A Machine Protection Beam Position Monitor System*

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Abstract. Loss of the stored beam in an uncontrolled manner can cause damage to the PEP-II *B* Factory. We describe here a device which detects large beam position excursions or unexpected beam loss and triggers the beam abort system to extract the stored beam safely. The bad-orbit abort trigger beam position monitor (BOAT BPM) generates a trigger when the beam orbit is far off the center (>20 mm), or rapid beam current loss (*dI*/*dT*) is detected. The BOAT BPM averages the input signal over one turn (136 kHz). AM demodulation is used to convert input signals at 476 MHz to baseband voltages. The detected signal goes to a filter section for suppression of the revolution frequency, then on to amplifiers, dividers, and comparators for position and current measurements and triggering. The derived current signal goes to a special filter, designed to perform *dI*/*dT* monitoring at fast, medium, and slow current loss rates. The BOAT BPM prototype test results confirm the design concepts.

INTRODUCTION

The maximum stored energy in the PEP-II rings, 200 kJ for the high-energy ring (HER) at 3 A current and 9 GeV energy, and 77 kJ for the low-energy ring (LER) at 3 A and 3.5 GeV, can melt through the vacuum chamber if the impact is localized. A beam abort trigger system (BATS) protects each ring by kicking the beam into a dump in one turn, spreading it across the exit window to avoid damage. The BATS has been installed around the rings to receive triggers from a variety of faults (such as loss of rf power, loss of dipole current, etc.) and abort the appropriate ring. A new addition to this trigger network is the bad-orbit abort trigger beam position monitor (BOAT BPM). This device acts like rescue boat, reacting quickly to a call for help. The BOAT sends a trigger to the abort system if the orbit is far off center, or if a rapid current loss is detected. One BOAT BPM will be placed on each ring. This paper discusses design of the BOAT BPM and prototype tests results.

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DESIGN

To detect large beam position offsets for the beam-abort system trigger, two sets of capacitive pickup electrodes (buttons) are installed in HER and LER (Figure 1), separated by roughly 90° in betatron phase in each ring for the position measurements. A third set of buttons is used for additional measurements of the X position at a dispersive point, to trigger on a rapid change in position (dX/dT) due to energy loss in the first ten turns after an rf trip.

The sum of the signals from one of the sets of buttons is proportional to the total current in the ring. This signal is used to normalize position measurements and to measure the beam-current loss rate (dI/dT). To minimize the number of abort system inputs, the X position outputs are OR'ed together, separately from OR'ed Y position outputs. An AND gate disables the outputs if the current is below 100 mA. The BOAT BPM does not depend on external control; all parameters and thresholds are set in hardware in the chassis.

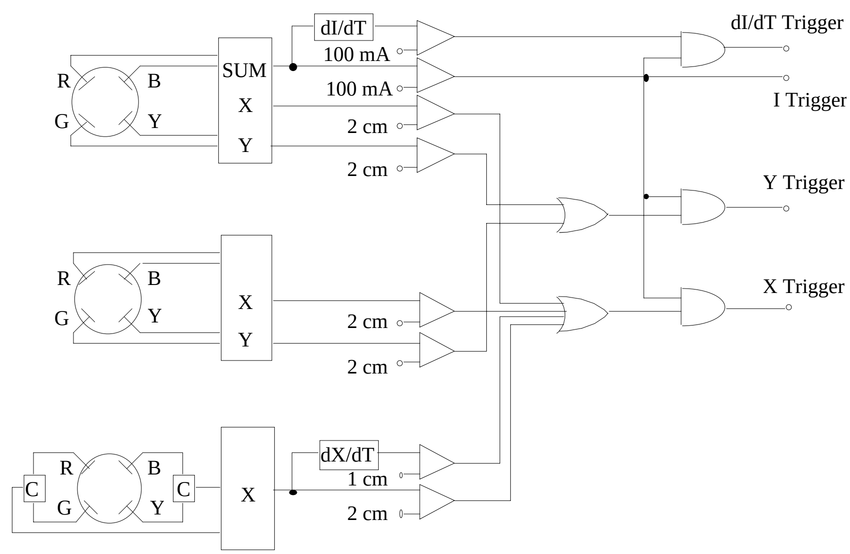

FIGURE 1. The BOAT bpm block diagram. R, G, B, and Y, refer to cable color codes. SUM is the sum of the signals from four buttons. C is a combiner. The comparator thresholds are labeled 100 mA, 2 cm, and 1 cm.

