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THE COMPARISON OF SIGNAL PROCESSING SYSTEMS FOR BEAM POSITION MONITORS

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At first sight the problem of determining the beam position from the ratio of the induced charges of the opposite electrodes of a beam monitor seems trivial, but up to now no unique solution has been found that fits the various demands of all particle accelerators.
The purpose of this paper is to help instrumentalist in choosing the best processing system for their particular application.
The paper will present the different families in which the processing systems can be grouped.
A general description of the operating principles with relative advantages and disadvantages for the most employed processing systems is also presented.

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At first sight the problem of determining the beam position from the ratio of the induced charges of the opposite electrodes of a beam monitor seems trivial, but up to now no unique solution has been found that fits the various demands of all particle accelerators.

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INTRODUCTION

Beam position monitors (BPM) can be found in every accelerator.

BPM systems have largely evolved since the early days, from the simple scope visualization of coaxial multiplexed P.U. signals into a very complex system. These systems are now capable of digitizing individual bunches separated by a few tenths of ns, with spatial resolution in the micron range, while the resulting orbit or trajectory collected from several hundred planes can be displayed in a fraction of second.

To obtain such a performance the processing electronics have to be optimized to the machine and beam parameters.

A unique solution capable of covering all the possible combinations with satisfactory results seems almost impossible to realize. This is the reason for the wide spectrum of signal processing in use today.

The BPM applications are not only limited to Orbit & Trajectory measurements, but can perform static and dynamic beam parameter measurements by exploiting the large amount of data collected and stored in their memories[i].

Turn-by-turn measurement can give information on; Betatron oscillation, transfer function, phase advance, optics checks, local chromaticity, etc.

The high resolution allows for energy calibration and machine impedance measurements.

The BPM is also employed in feedback systems to stabilize the beam and even as beam position interlock[ii].

These applications are much more performance demanding than a simple position measurement.

1. PROCESSING SYSTEM FAMILIES

The various signal processing systems can be grouped into different families according to the employed techniques. At least three different criteria can be used to group them.

1.1 Signal recombination

Four main categories are nowadays mainly employed:

- ***Individual signal treatment:*** The maximum signal information is still available, therefore a wide-band processing is the most suitable. Due to a very large Gain-Bandwidth, it offers a limited dynamic range.
- ***Time MPX***: Electrode signals are sequentially time-multiplexed and processed by a single electronic system. It offers an excellent long-term stability but cannot perform turn-by-turn measurements.
- ***Δ/Σ***: The individual signals are immediately converted by the use of hybrids into Δ and Σ. This offers excellent center position stability but requires switchable gain amplifiers.
- ***Passive Normalization***: The signal's amplitude ratio is convert into a phase or time difference. It is amplitude independent but loses the intensity information.

1.2 Normalization processes

The Normalization is an analog process that will produce a signal proportional to the position information that is independent of the input signal level. Three conditions apply to all normalization processes: 1) The intensity information is lost. 2) The digitization requires a smaller number of bits. 3) No gain selection is required.

Two active and two passive techniques are actually employed.

- ***Constant Sum:*** The Normalization is obtained by keeping constant the sum of the two electrode signals using AGC amplifiers. This approach is only valid for the time MPX process where the signals exploit the same amplification chain.
- ***Logarithmic conversion***: Since the ratio of the logarithm of two signals is equal to the difference of the logarithm, the signals can be converted by logarithmic amplifiers to give the normalized signal as the difference of the output. It offers a large dynamic range, but limited linearity.
- ***Amplitude to time:*** This is based on the sum of a direct and a delayed signal coming from the two

electrodes. The zero crossing of the sum signal varies with time proportionally to the signal ratio, and hence to the position. It offers large bandwidth but is limited to bunched beams.

- ***Amplitude to Phase:*** Is a similar process where time is replaced by phase and a single period by multiple oscillations. It is a simple solution but requires accurate phase matching (Filters).

