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MEASUREMENT OF THE CERN SLOW EJECTED BEAM TIME STRUCTURE

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ABSTRACT

The slow ejected beam time structure is measured to quantify its effect on physics experiments and to obtain information on the synchrotron behaviour. This paper provides an analytic basis for the measurements, describes the various equipment used and presents some results. A specially designed time interval measuring device, having no dead time, is used to analyse telescope pulse trains so as to give a measurement of the overall radio-frequency structure every synchrotron cycle. The pulse trains are also analysed using delayed coincidences. A flux monitoring scintillator is used to provide an analog signal proportional to the beam flux, permitting the time structure up to 50 MHz to be viewed directly. The low frequency structure is measured by computer sampling an analog burst signal at 10 kHz. The computer then calculates the effective spill time, the ripple duty factor and the frequency spectrum of the ripple.

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Introduction

This paper is concerned with the time structure of the slow ejected beam from the CERN proton synchrotron. The measurement techniques are described and typical results given. Both low and high frequency structures are discussed.

The slow spill is used in experiments which are often limited by problems of "accidental coincidences" and equipment dead time. To ease these limitations, much effort has been expended on lengthening the spill time. This effort may be largely negated, however, by a poor spill time structure. The commonly used[1,2,3] measure of this time structure is the 'effective spill time', denoted here as T_e, which is that time over which the ejected protons, if evenly spilled, would give the same number of accidental coincidences as the actual spill. T_e is less than the actual time T_s available for ejection, and the difference $T_s - T_e$ represents a loss of time which has been dearly bought in terms of ejection septum magnet design and synchrotron repetition rate.

The spill structure is discussed under two main headings: firstly the low frequency structure, comprised of the overall burst shape and the magnetically induced ripple due to power supplies; secondly the high frequency structure which modulates the low frequency structure and is due to the uneven distribution of particles round the synchrotron ring during ejection.

Low Frequency Structure

The low frequency structure is observed by filtering the output of a high counting rate glass Čerenkov counter placed near a beam interaction point, or from the current output of secondary emitting foils. This burst waveform is then sampled at 10 kHz by the on-line IBM 1800 and various calculations and displays made.

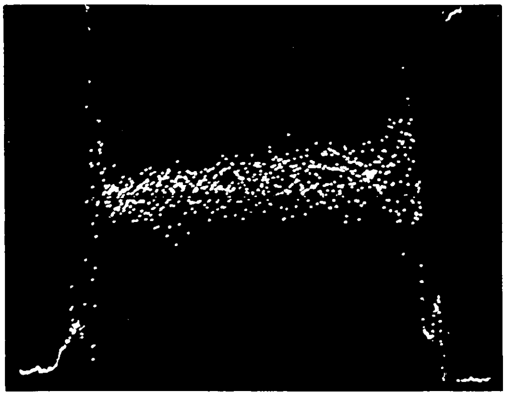

Fig.1 Reconstructed burst

Fig.1 is a reconstruction of the sampled burst to check the timing and gain of the sampler. 5120 samples are taken so that the display covers 512 ms. As the display is made on a 1024 x 1024 matrix, 5 samples are averaged for one point on the display. This greatly reduces the amplitude of the magnetically induced ripple so a further display of the central 1024 sample points is made, as shown in Fig.2.

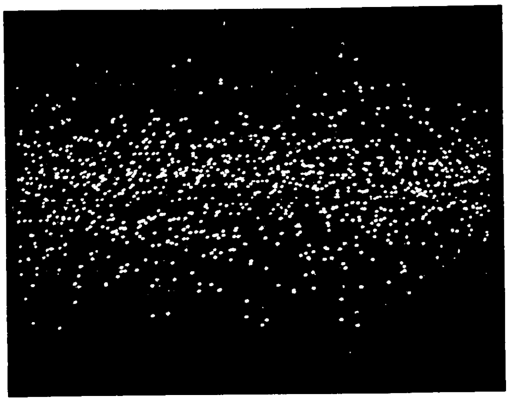

Fig.2 Central 1024 samples

Fig.3 shows the results of the computer calculations.

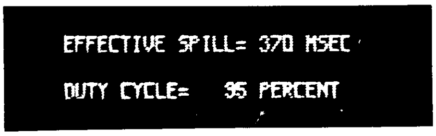

Fig.3 Computer results

The effective spill time is calculated from the formula[1]

$$T_{elf} = \frac{\left[\int_o^{T_s} l(t)\, dt\right]^2}{\int_o^{T} l^2(t)\, dt} \qquad (1)$$

where $l(t)$ is the low frequency burst waveform existing in the interval $0 \leq t \leq T_s$. The magnetically induced ripple duty cycle is obtained by calculating the effective spill time of the central 1024 samples, then dividing by the actual time of 102.4 ms.

Throughout 1970 effective spill times of 350-400 ms have been normal, being only a few tens of milliseconds shorter than the available time limit set by septa heating. The low frequency ripple duty cycle can be maintained at 95% by careful choice and adjustment of magnet supplies, though at times it has been below 80%. The frequency spectrum of this ripple has proved a useful tool for tracking down causes of the ripple and for checking the performance of the servo-spill loop. The spectrum is calculated by the computer using Fast Fourier transform analysis[4] of the central 1024 samples. The result is shown in figure 4, where the scale is in kHz. It is seen that the bulk of the remaining ripple lies in the range 1 - 3.2 kHz, the lower frequencies having been attenuated by the servo-spill system.

