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AN RF BEAM POSITION MEASUREMENT MODULE FOR THE FERMILAB ENERGY DOUBLER

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Summary

This paper describes the design, realization and performance of the RF Beam Position Measurement Module designed for the Fermilab Energy Doubler. This module measures beam off-axis position and intensity over a 60db dynamic range. For 20 or more contiguous 53MHz beam bunches, the unit will derive a position signal for 10^8 to 10^{11} protons per bucket with a position accuracy of ± 0.5 mm. Also, the unit will measure the position of 10^{10} or more protons in a single isolated rf bunch. A beam intensity signal is also generated for triggering purposes. Since 220 of these modules are to be built, cost and performance were optimized. The entire unit is housed in a 1-wide NIM module.

Introduction

Design of the beam position monitoring system for the Fermilab Energy Doubler has been completed. It will provide beam position information for low-intensity machine tuneup, orbit correction, generation of alarms to guard against beam-induced quenches of the superconducting magnets, and reconstruction of the orbit leading up to a beam abort. The system is composed of three fundamental components; 220 Beam Detectors which couple energy from the particle beam, 220 RF Position Modules which measure beam off-axis position, and 24 Beam Position Processors which collect and process data from as many as 12 RF Modules and interface with the host computer. The electronics is designed to operate in three distinct modes: first-turn (singlepass) studies, continuous beam monitoring, and isolated bunch operation. Data will be simultaneously processed for every detector.

Functional Description

A block diagram of the Beam Position RF Module is shown in Figure 1. The unit receives 2 nsec bipolar signals from the beam detector. The amplitude of each doublet is directly related to the transverse position of a beam bunch within the detector and to the particle number density. These signals are passed through the front-end filters to extract the 53MHz fundamental component, and then to the amplitude-to-phase (AM/PM) converter. This converter translates the A and B inputs into two equal-amplitude signals, whose relative phase corresponds to the amplitude ratio of A and B. These signals are then amplified, limited, and phase detected to produce an output proportional to off-axis position. Operating in parallel with the position circuitry in the same module is a coherent detector which operates on the vector sum of the A and B signals to produce an output directly proportional to beam intensity. The position and intensity outputs generated by this module connect to one of the Beam Position Processors. There, 50 nsec track and hold amplifiers feed 1 µsec A/D converters to generate digitized versions of position and intensity at a high throughput rate. Memory buffers store snapshots and averaged position information accesble by the host computer.



Figure 1 RF Beam Position Module Functional Block Diagram

Front-End Filters

The front end of the module consists of a bandpass and a lowpass filter in each channel. The bandpass filter is a distributed parameter type, chosen for its simplicity and long-term stability, using a half-wave resonant coaxial transmission line. Both the transient and the steady-state responses of this filter are used. For CW signals the filter performs a bandpass function centered around 53MHz, with a bandwidth of 5MHz. However, when a single doublet pulse is applied to this filter, its stable transient response allows the position of a single beam bunch to be measured. The network resonates at the center frequency when excited by an impulse, effectively stretching the impulse out to many rf cycles at the 53MHz processing frequency.

The lowpass filter is used to attenuate the natural harmonic responses of the distributed parameter filter, while contributing negligibly to the overall transient response of the network.

For accurate measurements both sets of filters must be phase and amplitude matched to within $\pm 3^{\circ}$ and ± 0.1 db. This requirement is more stringent for the bandpass filters, for in order to retain a $\pm 3^{\circ}$ match after about 10 cycles of the transient response, the resonant frequencies must be matched to within $\pm 0.08\%$.

AM/PM Converter

Beam position information is contained in the relative amplitudes of the signals received from each pair of pickup plates. These amplitudes can vary by 60 db due to changes in beam intensity. A variation of the phase monopulse² technique, often used in radar systems, was utilized in order to obtain intensity-independent position measurements at high speed over a wide dynamic range.

This technique is implemented with the AM/PM converter. It consists of in-phase and out-of-phase splitters and a delay cable adjusted for 90° at the operating frequency. Figure 2 is a functional diagram of this converter. Phasors have been included to illustrate the converter's operation. Regardless of the relative A and

^{*}Operated by Universities Research Association, Inc. under contract with the U.S. Department of Energy.

B in-phase signal amplitudes, the resultant outputs are equal in amplitude and have a phase relationship which varies from 0° to 180° with the ratio of the input amplitudes. When the inputs are equal (beam center) the output phase is 90° . Converter inputs need be phase matched only to within about 10° to limit output phase errors to acceptable levels. Higgins³ has described similar techniques; the main difference here is that the quadrature hybrids have been replaced with a delay cable for economy.



