amplitude function mismatch and a steering error or dispersion function mismatch, namely that the change in emittance due to an amplitude function mismatch is proportional to the incoming emittance. This fact led us to take the data set on 3/2/94 which compared the TEV emittance to the Main Ring emittance for a wide range of Main Ring emittances.

III. TEV vs MR 3/2/94

Figure 3 shows the result of this study. The data is for 7 Booster turns, 11 bunches, coalesced beam (with one noted exception), a value of quadrupole current in the transfer line IQUAD equal to 50 A (discussed below), and small injection errors as monitored by turn by turn data. Larger values of the Main Ring emittance were obtained by pinging the beam and smaller values of the Main Ring emittance were obtained by scraping the beam vertically at VF16 where the vertical dispersion is $\sim -0.2\,\mathrm{m}$ (this should imply that we were not momentum scraping). With no scraping and the pinger off, the Main Ring emittance was around 12π mm mrad with a corresponding TEV emittance of about 16.5π mm mrad.

One can fit the data with various parameterizations however, there are ways to present the data in order to try to deduce the mechanisms responsible for the observed emittance growth. If all the growth were due to lattice function problems then plotting the data as a ratio of TEV to MR as a function of MR emittance would yield a horizontal line, and Figure 4 shows that we certainly do not have that behavior.

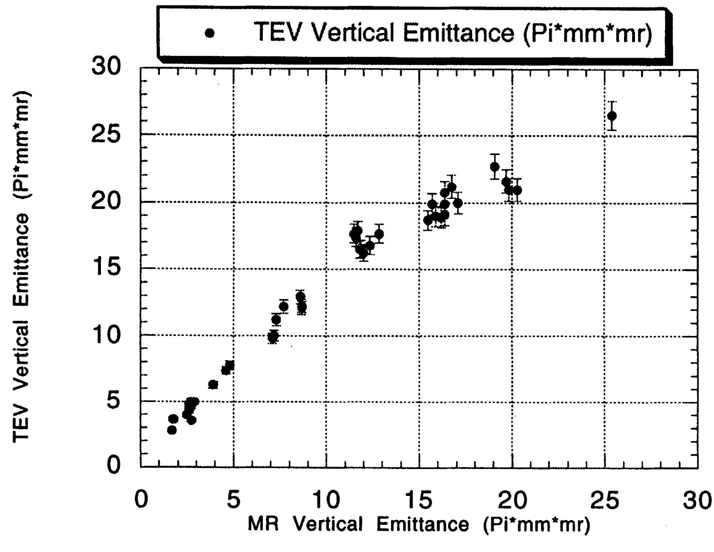

FIGURE 3 Measured Tevatron vertical emittance as a function of the measured Main Ring vertical emittance.

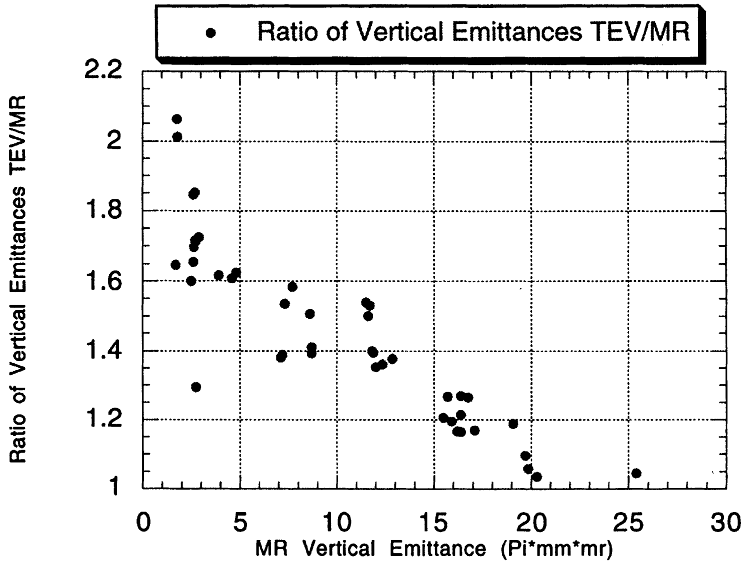

FIGURE 4 The ratio of measured Tevatron and Main Ring vertical emittances.