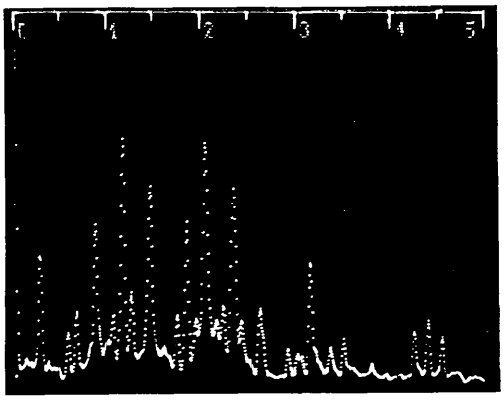

Fig.4 Burst spectrum (kHz)

High Frequency Structure

This structure consists of components at the revolution frequency and its harmonics. Two different approaches to the measurement have been made. Firstly a high bandwidth monitor giving a voltage proportional to the proton flux has been developed. Secondly the structure is extracted from the statistics of a train of pulses from a two or three scintillator telescope looking at a target in the ejected beam. The high bandwidth monitor has given good results in experimental situations, but for normal operation the structure is continuously displayed by a specially designed time interval analyser working on the telescope pulse train. Delayed coincidence measurements are also used.

High Bandwidth Monitor

This monitor was realized using a scintillator and photo-multiplier. Two configurations of scintillator have been used[5]: firstly a thin radiation resistant scintillator (e.g. 1 mm sapphire plate) placed directly in the ejected beam; secondly a scintillator collecting secondaries from a vacuum chamber window with a large solid angle. A low noise signal of about 50 MHz bandwidth was achieved. This required careful dimensioning of the scintillator - photo-multiplier system so that the scintillation rate was at least one per nano-second, and so that the photo-cathode flux was about one photo electron per nano-second. Care was also taken with the photo-cathode and the voltage divider, to avoid saturation at these high fluxes.

Time Interval Analyser

This instrument calculates and displays the time interval histogram of the telescope pulse train. It works by counting a 100 MHz clock between pulses to get the time interval, then incrementing the store corresponding to the count. The stores are made up of capacitors incremented by a well defined current pulse. Time intervals in the range 160 to 2560 ns are measured and recorded. The instrument has two special features for this application: the first is that a triple 'front-end' is used so that every time interval in the range is recorded, thus greatly speeding up the measurement; the second is that resistors can be connected across the storage capacitors so that the display gives a continuous running average of the structure. The time constant of the display is between two and three synchrotron cycles so that each cycle makes a considerable contribution to the display. The clock frequency can be varied, up to 300 mHz, for special purposes.

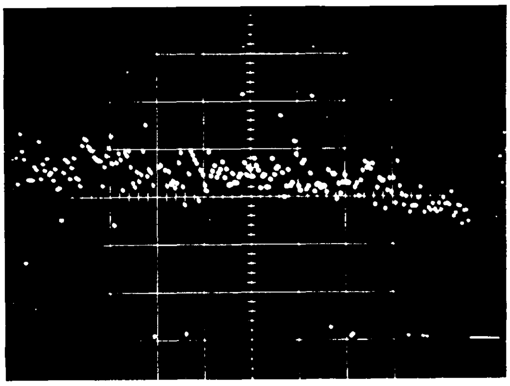

Fig.5 Time interval histogram, little structure

Figure 5 shows a typical display with the synchrotron operating well. There are 240 points covering the range 160-2560 ns. This display indicates virtually no RF structure as much of the scatter, especially the far out points, is due to the electronics, the current instrument being a prototype. There is also some statistical scatter due to the number, about 150, of intervals represented by each ordinate. Figure 6 shows the display when there is rebunching of the circulating beam during ejection. This shows the beam rebunched into 5

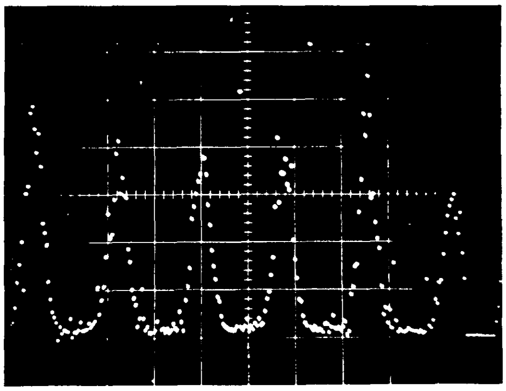

Fig.6 With 5 bunch rebunching

bunches. Rebunching has given much trouble in the past but has been cured, at least for current longitudinal phase-space densities, by 'stagger-tuning' the RF cavities during ejection. Figure 7 shows, on an expanded time scale, the structure at the beginning of the burst when the debunching is badly adjusted.