All other processes that require computing software to extract the position information from the recorded data are known as **un-normalized processes.**

1.3 Acquisition time

This is the time required for the BPM to supply a full set of data to the digital processor. Three categories can be created:

- ***Wide-band:*** It groups all processing systems capable of measuring individual bunches separated by >10 ns down to a single bunch. The bandwidth can be as high as 100 MHz. Systems that belong to this group include Sample/Track & Hold, Logarithmic amplifiers, Amplitude to Time normalizers.
- ***Narrow-band:*** It groups all processing systems capable of resolving one machine revolution period and in some cases can measure individual bunches separated by >100 ns. The bandwidth ranges from a few 100 kHz up to a few MHz. The Heterodyne and Amplitude to Phase processors belongs to this group.
- ***Slow acquisition***: A special class is reserved for the Time MPX processing which, while having an equivalent bandwidth relative to other heterodyne systems, is penalized in the acquisition rate by the time multiplexing. (See Fig. 1)

It should be pointed out that unexplored combinations among the present solutions could offer specific advantages. For example a turn-by-turn acquisition can be obtained from a time MPX processor combined with the Δ & Σ system. The Σ signal is first selected to establish the right gain for the AGC action, and then by switching to the Δ input and the use of a Peak & Hold circuit, consecutive position measurements can be obtained.

2. DETAILED PROCESSING DESCRIPTION

2.1 Time Multiplexed processor[iii]

The processor is conceived for closed orbit measurement of stable stored beams. (See Fig. 2)

The input MPX is usually realized with a multiple configuration of GaAs switches; the channel isolation should be >50 dB for frequencies up to 1 GHz.

A band-pass filter is used to select the largest line of the signal spectrum; its selectivity is not critical.

The essential element is the pre-amplifier which should handle a very large signal dynamic (>75 dB) and compress it by >50 dB. Its input admittance should be kept stable as function of the gain to avoid a zero offset drift. The global noise figure is increased by different insertion losses and should be optimized for the largest gain.

Figure 1 gives a schematic representation of the different families and their interconnections.