The most interesting way to present the data is shown in Figure 5 where the TEV–MR is plotted as a function of MR emittance. There is clear evidence for scraping even at values as small as 15π mm mrad in the MR. (A caveat is that this is also near the point where we switched from scraping to pinging.)

If we refit the lower part of the data before the kink to a straight line we have the fit shown in Figure 6 and it is the value of the slope and intercept from this fit that we will use later. We will give some reasonable estimate for the intercept of 1π mm mrad (dispersion mismatch and multiple scattering in the vacuum windows), however the value of the slope, 1.35, is difficult to explain without a very large beta (and/or alpha) mismatch between the machines.

IV. DISPERSION MISMATCH

There are reasons to suspect that there could be problems with a vertical dispersion mismatch between the MR and the Tevatron. Not only is the transfer from the MR to the TEV accomplished by a vertical dog

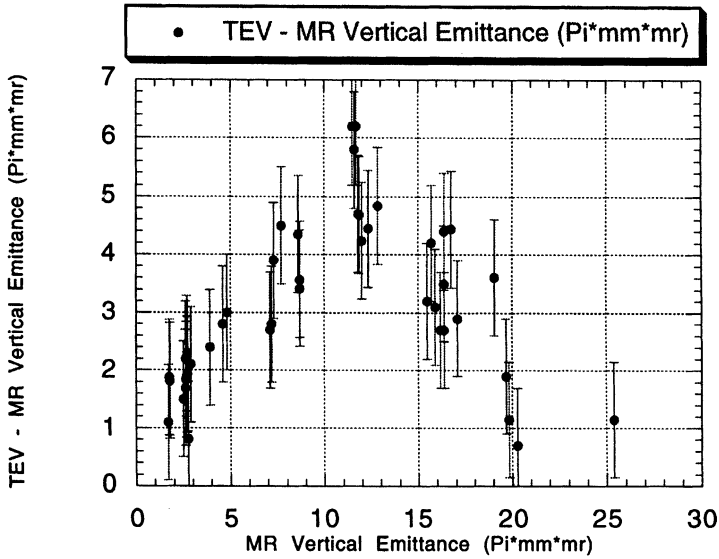

FIGURE 5 The measured difference between the Tevatron and Main Ring vertical emittance.

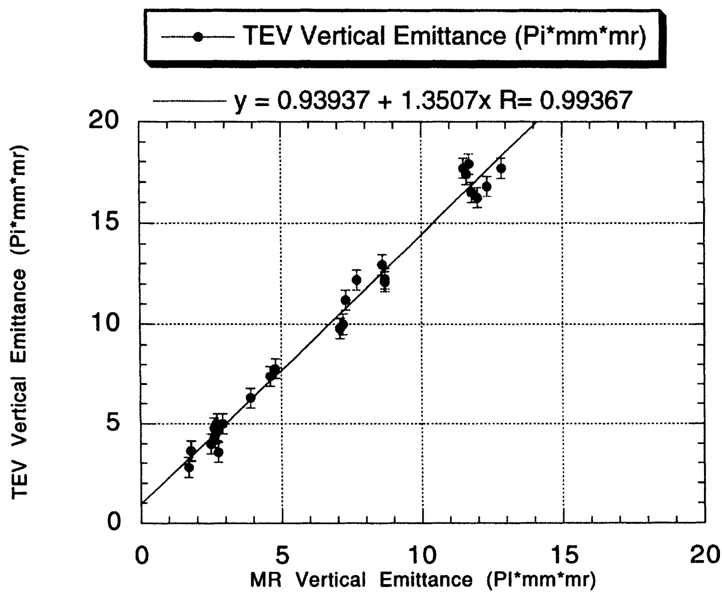

FIGURE 6 Functional relationship between the measured Tevatron vertical emittance and the measured Main Ring emittance assuming a linear form.

leg, but there is vertical dispersion in the MR due to the overpasses and there is supposedly zero vertical dispersion in the Tevatron. Ming-Jen Yang[3] has made a study of the vertical dispersion in the MR at 8 GeV and Table I shows his results.