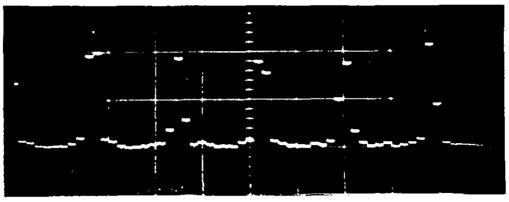

Fig.7 Expanded view of 105 ns structure

The significance of the display is calculated as follows. The spill rate is so high, of the order of 5000 protons per nano-second, that for practical purposes the spill can be considered the analogue signal $m(t)$ protons/second existing in the interval $0 \le t \le T_s$.

The production of a telescope count is proportional to m(t) so that the total number of counts is

$$N = k \int_{o}^{T_s} m(t)\, dt \tag{2}$$

where k m(t) is the probability of a count in the time interval dt at time t. The probability of observing the time interval τ is the joint probability of a count in the time dt, no count between t and $t+\tau$ and at least one count between $t+\tau$ and $t+\tau+L$, which gives

$$df = k\, m(t)dt\, \exp\left[-\int_{t}^{t+\tau} k\, m(t)\, dt\right]\left(1-\exp\left[-\int_{t+\tau}^{t+\tau+L} k\, m(t)\, dt\right]\right) \tag{3}$$

Assuming the resolution time short compared with variations in m(t) and $kL\, m(t) \ll 1$, eq.(3) becomes

$$df = k^2 L\, m(t)\, m(t+\tau)\, dt\, e^{-k \hat{m} \tau} \tag{4}$$

where

$$\hat{m} = \frac{1}{\tau} \int_{t}^{t+\tau} m(t)\, dt \tag{5}$$

In circumstances of low structure $\hat{m}$ is closely equal to the average flux $\overline{m}$ so that the time interval distribution $f(\tau)$ is

$$f(\tau) = k^2 L\, e^{-k \overline{m} \tau} \int_{o}^{T_s} m(t)\, m(t+\tau) dt \tag{6}$$

Equation (6) shows that the display $f(\tau)$ is proportional to the auto-correlation function $A(\tau)$ of the burst, defined as

$$A(\tau) = \int_{o}^{T_s} m(t)\, m(t+\tau) dt \tag{7}$$

multiplied by the decaying exponential of time constant $k\,\overline{m}$ which is the average counting rate of the telescope. Figure 8 shows bursts similar to those of Fig.5 but analysed with the clock frequency reduced to 4.3 MHz, i.e. a resolution of 233 ns and a full scale of 56 μs. The exponential has a time constant of approximately 10 μs which corresponds with the observed average counting rate of 100 kHz, from about 40,000 counts per burst of 400 ms.

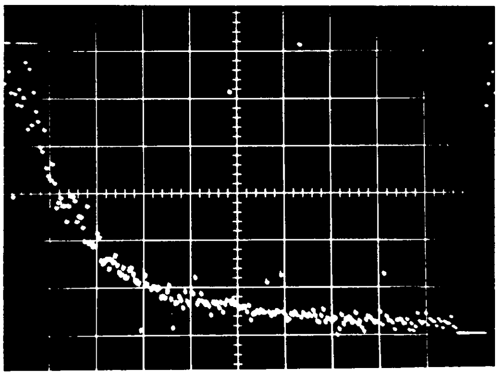

Fig.8 Display with longer time scale

The effect of the bunch structure in the synchrotron is to modulate the low frequency burst shape l(t), discussed previously, with the bunch structure r(t) so that

$$m(t) = l(t)\, .\, r(t) \tag{8}$$

where r(t) is quasi-periodic at the revolution frequency, i.e. period T = 2.1 μsec. It can be shown[1] that the overall effective spill time T_e is given by

$$T_e = T_{elf}\, .\, Dr \tag{9}$$

where T_{elf} is the low frequency effective spill time calculated above and D_r is the RF duty cycle

$$Dr = \frac{\left[\int_{o}^{T} r(t)\, dt\right]^2}{T \int_{o}^{T} r^2(t)\, dt} = \frac{\frac{1}{T}\int_{o}^{T} A(\tau)\, d\tau}{A(o)} \tag{10}$$

Equations (10) and (6) shows that the duty cycle can be calculated from the displayed time interval histogram as the average value over the first 2.1 μs divided by the peak value A(o). In the actual display A(o) is not given but since $A(\tau)$ is approximately periodic and if the exponential effect is small A(2.1 μs) can be used instead of A(o). Figures 6 and 7 show that the duty cycle can be very small under abnormal conditions.

Delayed coincidences

Another method of obtaining the auto-correlation function of the structure is by using delay coincidences. The telescope train is put into a coincidence unit of resolution L together with the train delayed by time τ and the number of coincidences N_c gives the normalized auto-correlation function $A(\tau)/A(o)$ as

$$\frac{A(\tau)}{A(o)} = \frac{N_c}{N^2} \cdot \frac{T_e}{L}$$

The auto-correlation function can thus be obtained by scanning the delay τ assuming that T_e is constant. At CERN several fixed sets of delays and coincidences are used[6] so that important points on $A(\tau)$ can be monitored by the computer every machine pulse.

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