ALS Beam Instrumentation

Beam Position Monitoring

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Introduction:
There are about 160 beam position monitors (BPM) distributed throughout the ALS accelerator complex. The function of all of them is to measure the position of the electron beam center of charge and report it to the control system. The Linac and transport line (LTB and BTS) BPMs perform single-shot measurements of low repetition rate beam. BPMs in the storage ring are required to make high-resolution position measurements of beam closed orbit. The sector arc BPMs are also capable of storing 1024 single-turn measurements for study of transient beam phenomena. Special insertion device BPMs (IDBPM) are used for very high beam stability measurements, beam interlocks, and recently, closed-orbit feedback. The booster BPMs can store 1024 turns of position data and can make a single measurement of beam position at a selected point in the acceleration cycle. To perform these functions we use a variety of beam sensors and electronics. A considerable portion of the control system database is filled with BPM data. A number of computer applications have been created to display and evaluate these data.

The purpose of this document is to acquaint the reader with BPM theory of operation, the ALS BPM hardware, and its performance. Photographs and drawings of BPM equipment are provided and, where relevant, some math will help explain BPM operation.

Typical BPM:
Figure 1 shows a typical BPM system composed of beam sensors, coaxial cables, detector electronics, and a control system. The pickups in the ALS are of two varieties; buttons and striplines. Ideally, buttons (Fig. 1b) are simply small disks connected to the end of a coaxial transmission line. They are mounted flush with the vacuum chamber wall and couple to the beam electric field. Buttons are used in the Linac area and in both rings. In the booster synchrotron the buttons are rotated 45 degrees off horizontal and vertical to avoid synchrotron radiation. The unusual shape of the storage ring vacuum chamber made it necessary to mount the buttons on the top and bottom of the chamber (not shown in Fig. 1).

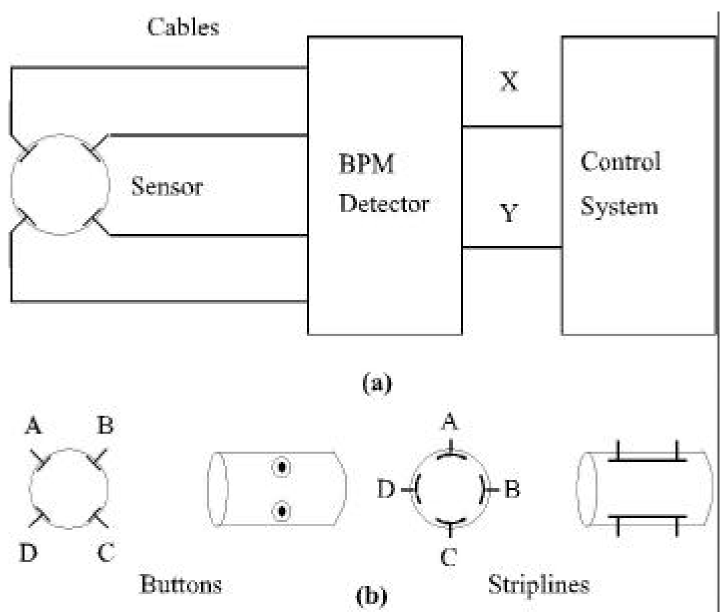

Figure 1. (a) Typical BPM system. (b) Typical BPM pickups.

Striplines (Fig. 1b) are traveling wave devices that couple to both the magnetic and electric beam fields. They are directional in nature and may be used as beam pickups or kickers (e.g., the storage ring transverse damping system). In the ALS the BPM striplines are found only in the transport lines (LTB and BTS). They are installed in the horizontal and vertical planes since synchrotron radiation is not bothersome in these locations. This arrangement also makes signal processing simpler. The main reason for using striplines as BPM pickups rather than buttons is higher coupling impedance. They couple at least 10 times more beam power to the measurement electronics than the buttons. This is important when the average power of the beam signal is low which is the case in the transport lines.

Heliax® ¼ inch coaxial cable is used to transport the beam signals from the pickups to the electronics. This is a high quality cable featuring 100 % shielding, low loss, and high stability. In the booster and storage ring we have installed 6 dB resistive attenuators in the signal path near the buttons. The main purpose of these attenuators is to provide a back-termination to signals reflected from the reactive impedance of the BPM electronics. A secondary purpose is to provide a resistive path to ground should the BPM cable be disconnected at the electronics.

There are two different BPM electronics chassis to be found in the ALS. The most common is a 3U Eurocard crate containing several BPM modules and an Intelligent Local Controller (ILC). The other BPM chassis contains two Bergoz multiplexed BPM receivers. The ILCs associated with the Bergoz BPMs are installed in standard ILC crates.

Beam Characteristics:
Consider a single bunch of electrons circulating in the ALS storage ring. An observer using an instrument connected to a beam pickup at some location in the ring will measure a periodic pulse recurring at the ring revolution frequency (the ALS revolution frequency, f_0, is 1.523 MHz). The nature of the measured beam signal will depend on the beam bunch characteristics, the response of the pickup, and the capabilities of the instrument. These topics are treated below.

On average we consider the beam bunch to have Gaussian longitudinal distribution, and for these discussions the beam is highly relativistic. We describe the bunch by its physical RMS length (σ) or its duration (τ). Tau is the duration at 2σ. For a relativistic beam bunch τ is

$$t = \frac{2s}{c}$$

where c is the velocity of light. For example, a 7.5 mm bunch is 50 ps long at 2σ.

The amplitude of the pickup output signal depends on the pickup transfer function, beam position, and the bunch peak current. A method for calculating the peak current is

$$i_{pk} = \frac{Q_b}{t}\sqrt{\frac{2}{p}}$$

where the per-bunch charge, Q_b, is

$$Q_b = \frac{I_{avg} t_r}{N}$$

where I_{avg} is the average current in the ring, t_r is the beam revolution time, and N is the number of bunches. The revolution time in the ALS storage ring is 656.44 ns. With a single 50 ps bunch and 10 mA average current the bunch charge is 6.56 nC and the peak current is about 105 amperes.

The energy in every periodic electrical waveform except a pure sine wave is contained in harmonics of the fundamental frequency. The storage ring electron bunch is periodic and may be described in the frequency domain by a line spectrum of the beam revolution frequency harmonics. In the case of the 50 ps Gaussian beam bunch occurring at 1.5233 MHz the harmonics extend from DC well into the microwave region. The –3 dB or half-power point for these harmonics is

$$f_{-3dB} = \frac{0.265}{t}$$

The 50 ps bunch half-power frequency is 5.3 GHz, over ten times the cavity RF. This means that if we had an appropriate pickup and spectrum analyzer, we could observe beam spectral lines of nearly equal amplitude from DC to about 5 GHz. Each line would be separated by the revolution frequency.

We calculate the amplitude of any bunch harmonic as follows

$$A_n = \exp\left[\frac{-\left(w_n\right)^2\left(\frac{t}{2}\right)^2}{2}\right] 2I_{avg}$$

where w_n is a beam harmonic in radian measure, and

$$w_n = 2pf_0 n$$

where f_0 is the revolution frequency, and n is a rotation harmonic, 1,2,3…., etc. It is interesting to note that the first harmonic amplitude for a pulse having a very low duty factor is just twice the average value.   In our example the value of the first harmonic is 20 mA. At 5.3 GHz (the 3479th revolution harmonic) the amplitude is still 0.707 of the fundamental.   Fig. 2 shows what the beam current line spectrum would look like if we had a current sensor with response from DC to 20 GHz and a spectrum analyzer with appropriate bandwidth and resolution. The harmonic lines are so close to each other that the curve appears to be solid.

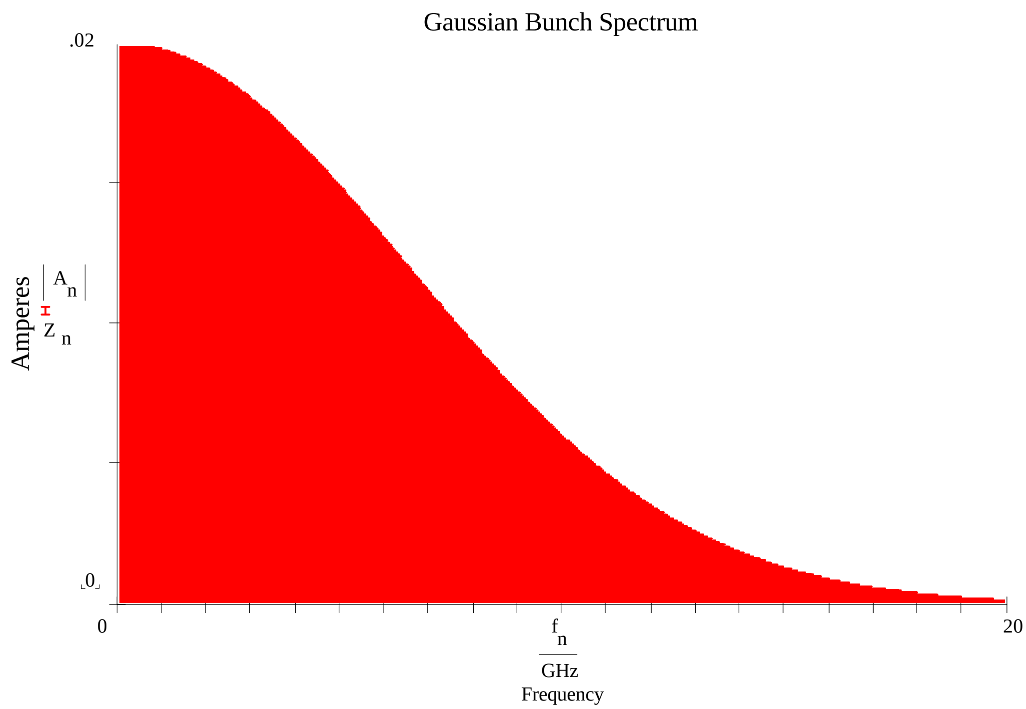

Figure 2. Bunch current line spectrum for 1 bunch, 10 mA average current.

