THE TEVATRON BEAM POSITION AND BEAM LOSS MONITORING SYSTEMS

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Introduction

This article discusses the main design features and the early operation of the Beam Position Monitor (BPM) and the Beam Loss Monitor (BLM) systems designed and built for the Fermilab Tevatron. The main features of the BPM and BLM systems were determined by the fact that the Tevatron is constructed of superconducting magnets, and in addition that it is designed to operate both as an accelerator for fixed target physics, and as a storage ring for colliding beam physics. Included in the design criteria were features to facilitate initial turn-on of the Tevatron as well as investigation of machine parameters such as tune, chromaticity, x-y coupling etc.

Superconducting magnets are known to be quenched easily by stray radiation. Tests at Fermilab showed that of the order of $5x10^9$ protons at 100 GeV could quench a superconducting dipole magnet. This lead to the requirement that the BPM system operate reliably from $5x10^9$ to $3x10^{13}$ circulating protons, a dynamic range of nearly 10,000 to 1 (in terms of protons per bucket (ppb) however, the dynamic range is from $1x10^8$ to $3x10^{10}$, or 300 to 1). During injection studies, being able to record all beam positions simultaneously, even for a single turn, was highly desirable, as recovery from quenches was likely to require many minutes. In addition, to protect the magnets during normal operation, the BPM system had to abort the beam if it strayed beyond preset limits. The BLM electronics also had to initiate a beam abort if the radiation level exceeded preset limits.

Operation in both fixed target and collider modes presented another set of design problems. In fixed target mode, the beam position detector signal has a 53 MHz modulation. This is absent in the collider mode, as there are only a few intense isolated bunches of particles circulating in the ring. Also, as the proton and antiproton bunches are counter-rotating, some way of preferentially selecting one direction over the other was required.

In addition, the normal requirements of a BPM system had to be maintained. These included being able to study the betatron oscillations during the first few turns after injection, to study the closed orbit of circulating beams, and to do machine studies: tune, tune spread, coupling, chromaticity, and aperture scans for slow extraction, to name a few.

Overall Layout

There are 216 BPM position detectors in all, half vertical and half horizontal, normally located at vertically and horizontally focusing quadrupoles respectively. As the design tune is about 19.4, there are approximately 5 detectors per betatron wavelength in each plane. The detectors are cabled to 24 Service Buildings spaced equally around the 6.28 km circumference of the ring, where the electronics is located. These stations are connected to the host computer by means of a 10 MHz serial link, which is shared with all the other control and monitoring systems in the Tevatron. This serial link is only used for parameter downloading and data readback. Fast timing and synchronization is handled by a 10 MHz diphase-encoded clock signal sent around the ring in the direction of the beam. Buffer memories in each station store the recorded data for later readback.

Control consoles in the control room can access the data thus stored, and applications programs can create color graphics displays and hardcopy. Data from the stations can be stored in the host data base for later analysis.

Hardware

The position detector is a pair of 50 ohm striplines about 20 cm long, each subtending approximately 110 degrees of arc, with a circular aperture of 6.6 cm[1]. This geometry is sometimes referred to as a directional coupler, as it is quite sensitive to the direction of the beam. The detectors are mounted on the ends of the superconducting quadrupoles, and therefore are at 4 degrees Kelvin. Four signals are brought out, one from each end of each electrode. The two downstream ports are back terminated in 50 ohms, and the upstream ports are cabled to the electronics in the adjacent Service Building. In fixed target operation, the signal power from each electrode in the 53 MHz component is about +4 dbm for a centered beam of 1×10^{10} protons per bunch(ppb). The signal amplitude ratio dependence on lateral beam motion is about 0.7db per mm near the center. The forward/backward directivity is about 24 db, as measured with circulating beams. When colliding beams operation is begun, coaxial relays will be installed in the tunnel near the detectors to select signals from either protons or antiprotons, and to back terminate the unused ports.

Cabling to the Service Buildings is done with foam dielectric RG 8 cable. Each pair is phase-matched to about +/- 3 degrees at 53 MHz, and the attenuation balanced to about +/- 0.3 db. Cable attenuation ranges from 2 to 8 db, depending on detector location. As the detectors cabled to each Service Building cover about 300 m of beam line, the signal arrival time at the electronics is skewed over about 1 musec, and is opposite for protons and antiprotons.

The signals from all detectors are simultaneously processed in amplitude-to-phase modulation (AM/PM) modules[2]. A block diagram of this technique is shown in Figure 1. This method of processing was chosen to provide both the very large dynamic range requirement as well as a real time position signal (the risetime of the output signals is about 70 nsec). The useful input dynamic range is from -40 to +20 dbm per electrode. Narrow bandpass filters (about 5 MHz bandpass, center frequencies matched to +/- 0.1%) ring at 53 MHz when excited by signals from isolated beam bunches, providing the needed sensitivity in collider mode operation. In addition to the AM/PM circuit, the two input signals are added to provide an intensity signal output. The output sensitivities are about 125 mV/mm displacement, and 1.1 volts/1×10^{10} ppb into 50 ohms. The inputs are especially designed to allow remotely controlled injection of RF signals to test the electronics, and currents to check cable and detector continuity to the 50 ohm back termination.

For reliable operation in the Tevatron, the order of 15 contiguous bunches of 2×10^8 protons each (i.e. 3×10^9 protons) are required for batch mode operation, and about 2×10^9 protons in a single bunch for collider mode.

Tests made with wires and with the main ring beam confirmed the position sensitivity of the detector and AM/PM circuit. Tests with the beam in the Main Ring confirmed the signal amplitude, directivity, and response to isolated bunches of protons. In addition the beam tests showed the resolution (repeatability on turn-to-turn measurements) to be about 30 microns rms at 3×10^{10} ppb, and about 500microns at 5×10^7 ppb.

The position and intensity signals are processed in the BPM Analog Box. Sample and hold circuits for the position and intensity signals from each detector are triggered by the individual intensity signals to overcome the time skewing problem. The sample and hold gate is edge triggered, firing at the leading edge of the beam intensity signal following a gap in the beam (a 1.5 musec gap is required for both injection into and single turn extraction from the Tevatron). The trigger threshhold is settable by the host computer. The sample and hold circuits are armed by the microprocessor controller, and disarmed by valid trigger signals to prevent multiple firing. The intensity sample and hold signal is compressed in a 3 decade logarithmic amplifier, and all the signals are digitized in parallel by 10 MHz ADC's in about 4 musec. The ADC least count resolution in the position channel is about 150 microns. Fast coincidences can be made between the intensity trigger signals and an encoded signal on the 10MHz Tevatron Clock. To allow for the propagation velocity of the encoded signal around the ring, downloaded coincidence gate delays (and widths) are remotely settable in 200 nsec (100 nsec) steps up to 51.2 musec (25.6 musec) by the host computer. A hard-wired Jumper board in each Analog Box allows for separately adjusting the time skewing for protons and antiprotons at each detector. The fast coincidence allows monitoring a single turn of beam such as during injection studies, or a single bunch of protons (or antiprotons) during colllder operation.