This is reasonable agreement, so we have assumed that we know the values of Dy and D′y at the end of the D49 MR quads at 150 GeV from Synch. J. Marriner[4] made a transport model and translated these values to the beginning of the TEV E11 quad, where the results are $DD = 0.236\,m$ and $DD' = 0.0073$. Assuming values of $\beta = 59.865$, $\alpha = 0.0449$, and using a value for coalesced beam[5] $\sigma_{p/p} = 5E-4$ in the formula for dispersion mismatch one can calculate an additive factor of 0.5π mm mrad. Uncoalesced beam has a momentum spread that is a factor of four smaller than coalesced,[5] and the effect goes as the square of the momentum spread,[2] hence we would expect to see very little effect from a dispersion mismatch for uncoalesced beam. Table II gives our experimental results from the 3/2/94 study. The table shows that the effect from the dispersion mismatch is small, even at the very low values of emittance where one could have hoped to observe a $\pi/2$ mm mrad addition. There can also be an effect from a momentum mismatch between the two machines, but for any reasonable value of the synchrotron oscillation amplitude the momentum mismatch is smaller than the internal momentum spread. In discussing shot 4749 later we will also indicate that momentum mismatch is not the main source of our problem.

TABLE I Vertical dispersion comparison at E0

	D49	E11
Predicted	−0.686 m	−0.414 m
MJY measurement	−0.83 m	−0.65 m

TABLE II Comparison of coalesced and uncoalesced vertical emittance (π mm mrad)

		Main ring	
Scraping	Coalesced	2.7	4.6
	Uncoalesced	2.7	4.6
3 Turn	Coalesced		
	Uncoalesced	9.4	13.3
Normal	Coalesced	12.1	17.2
	Uncoalesced	11.9	17.1

V. VACUUM WINDOWS

In the attempt to determine all the possible sources of injection emittance growth, the fact that there were vacuum windows between the MR and the Tevatron was rediscovered. The windows are for both forward and reverse injection and the windows are 0.002″ titanium.[6] Using the multiple scattering formula $\langle\Theta^2\rangle = [14.1\ \mathrm{MeV}/c/\mathrm{p}]^2 * (L/L_{\mathrm{Rad}})$, with the radiation length of titanium equal to 3.56 cm, we have $\langle\Theta^2\rangle = 1.24\mathrm{E}-11$ rad. This implies an emittance growth of 0.5π mm mrad independent of the initial emittance (where we have used a value of 90 m for the beta function at the window). Note for our reverse injection studies that we traverse two windows and hence we would expect 1π mm mrad growth from the windows alone in Figure 2.

VI. INJECTION STEERING

There have been a number of studies concerning injection steering errors and usually the coupling was confusing. We have chosen an ILAM study from 2/23/94 to discuss since the simple model from Edwards and Syphers, Chapter 7, which predicts a quadratic dependence on the error amplitude, appears to bear some resemblance to the data as shown in Figure 7. Again one can speculate that the data at large oscillation amplitudes has some scraping which is why there is better agreement at small oscillation amplitudes and the data lies systematically below the model at larger amplitudes.