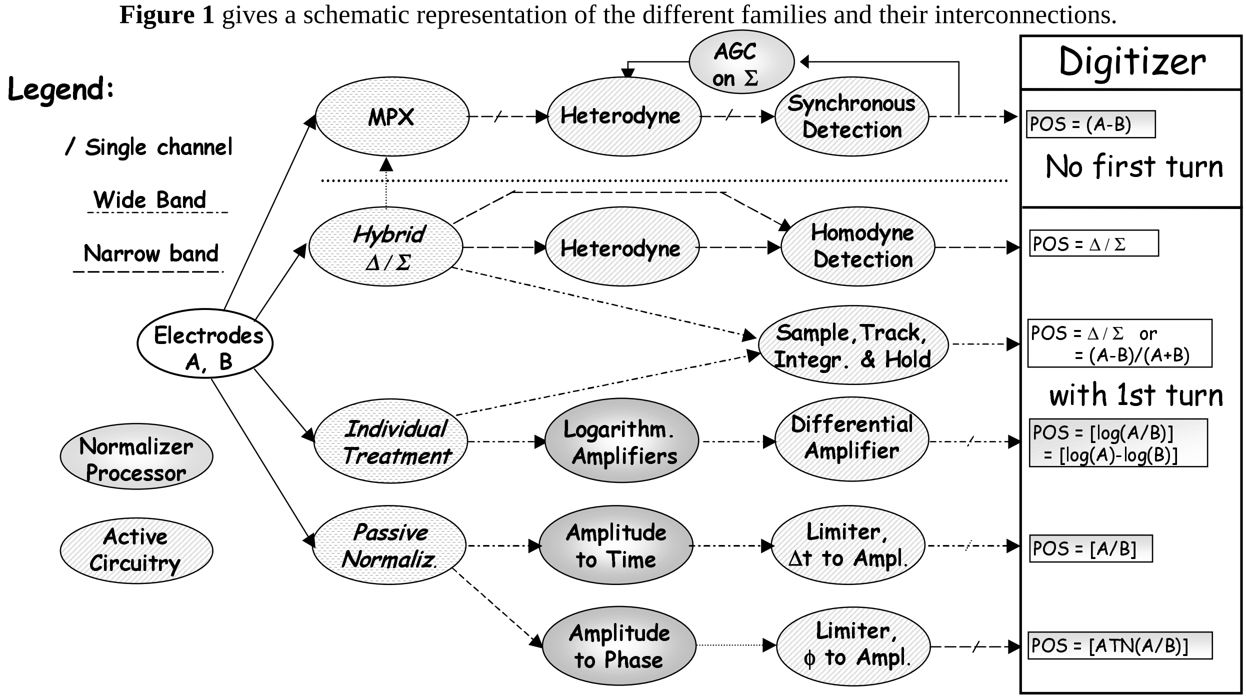
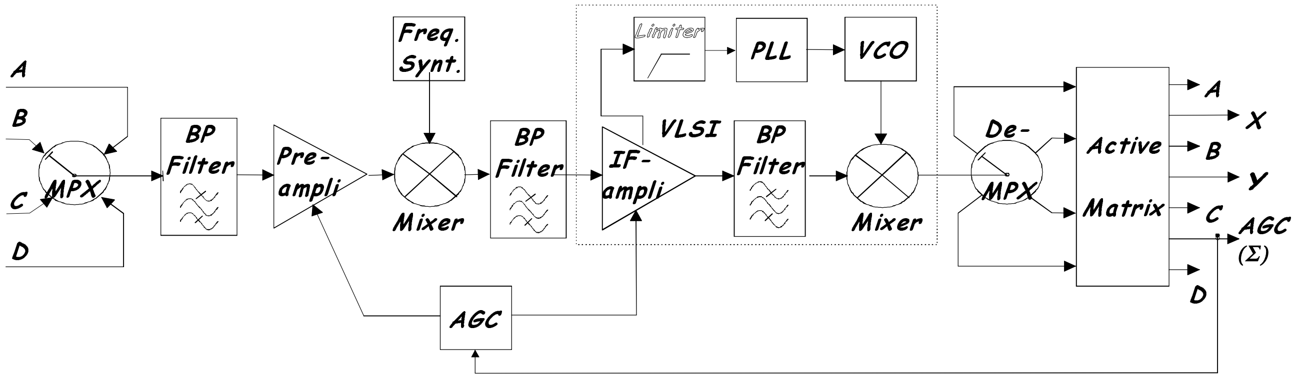


Figure 2



An active mixer, making use of a frequency synthesizer to reduce the noise contribution, is used to down convert the signal to a standard intermediate frequency (IF usually 10.7 MHz or a multiple). The IF amplifier and the demodulator are usually integrated telecom circuits. The IF bandwidth is selective enough to suppress side bands at the revolution frequency (multiple bunches) but sufficiently wide to allow for fast switching among channels (100 kHz > BW < 1MHz). Synchronous detection is obtained by comparing the phase of a sample of the carrier frequency with a reference signal and driving a VCO in a phase locked loop. Synchronous detection offers a clean detected DC signal but it slows down the MPX switching time since the PLL has to relock after each switching (even with accurate phase adjustment).

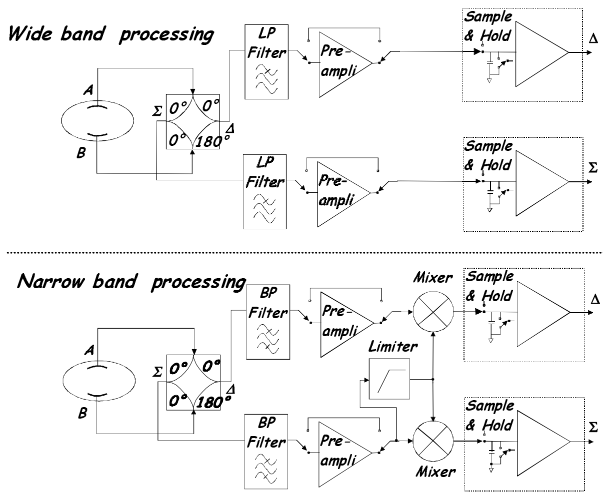
The last part of the chain is composed of an output de-multiplexer, four track & hold amplifiers and an active matrix of video amplifiers to produce the AGC sum and X,Y positions[iv].

