MEASUREMENT OF BUNCH-LENGTH BY A MODE-LOCKED LASER WITH A TIME RESOLUTION OF 10 PICOSECONDS

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Abstract

In accelerators working at accelerating frequencies of several 100 MHz the bunch length is in the order of several hundred picoseconds. For obtaining good measurements the time resolution of the measuring apparatus should be 10 ps. With convenient electronic components such a high time resolution cannot be obtained. In this paper a method is described for measuring the bunch length optically by measuring the time structure of the light emitted by relativistic particles (synchrotron or Cerenkov radiation). The heart of the system is a wideband Nd^{3+}-Glass Laser emitting infrared light at 1.06 μm. With a special technique, the so-called mode-locking, the laser is forced to emit high-intensity optical pulses of several GW peak power and a pulse-length of about 5 ps. These pulses enter a cell filled with a Kerr medium, e.g. CS_2, and induce birefringence. Since the relaxation time of CS_2 is small, the birefringent zone travels with c/n through the Kerr medium. Combinated with two polarizers the system works like a camera with a slit-shutter traveling at the velocity of light. By photographing a total time resolution of 10 ps is obtained.

Introduction

Up to this time several attempts have been made to detect the bunch structure. Three different kinds of detection apparatus were developed:

a) Destructive coaxial pick-ups. This system is used especially in linac's and proton synchrotrons, where no synchrotron light exists. The beam is stopped on the center conductor of a cable and the signal is transmitted to the detection apparatus.[1]

b) Nondestructive electromagnetic pick-up. The bunch is detected by the electromagnetic fields surrounding the beam. Such a system is limited by the bandwidth of the pick-up system. The frequency limit is in the order of several GHz.[2]

c) Detection of the timestructure of the synchrotron light.[3] This system is similar to the destructive detection apparatus of point a). The front end of the coaxial cable is a vacuum-photodiode. Since fast vacuum photodiodes are very insensitive, the high energy part of the synchrotron light must be used. All systems have the disadvantage that the signal must be transported in a cable, and such cables again distort the signal. The signal is detected by a scope. The fastest commercial scopes have in real-time display an upper limit of a few GHz, so that the minimum rise-time is more than 100 ps.

In order to increase the bandwidth of the detection system, the synchrotron light itself and not an electrical signal must be sent to the detector. Using conventional optical components, only the weak visible fraction of the synchrotron light can be used. This white light cannot be detected by a photodiode or a photomultiplier, since both are limited again to rise-time of several 100 ps. In the following an unconventional detection apparatus is described having a time resolution of about 10 ps. (3 db bandwidth: 35 GHz).

Principle of detection apparatus

For measuring the time structure of the bunch a combination of a Kerr-cell and a mode-locked laser has been used.[4] The laser described in this paper is a Nd-doped glass laser with a centre frequency of 1.06 μm (near infrared).

Since the effect of stimulated emission is a resonant effect, the different wavelengths of a free running laser oscillate independent from each other. At the output of a freerunning laser one has a random amplitude distribution due to random phase distribution. A periodic pulse train is obtained by introducing a liquid with a nonlinear absorption coefficient into the resonator: Low intensities are more absorbed than higher intensities. After several turns only one pulse exists inside the laser with a pulse length of 5 to 10 ps as given by the bandwidth of the laser transition.

The pulse repetition time is:

$$t_{rep} = 2L/c$$

L ... optical length of the resonator

In these small pulses the whole power of the laser is concentrated: Pulse powers up to 1 GW are achieved. The pulse train consists typically of about 100 pulses. In fig. 1 such a pulse train detected by a vacuum-photodiode is shown.