Another case worth considering is when all 328 storage ring RF buckets are filled with equal charge. The observer measures pulses occurring at 2 ns intervals (500 MHz). From this measurement the observer cannot determine the beam revolution frequency because all bunches appear to be identical. The line spectrum for this condition is quite different from the single-bunch case. The first spectral line above DC occurs at exactly 328 times the revolution frequency, or at 499.66 MHz (the cavity RF). Subsequent spectral lines are found at harmonics of the RF extending well beyond the bunch cutoff frequency. In practice the storage ring is never filled with equal charge in all buckets. This is because we do not have a way to precisely control the charge in the injected beam bunches, and we usually leave a gap in the fill pattern. Consequently in the storage ring one may always measure bunch harmonics separated by the revolution frequency. The amplitude of these revolution harmonics varies widely with the fill structure. Figure 3 shows the ideal bunch line spectrum for 400 mA average current in 328 bunches. Notice the space between lines equals 500 MHz. There is no energy below 500 MHz except at DC.

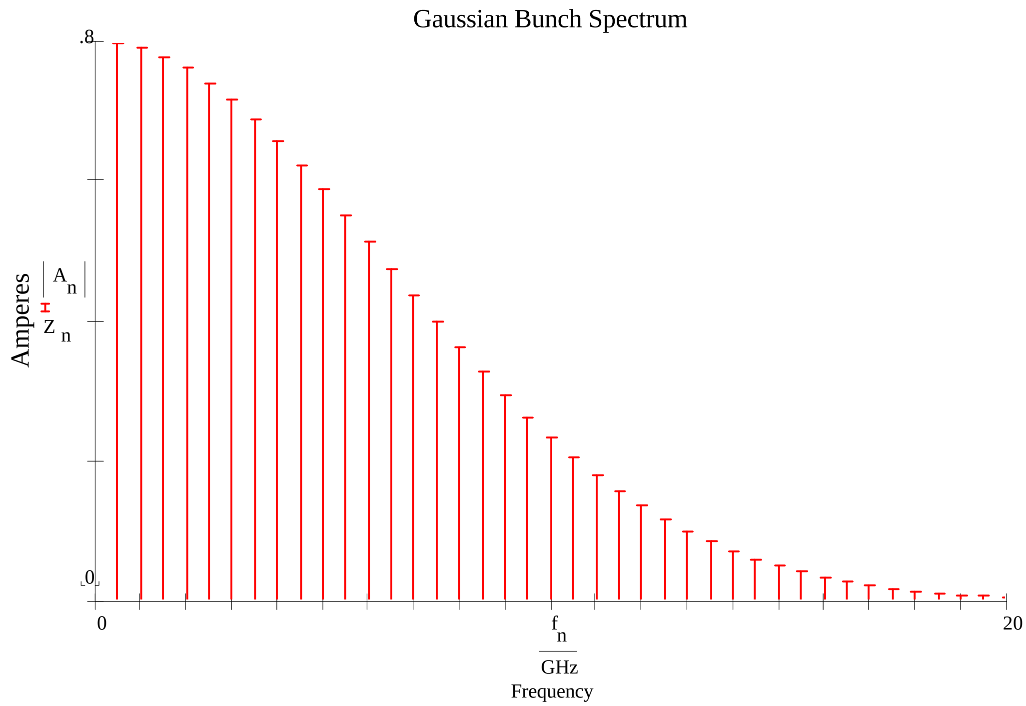

Figure 3. Bunch current line spectrum for 328 bunches and 400 mA average current. τ = 50 ps.

Figs. 2 and 3 are highly idealized spectra of perfectly stable beam with perfect diagnostics. The electron beam normally executes longitudinal and transverse oscillations to some degree. These oscillations may be observed in the frequency domain with a spectrum analyzer. Longitudinal oscillations constitute phase modulation of the beam, which results in the creation of sidebands about beam harmonics. Any beam sensor with adequate bandwidth is satisfactory for these measurements. Using a pickup sensitive to beam position, we can detect transverse oscillations. This beam motion generates amplitude modulation sidebands about the beam harmonics. Usually the phase modulation sidebands represent synchrotron oscillations at about 12 kHz in the ALS storage ring. Transverse oscillations are normally due to betatron beam motion. This motion creates sidebands at about 300 kHz to 500 kHz about a beam rotation harmonic. The vertical betatron sidebands are usually lower in frequency than the horizontal sidebands.

A wide band BPM receiver with turn-by-turn capability can detect the transverse oscillations. Phase oscillations in the beam may or may not show up in the BPM output. Some BPM receivers are very sensitive to beam phase. Others are not sensitive at all. Phase sensitivity depends on signal processing methods.

Pickup Function:
The function of all of the BPM pickups is to extract a portion of the beam bunch energy for measurement in the electronics. The buttons and striplines used to extract energy from the beam for position measurement fall into the category of electromagnetic detectors [1] that respond to the time-changing EM fields of the beam. None of these devices has DC response which implies two things: (1) If we want to measure the

position of a DC beam, we cannot use buttons or striplines. (2) In order to use buttons or striplines a bunched beam is required, and we must design detector electronics that respond to some high frequency component of the beam signal. Beam position is determined by comparing the relative amplitude of the pickup signals. We must have sufficient signal to work with and the pickups must be sensitive to beam motion. Apart from vacuum and beam impedance considerations, we are most interested in the pickup coupling impedance and beam position sensitivity over the desired physical beam aperture. We define the coupling impedance as

$$Z_t = \frac{V_B}{I_b}$$

where V_B is the button voltage and I_b is the beam current.

Buttons:

Buttons are used in the storage ring because of their low beam impedance (important for beam stability). They also have relatively low coupling or transfer impedance. The average current in the storage ring is usually quite high, so there is no problem obtaining adequate signal strength. In a round beam pipe button coupling impedance as a function of frequency is

$$Z_t(w) = \frac{a^2}{2r}\frac{w}{bc}Z(w)$$

where a is button radius, r is the beam pipe radius, b is relative beam velocity, and c is the velocity of light. At 10 MeV electron beam b is 0.999. Most of our position measurements are made at higher energy, so we consider b being unity. $Z(w)$ is the impedance of the parallel combination of the system impedance (usually 50 ohms) and the reactance of the button capacitance. It is a complex quantity. We find $Z(w)$ from

$$Z(w) = \frac{R}{1 + jwRC}$$

where R is the system impedance and C is button capacitance. As an example we consider the buttons installed in the BTF beam transport line. Here the button radius is 5.5 mm, the pipe radius 31 mm, the button capacitance is 3 pF and R equals 50 ohms. The beam is in the center of the pipe. Figure 4 is a plot of the magnitude of the coupling impedance clearly showing the high-pass nature of the button response.

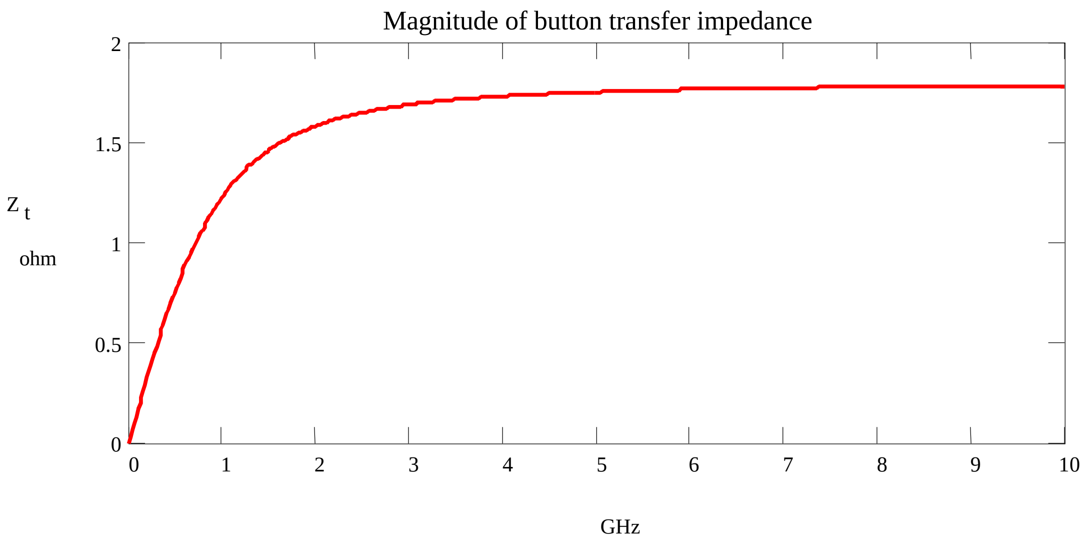

Figure 4. Calculated BTF button coupling impedance vs. frequency.

