

## BEAM POSITION MEASUREMENT SYSTEM DESIGN

H. Schmickler, CERN, Geneva, Switzerland

### Abstract

For newcomers, but also with interesting details for oldies, all components of a modern beam position measurement system are reviewed and explained. From specifications, sensor types, analogue and digital electronics over calibration methods the whole field will be covered.

### INTRODUCTION

The Beam Position Monitor (BPM) can be found in every accelerator. Its role is to provide information on the position of the beam in the vacuum chamber at the monitor location. For linacs and transfer lines the BPMs are used to measure and correct beam trajectories, while for synchrotrons such monitors are distributed around the ring and used to calculate the closed orbit. In circular machines, their location is usually chosen close to the main quadrupole magnets where the  $\beta$ -functions are largest and so any orbit distortion a maximum. For 90° lattices a typical layout involves placing horizontal monitors near the focusing quadrupoles (where the horizontal  $\beta$ -function is large) and the vertical monitors near the defocusing quadrupoles (where the vertical  $\beta$ -function is large). Apart from closed orbit measurements, the BPMs are also used for trajectory measurements (the first turn trajectory is particularly important for closing the orbit on itself) and for accelerator physics experiments, where turn-by-turn data, and even bunch-to-bunch data is often required.

In the early days a BPM monitoring system simply consisted of an oscilloscope linked directly to the pick-up signals. Since then, enormous advances in the acquisition and processing electronics have been made, turning beam position monitors into very complex systems. Modern BPMs are capable of digitising individual bunches separated by a few nanoseconds, with a spatial resolution of a micrometre or less, while the resulting orbit or trajectory collected from several hundred pick-ups can be displayed in a fraction of a second.

In the next chapter the mostly used sensors will be described (Pick-ups), followed by a detailed description on the acquisition electronics. Other important aspects, like calibration, timing and synchronization, large scale maintenance and component obsolescence are not treated.

### PICK-UPS

The measurement of beam position relies on processing the information from pick-up electrodes located in the beam pipe. Here we treat the three most commonly employed:

- Electrostatic – including so-called ‘button’ and ‘shoe-box’ pick-ups
- Electromagnetic – stripline couplers
- Resonant cavity – especially suited for high frequency linacs
- Frequency linacs

An excellent in depth analysis of most of these pick-ups is presented in Ref. [1]. Here we will briefly describe the three most commonly used, namely the electrostatic, electromagnetic and cavity pick-up.

#### *Electrostatic (Capacitive)*

The electrostatic or capacitive pick-up is the most widely used in circular accelerators. It consists of metallic electrodes situated on opposite sides of the vacuum chamber at the location where the beam is to be measured. As the beam passes through, electric charges are induced on the electrodes, with more induced on the side which is closer to the beam than the one furthest from the beam. By measuring the difference in the charge induced, the position can be calculated.

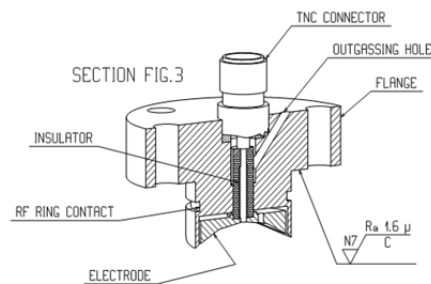


Figure 1: Cross-section and photo of an LHC button.

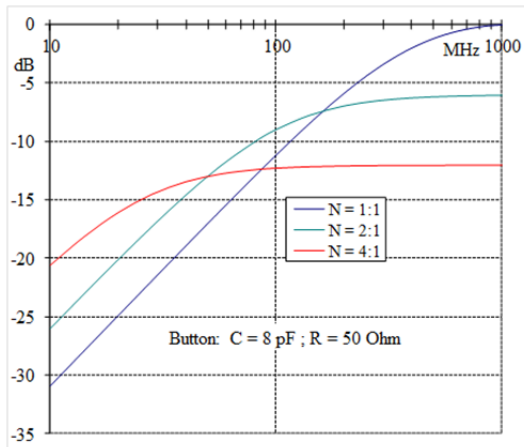
electrode.