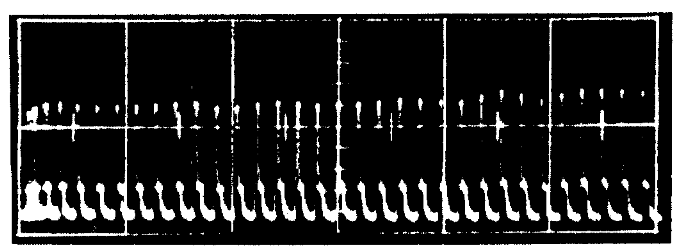

Fig. 1: Pulse train emitted by a mode-locked laser, 20ns/div

The laser beam is linearly polarized by using only Brewster angles for the transitions between air and glass.

When this linearly polarized high power pulse train enters a cell filled with Kerr liquid, the electric field induces birefringence along its path. Duguay and Hansen demonstrated that this so-called optical Kerr effect in CS_2 has a relaxation time of about 2 ps.[5] The birefringent zone produced by the laser pulse travels along with it through the CS_2 at a velocity of c/n (n = refractive index), and several picoseconds after the laser pulse the birefringent zone vanishes.

The equipment for testing the time resolution of the apparatus is shown in fig. 2.

Outside the resonator part of the infrared light is converted into green light by a KDP-crystal (second harmonic). The KDP is slightly mismatched, so that the conversion efficiency is less than 1 %. After conversion, the IR pulse and the green pulse are separated by means of their different polarization given by the phase-matching condition. IR and green beams are delayed relative to each other by 3 prisms and can thus reach the Kerr cell at different times. The green beam is expanded to a width of 4 cm by an inverse telescope. The IR beam is focused by a lens into a focus near the end of the cell. With this lens a stable birefringence zone along the whole cell was produced. (f = 200 mm, beam cross section = 1 mm^2.) With this setup not the pulse itself but the intensity cross-correlation-function of the pulse can be measured. The coordinate system is explained in fig.2. Assuming that the intensity of the pulse to be measured can be described by

$$f(x)g(y-\nu t),$$

and the transmission of the birefringent zone by

$$f_1(y)g_1(x-\nu t),$$

the local distribution measured by the camera is:

$$\iint_{-\infty}^{+\infty} f(x)g(y-\nu t)f_1(y)g_1(x-\nu t)\,dy\,dt.$$

The functions

$g(y-\nu t)$ and $g_1(x-\nu t)$

are related by nonlinear processes: second harmonic generation and Kerr effect.

In fig.3 a glass plate was introduced perpendicular to the green beam, so that the green pulse is accompanied by weak pulses due to multiple reflections. The "ghost pulses" are about 25 ps apart in good agreement with the pulse distance estimated by the thickness of the glass.

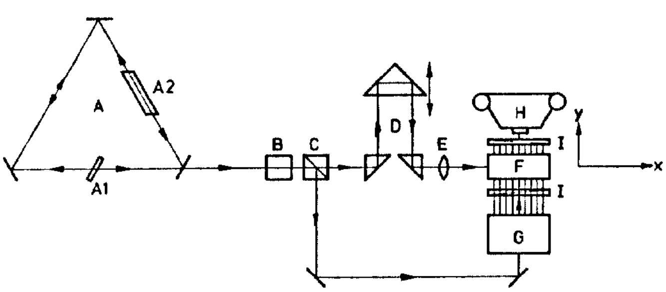

Fig.2 Experimental set-up. A laser resonator, A1 saturable dye, A2 laser rod, B KDP-crystal, C beam split for dividing green and IR-pulses, D delay, E focusing lens, F Kerr cell filled with CS_2, G beam expander, H camera, I crossed polarizers.

In fig.4 the intensity along one measured pulse is shown. Defining the time resolution to be given by the 1/e points, a resolution time of about 10 ps is achieved. Using several pictures, a mean resolution time of 10 ± 2 ps is measured.

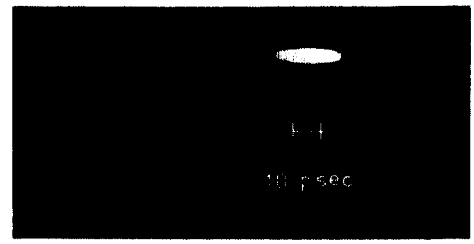

Fig.3: Photograph taken of a pulse accompanied by weak "ghost pulses" due to multiple reflection.