When specifying a button, one must consider the button capacitance since it directly impacts the signal coupling. Figure 4A shows coupling impedance vs. lumped button capacitance. If the BPM electronics are phase sensitive or have wide bandwidth, the capacitance should be large enough so signal phase isn't changing over the operating frequency range. If maximum signal amplitude is desired, the capacitance should be small.

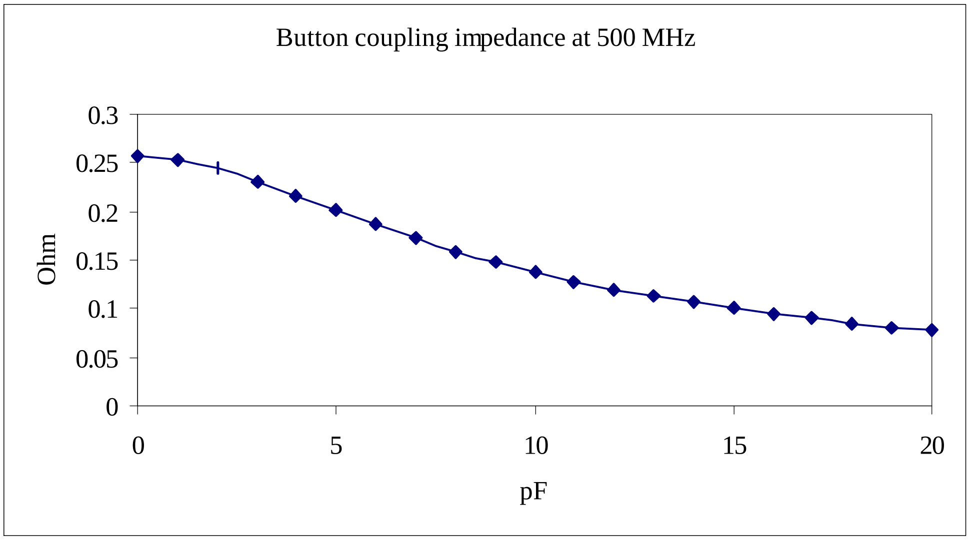

Figure 4A. Calculated coupling impedance at 500 MHz.

For another look at the button capacitance issue, see Figure 4B. Here we show the 500 MHz response of 11mm diameter buttons in the ALS sector 2 straight section. The beam pipe is round and 50 mm in diameter. We show signal voltage for 328 bunches of 0.8 nC each (400 mA). Three bunch lengths were

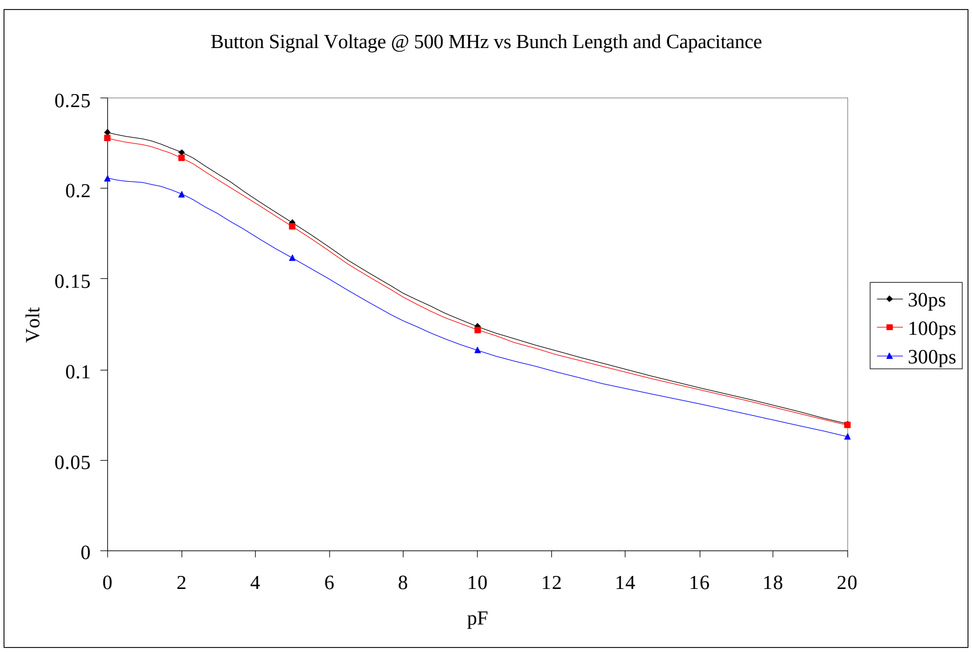

Figure 4B. Calculated signal strength vs bunch length and button capacitance.

evaluated. The data shown in Fig. 4B were generated in SPICE simulations of button response to beam. We can see the effect of bunch cutoff frequency in the 300 ps trace. At higher RF harmonics the bunch length effect would be much stronger. We can also see how small difference in button capacitance can cause BPM errors. Near zero capacitance the slope is minimum, indicating low sensitivity to small differences. Sensitivity to differential capacitance is highest between 2 and 10 pf.

The button transfer impedance shown in Fig. 4 is idealized. In practice several phenomena corrupt an otherwise smooth response. A round button will resonate at wavelength roughly equal to its diameter. This causes a peak in the response at very high frequency. The 11 mm diameter MetaCeram buttons in the storage ring resonate at about 6 GHz. Some button coaxial structures may not be designed for very high frequency operation and may resonate at several frequencies.

The short beam bunches deposit energy in beam pipe discontinuities. The resulting EM fields propagate in the pipe above cutoff. For a round pipe the $TE_{1,1}$ mode cutoff frequency is

$$f_c = \frac{c}{l_c} \qquad\qquad l_c = 3.412r$$

where r is the pipe radius. The LTB beam pipe radius is 31 mm, and the cutoff frequency for the $TE_{1,1}$ mode is 2.85 GHz. The transverse electric (TE) components of these travelling waves couple energy to the buttons resulting in button signals not necessarily related to beam position. Fig. 5 shows the response of an 11 mm button to a single bunch in the LTB. The signal ringing following the bunch signal is indicative of button resonance and travelling TE waves in the beam pipe.

While these undesirable signals make wide-band beam measurements difficult, they do not impact BPM function at the ALS. Our BPMs operate at frequencies well below the threshold for button resonance and wake fields. Because the storage ring vacuum chamber is much smoother than the transfer lines, we don't observe large effects from TE fields in the pickup signals. Button resonance, however, is quite apparent in the arc BPM buttons.

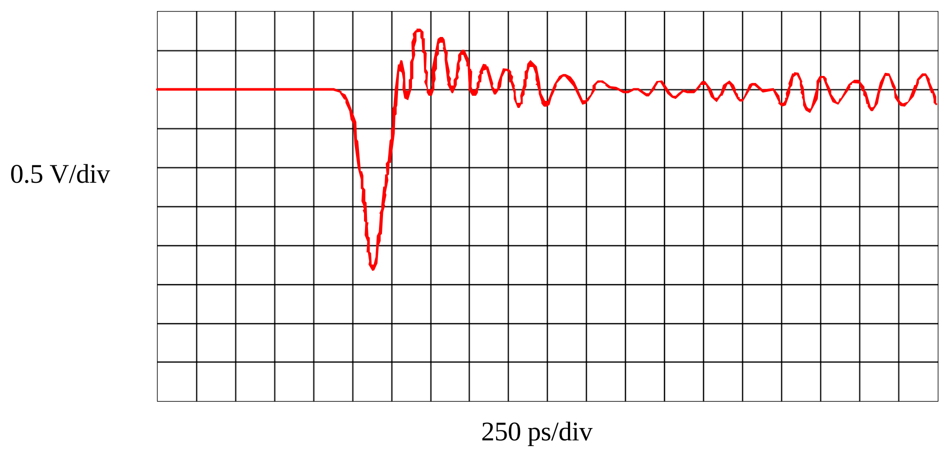

Figure 5. 11 mm button response to a single bunch in the LTB.

Striplines:
Striplines couple to TEM fields surrounding the beam. The transfer impedance of a stripline in a round pipe to a centered beam is

$$Z_t(w) = 60ohm \ln\left(\frac{r}{r-d}\right)\sin\left(\frac{wl}{c}\right)$$

where r is the beam pipe radius, d is separation between the stripline and the beam pipe, and l is stripline length. The width of the stripline should be 4.75 times the separation to obtain 50 ohm self-impedance (air or vacuum dielectric and non-magnetic materials). The equation above agrees well with computer simulations using a 2-D electrostatics transmission line solver. Fig. 6 shows transfer impedance vs. frequency for a thin stripline in a 63.5 mm pipe (diameter). Stripline width is 14.7 mm. Separation is 3.1 mm. Self-impedance of the stripline is 50 ohms. As in the case of the buttons, this response is idealized.

