The Log-Ratio Beam Position Monitor

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Abstract. Bergoz Instrumentation has designed a new Log-Ratio Beam Position Monitor (LRBPM). It can be used to measure position of a single short bunch, a bunch train, successive and repetitive (circulating) bunches/trains. The monitor has four parallel channels with band pass filters and logarithmic demodulating high dynamic range amplifiers. The amplifiers detect the envelopes of the RF-bursts brought about by the pickup signals in the filters. Log-ratio processing and conversion of the pickup axes to X,Y is done using a broadband analog technique. The monitor can be used either in a continuous mode, or Sample&Hold or Track&Hold modes. In the last two modes, the LRBPM can be triggered by the beam signal itself. The accuracy limits coming from an inherent demodulator noise, logarithmic nonlinearity, speed of response, etc. of the amplifiers (Analog Devices) are discussed. An accessory developed to determine the LRBPM center offset and resolution with the present beam signals is described.

INTRODUCTION

Logarithmic-ratio signal-processing technique [1] is presently in common use for beam position monitoring. It is based on an integrated circuit family of demodulating logarithmic amplifiers, manufactured by Analog Devices, Inc. The family is intended mainly for telecommunication and some characteristics of the amplifiers, sufficient for communication tasks restrict an ultimate accuracy in beam monitoring. This manifests itself mainly as a beam intensity dependence of monitor’s readings.

The advantages and disadvantages of the amplifiers available outline the beam diagnostic tasks where the logarithmic-ratio technique is now fruitful. It is mostly beam trajectory measurements in linacs and transfer lines and a similar task of first turn trajectory measurements in circular machines. Besides, coherent betatron and synchrotron oscillations of the circulating beam can be measured and the relevant tasks of betatron dynamics can be solved. Interlock systems for dumping a beam should be mentioned as well. The monitors can perform well with various beam patterns as a single short bunch, a single train of bunches, successive bunches/trains and repetitive bunch/trains in a circular machine. Some of the amplifiers offer a possibility to realise a fast and high dynamic range beam trigger which can be used in a LRBPM to provide it with self-triggering which is especially useful in single pass measurement.

A new Logarithmic-Ratio Beam Position Monitor developed and manufactured [2] at Bergoz Instrumentation and described below, answers to the requirements of the beam diagnostic tasks mentioned above. A number of the LRBPMs have been used on Linacs, Transfer Lines and Storage Rings, mostly for single bunch position...
measurements and betatron oscillation measurements. The LRBPM is made as an independent card with analog outputs. A beam trigger is built in to sample and hold the X,Y signals and to trigger external ADCs. To eliminate a center offset of the LRBPM, an independent device is developed. For a beam as successive/repetitive bunches/trains, the center offset can be measured using the beam signal, and then subtracted from the readings. A noise resolution at the present beam intensity as a dispersion of the center offset can also be measured.

For a single bunch measurement with resolution \(\pm 3 \times 10^{-3}\) of pickup’s radius, the LRBPM’s dynamic range extends 40dB starting from bunch charge 0.1nC.

**CONDITIONING OF PICKUP SIGNALS**

In a LRBPM, a pickup signal with a short time span is to be converted either to some signal of a band which is within the logarithmic amplifier’s base band, or to a RF-signal with an envelope which would have same band. This conversion can be done using correspondingly a low-pass filter or a band-pass one. It is a well-known method.

The band-pass conversion was preferred for the LRBPM to have it applicable to various beam patterns, from a single bunch to a continuous train of bunches. Such a LRBPM can be used, for instance, on circular machines where the beam pattern may be varied just in such limits.

To detect a continuous train, the band-pass filter center frequency is to be chosen equal or multiple of the bunch repetition rate. Reaction of the filter on a single pulse is a RF-burst. Filter’s half-band is to be taken within the amplifier’s base band.

While design of the LRBPM whose filter center frequency is specified in range (360-500)MHz, different approaches to arrangement of its input network were considered.

The band-pass conversion can be done immediately on the pickup output, using a filter which would include the pickup electrode as one of its elements. In this scheme, a pickup electrode is loaded on some complex impedance.