We will now discuss one of the most important data sets that we have, and it is not a deliberate study but rather just an examination of one shot, #4749. This shot had a spread in injection errors for the 6 proton bunches and the emittance growth was measured for each bunch. Figure 8 shows the emittance growth as a function of the estimated oscillation amplitude along with the prediction of the model from Edwards and Syphers. Please note the different scales! An additional piece of information is that there was essentially no synchrotron oscillation for this shot. The data in Figure 8 appears to have some relationship to the model and if we extrapolate to zero oscillation amplitude (and small synchrotron oscillation amplitude), we see that there is still an appreciable apparent growth in emittance. (The first

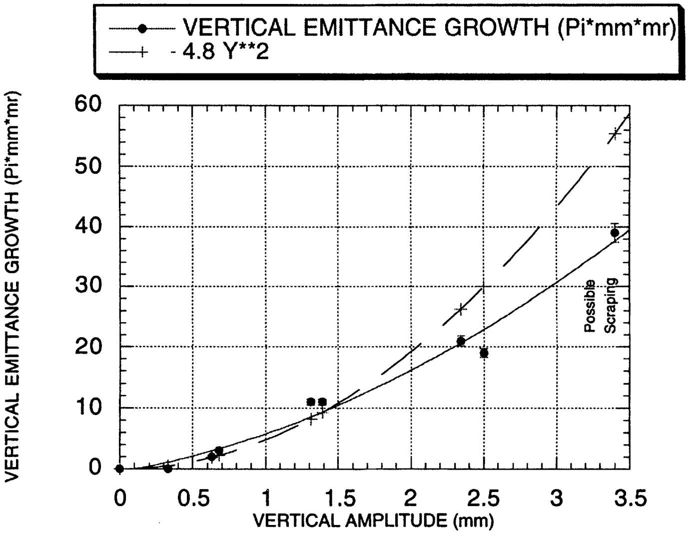

FIGURE 7 Vertical emittance growth as a function of injection error amplitude induced by missteering the injection Lambertsons compared to theoretical expectations.

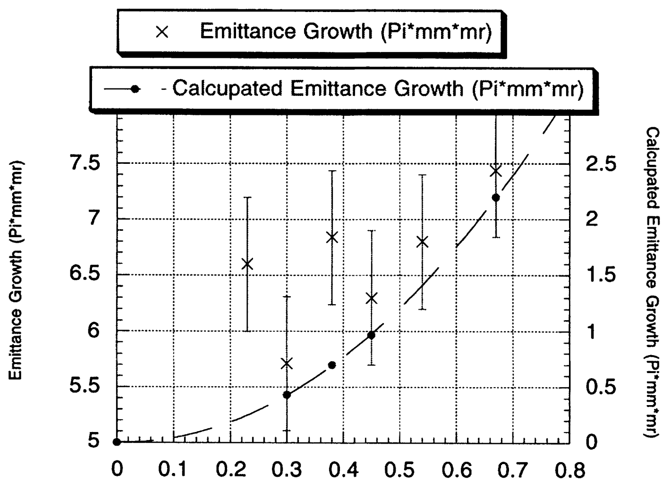

FIGURE 8 Measured emittance growth during Shot 4749 as a function of the observed injection oscillation compared to the expected growth from the injection oscillation. Note the different scales.

section notwithstanding, we have to use "apparent" here since some of this effect may be due to the assumed beta function at the flying wire (see the discussion preceding Figure 13), but remember that we know that not all of the growth can be explained this way due to the behavior shown in Figure 2.)

VII. T:IQUAD STUDIES

The preceding measurements indicate that there was an amplitude function mismatch between the machines. This mismatch could be the result of the lattice functions of the machines being different from their design values, or the transfer between the machines could be at fault. Fortunately (for the study) there is only one focusing element in the transfer line from the MR to the TEV and the name of this quad is T:IQUAD. One success of this study was to discover that the current in T:IQUAD had been incorrectly read back by a factor of two probably from its installation. This has not led to any breakthrough however. The conclusion of the study is that the quad had been empirically tuned to produce the best matching available.