Advantages	Limitations
Normalization process	*Requires a stable beam during the scanning*
Reduced number of channels (x4)	*No turn by turn acquisition*
Identical gain for all the channels	*Slow acquisition rate* (MPX)
Large dynamic range (>80dB)	*Reduced Noise Figure* (gain matching & MPX insertion losses, AGC pre-ampli.)
Excellent position stability	*Reduced linearity, for non-linear PU's since the Σ is not constant*
No temperature dependence and components aging	*Large engineering*

2.2 Δ & Σ Processor

When using this approach it is convenient to convert the input signals into their equivalent difference and sum at the earliest possible stage. This action is realized by a simple and reliable passive element called the **"180°hybrid".** The input signals should be in-phase, which means tight tolerances on the interconnection cables. Since the hybrid is radiation resistant, it can be connected directly to the electrodes.

Figure 3



Narrow Band: In most of the cases, the hardware is similar to that of the time MPX. In some application, the heterodyne conversion is suppressed. The pre-amplifiers have low NF (< 2dB), programmable gain through pin diodes switches, and will absorb a large input dynamic (> 90 dB). A fraction of the Σ signal is limited and used as a local oscillator in a homodyne detector. The Δ & Σ signals are digitized by a track and hold circuit and externally triggered ADCs. This scheme is also used for single bunch measurement in complex injector machines[v] (SPS), where the bunch excites the BP filter to resonate on its central frequency (see amplitude to phase normalizer). No hardware modifications are necessary but even tighter tolerances on the phase matching are required.

Wide-band: The LP filters will just stretch the pulses. The pre-amplifiers have a large BW and programmable gain but a limited dynamic range. For long bunches, the S & H circuits are suppressed and FADCs (1 GS/s) directly digitize the signal[vi].

Advantages	Limitations
The central position is independent on input intensity	*Programmable gain amplifiers*
Intensity measurement is available	*Multiple calibration coefficients*
Excellent Noise Figure	*The absolute position is f(gain)*
[Wide band allows measurements on multiple bunches (Δt <20 ns)]	*{Tight phase matching (Δ, Σ) at all the gains required by the synchronous detection (±5°) }*
{Large dynamic > 90 dB}	*{ Pedestal error on Σ }*

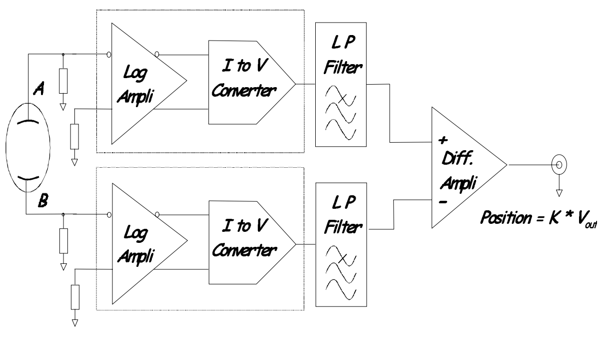
[W.B.] & {N.B.}

2.3 Logarithmic amplifiers[vii, viii]

The demodulating logarithmic amplifiers compress each signal. The outputs are filtered and applied to a differential amplifier. The position response is:

$$\text{Pos.} \equiv [\log (A/B)] = [\log (A)-\log (B)] \equiv (V_{out})$$

Figure 4



Behind such a simple equation is hidden a very sophisticated electronic circuit which is required to approach the ideal function[ix]. New generation circuits use several cascaded limiting amplifiers, with fixed gain and a wide bandwidth. Full wave rms detectors are applied at each stage and by summing theirs output signals, a good approximation to a logarithmic transfer function is obtained.