To provide loading the pickup electrodes on a resistive impedance in the bandwidth of the beam signal, some passive circuit can be used inserted between the electrode and the narrow-band filter which forms the envelope. A circuit as a buffer broad-band filter with bandwidth around 1/10 of the center frequency is developed for the LRBPM. It has 50\(\Omega\) input impedance, the SWR is less than 1.6 in range 100MHz-3GHz. In addition to purpose to load the pickup electrode, the buffer attenuates high frequency (>1GHz) components more than 40dB. Insertion loss measured on the center frequency is lower than 3dB.

With use of a buffer filter, the basic narrow-band filter can be replaced to amplifier’s input. That is convenient from practical point of view. Note that such buffer filters can also be used for increasing dynamic range of narrow-band BPMs used for orbit measurements in circular machines with a high intensity single bunch. Some BPMs
may have on the inputs active circuits as switches, amplifiers, etc. Their performance may degrade if a pulse signal with amplitude which may become extremely high with increasing beam intensity is directly applied. The buffer converts the pulse to a RF-burst. Its amplitude is substantially lower that the pulse amplitude. Other properties of the buffer filter may be useful for these BPMs as well.

The same functions of loading the pickup electrode on a broad-band resistive impedance has the device designed for elimination of the center offset, mentioned in Introduction. In the range 30MHz-2.8GHz, the device has input/output impedance 50Ω with SWR less than 1.4 and 1.3 correspondingly. Designed for subnanosecond bunches, it like the buffer filter, converts a pickup pulse to a burst which is now a single sine wave of period 2ns. The central frequency is 500MHz, insertion loss 10dB, bandwidth is (200-800)MHz, attenuation in range (1-3)GHz is more than 15dB.

The LRBPM has the narrow-band filters on the inputs of the logarithmic amplifiers. The buffer filters and the devices are used at user’s option.

Designing the input network, it is necessary to take into account signal reflection in the cables. If multiple reflections of the signal occur, a signal on the amplifier’s input is a superposition of the bursts caused by the primary signal and by the reflected signals. In two channels, the secondary bursts have different phase relations to the primary bursts, if the cable lengths are not equal and/or the filter center frequencies are different. This manifests itself as a difference of envelope shapes on the channel outputs, which may result in some extra (and uncertain) monitor’s center offset. For the case of a continuous train, this effect of reflected signals is characteristic of any BPM if narrow-band conversion has been used. For a single bunch/train, the effect does not manifest itself in a LRBPM if the first reflected signal comes to the input after having the envelope sampled and held. Note that for any length, the reflected signals can cause false triggering in LRBPM's beam trigger.

**LOGARITHMIC PROCESSING**

For frequency up to 500MHz, two groups of the amplifiers are available: DC-500MHz and (0.1-2.7)GHz. The former has higher accuracies and dynamic ranges. In this group, the only AD8307 [3] has such a converter of the demodulator’s signal to the output voltage, that its speed can be increased by use of elements external to the chip. This feature is important practically because first, increase of the base band yields increase of output signal-to-noise ratio, second, requirements to input filter parameters relax.

The possibility to increase the speed was investigated. A RF-burst 500MHz was used as a test signal. Its envelope close to (1-exp)-shape had rise time around 10ns and reached its apex at 15ns. Converter’s speed was varied by varying its equivalent load.

The converter response time versus the load was measured for two settings of RF-burst’s amplitude: 0dB and (-50)dB. The setting 0dB corresponded to the upper end of
amplifier’s input dynamic range. It was seen that demodulator’s speed and converter’s speed change with burst’s amplitude in opposite ways. It was found that for some load, when each response time becomes equal to approximately 30ns, the speed changes counterbalance each to other. The response time 30ns can be considered as an optimal one. The amplifier’s base band can be estimated, correspondingly, at 5MHz.

Then, an interesting feature of the amplifier was discovered. The logarithmic amplifier output noise consists of a demodulator-converter noise which does not vary with increase of amplifier’s input signal (a noise floor) and an input resistor-amplifier noise which comes to the base band and manifests itself increasing linearly with decreasing the input signal. A demodulator-converter noise on the floor can be easily observed, if some DC-bias is applied to amplifier’s input, which blocks amplification of the input noise. It was discovered that for settings in range (10-40)ns, the time of reducing of the output noise to the floor value which would correspond to the burst’s amplitude, is considerably longer than the response time set. By other words, the noise is still high when the output envelope is reaching its apex.

