SINGLE SHOT BUNCH LENGTH MEASUREMENT AT LEP BY STOCHASTIC SAMPLING OF SYNCHROTRON LIGHT PHOTONS

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Abstract Synchrotron light extracted from LEP is fed into a system of photon storage rings made of monomode fibres linked by optical couplers. The system acts as a single photon generator producing a periodic function (period of 12 ns) to fill the gap of 22 µs between LEP bunches. Times of flight of single photons are measured with an accuracy of ~10 ps and histogramed to restore the pulse shape.

INTRODUCTION

Sampling techniques are frequently used in order to measure the shape of repetitive pulses. They imply a synchronous trigger plus a variable delay and a peak sensing device which often sets the limit to the time resolution thus achievable. The best sampling oscilloscopes have a rise time of 25 ps and cannot be used for single shot measurement.

A streak camera with a display of the pulse on a memory tube, after a sudden electric deflection, makes it possible to reach a resolution of 1 ps. However, the use of a streak camera cannot always be contemplated because of its large dimensions and of its high cost. In addition, exploiting the results is difficult : it requires a second camera for analysing the image and needs a considerable time for digital evaluation.

In some cases, transient recorders may also be used, but the passband of such apparatus is at present only 6 GHz, which is insufficient for studying very brief light pulses.

An alternative procedure consists in measuring the times of occurrence of events whose probability is proportional to the pulse height. The histogram of these occurrences reproduces the pulse shape, provided the event probability is small enough for multiple event rate to be negligible. This method called here *stochastic sampling* is attractive because it consists in measuring the time of flight between a starting clock and a detected photon; and time measurements can easily be performed with TDCs or TACs to an accuracy of 10 ps. Detecting single photons with no time jitter is an art that will be described in the last paragraph. Since there are millions of photons available from synchrotron radiation at each bunch passage it is proposed to store them in a system of optical fibres which will deliver them as a periodic function. This will speed up the sampling by orders of magnitude, and eventually allow for single shot measurements. The whole process is illustrated in Fig. 1.

SAMPLING PROCEDURE

LEP electron and positron bunches are expected to have a Gaussian shape with standard deviations ranging between σ=40 ps and σ=150 ps, depending on machine conditions. The four bunches in each beam are separated by t_b=22.5 µs. In order to perform a stochastic sampling of the pulse shape, the time of flight counter is started by the detection of a single photon of the synchrotron radiation and the stop is set by a clock synchronized on the bunch passage. These photons are in perfect synchronism with the electrons from which they originate and their time distribution is identical, provided they are produced in short magnets like the mini-wigglers [1] in LEP. The first photon seen by the detector will stop the counter. Therefore if one wants to preserve the shape of the distribution, multiple events must be kept as rare as possible (this point will be quantified below). Stochastic sampling implies recording low probability events and, since a large number of points is required to build a credible histogram, the number of bunch passages must be large, say, ten thousands. Various ingredients will be described which concur to reducing this acquisition time by several orders of magnitude. Let us examine first the influence of the event probability λ.

Shape distortion due to multiple events

Let g(t) be the normalized electron distribution. A histogram constructed with the observation of the first detected photons has the shape :

$$h(t) = g(t)\,\exp[-\lambda\int_0^t g(x)dx]\,, \qquad (1)$$

where λ is the expectation value for the number of detected photons at each bunch passage. When $\lambda \ll 1$ the histogram h(t) represents very closely the bunch shape g(t). Fig. 2 shows h(t) for various values of λ=0.01, λ=0.3 and λ=1, corresponding to a Gaussian shape for g(t) with σ=1.

