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A REVIEW OF ACCELERATOR INSTRUMENTATION *)

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ABSTRACT

Some of the problems associated with the monitoring of accelerator beams, particularly storage rings' beams, are reviewed along with their most common solutions. The various electrode structures used for the measurement of beam current, beam position, and the detection of the bunches' transverse oscillations, yield pulses with sub-nanosecond widths. The electronics for the processing of these short pulses involves wide band techniques and circuits usually not readily available from industry or the integrated circuit market: Passive or active, successive integrations, linear gating, sample-and-hold circuits with nanosecond acquisition time, etc. This report also presents the work performed recently for monitoring the ultrashort beams of colliding linear accelerators or single-pass colliders. To minimize the beam emittance, the beam position must be measured with a high resolution, and digitized on a pulse-to-pulse basis. Experimental results obtained with the Stanford two-mile Linac single bunches are included.

1. FOREWORD

This presentation constitutes an attempt to review the field of accelerator instrumentation. This field is so wide that large cuts were necessary in every direction. First, all devices whereby the beam is intercepted were eliminated. Second, it was decided to leave out all techniques involving the observation of radiation as well as techniques requiring sophisticated, commercial pieces of equipment. Finally, the author preferred to narrow the field even further to the problems which he understands best, and also to the problems which might survive the present generation of machines, and hopefully will be improved during the next generation of machines.

Any resemblance between the graphics presented here and objects or people, dead or alive, is absolutely fortuitous and is definitely coincidental. On the other hand, those who wished they had recognized familiar pictures and failed to do so, should be assured that this is also accidental, due to the wide scope of this subject and to the proliferation of accelerators in the world today.

2. INTRODUCTION

There is no limit to the number or to the shape of non-intercepting obstacles that are introduced near the trajectory of accelerator beams to probe their intensity, their position or detect their oscillations.

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All these devices couple to the fields associated with a moving charge; their response can be calculated in the frequency domain[1] or in the time domain[2] from the potential of a point charge, the total vector potential being expressed as a summation over all particles in the bunch.

Since the electrodes are never infinitely long in the direction of propagation of the beam, the first observation to make is that the integration of the potentials around the contour of these electrodes always yields two antisymmetric solutions giving rise to a bipolar signal; in other words since the process of signal formation involves two antisymmetric discontinuities, no DC component can ever appear in an electrode response to a coasting beam. Therefore, one should distinguish between two kinds of pick-up systems: those having their longitudinal discontinuities far apart compared to the bunch length, and those having their discontinuities very close to each other, the bunch being much longer than the electrode. Under both of these headings one can list all kinds of non-intercepting obstacles: loops,[3] waveguides,[4] cavities,[5] buttons,[6] strips,[7,8] gaps,[9,10] plates,[11,12] half-moons,[13] sections of cylinders,[14] coils,[15] etc. The systems associated with these various types of beam detection are Position Monitors, which can also operate in the single turn mode for the case of not-yet-storing storage rings or for beam transport lines, Current Monitors, Beam Dampers using feedback on a turn-to-turn basis to prevent the rise of transverse or logitudinal coherent oscillations, measurement of tunes, investigations of beam damping parameters, or diagnostic techniques probing bunches' multipole oscillations.

New colliding machines are imposing tighter tolerances on the trajectory measurements than the tolerances acceptable on earlier machines. The number of beam detectors required is rather large so a special effort toward low cost will have to be made, without compromising on the system resolution and precision.

3. SOME COMMONLY USED ELECTRODE SYSTEMS AND CAPS

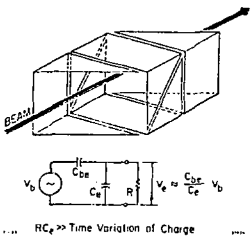

Fig. 1. A set of electrostatic pick-up electrodes with large time constant.

Circular accelerators used to be fitted with fairly large electrode structures. Thirty years ago, a pair of 1-meter, V-shaped, radial electrodes was built into the Cosmotron vacuum chamber;[16] a single monitoring station was used to track the beam orbit during acceleration. As strong focussing machines appeared, the vacuum chambers became smaller and the number of monitoring points was increased.