Digitized position and intensity measurements thus obtained are read into the microprocessor-controlled digital processor in a Multibus crate. Digital processing includes a digital averaging process, in which 8 to 64 measurements are added in TTL adders and averaged by bit shifting. The averaging of many turns of beam position data smoothes out the coherent betatron oscillations, and gives a good measure of the closed orbit. This averaging period, repeated at 1 to 15 msec intervals, is settable by the host computer, as is the number of measurements in the average. Two of the twenty-four stations are equipped with additional electronics to record the turn-by-turn (TBT) position of all 12 detectors in that station. The host selects any two detectors for readback, the number of turns recorded (up to 1024), and the time at which the recording is begun. This latter feature was installed to perform tune, tune spread, and chromaticity studies with a "pinged" beam (A "pinger" is a pulsed magnet to induce coherent betatron oscillations in the beam).

The BLM detector is a sealed glass ion chamber with a 110 cc active volume filled to about 1 Atm with pure argon gas. The detector calibration is about $7x10^{-8}$ Coulombs per Rad, and has been found to be nearly linear to 100 Rads instantaneous dose, when operated at 2.5 kV. Leakage currents at this voltage are held to approximately 20 femptoamps due to electrode geometry and guard ring construction. There are approximately 216 BLM detectors located adjacent to the Tevatron quadrupoles, plus additional units in straight sections and injection/extraction lines, where there are aperture restrictions.

The BLM electronics box includes a 4 decade integrating logarithmic amplifier for each BLM detector. This log amplifier, like the one in the BPM intensity channel, uses a matched transistor pair in a transdiode configuration, as shown in Figure 2. The integration time was selected to match the known integration time of 1/16 sec in the beam-induced quench properties of the Tevatron dipoles (800 Rads/sec(slow) or 50 Rads (instantaneous) will cause a quench in a superconducting coil). In this way, the output voltage has a direct correlation to the probability of quenching a magnet. The logarithmic response allows compressing a large dynamic range (1 nanoamp to 10 microamps) into an 8 bit ADC. This in part reflects the uncertainty in predicting the sensitivity of superconducting magnets to beam-induced quenches, as well as the unpredictability of the beam loss point relative to the detector (they are located at 30 m intervals).

Other features of the BLM electronics include an internal host-computer-settable high voltage supply, normally operated at 2kV, and an asynchronous 8 bit ADC continuously updating data in a dual- port memory. This memory is read at 8 msec intervals by the microprocessor controller (i.e.

about 8 times per integrating time constant). The combined risetime of the ion chamber and the log Integrator is about 200 musec, which is equivalent to about 10 turns of the beam. The beam abort threshhold setting is downloaded from the host computer, and is continuously compared to the amplifier analog output signals. Any signal exceeding this level will generate a beam abort demand signal. This signal can be generated in less than 200 musec. A self-testing feature of the input electronics is that about 0.5 nanoamps is leaked into each input, creating a small digitizable offset voltage. The presence of this offset in the BLM data read back by the host is an indication that the electronics is working.

A test interface module was built into the system especially to perform computer-controlled tests on the hardware. This box on command can digitize and send back to the host the digitized values of about 60 dc voltages. In addition, it can generate a gapped 53 MHz signal of several amplitudes suitable for injection into the inputs of the RF modules for checking the BPM electronics. Another hardware test is to put 10 ma dc into each BPM detector cable and digitize the voltage, hence measuring the presence of the back termination. Another test, performed without the test interface module, is to turn the BLM high voltage off and on over a period of many seconds. Due to the interelectrode capacitance of the BLM detector, This test induces charge at the input of the log Integrator circuit, creating a digitizable signal. Thus a complete test of all BLM cabling is performed. A block diagram of a typical BPM/BLM station (without TBT) is shown in Figure 3.

BPM Software

Each of the 24 BPM Multibus crates contains two Zilog Z80 microprocessors. One microprocessor, with 2kbytes of RAM and 4kbytes of PROM, manages the BPM hardware. The second microprocessor, with 32k of RAM and 10k of PROM, is responsible for management of the data memory, execution of the applications programs, and communication with the host computer. An additional 16k of RAM is used in those stations where TBT is implemented.

All of the downloaded data to each station is sent from the host via the serial link. These data are the settings required to control the hardware. The microprocessor applications programs are stored in PROM. All downloaded data are loaded into write/read registers, for readback verification. As the serial link is a point-to-point transmission with considerable protocol, it is not suitable for real time applications, i.e. fast triggering, or for timing signals which are to be sent simultaneously to all stations. The 10 Mhz Tevatron Clock can for this reason be encoded with up to 256 timing signals with a timing accuracy of 100 nsec. Sixteen of these timing signals are reserved for use by the BPM/BLM system. The 10 Mhz carrier is the time base for all Tevatron control systems. Most of the encoded timing signals used by the BPM system are queued in a FIFO interrupt register and are handled by software applications programs. The two signals which require fast timing accuracy, the flash trigger and the master clock reset, are hardware functions. Software functions include "prepare for beam", "end of beam", "high magnetic field", "low magnetic field", "write profile frame", and "write display frame". These specific event triggers will be described later.

At the end of each averaging cycle, a 20 byte "frame" of data is assembled. This frame includes 12 bytes of position data, 3 bytes of time data (1 msec least count), 3 bytes of data indicating whether individual position averages exceeded the downloaded limits (there are four limits per detector, an alarm level and an abort level, for low and high magnetic field), and 2 bytes of data validity checks. If the average position of any detector exceeds the preset alarm level, the host is notified. If the required multiplicity of average positions exceed the abort level, then a beam abort is demanded via a hardware output.

This frame is then routed to any of three memories depending on pending interrupts. Each frame is always written into a 512 frame deep circular "snapshot" memory. This memory, which contains all the position data for the most recent 512 averaging cycles, is stopped whenever the processor receives a hardware signal that there is an abort in progress. If there is a pending request from the signals encoded on the Tevatron Clock, this frame is also written into the non-volatile 128 frame "profile" memory. This data is held for later readout in order to carry out closed orbit analysis. Another pending request will write the frame into a single 20 byte "display" memory, to be read back by the host for graphic display. This display memory insures that all displayed data is synchronized to within one averaging cycle.

If a "flash" event trigger is encoded on the Tevatron Clock, the normal averaging cycle is stopped and a flash delay and gate circuit with 100 nsec resolution is started. The flash gate signal is then individually delayed for each detector by Jumper-selected taps on a 1.6 musec shift register. If there is beam within this gate for any detector, both the position and the intensity will be digitized. This flash data is then loaded into a 30 byte "flash" frame, and the processor reverts back to the normal snapshot cycle. The time resolution of the flash cycle is such that it can digitize a single turn (or partial turn) or an individual isolated bunch of beam.