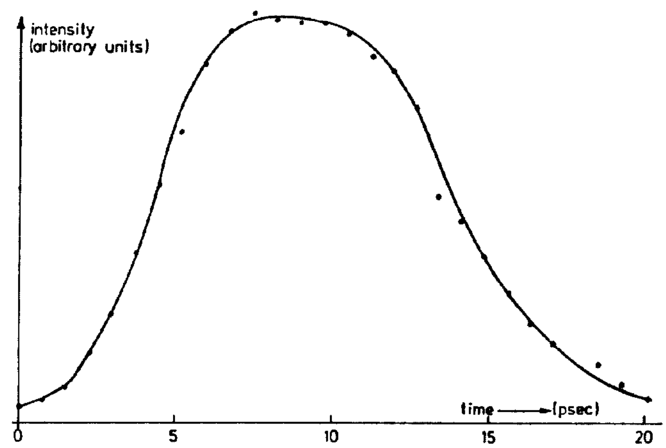

Fig.4: Intensity versus time of a measured pulse.

Measurements at the DESY synchrotron

With such an equipment two methods can be used for measuring the bunch length in the synchrotron:
a) With a single laser-pulse selected from the pulse train the time structure of a single synchrotron light pulse can be detected. The light pulse to be measured is widened along the path of the laser pulse in the Kerr-cell. So the light arriving at the Kerr-cell at a certain time can only pass it at the point where the laser pulse is. The time structure is converted into a local structure which can be photographed.

b) With the periodic train of identical laser pulses, having a repetition frequency slightly different from the repetition frequency of the pulse-train to be measured, the synchrotron light pulses can be detected by a sampling technique.

We have used the second method because the technical equipment installed thus far is not capable of selecting one laser-pulse from the pulse train.

In fig.5 the measuring system is sketched. The visible portion of the synchrotron radiation is separated from the high energy photons by two mirrors. The beam of visible light is compressed by a telescope system and enters the Kerr-cell via first polarizer. A part of the synchrotron light is splitted and detected by photomultiplier 3.

A pulse-train of about 100 laser-pulses is generated in the triangular-type laser resonator. The distance between two laser pulses is 94.535 ± 0.02 cm. The laser beam is focused into the interaction region of the two light-beams. Photomultiplier 1 gives a signal when a laser pulse has passed the Kerr-cell and triggers both oscilloscopes and a ramp generator. Both the signals from PM2 and the ramp generator are added and can be seen on the oscilloscope. The addition of the ramp signal to the signal has the following advantage: when the laser emits more than one pulse-train the signals detected by PM2 can be seen at different vertical positions on the scope.

A typical photograph is shown in figs. 6 and 7. The time scale is 20 nsec/division in fig. 6 and 50 nsec/division in fig. 7. The distortion of the picture of fig. 3 is caused by an image converter tube which amplifies the picture of the oscilloscope screen. Without any knowledge of the light to be measured one can say by looking at the photographs that the measured light is not emitted continuously. With a continuously radiating light source no peaks could be measured, for the rise-time of photomultiplier and scope is nearly equal to the pulse-repetition time of the laser pulse: a continuous envelope of the beam transmitted through the Kerr-cell would be seen. The peaks in the pictures say that the light to be measured has a very pronounced time-structure: after a laser pulse has coincided with a synchrotron-pulse the following pulses see no light. The coincidence of laser pulse and synchrotron light occurs at defined distances: the light to be measured has a repetitive time-structure.

The beam current at both shots was 8 mA. The energy of the beam was not observed and is therefore unknown.