REQUIREMENTS

The BOAT BPM measures beam position, beam current, and beam current loss rate. The measurements must be averaged over one beam turn (the revolution frequency is 136 kHz) to respond to the total current in the ring and to avoid fill pattern sensitivity. There are three regimes of current loss (dI/dT): fast, where the current loss is greater than 20 mA in 20 μs; medium, where loss is more than 100 mA in a time between 50 μs and 1 s; and slow, where the loss is more than 100 mA in a time longer than 1 second.

The module must generate a trigger when the beam orbit is off center in X or Y by ±20 mm, $dX/dT \geq 10$ mm in a time less than 1 ms, or the fast or medium current loss threshold are exceeded. If the beam current is less than 100 mA, then no trigger is generated, since this current is below the threshold of damage.

The minimum required dynamic range, 30 dB, is the ratio of the maximum ring current, 3 A, to the lowest current which must be detected, 100 mA. Including a margin at each end of the range increases the requirement to at least 36 dB. Four triggers must be supplied to the beam abort system: X and Y positions, the current loss rate (dI/dT), and current status, to indicate whether the current exceeds 100 mA.

PROTOTYPE DESIGN

The BOAT BPM prototype was designed to accept signals from one set of buttons. The design and assembly were performed under time pressure in order to be ready to test the prototype and verify design ideas during the January HER run. The prototype was assembled in a chassis with connectorized components, evaluation boards, and a hand-wired circuit board.

The 476 MHz rf frequency is chosen as the input signal. Amplitude demodulation is used to produce a baseband voltage from the input signal.

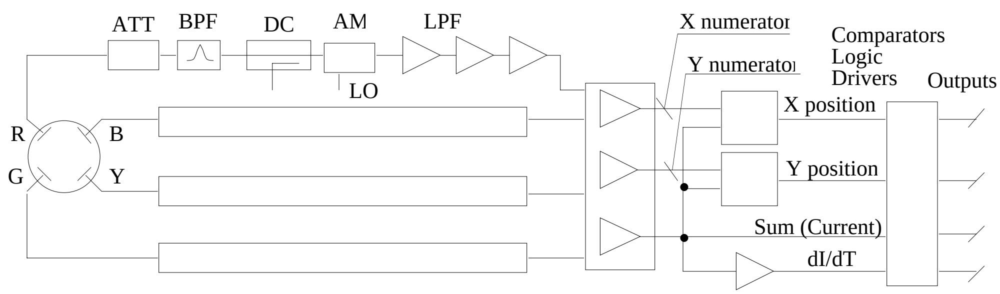

FIGURE 2. The BOAT BPM prototype block diagram.

The signal from a button (Figure 2) goes through a fixed attenuator to a 476 MHz rf filter with 14 MHz bandwidth. The signal from the filter is demodulated by an Analog Devices AD607 (1). This is an inexpensive rf receiver part that includes a UHF mixer, if subsystem, PLL, and an I&Q demodulator. While generally used for the communication industry, the specifications were suitable for our design. It first down-converts the rf frequency to a 10.7 MHz if. The if is then I&Q demodulated with a second LO generated by the on-board PLL. The I-component is taken as the amplitude of the button signal, since the PLL keeps the phase synchronized. A directional coupler in front of the AD607 is used to calibrate channel gains.

We intend the AD607 to operate with fixed gain, although it is normally used with internal automatic gain control. Useful linear dynamic range was an issue. Our first dynamic range measurements revealed an approximately 30 dB linear response, limited by a mismatch of the dynamic range of the I&Q converters to that of the PLL. After adjusting gains to the I&Q relative to the PLL, we achieved 38 dB of linear response.

After amplitude demodulation, the button amplitudes go through four-pole, low-pass filters to suppress the revolution frequency. Op-amps derive X and Y differences and the button amplitude sum. Analog divider chips are used to get X and Y positions. Position is calculated by:

$$X = K \times \frac{R + G - Y - B}{R + G + Y + B}$$
$$, \qquad (1)$$
$$Y = K \times \frac{R + B - Y - G}{R + G + Y + B}$$

where, for a round pipe,

$$K = \frac{d}{2\sqrt{2}} \ .$$

Here R, G, Y, and B are signals from the buttons in volts (Figure 2) and d is the beam pipe diameter. The position signals from the dividers go to comparators with adjustable threshold levels, which set the trip points for the beam-abort system.