Let us analyse the properties of button pick-ups (see Fig. 1) since they are the most popular due to their low cost and ease of construction.

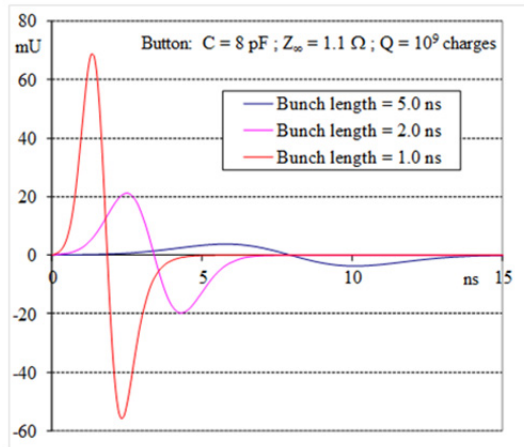
The image current associated with the beam will induce a charge on the button which is proportional to the beam intensity and inversely proportional to the position of the beam from the electrode.

The figure of merit for any electrode is its transfer impedance (the ratio of the pick-up output voltage,  $V$ , to the beam current,  $I_B$ ). For a capacitive pick-up the signal is proportional to the rate of change of beam current at low frequencies, while for high frequencies the capacitance ‘integrates’ the signal and the transfer impedance tends to its maximum.

Impedance transformation can be used to improve the low frequency response at the expense of that at high frequency. Figure 2(a) shows the frequency response of an 8pF button electrode for the matched 50Ω impedance case (1:1) and after two different impedance transformations. The time response of the button for different bunch lengths can be seen in Fig. 2(b).



(a)



(b)

Figure 2: (a) Frequency response and (b) time response of a button electrode.

When designing such pick-ups care must be taken to limit the impedance variations when the transmission line used for signal extraction passes from the vacuum to a feedthrough or cable dielectric (such as ceramic, glass or air). Any such mismatch will produce unwanted reflections, often at high frequency, which could perturb the processing electronics. For this reason most processing chains introduce a low-pass filter on the button output. Special care must also be taken to pair the electrodes on opposite sides of the chamber to minimise offsets in the position reading. This pairing can be made less sensitive to capacitance variations if the high frequency cut-off for the processing electronics sits on the linear part of the button response, with the disadvantage that the overall signal amplitude is reduced.

### Electromagnetic (stripline)

The electromagnetic pick-up is a transmission line (stripline) which couples to the transverse electromagnetic (TEM) field of the beam. The transmission line is formed between the stripline and the wall of the vacuum chamber and is excited by the beam only at the gaps on either end of the stripline where a longitudinal field occurs. Figure 3 shows the layout of such an electromagnetic stripline electrode.

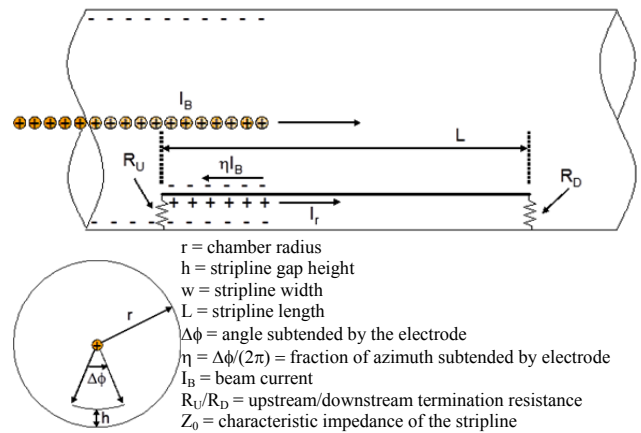


Figure 3: Schematic and photo of an electromagnetic stripline pick-up.

