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CERN SL/94-79 (BI) /

REAL TIME SINGLE SHOT THREE-DIMENSIONAL MEASUREMENT
OF PICOSECOND PHOTON BUNCHES

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Paper presented at the Beam Instrumentation Workshop,
Vancouver, Canada, 02.10.94 - 06.10.94

Geneva, Switzerland
September, 1994

REAL TIME SINGLE SHOT THREE-DIMENSIONAL MEASUREMENT OF PICOSECOND PHOTON BUNCHES

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Abstract

A new method using a streak camera to monitor the particle density distribution in three dimensions in space was developed for the LEP (Large European Electrons Positrons collider). This paper provides a basic overview of the experiment. The synchrotron radiation emitted by the particles creates the image of the density distribution of particles in the bunches. The optical set-up allows us to see the front view or the top and side view of the photon bunch simultaneously at successive turns. The practical limits of our set up are discussed and some examples of bunch oscillations in three dimensions are given.

INTRODUCTION

Small dipole magnets produce synchrotron radiation to monitor the shape of both LEP beams [1] [2]. The density distribution in space of the emitted photon bunches is proportional to the density of the particles in the e^+ and e^- bunches. The light is collected by two beryllium mirrors in the vacuum tube. Two achromatic lenses create the image of the source on the double sweep streak camera in an underground optical laboratory [3]. The optical set-up allows observation of the side view and the top view of both photon bunches simultaneously, and up to 50 single successive bunch passages can be recorded on one image. The front view of the photon bunches can also be displayed. The system gives the image of instabilities in all three dimensions and extracts the bunch length and transverse dimensions [4] of the photon bunches. But due to the synchrotron radiation they are also images of the e^+ and e^- bunches.

STREAK CAMERA

A double sweep streak camera built by A.R.P. [5] with CERN specifications, has been used at LEP for five years with increasing sophistication. A brief description of this instrument follows.

a) Focus

Photons hit the photocathode of the vacuum tube where electrons are emitted and accelerated, and the internal electrical focusing field gives the image of the input photocathode onto a phosphor screen.

Figure 1: Set-up diagram of the double sweep streak camera.

b)Fast sweep

After acceleration the electrons emitted by the photocathode are quickly deflected by an electric field as they pass between two horizontal plates. This causes the bunch of electrons to rotate in space and strike the phosphor screen leaving an image of its length, as if we were observing it from above.

It is very important to note that we never diaphragm the incoming photon bunches with a slit as in usual streak camera set-up. Thus the image on the screen is the density projection of the three dimensional bunch and two dimensions are preserved (the longitudinal and one of the transverse). The trigger of the fast sweep is very precisely synchronized with the RF (Radio frequency) signal.

c)Double sweep

A second pair of plates, perpendicular to the first, allows successive streaks to be staggered. The composite image on the phosphor screen is recorded by a CCD camera and digitized before being processed by a computer. The software displays the bunch projected density with colours and the frame is rotated by 90° so that the streaks (time scale direction) always appear horizontal.

With the readout system provided by the firm A.R.P., the streak camera can be left running at a rate of 10 to 25Hz. The data analysis is done locally with an IBM PC which creates and refreshes a colour displays in RGB standard. These images have been transmitted to the LEP control room by means of a commercial TV set, in PAL standard which degrades the resolution significantly. All pictures can be recorded in digital form and kept on file for off-line analysis.

A new digitizing system made by the firm DATACUBE in VME standard has been implemented by CERN. The system allows a fast remote control and easy transmission of the data. It works in parallel with the local A.R.P. set-up. DATACUBE images are transmitted to the main control room via dedicated high resolution RGB fibre optics channels.

OPTICAL SET UP

The synoptic of the equipment is shown in figure 2.

Figure 2: The Optical set-up provides side and top view at the same time.