Electrostatic pick-up electrodes of the plate type (Fig. 1) are still being used for various applications because they present some advantages. For the case of long, slow rising

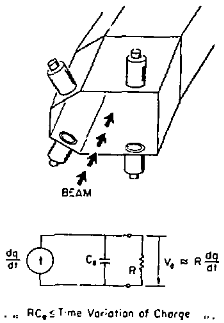

Fig. 2. A set of electrostatic pick-up electrodes with small time constant.

bunches, larger time constants have been obtained in conjunction with high input impedance head amplifiers; the monitors' sensitivity to beam current depends on the electrode capacity to ground and it can be easily controlled with the mechanical tolerances of the assembly. As for the linearity with the beam position, large structures offer the possibility of linearizing the response by making the area presented to the beam, a linear function of the transverse coordinate. This feature has also been applied to large magnetostatic pick-up devices.[17]

For shorter bunches, there seems to be little advantage in using large time constants. The most popular type of pick-up device has been the button (Fig. 2); however, a dual of this circuit has also been used,[18] i.e., pick-up loops, but the former has been favored because it is insensitive to the direction of propagation of the beam.

A more intriguing device, perhaps, is the traveling wave electrode or strip line (Fig. 3). The time response of the upstream port is always made up of two antisymmetric solutions, whereas the downstream port, in principle, yields no output when the beam velocity and the wave velocity on the strip are identical. This directive property has been used for the selective detection or excitation of counter propagating beams.[19] The frequency response of directional electromagnetic couplers[20] (Fig. 4) presents a null at all the frequencies where the strip length is equal to $n^{\lambda}/2$. This suggests that this type of pick-up can be very useful as a filter. Yet, couplers with almost flat frequency response to many gigahertz have also been reported.[21]

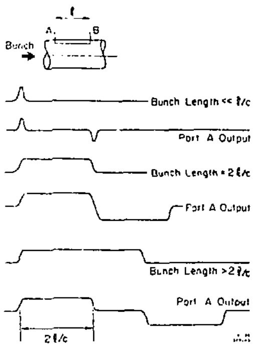

Fig. 3. A directional coupler and the waveforms observed at the up-stream port for different bunch lengths.

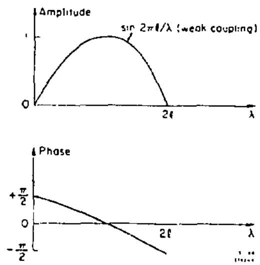

Fig. 4. Frequency response of the directional coupler.

Gaps in the vacuum chamber wall should also be separated into two categories depending whether the beam pulse length is much longer than the gap or whether the bunch length is comparable to the gap. It is customary to stack ferrites around the chamber on one side of the gap. For wide bunches or long accelerator pulses this ferrite amounts to loading the gap inductively and improves the low frequency response.[22] For narrow bunches, it serves an entirely different purpose and absorbs the reflections incurred in the gap enclosure. One should note that in either case no beam related DC current flows in accelerator vacuum chambers, and the signals obtained from gaps never have a base line at zero; this is precisely the reason why DC current transformers,[23] can measure the average beam current <u>outside</u> the vacuum chamber.

4. CIRCUITS FOR SIGNAL PROCESSING

Although most authors like to introduce their circuits as, "inexpensive, with a wide dynamic range, good reproducibility and high accuracy," it seems preferable to classify the processing circuits of beam induced signals after the type of technique used by the designers. Some of these techniques have sometimes been dictated by the problem requirements, but many times one can perceive a choice which depends on the designers' inclinations. We will find the usual dichotomy between single frequency and wide band electronics (which is similar, really, to synchronous detection as opposed to single shot measurement), and also between self-normalizing circuits as opposed to circuits relying on the main control system to perform the normalization.[24]

But even if there is no canonical way to process beam signals, there are some circuits which seem to appear regularly in the reports. Heterodyning is quite popular with multibunch machine and narrow bunches. Fig. 5 shows one approach[25] consisting in down converting both the sum and the difference signals as they are picked-up at the RF frequency, and in operating a synchronous detection at the intermediate frequency. Another type of high frequency processing is shown in Fig. 6 where detection is done before taking the difference between opposite electrode signals.[26] Note that the beam oscillation is normalized.

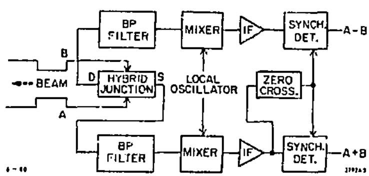

Fig. 5. A synchronous detection of the sum and difference signals after heterodyning.