Consider a bunch travelling from left to right (upstream to downstream). While it is over the upstream port there is a voltage  $V_r$  across  $R_U$ , causing a voltage wave of that amplitude to be launched to the right. The stripline forms a transmission line with the wall of the vacuum chamber of characteristic impedance  $Z_0$ . The voltage wave is therefore accompanied by a right travelling current wave of amplitude  $I_r = V_r / Z_0$ . This current flows along the bottom surface of the electrode whilst an equal and opposite current flows along the chamber wall. In addition an image current of amplitude  $\eta I_B$  travels along the top surface of the electrode. The voltage  $V_r$  across  $R_U$  can therefore be expressed as;

$$V_r = (-I_r + \eta I_B)R_U = \eta I_B \frac{R_U Z_0}{R_U + Z_0} \Rightarrow V_r = \frac{1}{2} \eta I_B Z_0$$

for a matched stripline ( $R_U = Z_0$ )

When the beam is over the downstream port it produces a voltage  $-V_r = -\frac{1}{2} \eta I_B Z_0$  across  $R_D$  in the same way as it produced a voltage  $+V_r$  across  $R_U$ . This launches a left-travelling wave of the same magnitude, but different sign to the right-travelling wave, which propagates along the transmission line formed by the stripline and the chamber wall and will produce an inverted signal upon arrival at the upstream port a time  $L/c$  later. The final signal observed at the upstream port will therefore be a bipolar pulse with the maxima separated by  $2L/c$  (see Fig. 4(a)).

When the RF wavelength of the beam is equal to multiples of  $2L$ , the reflection and the signal from next bunch will cancel and there will be no net signal from the stripline. A maximum in the frequency response will be observed when  $L$  is a quarter of an RF period, and hence the stripline pick-up length is usually chosen accordingly. The full frequency response of a 60cm long stripline is shown in Fig. 4(b) and has a lobe structure, with the minima located at multiples of  $c/(2L)$ .

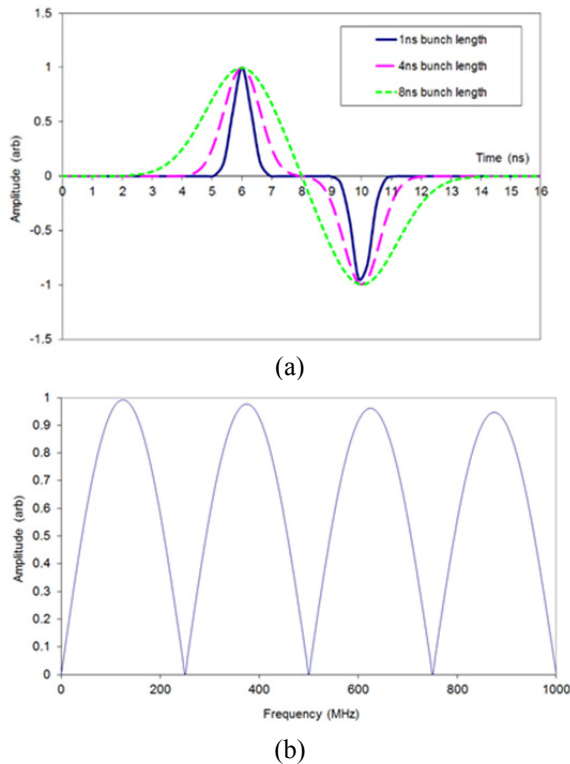


Figure 4: (a) Time response and (b) frequency response of a 60cm long electromagnetic stripline pick-up.

For a relativistic beam the voltage due to the beam passing the downstream port is produced at the same time as the right-travelling wave propagating between the stripline and the wall arrives at the downstream port. The two equal and opposite voltages therefore cancel producing no net signal at the downstream port. The electromagnetic stripline pick-up is therefore said to be

“directional”, i.e. a signal is only observed on the upstream port with respect to the beam direction. These pick-ups are therefore used in all locations where there are two counter rotating beams in the same vacuum chamber. Due to imperfections in the stripline and feedthrough impedance matching, the best directivity one can hope to obtain for a real stripline is generally around 25-30dB.

