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MEASURING THE ORBIT LENGTH OF THE TEVATRON

Cordon Kerns, Quentin Kerns, and Harold Miller
Fermi National Accelerator Laboratory*
P. O. Box 500
Batavia, Illinois 60510

Abstract

The orbit length in the Tevatron was measured when coasting beam was first obtained. The method was time-of-flight, using a vernier phase comparison between beam pickup signals and a synthesizer sine wave. Some effort was spent making a stable phase detector so that it would not be a limiting factor. The results exhibited a repeatability of a few Hz at 53 MHz, corresponding to a mean radius measurement to 0.1 mm.

Introduction

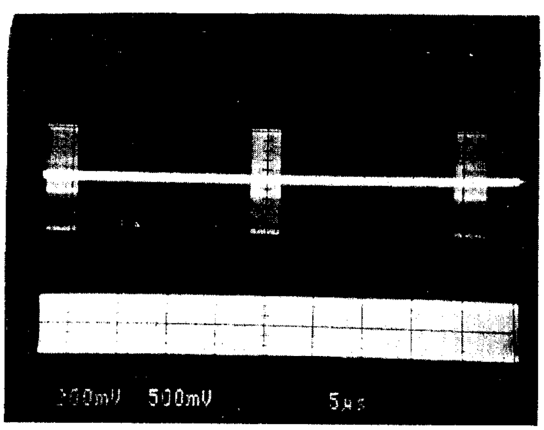
The commissioning steps in bringing up the Tevatron included measuring the Tevatron orbit length in order to improve our knowledge of the correct injection frequency. We were able to make the measurement using coasting beam, the first time coasting beam was obtained in the Tevatron.

The Main Ring accelerates beam up to 150 GeV and after a dwell time on Main Ring flattop, the 150 GeV beam is extracted from the Main Ring and injected into the Tevatron. The two synchrotrons, Main Ring, and Tevatron share the same tunnel and have the same design radius, 1000 meters, but we anticipated the possibility of slight orbit differences due for instance to limitations of survey and alignment.

The beam initially injected into the Tevatron for commissioning was purposely less than a full turn as well as reduced in bunch intensity in order to protect the superconducting magnets from an inadvertent quench. Even so, there was adequate signal level, several tenths of a volt, from beam detectors in the machine tunnel. The beam signals appeared as in Fig. 1a, three microsecond bursts. The reference signal is shown in Fig. 1b, a continuous 53 MHz sinewave.

Figure 1a

Figure 1b



The fine structure in 1a is due to the Main Ring rf, but the beam signal recurrence period is the Tevatron 1-turn circulation time. We wanted to precisely time the successive recurrences. As soon as 0.1 sec coasting beam was obtained, on June 26, 1983, we observed the bunches on a Tevatron beam pickup and made the measurements we will describe. The bunch structure persisted for the 0.1 sec the first time there was beam, but we required only 20 turns or so to make the measurement, hence debunching was not a problem. A block diagram of our system is shown in Fig. 2.

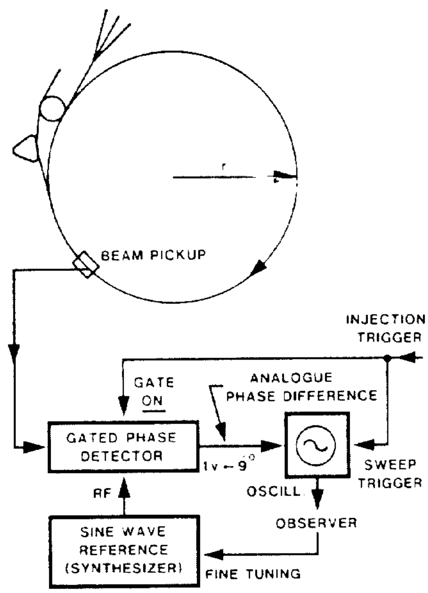


FIGURE 2 - MEASUREMENT PLAN FOR ORBIT LENGTH

Method

Referring to Fig. 2, we observed the gated phase detector output signal. Because this was a machine experiment we made the tuning adjustments by trial and error, observing the succession of signals from the phase detector, for 20 turns or so, upon every injection of beam from the Main Ring.