VIII. PBAR INJECTION

What about pbars? Do they suffer a similar fate? Stan Pruss[7] helped make Figure 9 which again plots TEV emittance as a function of MR emittance for the pbars. What is illustrative about this data is that the pbar emittances are usually smaller than proton emittances so that we can use shots to look in a different range than normal proton emittances. The fit to the proton data is also shown and there does appear to be the same qualitative behavior in the proton and pbar data.

IX. SUMMARY

We learned that:

1. MR to MR transfer shows definite evidence for emittance blowup.
2. There may be some scraping at 15–20π mm mrad.

3. Dispersion mismatch is not a big effect:
   (a) calculated to be 0.5π mm mrad for coalesced,
   (b) measured to be small,
   (c) momentum mismatch not big effect.
4. There is a 0.5π blowup from the vacuum window.
5. Steering is important and calculable:
   (a) coupling can be confusing but ILAM studies made sense,
   (b) Shot 4749 analysis made sense.
6. Shot 4749 demonstrates there is a residual problem after steering and momentum mismatch effects are taken into account.
7. T:IQUAD is probably ok but had a factor of 2 error in readback.
8. The minimum TEV emittance can be parametrized in terms of the MR emittance (with no scraping) as $\varepsilon(\text{TEV}) = 1\pi$ mm mrad + $1.35\varepsilon(\text{MR})$. The 1π mm mrad can be considered to be the sum of the window and dispersion mismatch, and the difference in the

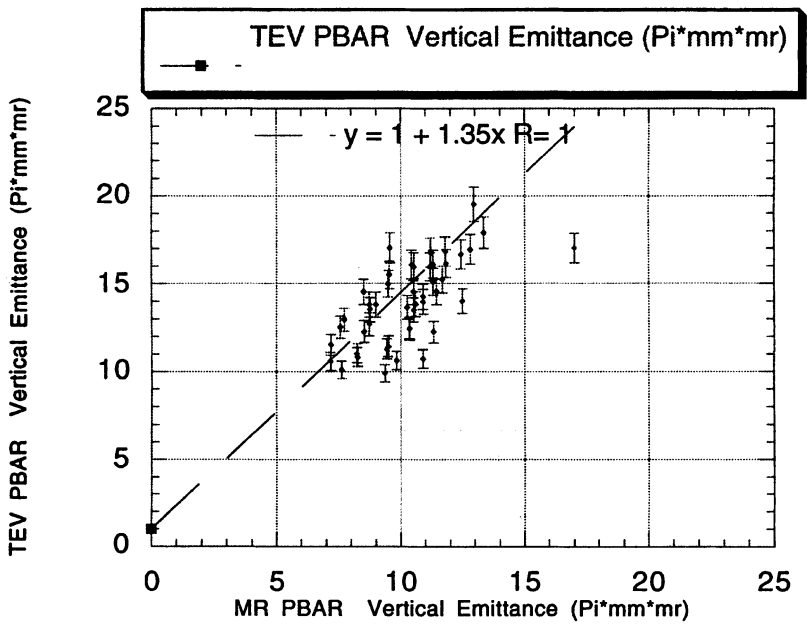

FIGURE 9 Measured pbar vertical emittance in the Tevatron as a function of the Main Ring vertical emittance. The fit to the proton data is given by the straight line.

slope from 1 can be considered to be compounded of lattice function mismatches between the two rings and scale errors at the flying wire.

X. INITIAL CONCLUSION

We had demonstrated that there was an amount of emittance growth that was related to a mismatch in β, α between the MR and the TEV.[8] The exact amount was difficult to tell since the mismatch also affects the β at the flying wire. Another source of confusion was the repeatability aspects and other systematic effects of the flying wires.[9] There were other indications that a portion of the source of the mismatch could be traced to the interaction regions (beta waves, coupling, . . .). Modeling efforts were underway to simulate the various effects by Goderre, Holt, and others. In particular J. Holt had determined that there was a misalignment in the downstream section of the B0 interaction region, in particular the model indicated a vertical misalignment of the Q3 quadrupole.