### Resonant Cavity

Resonant structures, e.g. “pill-box” or rectangular cavities, coaxial resonators and more complex waveguide-loaded resonators, have become very popular to fulfil the high resolution, single-pass beam position monitoring demands of next generation, high energy, linear accelerators [1,2], or for driving a SASE-FEL beam-line [3].

These are constructed to exploit the fact that an off-centre beam excites a dipole mode ( $TM_{110}$ ) in the cavity, with the amplitude of excitation almost linearly dependent on the off-axis displacement of the beam (Fig. 5). This dipole mode has a slightly different frequency from the main monopole mode ( $TM_{010}$ ) of the cavity, which allows the processing electronics to select only the frequency of interest (dipole  $TM_{110}$ ) and so suppress much of the large, unwanted, intensity related signal (monopole  $TM_{010}$ ).

Nevertheless, even with this frequency difference, the presence of the fundamental  $TM_{010}$  monopole mode still adds a strong common mode component to the dipole-mode position signal, limiting the performance of the cavity BPM. Rather than picking off the signal from the cavity using four symmetrically arranged pin antennas it is therefore preferable to couple to the cavity using waveguides. Selecting the width of the waveguides such that they have a cut-off frequency above the  $TM_{010}$  monopole mode results in a very efficient, internal high-pass filter and makes the cavity BPM quasi “common-mode free”. Such waveguide-loaded rectangular resonators (Fig. 6) have demonstrated a world record resolution of 8.7 nm at the ATF2 final focus test beam-line [4]

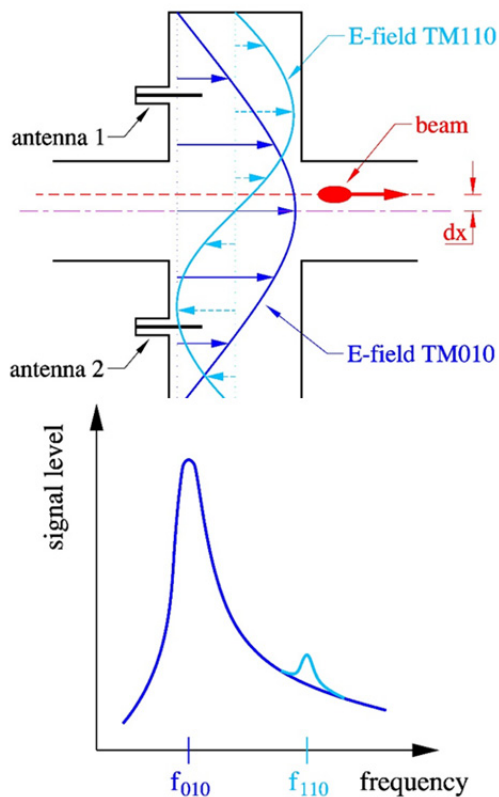


Figure 5: Principle and frequency response of a cavity BPM.