It is true that on successive injections (at the rate of several per minute) the initial phase was completely random. However, what we were looking for was a reference frequency such that the phase on successive turns of a particular injection shot did not drift over ≈20 turns. We were able to tune the reference frequency to the nearest 5 Hz, which is to say that we could adjust frequency of the reference until the observed rate of change of phase on successive turns was as small as $5\times 2\pi$ radians/sec, equivalent to $5\times 2\pi\times 20.9$ microradians/turn. This corresponds to an error in path length of 1 part in 10^7, hence a part in 10^7 on the average radius also.

Discussion of Errors

We are measuring the orbit length C by time of flight of 150 GeV protons. The distance around one turn equals the velocity times the time of one turn: $C=\beta ct$. To go from circumference to radius, we accept as a definition of the average radius R, $2\pi R=C$.

We tabulate some obvious errors we could think of (note c is not a problem because it equals 299,792,458 m/sec by international agreement). However, there are

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other sources of error:

1. Coherent β change in injection beam from shot to shot.

2. Tevatron magnet regulation, which results in a slightly changing orbit.

3. Reference frequency incidental phase modulation, which make the frequency source slightly imperfect as an instantaneous time base in both random and systematic ways.

4. Phase detector noise and drift, contributing random errors.

Item 1 contributes negligible error in the path length measurement based on a Main Ring observed magnet regulation of ±60 ma (the Main Ring beam control feedback holds radius constant):

$$\Delta\beta/\beta=\Delta P/P=(1/\beta^2)\Delta E/E=\pm 40 \text{ ppm}$$

$$\Delta C/C=(1/\beta^2)^2\Delta E/E\simeq\pm 1.3 \text{ parts in } 10^9$$

Item 2, because p is constant in the Tevatron here (no acceleration), changes in β do cause changes in R:

$$\gamma^2_{tr}dR/R=dB/B$$

Given a short term Tevatron magnet regulation of ±10 ppm,[1] and $\gamma^2_{tr}=289$ we find:

$$\Delta C/C=\Delta R/R=(1/\gamma^2_{tr})\Delta B/B,$$

$$\text{or } \Delta C/C\approx 3.5 \text{ parts in } 10^8$$

Therefore, item 2 is not large enough to be a serious problem.

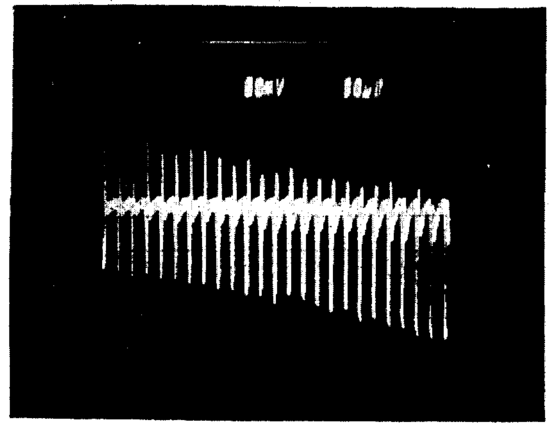
Item 3, phase modulation of the reference source was separately observed to be as much as a few Hz in 1 millisec, although the long term drift was well below 1 Hz. The long term stability is quoted by the manufacturer as $\pm 3\times 10^{-9}$/day for the internal quartz oscillator. Item 4, the phase detector, in bench tests can vary ±0.013° in a millisec, which corresponds to 6.7 parts in 10^8. The phase detector long-term drift did not accumulate to more than 0.02° in three days continuous running in bench tests with a fixed pair of signals. This corresponds to measuring a time difference of 1 ps.

In view of the above, the 5 Hz random error in 53 MHz, or one part in 10^7, appears reasonable to us. We could adjust the reference frequency in steps of 1 Hz (HP 8660C with option 001). This proved to be sufficiently small for our measurement.

