EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

European Laboratory for Particle Physics

CERN - SL DIVISION

CERN SL/94-28 (BI)

SW 9431

REAL TIME MONITORING OF LEP BEAM CURRENTS AND LIFETIMES

A.J. Burns, B. Halvarsson, D. Mathieson, I. Milstead, L. Vos

Abstract

The data acquisition system of the LEP beam current transformers has been upgraded to provide faster monitoring of the beam currents and associated lifetimes. Two identical systems monitor separately the intensities of the 8 bunches in each beam. A simple algorithm calculates the intensity lifetime of each bunch over a variable sampling interval (between 4 s and 2 min.) that optimises the conflicting requirements of precision and fast response to changes in the lifetime. To provide instantaneous and reliable monitoring of the bunch currents and lifetimes to the machine operators, a real-time video display is generated by each data acquisition system and transmitted to TV screens in the control room. On this display, numerical values of the individual bunch currents and lifetimes and a graphical display of the recent evolution of each beam lifetime are updated at 2 Hz. At times when the accelerator is filling, the evolution of the intensity of any bunch in the seconds, milliseconds, or even individual turns following each injection replaces the lifetime history plot. The paper also includes data on the relative precision of the bunch current measurements obtained in real operating conditions and the resulting limits on the lifetime measurements that can be provided.

Paper presented at the Fourth European Particle Accelerator Conference (EPAC'94), London, United Kingdom, 27.6.-1.7.1994

Geneva, Switzerland
27th June 1994

Real Time Monitoring of LEP Beam Currents and Lifetimes

A.J. Burns, B. Halvarsson, D.Mathieson, I.Milstead, L.Vos
CERN, SL Division, CH-1211 Geneva 23

Abstract

The data acquisition system of the LEP beam current transformers has been upgraded to provide faster monitoring of the beam currents and associated lifetimes. Two identical systems monitor separately the intensities of the 8 bunches in each beam. A simple algorithm calculates the intensity lifetime of each bunch over a variable sampling interval (between 4 s and 2 min.) that optimises the conflicting requirements of precision and fast response to changes in the lifetime. To provide instantaneous and reliable monitoring of the bunch currents and lifetimes to the machine operators, a real-time video display is generated by each data acquisition system and transmitted to TV screens in the control room. On this display, numerical values of the individual bunch currents and lifetimes and a graphical display of the recent evolution of each beam lifetime are updated at 2 Hz. At times when the accelerator is filling, the evolution of the intensity of any bunch in the seconds, milliseconds, or even individual turns following each injection replaces the lifetime history plot. The paper also includes data on the relative precision of the bunch current measurements obtained in real operating conditions and the resulting limits on the lifetime measurements that can be provided.

1. INTRODUCTION

The purpose of the present paper is to describe the improved data processing performed on the LEP beam current measurements and to analyse the quality of these measurements. The hardware of the Beam Current Transformers is a upgraded version of the system described in 2 EPAC 90 papers [1,2]. Although the new system has been running since the introduction of the 8x8 bunch pretzel scheme in autumn 1992, the injection monitoring and the optimised lifetime processing described here have only been operational since the beginning of the 1994 LEP run.

2. UPGRADED BCT ACQUISITION SYSTEM

2.1 Overview

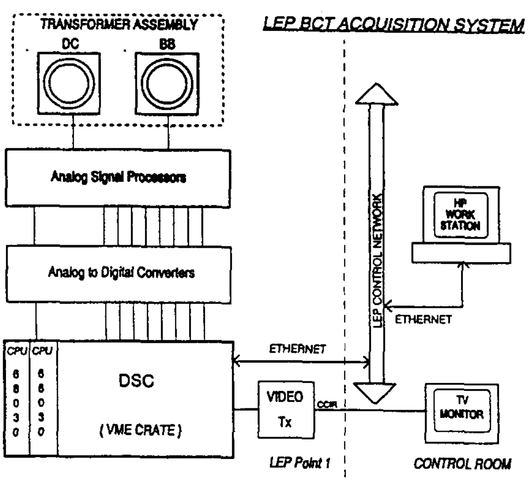

Fig. 1 : BCT acquisition system

Fig. 1 illustrates schematically the BCT acquisition system. Two such systems are used, one attached to the BCT158 for measuring e^- bunches, the other to the BCT142 for measuring e^+ bunches and the DC current. The VME acquisition cards that buffer digitisations from successive passages bunch have been modified to permit interleaved reading (by the "acquisition" CPU) and writing (from the ADCs), thus allowing the continuous acquisition of all bunch passages. The original 68010-based VME card running the RMS-68K operating system has been replaced with two 68030-based VME cards running OS-9. Additional hardware includes a video card for generating a real time display for the LEP control room and a special acquisition channel to record a timing synchronisation pulse required for the new injection monitoring facility. Communication with the control system is now via TCP-IP over Ethernet and Token Ring.