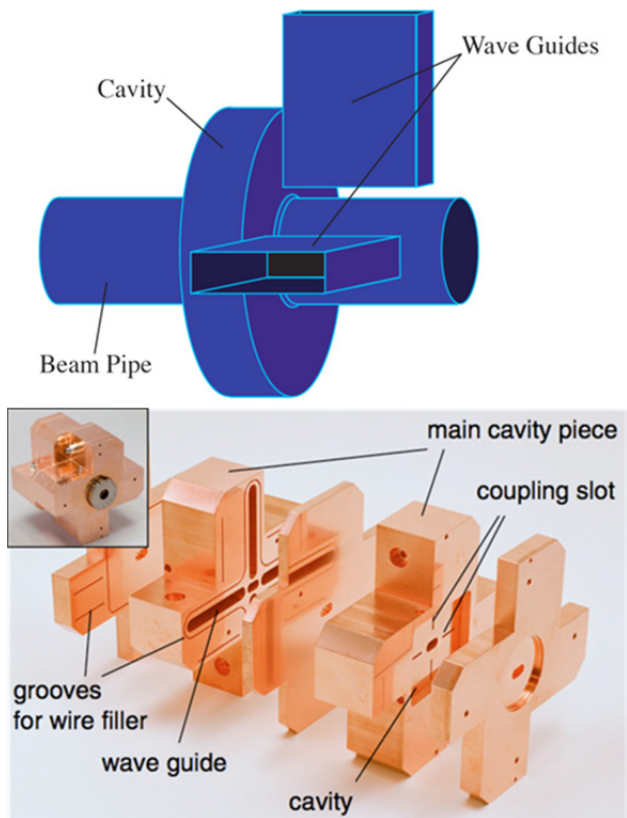


Figure 6: Principle and example of a waveguide coupled cavity pick-up (ATF2, KEK, Japan).

## BEAM POSITION ACQUISITION SYSTEMS

Once the signals from the opposite electrodes of a pick-up have been obtained, the next step is to convert these signals into a meaningful beam position. The first thing to do is to normalise the position, i.e. to make it independent of the signal amplitude (i.e. beam intensity). This is generally done using one of three algorithms, whose response curves can be seen in Fig. 7.

- **Difference over sum ( $\Delta/\Sigma$ )** - The sum and difference can be obtained either directly from a cavity BPM, or for the other pick-up types using a  $0^\circ/180^\circ$  passive hybrid, a differential amplifier or calculated by software (after digitising), to give:

$$\text{Normalised Position} = \frac{A - B}{A + B}$$

The transfer function of this algorithm can be seen to be highly linear.

- **Logarithmic ratio** - The two input signals are converted into their logarithmic counterparts and subtracted. In practice this is done using logarithmic amplifiers followed by a differential amplifier. This gives:

$$\text{Normalised Position} = \text{Log}(A) - \text{Log}(B) \left( = \text{Log} \left[ \frac{A}{B} \right] \right)$$

whose response curve is seen to be an reversed S-shape, which becomes highly non-linear when exceeding 70% of the normalised aperture.

- **Amplitude to Phase** - The two input signals are converted by a  $90^\circ$  passive hybrid into signals of equal amplitude but varying phase, with the position dependence of this phase given by:

$$\text{Normalised Position} = \phi = 2 \times \text{ArcTan}(A/B)$$

Here the transfer function again deviates from the linear in an S form, but does not diverge for large excursions. In addition, the gradient is larger around zero, making it more sensitive towards the middle of the pick-up. A variation on the amplitude to phase algorithm is amplitude to time conversion, the technique used for the beam position system of the LHC [5].