Figure 2 Amplitude to Phase Converter Block Diagram

Near beam center this system has a sensitivity of 6.5° per db of input level ratio, and displays the following characteristic:

$$\phi = 2 \operatorname{Tan} -\frac{1}{A} \frac{B}{A}$$

where \emptyset = Phase difference of converter output

A,B = Converter input amplitudes

Limiters and Phase Detector

Hard limiters are used to remove the 60 db amplitude variation of the converter outputs. The relative phase of the two limited outputs is then detected with a double-balanced mixer. The mixer output is filtered and amplified to produce a position signal of ± 2.5 volts into 50 ohms.

In order to obtain an accurate measurement of phase difference, the throughput phase of each pair of limiters must be matched over the entire dynamic range to within $\pm 2.0^{\circ}$. This gives an approximate position measurement error of ± 0.5 mm. For reasons of cost, a single chip, an AM685 comparator, is used for the limiter. These devices perform well over the required rangebut exhibit a large shift in throughput phase, necessitating the use of a sophisticated computerized matching scheme. The individual phase signatures of all limiters are obtained by the computer via an automatic test setup. Then these signatures are matched on a minimum mean-squared-error basis, producing pairs. Each limiter is mounted in an individual enclosure, allowing consistent measurements, while providing shielding and mechanical stability.

Coherent Detector

Between the input filters and the AM/PM converter, samples of each beam signal are summed to produce an rf signal proportional to beam intensity. This signal is then amplitude detected to produce an analog of intensity. A coherent detector is used because it operates linearly over the entire range and does not suffer from squaring $loss^4$ at low levels, as does an envelope detector.

This detector, designed for negative polarity output, gives a stable output of -5mV at 10^8 protons per bucket, and is reasonably linear to -2.5 volts. System offsets are also arranged to give a positive residual offset when no beam is present, increasing the trigger noise margin. An output amplifier supplies the required amplification and drive capability for a 50 ohm load.

Measured Performance

Figures 3, 4 and 5 are photos of the typical performance of the RF Module under bench simulations of single-pass beam (25 buckets), continuous beam with batch structure, and a single beam bunch, respectively. It is seen that the intensity output is a reliable trigger source in all cases. In Figure 5, the coherent intensity detector can be seen to follow the impulse response envelope of the input bandpass filter, and the position measurement has been effectively stretched in time. The position response is well behaved and can be conveniently sampled for measurement.

An RF Module and Doubler Beam Pickup were placed in service in the Fermilab Main Accelerator and the position output shown in Figure 6 was observed. A sample and hold circuit was appropriately triggered so that a single beam batch (about 82 rf bunches) was sampled with a 200 nsec aperture on each revolution. In the early part of the photograph, the machine's beam dampers can be seen to effectively damp the betatron oscillations, leaving only the synchrotron oscillations. It should be emphasized that this photo does not indicate the overall accuracy of the RF Module, but rather the repeatability of measurements on the same batch of particles. The dot spread in the latter half of the picture corresponds to approximately ± 50 microns of beam position.



Figure 3 Single-Pass Beam Response Top: Beam input signal, 1.0 volt/div. Middle: Position output with 2 db input offset, 0.5 volts/div. Bottom: Intensity output, 0.25 volts/div. All traces 200 ns/div.



Figure 4 Continuous Beam Response Top: Beam input signal, 5.0 volts/div. Middle: Position output with 2 db input offset, 0.5 volts/div. Bottom: Intensity output, 0.5 volts/div. All traces 1.0 μs/div.



Figure 5 Single Bunch Response

- Top: Single bunch input signal, 5.0 volts/ div., 5.0 ns/div.
- Middle: Position output with 2 db input offset, 0.5 volts/div., 100 ns/div.
- Bottom: Intensity output, 0.5 volts/div., 100 ns/div.



Figure 6 Main Ring beam position from Doubler detector and RF Position Module 0.5 mm beam position/div. vertically 1.0 ms/div. horizontally

Conclusions

Many engineering problems needed to be solved in the design of the RF Position Measurement Module. Due to the number of units to be made, cost and size were overriding considerations. Insuring that all of the subsystems in the module operate properly and independently in a small enclosure was a significant challenge. The results obtained with the module indicate that a proper balance was struck between price and performance.

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