Shortly after Holt had made his prediction, an obstruction was found in the B1 cryo system and that particular subsystem was going to be warmed up. This was an opportunity to correct a misalignment since there are stringent criteria about moving cryogenic elements. The surveyors were instructed to look at the Q3 and they asked if the Q2 should be checked also. Murphy smiled and serendipitously it was determined that the Q2 was not only off vertically but radially and badly rolled (7 mR). The quad was realigned and the effect was very pronounced on all aspects of the machine performance, not just injection emittance blowup. We had been mired at a luminosity around 6E30 and the first shot after the access was 12.6E30, refer to the jump in luminosity around day 220 in Figure 10.

XI. AFTERTHOUGHTS

Theoretical studies were made which postdicted that a rolled quad could produce these effects. Also some experimental studies were performed which demonstrated that a local source of coupling coupled

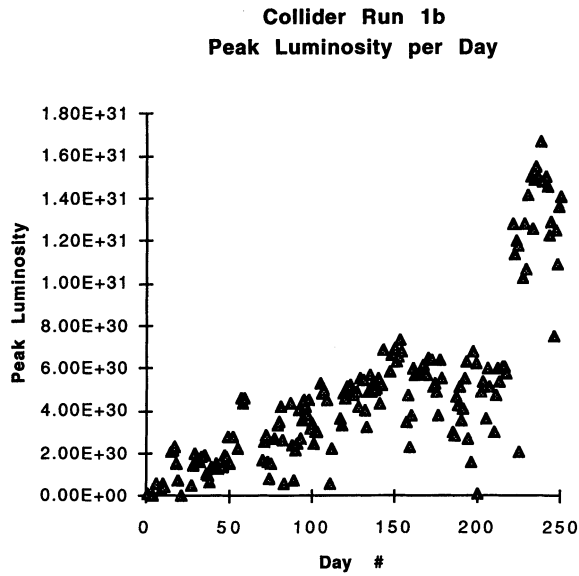

FIGURE 10 Initial luminosity for the first part of the collider run.

with nonlocal compensation could reproduce the apparent growth in emittance upon injection. The experiment was conducted by ramping skew quadrupoles (and other circuits) to mimic the situation with the rolled quadrupole and nonlocal compensation.

Since we now realized the importance of both planes we recorded the change in both planes. In the control situation depicted in Figure 11 the ⟨emittance growth⟩ in both planes was 2.5π mm mrad which was consistent with shots at that time.

In the case depicted in Figure 12 the ⟨emittance growth⟩ was 5π mm mrad in the vertical plane and 9.2π mm mrad in the horizontal plane, or 2.5π mm mrad more than the control case in the vertical and 6.7π mm mrad more in the horizontal, indicating that injecting into a coupled lattice does cause emittance growth.

In the case depicted in Figure 13 the ⟨emittance growth⟩ was 7.0π mm mrad in the vertical and 7.3π mm mrad in the horizontal, or 4.5π mm mrad larger in the vertical plane and 4.8π in the horizontal than in the control case, indicating how a coupled lattice can confuse flying wire measurements. Remember that the control case implies there is no real emittance growth.

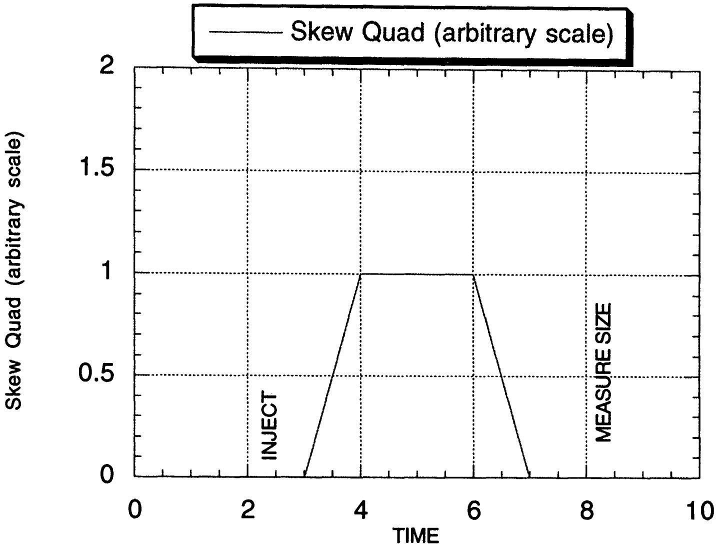

FIGURE 11 Schematic representation of the control sample which tested the question of whether the skew quads and tunes could be ramped without blowing up the emittances.