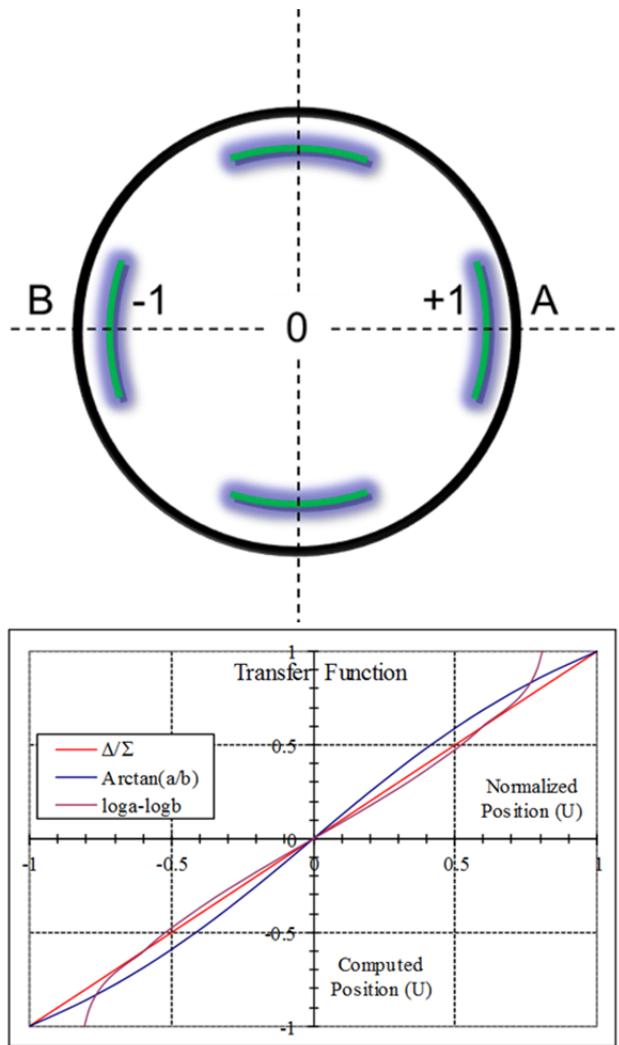


Figure 7: Transfer functions for three commonly used position normalisation algorithms.

The type of algorithm to be used will depend on the choice of processing electronics. In all cases the non-linearity is taken into account by calibration circuits and correction algorithms. A summary of commonly used beam position acquisition systems is given in Fig. 8. Here we will only briefly mention the various families in passing, but detailed descriptions along with the advantages and disadvantages of each system can be found in [7].

**MPX (multiplexed)** – each of the BPM electrodes is multiplexed in turn onto the same, single electronics acquisition chain. This eliminates channel to channel variations, but since the switching is generally quite slow such an acquisition only tends to be used in circulating machines where the average orbit is of main importance.

**Hybrid (Sigma & Delta)** – here a  $0^\circ/180^\circ$  passive hybrid is usually used to obtain the sum ( $\Sigma$ ) and difference ( $\Delta$ ) signal from the two electrodes. The position (or ratio of the sum and difference signals) can then be obtained in many ways including: direct digitisation, homodyne detection (mixing the sum and delta signals with the sum

signal itself) or heterodyne detection (mixing sum and delta signals with an external reference).

**Individual Treatment** – in this case each electrode is treated separately, but in parallel. The acquisition can either consist of directly digitising each signal or using logarithmic amplifiers as outlined above. The disadvantage of this method is that it requires two (or four depending on the pick-up orientation) very well matched chains of electronics, since the combination of the signals to obtain a position is performed at the very end of the chain.

**Passive Normalisation** – here the amplitude difference (i.e. position information) in the input signals is directly converted into a phase or time difference. Intensity information is lost in this procedure, but the result is a varying phase or time which is directly proportional to the position.

### Read-out Electronics

The read-out system interfaces the BPM pickup to the accelerator data acquisition (control) system. This requires signal conditioning, normalisation and linearisation of the BPM signals with conversion to a digital format somewhere along this chain in order to ultimately provide a time-stamped beam position.

Modern BPM read-out electronics are typically based on the individual treatment of the electrode signals using frequency domain signal processing techniques [ ]. These techniques were developed for the telecommunications market and make use of the high frequency and high resolution analogue to digital converters (ADCs) that are now readily available. In such schemes, bandpass filters in the analogue section convert the BPM signals into sinewave-like signal bursts for waveform sampling and processing in the following digital electronics. Microwave and RF analogue components, 12-16 bit pipeline ADCs, Field Programmable Gate Arrays (FPGAs) and clock distribution chips with sub-picosecond jitter are some of the key hardware elements. Figure 10 illustrates a typical electronics arrangement for a broad-band BPM pickup with only 1 of the 4 channels shown. For cavity BPMs the schematic is similar.