Wake fields and high-order mode resonances in the stripline and feedthrough corrupt the smooth calculated response.

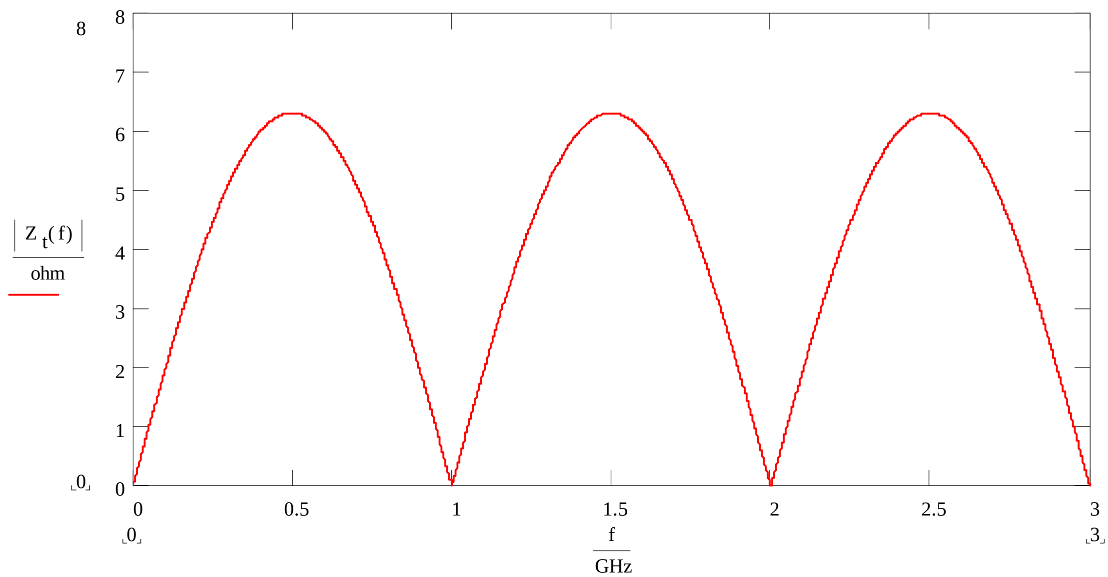

Figure 6. 150 mm stripline frequency response.

The time domain response of a stripline to a short bunch (shorter than the stripline) is a pulse doublet. The second pulse is the opposite polarity of the first pulse. The second pulse occurs at

$$t_d = \frac{2l}{c}$$

where l is the stripline length. The echo pulse may be exploited in a BPM receiver if circuit elements resonate in phase with the pulse doublet. For example, a 150 mm stripline produces an echo at 1 ns, ideal for driving a 500 MHz band-pass filter.

The time domain response of the upstream port on a stripline to a centered beam is

$$v(t) = \frac{\phi Z_l}{4\pi}\left[i_b(t) - i_b\left(t - \frac{1}{\beta_b c} - \frac{1}{\beta_s c} \right) \right]$$

where ϕ is the azimuthal width of the stripline, Z_l is stripline impedance, β_b is beam relative velocity, β_c is relative signal velocity on the stripline, and

$$i_b(t) = i_{pk} \exp\left(\frac{-2t^2}{\tau^2} \right)$$

where τ is bunch duration at 2σ, and

$$i_{pk} = \frac{-Q_b}{\tau}\sqrt{\frac{2}{\pi}}$$

where Q_b is bunch charge. Fig. 7 shows the predicted response for an LTB stripline to a 30 ps, 1 nC bunch. The azimuthal width of the stripline is 29.3 deg., Z_L is 50 ohm, β_b and β_c are unity.

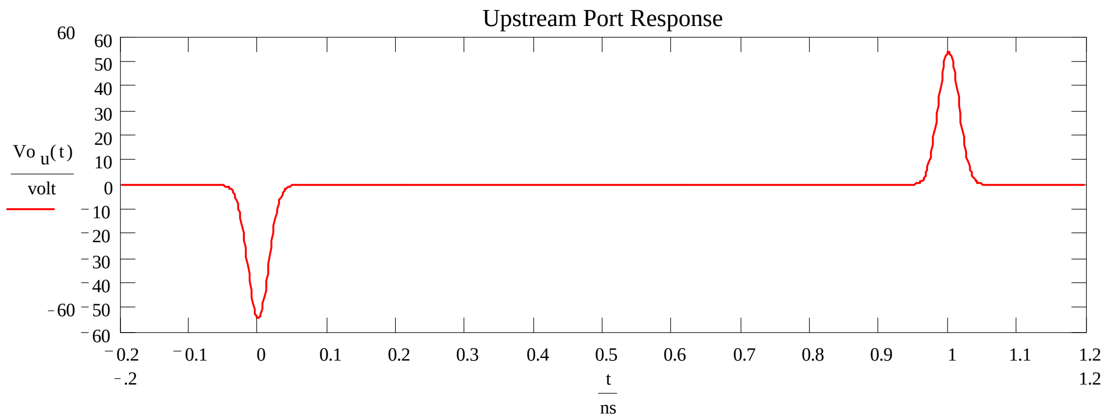

Figure 7. Calculated time-domain stripline response to a single bunch.

Obtaining such a waveform on an oscilloscope is difficult. The signal has very high bandwidth, and long cables attenuate the signal. High frequency resonances in the stripline structure and the vacuum feedthrough corrupt the signal, and the usual travelling waves due to wake fields add to the confusion. We have added 600 MHz lowpass filters on all LTB and BTS striplines to reduce the peak signal reaching the electronics. The 500 MHz component is allowed to pass and resonantly excite the BPM input tuned circuits. Even with the filters in place we must insert 12 dB attenuators at the electronics to keep the signals within the BPM receiver dynamic range.

System Response:
If we factor in button response with the beam current spectrum, we can determine the signal voltage present at the output of the button. Fig. 8 shows the sector arc calculated button signal spectrum for 400 mA, 328 bunch beam. Fig. 9 shows the calculated IDBPM button signal. In each case the beam is centered.

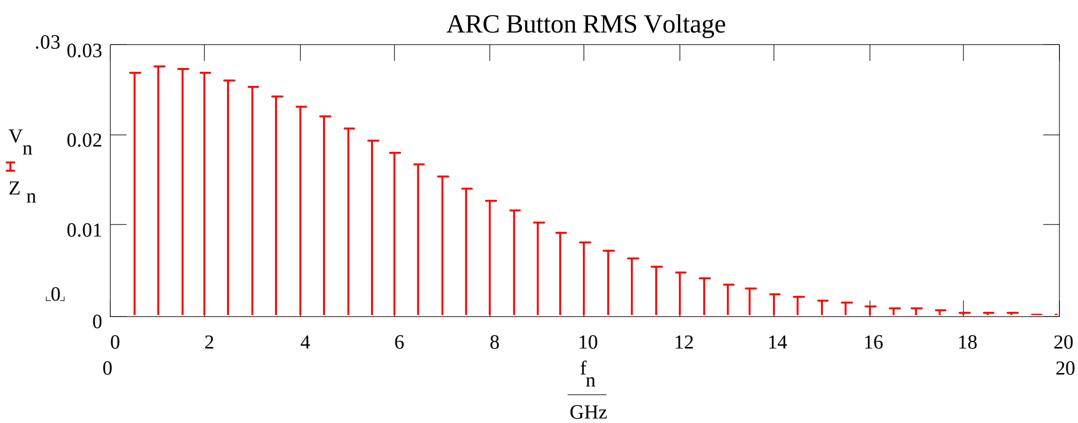

Figure 8 Sector arc button response.

The last component in the pickup signal path we must consider is the coaxial transmission line between the pickup and the electronics. All normal coaxial cables attenuate signals. Simple resistive loss in the conductors attenuate low frequency signals. At higher frequency skin effect becomes important. At even higher frequency signal energy may be lost in the cable dielectric material. We use Heliax cable on all BPMs in the ALS. This cable has about 4 dB loss per 100 feet at 500 MHz. The loss increases with frequency. BPMs in the storage ring and the booster have 6 dB resistive pads installed near the buttons. These attenuators reduce ringing in the cables due to impedance mismatch and protect the buttons in open-

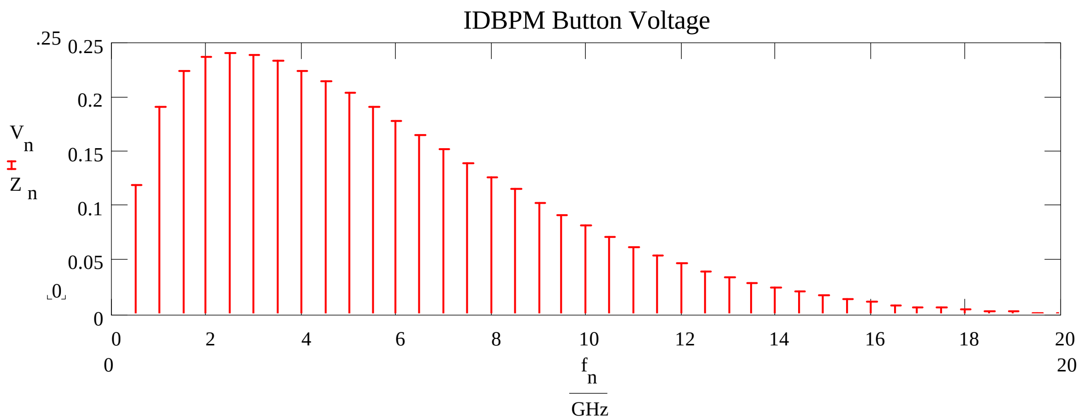

Figure 9 IDBPM button response.

circuit conditions. The attenuators and cable losses reduce the effective pickup coupling impedance. With 10 dB loss the effective coupling impedance is reduced by a factor of 3.16. The voltage loss in an attenuator is

$$dB = 20\log_{10}\frac{Vout}{Vin} \qquad \frac{Vout}{Vin} = 10^{\frac{dB}{20}}$$

From the forgoing we see that our button or stripline signal at the end of the coaxial cable has been altered by a number of things. Still, we have enough signal to work with and can make good beam position measurements. Fig. 10 shows an actual beam spectrum measurement taken at SR11 BPM8 with about 300 mA average current. The spectrum analyzer upper frequency limit is 6.6 GHz. The irregularity in the spectral line height can be attributed to button resonances and cable attenuation.