As a faulty input channel can interfere with the normal operation of the station, or cause unwanted beam aborts, two "mask" bits are downloaded for each detector channel. If a channel is not in use (an average of 9 of the 12 channels in each station are used) or is known not to be reliable, a detector mask bit is downloaded for that channel. This completely inhibits the channel at the hardware level. If a detector is to be excluded from the abort demand function, the abort mask bit is set.

Every 8 milliseconds, the BLM dual port memory is read out by the microprocessor and formed into a 16 byte BLM frame. This is written into snapshot, profile, and display memories depending on pending requests. As explained above, the beam abort function, unlike the BPM which is based on microprocessor analysis of digitized data, is completely carried out at the hardware level once the threshold level is set, and remains operational even if either the host or microprocessor controller fails.

The microprocessor controller can issue a service request (SRQ) to the control system if it detects an equipment failure or if the alarm level is exceeded by either the BPM or the BLM system. These unsolicited messages are polled by the host at a 15 Hz rate, and can identify equipment problems or situations which if not corrected could result in a beam abort demand.

Two stations are equipped with special electronics to record turn-by-turn (TBT) positions of selected channels. This data is recorded in either of two modes. In the parasitic mode the TBT information is recorded for the first 1024 turns without interfering with the normal operation of the station. In the second mode, TBT takes highest priority, even over flash, for up to 1024 turns. In this latter mode, the TBT cycle is initiated by an external trigger.

Host Applications Programs

The host, a VAX-780, communicates to all the Tevatron control systems via a PDP 11/34 front end computer[3]. It communicates to the user via applications consoles which include a PDP 11/31, a keyboard, a color monitor, a color graphics display, a storage osclliscope, a hardcopy unit, and a trackball-controlled curser. Specific applications programs are menu-selected and their specific variables inserted from the keyboard or called from the host database. The specific applications programs which are used by the BPM system are described below.

The parameter downloading and verification program is used to download the operating parameters to each station, either from the host database or from the keyboard, and to verify them. As the downloaded parameters vary somewhat from station to station, there are 24 sub-pages in this program, one per station.

The BPM/BLM system tests program exercises the built-in self testing features of the equipment such as the BPM and BLM cable continuity tests, the dc power supply tests, and the BPM RF tests. The design philosophy here was to create color graphic displays which at a glance identify the existence of problems and their severity, while at the same time producing a list of the specific problems and their precise location. This list can be hardcopied and used by personnel making the repairs.

The BPM/BLM data display applications program provides access to all the BPM/BLM data structures and produces displays, either on the color graphics display or on the storage scope for immediate hardcopy. The operator can select either a plot showing vertical orbit, horizontal orbit, and beam losses (or beam intensity on flash frame readback), or a display which plots either the vertical or horizontal orbit and a list of the numerical values measured at each detector. The vertical scale is user-settable for all these displays. In addition any readback data can be archived in the host database for later review and analysis. This includes the capability of displaying the differences between two archived files to emphasize specific orbit distortions. Typical flash and profile displays are shown in Figures 4, 5, and 6.

The position and intensity data as read into the host is in raw microprocessor units. The position data is linearized by a lookup table to correct for the known detector and AM/PM circuit response functions, and is corrected for measured detector misalignment4 and survey errors.

The turn-by-turn applications program controls and utilizes the turn-by-turn capabilities of the BPM system. It is primarily used to measure tune, coupling, and chromaticity. It displays up to 1024 turns of orbit data from two detectors (usually one vertical and one horizontal) and in addition displays a Fast Fourier Transform analysis of the position data to show the fractional tune and tune spread. It can also readily identify injection errors which cause either coherent betatron or synchrotron oscillations. Amplitudes of 0.5 mm are easily seen and transformed. Typical TBT displays are shown in Figures 7, 8, and 9.

The orbit correction applications programs use the output of the flash or profile data readback to adjust the correction dipole magnets. The specific applications programs include first turn analysis to adjust correction dipoles to achieve a complete turn, orbit closure to cause the second turn to lie on top of the first turn, and closed orbit correction to minimize orbit distortions. This latter application can smooth the orbit to about 200 microns rms, about the stability limit of the BPM system.

Operating Experience

The BPM and BLM systems have now been in operation for about 2 months, when injection studies into the Tevatron began. During this time many of the features of these systems have been used, but some features still have to be fully tested and utilized. As higher intensities are accelerated, and as single bunch (collider mode) studies are initiated, more of the functions built into these systems will be tested. However, even in the first few weeks of operation, many of the design features were utilized.

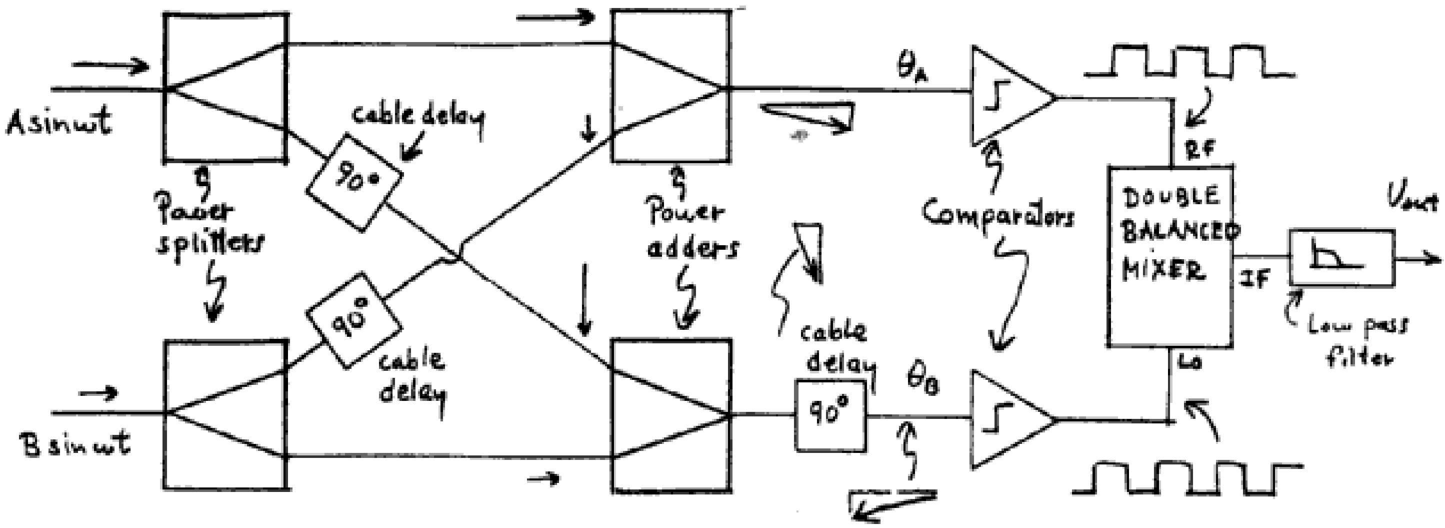
Obtaining first turn, including steering around aperture restrictions and obstacles, was done using the Flash mode operation, using both the beam intensity signal and the beam loss signal as well as the horizontal and vertical position information.