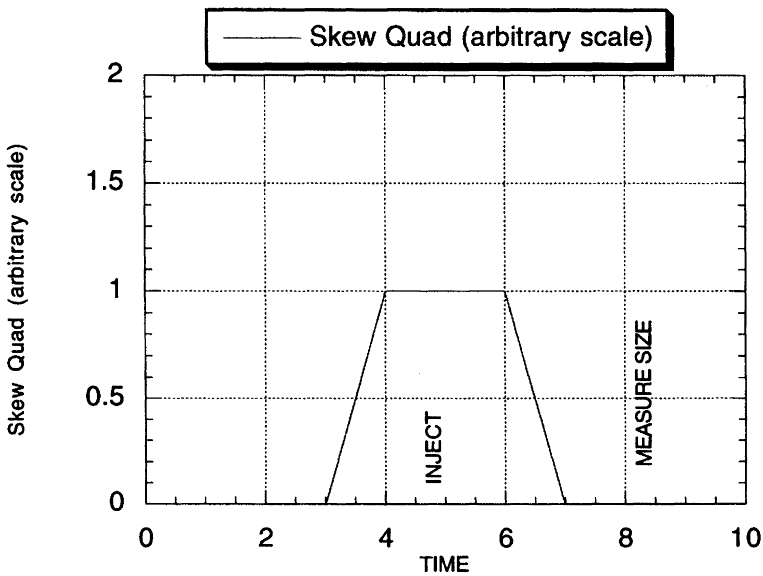

FIGURE 12 Schematic representation of the case in which the question was, does injection into a coupled lattice cause emittance growth.

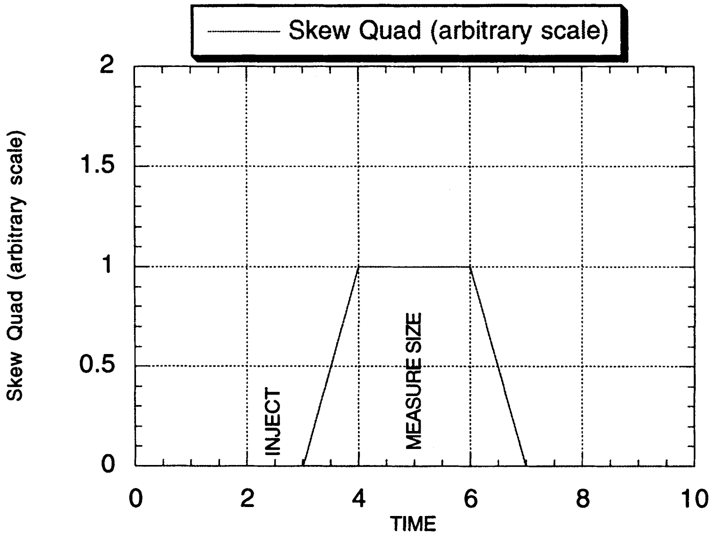

FIGURE 13 Schematic representation of the situation where the question was, does coupling effect beam size at the location of the flying wires.

Acknowledgments

The work on emittance growth at injection was started under the direction of John Marriner who had organized teams to look at various aspects of the problem with the luminosity. Many people were working on these problems including G. Jackson who utilized a crawling wire technique to also demonstrate a problem with the emittance growth at injection. In addition many other people were involved with taking portions of the data presented.

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