The bunch-to-bunch distance is expected to be 59.99879 cm, due to the frequency of 499,666 MHz. The distance of the laser pulses was 94.535 ± 0.02 cm. With these two pulse distances the real bunch-length can be calculated. In fig. 8 the bunch is drawn in real-time; the halfwidth is 6.7 ± 0.6 cm.

In fig. 7 the peaks can be explained in a similar way. The high peak at the right end has a distance of 3.52 cm from the assumed bunch-centre, but the peak produced by this bunch is higher than the other peaks. That may be due to this bunch transports more electrons than the bunches before it. But it is also possible that all bunches oscillate in a complicated oscillation mode.

Especially in the last example the disadvantage of the sampling system can be seen. The sampling method works well only when all bunches are equally filled, when they have equal length and when they do not oscillate. Therefore a single-bunch measuring device working similar to a stop motion camera will be installed in a few months.

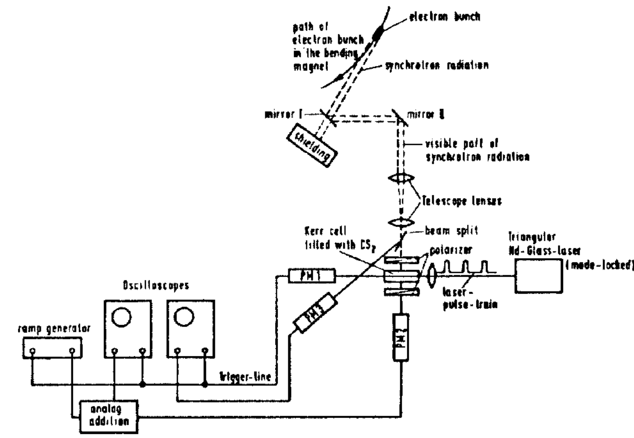

Fig.5: Experimental setup

Fig.6: Oscilloscope-trace of a sampled bunch. Time 20 nsec/div.

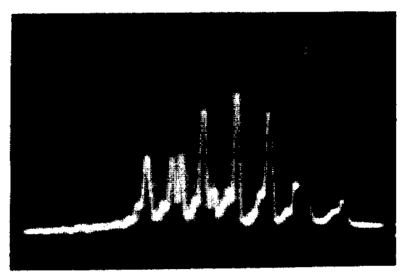

Fig.7: Oscilloscope-trace of a sampled bunch. Time 50 nsec/div. The scope picture was photographed by means of an image converter tube.

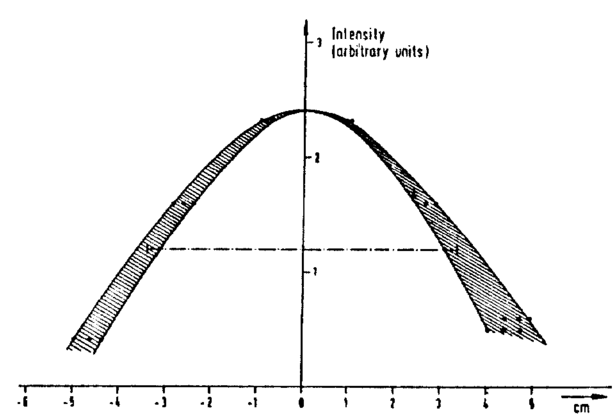

Fig.8: Translation of the scope-trace Fig.6 into real-time

References

1) Evans L.R. and Warner D.J.: Real Time Measurements of Proton Bunch Form, CERN/MPS/LIN 72-6

2) Norris N.J. and Hanst R.K.: Picosecond Beam Monitors and Data Acquisition System, IEEE Trans. on NS 16 (1969) 927

3) Sabersky A.P.: Fast Beam Monitor using Synchrotron Light, SLAC-PUB-874, March 1971

4) Fischer R.and Rossmanith R.: A Kerr Camera with Ten Picoseconds Time Resolution, Optics Communication, 5 (1972) 53

5) Duguay M.A. and Hansen J.W.: Optics Communication, 1 (1971) 399