States of the art parameters are:

Input dynamic range:	>90	dB
Input noise:	<1.5	nV/√Hz
Non conformance lin.:	<± 0.3	dB
Limiter Bandwidth:	D.C. to >2	GHz
Video Bandwidth:	D.C. to 30	MHz

The demand of the consumer market (primarily telecommunication) for these products has resulted in a wide variety of new circuits, each one optimized for a specific parameter.

Advantages	Limitations
Possible applications in the time and frequency domain (NB & WB)	*State of the art performances are not simultaneously available*
Very large dynamic range (>90 dB)	*Poor position stability vs. input level, for peculiar conditions*
Wide input bandwidth	*Limited linearity (few % of the NA)*
No bunch shape dependency	*Limited long term stability*
Simultaneous digitization of + and - charges	*Temperature dependence*
Simple engineering	

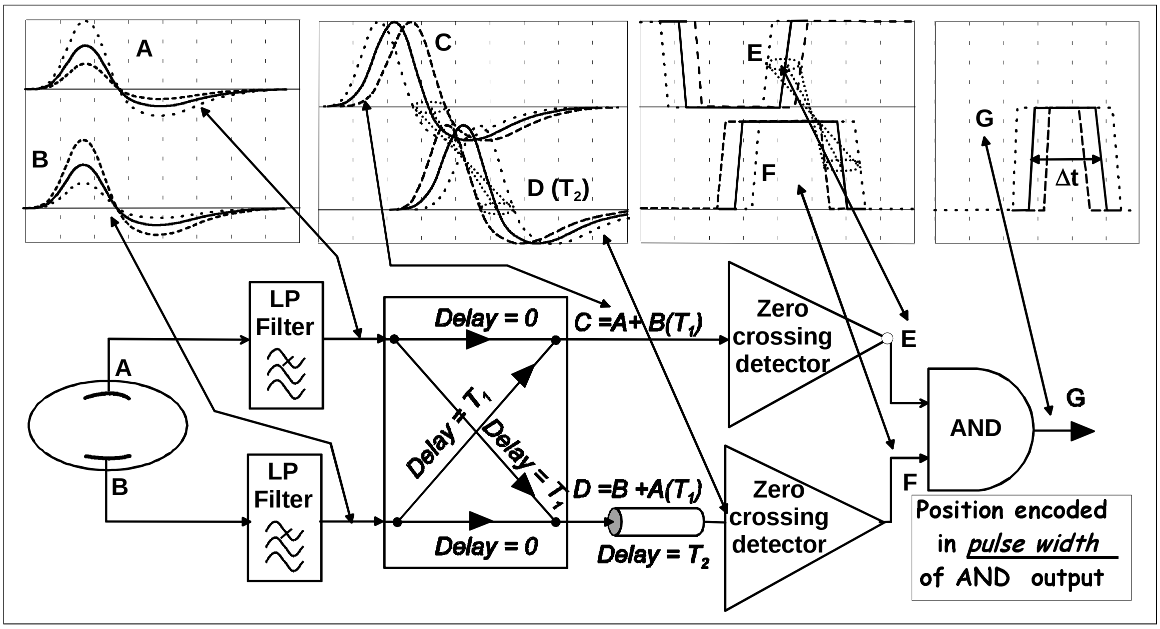
2.4 Amplitude to Time Normalization

This new normalization idea is derived from the “Amplitude to phase” principle where “phase“ is replaced by “time“ and the applied signal has a single oscillation period. It applies to bunched beams and works in the time domain[x, xi] (See Fig. 5).

The LP filters produce the correct pulse shape. The signals from both electrodes are split in two and one branch is delayed by a time T_1. The delayed signal of one channel is then added to the direct signal of the other channel, and vice versa. At C, the time of the zero crossing varies according to the signal ratio, up to a maximum of T_1. At the output D, you have the same signal amplitude but the time variation has opposite sign. The maximum time difference is therefore $2T_1$. The delay offset T_2 is required to avoid sign ambiguity and should always be larger than T_1. The zero crossing is independent of amplitude and easy to detect by fast comparator circuits. Their outputs drive an AND gate, which generates a pulse with a width proportional to the beam position.

$$\text{Position} \equiv \Delta t = 2T_1 \, [(A - B)/(A + B)] + T_2$$

Figure 5



By integrating this pulse, the time variation is transformed into amplitude that can be read by an ADC.