The analogue chain, consisting of bandpass filters, amplifiers and typically a frequency down-conversion stage prepare the electrode signal for sampling by an ADC. In order to reconstruct the input sine wave the ADC is either clocked at some sub-harmonic of the accelerator radio frequency or with an external clock (NCO – numerically controlled oscillator). This clock is typically chosen to give a sampling at 4 times the frequency of the input sine wave or to under-sample the input sine wave by a multiple of 4. This allows I/Q demodulation to be carried out in the digital domain. In-phase / Quadrature (I/Q) demodulation is nothing more than sampling at some 4th multiple or sub-harmonic of the input frequency. The knowledge that the sampled points are then all  $90^\circ$  apart on the sine wave allows for easy computation in the

digital domain without the need for sine and cosine lookup tables. If the frequency is correct, and the phase is locked, then all the quadrature samples are zero and only the in-phase samples need to be considered, giving directly the amplitude of the sine wave. These data can then be treated either in their raw form for bunch to bunch measurements, in a wide-band form for turn by turn measurements or in narrow-band for orbit measurements.

The narrow band orbit data is typically always available on-line from such systems, with the wideband and raw data available on request for a limited number of turns or bunches respectively. By producing the sum and difference of the amplitudes from opposite electrodes and applying calibration and linearization factors this data can then be converted into a meaningful beam position.

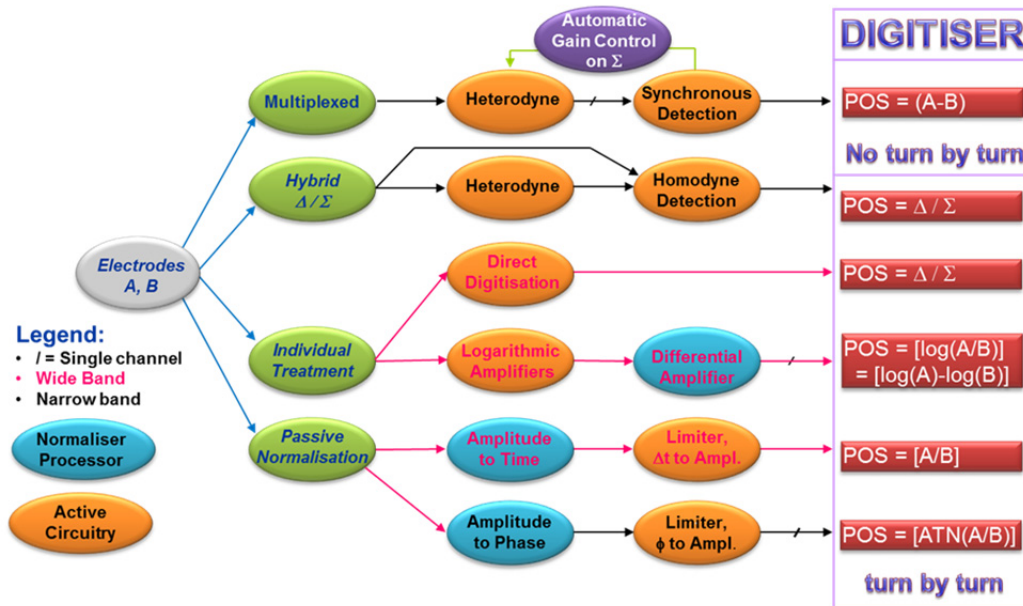


Figure 8: Schematic representation of the various beam position processing families.