The typical operating intensity, approximately 1×10^{10} protons at 150 GeV, typically caused 1 or 2 beam induced quenches per 8 hour shift (recovery time was typically 15-20 minutes). The repetition rate was usually one cycle per minute. Being able to simultaneously record the positions at all detectors was quite valuable. Once first turn was achieved, this operating mode was used to examine the second turn and smooth out the injection bump. When coasting beam was achieved, the beam intensity signals were not nearly as useful as the beam loss monitor signals. Their large dynamic range and sensitivity seems to be suitable for locating and minimizing relatively small beam losses. The built-in BLM time constant to match the beam-induced-quench properties of the superconducting magnets did not seem to cause any problems in tuning the machine. The dynamic range appears adequate to see small losses and also protect the magnets.

The Snapshot, Profile, and Display modes, which average out the betatron oscillations, had been especially useful in minimizing the closed orbit errors and in studying the machine aperture. The turn-by-turn equipment has been especially useful in exploring the tune diagram, and in setting the skew quadrupoles (x-y coupling) and the sextupole (chromaticity) and for minimizing coherent synchrotron and betatron oscillations at injection.

The inclusion of internal hardware tests to detect equipment malfunctions in retrospect was absolutely necessary. If this had not been done, valuable beam-on time would have to be used to diagnose BPM and BLM system problems. The major problem in the BPM system has been the internal detector connections. Approximately 5 of the 216 detectors (representing over 800 connections) measure "open" rather than 50 ohms in the continuity test. These detectors have to be masked off (using the downloaded Mask function) as the position signal readback is erroneous. It is not known at this time whether the problem is at the connector on the detector is a cold solder joint (time domain reflectometry can locate the problem to within 1 or 2 cm). In some cases the problem is known to cure itself when the magnets are warmed up.

The use of PROM's to control the BPM and BLM hardware provided the necessary flexibility to modify the operation of the equipment as our understanding of the needs of the system improved. Had this system been implemented entirely in hardware, modifying its operation in any way would have been very difficult. Had many of the PROM functions been transferred to the host computer, it would have put an enormous burden on the serial link.



$$\theta_A - \theta_B = 2\,\mathrm{TAN}^{-1}\left(\frac{A}{B}\right); \qquad V_{out} = \mathrm{const} * \left[\mathrm{TAN}^{-1}\left(\frac{A}{B}\right) - \frac{\pi}{4}\right]$$

Figure 1. Phasor block diagram of amplitude to phase (AM/PM) circuit.

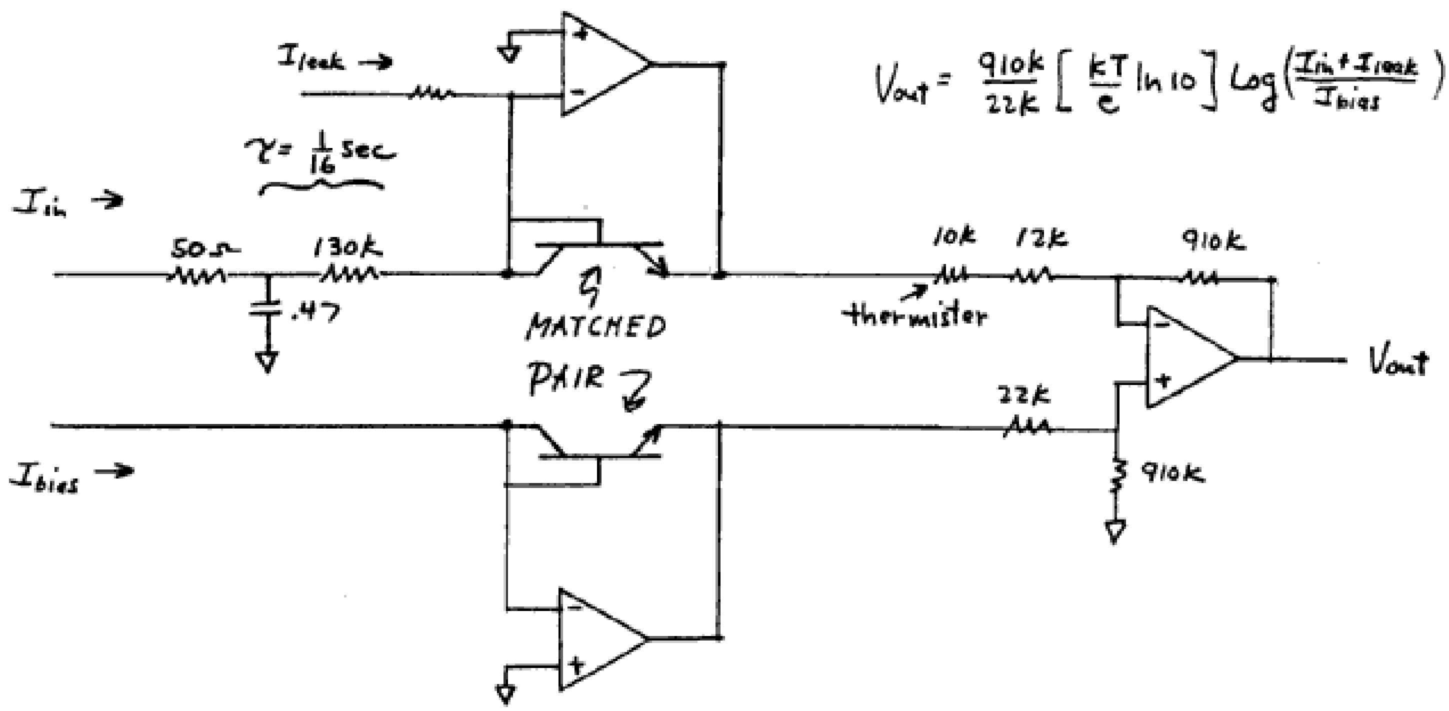


Figure 2. Basic circuit for a four decade integrating logarithmic amplifier.