A relatively small number of circuits are self-normalizing. The S-band position monitor[27] eliminates the dependency of its signals on the beam current[28] with a logarithmic amplifier (Fig. 7).

In a different approach,[29] normalization is accomplished with hard limiters operating at some intermediate frequency, and

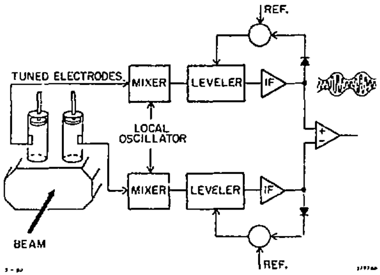

Fig. 6. Normalization of the beam oscillation at some intermediate frequency.

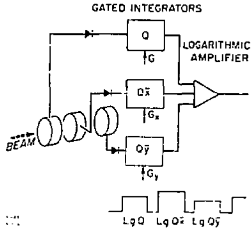

Fig. 7. Three S-band structures measuring the beam intensity and position.

with a phase comparison (Fig. 8) But frequency has not always been down converted.

Here is an example of up-conversion[30] (Fig. 9). This is a circuit performing a normalized oscillation detection on a bunch-to-bunch basis, using as above, a phase measurement. The conversion produces two phasors, the beam intensity dependency being contained in their amplitude and the position in their relative phase.

Whether they are dealing with amplitude or phase, the above circuits are all using mixers or diodes as square law detectors. Driving the I-F port hard with a positive or a negative gate, these circuits have also been used as linear gates with the added convenience that the output signal polarity can be determined by the gate polarity. From the mixer to the sampling bridge (Fig. 10), the change consists only in reversing two diodes.

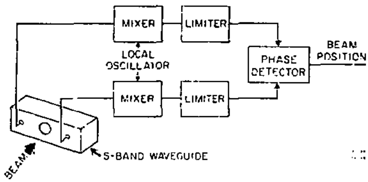

Fig. 8. A self-normalizing circuit by means of a direct phase comparison (narrow band).

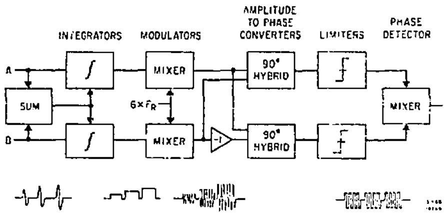

Fig. 9. A multibunch self-normalizing circuit (wide band).

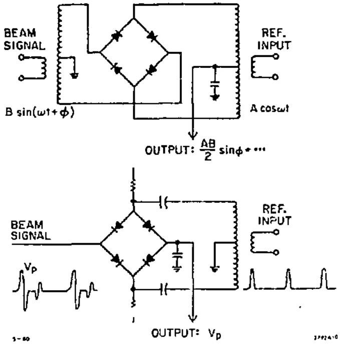

Fig. 10. Transformation of a double balanced mixer into a sampling bridge.

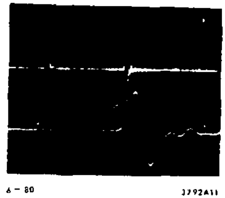

Fig. 11. e^+ and e^- beams of 1 mA each observed at 5 meters from their colliding point. 200 mV/div., 10 ns or 1 ns/div. Oscilloscope bandwidth: 350 mHz.

Wide band linear detection and gating is an attribute of the instrumentation of multibunch machines. Indeed, the time separation between the various induced pulses (Fig. 11) depends on the z location of the pick-up electrode; an attempt to detect at some harmonic of the revolution frequency can possibly yield no signal at some location around the machine. Gating of the individual bunches offers more flexibility. It usually is associated with an active DC restorer which can be as simple as a diode-capacitor and buffer,[11] or as elaborate as a sampling bridge.[32]

Active integrators have been used with nanosecond pulses,[33,34] and have shown a linearity quite comparable to the one given by double balanced mixers. Figure 12 indicates the most common configuration for a narrow pulse integrator.

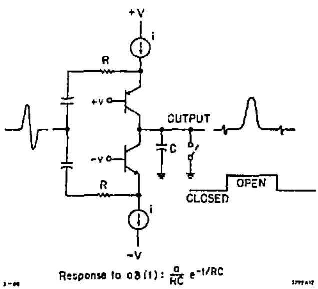

Fig. 12. Circuit for a fast, gated integrator.