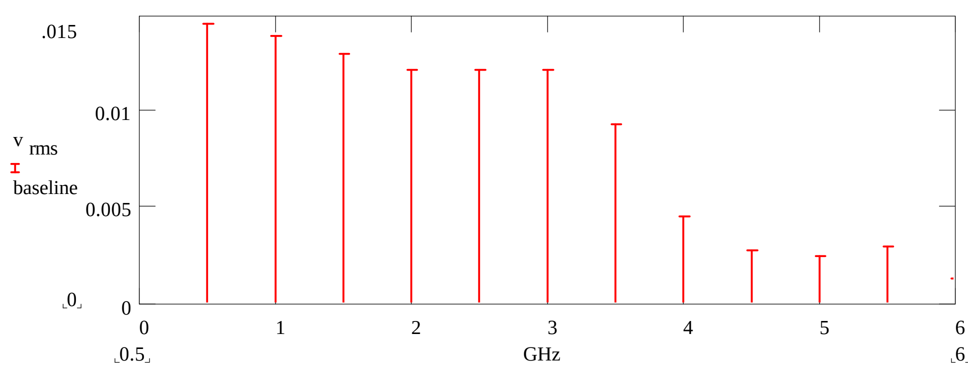

Figure 10. Actual beam signal spectrum from SR11 BPM8

Pickup Sensitivity:

In order to determine beam position we must know the sensitivity of the pickups. Sensitivity should not be confused with the coupling impedance. For example, a pickup could be designed for very high coupling impedance (a cylinder encircling the beam) and yet have essentially zero sensitivity to changes in beam position. We require pickups that couple sufficient signal to the electronics while also being sensitive to small changes in beam position. Sensitivity is expressed in several ways, dB/mm, mm/dB, and %/mm. Here we use %/mm which is the percent change in pickup voltage for a 1 mm change in beam position at the geometric center of the pickups.

The pickups may be arranged in single-function (one measurement axis) or combined-function (two measurement axes) geometry. All ALS BPM pickups are combined-function devices sensitive in X and Y. Fig. 1 illustrates typical striplines and buttons in combined-function geometry. When the pickups are rotated off the measurement axes we normally use all signals to determine beam position in both axes. If the pickups are not rotated (e.g. the Linac and transport lines), we may use only the two signals from pickups in the measurement axis. In some cases it is possible to determine beam position using only 3 of the 4 pickups. This is a useful technique for determining the relative condition of the pickups and associated electrical hardware.

We evaluate button and stripline sensitivity to beam motion using similar methods. We may test the actual pickups at the BPM operating frequency with antennas and RF equipment, but in some cases this is not practical (the pickups may be installed in a long section of beam pipe making tests with an antenna very difficult). At the ALS we tested prototypes of the pickups in short chambers and assumed the real components would perform identically with beam. 2D and 3D electrostatic solvers allow us to evaluate and optimize pickup geometry quickly. In a limited number of cases we can simply calculate pickup performance. In a round pipe with flush mounted buttons arranged in the X and Y axes, sensitivity at the geometric center is approximately

$$S_X, S_Y = 1/r$$

where r is the pipe radius in mm. For example, small buttons in a 25 mm radius round pipe have 4%/mm sensitivity at the center. If the buttons are rotated 45 degrees (as is often done to avoid a synchrotron radiation fan) the sensitivity is

$$S_X, S_Y = \sqrt{2}/r$$

The preceding two equations are valid for buttons with diameters that are small compared to the pipe circumference.

More complex BPM geometry requires testing with an antenna or computer analysis. The optimum location for buttons in a non-round beam pipe is not always obvious. Computer simulations with an electrostatic solver make finding the best geometry a relatively simple task without expensive machining and testing.

Once we have our signal data from an X/Y scan we can calculate sensitivity. In a non-rotated, four-pickup array (such as the striplines in Fig. 1b) we find sensitivity from

$$S_X = \frac{V_D - V_B}{V_A + V_B + V_C + V_D} \qquad S_Y = \frac{V_A - V_C}{V_A + V_B + V_C + V_D}$$

where V_A, V_B, V_C, and V_D are button voltages at 1 mm displacement in the appropriate axis. Note: In a symmetrical geometry with identical pickups the voltages would be exactly equal with the beam centered. Then we would move the "beam" 1 mm in X and Y and measure the new voltages. In practice the voltages will not be equal with the beam centered because of pickup and cable imperfections, so it is a good idea to subtract readings taken at 0,0 from readings taken at 1 mm. Also, it is best to take data with the beam displaced on both sides of center and average the results.

In a non-rotated geometry can also calculate sensitivity with just two terms in the denominator (those in the measurement axis). This operation yields higher sensitivity and essentially identical calculated position near the center. At large beam displacement from the center the results are quite different as shown in Fig. 11 and Fig. 12.

At the ALS we define positive X as increasing beam radius. In our pickup illustrations beam enters the page, and positive X is to the left. Therefore, we find X by subtracting V_B from V_D. Using the round pipe example from above we find good agreement between the simple calculation, electrostatic analysis, testing with antennas, and actual beam.

If our pickups are not installed in the measurement axes, we use all signals to find sensitivity.

$$S_X = \frac{(V_A + V_D) - (V_B + V_C)}{V_A + V_B + V_C + V_D} \qquad S_Y = \frac{(V_A + V_B) - (V_C + V_D)}{V_A + V_B + V_C + V_D}$$

Position Calculation:
At the ALS we use the difference over sum method to determine beam position in most of the BPMs. This involves digitizing the pickup signals and performing the position calculation in an ILC. In the booster synchrotron and storage ring beam position is calculated as follows

$$X = \frac{(V_A + V_D) - (V_B + V_C)}{V_A + V_B + V_C + V_D} \frac{1}{S_X} \qquad Y = \frac{(V_A + V_B) - (V_C + V_D)}{V_A + V_B + V_C + V_D} \frac{1}{S_Y}$$

where all terms have been previously defined. Note that the inverses of S_X and S_Y become simple gain constants expressed in millimeters.

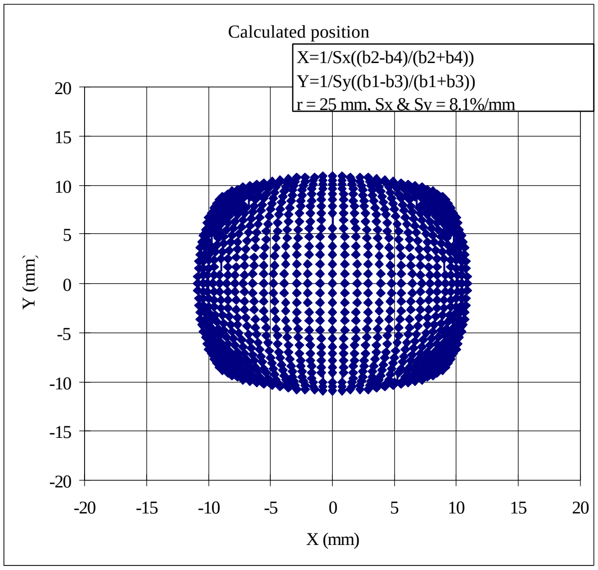

Figure 11 2- button position calculation

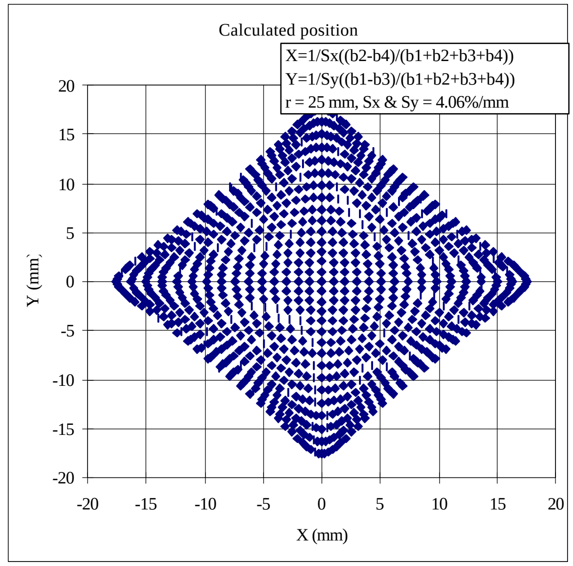

Figure 12 4-button position calculation

From Figures 11 and 12 it is apparent that X and Y sensitivity is not constant throughout the available beam aperture. This is true for all BPMs using striplines or buttons. Using sensitivity constants obtained at the center for all position calculations results in a distorted picture of beam position. In many cases the distortion is not important. If the beam is not in the center, we simply want to put it there and regain accurate position calculations. In some situations we must have accurate knowledge of beam position at large displacement. This may be achieved using computer algorithms such as look-up tables and interpolation or by non-linear position solvers. We are not using these techniques at the ALS at this time.