The signal and noise transients become close each to other, if the RF-burst envelope rise time is twice as much as the response time 30ns. Thus, the filter half-bandwidth is to be taken at least half as much as amplifier’s base band width 5MHz.

In the LRBPM, a compromise solution is taken. The response time is set to an optimal one 30ns, but the envelope rise time is less than the optimal one above. It is that time which can be achieved with use of commercial band-pass filters. A filter available (so called a double-tuned helix filter) has the rise time 10ns. A simple way to achieve some stretch of envelope is to cascade two such filters. The rise time comes to 25ns, and a resulting rise time on the amplifier’s output is around 40ns.

**LOGARITHMIC-RATIO PROCESSING**

An analog logarithmic-ratio processing in the LRBPM is done by taking difference of the output signals of the logarithmic amplifiers. Preliminary, the output signals are amplified. The buffer amplifiers are made with built-in gain and zero offset adjustments for equalising the logarithmic slopes and intercept parameters. For obtaining an accurate difference, a fast OA AD8138 is used.

The difference signal is filtered by a LPF to suppress the logarithmic amplifier’s output noise beyond a band required for the measurement task. For instance, the bandwidth is to be set to a maximal one 5MHz for a single bunch measurement. For turn-by-turn measurements of a long train, the cut-off frequency can be reduced and be of the order of the revolution frequency.

Signals of the LRBPM are shown in Figure1. The oscillogram was taken with input signals differing each from other by 3dB and falling approximately in the middle of LRBPM’s dynamic range.
FIGURE 1. Signals of the LRBPM. Trace A shows one of the input signals. It is a 0.5ns-pulse which imitates a single bunch. Trace B shows one of the output signals of two logarithmic amplifiers, and trace C shows the difference signal on the LPF output.

On the picture, one can see that a noise in the difference signal, reducing, reaches some floor value 25ns later then the amplifier’s output signal reaches its apex. This moment has happened to be a particular point: in this point, the difference error due to mismatching of transitional characteristics of a pair of logarithmic amplifiers has been minimal as well. It can be clearly seen, when the input signals are equal. Typically just in the vicinity of this point, the transitional zero shift has been passing zero.

Thus, at this moment, the difference signal is to be sampled and then held to be used for further processing. A fast Track&Hold IC AD9101 is used which has Track-to-Hold Settling Time 4ns. In Figure 1, trace D shows its CLK signal with a Track-to-Hold transient.

Optionally, the Hold signal which lasts 50ns, can be used for turn-by-turn measurements on small machines with revolution frequency up to 5MHz. For other tasks, is is convenient to have a longer Hold time. This is achieved by use of a Sample&Hold IC AD783 which samples the Hold signal. Its Hold time is set to 100ns for maximal sampling rate 2MHz. For a lower rate, the Hold signal keeps lasting till the next bunch/train/external trigger comes (but not longer than 100ms).

X,Y PROCESSING

By logarithmic-ratio processing, a pair of signals U,V is yielded which represent a position of the beam center of mass with respect to the pickup’s own coordinate system. Each axis of this system can be defined (and determined as well) as a population of such positions where the other signal of the pair is equal to zero. The axes intersect in the pickup center. Let the axis of the pair of opposite electrodes A,C/B,D be U-/V-axis correspondingly, and an angle (from U-axis to V-axis) between the tangents in the center be \( \alpha \). Near the center one can use just the U, V-tangents as own pickup axes. Introducing scale coefficients \( \zeta, \eta \) as \( \zeta U[\text{volt}] = U[\text{mm}] \) and \( \eta V[\text{volt}] = V[\text{mm}] \), and some output coefficient \( M[\text{volt/mm}] \), the conversion to X,Y-
axes can be written for the LRBPM output signals \( U, V \):

\[
X[\text{volt}] = M[\zeta \cos \theta + \eta \cos(\alpha + \theta)], \quad Y[\text{volt}] = M[\zeta \sin \theta + \eta \sin(\alpha + \theta)].
\]