In this case the second moment of the distribution h(t) can be written :

$$m_2 = \frac{\int_0^{\Delta t} e^{-t^2/2} \exp[-\lambda\int_0^t e^{-x^2/2}dx]\, t^2\, dt}{\int_0^{\Delta t} e^{-t^2/2} \exp[-\lambda\int_0^t e^{-x^2/2}dx]\, dt} \qquad (2)$$

and $\sigma=\sqrt{m_2}$ was computed by numerical integration of Eq. (2). The result appears in Fig. 2 and is striking ! Although the bunch shape is violently distorted, while using a high photon counting expectation, λ=1, the standard deviation σ hardly changes. This means that a valuable measurement of σ can be achieved with $\lambda \approx 1$. (Note that the shape of h(t) measured with λ=1 could also be corrected for the distortion due to multiple events, since the exact value of λ can be traced from the event rate). The number of photons that are produced by one mini-wiggler at each bunch passage in LEP is very large, say, 10^6 per nanometer of spectral window, and it would be tempting to use more than one of them, if only the pulse could be *stretched* (repeated) over the whole time interval between two bunches.

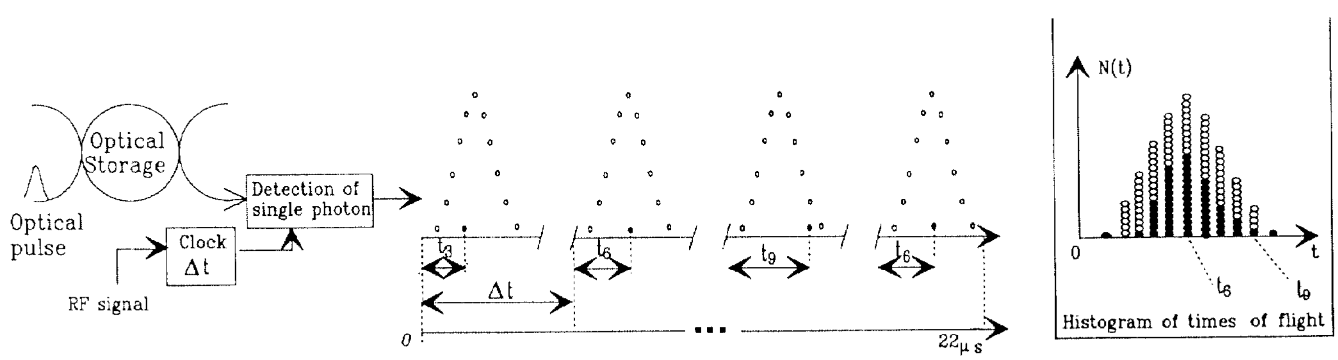

Fig. 1. Principle diagram of a single pulse storage and stochastic sampling

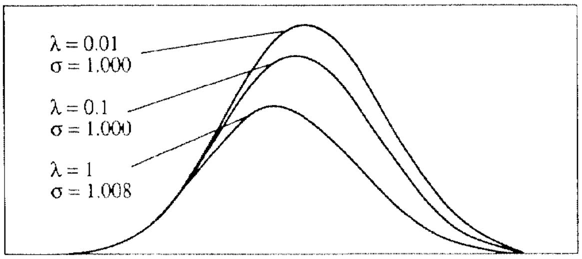

Fig. 2. Histogram h(t) obtained from g(t) in a computer simulation of stochastic sampling, with various event expectation values λ.

PHOTON STORAGE RINGS

Monomode fibres have been developed for telecommunications and are available on the market with attenuation of only 0.2 dB/km and with a dispersion at 1318 nm of about 1 ps/km/nm which is adequate to keep the bunch shape during, say, 10 μs. Couplers are commercially available with typical performances of 1% to 10% coupling, 1% loss and 98% to 90% transmission.

With the help of such couplers various schemes of storage rings can be designed where the loops are closed by using low loss connectors, as illustrated in Fig. 3. Two couplers with k=1% can be connected to form a storage ring, delivering pulses of 10^{-4} times the input level, and the decay rate would be of 4% per turn (2% coupling plus 2% loss).