The BPM designer should compensation for non-linear pickup response when designing the detector electronics. While beam signals may be nearly equal when the beam is centered, they can be significantly different with large beam displacement. This can place rigorous demands on the signal detector electronics. In Fig. 12 the buttons signals differ by 18 dB (nearly 10X) at the extremes. Achieving such dynamic range with envelope detectors is not trivial.

Signal Processing Methods:
There are several ways to process BPM signals. Some common methods are briefly described below.

Δ/Σ

The most often used method for signal processing and position calculation (especially in light sources) is the difference over sum (Δ/Σ) method which is used at the ALS. This involves determining the amplitude of the band-limited beam signal envelope and performing calculations in the manner previously described.

AM/PM

Another method of signal processing is the amplitude to phase conversion method (AM/PM). Fig. 13 is a block diagram of an AM/PM receiver.

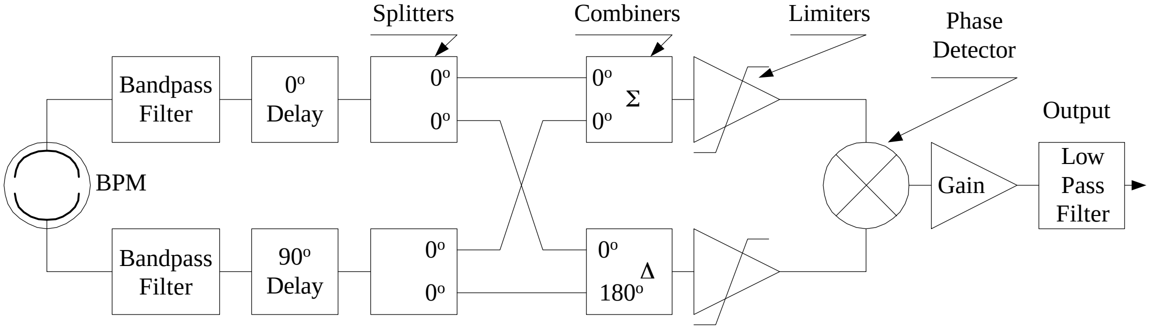

Figure 13. Block diagram of an AM/PM receiver.

In this technology beam signals are processed in closely matched bandpass filters to select the desired component of the beam spectrum. A 90° phase delay is introduced into one signal. The signals are split and combined in quadrature. At this point the amplitude differences between the pickup signals have been converted into phase differences. The signals are applied to electronic limiters that strip all amplitude components while preserving signal phase. The phase detector produces an output voltage proportional to beam position. This method of signal processing provides self-normalized, wide band beam position measurements and is most often used with single function pickups. AM/PM is used at Fermilab and the APS storage ring. The LHC at CERN will also use this method. The APS uses the AM/PM method with combined function pickups. This method provides good bandwidth at the expense of accuracy. It is very sensitive to phase matching and amplitude-dependent phase shift in the limiters. AM/PM is the most costly method of BPM signal processing.

Log-Ratio

Recently a new technique for signal processing has emerged. The availability of inexpensive, broad band non-linear amplifiers has resulted in the log-ratio BPM detector. Monolithic log amplifier integrated circuits operate from DC to 500 MHz and have over 80 dB dynamic range. These devices produce an output current proportional to the log (base 10) of the peak of the input RF. Video bandwidth is good, at least 50 MHz. Fig. 14 is a block diagram of a log-ratio BPM receiver.

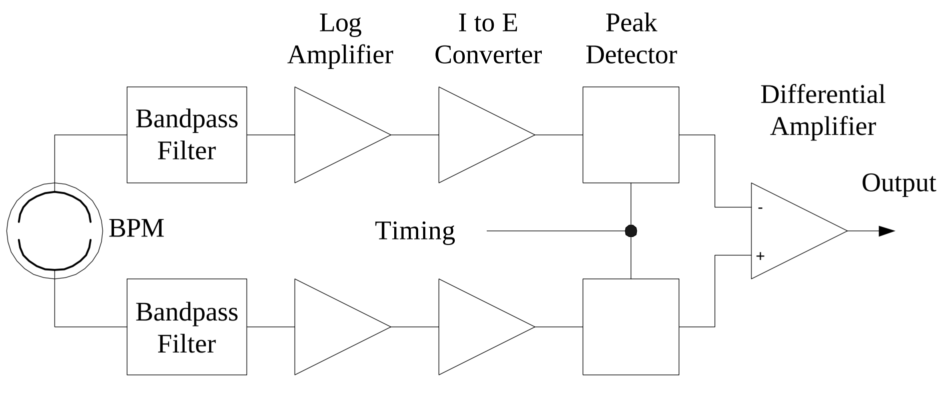

Figure 14. Block diagram of a log-ratio BPM receiver.

A portion of the beam signal spectrum is passed through band pass filters. For good transient response to single bunches we require the filters to ring sufficiently long for peak detection. If the RF component of the beam is 500 MHz or below, down-conversion to an intermediate frequency is not required.

With stored, multi-bunch beam the filters reach steady state response, and the log amplifiers produce essentially DC output current. The signal current is converted to voltage in I to E converters. The triggered peak detectors hold the peak value of the sampled signal. Beam position is found by taking the difference between the two signals. Normalization to beam intensity is automatic. This BPM detector provides excellent bandwidth and dynamic range. Log amplifier response deviates from perfect linearity as much as 1 dB. This causes an intensity dependence error.

The log-ratio detector is not well suited for high-accuracy closed orbit measurement, but its simplicity and low cost make it attractive for high speed, single turn measurements with very high dynamic range. As with the AM/PM detector, the log-ratio device is best suited to single-function pickups. They may be used with combined-function pickups by simply adding and subtracting detected signals in operational amplifiers.

Broad Band Time Domain

Another signal processing method uses fast peak detectors and/or gated integrators. No RF signal processing is done, that is, there are no bandpass filters or down-converters. This is basically a time-domain approach to signal processing and is used most often in situations when the beam has little RF content or low average power (few-bunch colliders and transport lines). An example is the SLAC Linear Collider (SLC). At the SLC striplines couple very high amplitude signals (> 1kV) into long transmission lines. The short pulses are stretched and attenuated in the cables before reaching the electronics. Special low pass filters with good pulse response further stretch the beam signals. Gated electronic integrators collect signal charge during the first part of the signal, which now looks like a single-cycle sine wave. It should be remembered that BPM signals have no DC content and the average value is zero. Integration of the signal requires precise timing.

Storage Ring ARC and Booster BPM Electronics:

The BPM electronics originally designed for the ALS are fully described in a 1991 paper [2]. The following description is a brief introduction to the electronics.

All ALS BPM detectors are basically super-heterodyne RF receivers, similar to AM radios. In the case of AM radio the desired information is contained in the instantaneous amplitude of a modulated RF carrier wave. Similarly, beam position information is contained in the instantaneous amplitude of a beam bunch signal. By detecting and comparing signal amplitude from four buttons surrounding the beam we can determine beam centroid position. All BPMs except those in the storage ring straight sections have one receiver for each button. Fig. 15 is a block diagram of a single channel. The BPM electronics are modular. Fig. 16 shows module connectivity. Fig. 17 is a drawing of the BPM front panel.

A portion of the beam bunch RF spectrum from the pickups is preselected in bandpass filters centered at 500 MHz. The selected beam harmonic (RF) is multiplied against a 450 MHz local oscillator (LO) signal in a doubly balanced mixer which produces an intermediate frequency (IF) at 50 MHz. The IF signal has in it the amplitude components of the RF signal in addition to some other mixing products. A 50 MHz bandpass filter following the mixer rejects the unwanted mixing products. As long as the LO signal is much stronger than the RF signal, the amplitude of the 50 MHz IF signal is linearly related to the RF signal amplitude.

The IF signal is boosted in a variable gain amplifier tuned to 50 MHz. Gain is adjusted by means of a DC voltage (AGC) generated in the BPM ILC. The amplified IF signal is envelope-detected in a quasi synchronous detector, LM1211, that outputs a video pulse proportional in amplitude to the envelope of the IF signal. The shape and duration of the pulse are determined by the number of consecutive beam bunches and Q of the various tuned circuits. The video pulse drives three circuits: a buffer amplifier that outputs video signals for oscilloscope monitoring, a fast peak detector for the single-turn monitoring circuits, and a slow peak detector and low pass filter. The single-turn electronics store up to 1024 measurements of position data. The output of the lowpass filter is digitized by the ILC for beam closed orbit measurement.