The AC-coupled signal from summing amplifier feeds the dI/dT active filter. This filter has a response crafted to detect three regimes of current loss. The signal from the filter drives a comparator; the time-domain response of the filter enhances fast current losses (peaking) and suppresses very slow current responses (ac-coupling) so that a single threshold level provides all the logic for the three timescales of current loss.

TEST RESULTS

Bench tests showed that the BOAT BPM prototype is functional. X and Y have small offsets. After bench testing, the module was moved to the HER for tests with beam.

Revolution Frequency Filter Performance

Three active filters, one a 0.5 dB ripple, two-pole Chebyshev filter plus two one-pole filters, make a smooth frequency response. With a cutoff frequency of 50 kHz, the four-pole filter should give about 44 dB suppression at 136 kHz. The two following pictures (Figure 3), show a sine wave at 136 kHz frequency at the filter input (on the left) with 270 mV peak-to-peak amplitude, and at the filter output (on the right) at about 4 mV peak-to-peak. The filter gain is 1.9, so the revolution frequency suppression is 42 dB, close to the prediction of 44 dB.

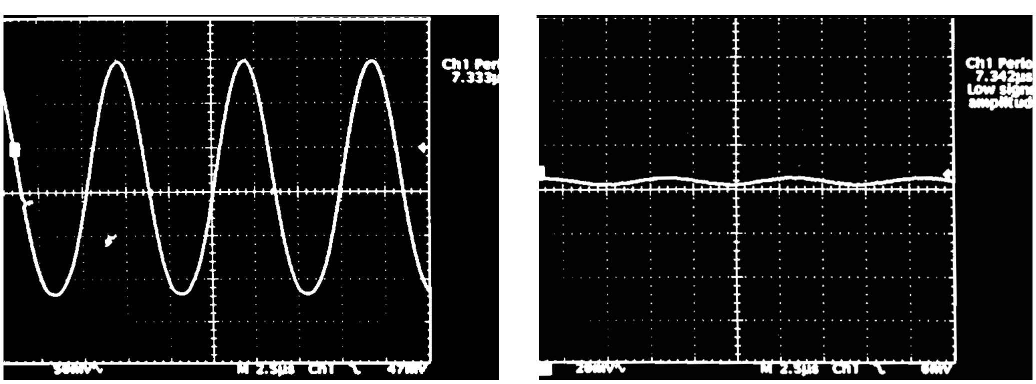

FIGURE 3. Signal at the filter input (left, 50 mV/div., 2.5 μs/div.) and at the output (right, 20 mV/div., 2.5 μs/div, AC coupled).

Beam Position Measurement

During the measurements, a few test points were observed: the output of the revolution frequency filter for each channel, the dividers' outputs, and the numerator and summing amplifiers' outputs. An example of the measurements taken with 360 mA of beam is shown in Table 1. The calculated results match the measured data well.

TABLE 1. The Example of the Beam Position Measurements

Test points*	**R**	**B**	**Y**	**G**	**Xn**	**Yn**	**Xp**	**Yp**	**Sum**
Measured data, V	–1.88	–1.47	–2.01	–1.81	0.21	–0.47	0.56	–1.07	4.07
Calculated data**, V					0.21	–0.47	0.53	–1.18	

* R, B, Y, G are the output of each channel's filter; Xn and Yn are the *X* and *Y* numerator voltages; Xp and Yp are the *X* and *Y* position voltages; Sum is the summing amplifier output (Figure 2).