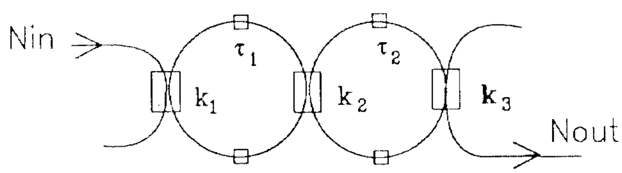

Fig. 3. Rings of monomode fibres closed with low loss connectors and linked by optical couplers made to produce a periodic function out of a single photon pulse.

Since large numbers of revolutions are concerned, we may use a continuous function of time to express the decay of the ring current:

$$f_1(t) = I_0\, e^{-\kappa t/\tau}\,, \qquad (3)$$

where κ is the fractionnal decrement per turn and τ is the revolution time of the photons, see Fig. 4.

τ must be chosen small enough for the remaining photons not to spoil the measurement of the next bunch; lets call ε this acceptable background, we have :

$$\tau = -k\, t_b / \ln \varepsilon\,. \qquad (4)$$

The duty cycle d_c of the ring is :

$$d_c = 1/t_b \int_0^{t_b} \varepsilon^{\,t/t_b}\, dt = (\varepsilon-1)/\ln \varepsilon, \qquad (5)$$

it depends only of ε and amounts to 22% for ε = 1%.

When two rings are used in series, as suggested in Fig. 3 the time distribution of output photons is more favorable. Indeed the decay of the second ring is compensated for a time by its feeding from the first ring so that the detector sees a flux f(t) given by :

$$f_2(t) = (e^{-\beta t} - e^{-\alpha t})/(\alpha-\beta)\,, \qquad (6)$$

where $\alpha = \kappa_1/\tau_1$ and $\beta = \kappa_2/\tau_2$, see Fig. 4.

This flux rises to a maximum and then decays like the radioactivity of a daughter nucleus. Consequently the duty cycle reaches a value d_c=40% for the same background (ε = 1%).

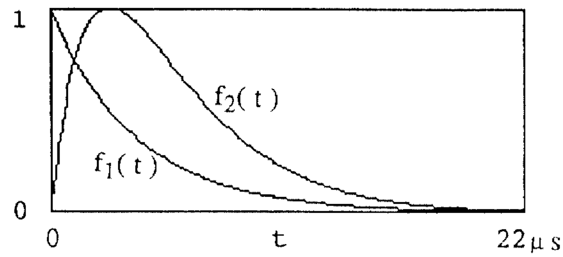

Fig. 4. Output fluxes $f_1(t)$ and $f_2(t)$ of storage systems using one and two rings of optical fibre

Systems of more than two rings have about the same duty cycle but can be useful to raise the total number of photons received by the detector.

Optimizing the number of rings

In order to get only one photon at the detector the coupling coefficient k must be adjusted to :

$$k = N_{in}^{\,-1/(n+1)}\,, \qquad (7)$$

where n is the number of rings.

But a good photon conservation implies that the coupling coefficient k should not be smaller than the losses in one ring. Hence, for some given losses, a better yield might be obtained by increasing the number of rings, which raises the value of k according to Eq. (7). This point is illustrated in Fig. 5 which shows the number of photons reaching the detector, N_{out}, obtained with 2% and 4% losses per ring, in systems of one, two or three rings. The results shown in Fig.5 state an upper bound to the number of photons that can be made available at the detector but in reality the number of counted events useful for sampling will be smaller because of the time structure that must be arranged in order to assure the proper functioning of the process and to best fit the peculiarities of the data acquisition system.