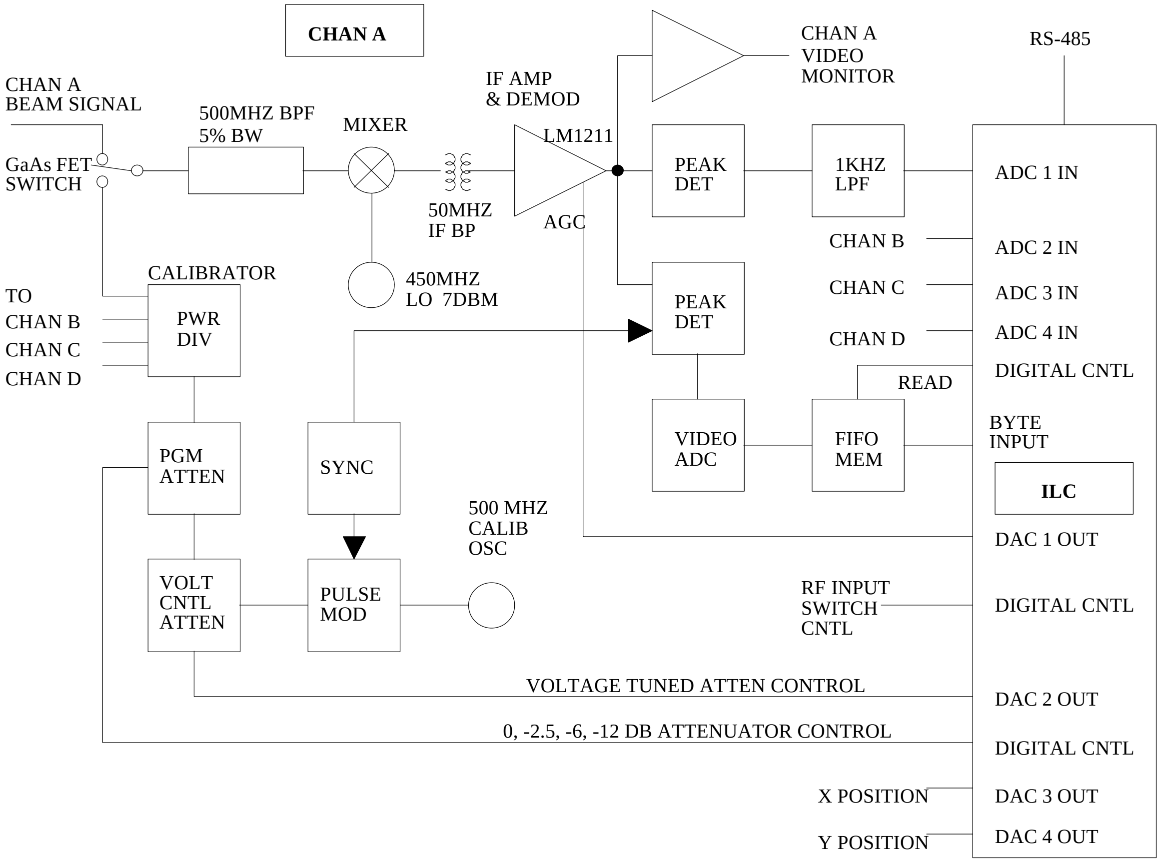

Figure 15. Block diagram of a booster or storage ring arc BPM. One channel is shown.

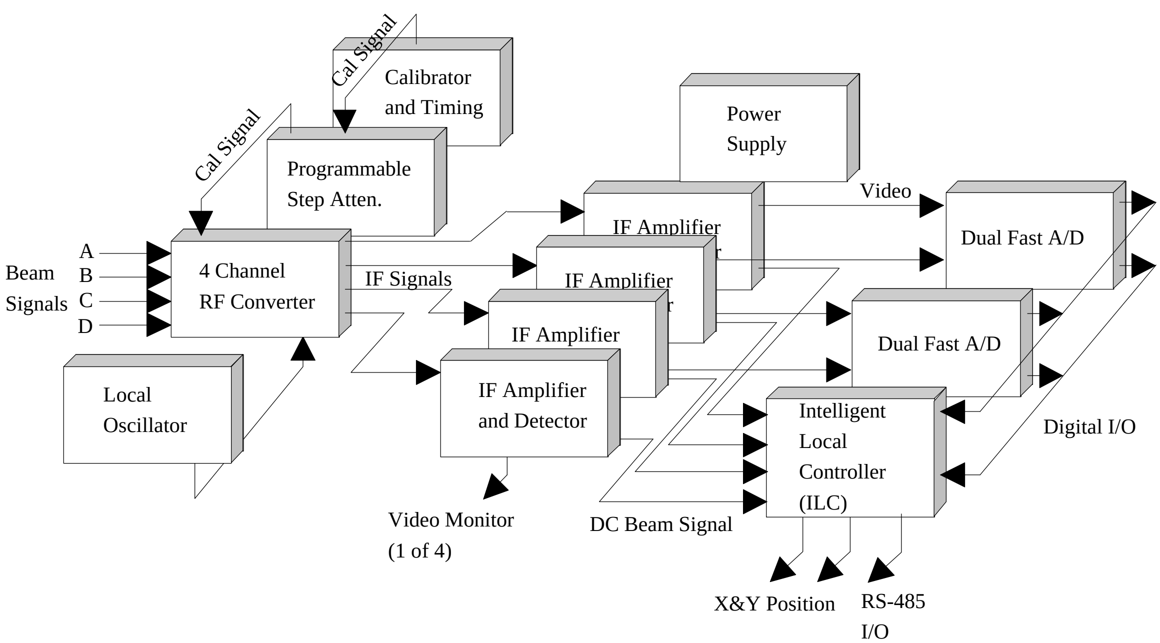

Figure 16 Diagram of BPM module connectivity.

Since each button has its own receiver, errors in the beam position calculation can be expected. The receivers do not have identical gain. Moreover, as the AGC voltage adjusts the gain, the receivers do not track. One receiver may have the highest gain at one AGC setting and the lowest gain at another setting. Consequently, a means of measuring and compensating differential gain errors must be employed.

A 500 MHz calibration signal is provided in the BPM electronics. Each time the AGC voltage is adjusted to optimize detected beam signals the calibrator should be used. The BPM ILC software performs calibration automatically when calibration is activated. The calibration sequence works as follows:

[1] The GaAs switches in the front end of the BPM receiver switch to the calibration RF source.
[2] The calibrator RF level is automatically adjusted until the detected output of one of the four channels equals the highest detected beam signal.
[3] Differences in the detected calibrator signals are stored as gain compensation constants.
[4] The calibrator is turned off and the input switches return to the beam signal.
[5] Subsequent beam signal data are multiplied by the gain constants before the position calculation is performed.

Obviously the BPM is not measuring beam when the calibration routine is running. In some cases this is not acceptable. The storage ring BPM design was modified to increase the range over which accurate readings are obtained without the need for frequent calibration. At the end of the calibration signal level adjustment routine a precision, stepped attenuator decreases the signal in known increments. This procedure provides four data points for each detector. These data are used to compensate differential gain and slope in detector response. By using this method the storage ring BPMs can report beam position over a 10 dB range (roughly factor of 3) with an accuracy of ± 50 microns.

The Linac and transport line BPM electronics are identical to the booster and storage ring electronics except they have no fast digitizers. These BPMs operate at 1 Hz, and multiple measurements are not required. The measurements are single-shot in nature. The video signals at the output of the IF detectors drive sample-and-hold circuits that hold the peak value of the pulses for the ILC digitizers. The calibration sequence is required for these BPMs also. When the calibration routine is run a special clock (about 20 kHz) replaces the normal 1 Hz beam trigger so the routine finishes quickly.

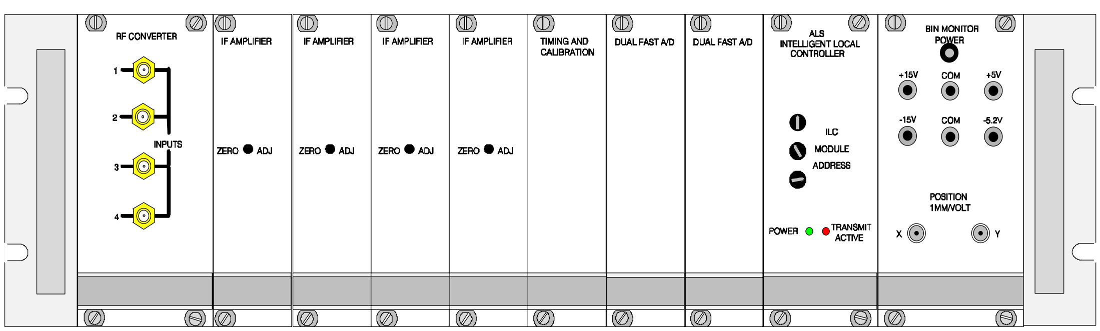

Figure 17 Drawing of a typical Eurocard BPM crate.