** Data are calculated according to equation 1, based on the measured R, B, Y, G and Sum.

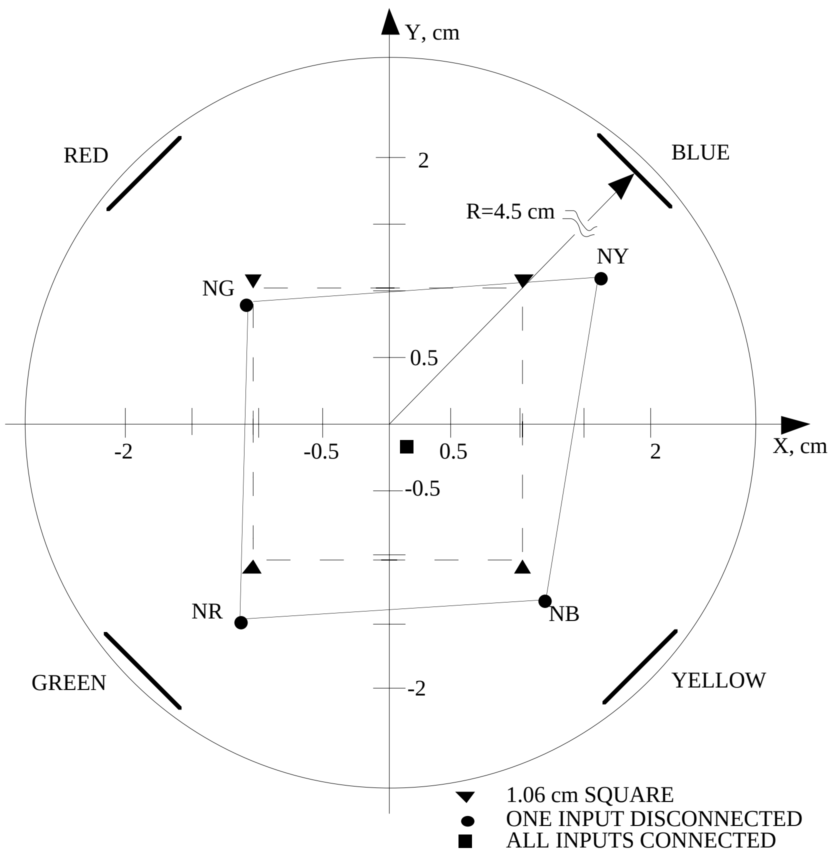

FIGURE 4. Measured position and beam offsets simulated with one input cable disconnected at a time. NR indicates no red cable, etc.

The position response was tested by disconnecting one button cable at a time. According to the position calculation equation (Eq. 1), if one of the signals is zero, the position values, both X and Y, should have the proper sign and a magnitude of $K/3$=1.06 cm for our 9 cm diameter beam pipe. The test results are shown on Figure 4, along with a square with corners at ±1.06 cm to guide the eye. The measured beam positions are in the correct quadrants, close to the ±1.06 cm coordinate square. A position offset can be seen.

dI/dT Filter Performance

The filter response to a step function input has peak at 12.5 µs (about two beam turns) in the time domain, followed by a "flat" part (Figure 5). The flat part is not really flat; it slowly decays to zero with a 1-second time constant, which roughly corresponds to the thermal conduction time for heat to spread away from a small hot spot. The peaking of the step function response makes the system more sensitive to rapid current loss. This defines the "fast" response sensitivity. The ratio between the peak and flat parts should be 5, according to the ratio of the requirements for the medium-speed to fast dI/dT trip thresholds, i.e., the ratio of 100 mA to 20 mA.

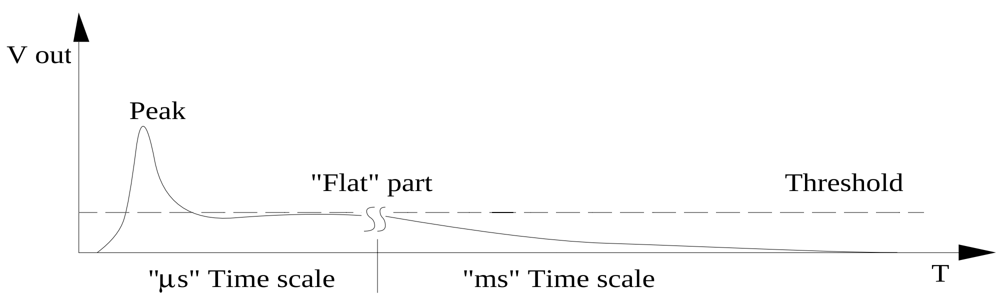

FIGURE 5. Sketch of the *dI/dT* filter pulse response in time domain.

During HER commissioning, fast beam losses were rare (and unpredictable, as we were not trying to lose the beam). Therefore, to test the response of the system, we simulated fast current losses by abruptly disconnecting one button input to the BOAT chassis. The transient response of the dI/dT signal is shown in Figure 6.