A periodic 0.5 s interrupt on the acquisition CPU triggers the readout of the last 0.5 s of turns from each ADC memory buffer. The raw data is stored in a 5 s circular buffer in the acquisition card memory that is available on request via the control system, and is also used for injection monitoring. Calibrated current averages are generated from the 5622 turns recorded for each channel and written via the VMEbus into the memory of the "master" CPU card. Finally the waiting lifetime calculation process on the master is awoken via a message sent on a RS-232 link between the 2 cards. Once the lifetime process has completed evaluating the intensity lifetimes of all bunches, it notifies the other waiting processes via an OS-9 event. The video process then updates the control room video display and a communication process sends the new current and lifetime data to a control room workstation for storage in a database and subsequent display. This sequence of processes means that, in the worst case, the data appearing on the video is 1 s old. In the original system, the processed data displayed in the control room was 5-10 s old.

2.2 Video display

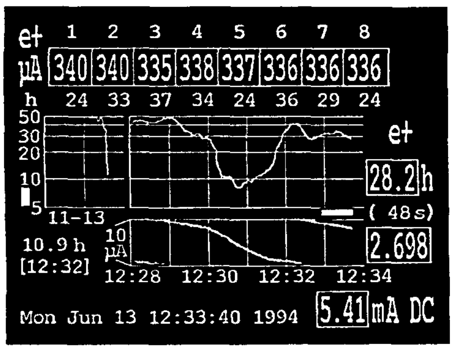

Fig. 2 : BCT video display

The colour video display (Fig. 2) has been designed to include all the intensity information from one beam needed by the operators to run LEP. At the top, the values of all 8 bunch currents (μA) and lifetimes (h) are shown. On the right hand side are the single beam lifetime (h), the interval currently used to calculate it (s), the single beam current (mA) and the DC current monitor reading (mA). In the centre are plots of the single beam lifetime on a logarithmic scale between 5 and 50 hours (or between 0.5 and 5 h), and a 10 µA zoom of the single beam current, both during the previous 2-6 min.

All data and graphs are updated at 2 Hz, except for the small plot on the left which shows the evolution during the previous 1-2 hours of measurements of the single beam lifetime made with a fixed 128 s interval and to which a data point is added every 2 min. This plot is useful for detecting slow lifetime trends during stable conditions.

2.3 Injection monitoring

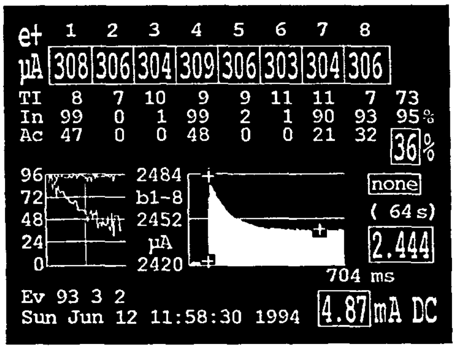

Fig. 3 : BCT video display during injection

During the injection and accumulation process, the video display changes automatically to that shown in Fig. 3. The beam currents are still updated at 2 Hz; but otherwise there is one refresh in the 2-3 s following each injection into LEP (normally every 14.4 s). Three lines of data are displayed : *TI*, the intensity (10^9 particles) measured by directional couplers at the end of each injection line; *In*, the percentage of this intensity measured as an increase in the circulating beam current about 20 turns after injection ; and *Ac*, similar to *In*, but measured about 500 ms after injection. In normal conditions, the values *Ac* then give the percentages of the injected bunch intensities accumulated in LEP.

The left hand plot shows the evolution during the last 30-60 injection cycles of the averages of *In* and *Ac* for the bunches actually injected. The other plot shows the detailed behaviour of the beam current around injection and an operator console program allows the selection of the bunch (or sum of 8 bunches) and time interval (< 5 s) to display.

This display has recently assisted in improving the accumulation efficiency from below 10% at the end of filling to the 40% seen on Fig. 3, by adjusting the trajectory of the injected beam.

