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BEAM POSITION MEASUREMENT SYSTEM AT THE FERMILAB MAIN ACCELERATOR

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SUMMARY

The beam position system of the Fermilab Main Ring contains one horizontal and one vertical Electrostatic Beam Pickup in each of the 96 cells of the machine. A pair of 75 ohm cables transmits the induced signal from the machine tunnel to the nearest service building. In each of the 24 service buildings, there is a solid-state multiplexer and a beam position detector which processes the A-B signal pairs to produce an intensity-normalized voltage proportional to beam displacement. This voltage is digitized, read into buffer of the Lockheed MAC A, and in turn transferred to the Xerox 530. Horizontal or vertical orbits can be obtained in 50 millisec. Orbits are obtained at injection, and at a Main Ring Sample time, if requested, anywhere on the acceleration cycle. Injection orbits can be flattened automatically by a program that sets dipole trim magnets.

INTRODUCTION

The Main Ring radius is 1000 meters. The accelerating RF, 53 MHz, is the 1113th harmonic of the circulation frequency. The 53 MHz component induced on the pickups by beam is used to determine beam position. The position signal amplitude at the pickup corresponds to ~1 Volt RMS at design intensity, 5×10^{13} protons/pulse.[1]

Normalization is effective from 1 millivolt to 2 volts, and completely independent of whether the Main Ring contains only one Booster Batch, several, or is full. The system always follows the highest-intensity bunches, and will track even if large intensity losses occur during acceleration.

MULTIPLEXER FOR 53 MHz SIGNALS - See Fig. 1

The RF Multiplexer under either local or computer control selects one pair of 75 ohm RG59 signal cables from a set of 12 pairs and delivers output at 50 ohms, locally indicating the selected channel by decimal LED's.[2] The multiplexer is built in a 5-wide NIM plug-in. See Fig. 2, showing beam detector box at left, multiplexer at right.

An on-board 53 MHz oscillator provides test signals to channel 11 independent of machine operation. Front panel test jacks permit pin-pointing cable faults in the 75 ohm 50 to 500 foot cable runs from service building to tunnel. Front panel LED's indicate supply voltages ON.

The on-line cable test feature as well as switch operation can be understood via Fig. 3, Single-pole 12 position PIN DIODE SWITCH (simplified, showing only one circuit of the 12). In-situ cable testing depends on a current traversing the cable and developing a D.C. voltage across the 75 ohm terminator in the tunnel. For the given current, a shorted cable will give too low a D.C. level at the test jack; an open cable or terminator will give too high a D.C. level.

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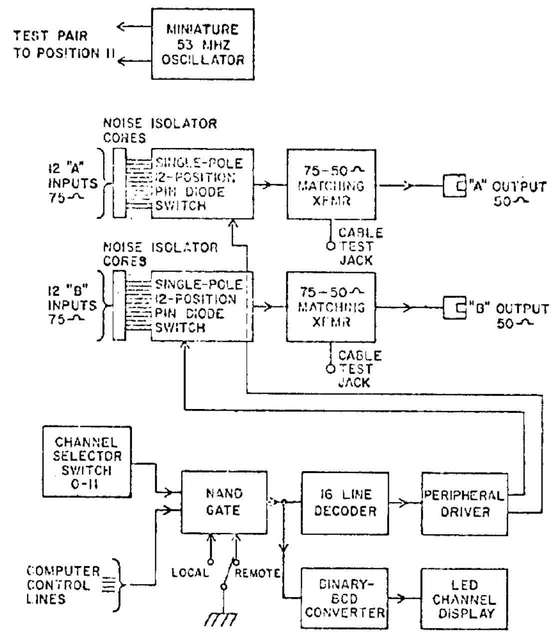

Fig. 1. R.F. Multiplexer Block Diagram.

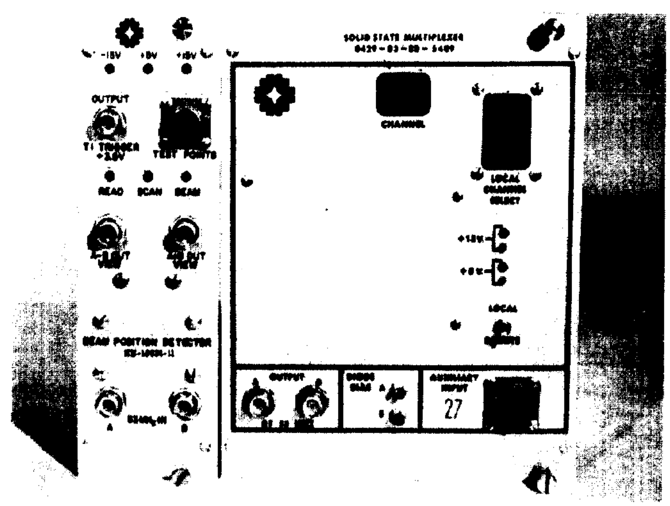

Fig. 2 - Photo of beam detector box (left) and multiplexer, (right).