Another grand favorite of many designers has been the hybrid junction which conveniently yields the sum and the difference of two voltages. Although this component in its various configurations (Fig. 13) seems to be predestined to be applied to beam position detection, it can be rather disappointing at very high frequencies. For the detection of bunch oscillations one can do away with hybrid junctions and extract the useful signal from the crest of a single electrode waveform.[35,36] Figure 14 proposes a scheme whereby the same circuit

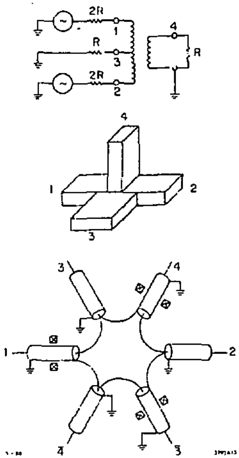

Fig. 13. Three configurations for 180° hybrid junctions.

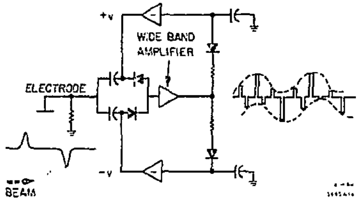

Fig. 14. A wide band, bi-polar bunch *oscillation detector.*

detects the oscillation riding on the crest of positive and negative bunch signals; on Fig. 15 the same type of threshold circuit is dedicated to a single polarity and normalizes the bunch oscillation using a wideband attenuator. We turn now to a qualitative review of these circuits outputs.

5. BEAM DETECTION RESOLUTION

It can be misleading to compare the figures quoted by the designers regarding the precision and the resolution of their measurement, since they all apply to different types of electrodes and vacuum chambers. The quantities of interest are not always clearly enunciated; they are (1) the overall signal-to-noise ratio, (2) the linearity of the detection, (3) the location of the electrode system electrical center, and (4) the alignment error associated with the installation of these electrodes in the machine.

Two trends in system organization have been noted: (1) systems that have a single detector alternately switched to the different electrodes by means of a multiplexer, or (2) systems with individual detectors for each electrode. Whereas the first solution allows the use of more expensive electronics, it suffers from the diseases of fast pulse multiplexers which have insertion loss variations as large as 0.1 percent. The second solution requires matching the various channels or controlling their detection efficiency to a fraction of a percent; however, this type of system permits single turn measurements.

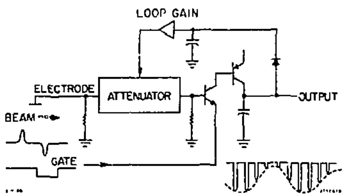

Fig. 15. A wide band, normalized bunch oscillation detector.

If one studies the references quoted so far, one can approximately state that beam pulses have been measured with wide band systems, perhaps to 0.5 %. This corresponds to a 0.25 mm for a vacuum chamber of 10 cm diameter, give or take a factor of $\sqrt{2}$ depending on the geometry. Resonant or sychronous systems have probably achieved an order of magnitude better in resolution. Yet a remaining problem is the determination of the absolute beam position. This calls for the calibration of each set of pick-up electrodes under conditions sufficiently analogous to the propagation of a bunched beam. Whether we like it or not, chances are that calibration of the next generation of position monitors will have to be made with a fair degree of accuracy; our last topic is going to make this point clear.

6. POSITION DETECTORS FOR A SINGLE PASS COLLIDER

Instrumentation problems on linear accelerators or single-pass colliders[37] are dominated by the precise monitoring of the beams trajectory. The parameter of interest, for this monitoring, are the following:

Bunch charge during initial orbit correction:		5×10^9 particles
Bunch length:		4 to 10 pSec.
Vacuum chamber diameter:	Linac	20 mm
	Collider	8 mm
Absolute beam position requirement:	Linac	± 0.05 mm
	Collider	± 0.10 mm
Total number of monitoring stations:		600 minimum

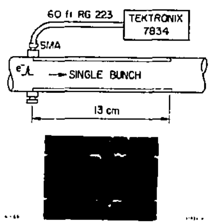

Fig. 16. Single Bunch response of a strip line on the Stanford Linac. Upper trace, proper steering; lower trace beam scraping. Horizontal sensitivity 1 ns/small div. Vertical sensitivity 100 mV/small div. Approximate charge: 10^9 electrons.

