REAL TIME FOURIER ANALYSIS FOR THE OBSERVATIONS OF FAST $e^+ e^-$ INSTABILITIES IN THE CERN SPS

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Abstract

An instrument to acquire data on fast longitudinal and transverse bunch motion is presented. The instrument acts as a real time Fourier analyser acquiring information at the revolution frequency. Subsequent data treatment allows portrayal in frequency or time domain.

Introduction.

A recurrent problem in accelerators is the observation of fast growing instabilities with e- folding times of several machine turns. These turbulent instabilities, transverse or longitudinal, occur on the short, intense, bunches circulating in the machine. The wide bandwidth given by the short bunches requires very high sampling rates and the fast growth rates imply fast data rates.

Fast data acquisition systems or digital oscilloscopes with sampling rates of many Giga samples per second have restricted triggering speeds and are usually limited in data storage capability thus limiting the length of the phenomenon that can be recorded. The instrument described here treats the problem differently by measuring and acquiring directly in the frequency domain. The Fourier components, at multiples of the RF frequency, of the longitudinal and transverse signals obtained from the beam monitor are digitised and stored. A measurement is made at each turn of the bunch in the machine and the acquired data is stored in real time in a buffer memory and subsequently transferred to a small computer for permanent storage and treatment. As the data is taken directly from the frequency domain, corrections for the monitor response and transmission distortion can easily be introduced. The corrected signals can then be displayed in the frequency domain as acquired or a time domain picture can be reconstructed by inverse Fourier transform techniques and the instability portrayed as a mountain range.

Design principles.

A single bunch of length t_0 is rotating in the accelerator with a revolution frequency, F_{rev}. The RF frequency, F_{rf}, h times the revolution frequency where h is the harmonic number, defines the bucket length and hence the maximum bunch length. The signal produced by this bunch in a longitudinal beam monitor can be observed on a spectrum analyser. The repetition of the bunch at the revolution frequency produces a line spectrum with lines at the revolution frequency multiples, the envelope of these lines being determined by the bunch profile. If all buckets in the machine are imagined to contain a similar bunch then the line spectrum would comprise lines at multiples of the RF frequency only, even though no information about the bunch of interest has been removed. The conclusion is that the single bunch shape can be defined by measuring the complex amplitudes at multiples of the RF frequency only. The lines present at all other frequencies in the real spectrum as seen on the analyser give information about what is happening between two bunch passages, i.e that the signal is zero during this time.

The instrument will be used to measure intra bunch oscillations, i.e. higher modes, and consequently the frequency bandwidth will be a multiple of the inverse bunch length. The number of channels, M, required will thus be:

$$M = K/(t_0.F_{rf})$$

where K is the mode number.

For the SPS in Lepton mode,F_{rf} = 200 MHz, and t_0 is typically 1 ns, Hence M=10 for mode 2. It is clear that the fundamental frequency could in principle be the inverse bunch length in which case the number of channels would be only 2. However the maximum possible bunch length is defined by the RF frequency and hence this is the basic frequency. To define the bunch shape 20 numbers must be acquired each revolution period, i.e. every 23 μs, since each channel produces information about the amplitude and the phase, (i.e. the real and imaginary parts), of the frequency component. The monitor to be used gives information about the transverse planes as well as the longitudinal plane; the number of data points per revolution increases by 3 times to 60.

Each acquired number is defined by N bits and the maximum mean data rate will be given by:

data rate = 3.2. M.N. F_{rev} bits/s.
for N=8 and K=2, this gives 20.8 Mbits/s.

Instability growth rates vary from microseconds, in which case data taking must be at the maximum rate, to much slower times when data can be taken at sub multiples of the revolution frequency. For a good representation of the instability growth and bearing in mind that it is not possible usually to predict the start time of the instability, the acquisition of 1000 separate bunch measurements is reasonable. This implies a total memory size per acquisition of at least 60 Kbyte.