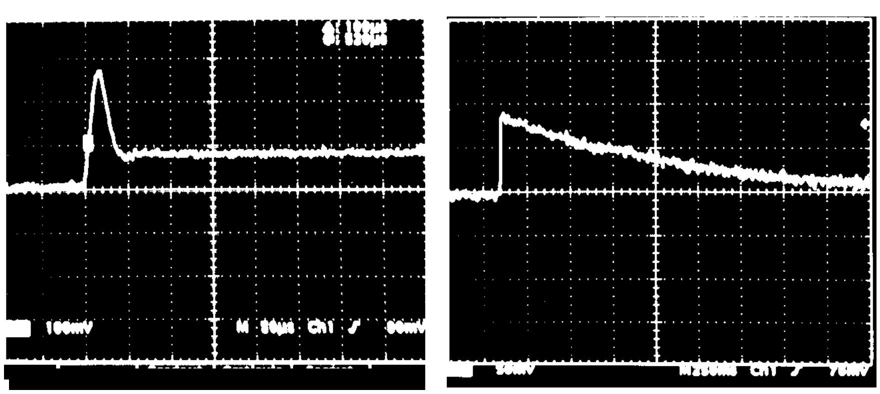

FIGURE 6. The *dI/dT* filter response seen on two different time scales. The left picture shows the peak and "flat" part at 50 ms/div. The right picture shows the "flat" part at twice the vertical sensitivity and 250 ms/div.

The ratio between peak and “flat” parts is approximately three (Figure 6, left). The bench test gave six for the peak to flat ratio. This disparity may be due to the finite fall time of an rf signal switched by a human hand disconnecting an SMA connector.

Dynamic Range

The BOAT BPM dynamic range is 37 dB. Figure 7 shows the dependence at the summing amplifier output signal in volts versus input signal, in volts rms. The non-linear parts correspond to the dynamic range limits of the AD607.

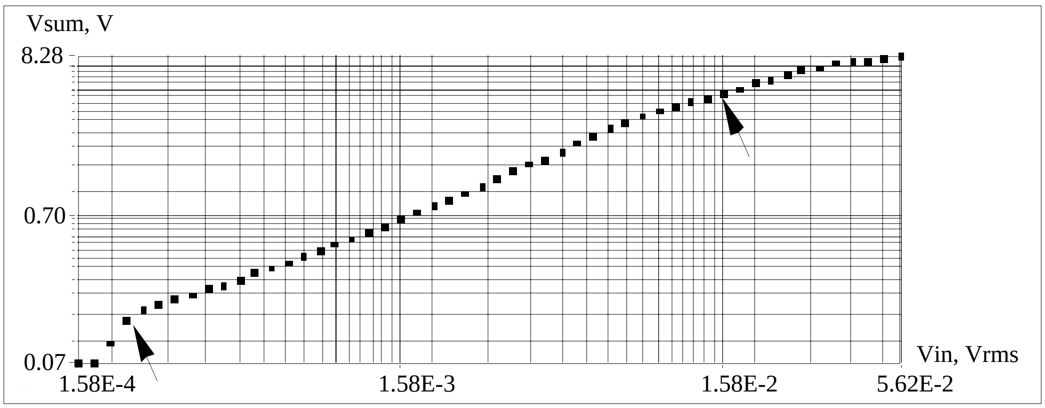

FIGURE 7. The Sum signal, Vsum versus input signal, Vrms.

FURTHER PLANS

Two BOAT BPM chassis will be built, one for each of the PEP-II rings. For the production devices, the rf circuitry for each opposing pair of buttons will be integrated on an rf daughterboard. Each rf board will produce one position signal and one sum signal, which are further combined and processed on a motherboard. The rf boards will be tuned and calibrated on a test bench. The mother board will carry five rf boards, four to measure position from two sets of buttons, and a fifth to measure the X position in the dispersive region. The comparators, logic, dI/dT and dX/dT filters, and Sum amplifier shall be located on the mother board.

SUMMARY

The BOAT BPM is intended to perform fast detection of large beam offsets or rapid current losses. The device’s purpose is to trigger the beam-abort system to protect the PEP-II rings. AM demodulation allows us to use inexpensive commercial components. Prototype test results confirm design concepts.

ACKNOWLEDGEMENTS

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[1] Analog Devices, Inc., "Low Power Mixer/AGC/RSSI 3 V Receiver IF Subsystem," 1995, www.analog.com.