We first set out to look at the response of a set of electrodes to a single accelerator bunch.[38] Since we do not intend to have a detector operating at very high frequencies, the use of an ordinary coaxial cable (RG 223, 60 feet, rise time to 50% point: 0.45 ns) and an oscilloscope with 400 MHz bandwidth is acceptable. The geometry of the electrode system is indicated on Fig. 16 along with the waveforms obtained at one upstream port: the upper trace corresponds to a normal beam steering, the lower trace shows what happens when the beam is scraping the strip. For a reliable digitization of these pulses, more integration is necessary; then it becomes apparent that if the second impulse could be suppressed, a much larger signal would result. A possible solution consists in attenuating the backward pulse by loading the strip line with a lossy material, (Fig. 17).

Also of interest is the effect of RF coupling to the position monitor. A strip with a length of

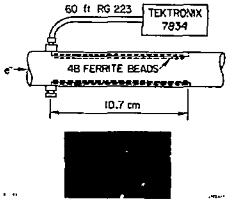

Fig. 17. Same test as Fig. 16, but with a lossy strip.

10.7 cm (free space wavelength at F = 2856 MHz) was also tested in the proximity of one of the accelerator output couplers; the peak induced RF pulse was about 26 dB below the bunch induced pulse. On the collider arms, space does not allow the use of traveling wave couplers; however, we believe that a similar response can be obtained with a ferrite loaded gap. Wall current monitors have been in favor on the SPS[39] and at KEK[40] among others, because of their ease of construction. Beam tests have not yet been conducted with ultra-short bunches, but Fig. 18 shows a bench experiment carried with a 100 psec pulse length. Whereas this signal formation seems well in hand, one problem remains: how does one calibrate such a structure and determine the electrical center to a tenth of a millimeter or less? It seems doubtful that we can rely on mechanical tolerances; perhaps the monitor could be calibrated by making it part of a precision cathode ray tube?

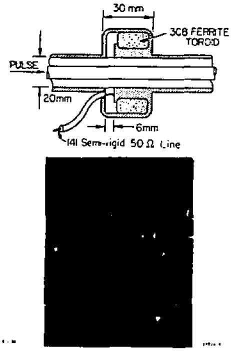

Fig. 18. A possible position monitor for short bunches. Top trace: the test pulse, 200 mV/div. Second trace: response with ferrite, 50 mV/div. Note that the pulse integral is non-zero. Bottom trace: response without ferrite, 50 mV/div. Note that the pulse integral is zero. All photographs 100 ps/div.

The electronics associated with these detectors has a lot in common with the proposed circuits for $\bar{p}$ in the ISR.[41] The salient features include (Fig. 19):

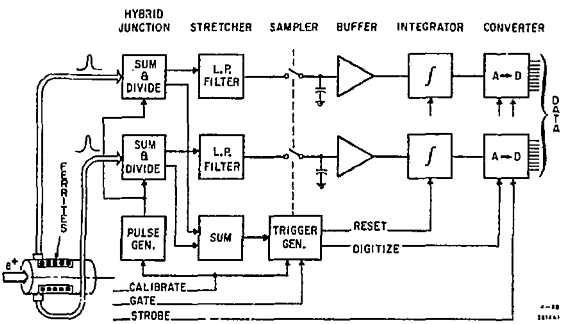

Fig. 19. Proposed processing electronics for the collider position monitors; two channels only are shown.

(1) individual, on-the-spot digitization of each electrode signal; (2) self-triggering using the sum signal as a decision maker; (3) passive stretching with no, or minimum, gain; (4) digital multiplexing; (5) channel calibration with the injection of a standard pulse. Our goal is to digitize these pulses on a shot-to-shot basis, with a reproducibility of 0.5% of full scale and for a pilot beam of 5×10^9 particles. For monitoring the nominal colliding beams, some way of range changing will have to be found.

7. CONCLUSION

This review has attempted to show a progression and a continuity in the art of beam monitoring. If the principles have certainly not changed, fortunately the techniques have evolved; let us hope that they will meet the increasing need for finer and faster measurements.

The contributors to this presentation cannot all be acknowledged. While those who have been mentioned here did work of prime importance, there is little doubt that others who have not been mentioned made equal contributions. I wish to thank more particularly those of my colleagues who, upon my request, accepted to research, describe, explain and write about their work.

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