The normalization is obtained by the use of hybrids and cables which can be directly connected to the electrodes.

Advantages	Limitations
Fastest normalization process (> 40 MS/s)	*Can only be employed with bunched beams*
Reduced number of channels (x2)	*No Intensity information*
Input dynamic > 50 dB	
~10 dB reduction on the position dependent dynamic due to signals recombination	*Tight time adjustment*
Dynamic is independent on the number of bunches	*Propagation delay between comparators*
Almost independent on the bunch length	

Remark: A specifically designed monolithic Ga-As chip will allow for a large speed breakthrough.

2.5 Amplitude to Phase Normalization

This technique was first developed for RF signals working in the frequency domain and rapidly adapted to short pulses working in the time domain[xii] (See Fig. 6)

The two electrode signals are converted into a RF burst or a permanent RF signal, according to the beam shape, by the use of a BP filter. These in-phase signals are applied to the inputs of a "90° Hybrid". Each signal is split into two branches; one of them is shifted by 90° and added to the opposite in-phase signal, and vice versa. The outputs are of equal amplitude and have a phase difference (Δφ) proportional to the position.

$$\text{Position} \equiv \Delta\varphi = 2*\text{Arc-tangent}\,(A / B) - \pi/2$$

This relation is valid for both a continuous wave or for a burst after proper settling time, which depends on the bandwidth. To avoid an ambiguity in sign, one output is delayed by 90 degree.

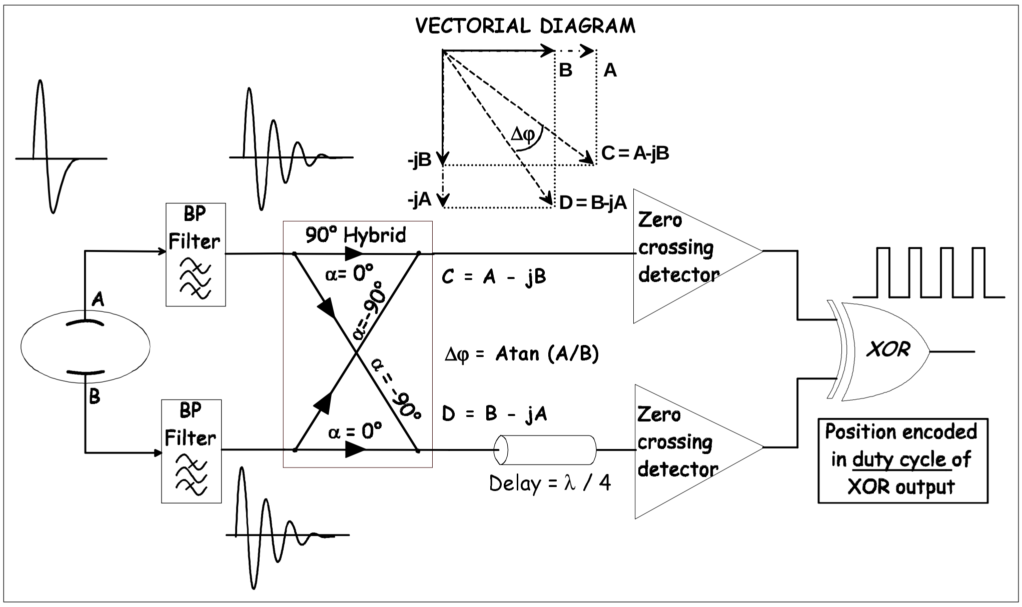
The two signals are applied to comparators that suppress the amplitude dependence. The phase difference is reconverted into an amplitude variation by the use of XOR logic. The position information has a variable duty cycle at twice the filter frequency, and is digitized by an ADC driven by LP filter and a video buffer.