The parameters \( \zeta, \eta \) and the angles \( \alpha \) and \( \theta \) can be determined by bench measurements of signals of the electrodes and applying the logarithmic-ratio algorithm. Another way is to determine these parameters from the data obtained on a bench with use of the difference-by-sum algorithm. Assume that the scale coefficients \( \delta[\text{mm}] \) and \( \gamma[\text{mm}] \) are available. Using \( X = \delta[(A-C)-(B-D)]/(A+B+C+D) \) and \( Y = \gamma[(A-C)+(B-D)]/(A+B+C+D) \) which are for the case of a symmetrical about \( X, Y \)-axes positions of the electrodes, \( 2\theta = \pi - \alpha \) (\( \theta \neq 0 \)), and noting that \( B = D \) on \( U \)-axis and \( A = C \) on \( V \)-axis, one can obtain the angles as:

\[
\alpha = \arctg\left[\frac{2(-\gamma/5)}{\delta^2/5}\right], \quad \theta = \arctg\left(\frac{\gamma}{\delta}\right).
\]

For a symmetrical pickup, \( \zeta = \eta = K \). Again on \( U \)-axis, taking \( A = 1+u \), \( C = 1-u \), \( u \ll 1 \), one can obtain: \( X = \delta[1/(1+D/C)]u \), \( Y = \gamma[1/(1+D/C)]u \). From other side, \( U[\text{mm}] = K\log(A/C) = 2Ku \). Using a segment \( U \), \( U^2 = X^2 + Y^2 \), and letting its length tend to zero, one can obtain the scale coefficient \( K \):

\[
K = (1/4)\sqrt{\delta^2 + \gamma^2}. \quad (2.2)
\]

Note, that for some pickup configurations, the logarithmic-ratio algorithm proves to be the least non-linear. [1] With \( 2.1, 2.2 \), it can be adopted in BPMs instead of the difference-by-sum algorithm used.

For a symmetrical pickup, (1) yields:

\[
X[\text{volt}] = MK\sin(\alpha/2)(U-V),
\]
\[
Y[\text{volt}] = MK\cos(\alpha/2)(U+V). \quad (3)
\]

Thus, for conversion to \( X, Y \) signals, one has to obtain a difference signal \( \Delta = U-V \) and a sum signal \( \Sigma = U+V \). The coefficients can be realised by attenuation/amplification of the signals. In the LRBPM, for a circular pickup with \( \alpha = \pi/2 \), \( \theta = \pi/2 \), the outputs 0.245V are factory-set for displacement by 6dB, i.e. when the ratio of the signals of one pair of opposite electrodes is equal to 2. With such a scaling, if the pickup were linear, the output would reach \( \pm 2V \) for the full radius displacements. This conditional radius is used below as a LRBPM’s characteristic measure.
RESOLUTION AND ACCURACY

A residual X,Y zero offset of the LRBPM can be set in the limits ±1⋅10⁻² of pickup’s radius (i.e. ±20mV). This can be achieved typically in the range (55-60)dB without selection of pairs of logarithmic amplifiers, by adjustment of the mean slopes and the intercept parameters only using a sine input signal. A zero offset measured with a single pulse, may exceed the limits above. There is no means in the LRBPM to adjust each zero offset in the limits.

The LRBPM’s resolution is measured in a full bandwidth 5MHz. The input signal is 0.5ns-pulses with repetition rate around 600Hz. The LRBPM is triggered by the input signal through its built-in trigger. Rms and peak-to-peak values of the Hold signal are measured by a digital oscilloscope for number of the pulses around 150. An oscillogram of the X,Y noise on the floor is given in Figure 2.

![Oscillogram of the X,Y noise on the floor.](image)

The rms value is typically less than 7mV, i.e. resolution is ±3⋅10⁻³ of pickup’s radius. The peak-to-peak value is around 40mV, i.e. the fluctuations may reach ±20mV. That is three times more than the rms value. The floor stretches from the upper end of the LRBPM’s dynamic range to approximately (-40)dB, where the rms and peak-to-peak values get increasing due to the logarithmic amplifiers’ input noise. Thus, for a single pass measurement, the LRBPM’s dynamic range with a fixed resolution is 40dB.