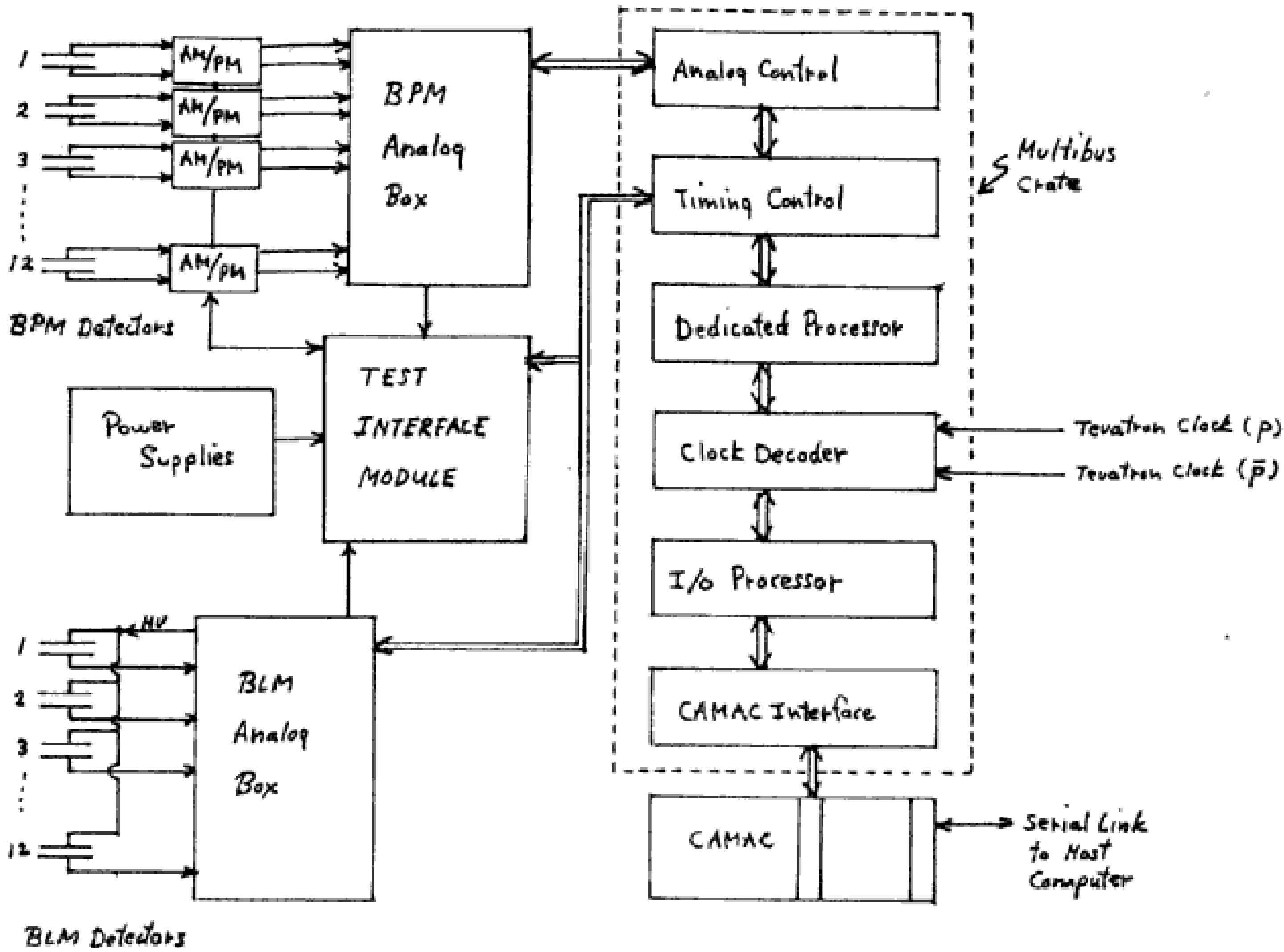


Figure 3. Block diagram of a typical BPM/BLM station.

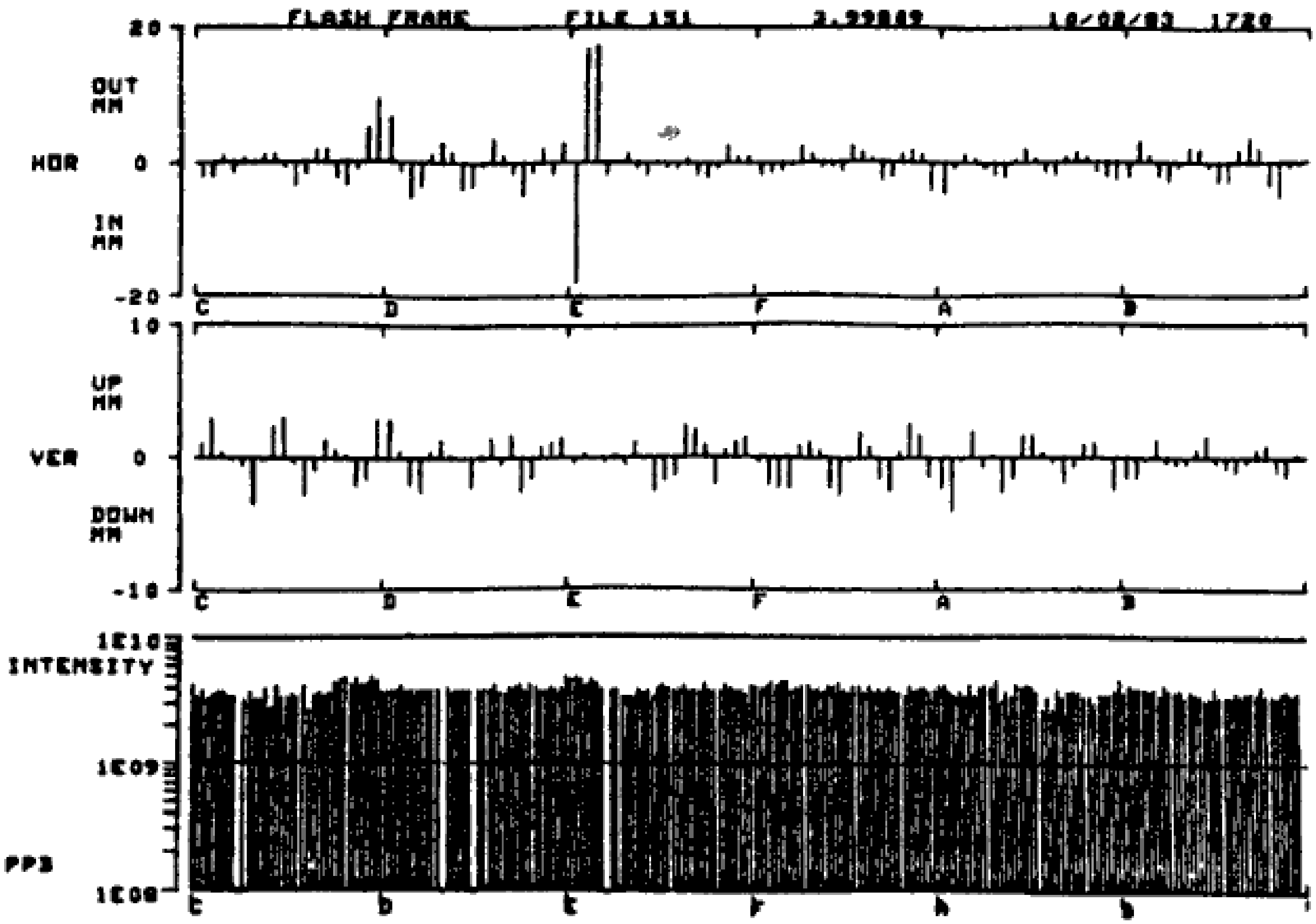


Figure 4. Flash display showing horizontal position, vertical position, and intensity vs. location around the Tevatron for the first turn.