Description of the Instrument

The instrument can be divided into three parts, the monitor and associated hybrids, the RF converter, and the digitiser/computer [1]

The monitor and hybrids, fig. 1

A directional coupler monitor with four striplines at 45 degrees to the horizontal, symmetrically placed around the beam is used. The individual couplers are exponentially tapered to improve the frequency response. The low and high frequency 3 dB cut-offs of the couplers measured separately are 100 MHz and 4Ghz, the pass-band ripple is +-2db and the beam-coupling impedance is 2.1. ohm per coupler.

The four output signals, each a pulse with amplitude proportional to the line density and also a function of the beam position, are added using 5 sum and difference hybrids and 2 delay cables as shown. The sum signal proportional to the line density and the two difference signals giving the position of each beam sample along two perpendicular axes are combined onto a single output cable in time division multiplex, the pulses being separated in time by 72 ns. This allows a single long high quality cable to carry the information between the monitor and the observation point on the surface, (200 m) and prepares the signals in a suitable form for the remaining parts of the instrument. The production of the difference signal before acquisition allows improved resolution for a fixed number of bits.

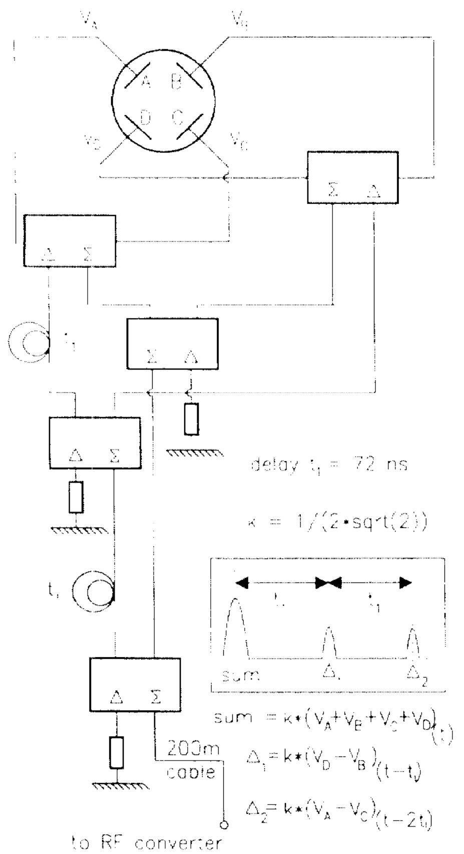

Fig. 1 Monitor and Hybrids

The RF converter, fig. 2

At the surface the signals enter the RF converter board. The sum signal is typically 20 dB higher than the difference signals. To improve the resolution of the digitised delta signals the sum signal is selectively attenuated by a fast gate triggered at the revolution frequency. The signal is divided into 11 parts, 10 of which are for the 5 lowest channels and 1 for the board which in the future will cover the next 5 channels. The extension to 10 channels, at present underway, increases the number of modes observable and also improves the reconstructed bunch profile. In effect the restriction to an exact frequency maximum due to the fixed number of channels creates a perfect rectangular filter, introducing ripple at the highest channel frequency. The division of the input signal is at present made with a wideband hybrid power divider. A more efficient method under development divides the signal in the frequency domain by means of a contiguous multiplexer this having the added advantage of improving the dynamic range at the input to the mixers.

The 10 signals are mixed synchronously with the RF frequency and its multiples to give the real part of each component and the same frequencies shifted by ninety degrees to give the imaginary parts. The intermediate frequency, IF, bandwidth is very much greater than the revolution frequency so that the signals at the IF output are still pulses of length sufficiently short that the longitudinal and transverse signals can be resolved. The amplitude of each pulse is proportional to the component in the original pulse at the frequency of the local oscillator, LO. These LO's, apart from the fundamental at the RF frequency, are generated by multiplication of the RF frequency using a varactor diode. The varactor diode forms the input coupling element of a comb-line filter tuned to n^*F_{rf}.

The remaining elements on the board are used for phase and amplitude adjustment.