The cable test current is free because it is the diode current. When a channel is selected, the corresponding D1 is forward biased (30 ma) and D2 is reverse biased. The test jack reports the drop across 75 ohms plus one diode forward drop.

When a channel is not selected, D2 is forward biased (68 ma), D1 is reverse biased, and the test jack signal is that for the newly-selected cable. Cabling troubles are identified by stepping through all positions while observing the test jack D.C. levels.

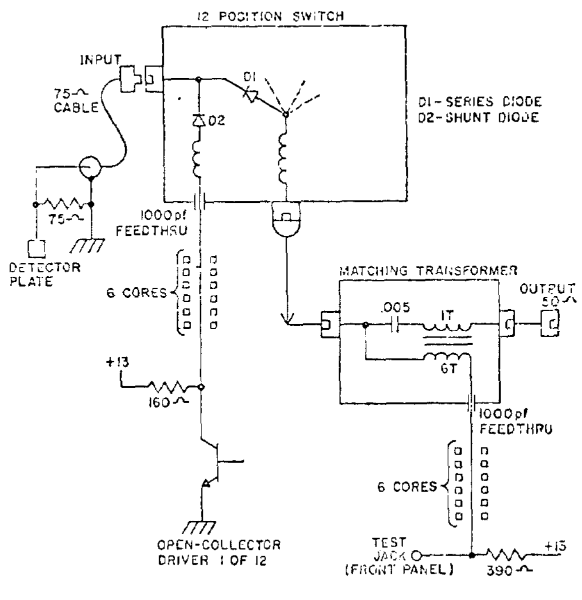

Fig. 3. Single-Pole 12 Position Pin Diode Switch.

The PIN diodes are Unitrode UM7001-B, (about $2.00 each).[3] They are mounted in an impedance-matched enclosure. A forward-biased PIN diode presents a low R.F. resistance, about 1.5 ohms, while a reverse-biased PIN diode presents a small shunt capacitance, ~0.7 p.f. and high shunt resistance, ~10 KΩ.

The shunt path (D2) contains an inductance (part of the diode lead) series-resonated with the 1000 p.f. feedthrough to optimize D2 as an RF short. The series path (D1) contains an inductor to tune out the parallel capacitance of eleven unselected D1's.

Multiplexer Performance

1. Potential cable noise pickup is alleviated by 10 turn RG187 coax windings on 3E2A ferrite cores.
2. Cabling faults are readily pinpointed via the test jack.
3. Channels can be switched in 2 microseconds or held indefinitely.
4. Signal level dynamic range is 100μV to 2 Volts.
5. On to off ratio > 4,000 to 1.
6. Interchannel cross talk is below 1/1000.
7. Amplitude error between channels is 0.1 db maximum.
8. Phase unbalance between channels ± .7° maximum.

These electrical errors would introduce less than 1/2 mm beam position error. It appears that passing a D.C. current through the cabling helps keep it working well for low-level RF signals. The parts cost of 1 multiplexer is $543. Early failures with an on-board power supply led us to change to another supply. Otherwise, the multiplexers have been trouble-free during the 2-1/2 years they have been in use. No PIN diodes have ever failed of the 1,800 in service.

BEAM POSITION DETECTOR

The beam position detector accepts a pair of signals A and B from the pickup and produces a voltage proportional to beam displacement.[4] The pickup difference signal A-B is divided by the sum signal A+B for intensity normalization. The physical size of the box is a 2-wide NIM plug-in. See Fig. 2.

A principal problem in devices like this is to maintain equality between channels through all stages so that a final output difference A-B is really meaningful, despite the large amplitude range. If separate amplifiers are used, tracking is the problem. The solution adopted here is to use a single amplifier and share it between channels by switching. "Chopper stabilization" conveys the general idea.

Figure 4, Beam Position Detector Block Diagram, shows the method.