PROFILE FRAME 7.598

FILE 12909/27/83 0723

AFTER CORRECTIONS

(MM) 10/02/83 1722

	C	D	E	F	A	B
11	-1.54	2.8	3.93	-3.93	.46	1.39
13	-1.7	-.61	-7.98	1.85	3.28	0
15	1.23	-1.54	3.93	3.44	-.3	-2.8
17	-1.23	-.92	.15	.77	-3.93	-1.54
19	NOBEAM	2.48	2.64	-1.08	-2.8	2.17
22	.3	1.85	-2.01	-1.85	1.85	3.12
24	.77	-.46	-4.42	1.23	2.8	.3
26	1.08	-3.76	-.77	3.93	0	-1.54
28	-.15	-1.39	4.26	.92	-2.8	-.92
32	-2.32	1.54	2.48	-.61	-2.8	1.39
34	-1.39	2.96	-2.17	-2.32	1.23	1.39
36	1.7	-.46	-3.6	.92	3.44	1.23
38	2.01	-2.17	-2.01	1.39	2.64	-.46
42	-1.85	-2.8	2.17	1.85	-1.7	-.3
44	-2.48	.77	4.26	.15	-3.12	-1.54
46	-.3	2.48	2.01	-2.8	-.3	-1.08
48	2.17	-1.39	-3.12	-.77	2.64	.77
49	3.93	3.12	-3.28	-3.44	2.01	.46

RMS (MM) = 2.336 DP/P (X) = .0015 MOM CORR RMS = 2.338

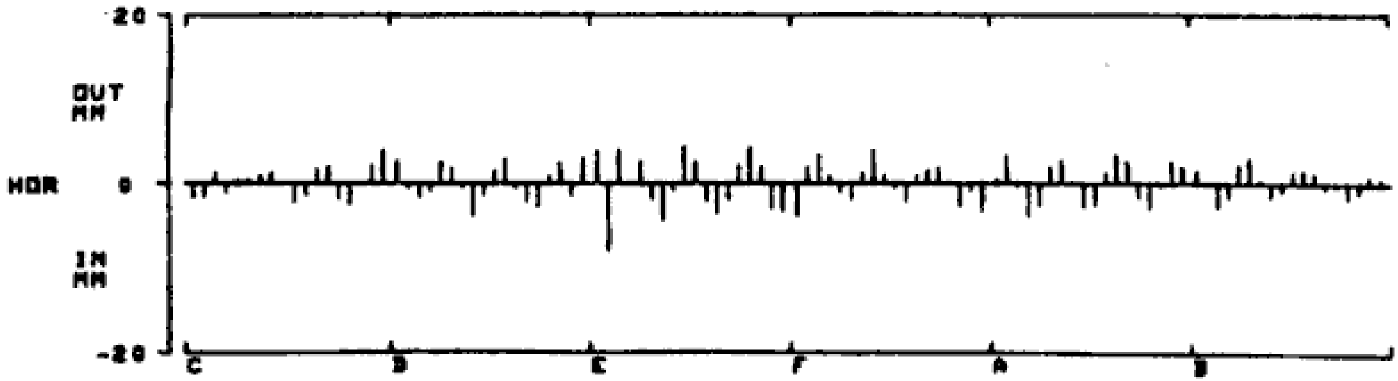


Figure 5. Profile display showing details of the horizontal orbit vs. location around the ring.

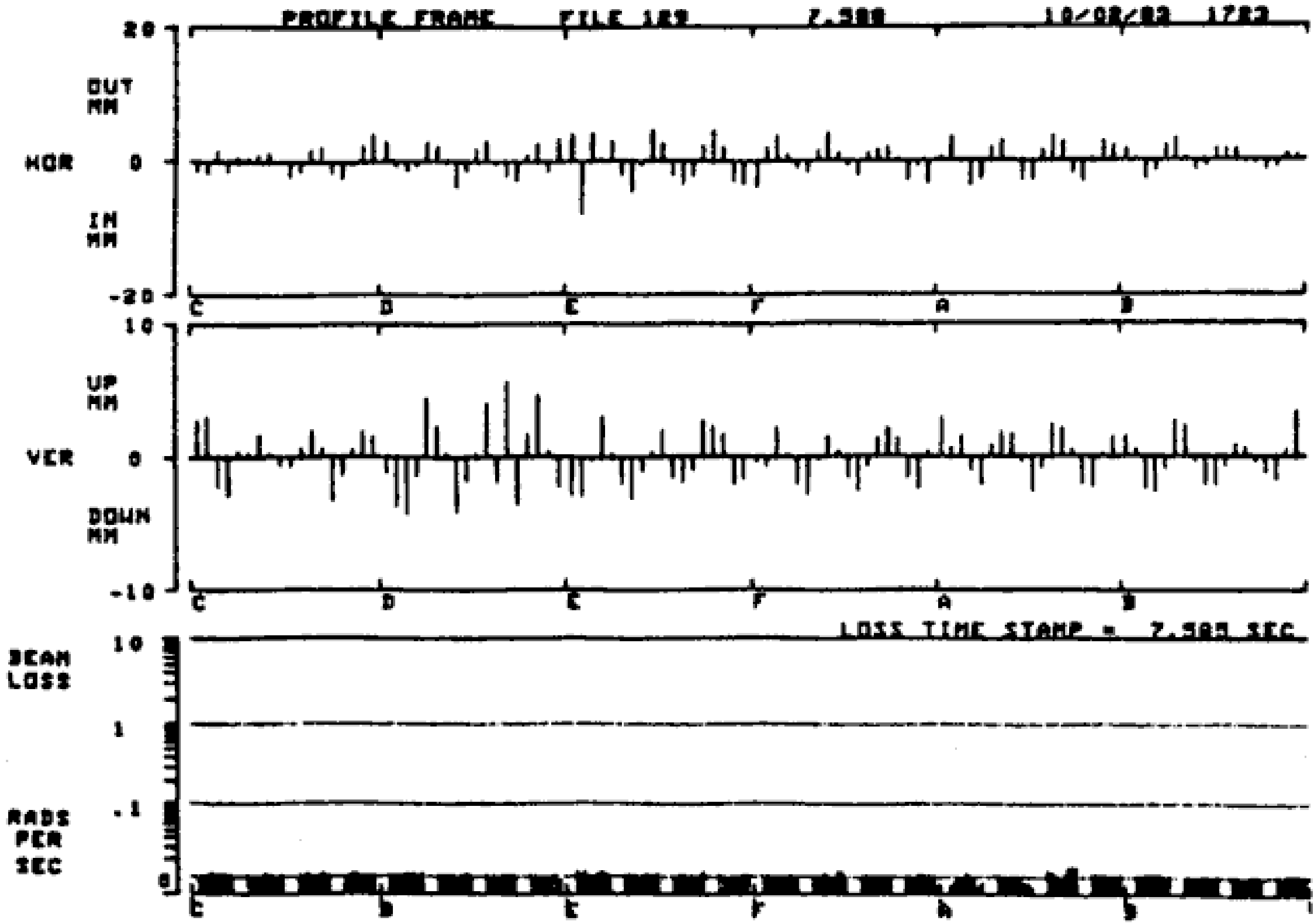


Figure 6. Profile display showing horizontal and vertical orbits, and beam loss vs. location around ring.