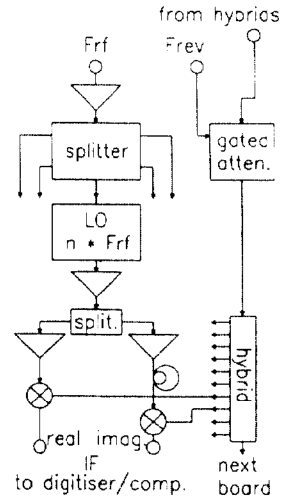

Fig. 2. RF Converter (one channel)

The Digitiser/Computer, fig 3

The ten separate outputs from the RF board each give three pulses at 72ns intervals the whole repeating at the revolution frequency. Each output is digitised by a fast 8 bit flash ADC, the converted output being stored in a local memory, (8kbyte), whose maximum speed determines the 72ns interval. The process is initiated in the write and read logic by a computer interrupt. Subsequent triggers at F_{rev} from an external beam synchronised pulse generator each produce three pulses separated by 72ns which start the conversion and clock the result. When all local memories are full a request from the digitiser to the computer initiates a DMA transfer. The data passes to the computer memory in bursts of 64kbytes at 250 kbytes/sec.

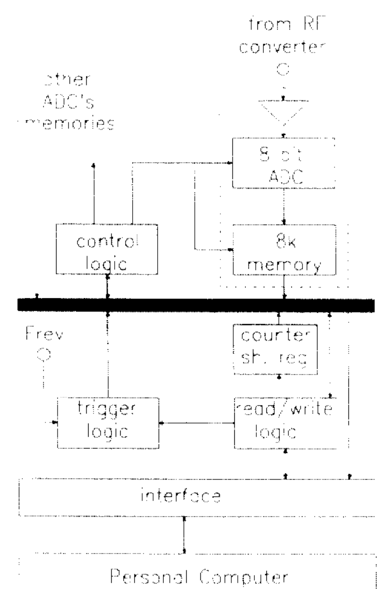

Fig. 3 Digitiser (one input)

Instrument Calibration.

The beam transfer function of the monitor is well known. This information is combined with the measured response, at each RF frequency harmonic, of the hybrid network and 200m cable to produce global correction factors. One set is obtained for each of the three different planes. These calibration factors are used in the data analysis.

The RF converter is set up using synchronised oscillators. Two synthesisers are locked to the same reference generator. One is set to give the RF frequency plus a small offset and the other a multiple of this frequency. These are added in a hybrid, the phases being equalised and the result applied to the input of the RF converter. At the IF outputs corresponding to the harmonics chosen a low-frequency sinusoid is produced. These IF signals allow the relative gain and the DC offset errors to be found and corrected from the amplitude and symmetry of the sinusoid and also allow the inter channel phasing and real/ imaginary phasing to be adjusted since the phase relationship at the input should be recovered at the output.

The ADC and associated amplifiers are adjusted using normal techniques.

Fine calibration, if necessary, can be done using the beam as a source. At high energy and low intensity the synchrotron radiation damping produces short Gaussian shaped bunches of known length which can be used to check and fine tune the instrument calibration.

Results.

Three examples of the output are given. In the frequency domain, fig 4, a small part of the acquired data is shown. The 200 MHz real and imaginary data for the sum and delta signals is given. The traces start just before injection, one point per machine turn being displayed. Quadrupole oscillations can be distinguished on the sum signals while the delta signals show the injection error oscillations at the betatron frequency. Figs 5 and 6. give a reconstruction in time domain of the longitudinal signal obtained using an inverse Fourier transform on the ten sum signals. Fig 5 shows the quadrupole oscillations at injection previously seen in fig 4. Fig 6. shows the whole cycle, injection to extraction.