3. LIFETIME CALCULATION ALGORITHM

The intensity lifetime τ is defined as that characterising an exponentially decaying beam current, $I = I_0 e^{-\tau/t}$. For sampling times $\Delta t \ll \tau$, a good estimate of τ is given by $\tau = I\Delta t/\Delta I$, where ΔI is the current change over interval Δt. To obtain the best precision, all the current values in 2 consecutive Δt intervals are averaged to calculate ΔI. There is inevitably a time lag in the response of the lifetime measurement and one should aim to use the shortest interval Δt possible, consistent with a certain level of precision on the result. The relative error on the calculated lifetime is given by $\sigma_\tau/\tau = \tau\sigma_{\Delta I}/(I\Delta t)$. Assuming random statistical errors on the 0.5 s averages (with rms value σ_I), one obtains $\sigma_{\Delta I} = \sigma_I/\Delta t^{0.5}$, where Δt is in seconds. In fact, as is discussed in section 4, the noise on the current measurements has large low frequency components, which reduces the value of the power of Δt to 0.3-0.4. Hence one obtains :

$$\sigma_\tau/\tau \sim \tau\sigma_I/(I\Delta t^{1.35}) \qquad (1)$$

For any given σ_I/I, it would be possible to use formula (1) to calculate the interval Δt corresponding to any required precision on lifetime τ. However, it is likely that the continuous variation of sampling interval would be unstable in conditions of varying lifetime. The scheme adopted instead consists of a fixed series of intervals that, for given σ_I/I, cover an overlapping set of lifetime bands. The bands are centred at the lifetime giving the required σ_τ/τ and the overlap ensures that there is no oscillation in interval selection when the lifetime is close to the edge of a band. The next higher interval is chosen when the lifetime moves above the high end of the band and the next lower interval is chosen when the lifetime falls below the low end of the band. Current sums associated with the 2 Δt intervals for each of a series of 11 intervals (2, 3, 4, 6, 8, 12, 16, 24, 32, 48, 64, 96, & 128 s) for each bunch and the bunch total are updated at 2 Hz, allowing to switch instantly from one interval to another.

When the lifetime falls, the interval is allowed to drop from one interval to the next at every acquisition (i.e. at 2 Hz). This produces a fast response to drops in lifetime. However, when the lifetime rises, a special procedure smoothly increases the interval to the next highest one at the same rate as the acquisition proceeds. This is necessary to ensure that the sampling interval is never extended backwards in time. This would result in data corresponding to lower lifetime being included and generate rapid oscillations in the interval selected and calculated lifetime. The behaviour of the lifetime algorithm is illustrated in Fig. 4 below. The dotted line on the lifetime part of the figure indicates the result that would be obtained if a fixed interval of 32 s were always used.

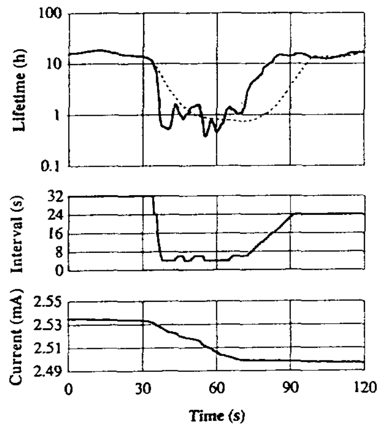

Fig. 4 : Example of application of lifetime algorithm

4. MEASUREMENT PRECISION

4.1 Noise on current values

Fig. 5 shows the variation of rms noise on individual bunch measurements, as a function of the number of consecutive beam turns averaged to produce each data point. The final points of the curves are close to the 5622 turn averages used for the lifetime measurements. The $1/\sqrt{N}$ behaviour of random statistical noise is evident on the lowest curve obtained by grounding the input of an ADC. The degree of flatness of the other curves is linked to the extent that low frequencies dominate in the noise spectra.

The top curve was measured when the Beam Synchronous Timing (BST) turn-clock was still being used to generate the acquisition gates. The use of a more stable RF-based turn-clock from 1992 reduced the noise by a factor of 3. The other 2 curves represent the average of all bunch channels for a each BCT, for an average bunch current of 250 μA, and replace the much lower BB noise curve previously published [2]. The BCT158 is seen to have twice as much noise as the BCT142 on averages from more than 2000 turns and a higher proportion of low frequencies in its noise spectrum; but as this problem is still under study, further analysis is limited to the BCT142 used for the e^+ beam.

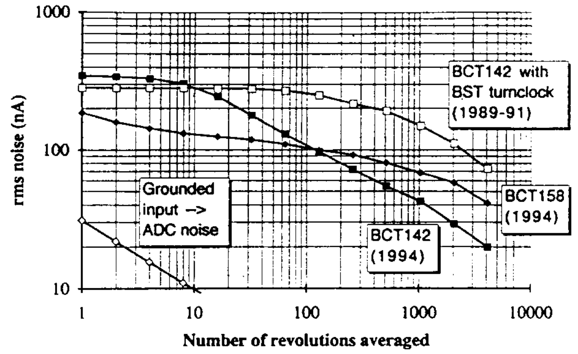

Fig. 5 : Rms noise levels as a function of the number of revolutions averaged.