Two cases should be distinguished:

Current modulated beam: The BP filters are tuned to the largest line in the frequency spectrum. Theirs selectivity (BW) should suppress all spurious frequencies (rejection > 40 dB) but be wide enough to accept the small frequencies changes that may occur during the accelerating cycle. The BP filters are not a critical element and the phase shift need only be matched to within a few percent.

Frequency down conversion[xiii]: For frequencies above 150 MHz, comparators are getting less performant and signal is therefore down converted by using a heterodyne. The acquisition time is increased by the ratio f_{RF}/f_{if}.

Figure 6



Bunch modulated beams (single or multi bunches) the induced signals charge the BP filter, which in turns will start a free oscillation on its central frequency for a predetermined time. The pulse width should be shorter than the oscillation period ($W_{(fwhm)} < 1/4*f_o$) to obtain the maximum signal. The bunch spacing should be larger than the damping time of the filter to allow for individual measurements. Acquisition rates up to a few MHz can be achieved, so that turn-by-turn and individual bunch acquisition is feasible. Since the BP filter selectivity is not critical, a single resonator can be employed. However, this results in a longer dumping time and therefore requires a longer bunch separation[xiv]. Several BP filter parameters should be accurately matched in order to preserve the correct relative phase over several oscillation periods.

Advantages	Limitations
Normalization process	*Upper frequency limit < 150 MHz*
Reduced number of channels (x2)	*Tight phase adjustment*
Input dynamic > 50 dB	*[Minimum bunch spacing (> 100 ns)]*
~10 dB reduction on the position dependent dynamic due to signals recombination (90° sum)	*[Matched pair BP filters (tight tolerances)]*
[Dynamic is independent of the number of bunches]	*Hardware; limited technological improvements foreseen*
Simultaneous digitization of + and - charges	*{Current modulated beams}*
Simple & Reliable	*[Bunched beams]*

3. APPLICATION EXAMPLE

Lets try to choose the best processing system for a future machine like the Large Hadron Collider (LHC) where a large scale, cost effective processor is required.

The tables present some of the main parameters of the machine and the BPM system.

LHC Machine Parameters		
Circumference	27	Km
Rev. period	89	ms
Bunch length	10/30	cm
Bunch separation	>25	ns
Intensity (pilot)	5E9	p/b
N of bunches	1 to 2835	
Bunch dynamic	>32	dB
Pos. dynamic (.5 NA)	>12	dB

BPM Specifications			
~2000 planes (Button type electrodes)			
Single turn & Orbit measurements			
Simultaneous 16 bunches (among any), turn-by-turn measurements			
Beam	Pilot	Nominal	
Scaling Factor accuracy	2	.5	%
Linearity	2	.5	%
Resolution	1	.1	%
Position stability vs. intensity	.3		%
Offset	1	.3	%
(Single shot)	rms	rms	NA

The first choice will concern the acquisition rate. Specifications impose a wide-band processor to satisfy the first turn and the measurement of any bunch among the 2835, spaced by 25 ns.

An un-normalized processor (wide-band Δ/Σ,

S & H) will require at least a 13 bit ADC running at 40 MS/s, to satisfy the single shot resolution and the scaling factor accuracy. This coupled with the high cost of such a system makes this choice quite problematic.

The logarithmic amplifier offers an excellent dynamic range and an insensitivity to bunch length variation but can not satisfy the bunch separation, the linearity and the position stability.

The Time Normalizer appears to be the unique solution to the required specifications and that's why it has been adopted for the LHC machine.

CONCLUSIONS

Experience has proved that every new machine requires a new approach to the same problem. This provides engineers with a challenge for new ideas.

Several different combinations among the currently available processing systems have still to be explored and may prove to provide solutions for particular cases.

The telecommunications field has similar needs and is extremely dynamic. Full advantage should be taken of their technological progress and of the reduced prices of components on the consumer market.

Technology improvements (speed) will allow some signal processes systems to excel.

My personal feeling toward the ideal solution will pass trough a passive normalization combined with a wide-band signal processing system; this will cover the widest range of possible applications.

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