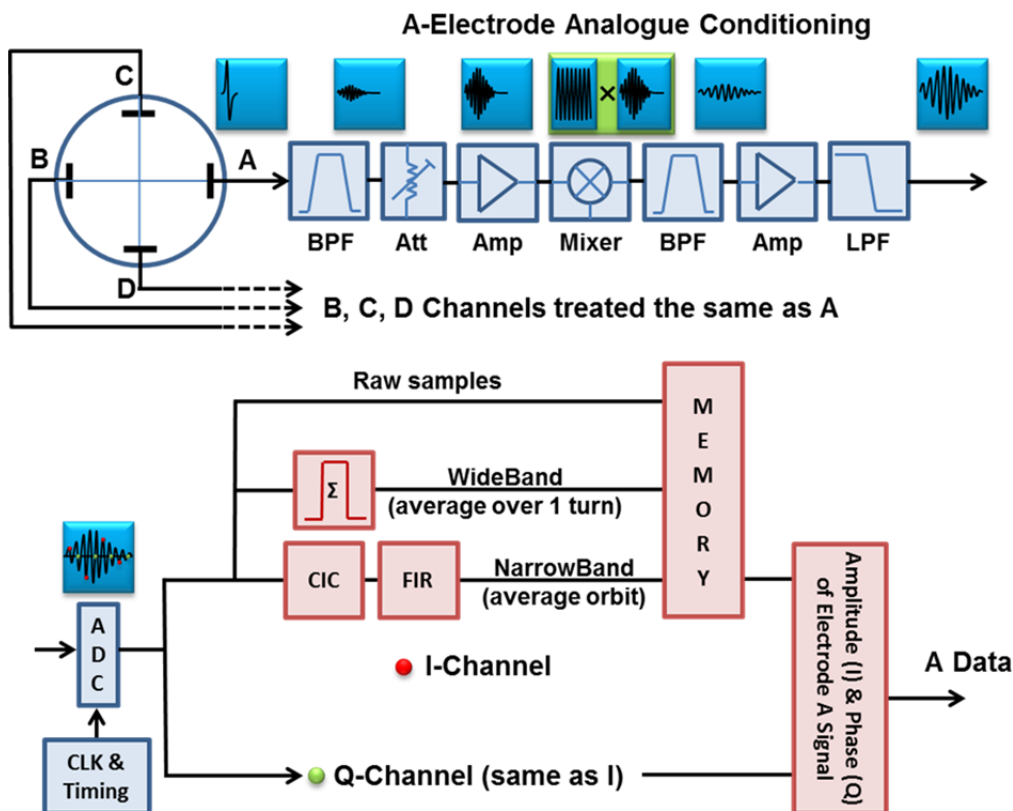


Figure 9: Key elements of modern BPM read-out electronics.

## REFERENCES

- [1] D.A. Goldberg, G.R. Lambertson, "Dynamic devices : a primer on pickups and kickers ", US Part. Acc. School, 1991. AIP Conf. Proc., 249,1992.
- [2] S. Walson, et.al., "Performance of a High Resolution Cavity Beam Position Monitor System," NIM-A, 578 (2007), pp. 1-22.
- [3] S. T. Boogert, et.al., "Cavity Beam Position Monitor System for ATF2," IPAC'10, Kyoto, Japan, May 2010, MOPE070, pp. 1140-42 (2010).
- [4] S. Smith, et.al., "LCLS Cavity Beam Position Monitors," DIPAC'09, Basel, Switzerland, May 2009, TUOC03, pp. 285-287 (2009).
- [5] T. Nakamura, et.al., "High Resolution Cavity BPM for ILC Final Focus System (IP-BPM)," LCWS/ILC 2007, Hamburg, Germany, May/June 2007, arXiv:0709.2254v1, eConf C0705302.
- [6] D. Cocq, "The Wide Band Normaliser : a New Circuit to Measure Transverse Bunch Position in Accelerators and Colliders", Nucl. Instrum. Methods Phys. Res., A 416 (1998) 1.
- [7] G. Vismara, "Signal Processing for Beam Position Monitors", 9th Beam Instrumentation Workshop, BIW 2000, Cambridge, MA, USA , May 2000, AIP Conf. Proc. 546, pp36-60.
- [8] V. Schlott, et.al., "First Operational Experience with the Digital Beam Position Monitoring System for the Swiss Light Source," EPAC'00, Vienna, Austria, June 2000, pp. 1809-11.