Insertion Device BPM (IDBPM)

Introduction: The powerful x-ray beam from insertion devices can melt the curved aluminum vacuum chamber in a few seconds if the electron beam orbit in a wiggler or undulator becomes sufficiently vertically offset or tilted. Thermocouples were imbedded in the vacuum chamber in the threatened areas to sense temperature rise from miss-steered photons. Special electronic interlocks (Errant Photon Beam Interlock or EPBI) abort the beam if these thermocouples become too warm. Testing the thermocouples requires actual heating with beam and is time-consuming. The thermocouple system was viewed as a backup to an electron beam orbit interlock which is easier to test. Special button pickups were installed at the entrance and exit of 10 storage ring straight sections. An all-analog BPM signal processor was developed to sense small beam offsets and actuate a beam abort. This newer BPM receiver is currently installed in 22 locations around the storage ring. The stability of this instrument is very high. The IDBPMs

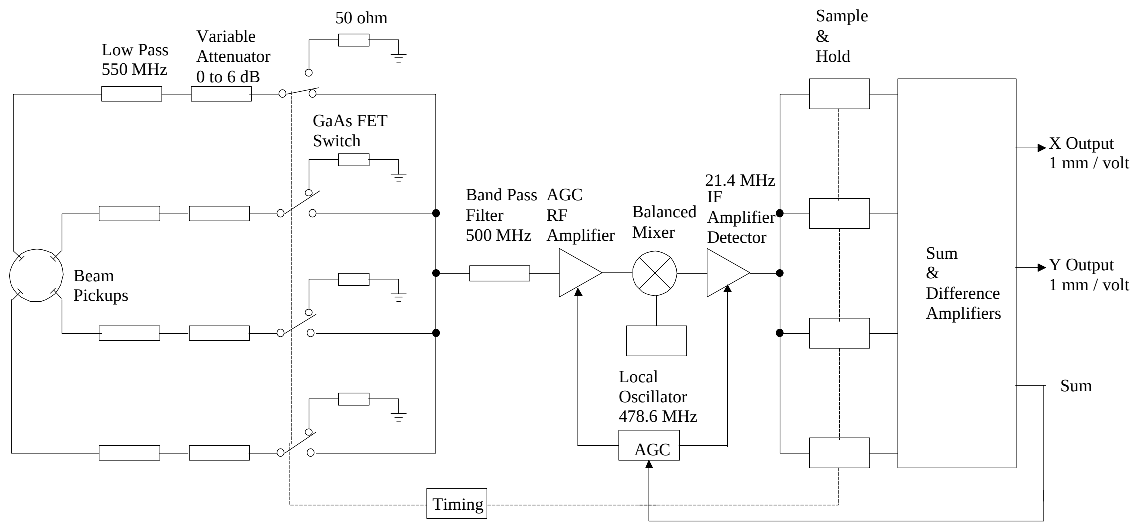

Figure 18 Prototype IDBPM receiver.

have become important tools for study of beam stability and recently, closed orbit feedback. Because the IDBPM electronics were to be part of an equipment protection interlock, a completely analog (no computers or software) instrument was developed. Fig. 18 is a block diagram of the prototype receiver. This circuit is based on an NSLS BPM design [3].

Beam signals from four buttons are shipped to the BPM electronics where 550 MHz low pass filters reject all signals above cutoff. After passing through variable attenuators the four signals are multiplexed into a single bandpass filter centered at 500 MHz. The multiplexing rate is a few kHz. A low-noise, adjustable gain RF amplifier boosts or attenuates the 500 MHz beam signals which are then down-converted to 21.4 MHz in a balanced mixer. A National Semiconductor LM1823 TV IF processor chip further amplifies the beam signals and detects the IF envelope of each successive beam signal. The LM1823 uses a true synchronous detector with good dynamic range and linearity. At the output of the detector the beam signals are DC voltage levels representing the amplitude of each button signal at 500 MHz. Each signal is present for about 100 μs. Sample and hold (S-H) circuits de-multiplex the signals. At the output of the S-H circuits we have the four decoded beam signals. Beam position is determined in sum and difference amplifiers. The gain of the output amplifiers is adjusted such that the X and Y outputs are 1V per mm.

The method used to find beam position is the Δ/Σ technique previously described. Normally, division (normalization to intensity) would be performed numerically in a computer or in non-linear analog circuits. In the IDBPM normalization is provided by automatic gain control. The four beam signals are summed after decoding. The sum signal is used in a feedback circuit that adjusts RF and IF gain to keep the sum signal constant.

The prototype IDBPM electronics became useful immediately after installation. Small changes in beam orbit were detected and ultimately attributed to the storage ring thermal environment (cooling water and air).

The IDBPM design was published [4] and offered to industry. The Bergoz company in France developed the BPM receiver and produced an instrument with superior performance. We now have 25 Bergoz BPMs and will probably install more. Fig. 19 is a block diagram of a Bergoz BPM. Fig. 20 is a photograph of the electronics. In function the Bergoz BPM is similar to the original ALS design. The physical package is considerably smaller than the ALS prototype.

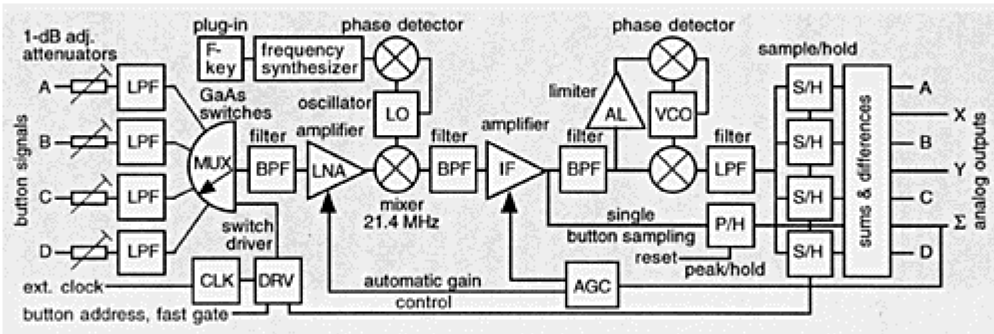

Figure 19. Block diagram of the Bergoz BPM receiver.

The beam intensity dependent position error in this design is very low, a few microns worse case. This is because the AGC loop continuously adjusts gain to keep the sum signal constant maintaining the operating point on the detector response curve. When the beam is offset from center a small intensity dependent error develops because the RF signals are not equal. The error is still much smaller than in the arc BPMs. The adjustable attenuators in the front end of the receiver are tuned to equalize the input signals when the beam is in the desired position. This yields optimum detector performance.

The multiplexed BPM has some faults. Since the four buttons are sampled, there is a possibility for aliasing. If transverse oscillations occur at or near the sampling frequency, the X and Y outputs may show a low frequency motion that is not real. Large beam phase oscillations can also upset the receiver. Slow changes in beam phase are tracked by the synchronous detector phase locked loop. Fast phase changes may be outside the loop frequency response and will develop a small error. The bandwidth of the post-detection processing circuits is kept low to minimize this problem. The analog bandwidth of the X and Y outputs is DC to about 200 Hz. The noise floor of the receiver is very low. At 200 mA beam current, the RMS noise floor is less than 100 μV (100 nm equivalent).

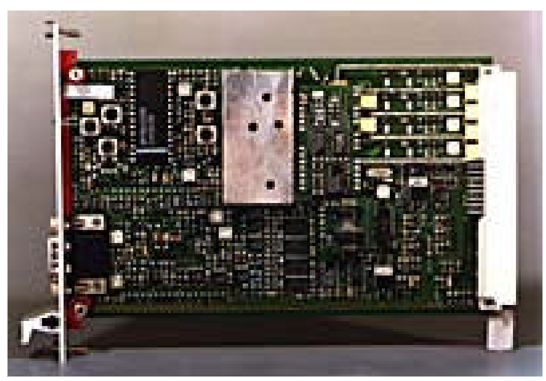

Figure 20. Photograph of Bergoz BPM electronics 3U Eurocard module.

Conclusion:
We have attempted to describe the beam, the beam sensors, and the beam position monitor electronics found at the ALS. Readers interested in more information are referred to proceedings of the US Beam Instrumentation Workshops (BIW), the US Particle Accelerator Conference, the European Particle Accelerator Conference, and the European Beam Instrumentation Workshop (DIPAC).

References:

[1] G. Lambertson, "Dynamic Devices: Pickups and Kickers", Presented at the 5th U.S. Summer School on High Energy Particle Accelerators, Stanford, CA, July 15-26, 1985. LBL 22085

[2] J. Hinkson, "Advanced Light Source Beam Position Monitor", Accelerator Instrumentation Third Annual Workshop, Newport News VA 1991, AIP Conference Proceedings No. 252, Particles and Fields Series 46

[3] R. Biscardi, J. W. Bittner, "Switched Detector for Beam Position Monitor", Proceedings of the IEEE Particle Accelerator Conference, Vol 3, p. 1516, (1989)

[4] J. Hinkson, K. B. Unser, "Precision Analog Signal Processor for Beam Position Measurements in Electron Storage Rings", Proceedings of the 2ns European Workshop on Beam Diagnostics and Instrumentation for Particle Accelerators, Travemunde, Federal Republic of Germany, 28-31 May, 1995,