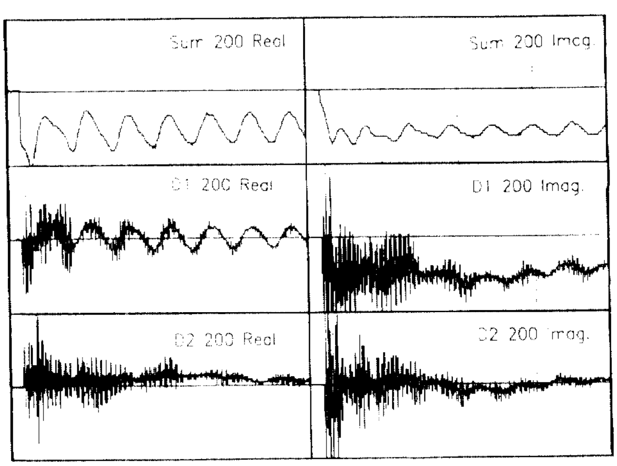

Fig. 4 Frequency Domain Representation

Dipole and quadrupole oscillations are apparent although the coarse display step, every 50 machine turns, tends to obscure them. At the beginning of the cycle a strong gradual loss causes a reduction in the pulse height which is reversed as the bunch shrinks in length and grows in amplitude during acceleration.

A very interesting display technique is to 'play' the mountain range as a moving picture on the computer, the various bunch shape or position oscillations being much more easily seen.

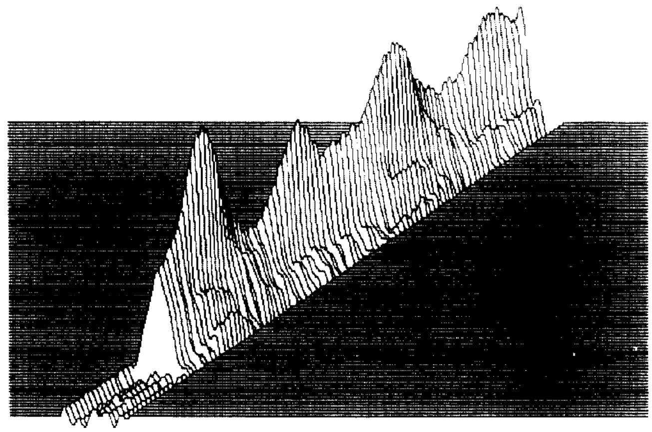

Fig. 5 Time Reconstruction, Injection

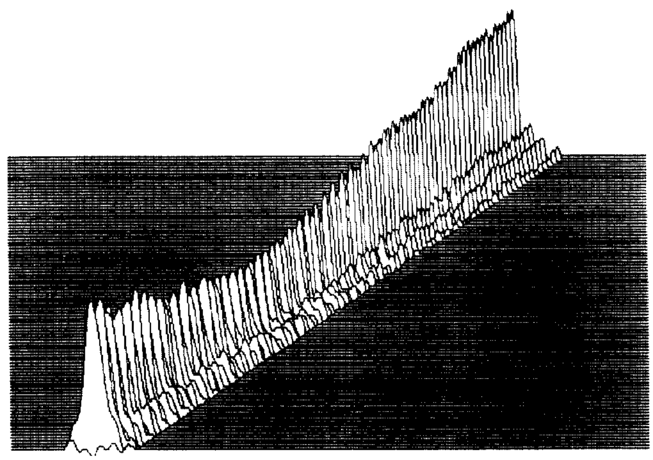

Fig. 6 Time Reconstruction, Cycle

Conclusions.

Even with only five channels in operation the instrument is powerful and provides a wealth of data. Although several sophisticated display routines have been developed it is clear that different ways of viewing the data are constantly suggesting themselves and work in this domain will continue.

The instrument itself is particularly interesting in that the techniques used allow expansion to higher frequencies without special difficulties. The calibration of the various elements at the different harmonics is straightforward and the beam pulse technique for calibration checking can always be used up to the maximum frequency in the beam.

References

[1] W.Wingerter, .Acquisition of spectrum components for observation in time. (A.S.C.O.T.) SL/RFS/NOTE 90-5