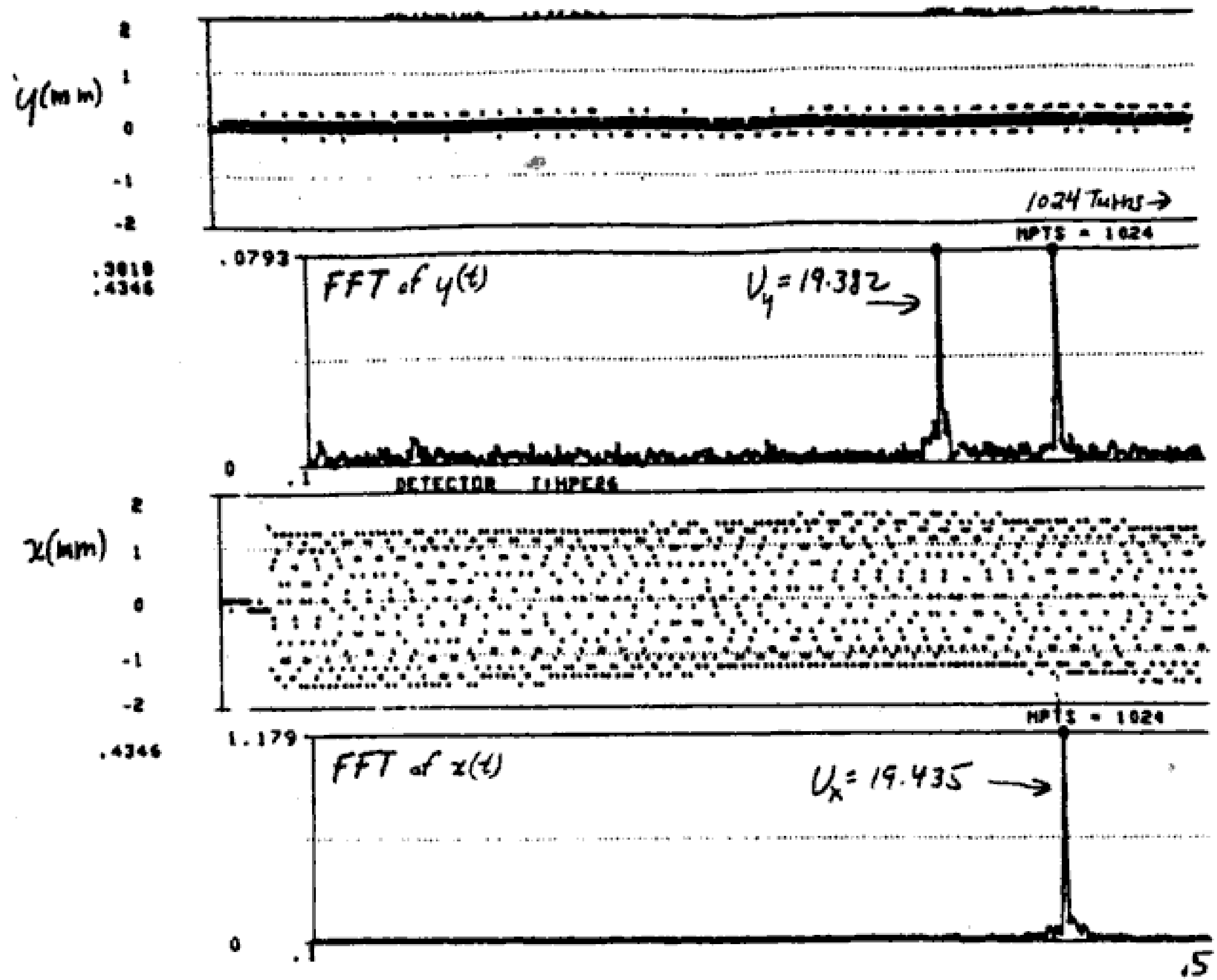


Figure 7. Turn-by-turn plots for "pinged" beam. In this case, the coupling is weak and the tune spread is small. The x and y positions are shown for 1024 turns. The Fast Fourier Transform represents the tune range from 19.10 to 19.50.