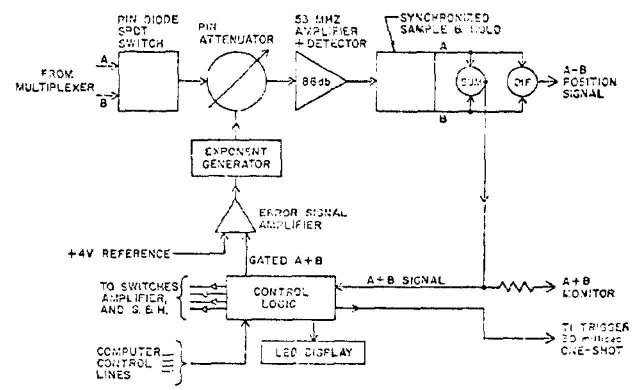

Fig. 4. Beam Position Detector Block Diagram.

Input RF from the multiplexer is fed to a PIN diode switch. Chopping at a rate of 5 Khz, (the dwell time on a channel ≈ 5 Main Ring turns), the switch alternately connects A and B to the amplifier input. At the detected amplifier output, there are corresponding A and B sample-and-hold circuits, synchronized with the input RF switching. As a result, both the A and the B signals are amplified identically, irrespective of the required gain at the moment; the large gain range (1000:1) presents no tracking problem. The detector boxes are designed to deliver ± 4.455 V output for ± 5 db. offset between A and B, with an acceptance window of 4.50 to 4.41.

For intensity normalization, the A and B sampled-and-held signals are summed and compared with a 4 V reference to control a PIN diode attenuator in the amplifier input line. The amplifier itself operates at fixed gain, except for a step gain shift during acquisition.

Control logic is used extensively to permit rapid adjustment ("acquisition") for each acceleration cycle in the main ring. Just prior to injection, there is no beam, no pickup signal, and an unknown gain requirement. The control logic, at the first beam, scans the attenuation range to achieve the proper gain quickly, starts the chopping action of the switches, erases any previous history, and issues a T1 trigger pulse indicating beam presence. To describe the states of the control cycle, the terms READ, SCAN, and BEAM were coined, and are explained in a table to follow.

The control logic is a TTL-processor that sets up the state of the detector box system at any instant, based on the beam intensity (A+B) signal and its changes.

Logic Cycle

There are three mutually-exclusive states, READ, SCAN, and BEAM, indicated by panel-mounted LED's.

When there is no beam, the box is in READ, waiting for a beam signal. At the first beam, the box goes into SCAN for about 2 millisec, into SET for 250μsec the instant the attenuation matches the required value, and then to BEAM where it tracks beam intensity variations from then on. When beam (at extraction) falls below the minimum threshold, the logic reverts to READ, waiting for the next injected beam. The following chart shows what the control logic does in each system state.

CONTROL LOGIC FUNCTIONS

UNIT	SYSTEM STATE		
	READ	SCAN	BEAM
PIN DIODE SPDT R.F. SWITCH	TRANSMITS A&B, not chopping	TRANSMITS A&B, not chopping	TRANSMITS A or B, chopping
PIN DIODE ATTENUATOR	MINIMUM ATTENUATION	FULL ATTENUATION, FOLLOWED BY A -25 db/millisec scan	Regulating Attenuation to keep A&B constant
53 Mhz Amplifier Gain	FULL	0.7	FULL
AMPLIFIER OUTPUT	RESTING AT NOISE LEVEL	10 V pulse, drop to zero and rise to 4V average	Maintain 4V average
SYNCHRONIZED SAMPLE-AND-HOLD	BOTH A&B clamped off	BOTH A&B ON	SAMPLING A&B synchronously
A+B Output Signal	Zero	Apparent A+B, but ficticious	TRUE A+B
A-B Output Signal	OFF (Inhibited)	OFF (Inhibited)	TRUE A-B
T1 TRIGGER	OFF	ON AT FIRST BEAM PULSE	ON FOR 30 millisec, then off

Pin Diode SPDT Switch

The pin diode switch during BEAM alternately connects A and B to the attenuator input. During READ and SCAN, both A and B signals are summed and fed to the attenuator input. The Pin Diodes and the shunt-series switching circuit are like that in the multiplexer.