The convention for the axes is defined in this figure 2: X, Y, S are respectively horizontal, vertical and longitudinal axes of the bunches in the machine. The synchrotron radiation of the e^+ and e^- bunches arrives slightly separated in time (≈ 500 ps). An automatic attenuation system consisting of motorized, continuously varying, neutral density filters and a photomultiplier keeps the intensity of the light constant. A semi-transparent mirror divides the light, and a dove prism rotates one photon-beam by 90° about the longitudinal axis. The achromatic lenses create the image of the light source, (e^+ or e^- bunch in the dipole magnet) on the surface of the photocathode. Hence the streak camera displays both top and side view which are the density projection of the beam in the horizontal and vertical plane respectively. The side- and top-view of both beams can be shown simultaneously in one streak of the camera. So one single streak gives the following views (figure 3)

The software is tracking the bunches in real time and extracts the length, transverse dimensions and the center of gravity of each photons-bunch.

Figure 3: Example of image obtained in single streak for one passage of one bunch of positrons and one bunch of electrons.

RESOLUTION LIMITS OF THE ENTIRE SYSTEM

The limits of resolution, at the input photocathode plane, for the streak camera and the digitizing system are listed below:

Maximum sensitivity = 1 photon/count per pixel	
Light intensity digitized by 8 bits A.D.C.	
X (transverse)	< 15 μm
Y (transverse)	< 15 μm
S (length)	< 0.8 mm
Jitter (fast sweep)	< 2 ps (< 0.6 mm)

The transversal spatial resolution limit has been obtained by measuring the smallest possible spot size. A picosecond laser pulse measured with the S.C. has shown [3] a F.W.H.M. of 6 ps which corresponds to $\sigma = 0.8$ mm. Which means that the resolution of the S.C. itself is better than this. We have measured the trigger jitter, with a laser diode pulse of $\sigma = 12$ ps, by taking the standard deviation of the center of gravity on the S.C. The 2 ps measured hence also include the jitter of the laser diode.

INFLUENCE OF THE TRANSVERSE SPOT SIZE ON MEASURED LENGTH

The streak camera in this application is used, contrary to other applications, without a slit in front of the photocathode in order to get a complete image of bunch size with instabilities in all dimensions. Thus there is a finite spot size in the direction of the fast sweep which broadens the measured bunch length. For a Gaussian distribution, with a transverse dimension σ_x of the light spot on the phosphor screen of the streak camera, the broadening of the measured bunch length σ_{meas} is expected to be:

$$\sigma_{\text{meas}} = \sqrt{\sigma_{\ell}^2 + \sigma_x^2} \quad (1)$$

σ_{meas} is the length measured on the phosphor, and σ_x the finite spot size there. Hence the correction to achieve from the measured σ_{meas} the real σ_l is

$$\sigma_l = \sqrt{\sigma_{\text{meas}}^2 - \sigma_x^2} \quad (2)$$

Figure 4: Influence of spot size on measured length.

To verify this effect, the light pulse of a laser diode was projected by a lens onto the S.C. The light was strongly attenuated to have no intensity effects as described later. The position of the lens was varied to achieve different spot sizes on the photocathode. The gain on the micro-channel-plate of the S.C. was adjusted to have a good signal/noise ratio. The spot size was measured in focus of the S.C. Then the fast sweep was set to the maximum streak speed and the length of the pulse was measured. Figure 4 shows the result obtained.

This proves that the correction according to equation 2 is valid for a wide range of spot sizes σ_x . Even when the spot dimension on the phosphor becomes comparable to the dimension of the longitudinal bunch profile the correction still yields the correct result.

INFLUENCE OF LIGHT INTENSITY IN A SINGLE SHOT MEASUREMENT

It is known that the measured pulse length increases with higher intensity of the incident light pulse especially for short pulses [7]. The influence of total intensity is plotted in figure 5.

Figure 5: Influence of light intensity on measured length

The horizontal scale is 1 femtojoule per unit. The measurements taken in our set up [8] [10] of the influence of the total light intensity lead to the following conclusion:

- 1) When the light level is very low, on average smaller than 1 photon per pixel, then the noise starts to contribute to the tails of the distribution and the measured sigma increases by more than 5%.
- 2) When the photon flux reaches 30 femtojoules per pulse then the measured values increase by 5%.