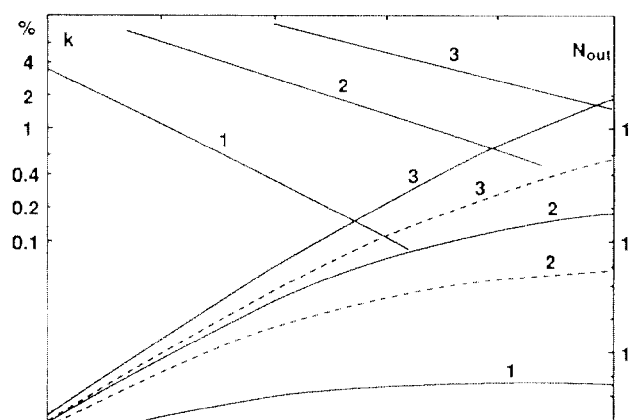

Fig. 5 Diagram showing the maximum number of single photons output, N_{out}, from systems of one, two and three rings (1 , 2 , 3) Solid lines are for 2% loss per ring, dashed lines for 4%.

Bunch structure at the detector

The aim of the photon storage is to provide the detector with as many single photons to count as possible within the sampling period t_b. Two times are characteristic of the acquisition system :

i) Δt, is the time needed to reset the photo-diode when no photon has been detected. Δt will be chosen as the natural period for the periodic function generated by the photon storage system. This can be achieved for one ring with $\tau=\Delta t$ or for two rings with $\tau_1=p\Delta t$ and $\tau_2=q\Delta t$, and p, q chosen prime numbers within themselves. As an example the resulting sequence of bunches obtained with two rings

(p=5, q=4) is shown in Fig. 6 where it is apparent that pulses are beginning to pile up as from the time $pq\Delta t$. One has to make sure that the pile up does not boost the amplitude of individual bunches beyond $\lambda=1$, which is an additional requirement to the constraint expressed by Eq. (7),

ii) t_d is the dead time of the acquisition system which will of course limit the total number of events that can be accumulated. But it is of great interest to have Δt smaller than t_d because it will increase the chances of counting photons when the probability function f(t) runs down.

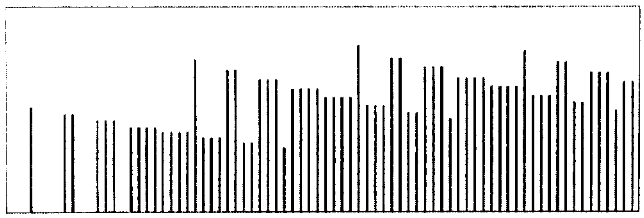

Fig. 6. Expectation values for single photon appearance at the output from a two-ring storage system with p=5, q=4.

Synchronization

A time base must be provided during the whole sampling period $t_b=22$ µs, with a stability of, say, 2 ps which is feasible with a quartz clock. It would be advantageous to choose a clock frequency equal to a multiple of the RF frequency so that the ghost photons, ε, remaining from the preceding pulse sit in phase with the pulse under scrutiny and do not create an asymmetric tail. The ring periods t_i must also be adapted to within 10^{-7} of the clock. This has been achieved in three steps : i) the fibres have been cut to an accuracy of 10^{-4}, ii) further mechanical adjustment was made by polishing the mating surfaces at the connectors and iii) the final tuning and the compensation of drift is reached with individual thermal control of the fibre rings ($\Delta T=0.1K$ corresponds to 10^{-7}).

DETECTION OF SINGLE PHOTONS

The job of the detector is to not only register the arrival of single photons, but to provide a signal which may be timed with an accuracy of several picoseconds.

A photomultiplier cannot be used because the quantum efficiency of the photocathode is very low at 1300 nm, and there is also a large intrinsic time jitter.

We have instead used a germanium device called an Avalanche Photo Diode (APD). This device has a gain caused by an avalanche process, but unlike a photomultiplier, the multiplication occurs in both directions (electron and hole multiplication), The APD was originally developed for long-haul high speed fibre-optic communications, at gains of 10-30, many orders of magnitude too low for our purposes.

However, by biasing the APD well above its breakdown voltage several nanoseconds before the photon arrives, the gain may be made infinite i.e. the resulting avalanche continues indefinitely unless *quenched* externally,[2, 3, 4].