Pin Diode Attenuator - See Figure 5

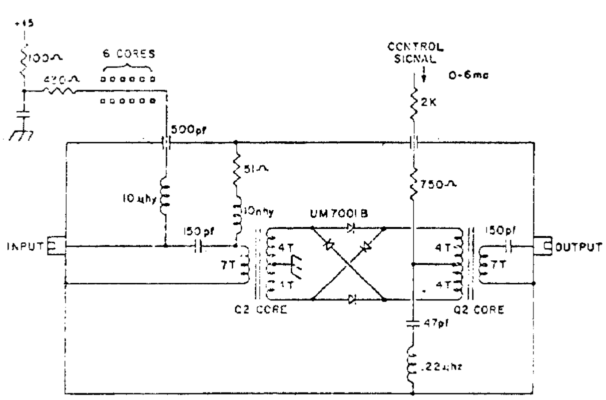

Fig. 5. Pin Attenuator.

This is a double-balanced mixer constructed with Pin diodes, and operated as a current-controlled attenuator. It functions during BEAM to continuously adjust the transmitted RF signal to a level suitable for the amplifier, 300μV RMS. During READ, the attenuator is at minimum attenuation; during SCAN, the attenuation is swept at 25 db/millisec from maximum attenuation toward minimum. The attenuation range is from 2 db to 65 db. Hot-carrier diodes were first tried in this circuit. They were abandoned because their intermodulation distortion drastically limited the attenuator performance.

Securing reproducible minimum attenuation proved simple. On the other hand, to reach a maximum attenuation of 65 db, careful assembly of capacitance-matched diodes was necessary. The control current for the attenuator is derived from an exponential curve generator.

Exponential Generator

The exponential generator serves to linearize attenuation vs. a control voltage. A silicon diode forward conduction characteristic in the feedback loop of operational amplifiers generates the desired curve. The end result of the product of attenuator and exponential generator response is a nearly straight-line relation between control voltage and db attenuation.

53 MHz Amplifier Detector

The RF amplifier provides about 90 db gain with a 3 db Noise Figure.[5] There is a dual-gate FET input stage followed by 3 stages of bipolar transistors, a full-wave detector, and an op-amp output capable of 0 to +12 V signal. 300μV RMS input produces +4V D.C. output. There is little amplitude compression below +10 V output; hard limiting occurs at +12 Volts output. Amplitude response is flat from D.C. to 600 KHz, 3 db down.

An input impedance of 300 ohms is achieved by resistive loading at gate #1 of the 3N200 FET stage. Gate #2 is pulsed by the control logic to step the amplifier gain down during the SCAN portion of the logic cycle, as noted in the table, to permit the fastest acquisition of the correct gain.

The synchronized Sample and Hold routes the detected output to the proper channel. It includes a hot-carrier diode peak detector feeding a silver mica holding capacitor read by a unity-gain op-amp. The holding capacitor can charge on a single beam pulse, and discharge either in small increments during BEAM to track beam changes, or discharge abruptly to erase old readings.

Remarks on Performance

The detector box operates over a signal range of 0.5 millivolts to > 1 volt. The A-B (position) output is zero when the A and B signals are equal, and is 4.455 volts (bogey value) for a 5 db difference. Signal acquisition time is not a limit because it is less than the computer acquisition time. The T1 output at each detector follows the first turn of beam around the machine, and has been used to locate obstructions. The box was built with MIL-spec I.C.'s because of the wide swing in service building ambient temperature. Typical construction problems with p.c. boards and random infant mortality of I.C.'s were met and overcome.

ACKNOWLEDGMENTS

The need for this system was demonstrated by Rae Stiening of the Main Ring Group, who accumulated the first reliable Main Ring orbit data with hand-held equipment, and spearheaded the development and installation effort. W. Lee of the Accelerator Theory Group, J. Zamie and A. Meier of the Controls Group provided programming. This effort was supported by many people in both the Accelerator Division and in Research Services.

REFERENCES

1. The pickups are conventional split boxes, non-ideal due to internal 600 MHz ringing, but serviceable at present beam intensity. The measured response is $\frac{A-B}{A+B}$ = .1406/cm (≈1.2 db/cm), constant over ± 4.5 cm, for a horizontal pickup.

2. Fermilab Schematic Diagram 0429.03-ED-5409 gives circuit details.

3. These PIN diodes have a carrier lifetime ~2μsec, and act as current-controlled variable resistors for the 53 MHz RF.

4. Fermilab Schematic Drawing 0453-EE-16631 gives circuit details.

5. A modification of the amplifier designed by C. R. Kerns, Fermilab.