The data presented in Fig. 5 are based on data samples consisting of every beam passage during 5 s. To include the effect of the sub-Hertz frequencies in the noise spectrum, constant lifetime fits were made to the 0.5 s current averages over periods of about 10 minutes when the lifetime seemed stable. The resulting standard deviation of the data about the fit included any small low frequency oscillations. That such oscillations are instrumental and not beam related had been previously verified during a run with 4 e^+ and 4 e^- bunches in which both BCTs were monitoring all 8 bunches. It was observed that there was a correlation between the slow current fluctuations seen on all bunches measured on the same BCT, but no correlation between the fluctuations observed on the same beam observed on different BCTs

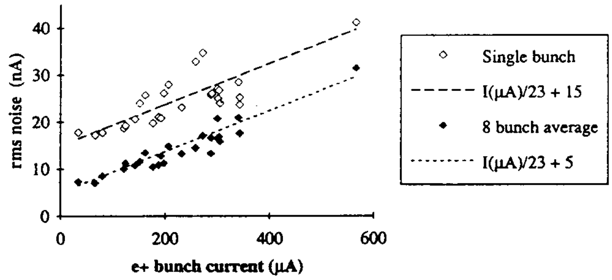

Fig. 6 : Rms noise on the 0.5 s averages as a function of e^+ bunch current

Fig. 6 shows the rms noise values resulting from the above fits as a function of bunch current for the BCT142. Plotted separately are the average of the noise values obtained from each of the 8 bunch channels and the resulting noise on the average of the 8 bunches There are two different components in the observed noise. One is random uncorrelated noise on the different electronic channels used to measure the individual bunches. This noise scales as $1/\sqrt{N}$ when the data from N channels are summed, and it dominates at low beam current (< 100 μA per bunch). The other component is highly correlated between the different channels and increases with beam current. It therefore dominates at higher beam currents. The correlated nature of this noise means that it is little reduced when the bunch channels are summed. One may identify this noise component with the "phase noise" that is generated by jitter on the integration gate and which is directly proportional to the integrated intensity [3].

The following formulae describe the observed total noise, for individual bunch channels :

$$\sigma_I \text{ (nA)} = I(\mu A)/23 + 15 \qquad (2)$$

and for the 8 bunch average :

$$\sigma_I \text{ (nA)} = I(\mu A)/23 + 5 \qquad (3)$$

For a typical beam of 8 e^+ bunches of 250 μA, σ_I is therefore about 16 nA and σ_I/I is 63 10^{-6}.

4.2 Effect on calculated lifetime

As explained in section 3, the relative error on the lifetime is kept near a fixed value by changing the sampling interval. This value of σ_τ/τ is, however, a parameter of the acquisiton system for each BCT, and may be changed for special beam conditions. The formulae (2) and (3) given above for σ_I (for e^+ only) are used to adjust in real time the lifetime bands within which each interval is selected, as the beam current changes. The result is that the higher σ_I/I at lower current is compensated by a longer interval (via formula (1)). As an illustration, Fig. 7 shows the lifetime bands used for an e^+ beam of 8 bunches to ensure σ_τ/τ = 10±4%, for 3 different average bunch currents. The bands are labelled with the total sampling interval ($2\Delta t$, in notation of section 3) in seconds. When the lifetime is in the overlap zone between 2 intervals, the interval chosen depends on whether the lifetime is increasing or decreasing.

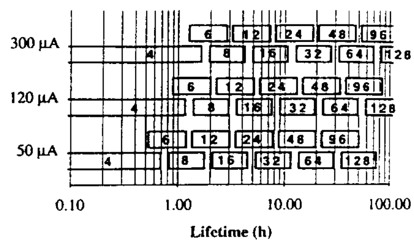

Fig. 7 : Sampling intervals versus lifetime and average bunch current for e^+ beam

5. CONCLUSIONS

The LEP BCT digital processing described in this paper now extracts the best that can be obtained from the analogue current transformer data, by acquiring all bunch passages and by adapting in real time the lifetime calculation interval to maintain the error on the lifetime within a limited range. Although the system is not able to resolve beam intensity changes of a few parts in a million in a short time interval [1], its performance has significantly improved since 1990 and is adequate for normal operation of LEP. Better performance can only come from reductions in signal noise resulting from improvements in the analogue processing, where a factor of 2 gain should be within reach [3].

6. REFERENCES

[1] K.B. Unser, "Measuring bunch intensity, beam loss and bunch lifetime in LEP", Proceedings of the 2nd European Particle Accelerator Conference, Nice, France, June 1990, pp. 786-788.

[2] G. Burtin et al., "Mechanical design, signal processing and operator interface of the LEP beam current transformers", Proceedings of the 2nd European Particle Accelerator Conference, Nice, France, June 1990, pp. 794-796.

[3] L.Vos, "The LEP monitor for the measurement of bunch intensity", CERN SL/94-18 (BI), May 1994.