Because the avalanche process is two-way, and the germanium band-gap is small, the APD is inherently more noisy than a photomultiplier and cannot be used for single photon detection at room temperature. For this reason the APD is cooled to -200° C by immersion in liquid nitrogen. When biased correctly the APD gives a very large signal (200-500 mV), but there is also a large "feed-through" spike from each edge of the bias pulse, because of the 2 pF diode capacitance and the rapid rise and fall times of the bias pulse (500 ps). This feed-through can be cancelled to produce a clean signal.

The length of the avalanche pulse is measured, giving the arrival time of the photon relative to a fixed reference i.e. the falling edge of the bias pulse. The time to amplitude converter is very stable and has an integration rate of 1 V/ns. In conjunction with the pulse height analyser module Lecroy 3001, which has a 1V input full scale and 10 bit conversion, we arrive at a 1 ns full scale with 1 ps resolution. The Time to Digital conversion process has been measured to have a short term jitter of only several picoseconds.

Much experimental work has been done on the APD, as literature on using the diode in single photon mode for timing purposes is not readily available. Running the APD at low repetition rates, it has been found to have the following characteristics :

i) Avalanche probability of 0.5 for each photo-electron,
ii) Noise background count of several percent (this is spontaneous thermal breakdown of the diode; even at -200° C!)
iii) Inherent time jitter of 20-30 ps FWHM caused by the noisiness of the avalanche. However this will increase the apparent size of a 100 ps FWHM synchrotron light pulse by only 5 ps.

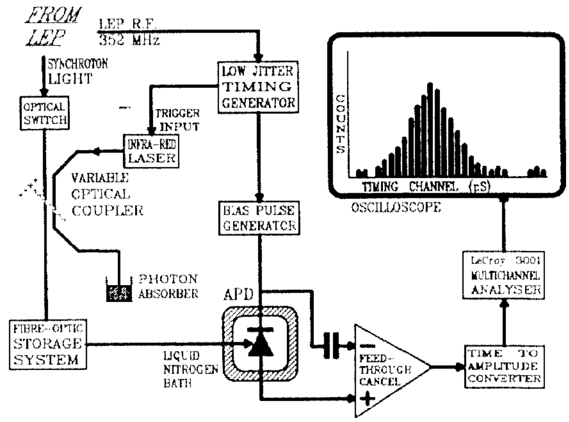

Fig. 7. Schematic of the measuring setup

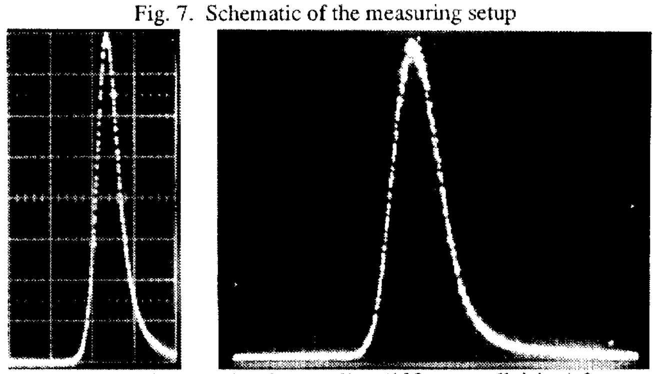

Fig. 8. Result of stochastic sampling (100 ps per division) for : a) a short laser test pulse, b) positron bunches of LEP

RESULTS AND PERSPECTIVES

Synchrotron light photons from LEP bunches have been focussed into a monomode fibre and used for stochastic sampling of the bunch length (Fig. 8) thus demonstrating the quality of the detector and the proper functioning of the process. Systems of photon storage have been assembled with two and three rings, with total losses ranging between 2% and 4% per ring. Their synchronization to within 10^{-7} is assured and the effect of dispersion after 10 µs has been measured and found negligible for LEP, when using an adequate spectral filter. A fast pulsing ($\Delta t=12$ ns) of the detection diode is being implemented and should be tested this summer to allow single shot measurements. More work remains to be done, running at higher repetition rates, perhaps with an inherently faster APD such as the gallium-arsenide devices which are beginning to appear.

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