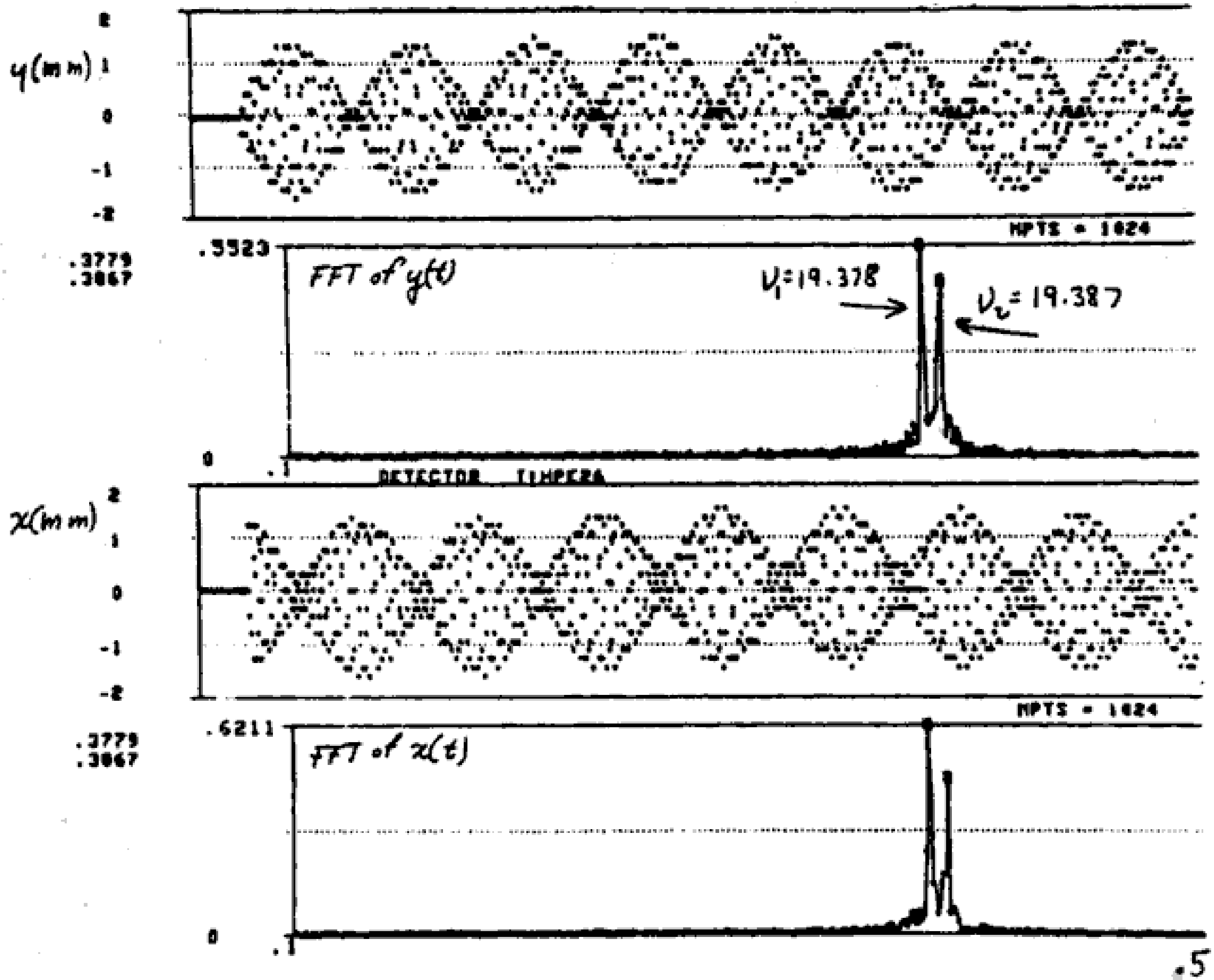


Figure 8. Similar to Figure 7 except that the betatron coupling is strong.

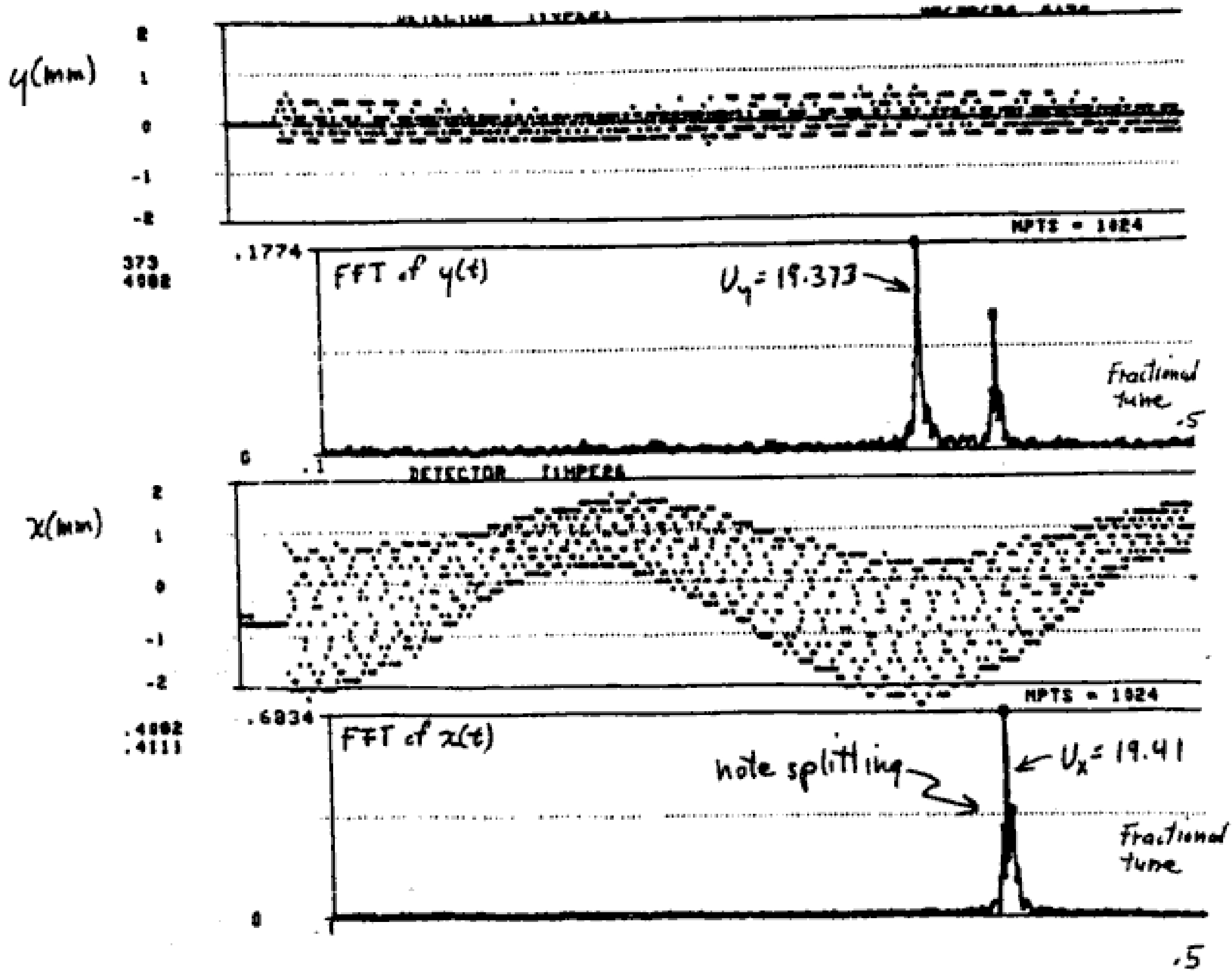


Figure 9. This rather unusual turn by turn plot shows weak coupling between the two betatron modes, but an apparent strong synchro-betatron coupling.

1. "Fermilab Energy Doubler Beam Position Detector", R. E. Shafer, R. C. Webber, and T. H. Nicol, IEEE NS-28, 3, pg 2290, June 1981
2. "An RF Beam Position Measurement Module for the Fermilab Energy Doubler", S. P. Jachim, R. C. Webber, and R. E. Shafer, IEEE NS-28 3, pg 2323, June 1981.
3. "The Tevatron Control System", D. Bogert, L. J. Chapman, R. J. Ducar, and S. L. Segler, IEEE NS-28 3, pg 2204, June 1981.
4. "An RF Device for Precision Location of the Beam Position Detectors in the Tevatron", Q. A. Kerns et. al., IEEE NS-30, 4, pg 2250, August 1983.

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