A noise density on the floor is 2.2⋅10⁻⁶ of radius/√Hz. A rms noise in some abstract bandwidth 100Hz would be 2.2⋅10⁻⁵ of radius. For radius 40mm, the resolution would be 1μm. It is comparable with the resolution of most of the BPMs used for orbit measurements in same bandwidth. This evaluation being loose, however indicates that the inherent demodulator-converter noise has not been extreme and the LRBPM’s resolution of single pass measurement can not be much enhanced.

A beam intensity dependence of the LRBPM output signals manifests itself mainly when the beam is displaced. The first effect which causes variation of the output signal is that logarithmic amplifier’s response waves in the limits ±3% with a period around 12dB. It is a known effect. [4] One more, a bump effect of beam intensity, manifests itself on the upper end of the dynamic range. A change of the intercept parameter
occurs which results in a shift of the logarithmic response for the input signals higher than (-10) dBm. It is a local effect, on the interval 10dB only, but it is quite strong. The bump reaches 25%. In the LRBPM, this local non-linearity is compensated by non-linear dividers located ahead of the logarithmic-ratio processor. Totally, in the range from (-5)dBm to (-55)dBm, the LRBPM’s error is around ±3% if the frequency is 500MHz, and comes to ±4% for 360MHz.

For single bunch measurement, a beam intensity dependence manifests itself in other way. No waving effect is seen. In the middle of a 40dB range, a response to beam displacement may be few percent higher or lower than it is for the case of a sine input signal. On the lower end the response gradually lowers by (-15)% in the interval 20dB. The same bump effect is there on the upper end. The gradual effect would be less, if the envelope apex would be sampled. Generally, it is the penalty for the compromise of the envelope rise time against the amplifier’s response time, discussed above.

A typical X/Y LRBPM’s response to “beam displacement”, measured on a bench in a full dynamic range, is shown in Figure 3.

FIGURE 3. The LRBPM’s response to beam displacements by 0, ±6.5, ±13dB versus the input signal level. a) The input signal is a 500MHz-sine wave. b) The input signal is a single 0.5ns-pulse.

LRBPM CENTER ACCURACY ENHANCEMENT

To enhance a LRBPM accuracy in the vicinity of the pickup center, especially in single bunch measurement, an optional device can be used mentioned above. The device is based on an idea to measure a BPM center offset caused by its electronics, and its resolution as well, using the same beam signals which are used for the position measurement. The use of real beam signals at any present beam intensity provides a high accuracy of the center offset measurement.

The device intended for subnanosecond bunches, consists of a pair of 50Ω irregular directional couplers which convert the short pulse to a single sine wave, and a switch between their outputs. A pair of opposite electrodes is connected to the inputs. To measure the offset, its output signals, i.e. the BPM input signals, are made equal by the switch short. The position is measured when the switch is open. Then the offset can be subtracted from the BPM readings. To measure both the X,Y offsets, two devices are
to be used. To include the BPM cables into the process, the devices should be placed close to the pickup outputs.

When the beam is on the pickup’s center, a residual unequalness of the device’s output signals is few units by $10^{-3}$ of pickup’s radius. When the beam is displaced, an additional error appears proportional to the displacement. So, for 6dB-displacement, this error reaches $3 \times 10^{-3}$ of the radius.

A pin-diode is used as a switch. The switch is controlled by an external signal via the LRBPM and a corresponding pair of its input cables. Note that the device has two optional lossless outputs of the primary electrode signals and can be used as a precise splitter of the signals which have been used in some BPM, to a LRBPM as well.

**SUMMARY**

Features of a Logarithmic-Ratio Beam Position Monitor developed at Bergoz Instrumentation have been described. Problems and solutions concerning its input network, logarithmic and logarithmic-ratio processing, conversion of the signals to the X,Y-axes are considered. A residual X,Y zero offset, a noise resolution and an error due to beam intensity dependence of the readings are discussed. A beam-based method of enhancement of monitor’s center accuracy is proposed.

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**REFERENCES**