Since the pixel's signals are digitized by 8 bits ADC, the useful range is large enough for LEP beam diagnostics, where we have one automatic level controller to keep the light at the right value for a continuous and safe operation 24h per day. So the dynamic range in this application does not impose any limits for maximum intensity.

SUMMARY OF THE MAIN PERFORMANCES

Three views of the density projection of single bunches are available:

- *front view (focus mode)*: plane x, y respectively horizontal and vertical dimensions,
- *side view*: y, s respectively vertical and longitudinal dimensions
- *top view*: x, s respectively horizontal and longitudinal dimensions.

Thus the three dimensions of the photons-bunches can be extracted in real time.

The presented way of correcting the measured bunch length for the spot size allows us to very precisely determine the bunch length in real time, without losing the possibility of observing all kinds of instabilities in the bunches of LEP [9] [11].

Nevertheless in some particular cases, it is also possible to cut the photon bunches into slices [4] and display the density distribution in each slice, at each bunch passage as in a real time tomography.

This is a non-intercepting detector which could be used continuously to monitor the behaviour of the bunches 24 h per day.

EXAMPLE OF RESULTS OBTAINED IN THE LEP MACHINE

The next figures gives some typical results obtained with our equipment for the same bunch on successive turns. The first turn is recorded always at the top of the screen and the last at the bottom. Figure 6 shows an example of six successive bunch passages of stable beams at 45 GeV.

Figure 7 displays a dipolar oscillation for both beams, electrons and positrons. Then figure 8 shows a quadrupolar oscillation and figure 9 gives a clear head to tail effect. Finally, figure 10 demonstrates a very complicated evolution of a bunch from turn to turn. The side view shows a head to tail oscillation in the vertical plane, but there is also a longitudinal oscillation of the center of gravity superposed to the elongation clearly displayed by the top view (horizontal plane).

Figure 6: Stable beam at 45 GeV, with a plot of each longitudinal profile of the views selected by the rectangle.

Figure 7: Longitudinal oscillations of beam of positrons and of electrons when the longitudinal feedback is off.

Figure 8: Quadrupolar oscillations.

Figure 9: Head-to-tail in vertical plane oscillations

Figure 10: Simultaneous observation of the top view(left) and side view (right) of the same bunch on successive turns. This demonstrates a mixture of instabilities: elongation, oscillation and head to tail effects simultaneously.

NEW DEVELOPMENT

Remote control

A complete remote control system is being implemented. All the parameters of the experiment will be controlled from the main control room, 2 km away from the underground optic-laboratory.

Summary of the main parameters to be controlled:

- a) Light source:* The current in the small dipole magnet controls the direction and the intensity of the emitted light, but also a slight tuning of the angle of the beam in the vacuum chamber is useful.
- b) Optic channel:* All mirrors and achromatic lenses in the tunnel are motorized.
- c) Parameters of the streak camera:* All parameters of the streak camera must be remote controlled by the use of small stepping motors.
- d) Parameters of the timing:* The fine synchronization of the images on the CCD with the LEP turn clock and with the master RF source is done remotely.

Thus the bunch selection, number of turns, and bucket number could be done from the main control room. Moreover, a picosecond timing allows to continuously follow the phase change between the RF and the particle bunches. Although with the new bunch train project the time between bunches will be reduced, it will be possible to analyse each bunch in the train [12] separately.

Image processing.

A new software developed at CERN provides easy parameter control but also gives a very fast image analysis from the DATACUBE digitizer with automatic bunch tracking and calculation of all the dimensions of the bunches e^+ and e^- . Figure 11 shows a copy of the high resolution screen image obtained from the DATACUBE board. All the profiles, and the history of the dimensions, are displayed on the same screen and sent to the main control room via RGB transmission.

History of the dimensions

Figure 11: Display presentation in main control room.

ACKNOWLEDGEMENTS

The development on bunch diagnostics for the LEP machine could not have been done without the generous help of a number of people. Special thanks are due to C. Bovet for his permanent support, F. Tecker and K. Hanke for their very efficient work with the streak-camera, N. Adams, L. Disdier and F. Madeline for their contribution during their stay at CERN, all colleagues from BI and AP groups, F. Tomasini and J-M. Roth from the firm A.R.P.

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