Orbit Length

Phase detector output signals: Under the above conditions the phase detector output on successive machine turns, every 20.9 μsec, appears as in Fig. 3. For demonstration of the effect in Fig. 3 the reference frequency has been purposely offset by 10 Hz from the 1113th harmonic of the Tevatron circulation frequency. As is apparent in Fig. 3, successive turns show a phase detector output signal change that is progressive. Based on the phase detector output being 1V per 9° phase change and taking account of the time constant of the phase detector, we can estimate the expected rate of phase change, approximately 10 Hz. In practice we could adjust the envelope of Fig. 3 to a flatter slope consistently within ±5 Hz, or ±0.04° per Tevatron turn on the average.

Figure 3



Caveat

One caution concerning aliasing we were aware of is that the reference frequency must be selected to match the 1113th harmonic of the Tevatron circulation frequency, not the 1112 or 1114, etc., but these harmonics are 47.7 kHz apart and we know what frequency to look for to within 2 kHz (our surveyors are more accurate than that). In fact, the Tevatron survey turned out to be within 100 Hz; i.e., within 2 millimeters, of matching the Main Ring radius.

Finally, we can give a number for the absolute radius of the Tevatron orbit to one part in 10^7 and we find it to be 1000.006245m ± 0.1 mm, or 6.2 mm oversize.

Later, on June 28, 1983) we rechecked the Tevatron injection frequency by looking for synchrotron oscillations with high level rf on. Changing the injection frequency by ±12 Hz introduced synchrotron oscillations of ≈equal magnitude and opposite slopes. Thus, the original measurement with coasting beam was confirmed when rf buckets were established.

The Phase Detector

In view of the need for making accurate phase measurement, a stable low noise phase detector was developed. The basic approach was to use overlapping square waves formed from the input signals. Fast comparators provide square wave outputs near the zero-crossing time of the input sine waves. (See Fig. 4.) We found comparator time slewing was minimized by symmetrical push-pull inputs. A half-wave resonant line converts single-ended to push-pull.

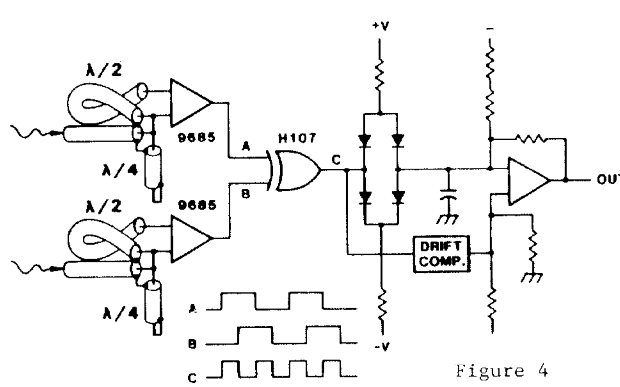


Figure 4

To eliminate the common problem of cross-modulation by stray 60 Hz fields, we coiled the λ/2 line into a zero-area figure 8 loop and used a λ/4 line as a dc short on the input. Early attempts at using any magnetic core baluns were abandoned because of stray 60 Hz pickup. (We were seriously attempting to reduce all non-fundamental sources of noise.)

The comparator outputs drive an exclusive OR circuit; its output provides a signal with the time overlap information in it. Current steering diodes, switched by the overlap signal, direct constant current sources into the integrator output stage.

We wanted the units to be interchangeable in 50Ω systems. To achieve this the calibration procedure requires selection of components and trimming of coaxial cables to make each input as close to 50Ω, zero degrees as possible. Since both the input impedance and output level, for 90° apart signals, are trimmed simultaneously a compromise is made in the impedance of IN(2). With the 90° angle between inputs the output was made to be less than 50 mV or ±1/2°. The output swing was set to +10V for in-phase signals and -10V for signals 180° apart. The overall calibration is 10V/90° within 5%.

We made output stability measurements using a pair of signals adjusted in-phase to give a zero output from the phase detector. Runs of 24 hours have shown the output to stay within 1.5 mV or ±0.015° of their calibration point.

Approximately 50 production units of the phase detector, constructed in two-wide NIM modules are in various accelerator systems including the Tevatron low level rf,[2] Tevatron accelerating stations,[3] p-bar low level rf, debuncher cavities[4] and synchronous phase measurement systems[5] in the Tevatron and Main Ring accelerating systems.

Acknowledgements

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